Optical readout of MPGDs: Applications and R&D

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Content

Optical readout of gaseous detectors
- Scintillation light emission
- Imaging sensors and optics

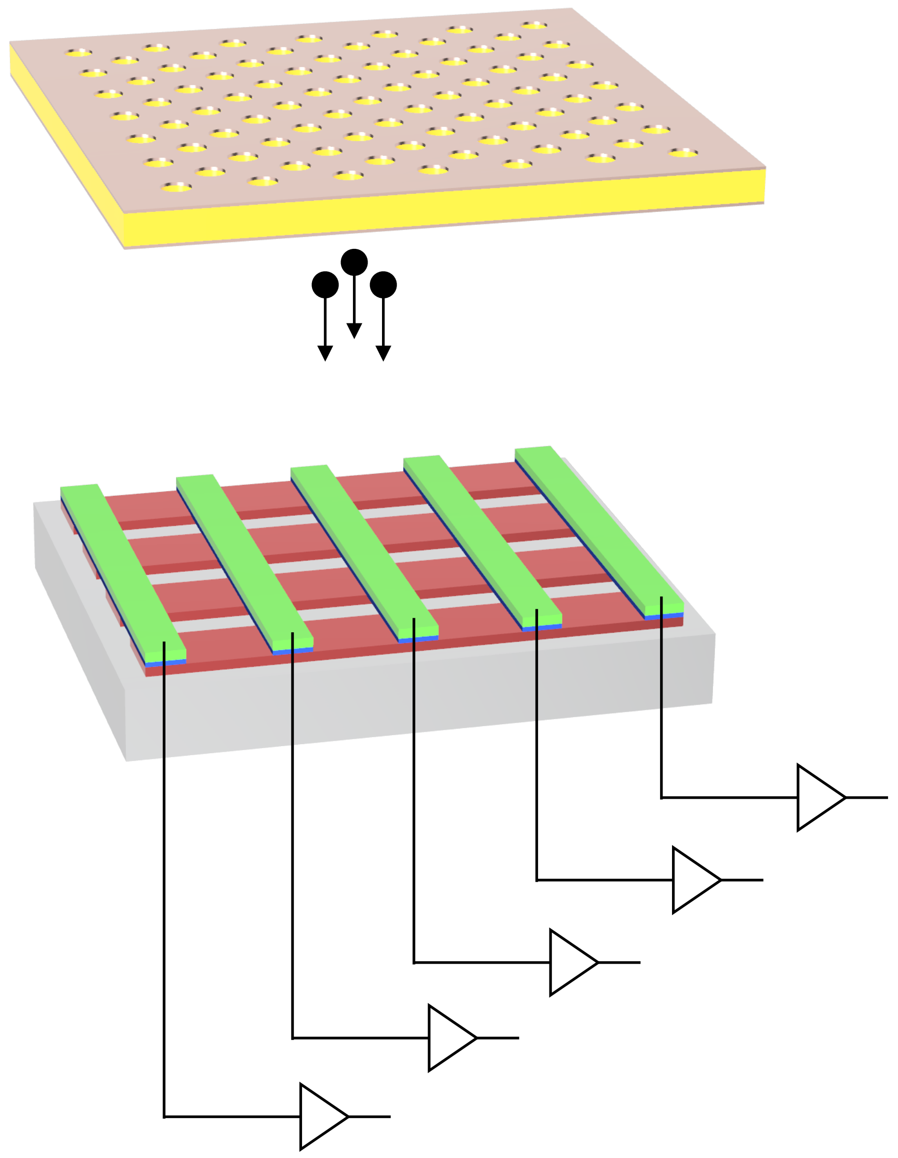
Applications of optical readout
- Radiation imaging and fluorescence
- High spatial resolution imaging
- Optical TPCs
- Neutron imaging
- Beam monitoring and medical applications
- Optical readout for detector R&D

New developments
- Alternative gases and wavelength shifters
- Ultra-fast imaging
- SiPM readout
- Optical readout of negative ion drift detectors

Readout of MPGDs

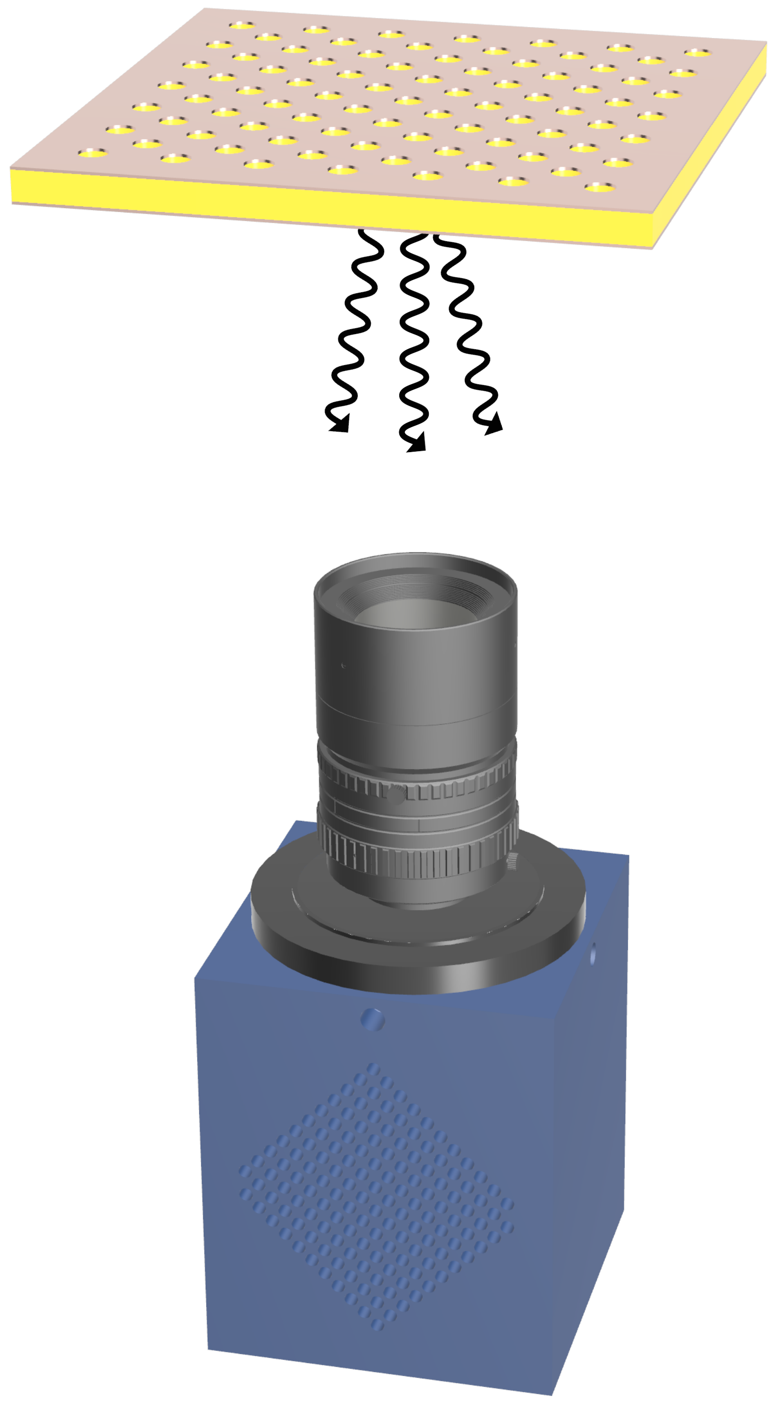
Electronic readout

Recording induced electronic signals with readout electronics



Optical readout

Recording scintillation light with imaging sensors or photon detectors



Schematics not drawn to scale

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

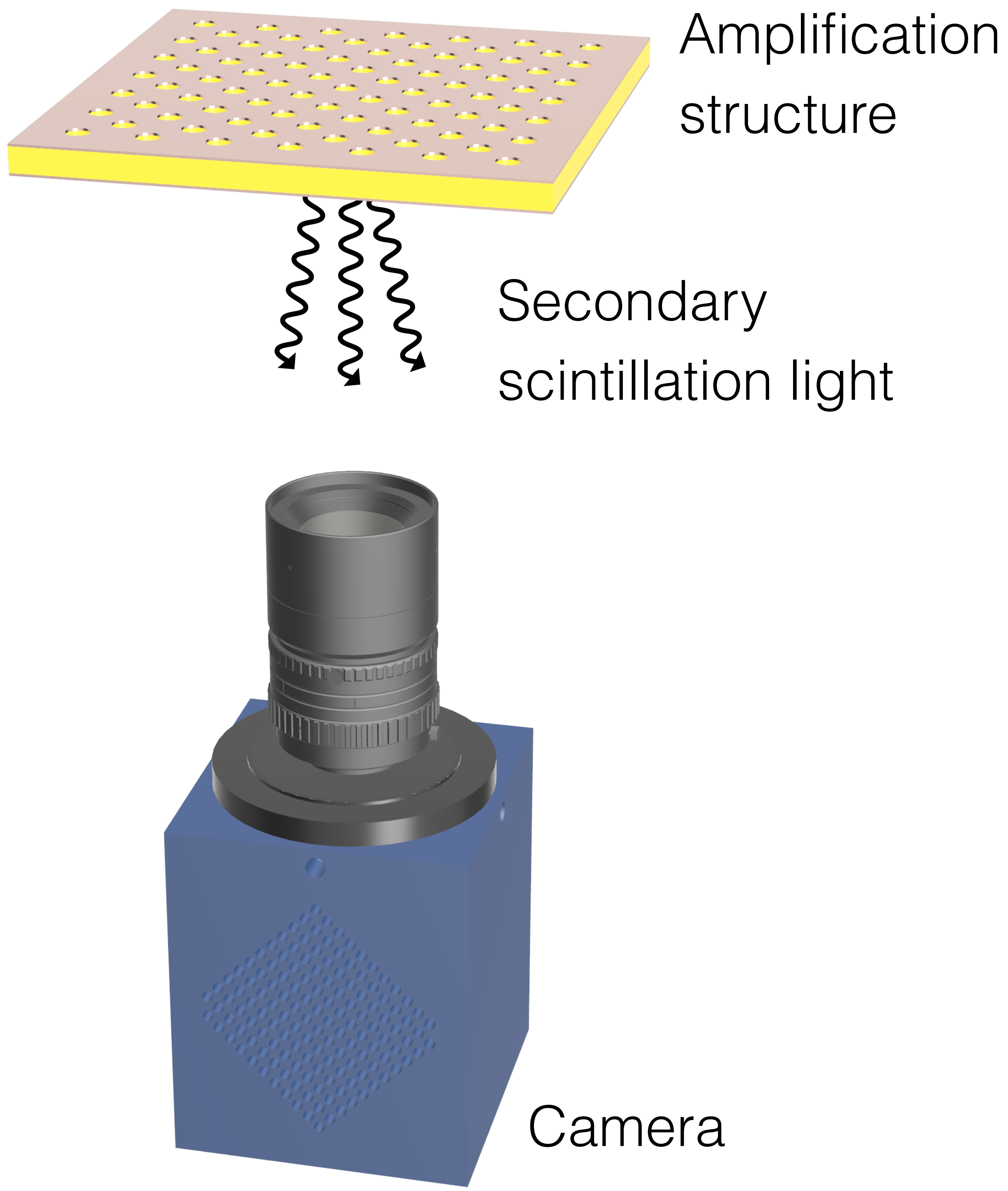
High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Limited **frame rate**

Low **radiation hardness** of imaging sensors

Matching of **emission spectrum** to image sensor QE
(e.g. CF_4-based gas mixtures)

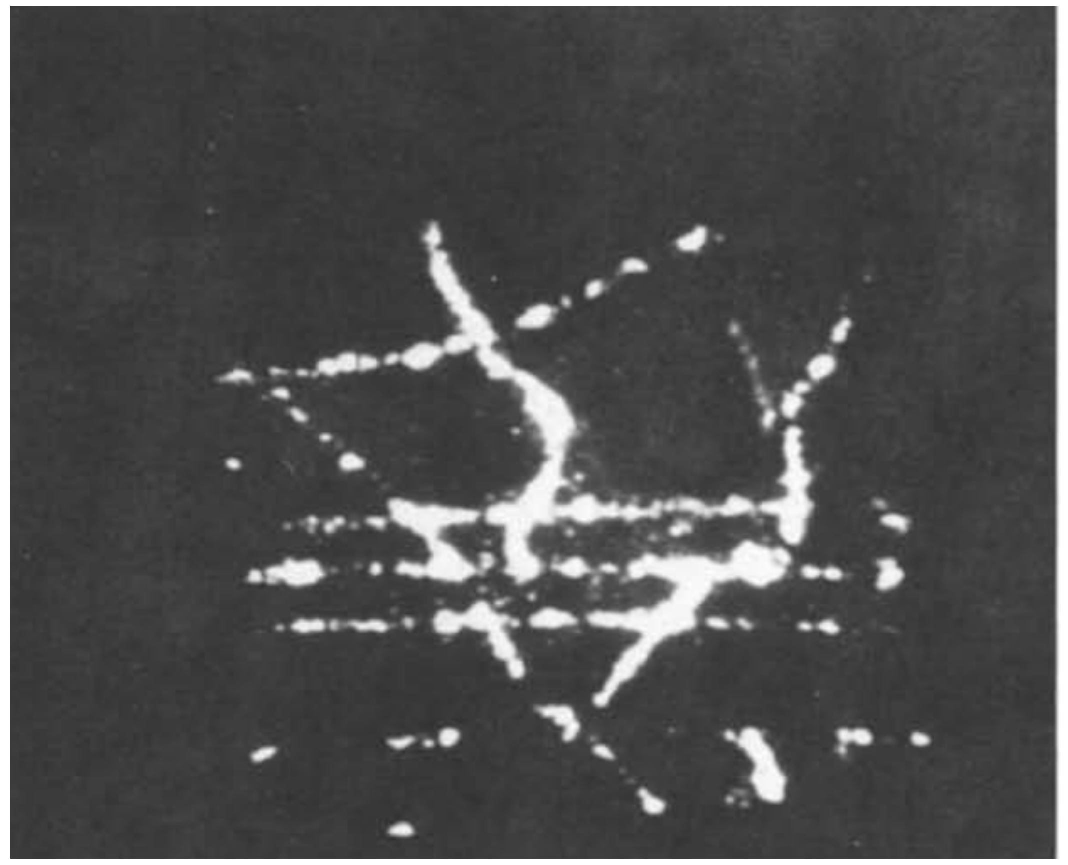


Schematics not drawn to scale

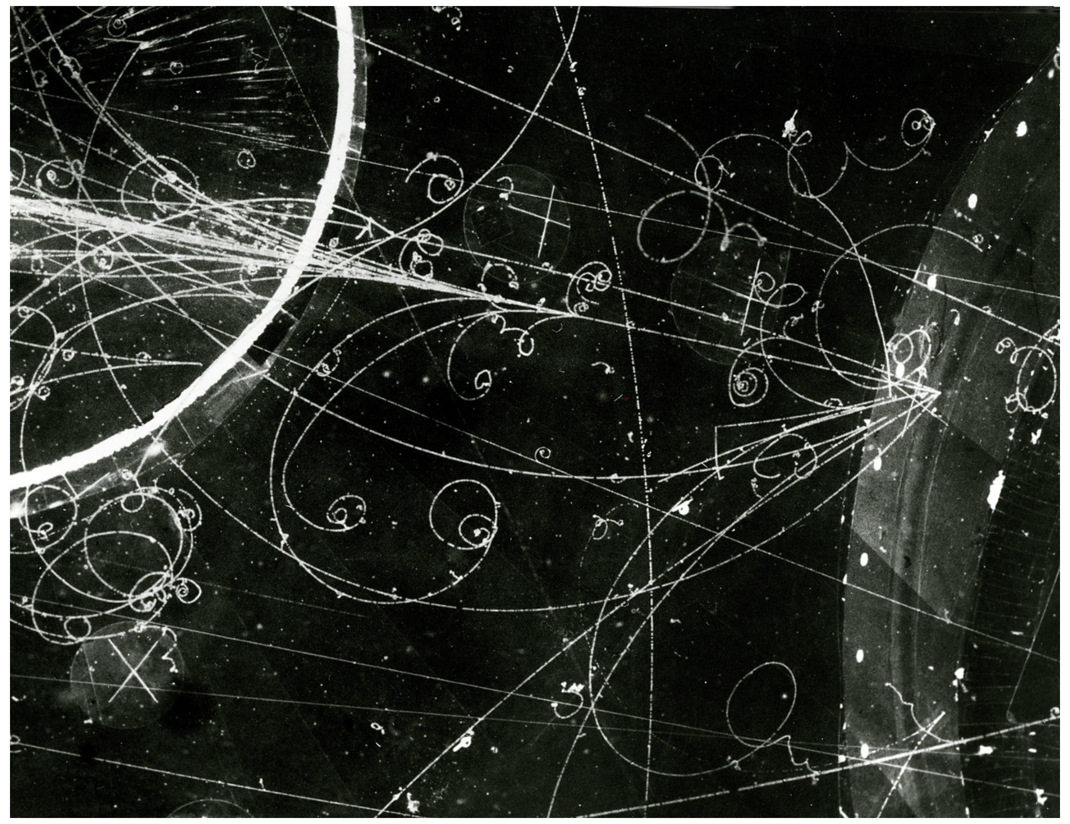
Optical readout

Not a new approach but profiting from **technological advances** in imaging sensors

- Readout of detectors with modern imaging sensors or fast photon detectors
- State-of-the-art CCD and CMOS sensors allow high resolution and low readout noise
- Inherent stability to electronic readout noise, separation of readout device from amplification stage
- Wide range of optical elements (mirrors, lenses, fibers) available

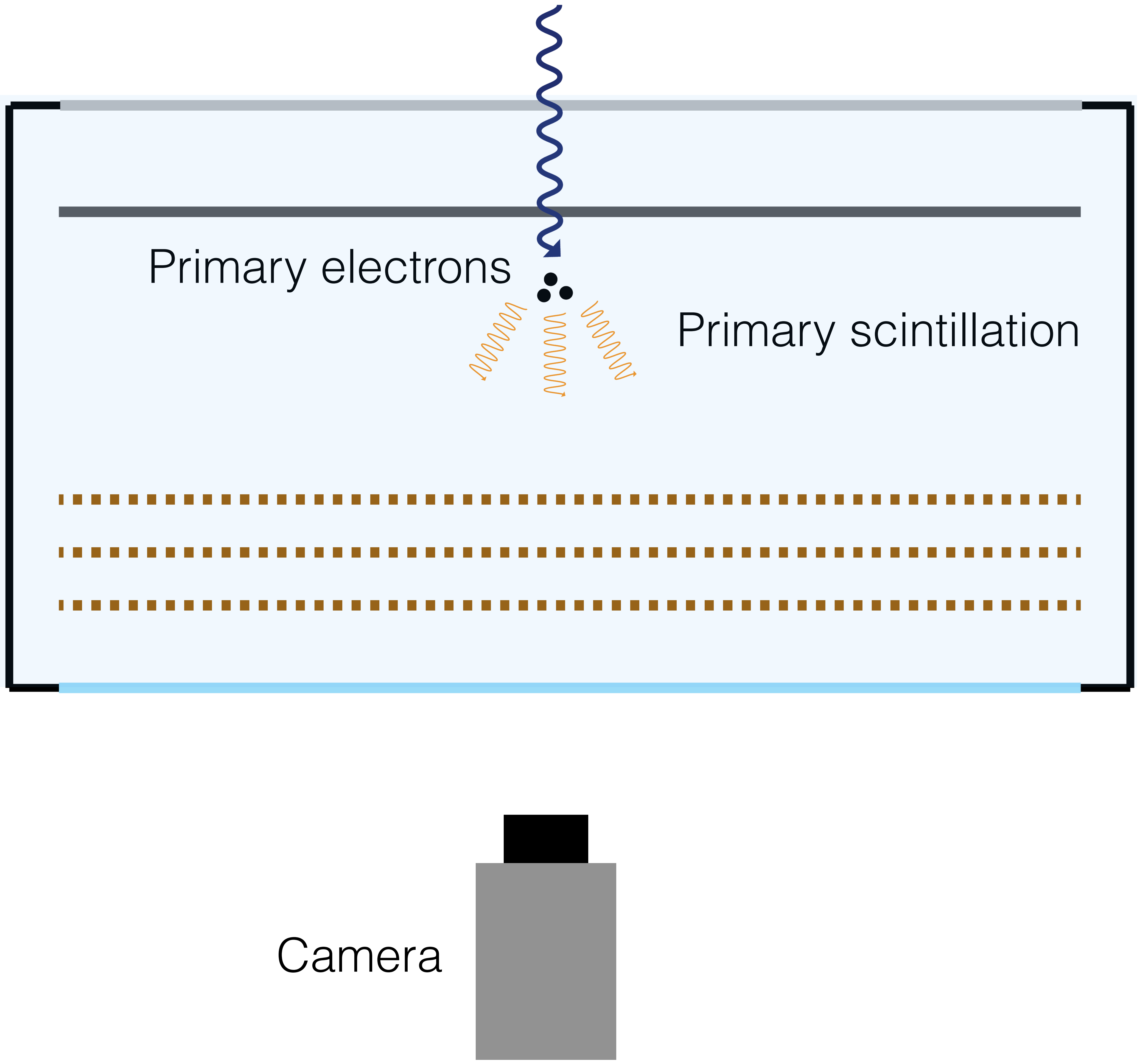


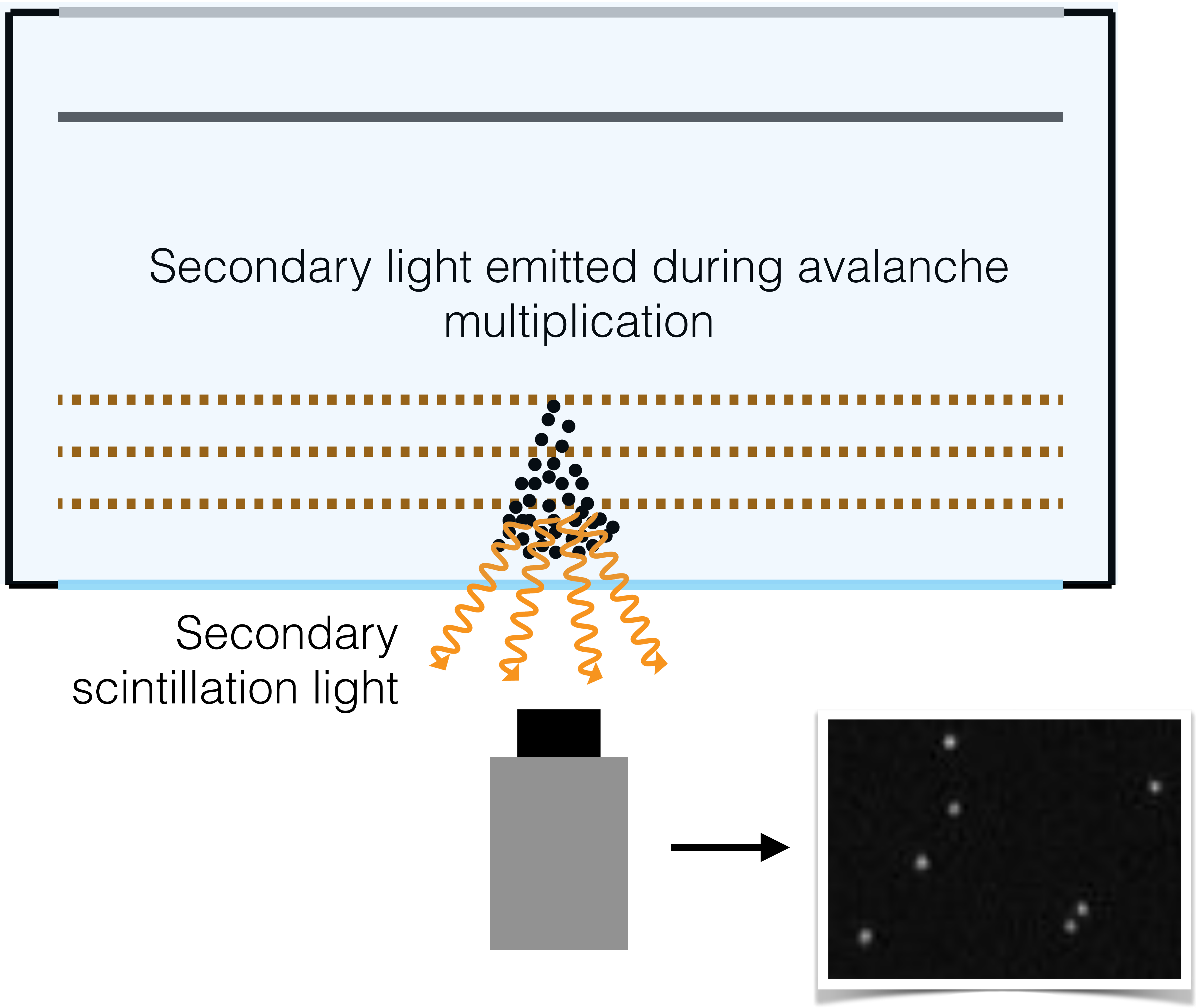
G. Charpak et al., NIM A258 (1987) 177



Courtesy of Brookhaven National Laboratory

Readout of MPGDs





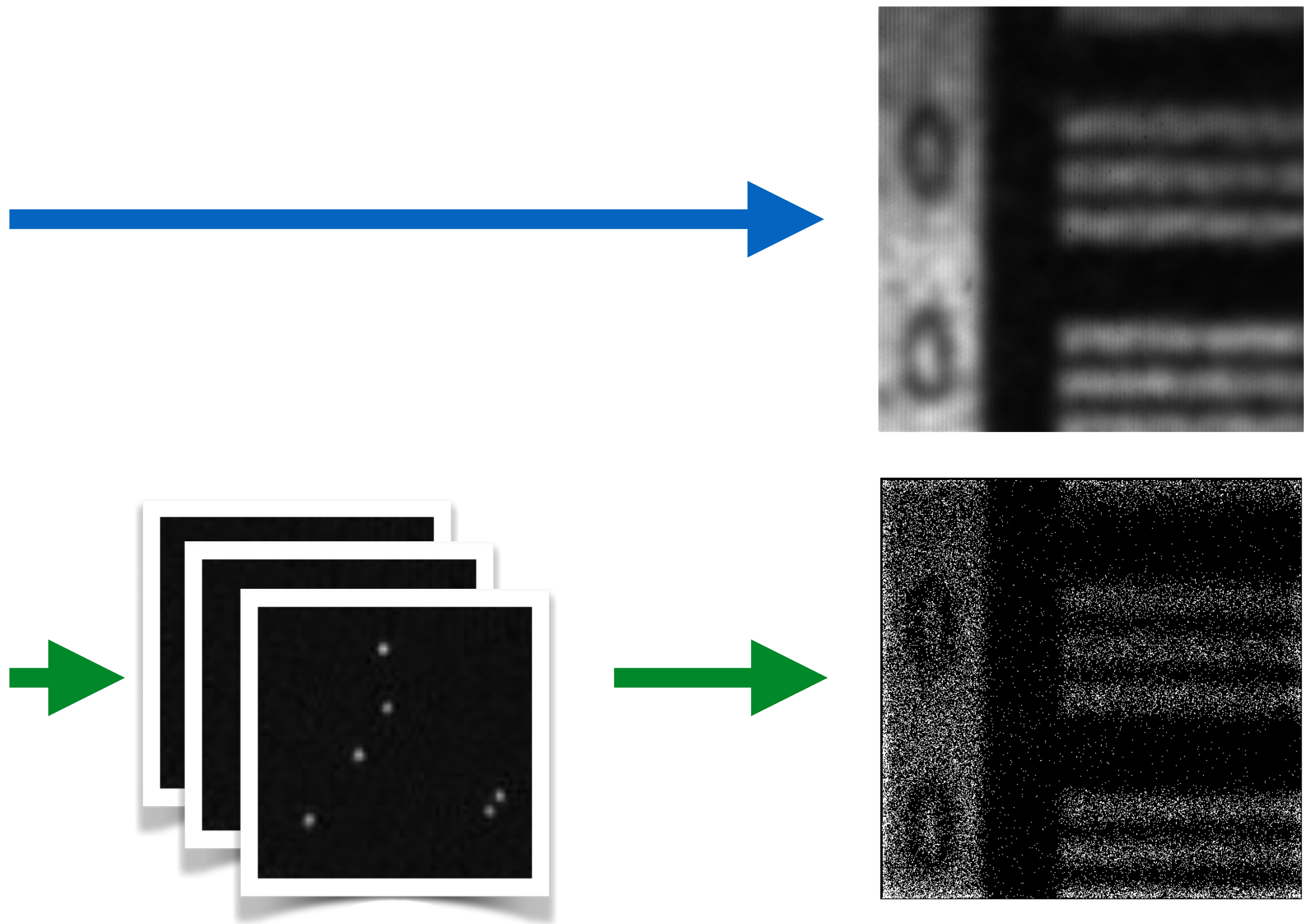
Schematics not drawn to scale

Optical readout

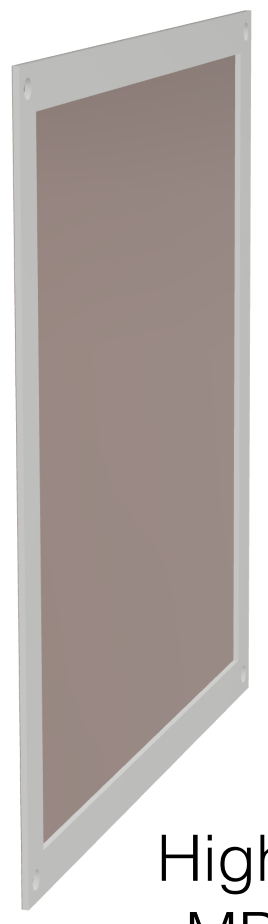
Image immediately available without need for reconstruction.

Two acquisition approaches:

- **Integrated imaging** collects all light within exposure time **without deadtime** with long exposure time
- **Event-by-event** recording with short exposure time for track reconstruction



Detector
(amplification and scintillation)



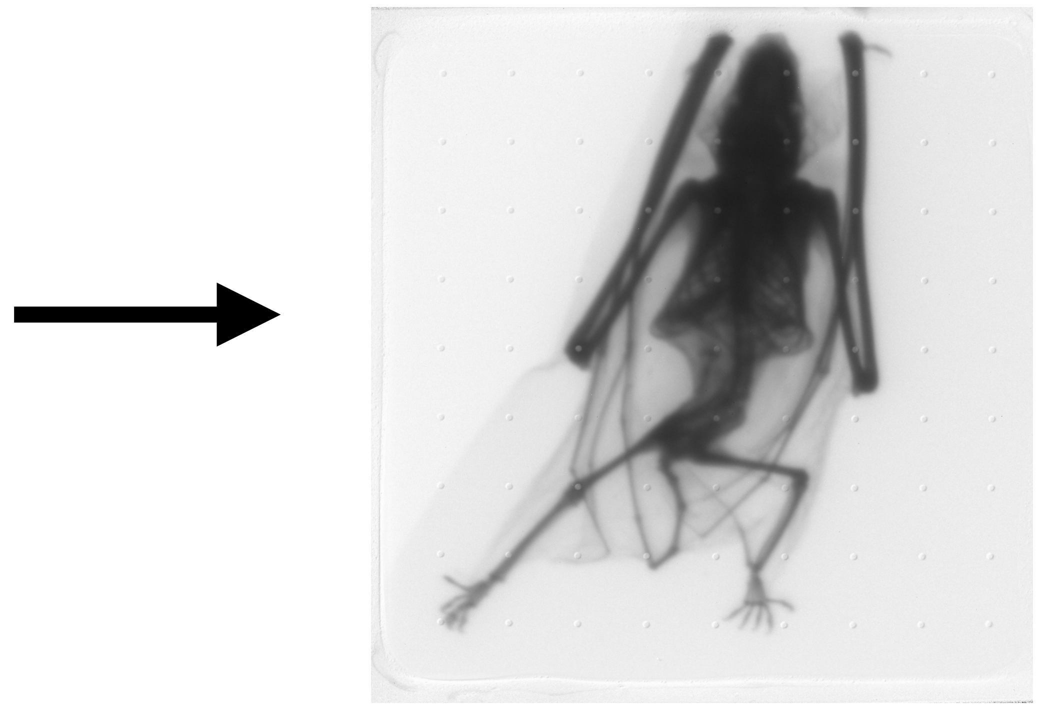
High gain MPGDs

Optics
(coupling)

Lenses, mirrors,
intensifiers, (tapered) fibers, Microlenses

Imaging sensor
(camera)

CCD, CMOS, ASICs

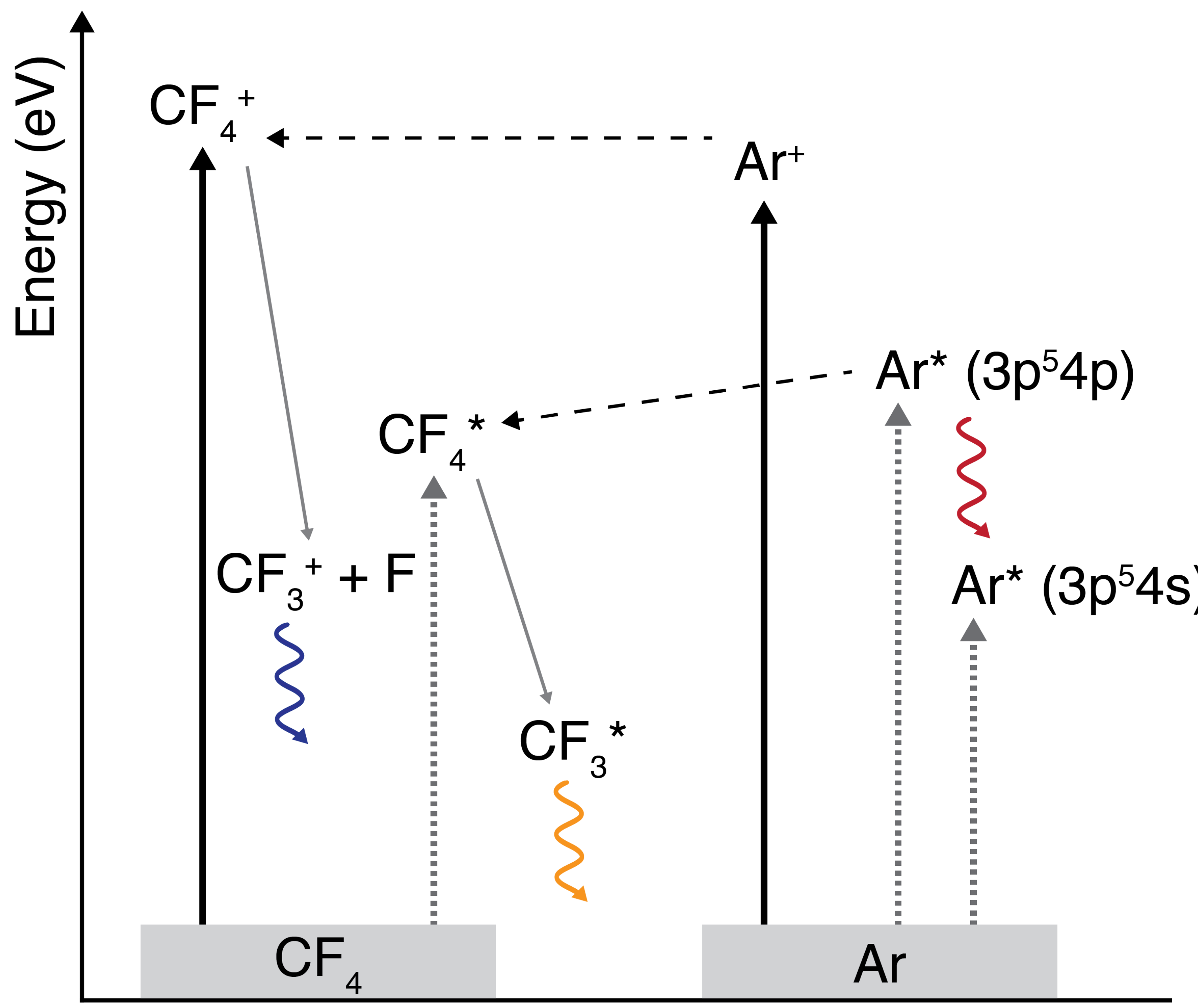


X-ray radiography
(Glass Micromegas)

F. Brunbauer et al., Radiation imaging with glass Micromegas, https://doi.org/10.1016/j.nima.2019.163320

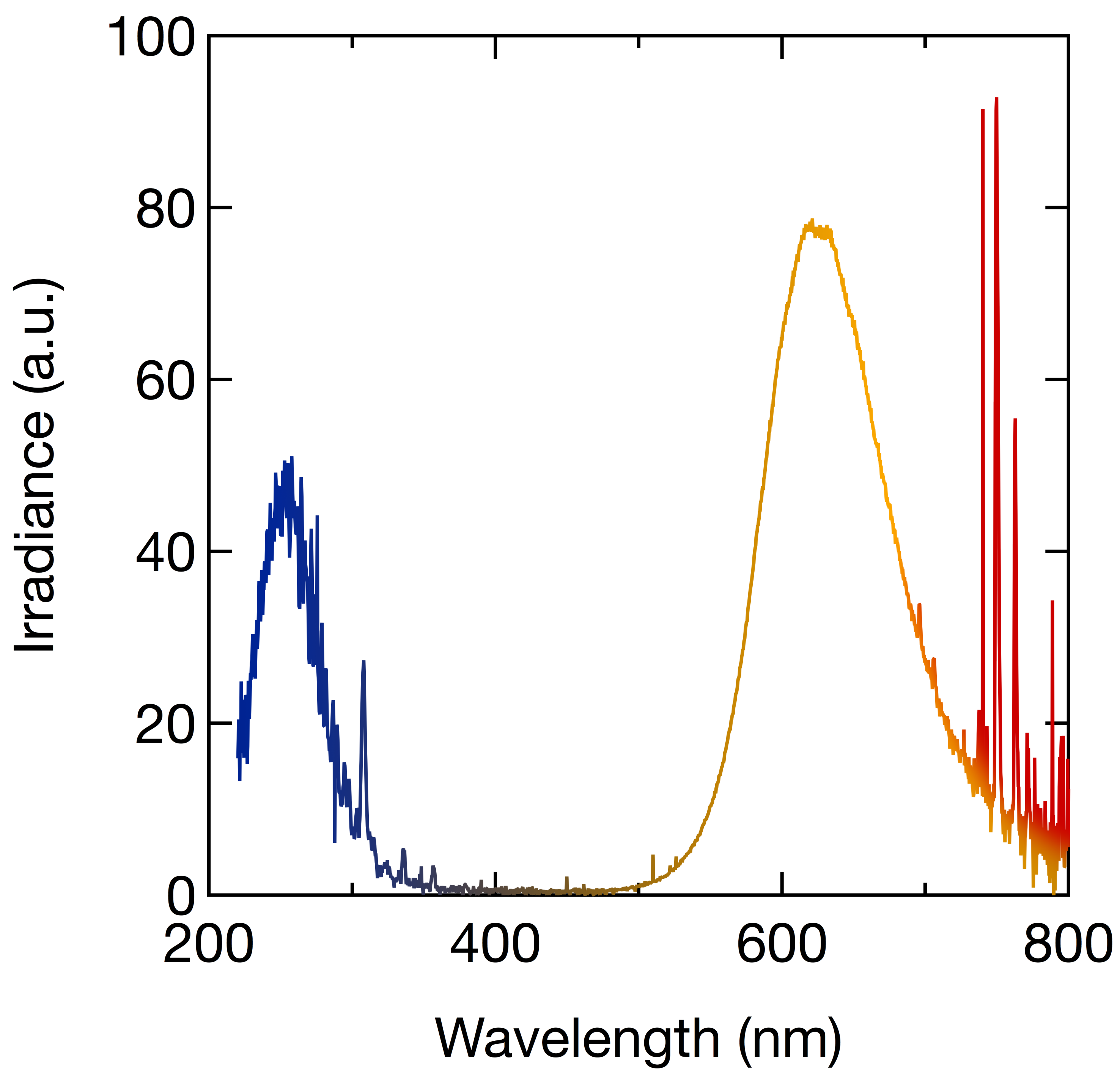
Optical readout scintillation spectra

Scintillation mechanism

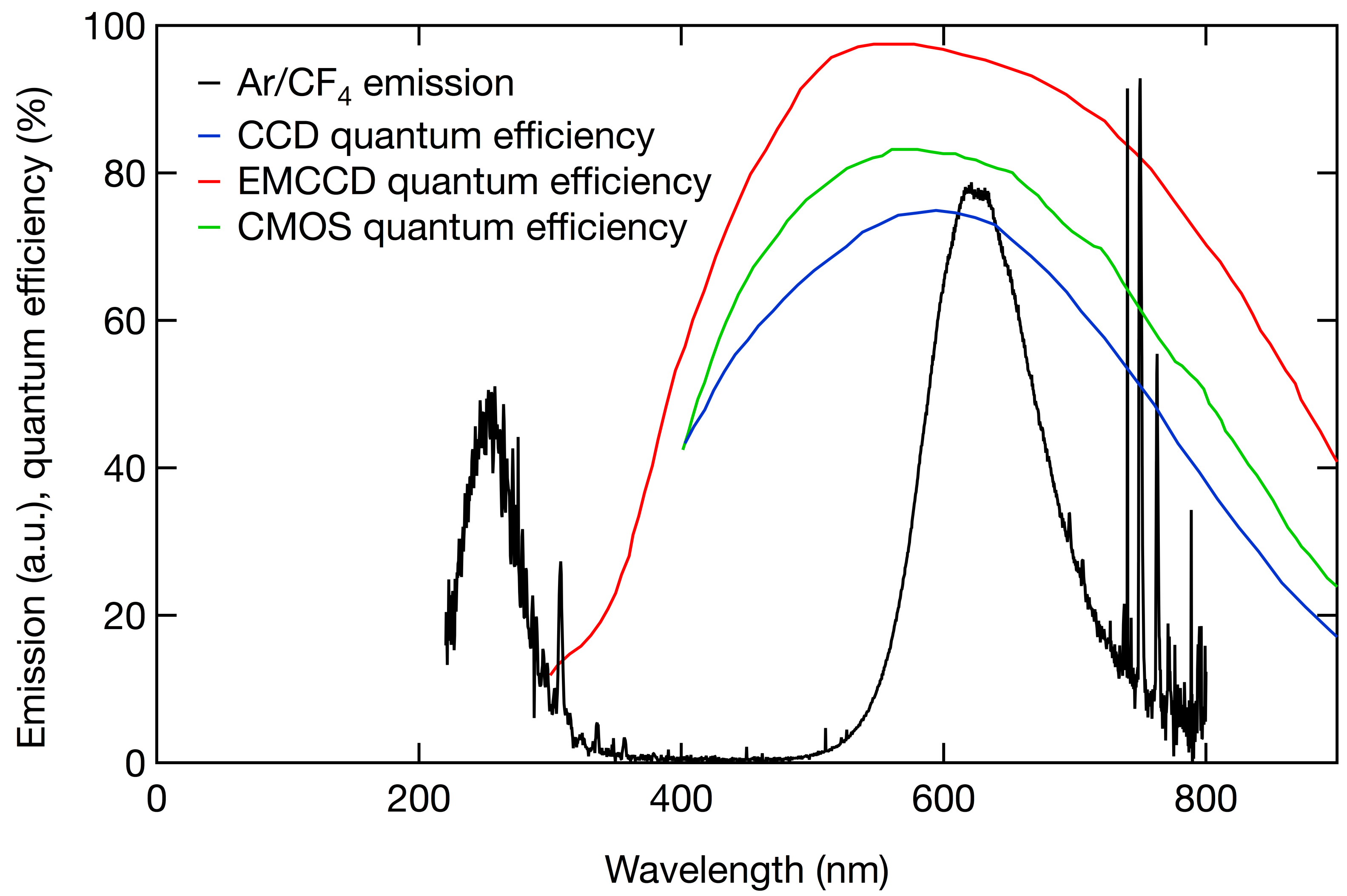


Adapted from Seravalli, E., PhD thesis, 2008

Scintillation spectrum



CF_4 emission matches sensitive wavelength range of many conventional imaging sensors



Schematics not drawn to scale

CCD / CMOS imaging sensors

Modern scientific imaging sensors with **low read noise** and high resolution are well-suited for optical readout.

Intuitive and simple to use with images directly available without need for extensive reconstruction algorithms.

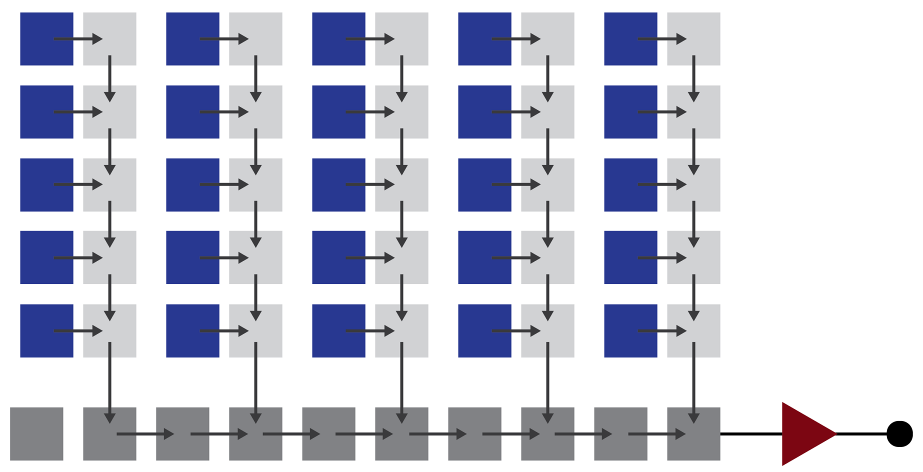
Frame rates of typically **10s to 100s of fps** impose integrated imaging approach or low-rate acquisition.

Resolution of CCD/CMOS imaging sensors well suited for MPGD readout (compatible with size scale of amplification structures).

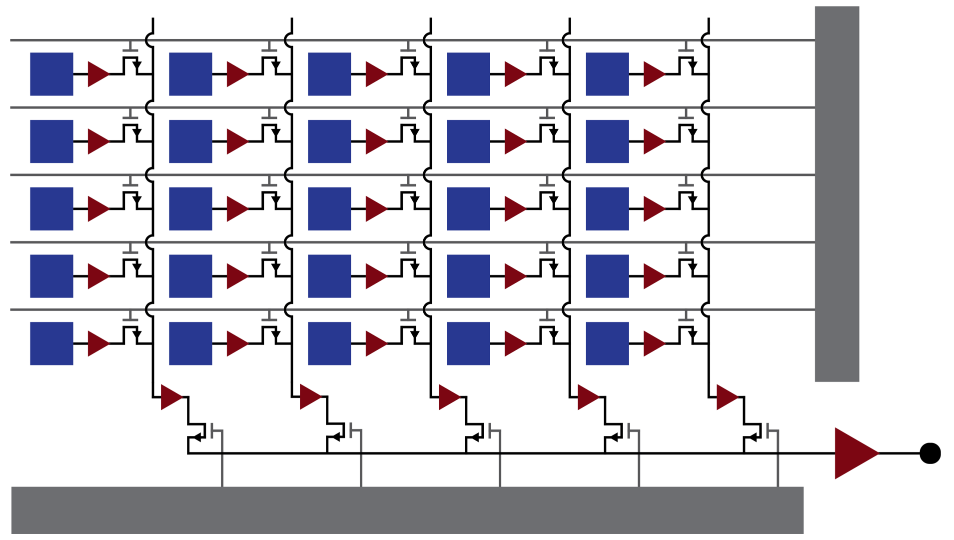
Advances in imaging sensors will offer potential for increased performance of detectors:

- Higher **frame rates** → decrease event pile-up, depth imaging, minimise motion blur
- **Larger sensors** (larger pixels at high granularity) → higher sensitivity
- **Low noise** (<1 e-) or **amplification**, internal amplification
- Extended **spectral sensitivity** (direct UV imaging)

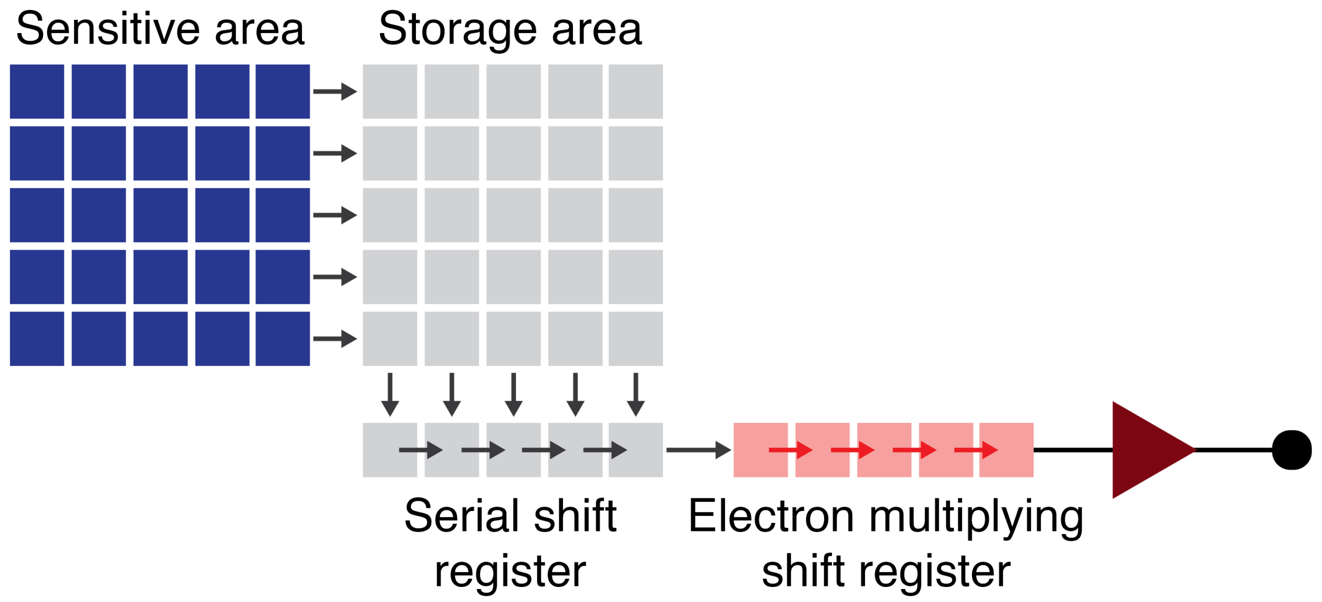
CCD sensors



sCMOS sensors



EMCCD sensors



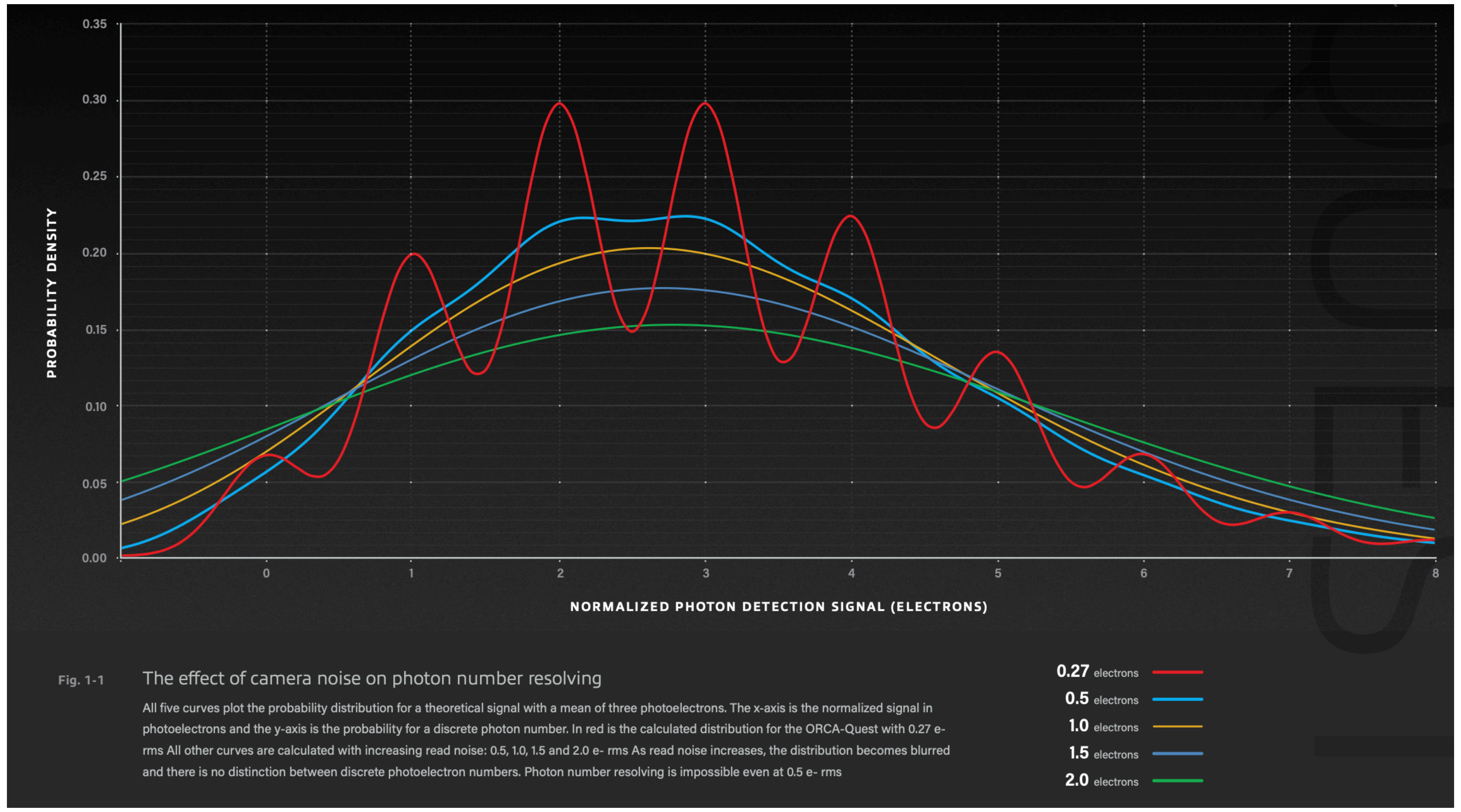
Imaging sensors

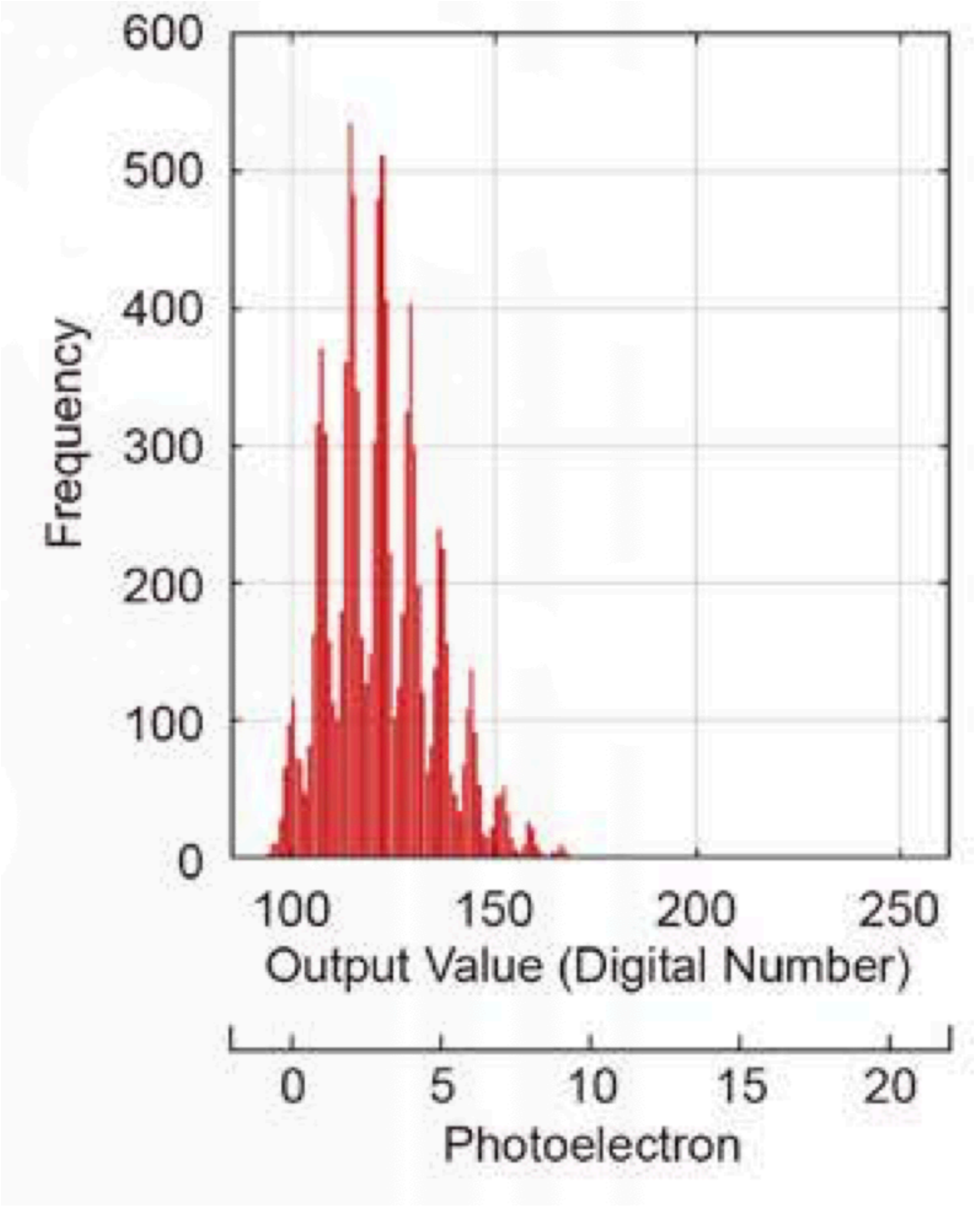
qCMOS sensor

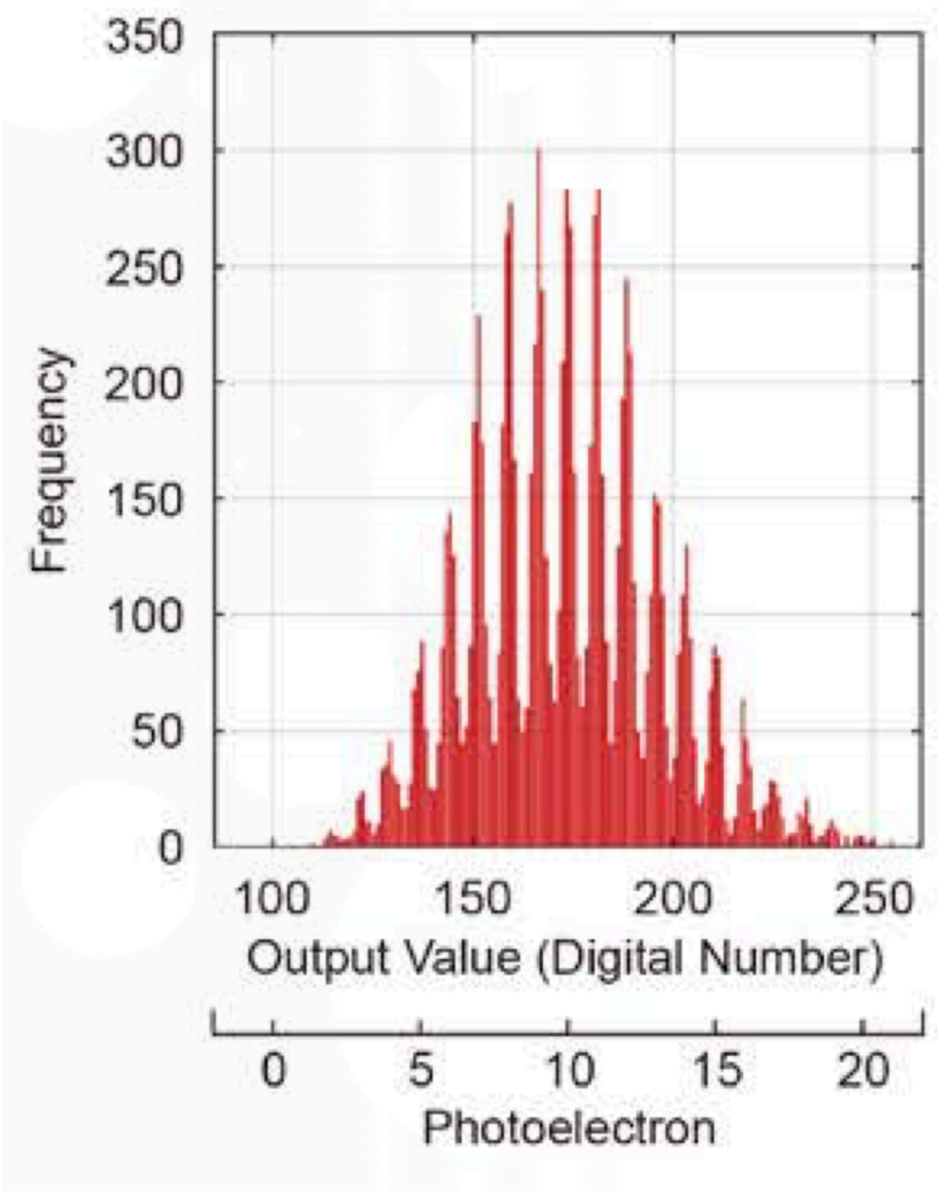
Unprecedented **low read noise** to allow quantitative imaging (**photon counting**) in state-of-the-art CMOS cameras.

Hamamatsu Orca Quest:

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/sys/SCAS0152E_ORCA-Quest_concept_brochure.pdf





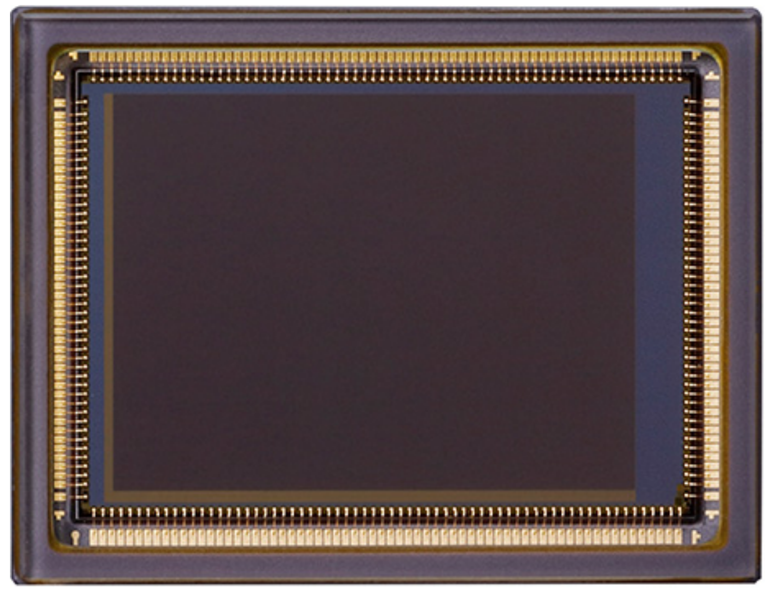


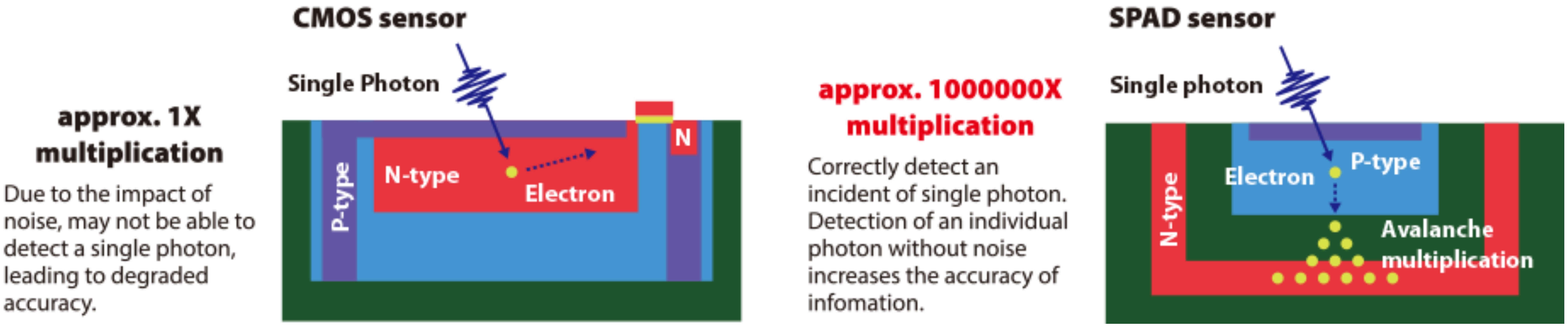
Imaging sensors - SPAD

World's first ultra-high-sensitivity interchangeable-lens camera for colc

CANON SPAD camera

Immediate multiplication of charge when interacting in image sensor. Counting of photons instead of integration of charge. Realised with 1” image sensor with 3.2MP resolution.



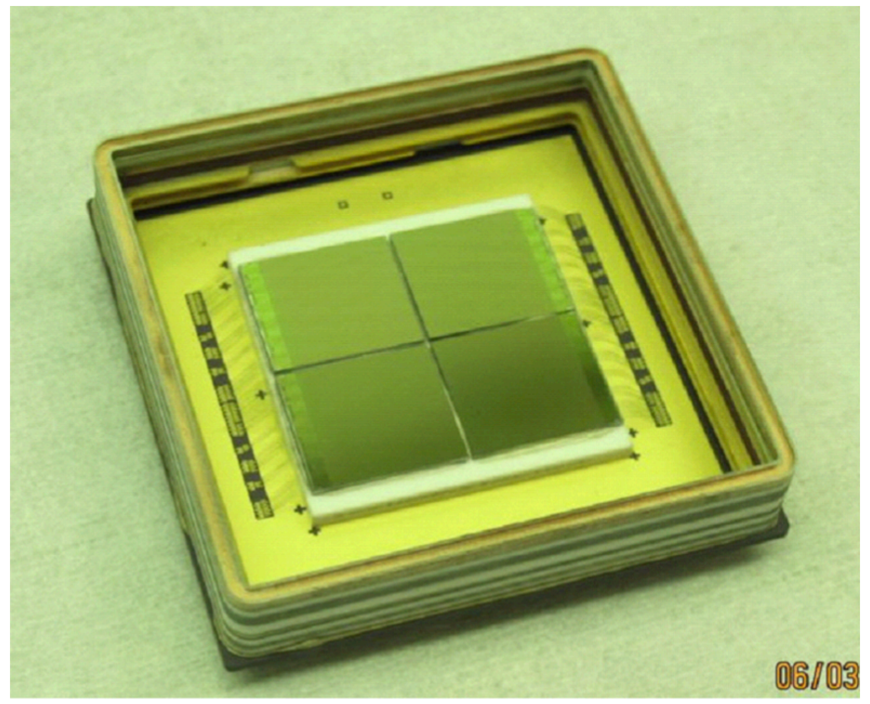


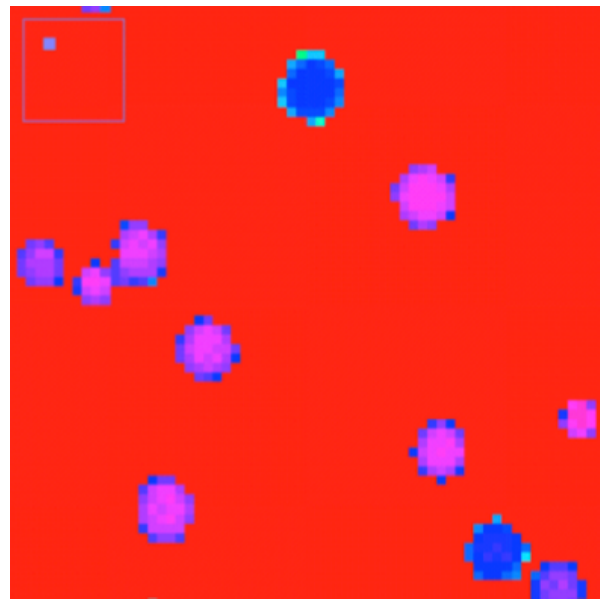
https://global.canon/en/technology/spad-sensor-2023.html

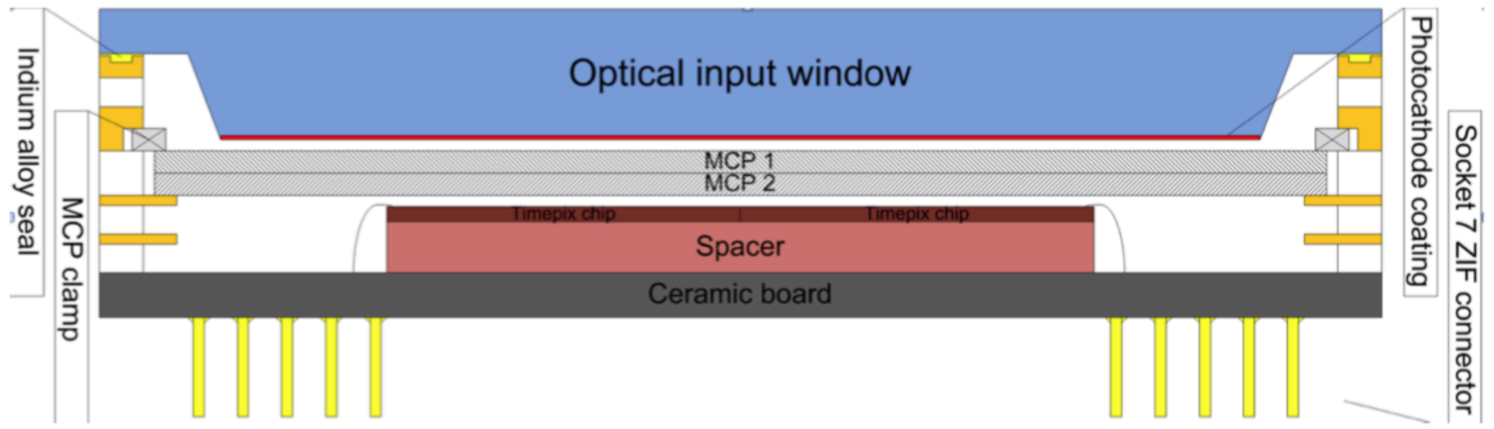
Hybrid sensors: Timepix cameras

Optical MCP image tube with **quad Timepix** with bi-alkali photocathode

Event counting with threshold or time of arrival recording

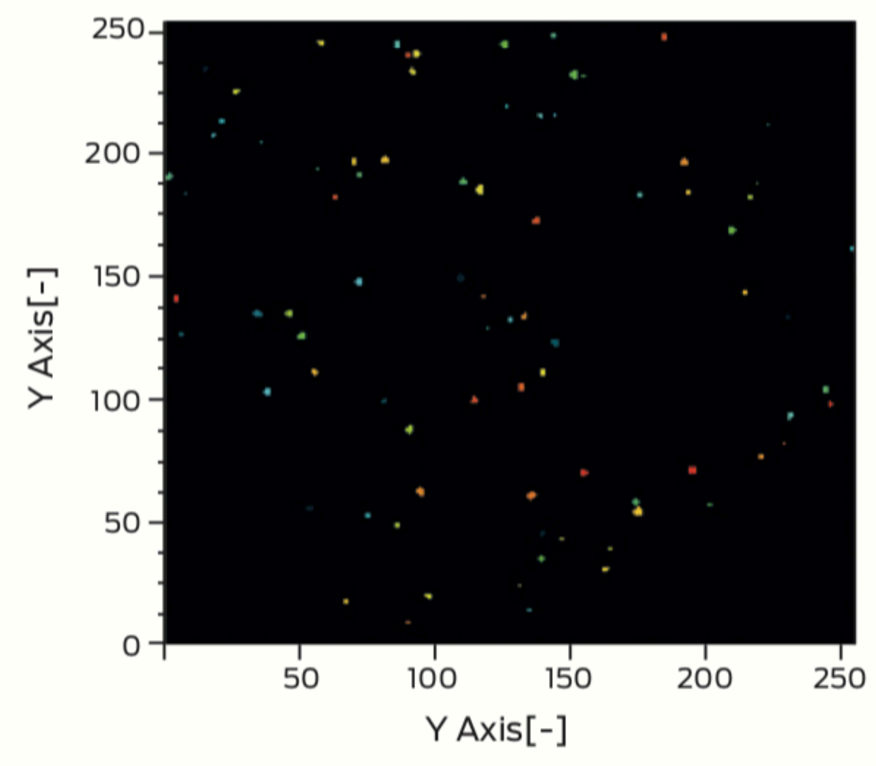


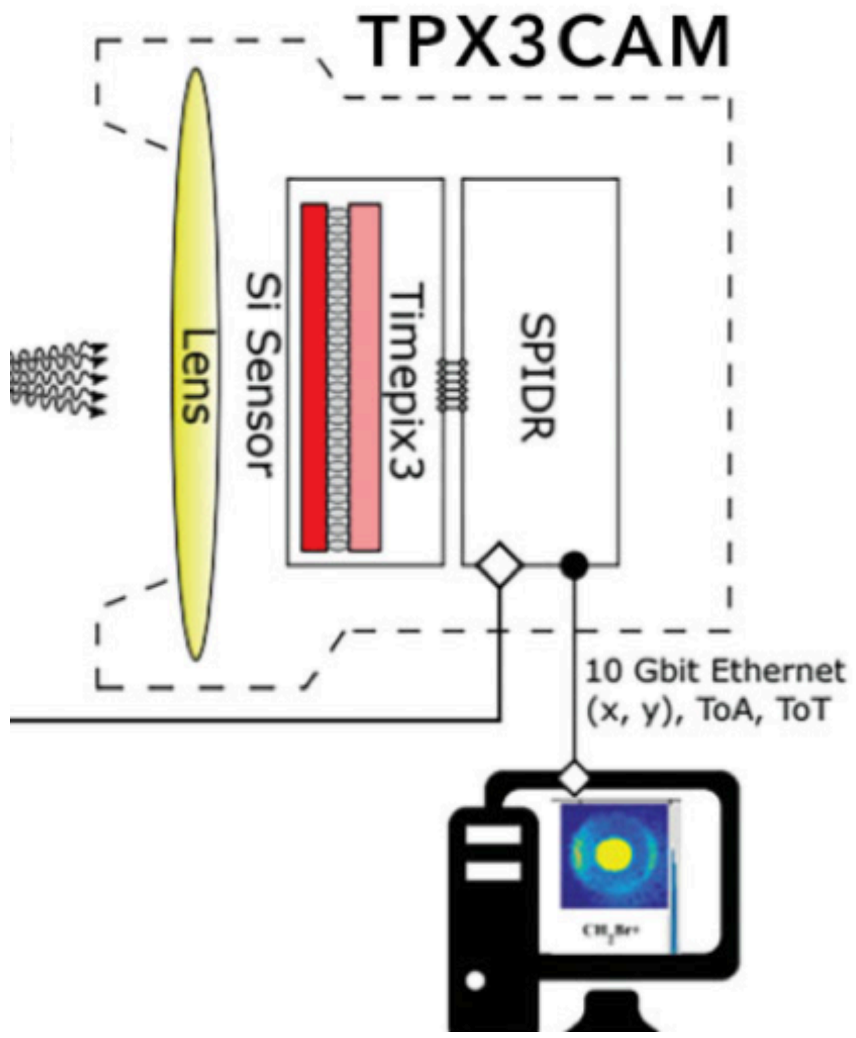




J Vallerga et al 2014 JINST 9 C05055
https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055/pdf

TPX3CAM
Optical detector for **time stamping** (1.6ns) of optical photons up to 80 Mhits/s rate. Commercially available.





https://www.amscins.com/tpx3cam/

Optics

Optical devices may be used to optimally **couple scintillation light** from amplification structure to imaging sensor. In addition to camera lenses, additional devices may be used for a flexible placement of imaging sensors or to match the wavelength emitted in certain gas mixtures.

Mirrors
Guide light from emission site to camera outside of beam path.

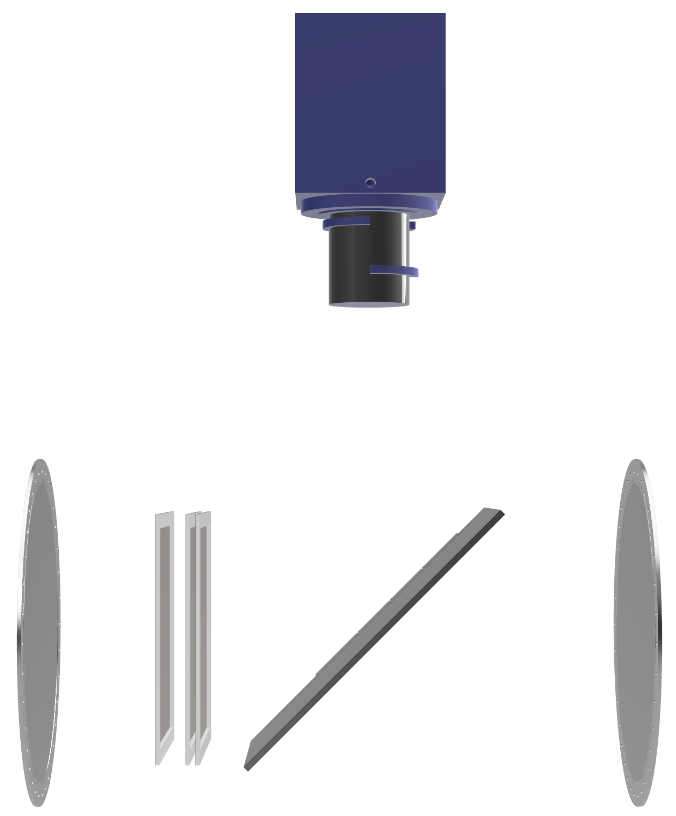


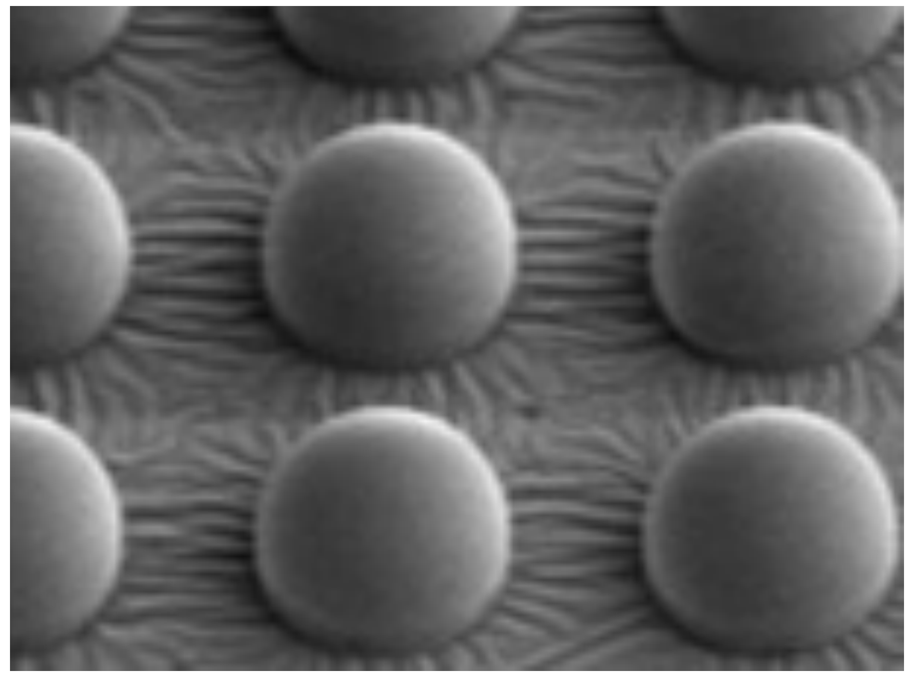
Image intensifiers
Increase sensitivity, various photocathodes available to match gas emission spectrum.

photonis.com

Tapered fibers
Optimally guide light from production site to imaging sensor or photon sensor.

szphoton.com

Microlenses
Resolve direction of incident light for light field imaging.



10.1016/j.apsusc.2018.01.253

Applications

Radiation imaging and fluorescence

High spatial resolution imaging

Optical TPCs

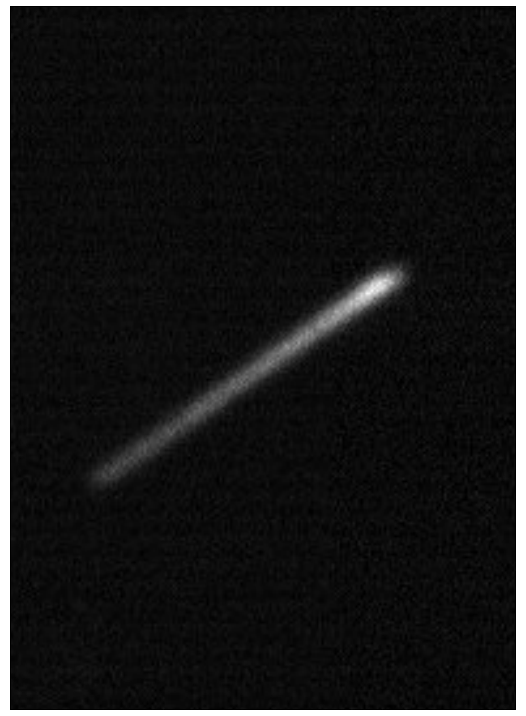
Neutron imaging

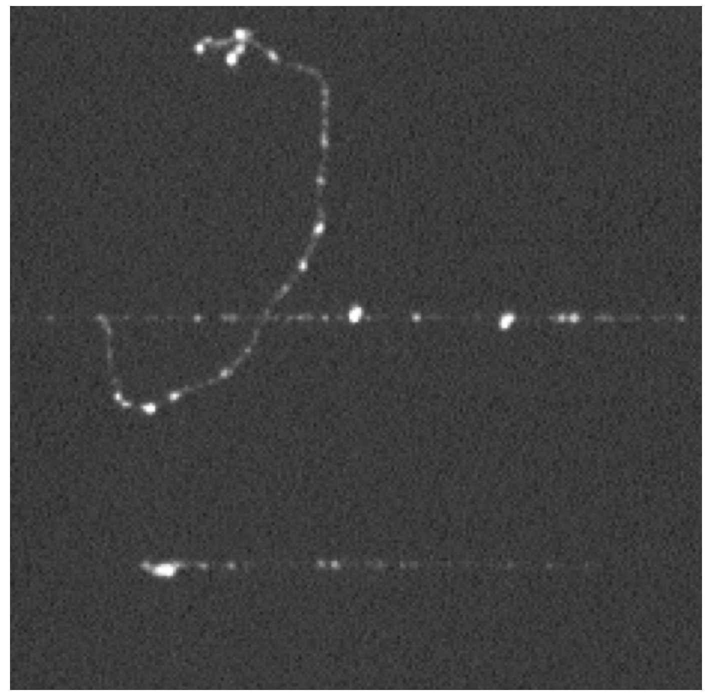
Beam monitoring and medical applications

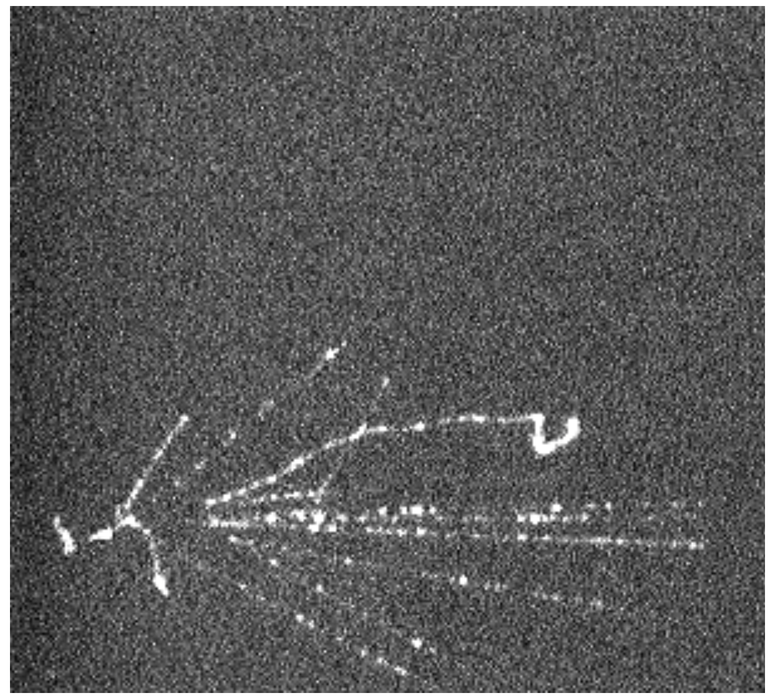
Optical readout for detector R&D

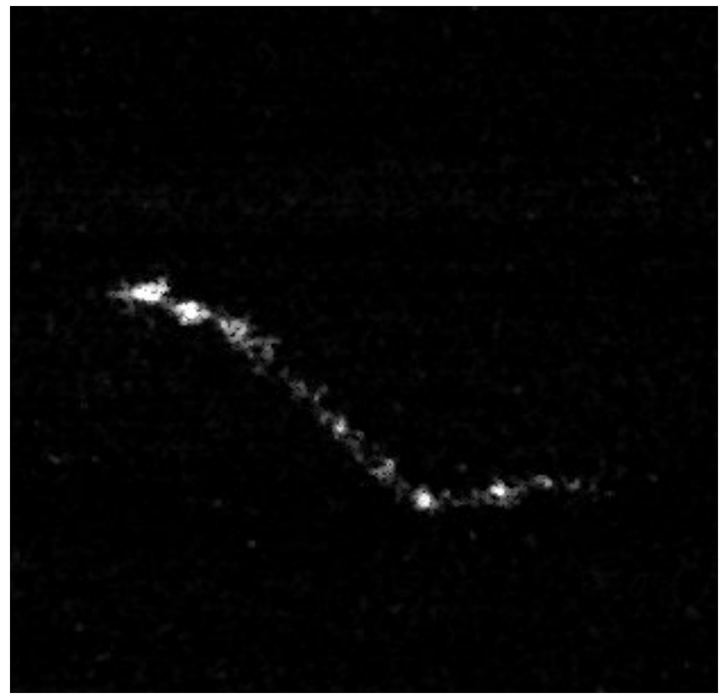
Optical readout of MPGDs

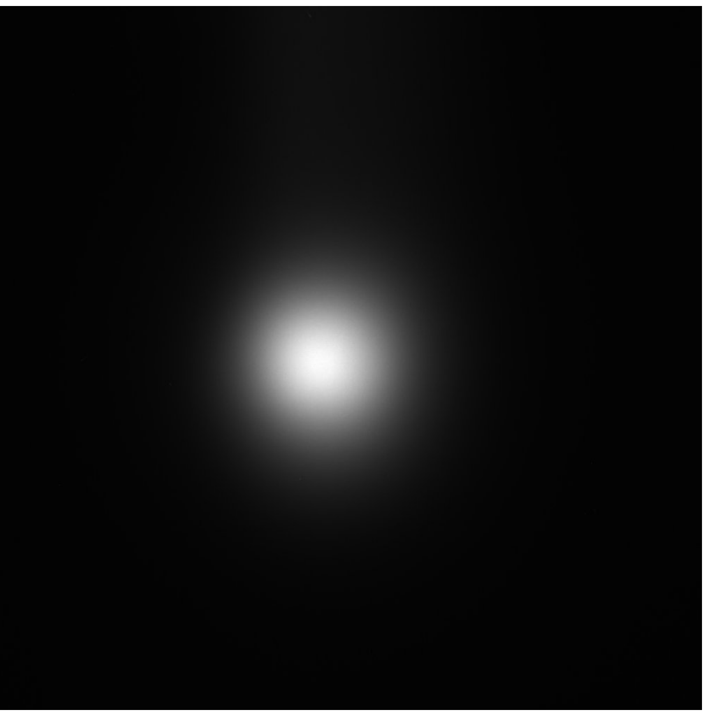

X-ray photons

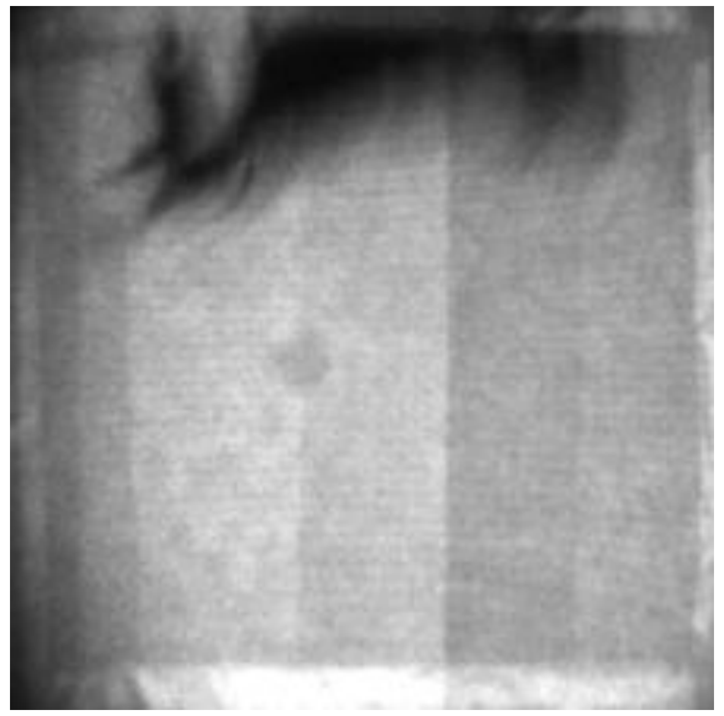

Alpha track

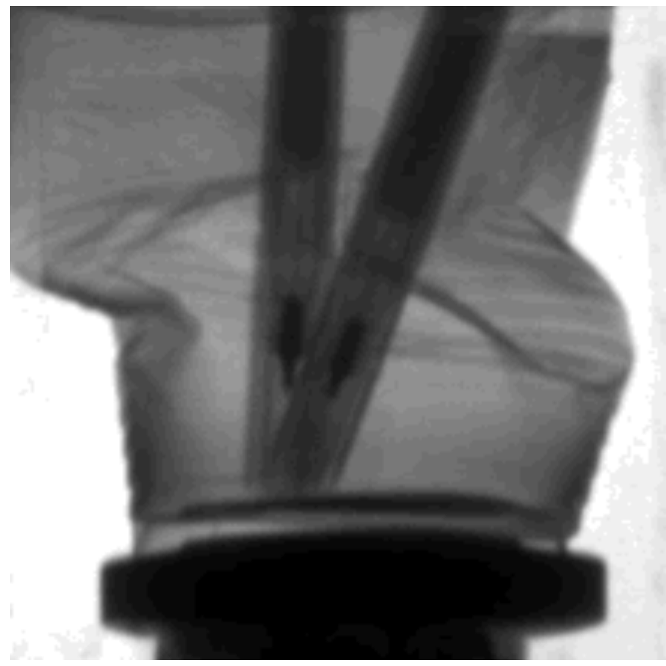

Muon tracks with δ-ray

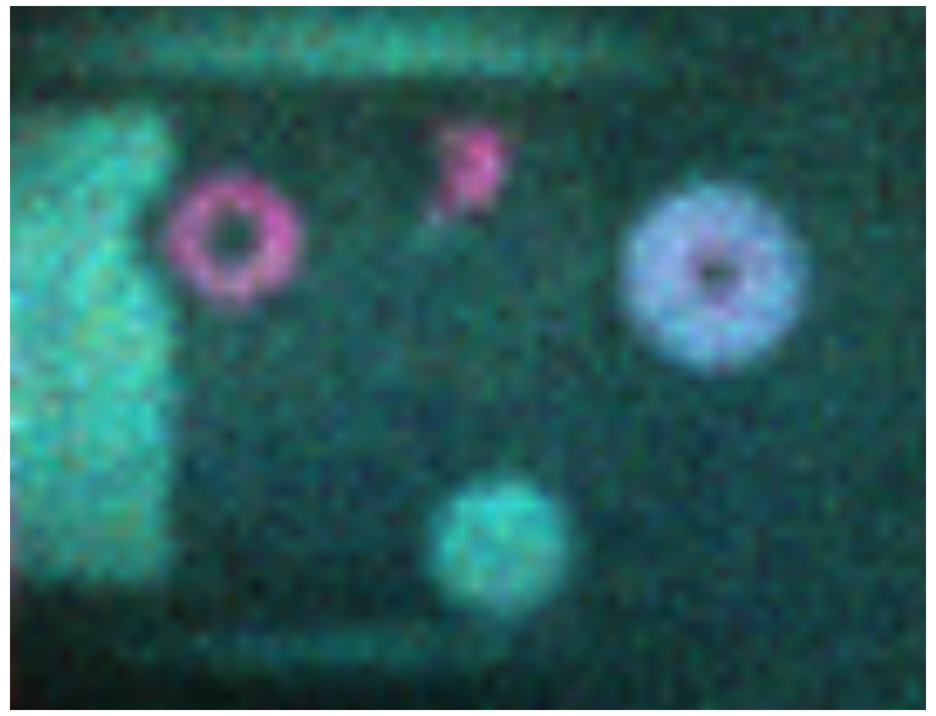

Hadronic shower

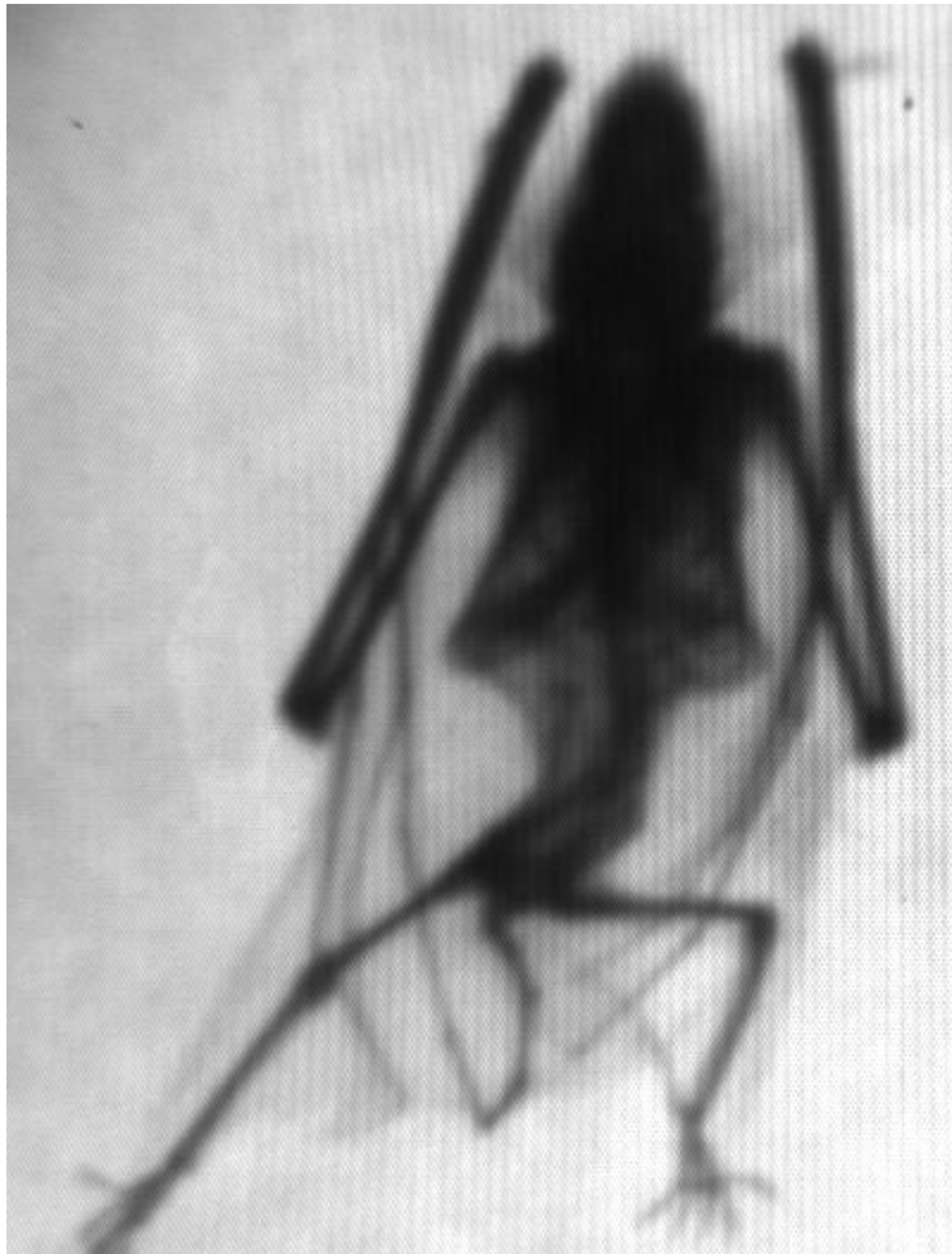

Cosmic event


Proton beam profile


X-ray fluoroscopy


X-ray tomography


X-ray fluorescence

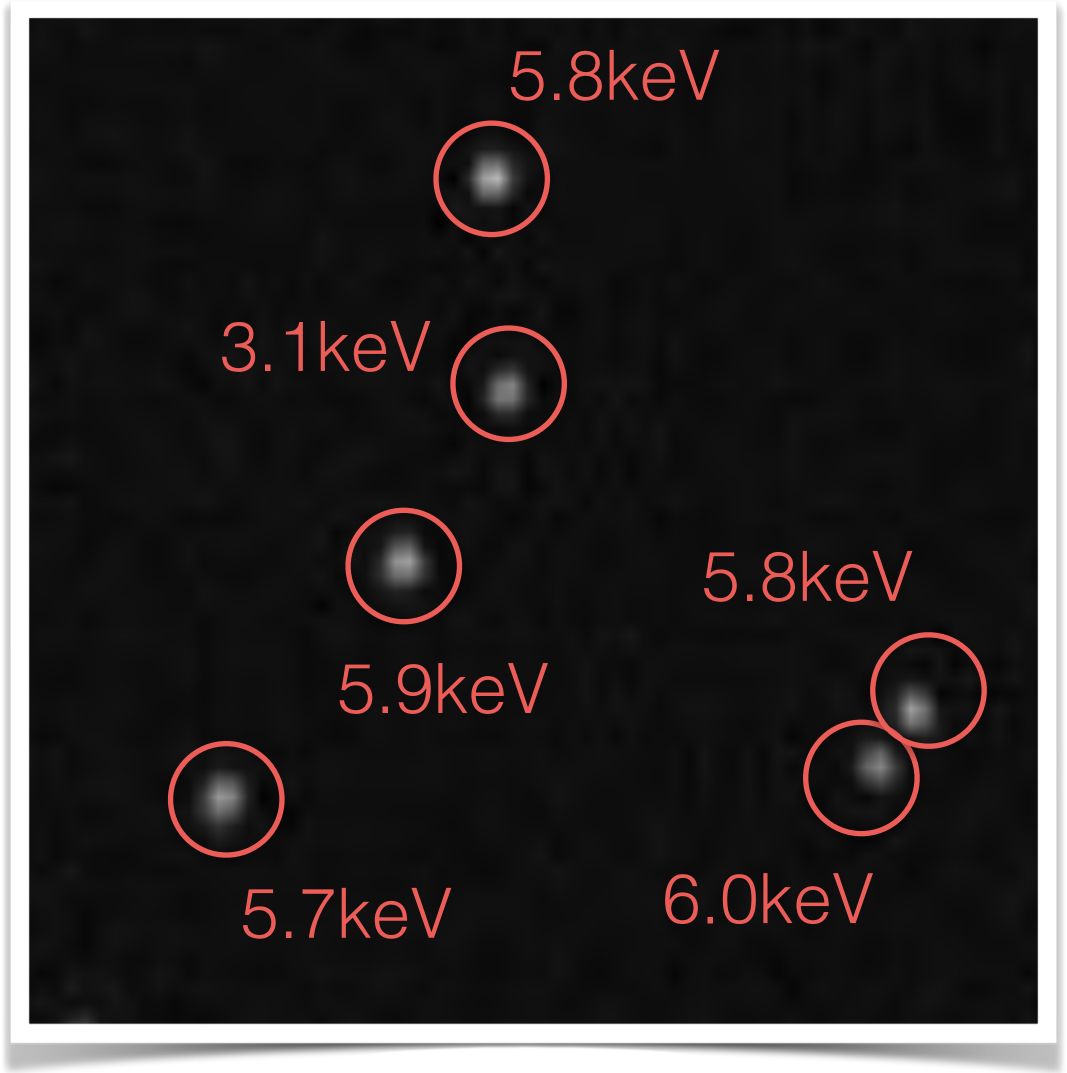

X-ray radiography

Energy-resolved imaging

Millisecond exposure image
with individual ^{55}Fe X-ray photons

Energy-resolved imaging

Millisecond exposure image
with individual ^{55}Fe X-ray photons

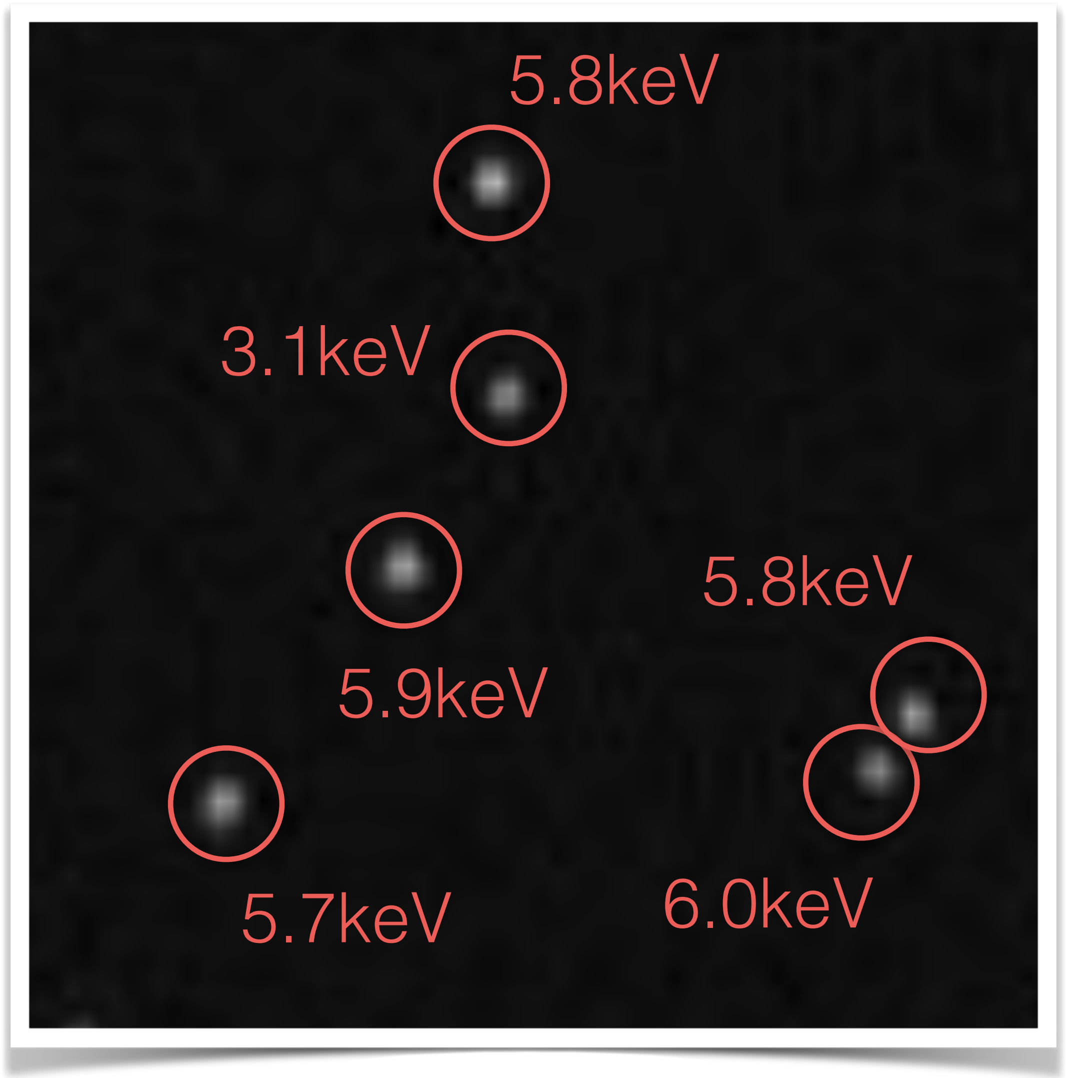


Brightness reflects
deposited energy

Energy values are schematic and not to scale for illustration

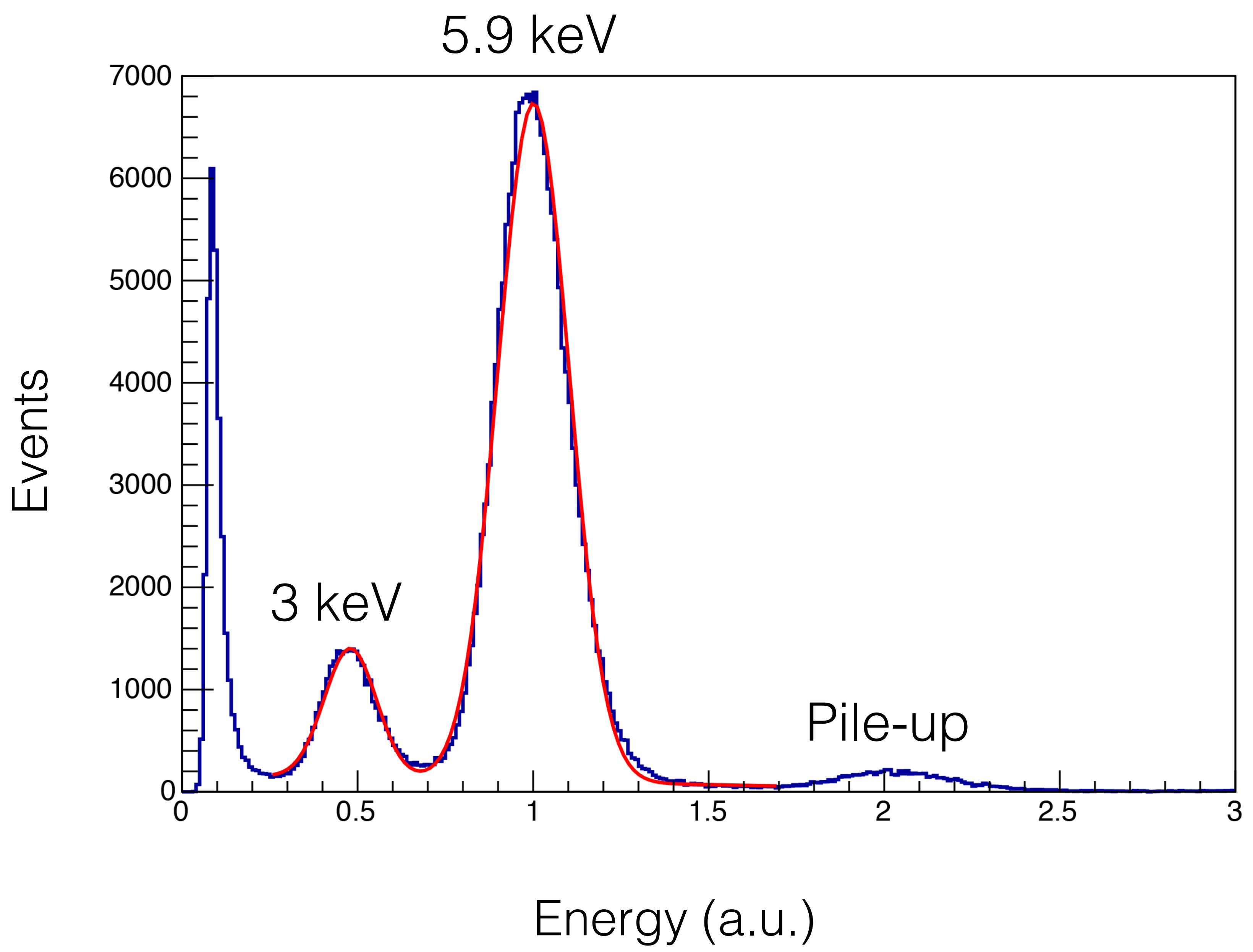
Energy-resolved imaging

Millisecond exposure image
with individual ^{55}Fe X-ray photons



Brightness reflects deposited energy

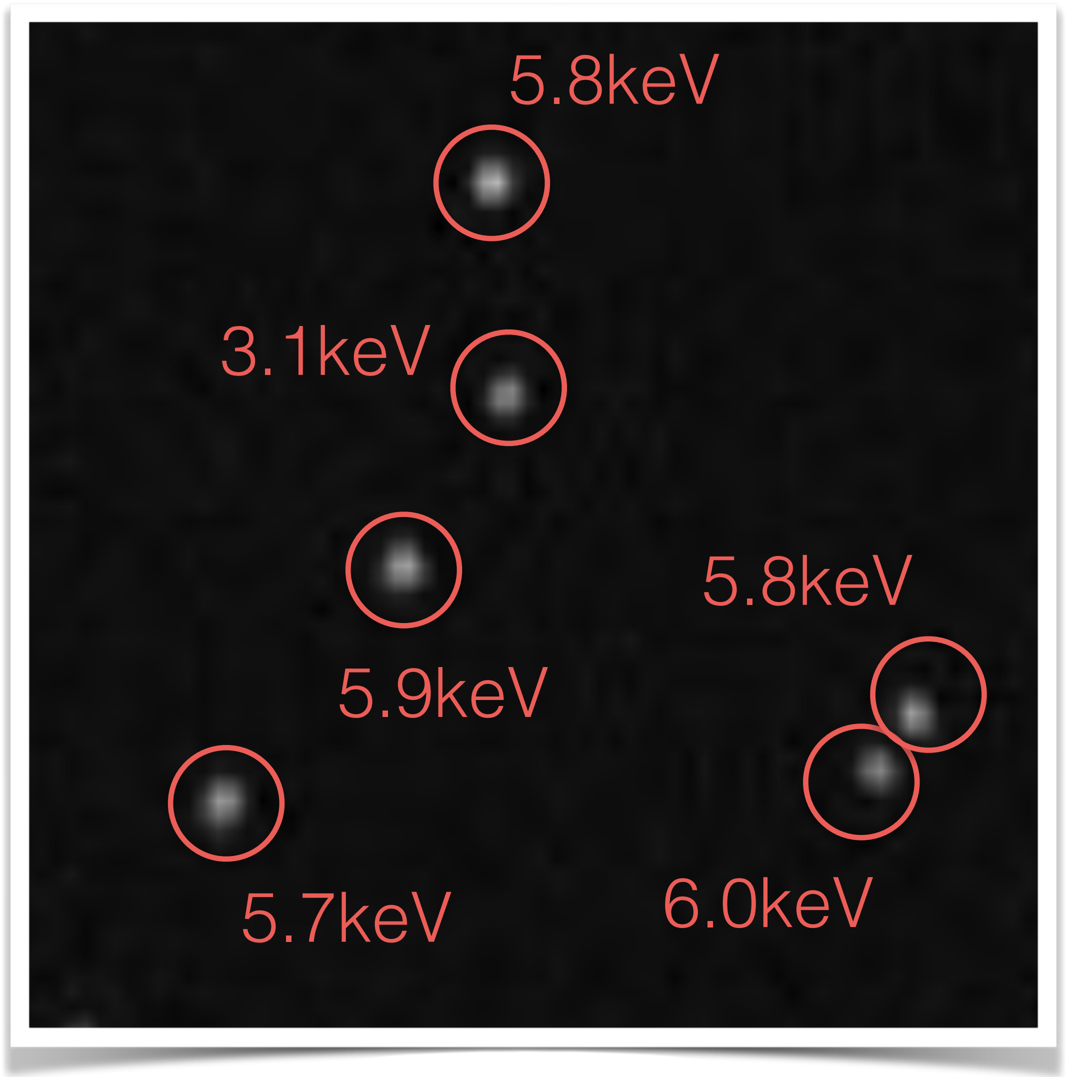
Energy spectrum of ^{55}Fe source
Optical readout



Energy values are schematic and not to scale for illustration

Energy-resolved imaging

Millisecond exposure image
with individual ^{55}Fe X-ray photons



Brightness reflects deposited energy

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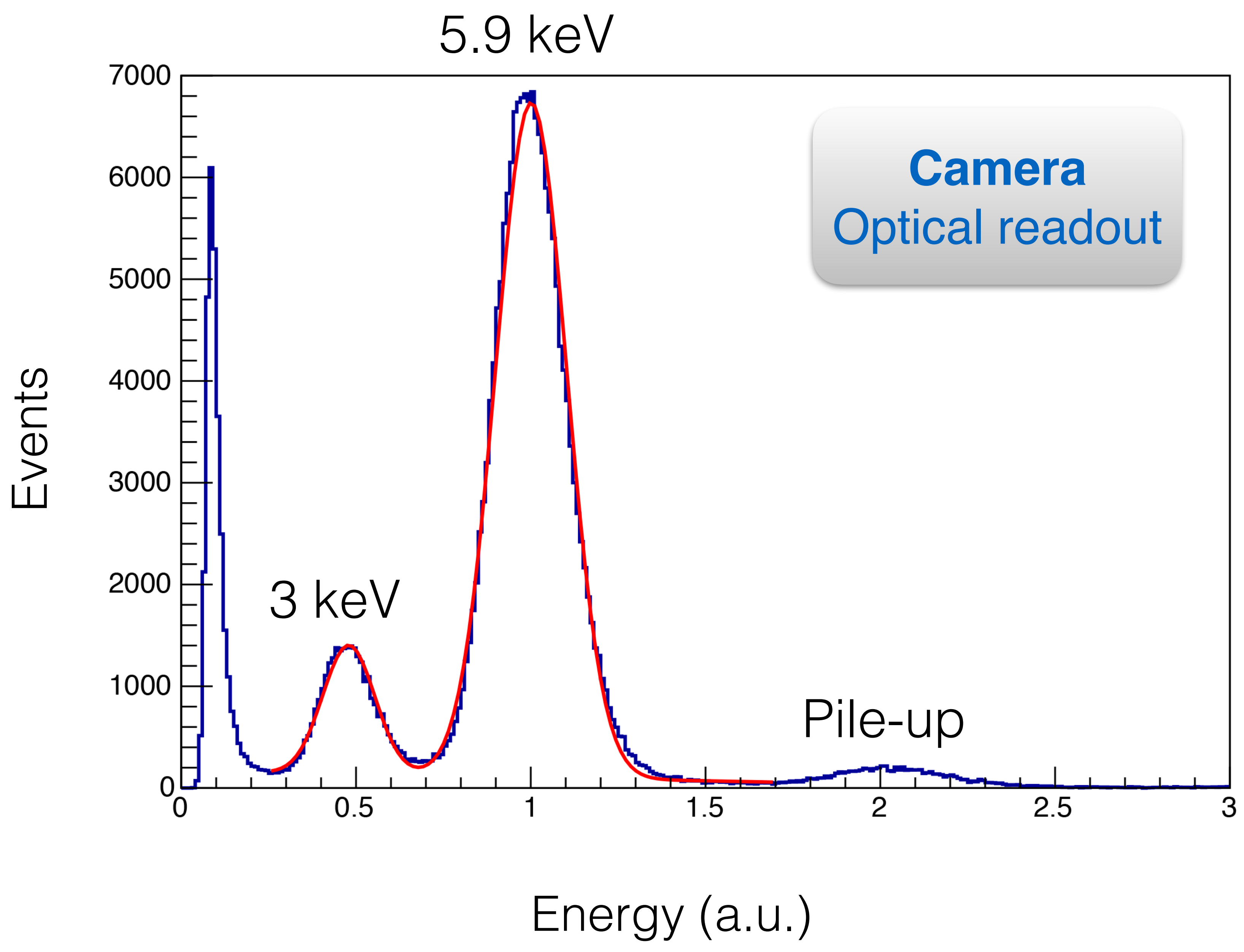
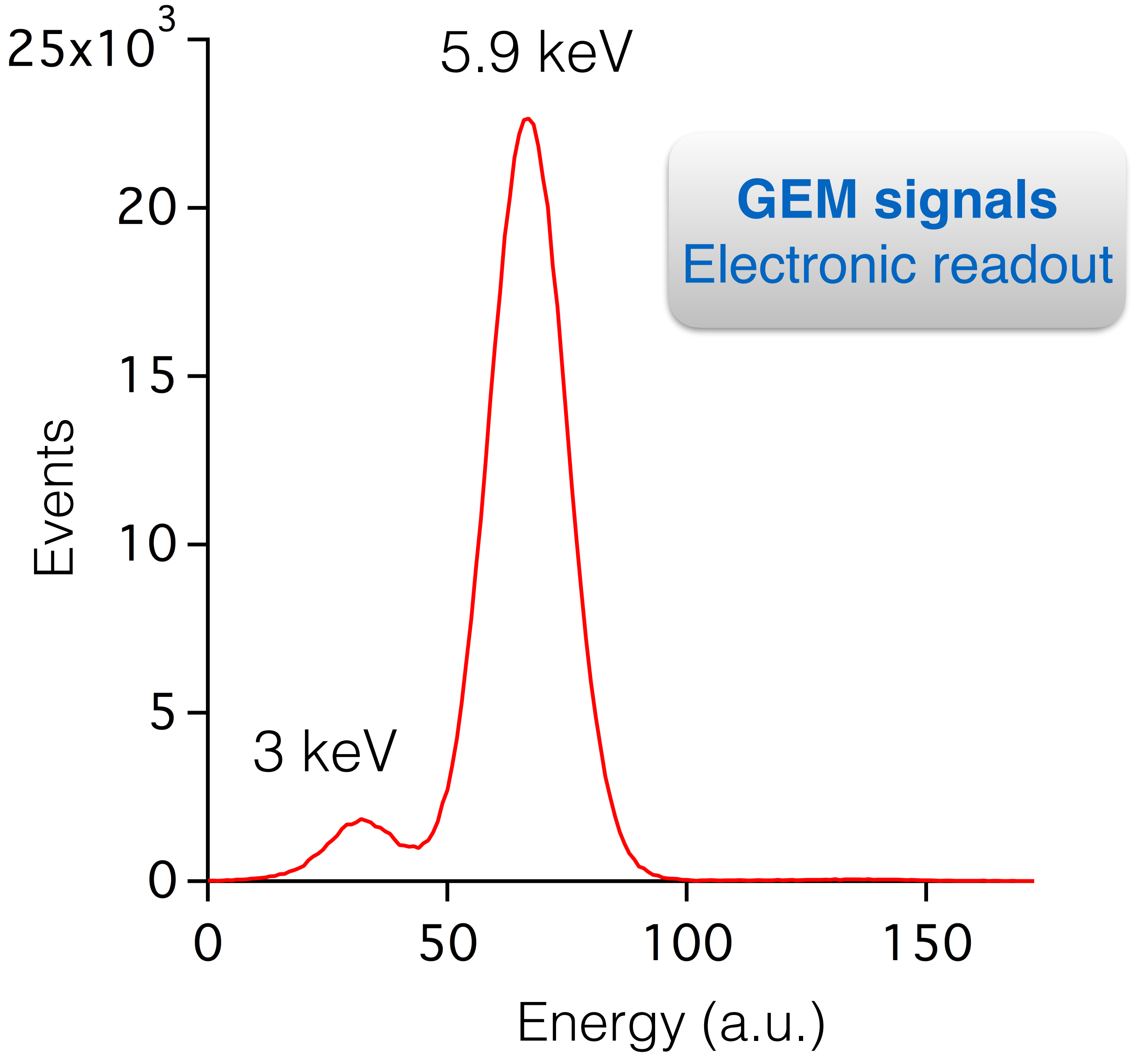
Optical readout

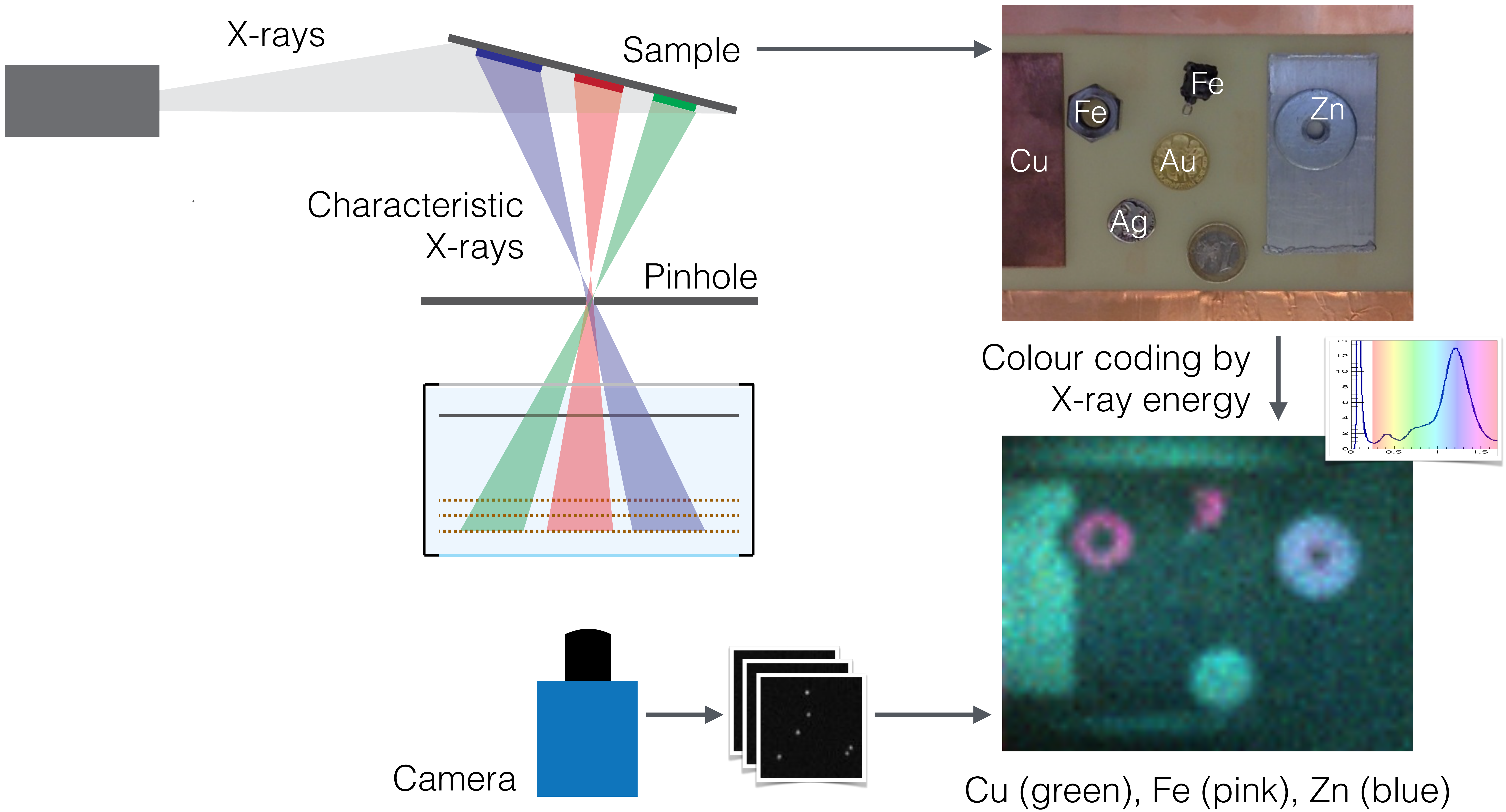


Energy spectrum of ^{55}Fe source
Electronic readout



Energy values are schematic and not to scale for illustration

Energy-resolved imaging: X-ray fluorescence



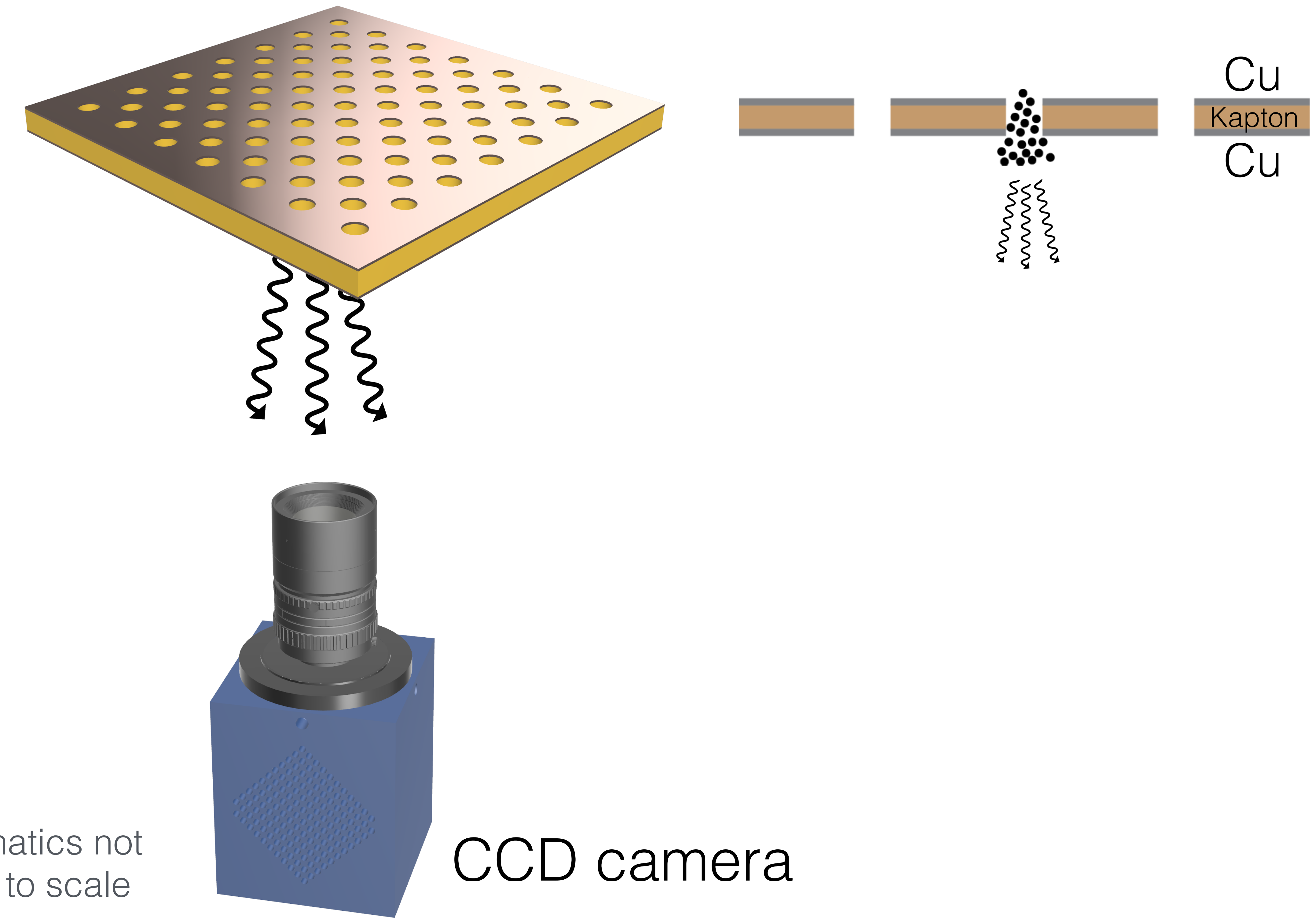
F.M. Brunbauer et al. JINST (13) 2018.

Schematics not drawn to scale

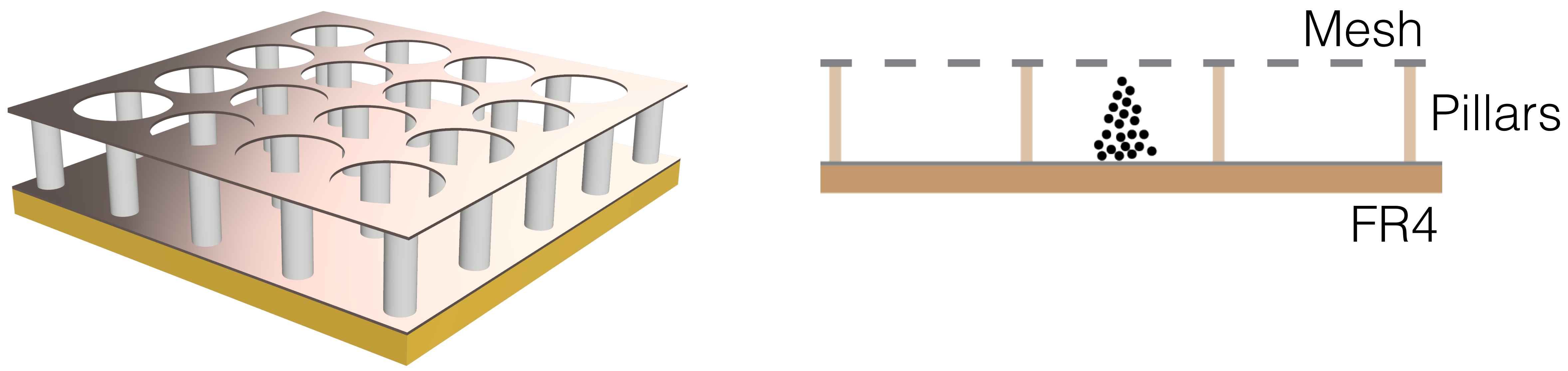
High spatial resolution imaging

Optical readout of Micromegas

Gaseous Electron Multiplier (**GEM**)



Micro-Mesh Gaseous Structure (**MicroMegas**)

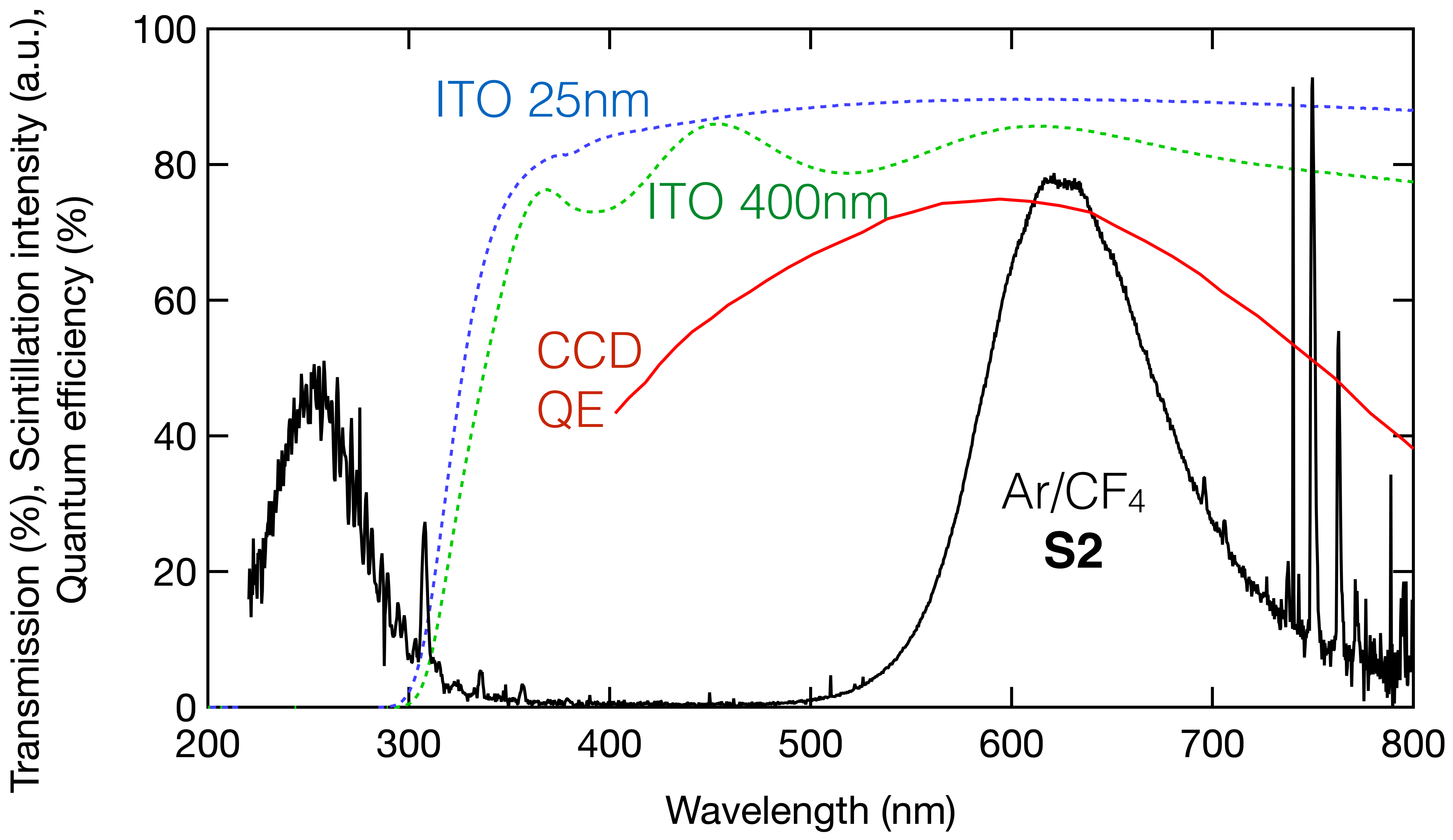


Schematics not drawn to scale

Indium tin oxide (ITO) for transparent electrodes

- Optically **transparent** (≈80% in VIS range)
- Electrically **conductive** (hundreds of Ω/sq)
- Simple deposition of thin films by **evaporation** (tens to hundreds of nm)
- Can be etched in HCl (structuring by **photolithography**)

Transparent strip anode

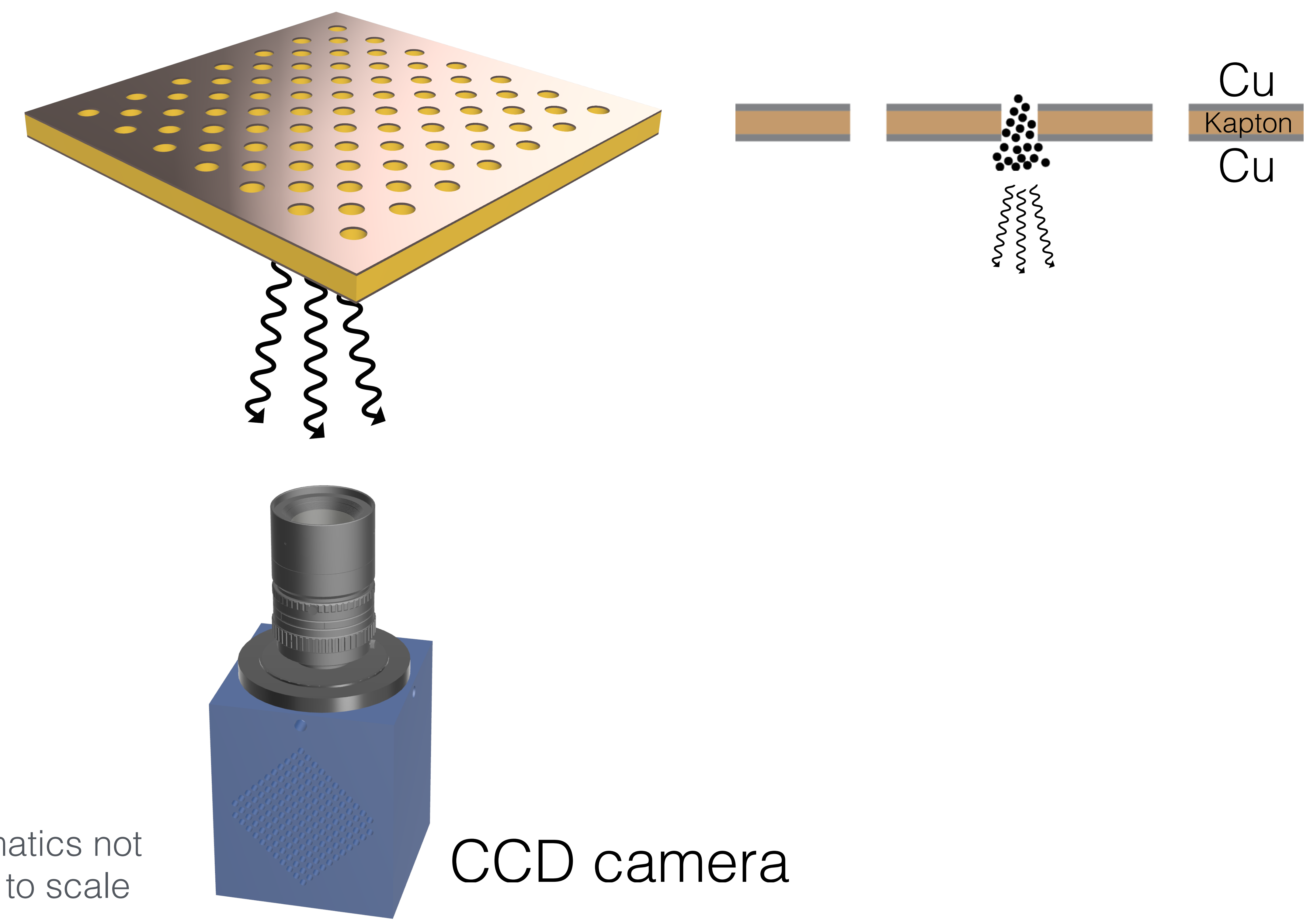


- May be used for **transparent anode** to read out electronic signals
- Substrate for **glass Micromegas**
- Can be used as **transparent cathode** for optical readout from cathode side (opaque MPGD substrates like μRWELL)

Optical readout of Micromegas

Exploiting uniform amplification region of MicroMegas detectors

Gaseous Electron Multiplier (**GEM**)



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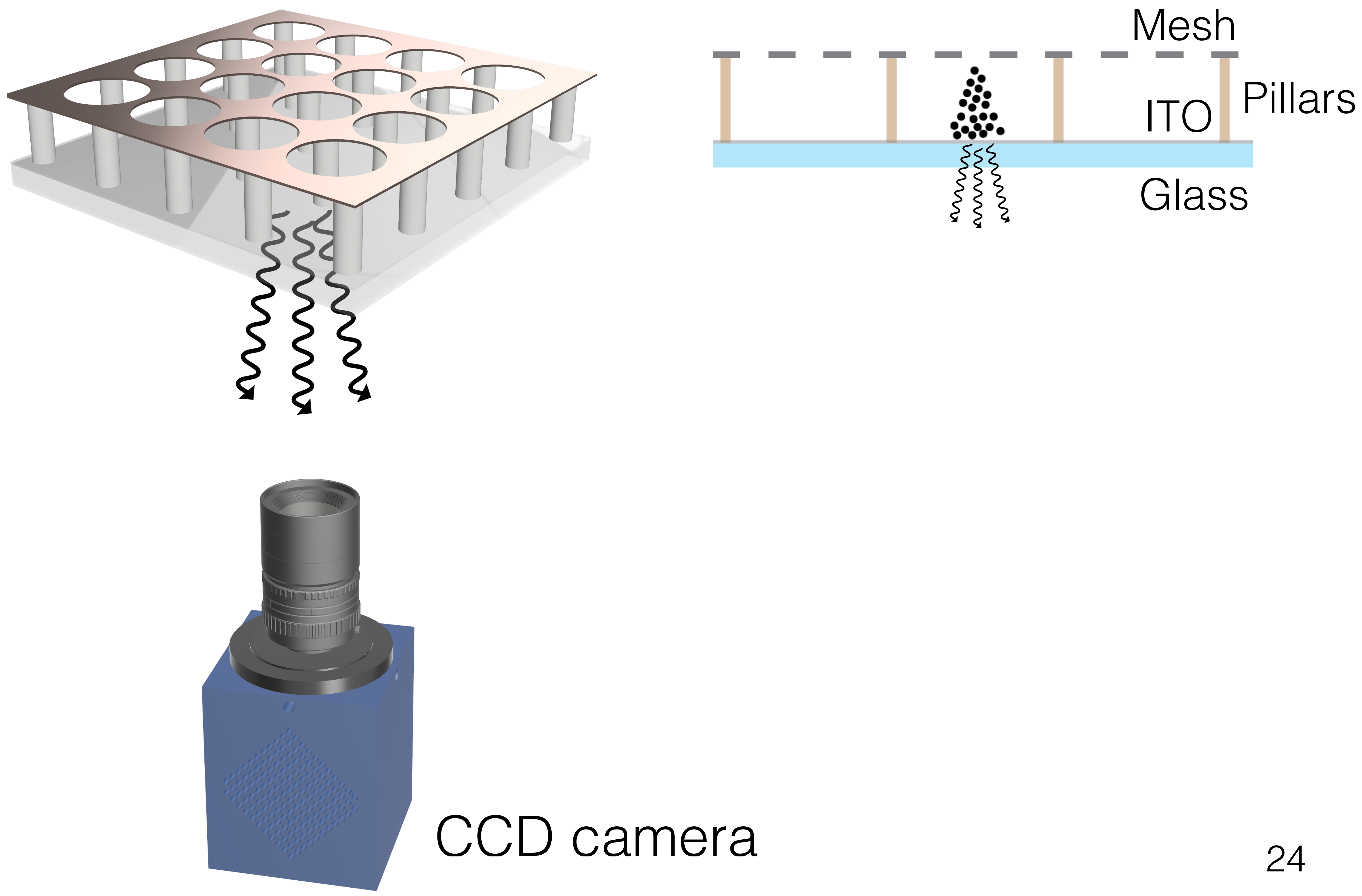
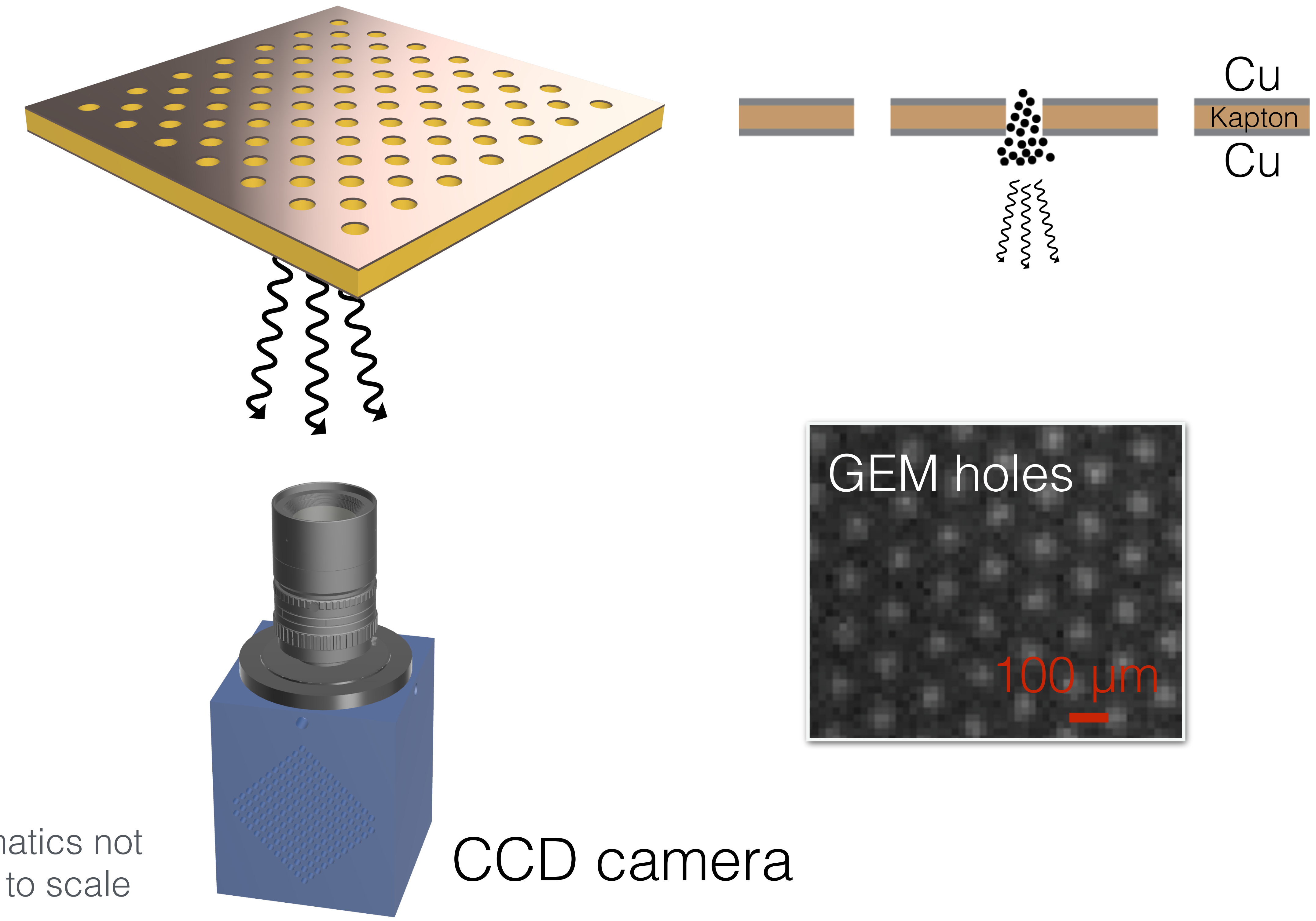


Schematics not drawn to scale

Optical readout of Micromegas

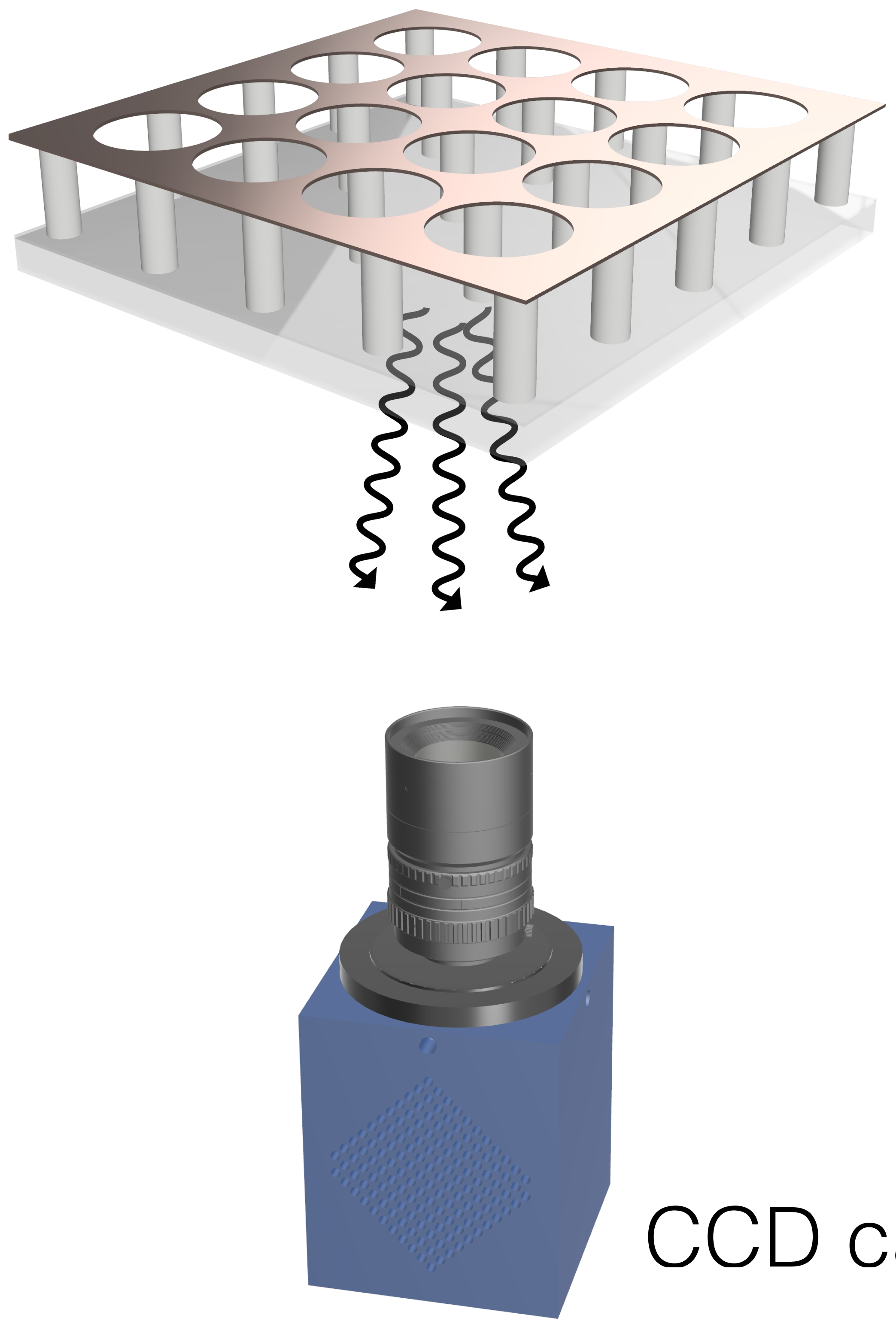
Exploiting uniform amplification region of MicroMegas detectors

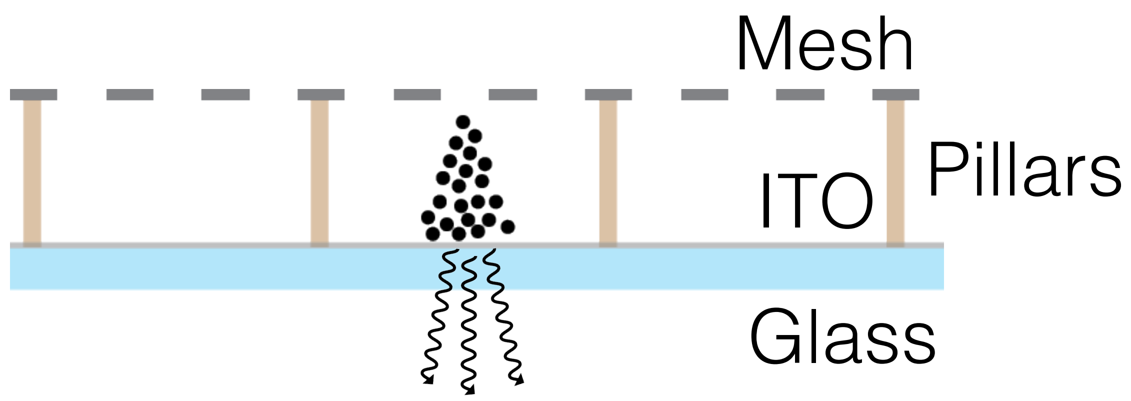
Gaseous Electron Multiplier (**GEM**)



Schematics not drawn to scale

Micro-Mesh Gaseous Structure (**MicroMegas**)





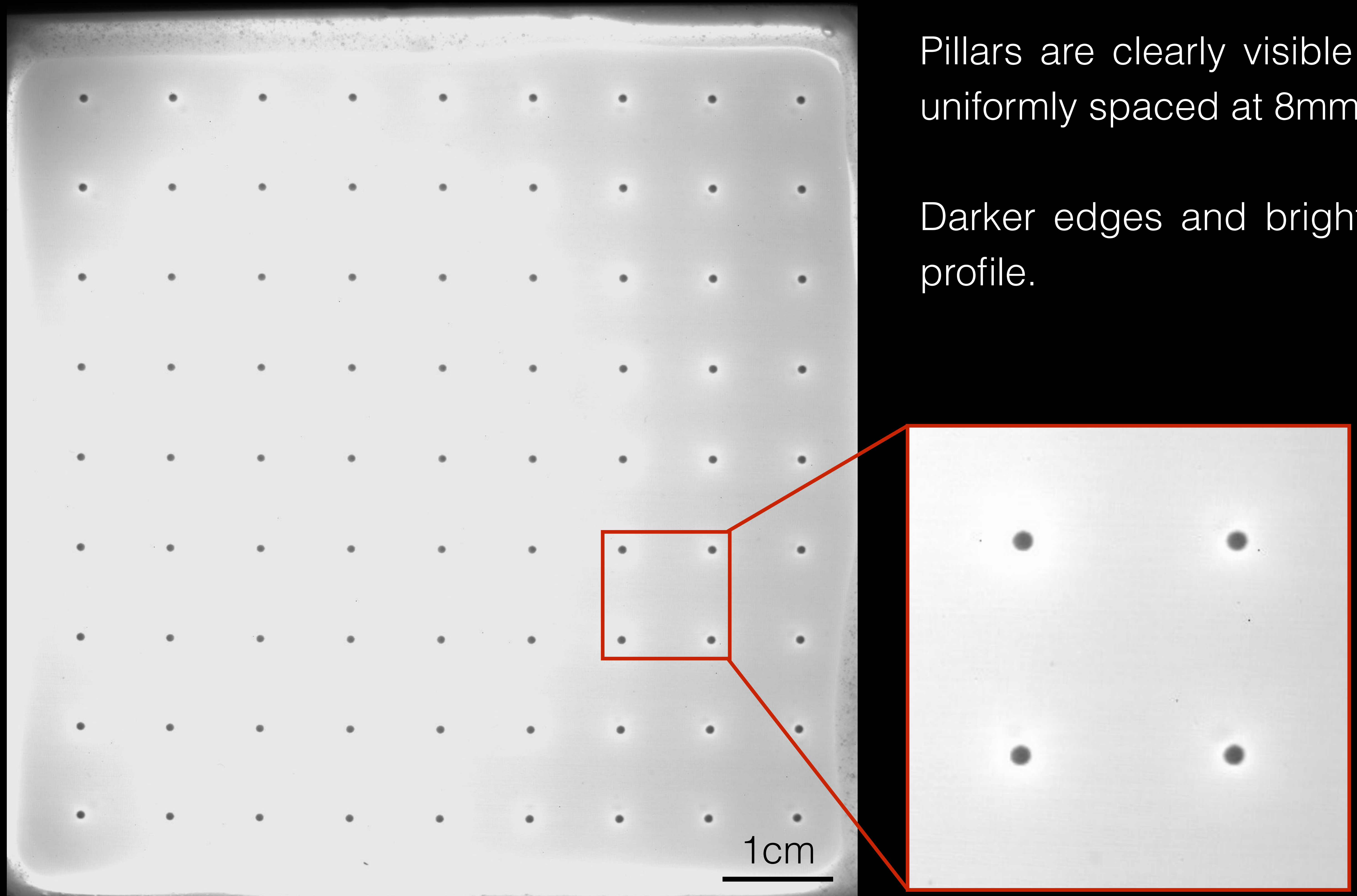
Potential advantages:

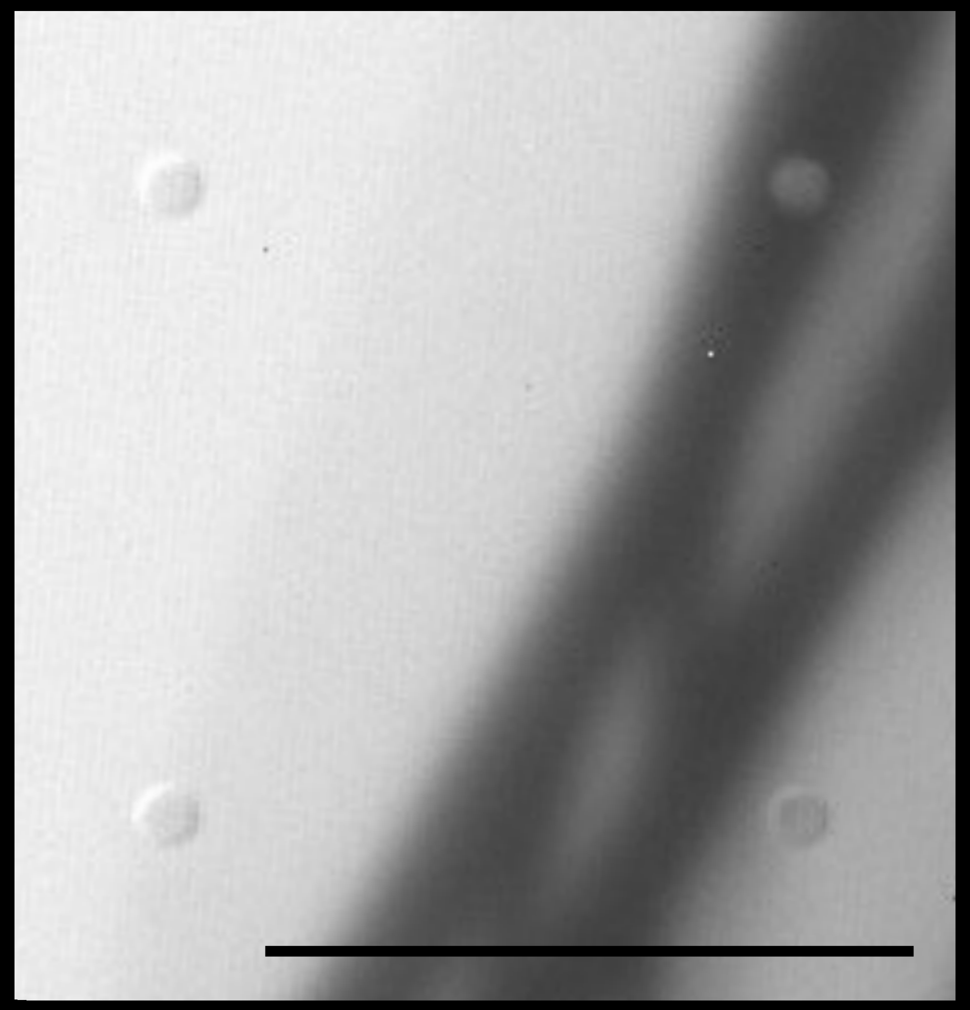
- Better energy resolution
- Higher uniformity for imaging (no hole structure)

Optical readout of Micromegas

Pillars are clearly visible in flood exposure images as dark spots uniformly spaced at 8mm pitch.

Darker edges and brightness variations attributed to X-ray beam profile.



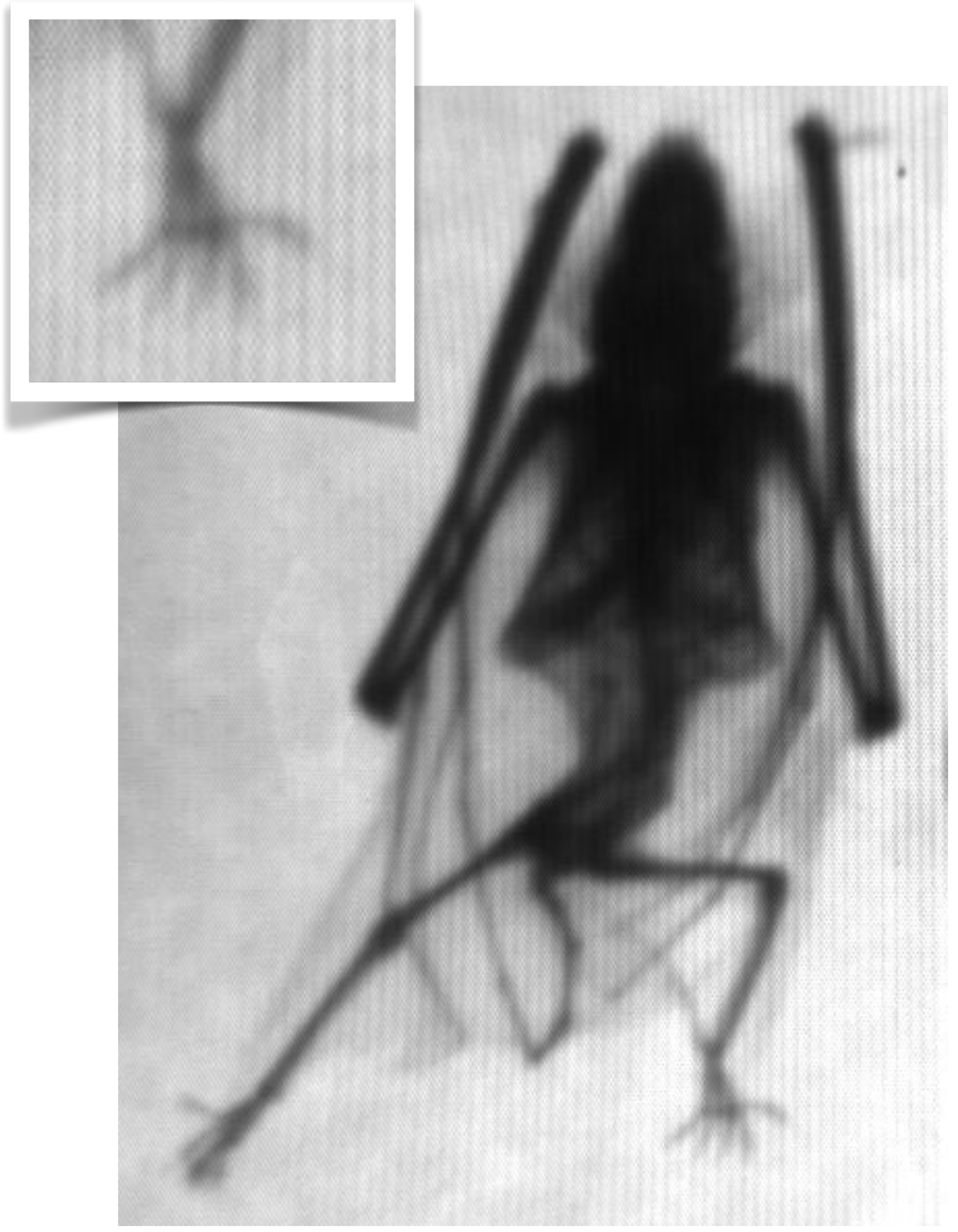


X-ray radiography comparison

Charge readout
(1998)

https://gdd.web.cern.ch/GDD/gemreadout.htm

Optically read out GEMs
(2016)



4x4 binning
thin drift gap triple-GEM

Optically read out MMs
(2018)

1x1 binning
long exposure, several mm active volume thickness

Spatial resolution comparison

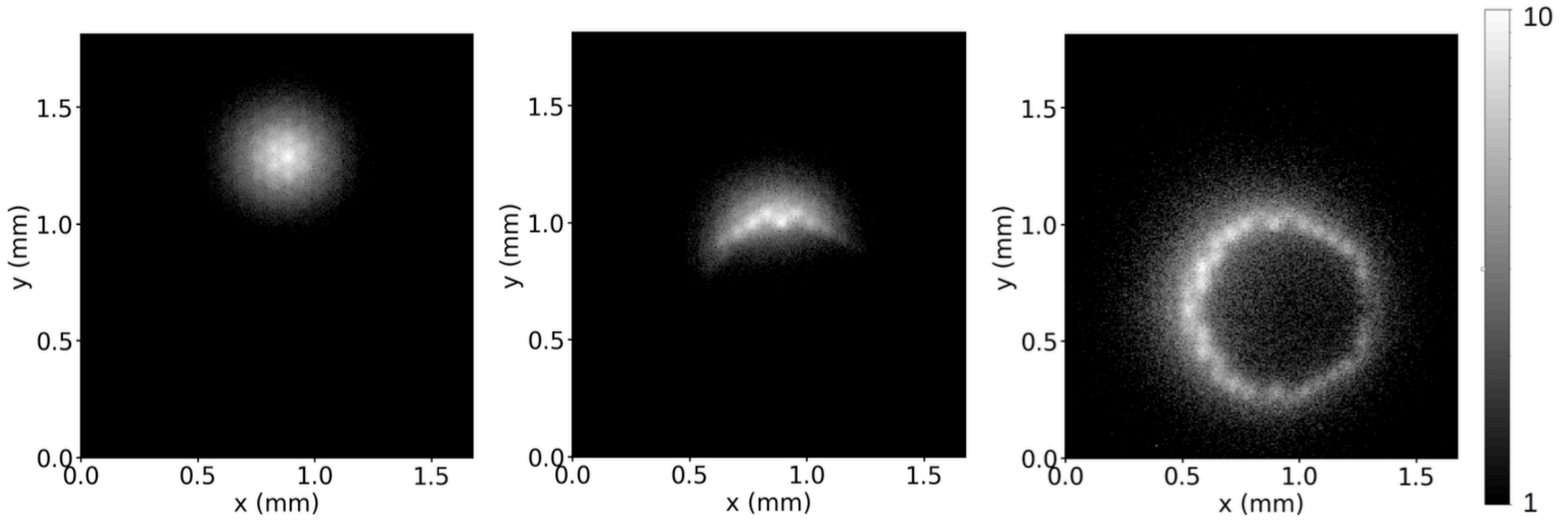
Line pair phantoms were used to measure the spatial resolution and compare it to the one achievable with an optically read out triple-GEM.

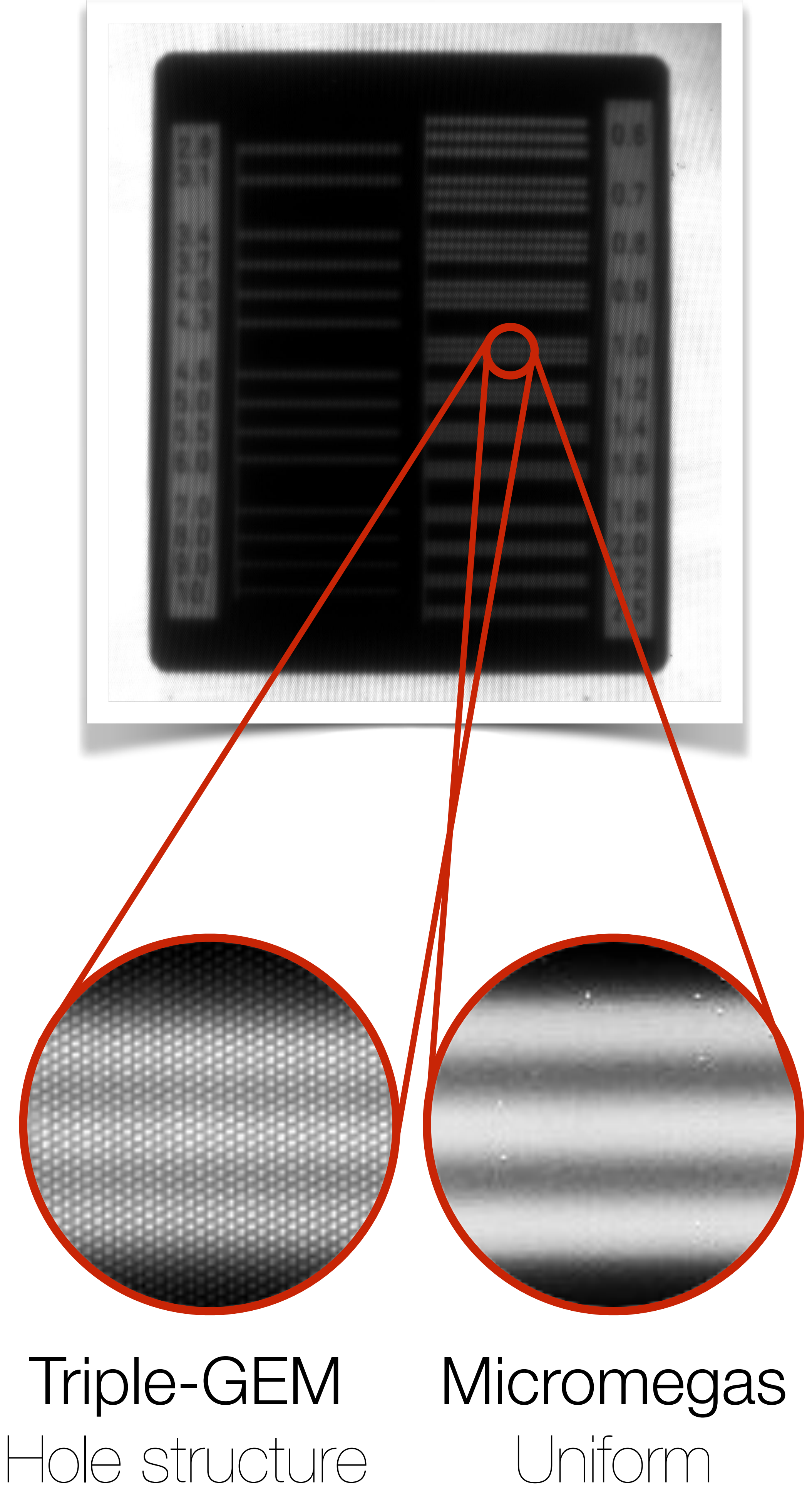
Spatial resolution:

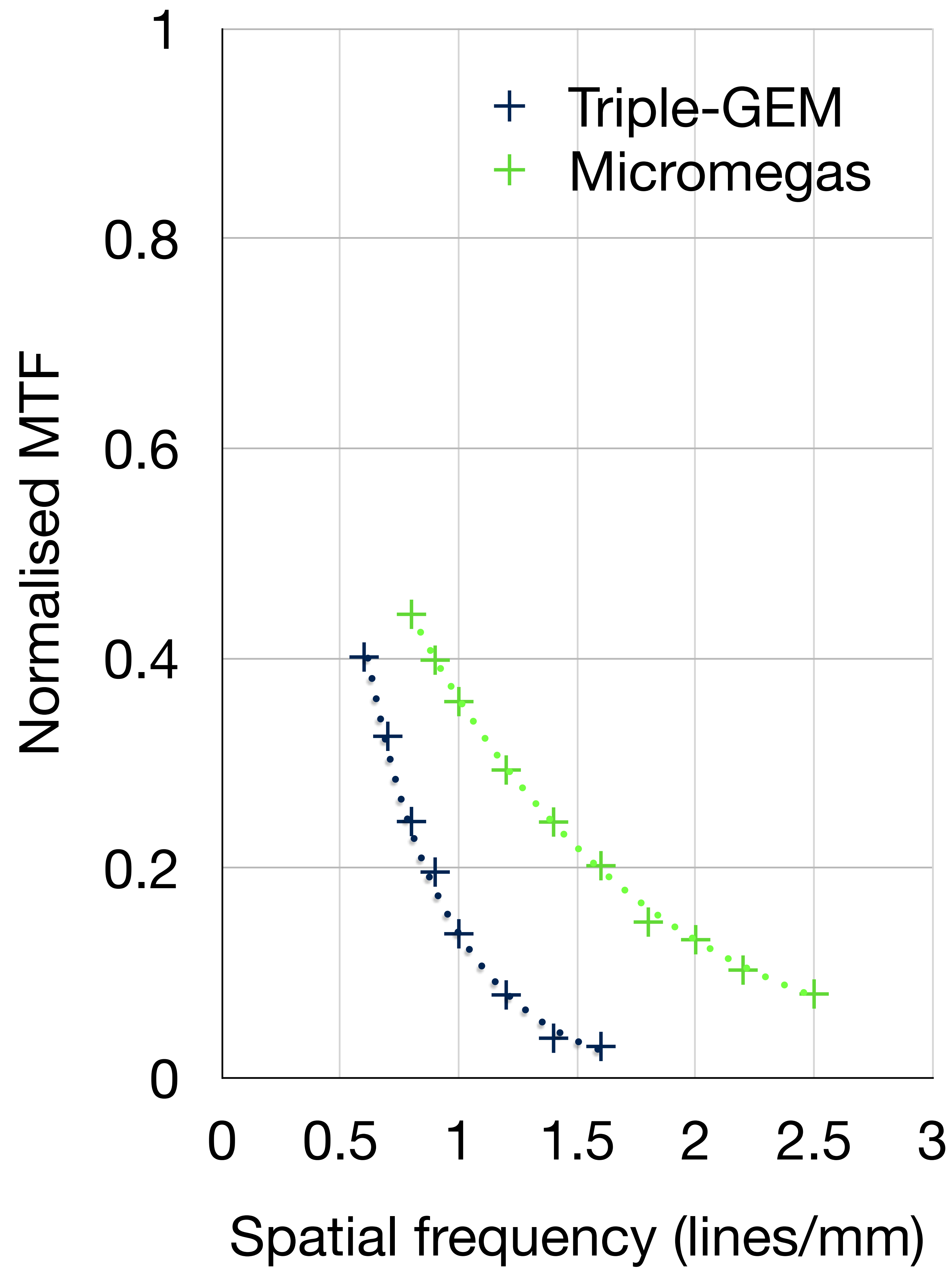
Triple-GEM: ≈**890 *μm*** (1.11 lines/mm)

Micromegas: ≈**440 *μm*** (2.25 lines/mm)

Electric field deformations close to Micromegas pillar with spot-like X-ray beam

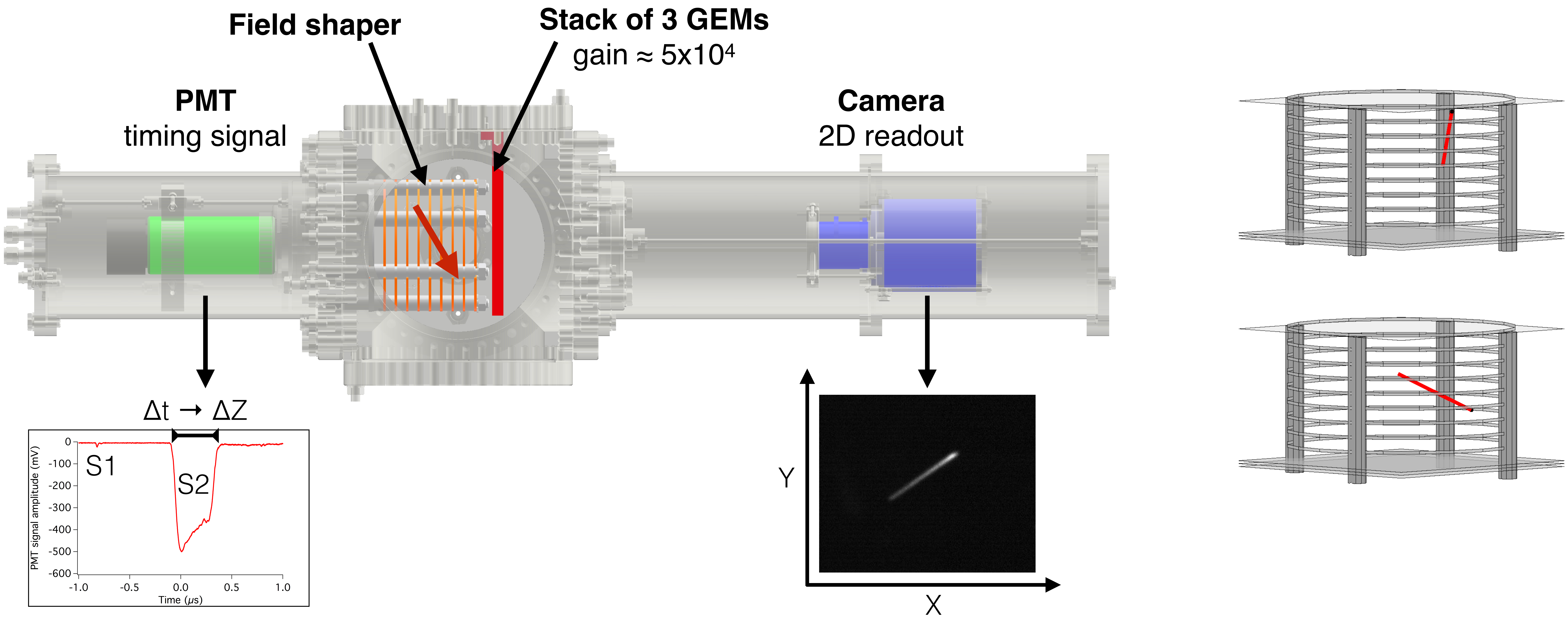






Optical TPCs

Optically read out TPC PMT + CCD



Timing information **+** **2D projection** **→** **3D track reconstruction**

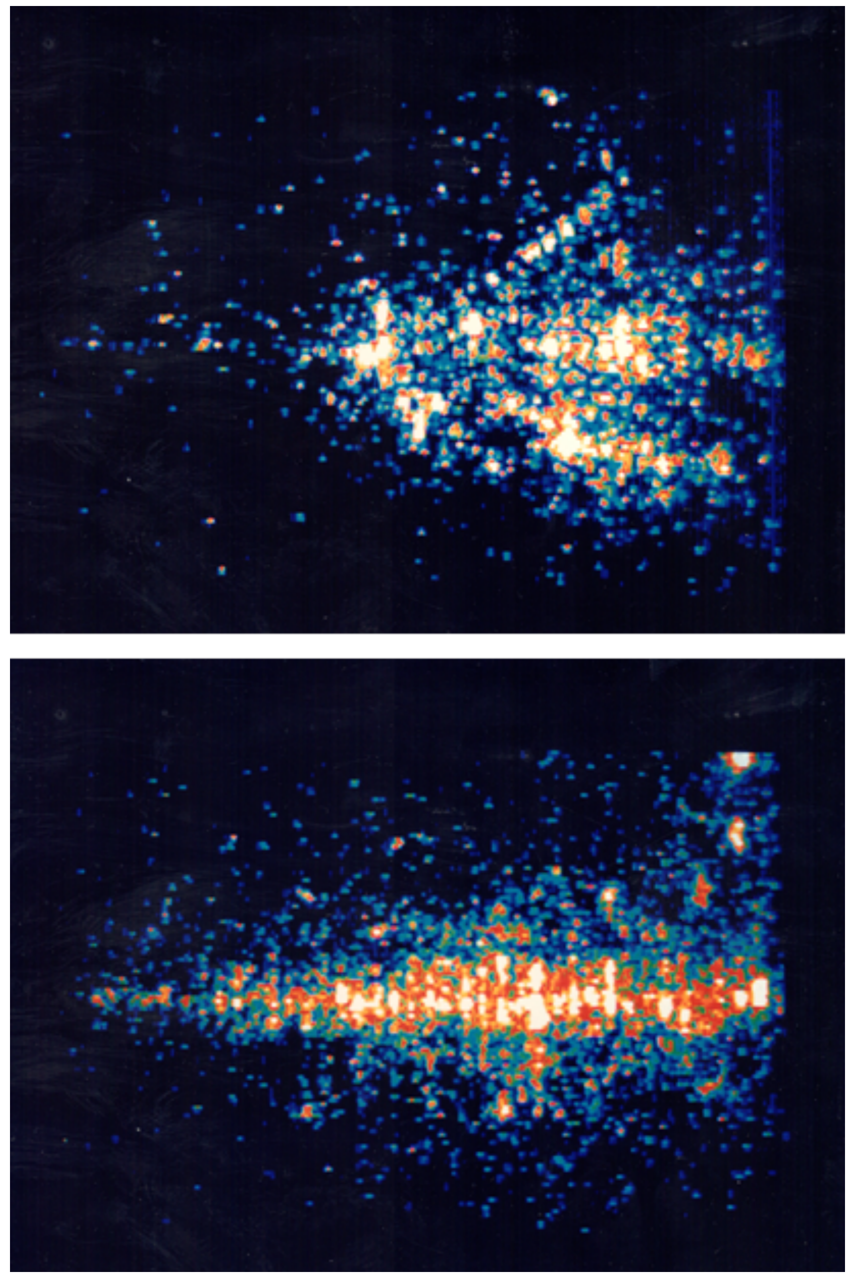
Schematics not drawn to scale

Optical TPCs

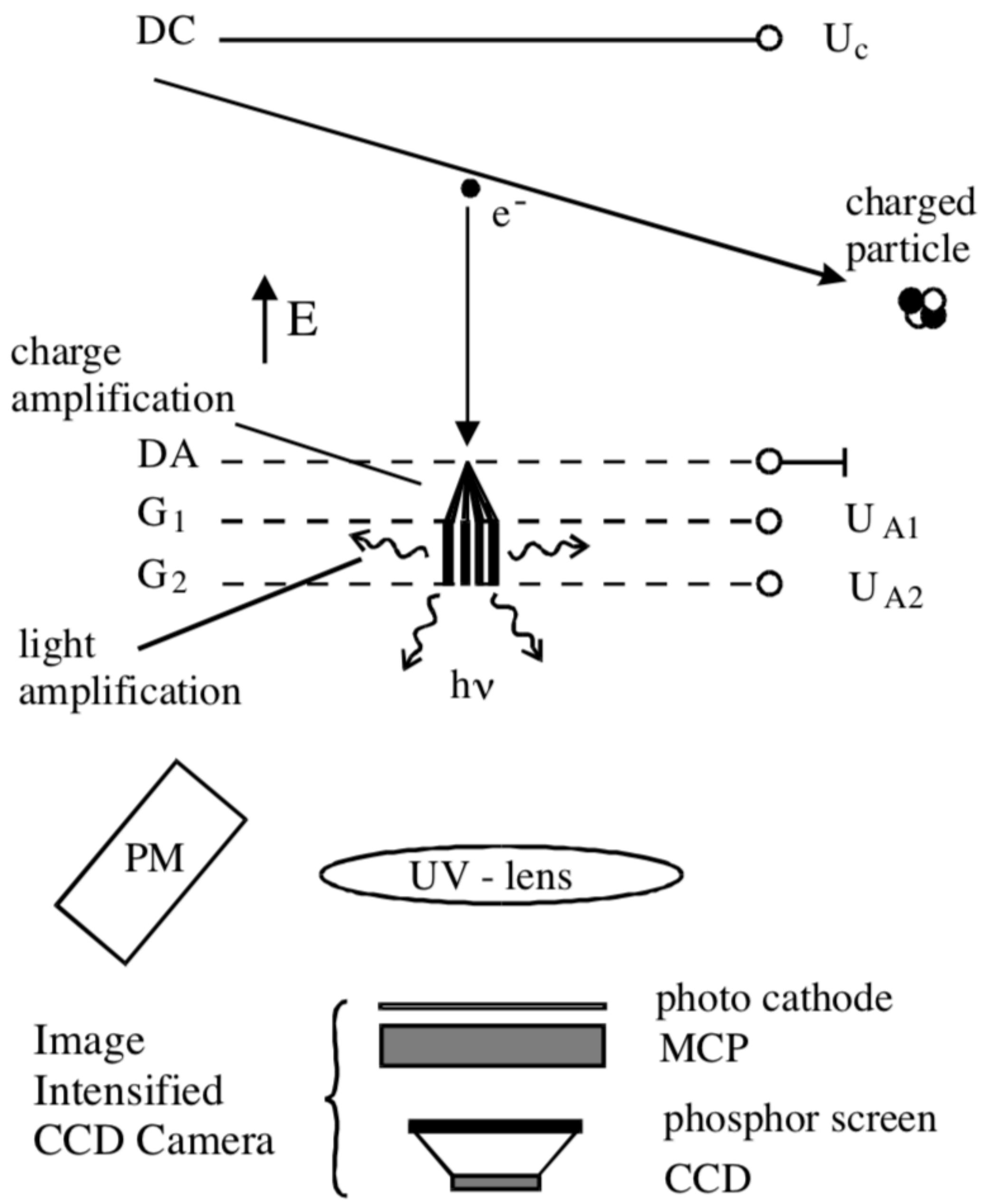
Long history of optically read out Time Projection Chambers (OTPCs)

Detailed **2D projections** (pixellated readout for energy loss measurement, head/tail distinction of recoil products) from camera

Requires **auxiliary timing information** for 3D reconstruction (can be provided by fast photon detectors like PMTs or SiPMs or supplementary electronic readout).

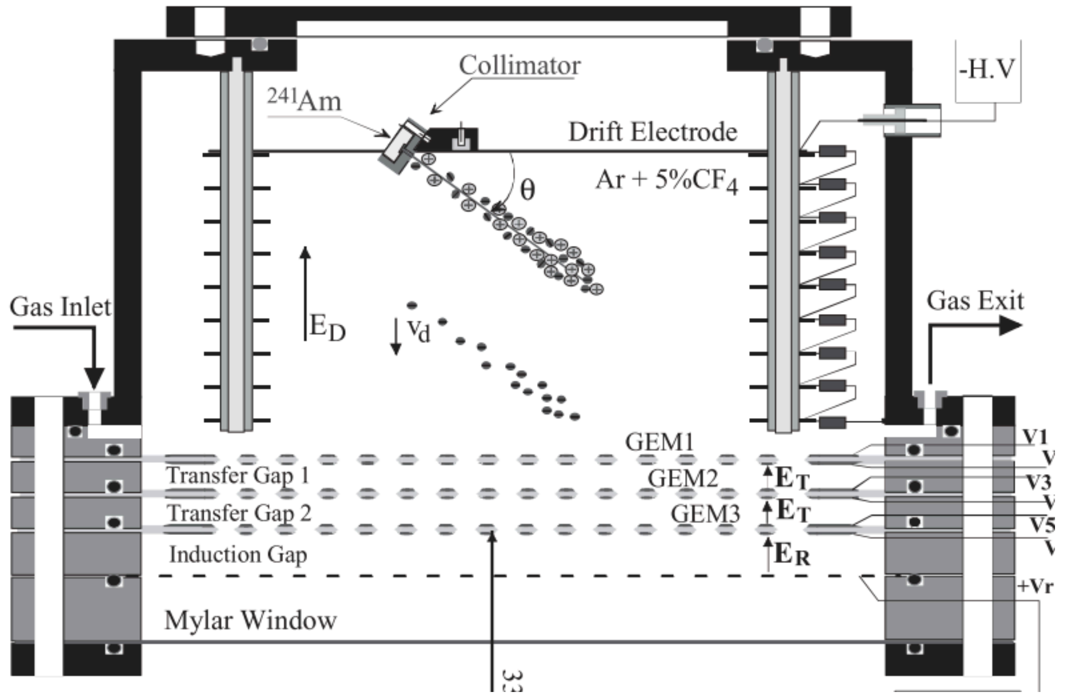


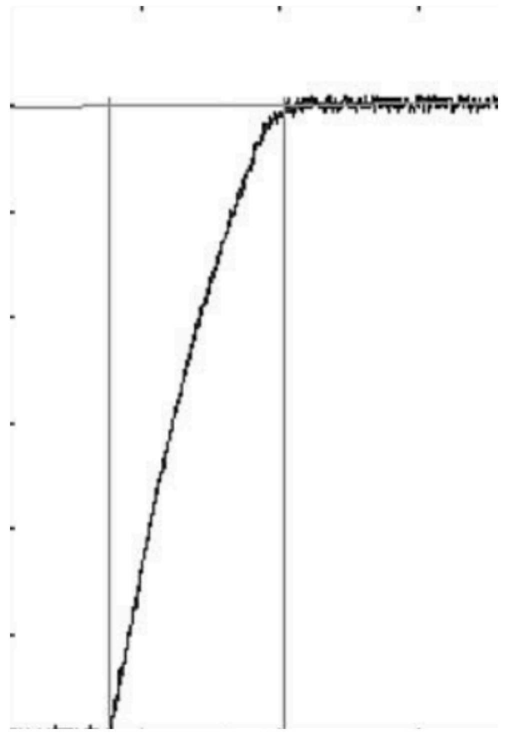
Fonte P., Breskin A., Charpak G., Dominik W. & Sauli F. (1989) NIM A. 283, 3, p. 658-664.



U. Titt et al. https://cds.cern.ch/record/800769/files/0410258.pdf

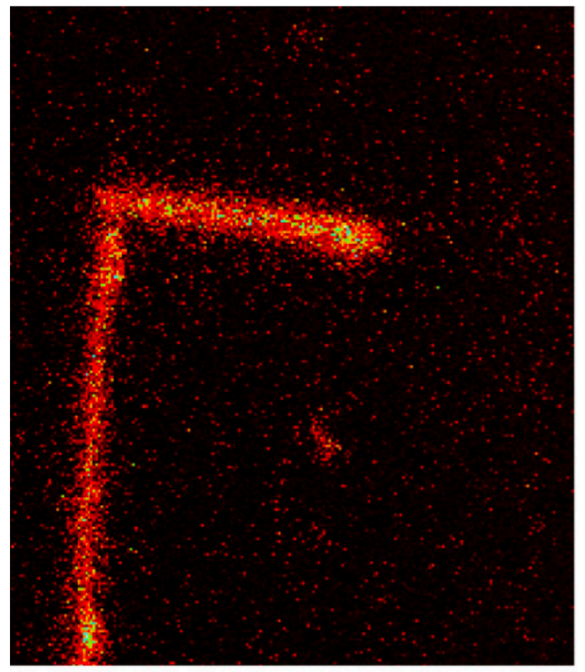
Z determination with PMT waveform

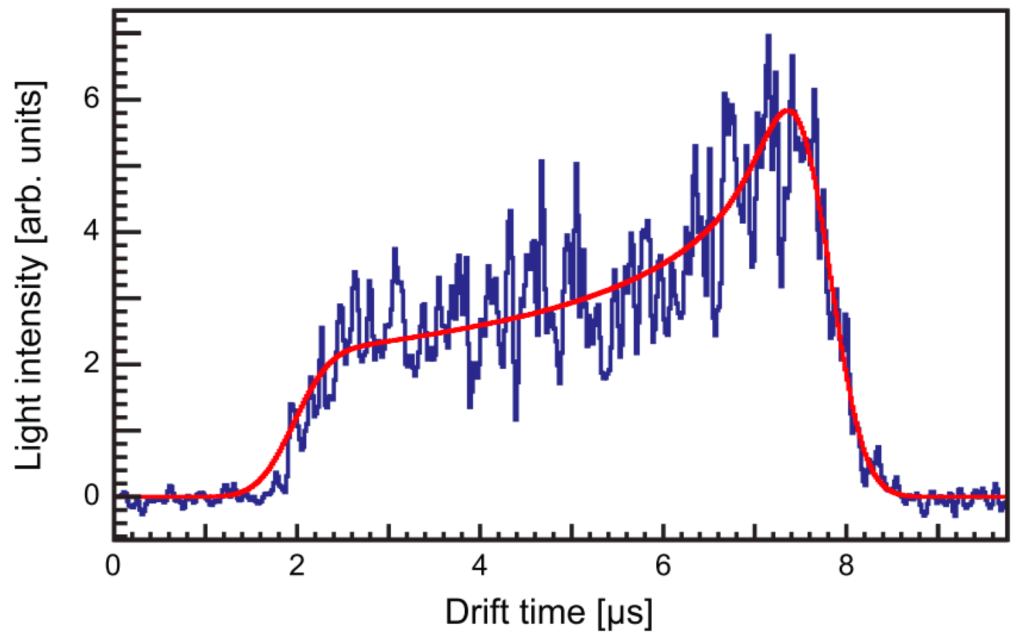




L.M.S. Margato et al., Performance of an optical readout GEM-based TPC, NIM A, 2004

OTPC for proton spectroscopy





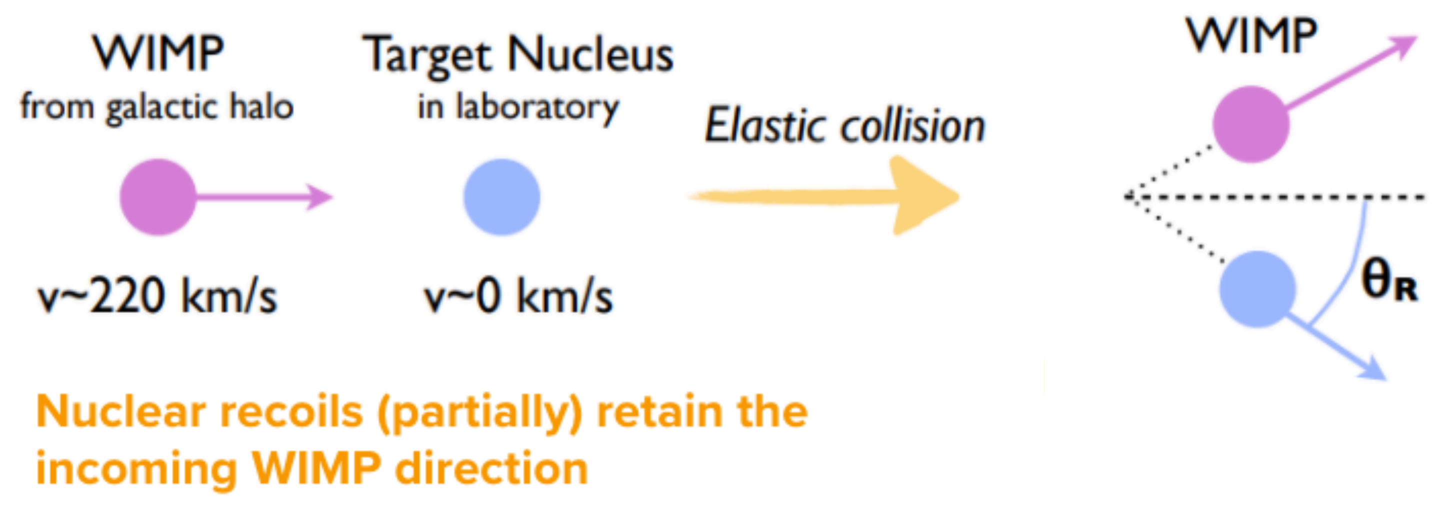
M. Pomorski et al. DOI: 10.1103/PhysRevC.90.014311

CYGNO TPCs

Atmospheric pressure Optical TPC

Rare event searches, directional dark matter

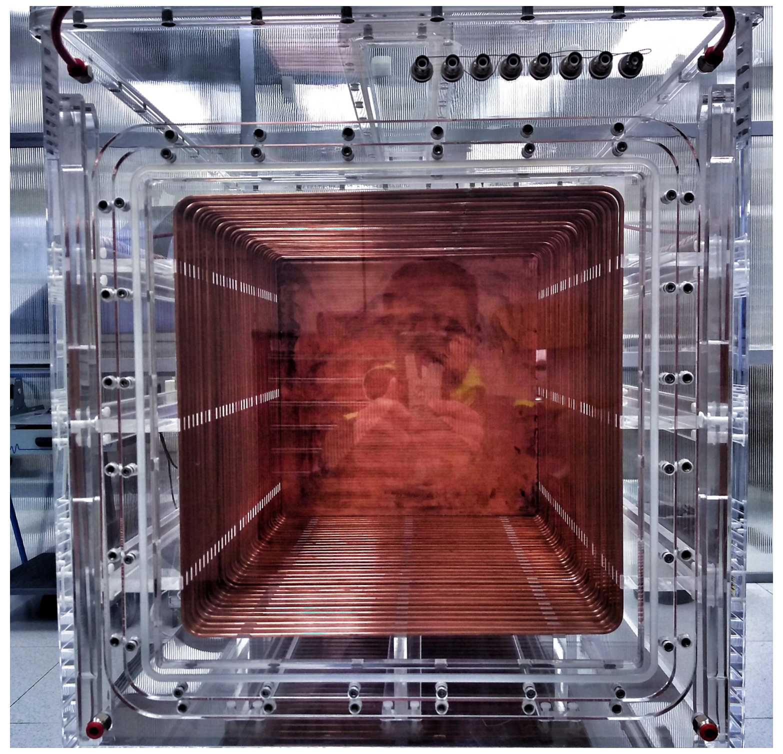
Triple GEM read out with high granularity CMOS + PMT/SiPM requiring low radioactivity background

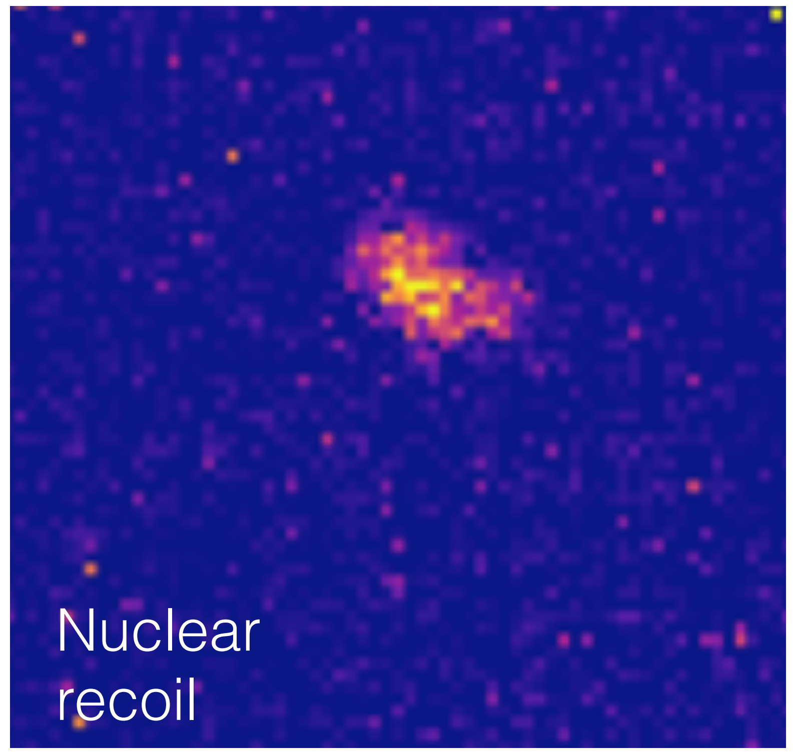


D. Fiorina, The CYGNO experiment, a Gaseous TPC for directional Dark Matter searches

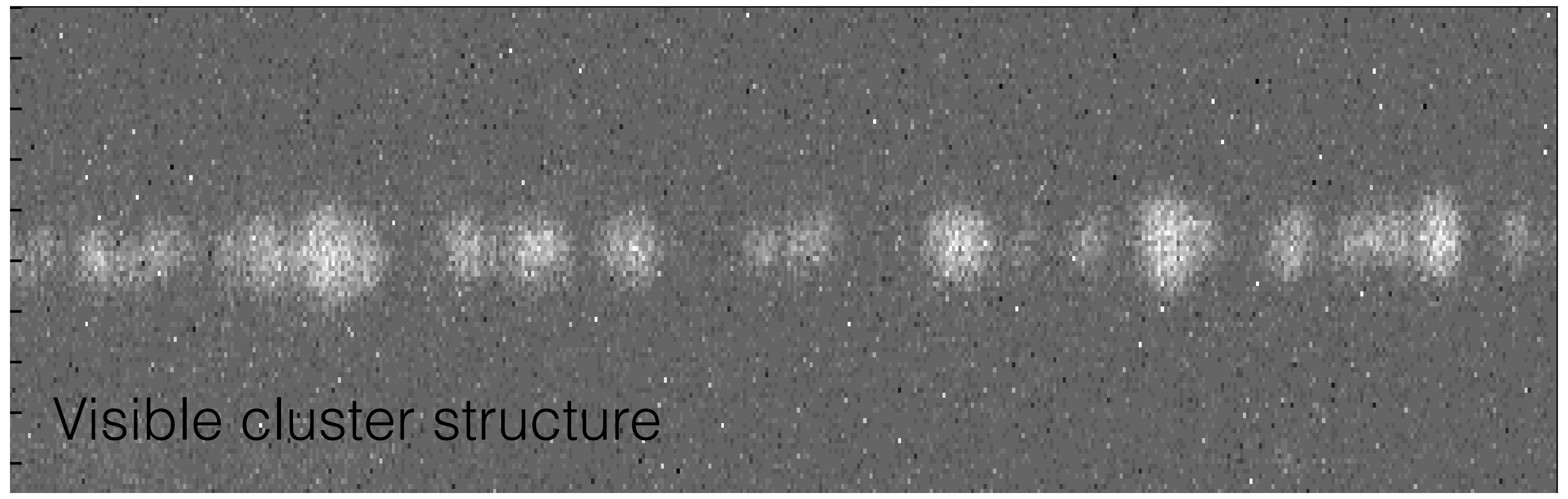
G. Dho, Impact of a strong electric field below the GEM on light yield and saturation in a He:CF4 based Time Projection Chamber

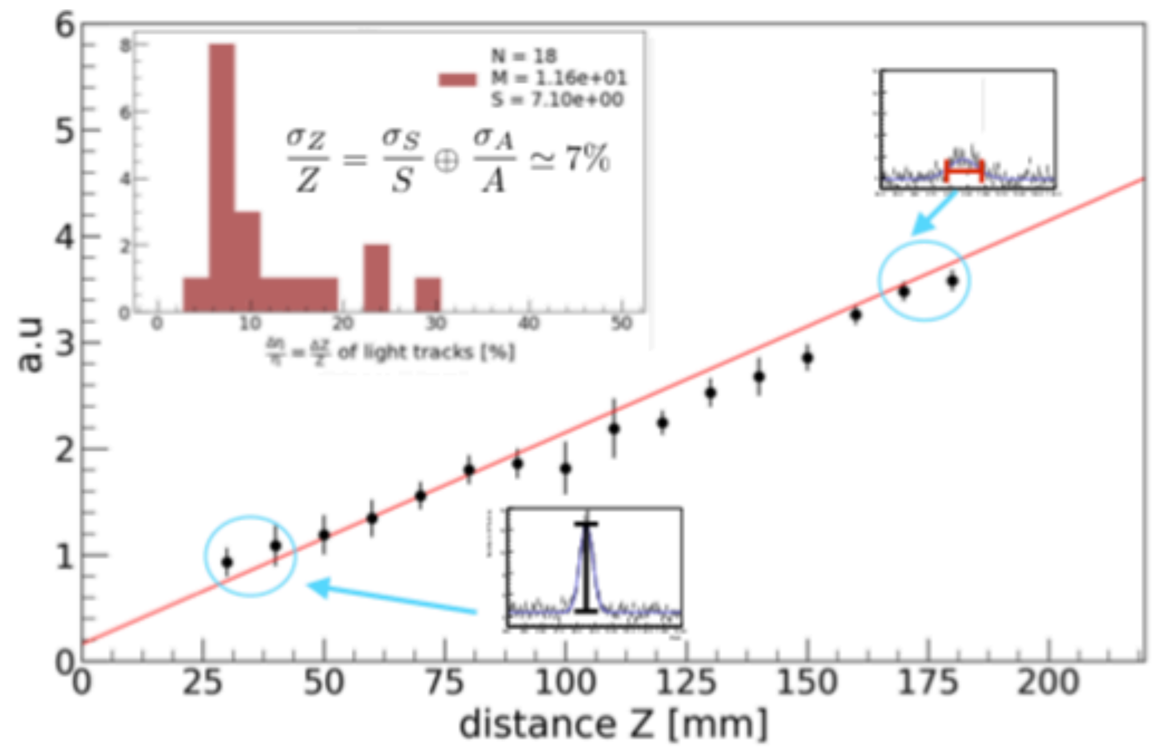
LIME prototype

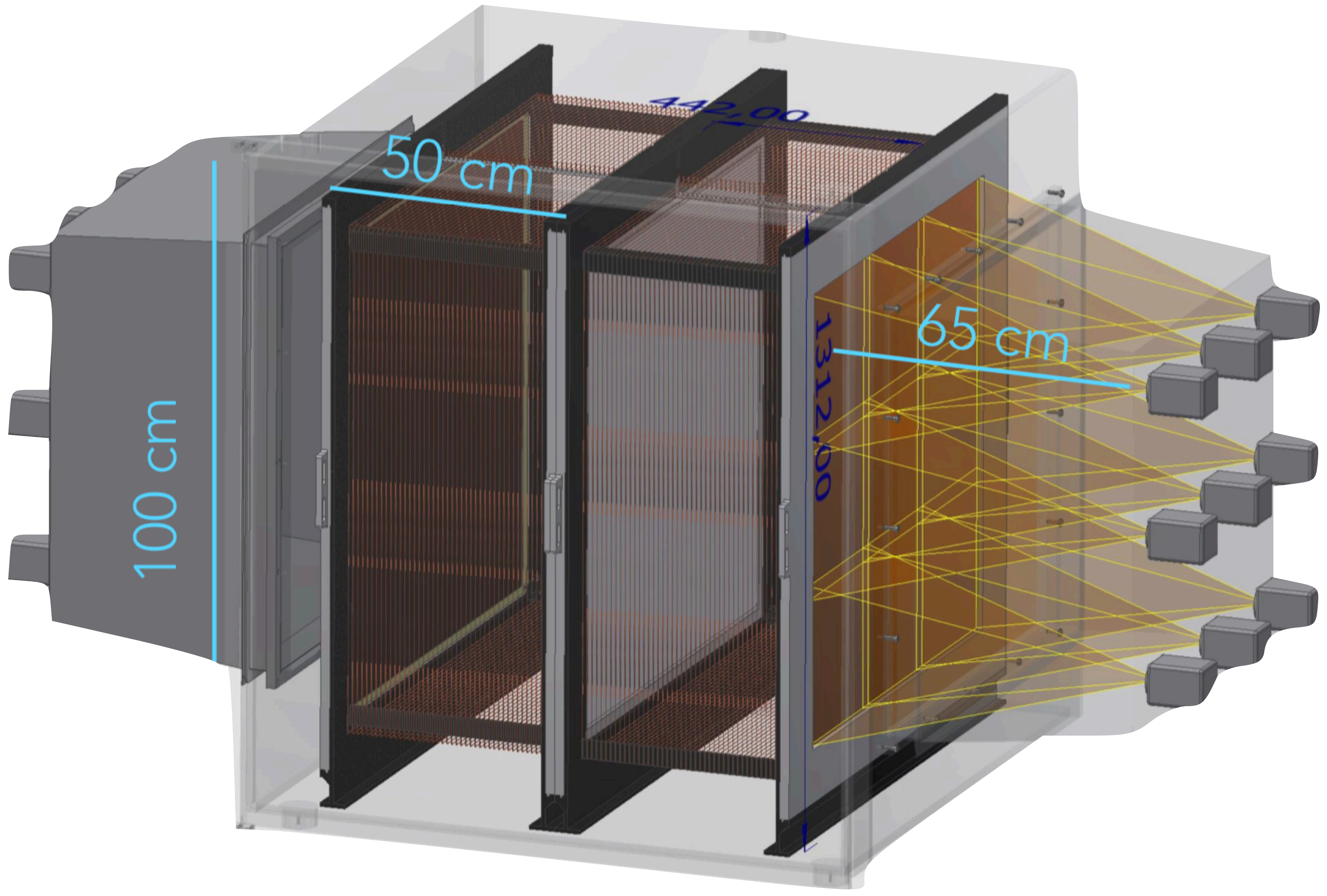




Demonstrated sizeable NR detection efficiency and efficient rejection of ^{55}Fe events exploiting images







1m^3 demonstrator for atmospheric pressure He/CF$_4$ 60/40 (1.6 kg)

D. Pinci et al., CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search, MPGD 2019
https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf

MIGDAL TPC

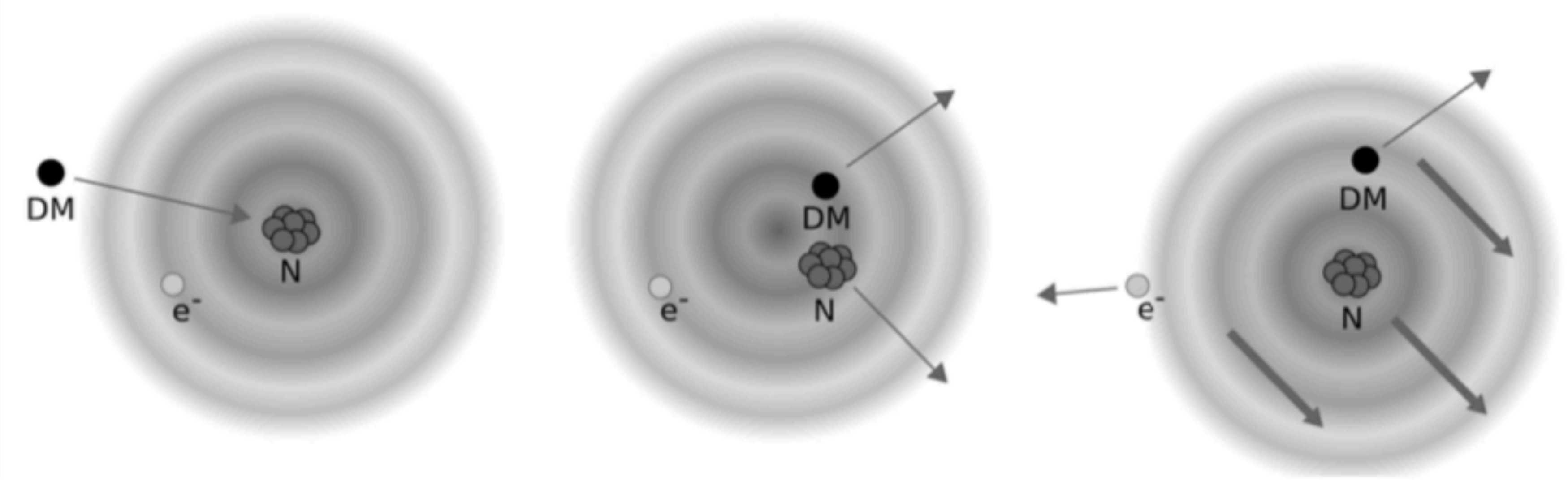
J. Schueler, Real time Migdal effect searches with deep learning–based object detection

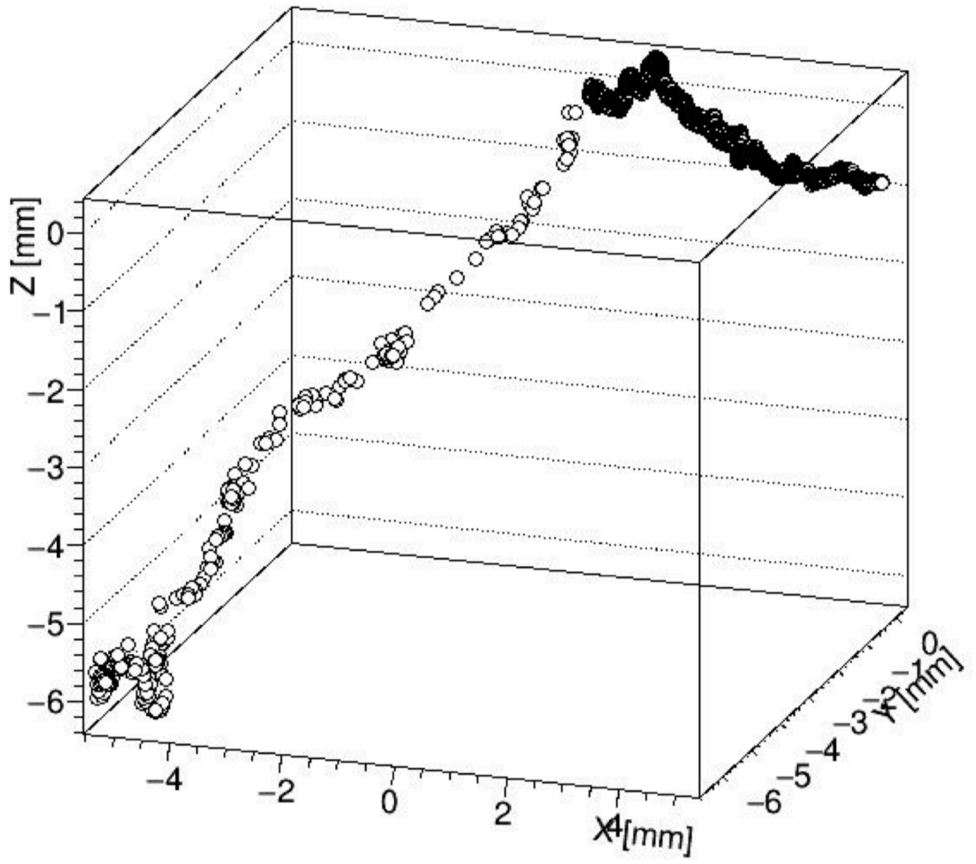
MIGDAL

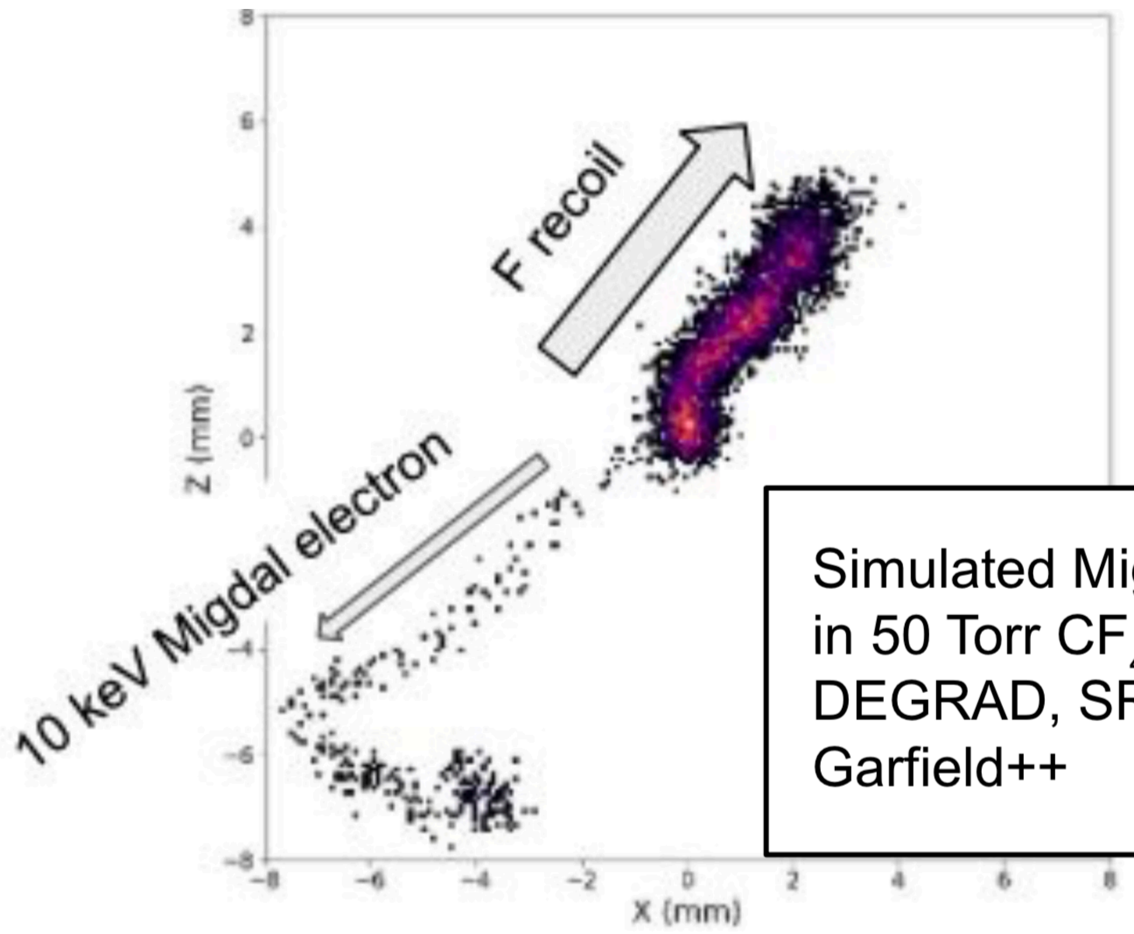
Migdal In Galactic Dark mAtter expLoration

Low-pressure TPC with optical + electronic readout

Migdal effect: nucleus moves relative to electron cloud. Individual electron might be ejected leading to ionisation.
→ extension to low mass region in DM searches

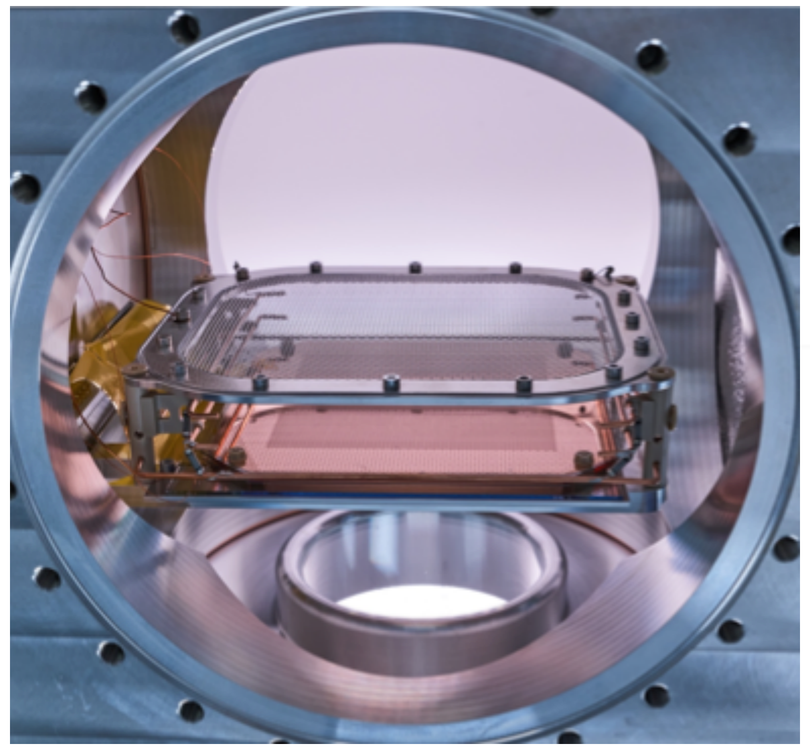




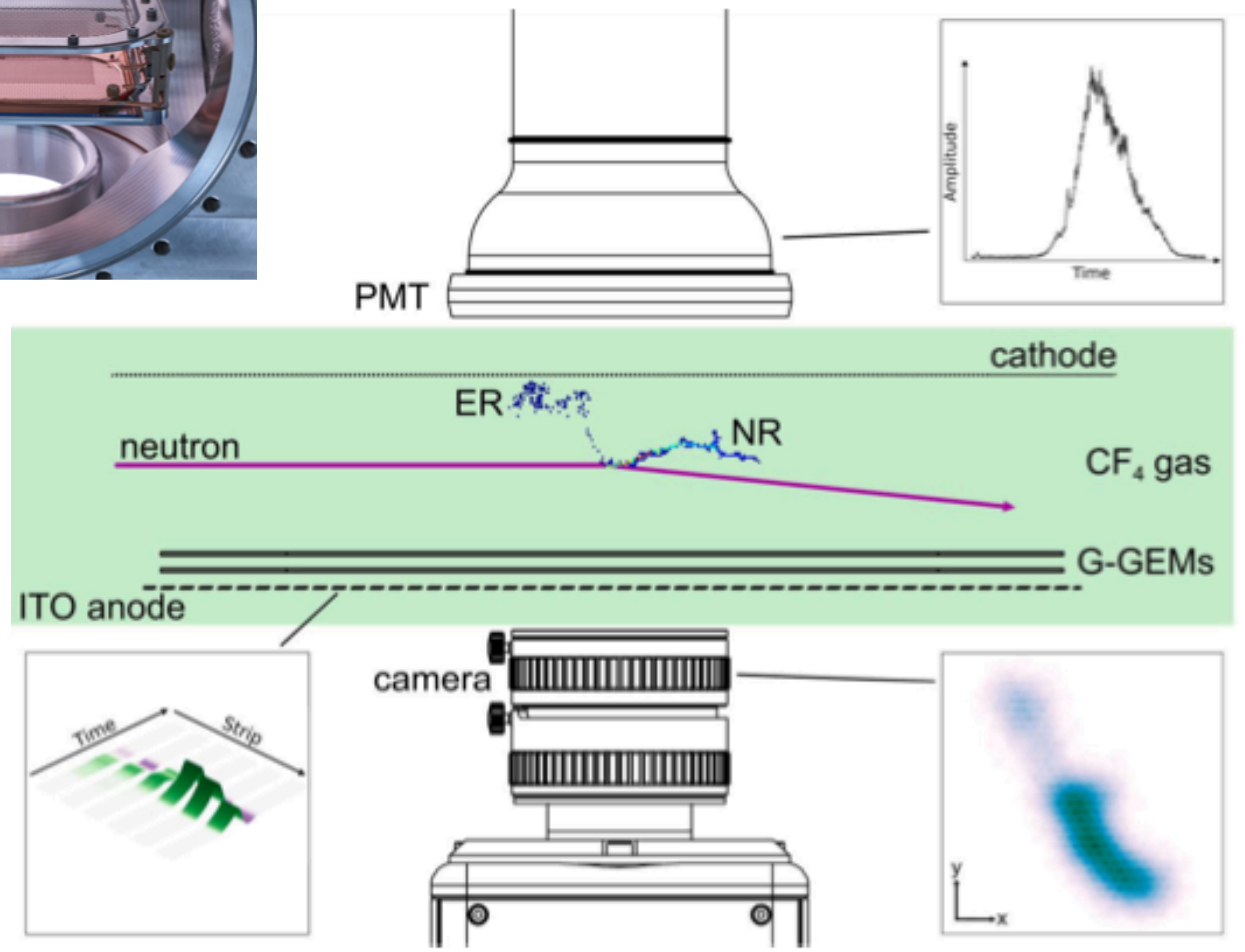


Simulated Migdal event in 50 Torr CF_4 using DEGRAD, SRIM and Garfield++

P. Majewski, RD51 Mini-Week 2020, https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

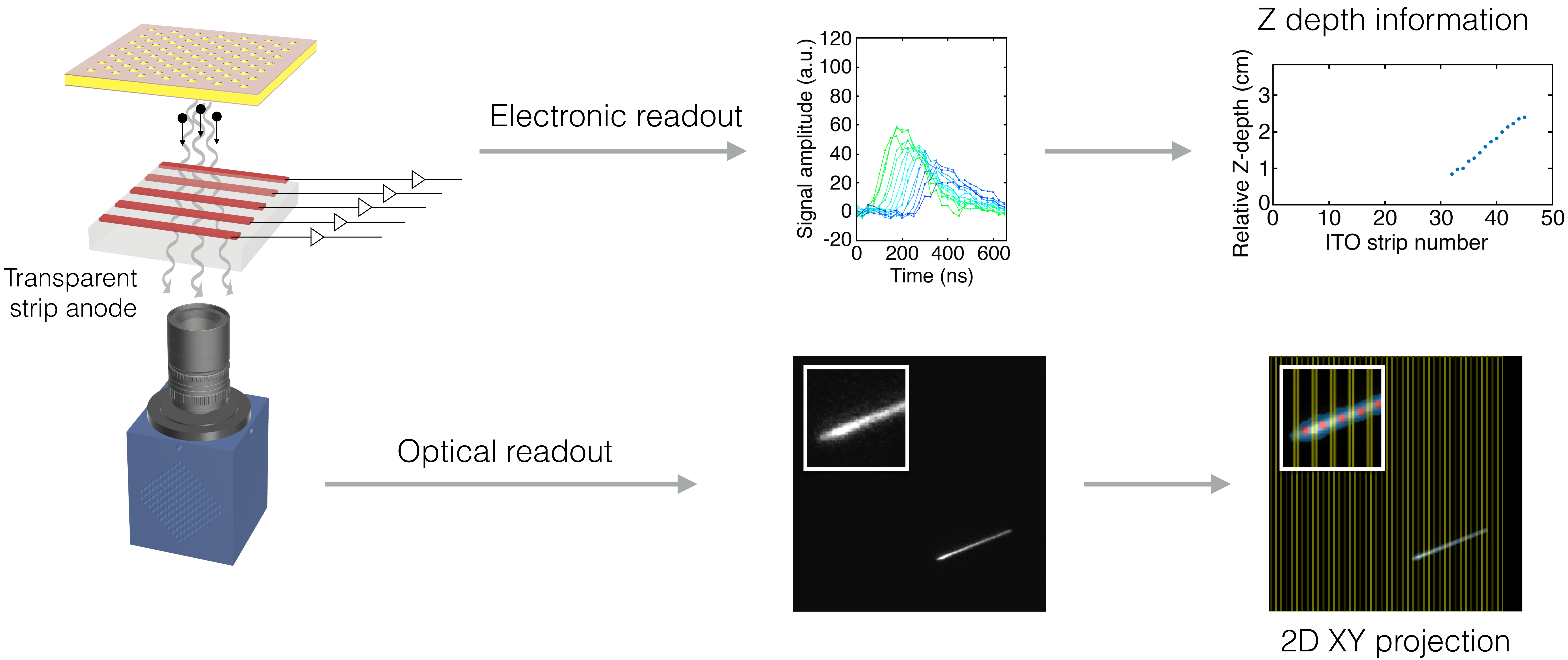


Optically read out glass GEM and ITO strip anode for combined optical + electronic readout operated in low-pressure CF_4 at DD and DT neutron generators.



H.M. Araújo et al 2023 Astropart. Phys. 151 102853 https://doi.org/10.1016/j.astropartphys.2023.102853

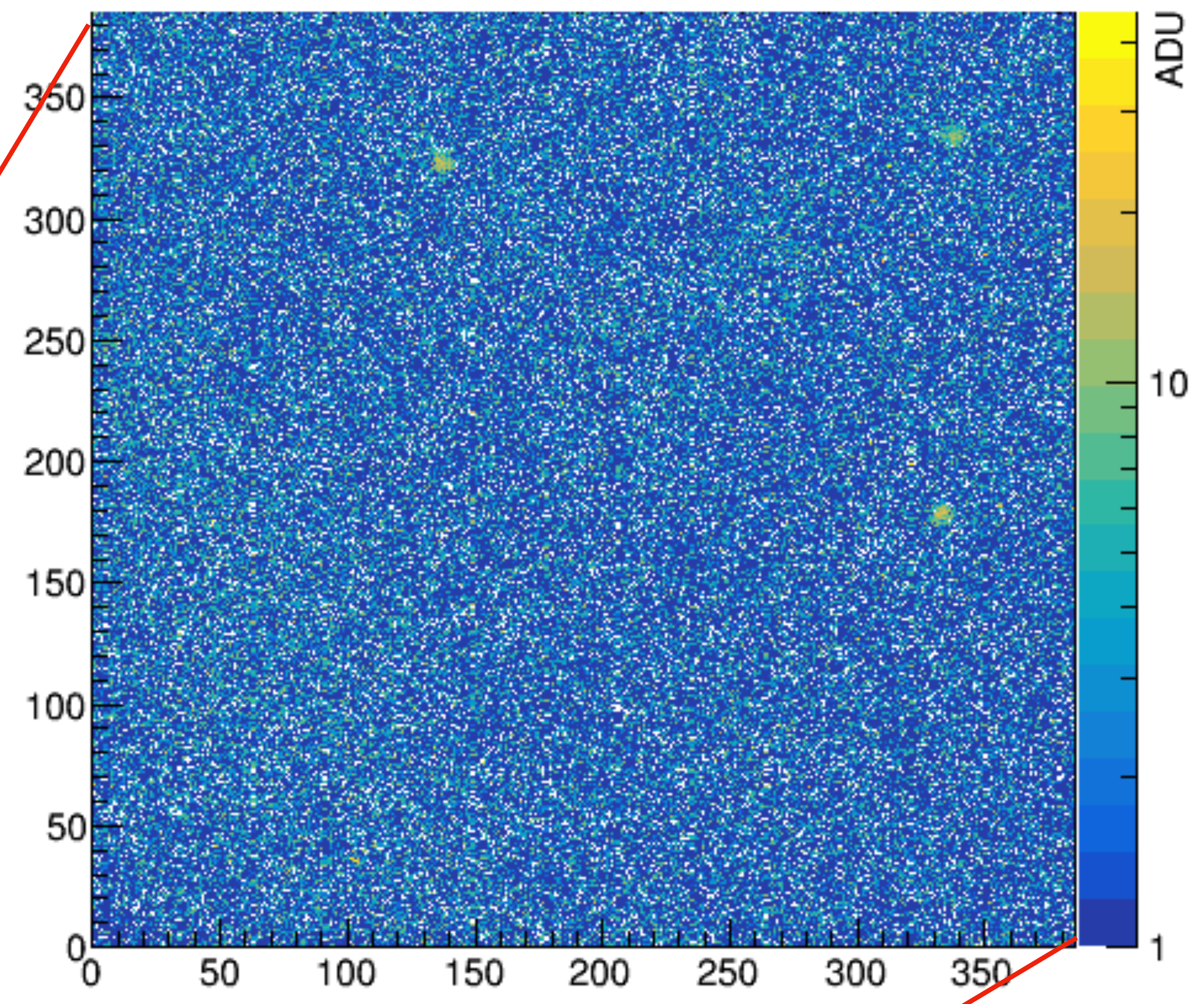
Combined optical and electronic readout



Schematics not drawn to scale

High Pressure TPC

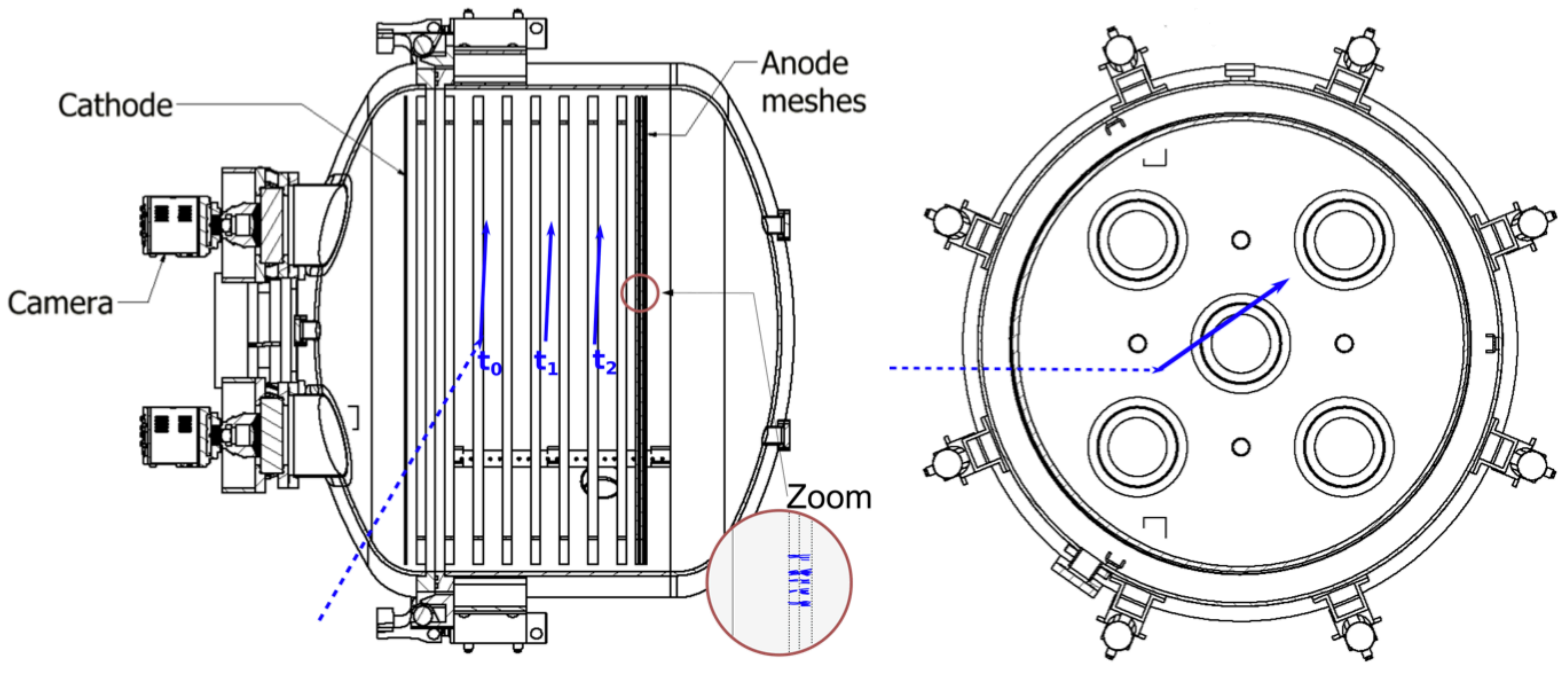
Stitched optical readout (4 CCD cameras) + **electronic signals** from meshes used for amplification



High Pressure TPC for neutrino-nucleus cross section experiments

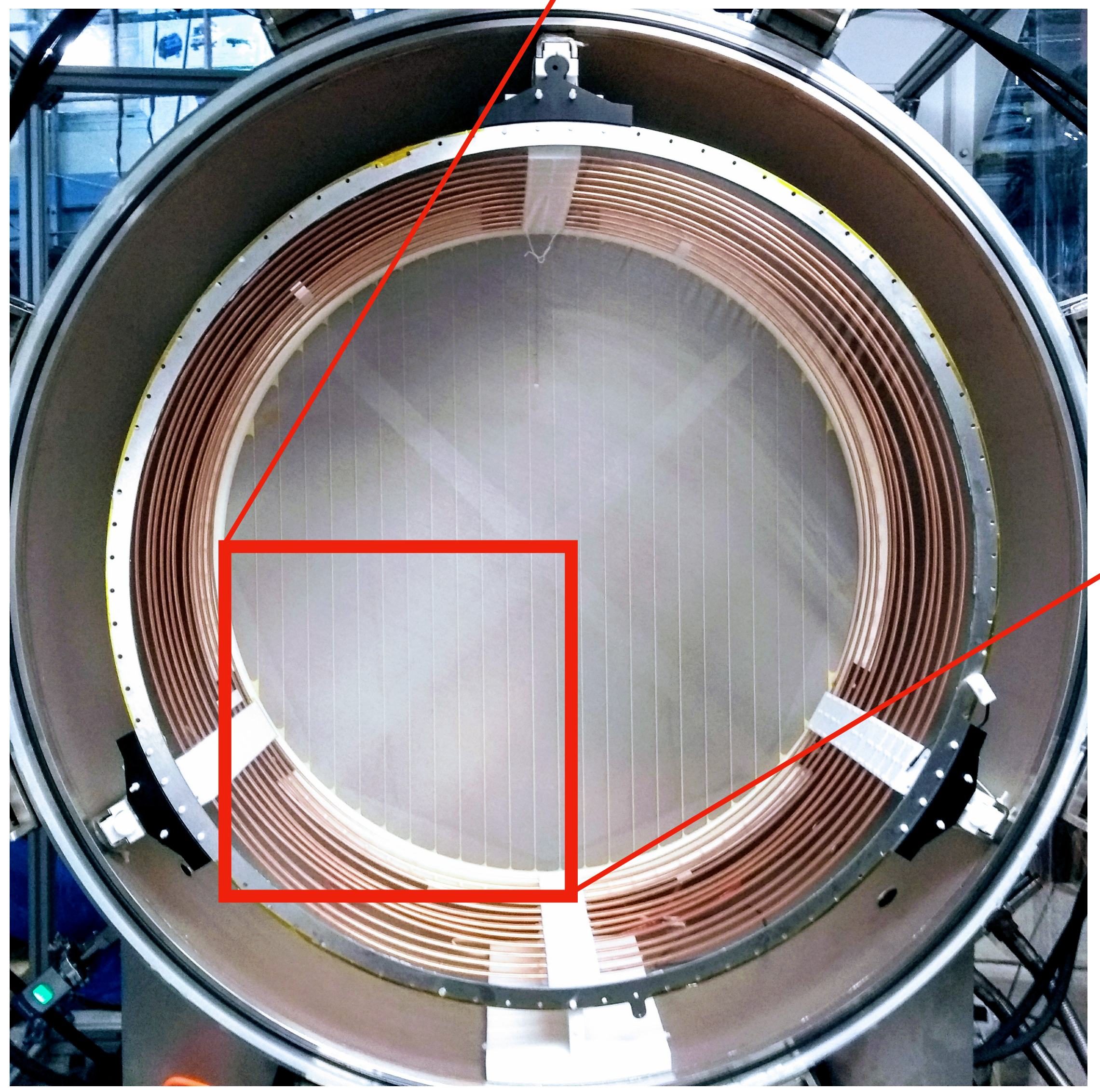
Explored as part of a future long-baseline **neutrino oscillation experiment** such as the Deep Underground Neutrino Experiment (DUNE), which considers HPTPC as part of its near detector.

“Gas TPCs are ideal for precisely characterising FSI effects because of their high track reconstruction efficiency, low momentum threshold and 4π angular coverage of final state particles.”



(a) longitudinal view **(b)** camera view

A. Deisting, HPTPC, https://arxiv.org/pdf/2102.06643.pdf



1 m³ high pressure TPC (up to 5 bar)

NEXT TPC

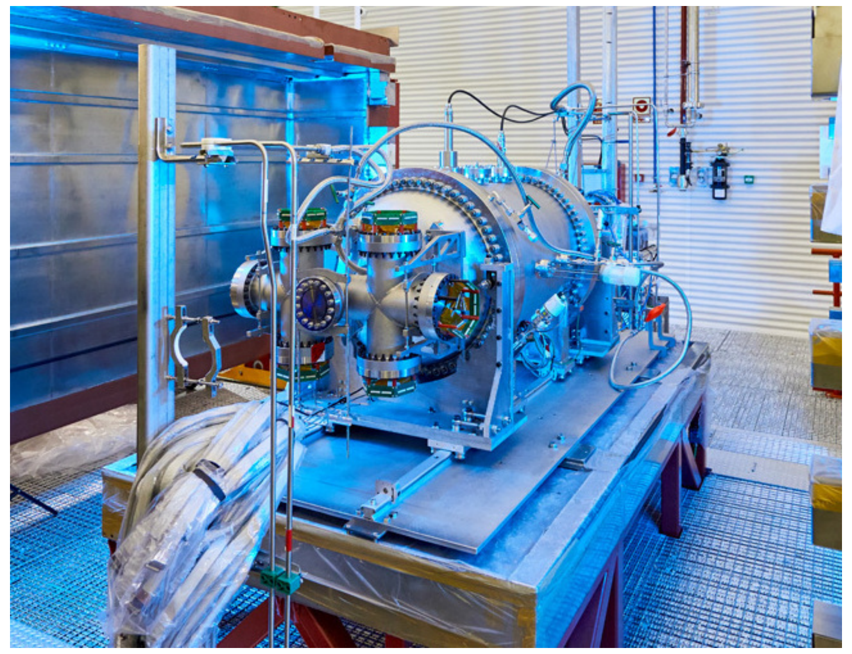
High Pressure Xe gas TPC with electroluminescent amplification

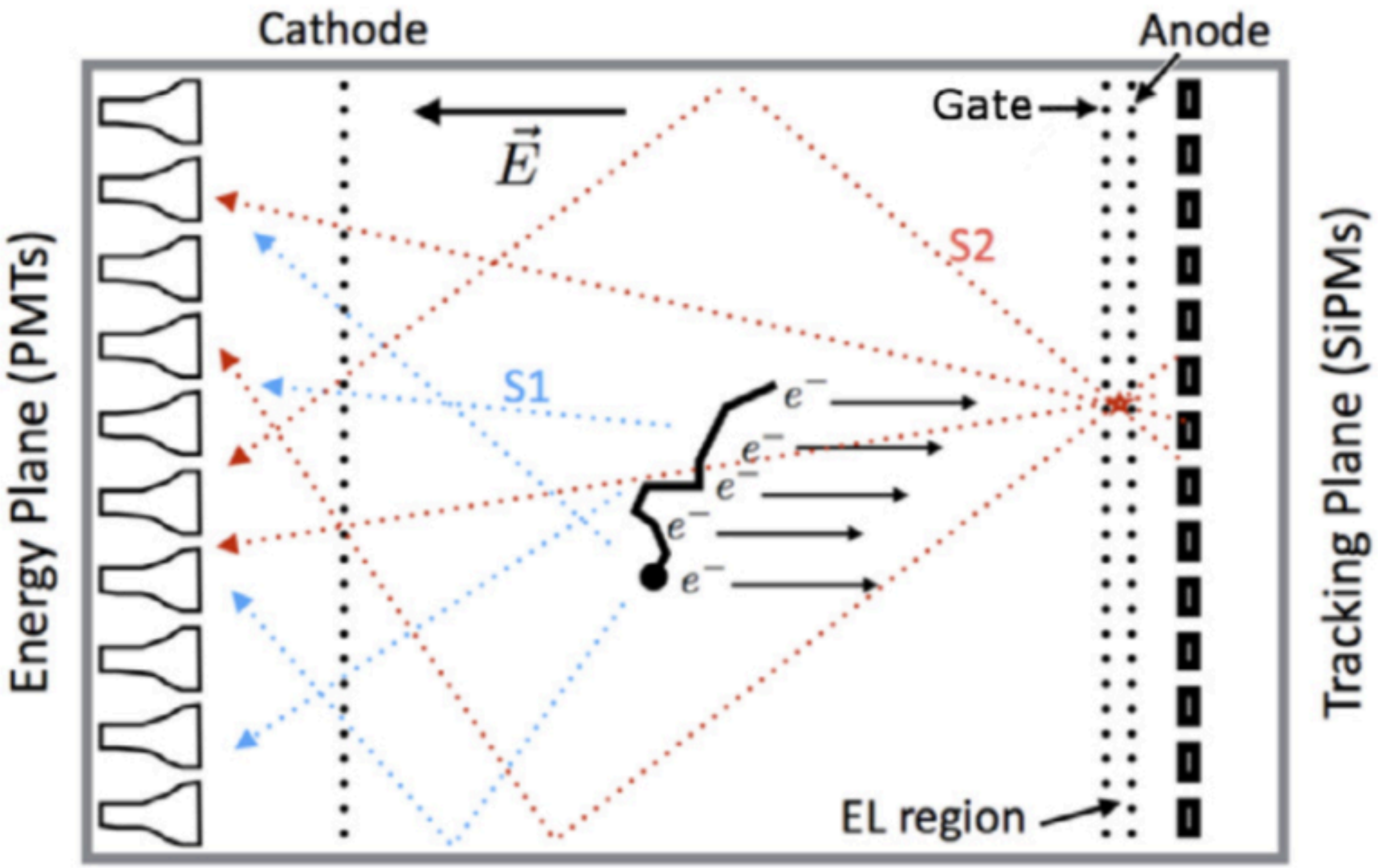
Neutrinoless double beta decay searches in ^{136}Xe

PMTs for energy measurement & t_0 from S1, **SiPM-based tracking** plane recording electroluminescence

Requires detector with very good energy resolution (<1%), very low background contamination (~10^{-4} counts/(keV kg y)) and large target mass.

Optimises energy resolution by use of proportional electroluminescent amplification (EL), which provides a large yield of photons as a signal.





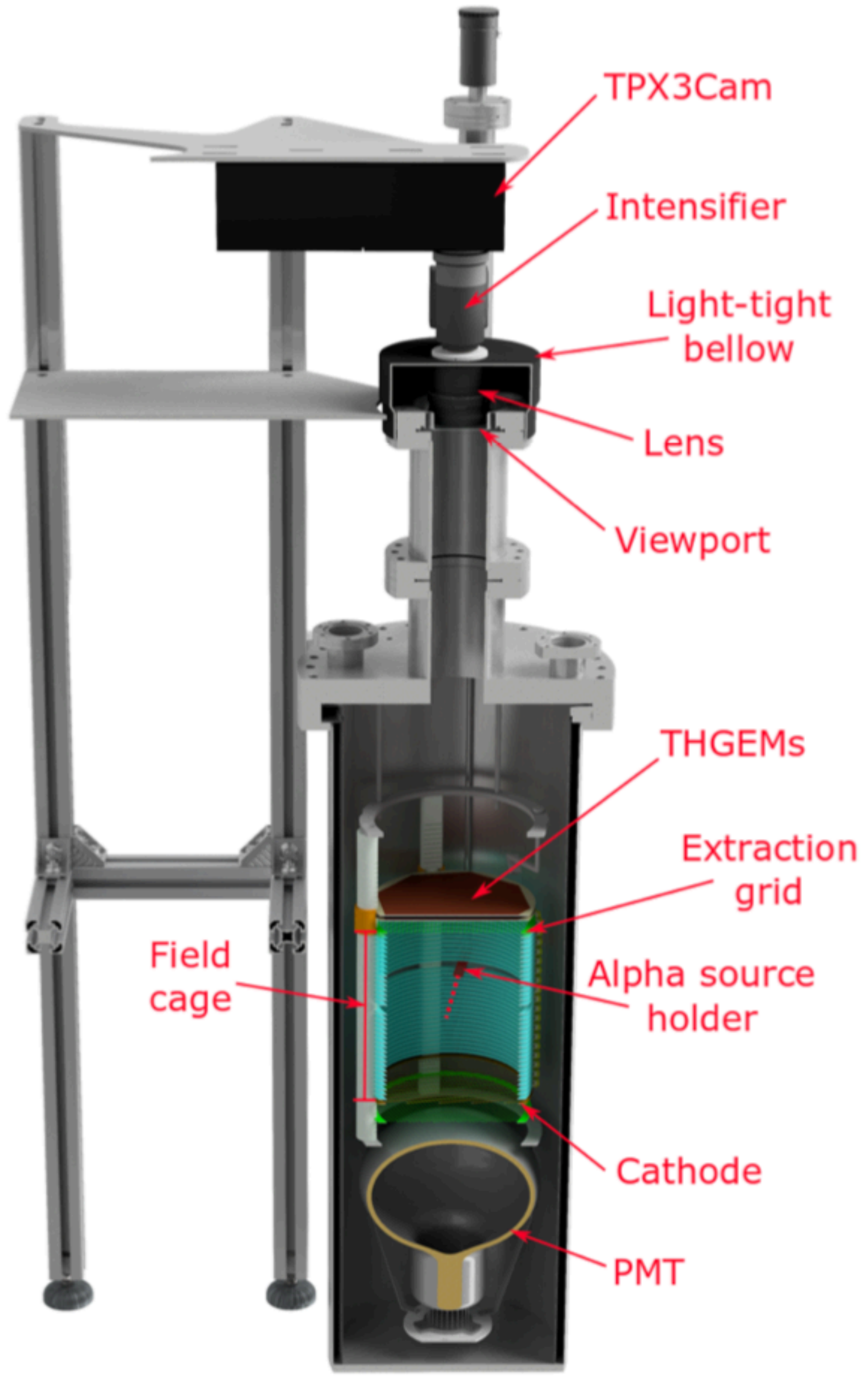
https://next-experiment.org/experiment/detector/
https://next.ific.uv.es/next/experiment/detector.html
L. Arazi, Status of the NEXT project, https://doi.org/10.1016/j.nima.2019.04.080

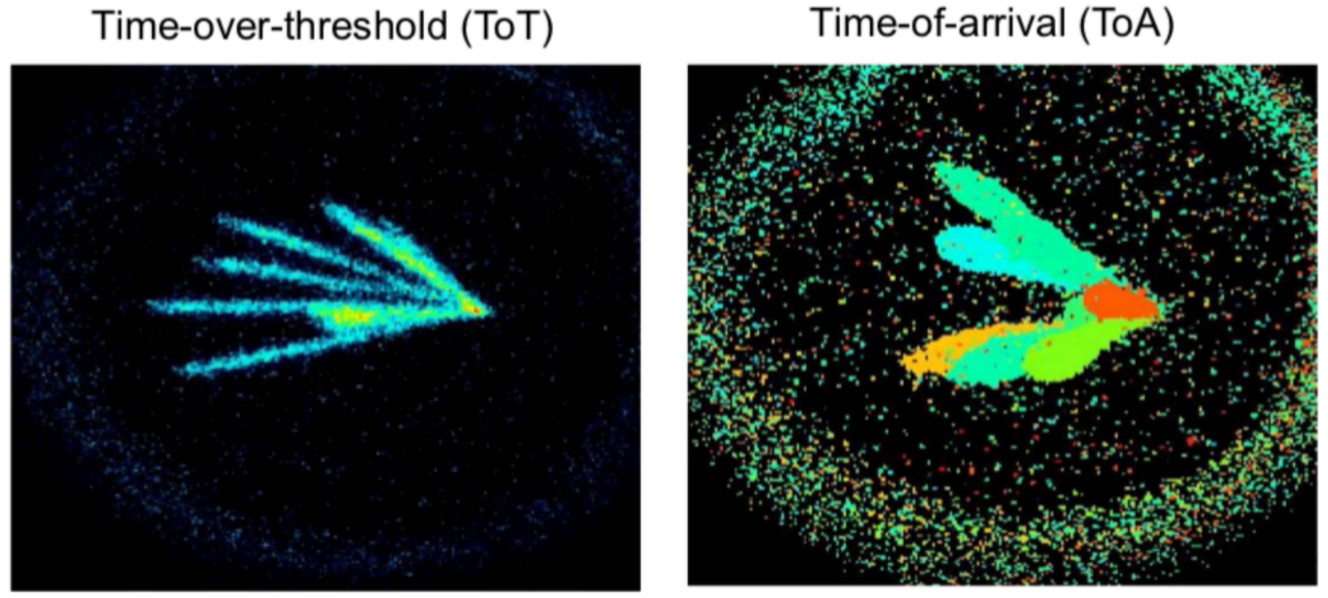
3D track reconstruction
Intensified TPX3Cam

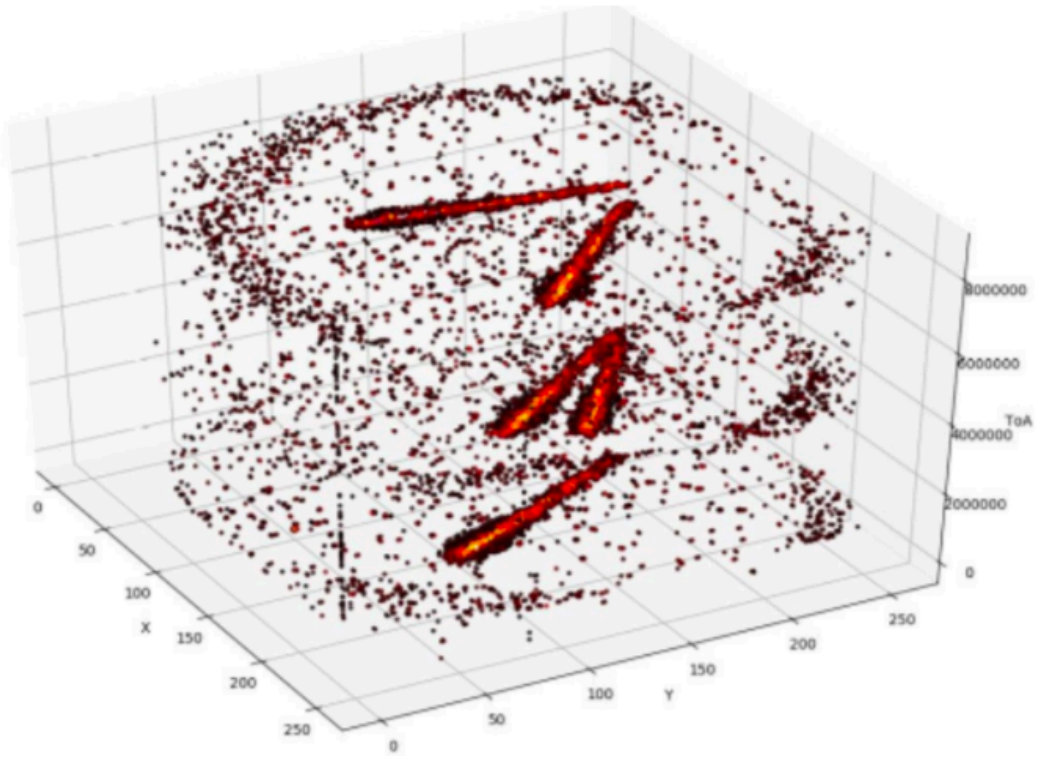
Readout of S2 scintillation in **dual phase TPC**

Light production with THGEM / GlassGEM in avalanche mode

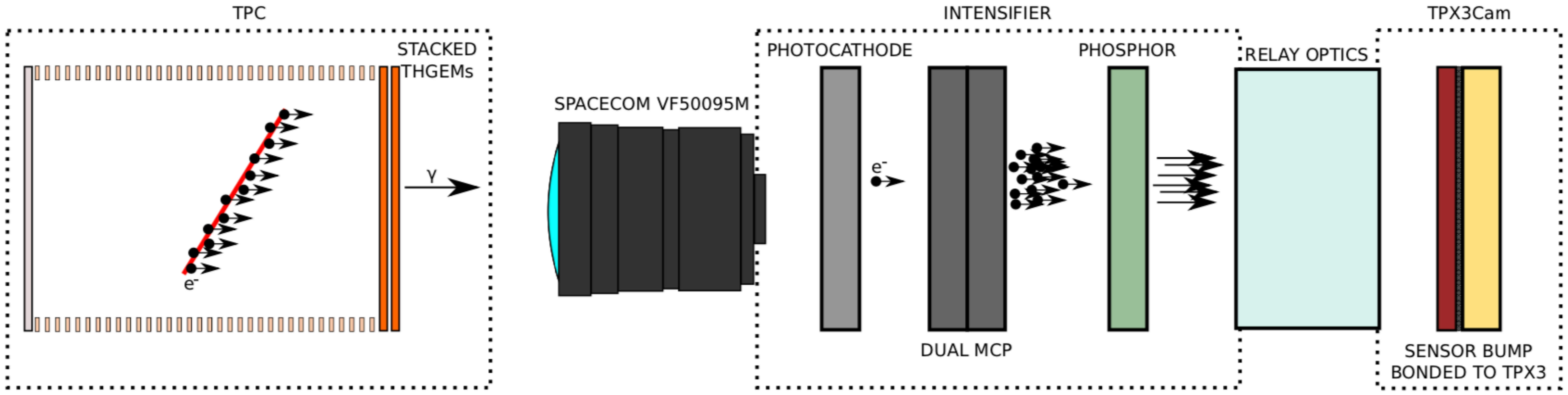
TPB wavelength shifter and VIS **photocathode** or **direct VUV imaging** with UV photocathode on intensifier

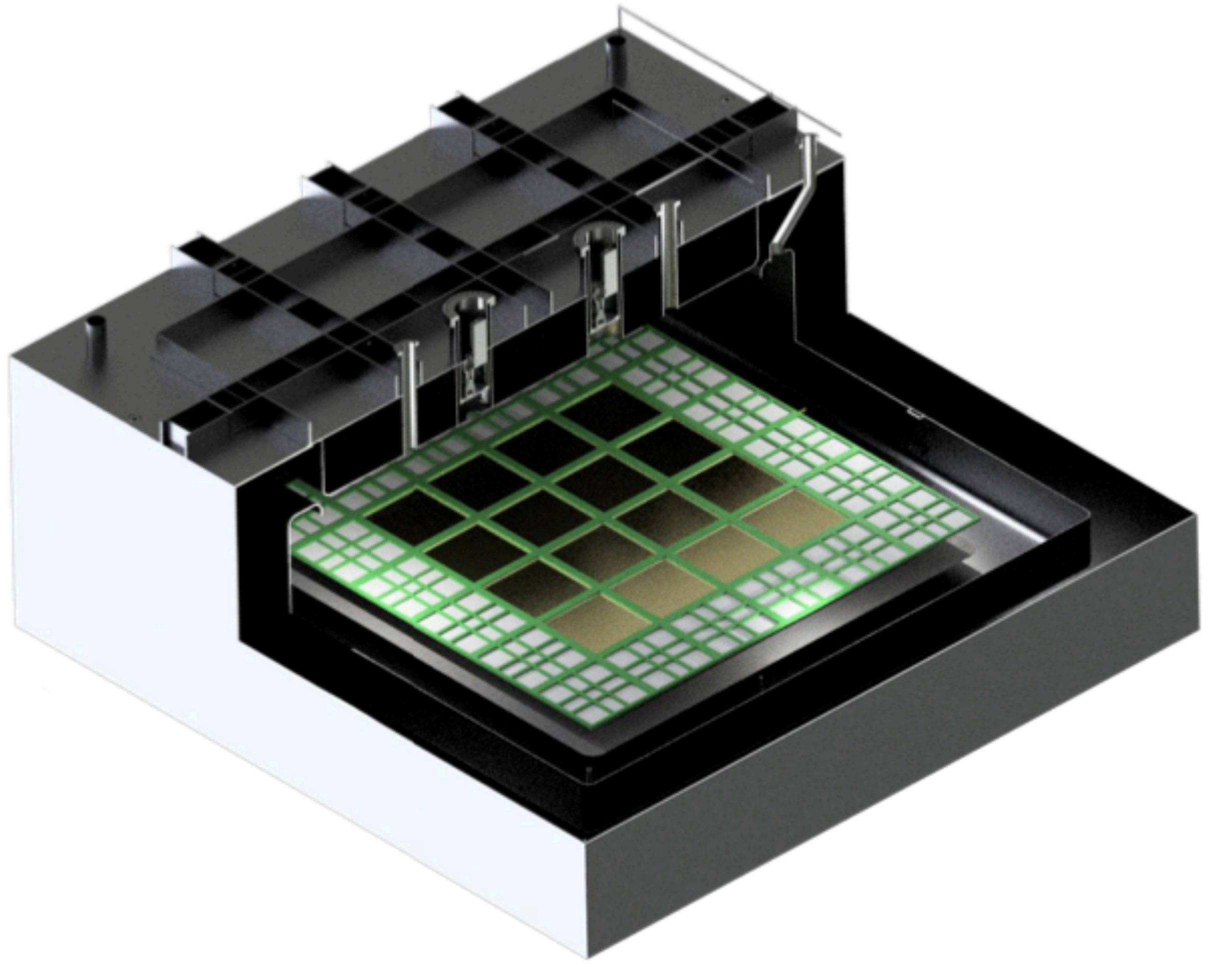






Next step: 2m x 2m test with large field of view and direct VUV imaging





A. Roberts, ARIADNE, arXiv:1810.09955v3
https://indico.cern.ch/event/989298/contributions/4217751/attachments/2190565/3702236/RD51%20Optical%20readout.pdf

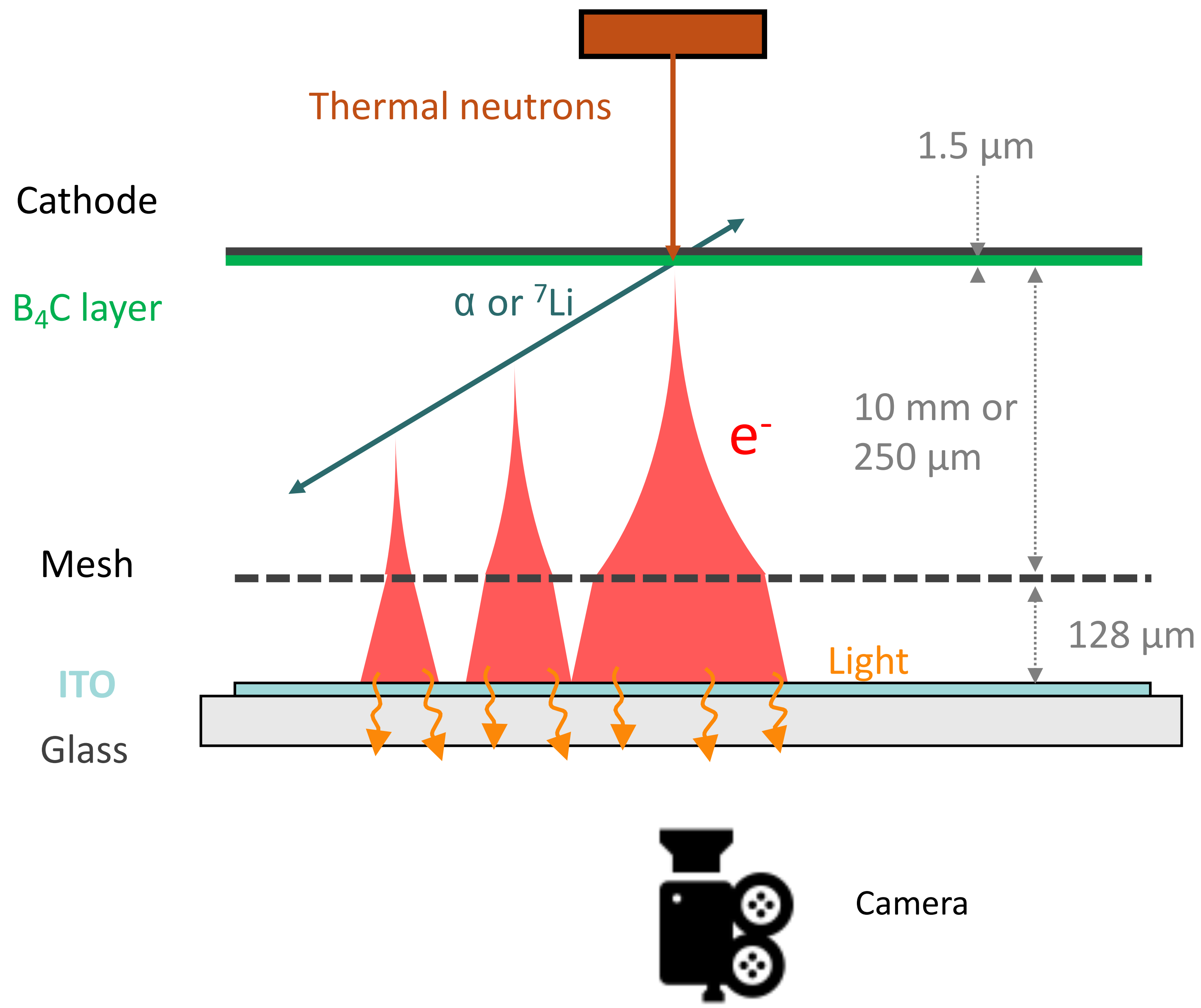
Neutron imaging

Neutron radiography

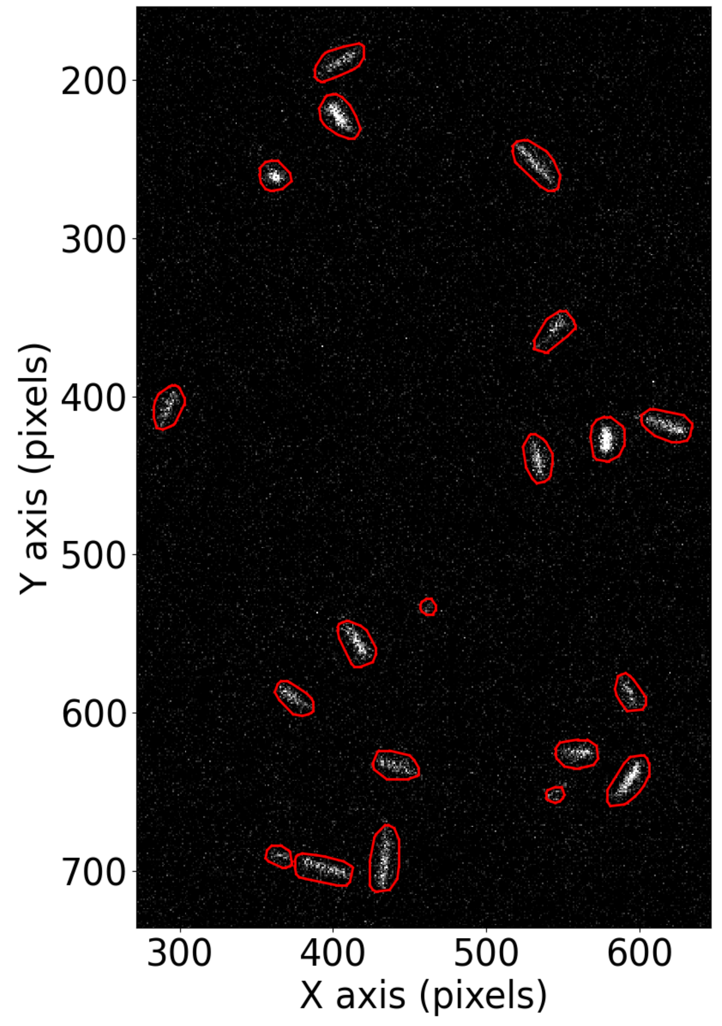
Use of converter layer (e.g. B_4C) coated onto cathode to detect neutrons

Alpha or ^{7}Li particles detected by optically read out glass Micromegas.

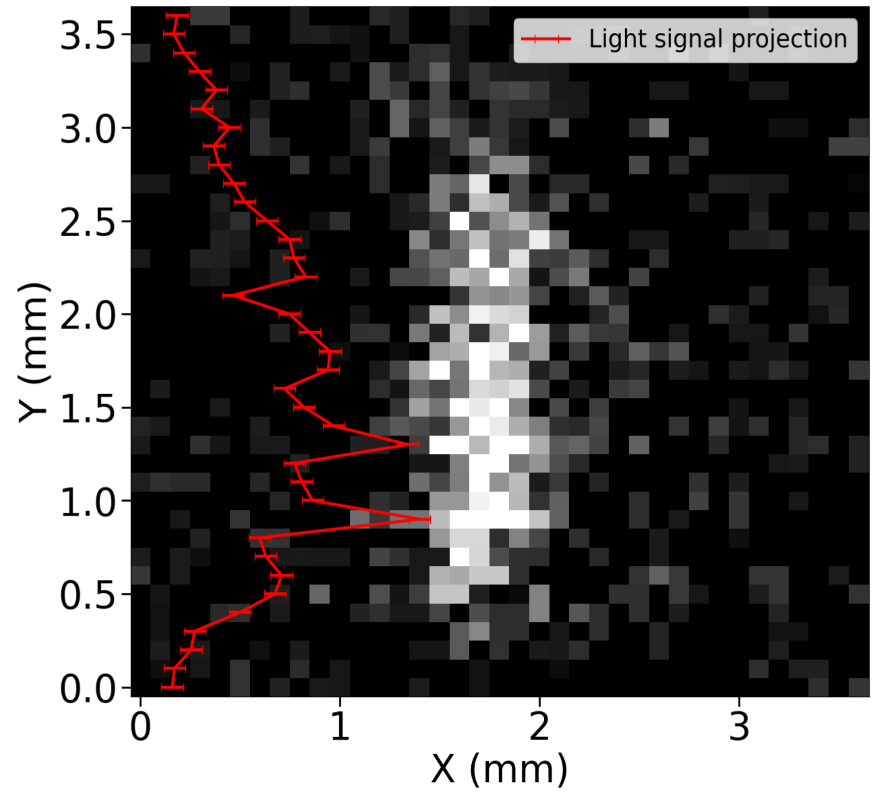
Pixellated readout and high dynamic range for accurate track imaging and construction of direction and origin point.



Event-by-event imaging

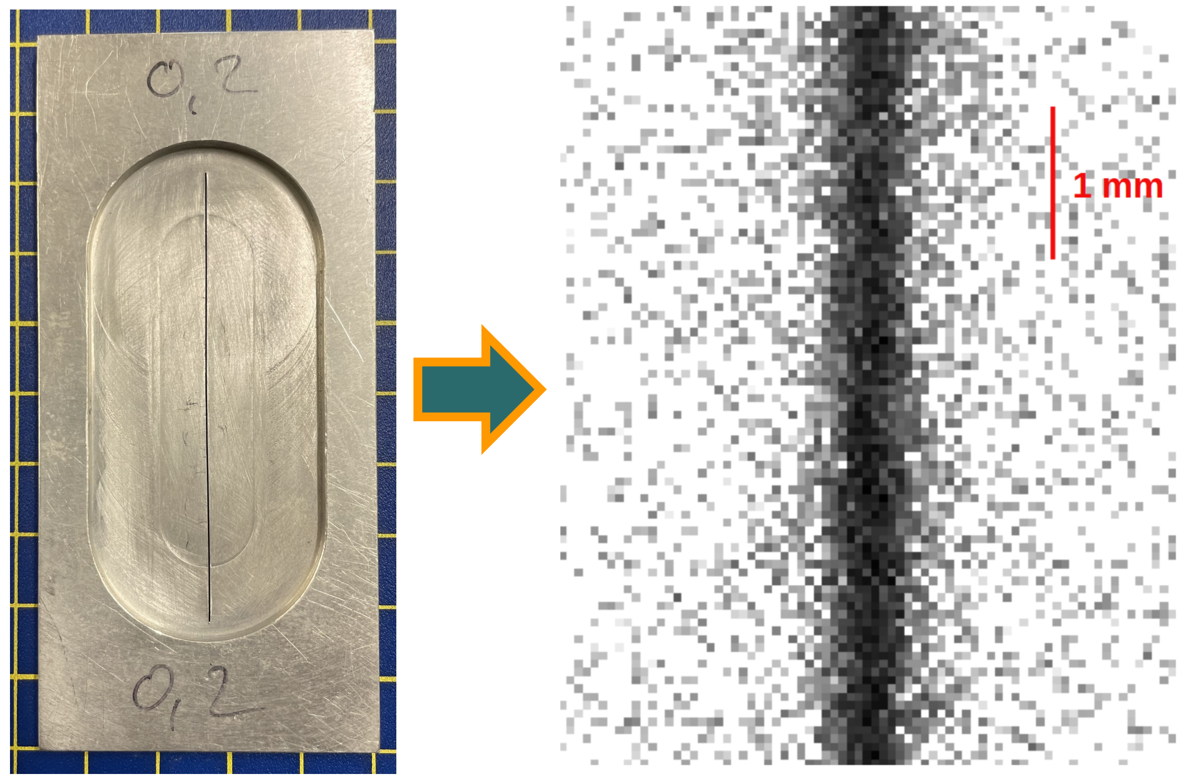


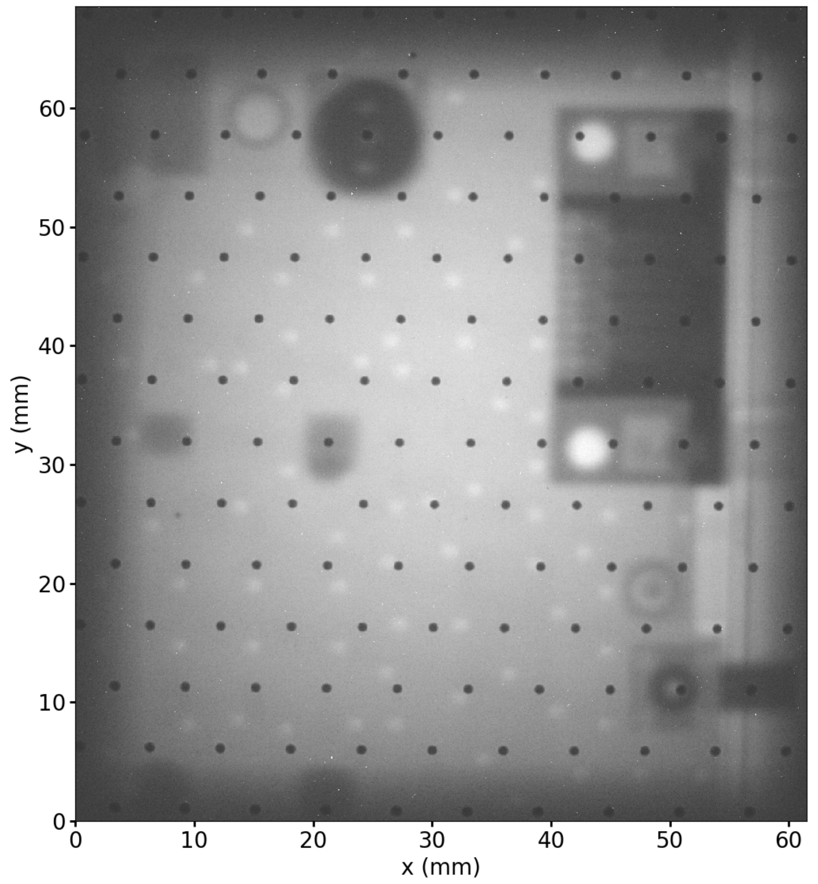
Single neutron event



Integrated imaging

Achieved high spatial resolution (LSF = 450μm)





Neutron radiography of PCB

A. Cools et al 2023 EPJ Web Conf., 288 07009, A. Cools PhD defense, 2024

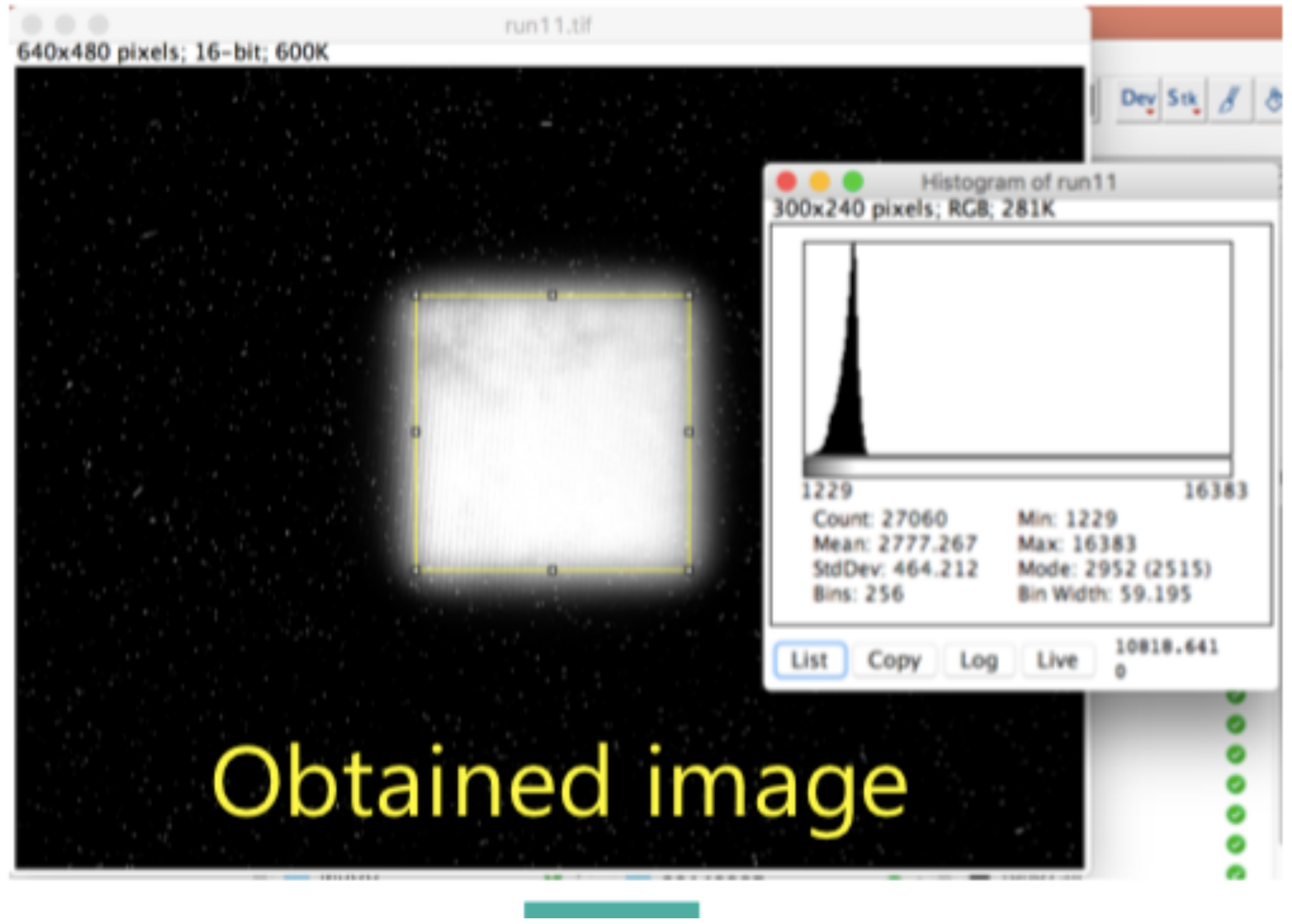
Beam monitoring and medical applications

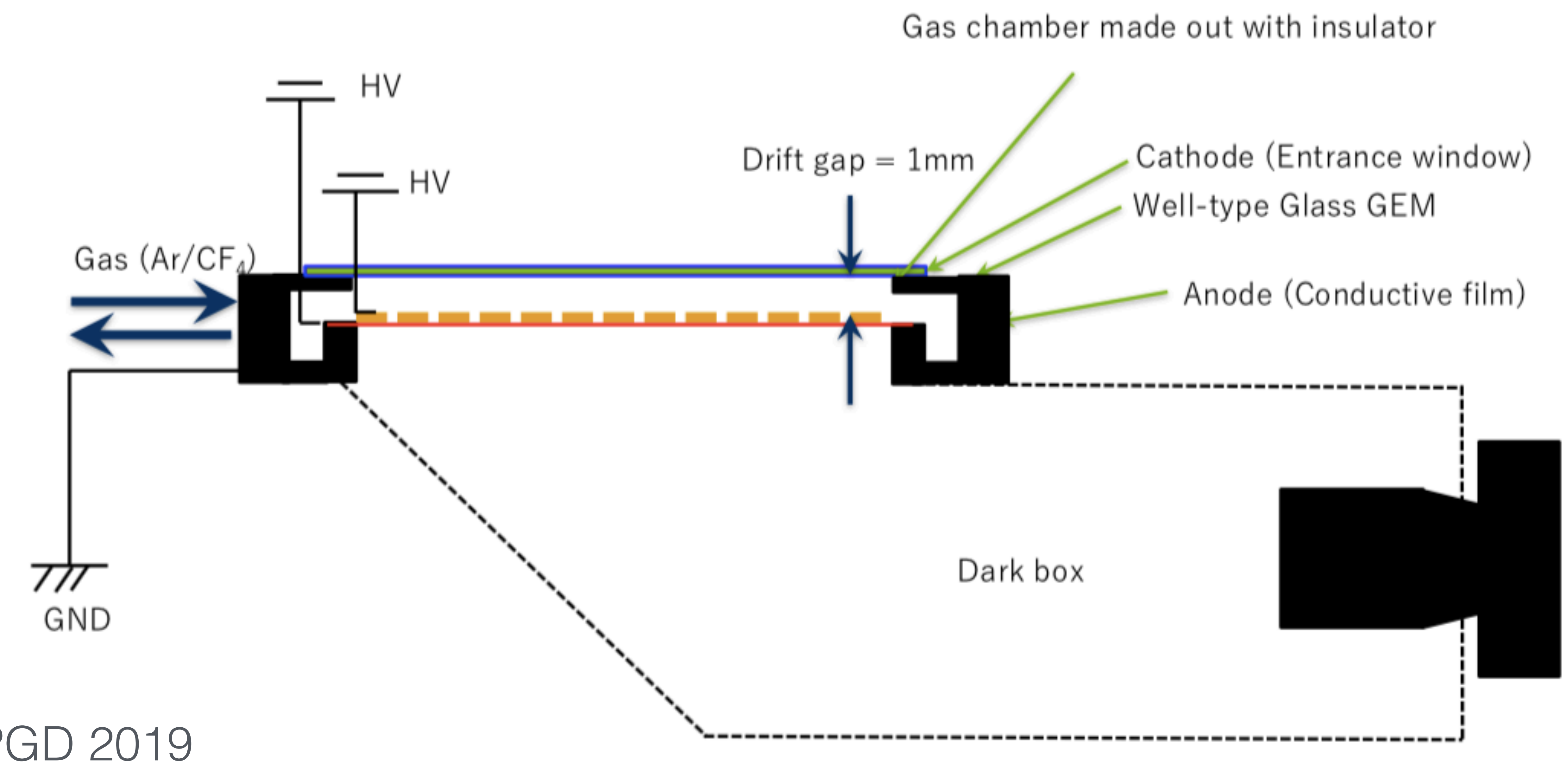
Hadron therapy monitoring

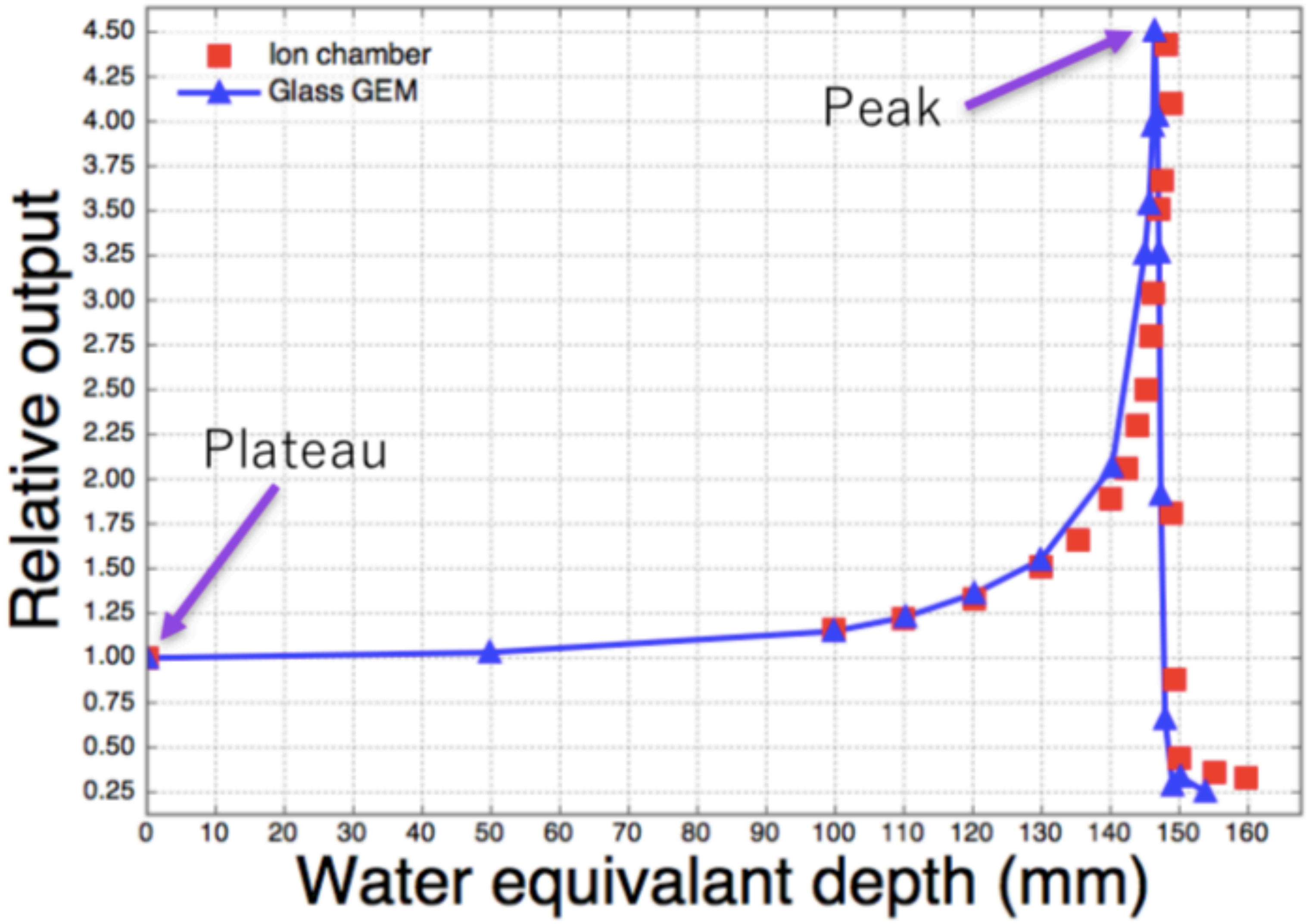
Optically read out **glass GEM** in well configuration is suited for dose imaging and dose depth curve measurement

Peak-to-Plateau ratio of dose depth curve of carbon beams accurately reproduced

Scanning pencil beams imaged with **high spatial resolution** and short exposure time (10 ms), low frame rate (3 Hz)







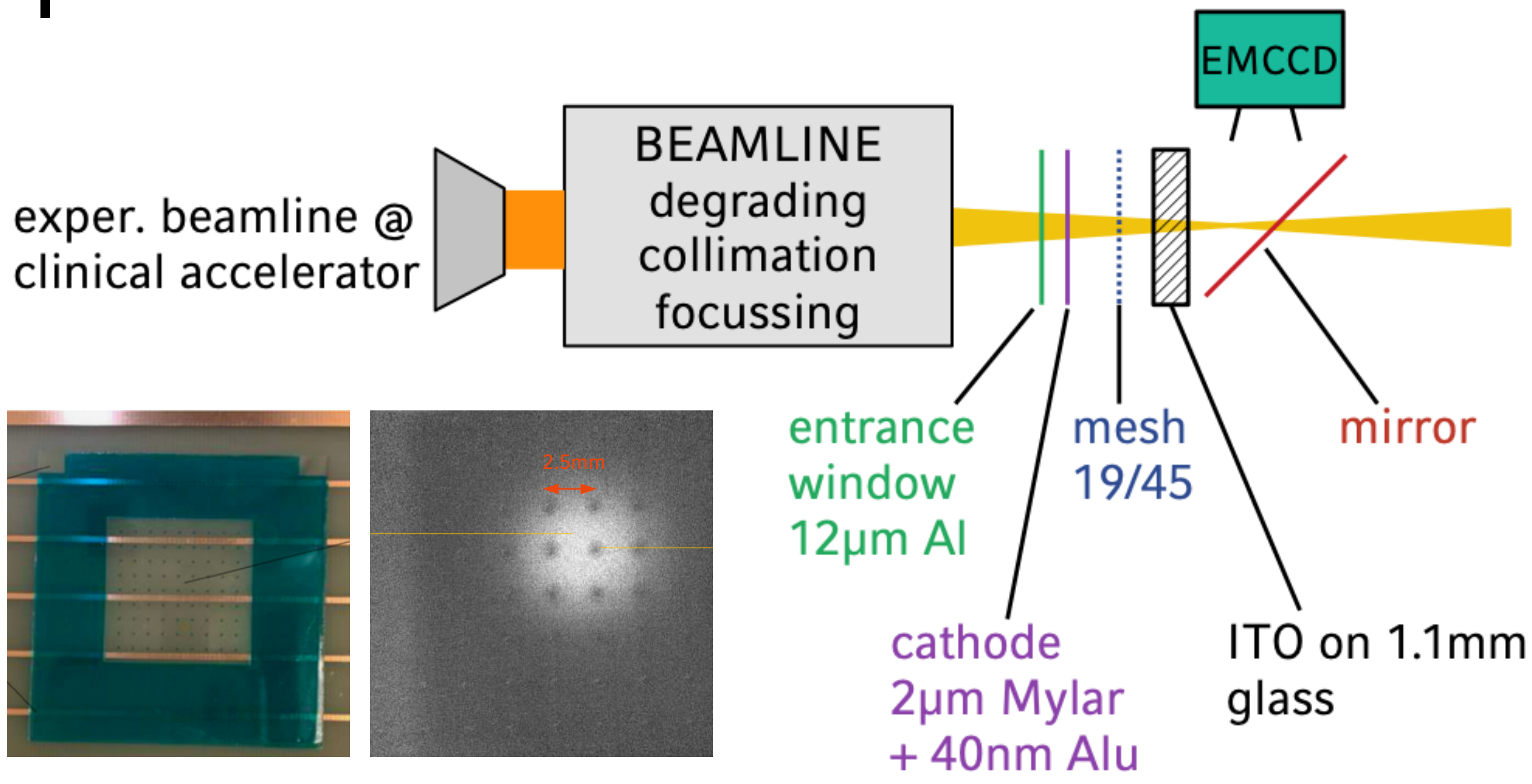
T. Fujiwara et al. MPGD 2019

Optical readout for beam profile QA

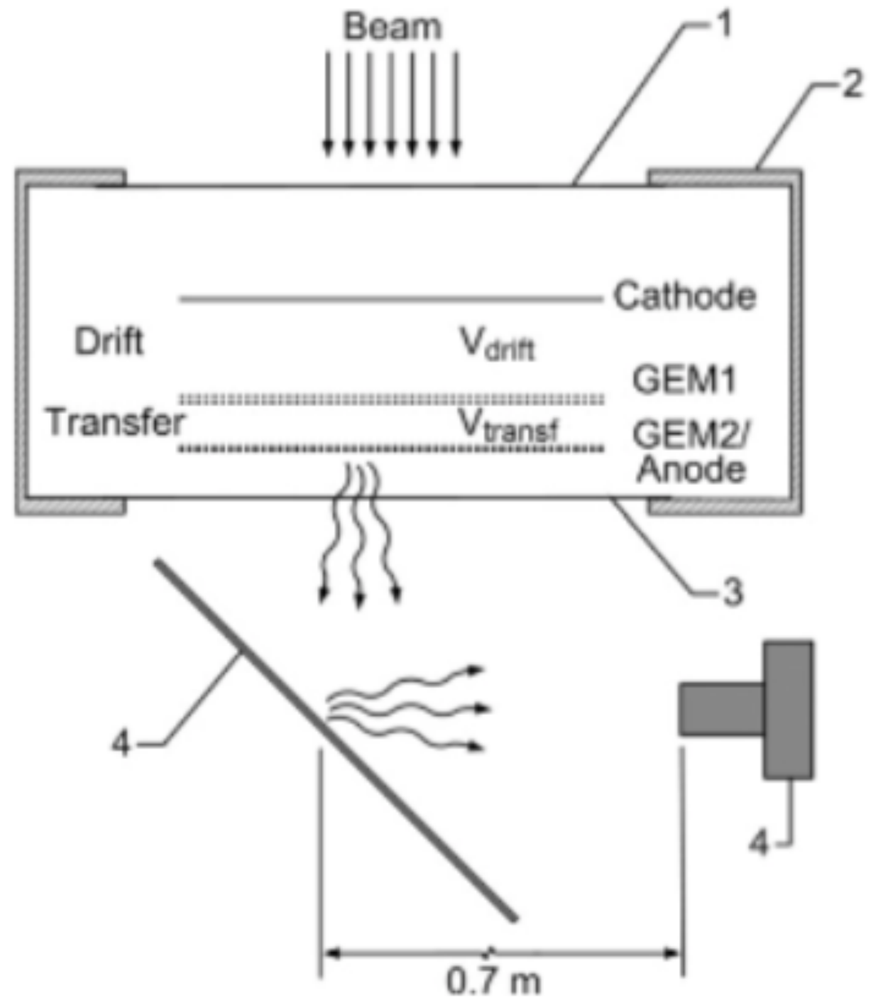
Low material budget beam monitoring with high resolution and large dynamic range

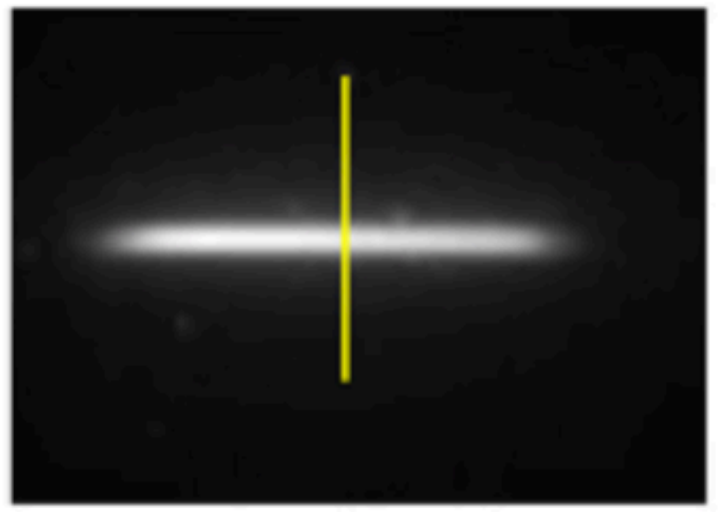
Scanning beam profile and position before irradiation for treatment planning

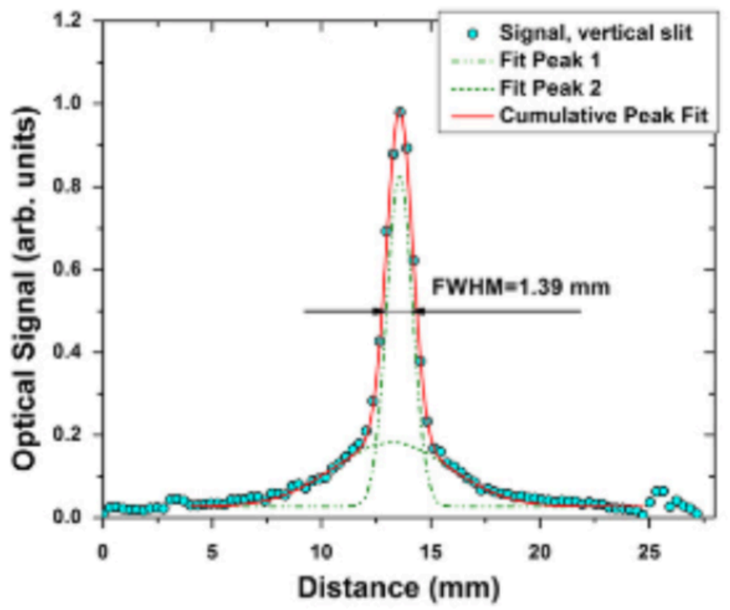
Requires high 2D resolution (choice of pixellated readout), large dynamic range and minimal effect on beam before measurement (20-70 MeV).
Use of optically read out Micromegas with mirror to place camera at and angle outside of beam path (thin materials in beam).



Jona Bortfeldt, RD51 Collaboration Meeting, virtual, October 2020;, https://indico.cern.ch/event/889369/contributions/4042751/attachments/2119709/3567276/bortfeldt_201009.pdf

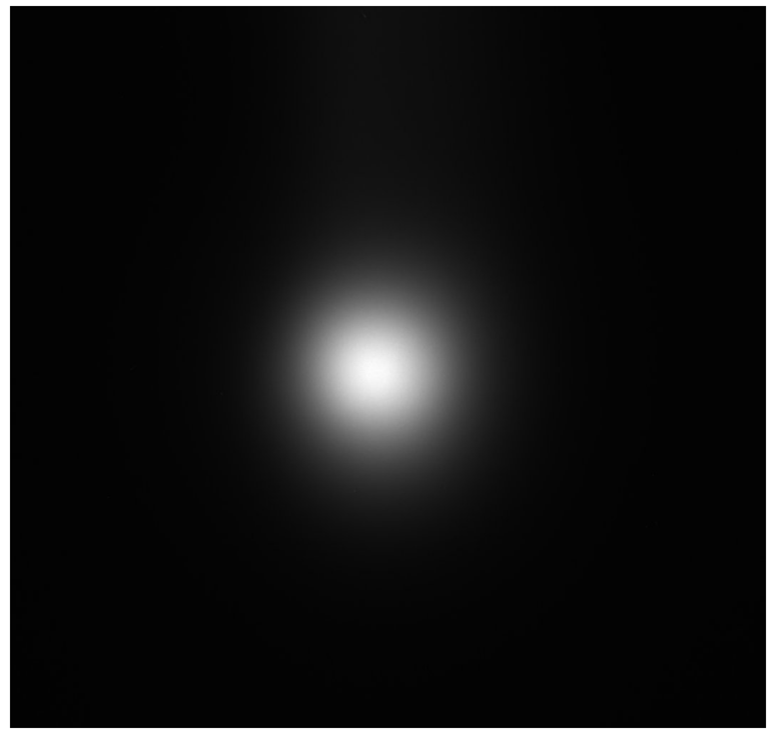






A.V. Klyachko et al. / Nuclear Instruments and Methods in Physics Research A 694 (2012) 271–279

Proton beam monitoring for beam profile measurement and treatment plan validation before treatments



200 MeV pencil beam

Activity measurement for cell samples

Beta-imaging (autoradiography) for activity measurement of tritated cells

Real time measurement of ^{3}H concentration in single cell samples.

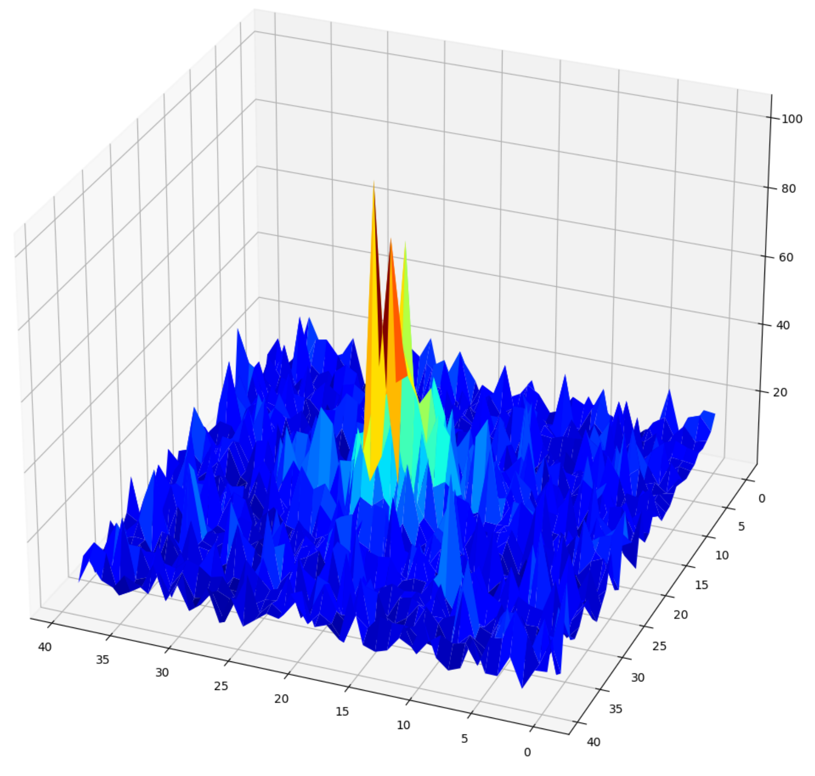
Samples are deposited on exchangeable cathode.

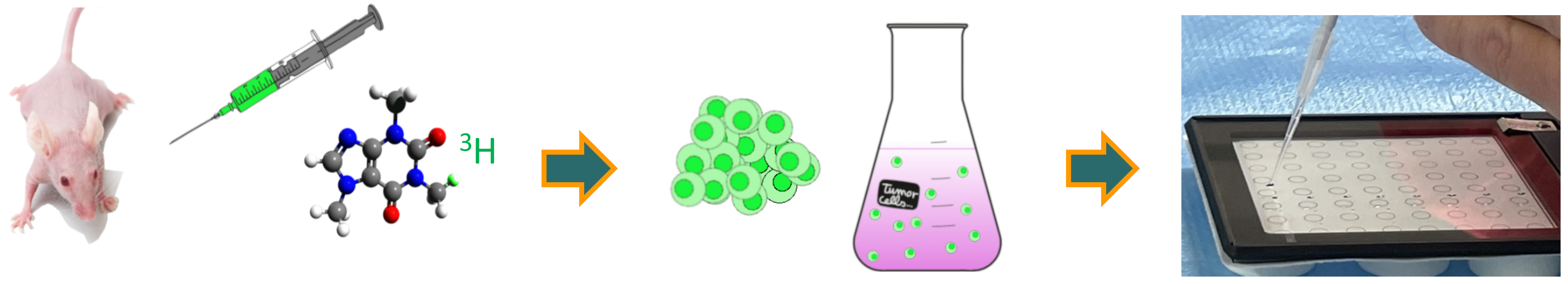
Requires **high detection sensitivity** and spatial resolution.

Glass Micromegas with optical readout used to take advantage of **integrated imaging approach** (no rate limitation) to achieve high dynamic range.

Images are directly available for quantification without need for extensive reconstruction.

Single event

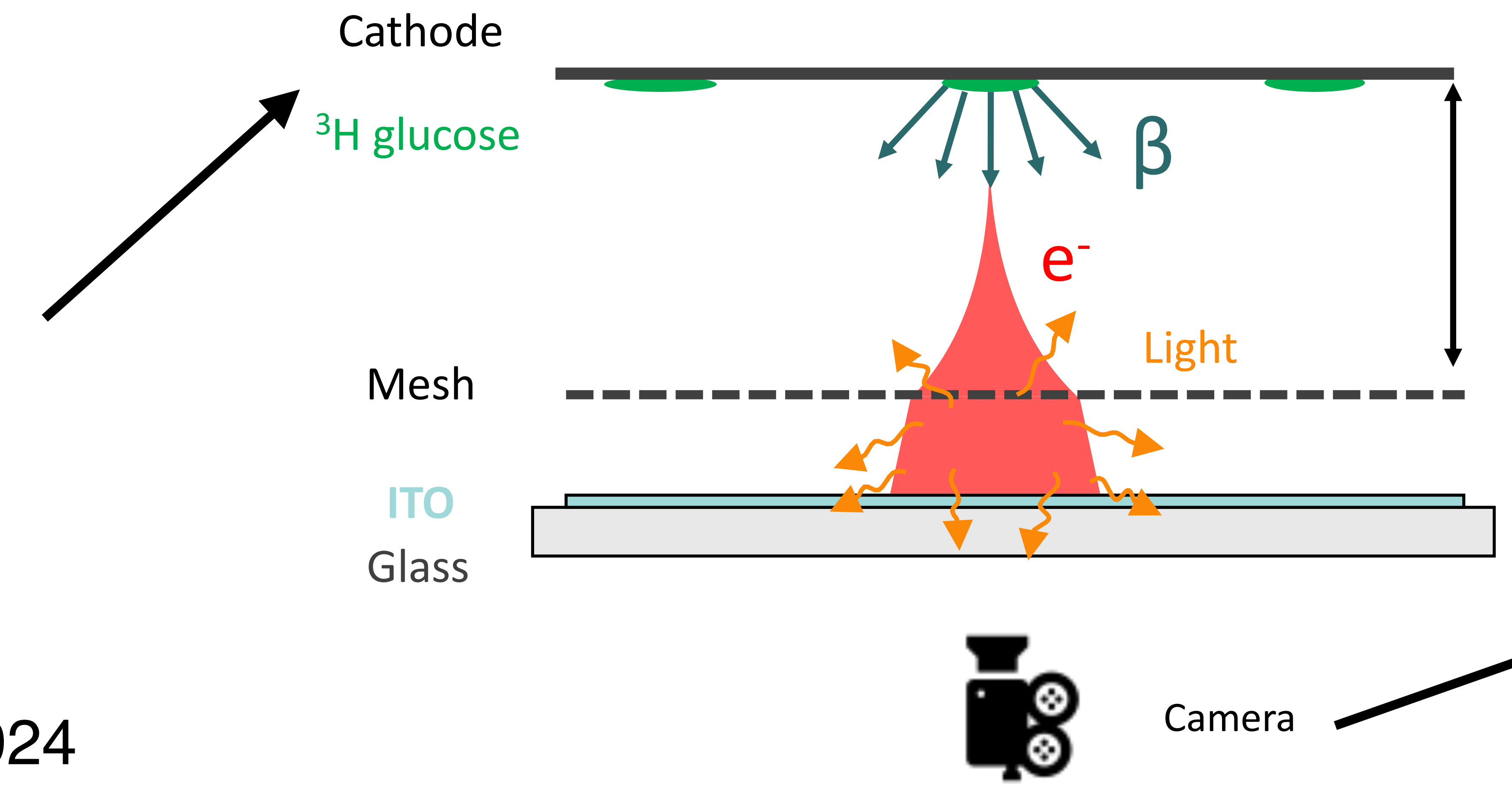


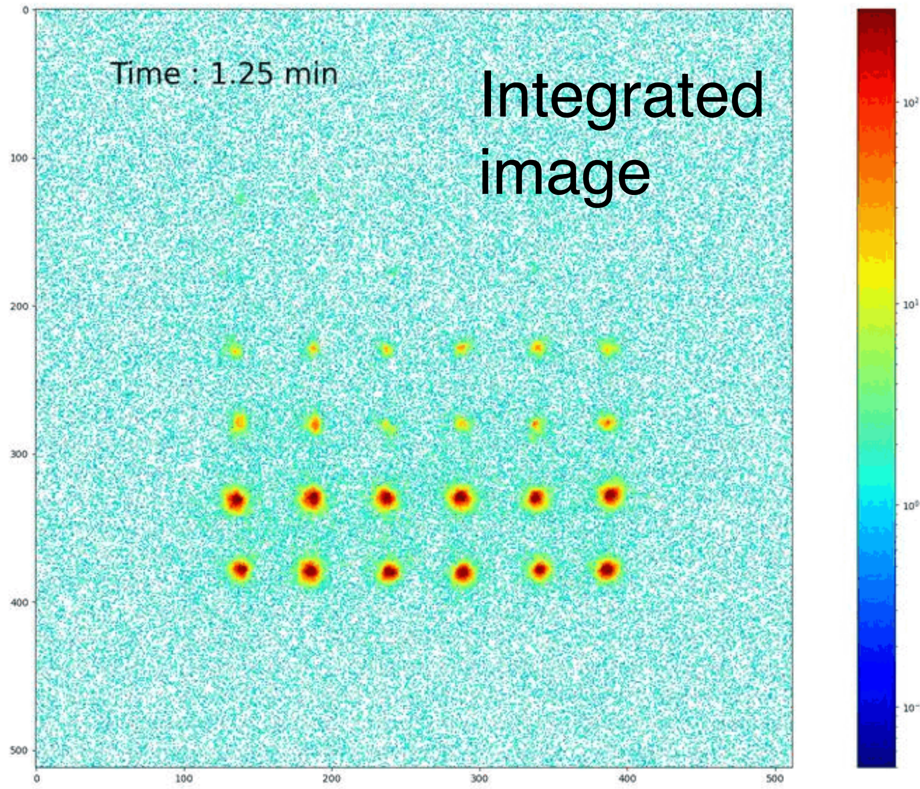


Tumour cells collection
Tritium tracking

Cellular culure

Tritiated cells deposit
on the cathode





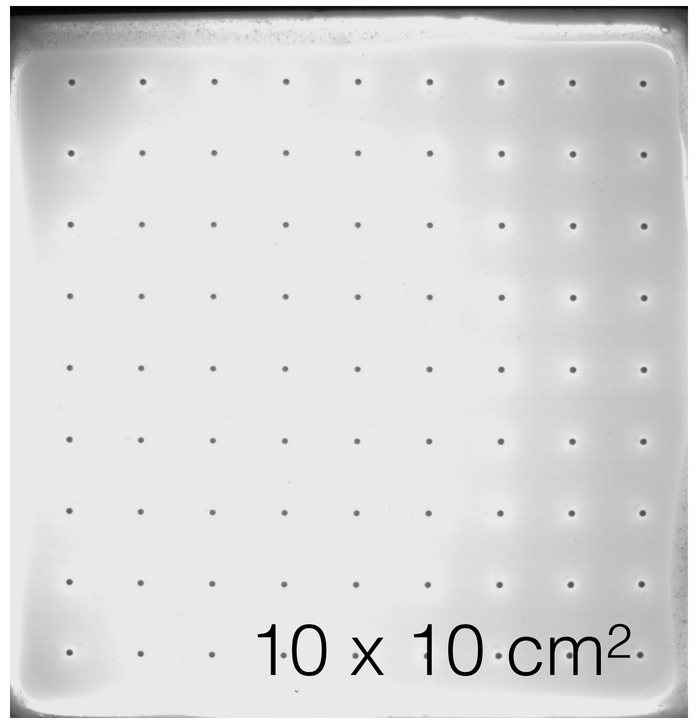
A. Cools et al., 2023 NIMA 1048 167910, A. Cools PhD defense, 2024

Optical readout for detector R&D

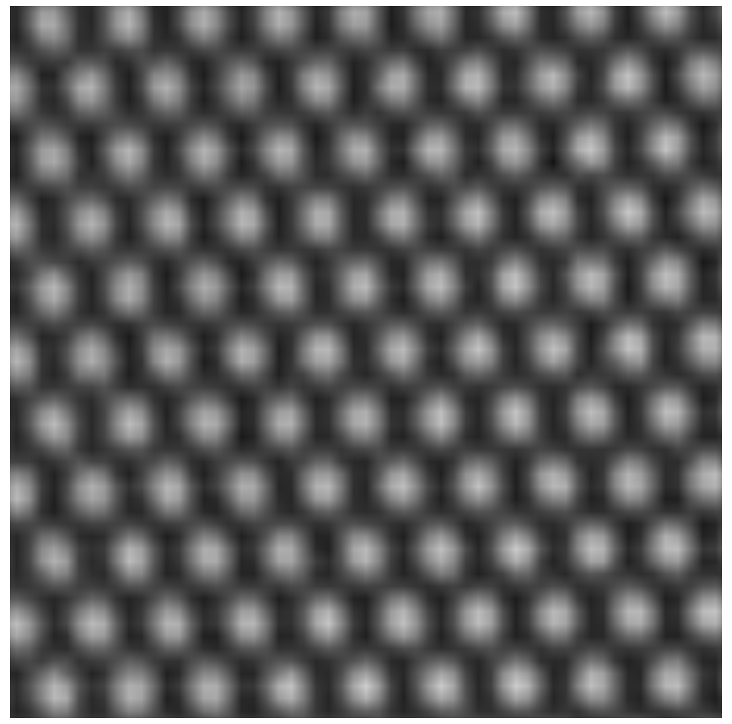
Detector uniformity

Gain uniformity of detectors can be visualised with optical readout either for **full active area** or with zoom lenses for a **detailed view** of smaller regions.

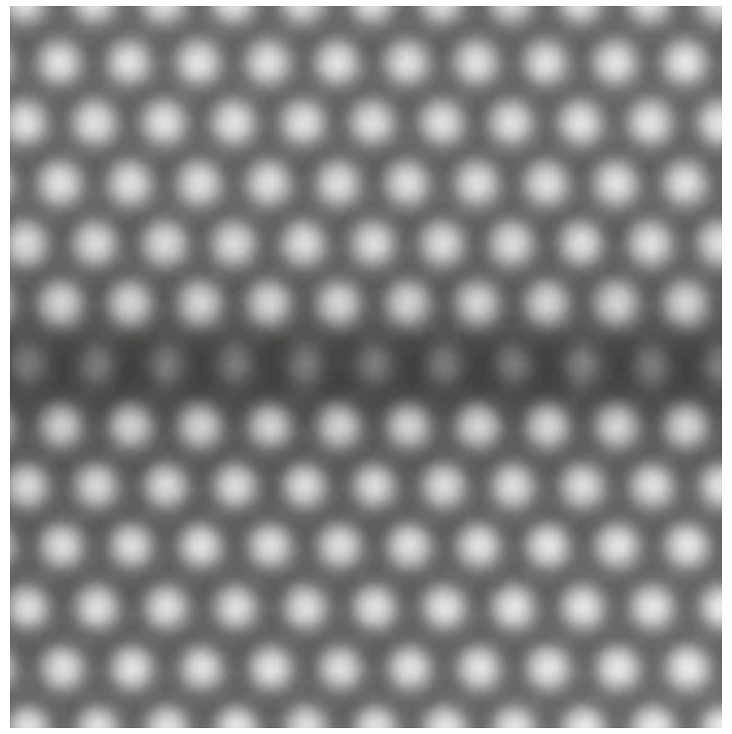
Glass Micromegas



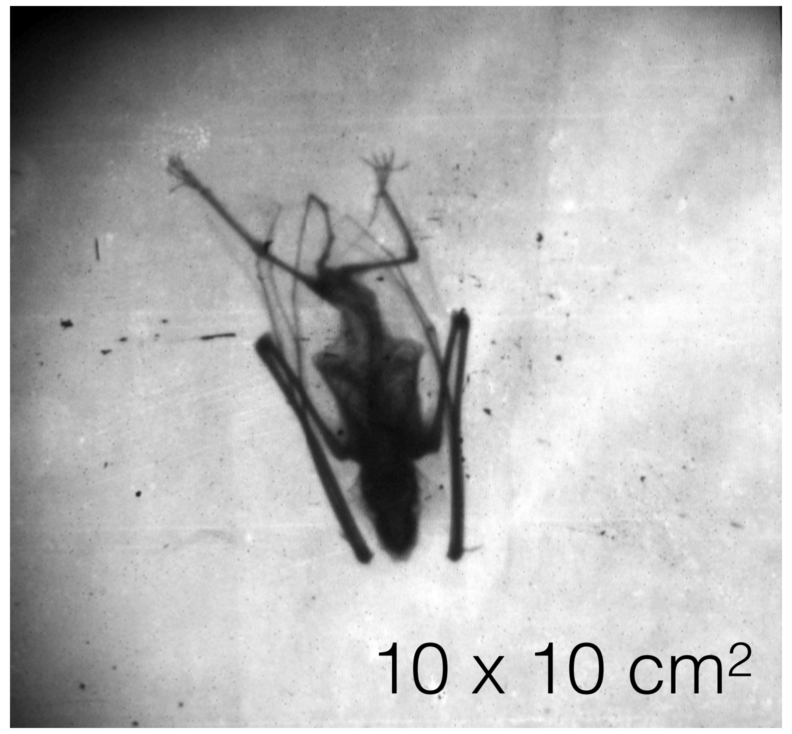
Fine-pitch GEM



Sectored GEM

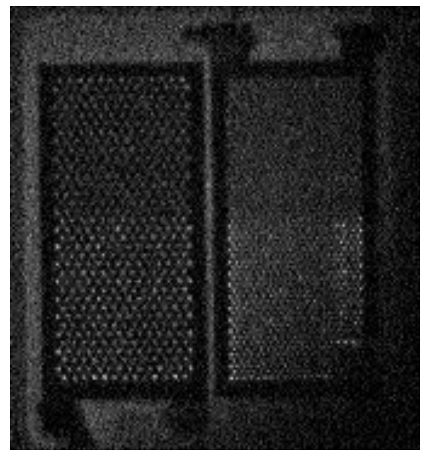


DLC GEM

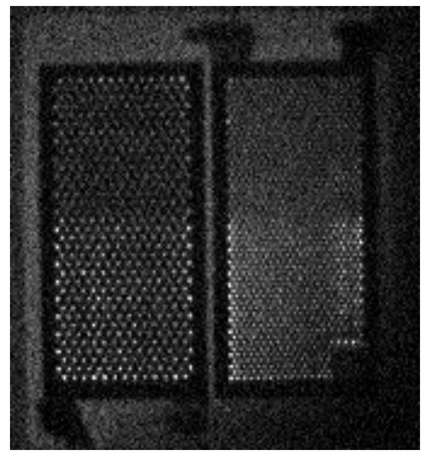


Characterisation of inkjet 3D printed THGEM with optical readout

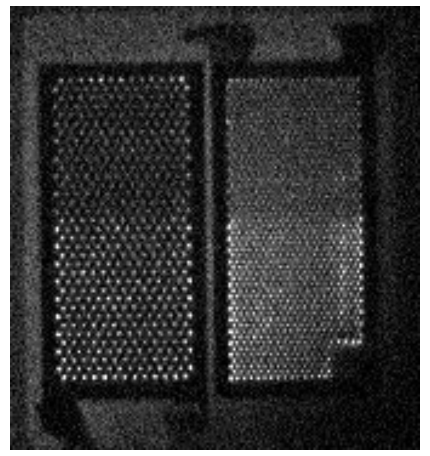
With increasing potential different between the top and bottom electrodes of the THGEM, electron avalanche multiplication sets in and leads to increasing scintillation light emission.



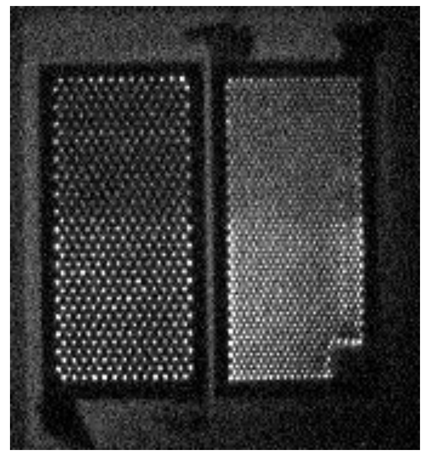
450 V
ΔV_{THGEM}



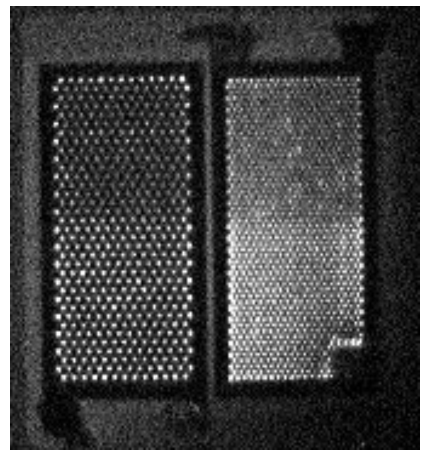
550 V
ΔV_{THGEM}



650 V
ΔV_{THGEM}

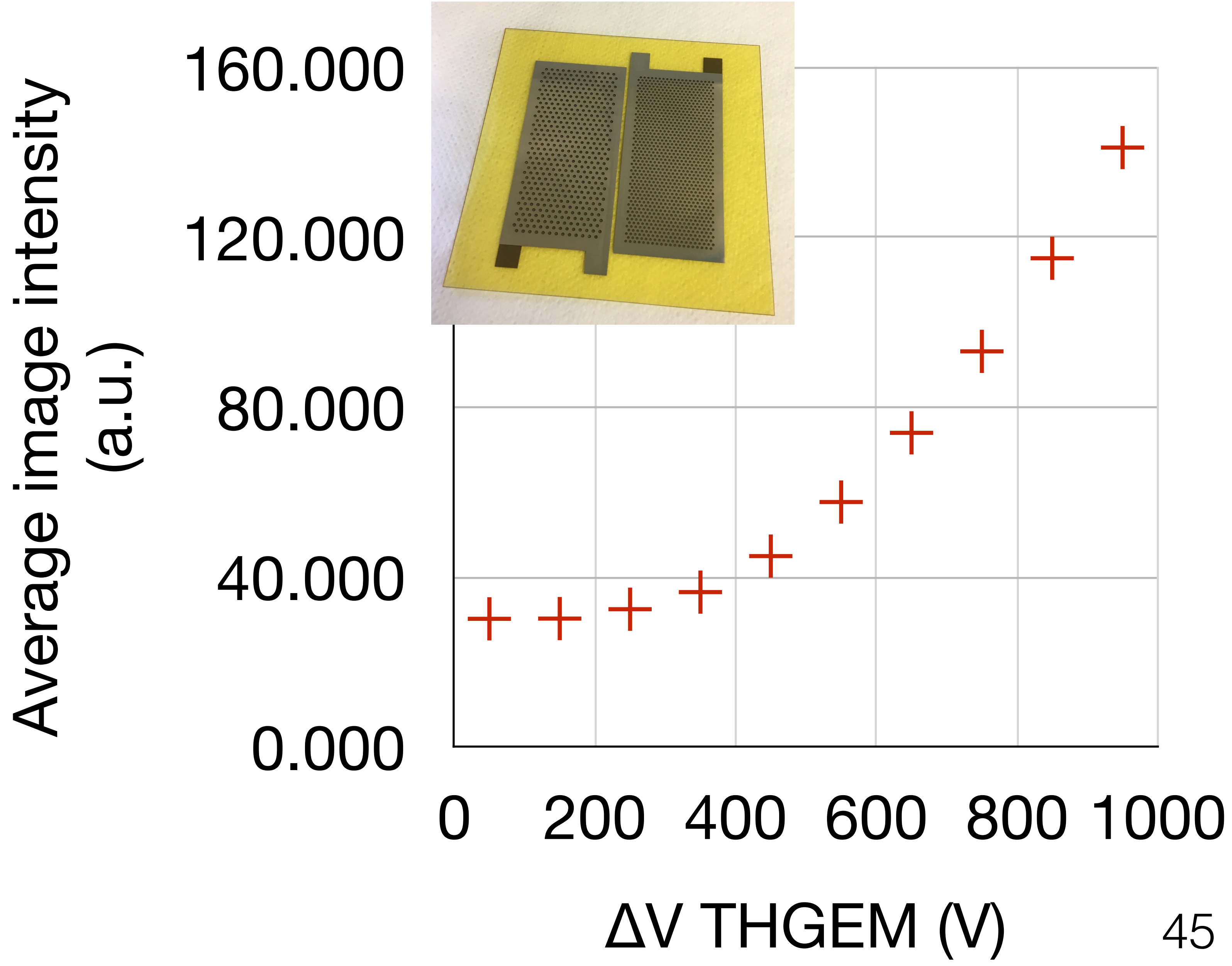


750 V
ΔV_{THGEM}



850 V
ΔV_{THGEM}

950 V
ΔV_{THGEM}

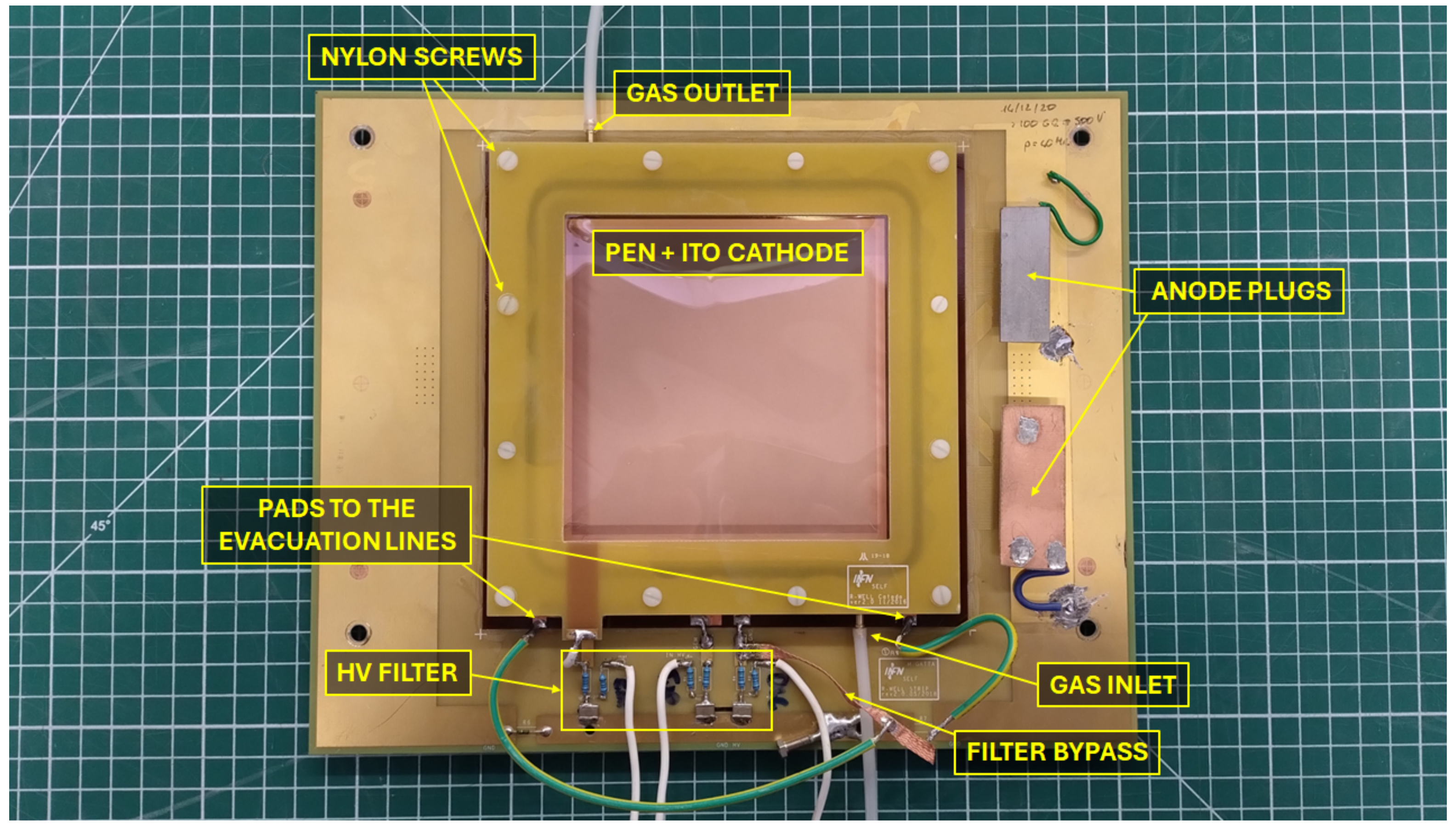


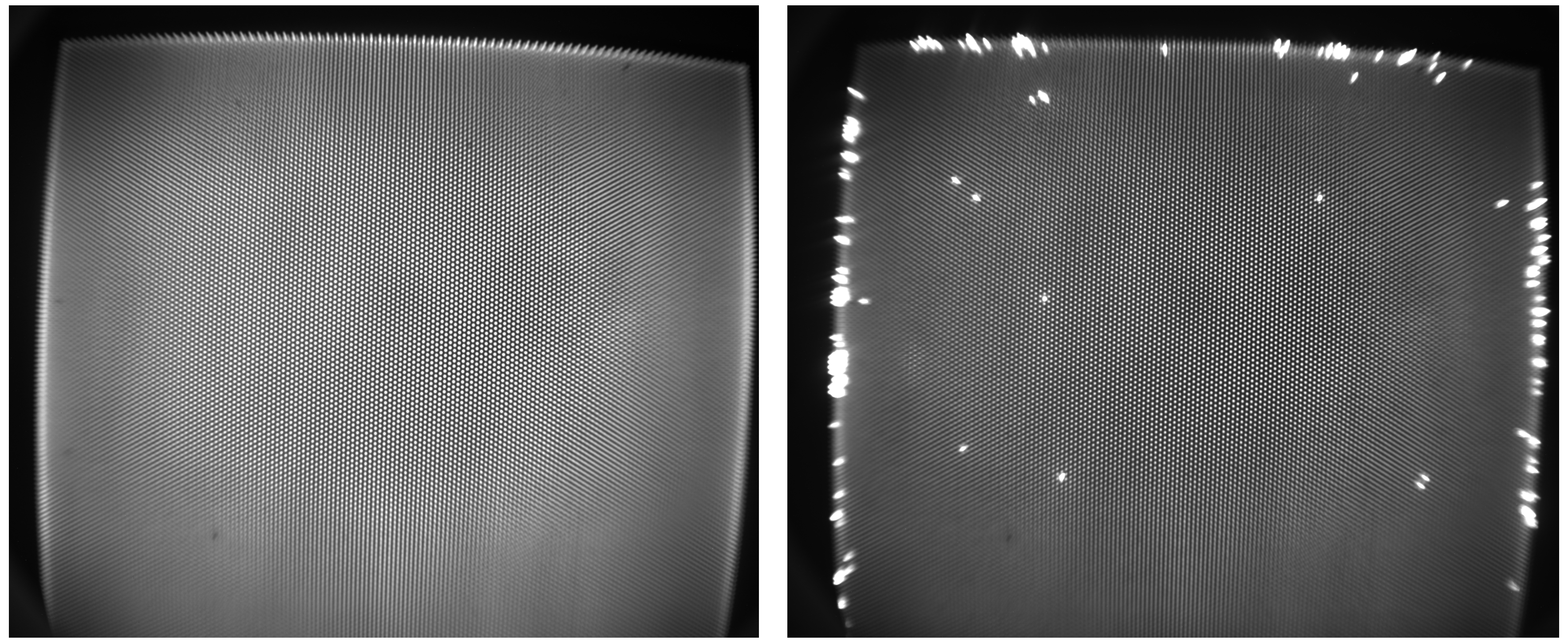
Response of MPGD structures

Optical readout can be used to get detailed response maps of MPGD structures for detector R&D and optimisation of amplification structures

Can be used for “open” amplification structures (GEM-like), for amplification structures integrated on transparent substrates (e.g. glass Micromegas) or for MPGDs on opaque substrates by reading out light through transparent cathodes.

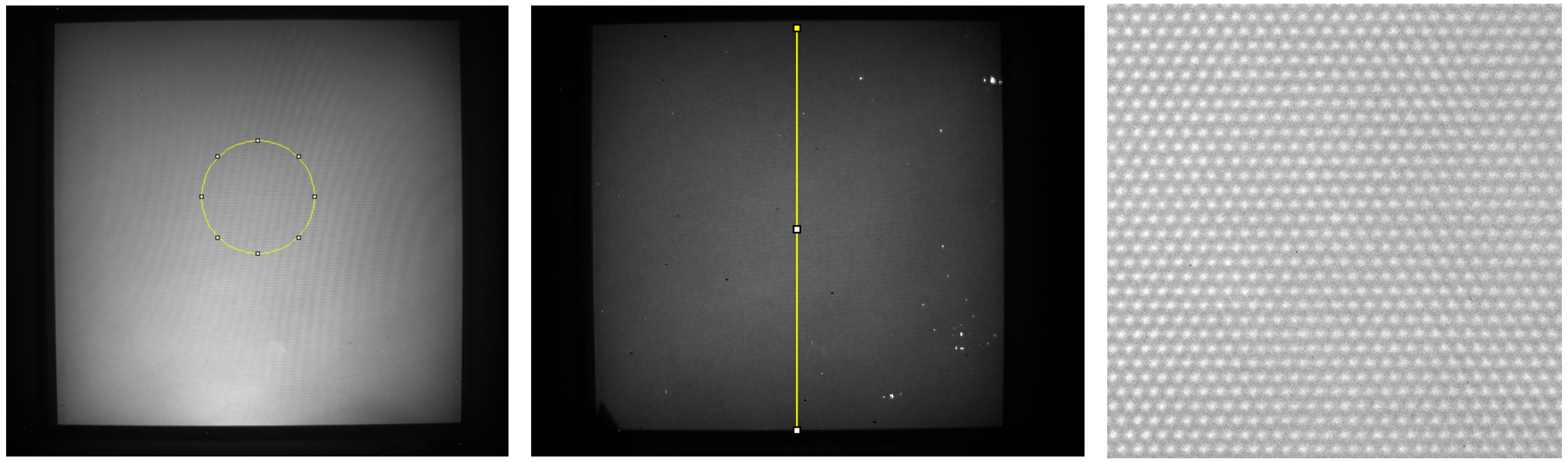
μRWELL with transparent window and ITO cathode





Visualisation of discharge hotspots
M-THGEM with outer row of holes predominantly discharging → modify outer row hole diameter

M. Lisowska, M. Cortesi, F. Brunbauer et al.



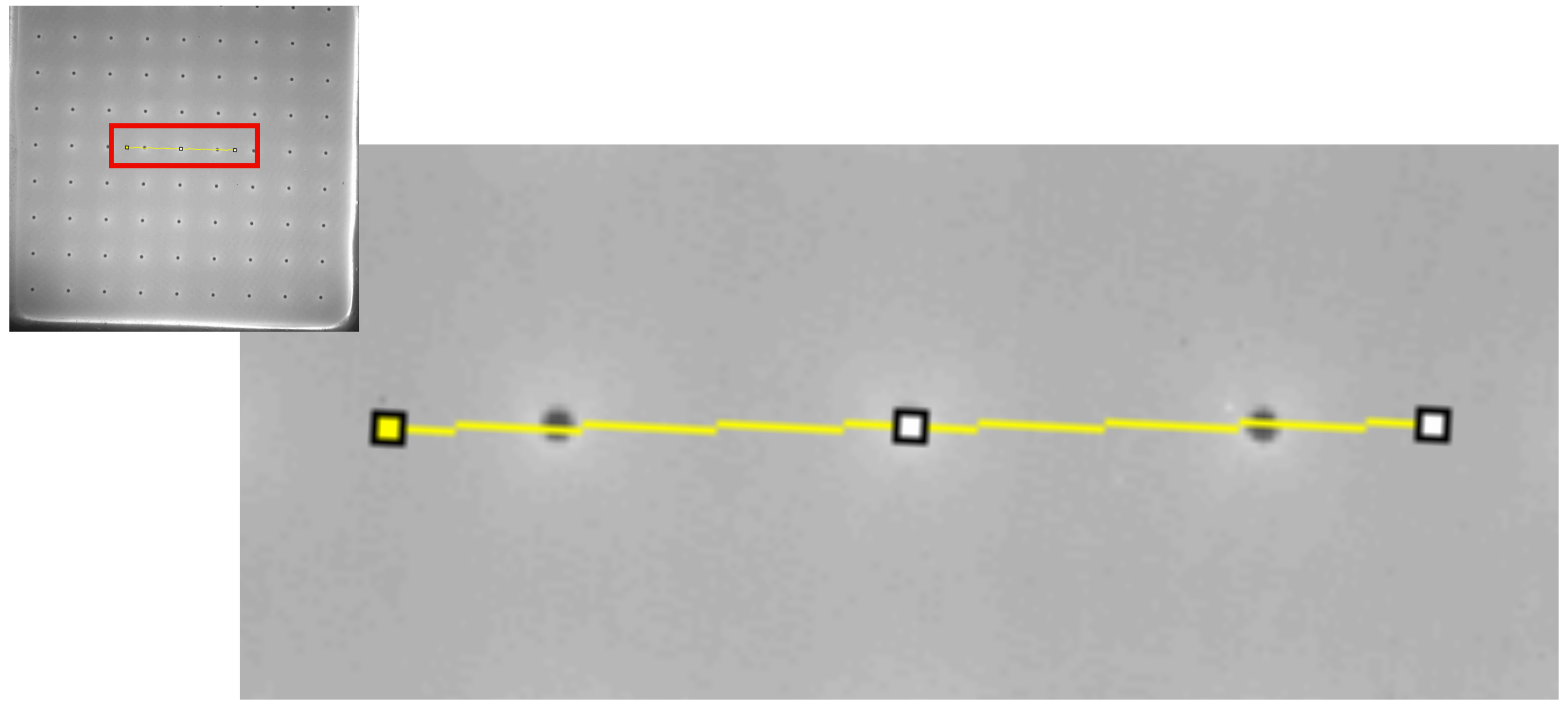
Gain map of μRWELL
Investigation of grounding schemes and effect of discharges / cleaning procedures, light emission visualisation from individual holes

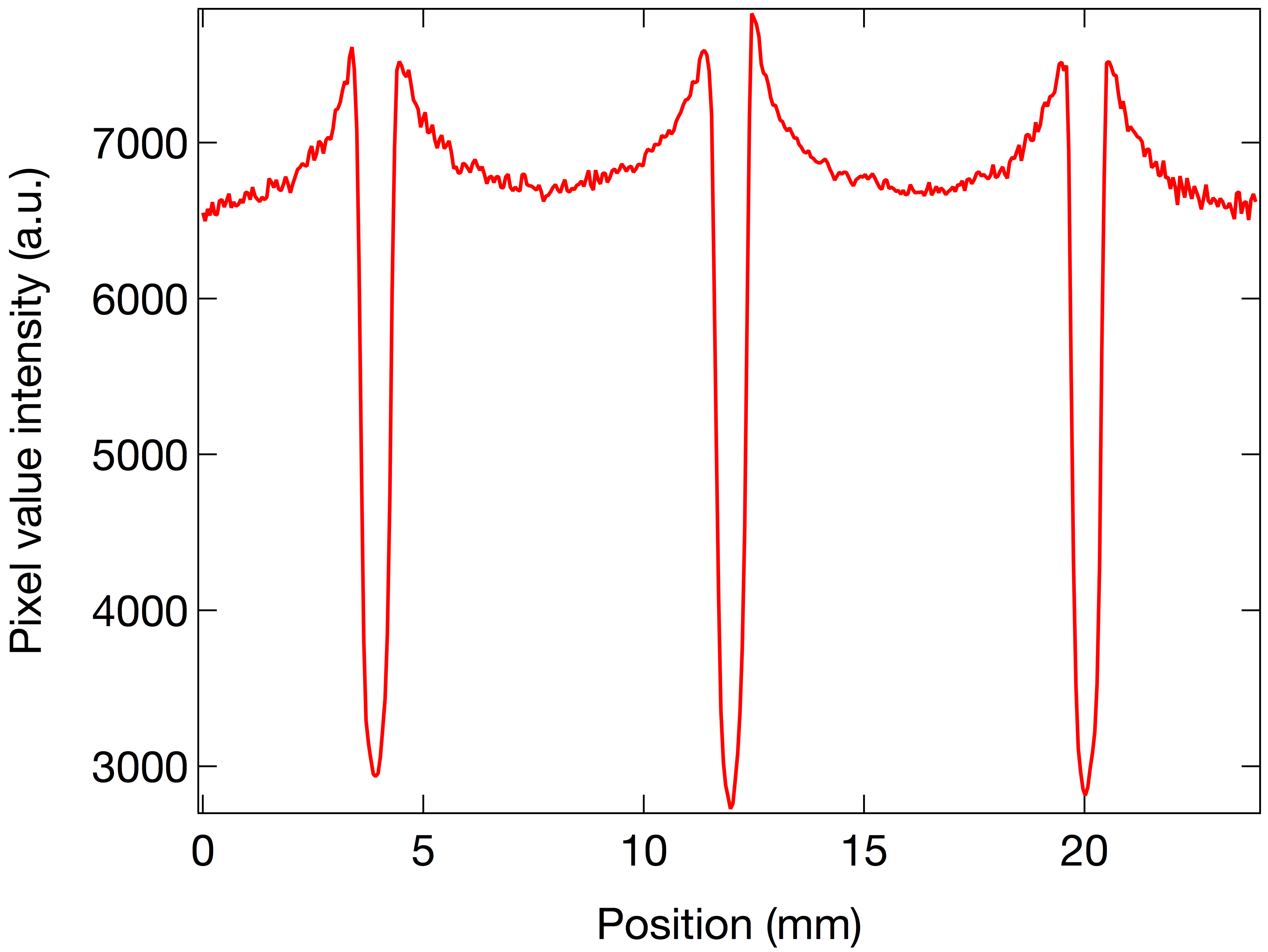
S. Gramigna, M. Giovannetti, R. Farinelli, F. Brunbauer et al.

Localised response non-uniformity

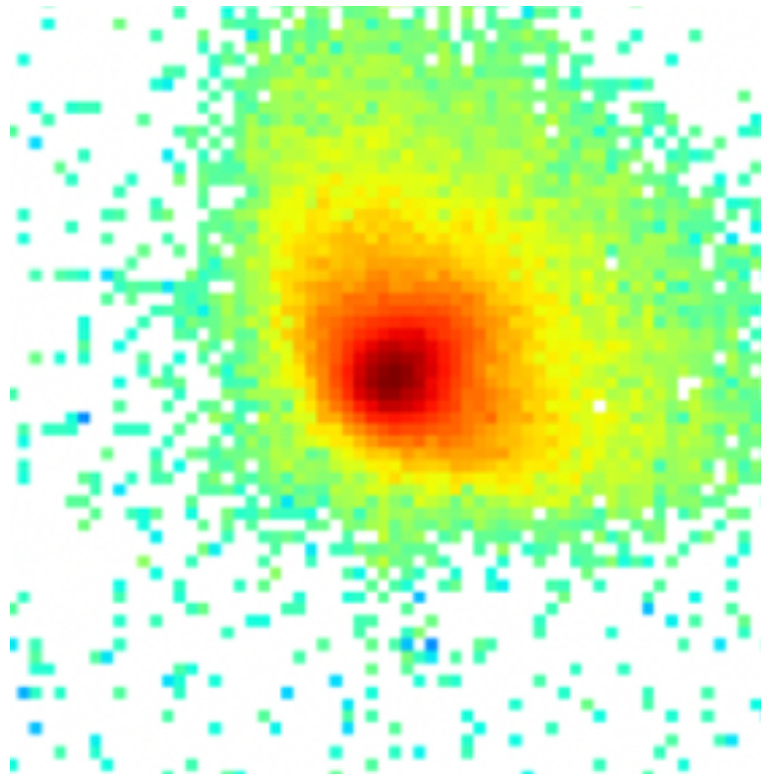
Micromegas non-uniformity of response
Around pillars, the recorded scintillation light intensity varies with brighter regions around the pillars and pillars themselves appear as dead regions (dark spots).

The brighter regions are attributed to an increased number of electrons in these areas surrounding the pillars due to modified field lines as a result of the presence of the pillars.

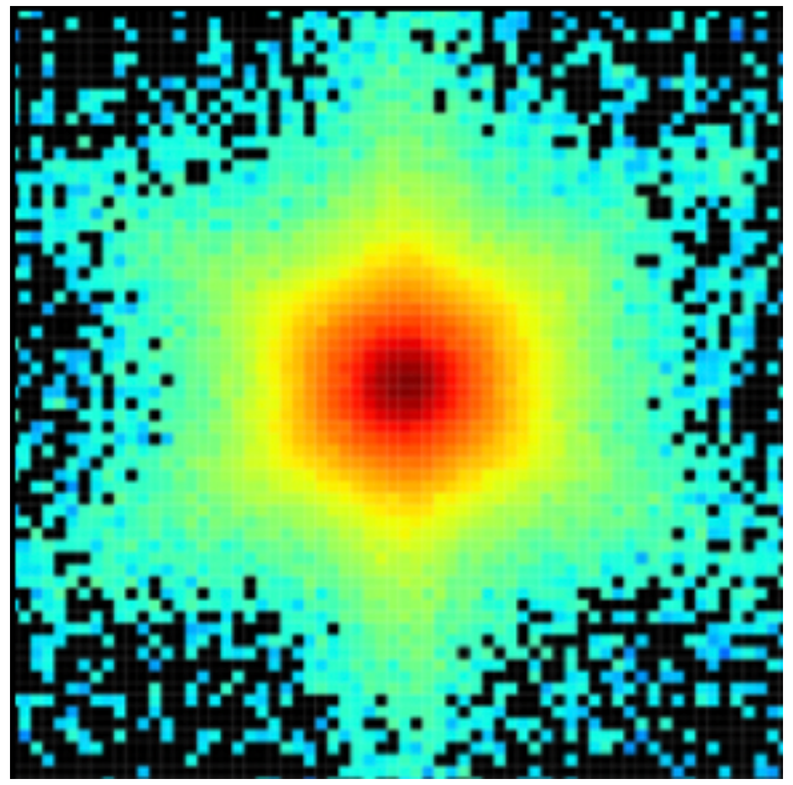


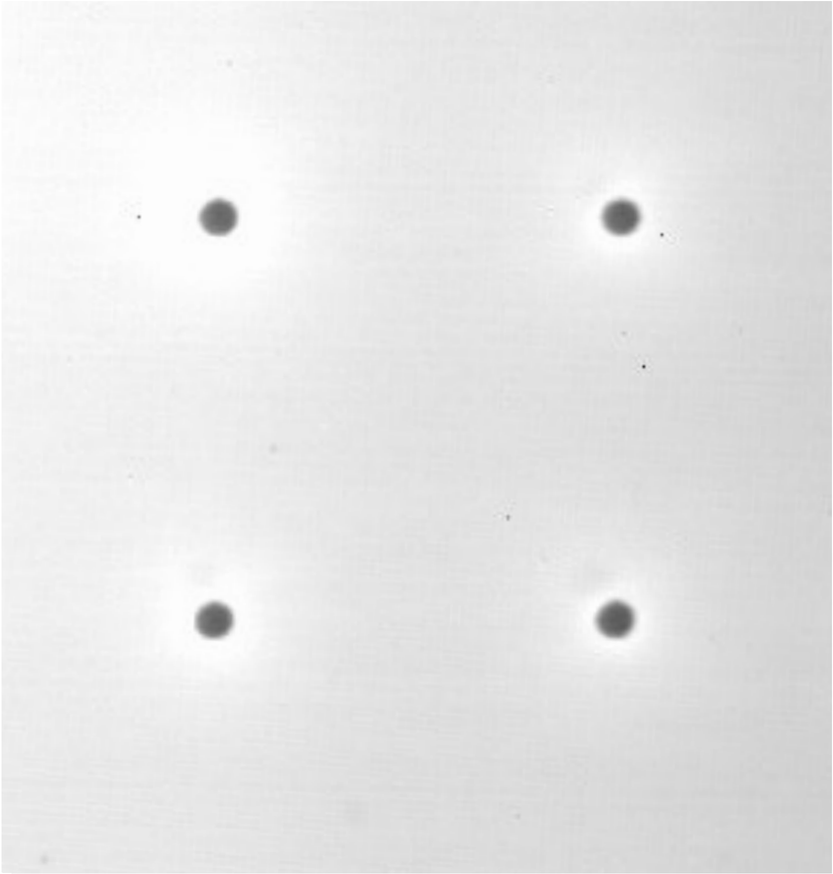


Aberration



Reflections





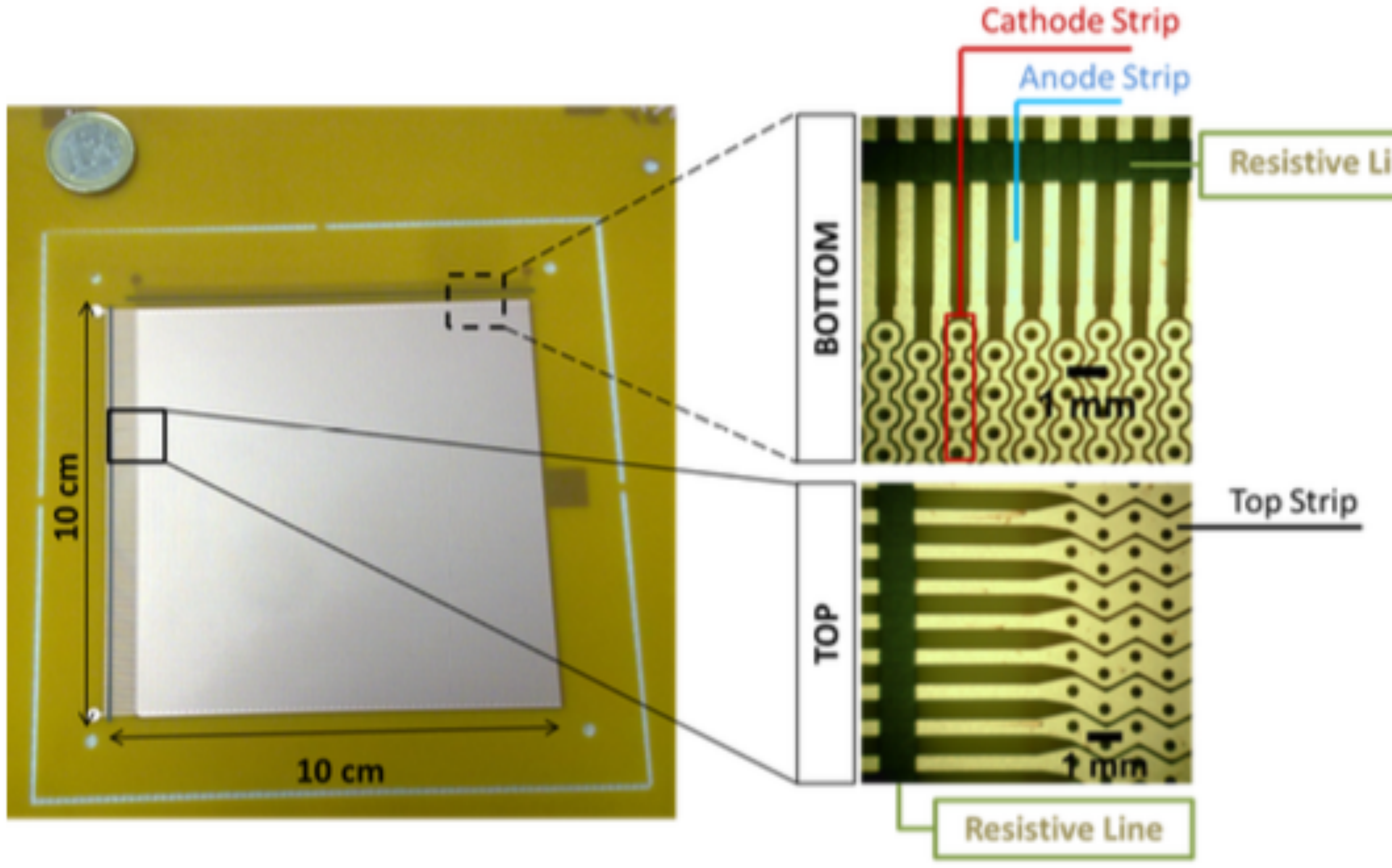
A. Cools, PhD defense

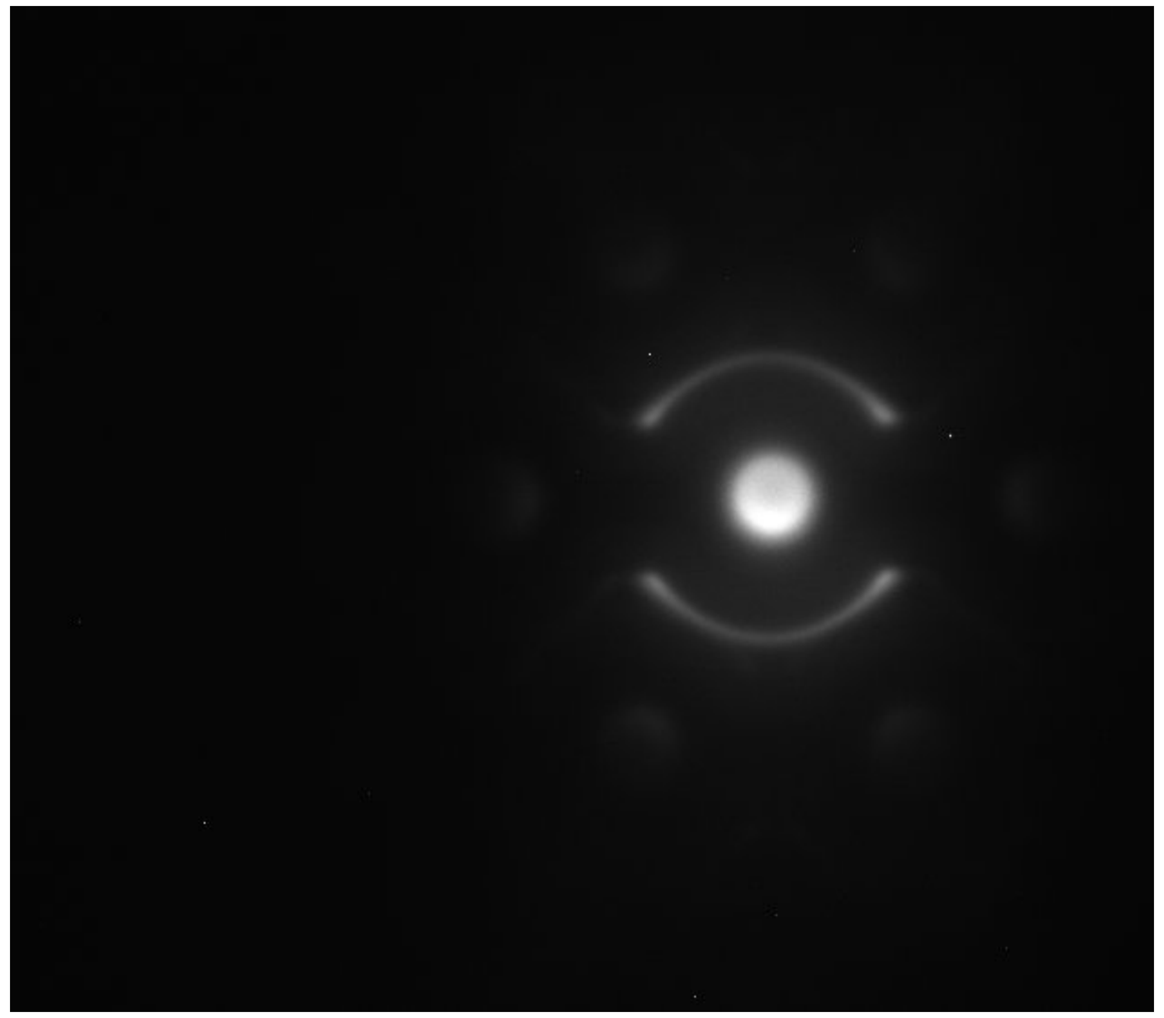
Response of THCOBRA

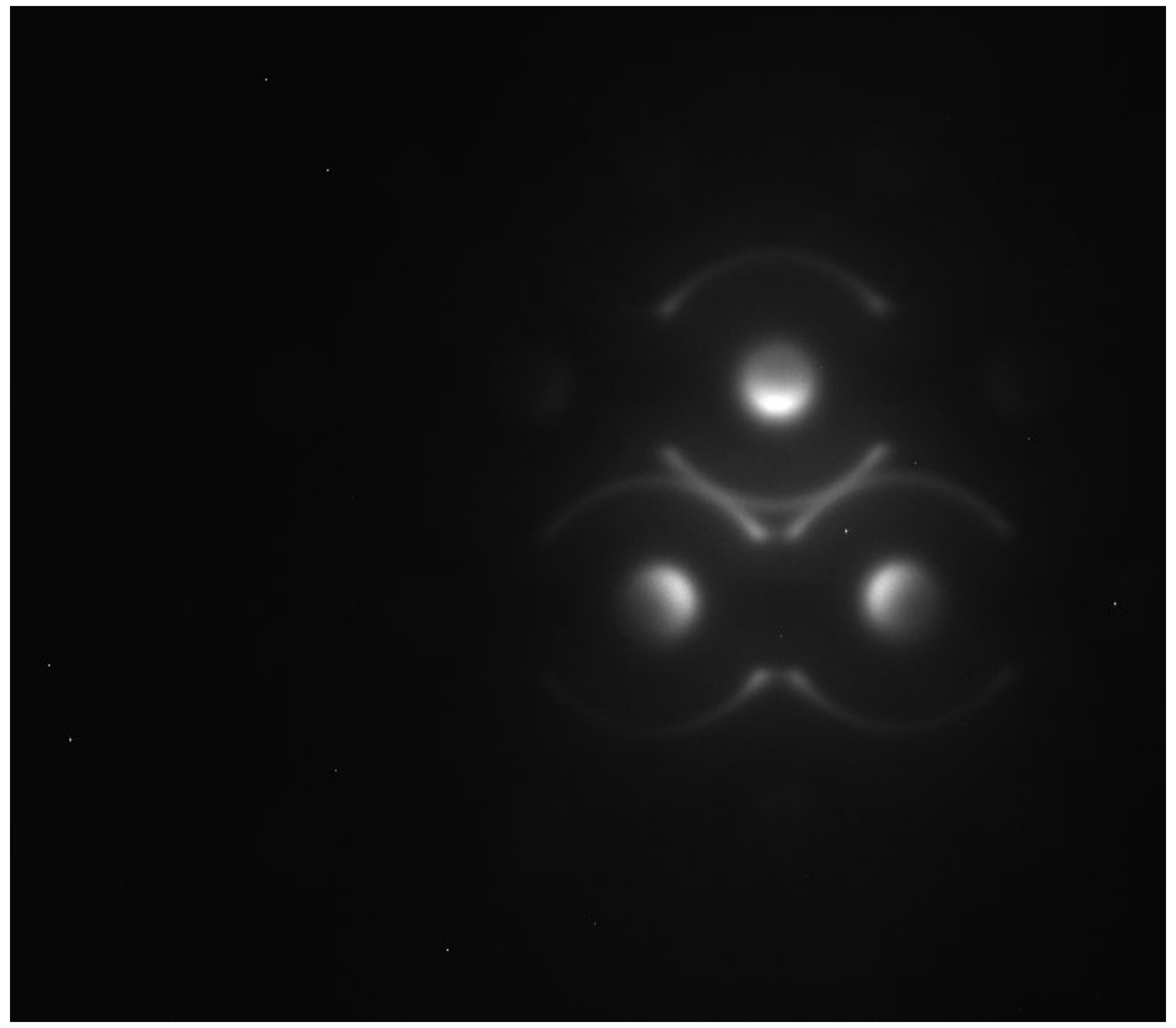
Visualisation of **two-stage gain** response of THCOBRA:

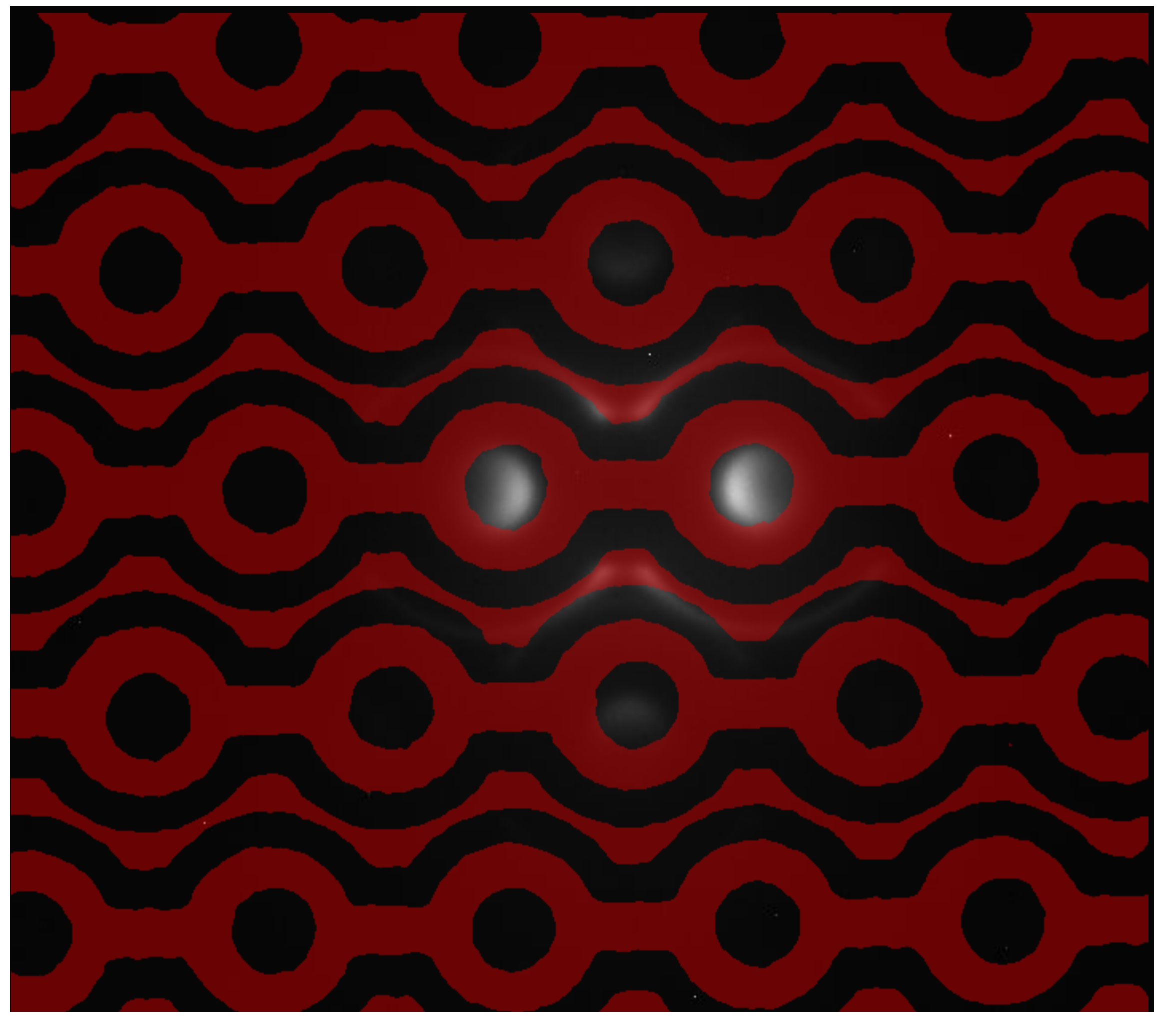
- Hole-type amplification
- MSGC-like amplification

Observation of **asymmetric gain response** in holes → preservation of position information in THGEM during avalanche amplification enables improved position reconstruction.





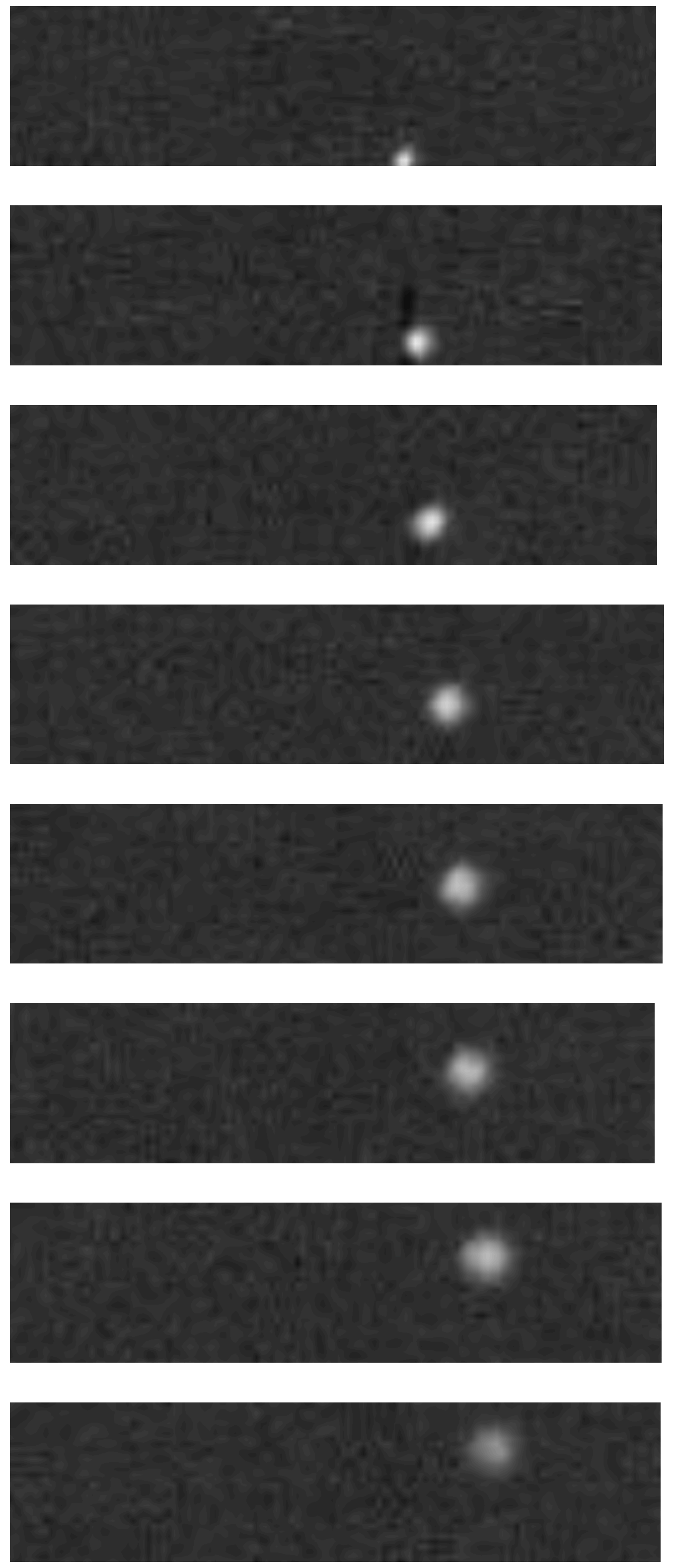




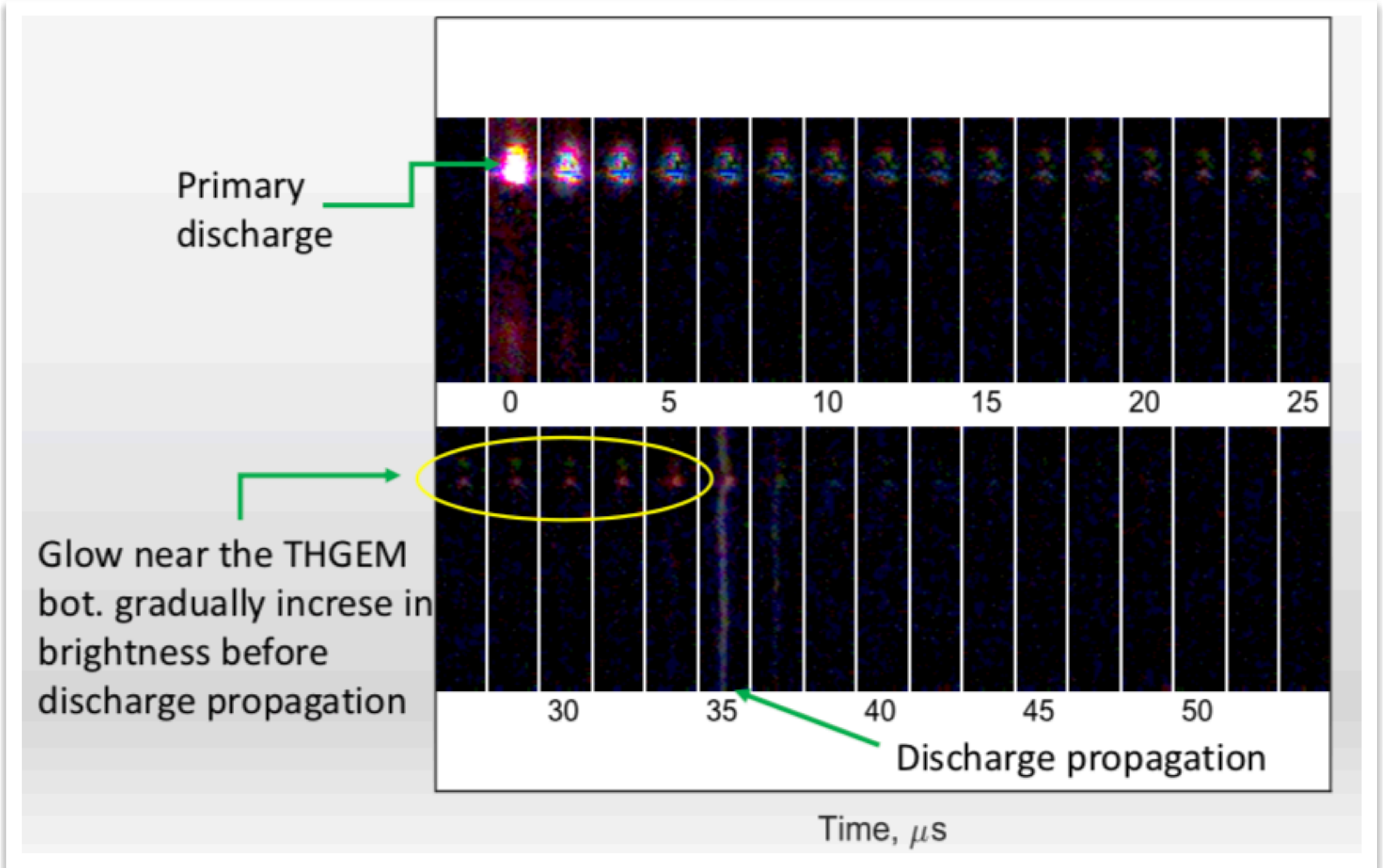
F. Amaro et al., JINST 5(2010);
JFCA Veloso et al. NIM A639(2011)
A. Silva et al. JINST 8(2013)P05016
L F N D Carramate *et al* 2015 *JINST* **10** P01003
L.F.N.D. Carramate *et al* 2017 *JINST* **12** T05003

Diffusion / discharge visualisation

Study of **transverse diffusion** in gaseous detectors



Study of discharges and **discharge propagation** with high speed camera from side of detector



A. Utrobičić et al., MPGD stability workshop, Munich, 2018

New developments

Alternative gases and wavelength shifters

Ultra-fast imaging

SiPM readout

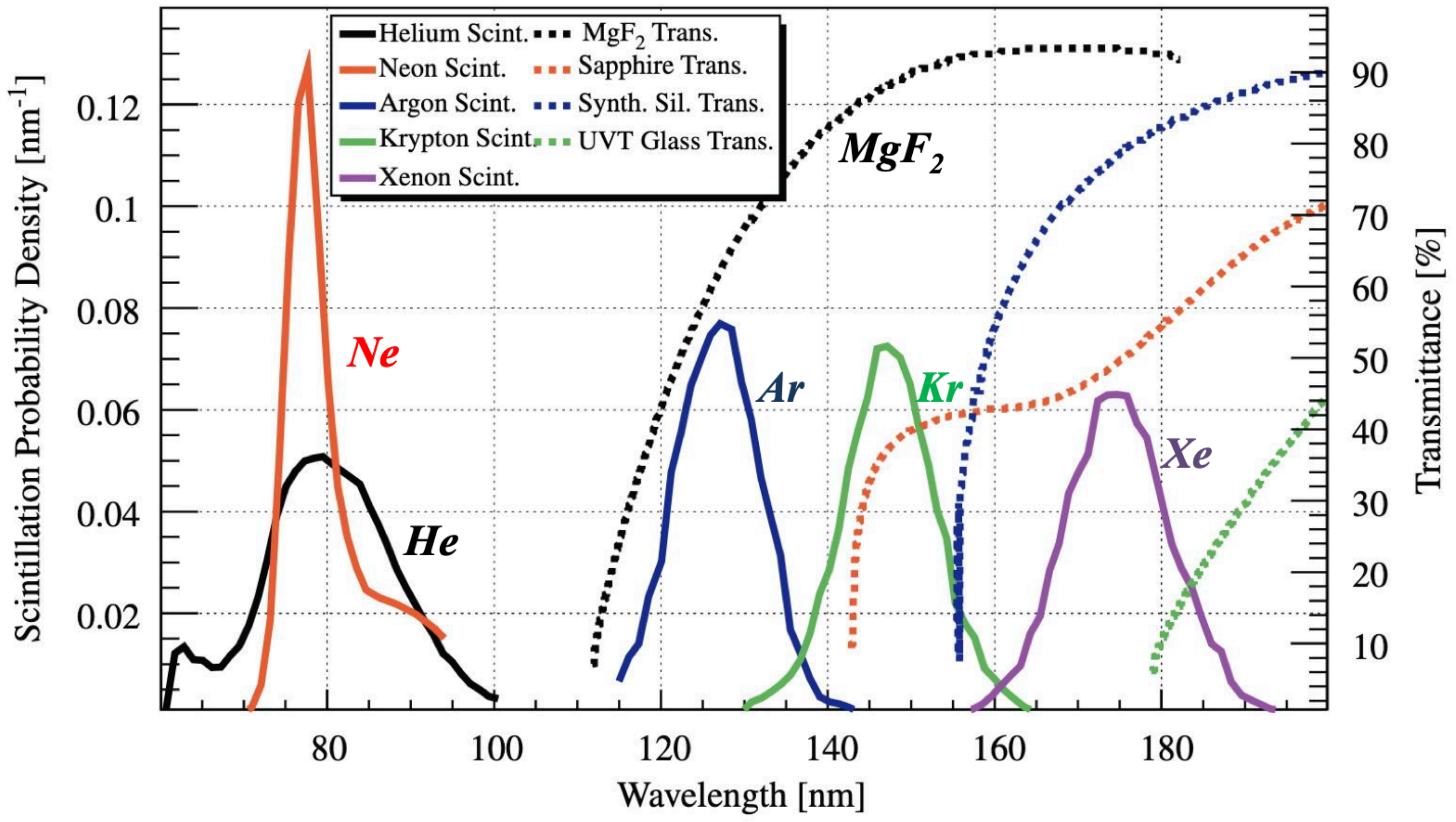
Optical readout of negative ion drift detectors

Alternative gases and WLS

F.M. Brunbauer, Wavelength shifters for optically read out MPGDs

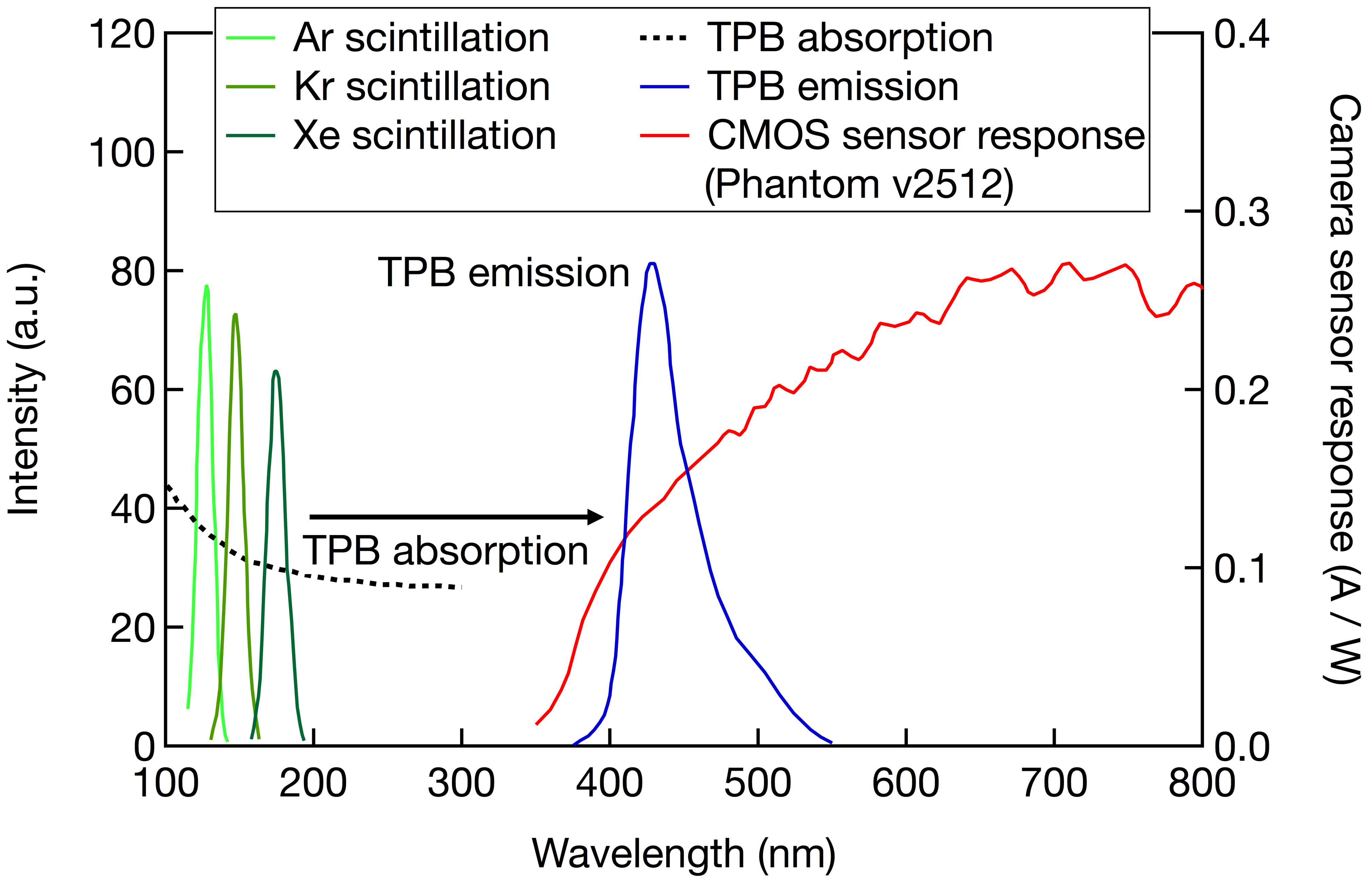
CF_4 is a **strong greenhouse** gas with GWP ≈ 7000.

In addition, **decreasing availability** and **increasing cost** of CF_4 pose issues for using it in future detectors with optical readout.



C. Benson et al, Eur Phys J C 78(2018)120

Using wavelength shifters



Data from: Ignarra, C.M. Physics Procedia 37 (2012): 1217–1222.
Scintillation data from: V. M. Gehman et al. NIM A 654 (2011) 1.

Wavelength shifters such as tetraphenyl butadiene (**TPB**) can be used to shift scintillation light spectrum to visible range with peak around **425 nm.**

Schematics not drawn to scale

Ultra-fast optical readout

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

Need of **CF_4**-based gas mixtures
or wavelength shifters

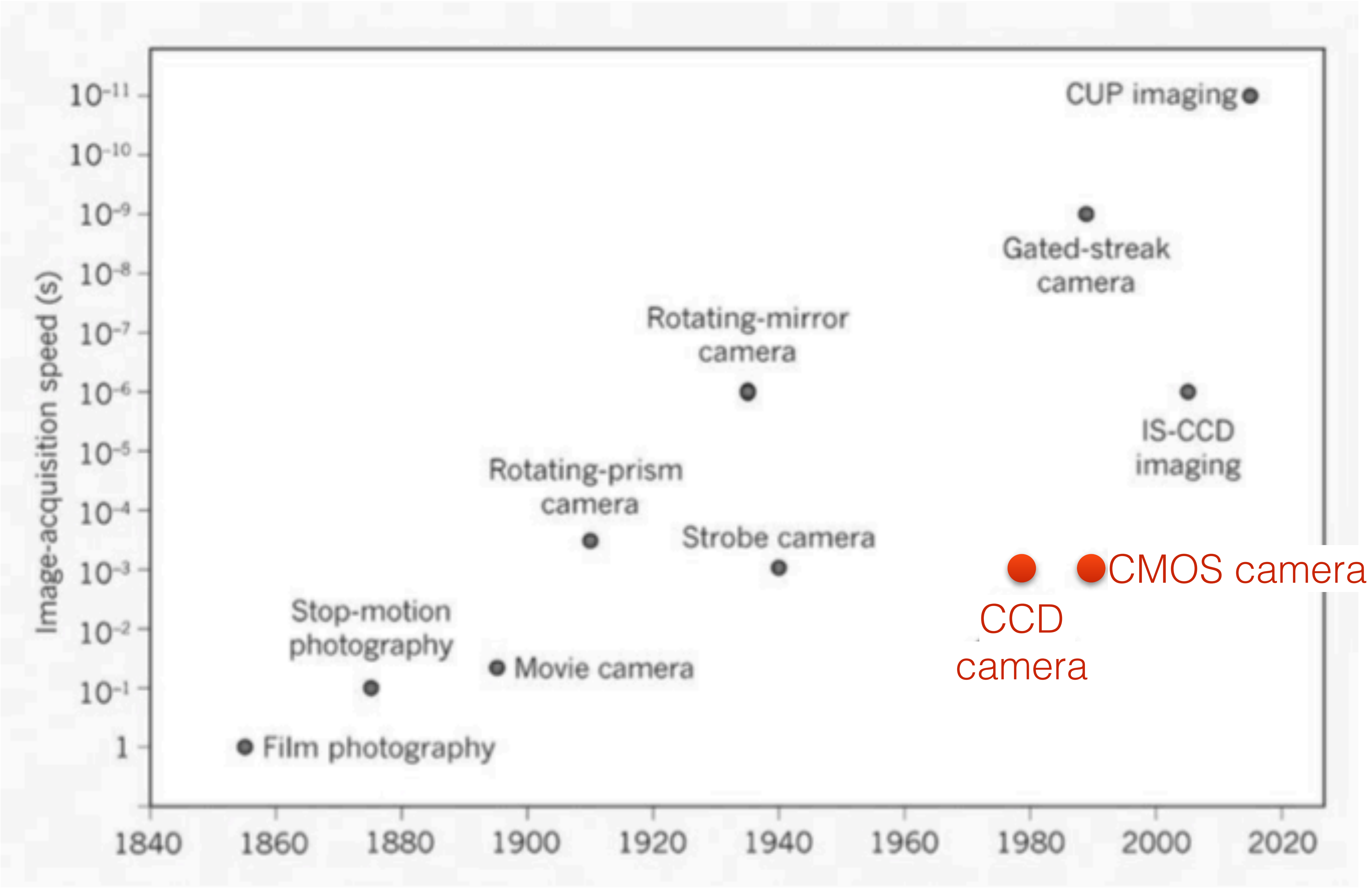


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

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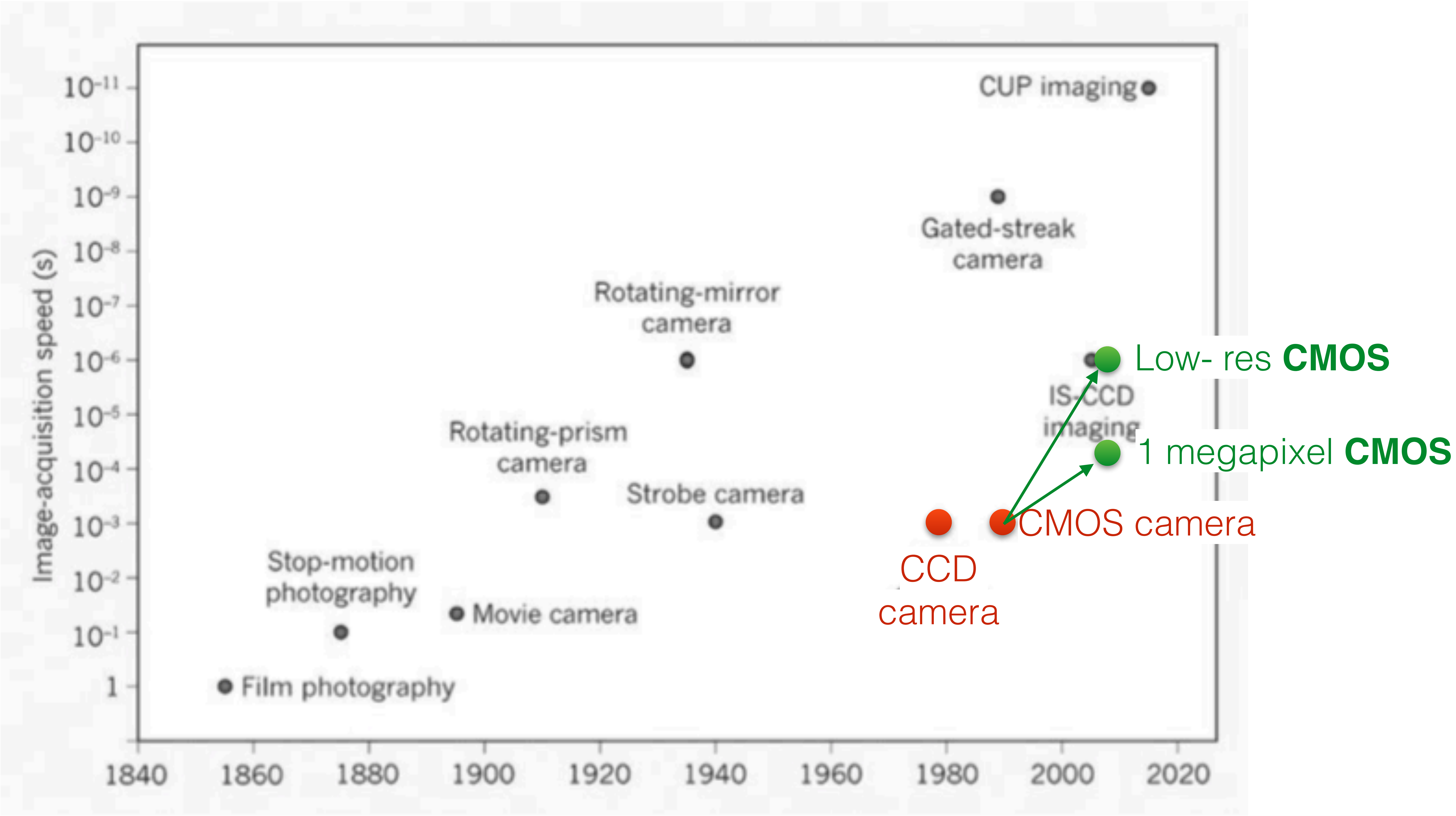

Image adapted from: B. Pogue, Nature 516 (2014) 46–47

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Need of **CF_4**-based gas mixtures
or wavelength shifters

Photron FASTCAM SA-Z

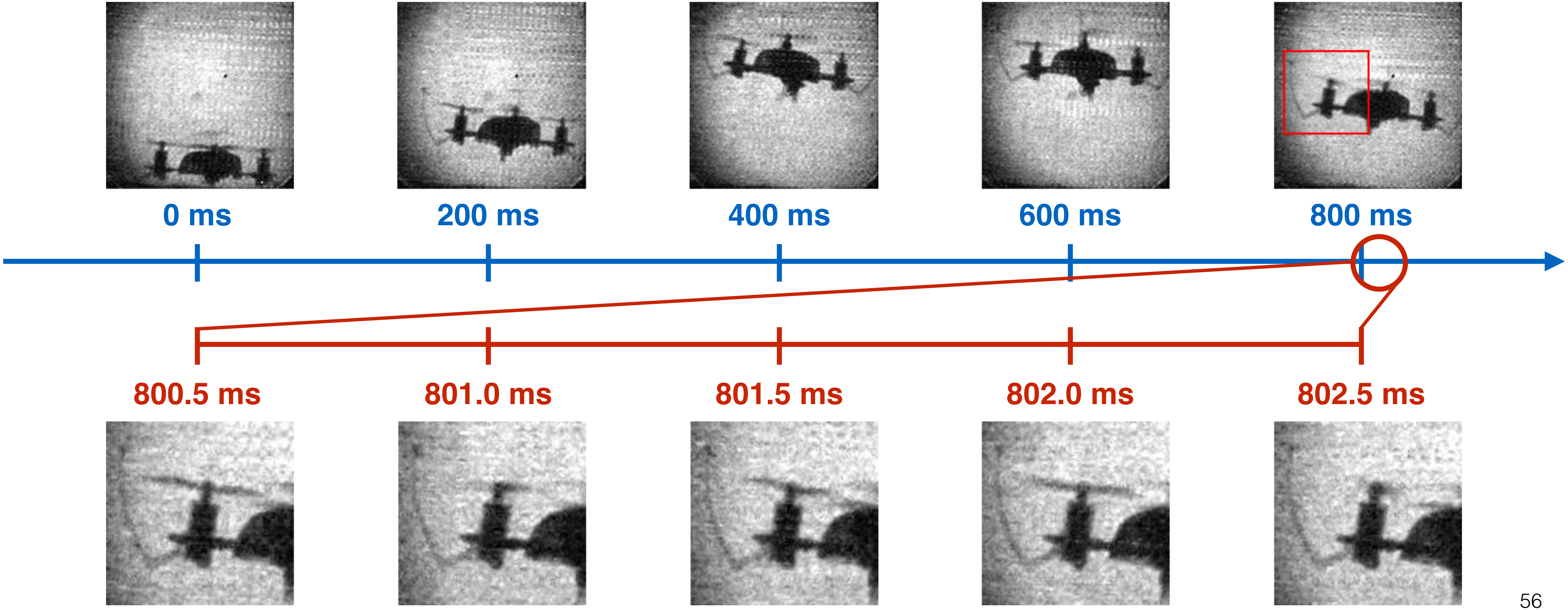
- 1 megapixel CMOS sensor
- 12 bit depth
- **20 kfps** at 1024x1024
- **2.1 Mfps** at 128x8
- ISO 50,000 sensitivity

Phantom v2512

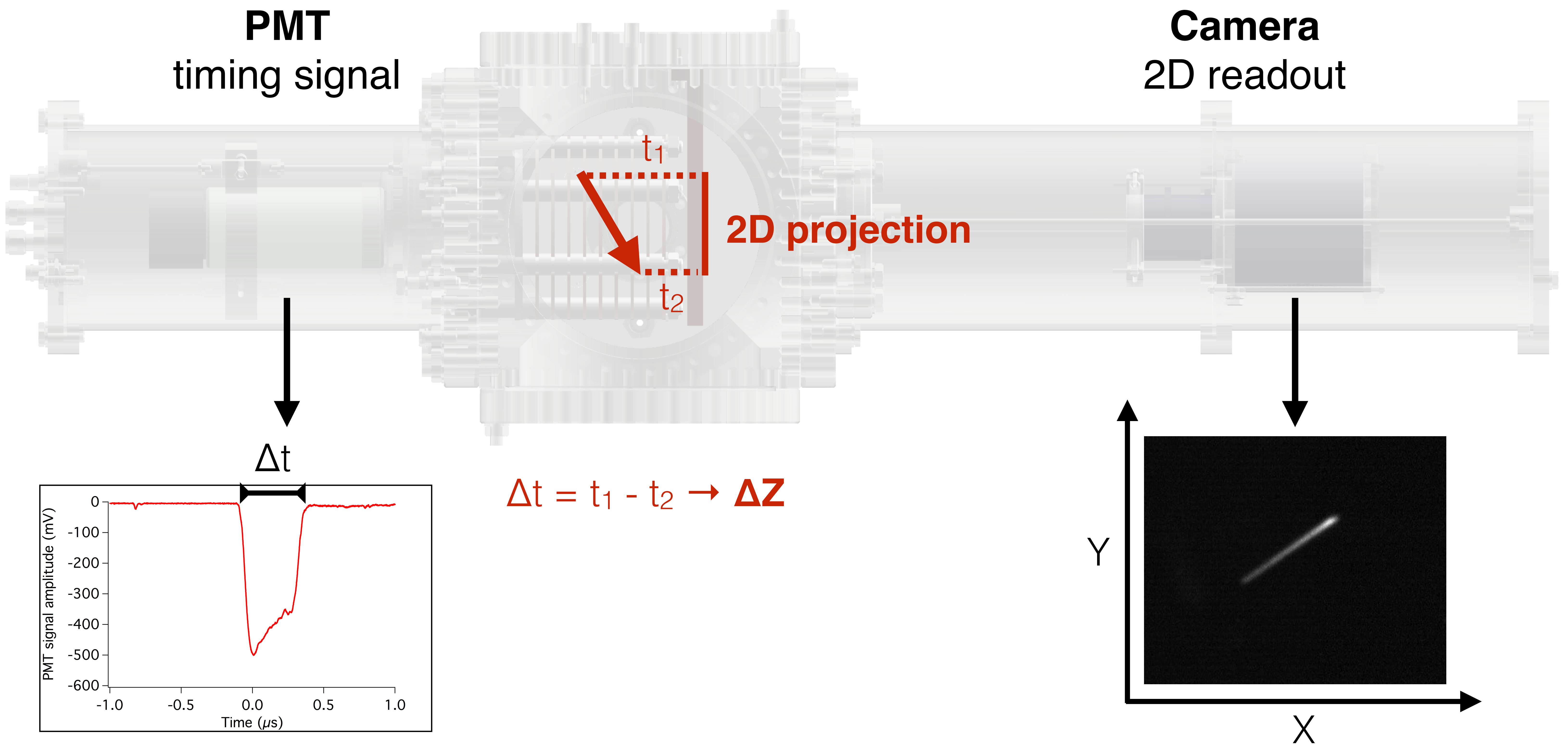
- 1 megapixel CMOS sensor
- 12 bit depth
- **25 kfps** at 1280 x 800
- **1 Mfps** at 128x32
- ISO 100,000 sensitivity

Sub-ms X-ray fluoroscopy

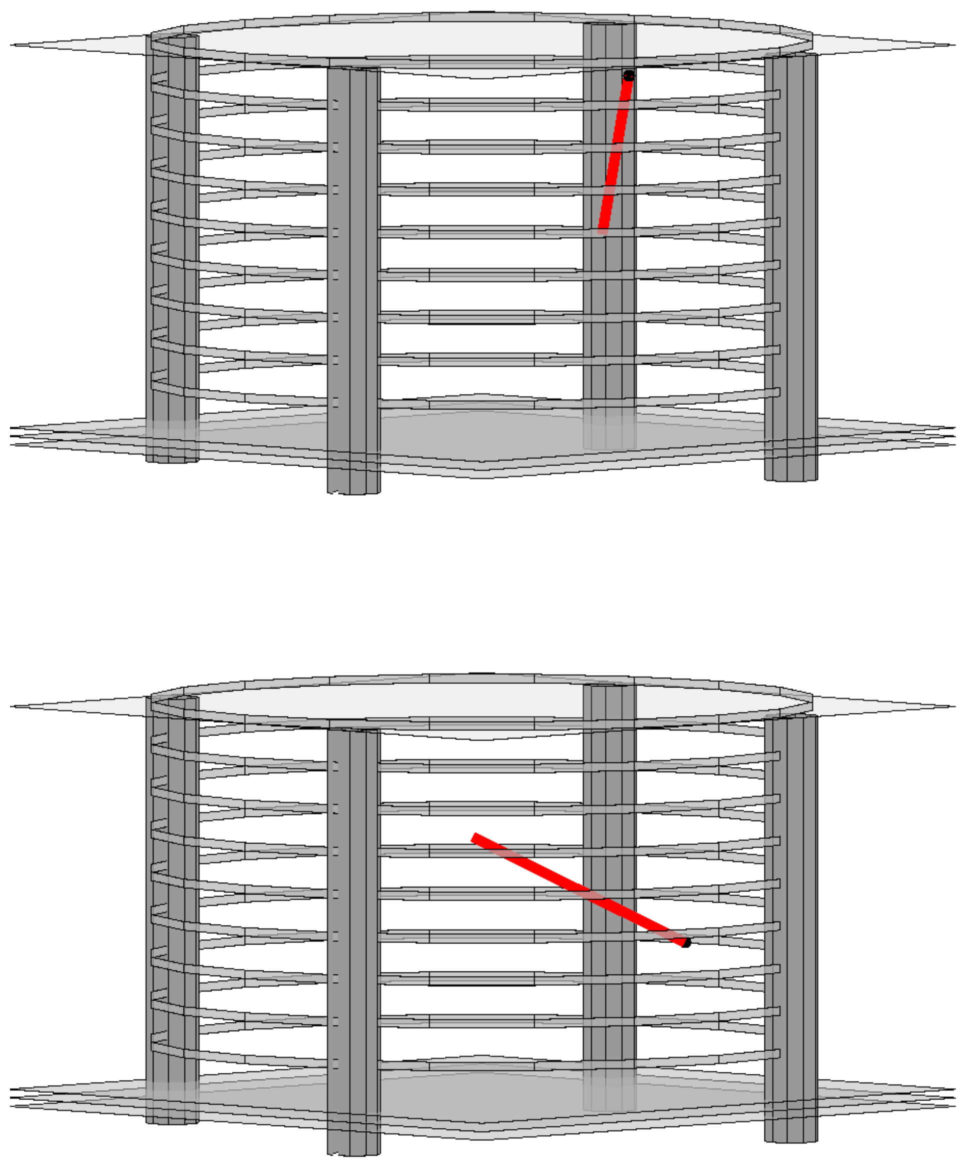
Integrated imaging limited by X-ray flux and detector rate capability
Short exposure times minimise motion blur (e.g. imaging of rotation of miniature drone propellor blades)



Optically read out TPC CCD + PMT



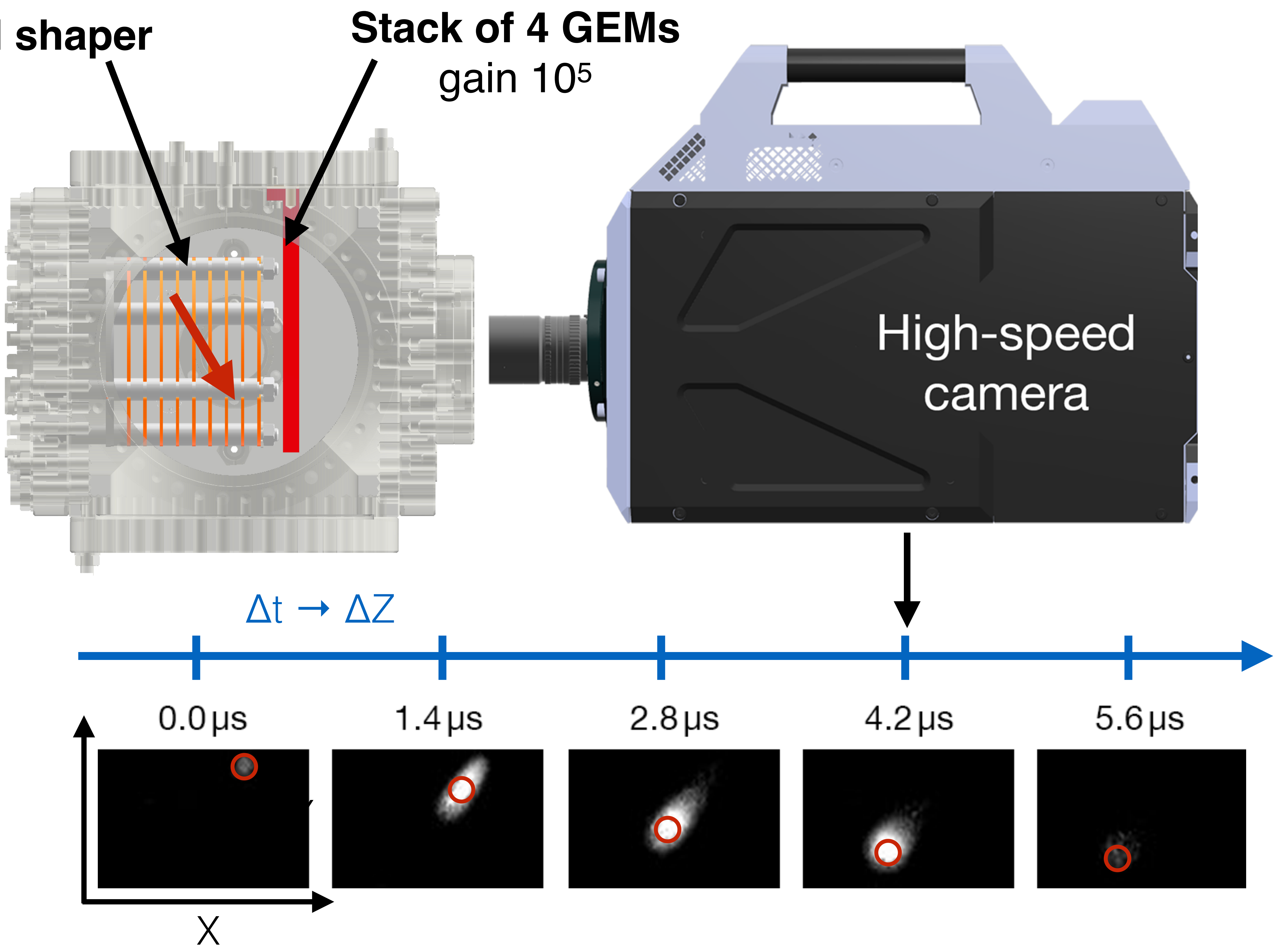
$\Delta t = t_1 - t_2 \rightarrow \mathbf{\Delta Z}$



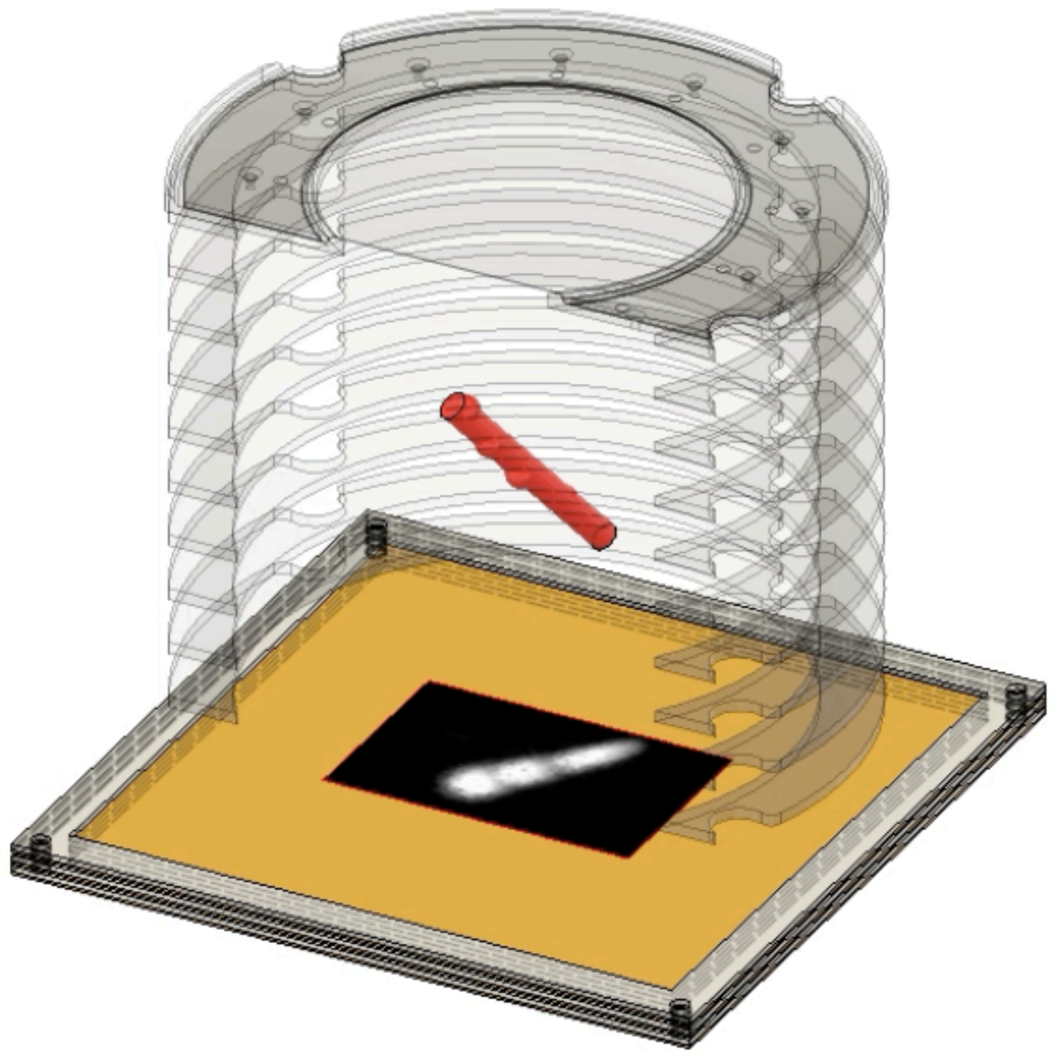
F. M. Brunbauer et al., IEEE NSS 2016

Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



Recorded with 10 V/cm drift field corresponding to ≈0.5 cm/μs in Ar/CF_4



3D alpha track reconstruction (schematic)

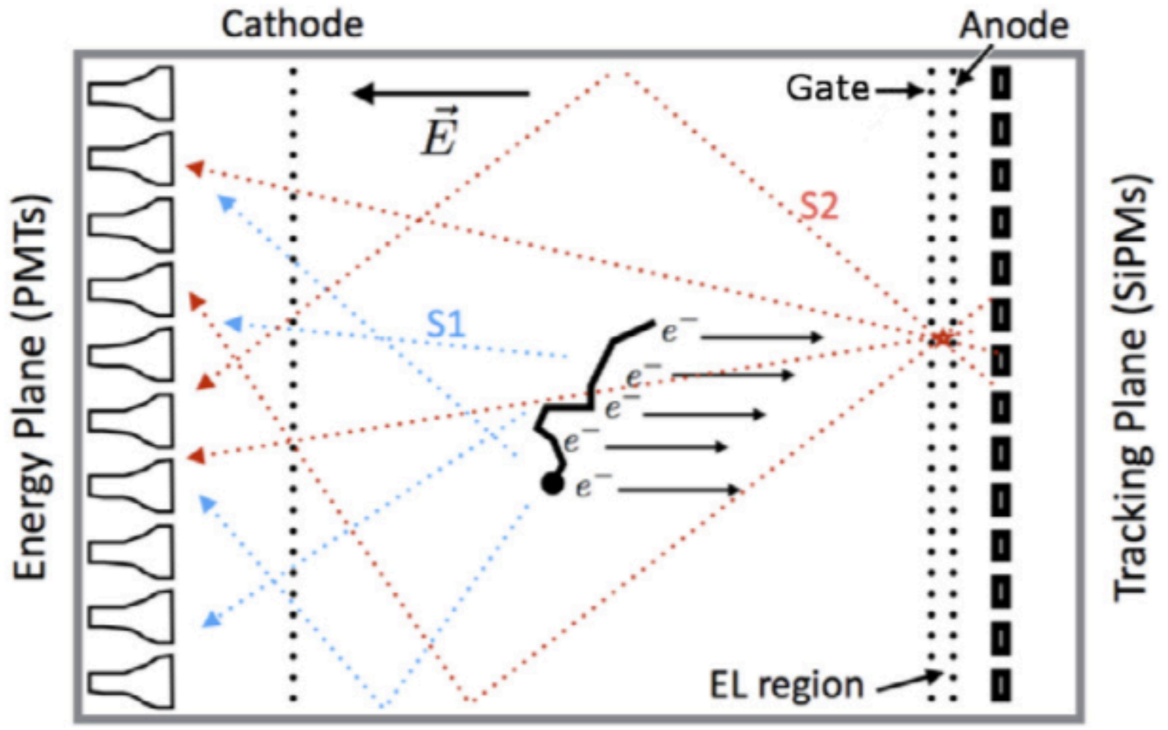
Schematics not drawn to scale

SiPM readout

SiPMs, LG-SiPMs

SiPMs

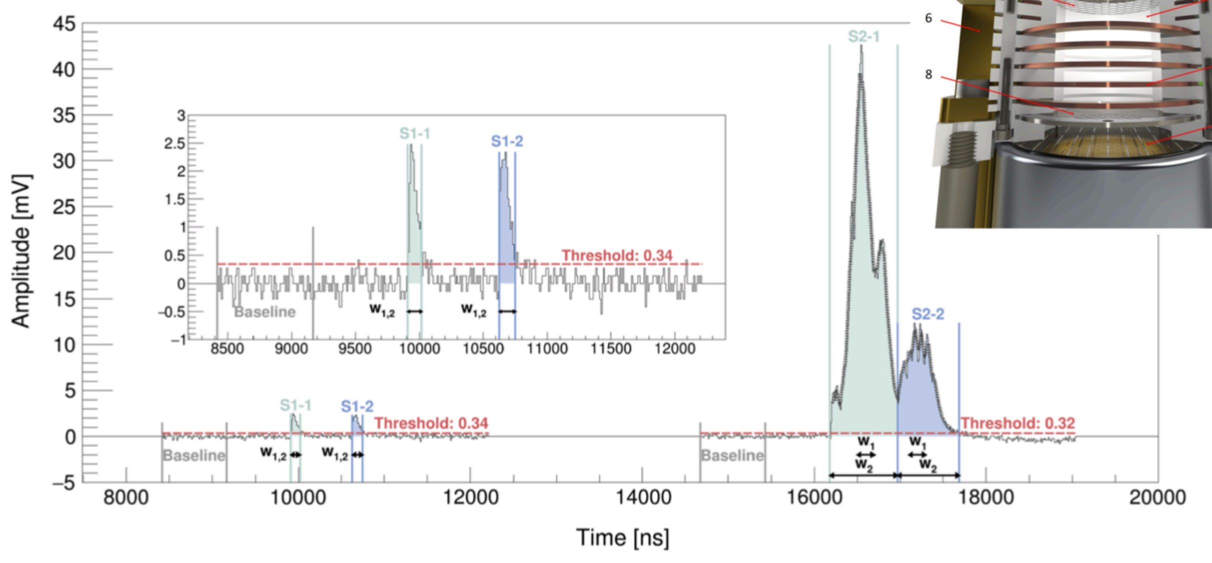
Time-slices of SiPM signals used to reconstruct hit locations as function of time.

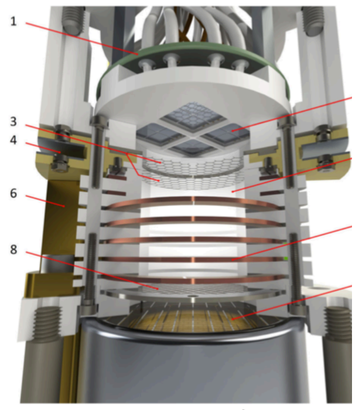


NEXT: SiPMs tracking plane

L. Arazi and NEXT collaboration, collaboration, NIM A 958 (2020) 162126

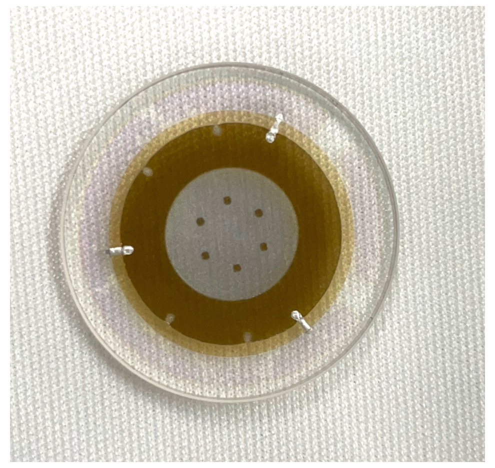
Dual-phase xenon Xurich II TPC



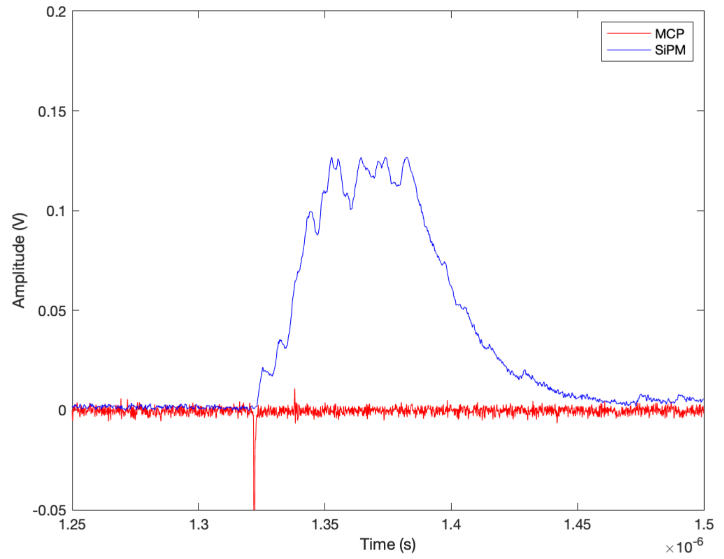


L. Baudis et al, https://doi.org/10.1140/epjc/s10052-020-8031-6

Glass MM



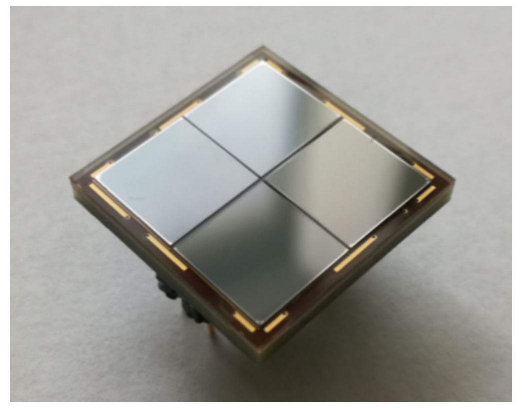
SiPM

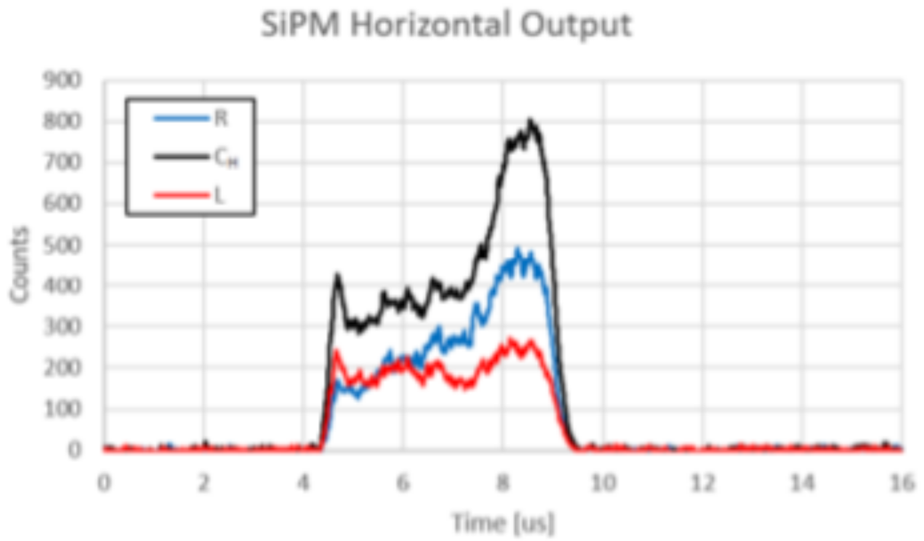


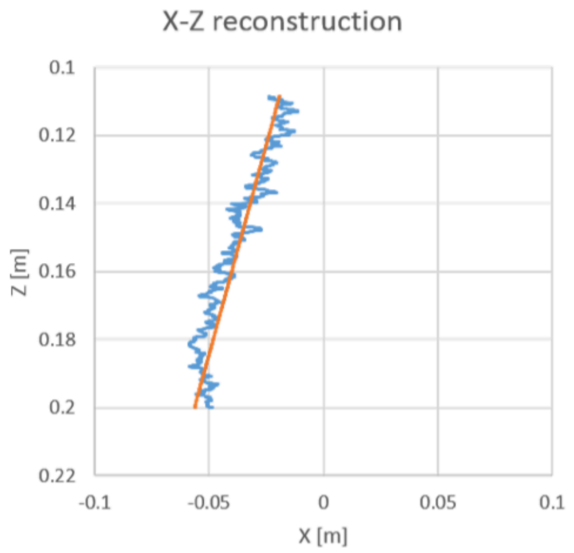
Slow (≈tens of ns) VIS emission from CF_4

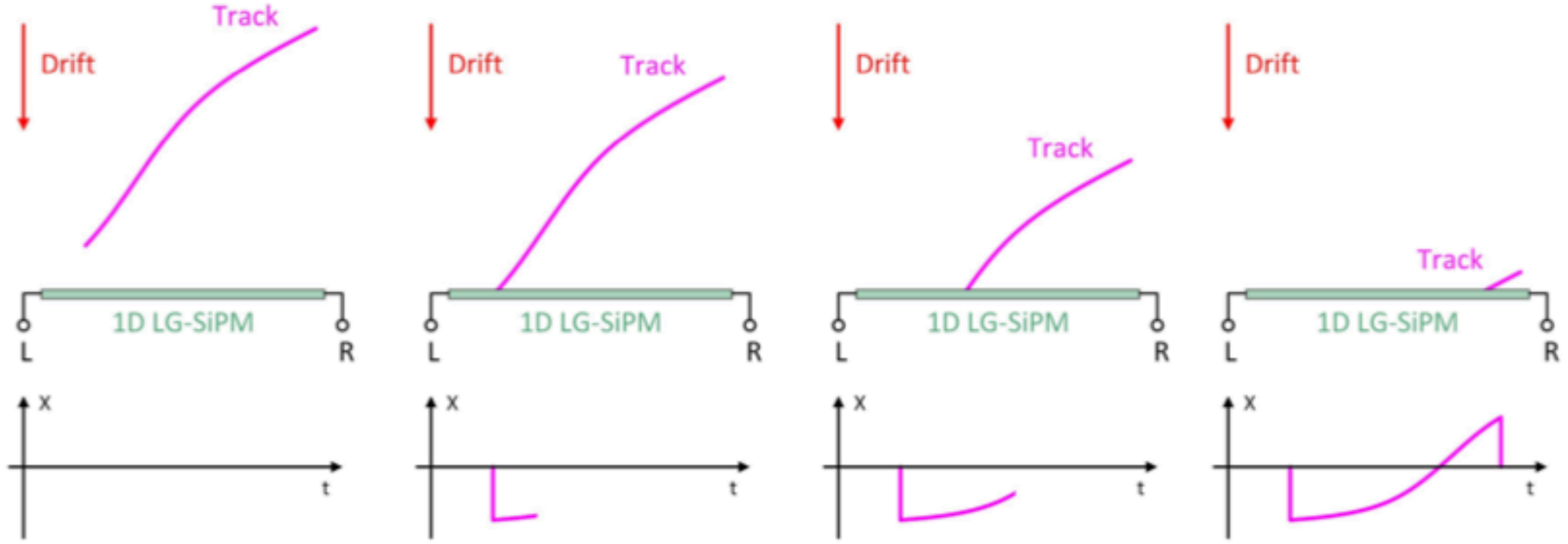
Linearly-graded SiPMs

Time-varying voltage signals are read out by multiple readout channels and ratios are used to determine position at a given time.









A. Gola et al, arXiv:2009.05086 [physics.ins-det]

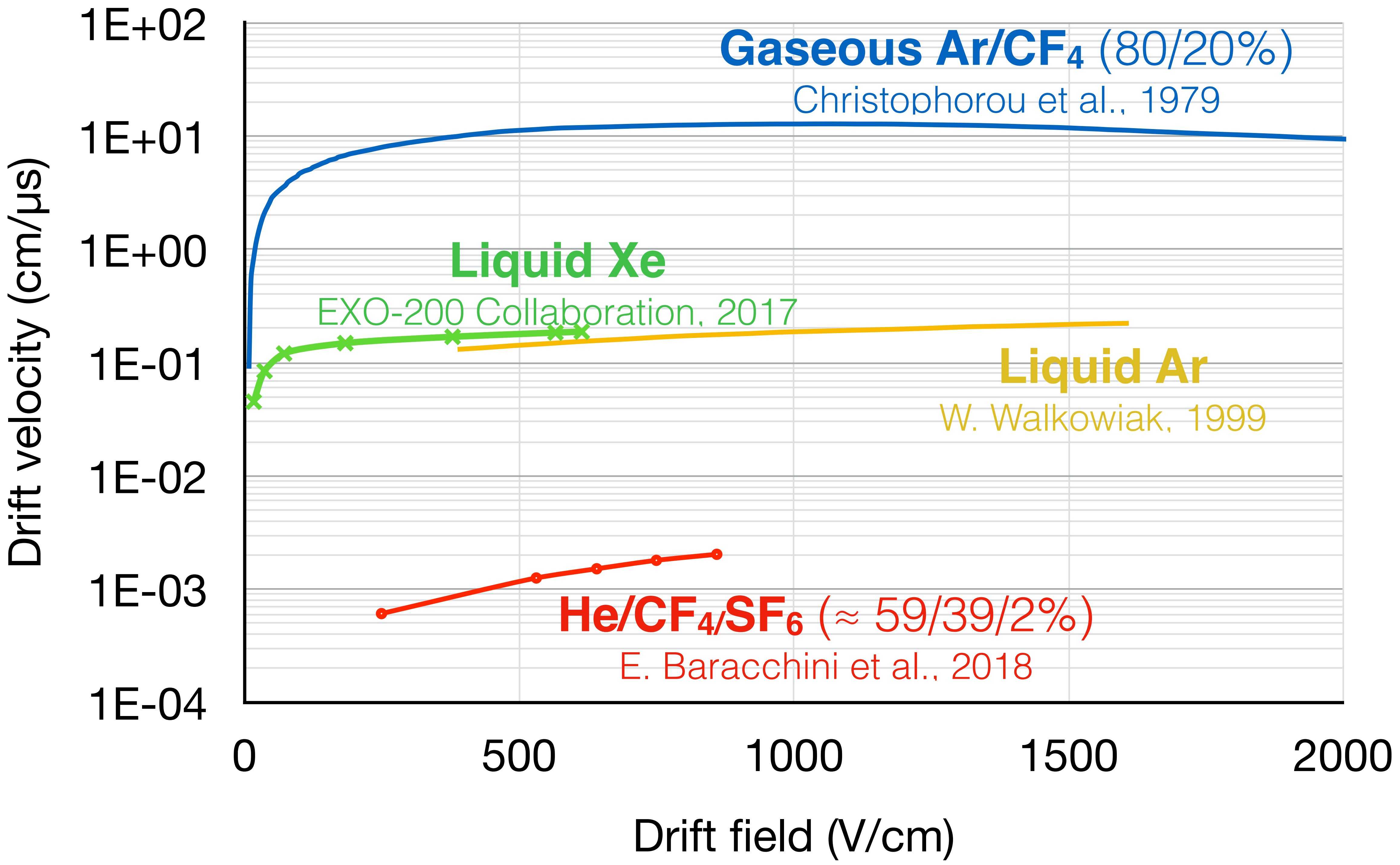
Optical readout of negative ion drift detectors

Negative ion drift for optical TPCs

Low drift velocities

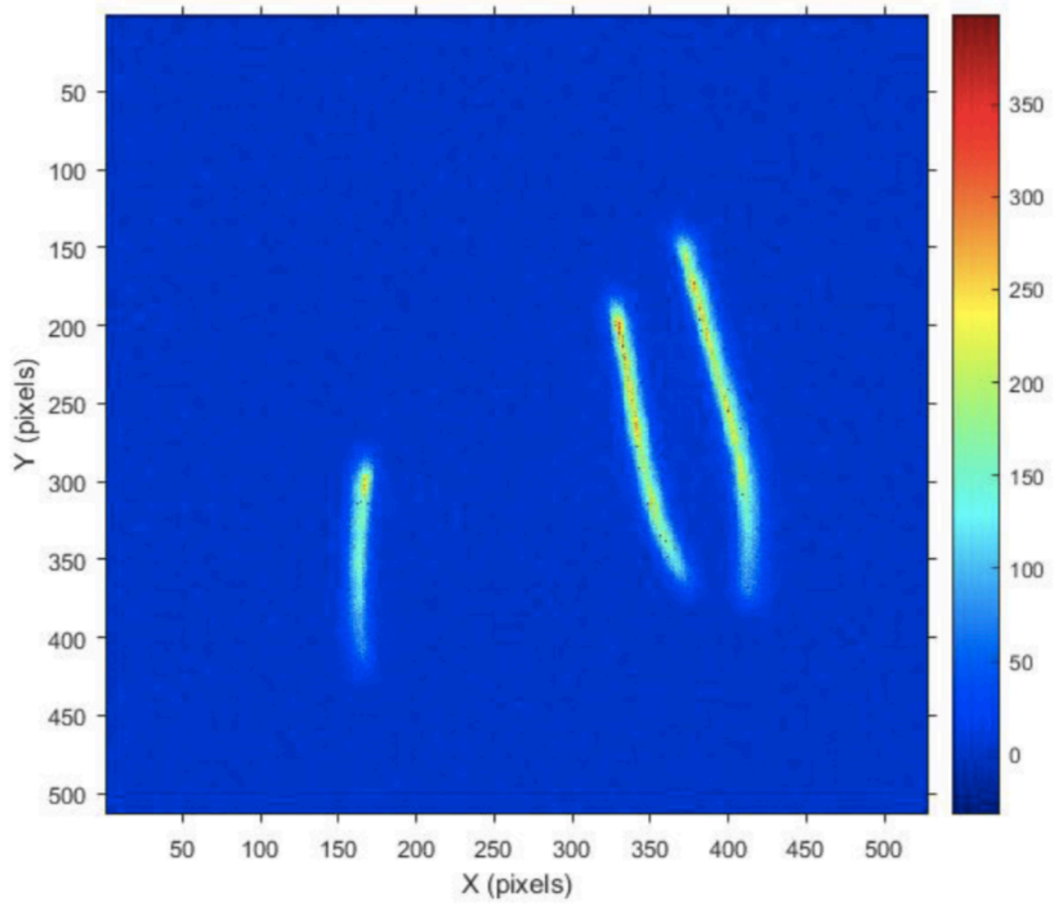
Negative ion drift can provide significantly **slower drift velocities**, which are ≈3 orders of magnitude slower than electron drift velocities.

This may permit the recording of multiple frames at high resolution during negative ion drift time.

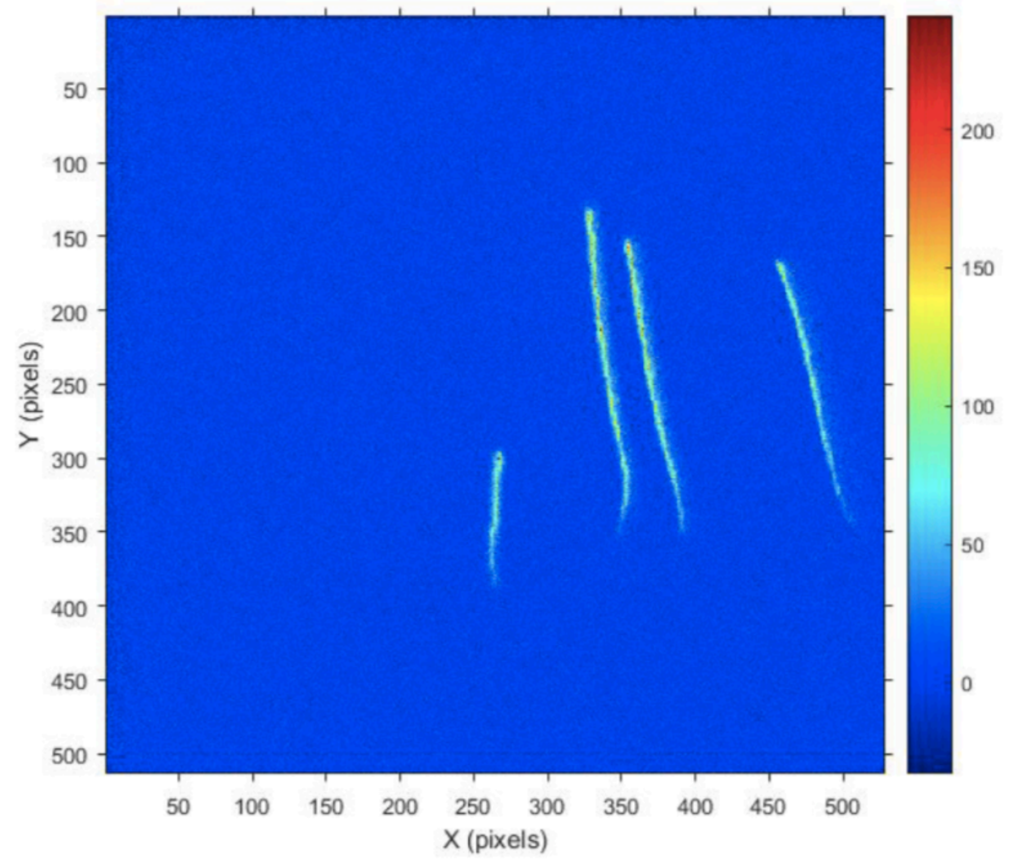


Low diffusion

Drift of ions strongly suppresses diffusion and can provide significant improvement in achieving well-defined images which profit from **high-granularity image** sensors.



150 Torr CF_4, **σ ~ 450 um**



150 Torr CF_4 + 5.9 Torr CS_2, **σ ~ 150 um**

D. Loomba, UNM

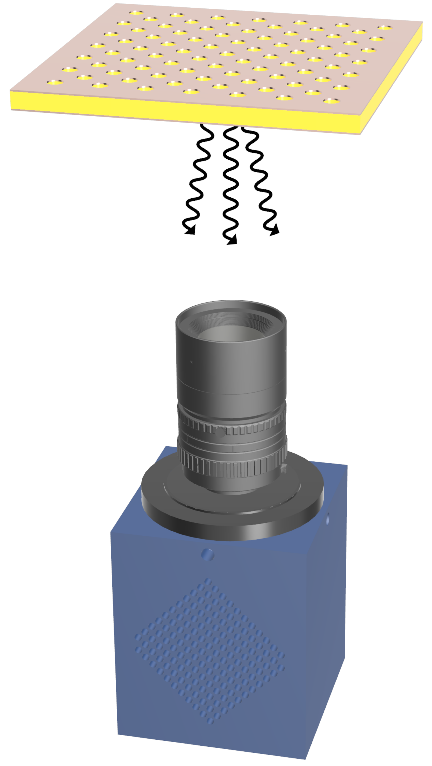
D. Marques, PMT analysis for Negative Ion Drift and 3D reconstruction

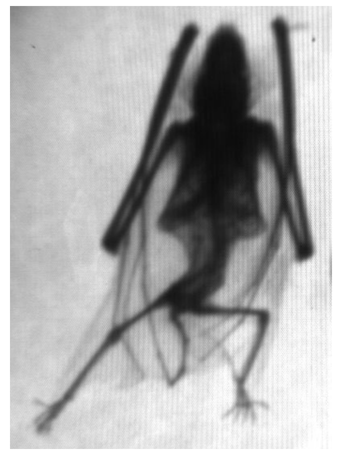
Conclusions

Optical readout

Exploiting combination of high-sensitivity imaging sensors with optics for versatile readout modality of various MPGDs.

High spatial resolution can be achieved without need for extensive reconstruction.

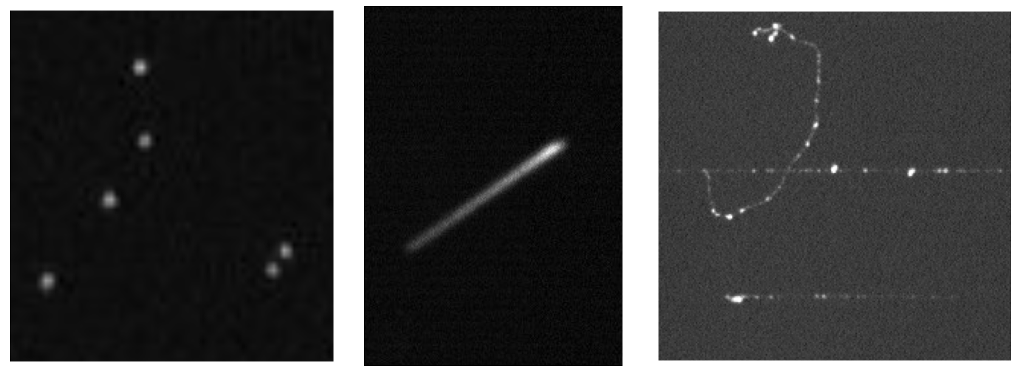


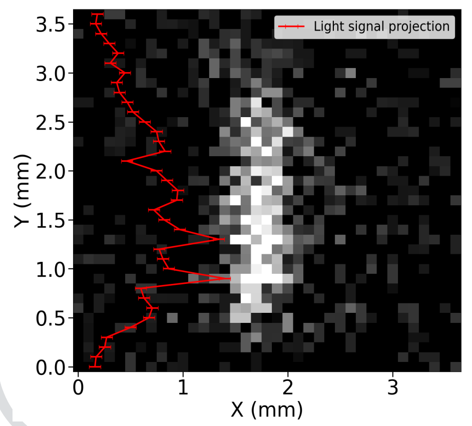


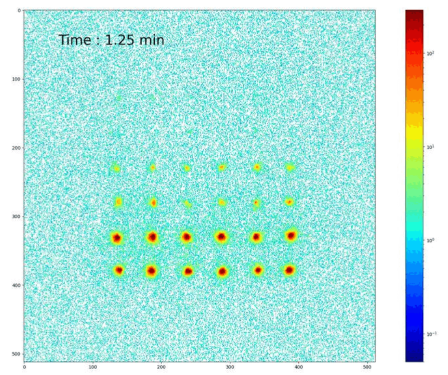
Imaging, high speed

Integrated imaging for intuitive X-ray radiography.

Single-event sensitivity can be used for efficient full-field X-ray fluorescence imaging, neutron imaging and beta autoradiography.



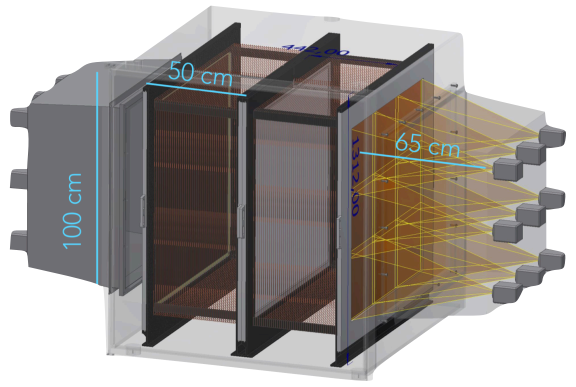


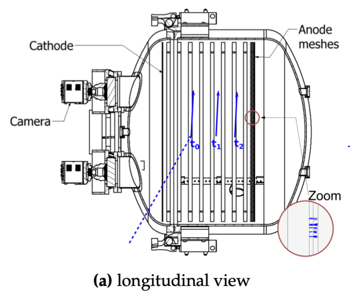


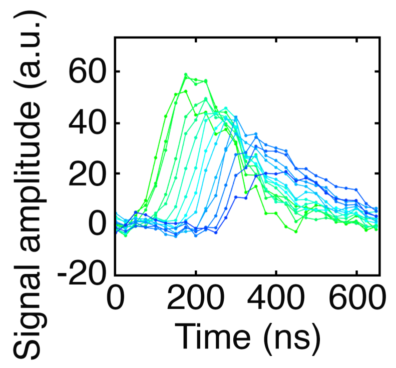
Optical TPCs and 3D

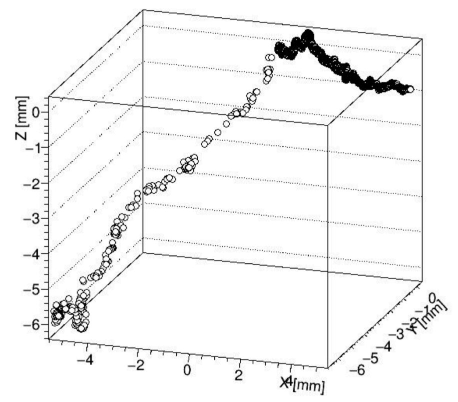
Optical TPCs combine high-granularity 2D readout with 3D track reconstruction.

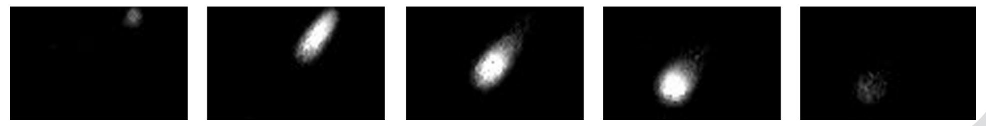
Compatible with complex event topologies at low rates.





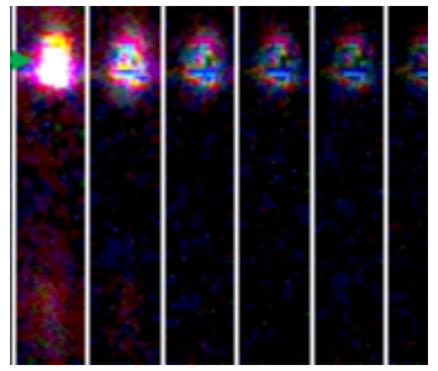


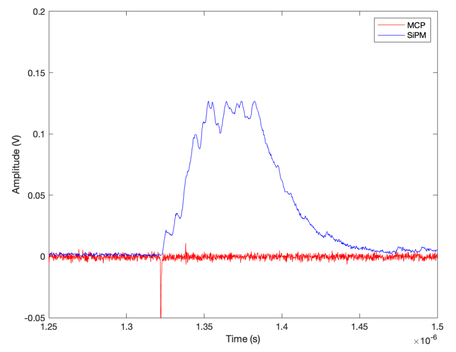


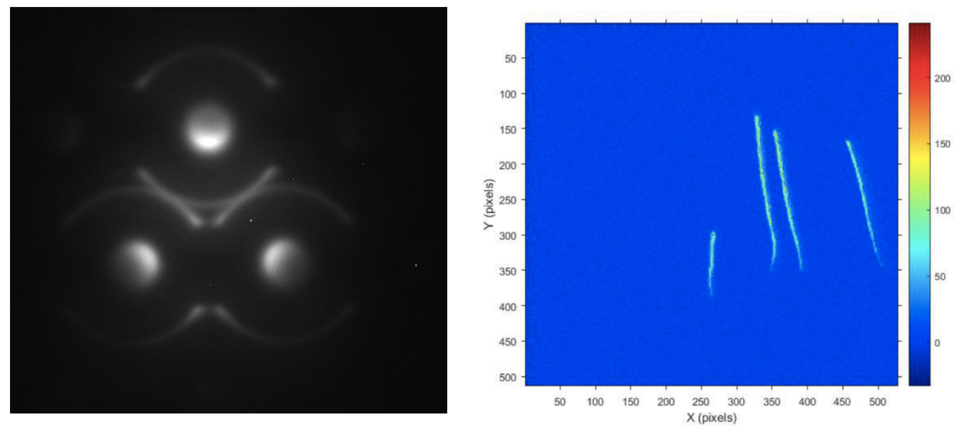


Detector R&D

Scintillation light readout is a powerful tool to visualise gain in detectors and can be used for recording detector uniformity maps, discharges as well as single event responses. Compatible with hole-type and planar MPGDs (MM, µRWELL, …).



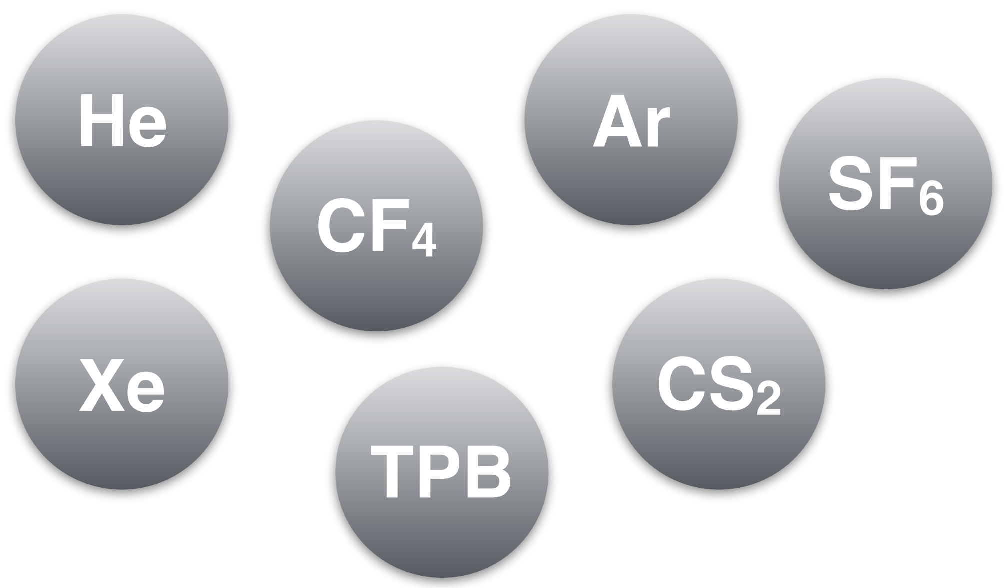




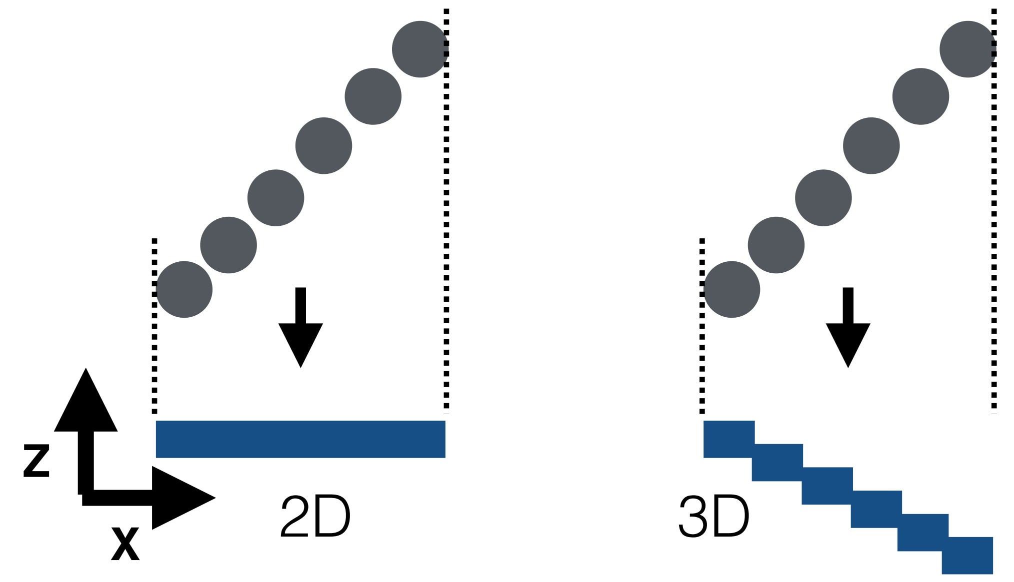
Challenges and outlook

High-gain MPGD technologies and **optimal matching** of amplification structure and pixel size

Sensor sensitivity: major advances in state-of-the-art cameras
- low noise CMOS sensors with <1e- read noise enable photon counting
- SPAD sensors for single photon counting

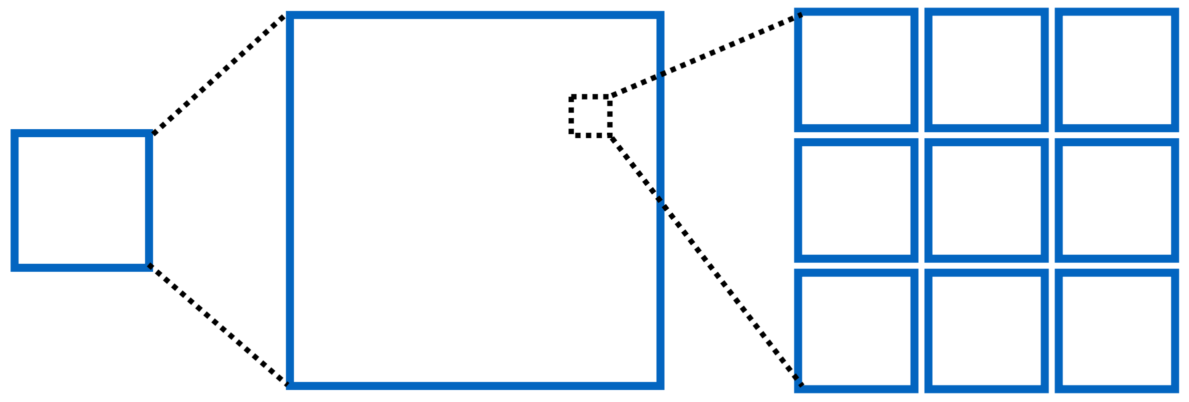


Scintillation emission spectra
- **Gas choice** may be driven by physics and not ideal match for imaging sensors
- Alternative gases and pure noble gases may be accessible with **WLSs**
- Extended **VUV sensitivity** of imaging sensors or image intensifiers (photocathode options)



Depth information in OTPCs
- **Combined** optical+charge readout, detailed waveform analysis
- **Negative ion** TPCs for superior diffusion characteristics
- **SiPM** readout

Readout speed
- **Ultra-fast optical readout** with Mfps, data rates and volumes
- **Data-driven** readout ASICs with <ns time resolution



Equipping large areas
- **Optics** / sensors: low geometric acceptance at **large focusing lengths**
- **Tiling** of readout ASICs with minimal dead area, cost

Pixellated readout approaches (optical, hybrid, ASICs) offer unprecedented levels of detail in recorded events.

?

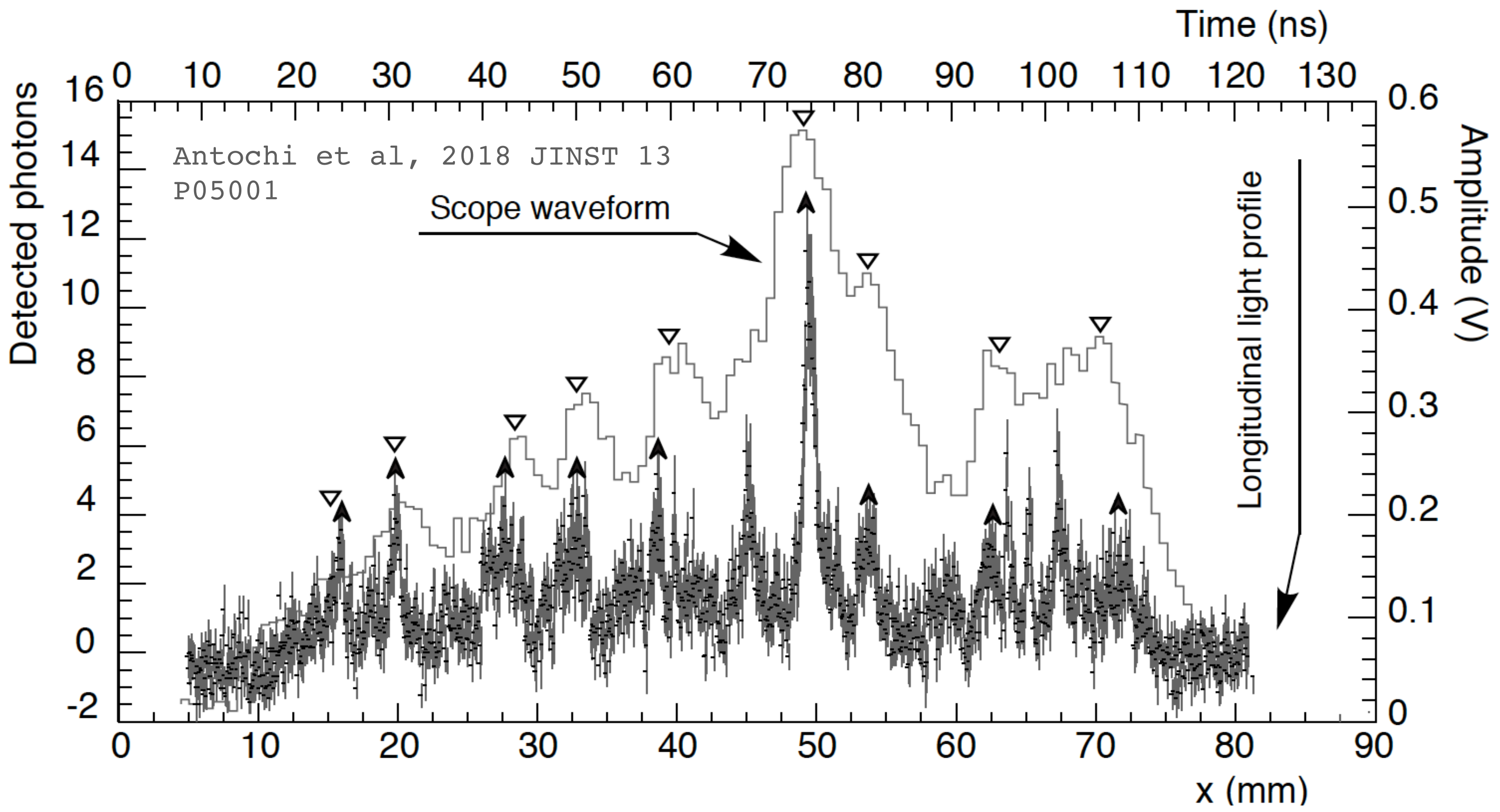
Backup

Depth reconstruction techniques

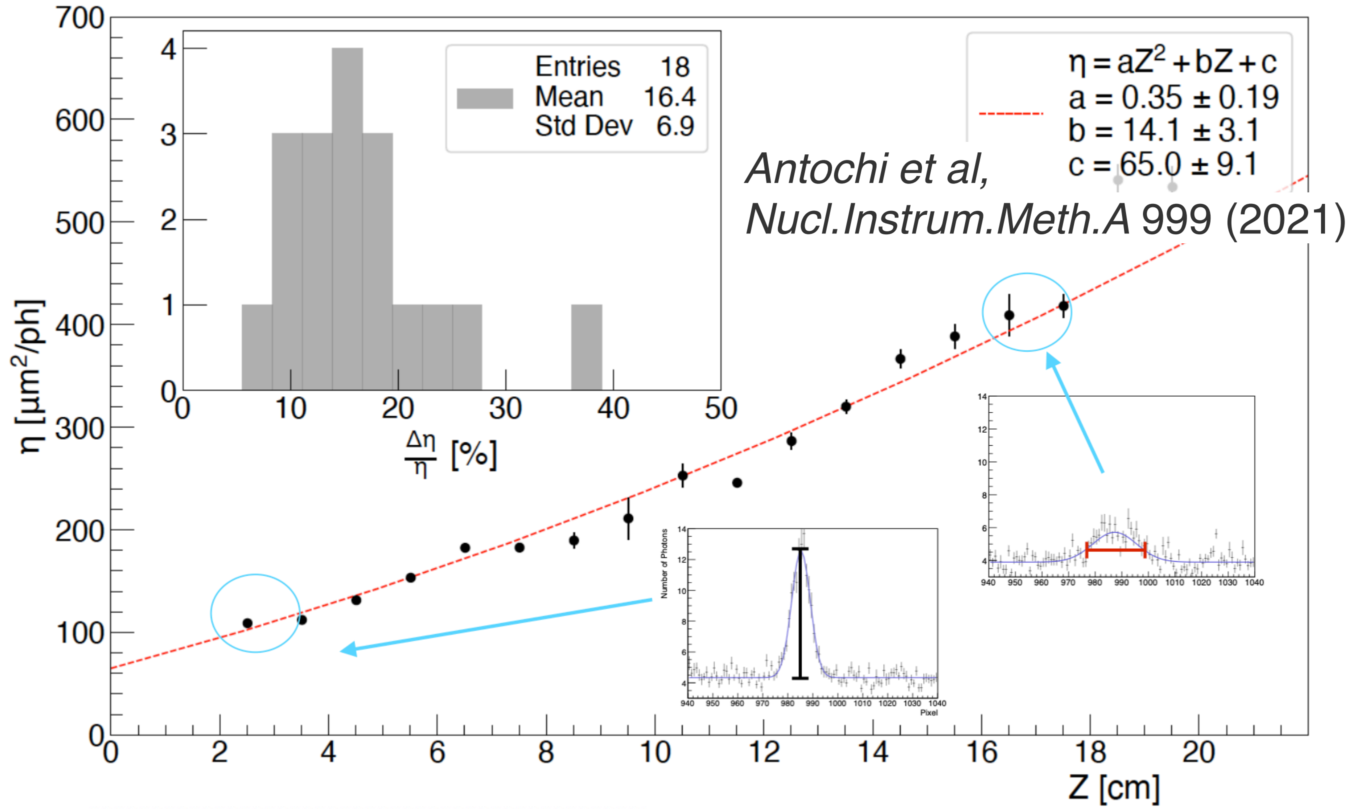
Fast drift velocity in CF4 mixtures (e.g. >10 cm/μs in Ar/CF4) make sub-mm scale depth resolution challenging

Alternative techniques for exploiting information in images and adding precise **auxiliary timing information**:

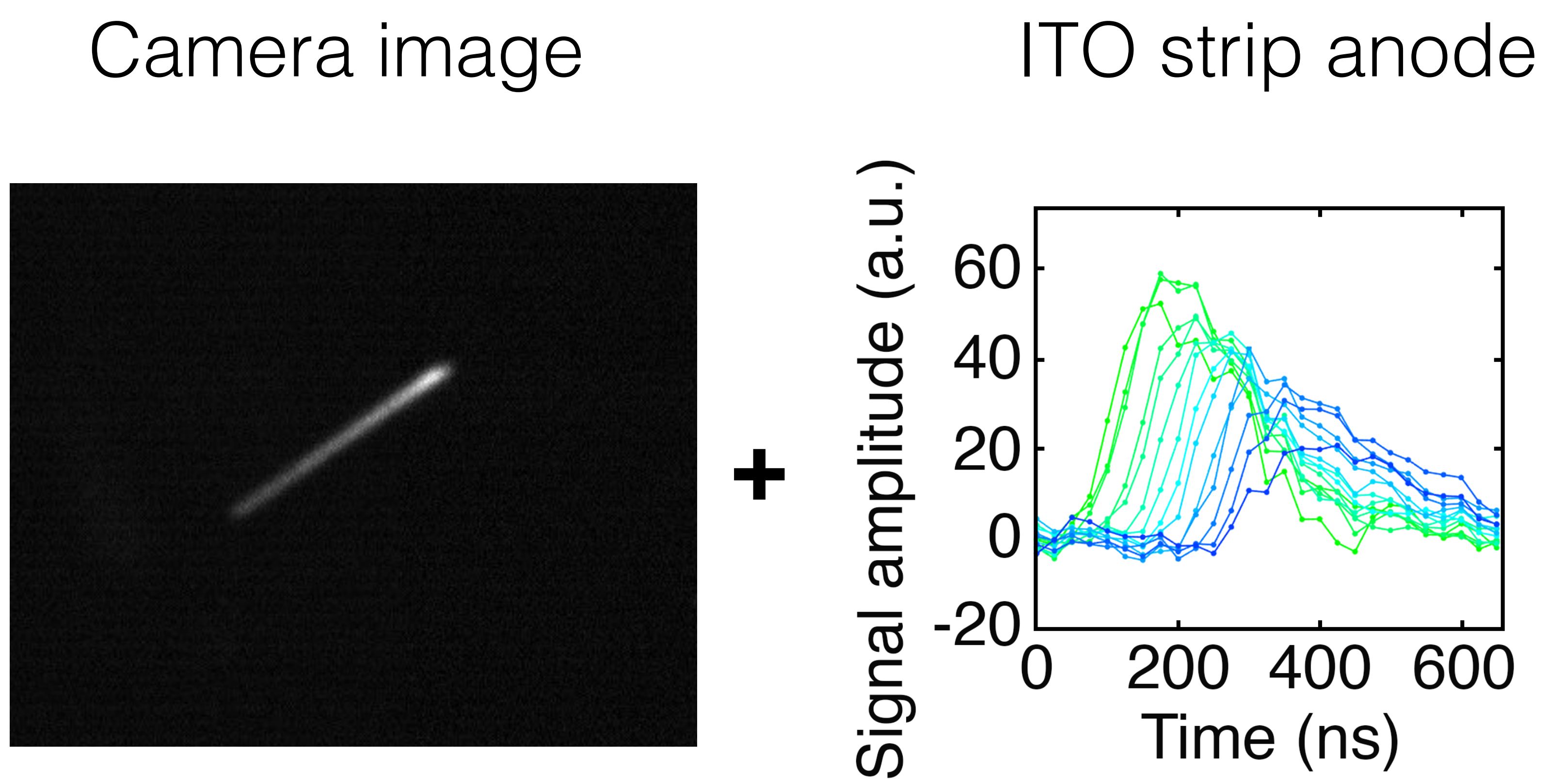
Matching of clusters in light intensity profile from image and in PMT waveforms for Z-determination



Exploit diffusion (amplitude vs. width of charge cloud) to determine drift distance



Combined 2D **image** with timing information from **electronic readout** from e.g. transparent strip anode with ITO



D. Pinci et al., CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search, MPGD 2019
https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf

F. Brunbauer et al. 10.1109/TNS.2018.2800775

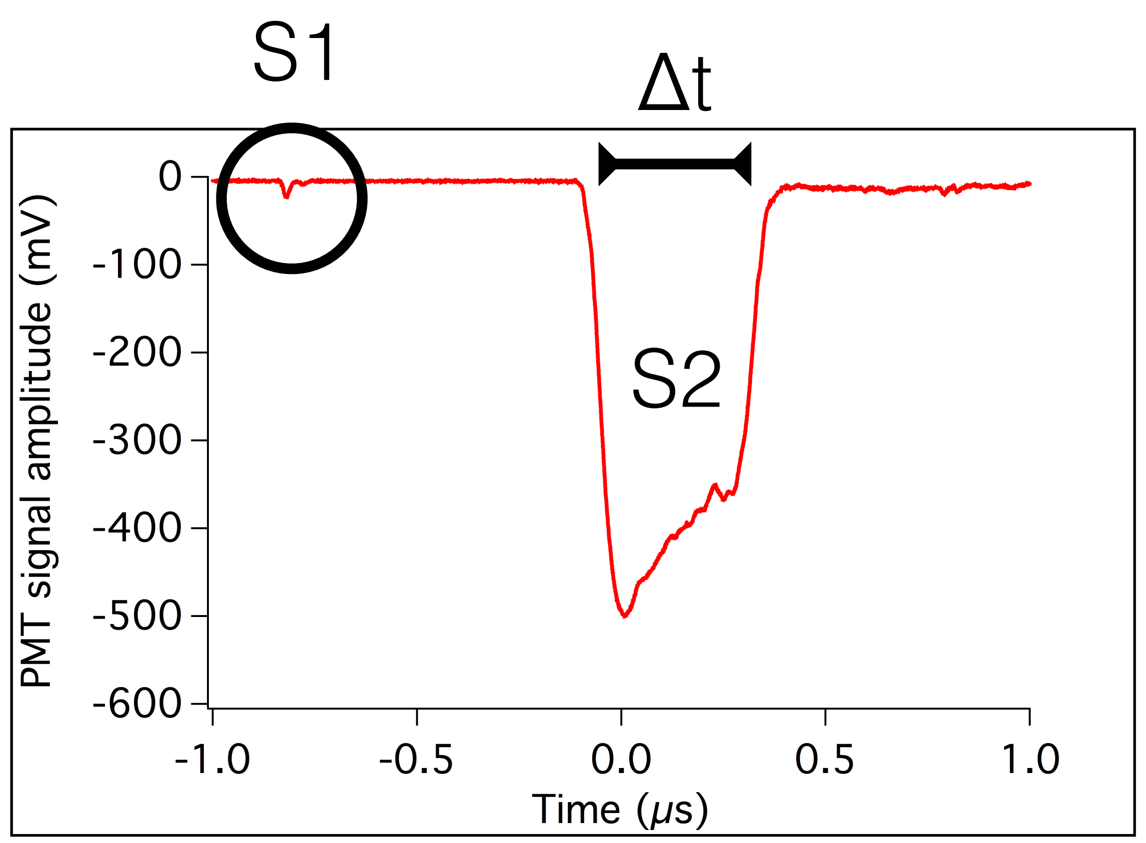
Depth reconstruction techniques

Depth information can be extracted from **fast photon detectors** (PMT, SiPM) for 3D track reconstruction

Limited granularity in **fast photo detectors** may enable more accurate reconstruction of particle trajectories

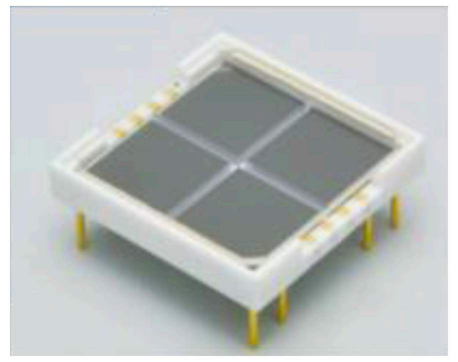
Photomultiplier Tubes (PMTs)

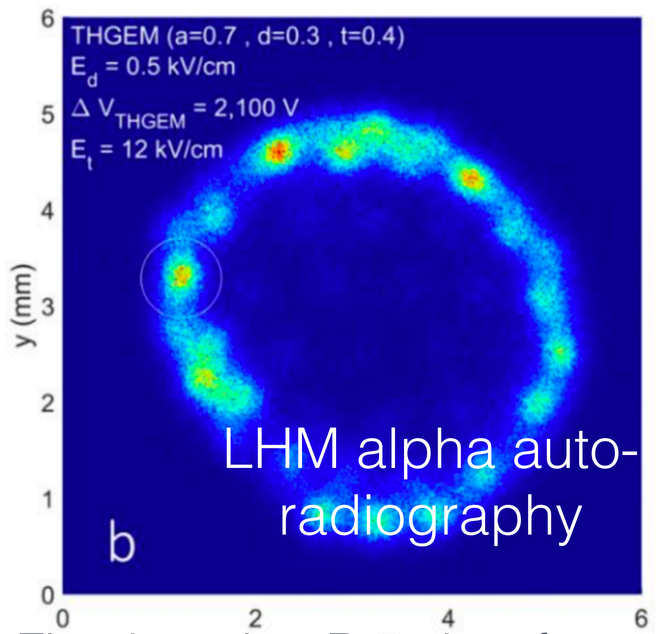
Hamamatsu R375 PMT



- Single waveform scintillation light
- Shape of signal used for determination of depth extent and energy loss profile

Silicon Photomultipliers (SiPMs)

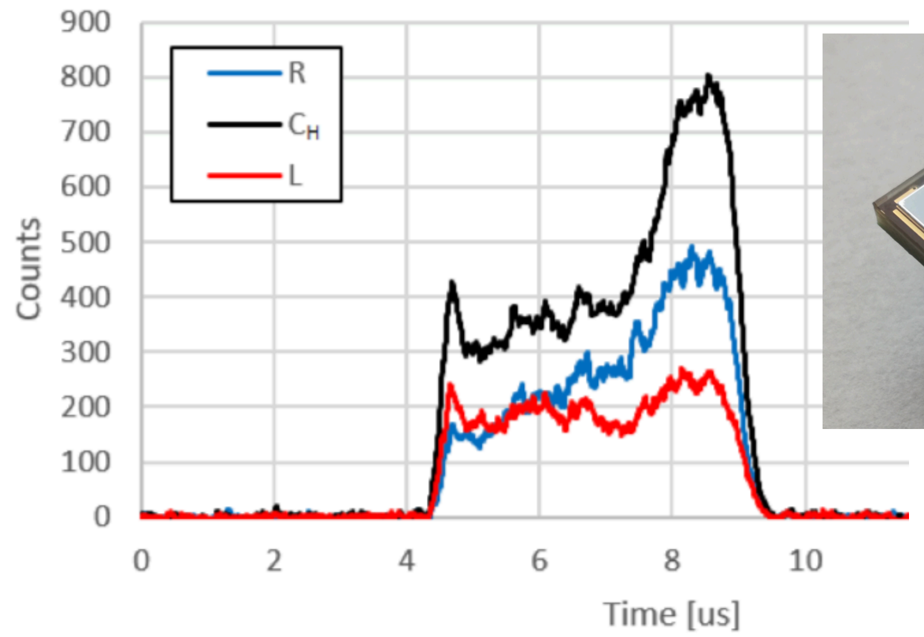


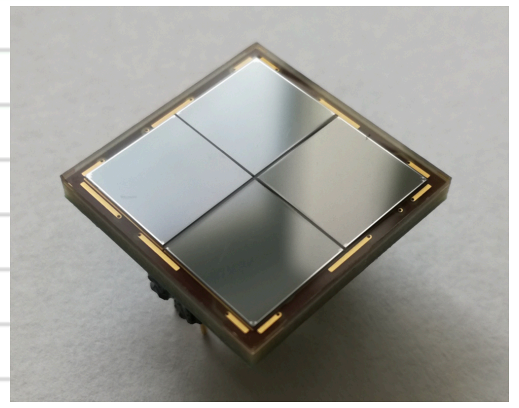


E. Erdal et al.. (2018). First Imaging Results of a Bubble-assisted Liquid Hole Multiplier with SiPM readout in Liquid Xenon.

- Arrays of SiPMs to reconstruct clusters
- Fast timing response can enable operation in higher rate environments and 3D tracking with known t_0 timing signals

Linearly Graded Silicon Photomultipliers (LG-SiPMs)





A. Gola et al 2020 JINST 15 P12017
https://doi.org/10.1088/1748-0221/15/12/P12017

- Current split in four outputs to calculate x and y coordinates from current signals
- Position resolution down to order of size of microcells (30μm)
- Fast response time of tens of ns

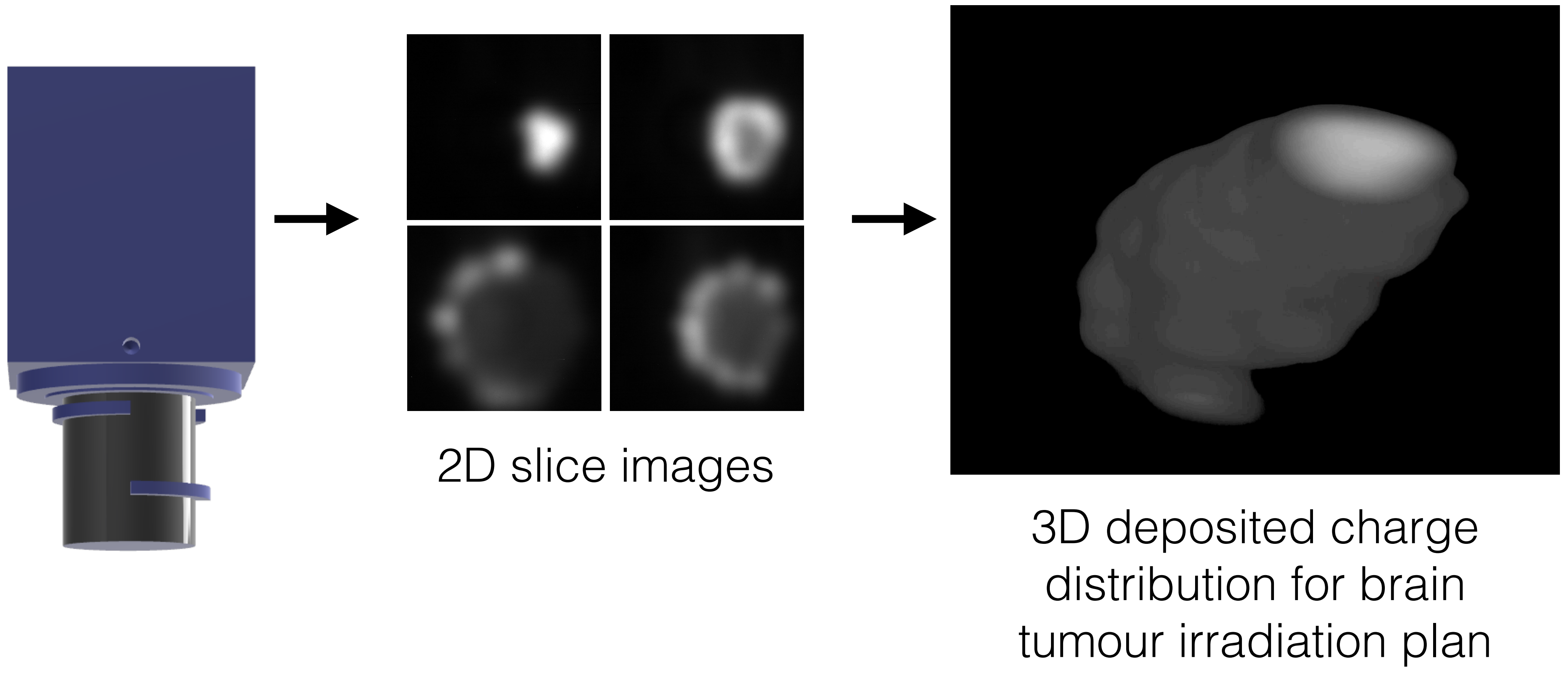
Hadron therapy monitoring

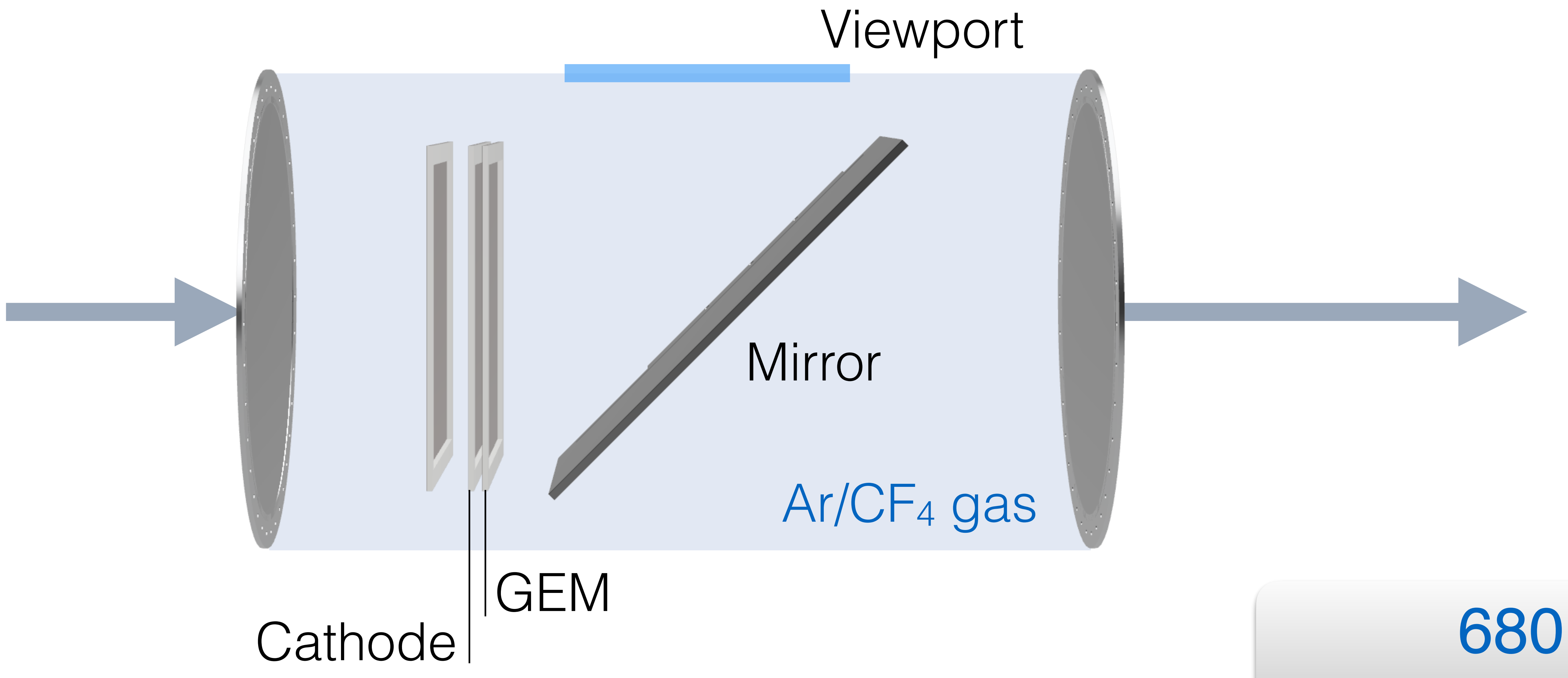
Optically read out GEMs can be used online monitoring in hadron therapy

Low material budget of gaseous detector minimises beam attenuation and multiple scattering

Optical readout permits placement of camera outside of beam path (lower material budget, lower radiation exposure of sensor)

This can provide **high spatial resolution** images of scanning pencil beams for beam characterisation and treatment plan verification



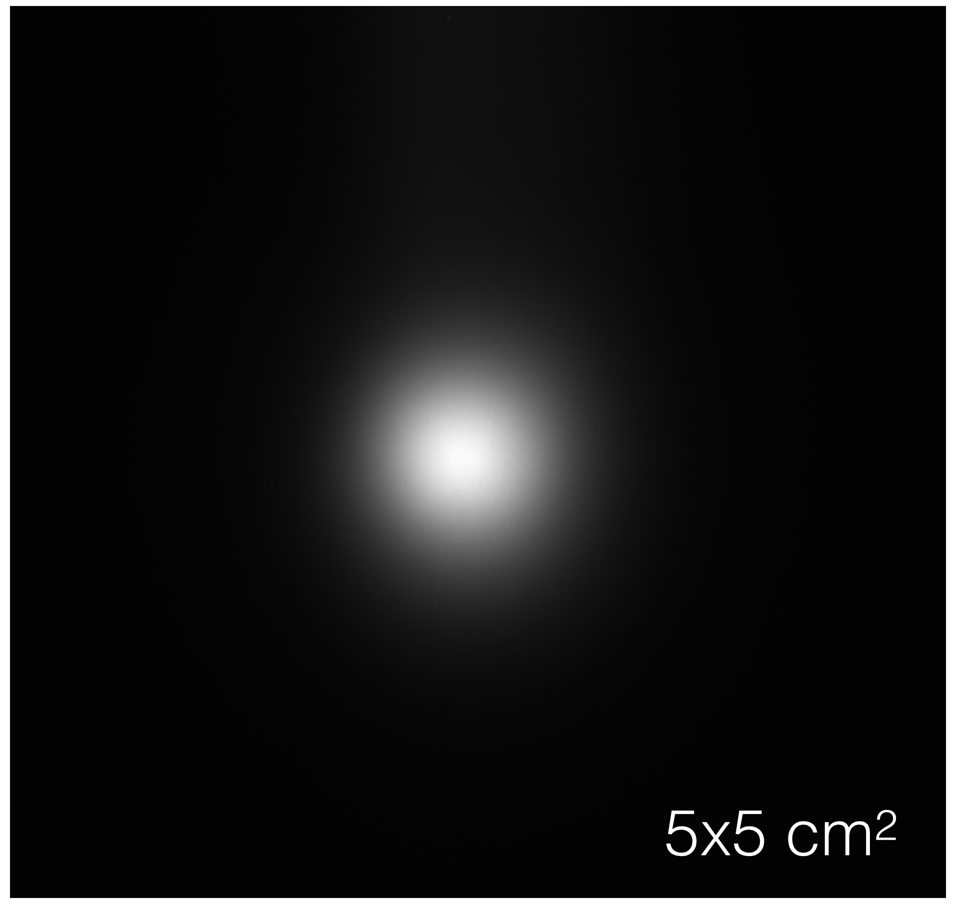


680 μm
Total water equivalent thickness

Schematics not drawn to scale

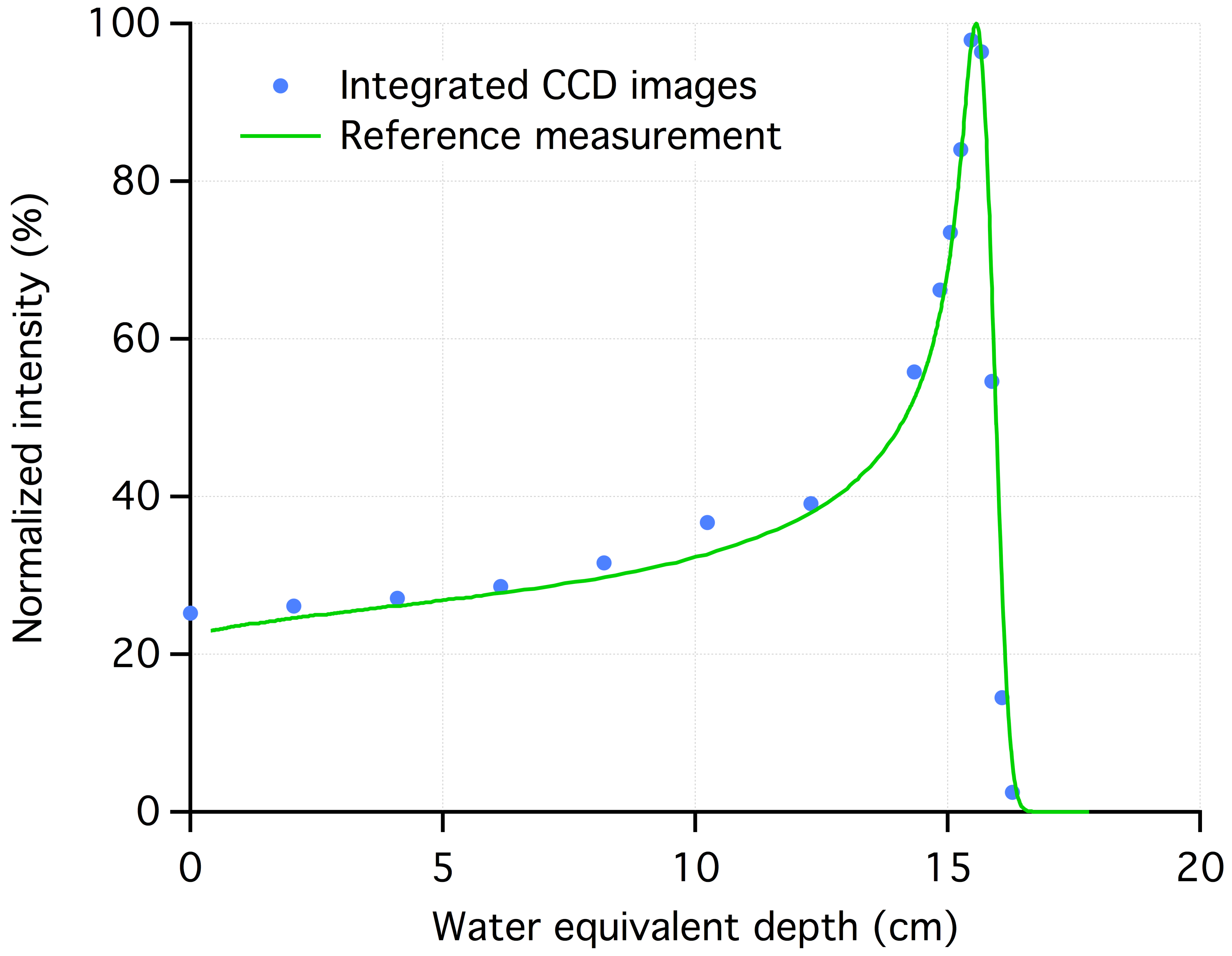
Dose depth curve recording

Proton beam profile

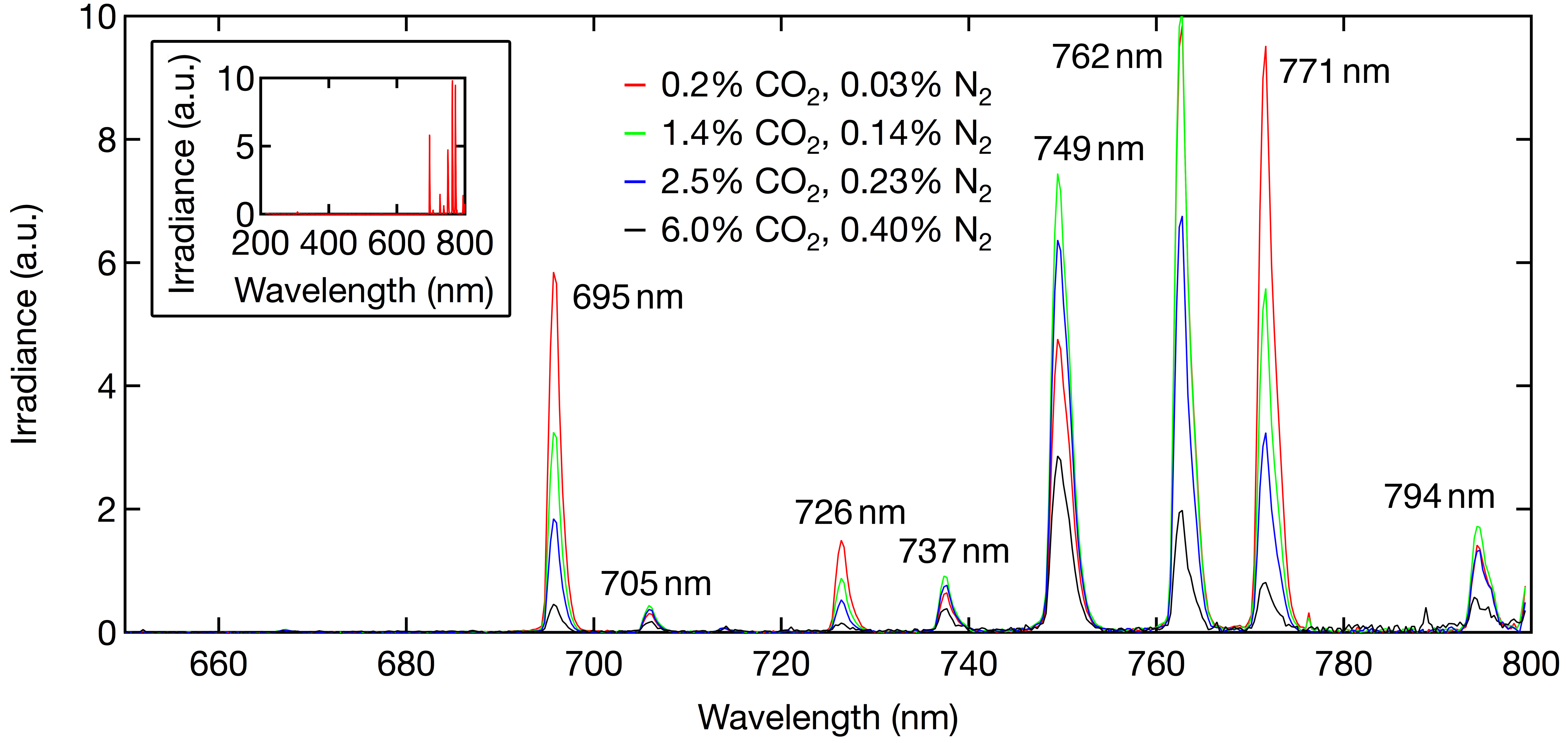


200 MeV pencil beam

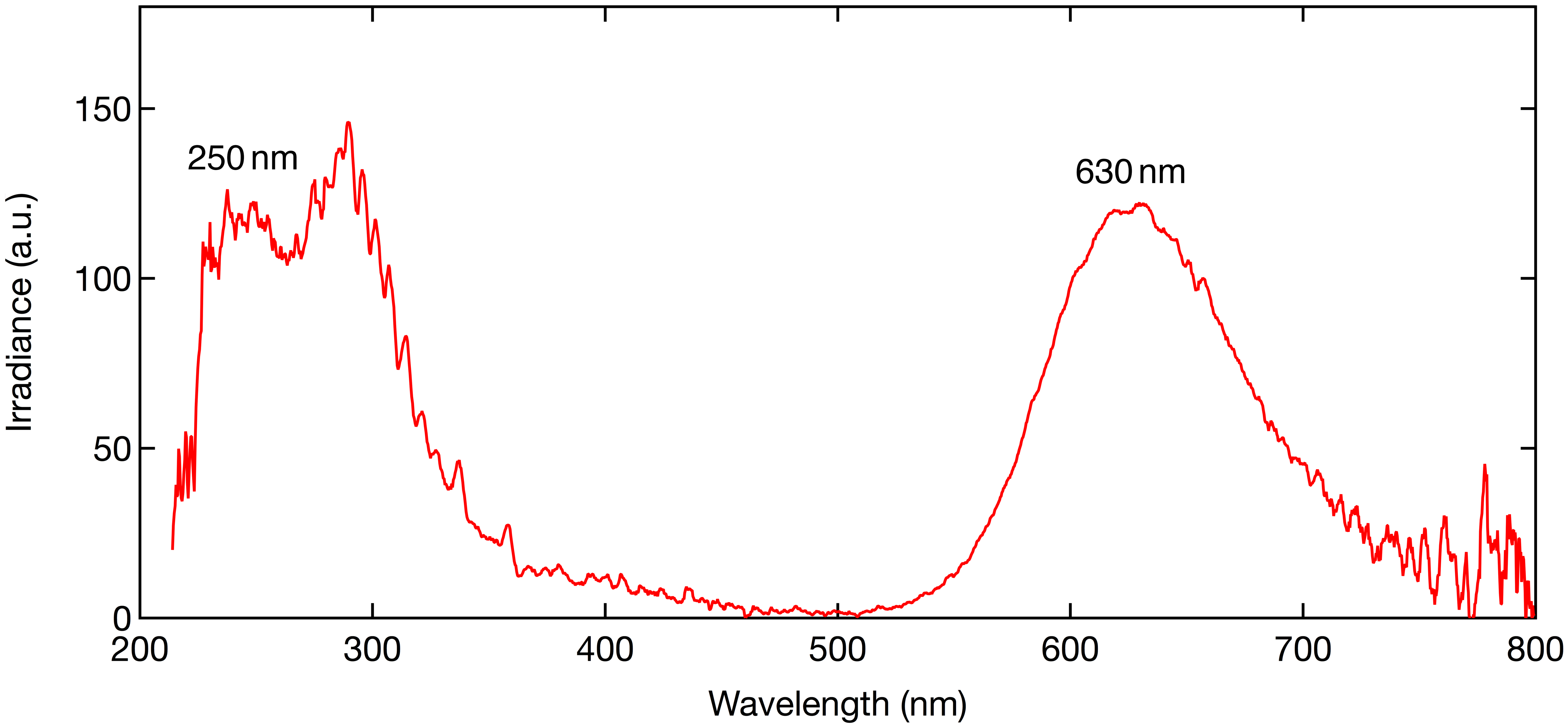
Dose depth curve



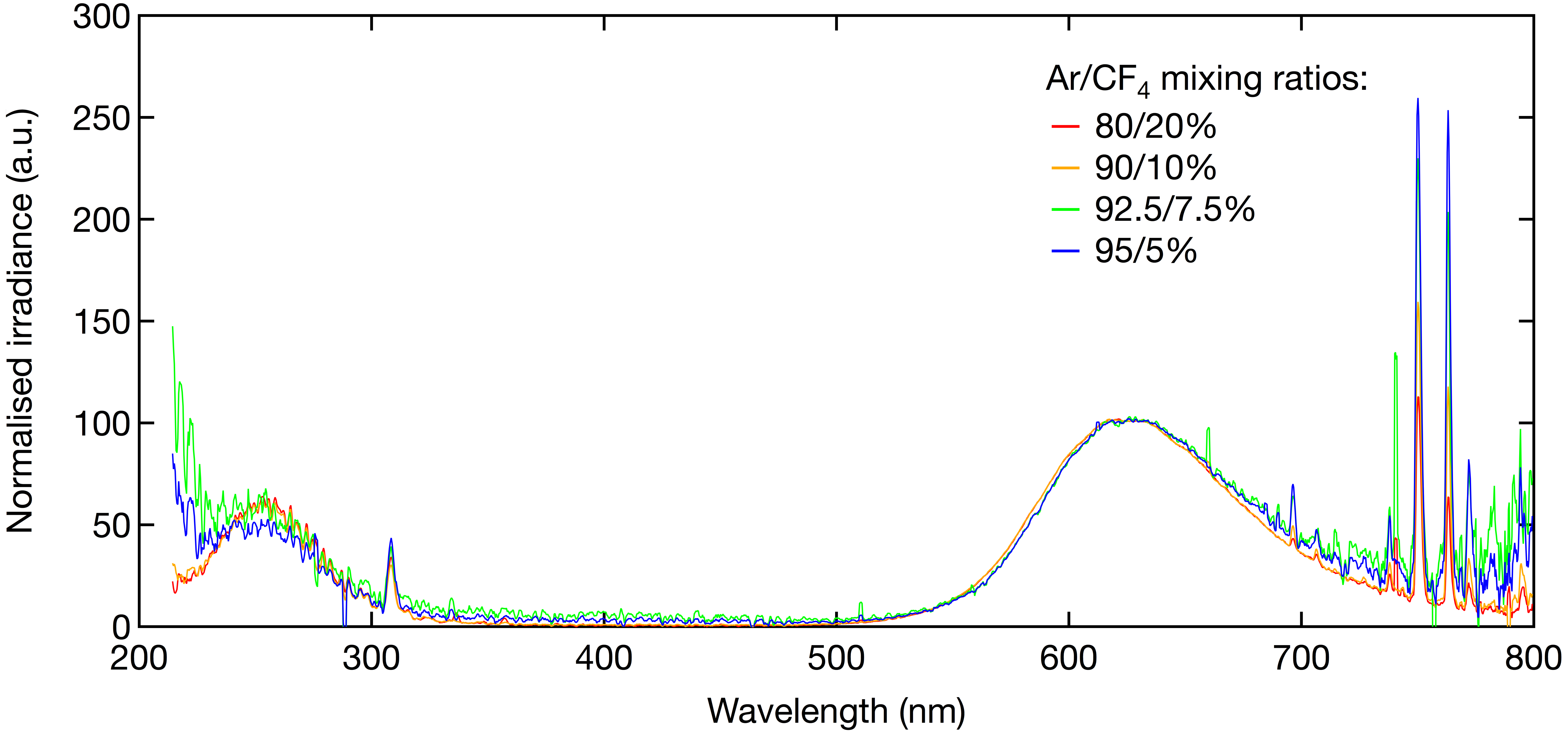
Ar scintillation



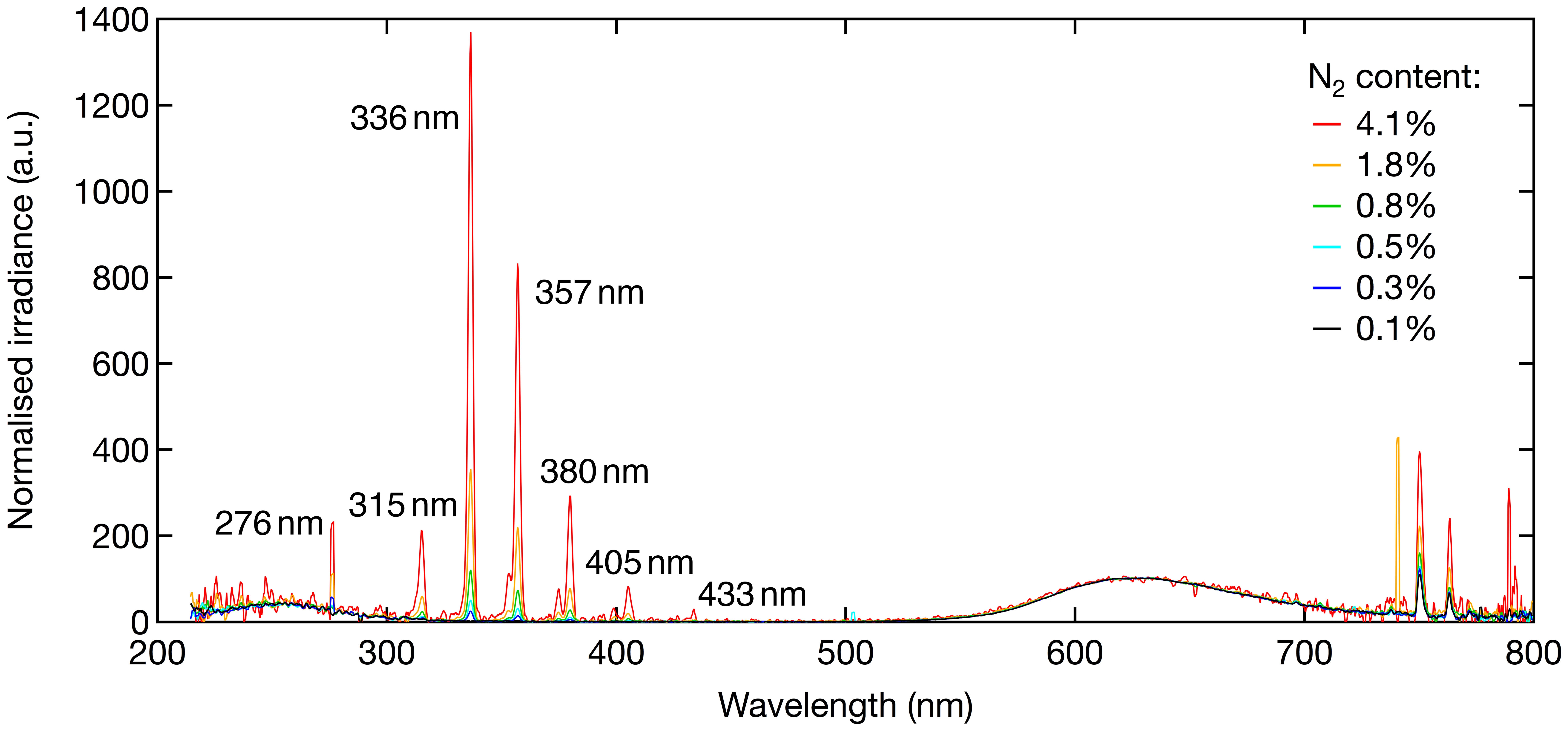
CF_4 scintillation



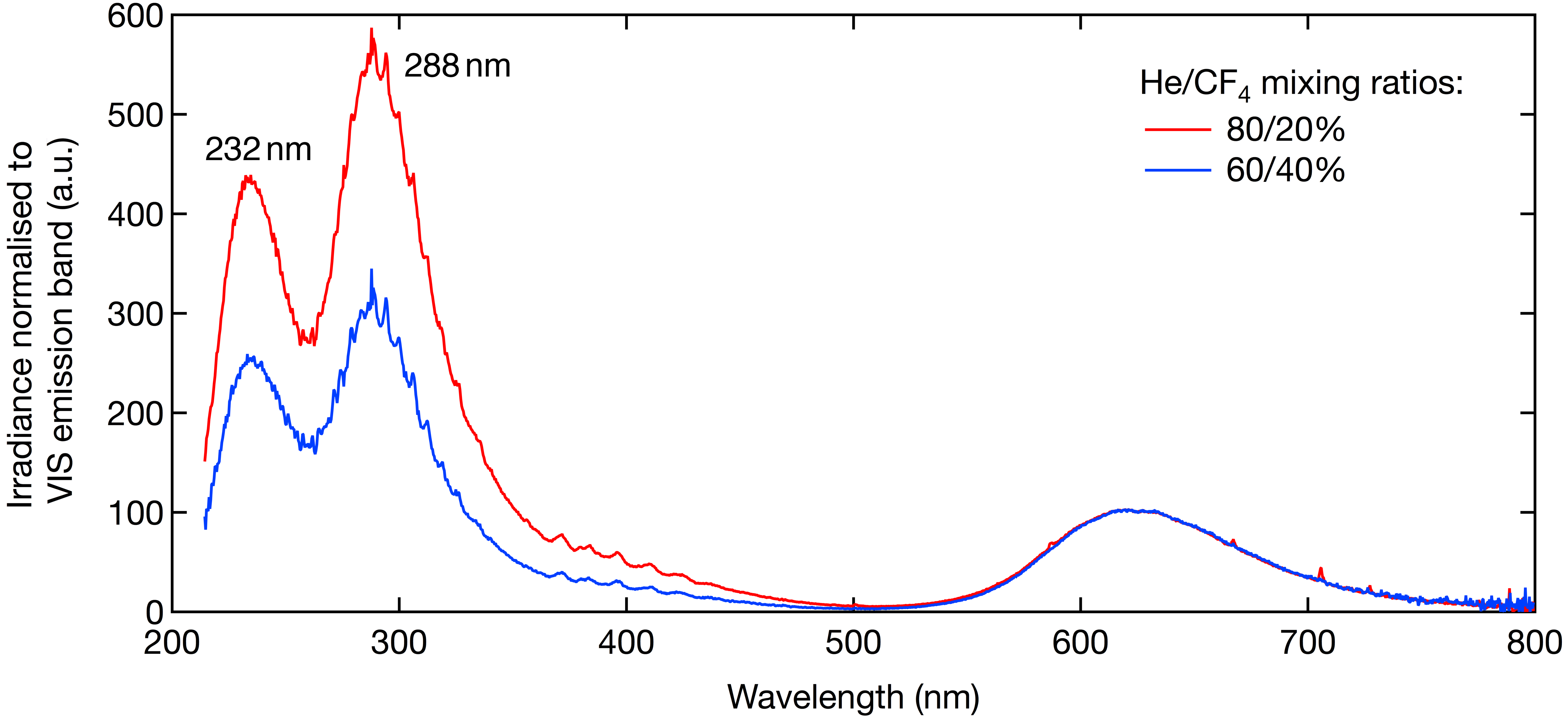
Ar/CF_4 scintillation



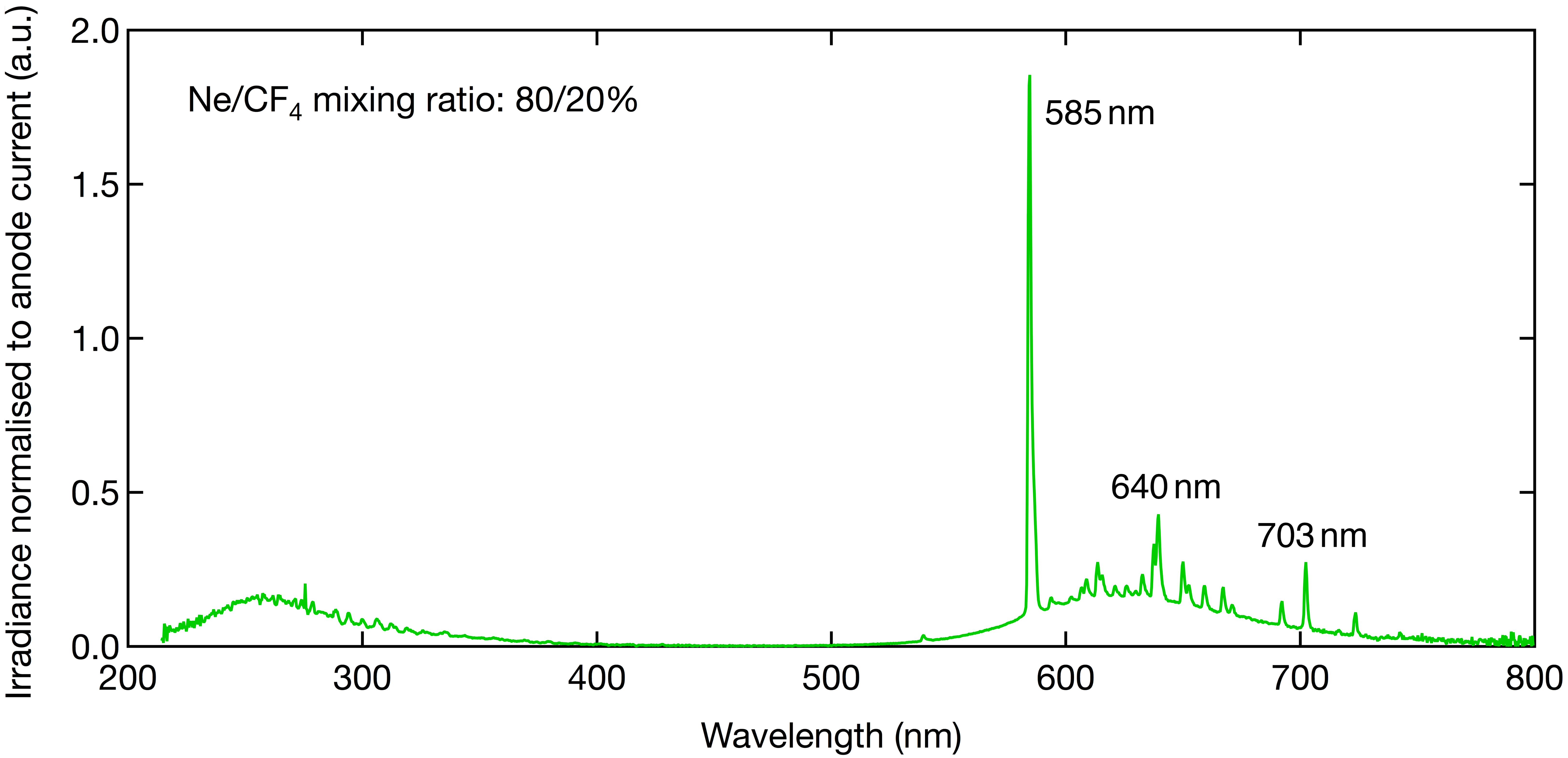
Ar/CF_4 scintillation
N_2 admixtures



He/CF$_4$ scintillation



Ne/CF_4 scintillation



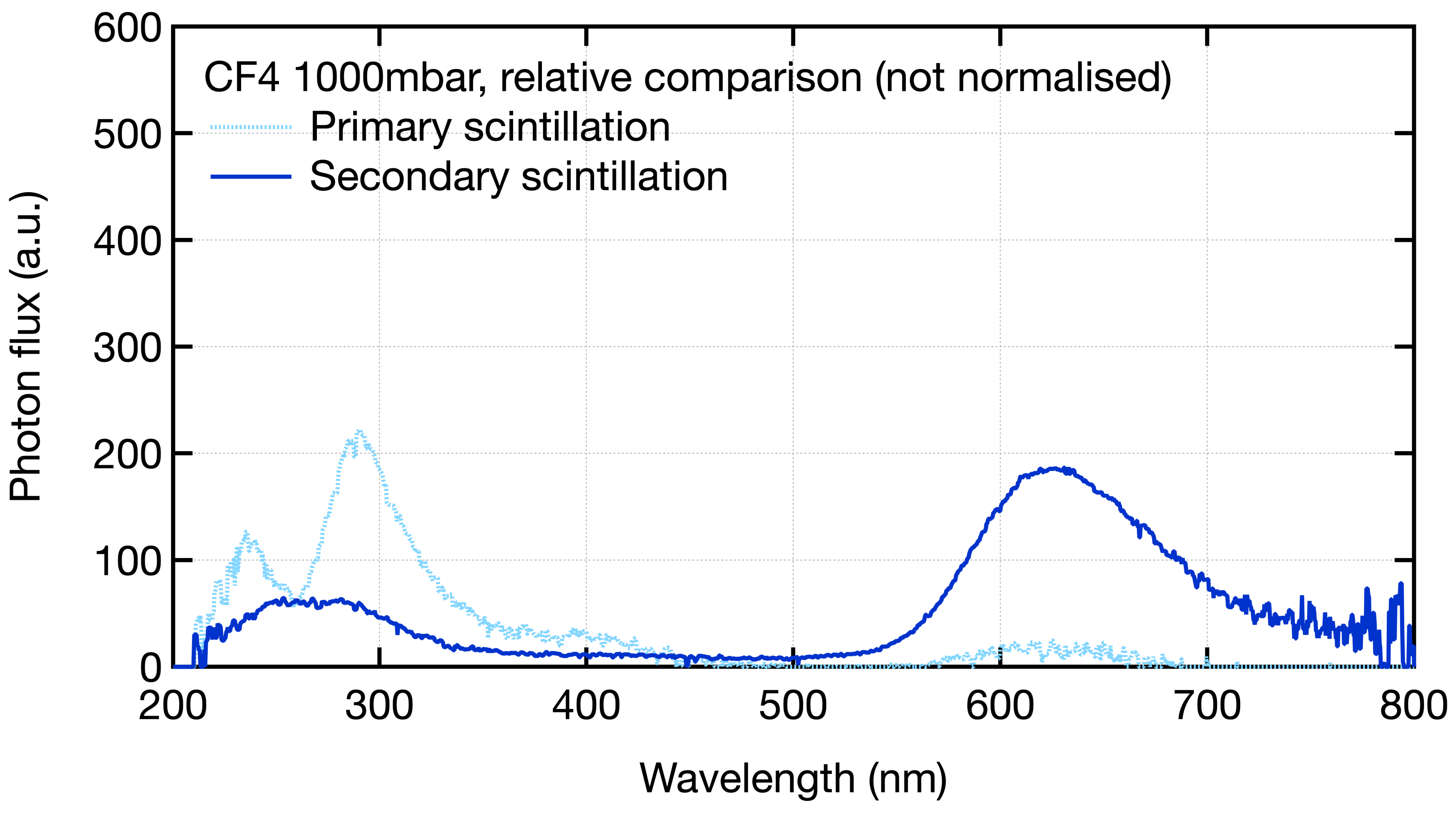
Primary / secondary scintillation spectra

Primary and **secondary scintillation** spectra exhibit similar characteristics but with different relative strengths.

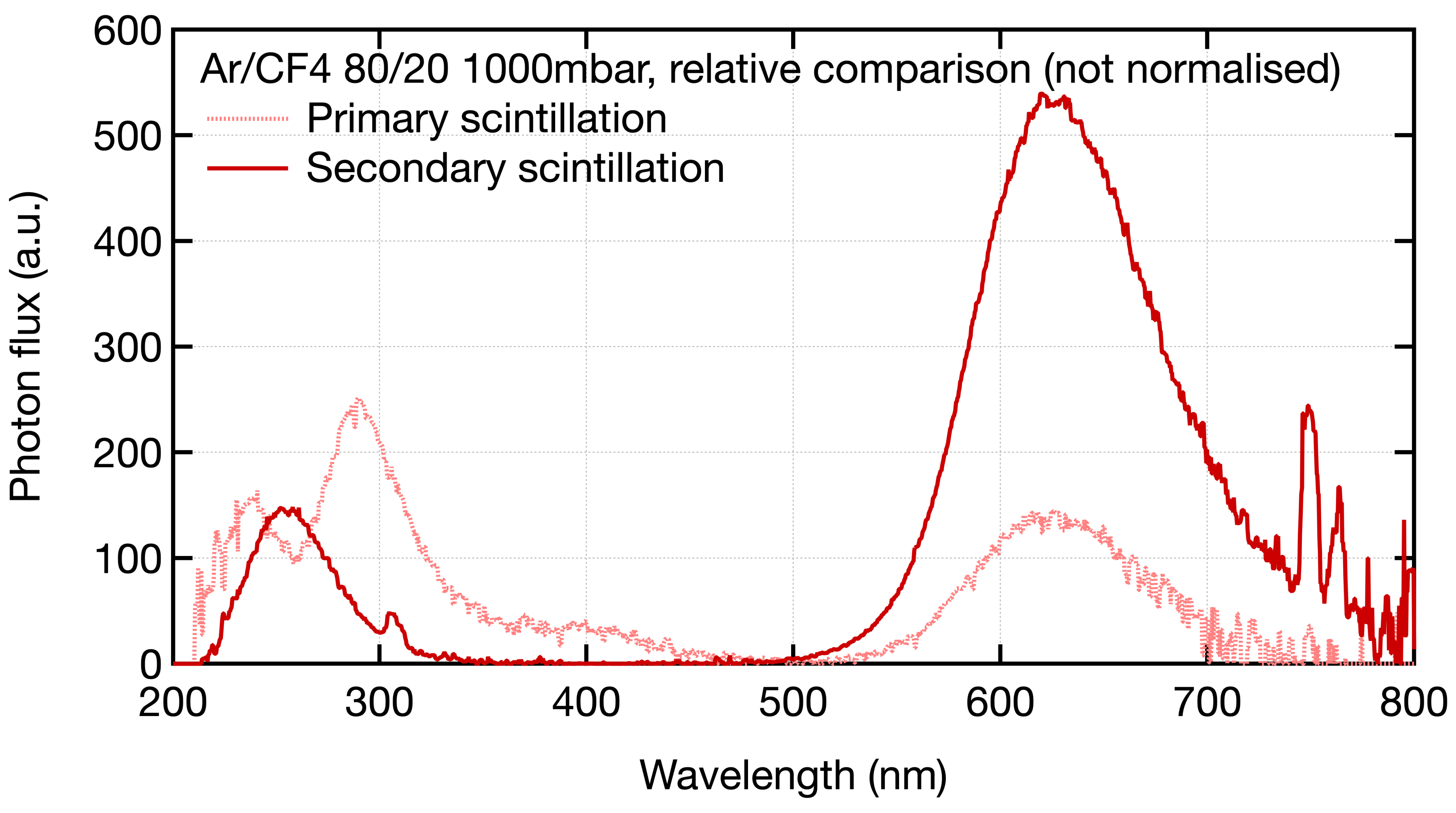
Different electron energies involved due to underlying channels of ionisation/excitation.

Comparison does not reflect relative intensity of primary and secondary scintillation (arbitrary normalisation of spectra)

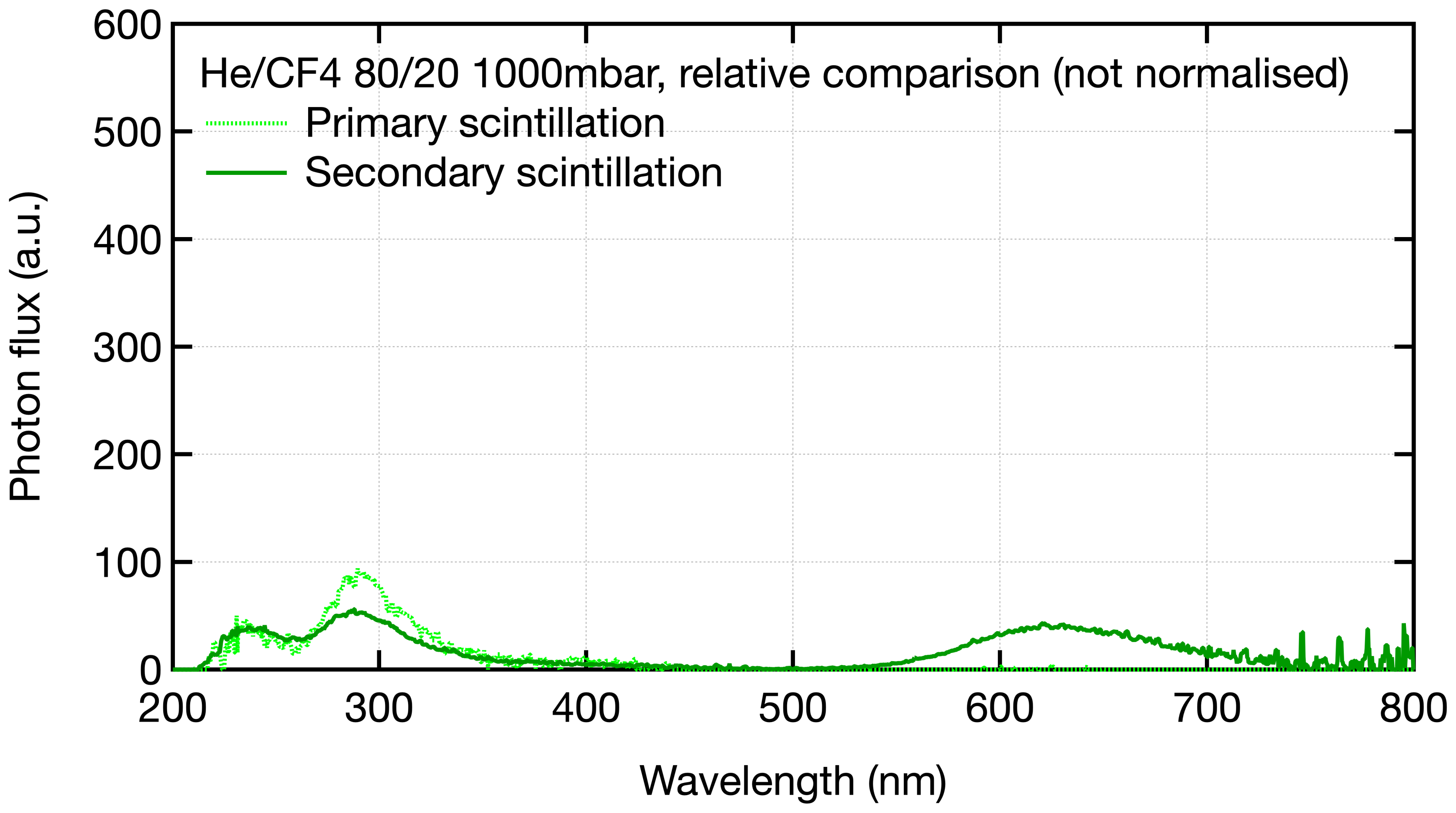
CF_4



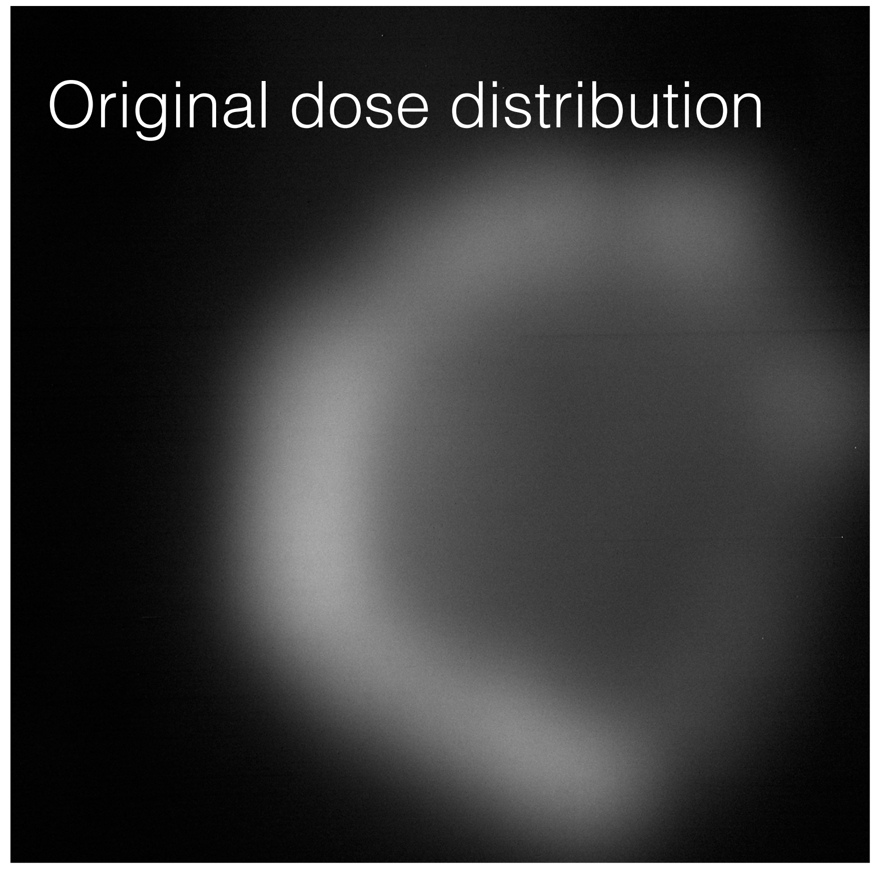
Ar/CF_4

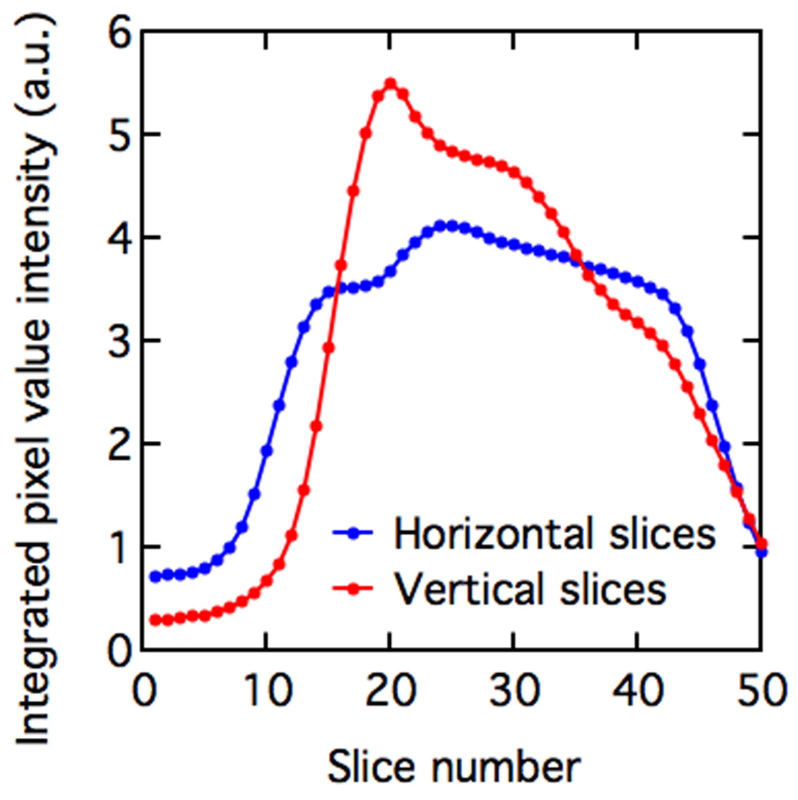


He/CF_4

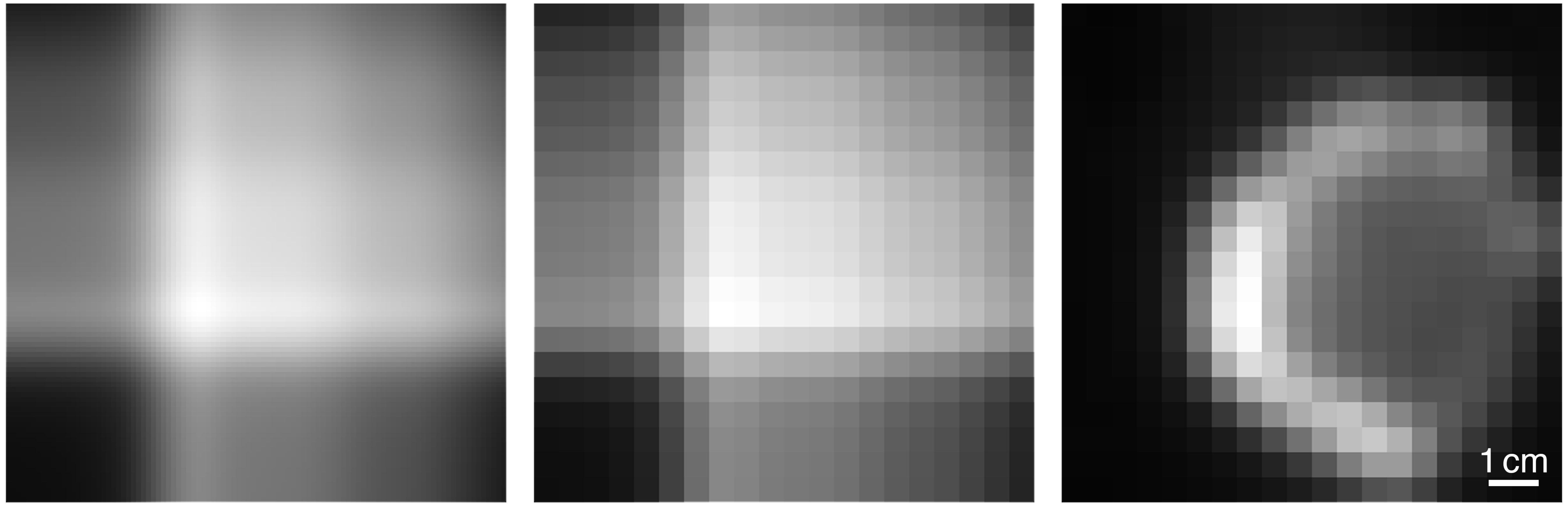


Strip vs. pixel readout





Pixellated readout can better reconstruct complex dose distribution



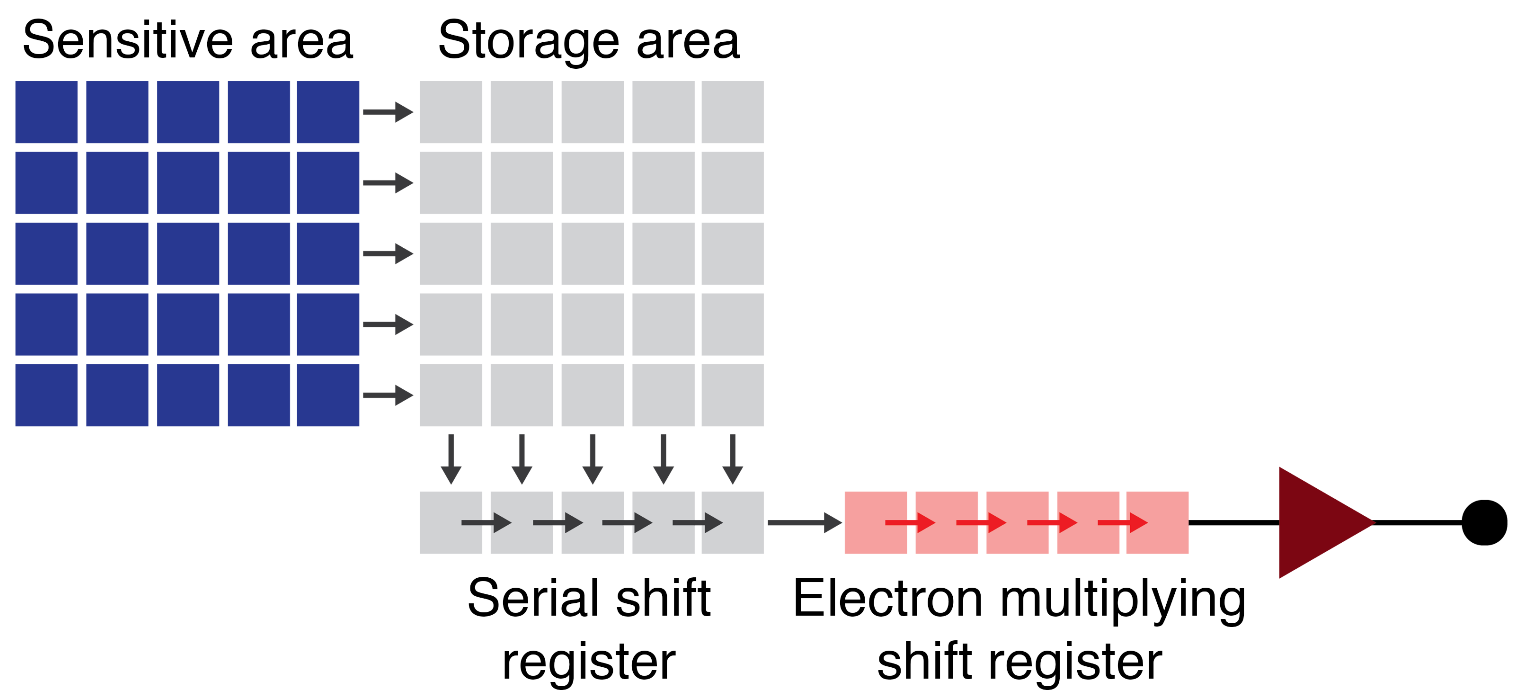
Reconstructed from strips

Reconstructed from pixels

Binning and EM gain

Achievable low energy sensitivity is determined by noise of imaging sensors. For short (≈ < seconds) exposure times, **read noise** is the dominating noise contribution. For longer exposure times, **dark current** can add significant noise. Read noise is added during every pixel read out operation.The relevance of read noise can be decreased by binning or electron multiplication.

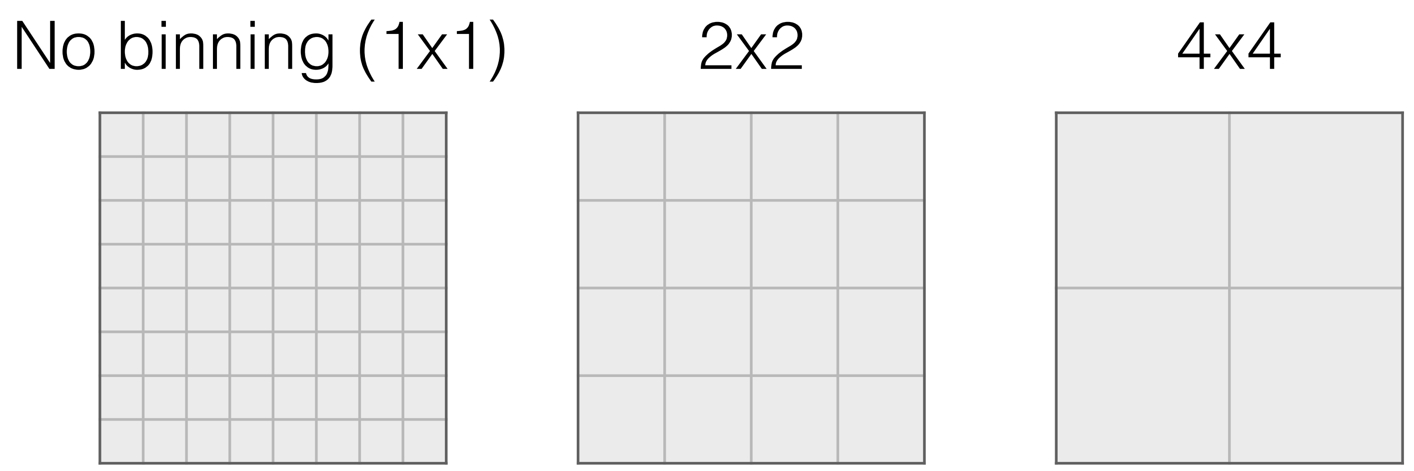
In **EMCCDs**, solid state electron multiplication before digitisation rendering the effective read noise <1e.



Binning increases the noise ratio by combining signal of N pixels together
Can be done in hardware (CCD) or in software (CMOS)

Hardware binning increases SNR with number of pixels N:

- Signal x N
- Readout noise constant

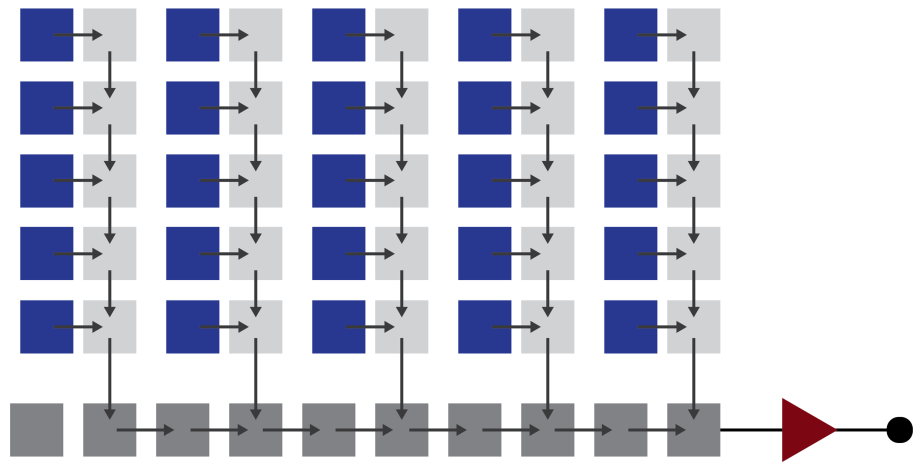


Software binning increases SNR only with √N

- Signal x N
- Readout noise x √N

Imaging sensors

CCD sensors



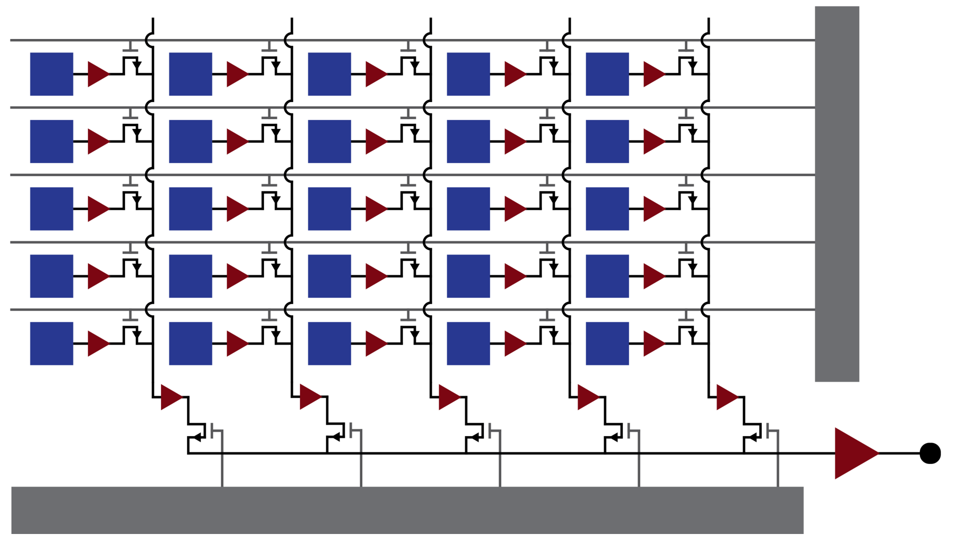
- **Moderate QE, higher read noise**
- **Low rate (≈tens Hz)**

Exemplary specifications

- 6 MP sensor (2688 x 2200)
- 4.54x4.54μm^2 pixels size
- 5.7 e- read noise

QImaging Retiga R6, Thorlabs 8 MP Scientific CCD Cameras

sCMOS sensors



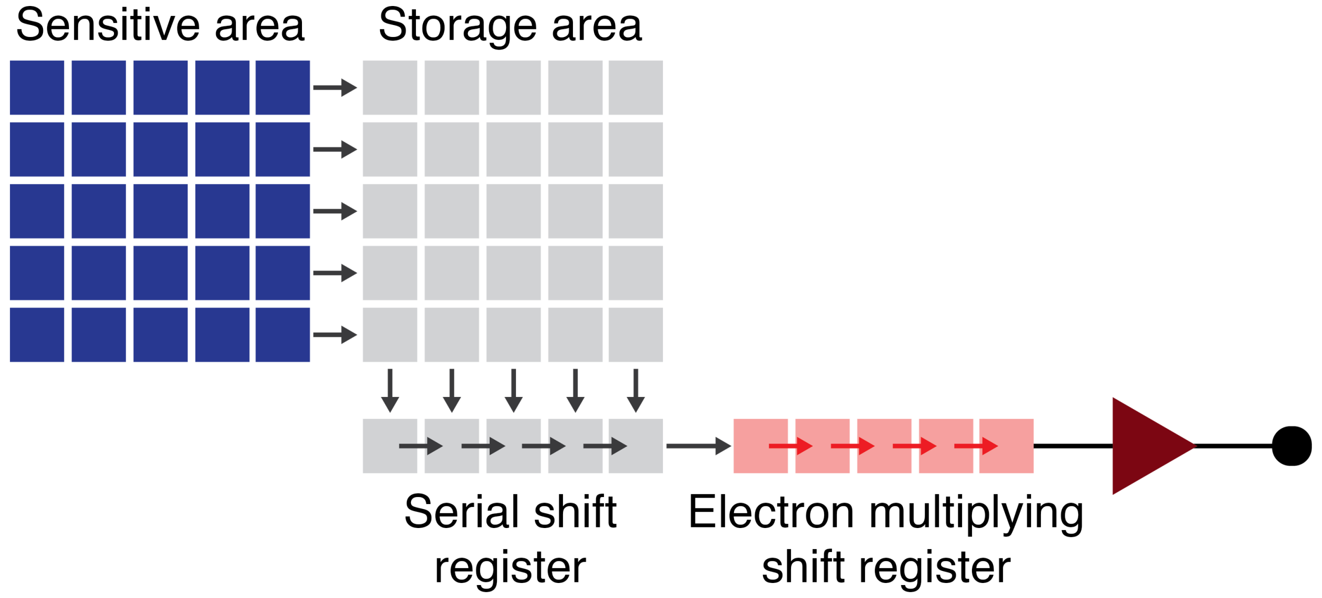
- **Low read noise**
- **≈100 Hz frame rate**

Exemplary specifications

- 5.3 MP sensor (2304 x 2304)
- 6.5x6.5μm^2 pixels size
- <1 e- read noise

Hamamatsu ORCA-Fusion, Andor Zyla

EMCCD sensors



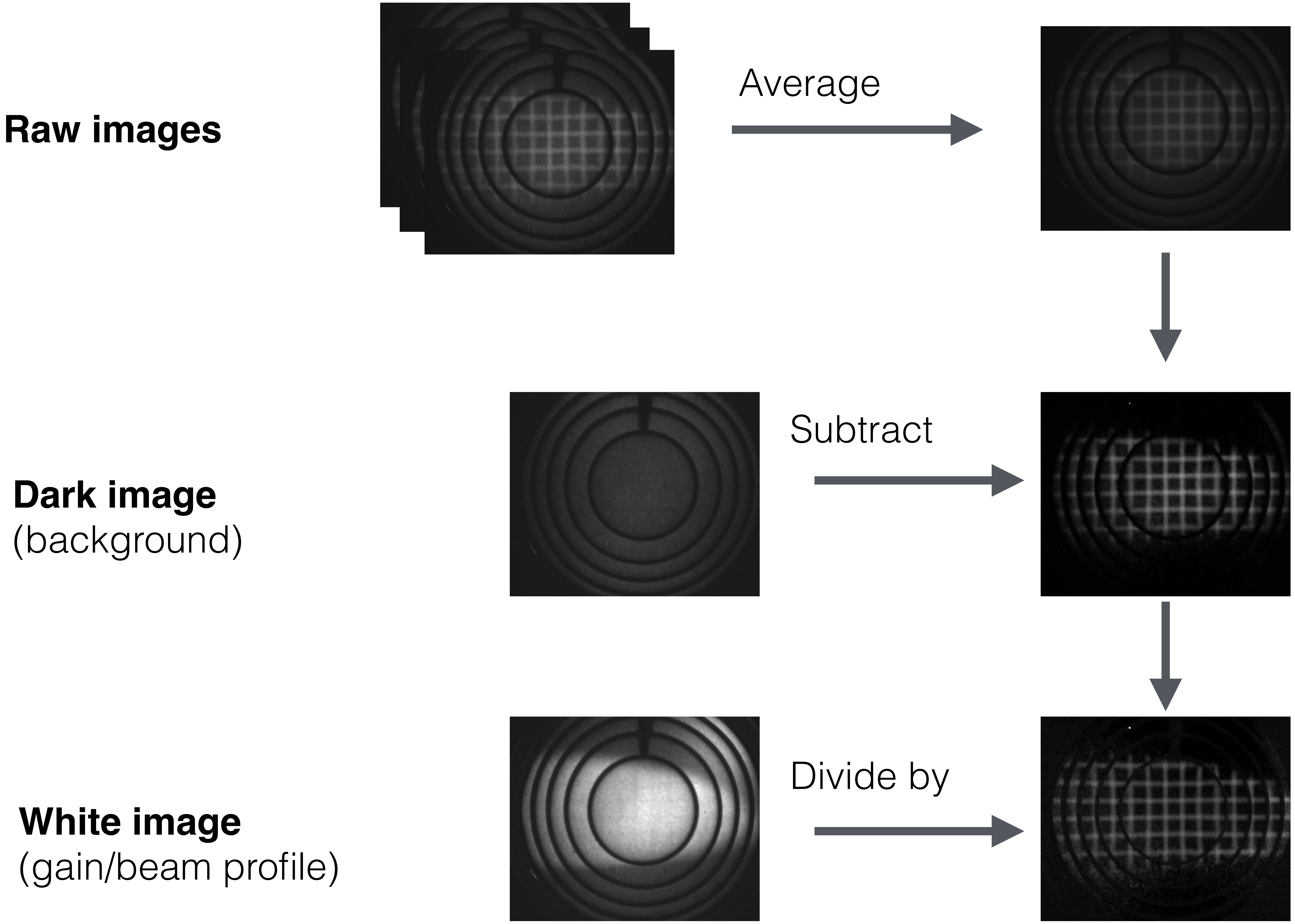
- **Limited resolution**
- **Internal gain, very high sensitivity**

Exemplary specifications

- 1 MP sensor (1024x1024)
- 16x16μm^2 pixels size
- <1 e- read noise

Hamamatsu ImageEM X2, ams technologies iXon

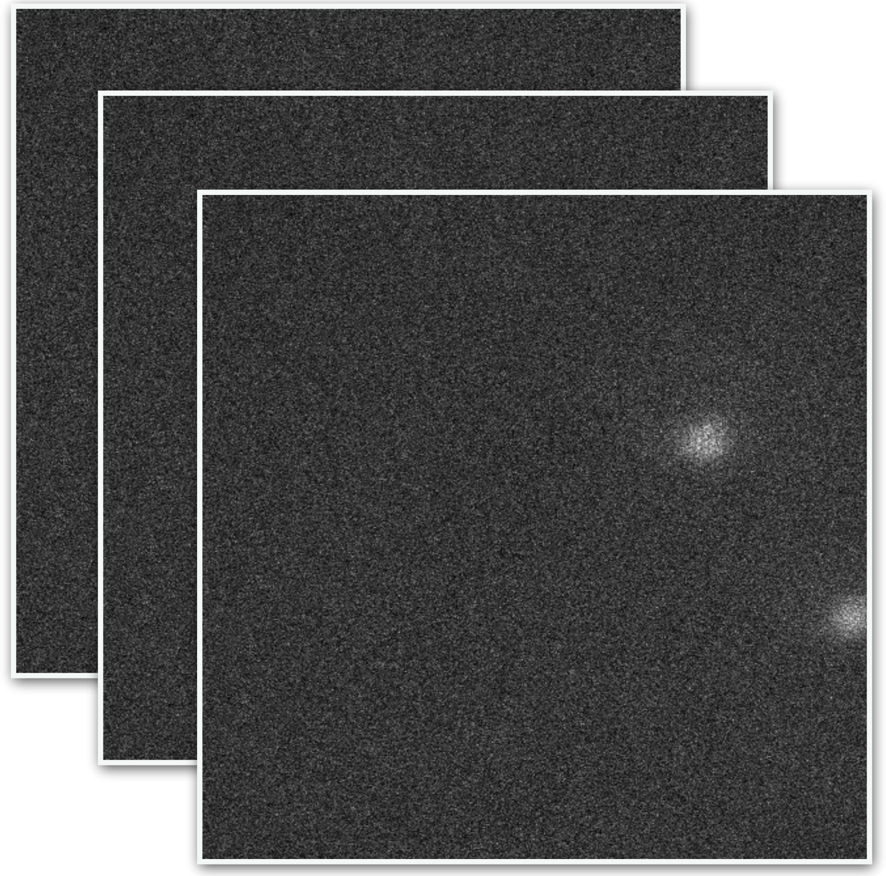
Basic image processing for radiography



Deconvolution

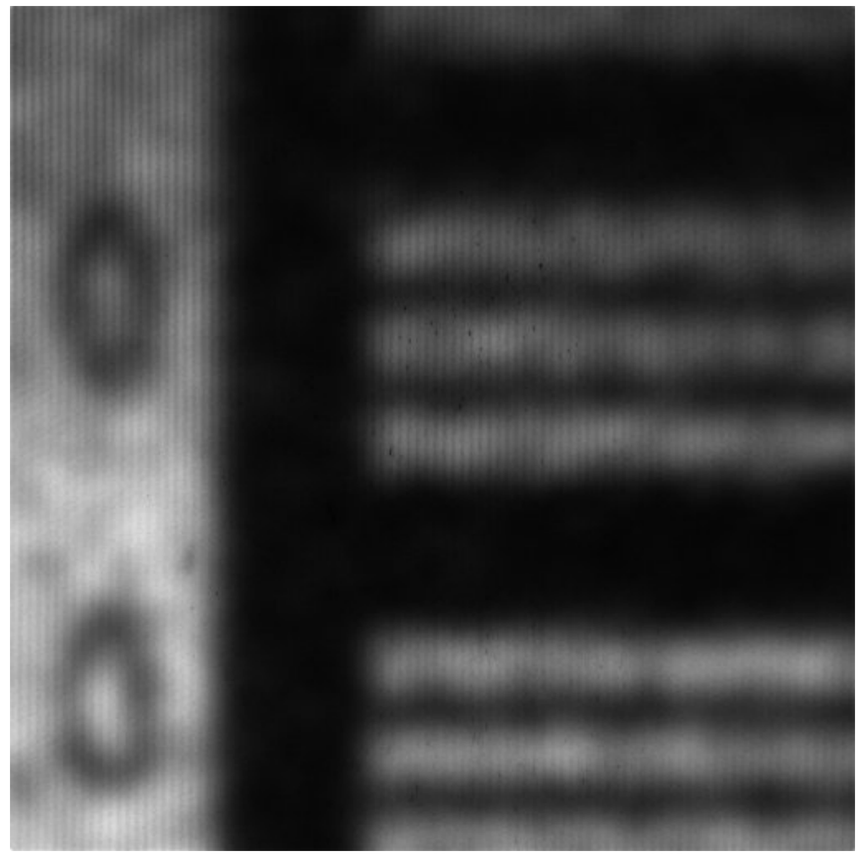
Integrated imaging approach collects all light within exposure time **without deadtime**. This allows for rapid imaging limited by incident radiation flux and detector rate capabilities but suffers from and blurring of recorded images.

Individual events occurrent during exposure time

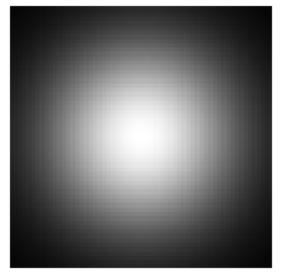


Exposure time

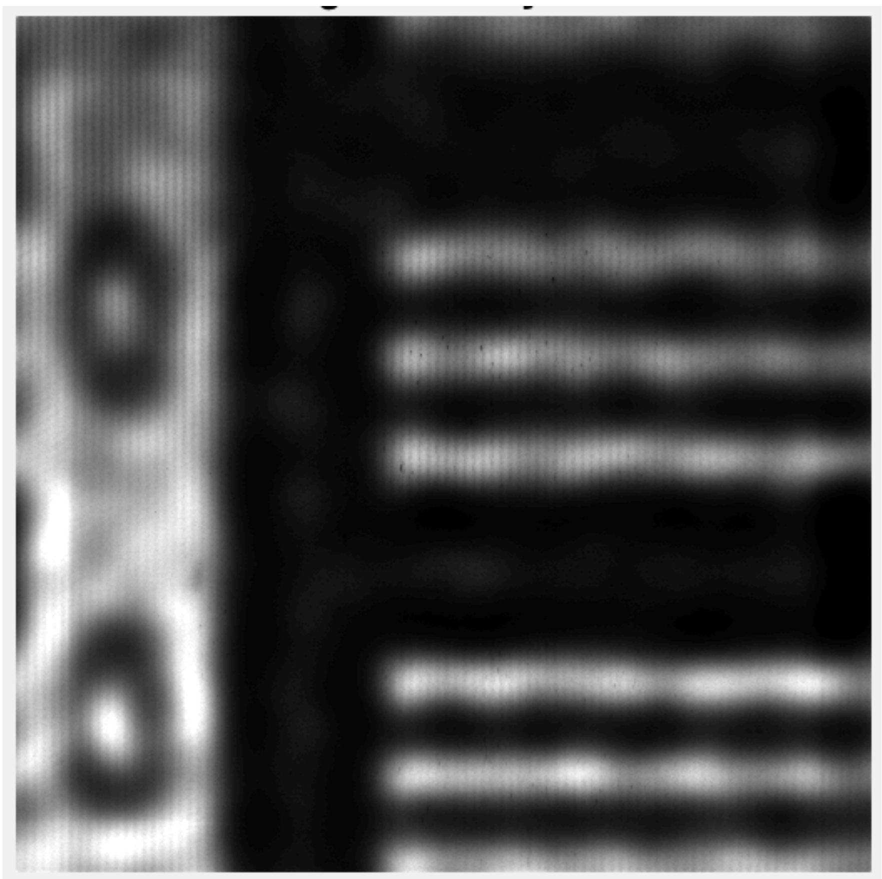
Integrated image (sum of all events during exposure)



Deconvolution

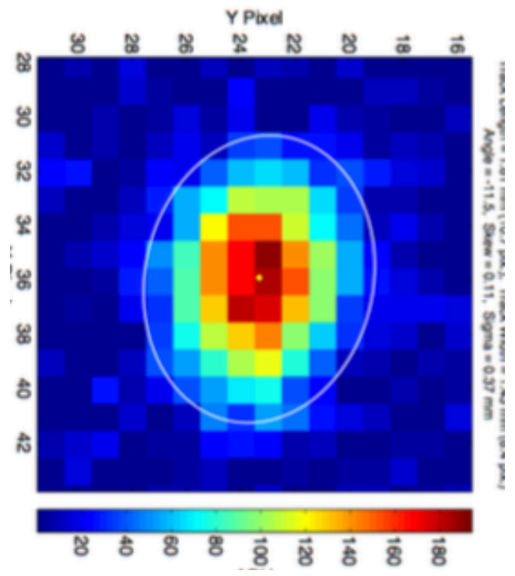


PSF

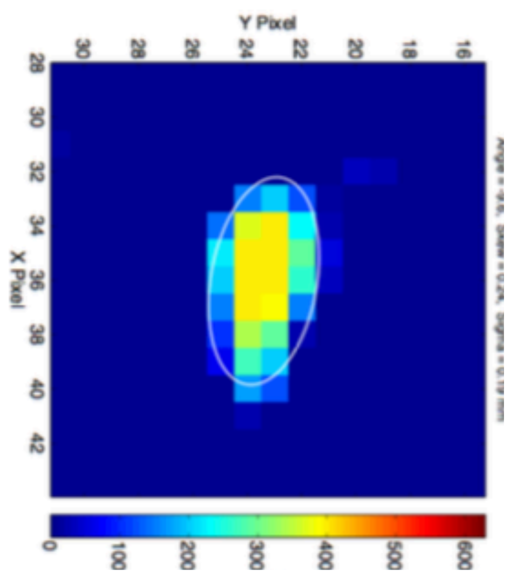


Deconvolution used for improved directionality determination of nuclear recoils

Image



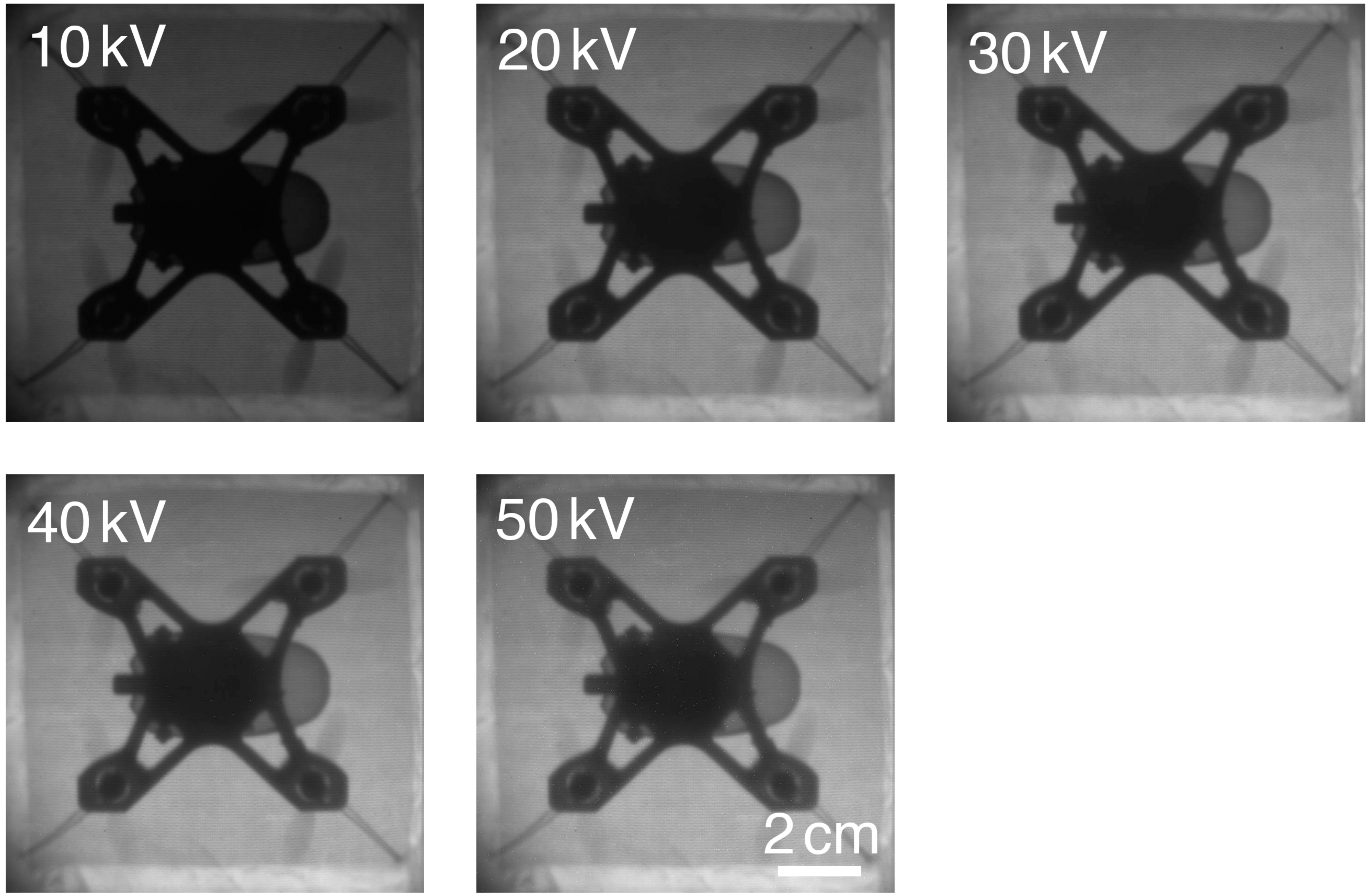
Deconvolved

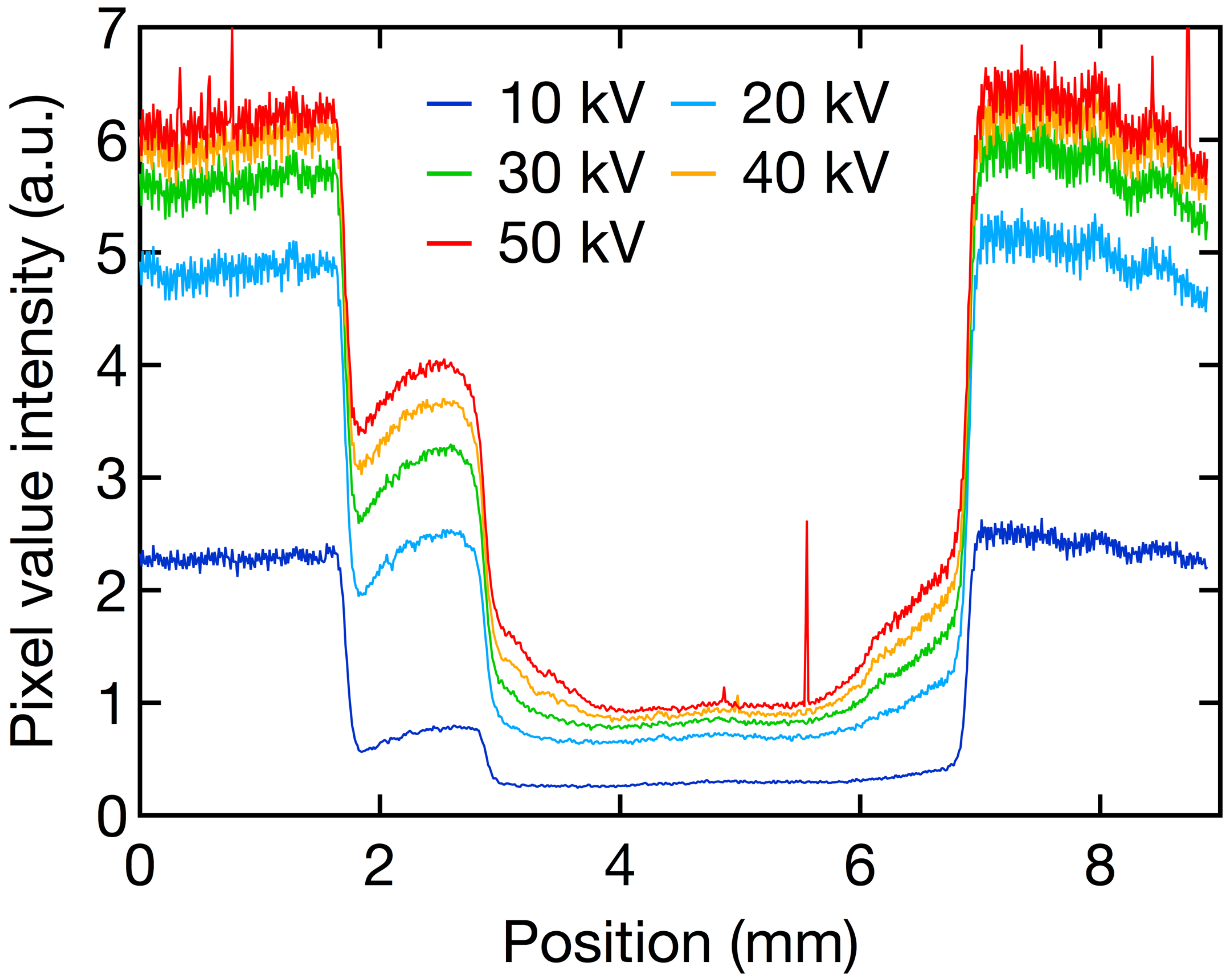


D. Loomba et al.,https://agenda.infn.it/event/17434/attachments/25756/29405/Dinesh_Loomba_INFN_seminar.pdf

X-ray radiography

Imaging at higher X-ray energies leads to photons penetrating deeper and resolving more internal structures but decreases spatial resolution due to larger primary cluster size





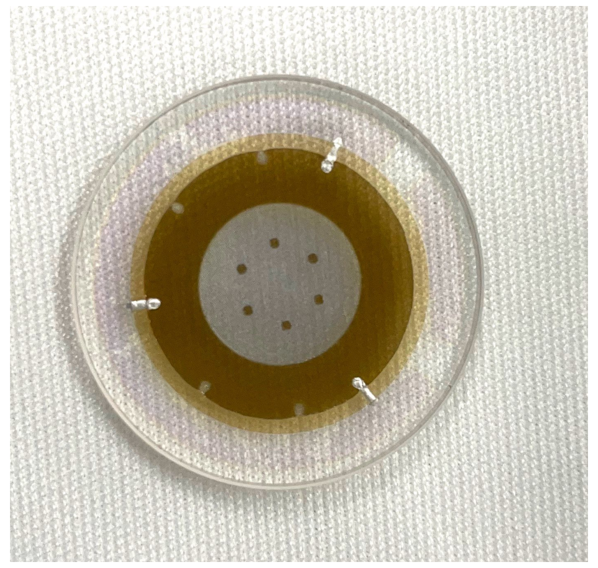
Optical MM with SiPM readout

Evaluated timing resolution with SiPMs and evaluate array configuration for reconstructing hit location from signal sharing on multiple SiPMs

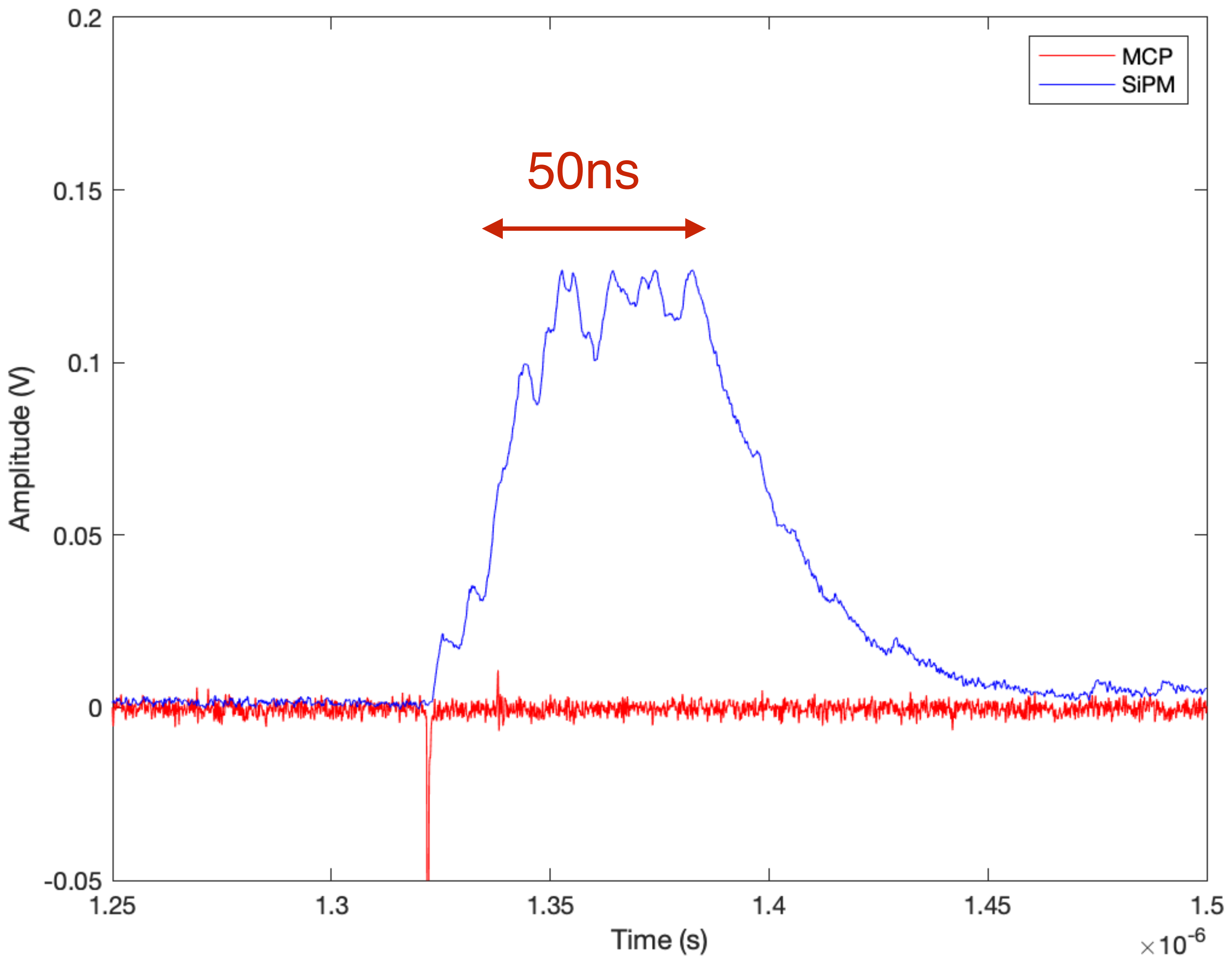
Optical Micromegas with semi-transparent ITO or Cr anode operated in beam and readout with SiPMs (small and 2x2 array)

- Test of available light intensity and timing performance
- Test of different SiPM devices
- Operated in Ar/CF_4 for VIS light emission

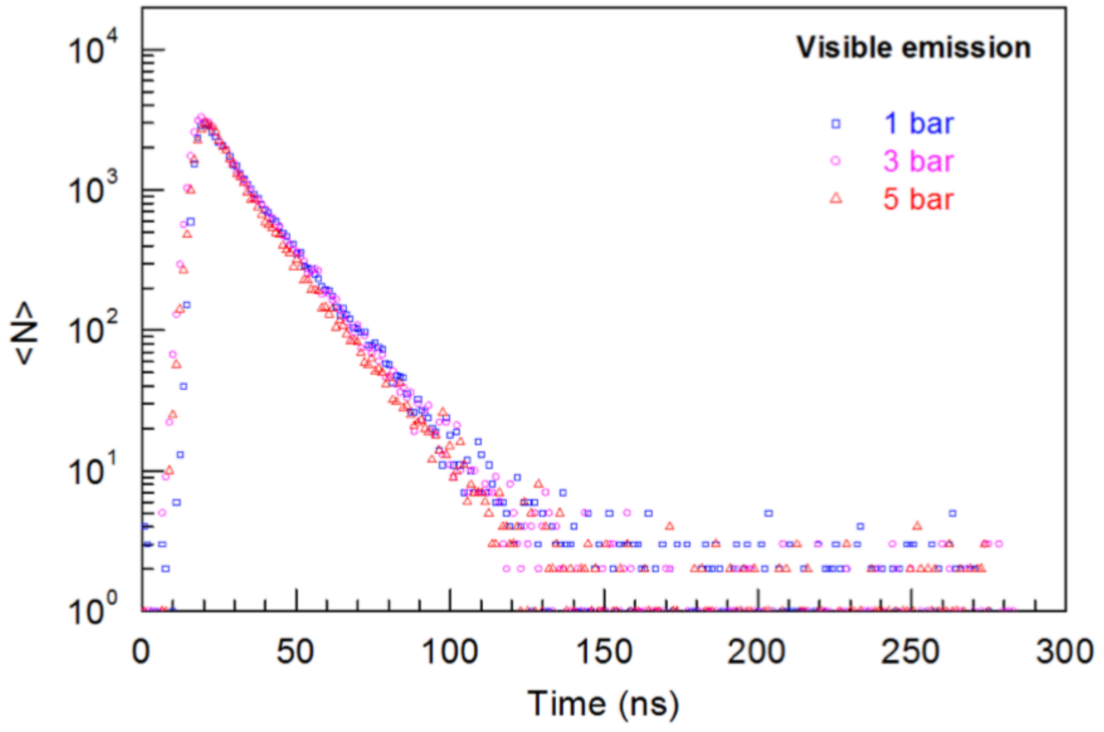
Optical Micromegas



https://www.hamamatsu.com/eu/en/product/type/S13360-1350CS/index.html

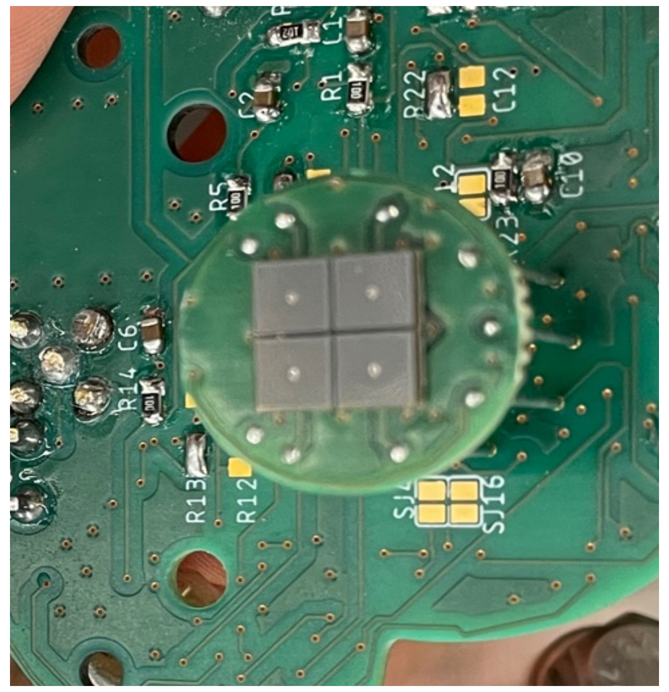


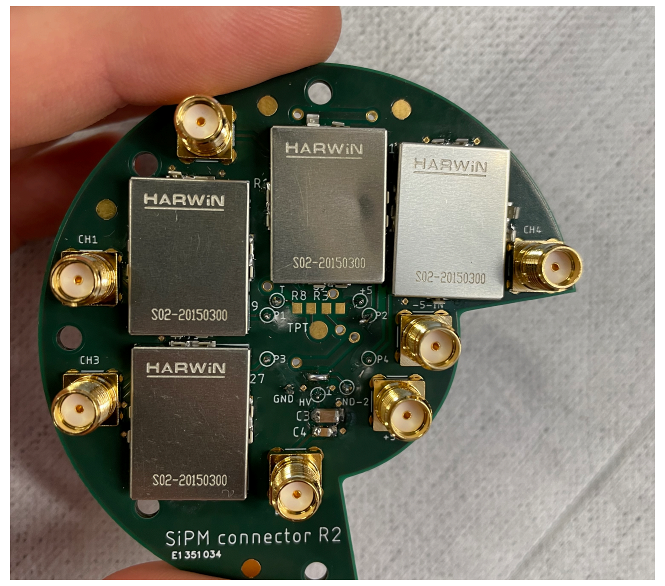
Slow VIS emission from CF_4



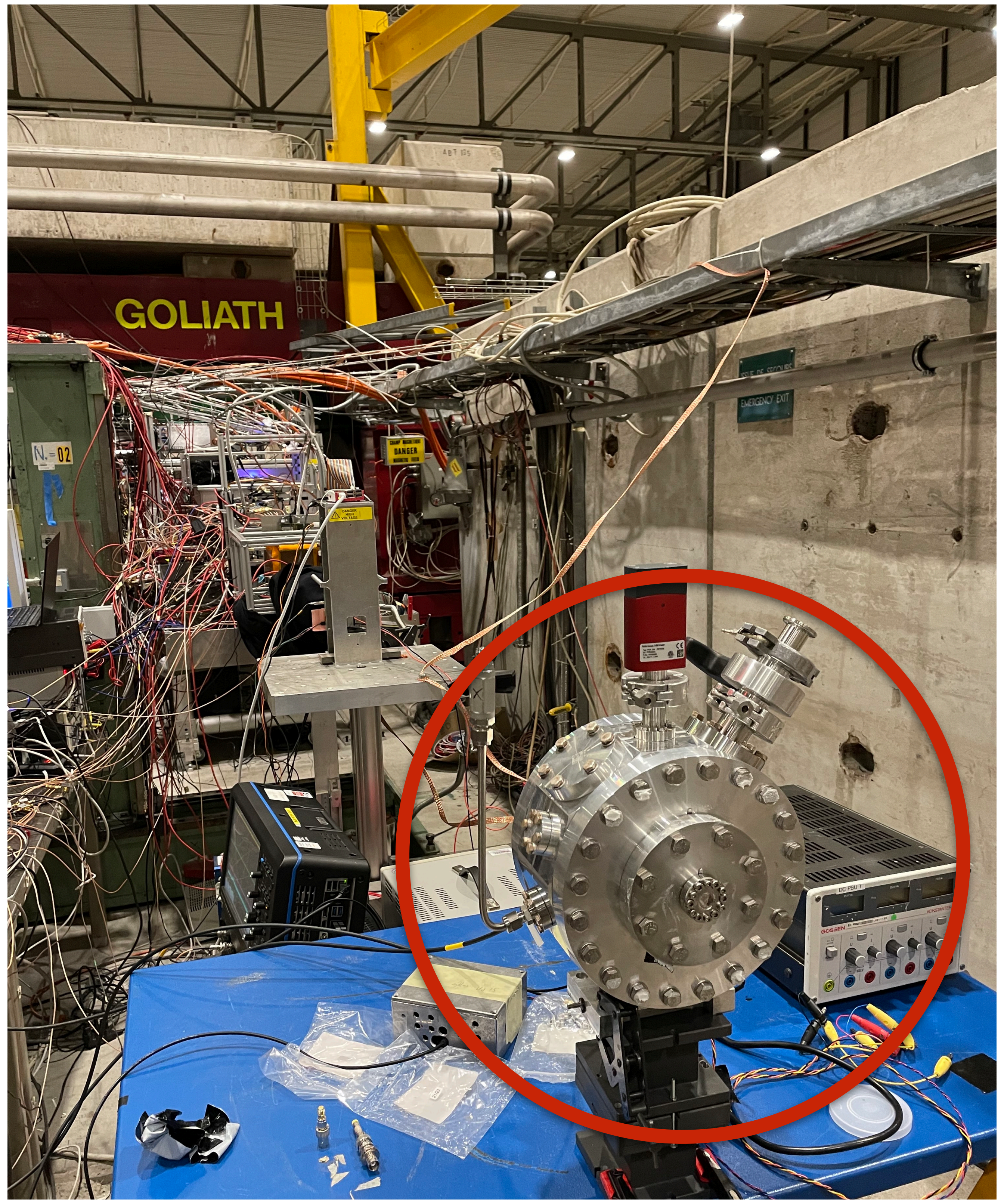
https://doi.org/10.1088/1748-0221/8/07/P07008

2x2 array of 4mm x 4mm SiPM



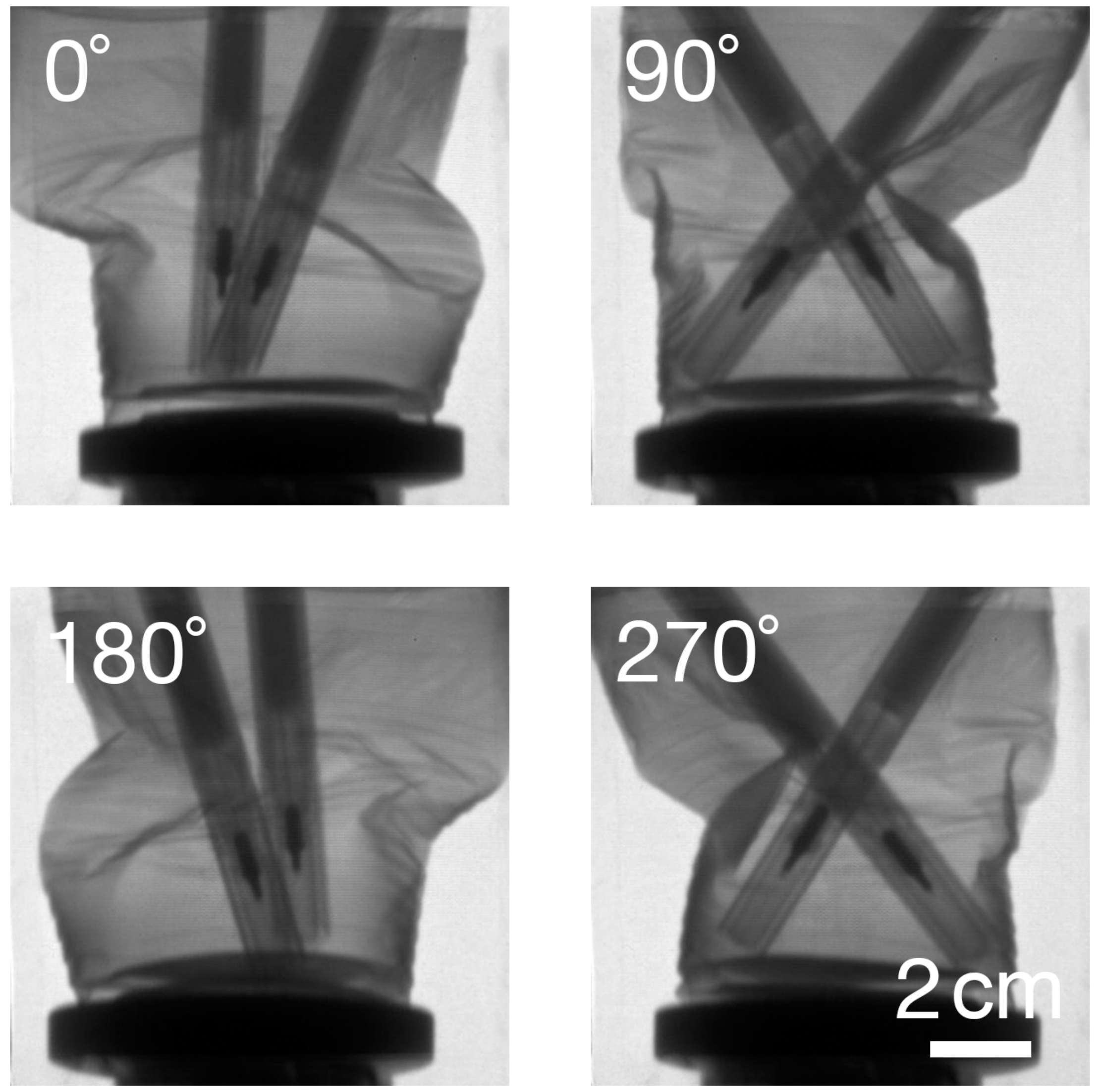


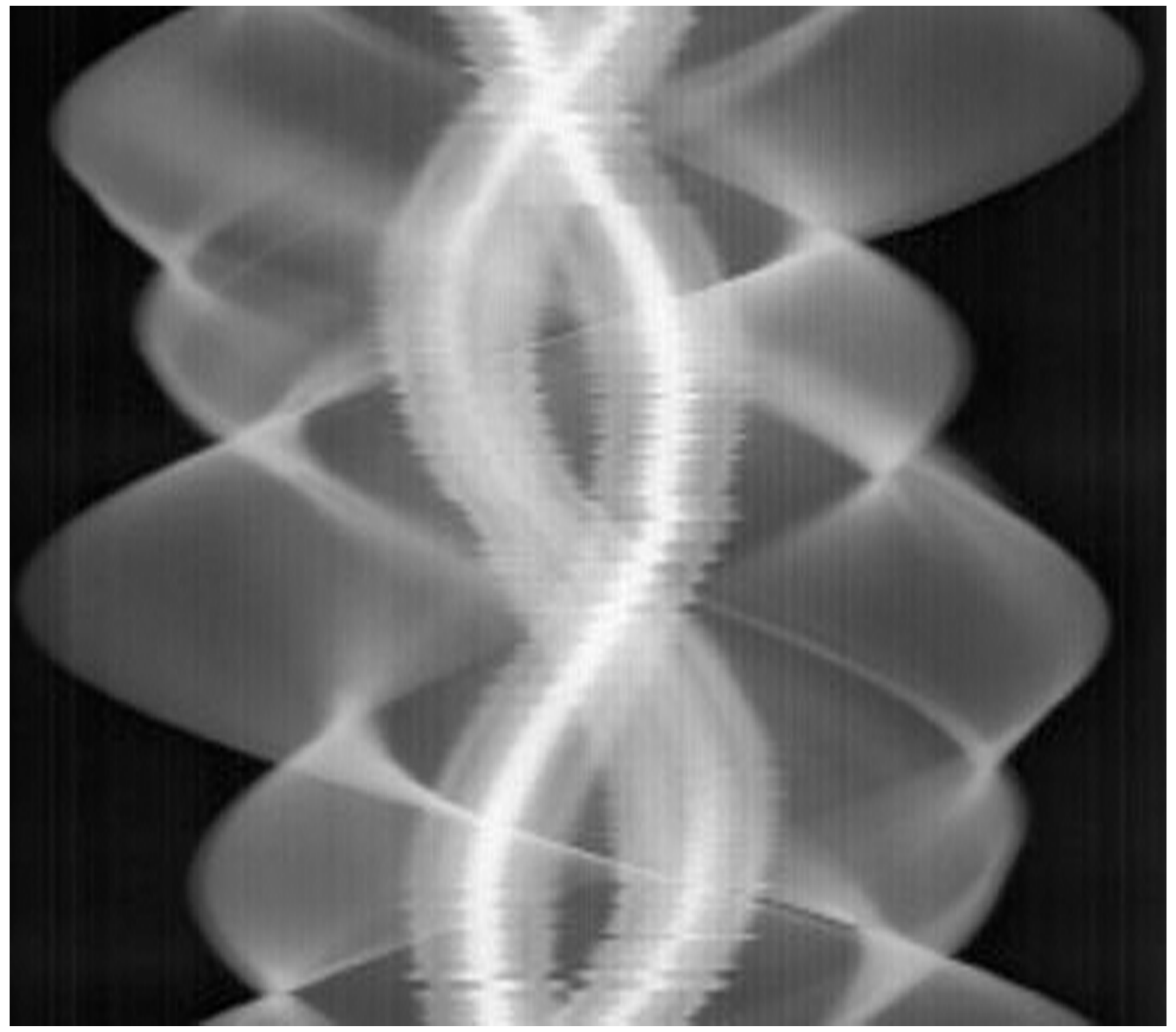
4-ch preamps



OpticalMM in sealed chamber with SiPM readout

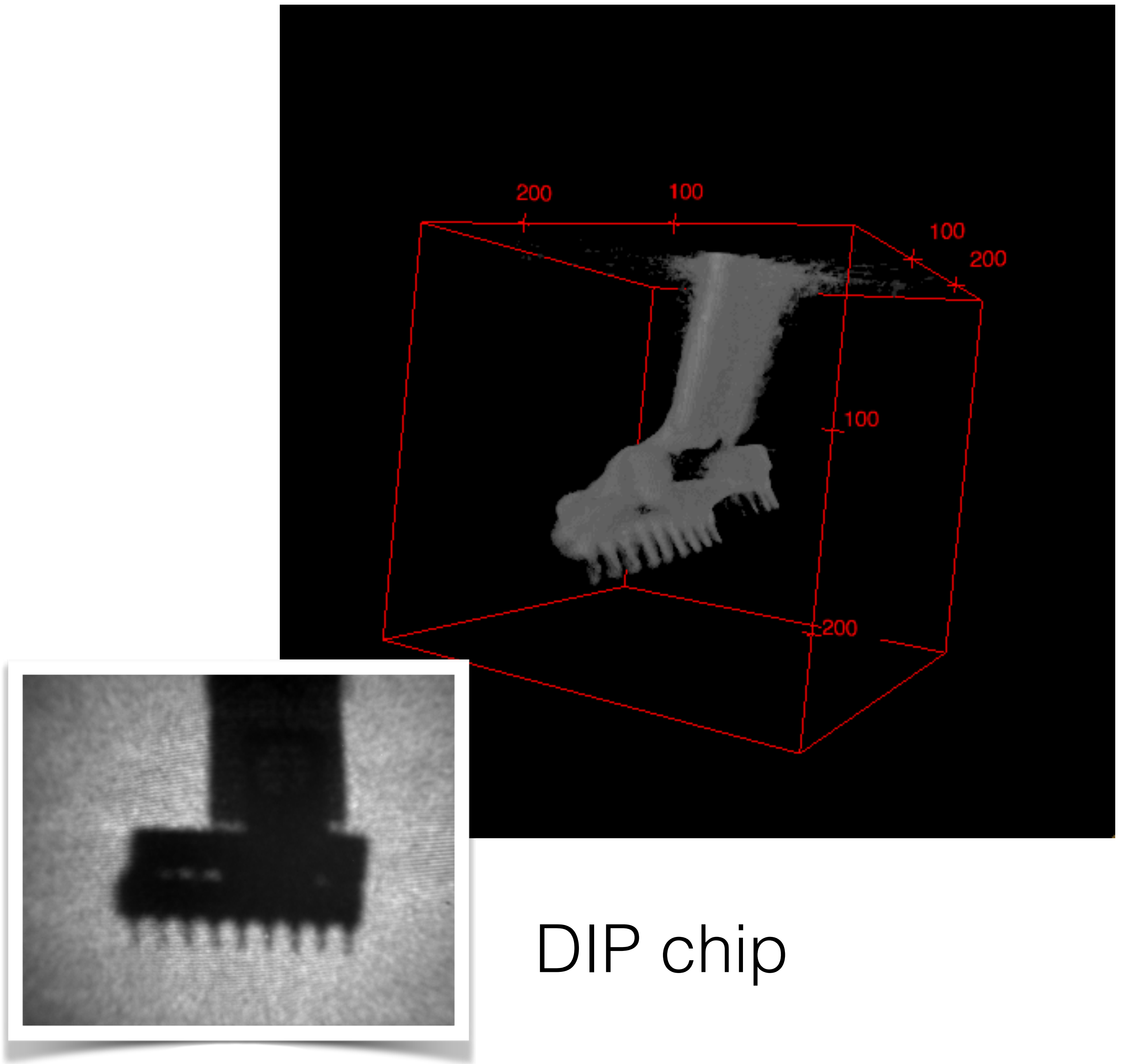
X-ray tomography



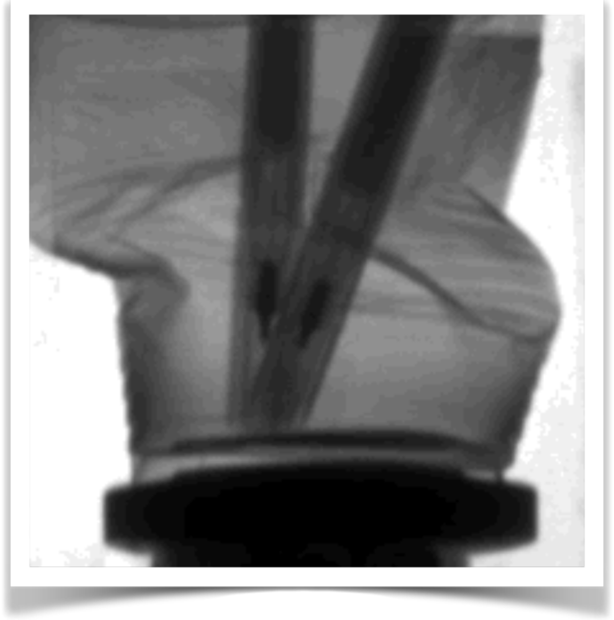


3D reconstruction of turning objects in front of detector

Images ➝ Sinograms ➝ Filtered back projection ⇒ 3D image

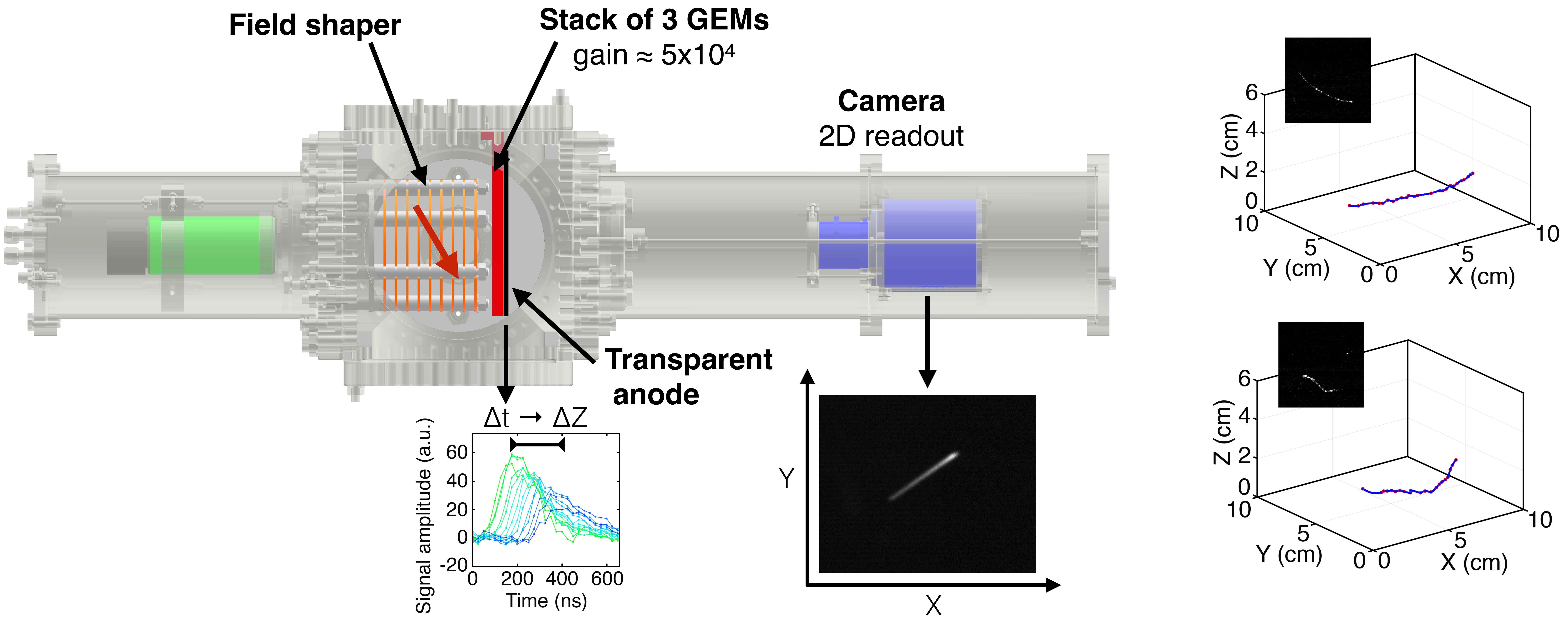


DIP chip



Crushed plastic cup with two pens
(changing pixel value threshold)

Optically read out TPC Electronic + CCD

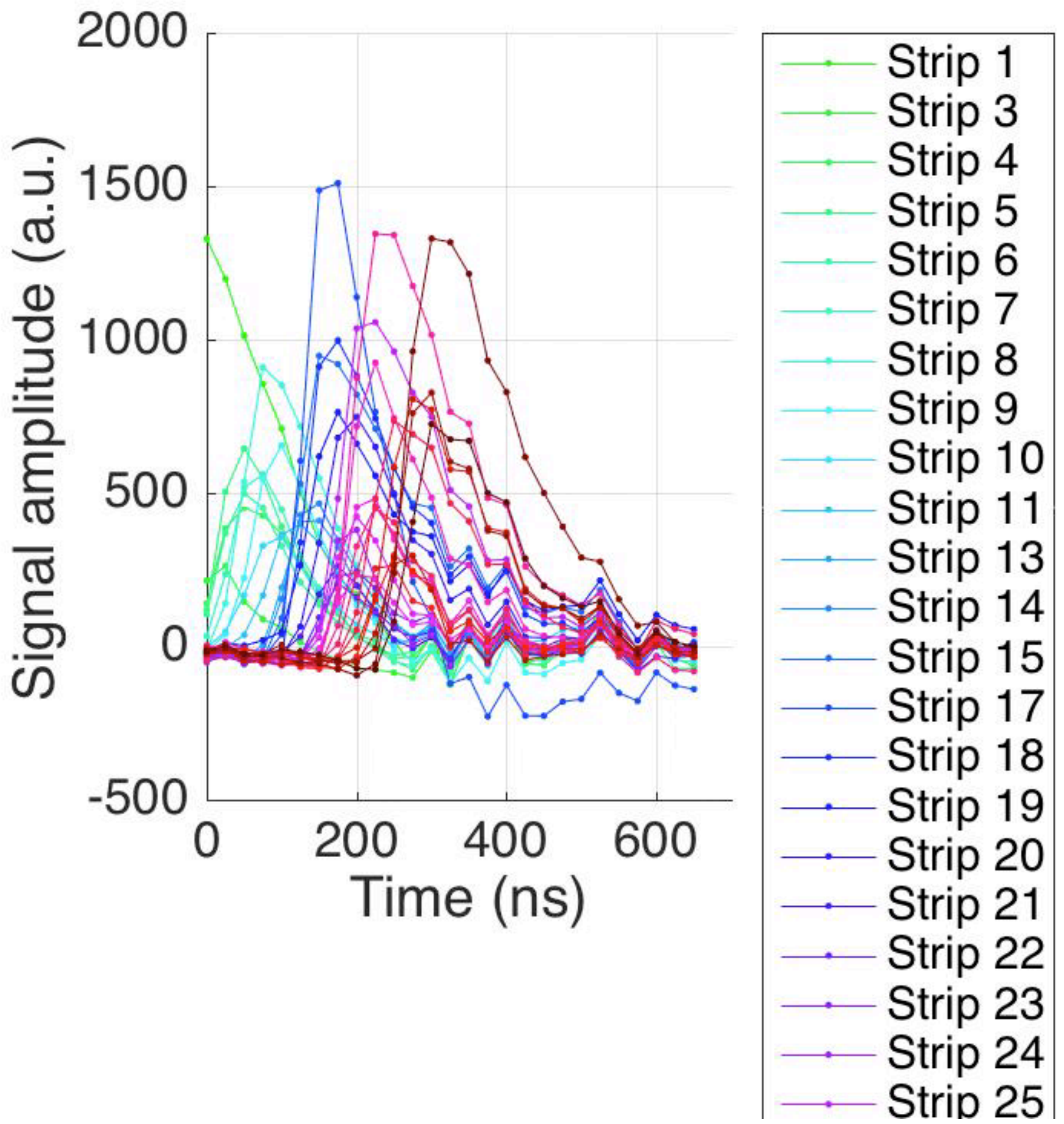


F. M. Brunbauer et al., IEEE NSS 2017

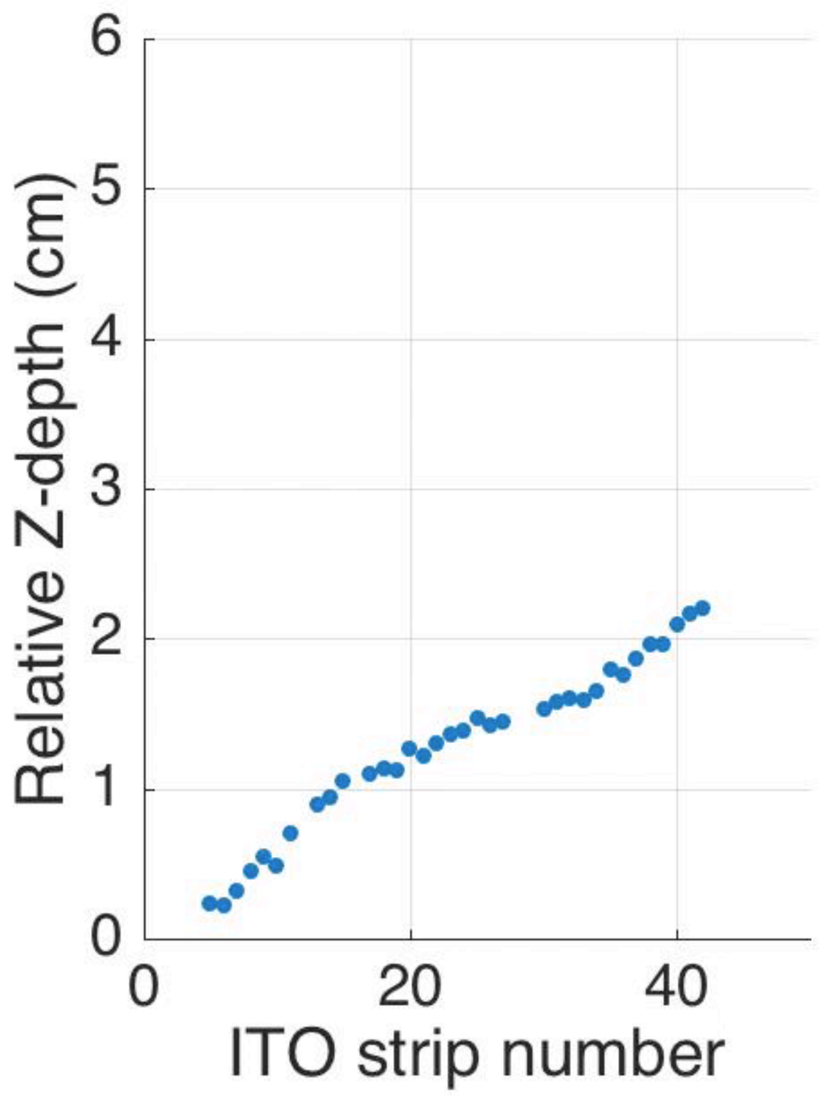
Schematics not drawn to scale

Reconstructed cosmic events

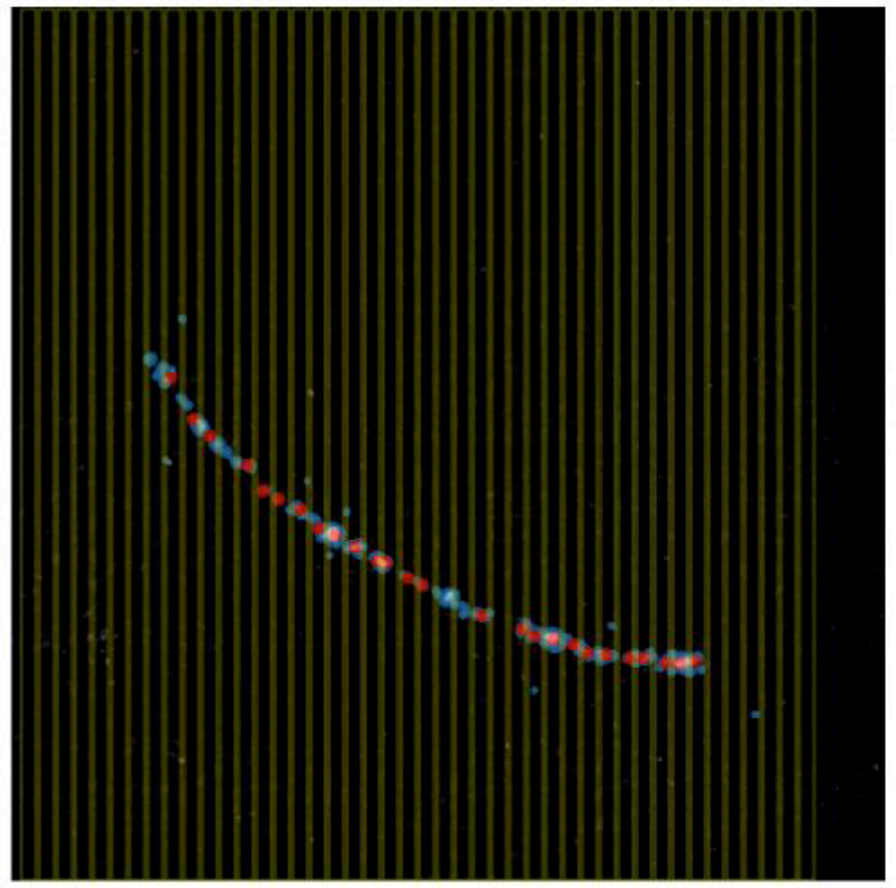
ITO strip signals



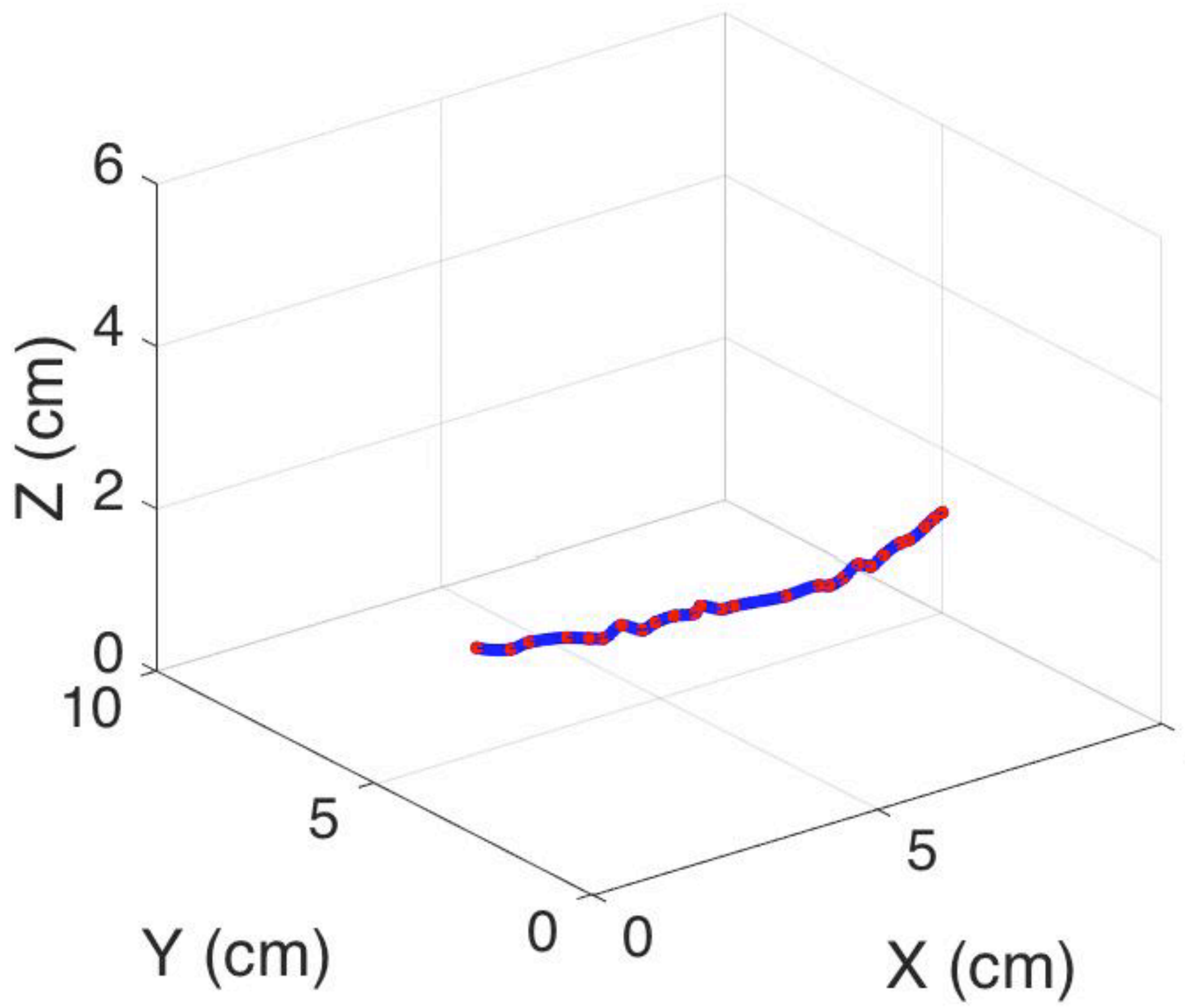
Depth information



Camera image



3D track visualisation



Projections