Towards an unambiguous observation of the Migdal effect in nuclear scattering

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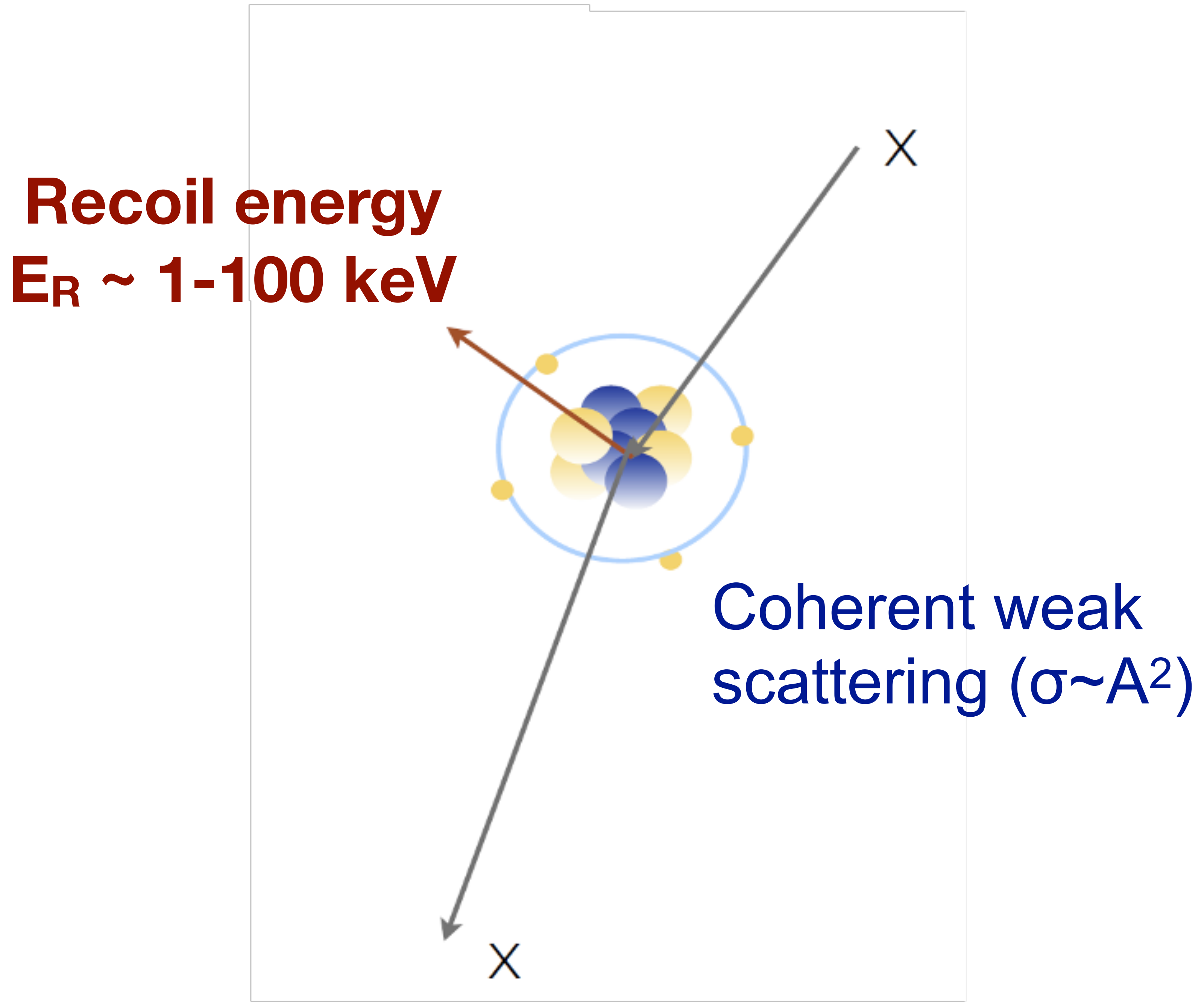
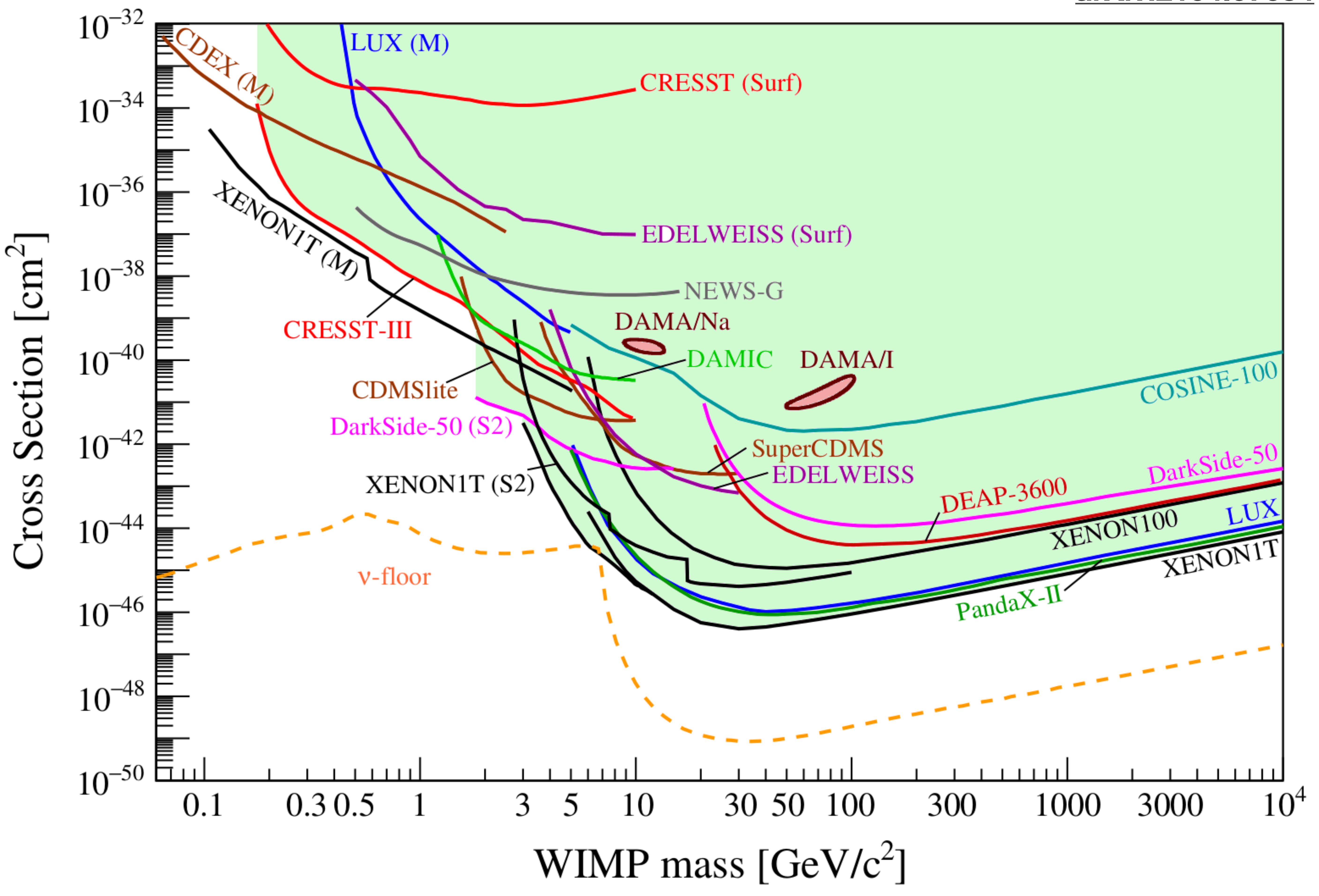
Direct Dark Matter detection landscape

Pushing towards the threshold frontier



arXiv:2104.07634

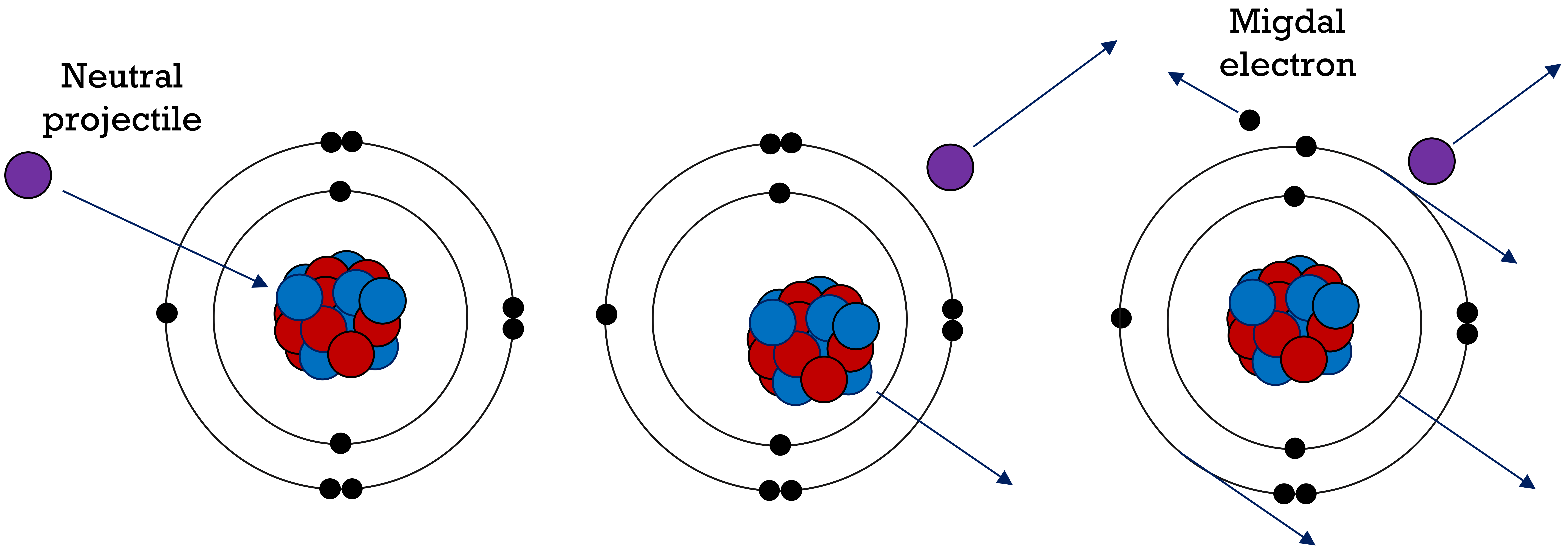


- Direct dark matter searches have made significant progress in ruling out WIMP-like dark matter.
- Increasing interest in pushing towards lower dark matter masses *O*(100 MeV)

The Migdal effect

Electron production in nuclear scattering

- Electron cloud take a short amount of time to catch up with the recoiling nucleus
- Ionisation and excitation of the atoms cause by this phenomenon can induce emission of one or more Migdal electrons
  - First described by A. Migdal in 1939 A. Migdal, ZhETF, 9, 1163-1165 (1939), ZhETF, 11, 207-212 (1941)
- Electronic recoil detection increases the sensitivity of our detectors to light WIMPs



Migdal for dark matter searches

Low mass sensitivity for canonical WIMP experiments

Migdal effect calculations reformulated by M. Ibe et al. with ionisation probabilities for atoms and recoil energies relevant to Dark Matter searches

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Migdal effect in dark matter direct detection experiments

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Over ~ 100 citations for the Ibe et al paper.

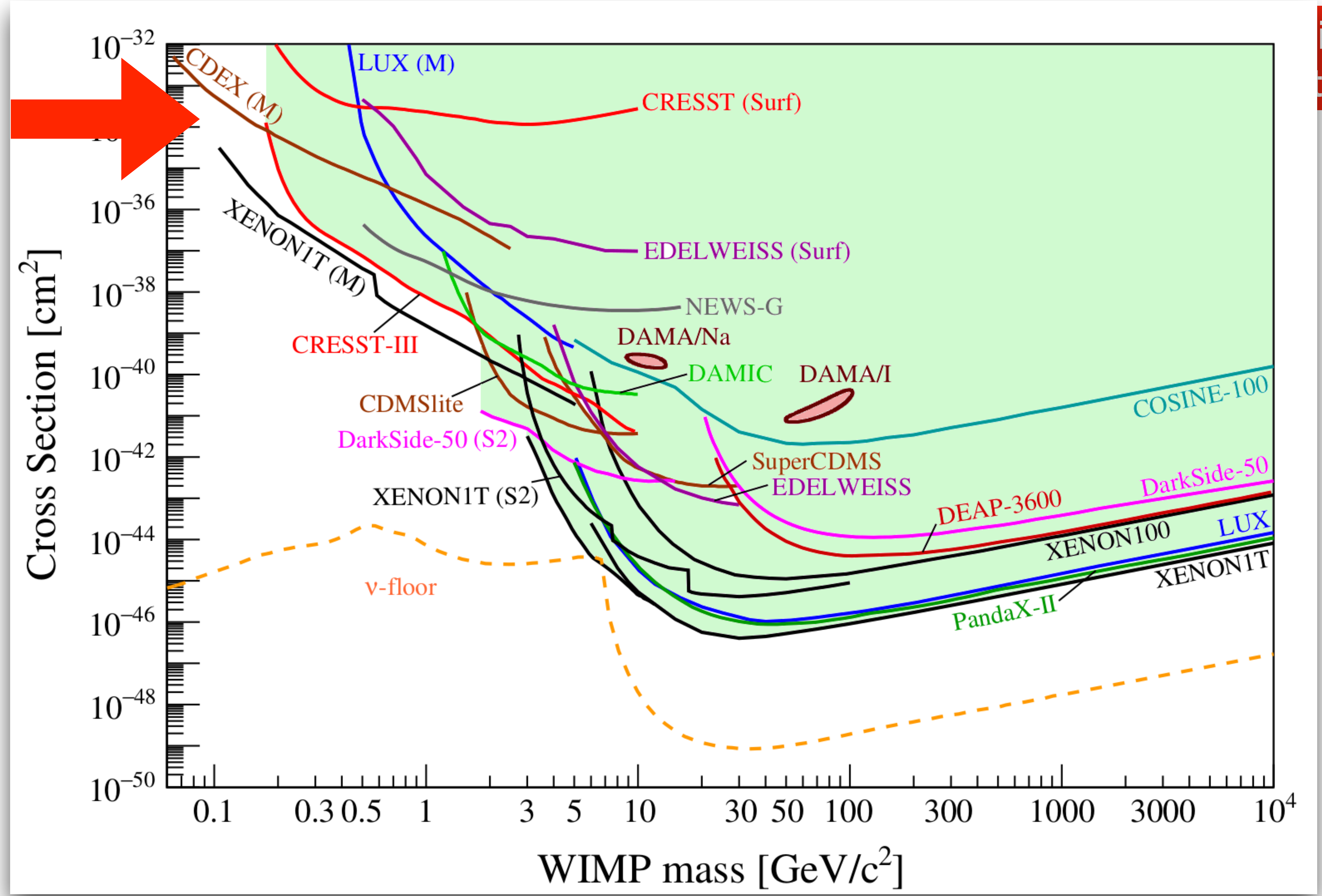
Constraints using the Migdal effect by: **LUX, XENON1T, EDELWEISS, CDEX-1B, SENSEI**

using targets such as: **Si, Ge, Ar and Xe**

claiming sensitivity below 1 GeV WIMP masses

Migdal for dark matter searches

Low mass sensitivity for canonical WIMP experiments



ionisation probabilities for atoms and recoil
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Constraints using the Migdal effect by: LUX, XENON1T, EDELWEISS, CDEX-1B, SENSEI

using targets such as: Si, Ge, Ar and Xe

claiming sensitivity below 1 GeV WIMP masses

Migdal In Galactic Dark MAtter expLoration

Capturing the Migdal effect

The Migdal effect has been observed in:

- ☑ α decay — Phys. Rev. C 11 (1975), 1740-1745
- ☑ β– decay — Phys. Rev. 93 (1954), 518-523
- ☑ β+ decay — Phys. Rev. A 97 (2018), 023402

→ **However not yet been observed in nuclear scattering!**

MIGDAL aims to make an unambiguous observation of the Migdal effect in nuclear scattering using an Optical Time Projection Chamber

This experiment is designed for observation in the most favourable conditions

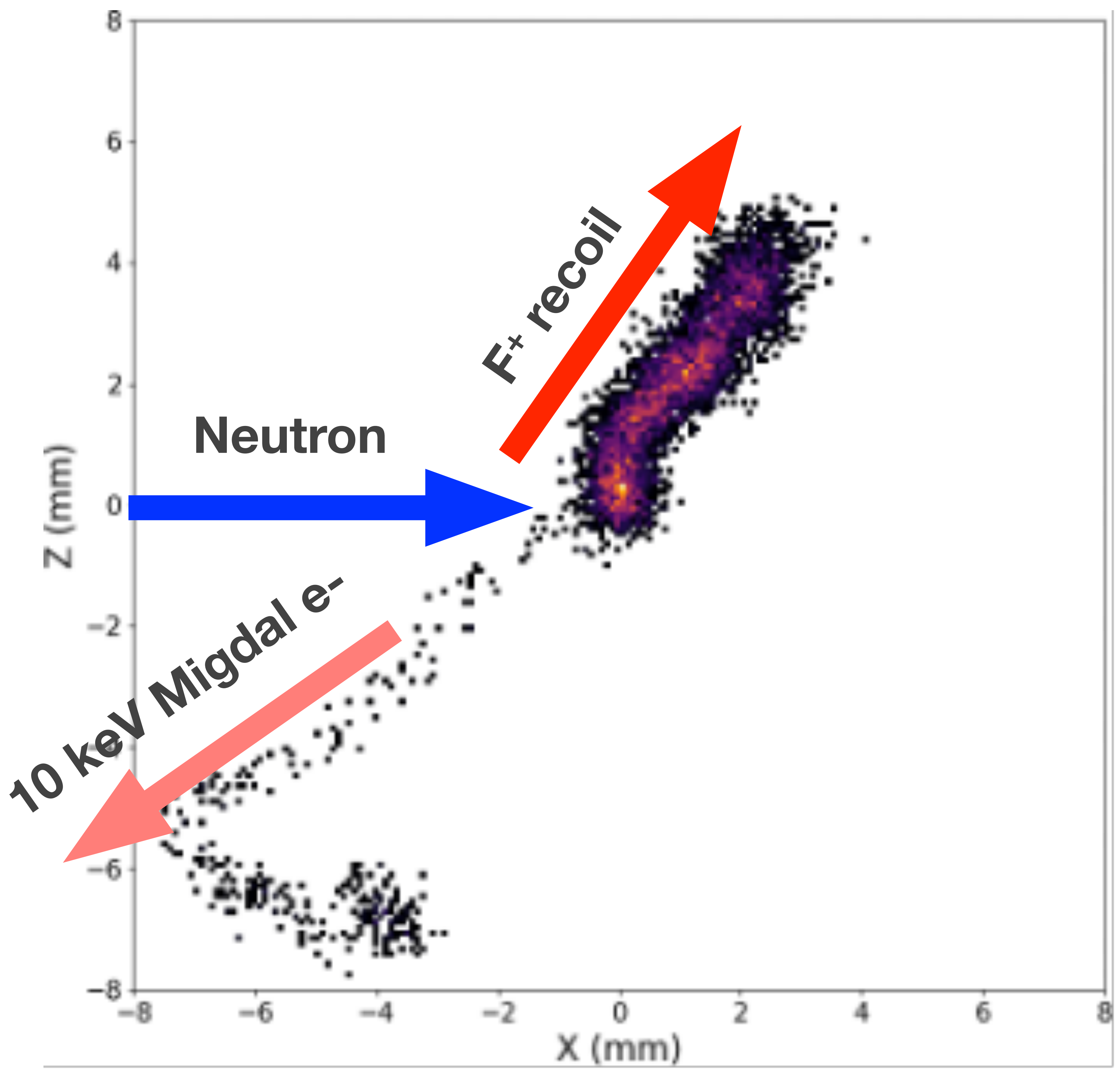
Method:

Searching for nuclear recoils with accompanying electronic recoils from the same vertex

Two phases:

1. Measure the Migdal effect in pure Carbon tetrafluoride (CF4)
2. Observe the Migdal effect in CF4 + other gas (Ar, Xe, . . .) mixtures

Migdal event signature

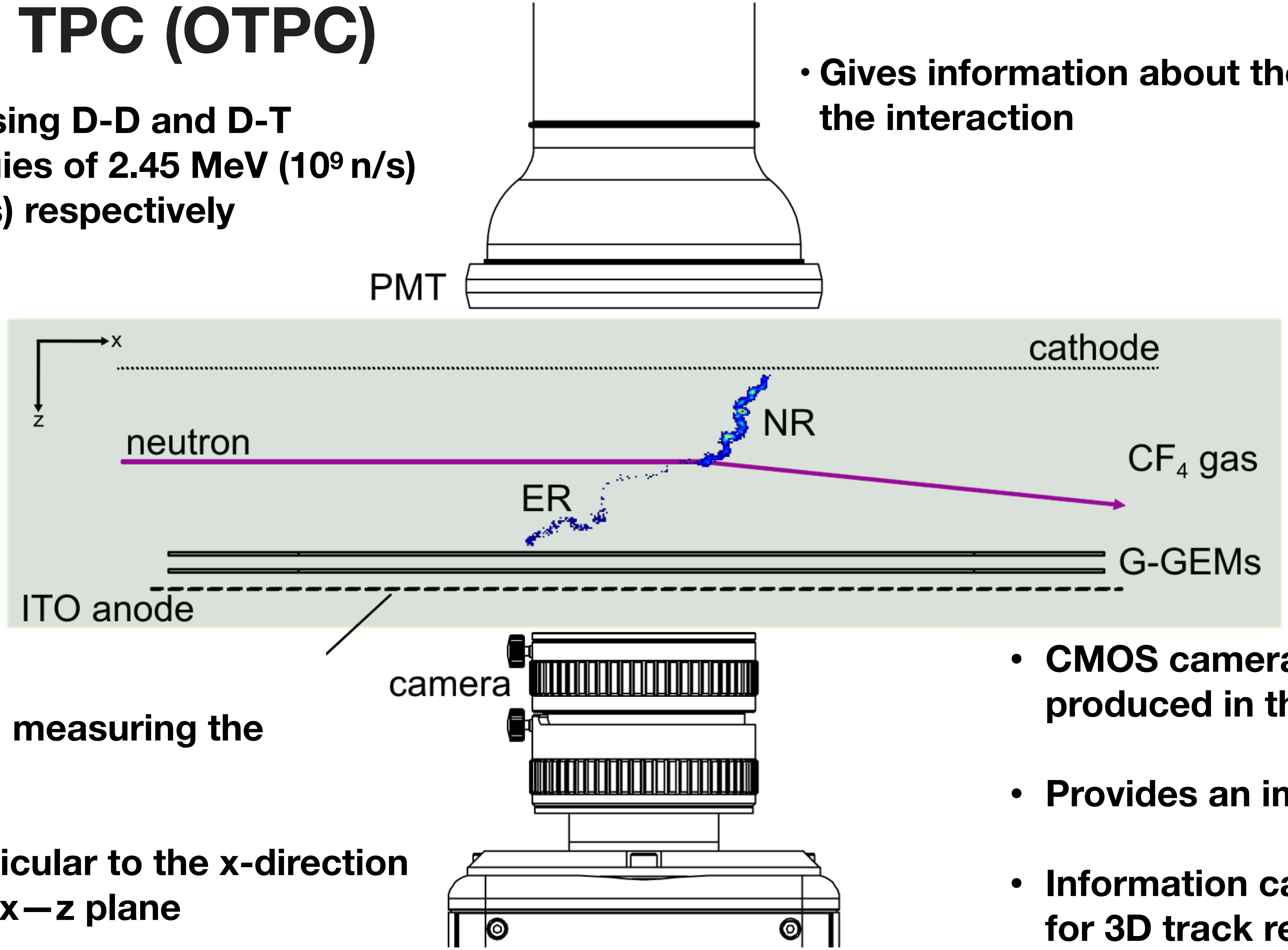


The MIGDAL detector

The Optical TPC (OTPC)

- Neutrons produced using D-D and D-T generators with energies of 2.45 MeV (10^9 n/s) and 14.1 MeV (10^{10} n/s) respectively

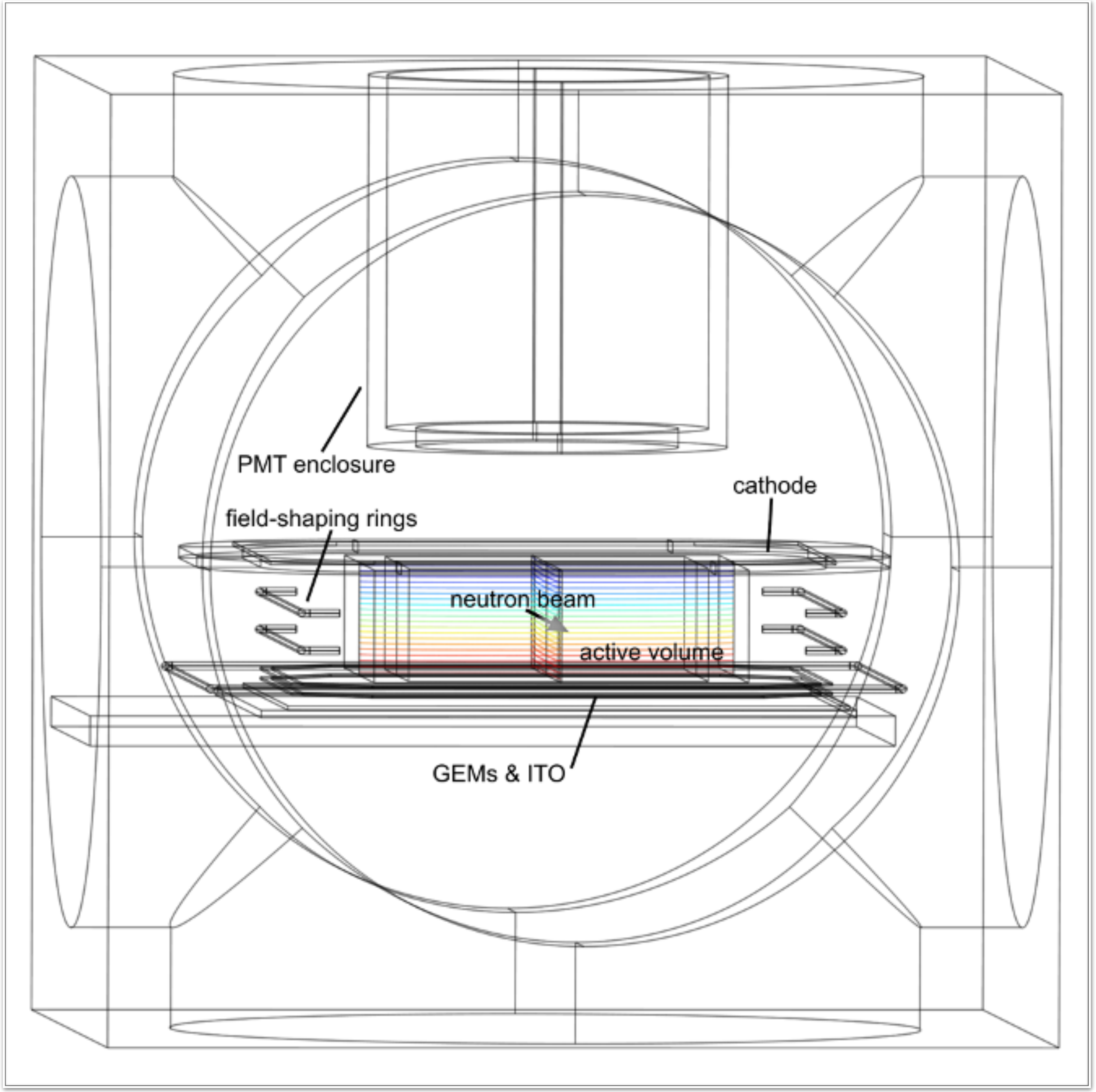
- PMT collects light from primary scintillation (S1) and the avalanche electroluminescence light (S2)
- Gives information about the absolute z-position of the interaction

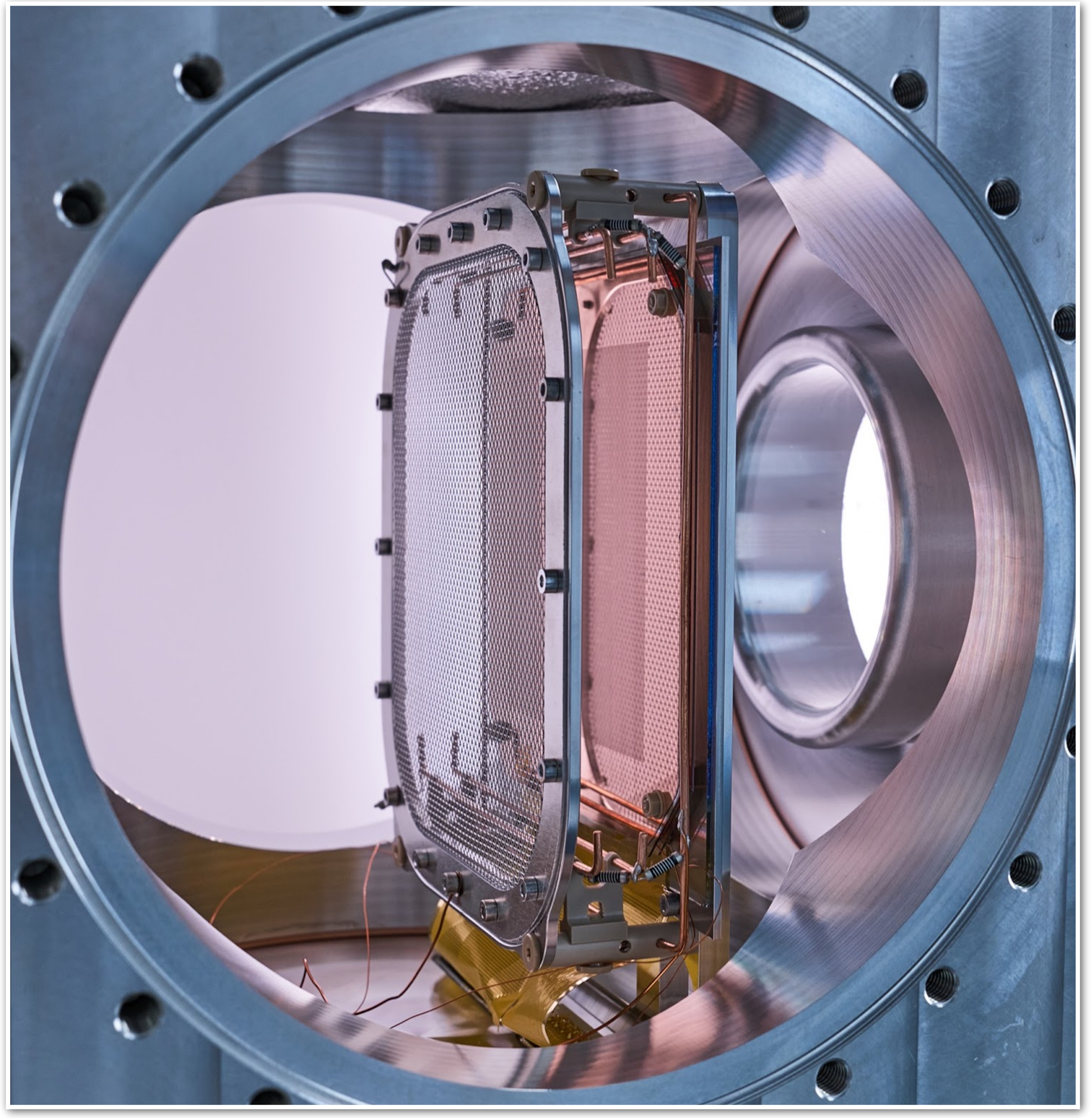


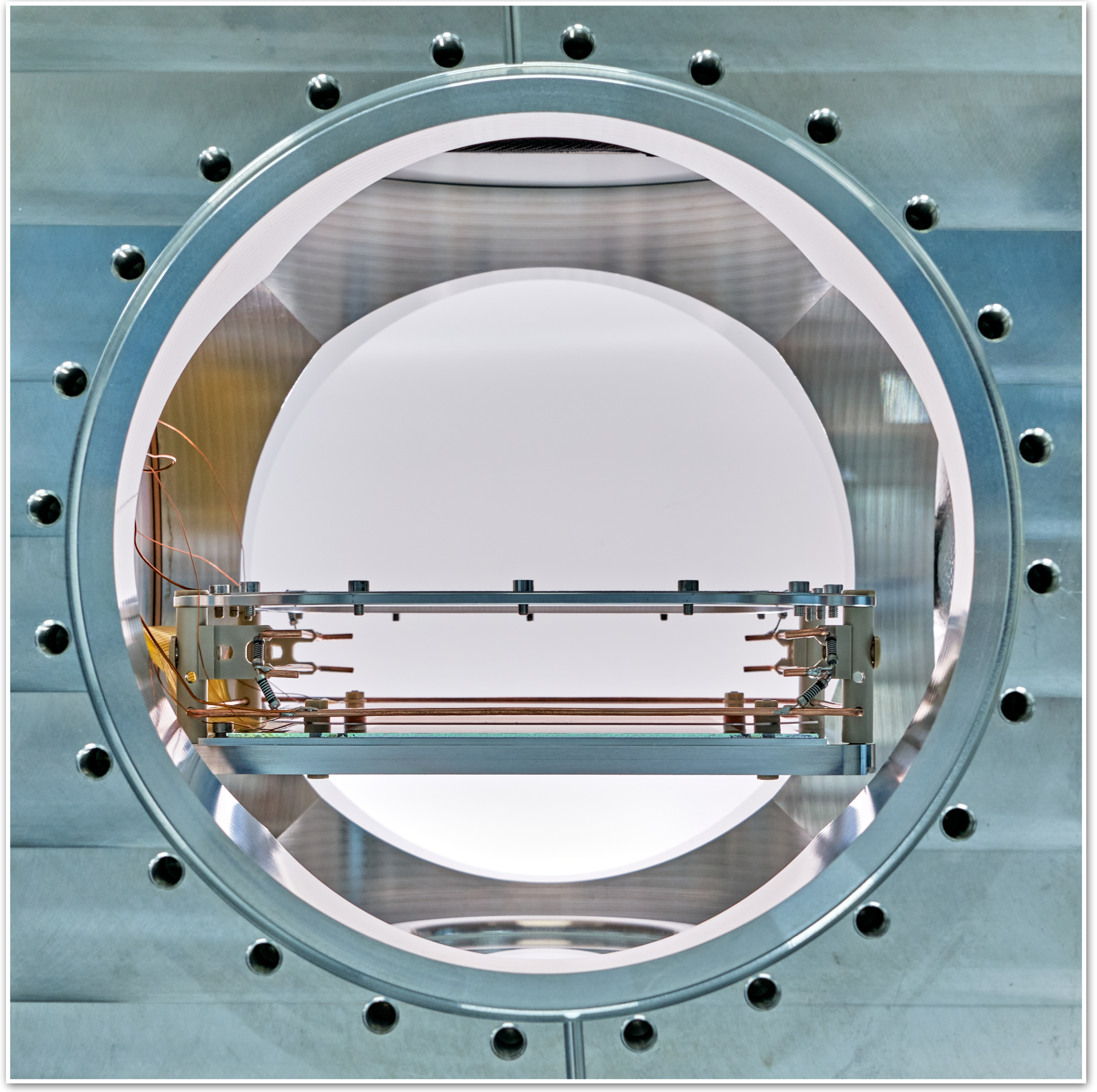
- Electrons avalanche in double glass GEM

- CMOS camera records the light produced in the avalanche
- Provides an image in the x—y plane
- Information can be combined with ITO for 3D track reconstruction

- ITO transparent anode, measuring the produced charge
- Strips running perpendicular to the x-direction give information in the x—z plane

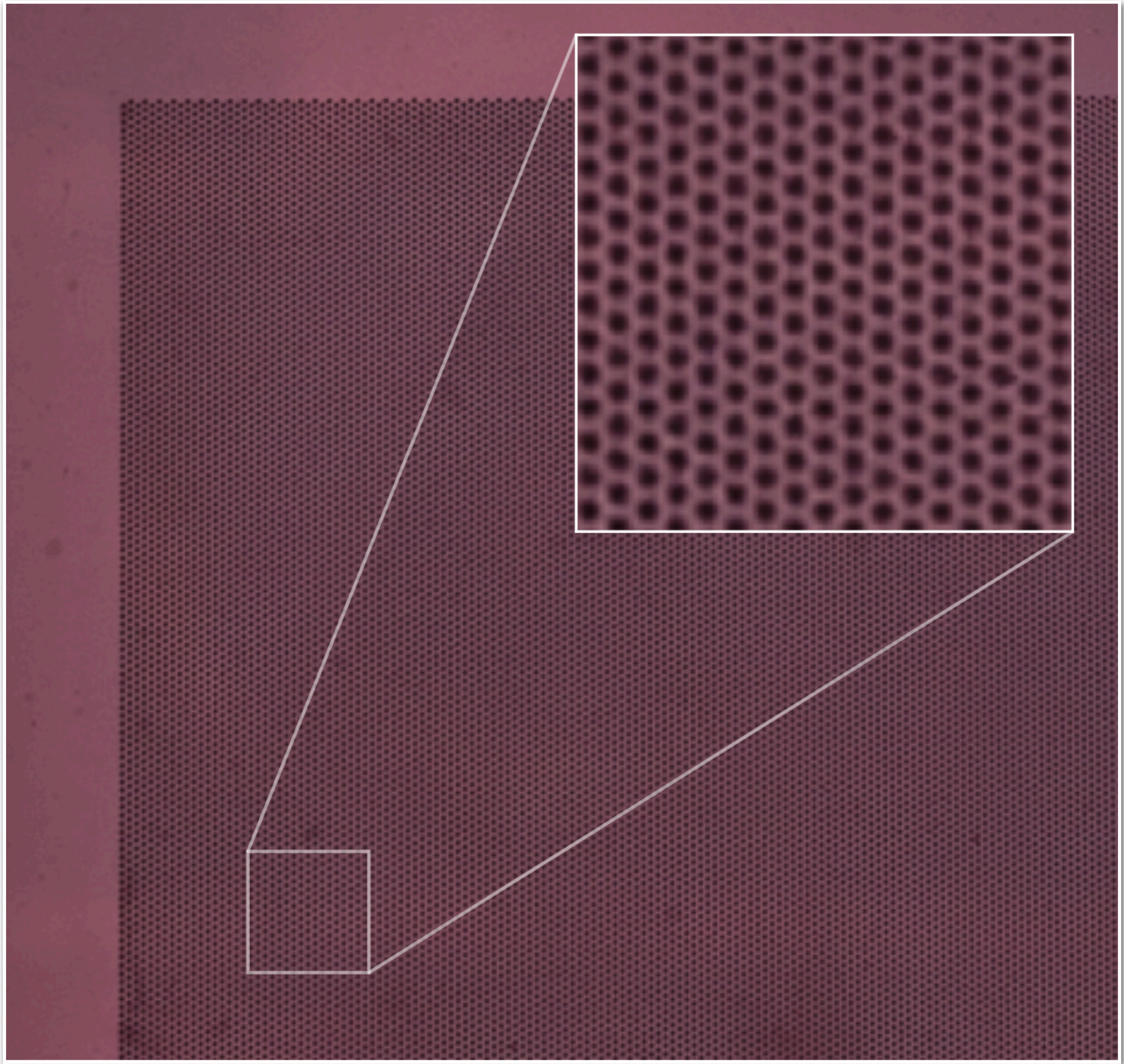

PMT enclosure
cathode
field-shaping rings
neutron beam
active volume
GEMs & ITO





Glass Gas Electron Multipliers

State of the art in thick hole-type electron multipliers



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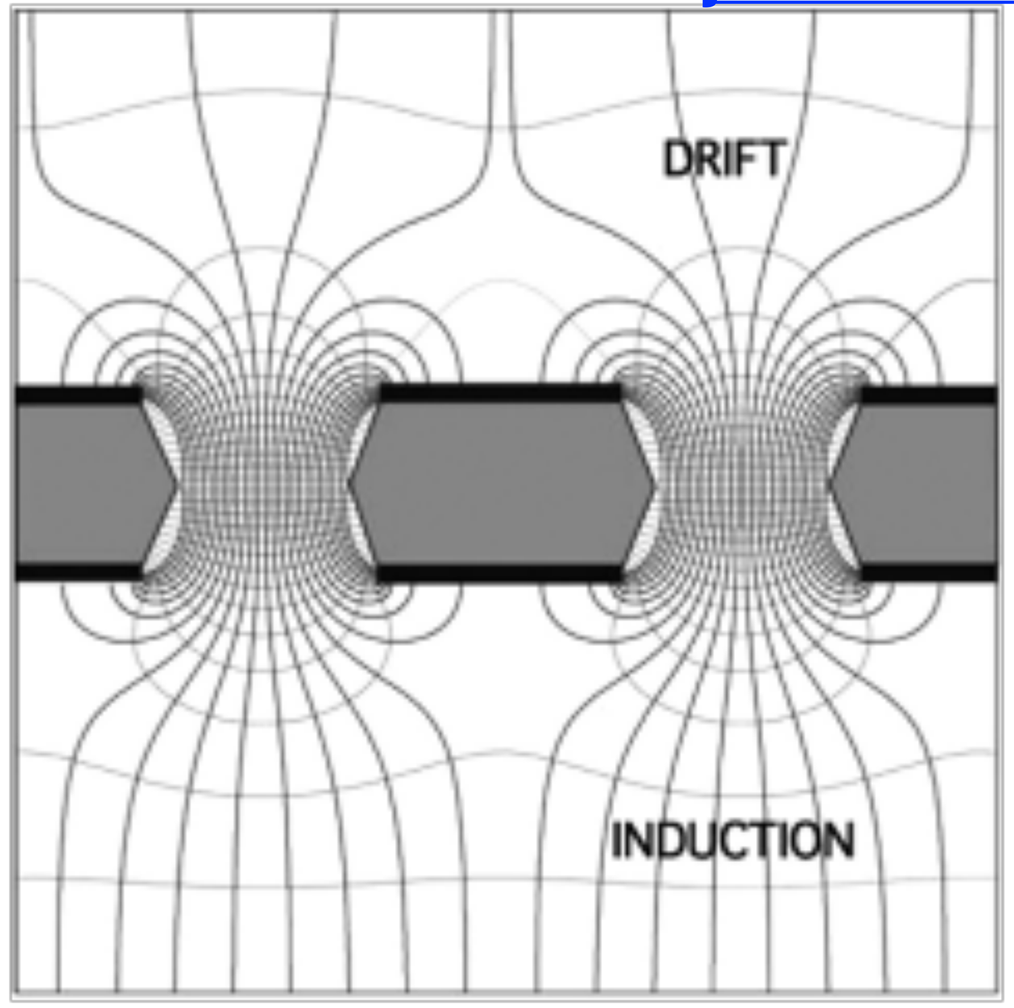
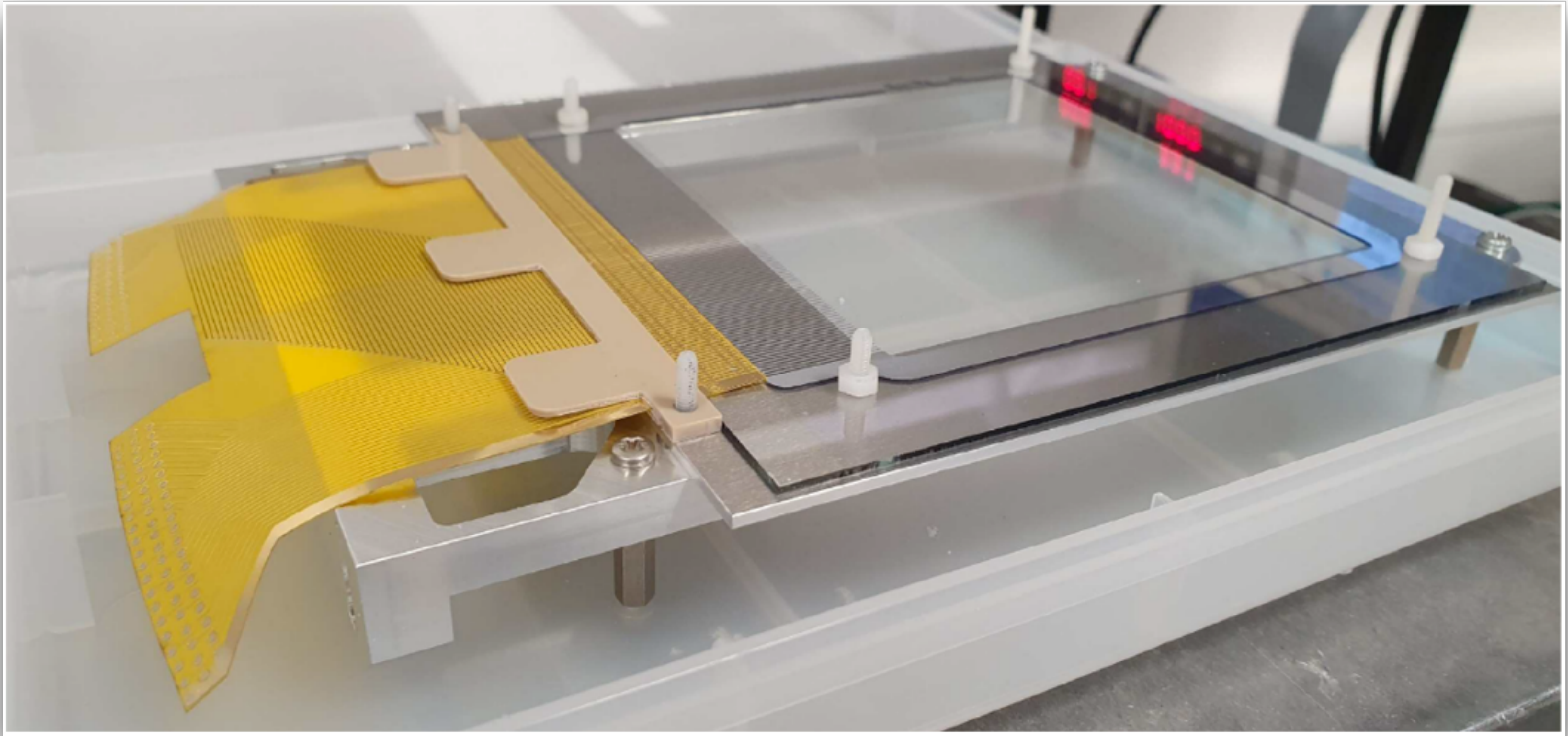
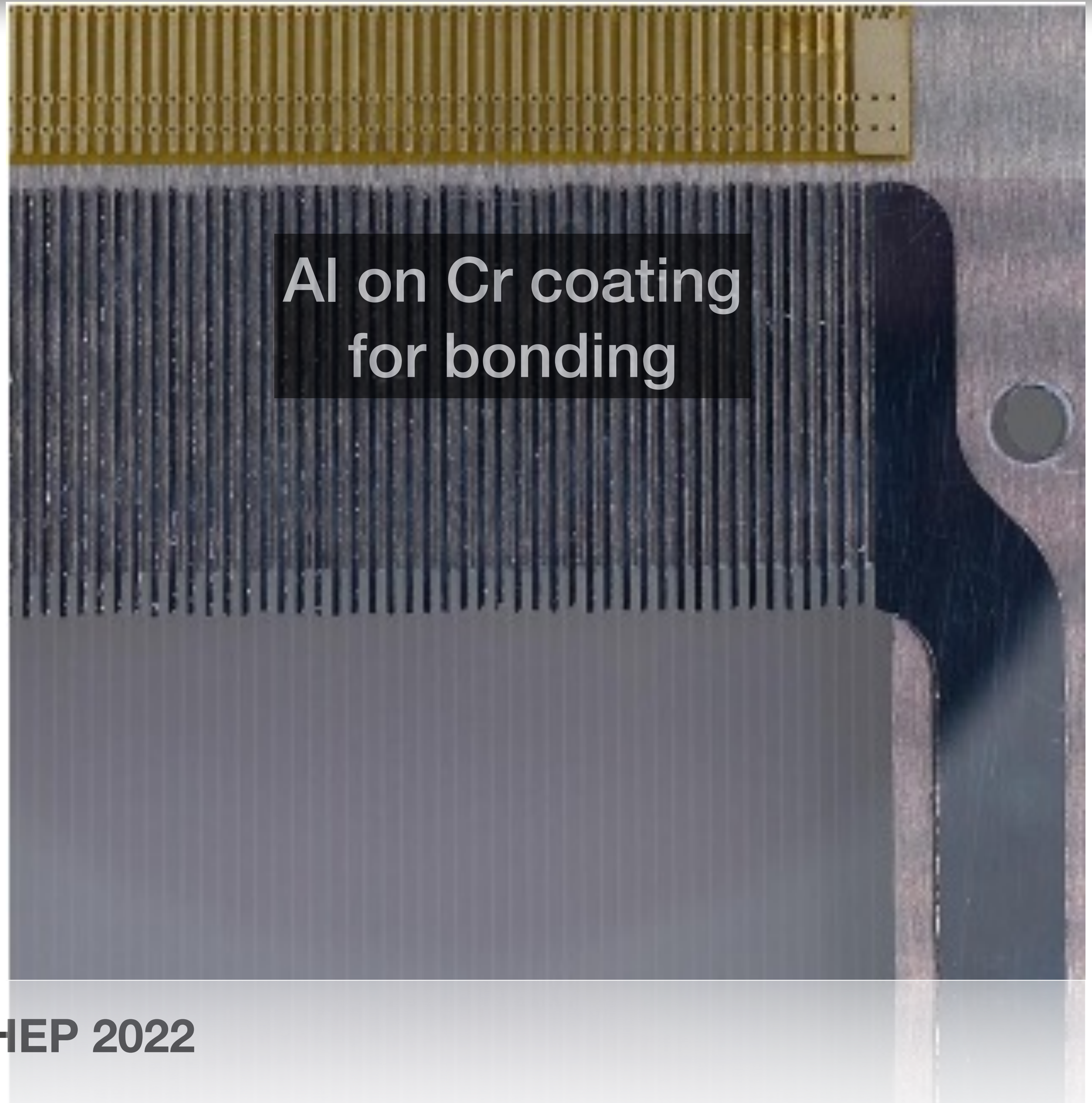


- Gas Electron Multipliers (GEMs) are a type of µ-pattern gas detector
- Hole-type structure,
  - Holes of 170 µm in diameter and 280 µm pitch
- Glass sandwiched with copper
  - 0.57 mm thick glass, 2 µm Cu on either side
- Voltage applied across dielectric
  - Strong electric field inside holes where e- multiplication occurs
- Double GEM configuration

The ITO anode
Transparent anodes strips

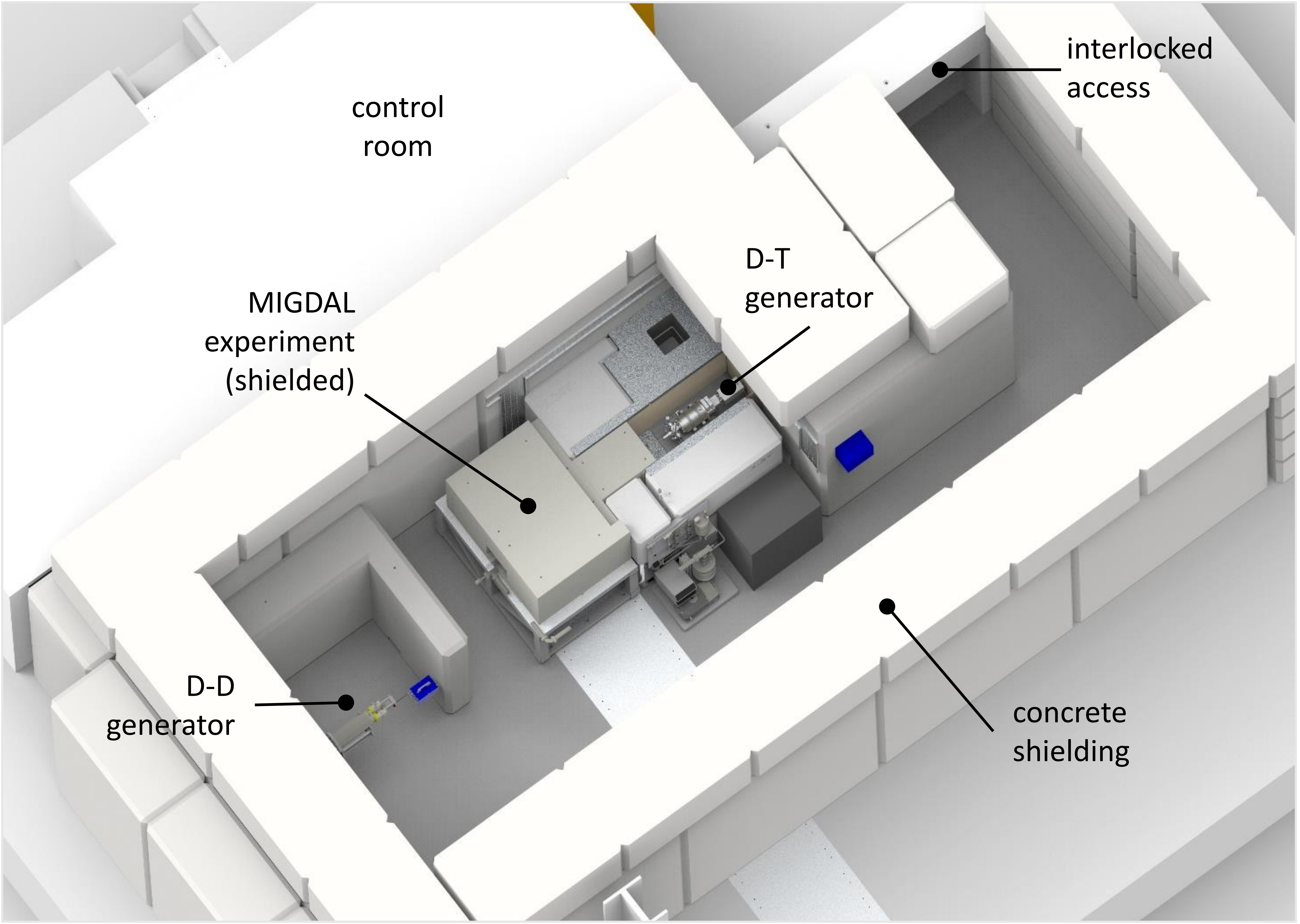
- Transparent (4 Ω/cm^2) anode strips pattern on glass plate
  - Allows light produced in the avalanche to be captured by the CMOS camera
- 120 Indium Tin Oxide (ITO) strips with 60 readout channels allow us to readout the charge produced
- Strips 600 um wide with a 833 um pitch
- Digitised with 2 ns sampling rate
- Charge arrival times give us information about the depth of the track in the z-direction

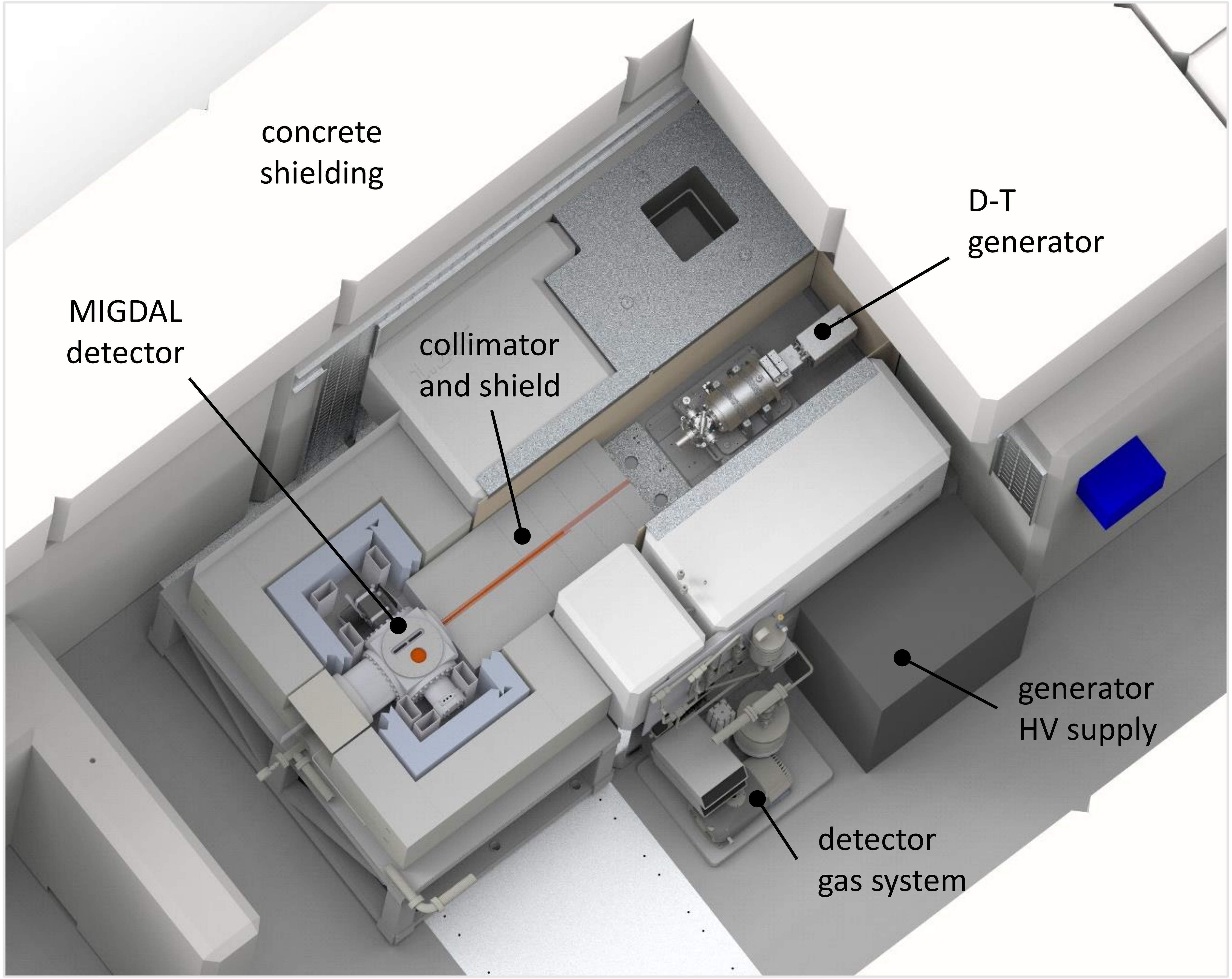




The NILE facility at ISIS (RAL, UK)

Neutron Irradiation Laboratory for Electronics (NILE)





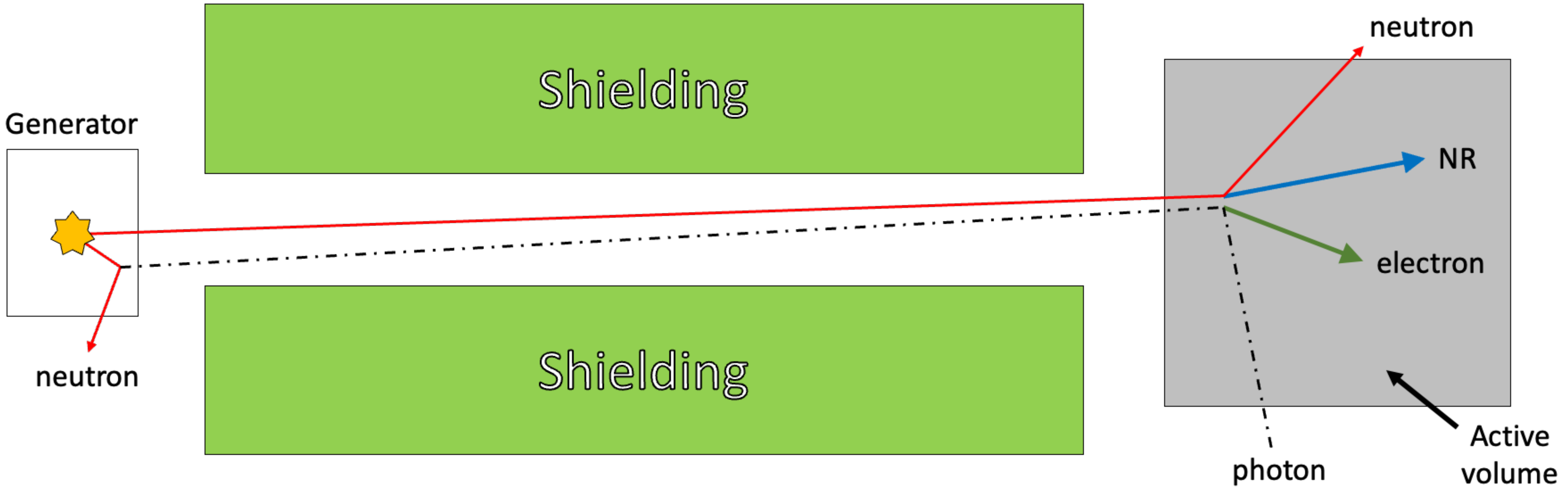
Background sources

- Dominant background source → Random combinations of NR+Compton electron tracks
  - Compton electrons in active volume produced by photons from inelastic interactions of neutrons with generator material
  - Atomic processes leading to particle emission in NR-induced tracks
- Placing 1.3 mm Pb+1 mm Sn layers between neutron generator and active volume reduces low energy photons from the generator head
- Total BG rate for D-D ~0.48 events/M NR and for D-T ~0.27 events/M NR

- *Migdal is not expected to be BG limited*

Background mitigation strategies:

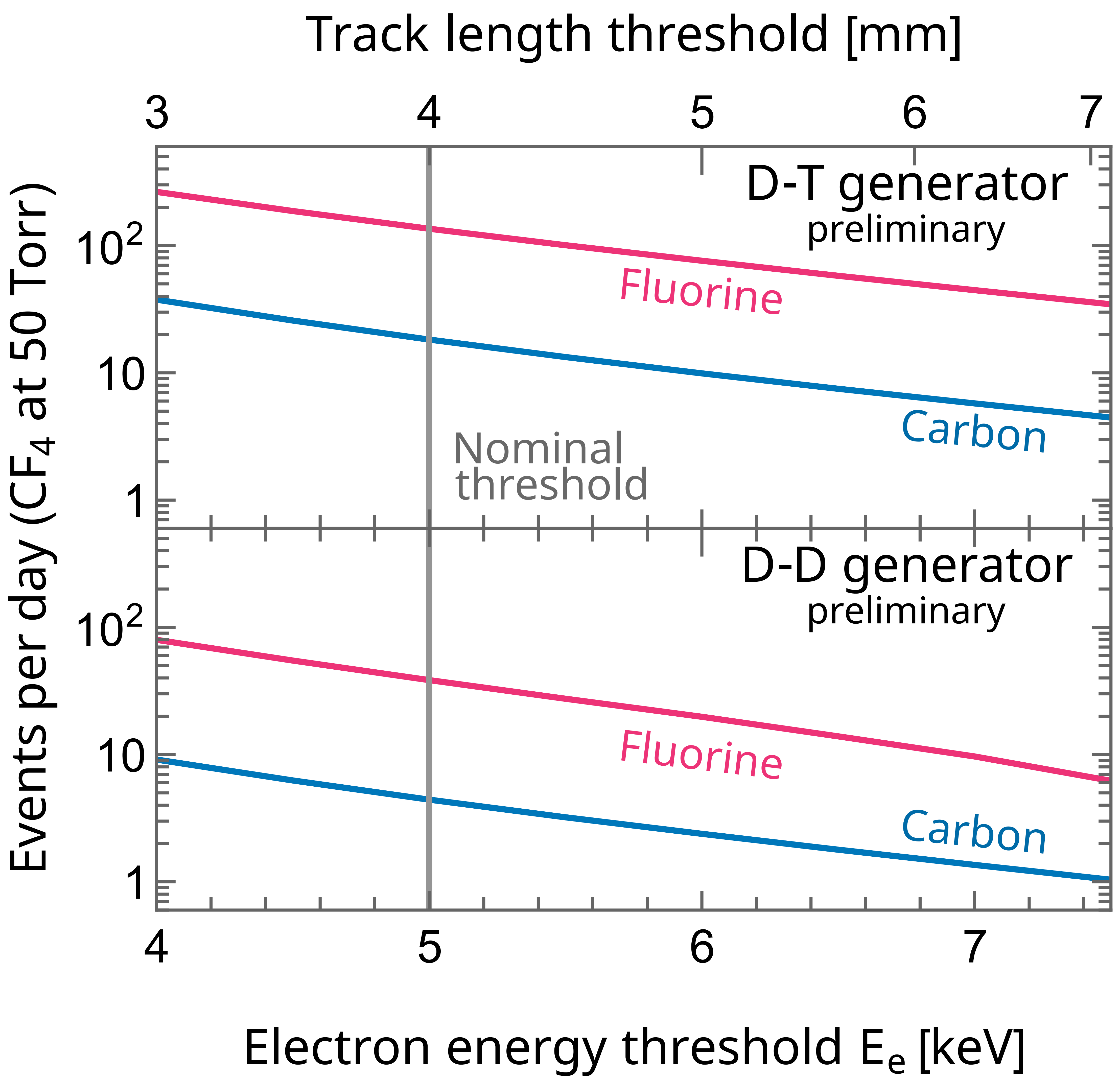
1. Track reconstruction
   - ☑ Taking advantage of the distinctive Migdal topology
2. Reducing photon interaction probability near NR tracks
   - ☑ Low pressure operation
   - ☑ Shielding



Expected event rate

Simulation studies

- **Full experiment at the neutron source facility modelled in GEANT4**
  - **One billion neutrons per second produced by the D-D generator**
- **Expect ~60 nuclear recoils per second in the TPC fiducial volume**
- **Migdal event rate *O*(50) per day for D-D and *O*(150) for D-T**
  - **Including multiple “soft” electrons and a “hard” one**



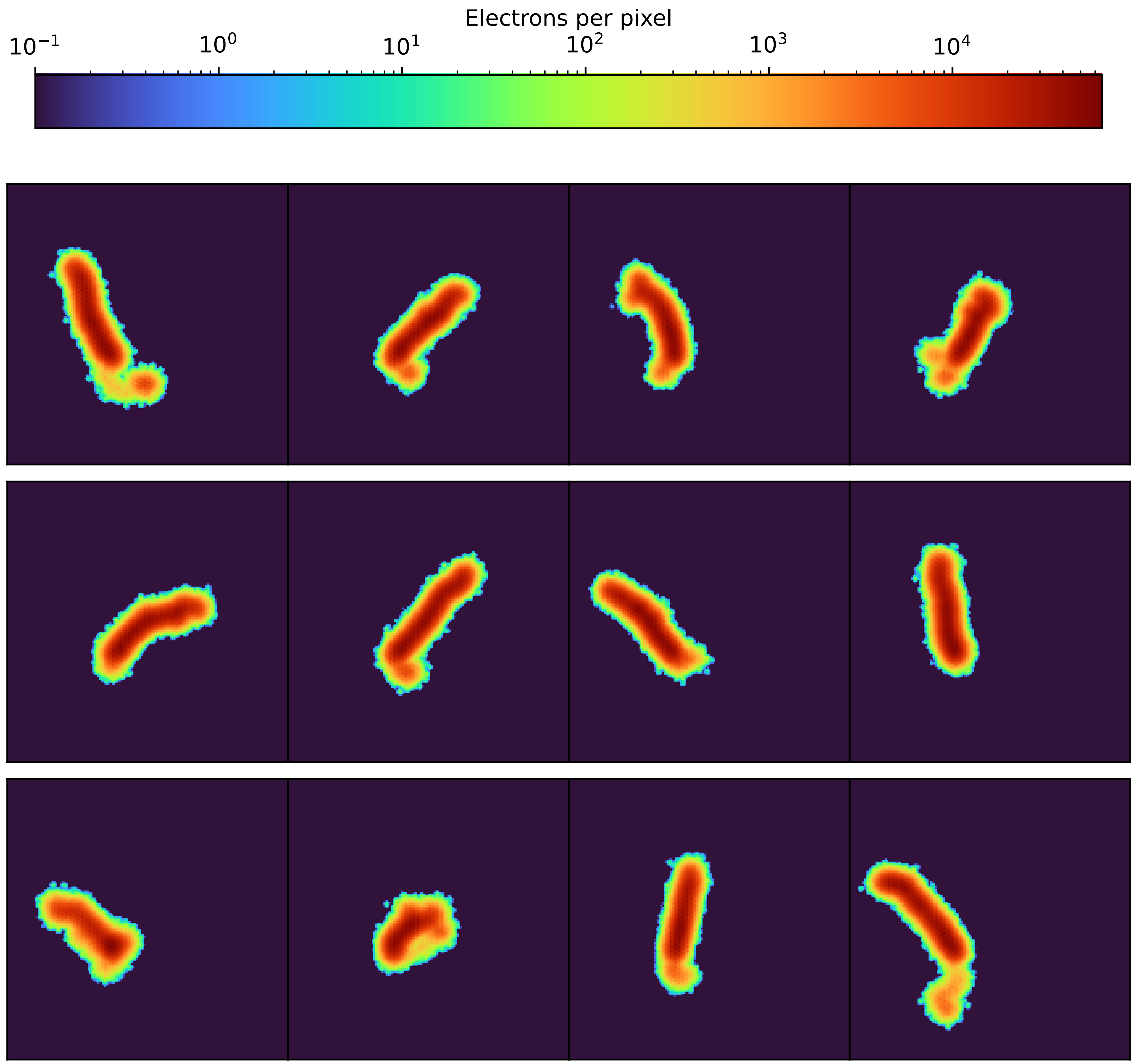
Challenging!

Calculations by C.McCabe (KCL)

Studies of the expected signal and BGs

End to End simulations

Migdal-like events with a 250 keV NR and a 5 keV ER



End-to-end simulation produced combining:

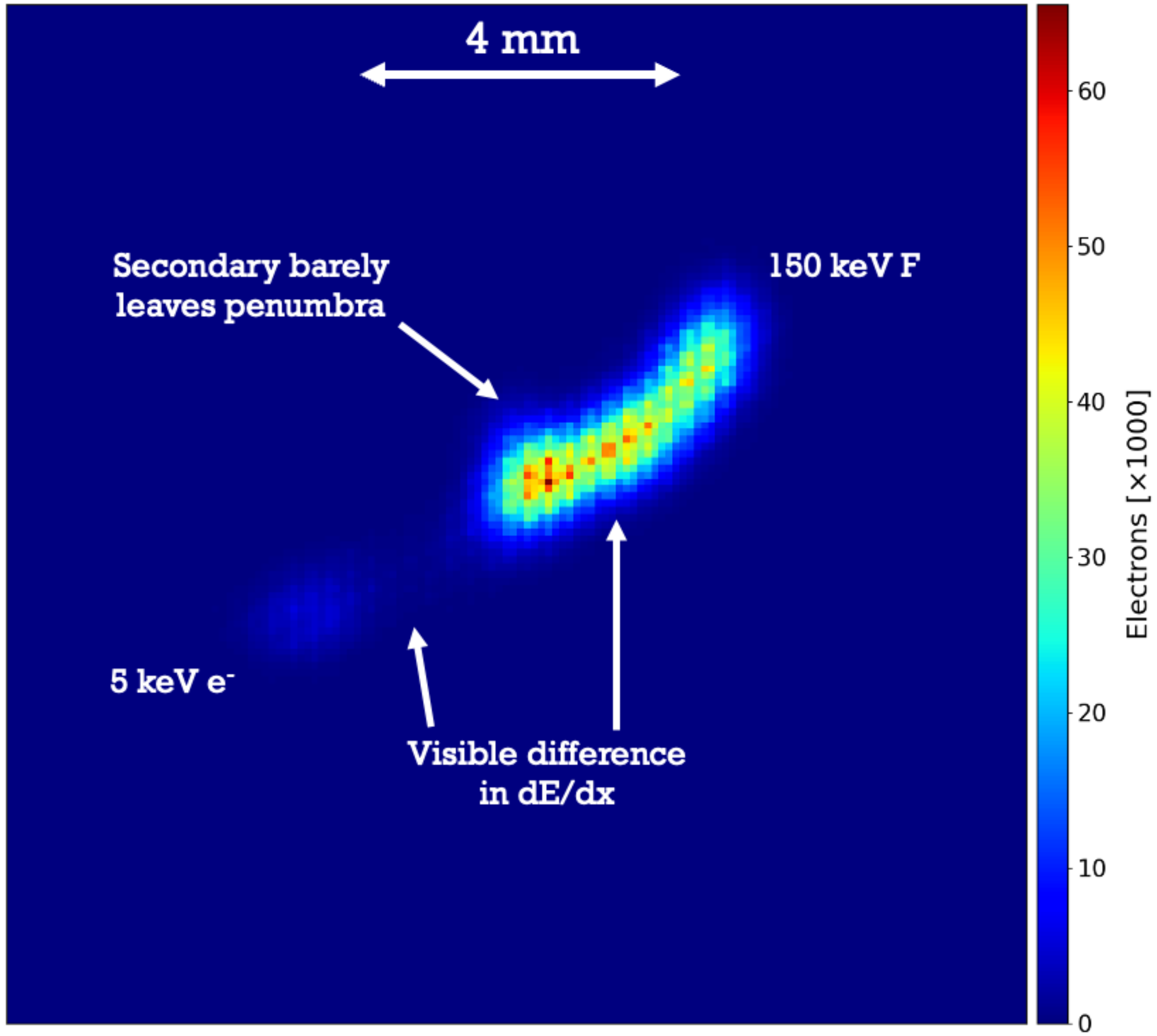
- DEGRAD
- SRIM/TRIM
- Garfield++
- Magboltz
- Gmsh/Elmer&ANSYS

- **Studying various methods to identify Migdal events (dE/dx, track lengths, etc)**
- **Currently estimate ≈ 75% Migdal identification efficiency for the most promising energies**

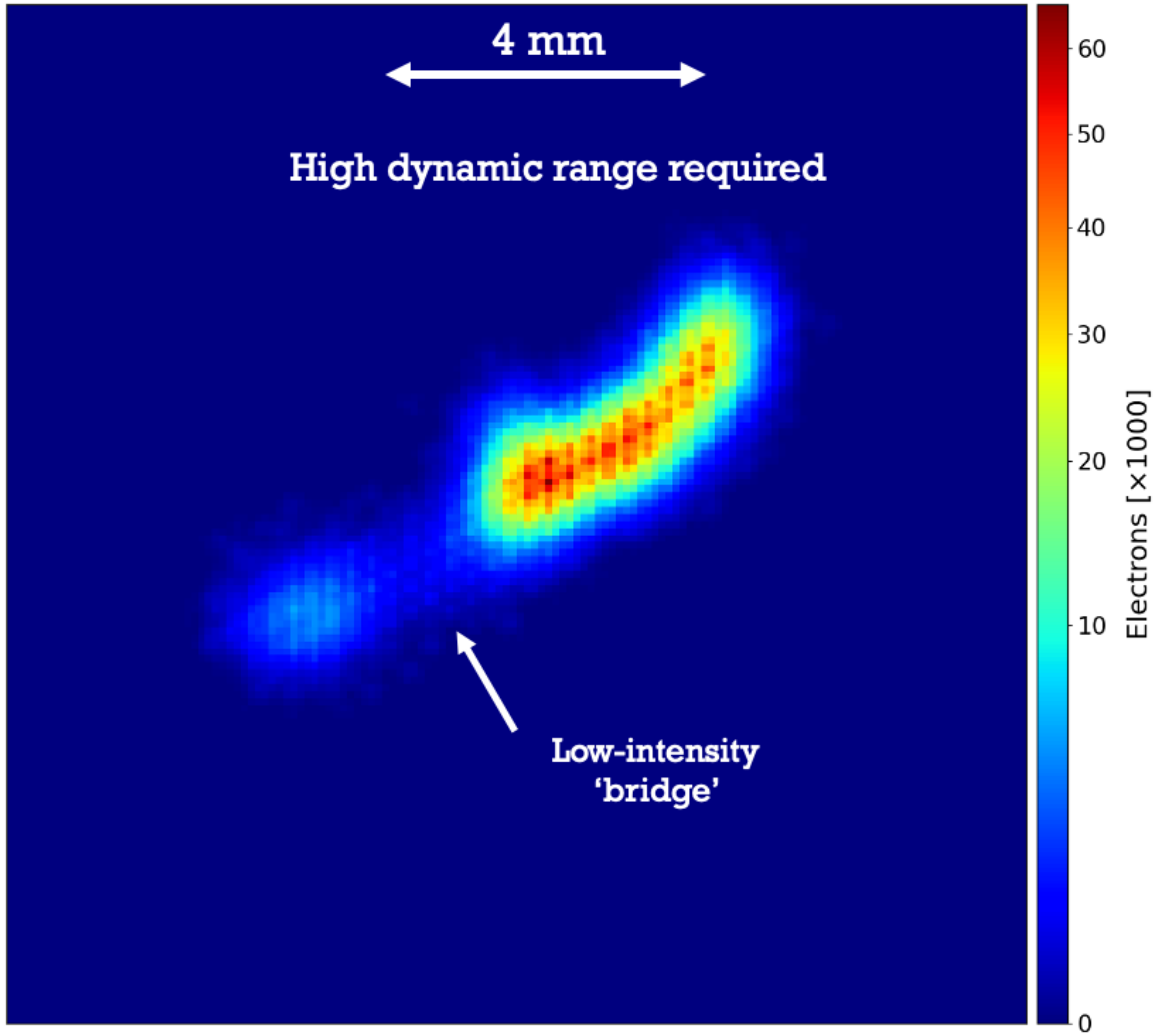
Studies of the expected signal and BGs

Migdal event characteristics

Linear-scale colour map

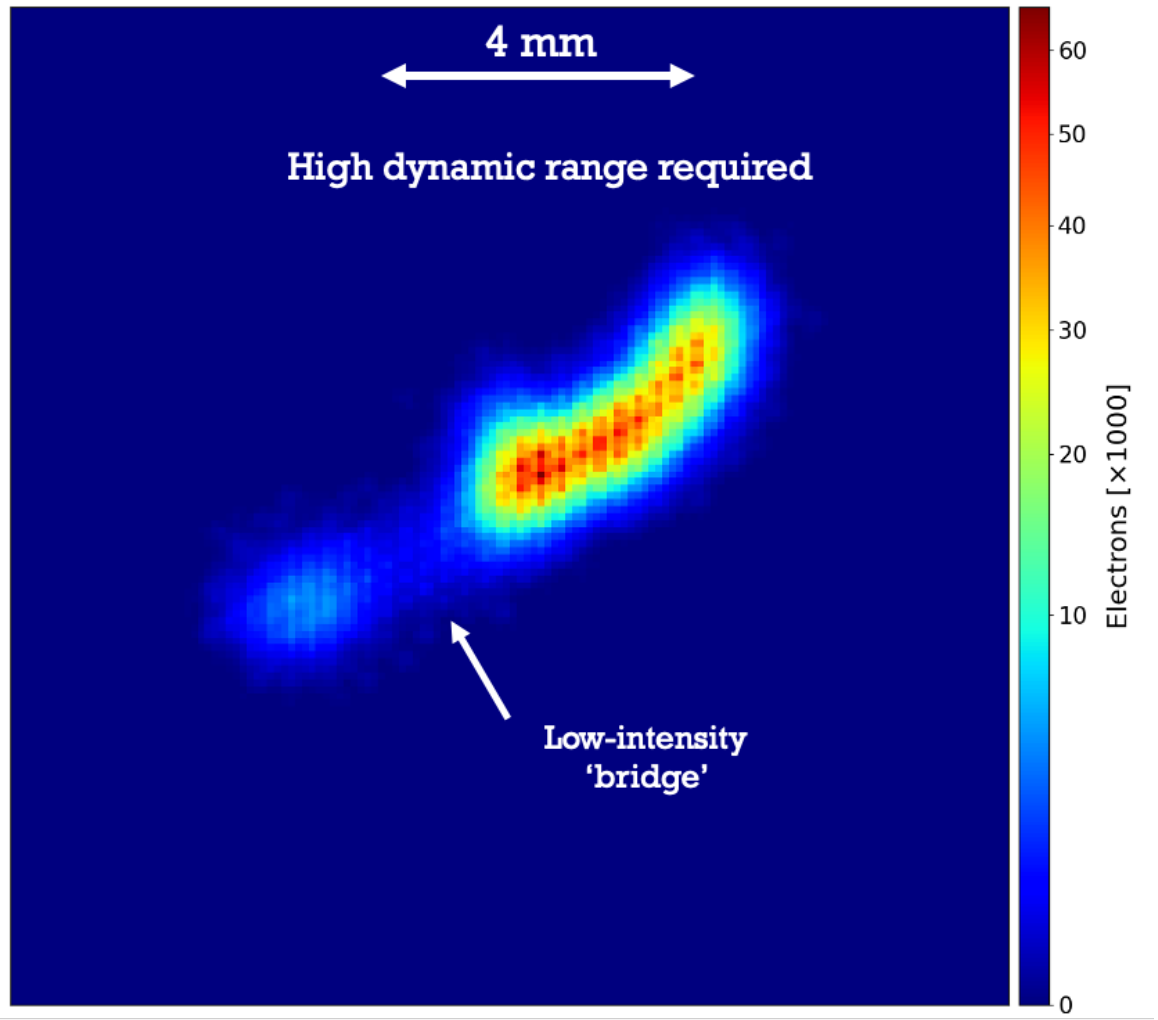


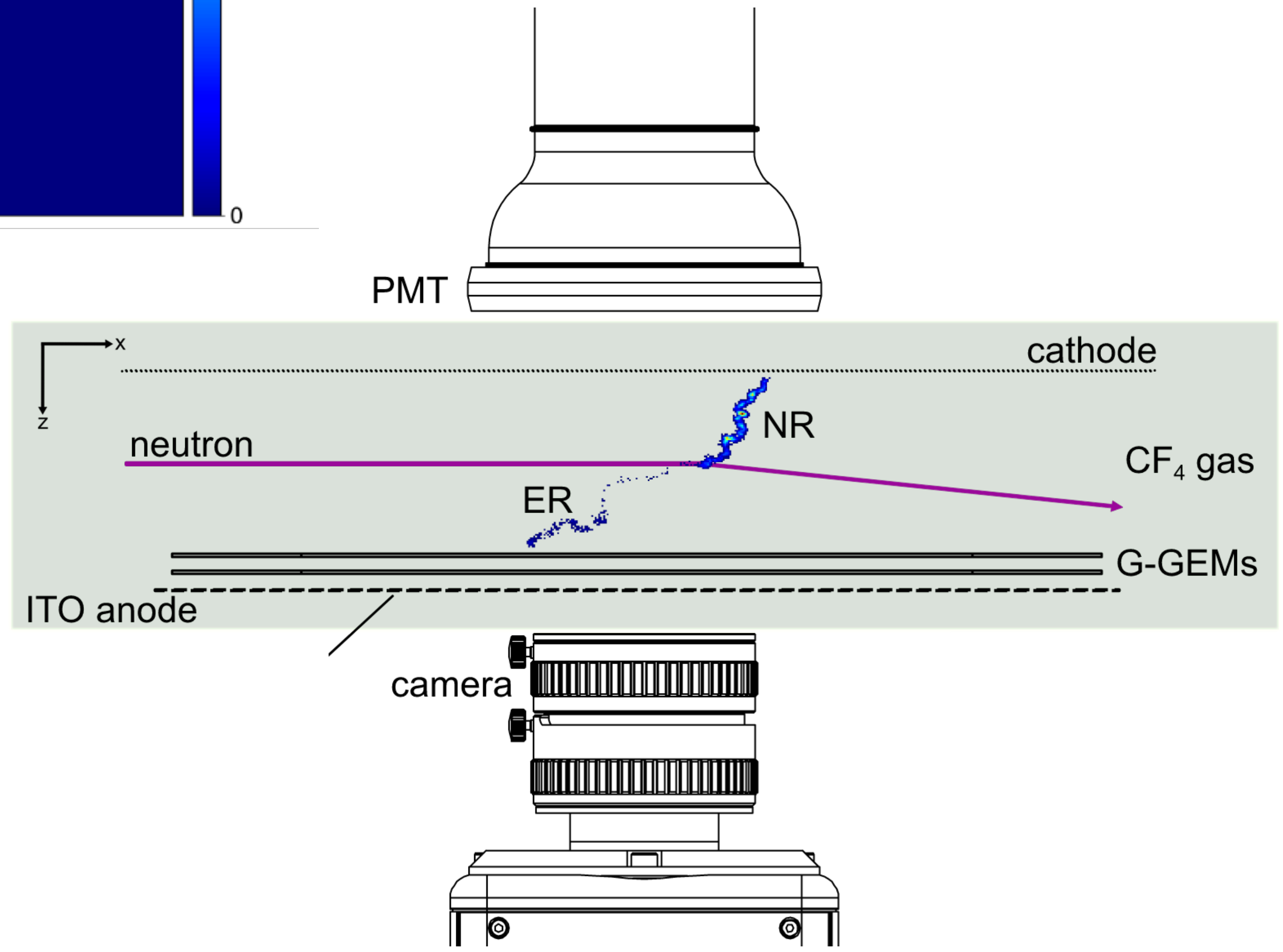
Log-scale colour map



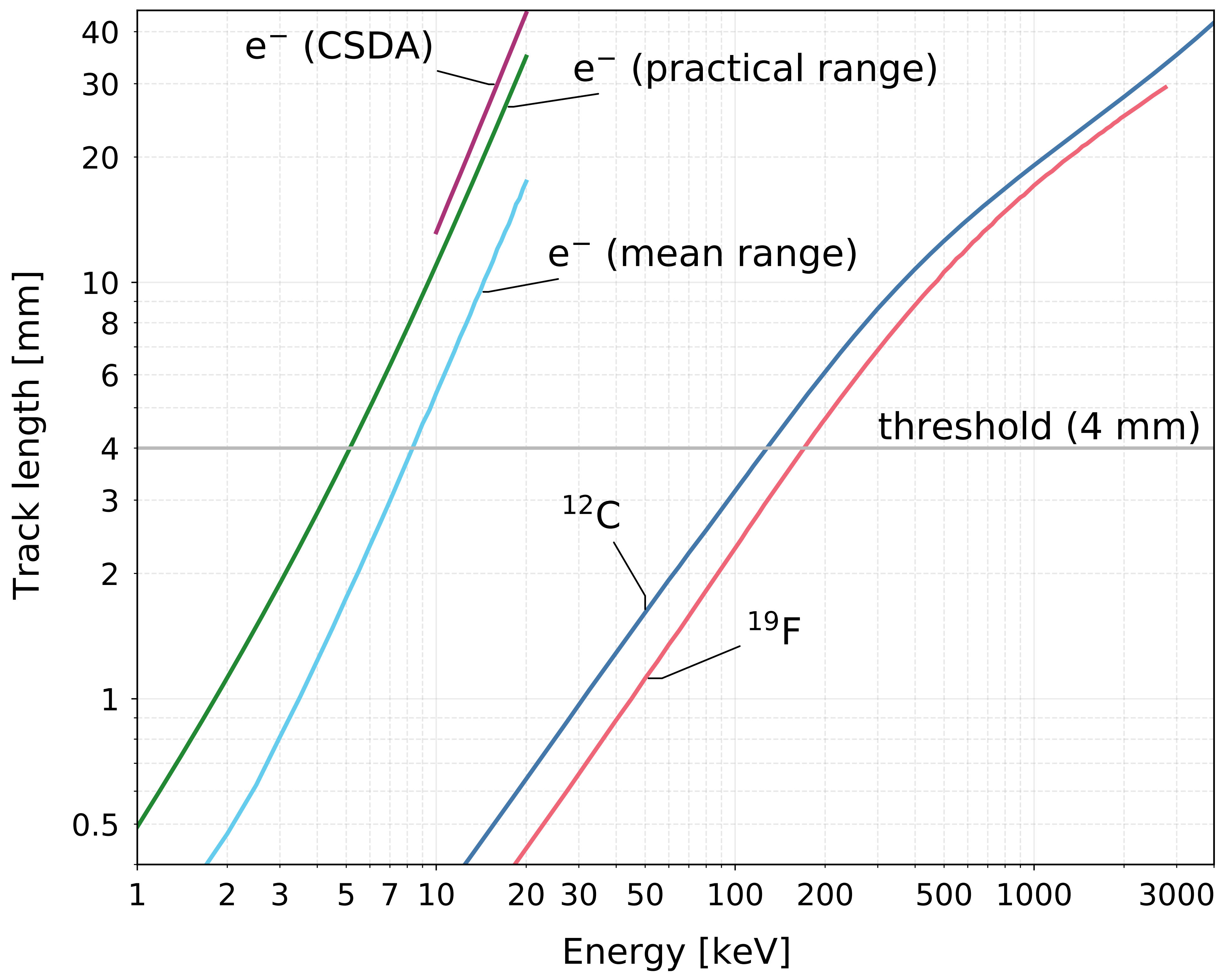
Summary

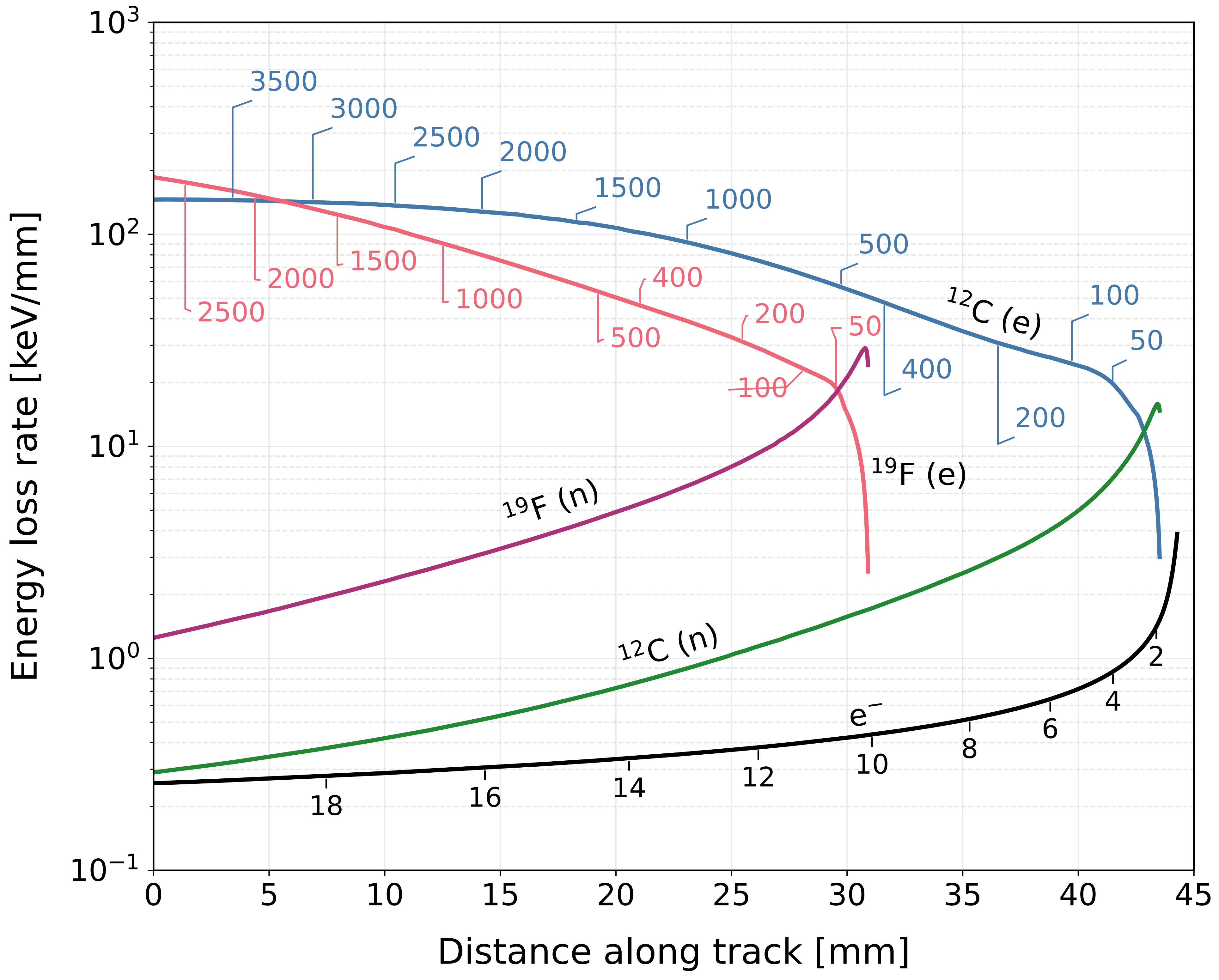
- The MIGDAL experiment aims to perform an unambiguous observation the Migdal effect
- Design of the experiment is complete
- Detector is constructed and is being tested
- End-to-end simulation chain in place
- Calibration with ^{55}Fe and fission-fragment sources are about to begin
- R&D on novel hole-type avalanche structures
- Runs with D-D generator and a Detector paper coming soon !





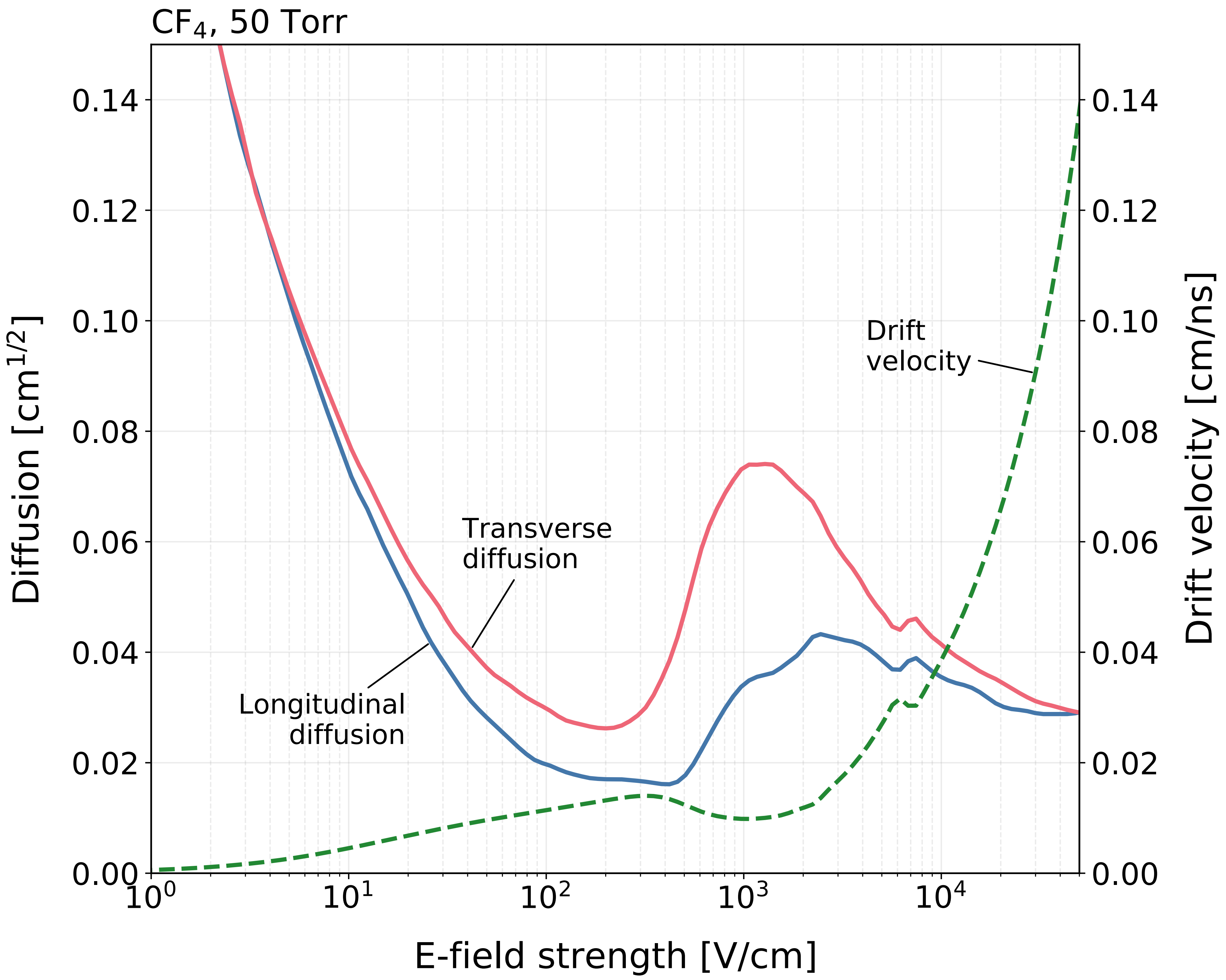
Tracks

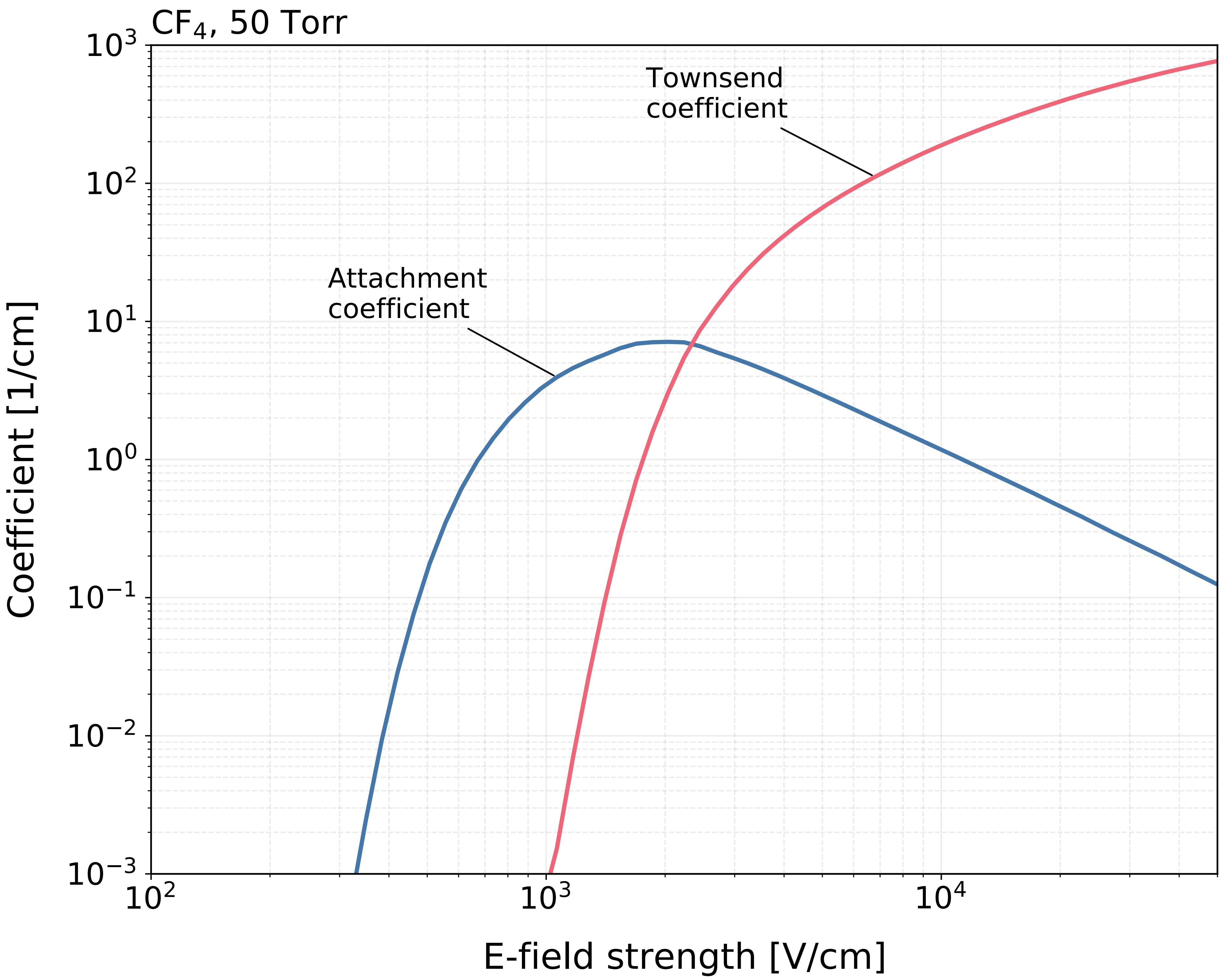




- We can exploit different track lenghts and dE/dx to distinguish nuclear and electronic recoils
- Nuclear recoils deposit more of their energy at the beginning of the track, while electrons deposit more energy at the end of the track

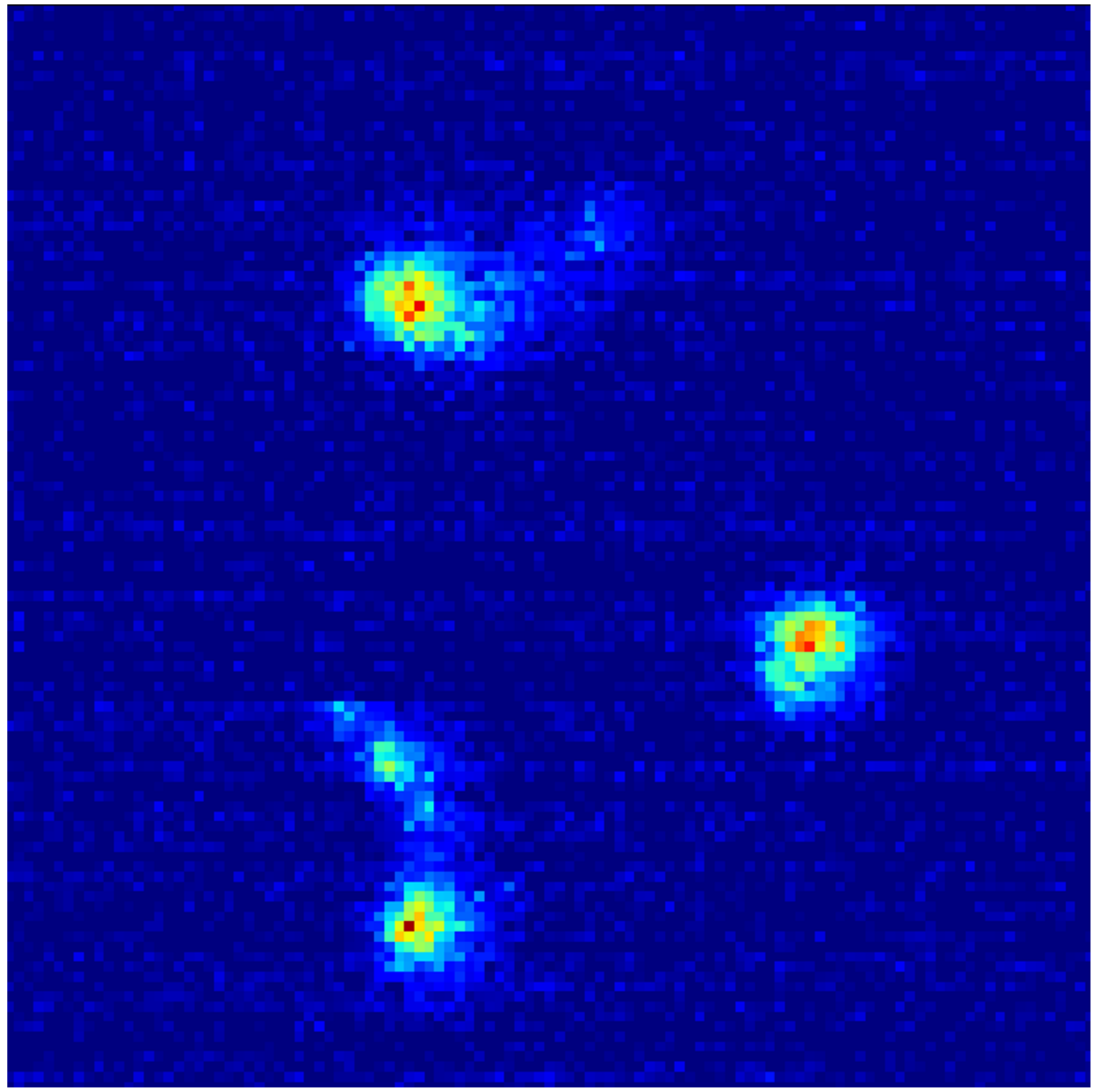
Gas properties

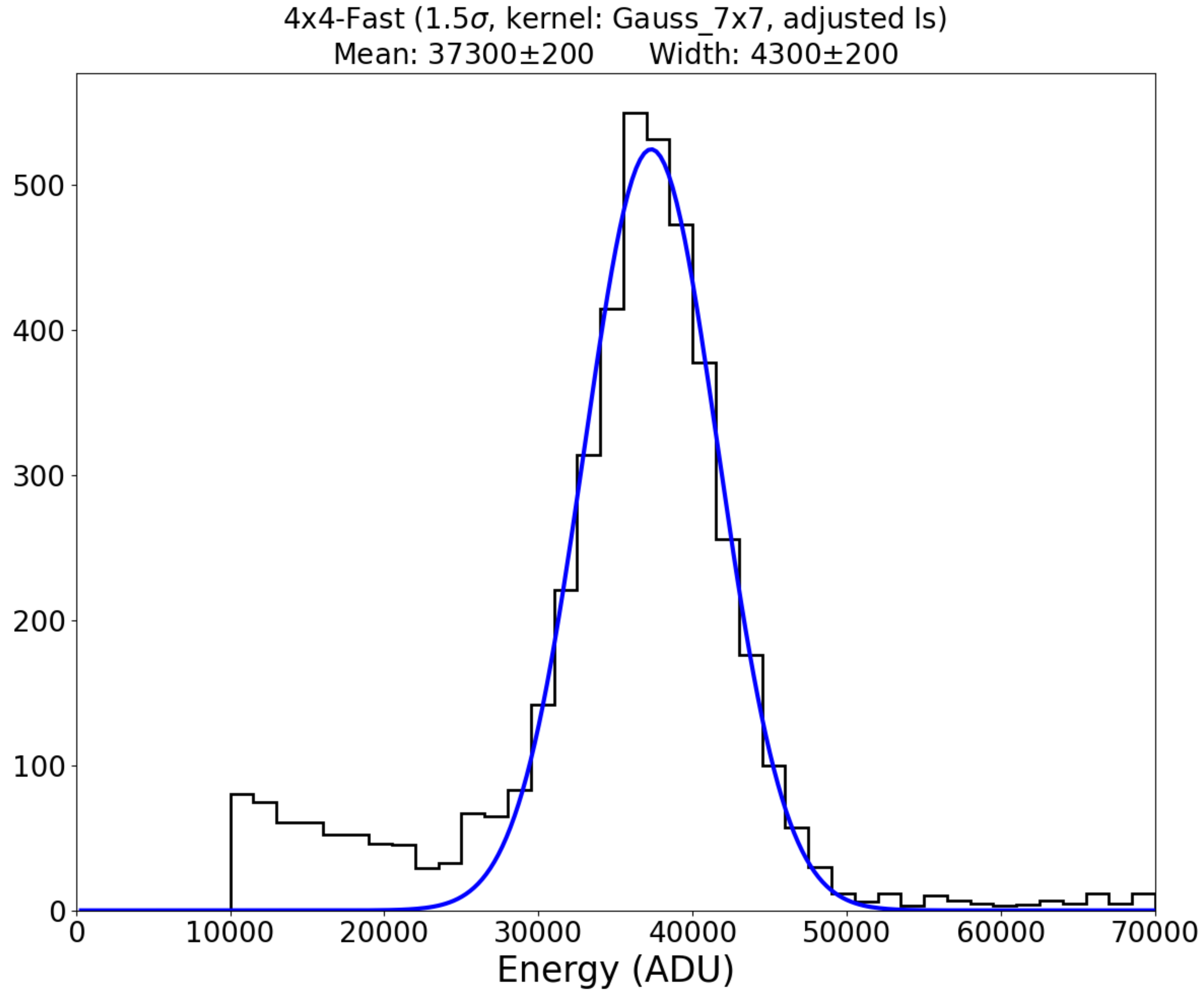




- **Gas properties for CF4 at 50 Torr, calculated with Magboltz**
- **Electric fields chosen to minimize diffusion and attachment**

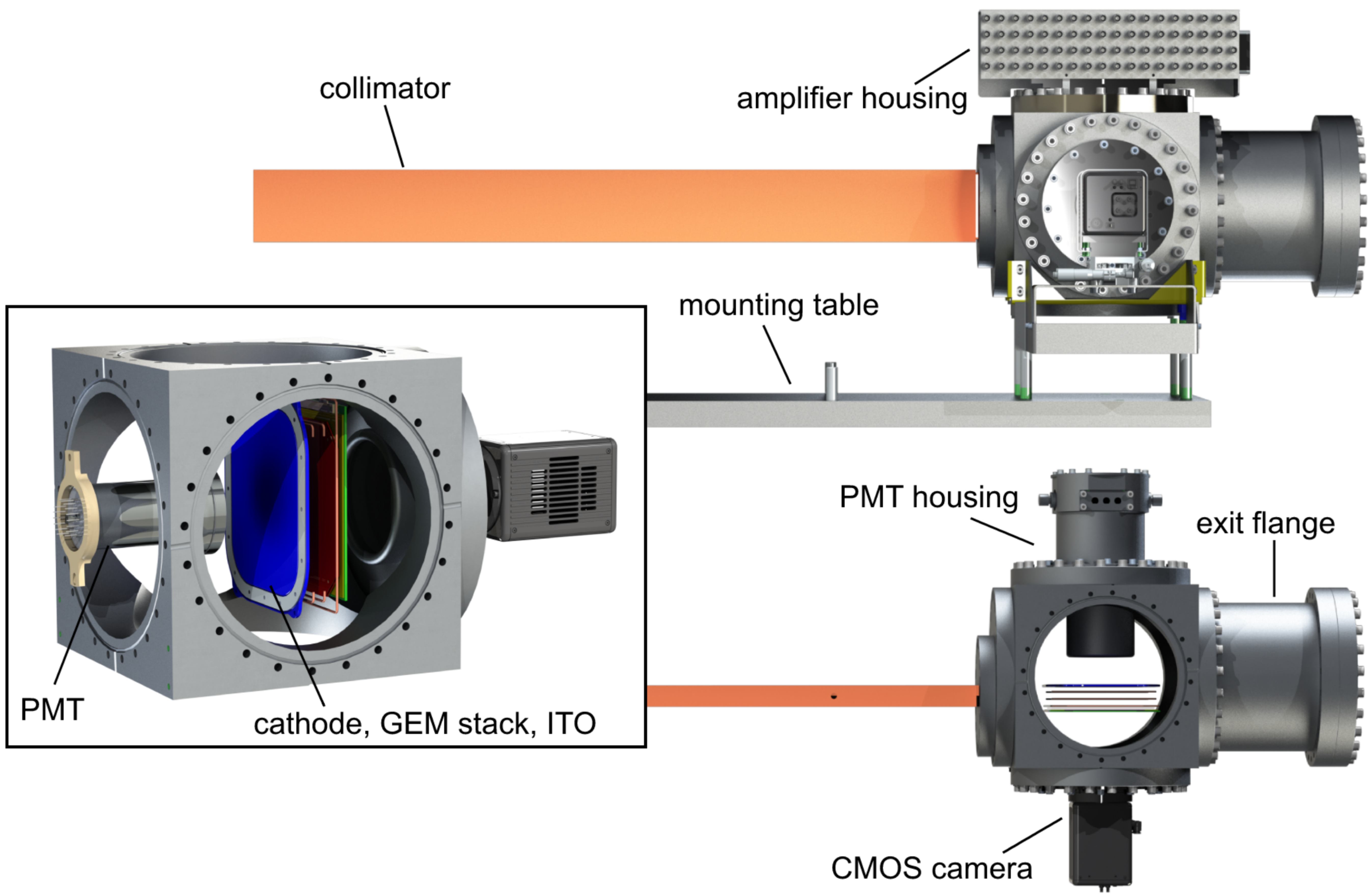
Measurements at GDD CERN

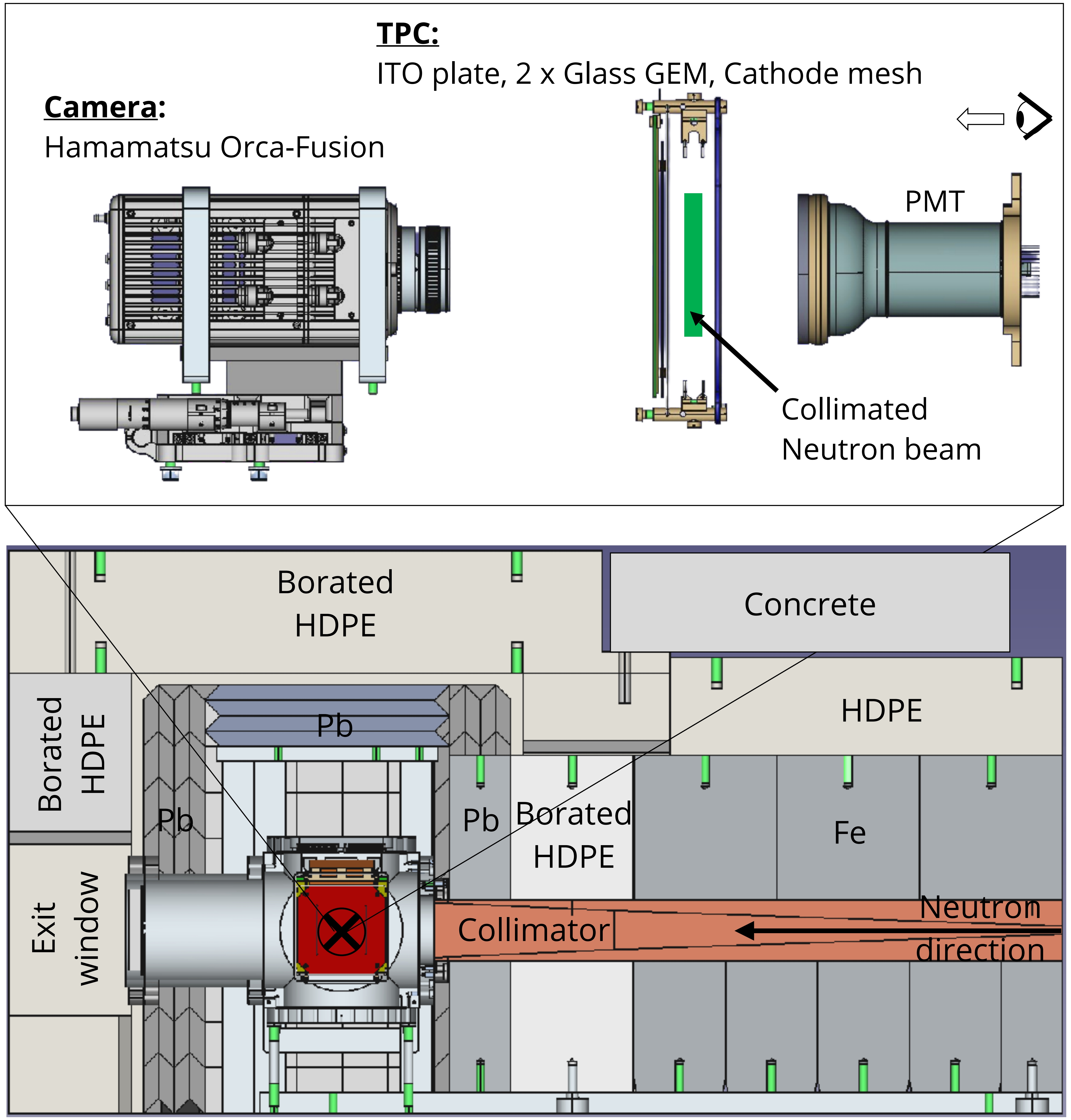




- Successful tests have been performed using glass-GEMs by the GDD group at CERN with CF4 at 50 Torr
- Tracks from 55Fe (5.9 keV γ) decays are well resolved with an energy resolution of 27%
- Track head and tail clearly resolved for low energy electrons

The experimental setup



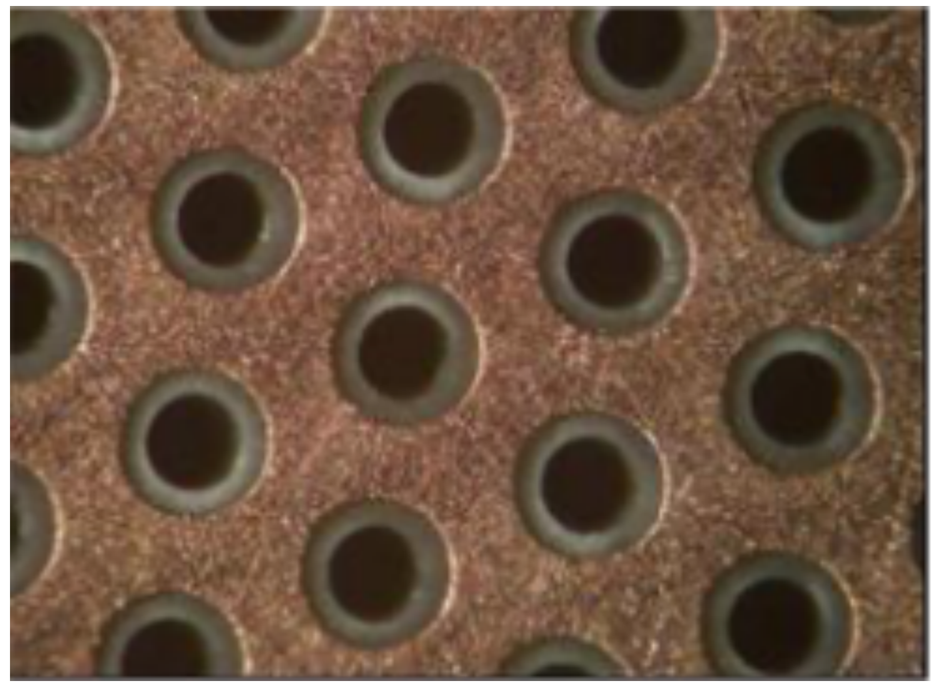


Detector R&D

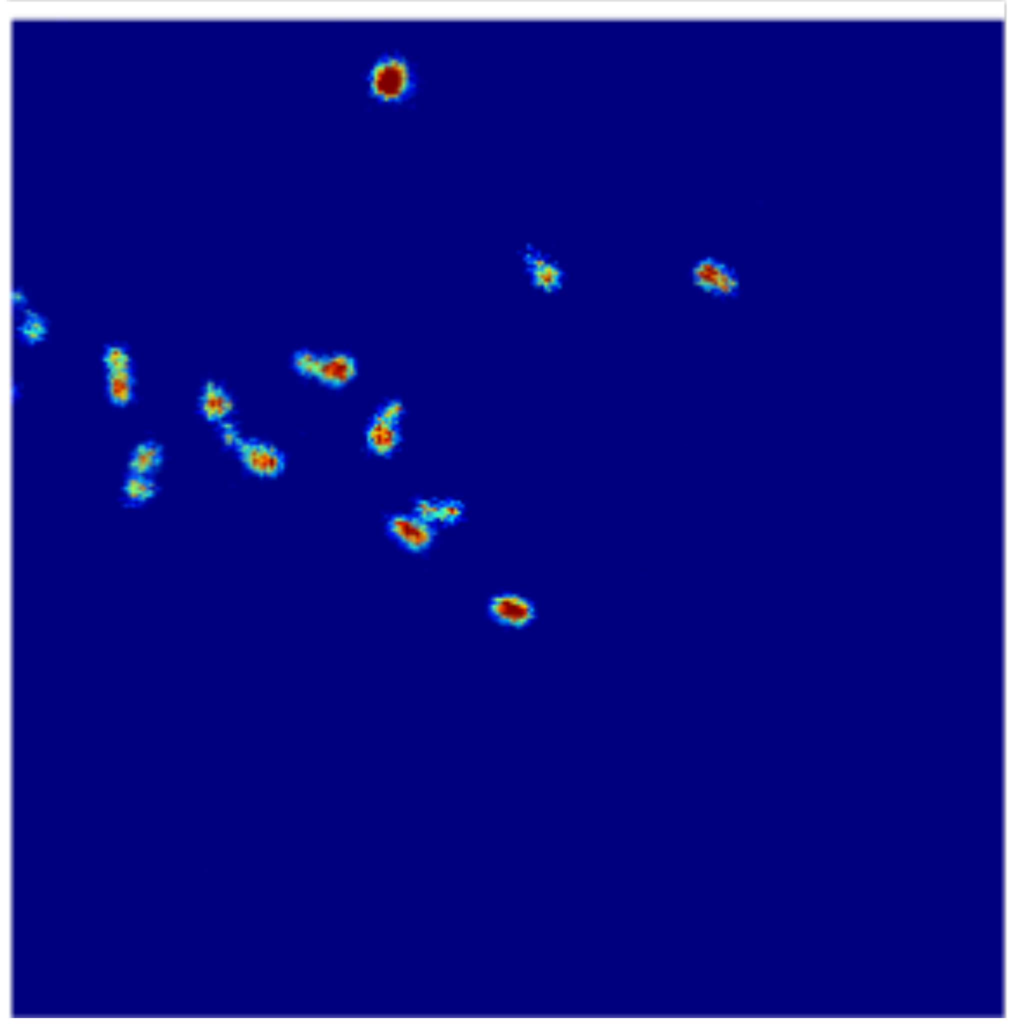
GEM technology comparison

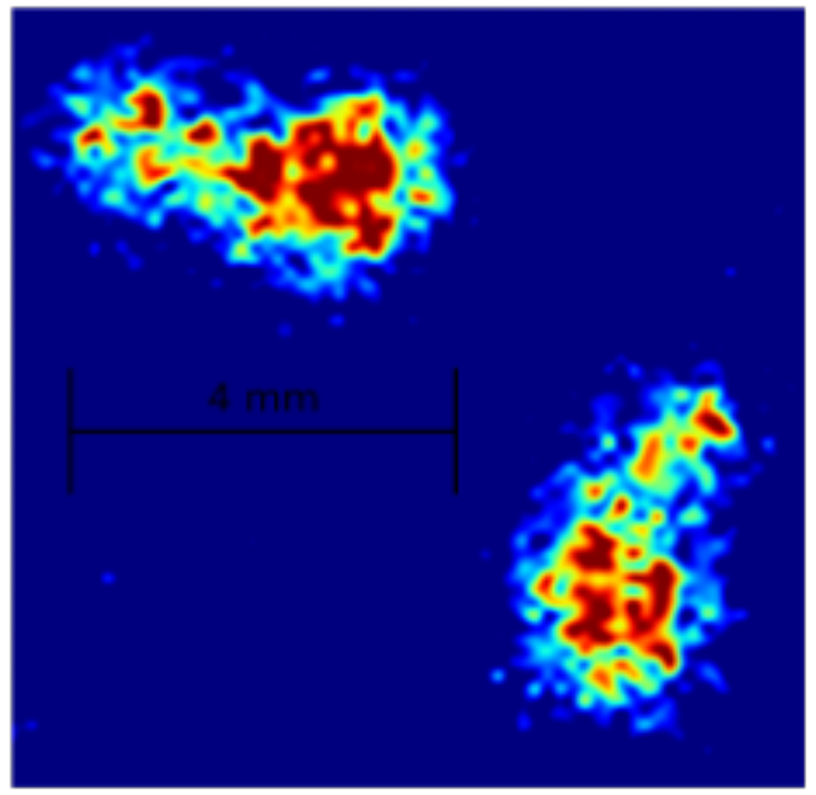
Image of low energy electron tracks from ^{55}Fe source in 50 Torr CF4. Tracks’ head and tail structure is clearly resolved with Glass GEMs!

THGEM



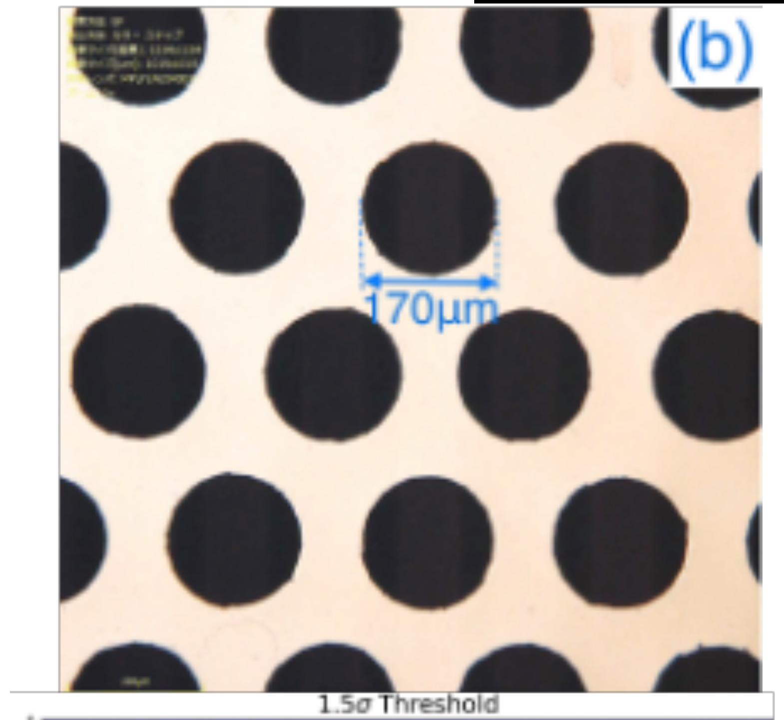
- 1 mm thick PCB
- 20 um thick Cu layer
- 700 um pitch
- 400 um hole diameter



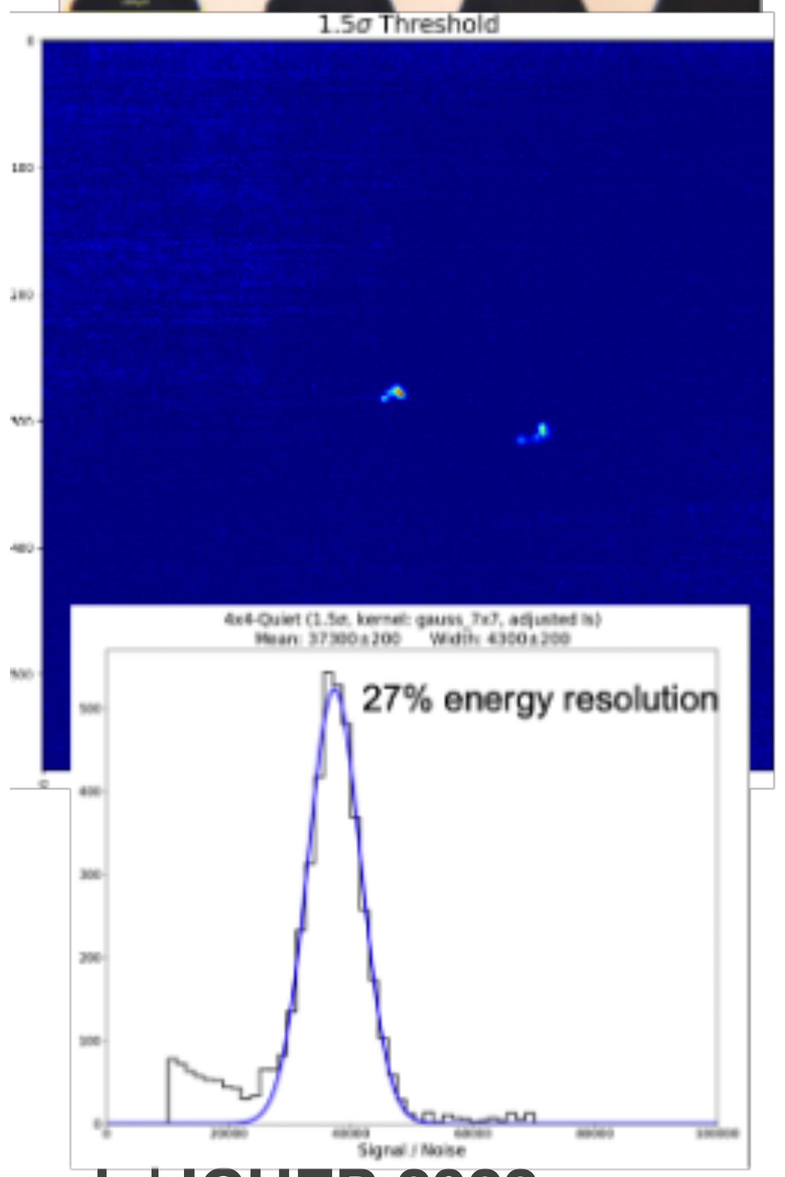


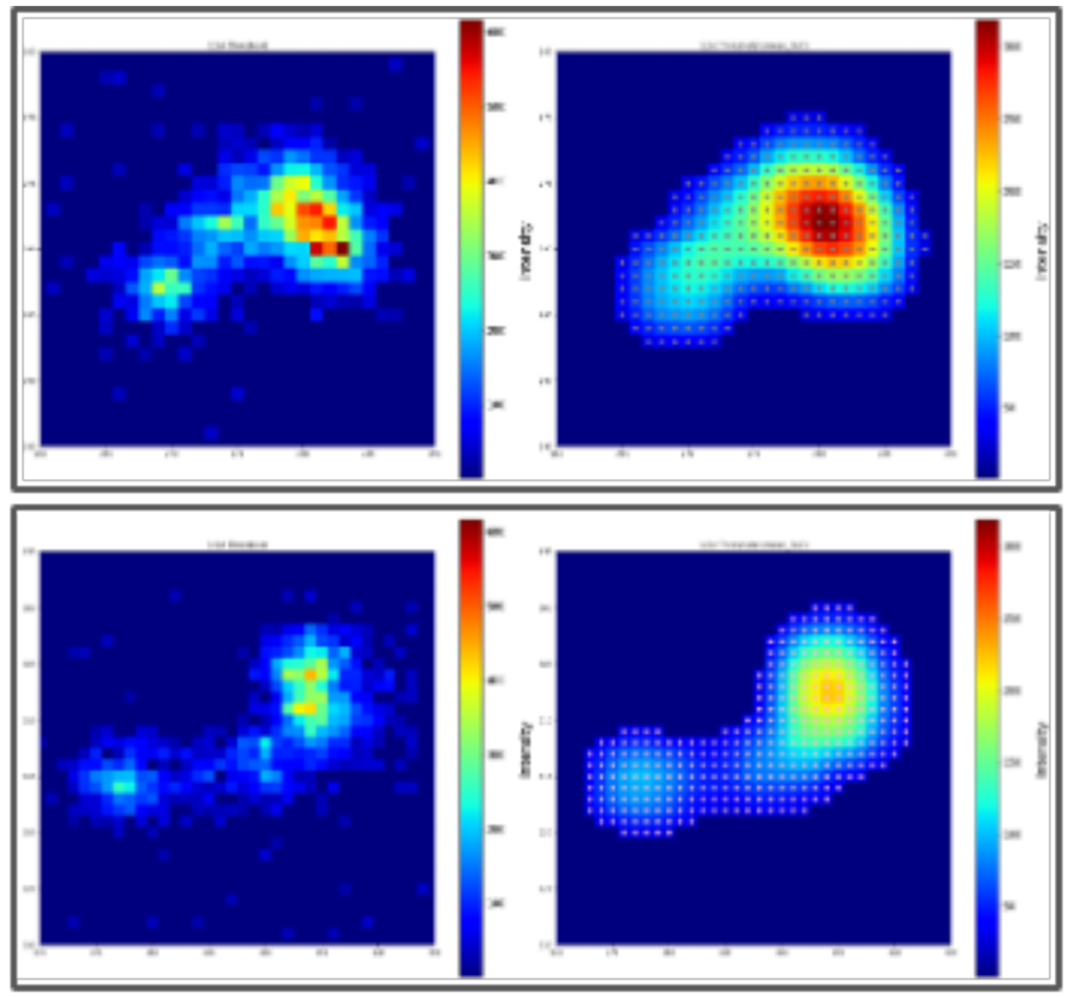
VS

Glass GEM



- 0.57 mm thick glass
- 2 um thick Cu layer
- 280 um pitch
- 170 um hole diameter





Detector R&D

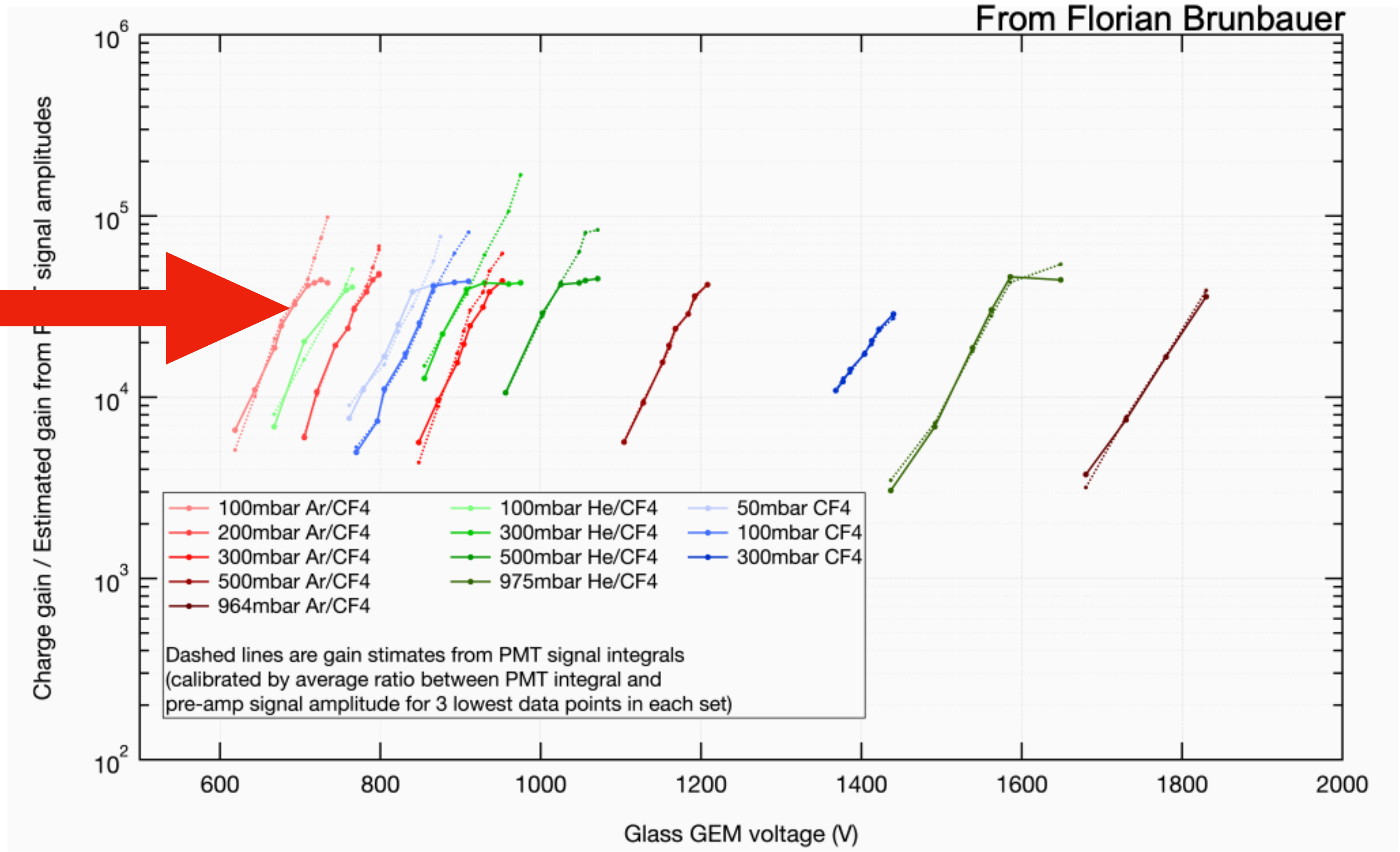
Working in high dynamic range

Potential issues

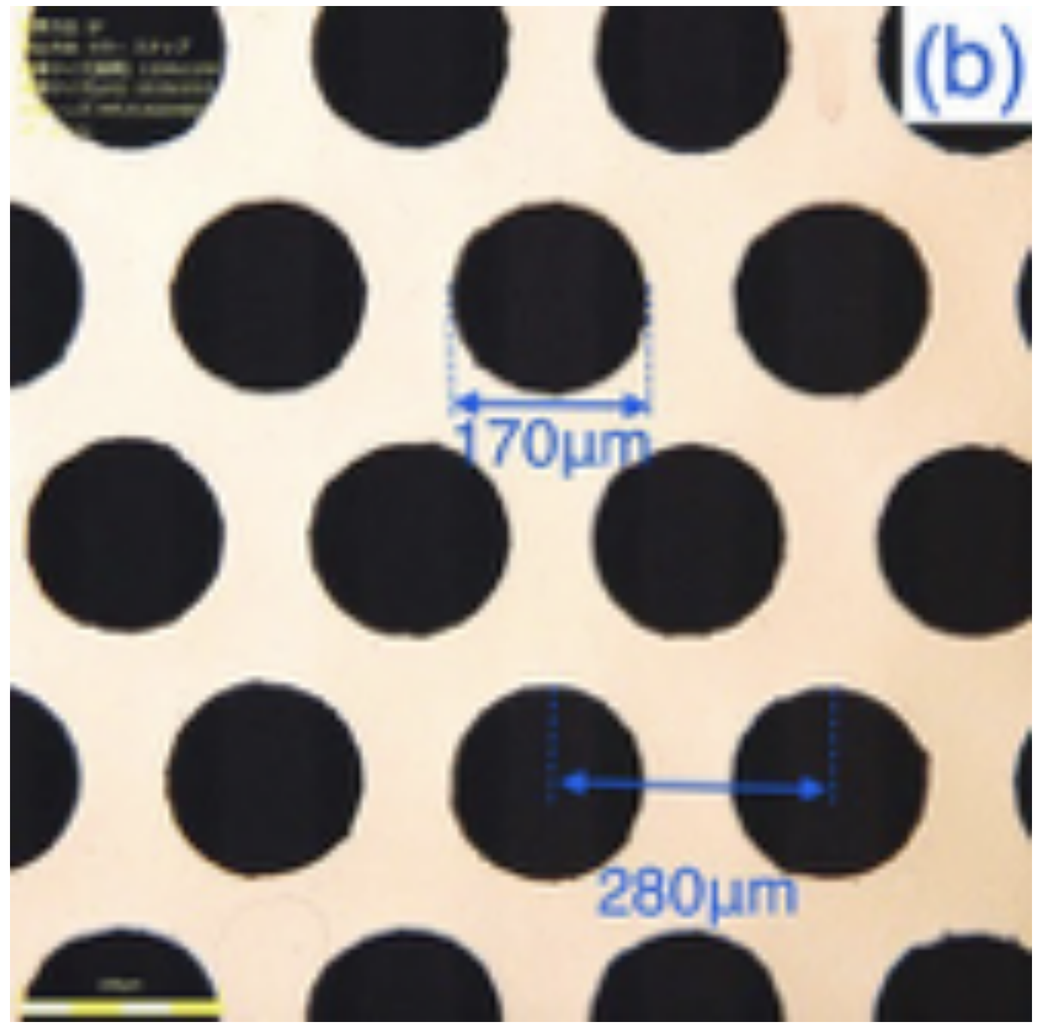
- Heavy ions produce a high number of primary electrons and with high ionisation density
- The dense electron cloud can be funneled through only one or few GEM holes
- $G \cdot n_0 \gtrsim 10^8$ (Raether limit) is reached, causing a breakdown.

Example scenario:

- E_{dep}= 144.4 keV by 5 MeV C^+ in CF_4
- n_0 = 4370 primary electrons (W=34eV)
- $G \cdot n_0 = \sim 2 \cdot 10^8 \rightarrow 34.88$ pC

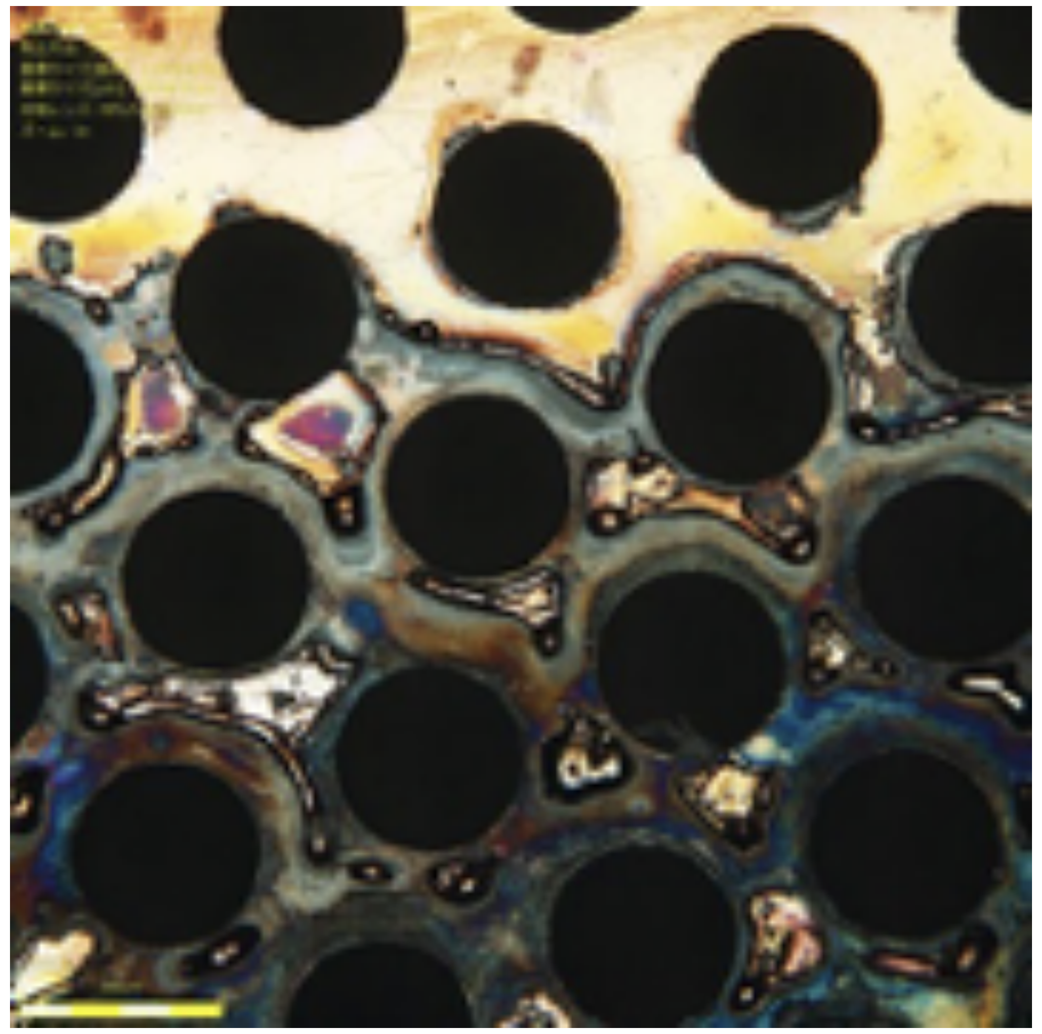


Glass GEM electrode



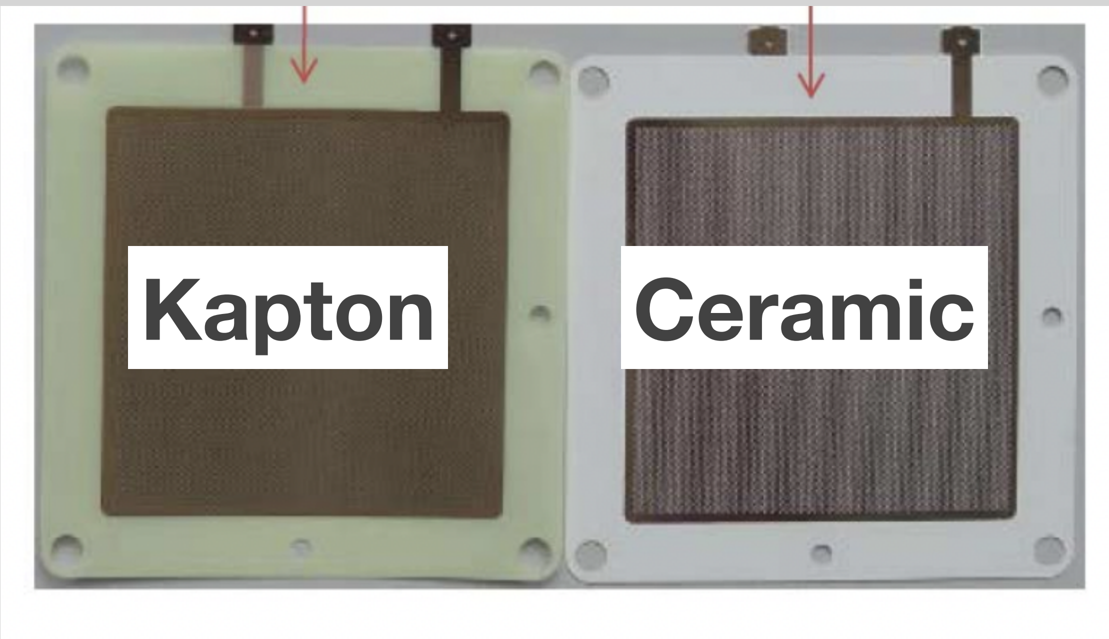
Spark!

Damaged GEM electrode

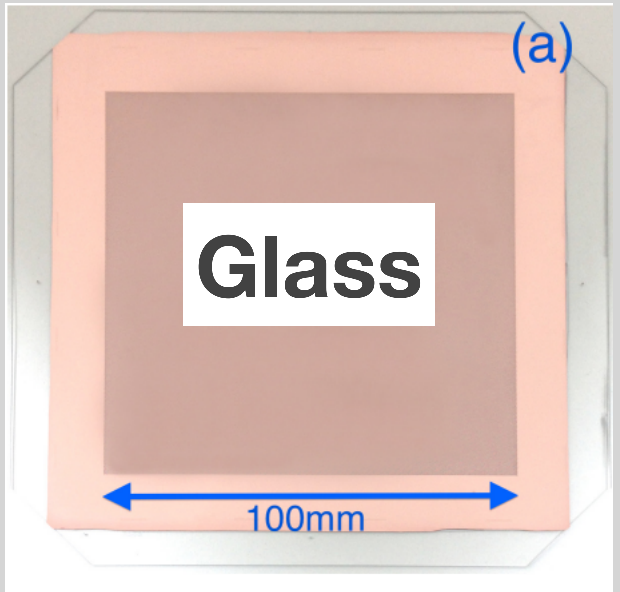


Detector R&D

RD51 common project



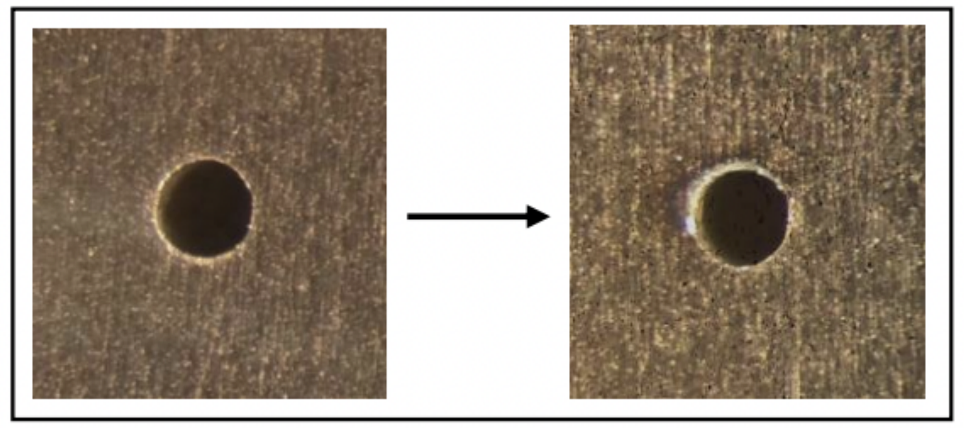
- Constructed in China
- Cost effective
- Large range for thickness, pitch, and hole diameter
- Large range of electrode materials and layer thickness



- Constructed in Japan
- High precision
- Small pitch and hole size combines with large thickness
- Thin layer of electrode material
- Only Cu and Ni layer
- Expensive

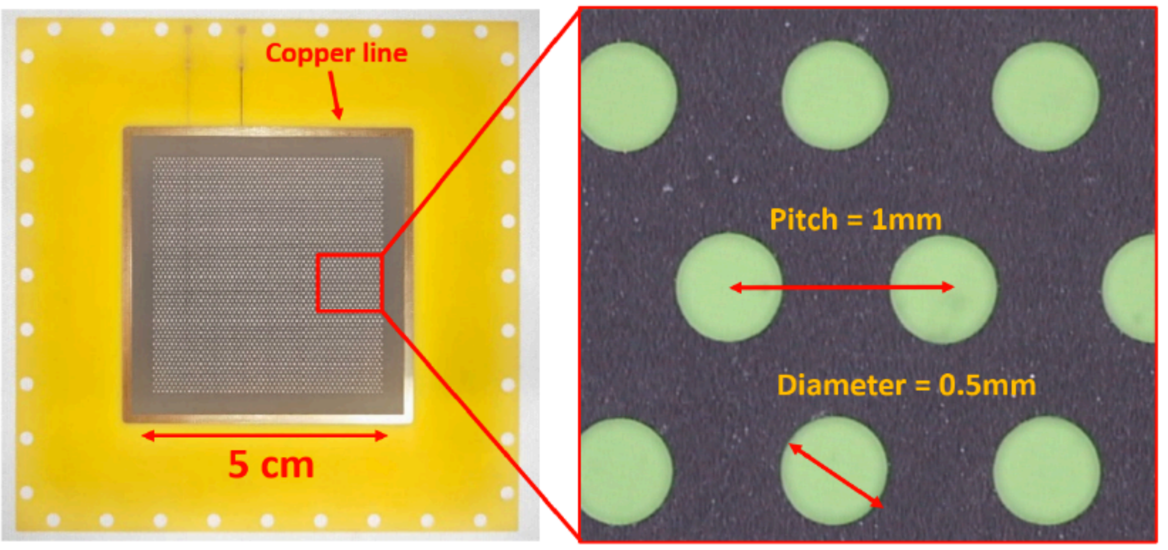
Alternative Coating THGEMS (Higher Fusion Point)

Cu → 1085 °C
Ni → 1455 °C
ITO→ 1926 °C
W → 3422 °C



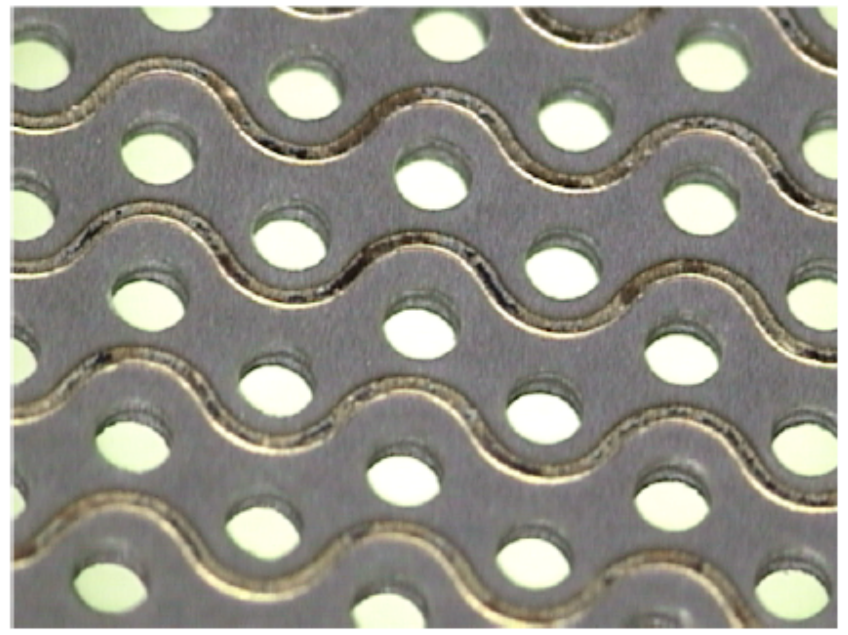
- Hard to damage
- High rate capabilities
- No spark quenching

DLC coated THGEMs



- High resistivity
- Spark quenching
- Robustness
- Rate limited

Stripped electrodes



- Decreased spark energy
- Contraction with both conductive or resistive material
- Harder to make