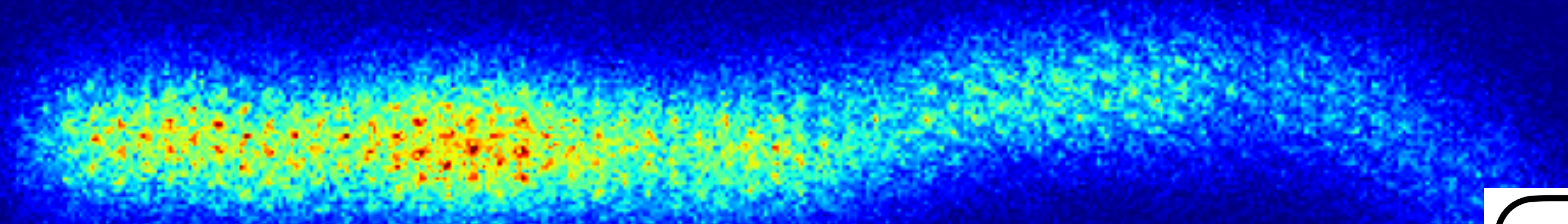
Science operations of the MIGDAL experiment at NILE



Lex Millins *on behalf of the MIGDAL collaboration*

University of Birmingham & STFC Rutherford Appleton Laboratory

UKHEP2025 - Wandering in the Dark

21st October, Abingdon

lkm892@student.bham.ac.uk

The MIGDAL experiment

- Aim to make the first unambiguous observation of the Migdal Effect in nuclear scattering
- Low pressure Optical Time Projection Chamber (OTPC) with **50 Torr CF_4**

Science and Technology Facilities Council

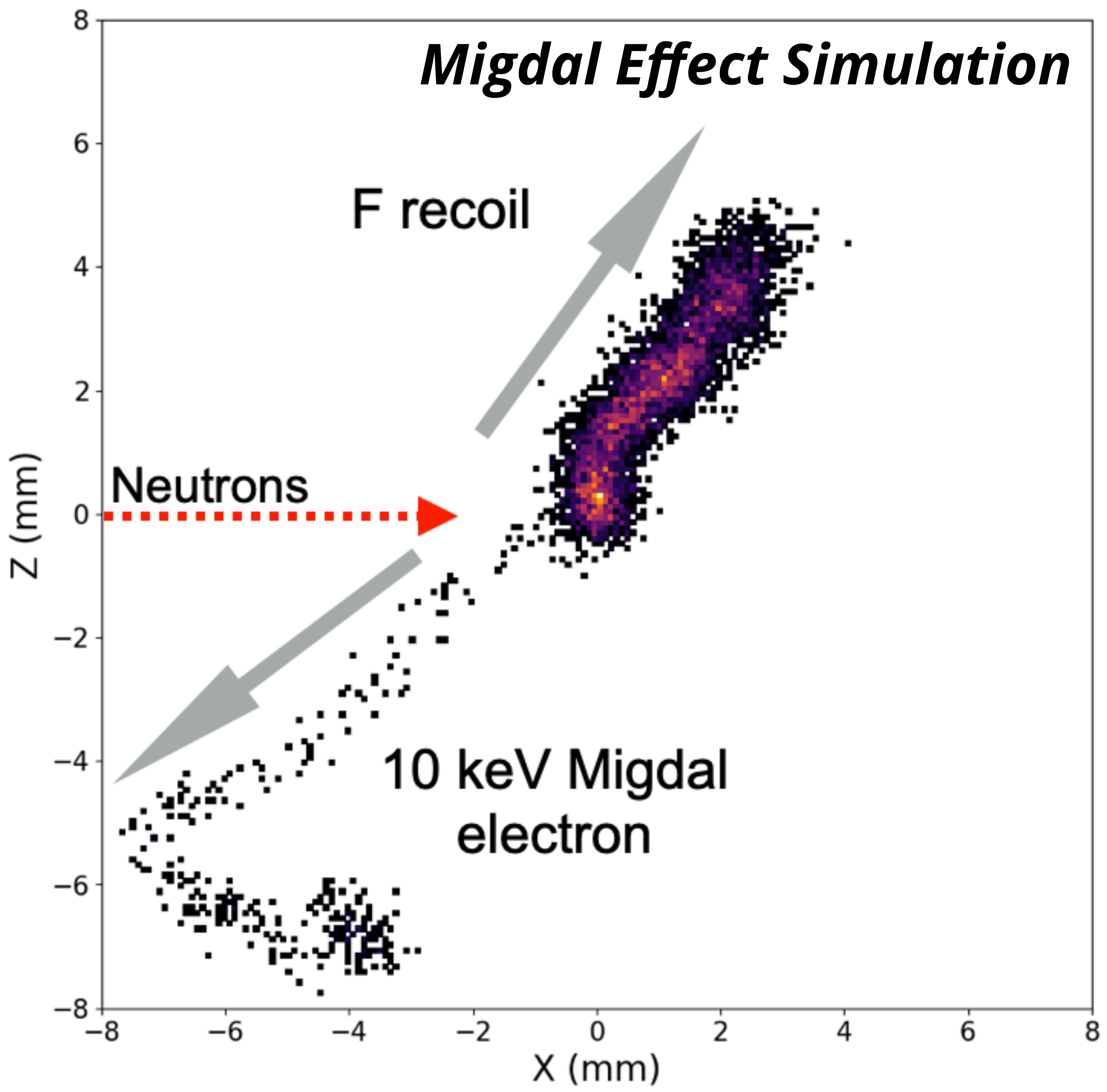
U.S. DEPARTMENT OF ENERGY

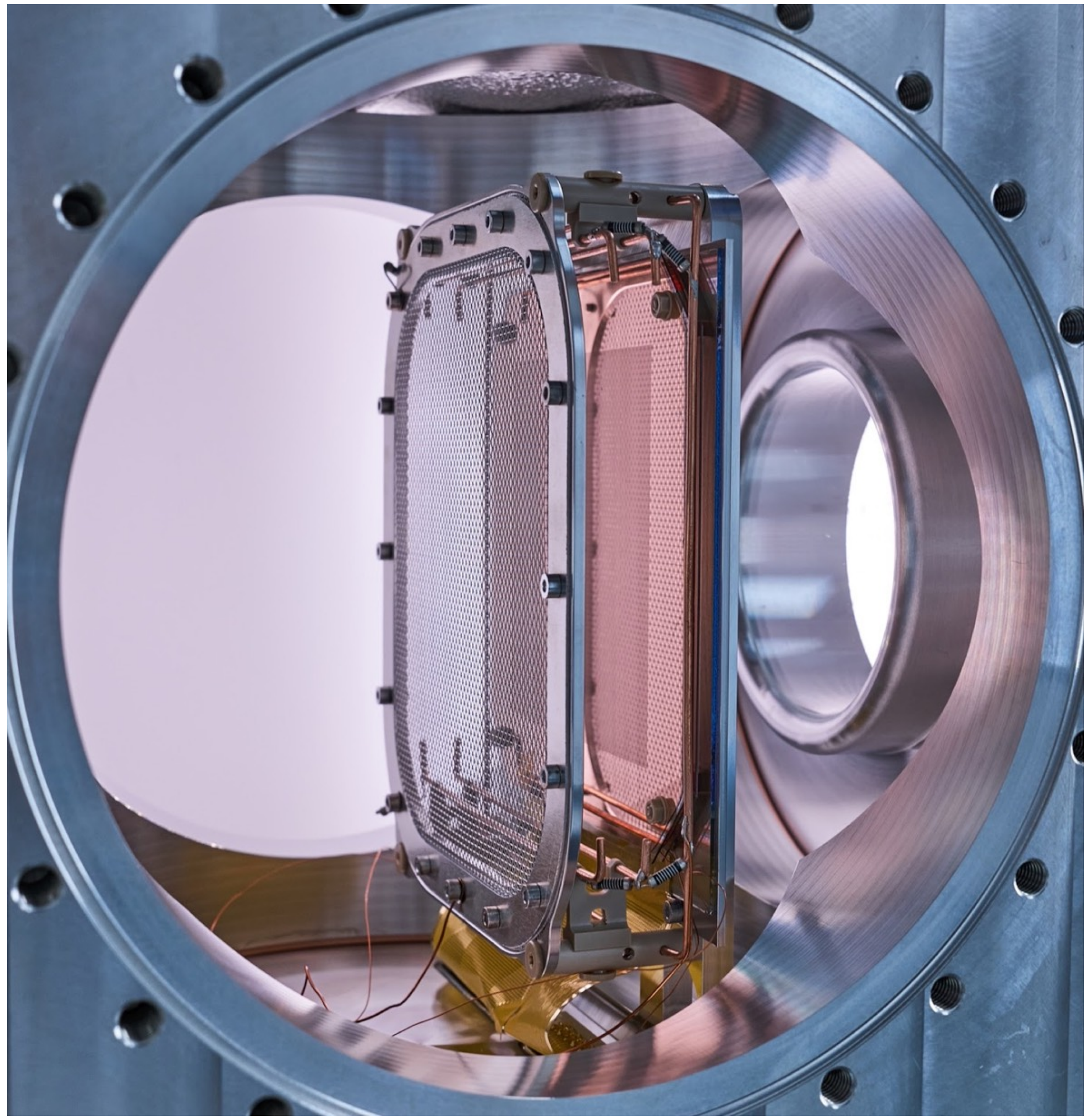
FCT Fundação para a Ciência e a Tecnologia

Horizon 2020 European Union Funding for Research & Innovation

National Science Foundation

MARIE CURIE ACTIONS

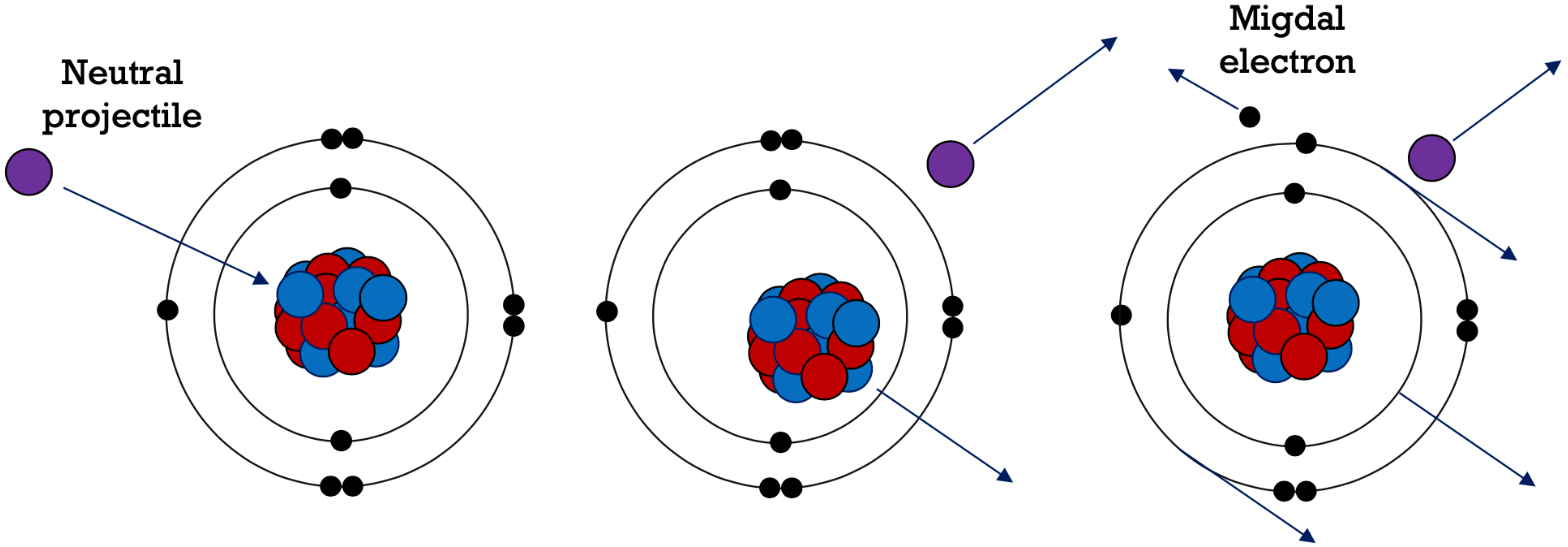




The Migdal effect

- During nuclear recoil sudden displacement of nucleus with respect to atomic electron cloud excites the atom
- De-excitation can result in emission of one or more Migdal electrons (with low probability)
- Observed in α, β decay (Phys. Rev. C 11 (1975), 1740-1745 & 1746-1754, Phys. Rev. 93 (1954), 518-523, Phys. Rev. A 97 (2018), 023402)
- For low mass WIMP-like DM energy deposited by electron can exceed *O*(keV) nuclear recoil

Not yet observed in nuclear scattering!



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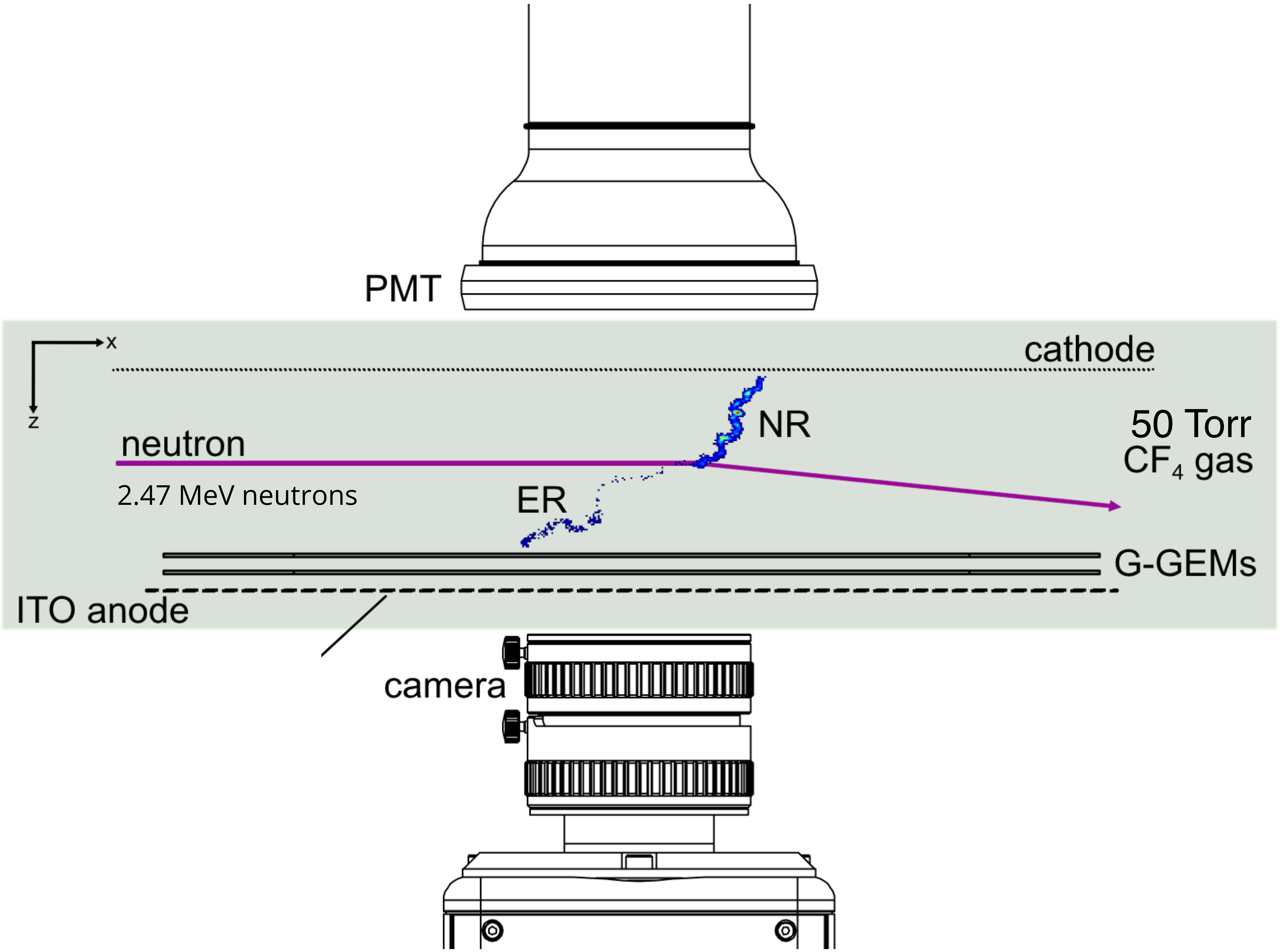
The MIGDAL Detector

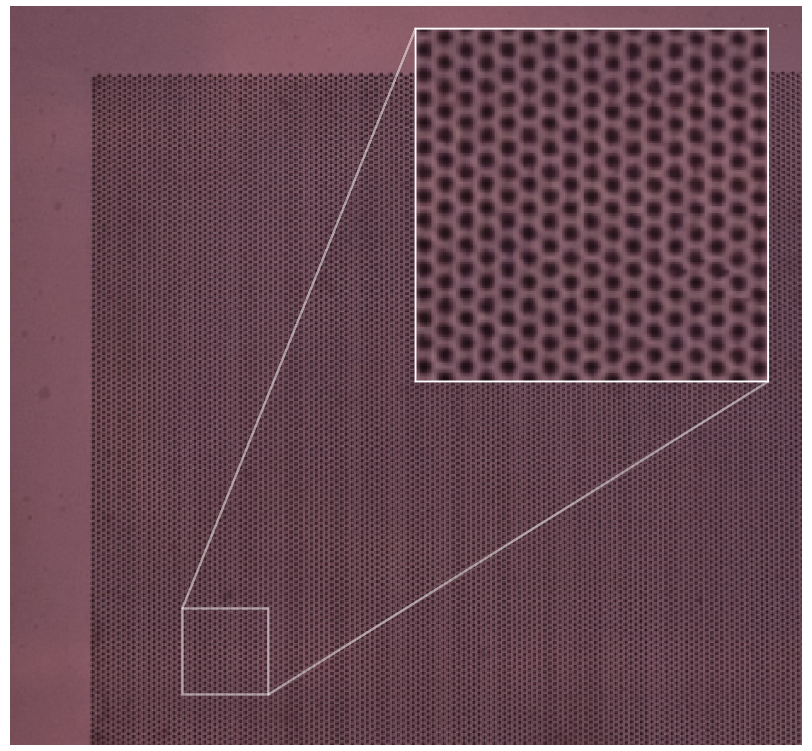


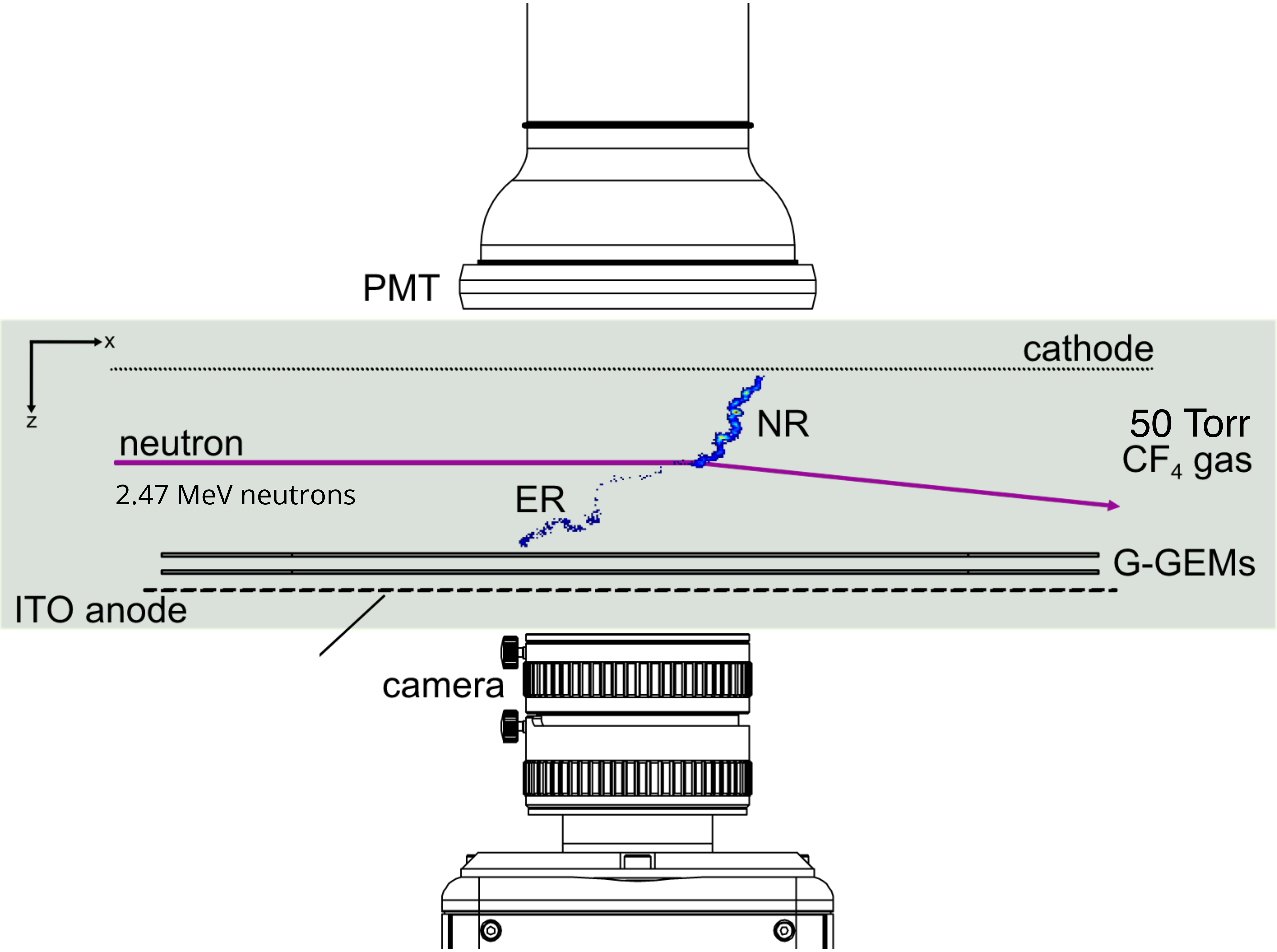
Astropart.Phys. 151 (2023) 102853

The MIGDAL Detector

Charge Amplification

Two glass GEMs





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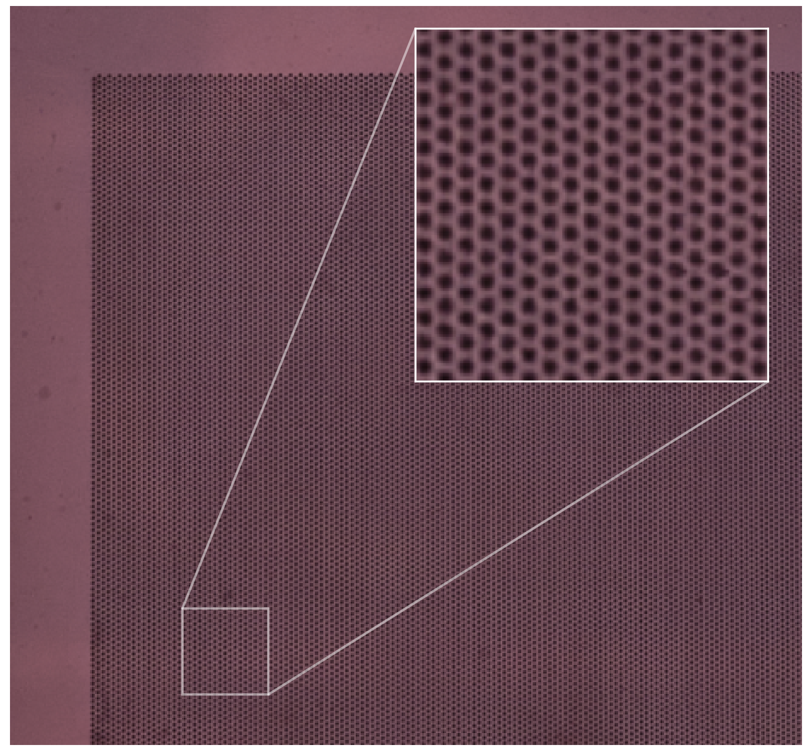
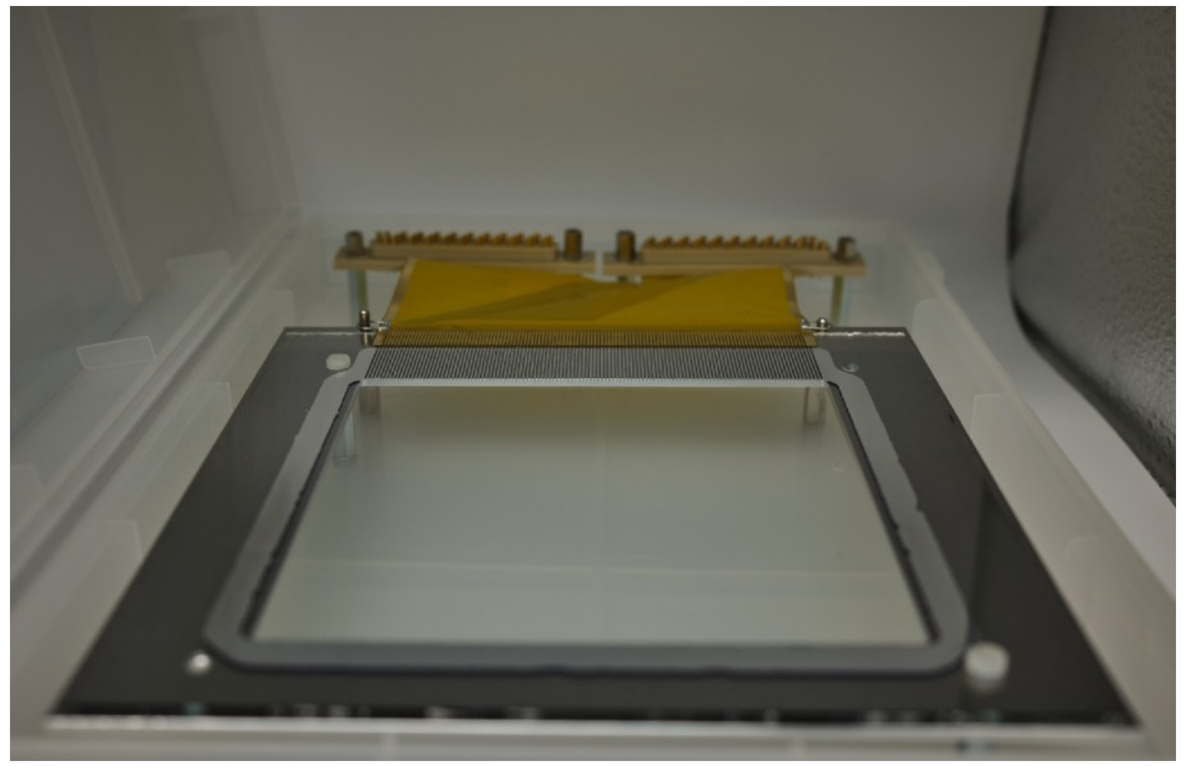
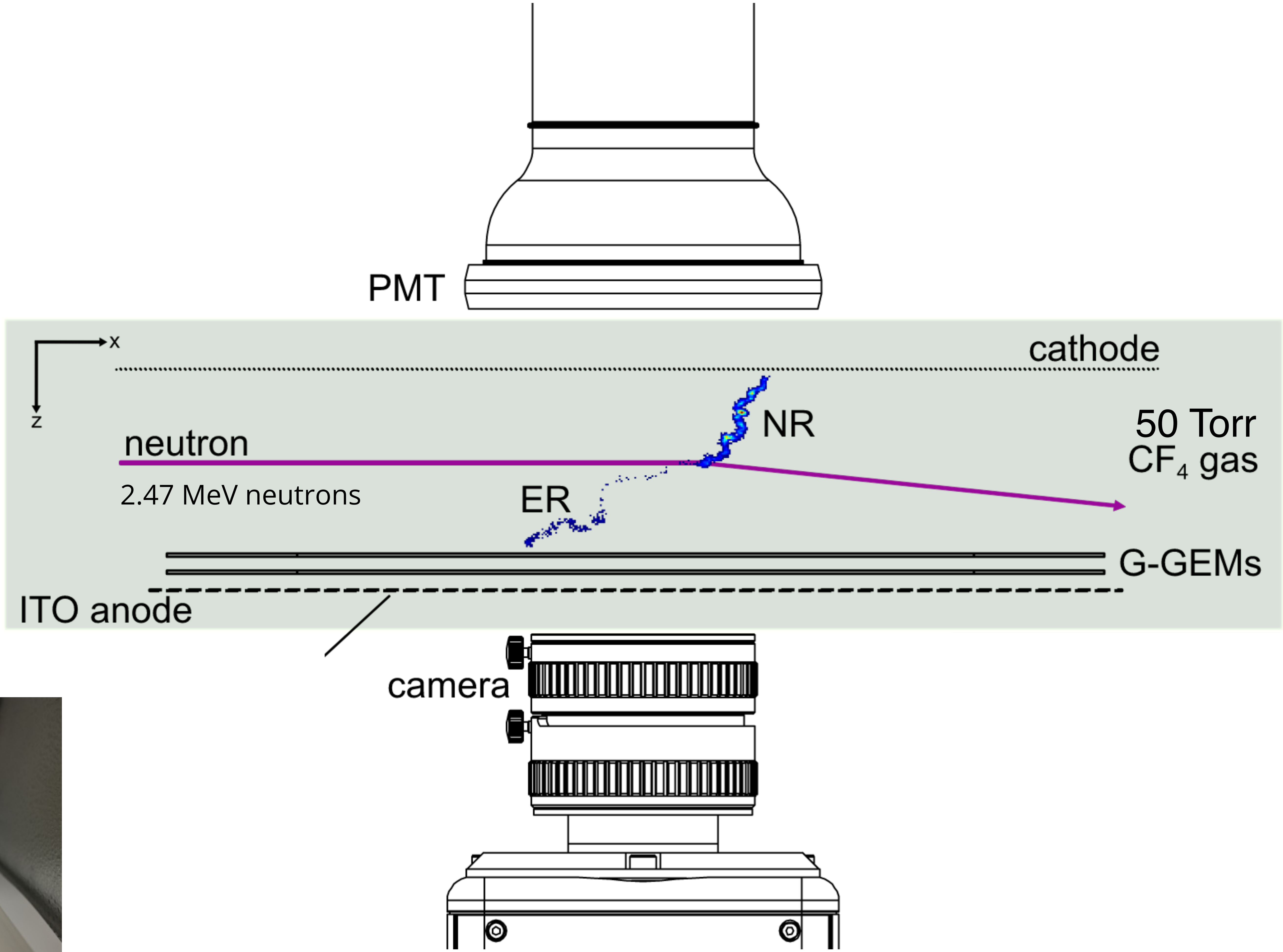
Two glass GEMs



Charge read-out
anode segmented into
120 strips





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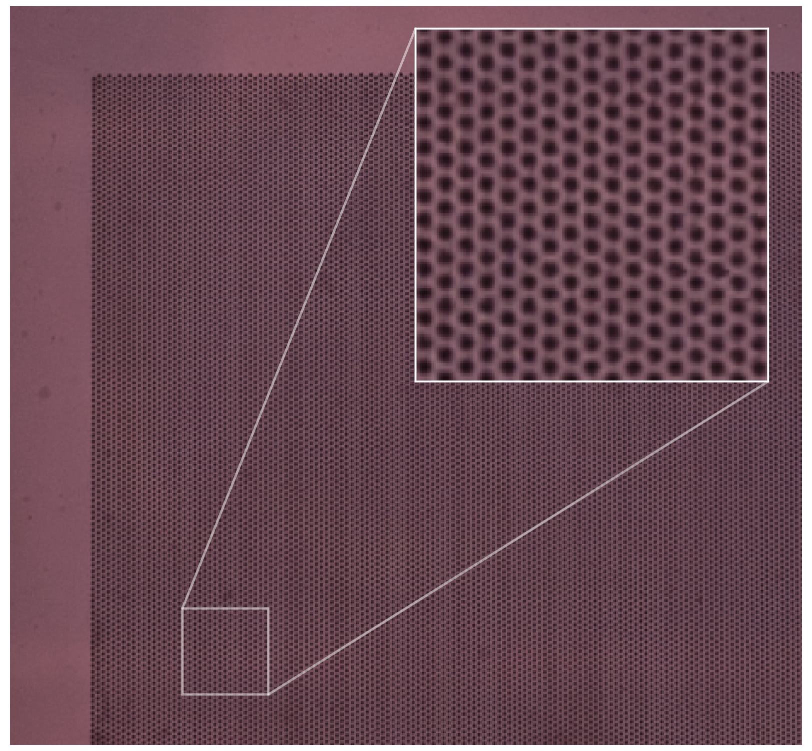

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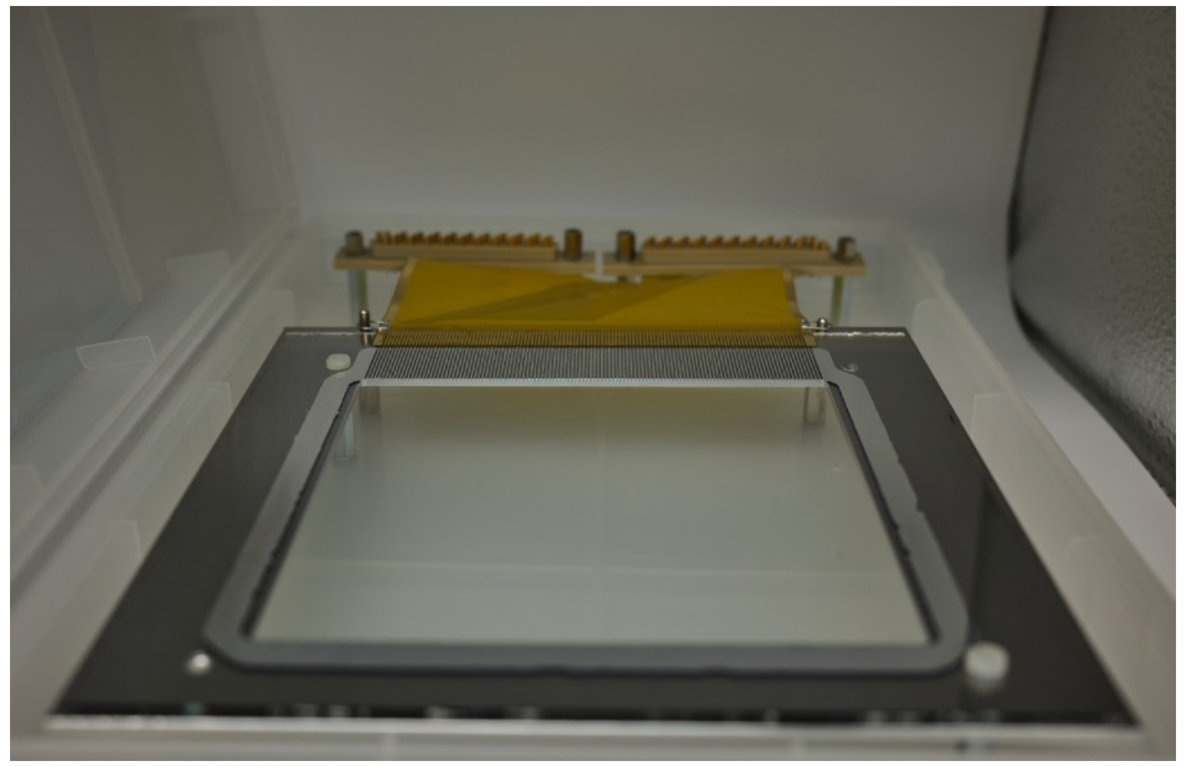
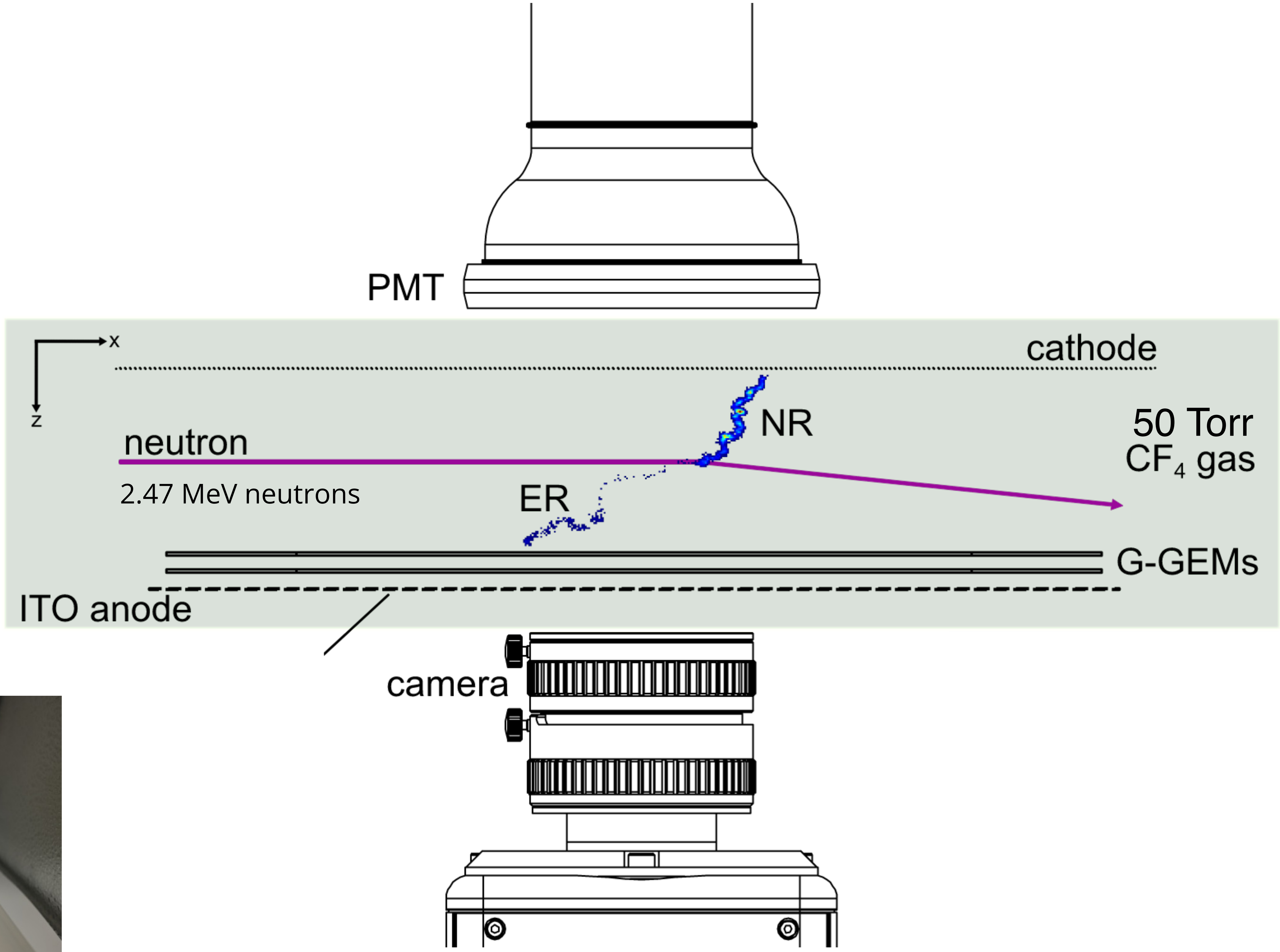
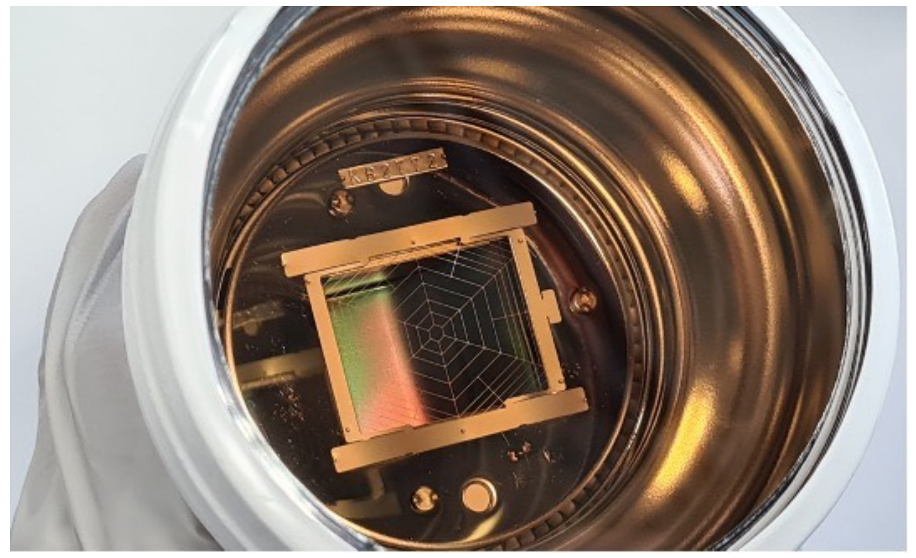




[Astropart.Phys. 151 (2023) 102853](https://doi.org/10.1016/j.astropartphys.2023.102853)

Trigger and timing
Hamamatsu R11410 VUV PMT



The MIGDAL Detector

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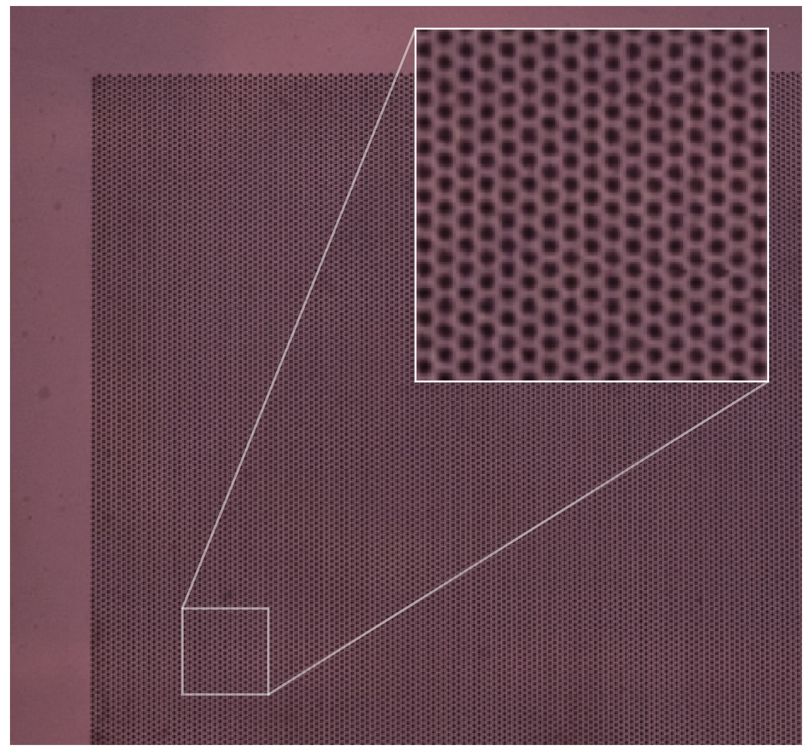
Two glass GEMs



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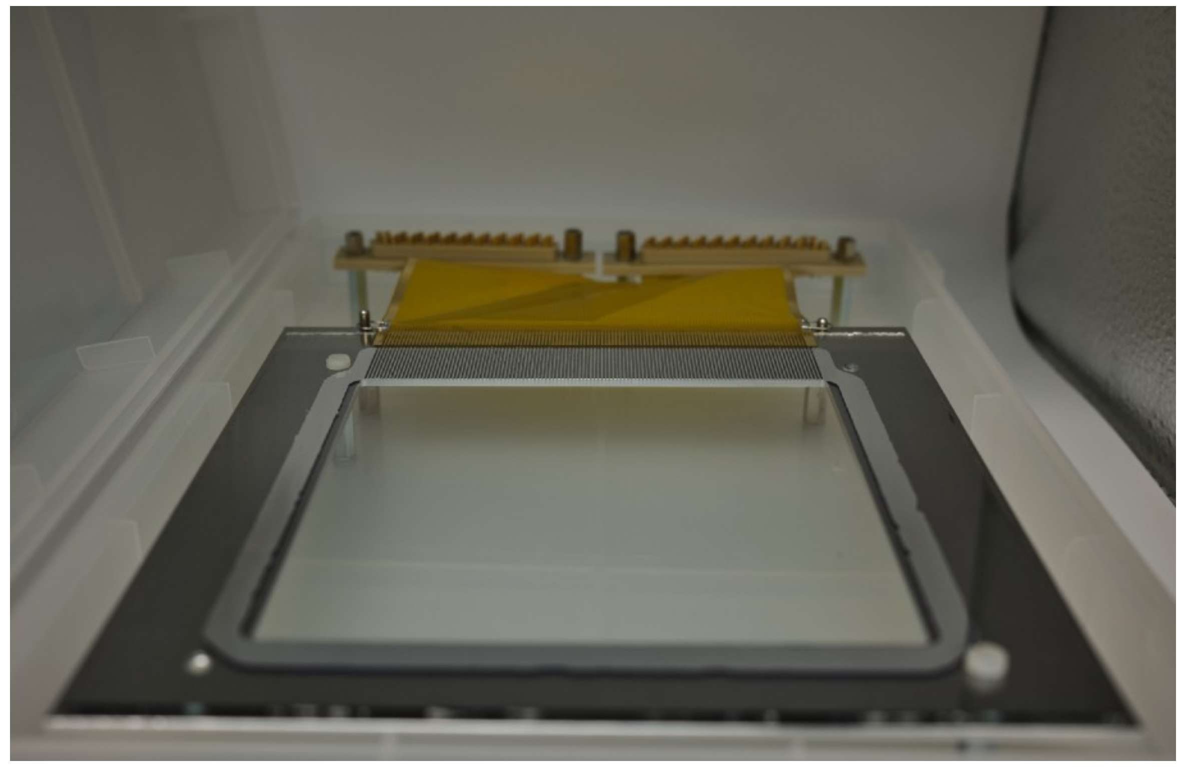

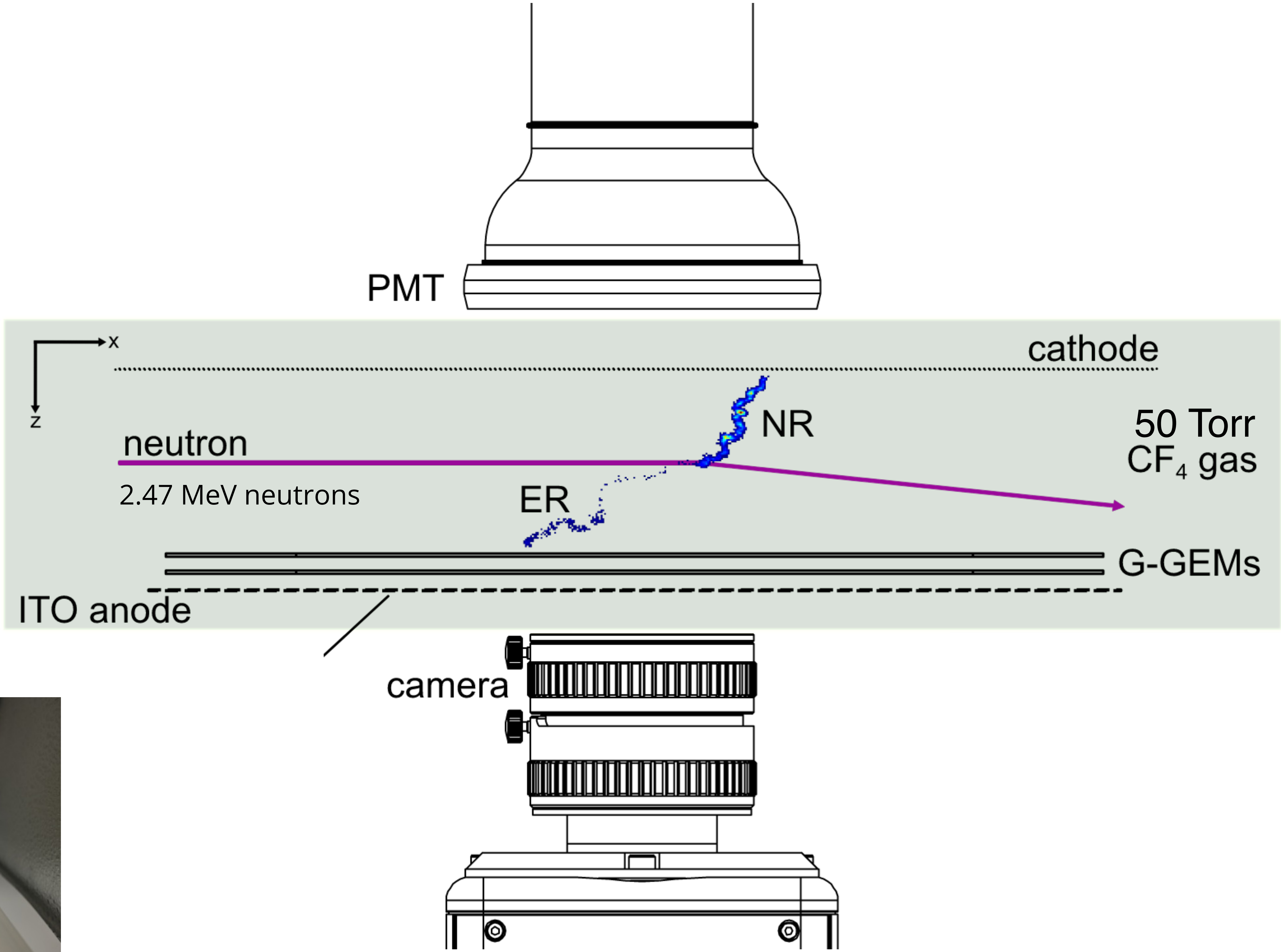

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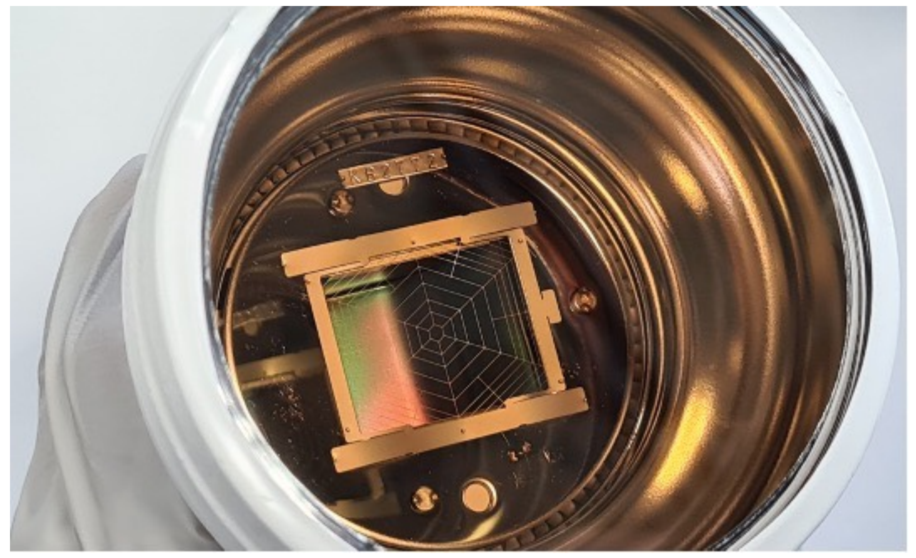
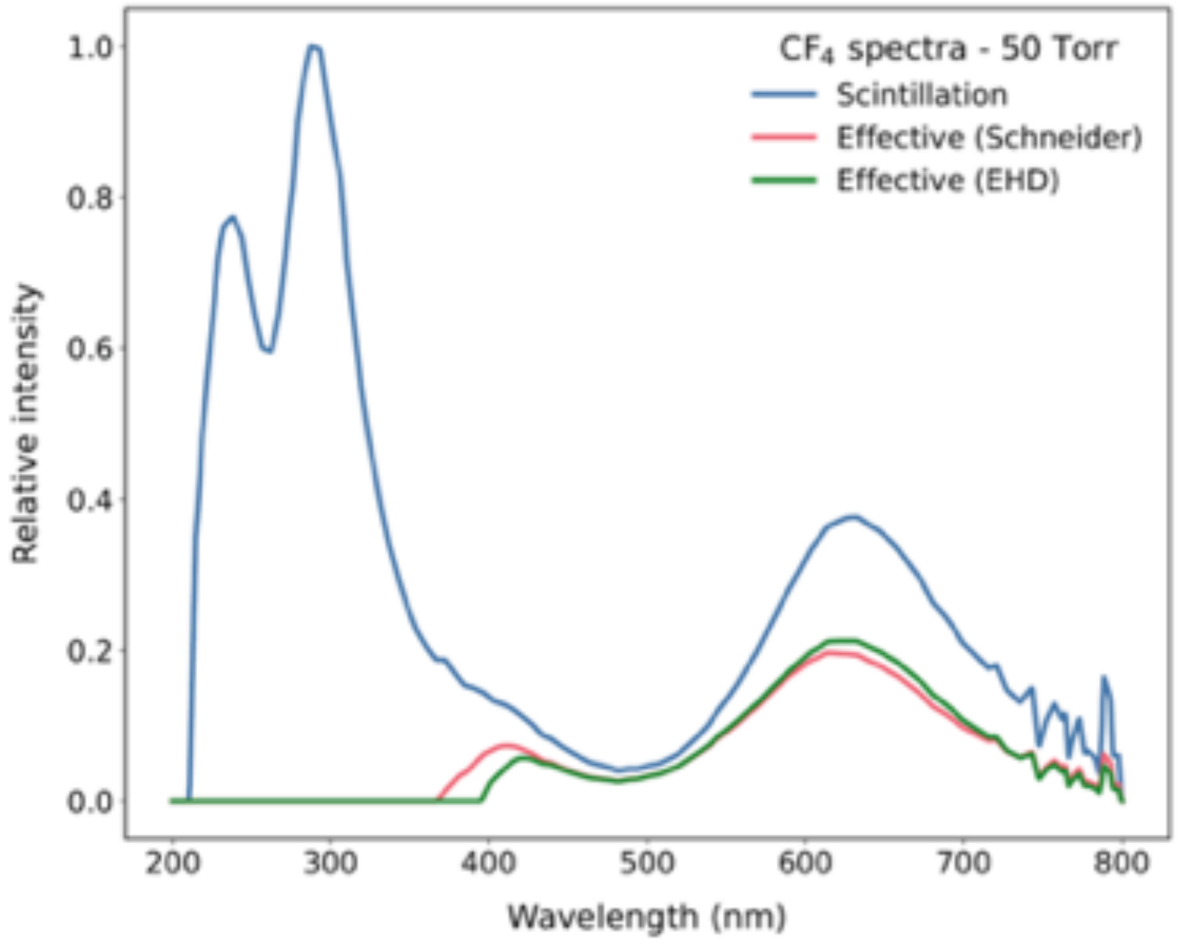


Light read-out
Orca Quest qCMOS camera
8.3 ms exposure



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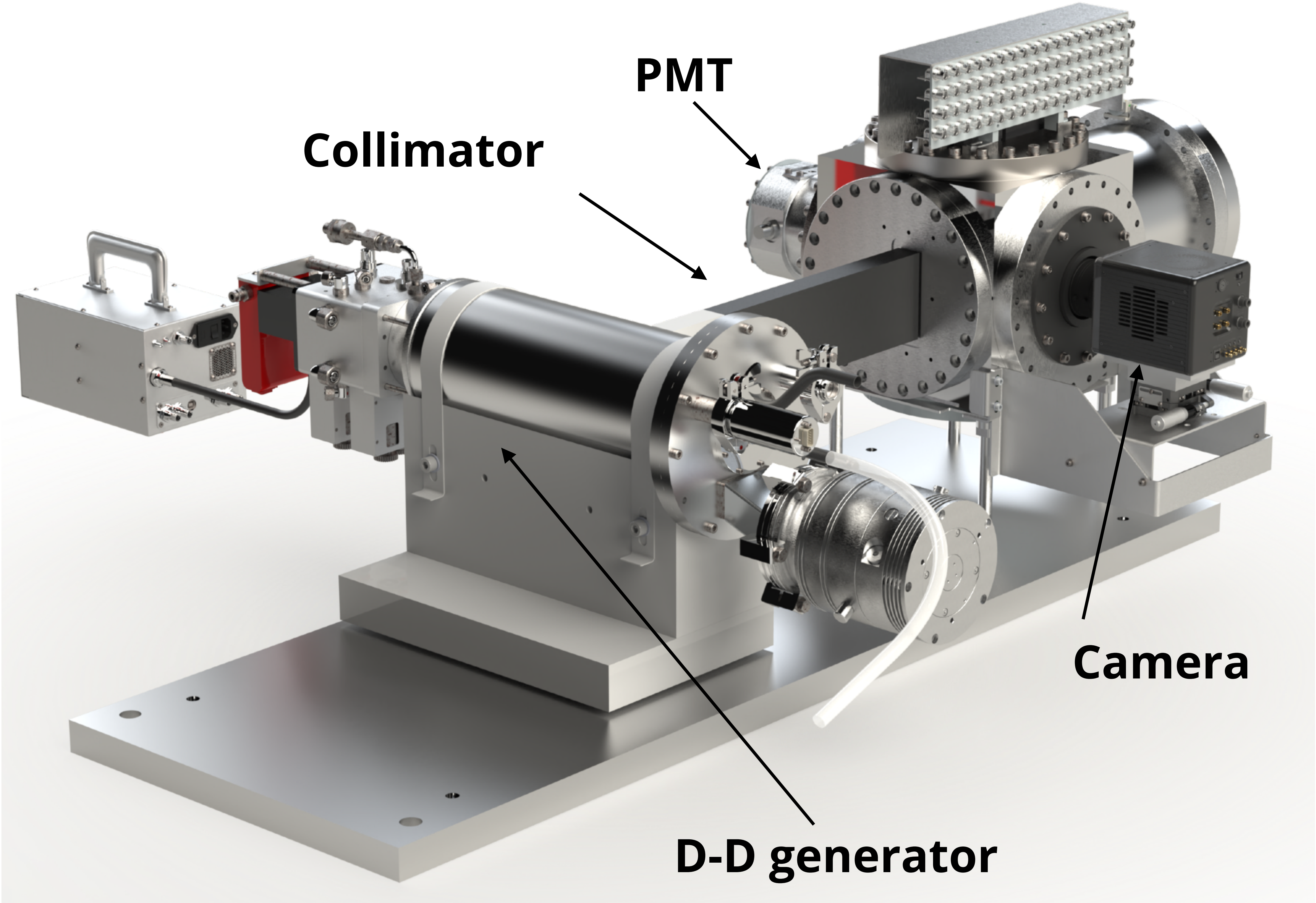
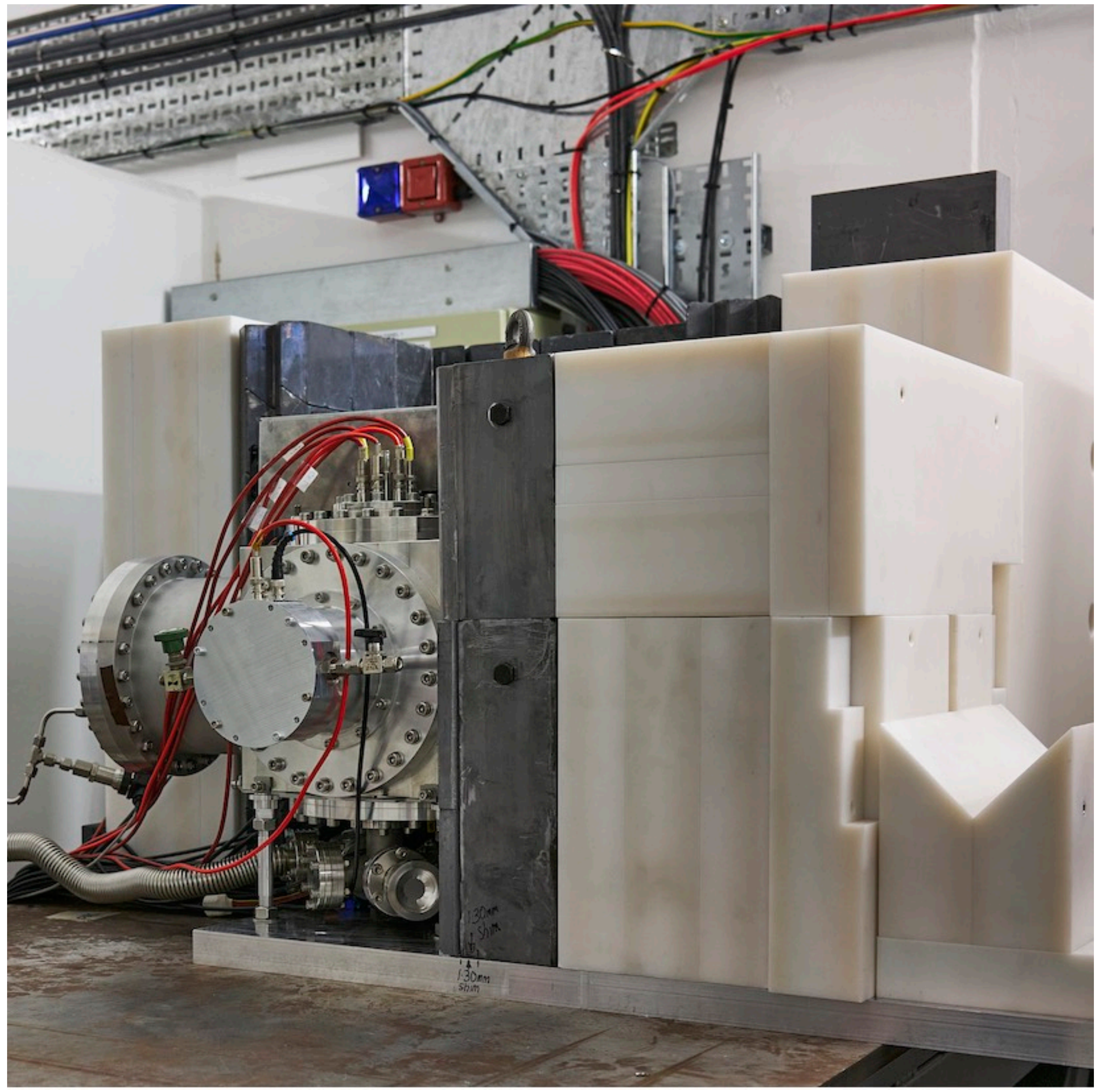
The NILE facility

- **N**eutron **I**rradiation **L**aboratory for **E**lectronics (NILE) based at the ISIS neutron and muon source at Rutherford Appleton Laboratory in the UK
- DD generator produces 2.47 MeV mono-energetic neutrons in 4π, MIGDAL uses 30cm collimator

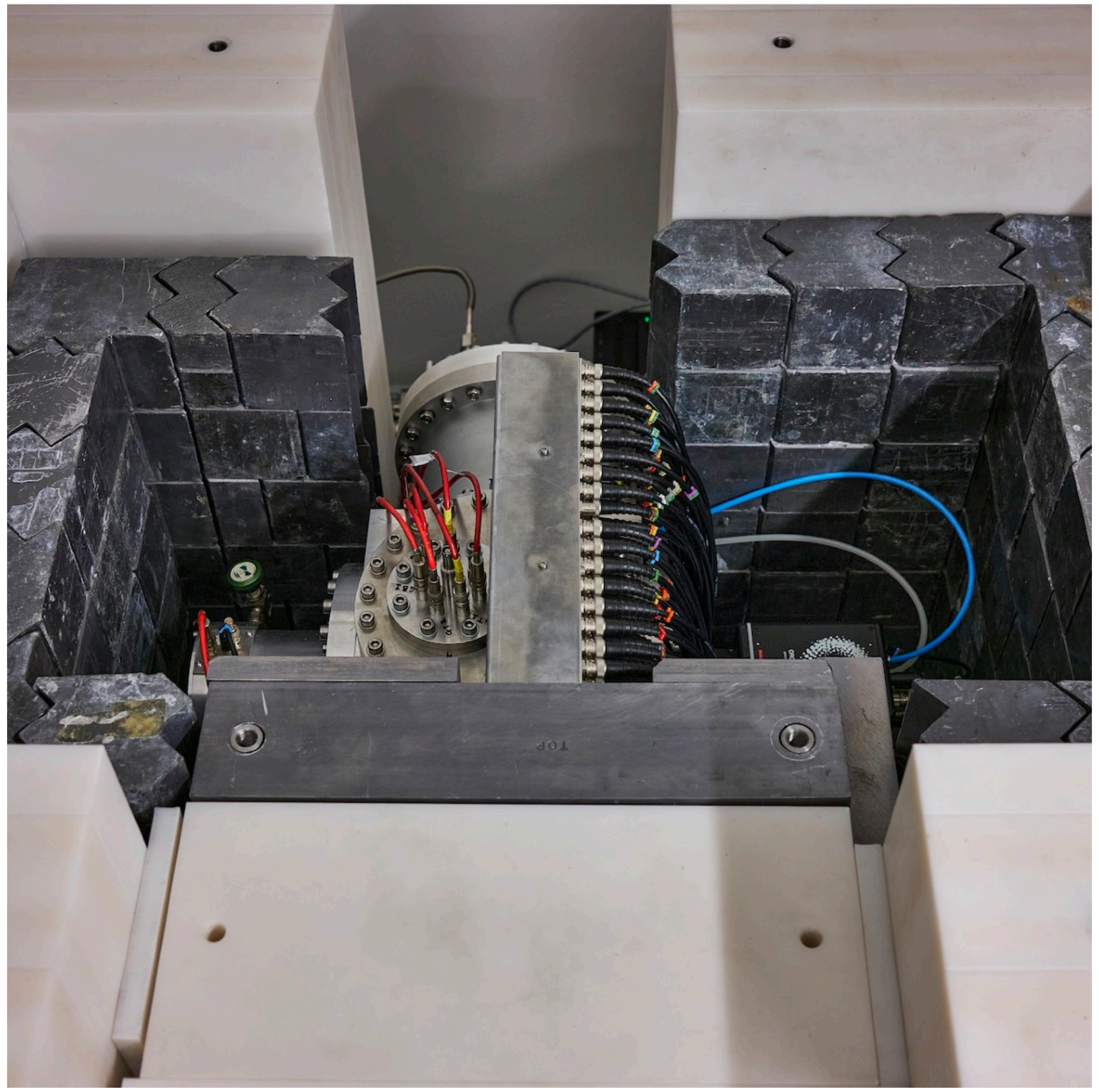


MIGDAL @ NILE

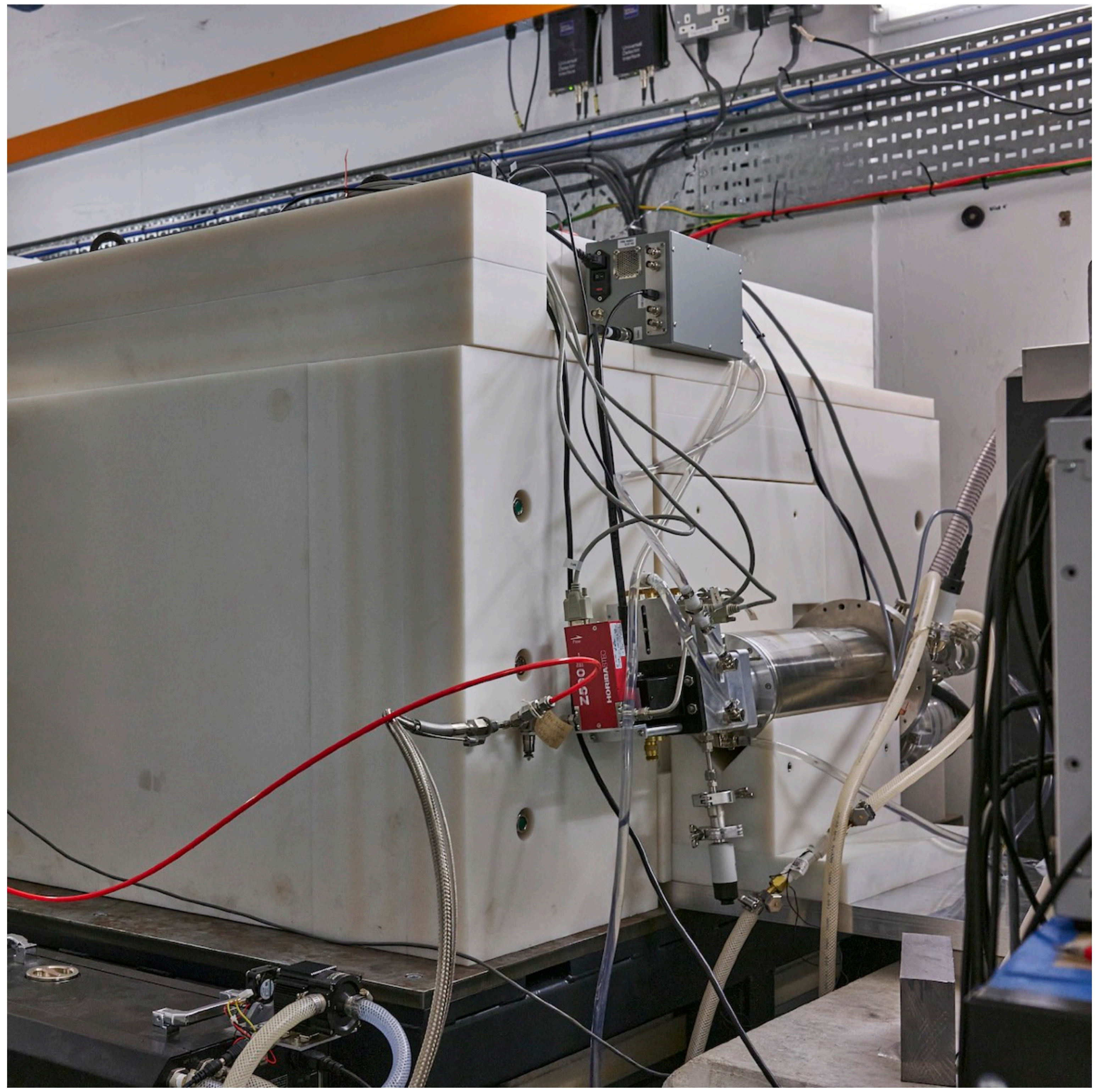
- Experiment installed in summer 2023
- Several weeks of DD data interspersed with calibrations



Experiment shielded by high density borated polyethylene



Detector with lead shielding



D-D generator positioned at collimator entrance

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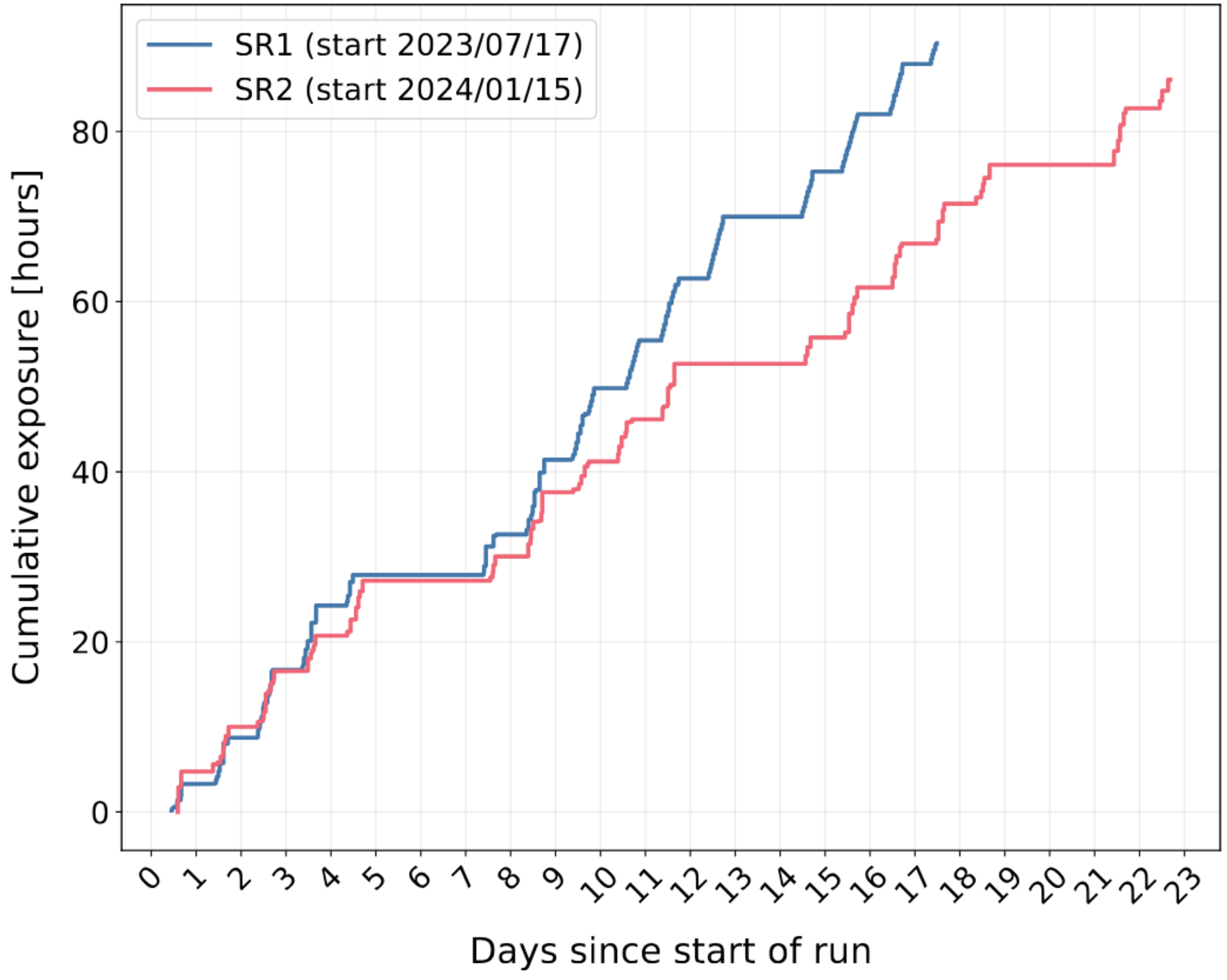
Science operations

- Two science runs performed taking data using D-D generator
- Calibration with ^{55}Fe every 3 hours
- Gas replaced ~ every 3 days
- Approximately 500,000 nuclear recoils
- Over 20 million camera frames
- Analysis ongoing
- Currently undertaking major upgrades for next science run:
  - Increased ITO strips
  - Newly optimised collimator
  - New higher dynamic range DAQ
  - New large hole glass GEMs
- More science data planned this year



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Summary

- The Migdal effect can improve sensitivity to low mass dark matter
- MIGDAL aims to make the first unambiguous observation of the Migdal effect in nuclear scattering
- Perform 3D reconstruction of tracks using a low pressure (50 Torr CF_4) optical time projection chamber
- Several weeks of DD data and calibrations recorded, more science runs planned this year
- Major upgrades undertaken this year - increase in ITO strips, optimised collimator, new DAQ, new GEMs
- Analysis ongoing (stay tuned!)

Publications:

Overlap-aware segmentation for topological reconstruction of obscured objects
Preprint: 2510.06194 (2025)

Transforming a rare event search into a not-so-rare event search in real-time with deep learning-based object detection
Phys.Rev.D 111 (2025) 7, 072004

Commissioning of the MIGDAL detector with fast neutrons at NILE/ISIS
Nucl.Instrum.Meth.A 1069 (2024) 169971

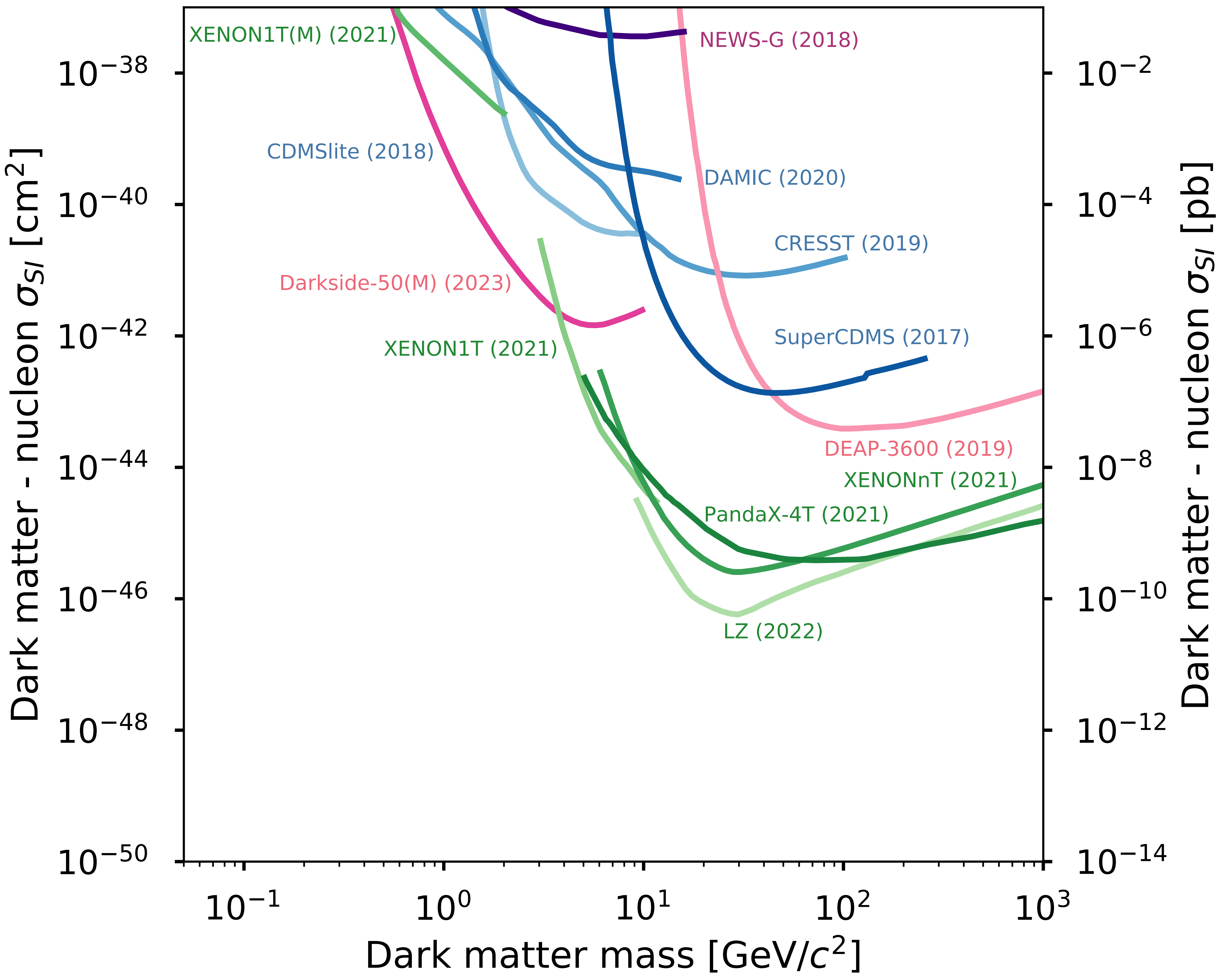
3D track reconstruction of low-energy electrons in the MIGDAL low pressure optical time projection chamber
JINST 18 (2023) 07, C07013

The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter
Astropart.Phys. 151 (2023) 102853

Backup

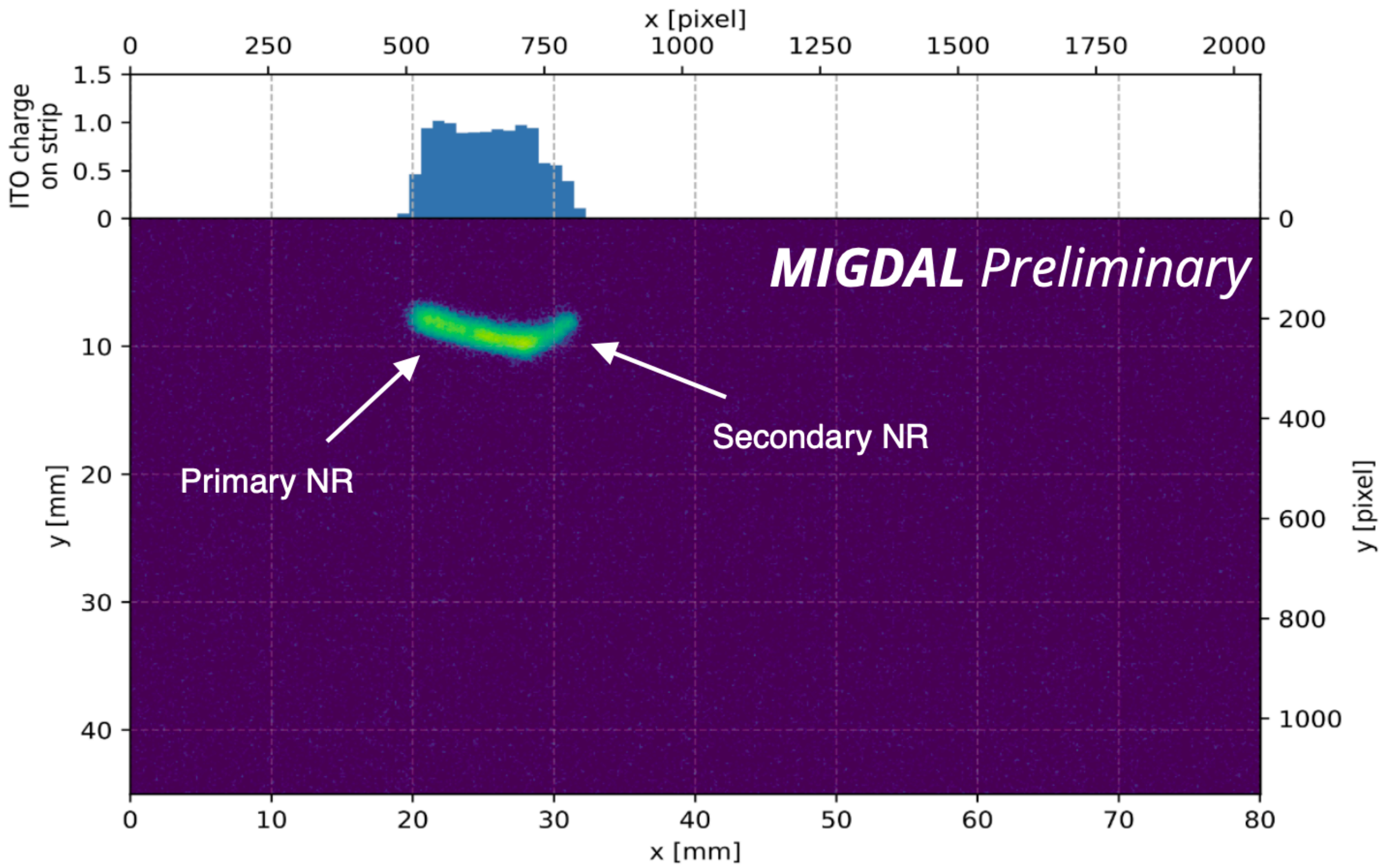
Improvements in sensitivity

- Sub-GeV DM less explored as experimentally more challenging
- Can exploit the Migdal effect which leads to additional energy above threshold
- Orders of magnitude lower masses can be probed with existing technology



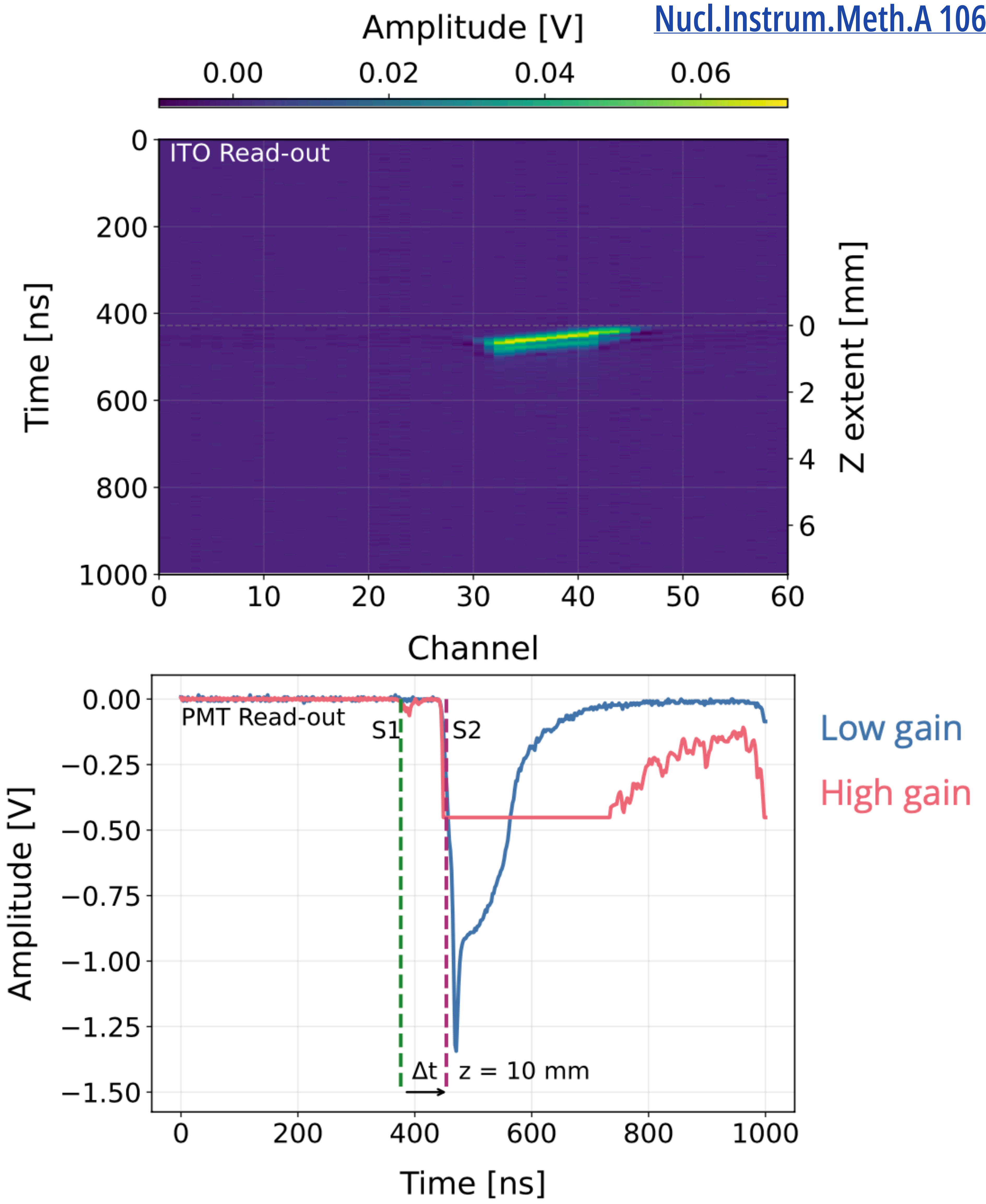
3D reconstruction

- Camera and DAQ events synchronised offline using timestamp information from an FPGA counter
- Timing between S1 and S2 in the PMT gives absolute depth



3D Reconstruction: JINST 18 C07013

Nucl.Instrum.Meth.A 1069 (2024)



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Backgrounds

Events per million NRs

Component	Topology	D-D neutrons >0.5	D-D neutrons 5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	$\approx$0	0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes†			
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track origin	112	$\approx$0
Secondary Electron Br. (SEB)	Photoelectron near NR track origin	115	$\approx$0
Atomic Br. (AB)	Photoelectron near NR track origin	70	$\approx$0
Nuclear Br. (NB)	Photoelectron near NR track origin	$\approx$0	$\approx$0
Neutron inelastic γ-rays	Compton electron near NR track origin	1.6	0.47
Random track coincidences			
External γ- and X-rays	Photo-/Compton electron near NR track	$\approx$0	$\approx$0
Trace radioisotopes (gas)	Electron from decay near NR track origin	0.2	0.01
Neutron activation (gas)	Electron from decay near NR track origin	0	0
Muon-induced δ-rays	Delta electron near NR track origin	$\approx$0	$\approx$0
Secondary nuclear recoil fork	NR track fork near track origin	–	$\approx$1
Total background	Sum of the above components		1.5
Migdal signal	Migdal electron from NR track origin		32.6

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Suppressed through energy threshold

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Backgrounds

Events per million NRs

Suppressed through energy threshold

Suppressed through timing resolution

Component	Topology	D-D neutrons >0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈ 0	0
Particle-Induced X-ray Emission (PIXE)			
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