Gaseous radiation detectors

The case of Thin Gap Chambers and Thick Gaseous Electron Multipliers

> New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained
>
> Freeman Dyson

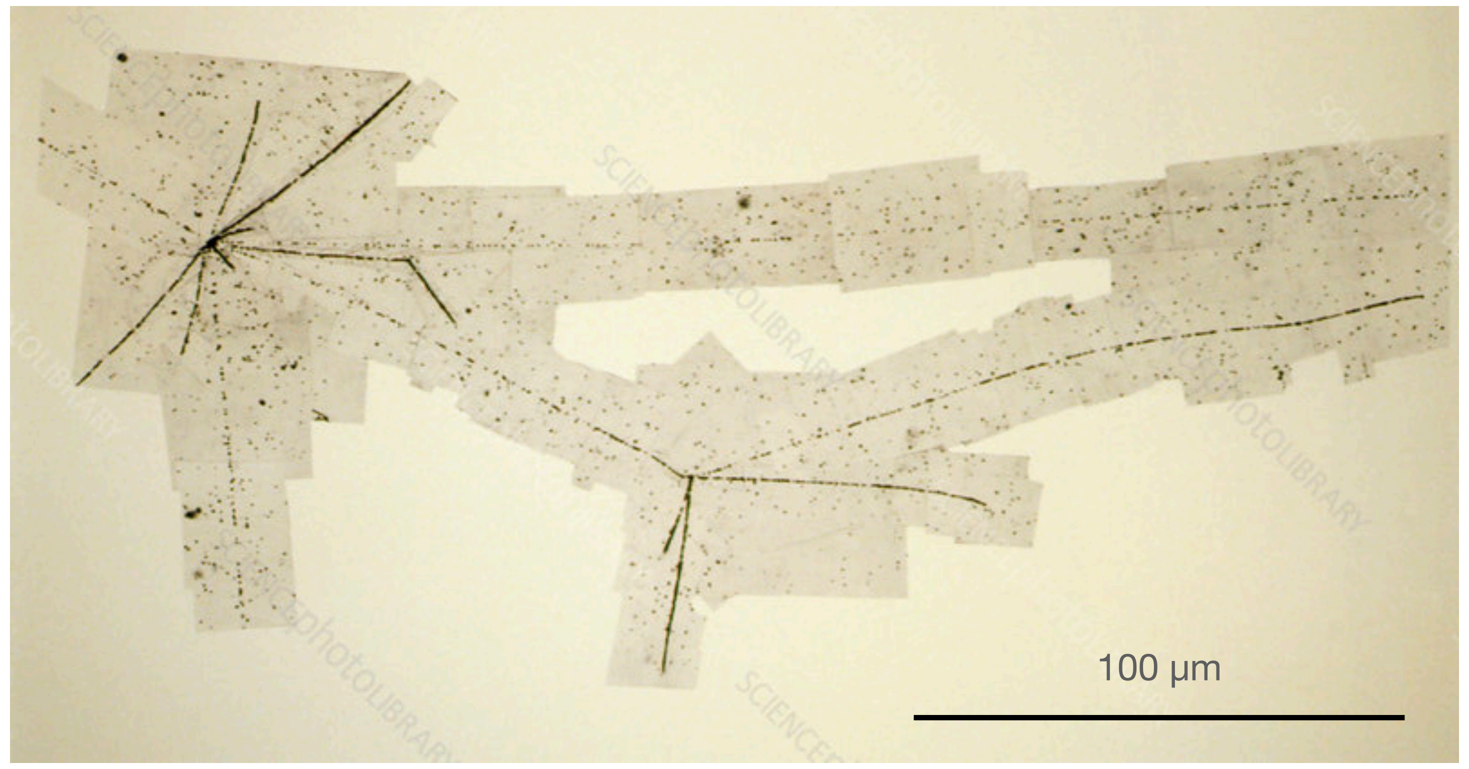
Luca Moleri - KMI seminar at Nagoya University - 20/02/24

Radiation detectors

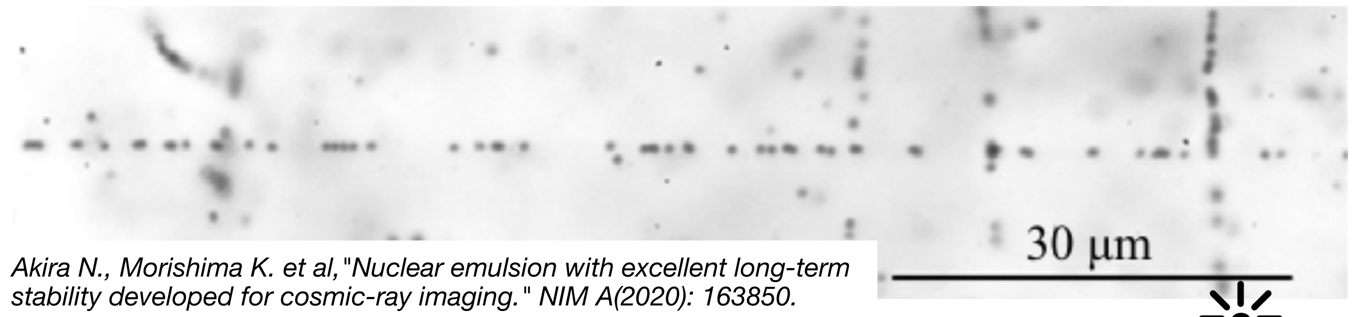
Electrometer
Discovery of cosmic rays (~1900)

photographic imaging
(emulsions, cloud chambers, bubble chambers)

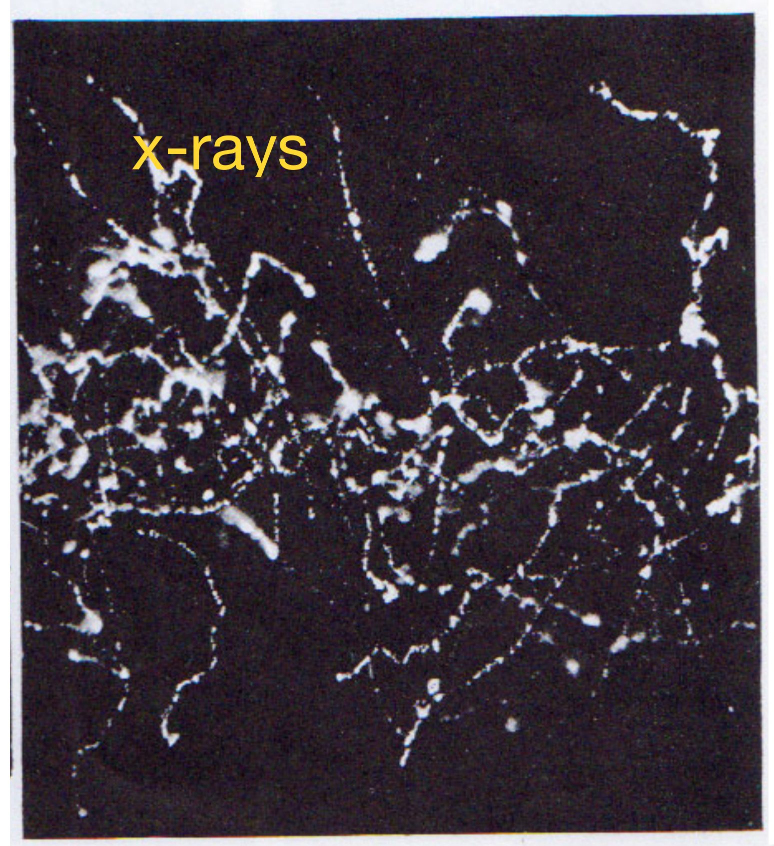
Discovery of the pion (1947)



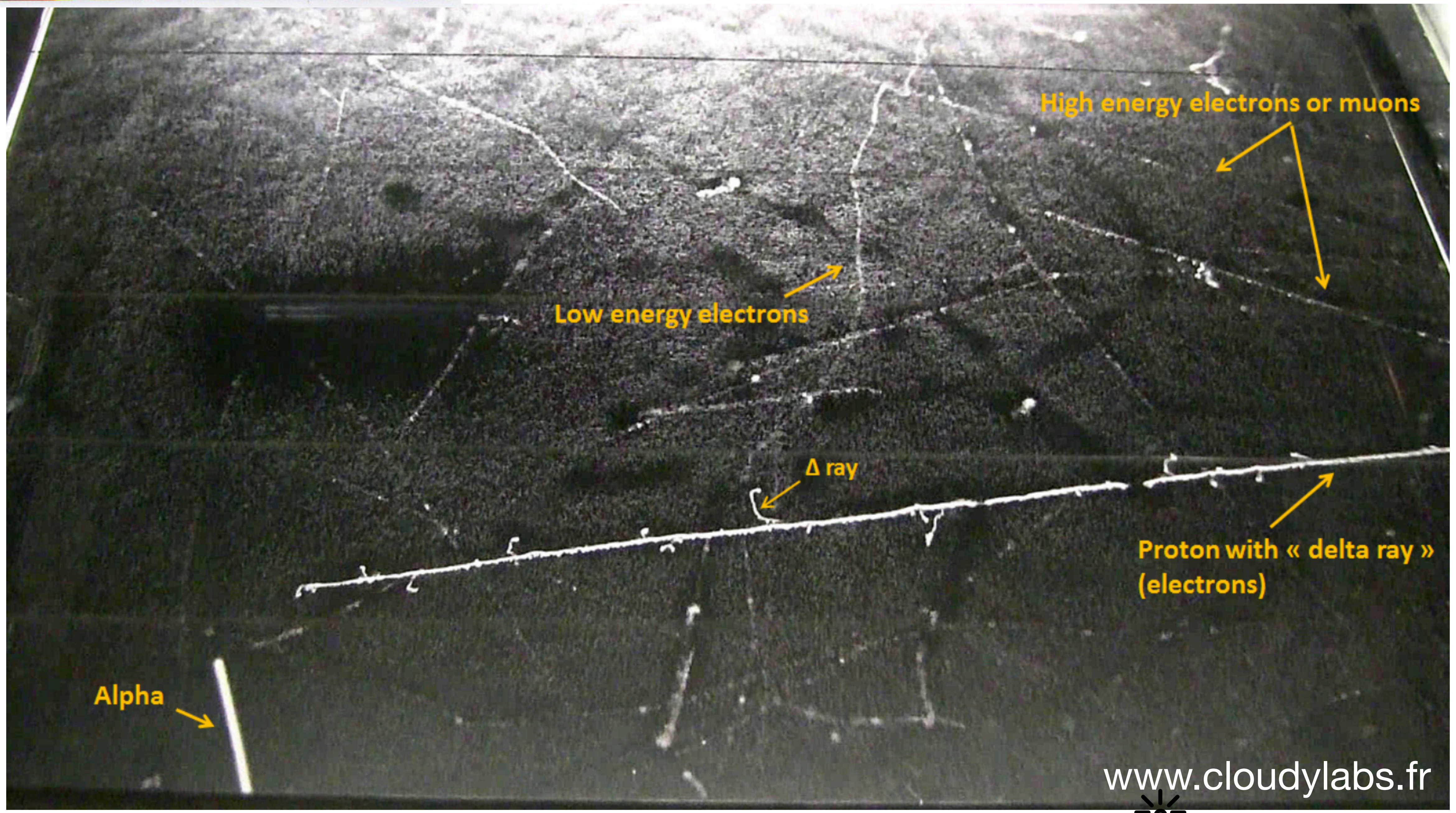
Modern photographic emulsions



Akira N., Morishima K. et al,"Nuclear emulsion with excellent long-term stability developed for cosmic-ray imaging." NIM A(2020): 163850.



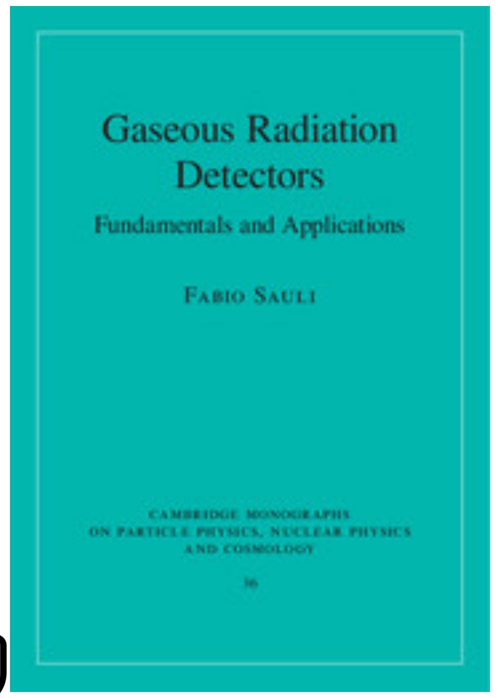
C.T.R.Wilson (1912).
"On an Expansion Apparatus for making Visible the Tracks of Ionising Particles in Gases and Results obtained by its Use"



The **discovery of fundamental particles and forces** is tightly bound to the development of **radiation detectors**

- **Fundamental principle of detection:**
  1. Energy deposition in a medium (solid, liquid or gas)
  2. Imaging the energy deposition
     - Optical readout
     - Electronic readout
     - Electronic+optical readout

Gaseous detectors allow optical or electronic imaging over a large area.

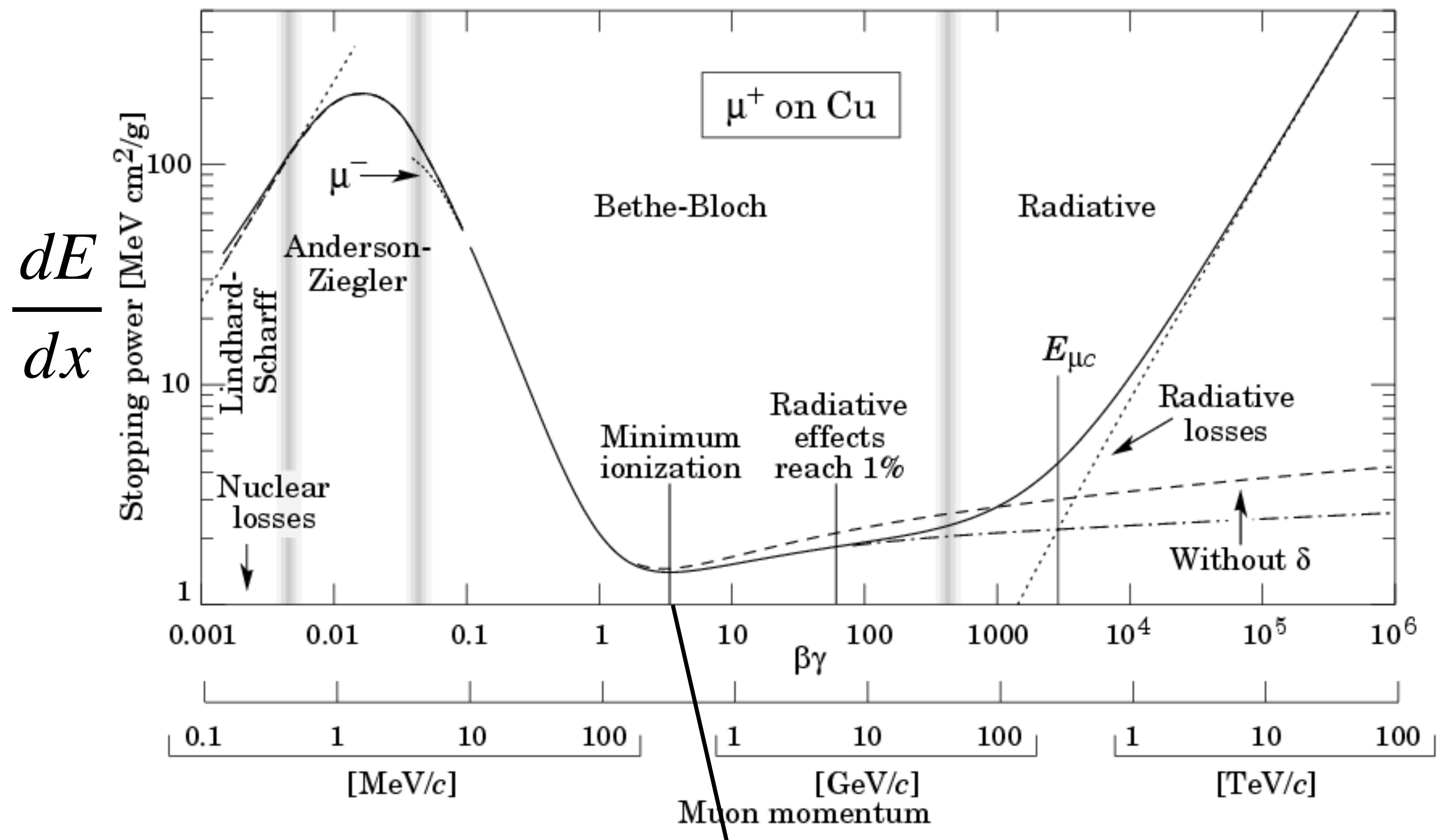


Primary energy deposition
(common to all detectors)

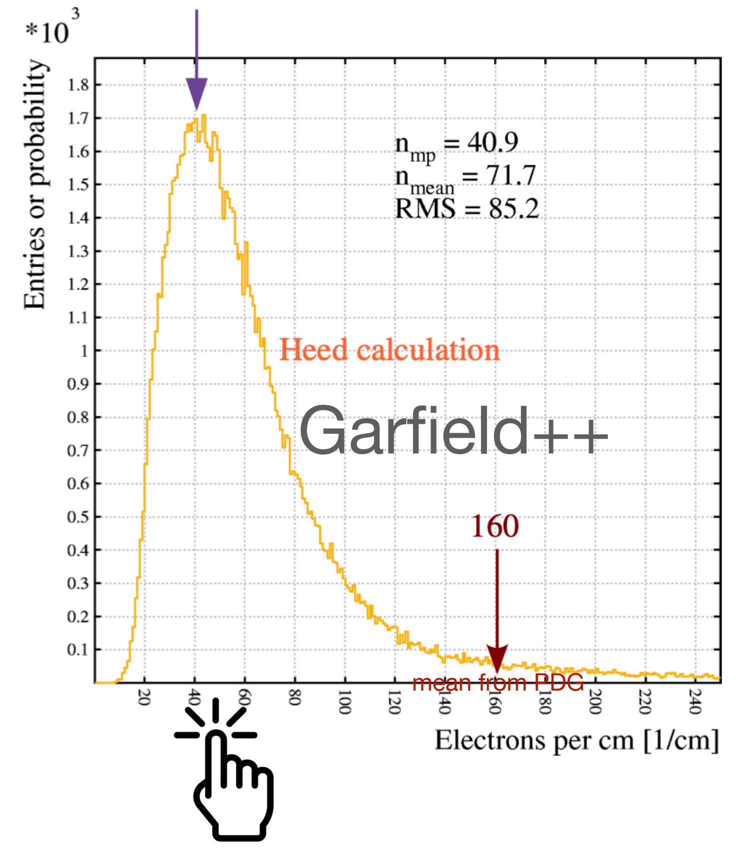
Radiation transfers energy typically by ionization
(but it could be also excitation → photons, phonons, …)

Primary ionization signatures depend on the kind of interaction:

- Coulomb (all charged particles) → particle dependent $\frac{dE}{dx}$
- Elastic nuclear recoil (e.g. fast neutrons, dark matter) → Coulomb
- Photoelectric (e.g. x-rays, γ-rays, UV photons) → Coulomb
- Nuclear excitation/reaction (e.g. slow neutrons, relativistic hadrons) → Coulomb
- Compton scattering, Auger effect, EM shower, … → Coulomb



Most probable number of e-i pairs produced by a MIP (e.g. cosmic μ) in 1cm Ar is ~40



- N of primary electron-ion pairs produced is a complex process involving all the atomic shells → statistical fluctuations
- For gaseous detectors the primary charge is small in most cases
  - **Charge multiplication** is required to have signal above noise
  - Electrodes are used to create an electric field for signal induction and charge multiplication

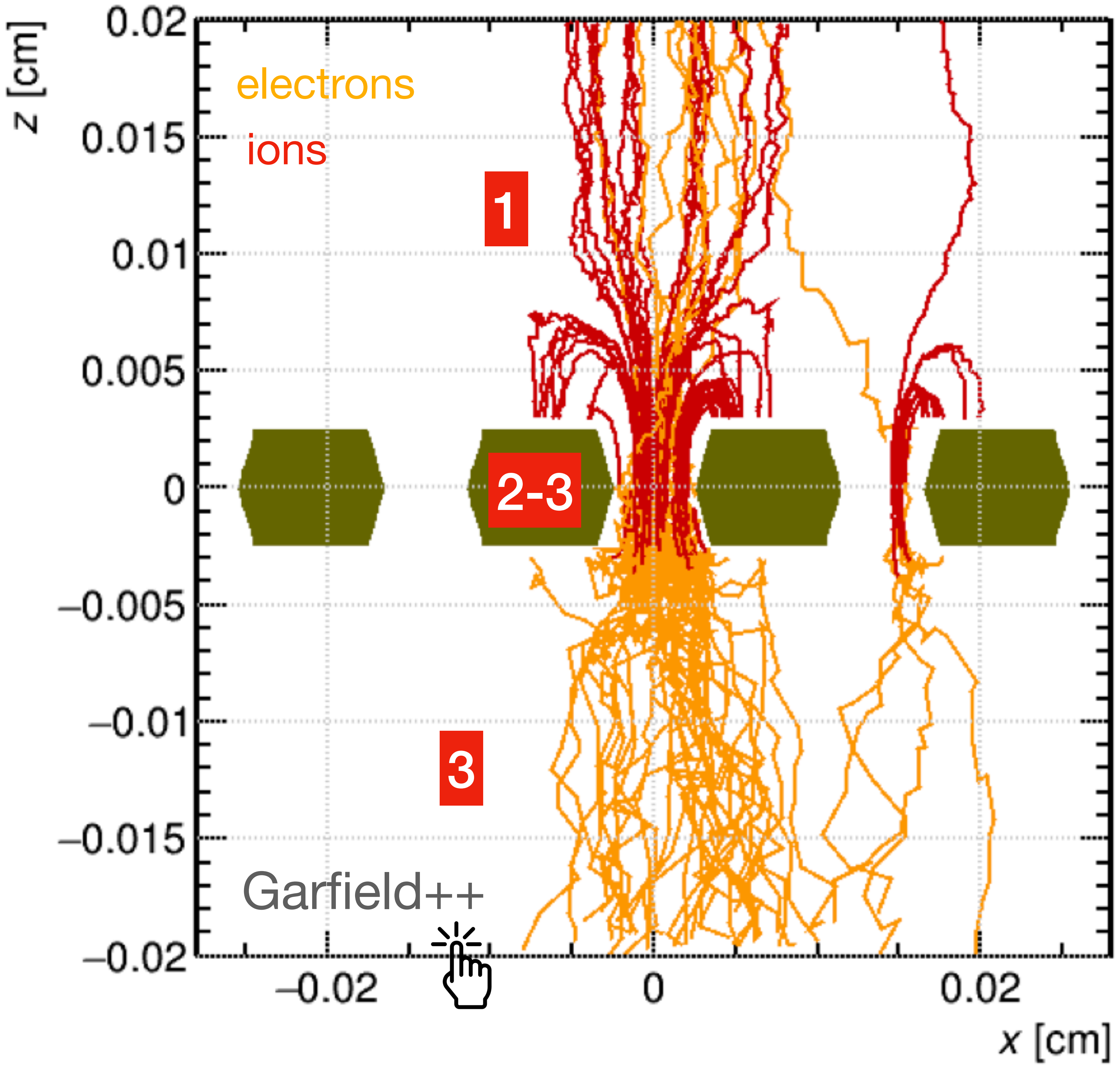
Electron avalanche multiplication and signal formation

1. **Primary ionization drift** to/in a high field region
   - Possible electron losses depending on field and geometry
2. Townsend **avalanche multiplication** gain: $G = e^{\int \mu(E(x))dx}$
   - **Light emission → optical readout**
3. **Drift** of electrons and ions until collected and neutralized
   - **Signal induction → readout electronics**

Townsend coefficient μ depends on

- Ionization cross sections of gas
  - more complex chemistry for gas mixtures (e.g. Penning effect, dimers, charge transfer)
- Gas density → Electron mean free path (~μm at STP)
- Electric field

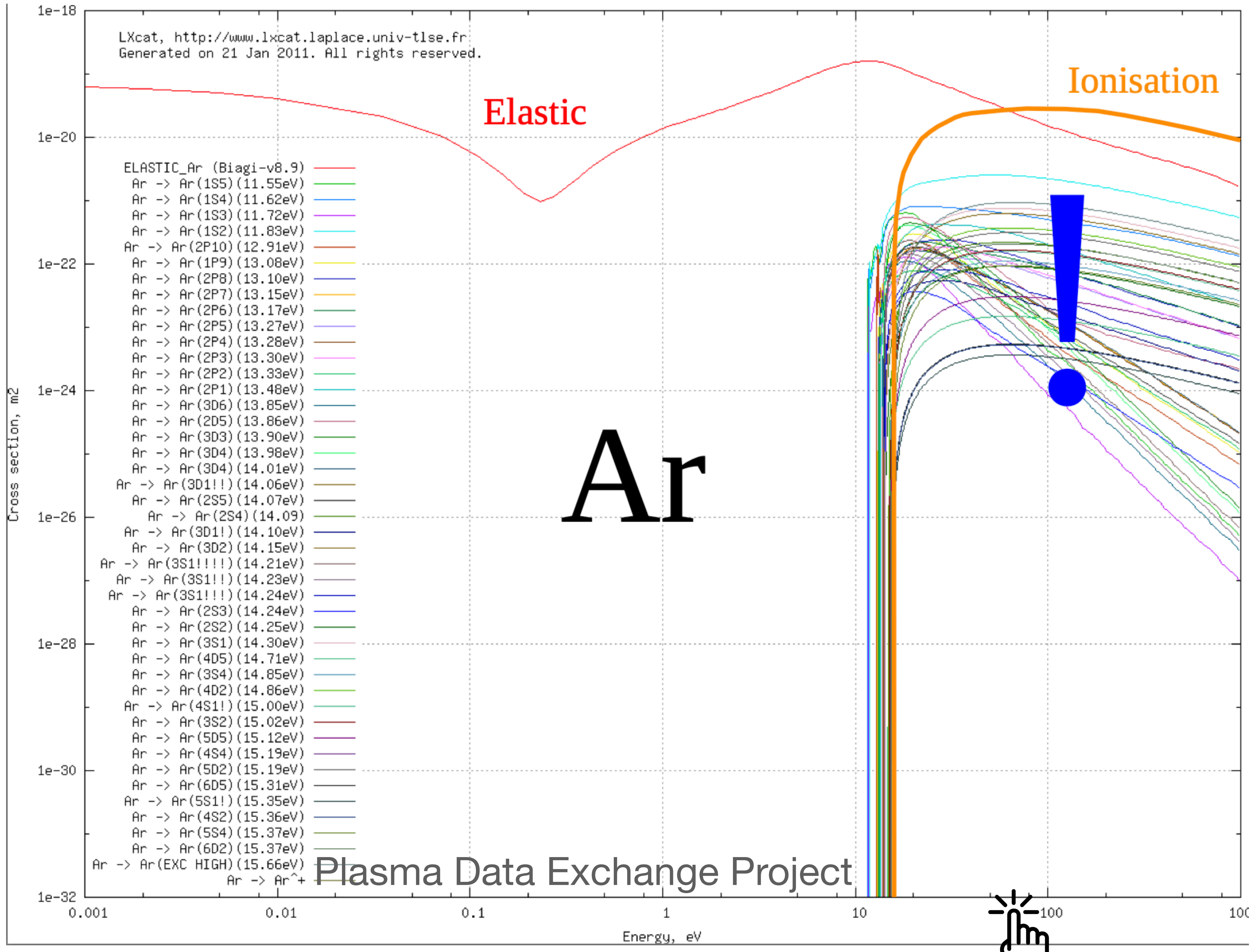
H. Raether, Electron avalanches and breakdown in gases.



Dynamics of charges in a gas

The performance of a gaseous detector is determined by the **properties of the operating gas** (pressure and temperature dependent)

- Swarm properties of electrons and ions:
  - Drift velocity
  - Diffusion (lateral and transverse)
- Microscopic collisions
  - Elastic
  - Inelastic: excitations, ionization
  - Electron attachment
    (for electronegative molecules)
- Ion chemistry



A reliable simulation requires an enormous amount of precise experimental data for pure gases and mixtures

- Existing databases and ongoing effort of dedicated groups (e.g. LXcat, Aachen gasDB)

Dynamics of charges in a gas

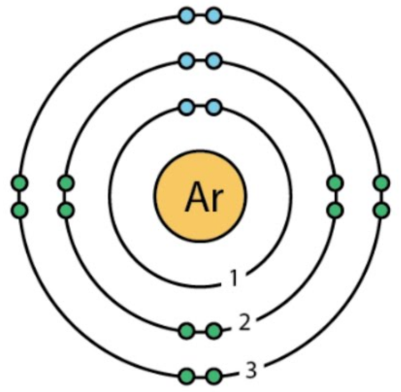
gas mixtures

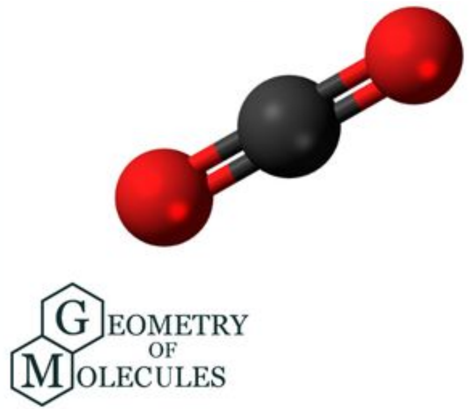
Typically a noble gas (high gain at low voltage) and a molecular additive
→ non-trivial properties

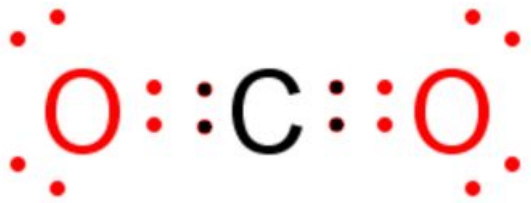
- More inelastic electron collisions → Faster electron drift, reduced diffusion
- UV photon quenching → Improved avalanche stability
- Penning effect
- Charge transfer between ion species → reduced effects of ion feedback
- Clusterization and dimerization → reduced effects of ion feedback

A good candidate: $Ar:CO_2$

18
Ar
Argon
39.95







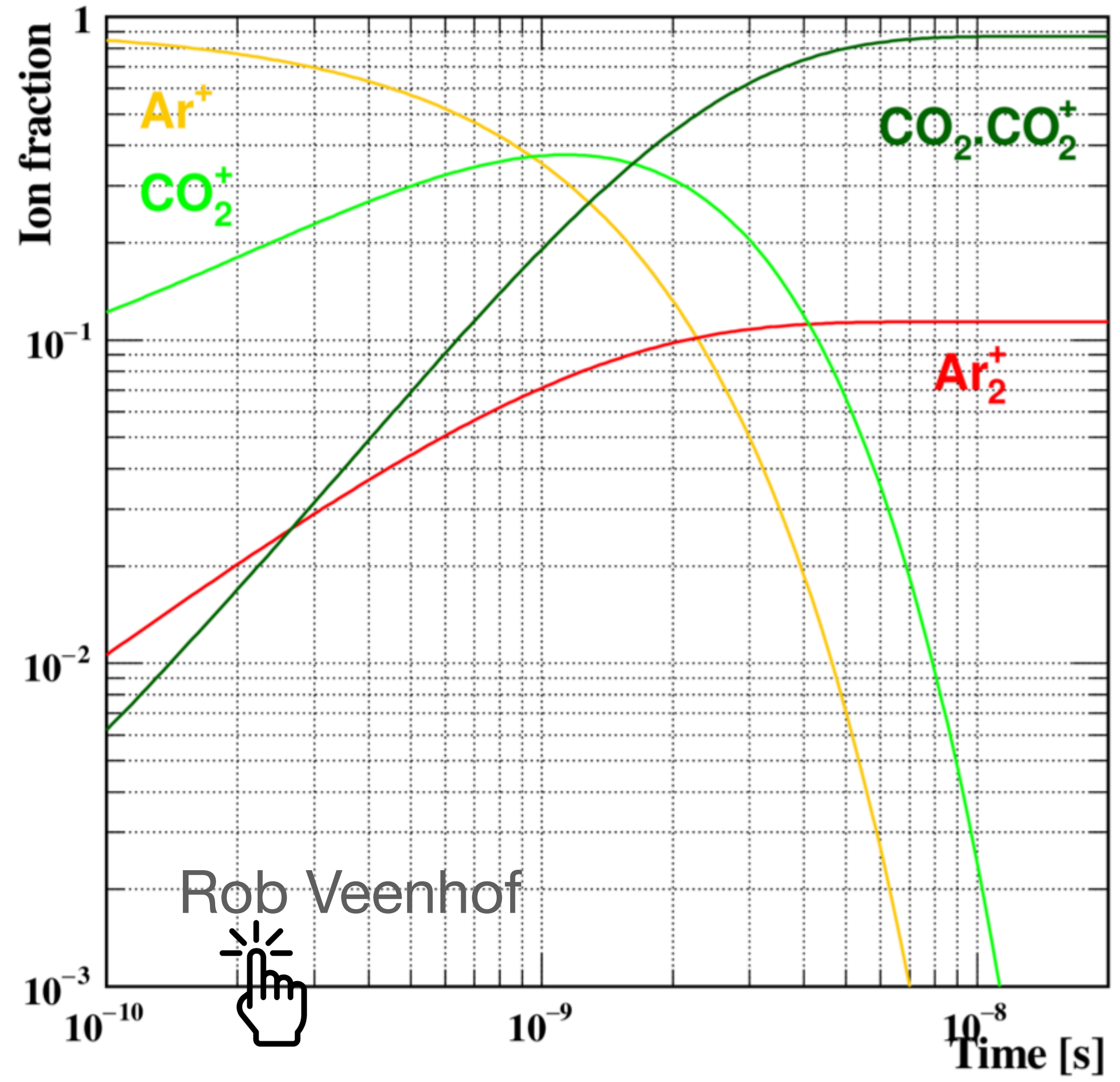
Other gas mixture desiderata:

- Cheap
- Non-flammable or toxic
- Environmental friendly
- Non polymerizing (detector ageing)

Example of avalanche ions composition evolution

- $Ar:CO_2$ (93:7)
- Start: Ar^+ (majority), CO_2^+
- Processes: $Ar^+ + CO_2 \rightarrow Ar + CO_2^+$ ($\tau \approx$ 0.85 ns)
  $Ar^+ + Ar + Ar \rightarrow Ar^+{\cdot}Ar + Ar$ ($\tau \approx$ 7 ns)
  $CO_2^+ + CO_2 + CO_2 \rightarrow CO_2{\cdot}CO_2^+ + CO_2$ ($\tau \approx$ 7-20 ps)
- End: Ar_2^+, $CO_2{\cdot}CO_2^+$

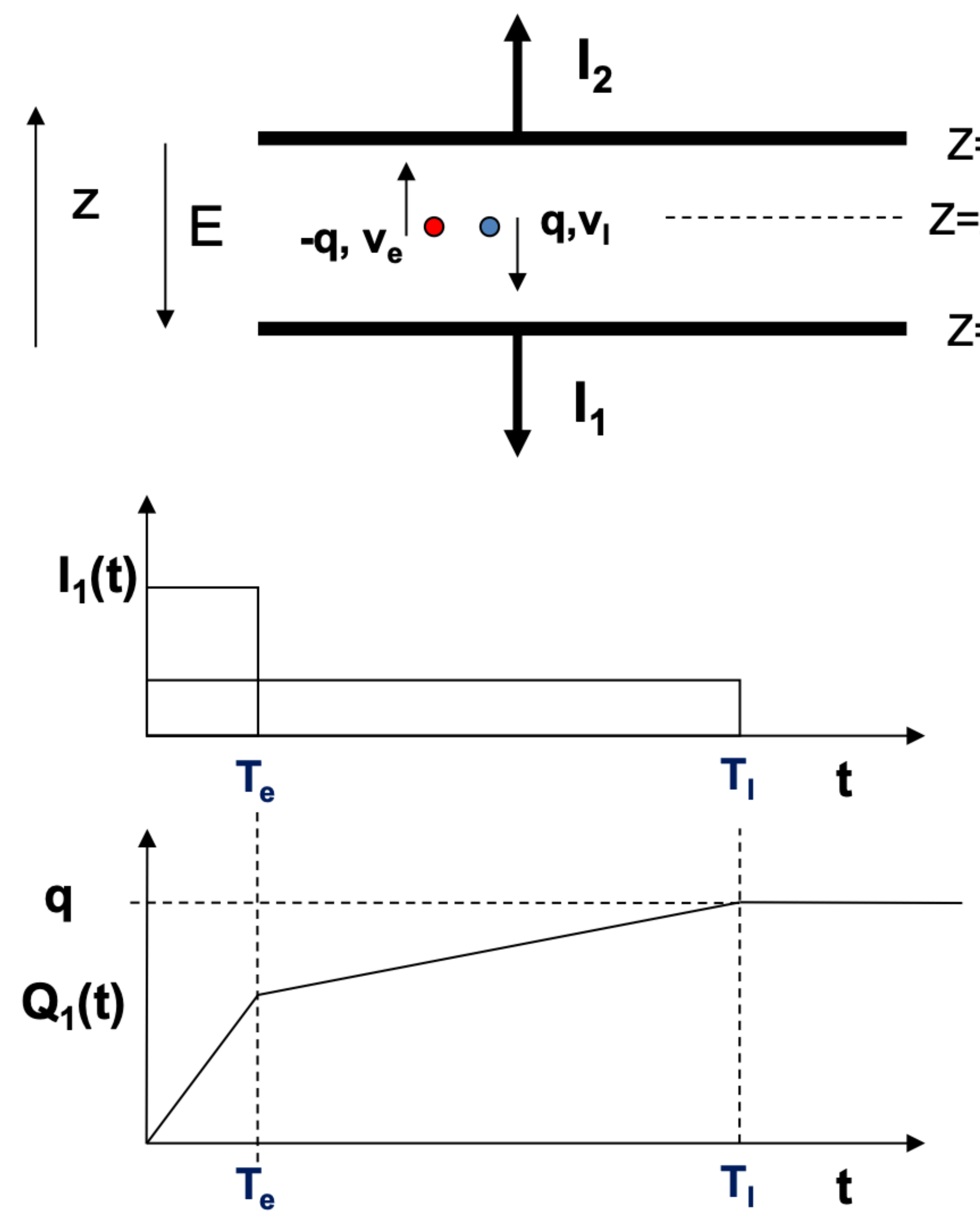
! The signal is mostly induced by the end products



Signal induction
by movement of positive and negative charges

Basic principles of signal induction:

1. Only <u>moving charges</u> induce currents (signals) in the surrounding electrodes
   - When the charge is collected at the electrode the signal is over
2. The signal development depends on the amount of charge moving, on its velocity and on the geometry of the system
   - the sign of the charge and its direction with respect to the electrode determines the signal polarity
3. If there is one electrode enclosing all the others, the sum of all induced currents on a set of “close by” electrodes is 0 at any time
4. After ALL charges have arrived at the electrodes, the total induced charge on a given electrode is equal to the charge that has ARRIVED at this electrode.
   - Current signals on electrodes that dont receive a charge are strictly bipolar.
5. The total induced charge is independent on the actual path of the charges



$$I_1 = \frac{q}{D}v_e + \frac{q}{D}v_i$$

$$I_2 = -I_1$$

$$Q = \int I_1 = q\frac{(D - z_0)}{D} + q\frac{z_0}{D} = q_e + q_i = q$$

W. Riegler - RD51 electronics school 2014

Riegler, Werner, and Philipp Windischhofer. "Signals induced on electrodes by moving charges, a general theorem for Maxwell’s equations based on Lorentz-reciprocity." NIM *A* (2020): 164471.

Gaseous detector concepts

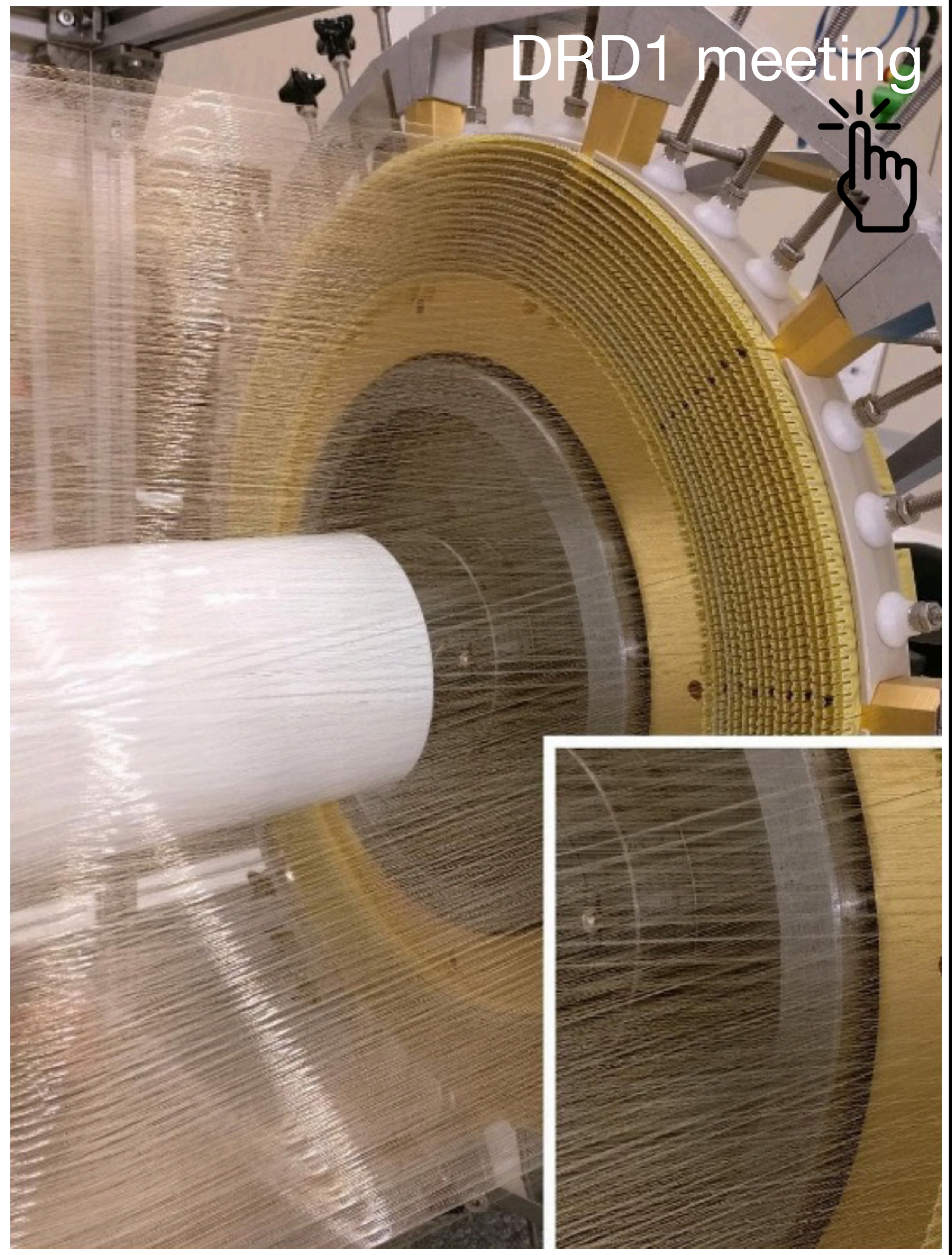
Electrodes for signal induction and charge multiplication

Wires

Geiger-Muller counter (1928)

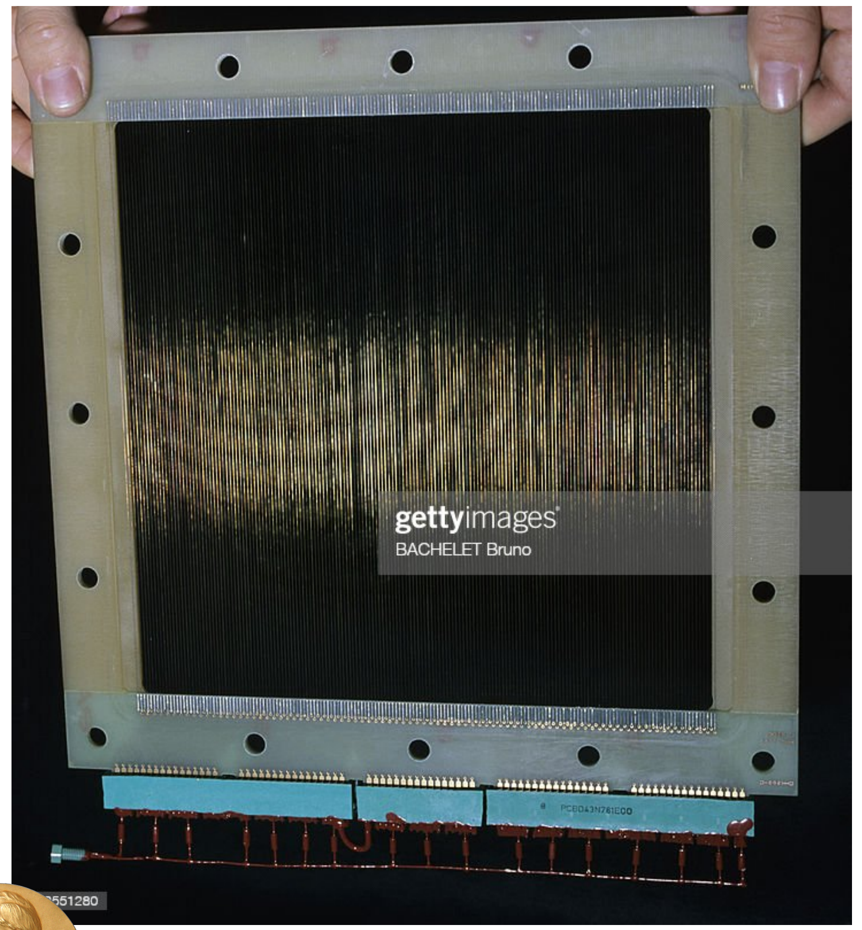
The first detector with electronic readout

Drift chamber



Volume filled with field and sense wires

Multi Wire Proportional Chamber (1968)



Georges Charpak 1992

Cathode Strip Chamber, Thin Gap Chamber, Time Projection Chamber, Multistep avalanche chamber, Monitored Drift Tube, Straw, …

Parallel plates

Parallel Plate Avalanche Counter (1949)

Breskin 78

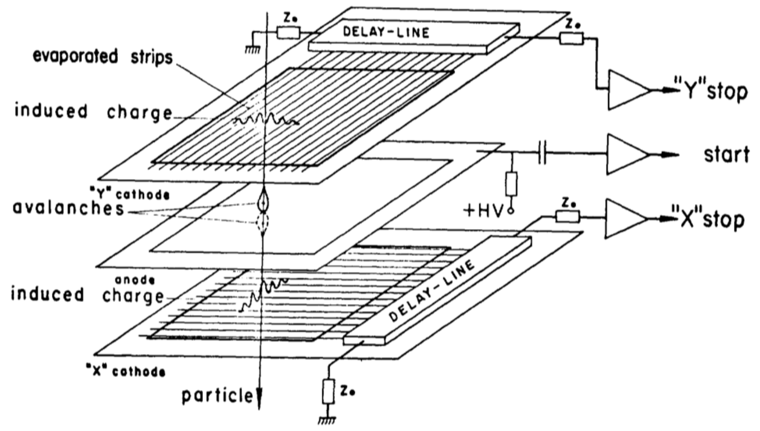
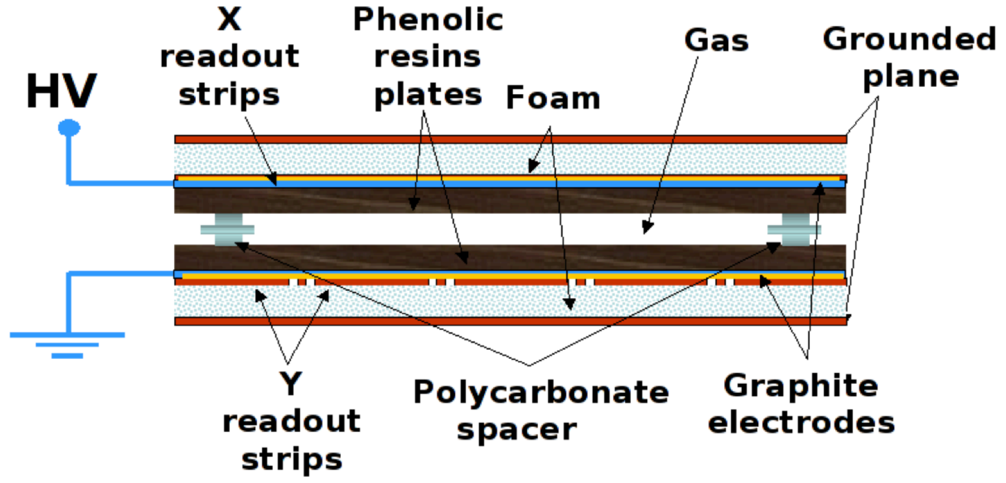


Fig. 1. Principles of bidimensional, induced charge, read-out from Parallel Plate Avalanche counters.

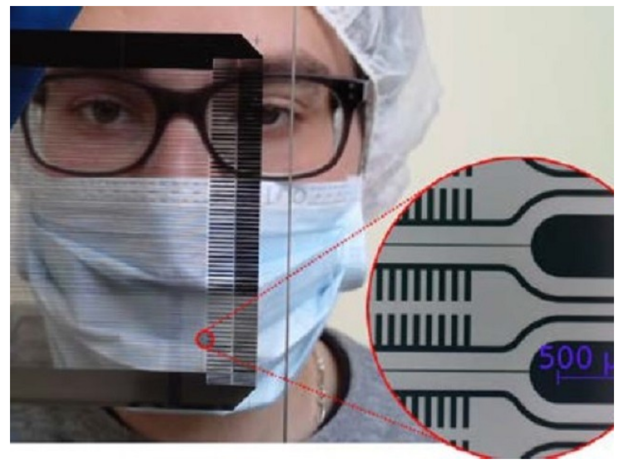
Resistive Plate Chamber (1981)



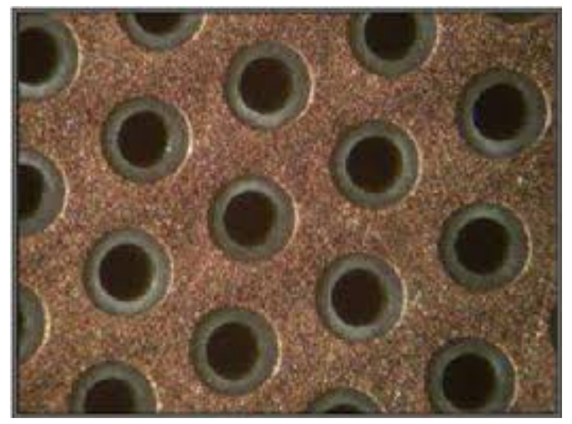
Scheme of ATLAS RPC

Micro-pattern (MPGD)

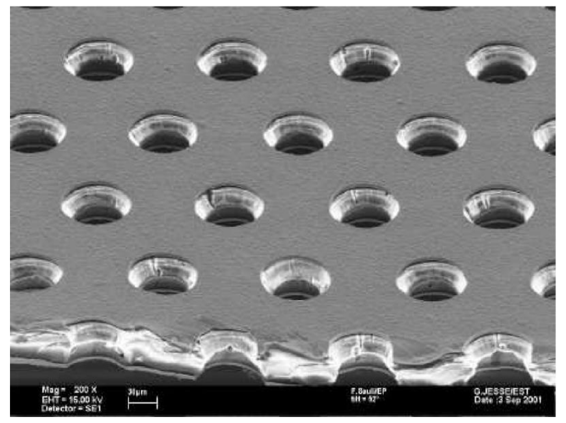
Multi Strip Gas Counter (1988)



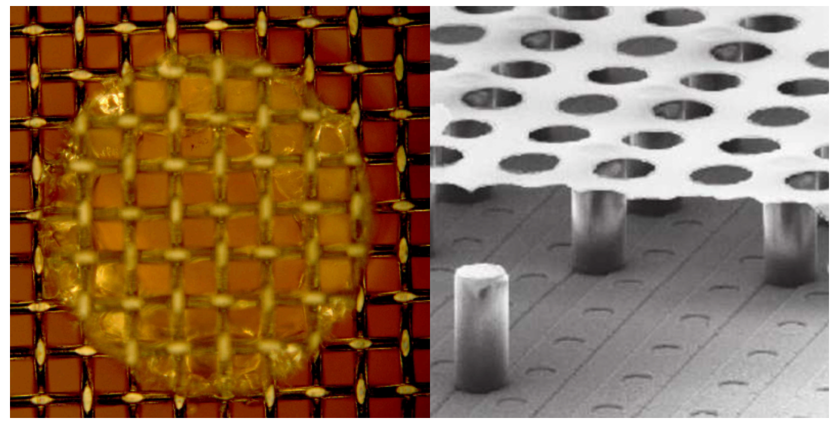
Thick GEM (2003)



Gas Electron Multiplier (1997)



Micro Mesh Gas Counter (1996)



Many more electrode shapes, hybrid and cascaded structures, photon and neutron converters, resistive materials, …

- Progress driven by technology: new materials and production techniques

Thin Gap Chambers (TGC)

- Part of the muon system in ATLAS @ CERN[1]
  - Trigger decision within 25ns
  - Japanese institutions involved in development of readout electronics[2] and trigger system[3] (present) and chamber production[4] (ended)

- Thin geometry with respect to traditional MWPC

- Resistive layer and highly quenching gas (CO_2:n-pentane)

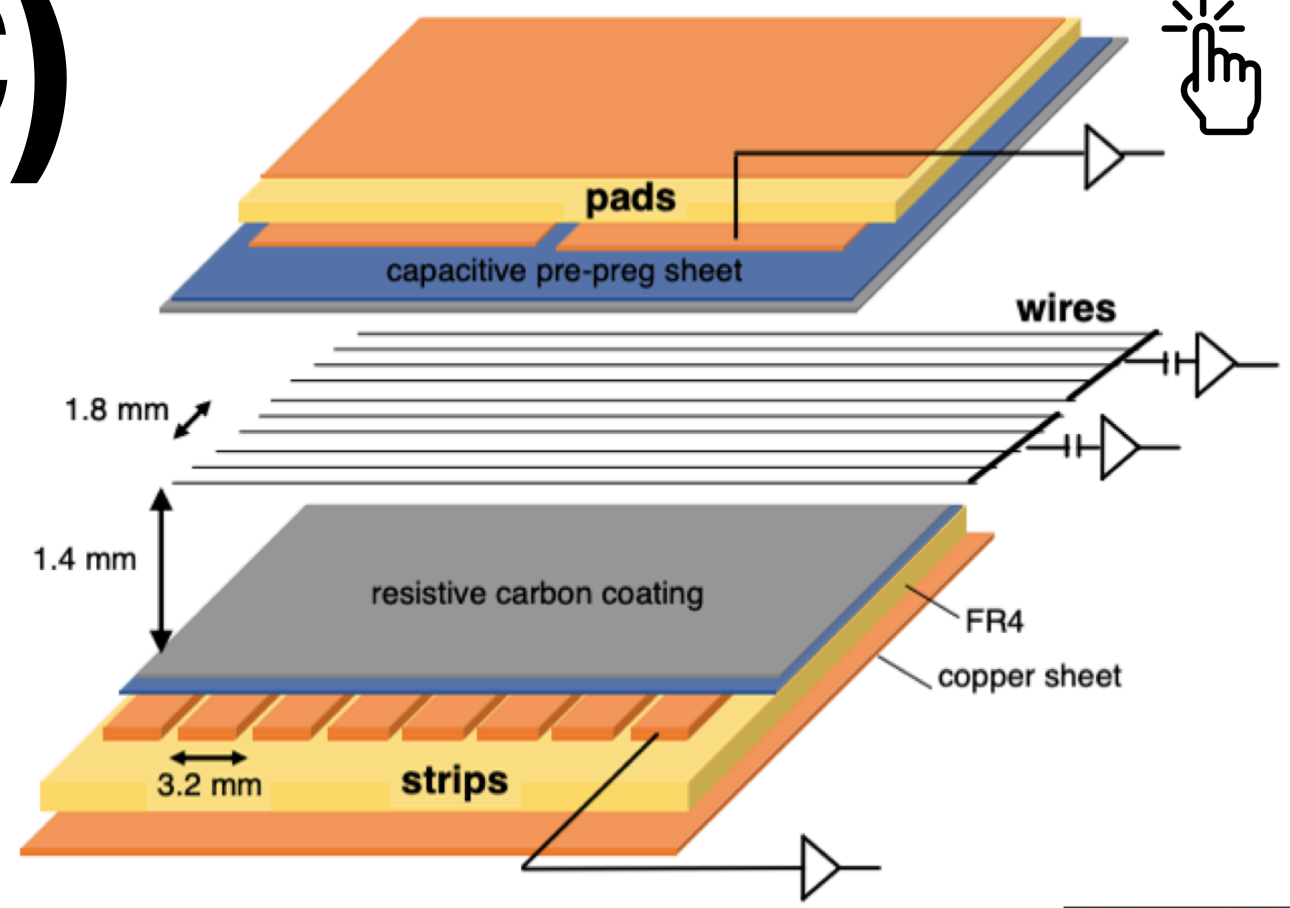
$$E \sim \frac{1}{R}$$

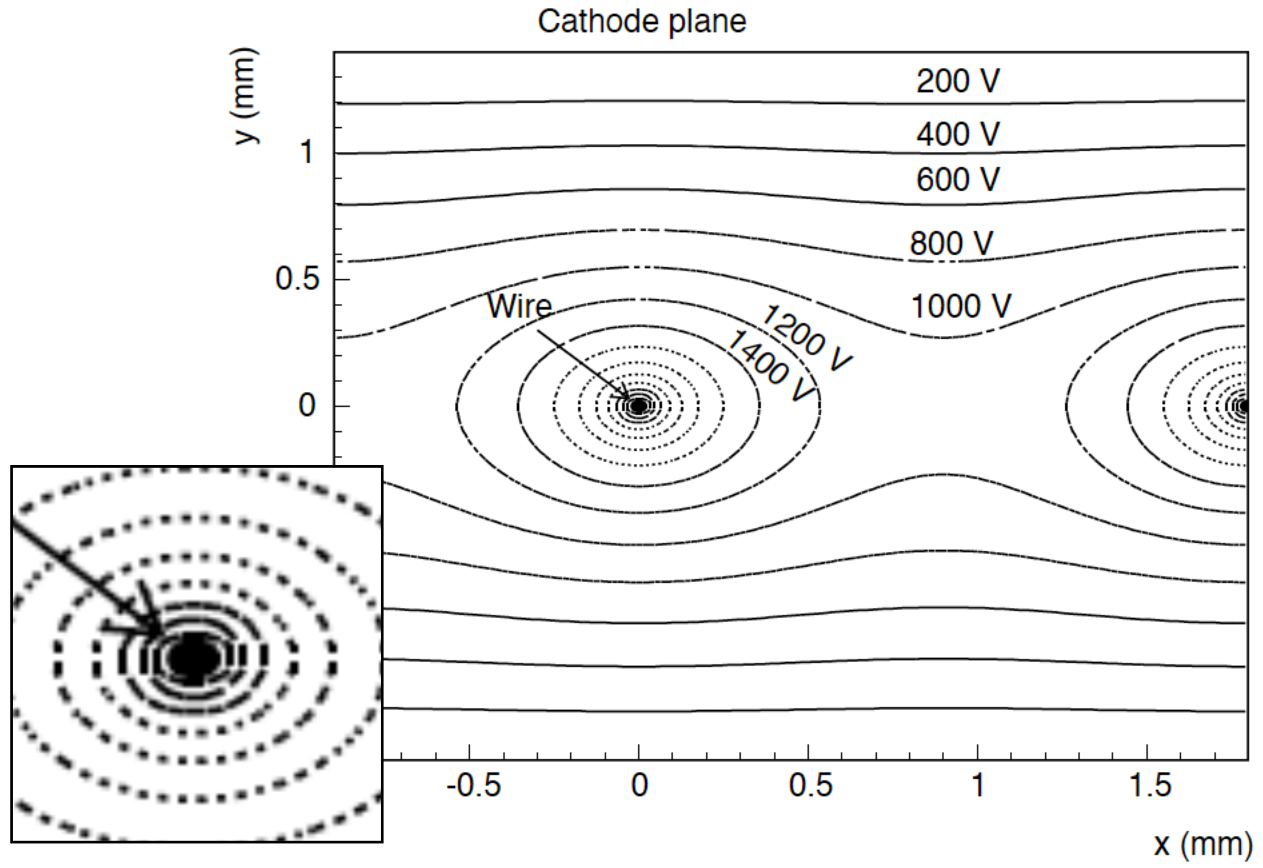
Present work

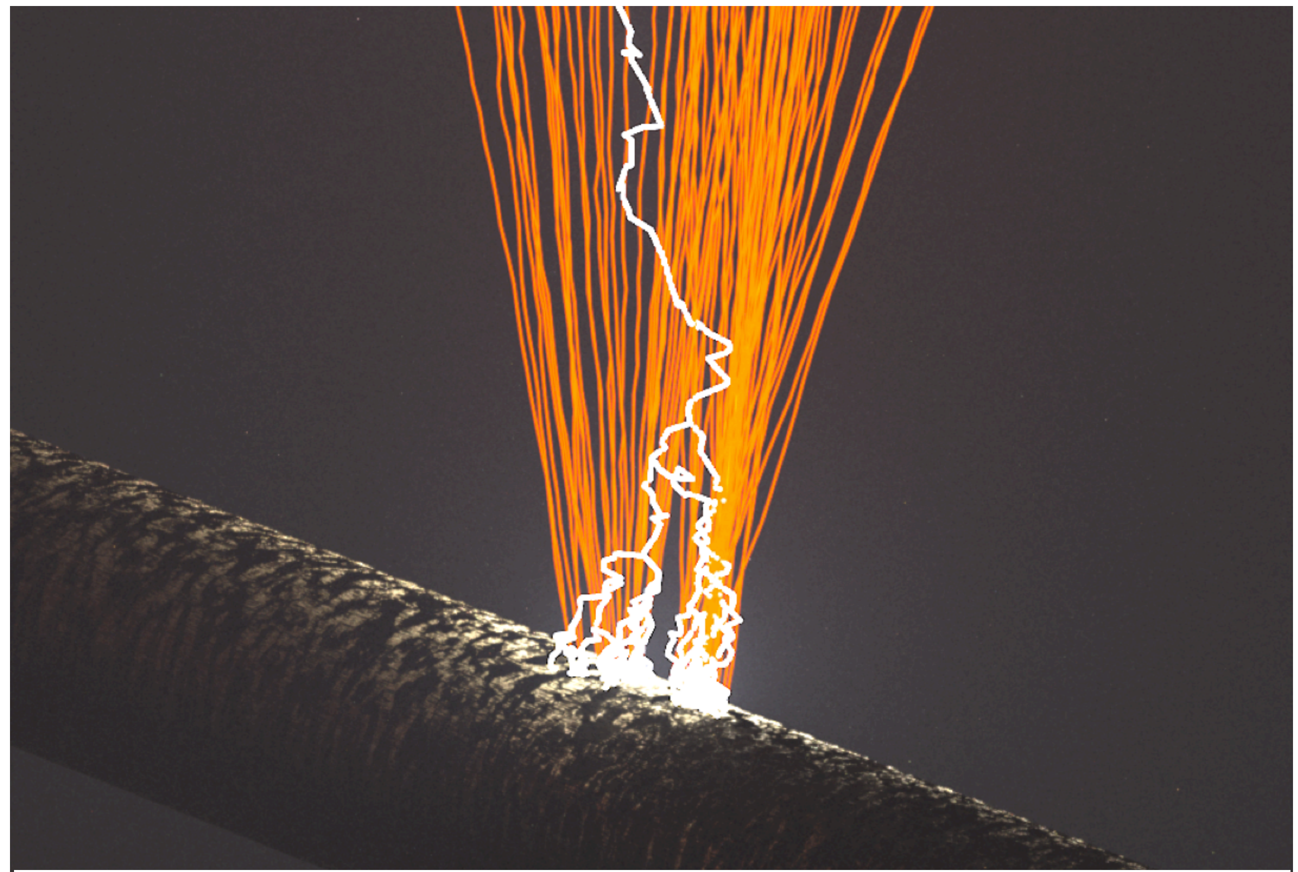
- Upgrade for Phase II of ATLAS

- Operate in mixture of noble gas and quencher to extend application beyond HEP (e.g. muography)

https://doi.org/10.22323/1.382.0245







Winkler, Alexander, et al. "A gaseous proportional counter built from a conventional aluminum beverage can." *American Journal of Physics* 83.8 (2015): 733-740.

- 50 µm wire → avalanche within 10s µm

- e^- immediately collected → signal induced mostly by ion movement

1) ATLAS Muon spectrometer TDR

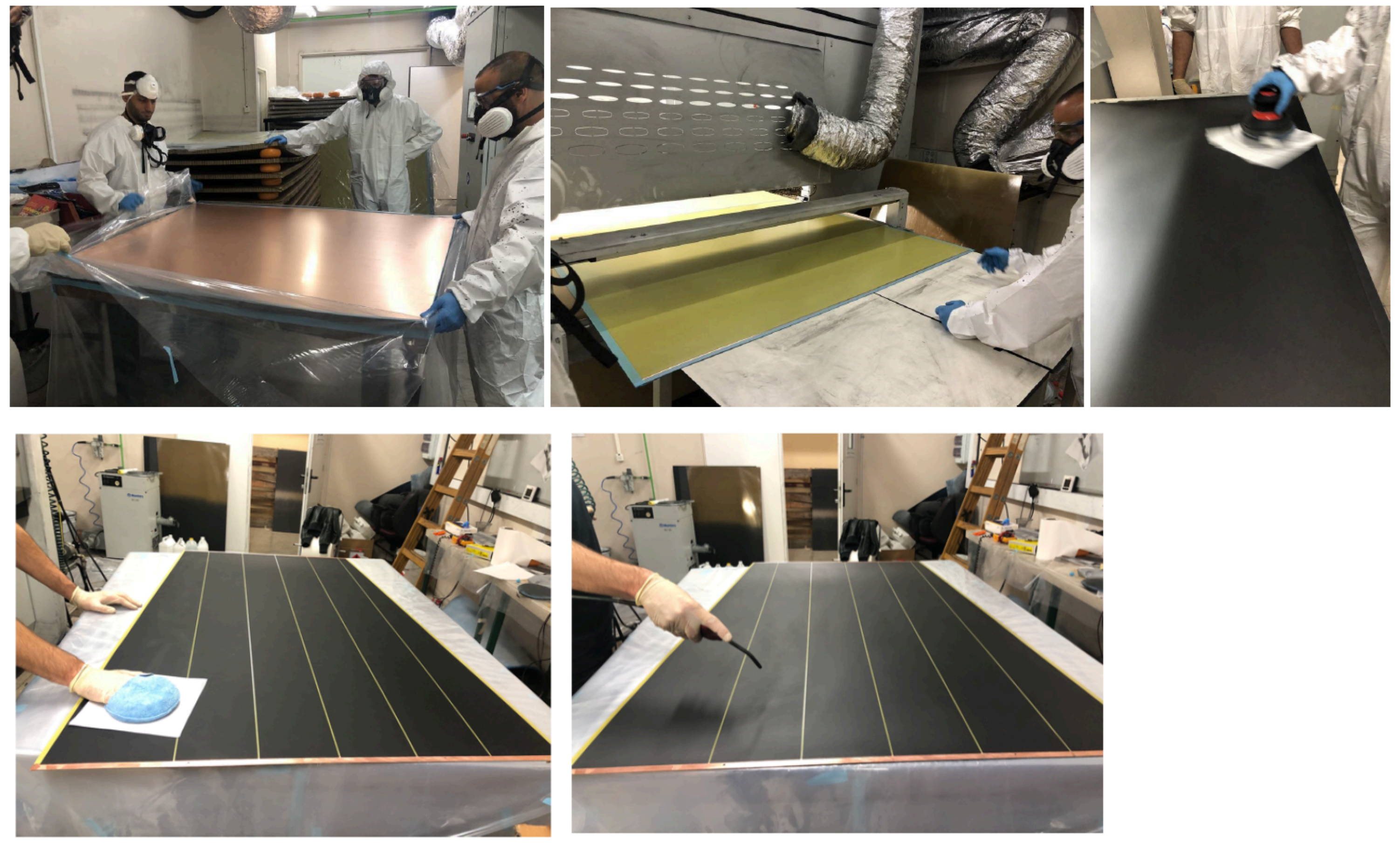
2) Sasaki, et al. "ASD IC for the thin gap chambers in the LHC ATLAS experiment." Vol. 1. IEEE, 1998.

3) Okumura, Y., et al. "The commissioning status and results of ATLAS level1 endcap muon trigger system." (2008).

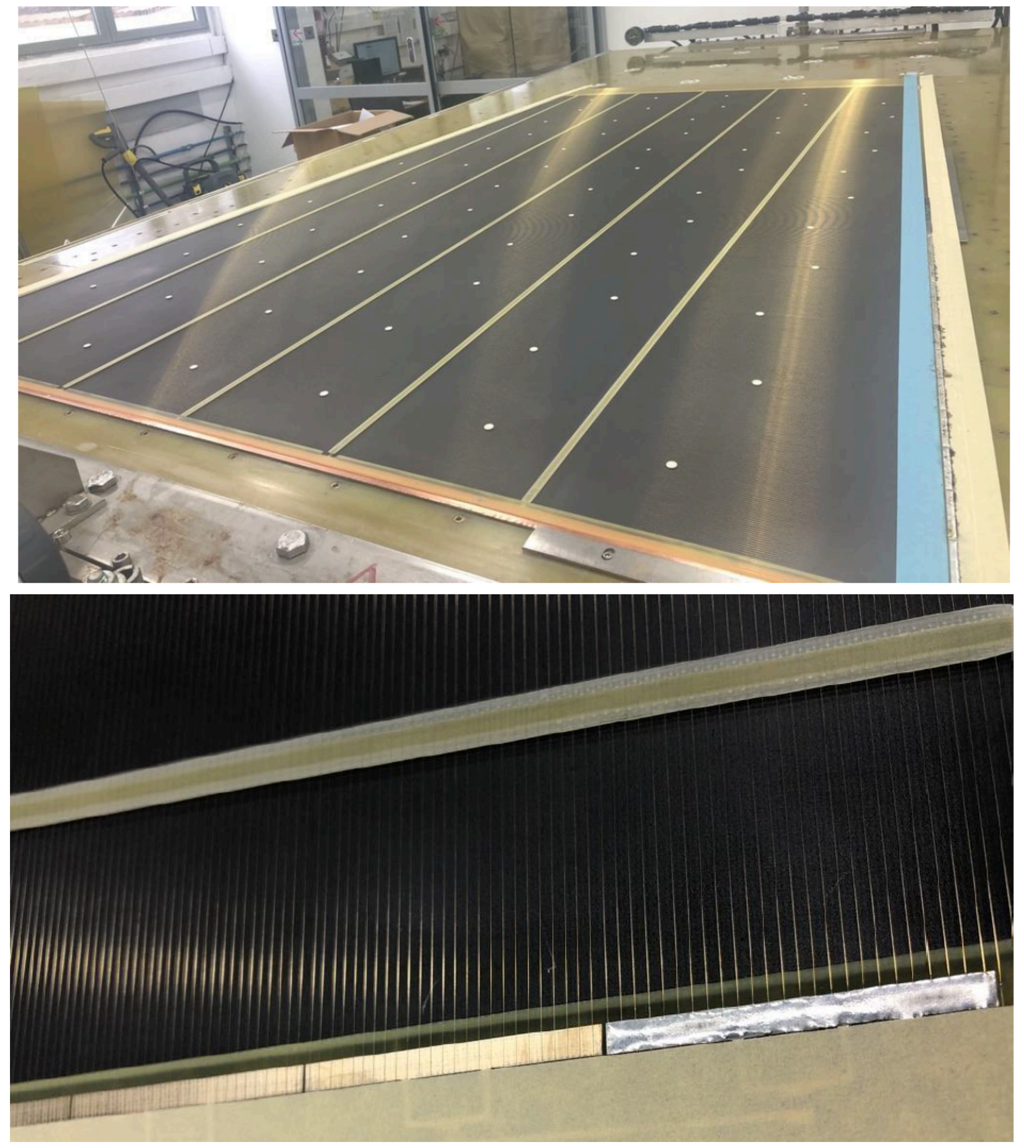
4) Tanaka, S., et al. "Development of mass-production technique of the ATLAS thin gap chamber in Japan." 2003 IEEE. Vol. 5.

TGC production and testing

Cathode board spraying with graphite

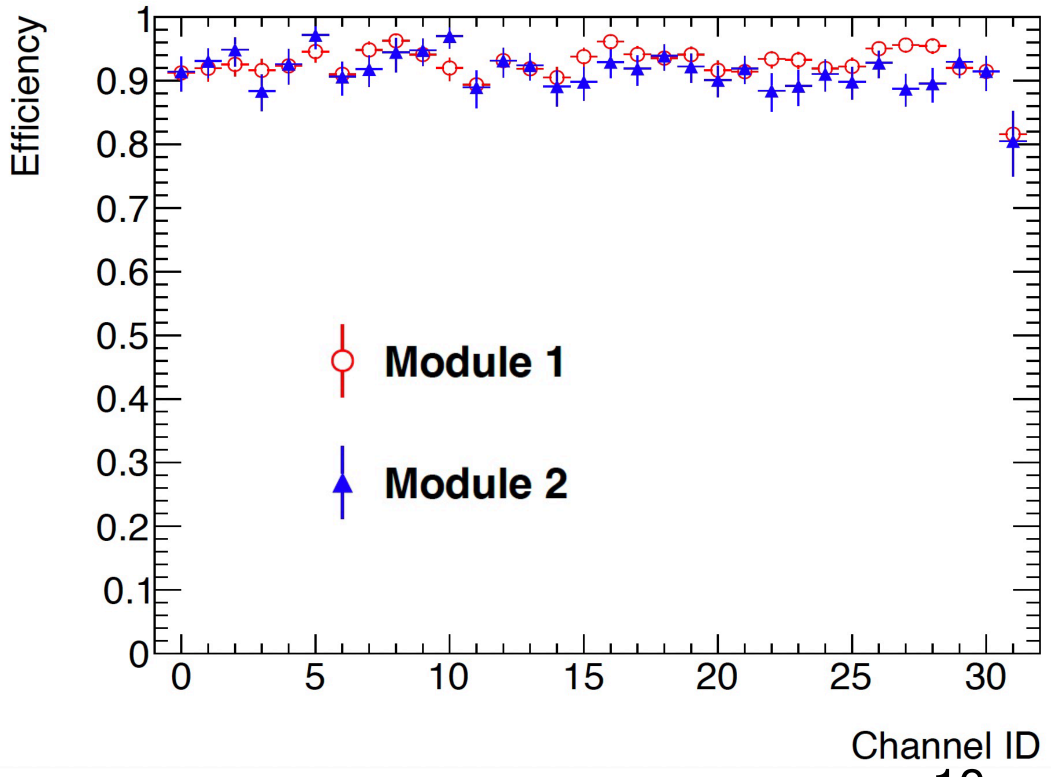


Wire winding and soldering

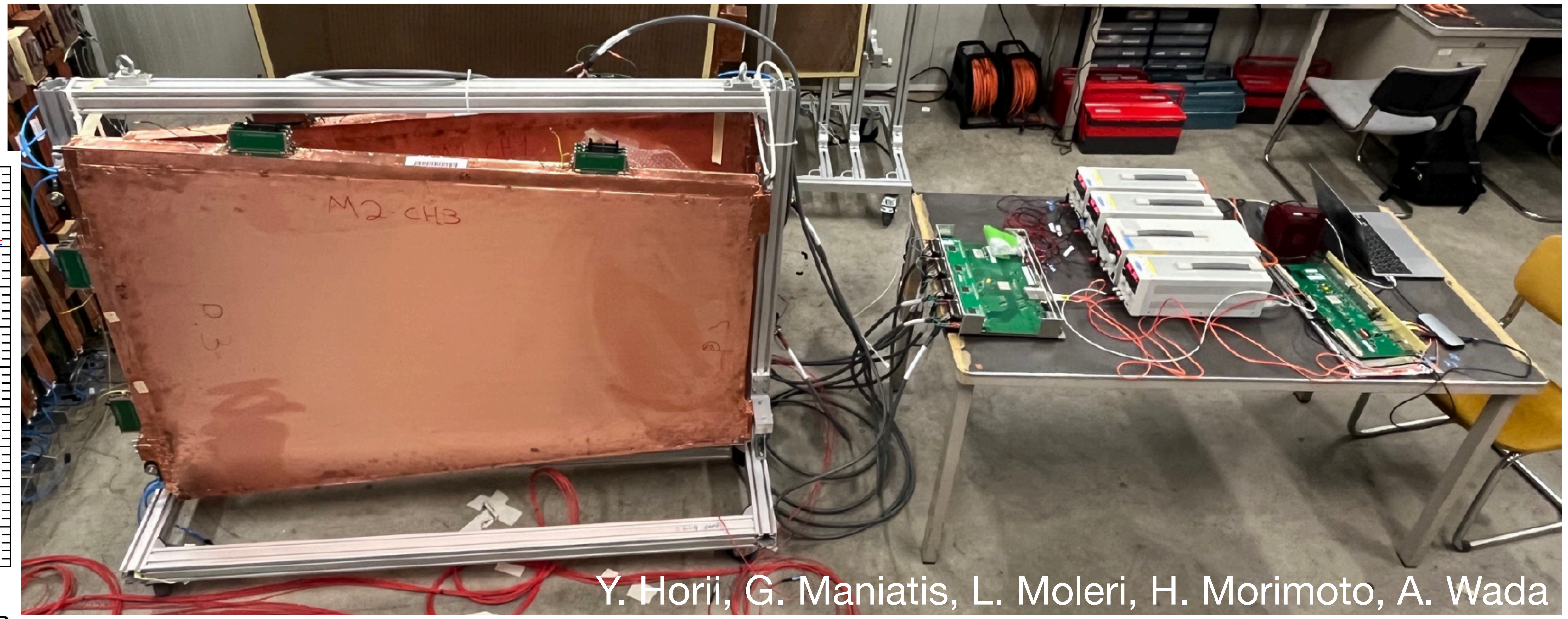


Single gap assembly

- Decades long experience at WIS developing TGC chambers for ATLAS
- Joint effort with Japanese groups from the electronics side



Cosmic ray test of EIL4 triplet with new ATLAS readout system



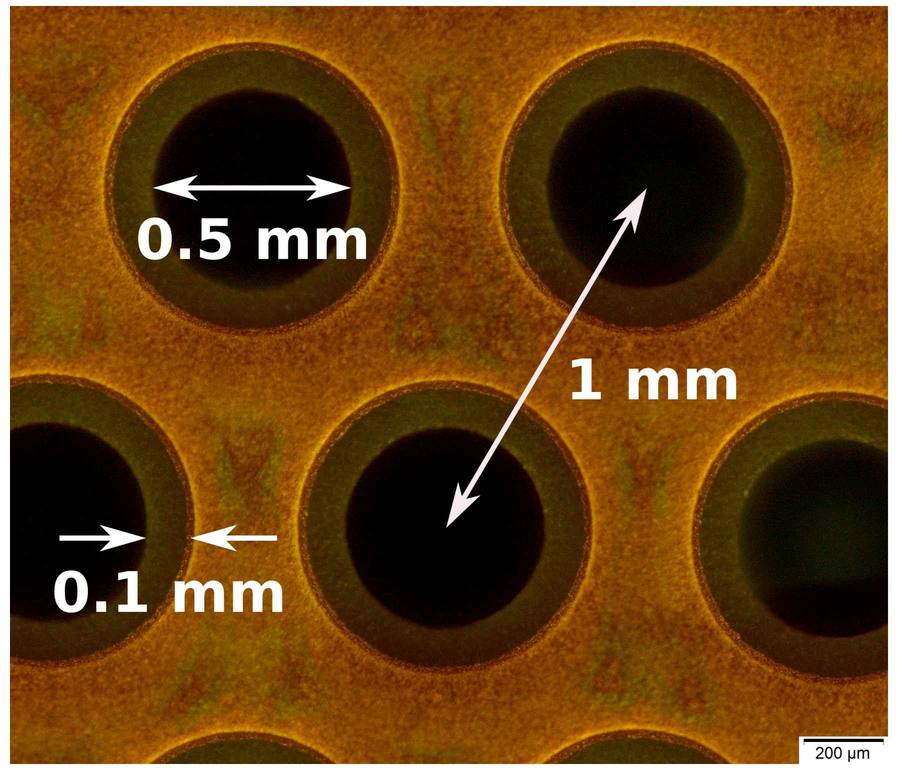
Thick Gaseous Electron Multiplier (THGEM)

The Thick Gas Electron Multiplier and its derivatives: physics, technologies and applications

Shikma Bressler[a], Luca Moleri[a], Abhik Jash[a], Andrea Tesi[a], Darina Zavazieva[a]

All the following figures are taken from here and references therein if not stated otherwise

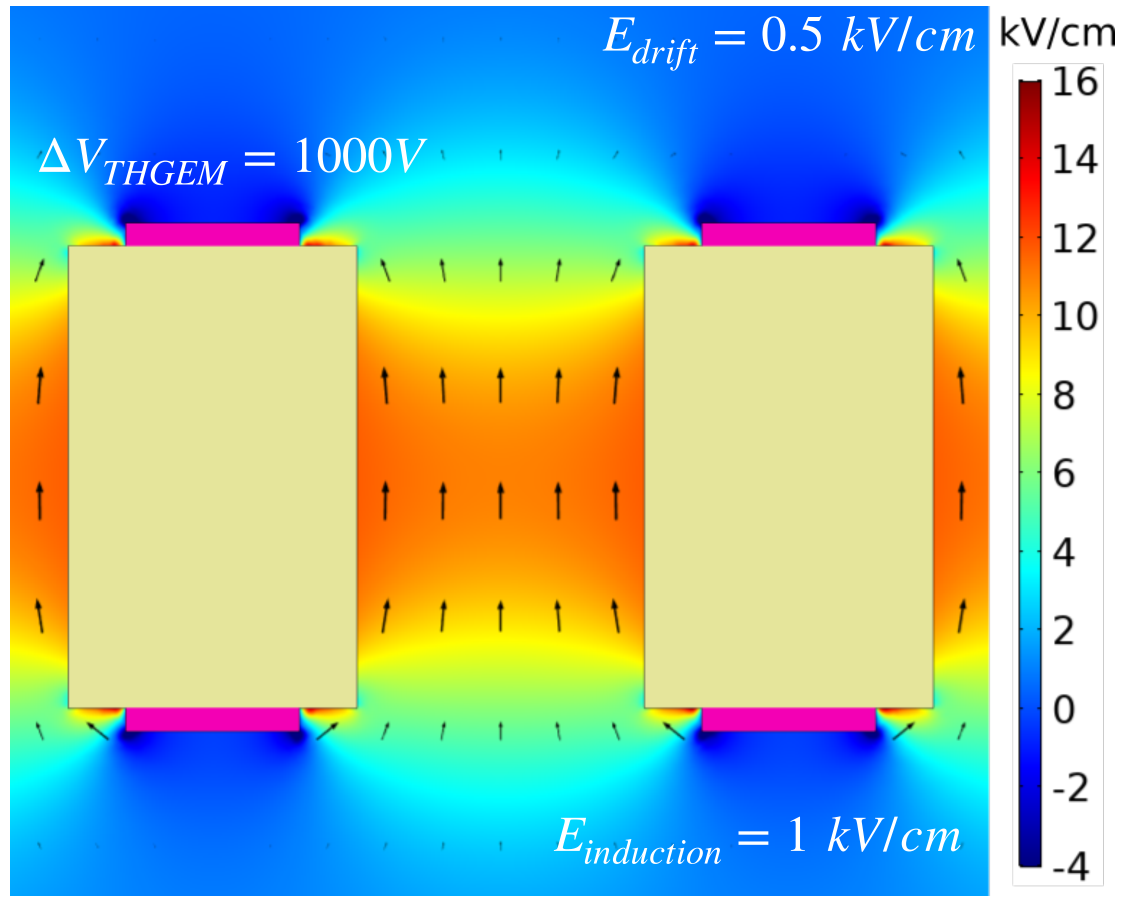
Typical parameters

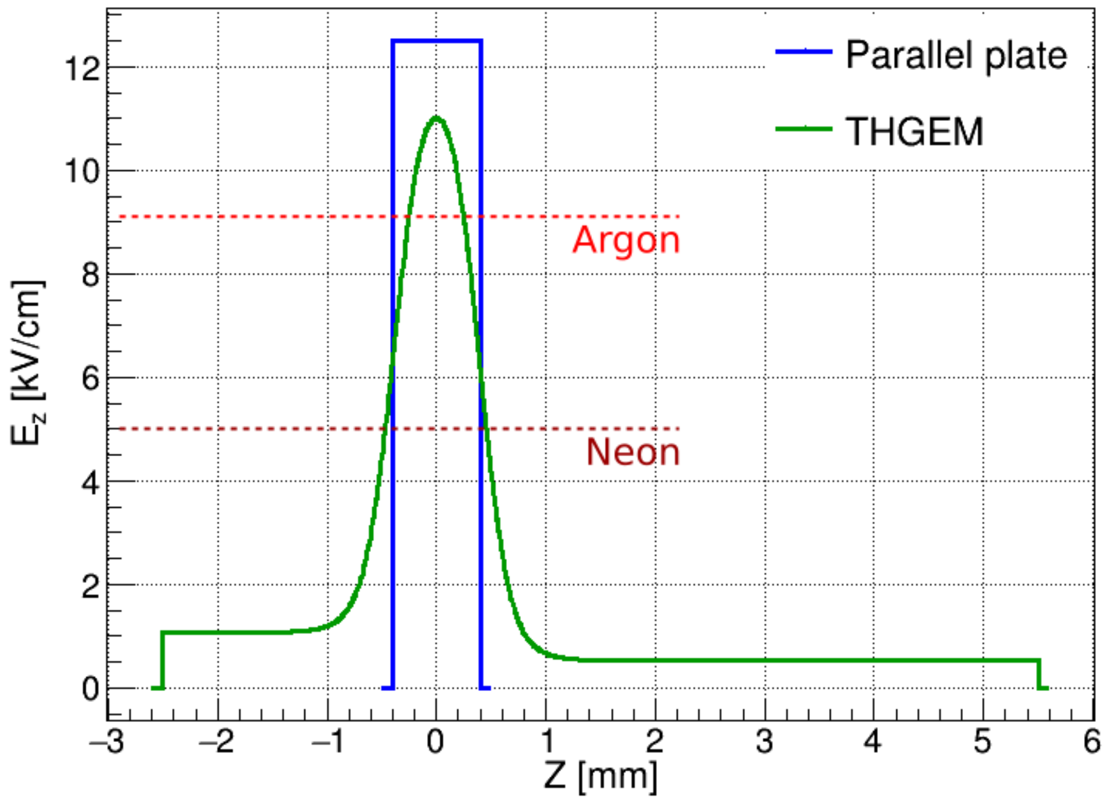


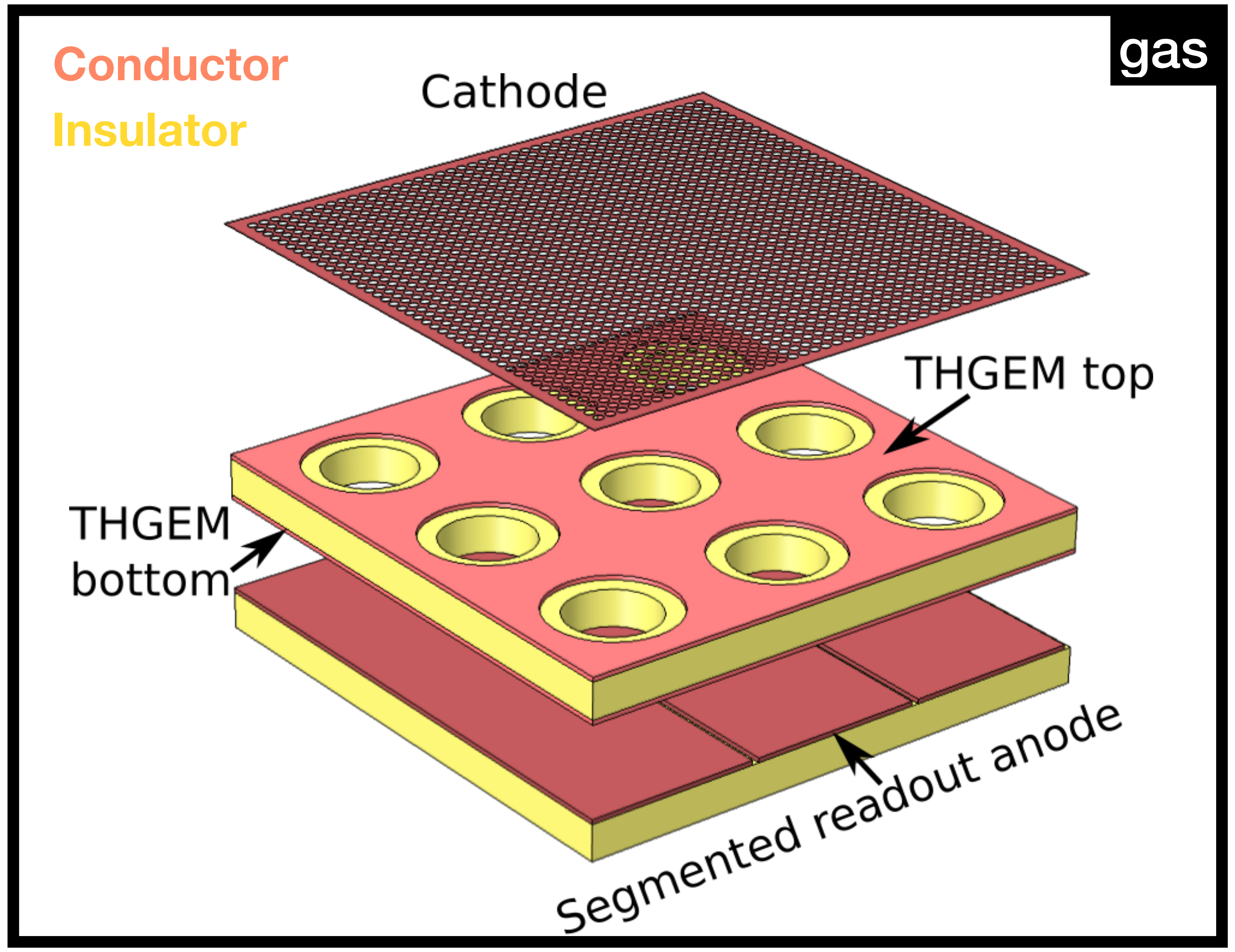
The inventor

Amos Breskin (2003)

- THGEM parameters: insulator thickness, hole diameter, rim, pitch, pattern
- Avalanche mostly contained in the hole → limited photon feedback effects
- Large hole structure → good electron collection and transfer
- Versatile configuration for different detection schemes (e.g. MIPs, X-rays, UV photons)
- Possibility to stack multiple amplification stages
- Easy to produce and scale up





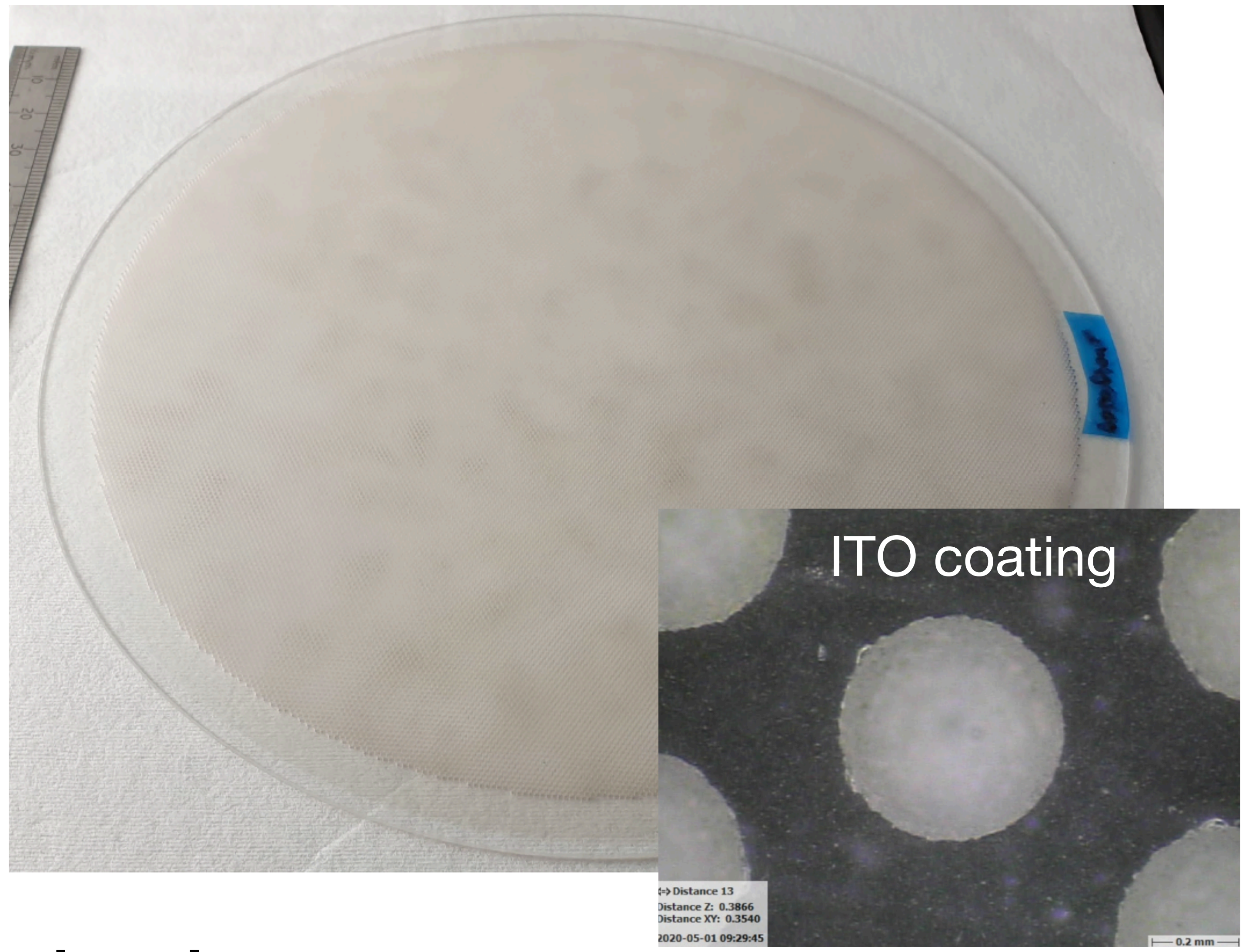


THGEM technology
methods and challenges

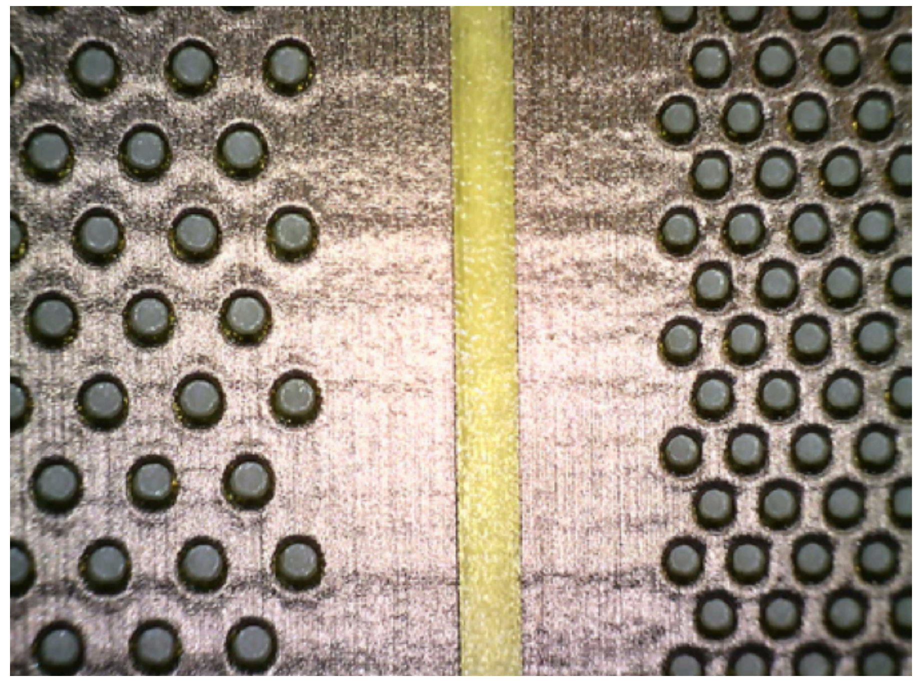
Technology: methods and challenges (partial list)

- Production of (large area) electrodes with precise and cost effective techniques
    - standard PCB (FR4, drill, etching)
    - additive manufacturing (3D-print)
    - glass sandblasting
    - etchable polymers
- Special substrates (transparent, radiopure, resistive, …)
- Coatings (photosensitive, neutron converters, resistive, …)
- Cryogenic temperatures
- Resistive materials
- Assembly methods for large areas

Glass THGEM

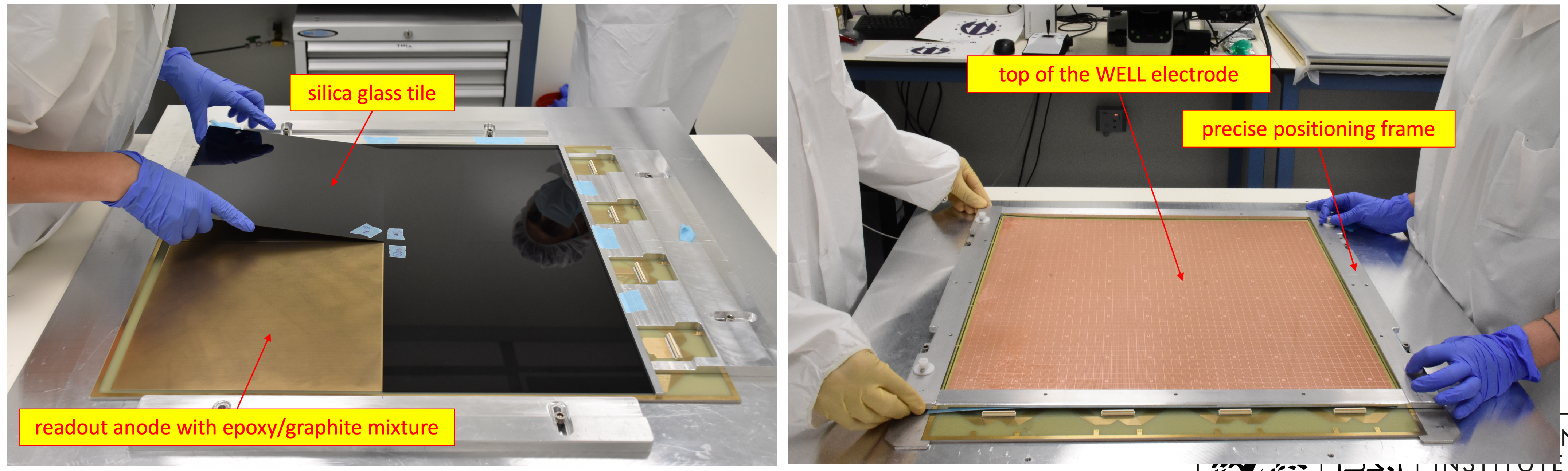


3D printed



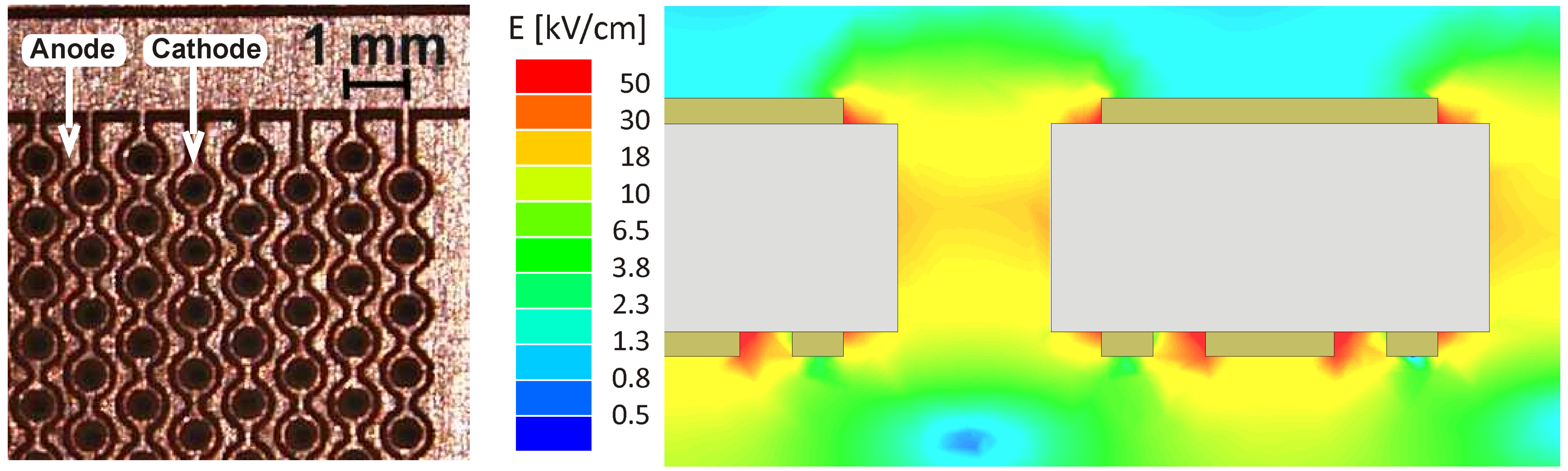
NANO DIMENSION

500mm x 500mm RPWELL

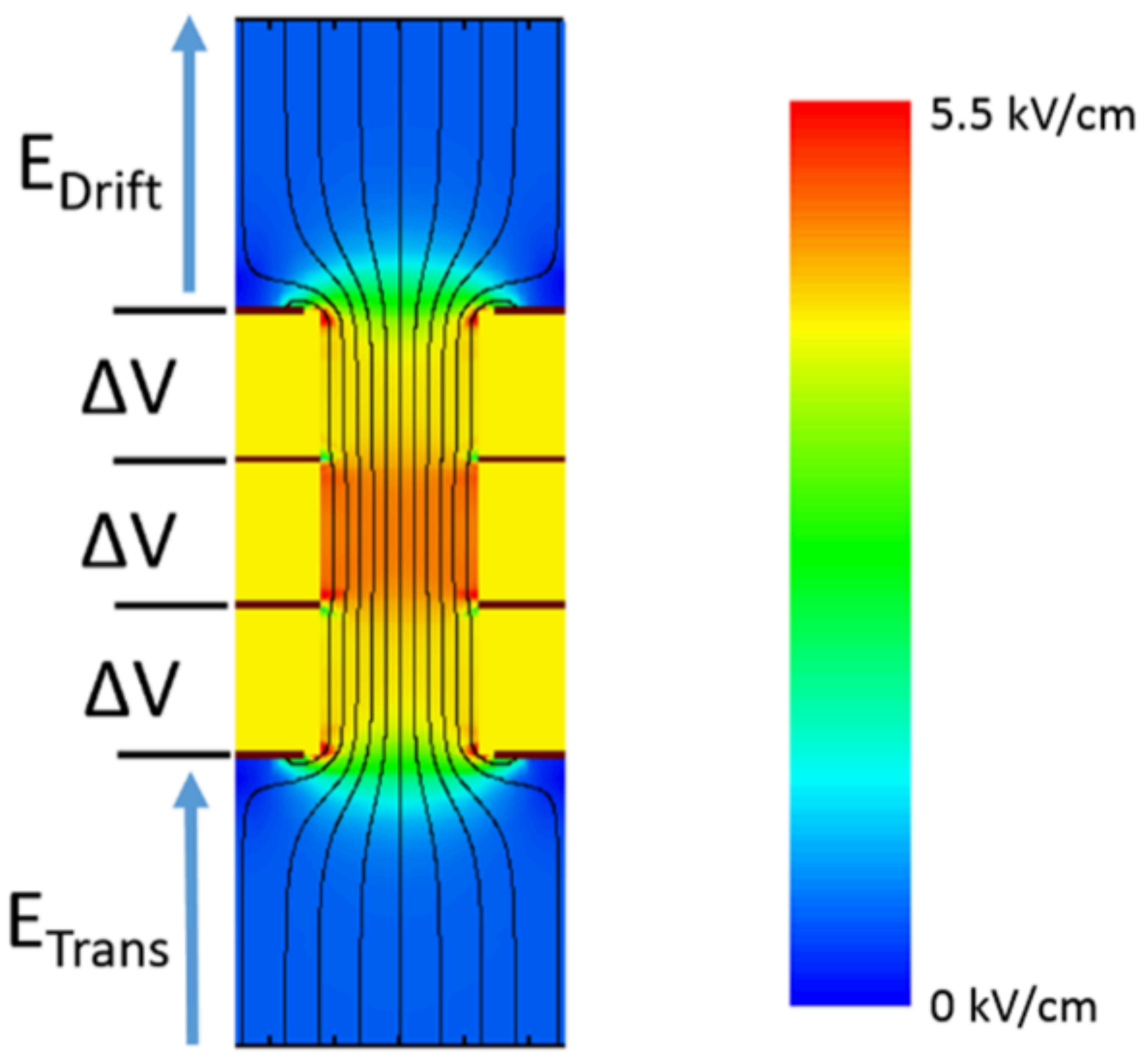


THGEM derivatives
incomplete list

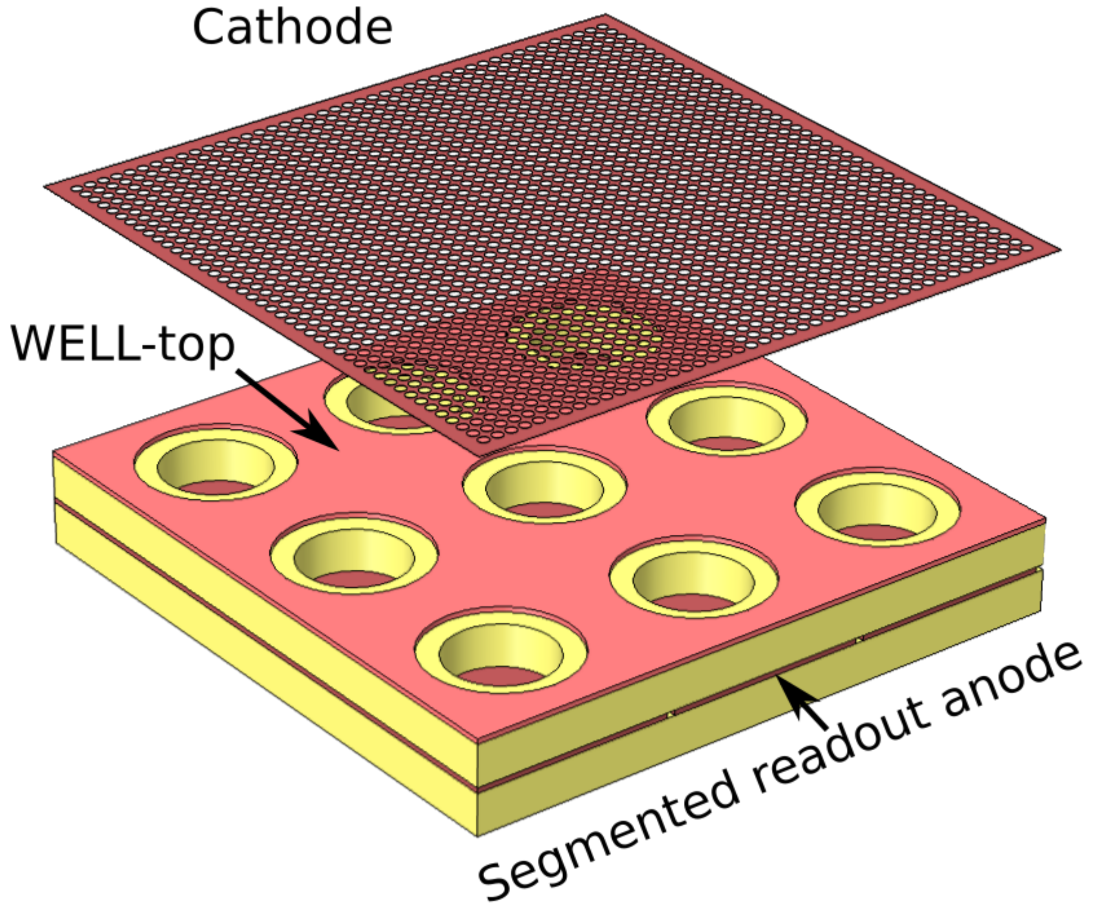
THCOBRA



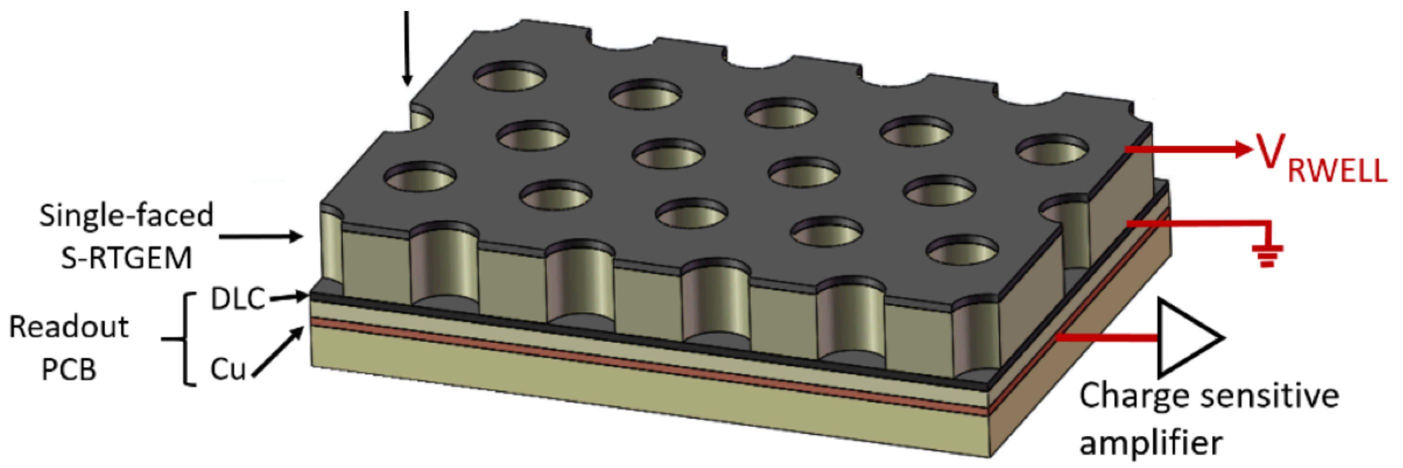
M-THGEM



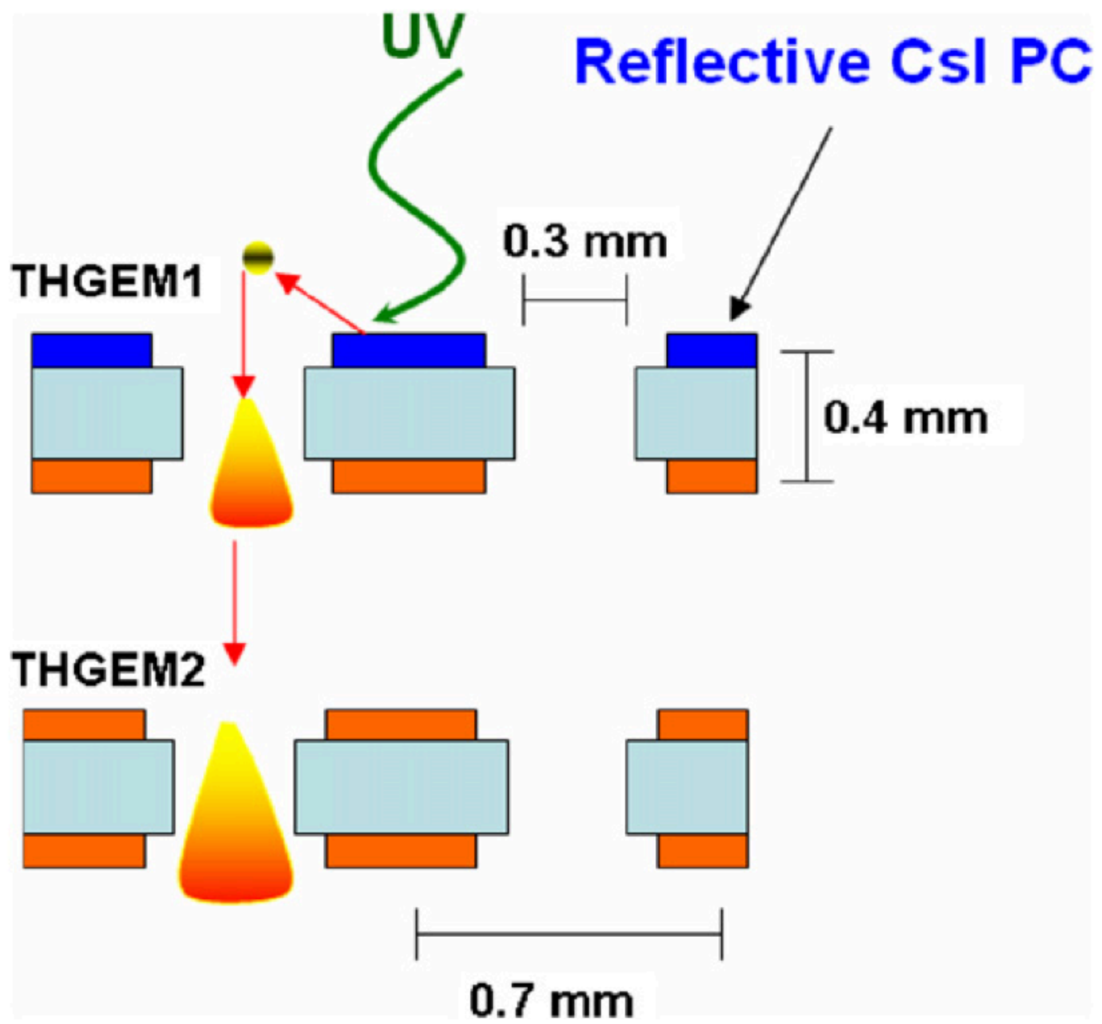
THWELL



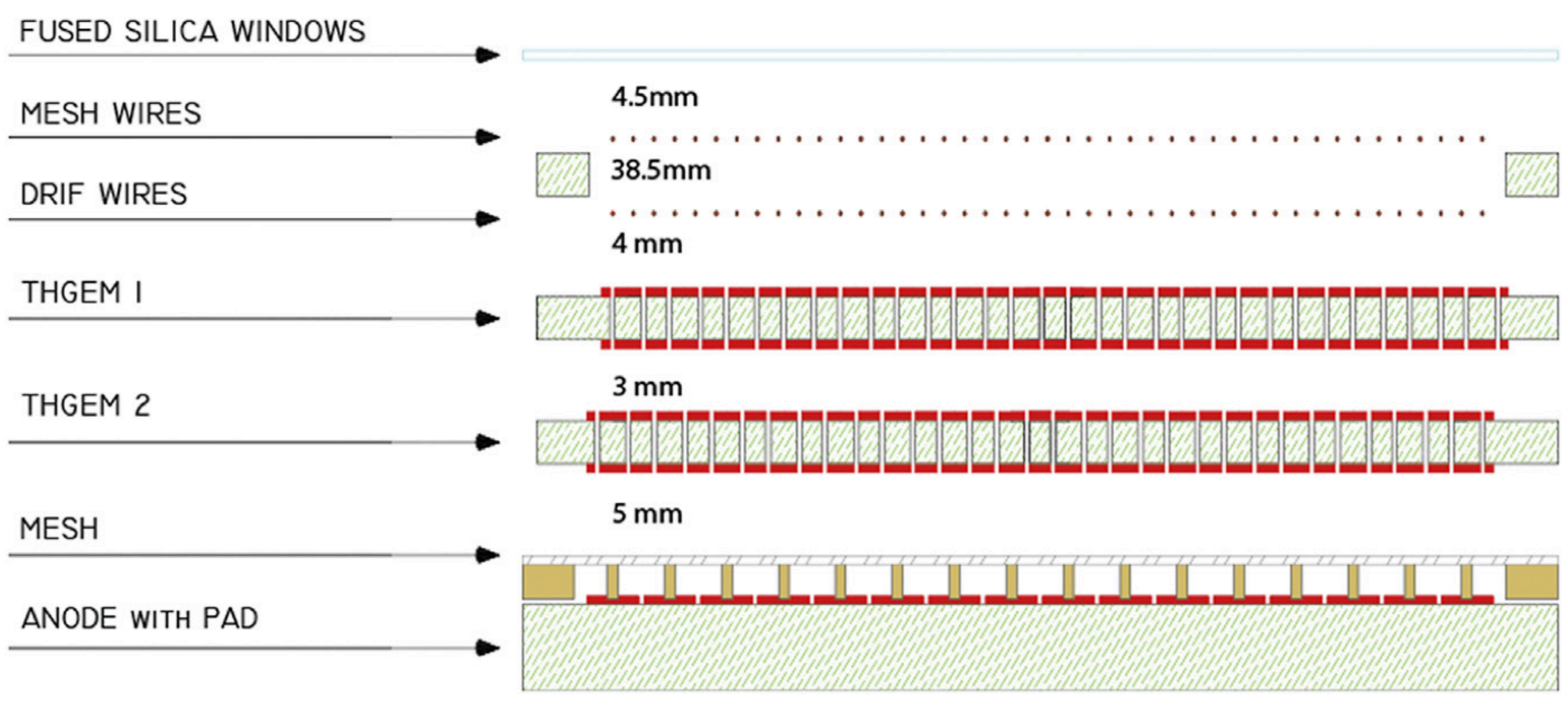
RWELL



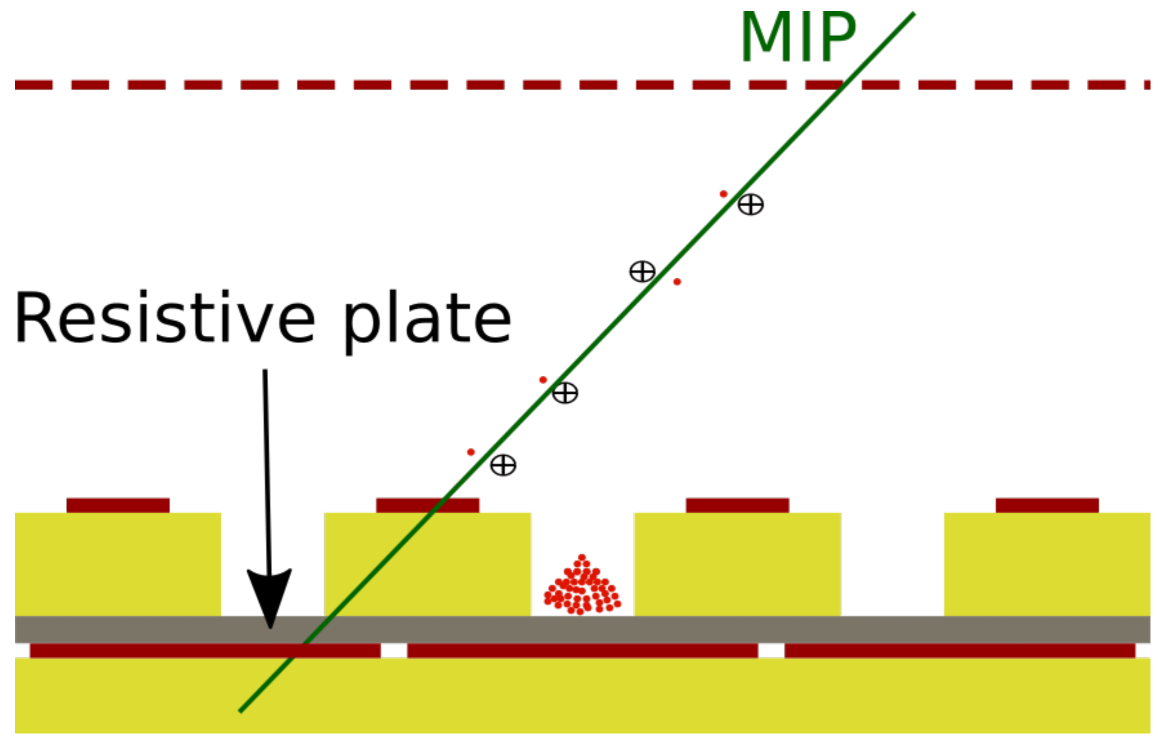
cascaded THGEM



hybrid 2THGEM + MICROMEGAS

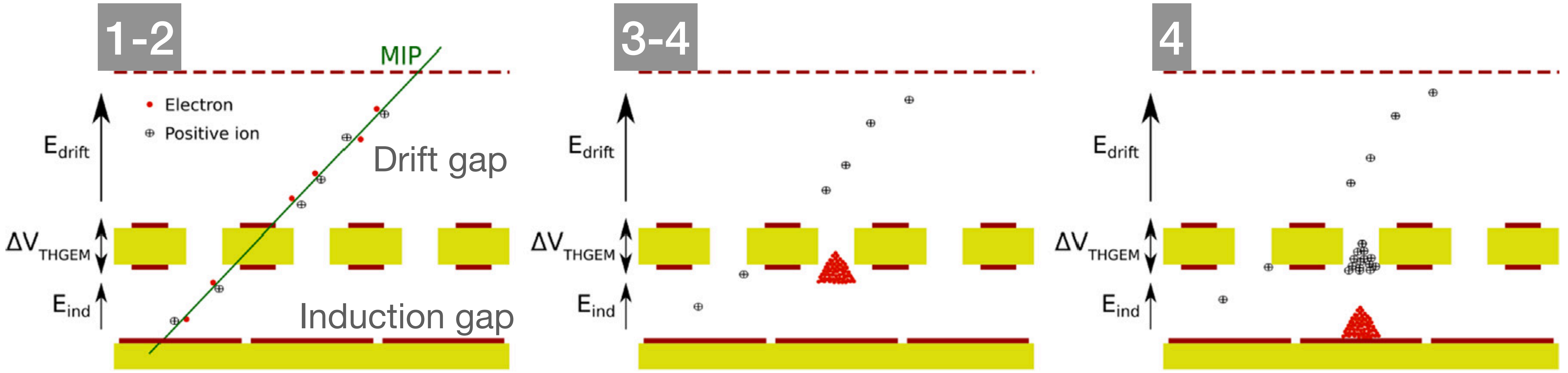


RPWELL

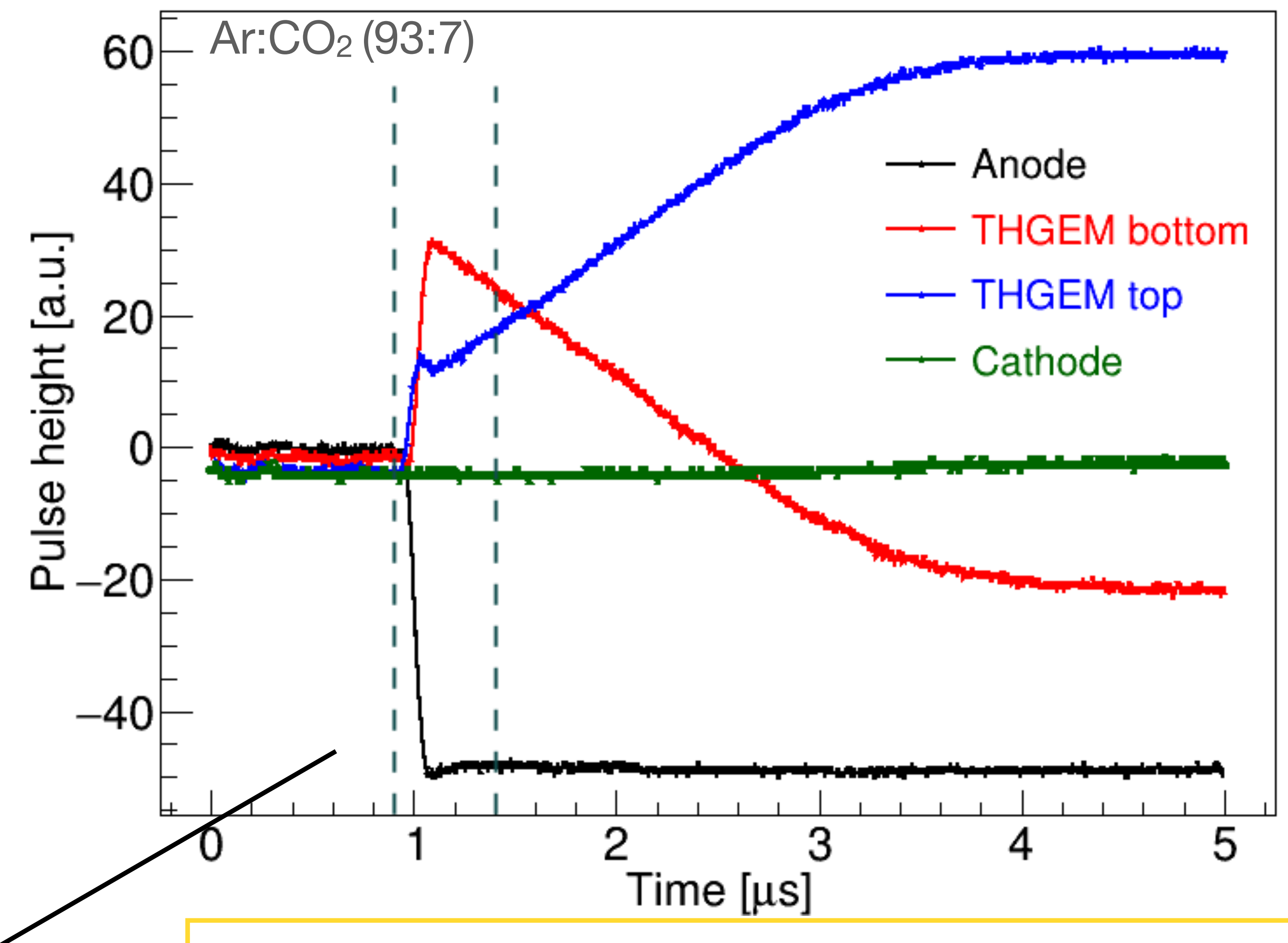


Signal formation in THGEM

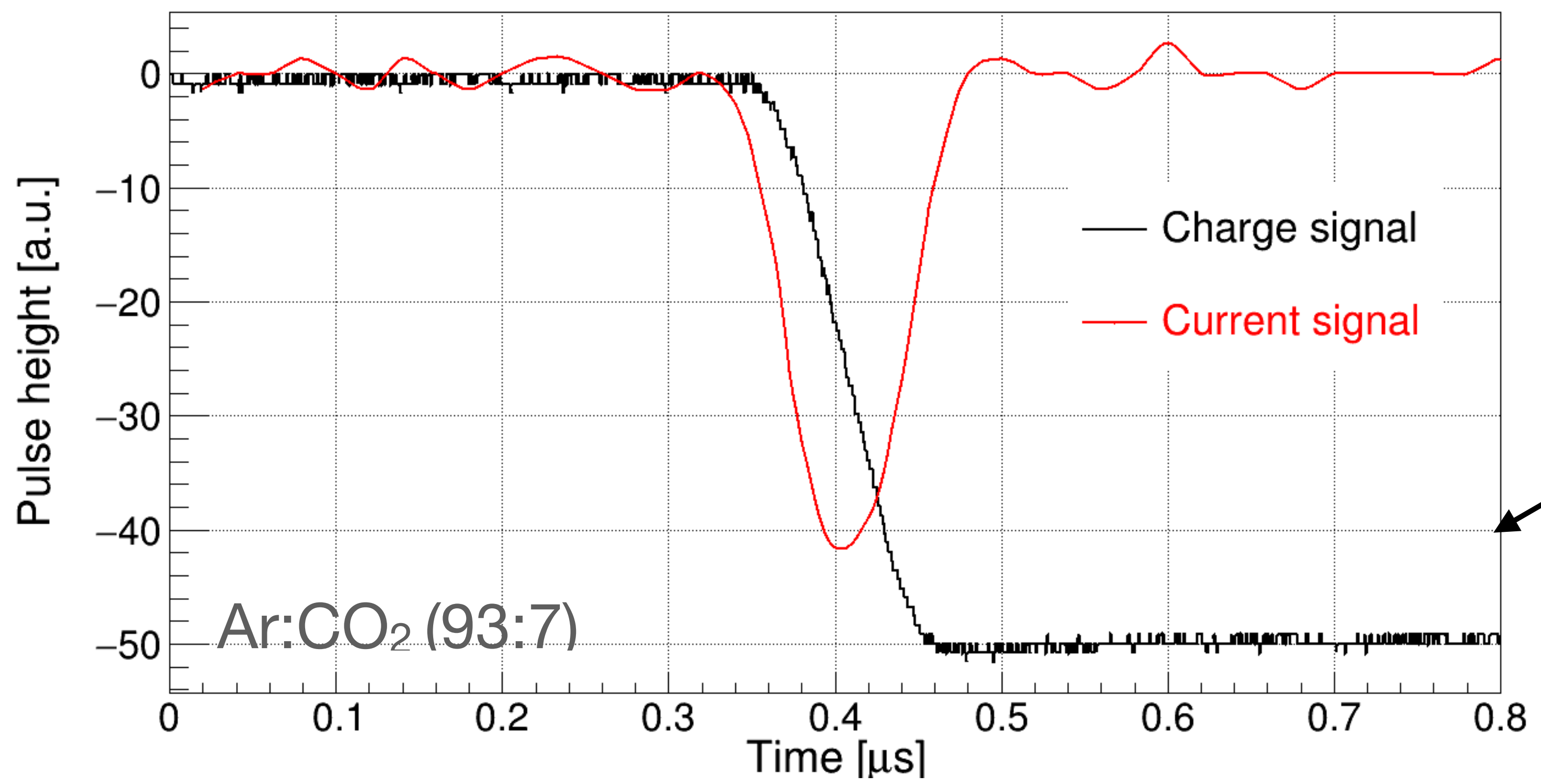
1. Primary ionization in the drift gap
2. Primary electrons drift to the THGEM holes
3. Electron avalanche
4. Signal induction
    - Electrons drift in the induction gap → Fast component
    - Slow ion backflow to the top electrode → Slow component



Integrated charge



Anode signal



The measured signal (current or integrated charge) is always a convolution of the induced current and the response function of the readout electronics

- Excess of electrons. Did ions get stuck in the insulator?
- Bottom signal ≠ 0. Some electrons were collected there?

Operation conditions
Application dependent

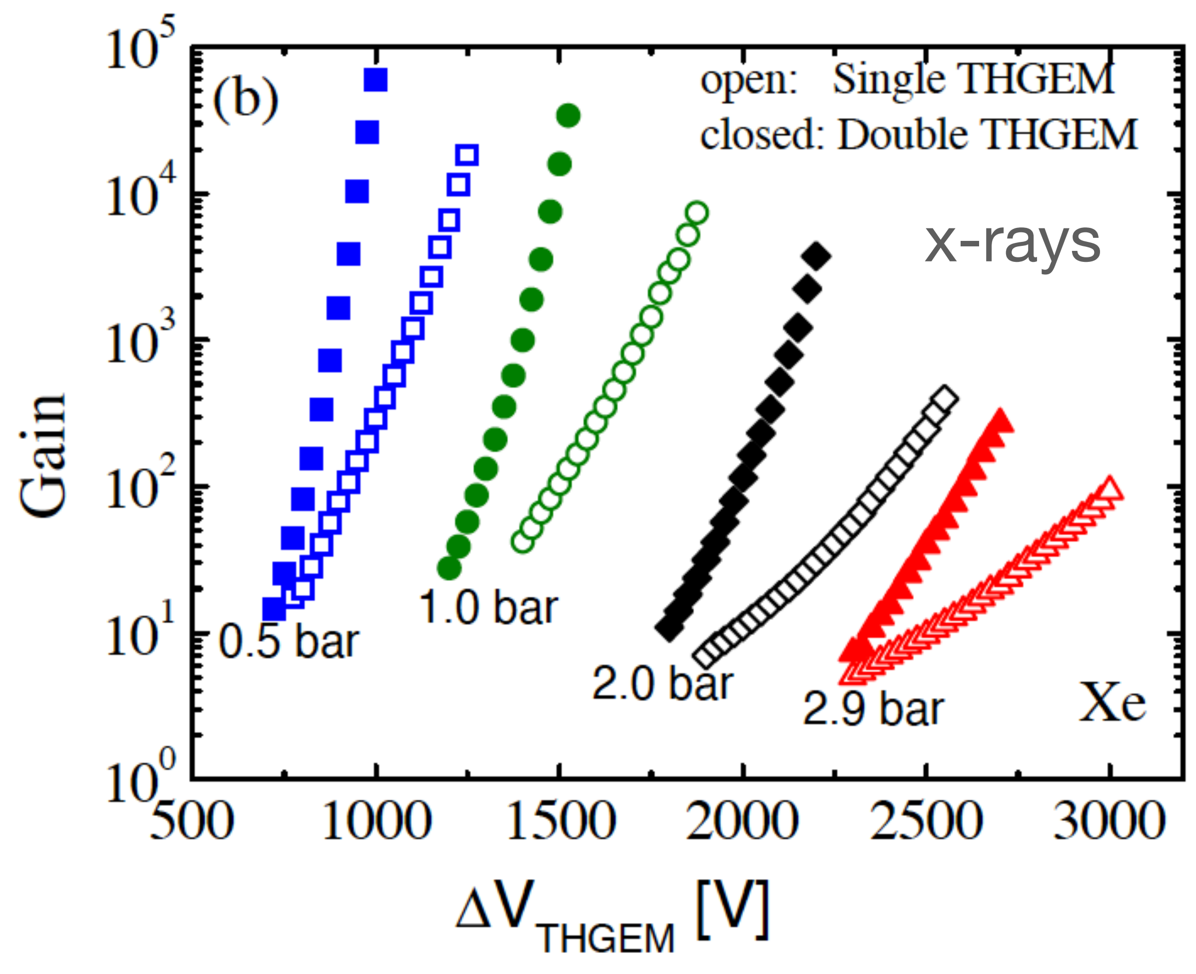
THGEM detectors can operate in a wide range of conditions

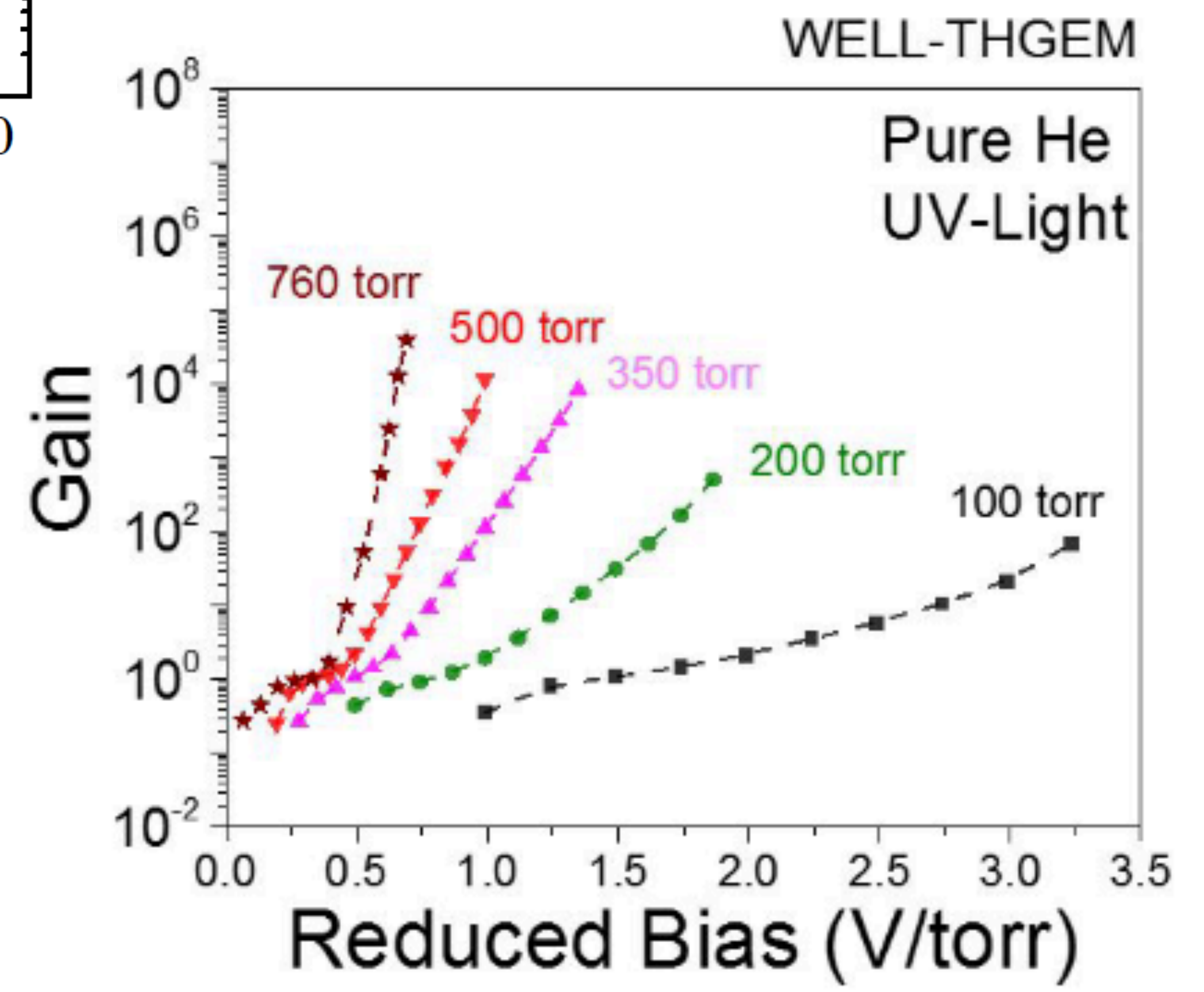
- Gases: pure noble, pure molecular, noble+molecular
- Pressure: from several bar down to 1 mbar (1Torr)
- Temperature: from room temperature down to LAr (~90K)

The most appropriate THGEM geometry and operating conditions are determined by

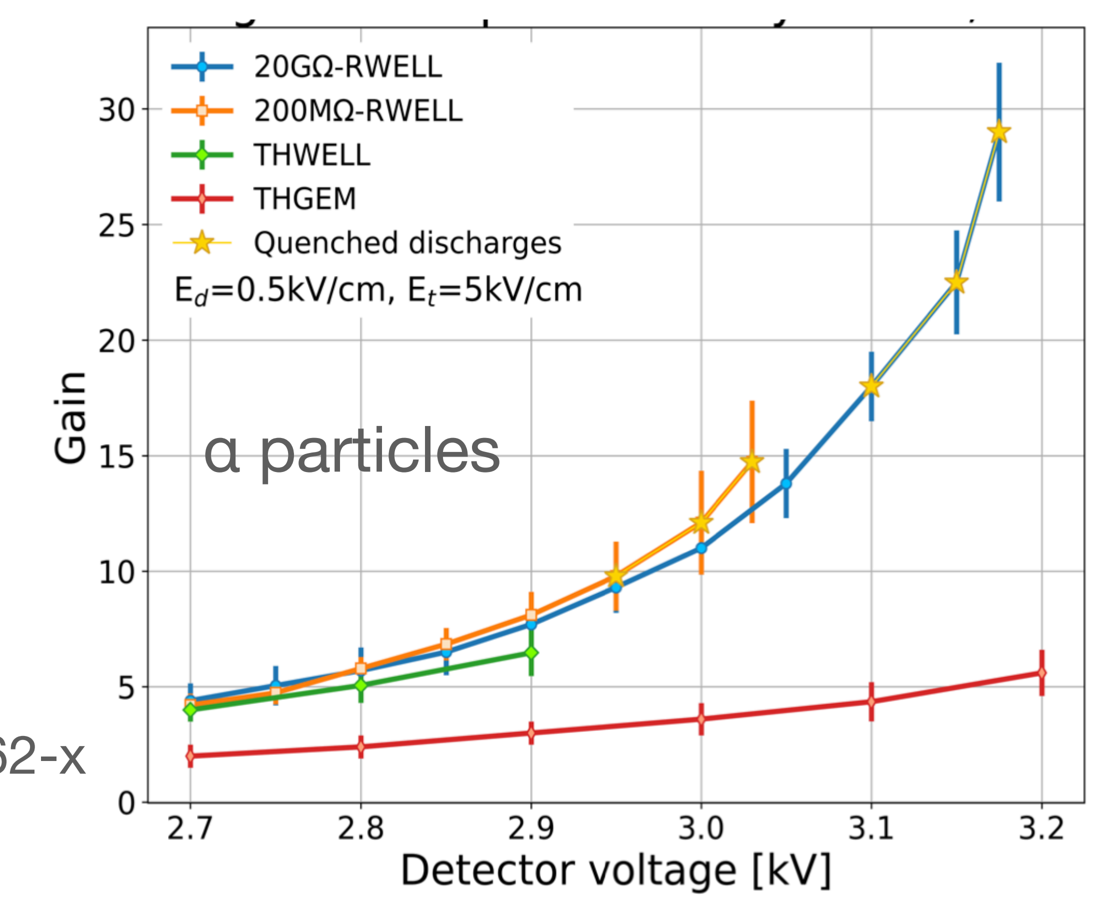
- The nature of the radiation to detect soft x-rays, MIPs, UV photons, α particles, neutrons, β electrons, nuclear fragments, neutral particles, …
- The intensity and energy of the radiation to detect
- The kind of information required by the specific application (e.g. spectroscopy, imaging, counting)

Xe





Ar vapor at 1.2 Bar, 90K



https://doi.org/10.1140/epjc/s10052-023-12162-x

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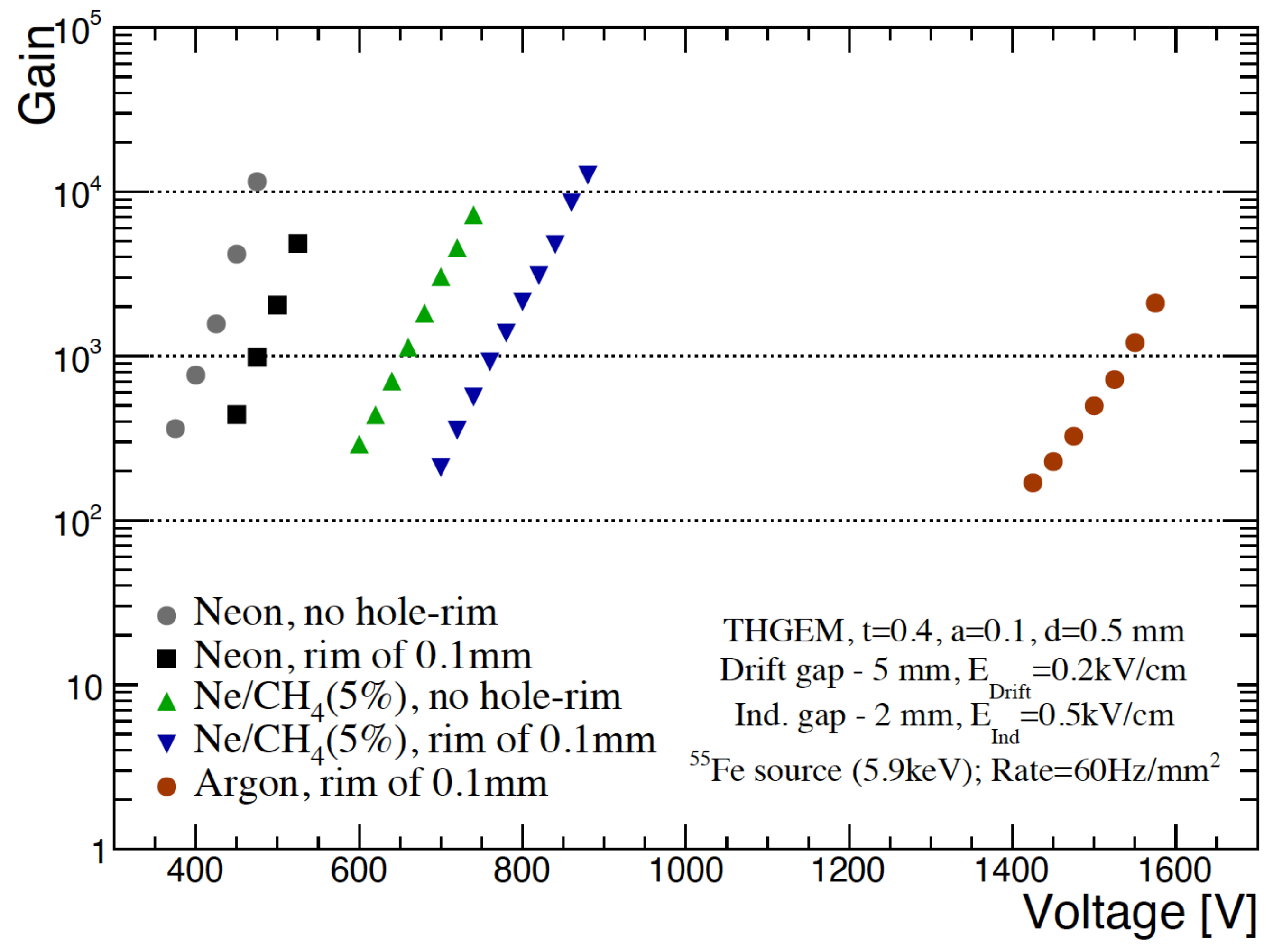
Detector performance

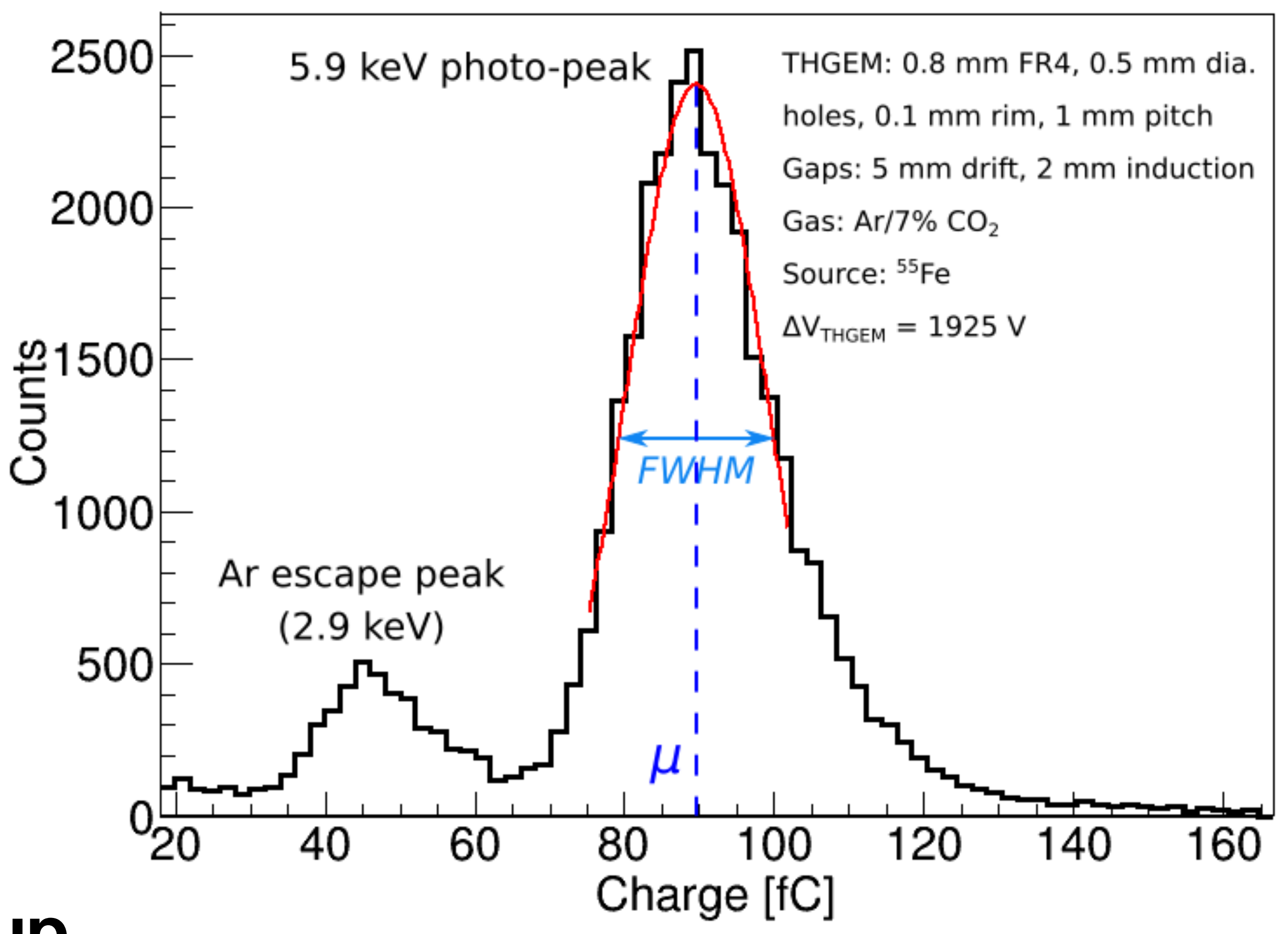
According to the application, the detector performance must be evaluated

- Charge (effective/absolute) gain
- Efficiency
- Spatial resolution
- Energy resolution
- Time resolution
- Uniformity
- Dependance on source rate
- Electrical stability
- Operation stability in time
- Aging

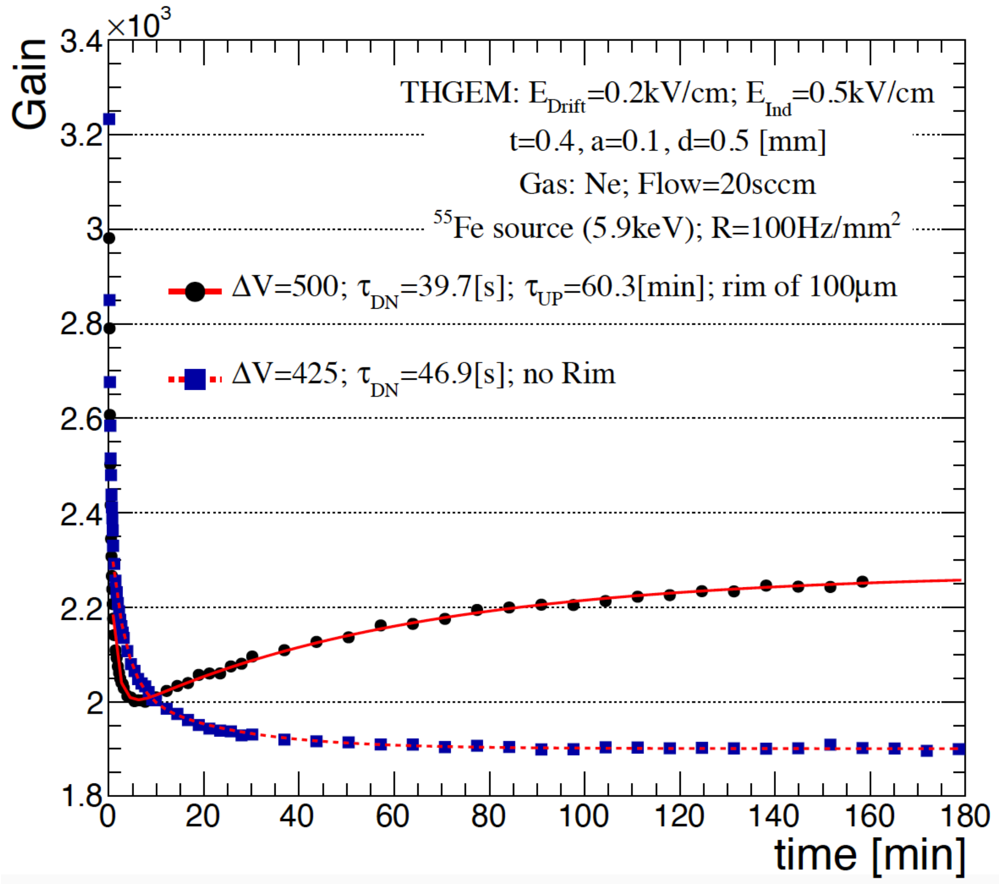
Charge effective gain



Induced signals' distribution (spectrum)



Insulator charging up

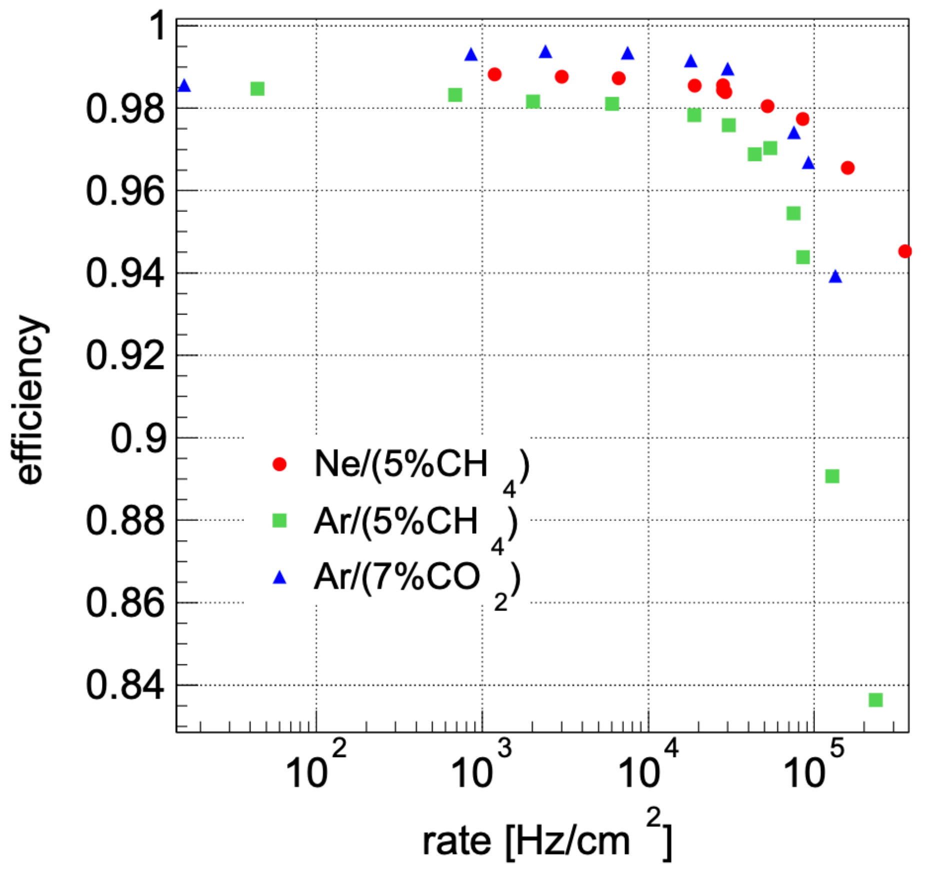


Detector performance

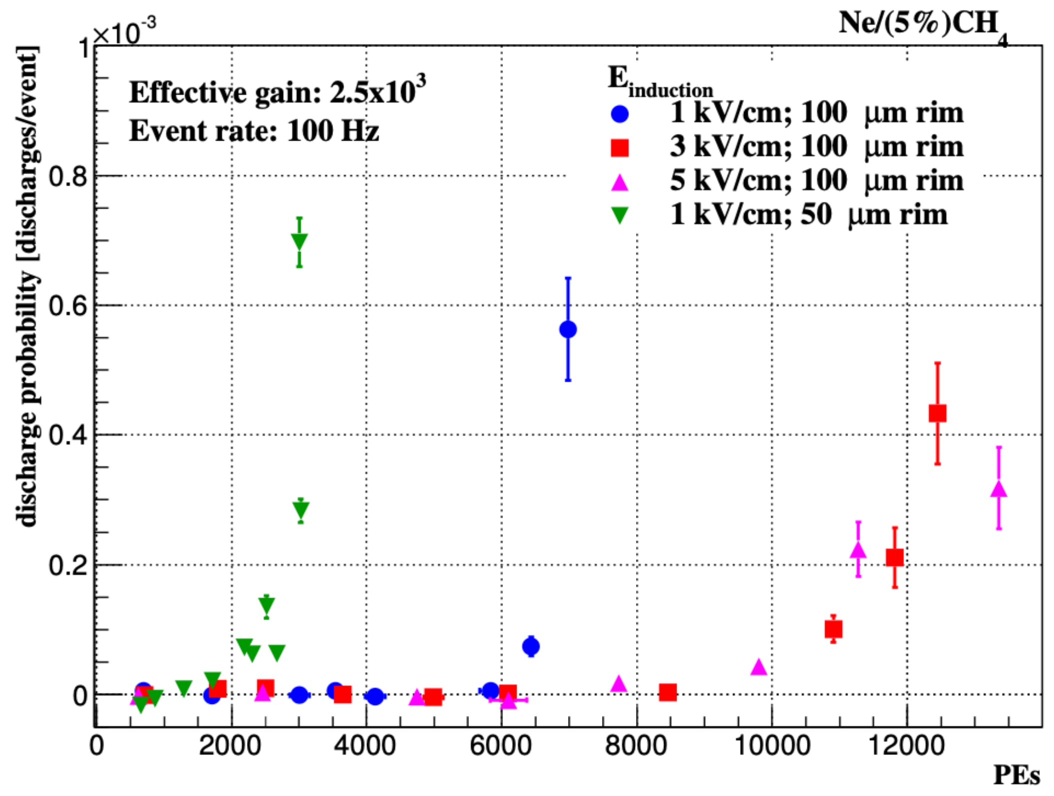
According to the application, the detector performance must be evaluated

- Charge (effective/absolute) gain
- Light yield
- Efficiency
- Spatial resolution
- Energy resolution
- Time resolution
- Uniformity
- Dependance on source rate
- Electrical stability
- Operation stability in time
- Aging

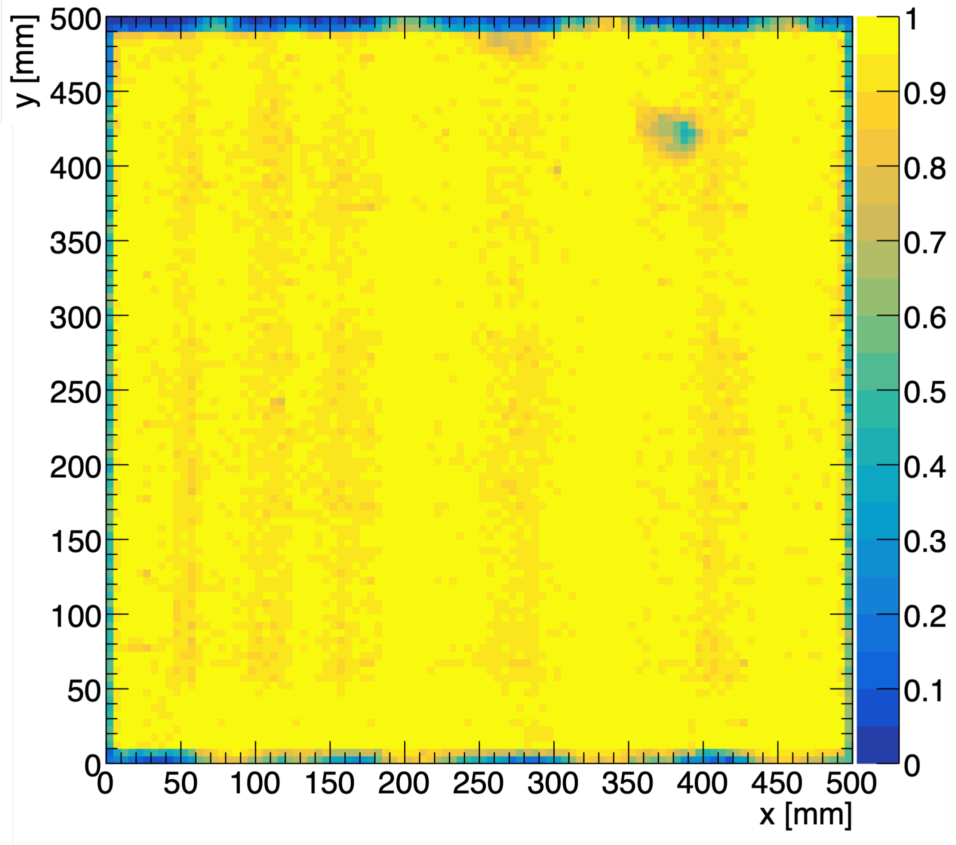
Detection efficiency



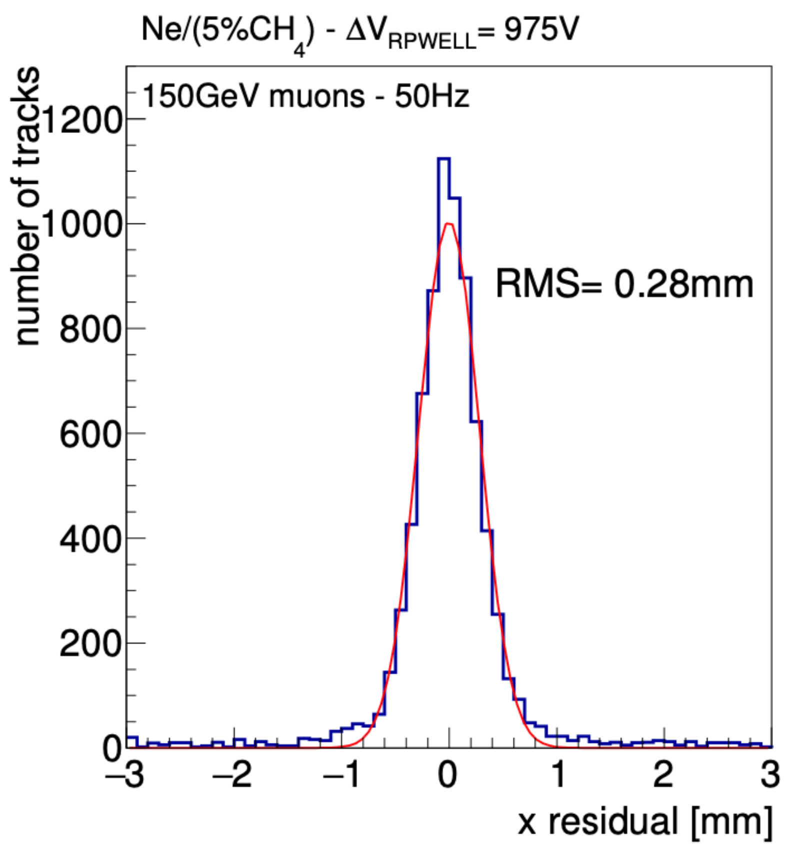
Discharge probability



Uniformity

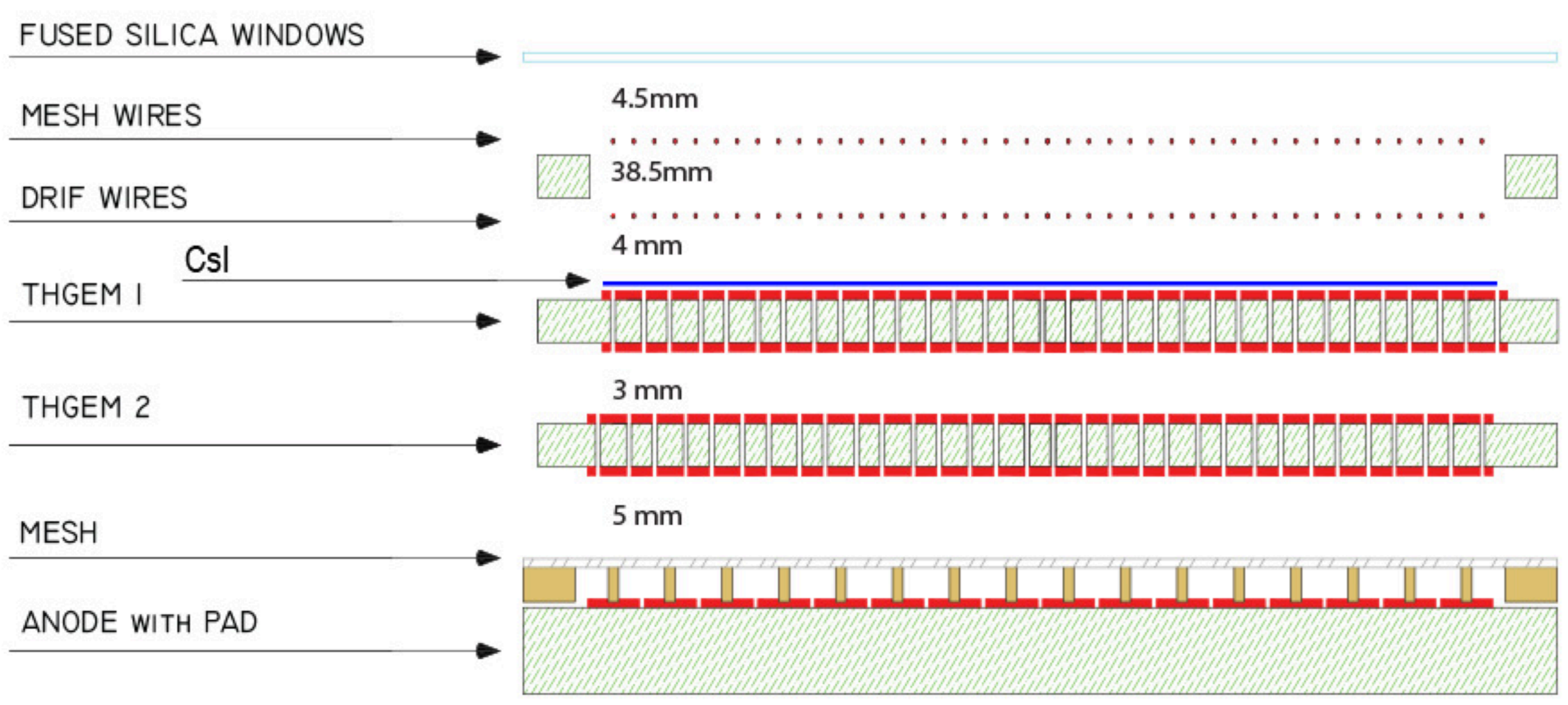


Position resolution

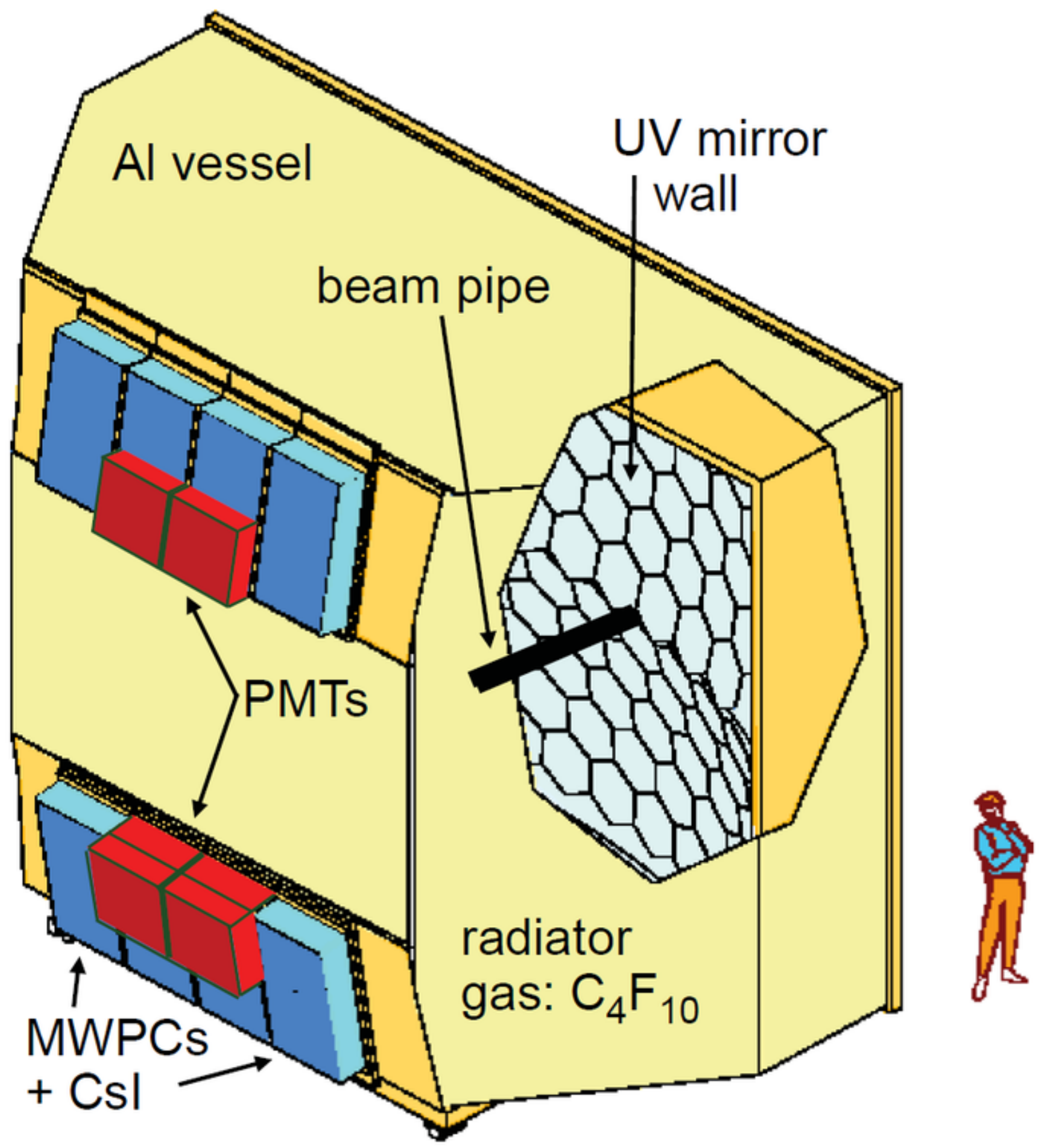


Applications of THGEM

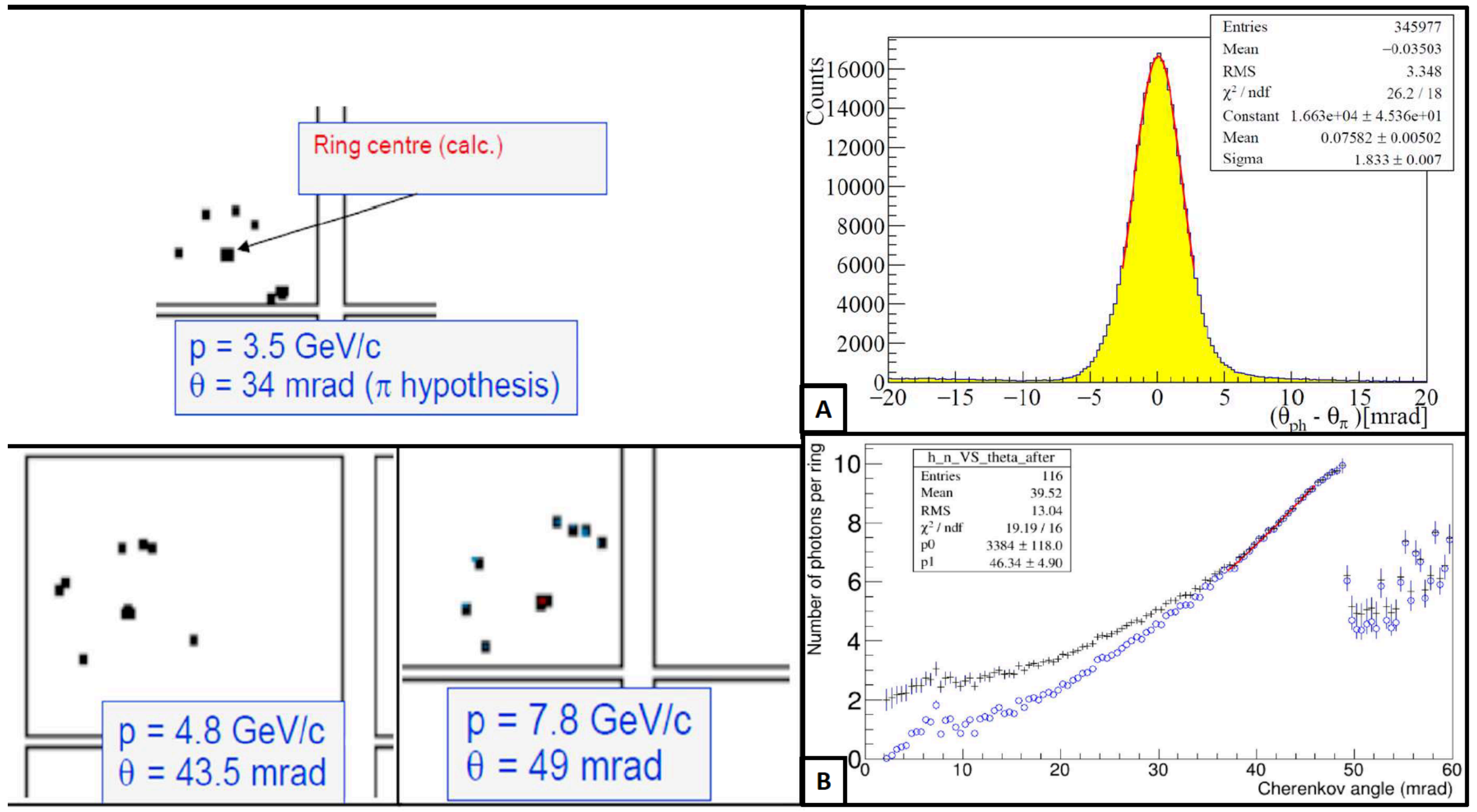
Ring Imaging Cherenkov counter (RICH)

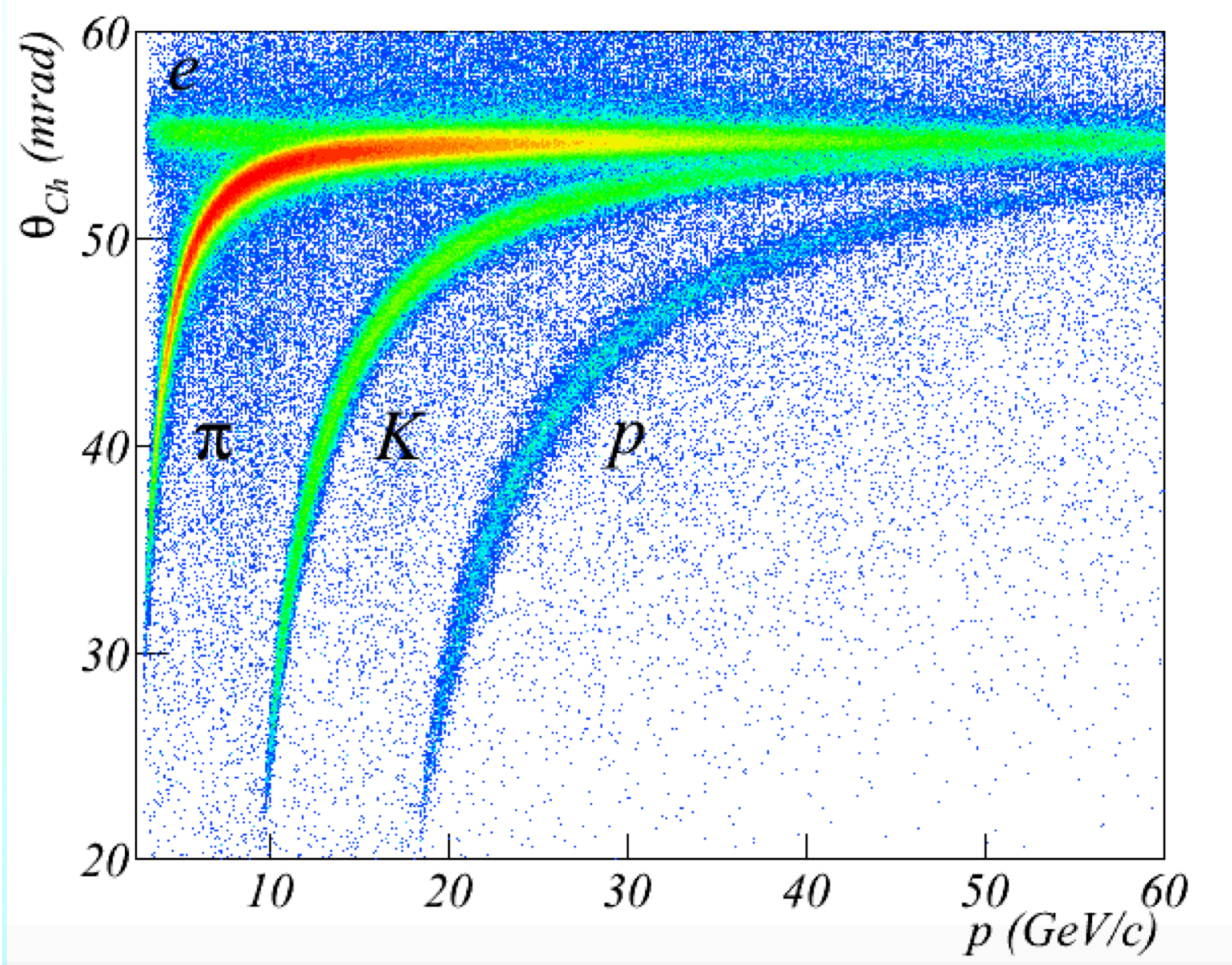


- Single UV photon sensitivity thanks to photocathode
- Particle identification by Cherenkov light cone aperture
- Successful implementation of a hybrid THGEM + Micromegas structure in COMPASS
  - High detection efficiency
  - Low ion backflow



2THGEM+MM @COMPASS RICH



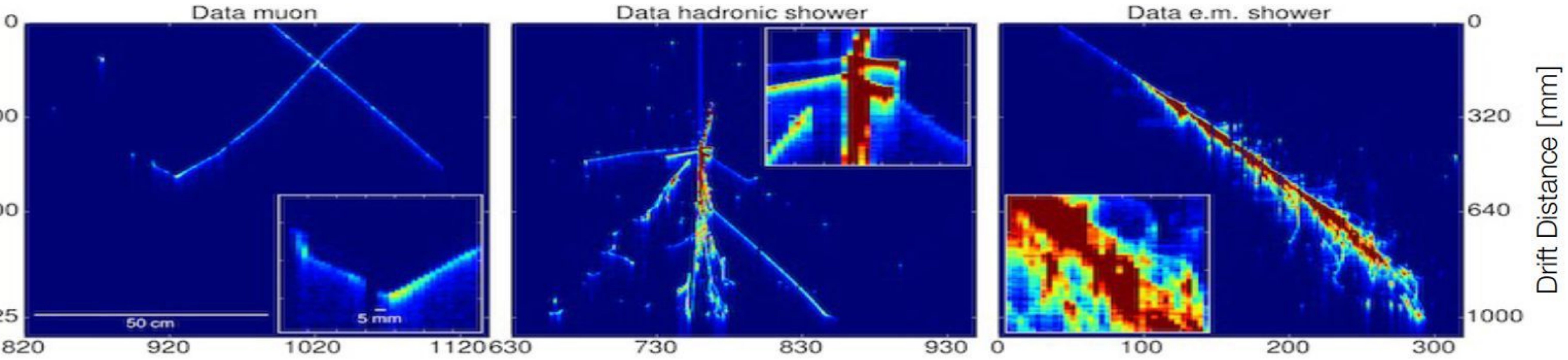


Agarwala, J., et al. "The MPGD-based photon detectors for the upgrade of COMPASS RICH-1 and beyond." NIM A 936 (2019): 416-419.

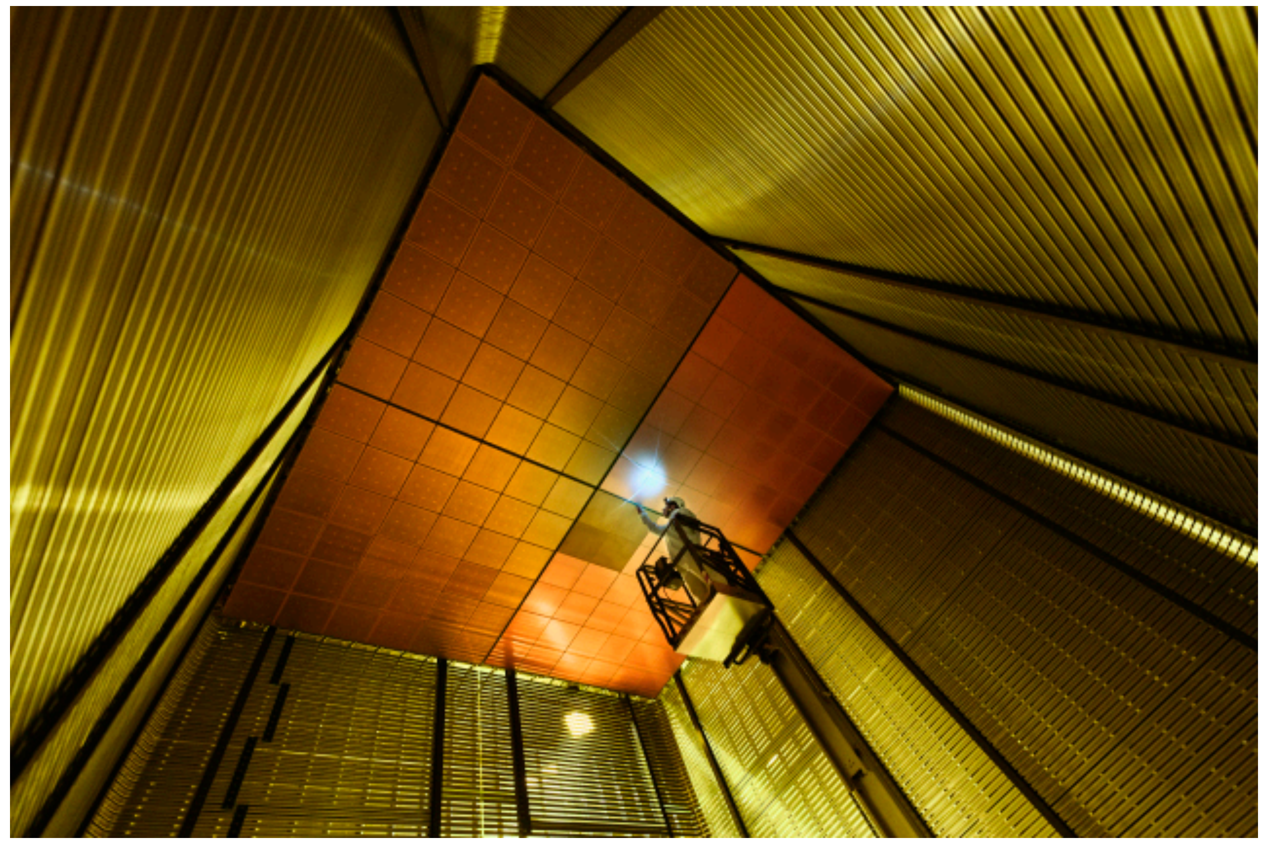
Applications of THGEM

Charge/light readout in noble liquid Time Projection Chambers (TPC)

cosmic events in WA-105



LEM (i.e. THGEM) in proto-DUNE



- Rare event experiments (neutrino, dark matter)
- Main limitations: signal-to-noise, diffusion
- Optical readout vs charge readout
  - Large area coverage with a single light sensor vs large number of readout electronic channels
  - Lower field required to produce scintillation than to multiply electrons
- Dual phase: charge multiplication/scintillation in cryogenic vapor
  → high density, low T effects, liquid-vapor interface
- Single phase: primary charge drift or charge multiplication/scintillation around very thin (μm structures)[1]

Our current developments

- RWELL and RPWELL detectors for dual phase[2]

1) Martinez-Lema, G., et al. "First observation of liquid xenon electroluminescence with a Microstrip Plate." *arXiv preprint arXiv:2312.14663* (2023).

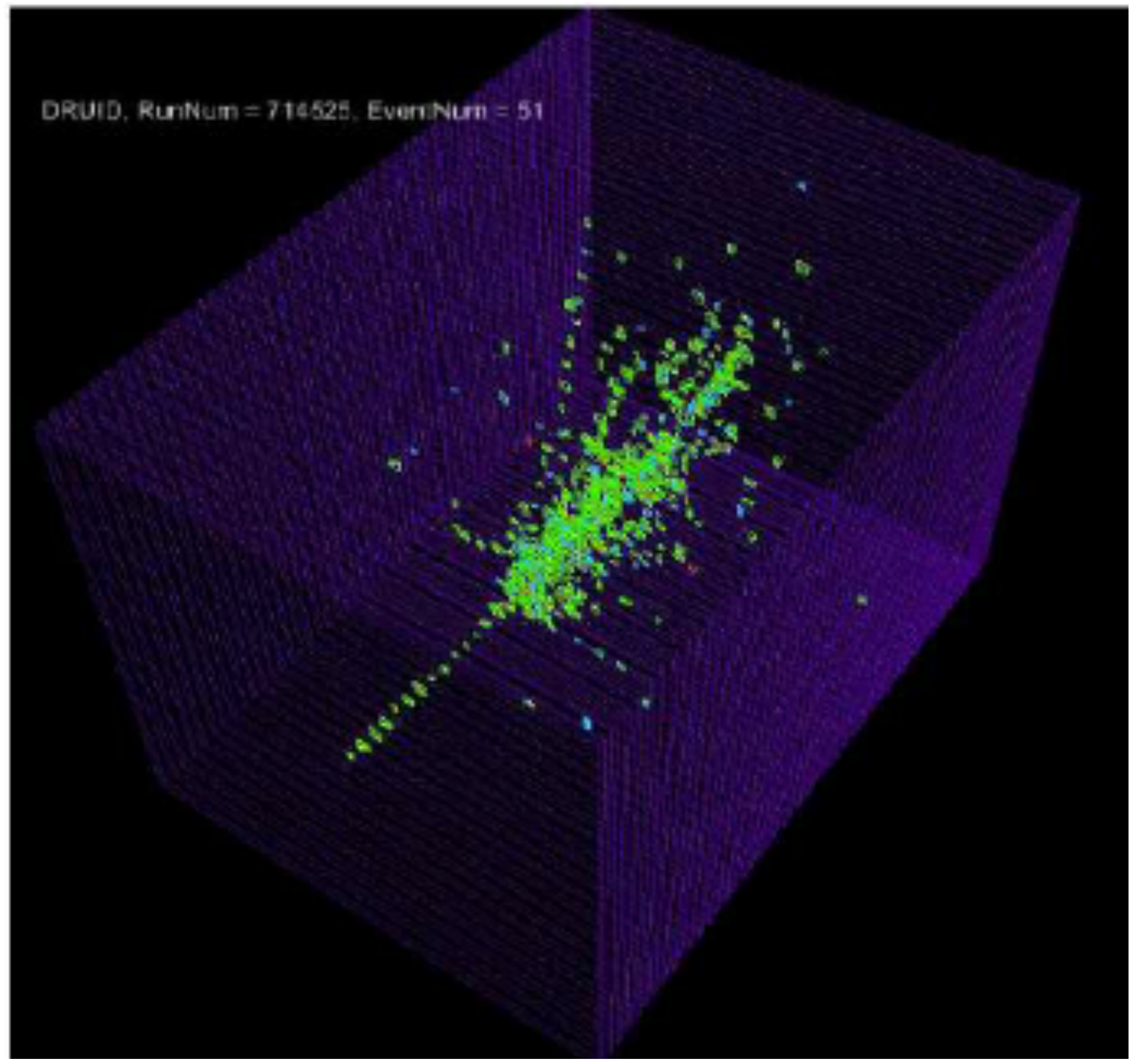
2)Tesi, A., et al. "Novel resistive charge-multipliers for dual-phase LAr-TPCs: towards stable operation at higher gains." *Journal of Instrumentation* 18.06 (2023): C06017.

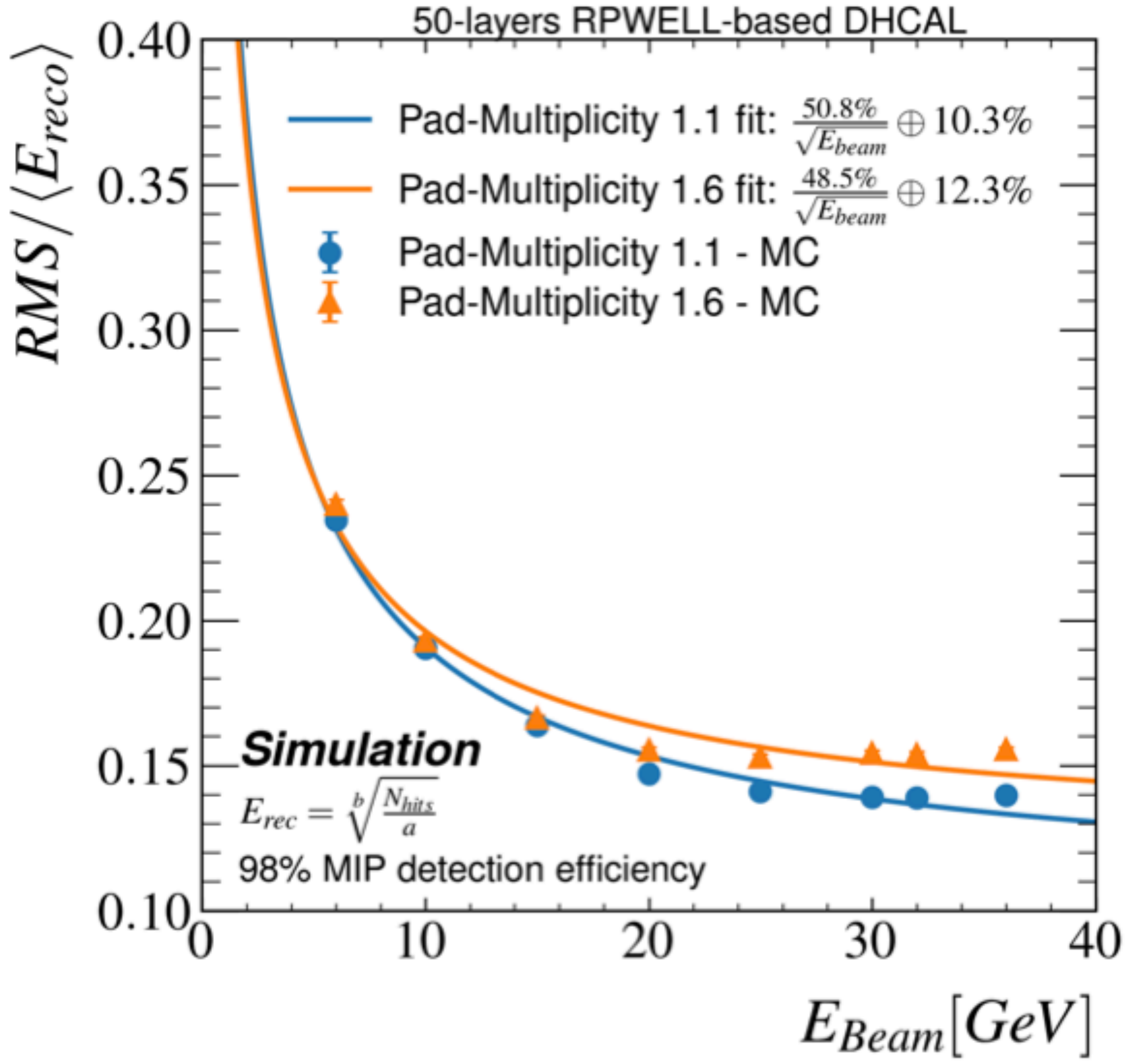
Applications of THGEM

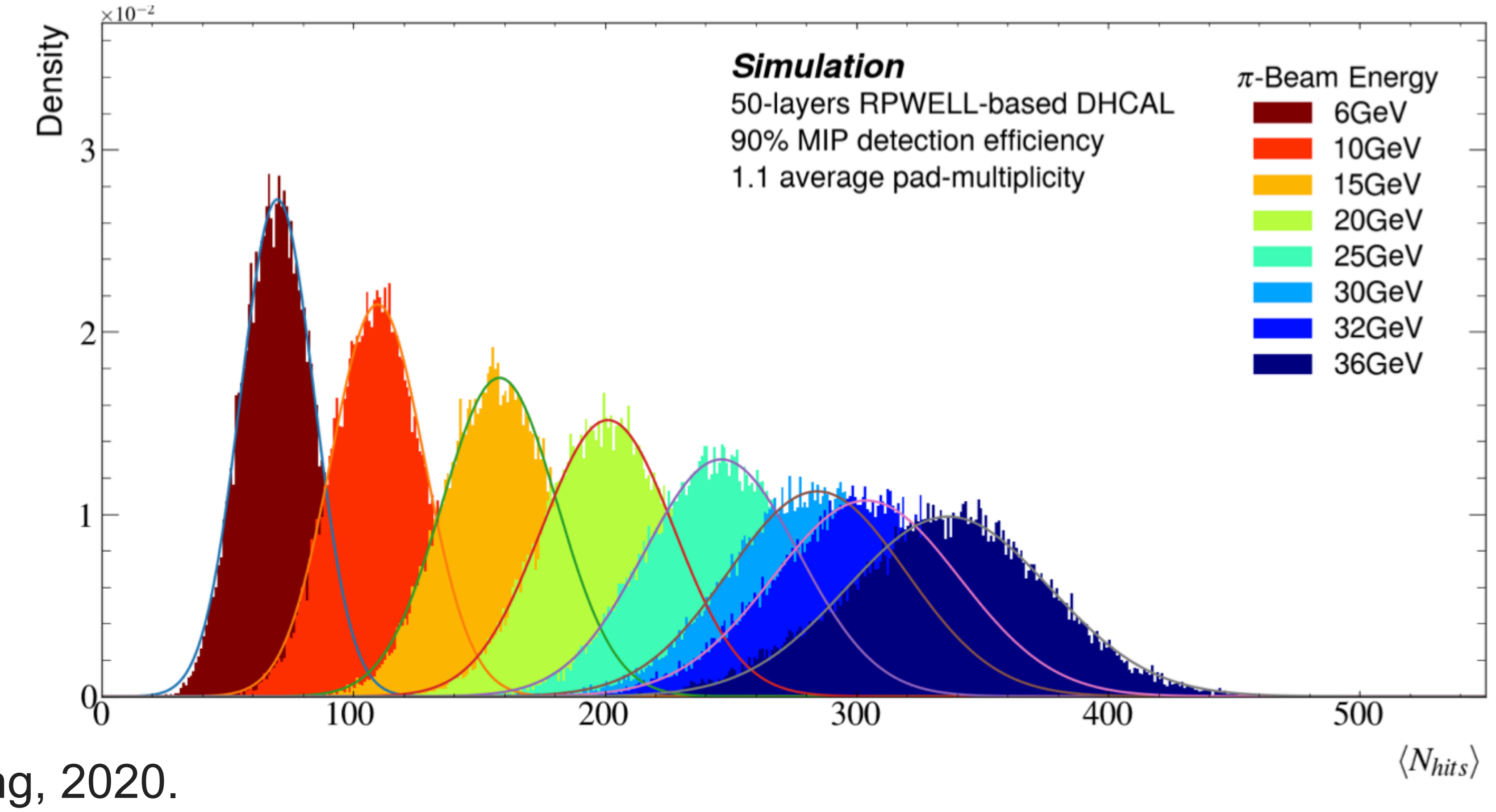
(semi) Digital Hadron Calorimetry

- Particle flow approach
    - Energy deposits in the calorimeters are associated to charged particle tracks or reconstructed as neutral particles
    - Charged particles are measured with the precision of the tracker
    - The energy of neutral particles is estimated from the number of associated hits
- Highly segmented sampling calorimeter to grant correct association of hits to particle
- Very large total area of thin sampling elements
- We are developing RPWELL with semi-digital readout as a candidate technology

simulated shower in DHCAL







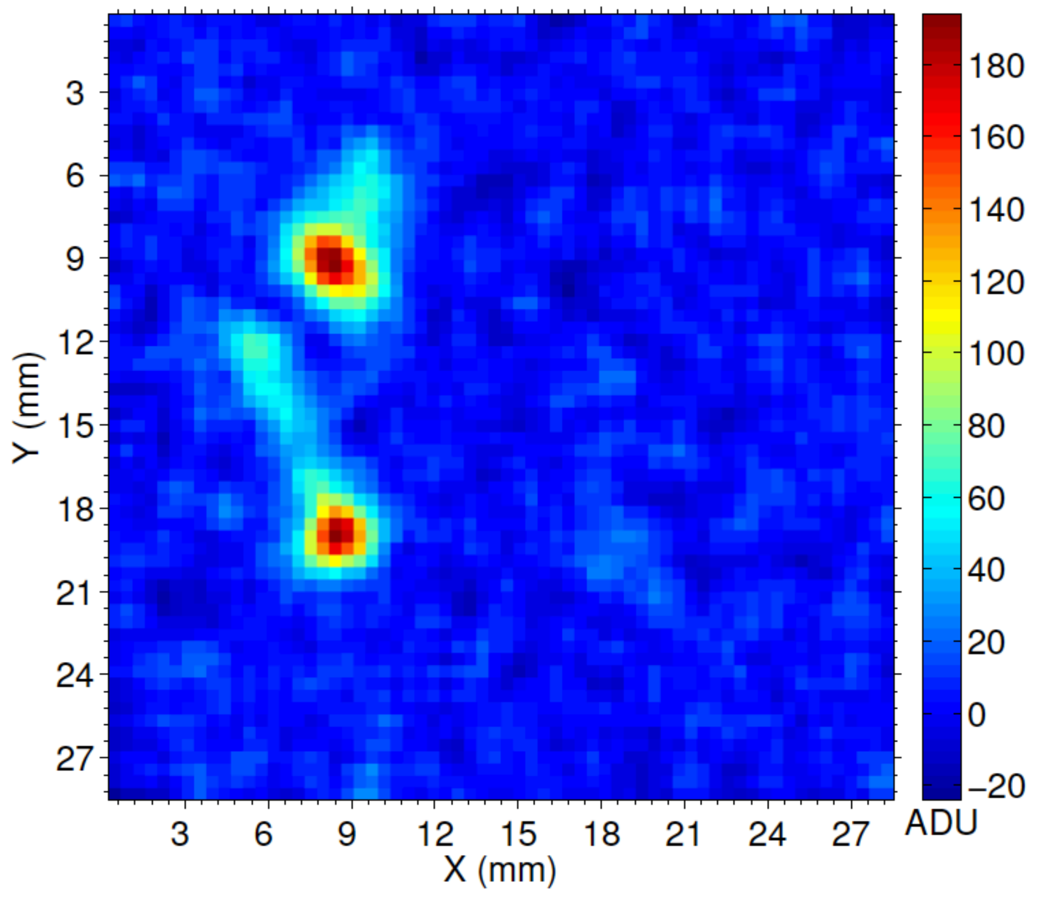
Renous, D. Shaked, et al. "Towards MPGD-based (S) DHCAL." *Journal of Physics: Conference Series*. Vol. 1498. No. 1. IOP Publishing, 2020.
Zavazieva, D., et al. "Towards a large-area RPWELL detector: design optimization and performance." *Journal of Instrumentation* 18.08 (2023): P08009.

Applications of THGEM

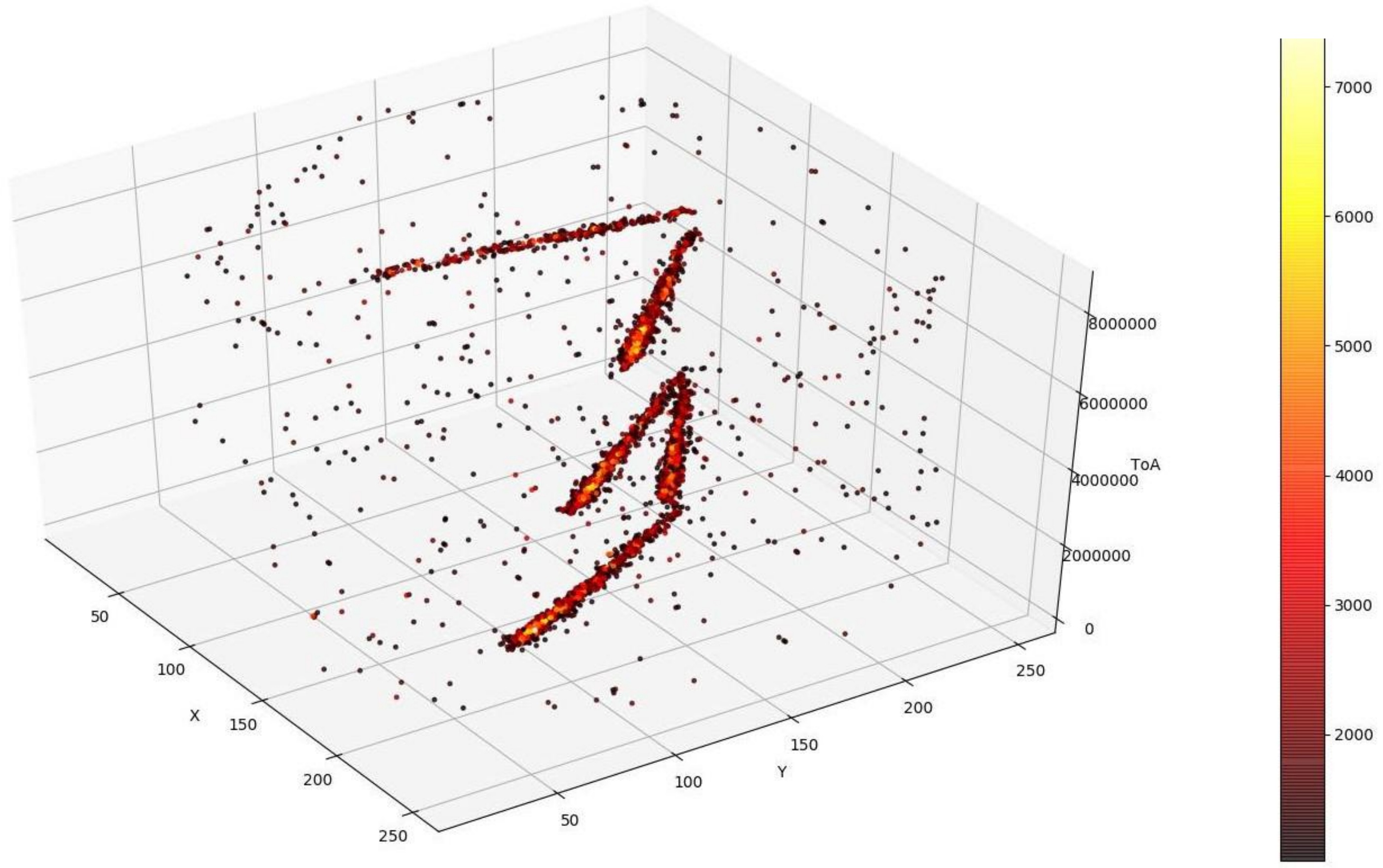
Low-pressure TPCs for low energy tracking

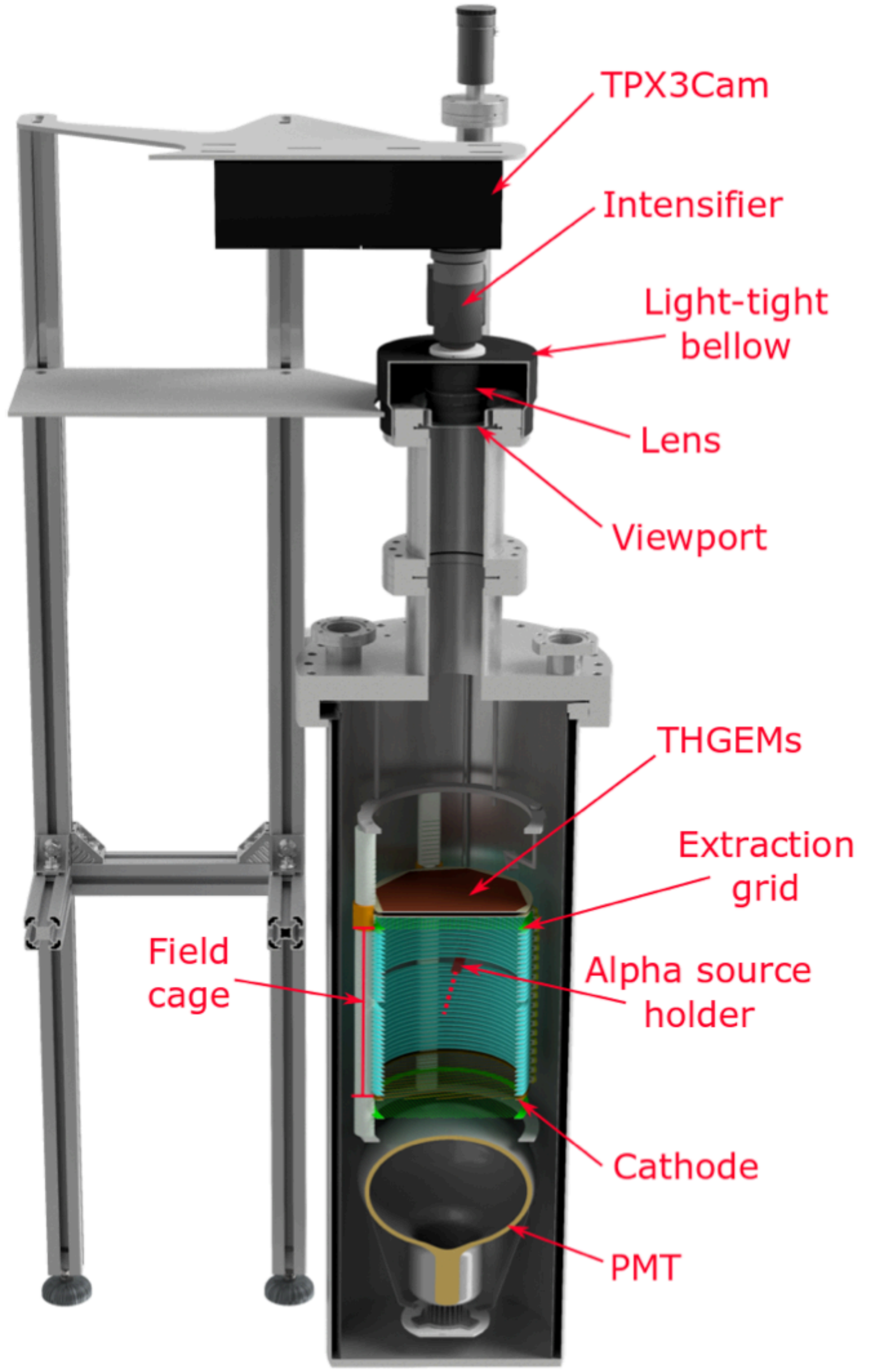
- Low energy particles (x-rays, electrons, nuclear recoils, nuclear reaction products, …) are seen as tracks at low pressure
- TPC with optical readout from 1THGEM and 2THGEM scintillation
- A similar concept can be applied to x-ray polarimetry, directional dark matter, nano-dosimetry, geology and nuclear experiments

soft x-ray tracks in 25 Torr CF_4



α particle tracks in 75 Torr CF_4



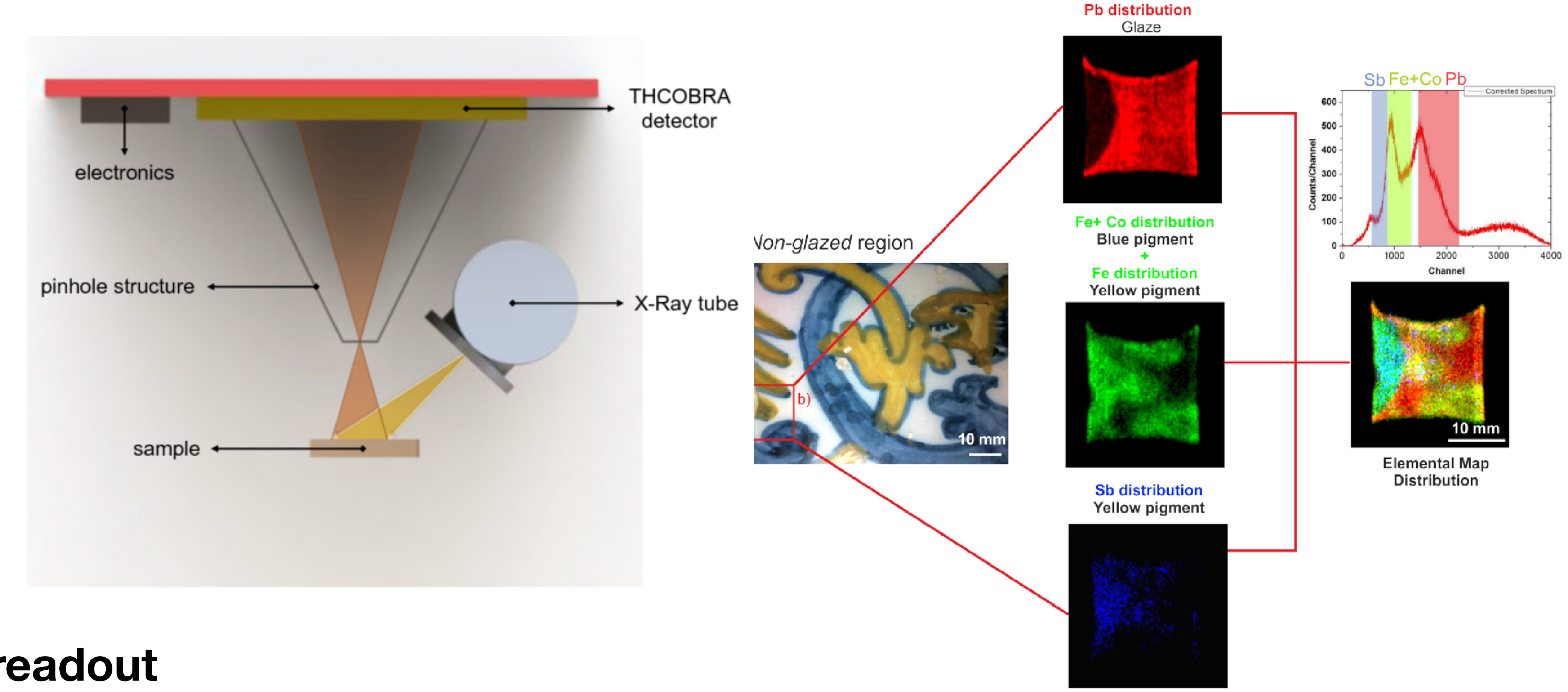


Roberts, Adam, et al. "First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera." *JINST* 14.06 (2019): P06001.

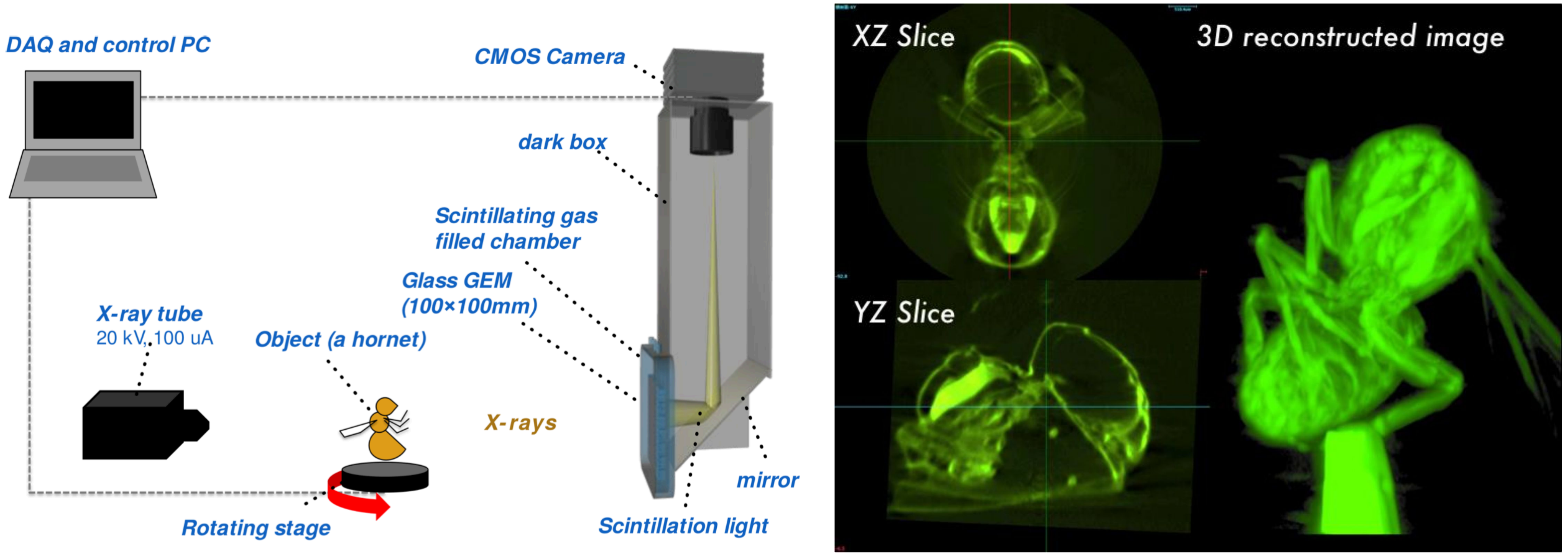
Applications of THGEM
x-ray imaging

- Non-invasive inspection of materials
- Elemental imaging
- Wide range of scientific and civil applications

x-ray elemental imaging with THCOBRA



CT scan with THGEM optical readout

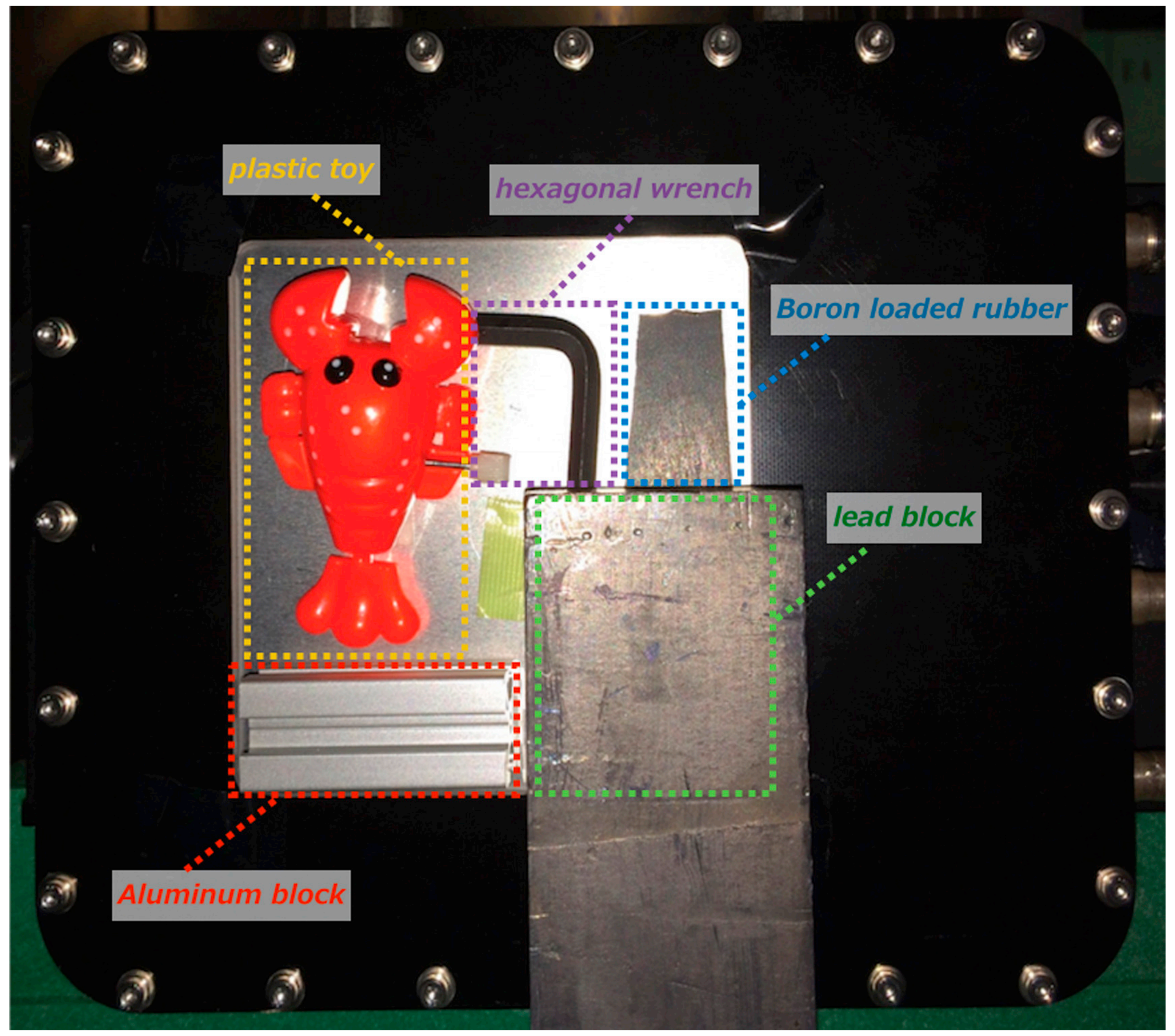


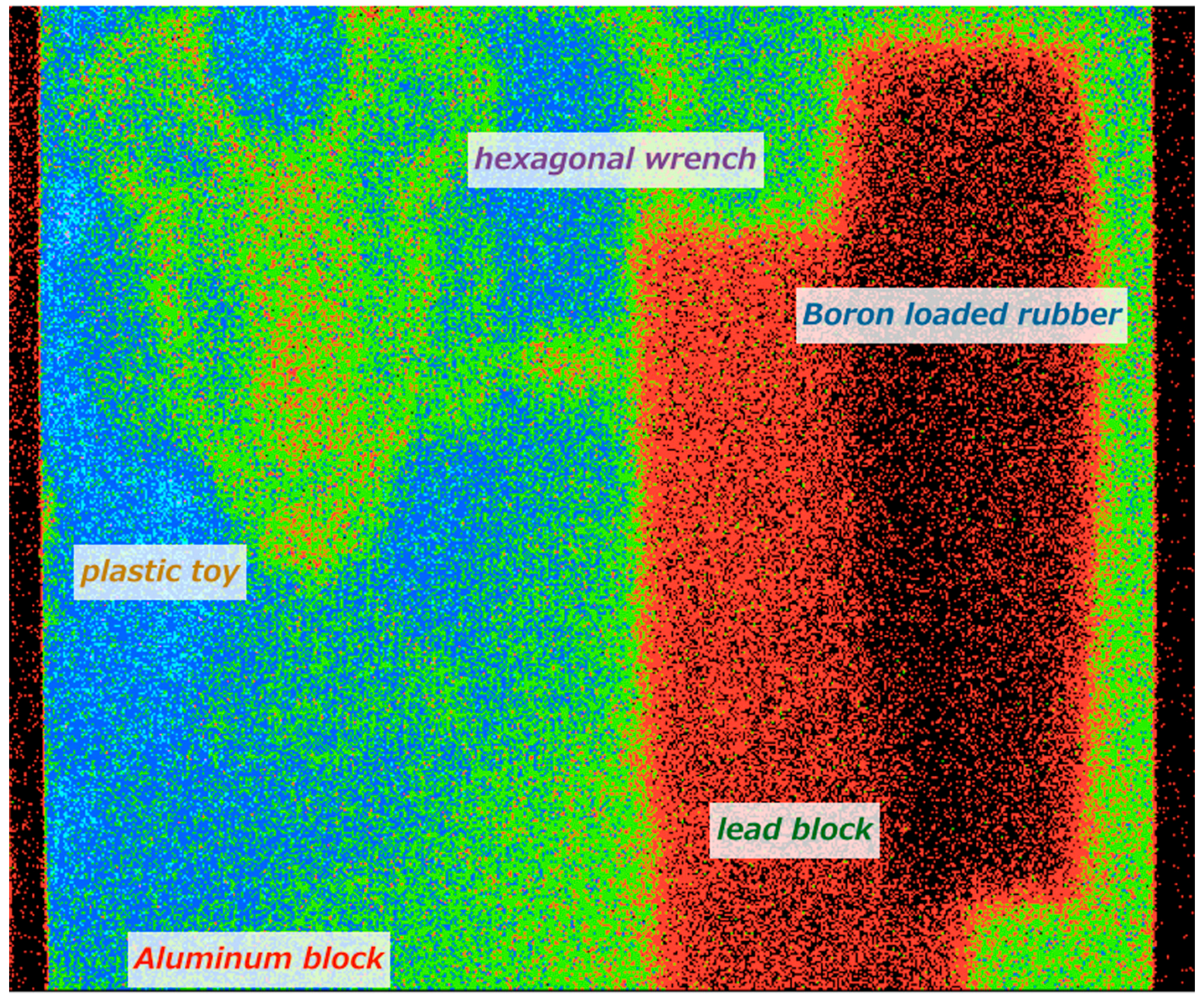
Fujiwara, T., et al. "Demonstration of soft X-ray 3D scanning and modeling with a glass gas electron multiplier." *Journal of Instrumentation* 14.11 (2019): P11022.
Veloso, J. F. C. A., and A. L. M. Silva. "Gaseous detectors for energy dispersive X-ray fluorescence analysis." NIM A 878 (2018): 24-39.

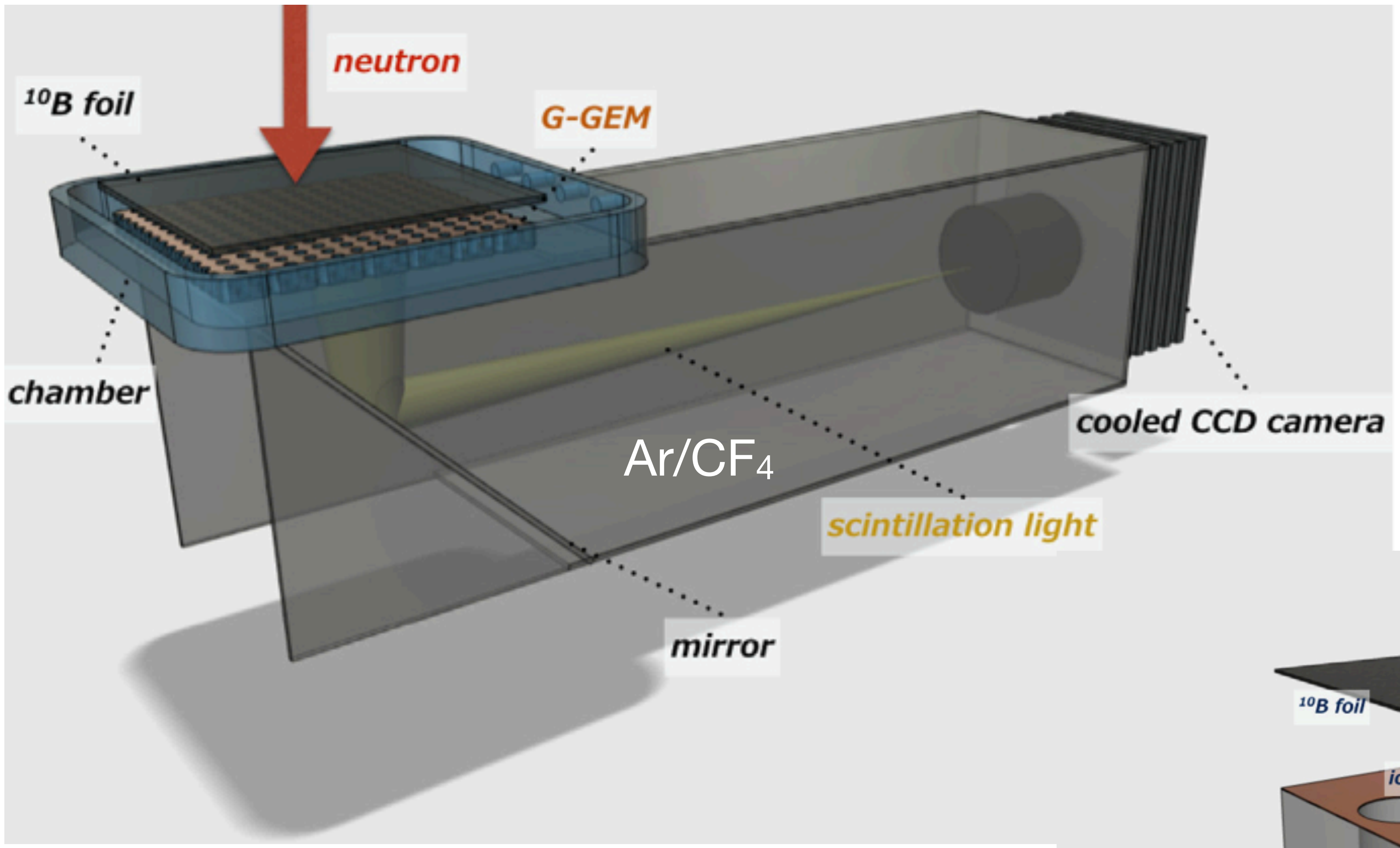
Applications of THGEM
neutron imaging

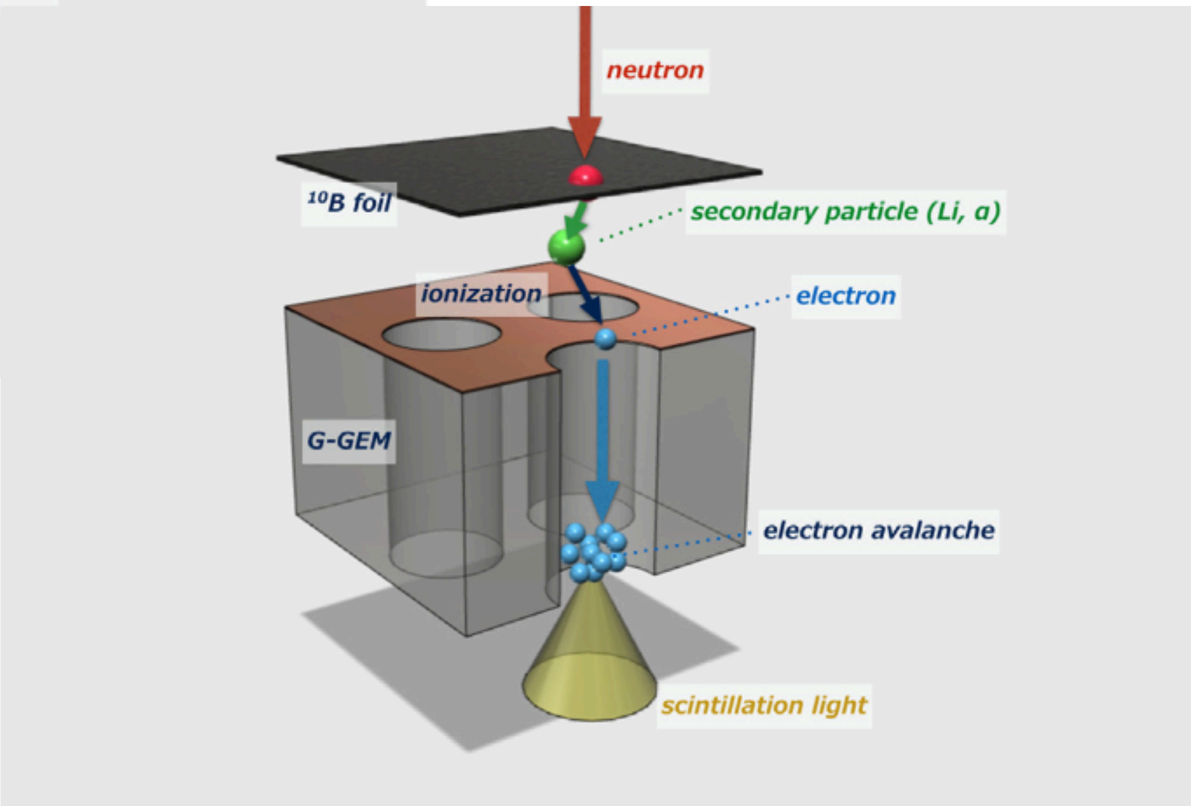
- Slow and fast neutrons for material identification
- For slow neutrons need coupling with converter (e.g. n + ^{10}B → ^{7}Li* + ^{4}He)
- Applications in safety and contraband detection
- Advantage: gaseous detectors are less sensitive to gamma background

neutron radiography with optical readout THGEM









Fujiwara, Takeshi, et al. "Microstructured boron foil scintillating G-GEM detector for neutron imaging." NIM A 838 (2016): 124-128.

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Challenges and future developments

for the gaseous detector community

- Novel detector concepts
- Gas and material studies
  (e.g. ecofriendly gases, resistive materials)
- Detector physics, simulations and software tools
- Electronics for gaseous detectors
- Detector production
- Common test facilities
- Training and dissemination

→

Applications

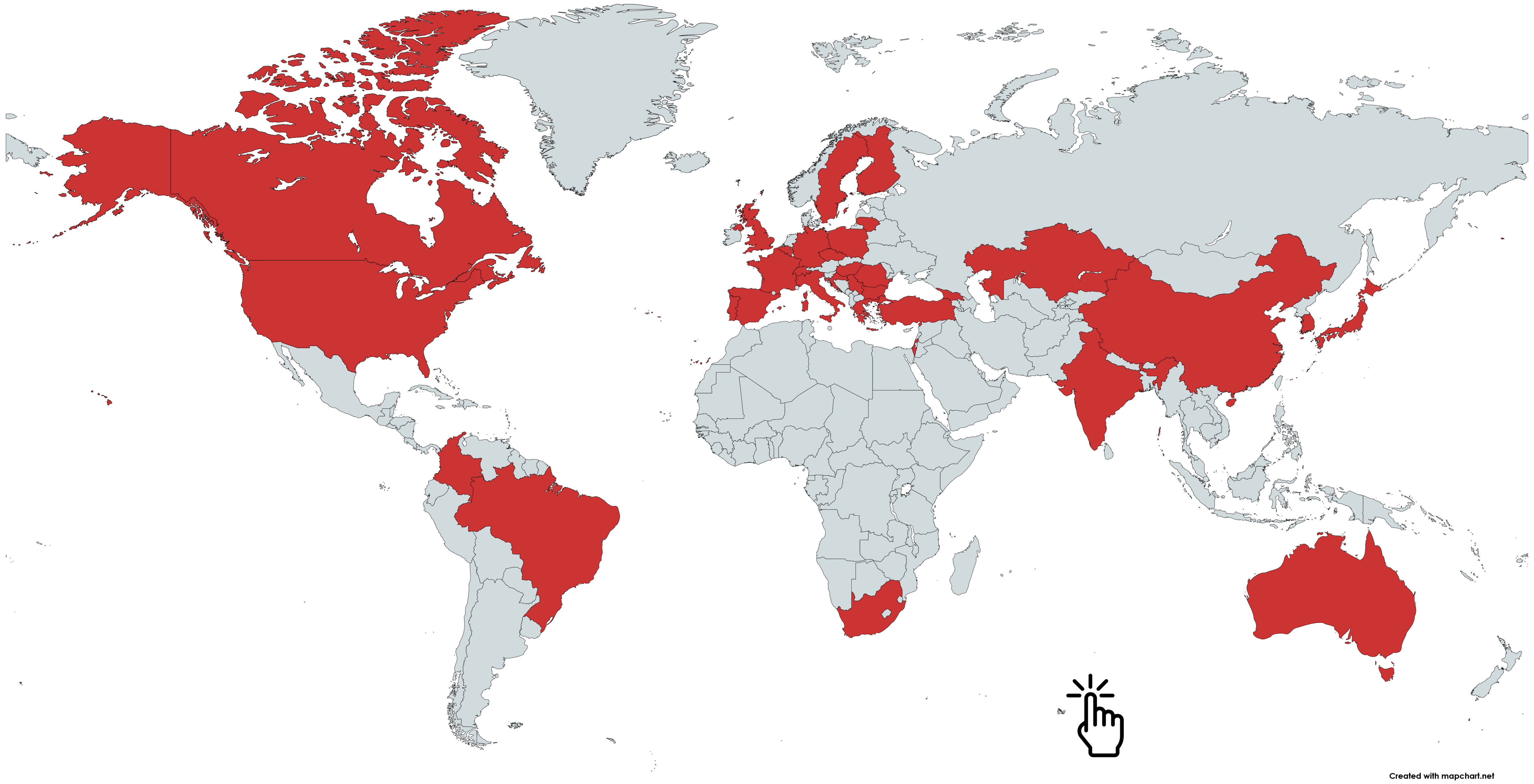
- Trackers, hodoscopes
- Drift chambers
- Straw chambers
- Tracking TPCs
- Calorimetry
- Photon detectors
- Timing detectors
- Nuclear reaction/decay TPCs
- Beyond high energy physics

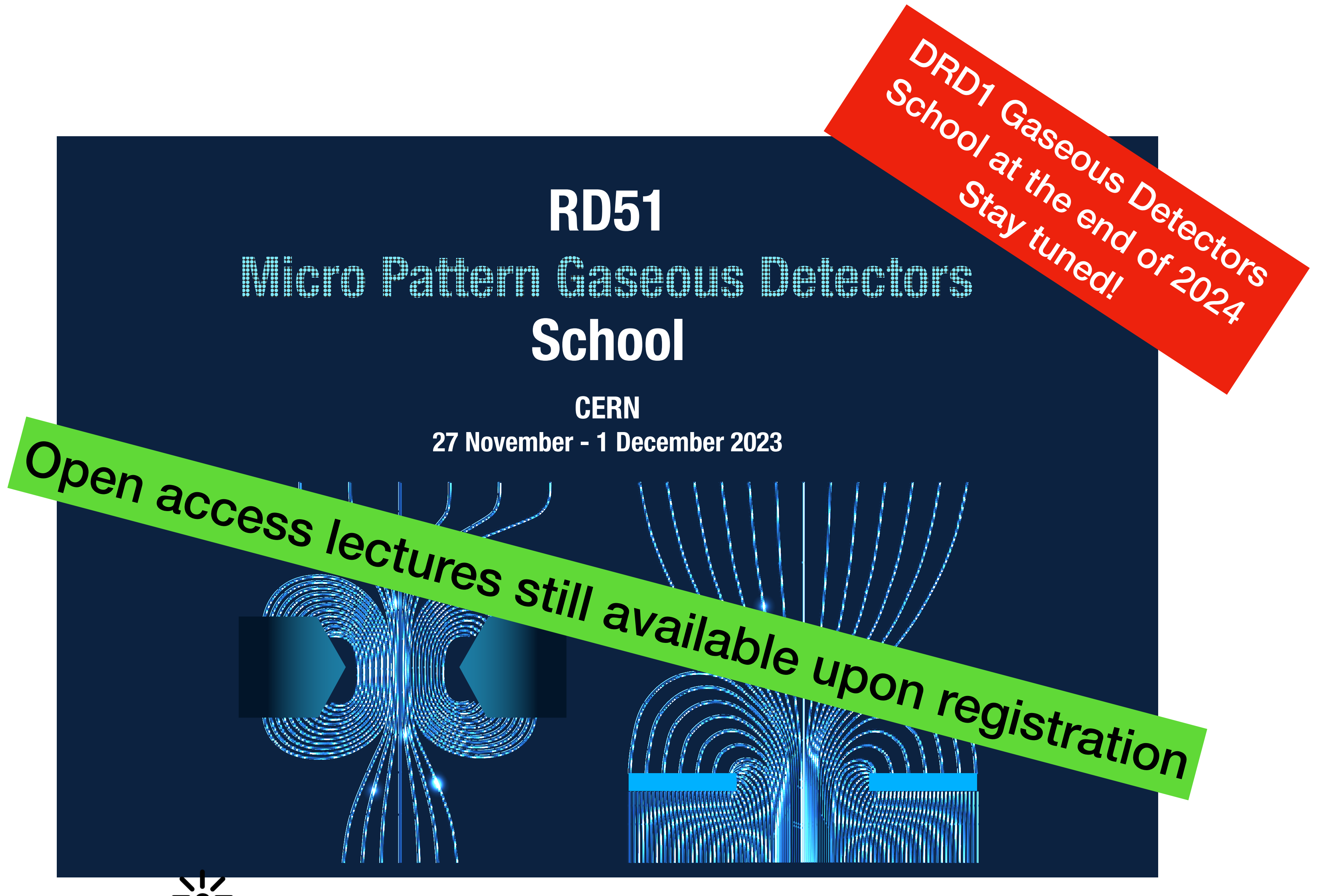
DRD1 R&D collaboration (ex RD51)

Development of gaseous detectors technologies

Joint effort of all gaseous detector communities:
MPGD, Wires, Resistive Plate Chambers (RPC)

1st DRD1 COLLABORATION MEETING, 29 January - 2 February, 2024, CERN





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Thank you. More questions?

ありがとう。何か質問がありますか?