High-granularity optical and hybrid readout of gaseous detectors: developments and perspectives

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on behalf of the CERN EP-DT-DD Gaseous Detector Development team

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September 13, 2021

Content

Optical readout of MicroPattern Gaseous

- Concept, advantages and limitations
- Optically read out MPGD technologies

Beam monitoring and dose imaging with low material budget

Ultra-fast optical readout

- Fast CMOS imaging sensors
- Negative ion drift

Hybrid readout approaches

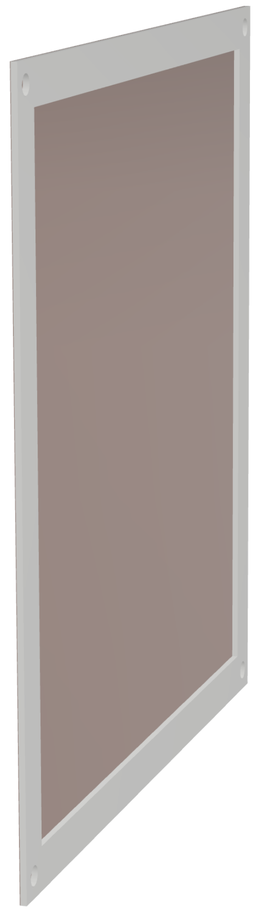
- Optical + electronic readout
- Pixellated readout ASICs
- SiPM readout

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)



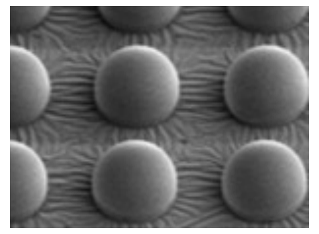
High gain MPGDs

Optics
(coupling)

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

photonis.com

szphoton.com

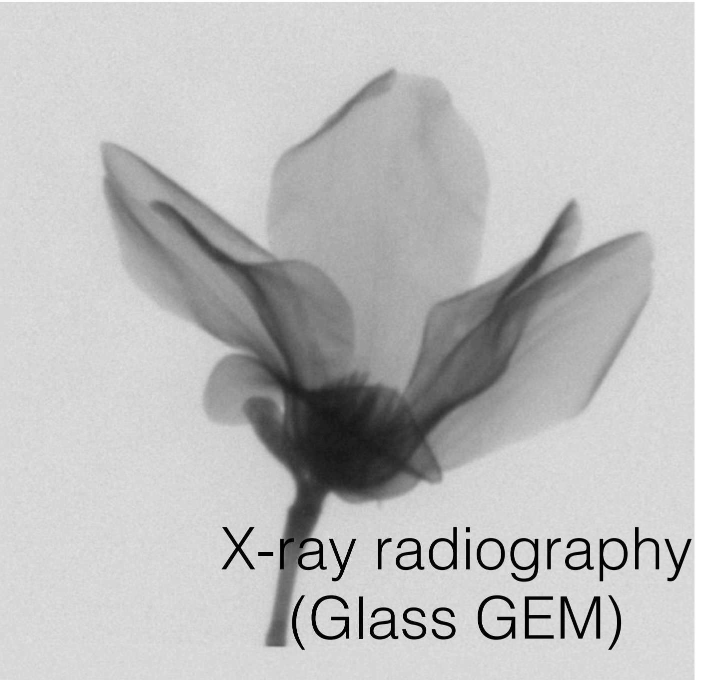


10.1016/j.apsusc.2018.01.253

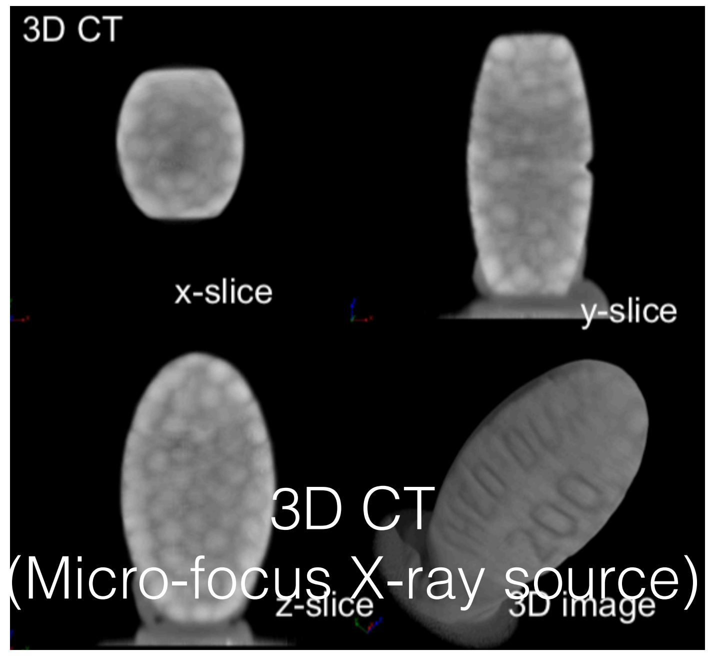
Imaging sensor
(camera)

CCD, CMOS, ASICs

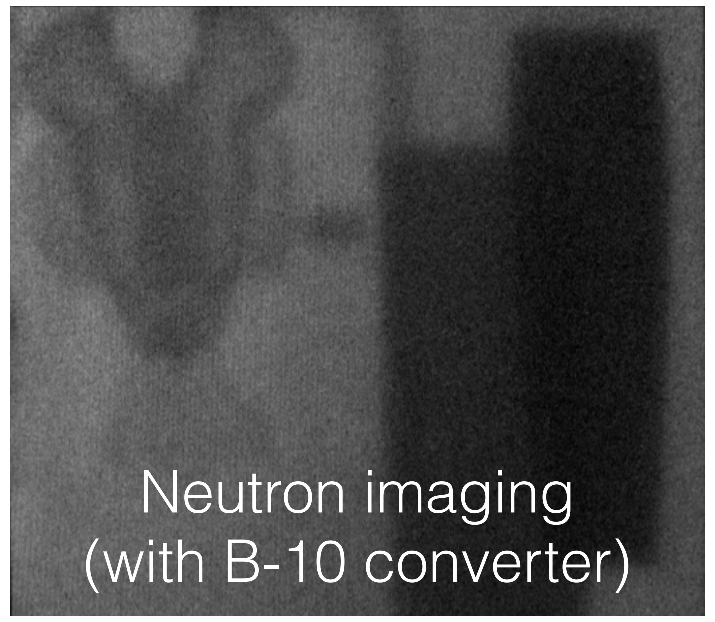
X-ray radiography
(Glass Micromegas)



X-ray radiography
(Glass GEM)



3D CT
(Micro-focus X-ray source)



Neutron imaging
(with B-10 converter)

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

T. Fujiwara, MPGD 2017, https://indico.cern.ch/event/581417/contributions/2556685/attachments/1464089/2262562/MPGD2017_fujiwara.pdf

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

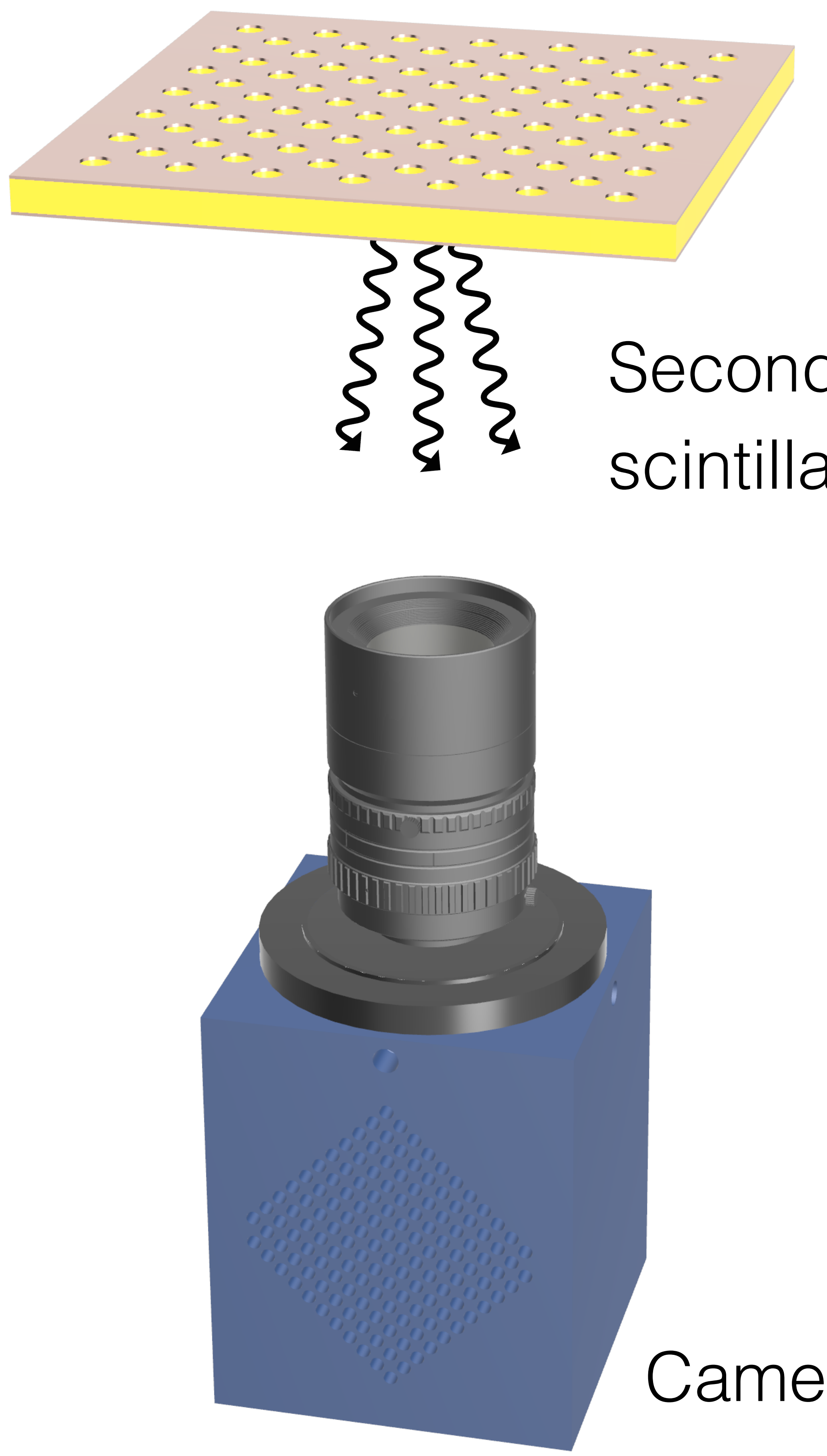
High spatial **resolution**

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



Schematics not drawn to scale

Scintillation spectra

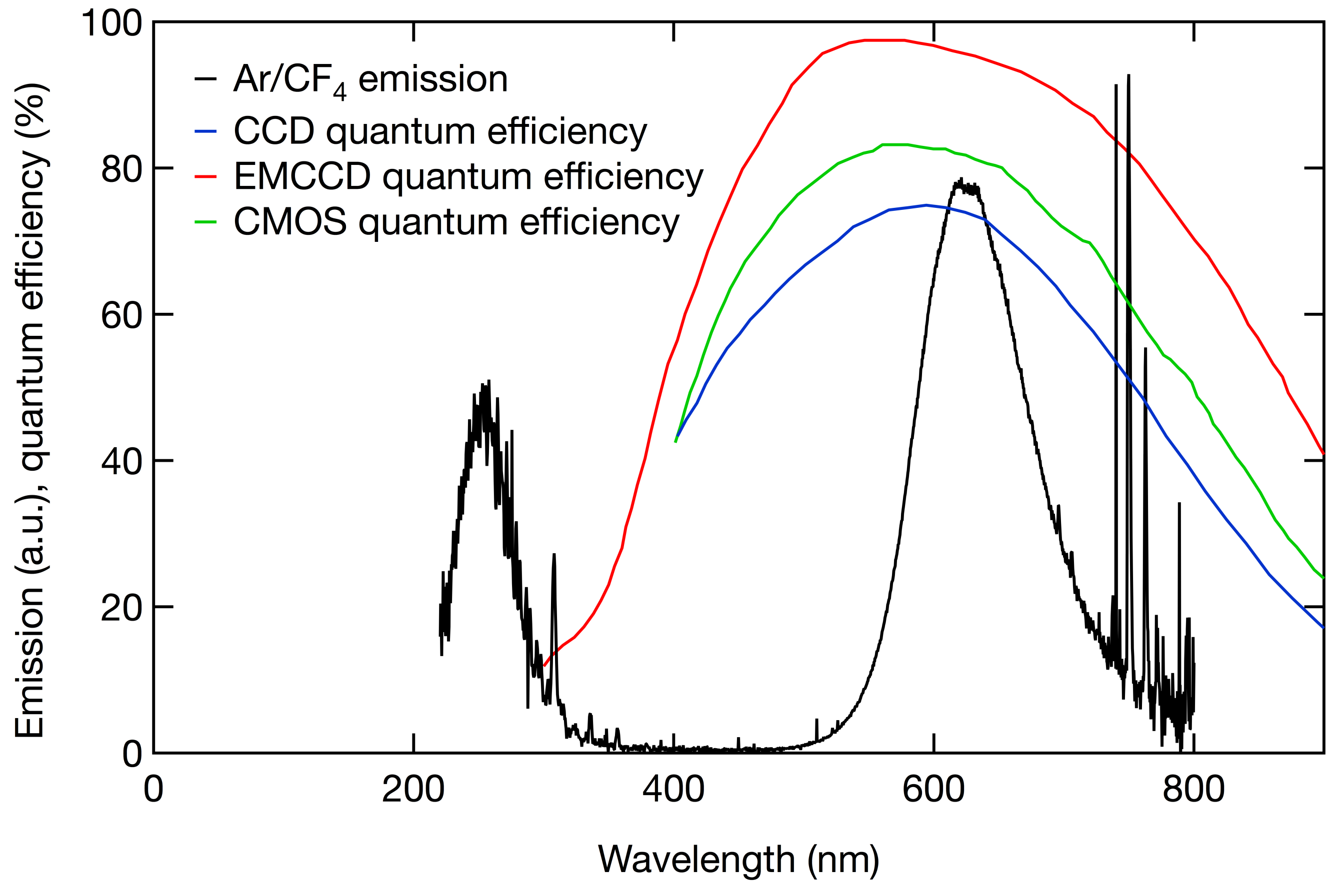
Reading out secondary scintillation light emitted during electron avalanche multiplication

Emission spectra and quantum efficiency of imaging sensors impose limits on choice of gases:
CF_4 or **wavelength shifting** to VIS.

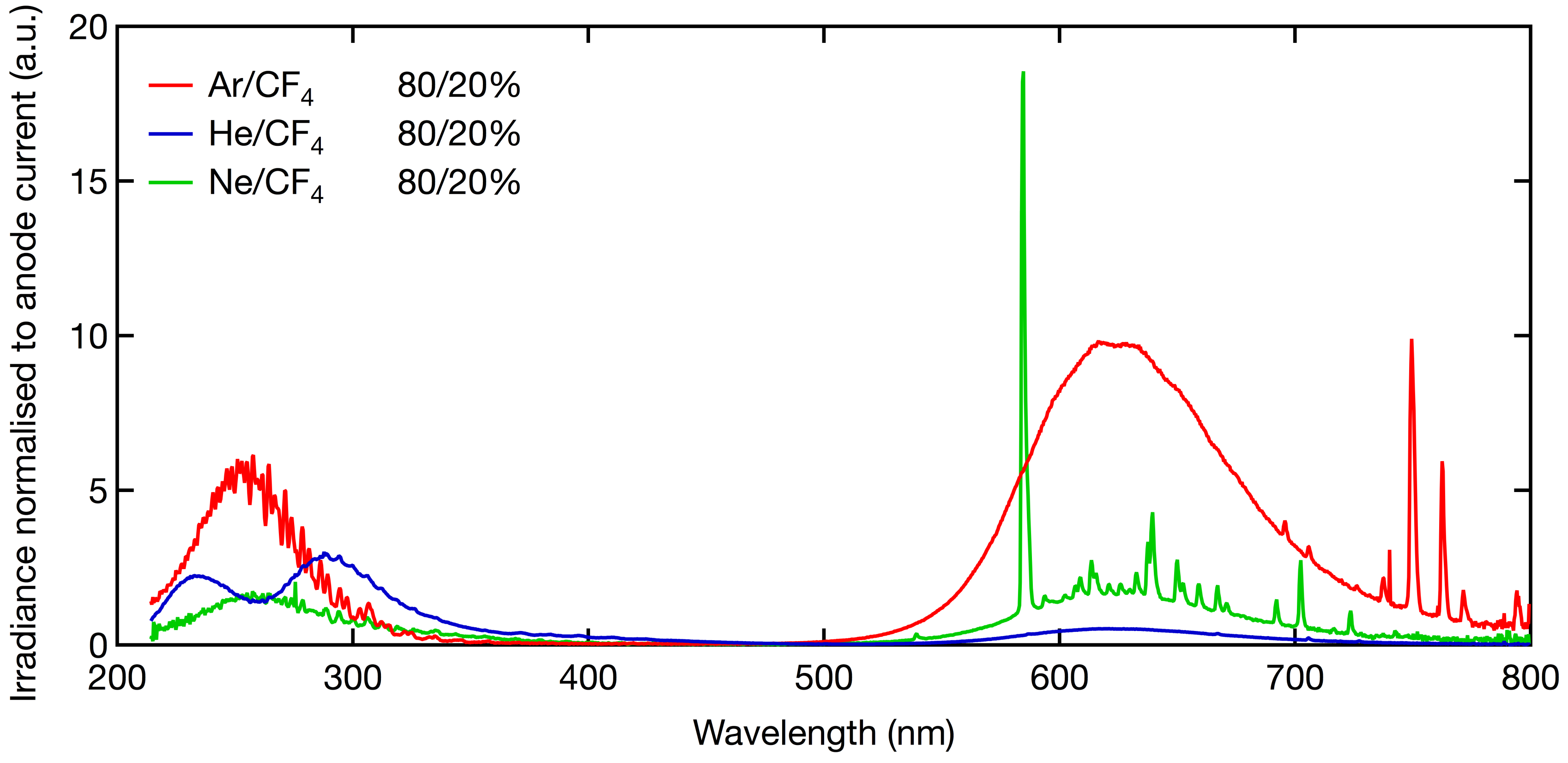
Alternative gases compatible with spectra sensitivity of imaging sensor?

Extension of **spectral sensitivity** to lower wavelengths for better performance in CF_4 based mixtures (UV band enhanced at low pressure) and alternative scintillating gases / wavelength shifters (TMA, TEA).

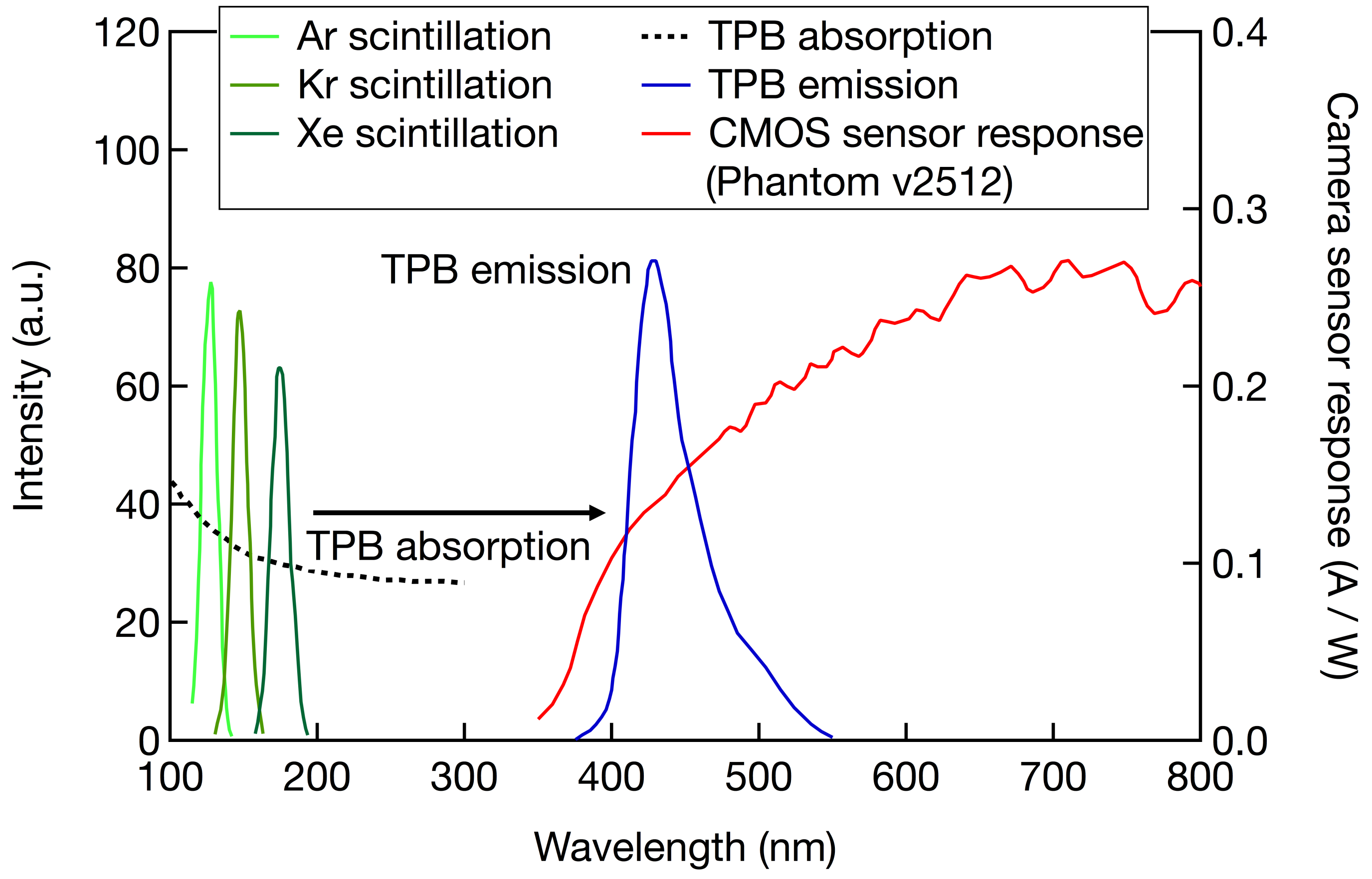
QE curves of cameras



Secondary scintillation spectra of mixtures with CF4



Wavelength shifting



Optically read out MPGDs

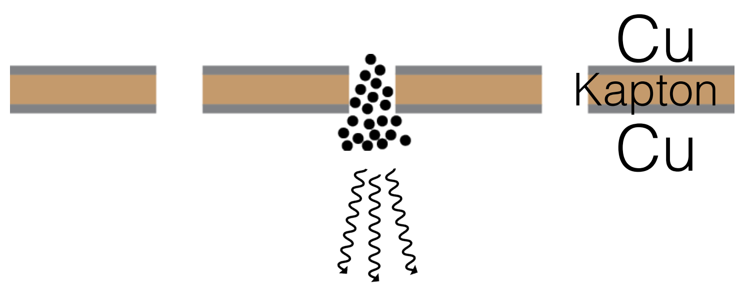
Different MPGD technologies have been used with optical readout for maximising spatial resolution (imaging), low pressure operation (glass GEM) and for detailed studies of detector physics.

Integration on transparent substrate (ITO-coated glass) for optical light transmission.

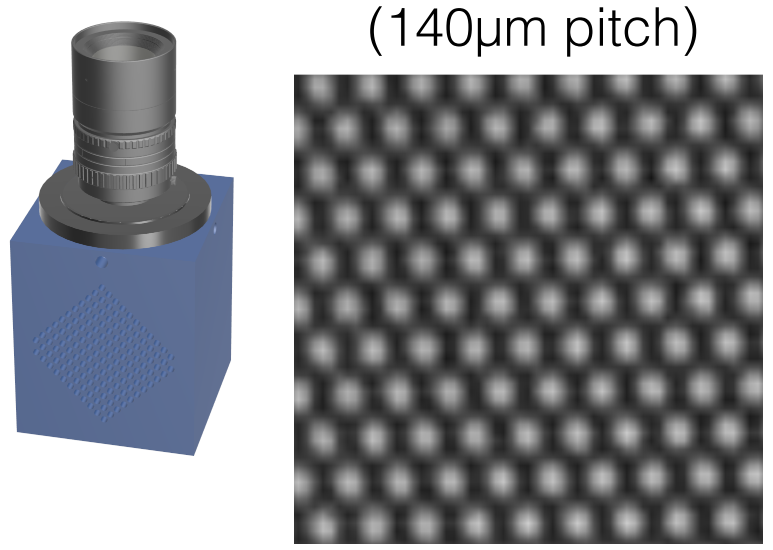
High gain (light yield) amplification **matched** with **pixel size** of imaging sensor

GEMs

Open structure inherently suited for optical readout
High gain in multi-GEM stacks

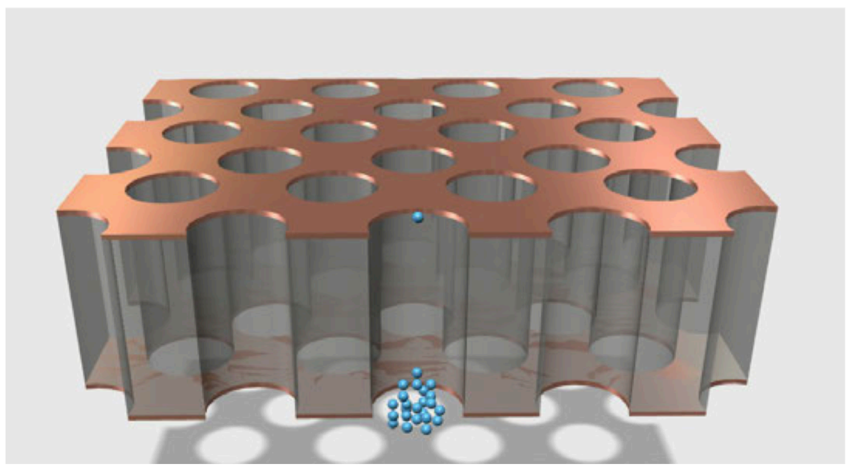


GEM holes
(140µm pitch)

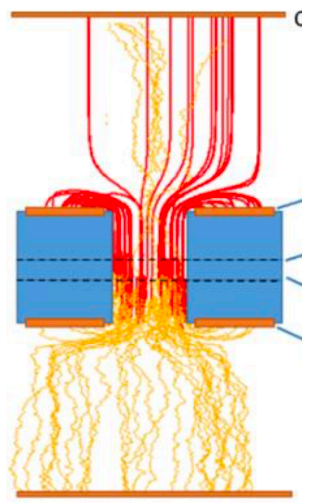


THGEMs

Long amplification region for e.g. low pressure operation
Variants: GlassGEM, MM,THGEM, …



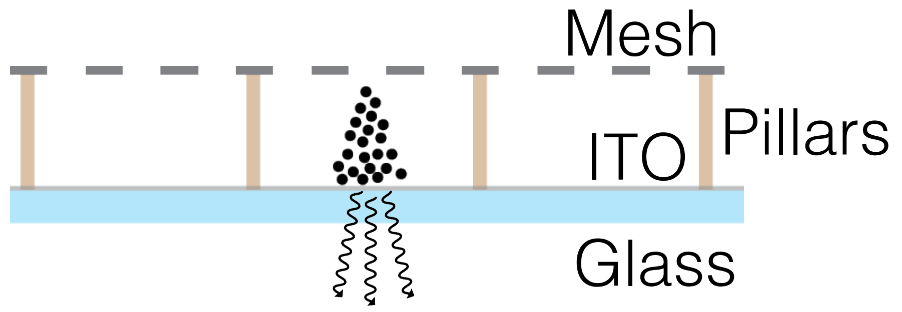
T. Fujiwara, MPGD2017



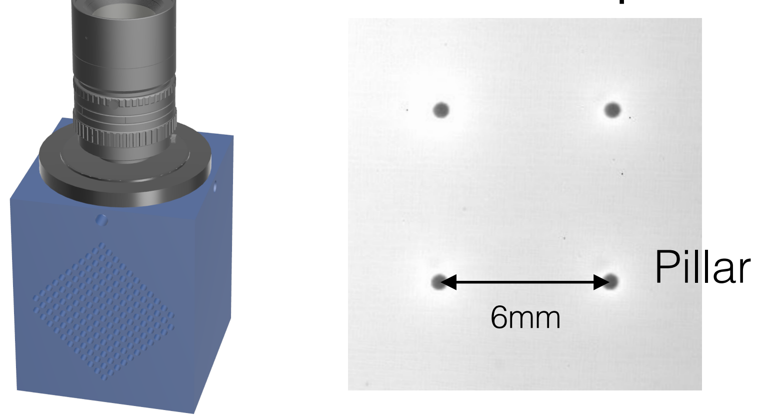
M. Cortesi, MPGD 2019

Glass Micromegas

High single stage gain, uniform amplification region and high energy resolution



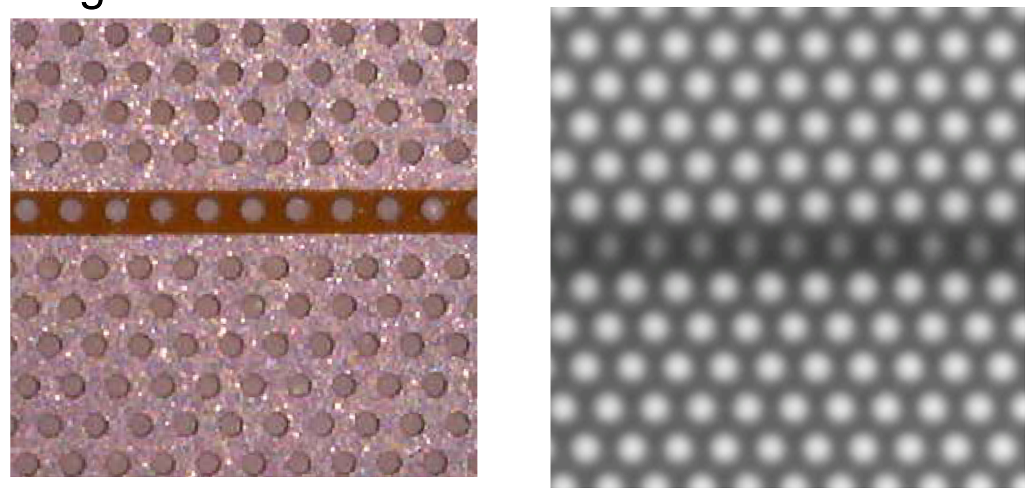
MM response

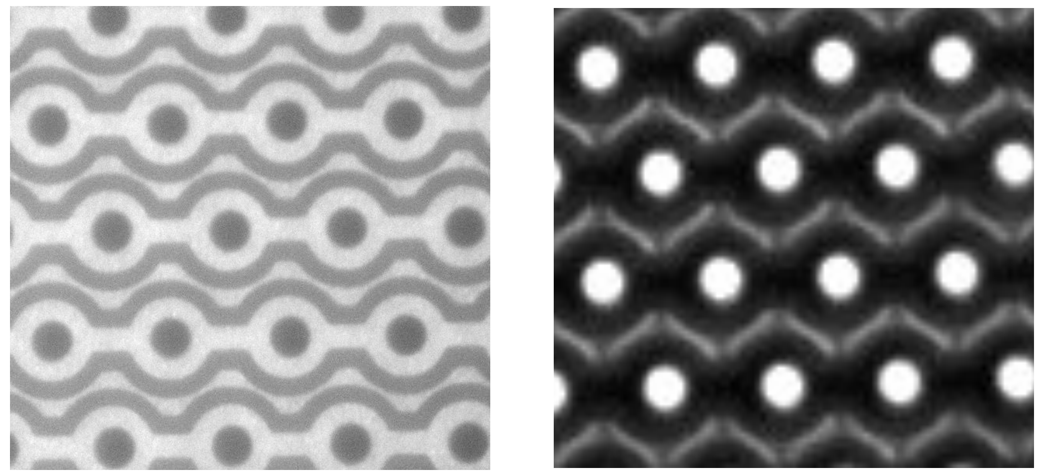


Glass substrates → other MPGDs

MPGD development and detector physics studies

Segmented GEM

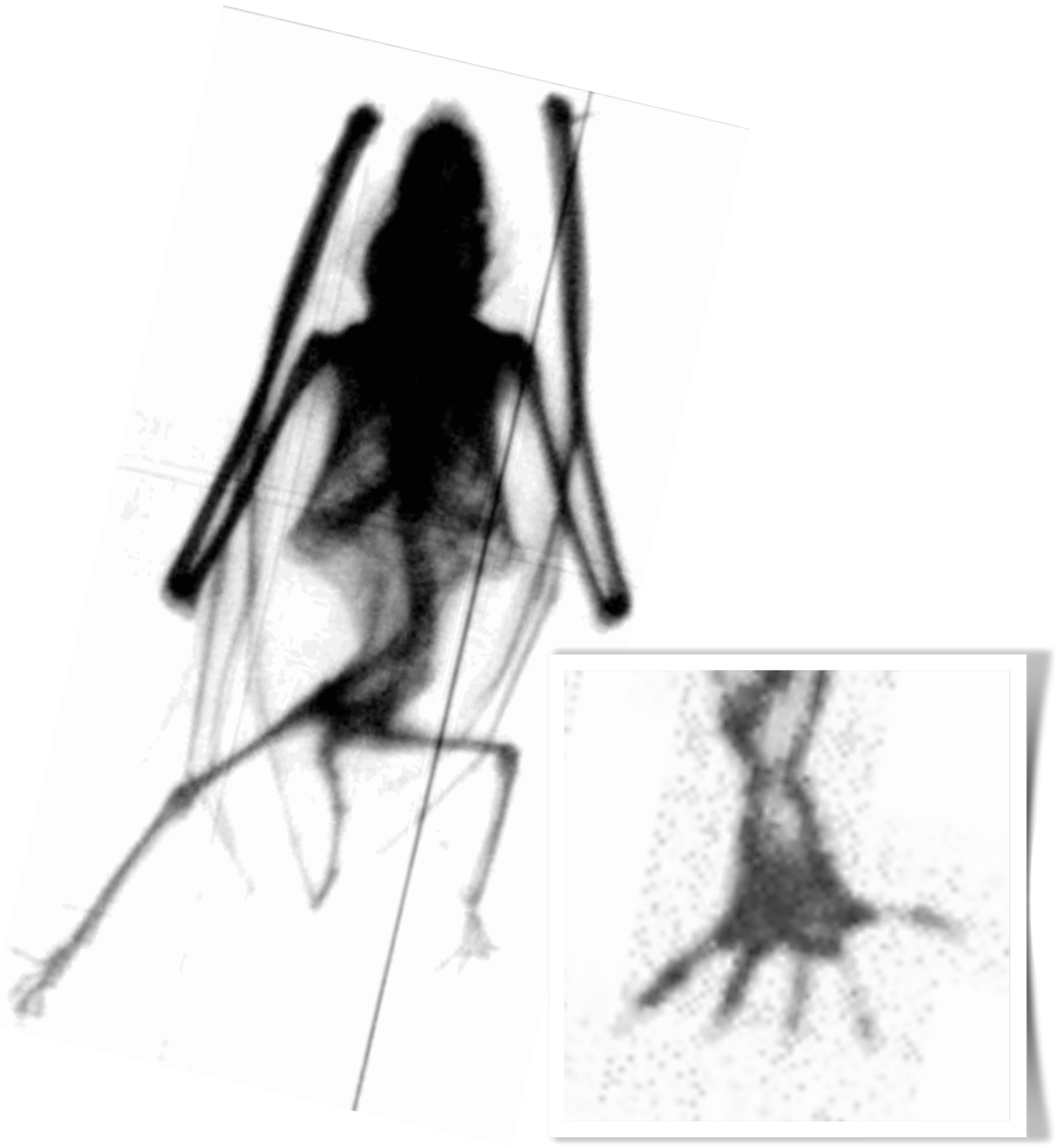




THCOBRA

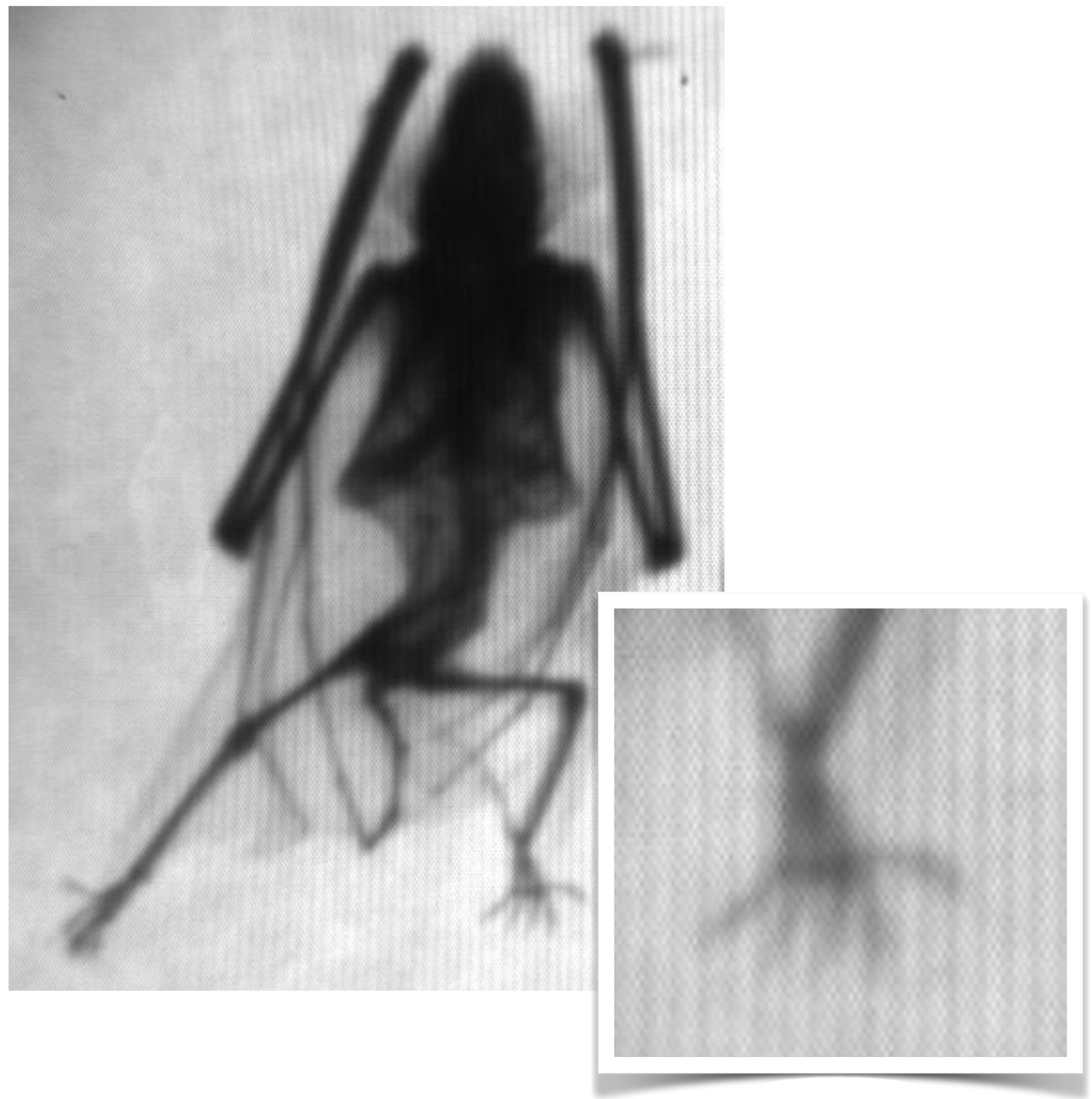
X-ray radiography comparison

Charge readout
(1998)



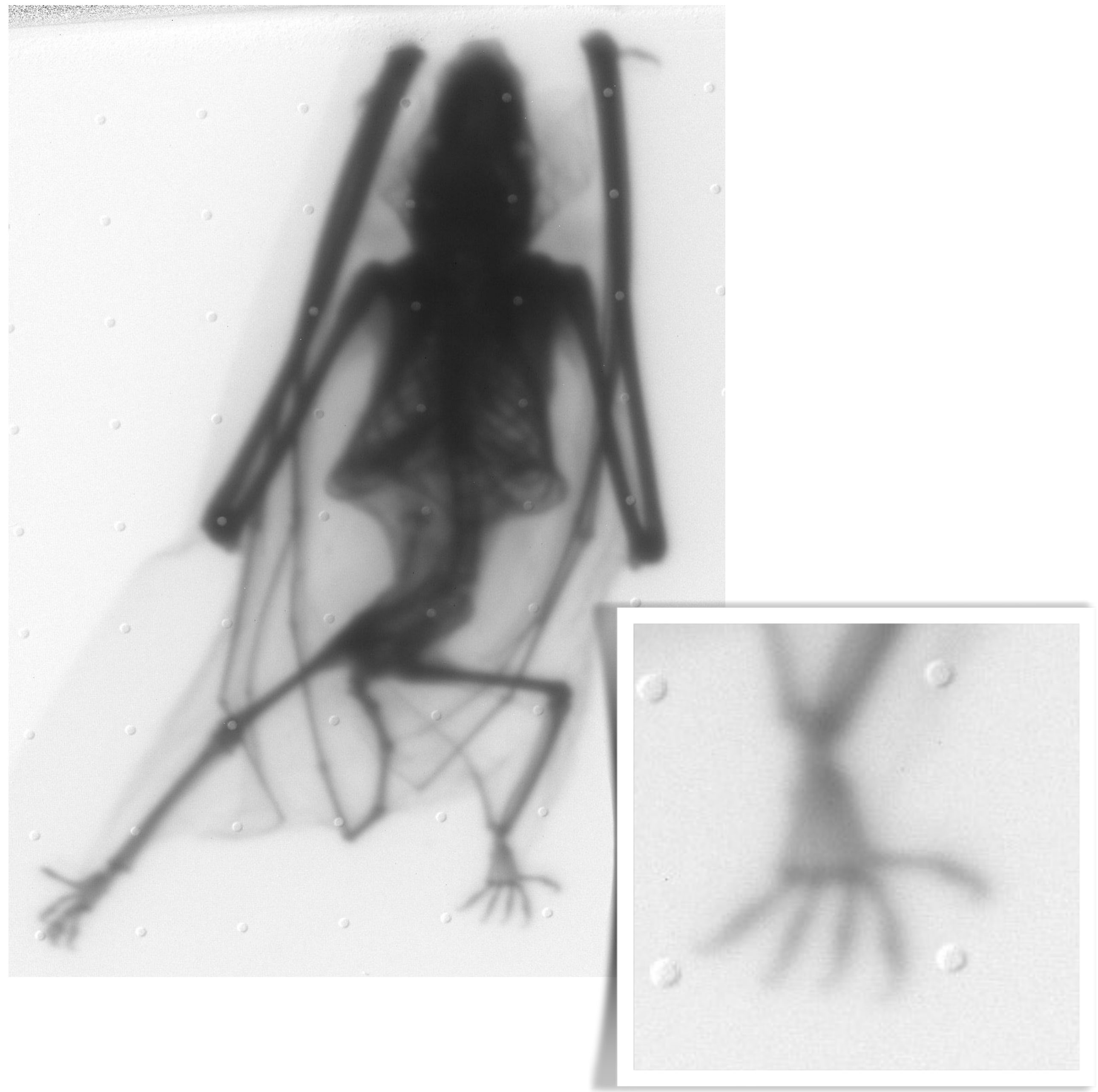
https://gdd.web.cern.ch/GDD/gemreadout.htm

Optically read out GEMs
(2016)



4x4 binning
thin drift gap triple-GEM

Optically read out MMs
(2018)

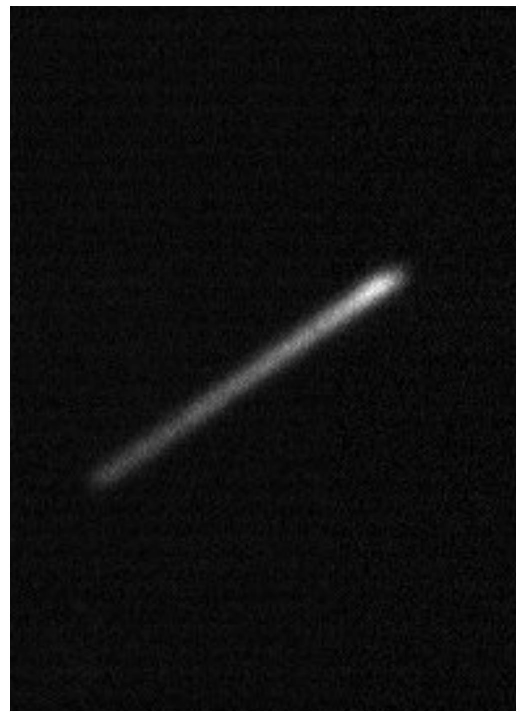


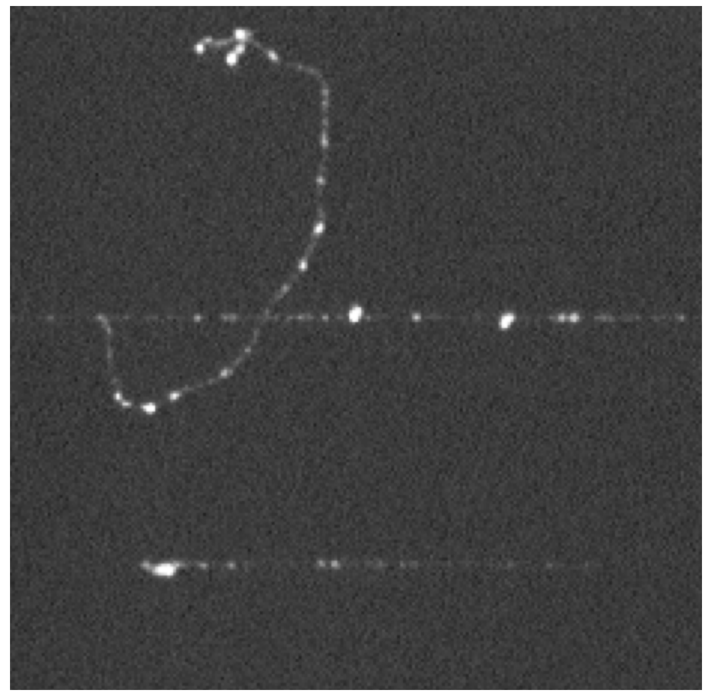
1x1 binning
long exposure, several mm active volume thickness

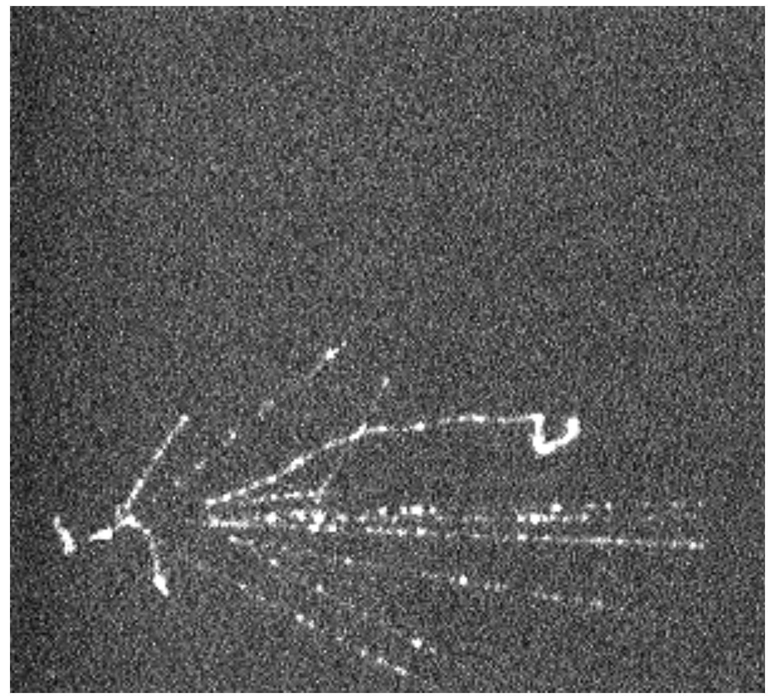
Gaseous radiation detectors optical readout

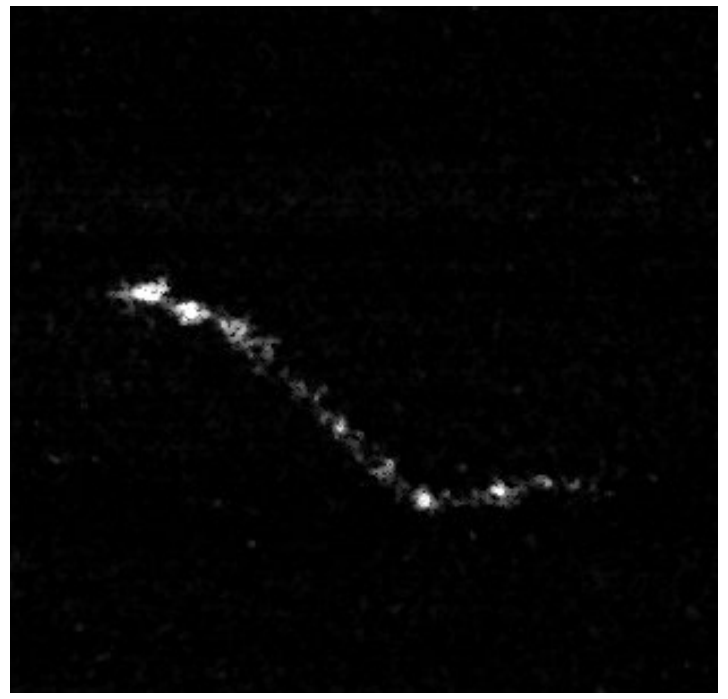
at the Gaseous Detector Development lab at CERN


X-ray photons

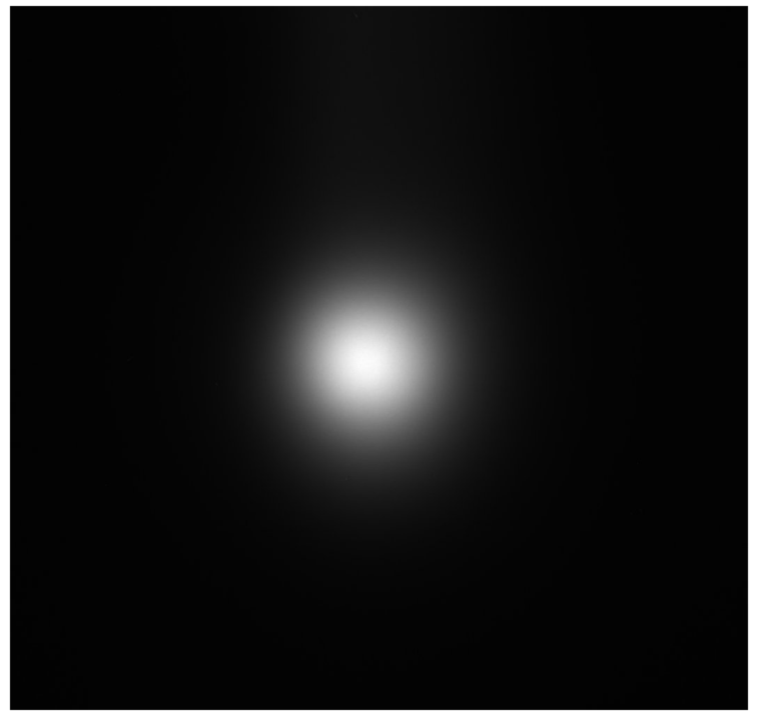

Alpha track

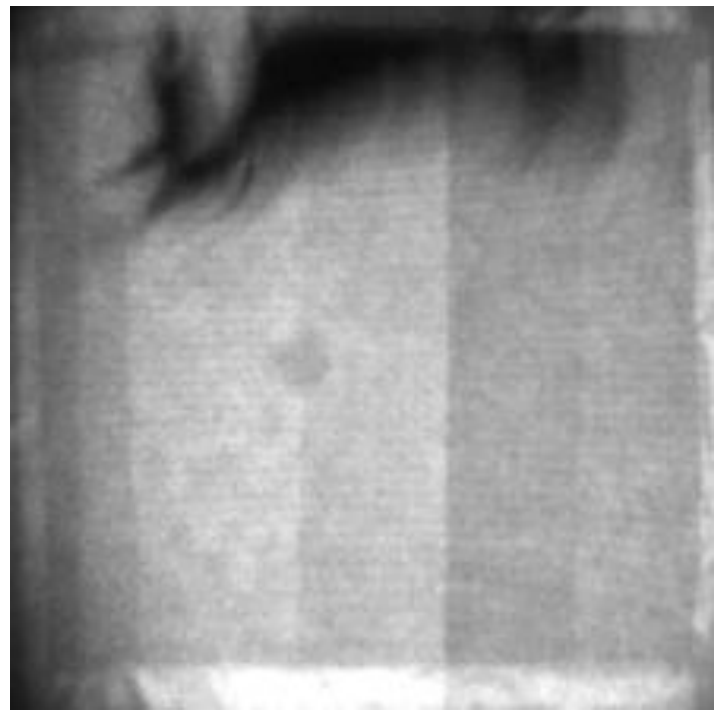

Muon tracks with δ-ray

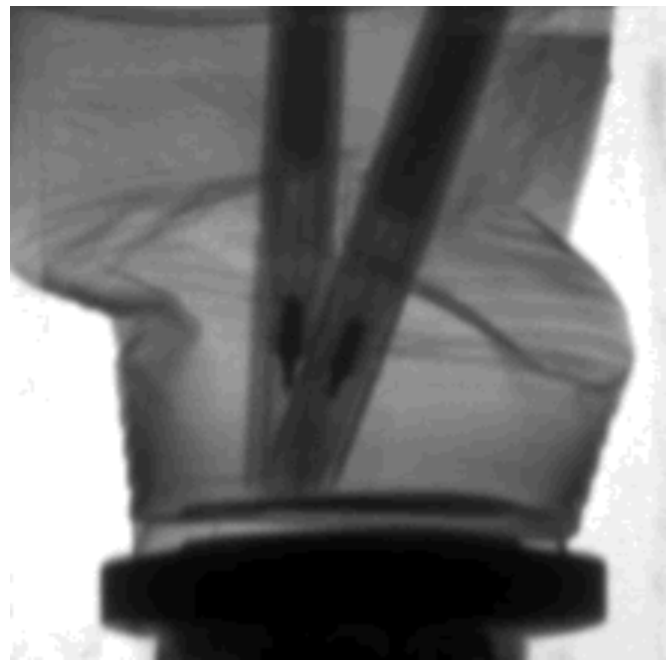

Hadronic shower


Cosmic event

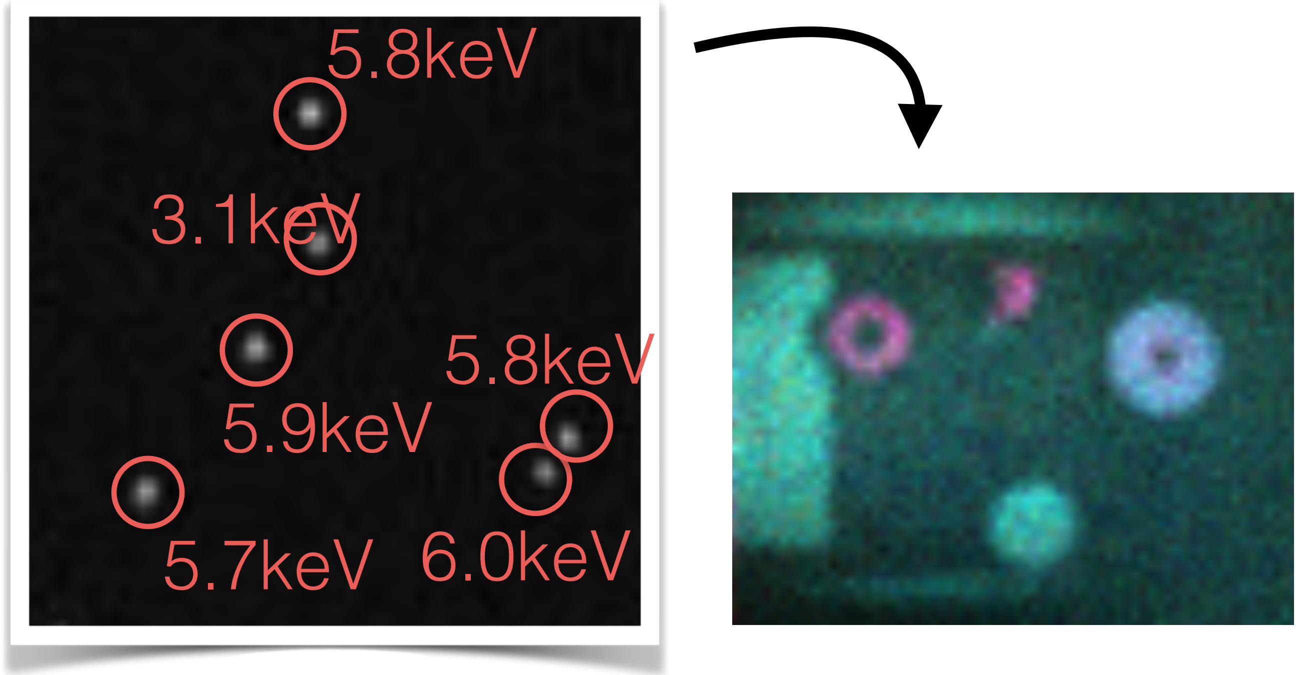
Detailed **track topology** visualisation for event classification


Proton beam profile


X-ray fluoroscopy


X-ray tomography

Brightness reflects deposited energy



X-ray fluorescence

Integrated imaging compatible with high intensity of incident radiation

Direct availability of integrated image without need for extensive reconstruction

Beam monitoring and dose imaging with optical readout

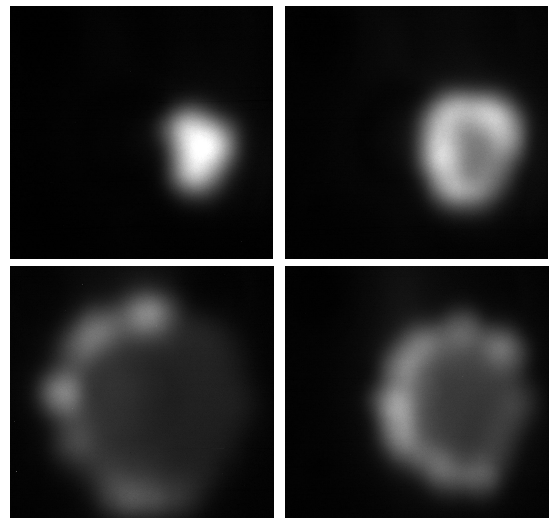
Hadron therapy monitoring

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

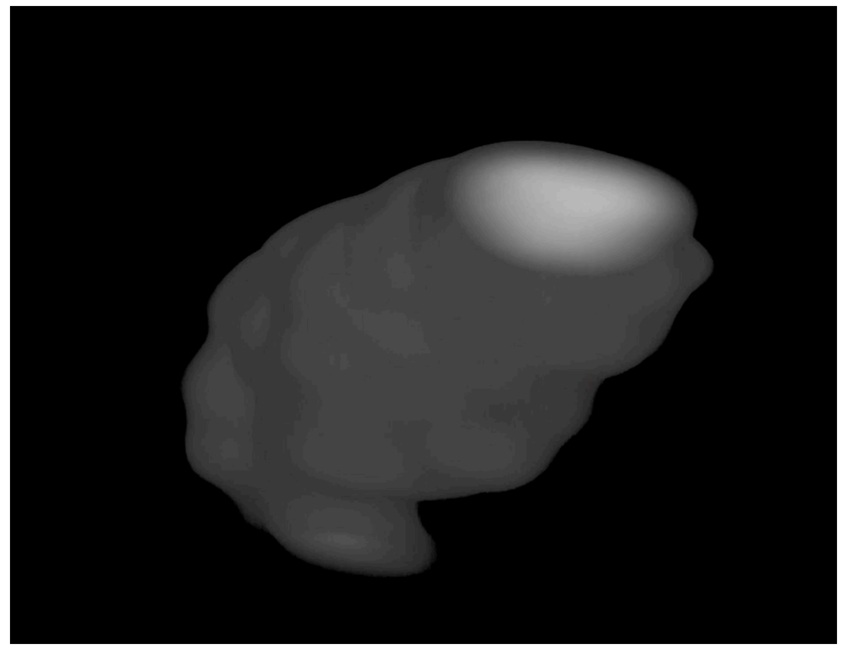
Low material budget of gaseous detector minimises beam attenuation and multiple scattering

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

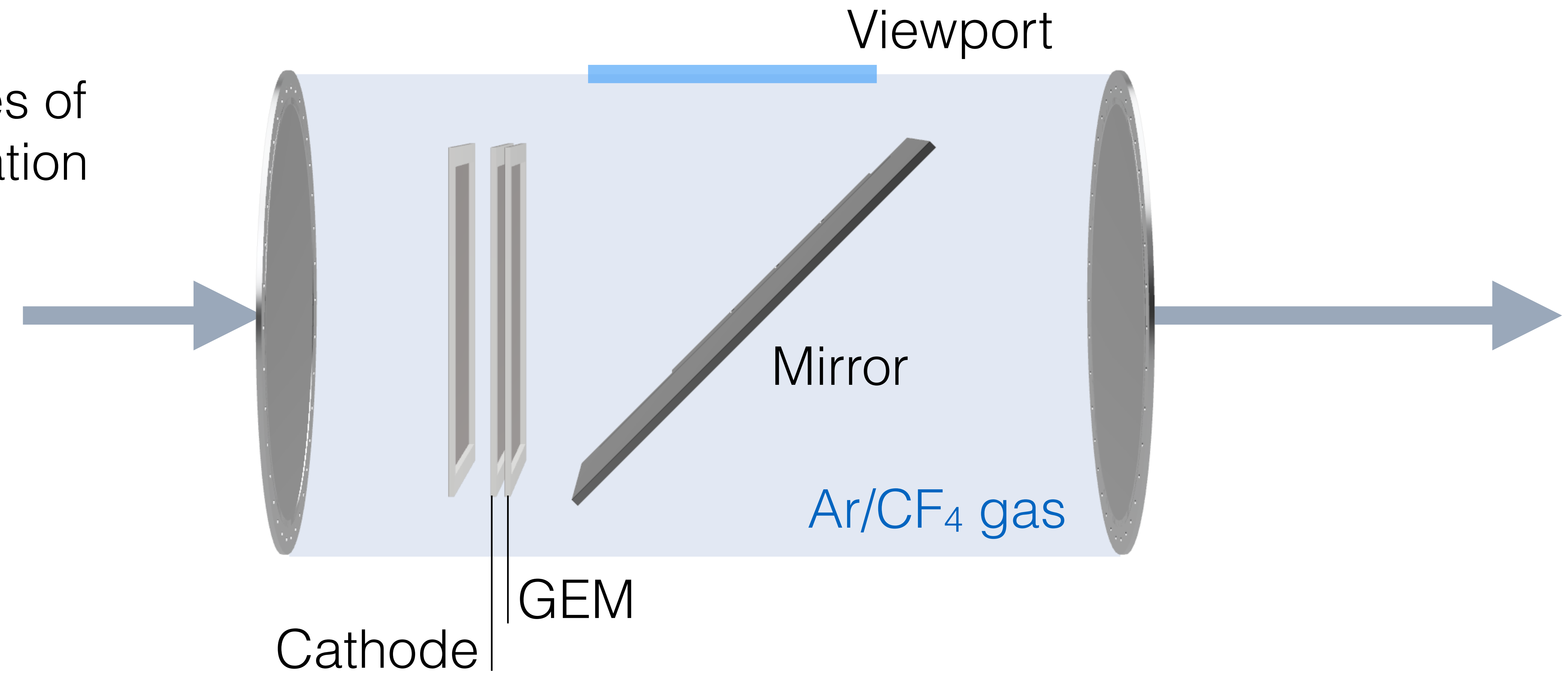
This can provide high spatial resolution images of scanning pencil beams for beam characterisation and treatment plan verification

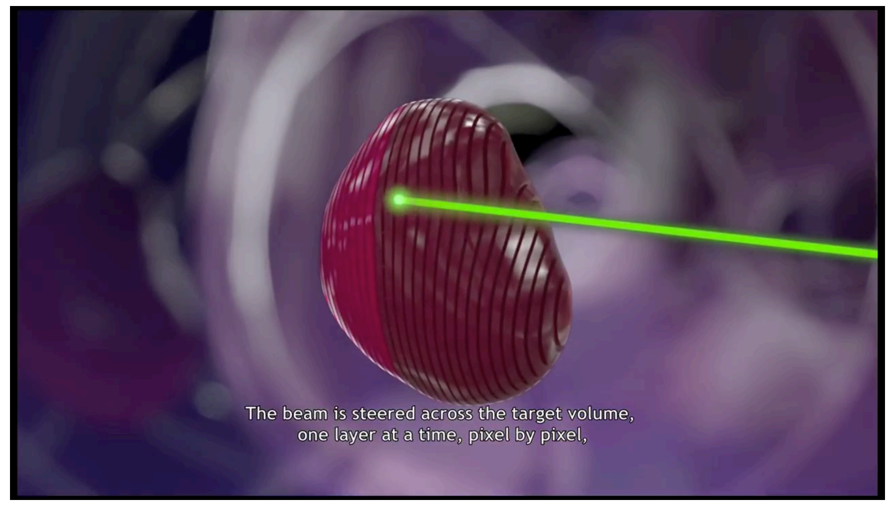


2D slice images



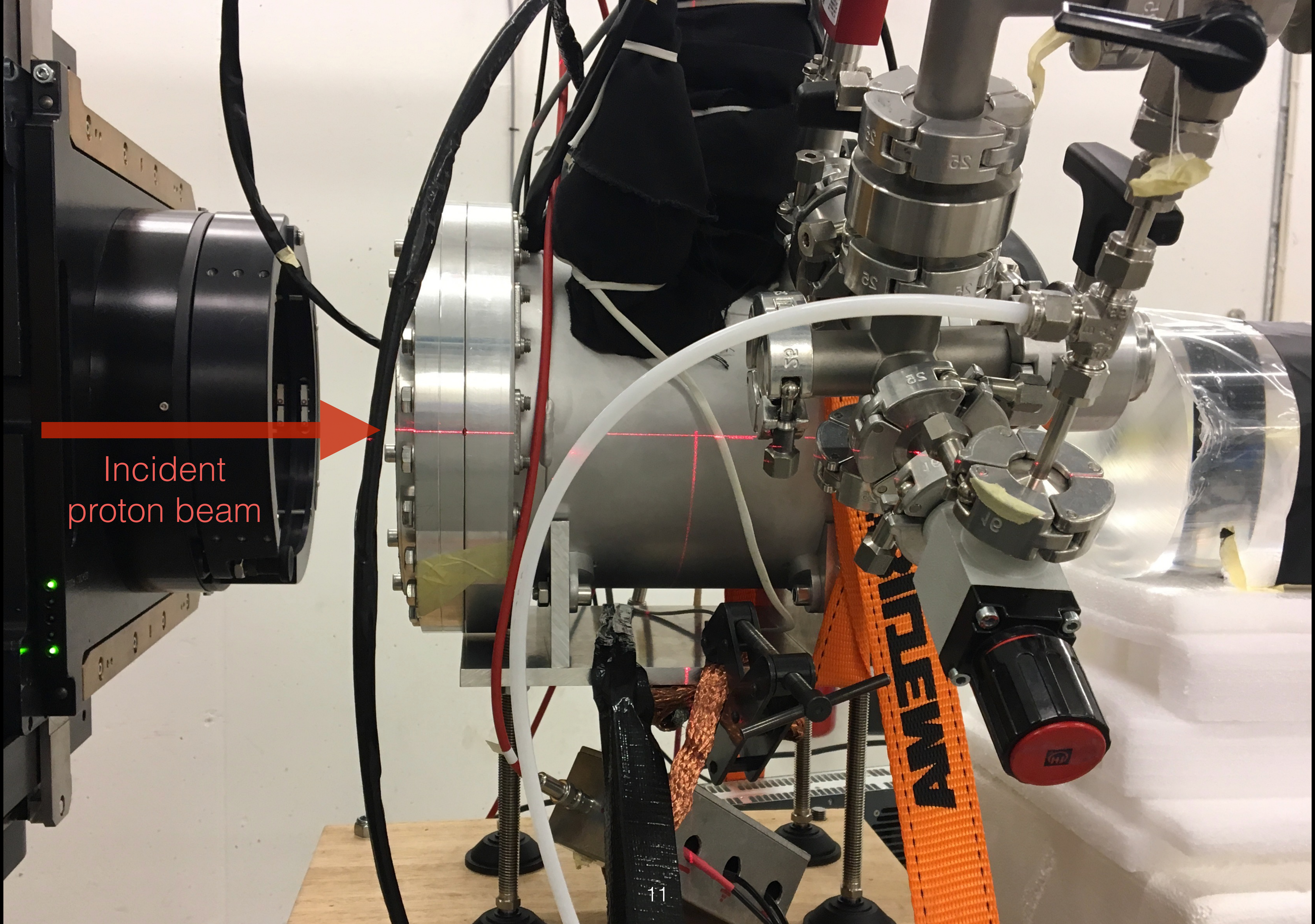
3D deposited charge distribution for brain tumour irradiation plan





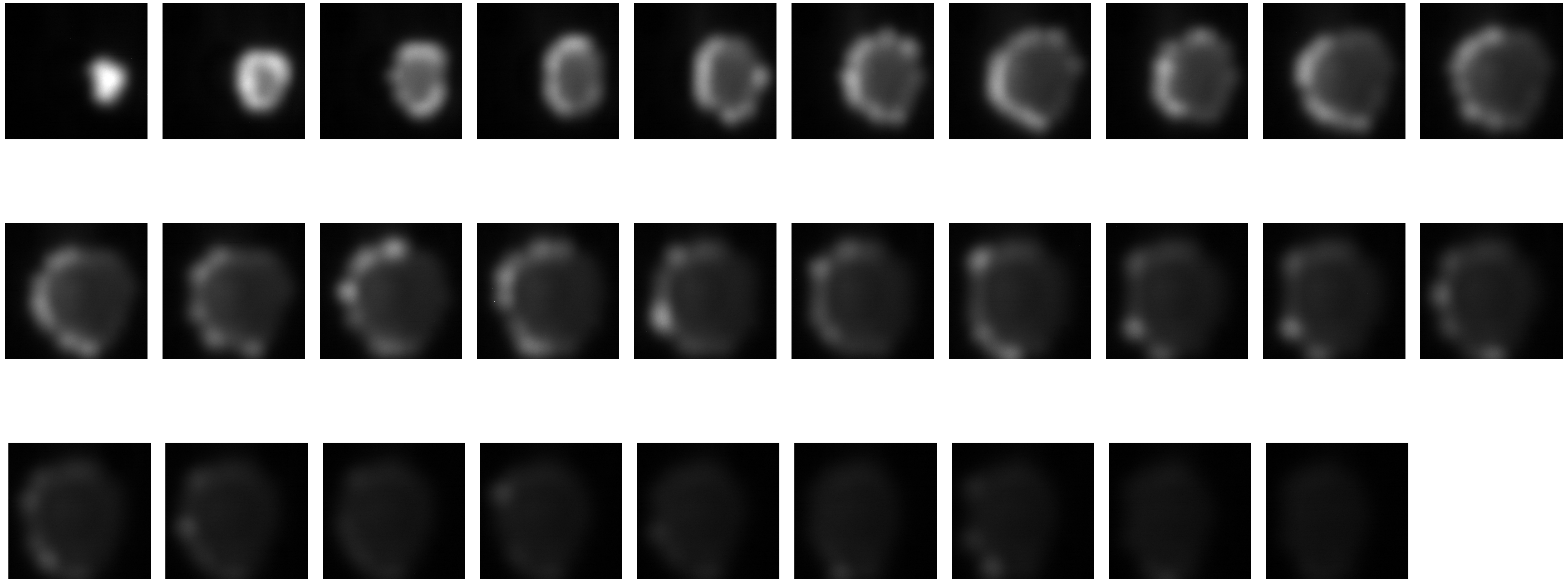
Scanning pencil beam irradiation

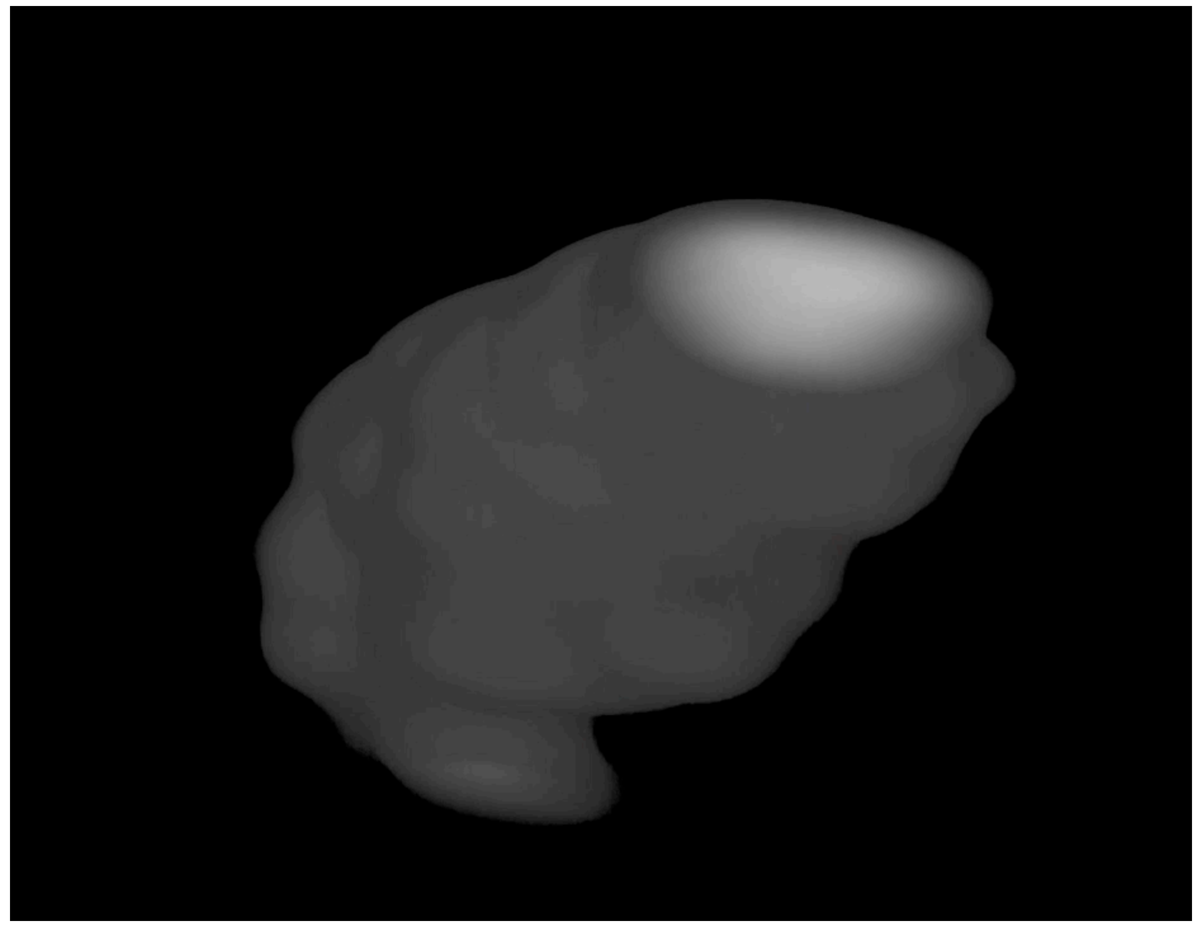
Adapted from iba Proton Therapy
https://www.youtube.com/watch?v=MS590Xtq9M4&t=5s


Incident
proton beam
AMETLIN

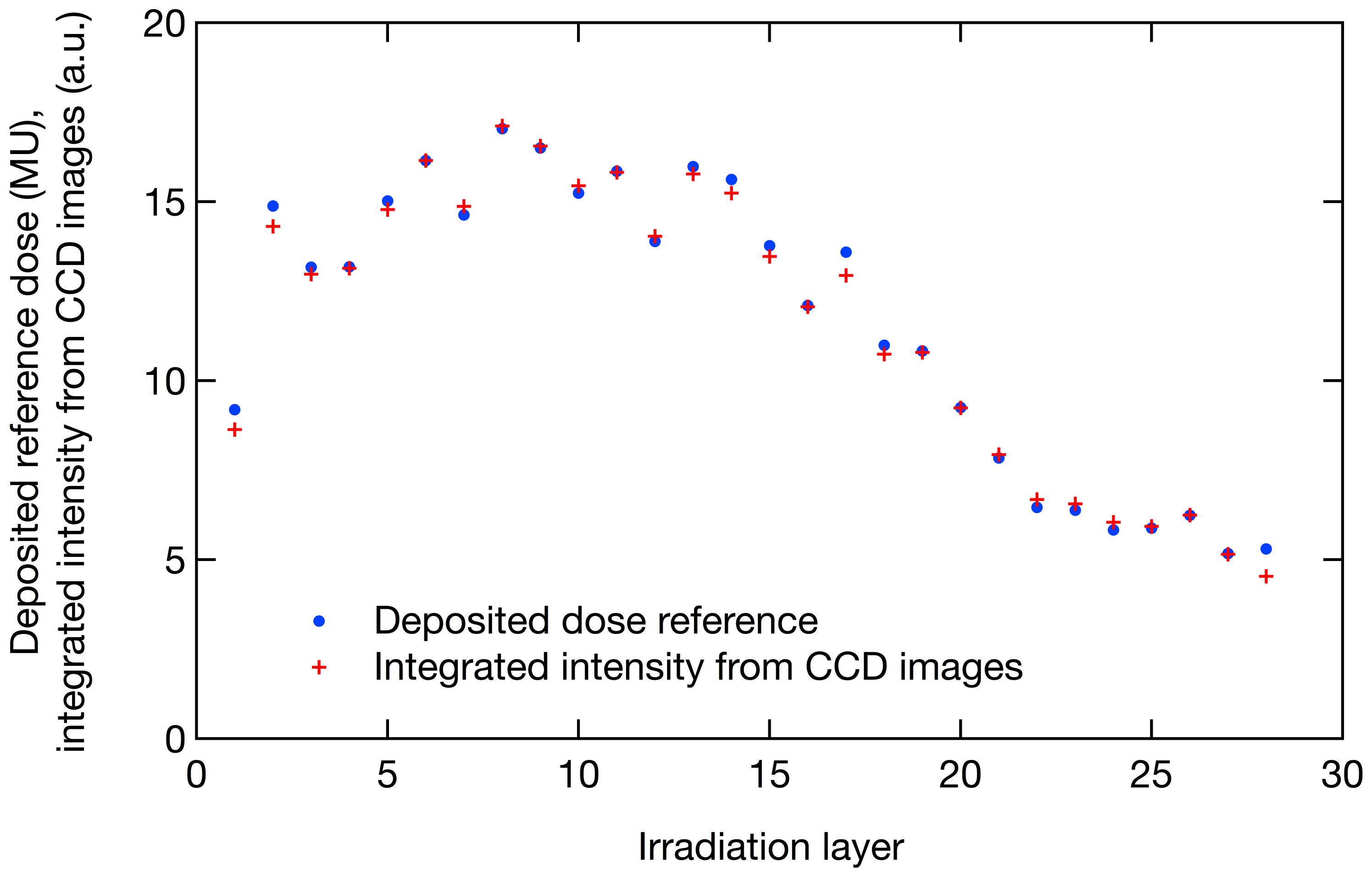
Dose distribution imaging

10x10 cm² images of treatment plan layers



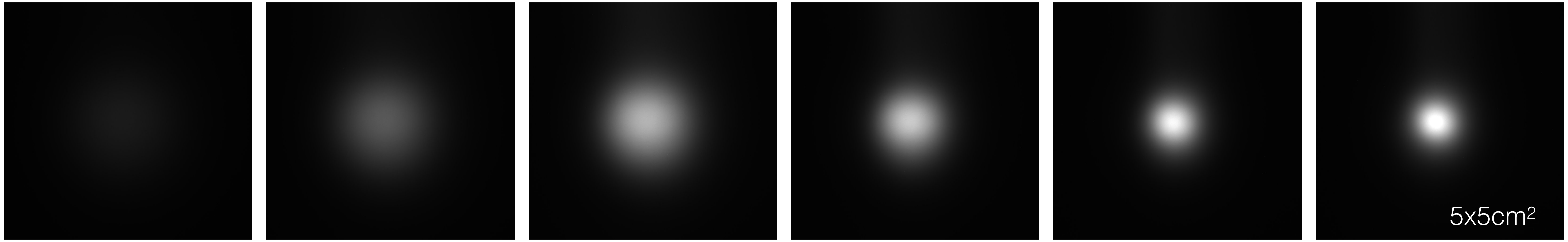


3D dose distribution



2D dose distribution images of individual layers of treatment plan irradiation can be recorded online and used to verify 3D dose distribution

Proton beam profile

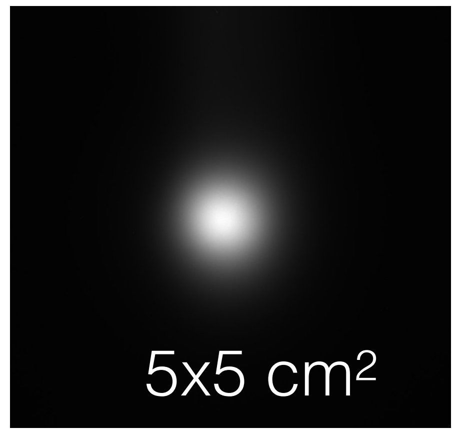


60 MeV, 0.4nA | 80 MeV, 1nA | 100 MeV, 2nA | 150 MeV, 2nA | 200 MeV, 2nA | 226 MeV, 2nA

Recorded CCD images of centered single beam spots at different energies show decreasing beam spot width with increasing beam energy

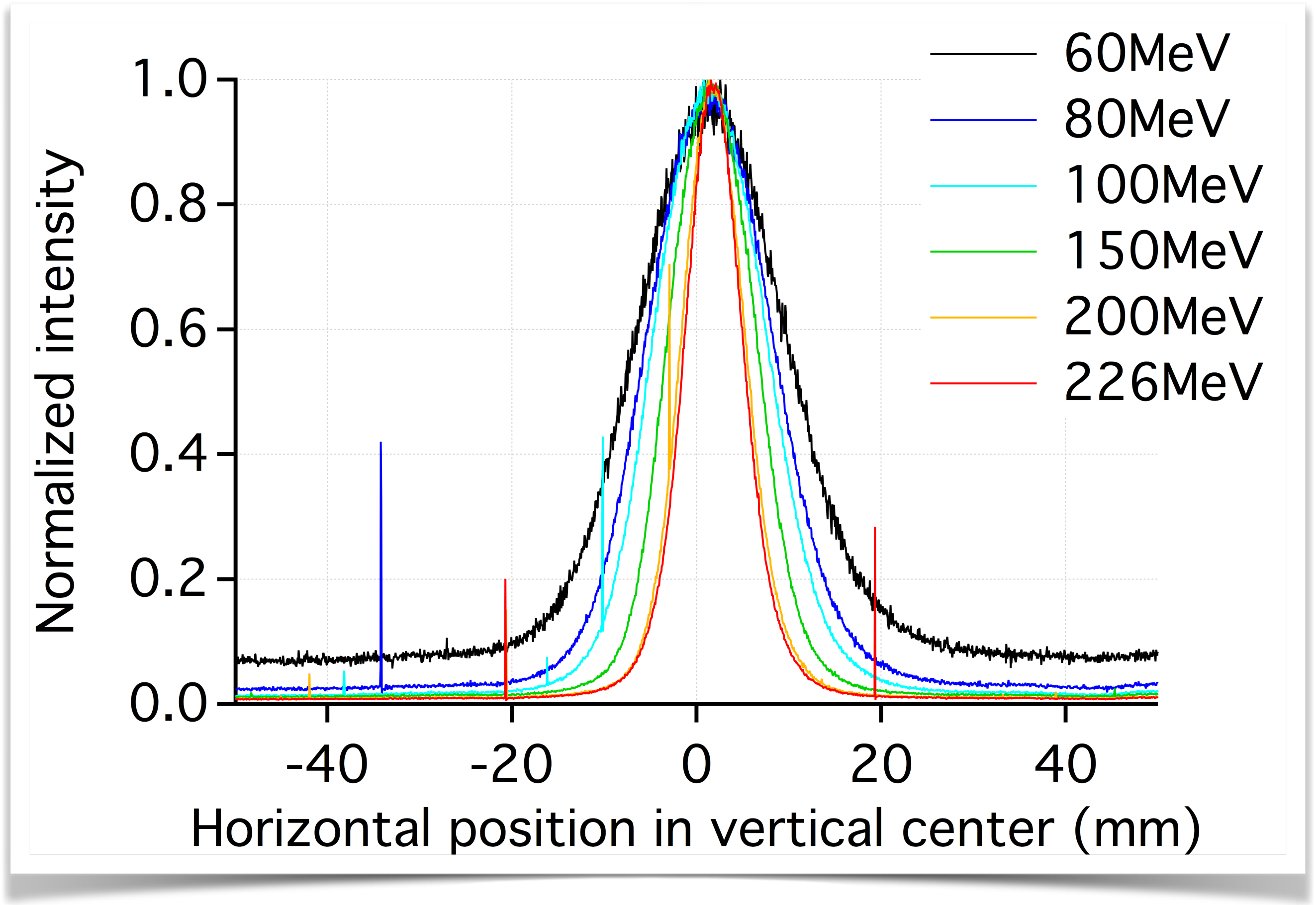
Scanning beam energy and current, profile images from highest possible current

Proton beam profile

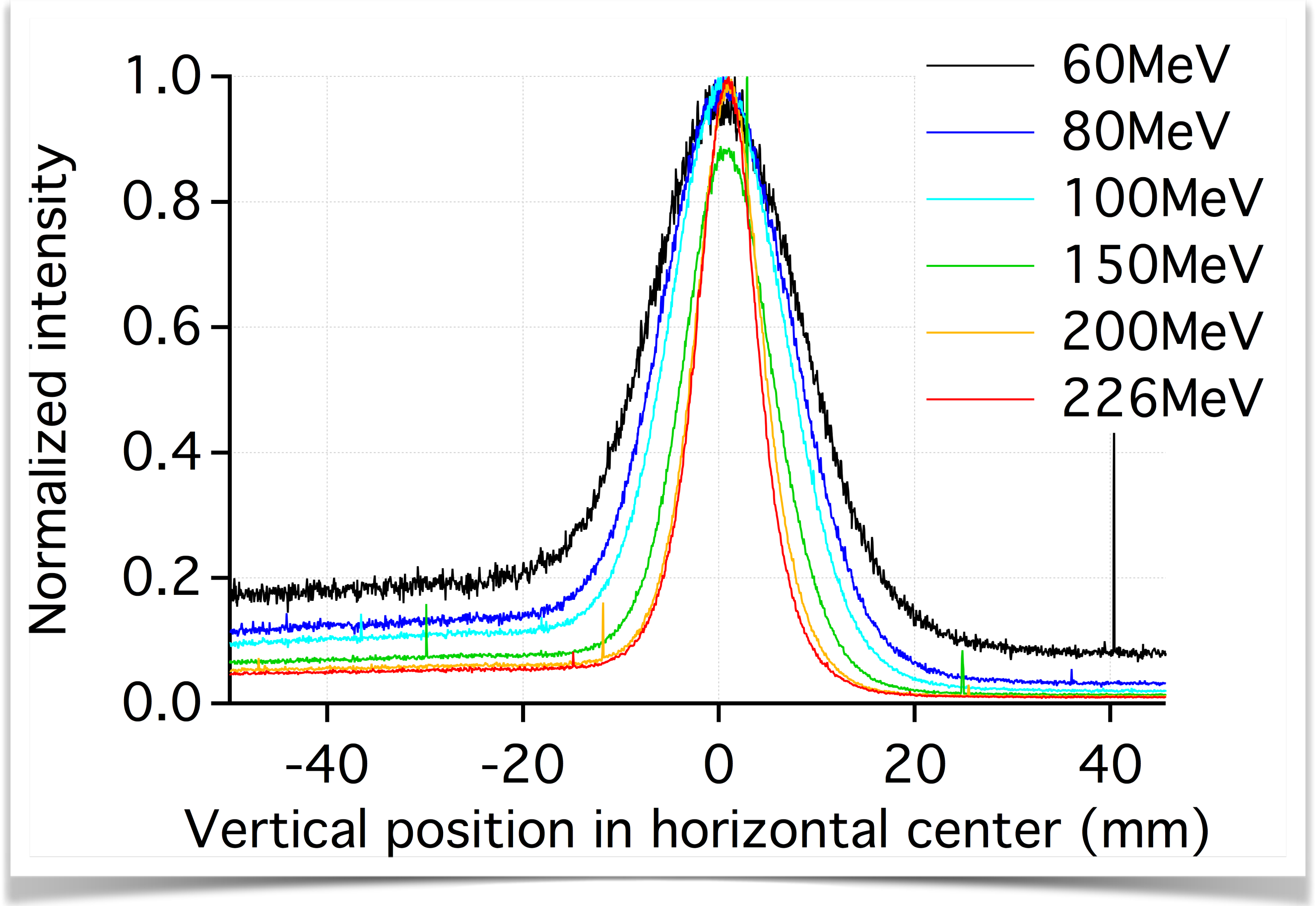


200 MeV pencil beam

Horizontal profiles

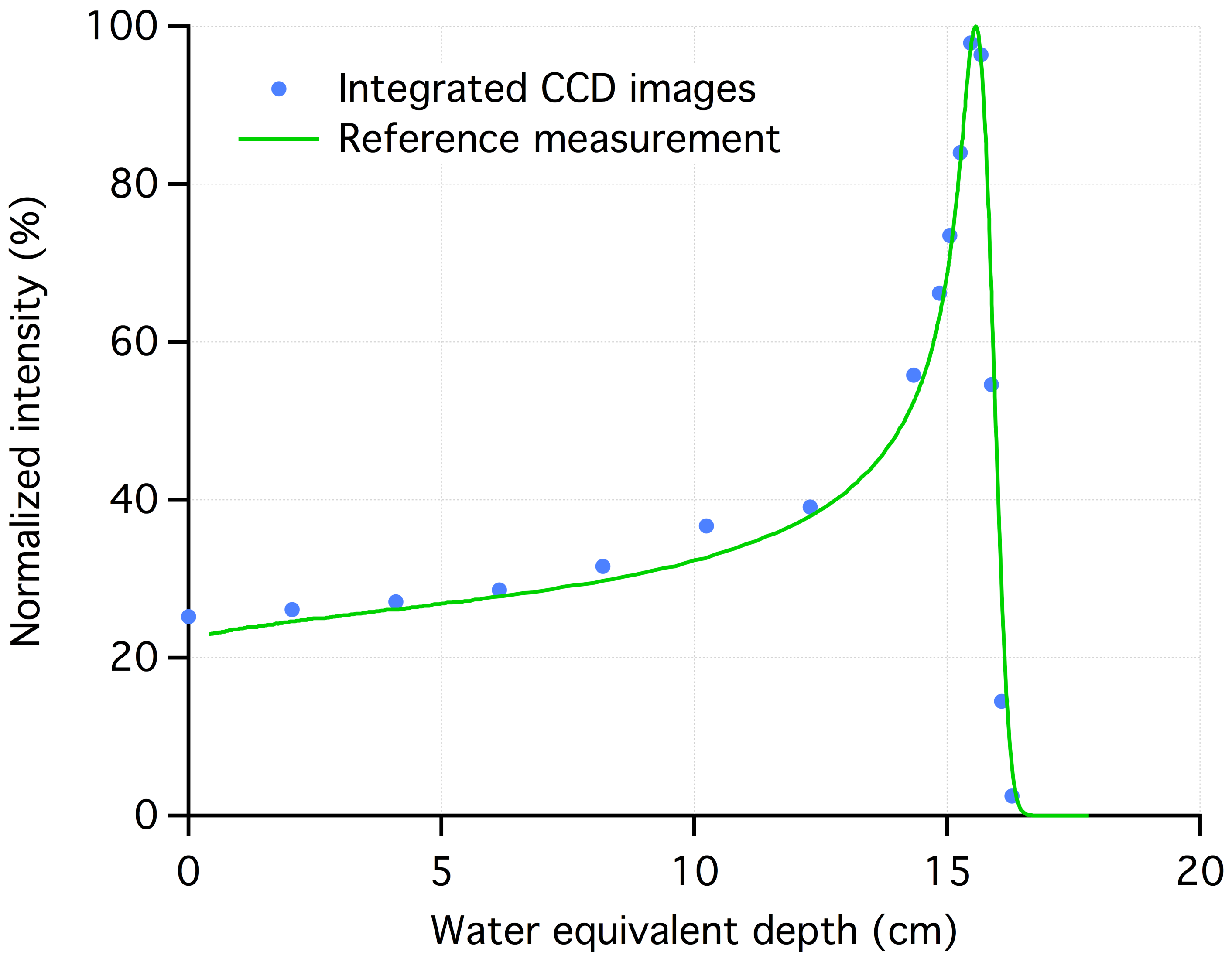


Vertical profiles



All profiles normalised to maximum intensity
Decreasing beam spot width with increasing beam energy

Dose depth curve



Scanning beam energy and current, profile images from highest possible current

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

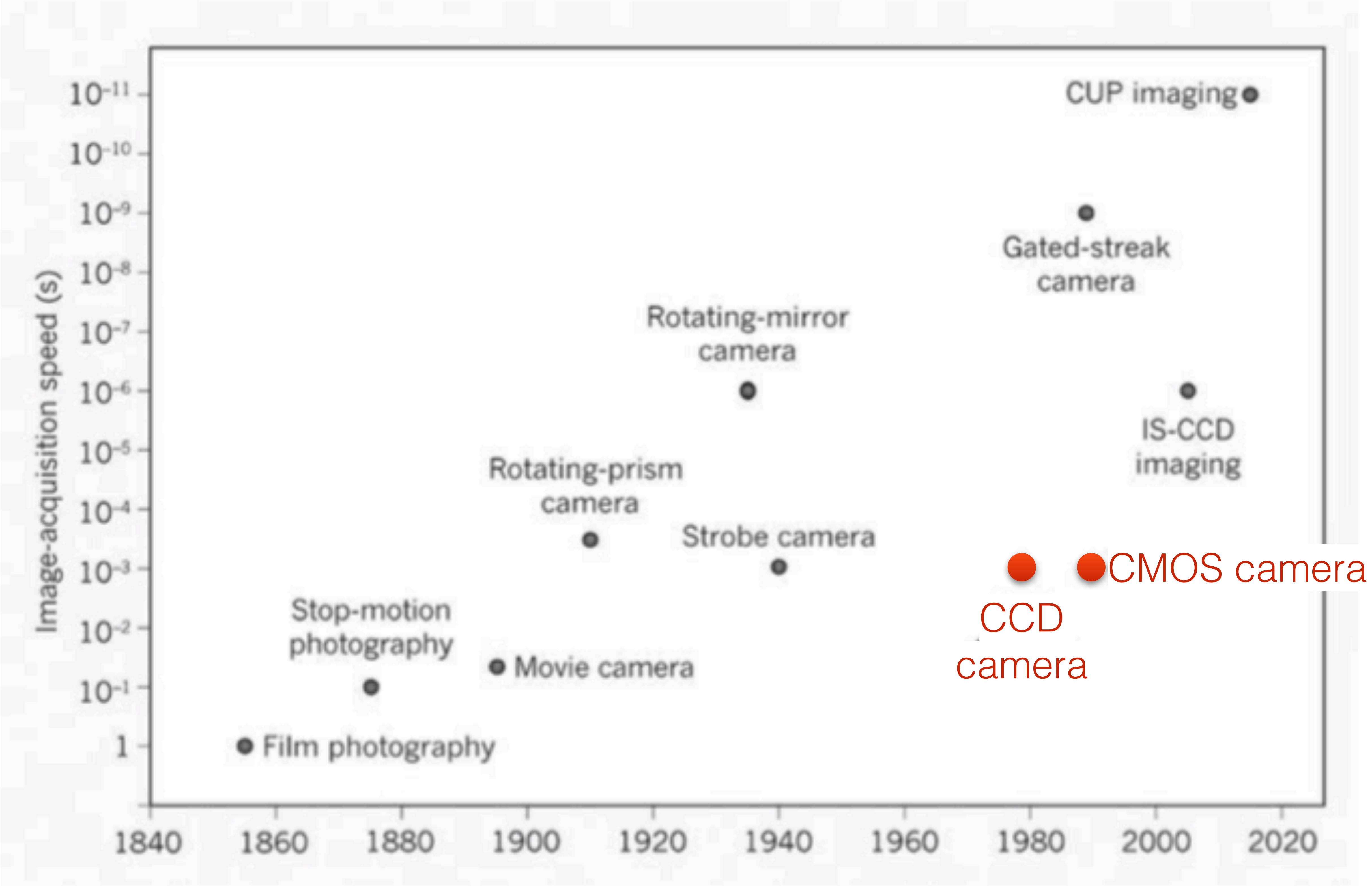


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Optical readout

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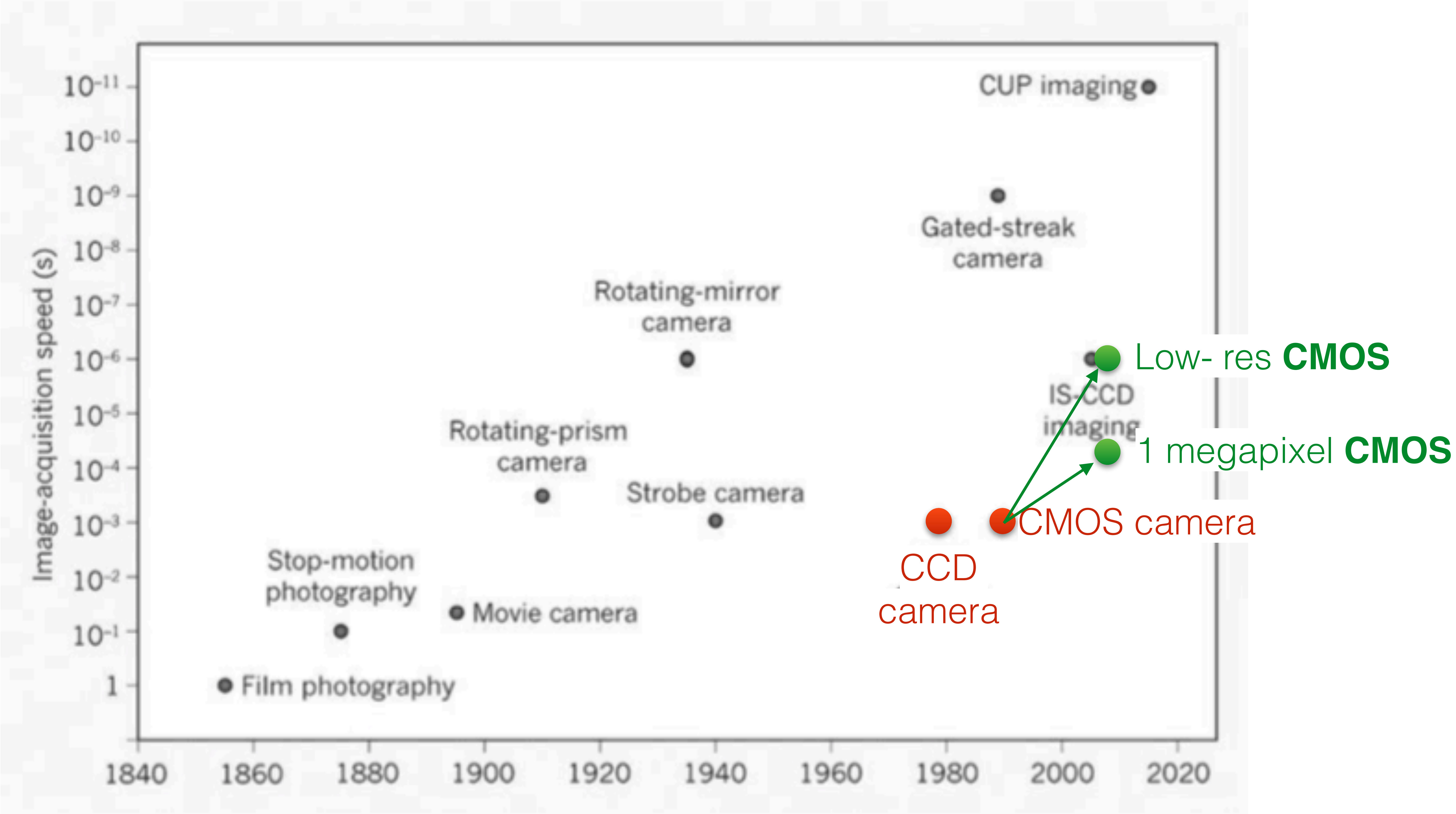
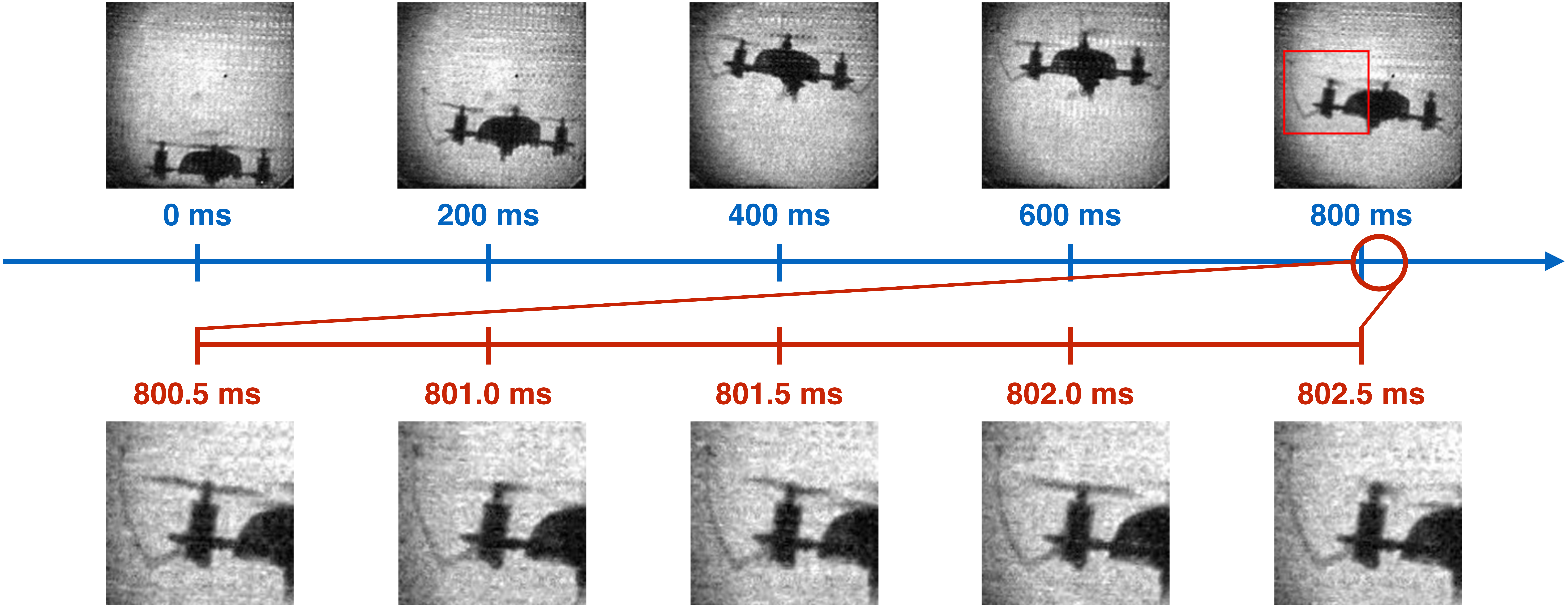


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Phantom v2512

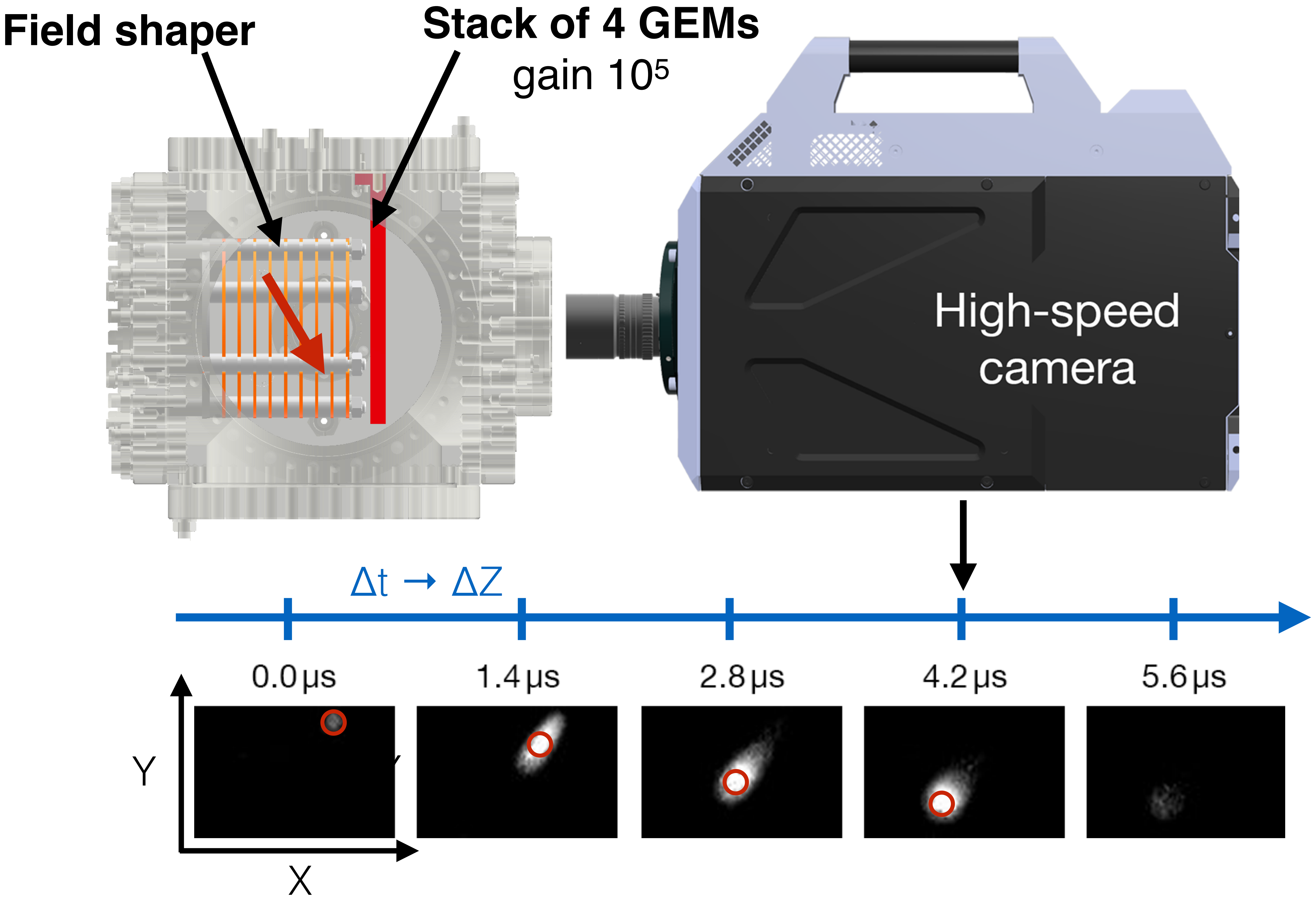
- 1 megapixel CMOS sensor
- 12 bit depth
- **25 kfps** at 1280 x 800
- **1 Mfps** at 128x32
- ISO 100,000 sensitivity

High-speed X-ray fluoroscopy

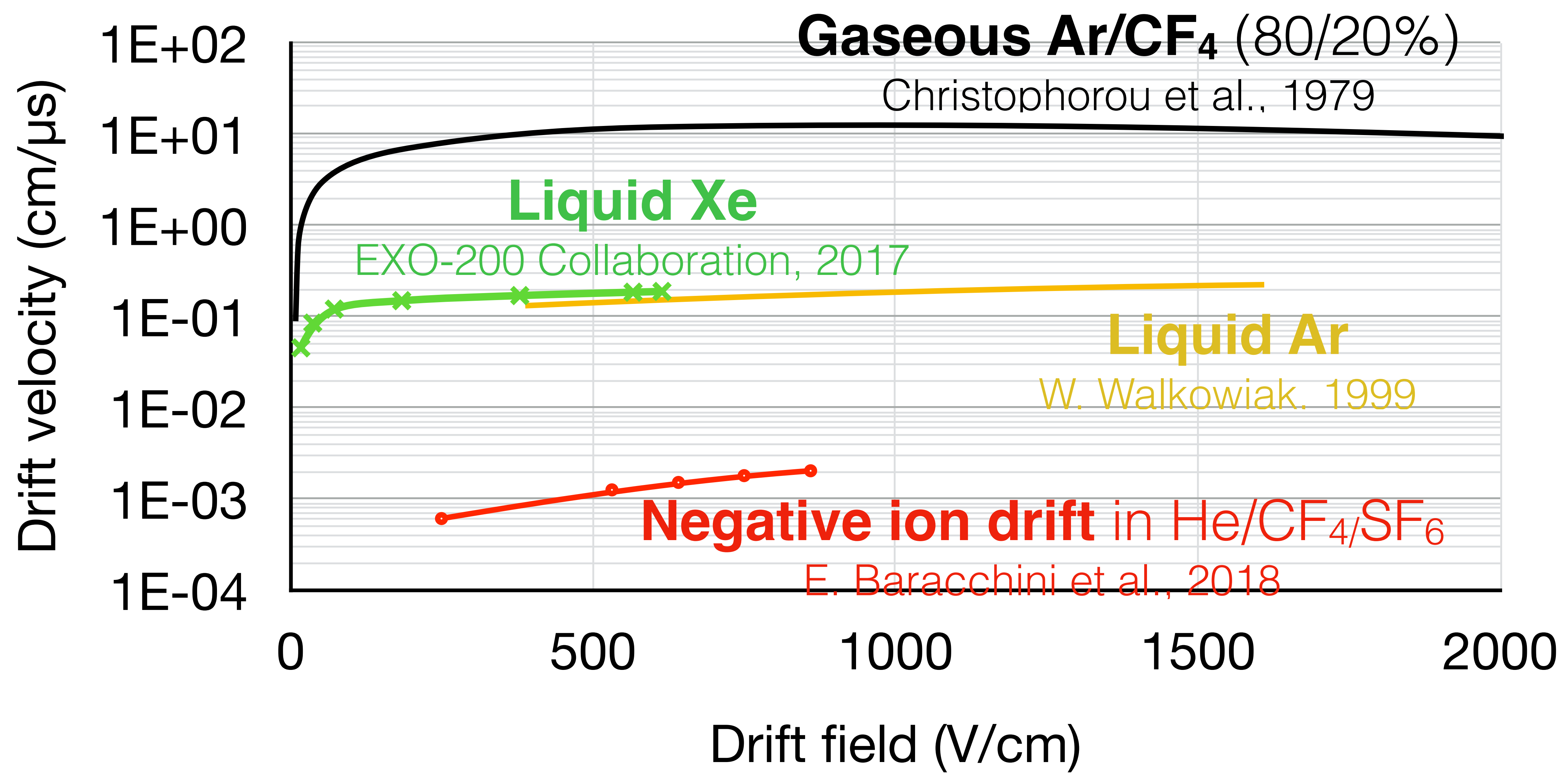


Ultra-high speed CMOS

- Recording sequence of images visualising **drift time differences** between track segments
- **Direct 3D track reconstruction** without need for auxiliary timing information from fast photon detectors
- With **electron drift**: recording close to MHz frame rates at **limited resolution** and poor depth resolution
- **Negative ion drift** (orders of magniture slower, lower light yield) may allow good depth resolution with ultra-fast CMOS readout



Resolving negative ion drift with fast CMOS

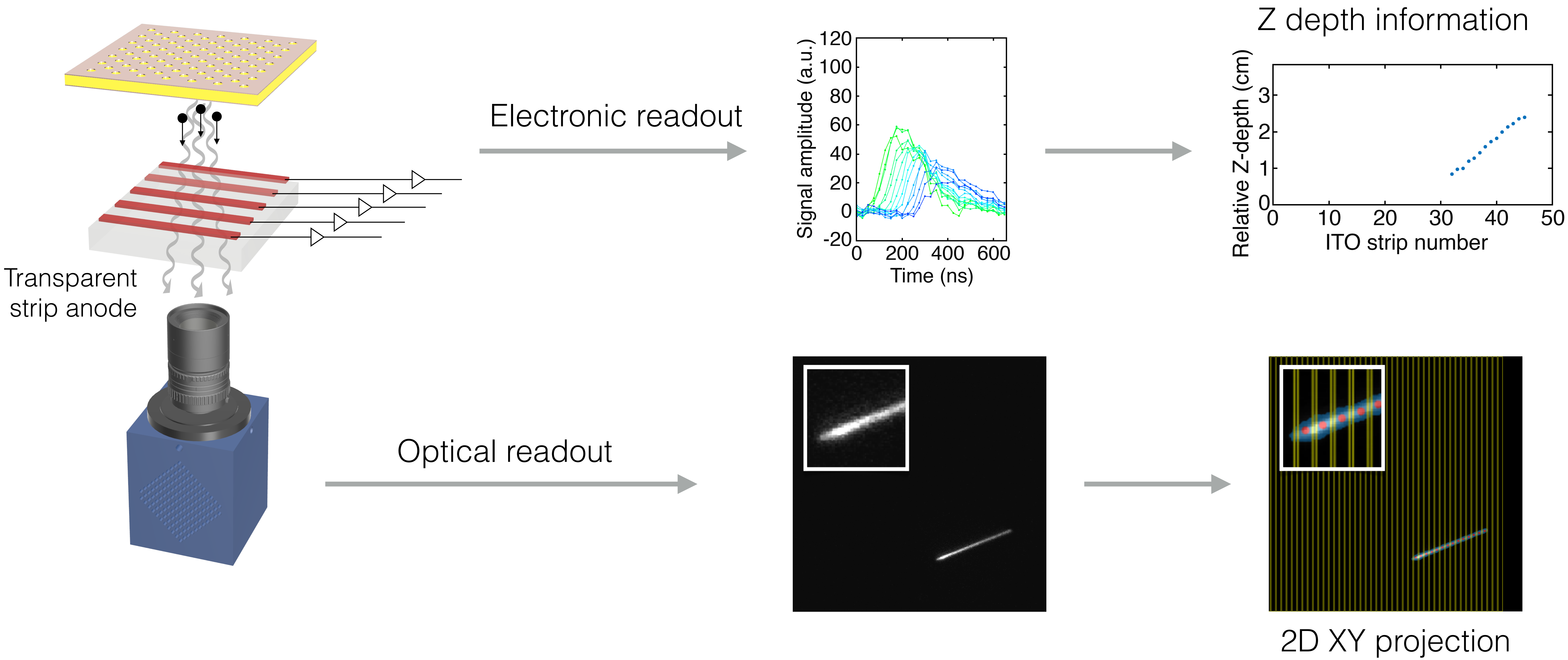


- **NI gas mixture**: Ar/CF4 80/20% + 1% SF6 at 200mbar
- 241Am source in gas volume
- 200V/cm drift field
- 2 GlassGEMs operated at high gain
- Photonis Cricket **image intensifier** at max gain
- Phantom S710 acquisition at 1Mpx with frame rate of 7kHz with (142µs exposures)

- **Several millimeter depth represented in each frame**

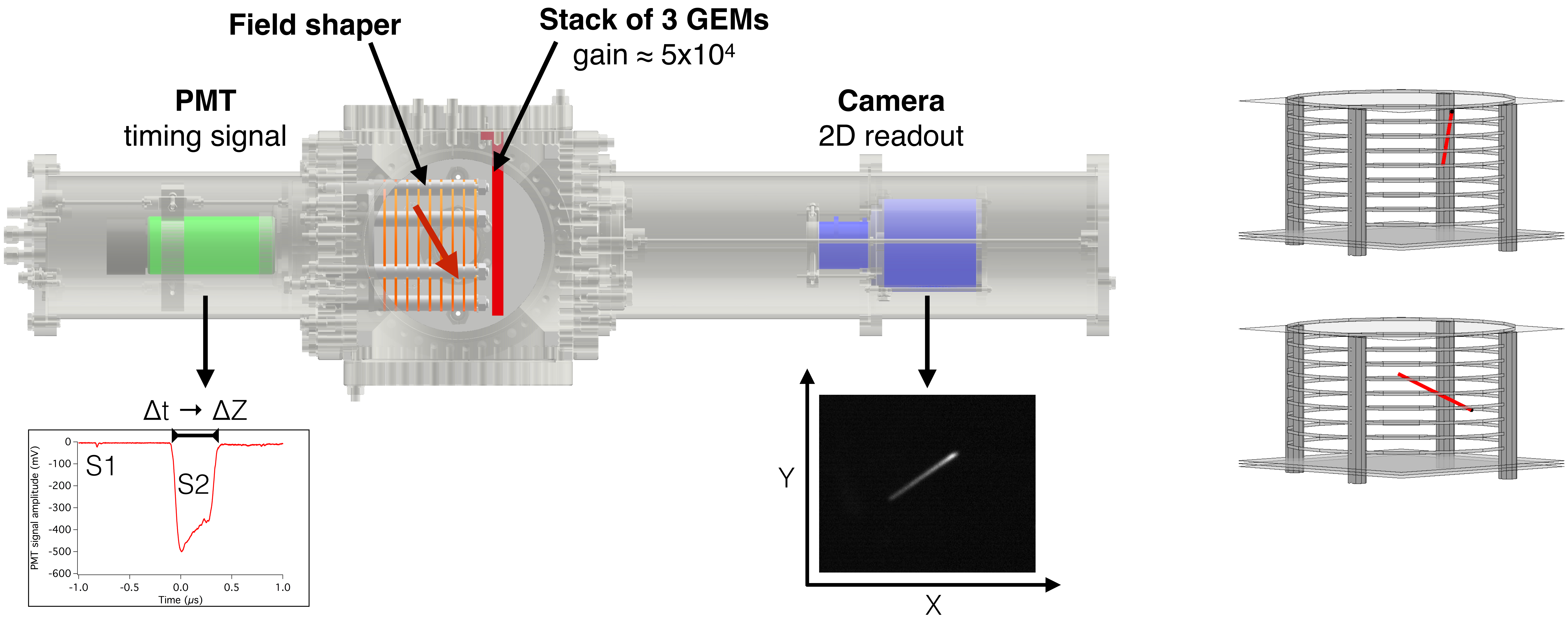
Hybrid readout approaches

Combined optical and electronic readout

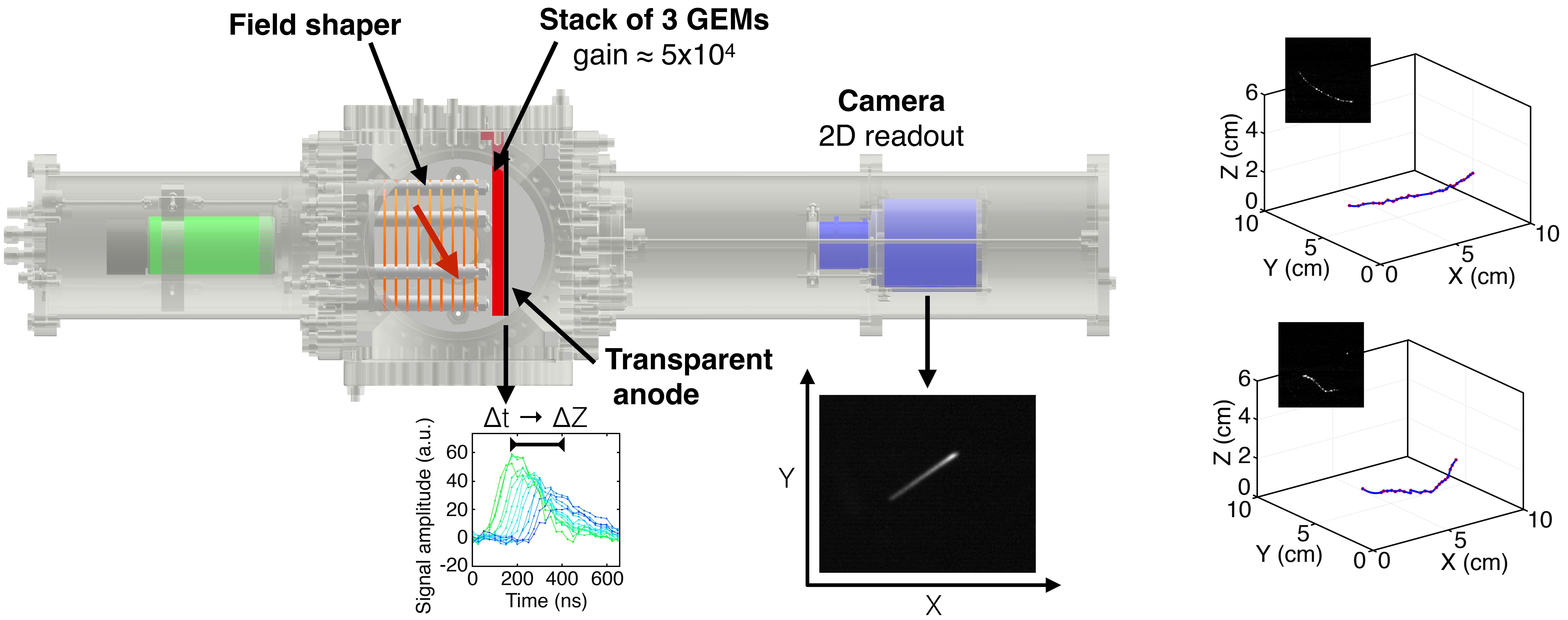


Schematics not drawn to scale

Optically read out TPC PMT + CCD



Optically read out TPC Electronic + CCD

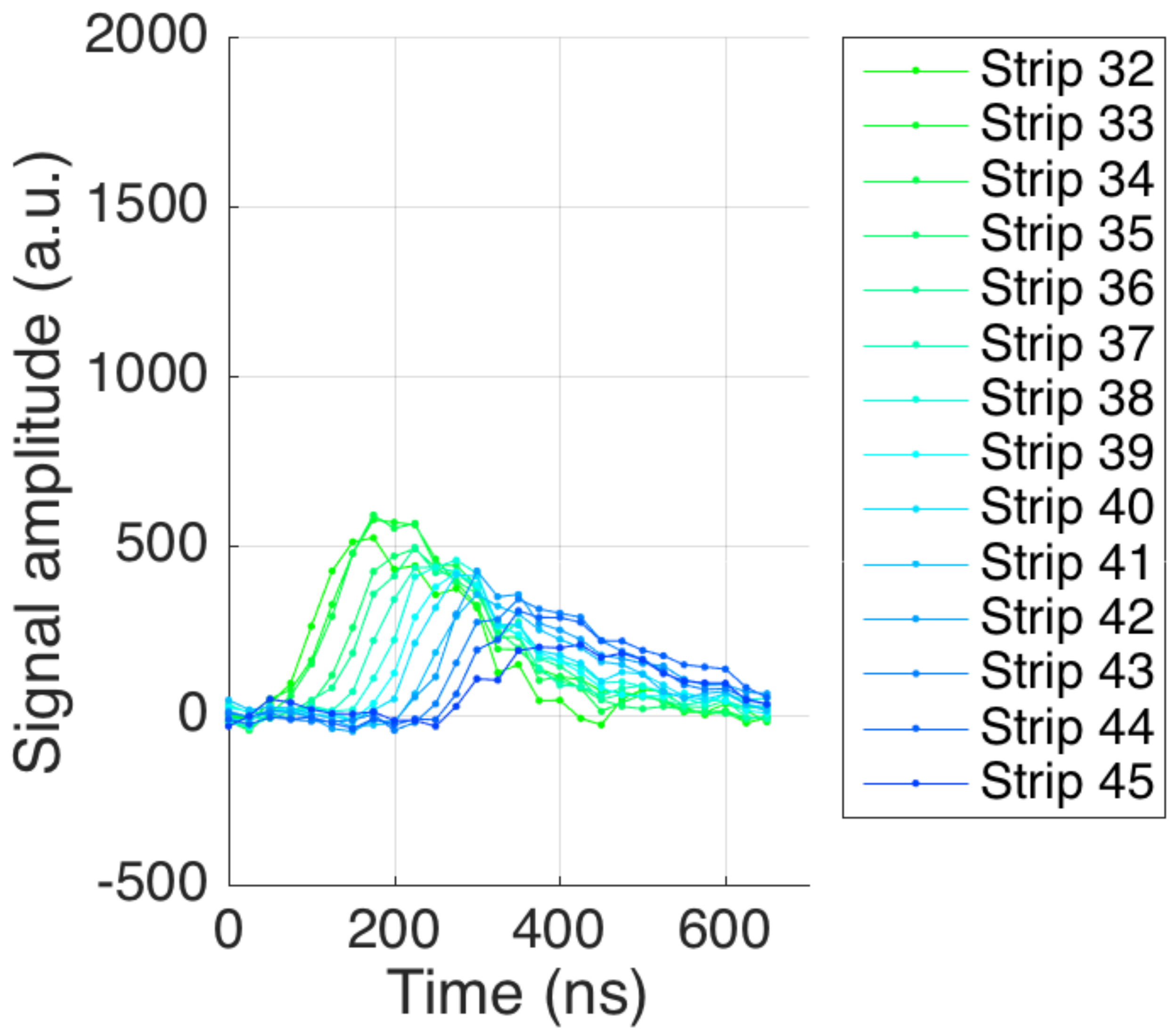


F. M. Brunbauer et al., IEEE NSS 2017

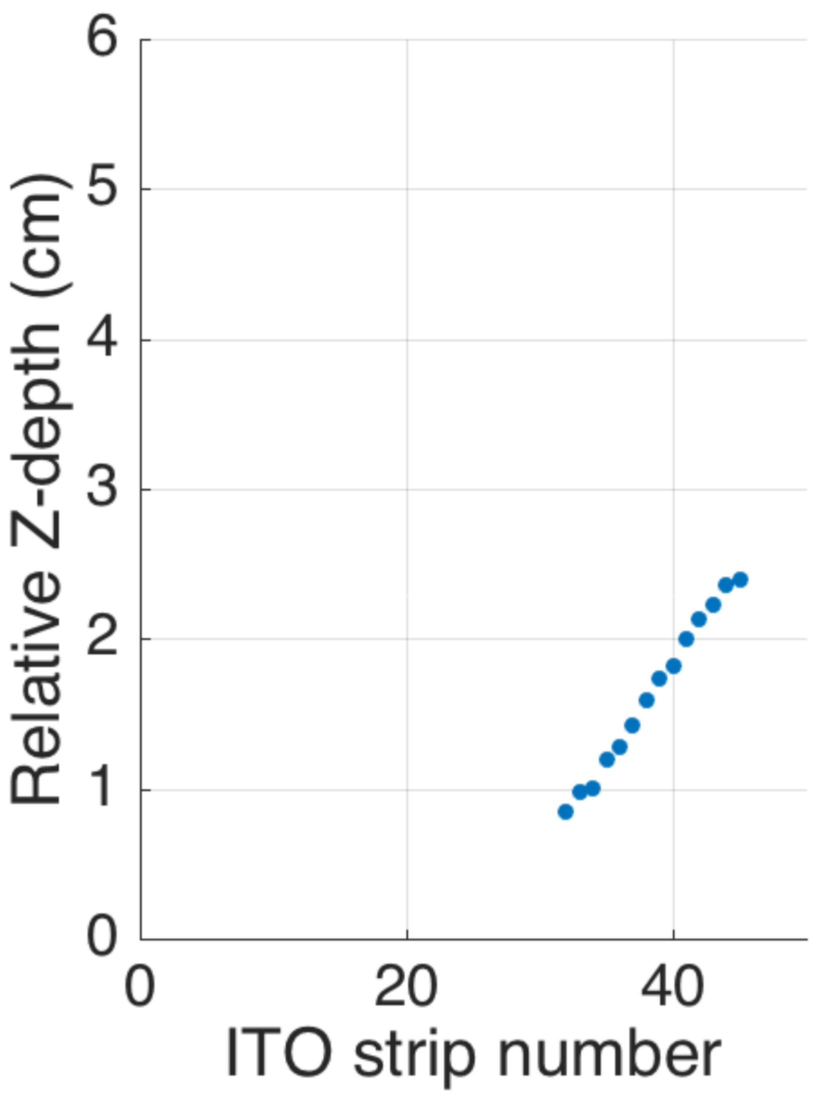
Schematics not drawn to scale

Reconstructed alpha tracks

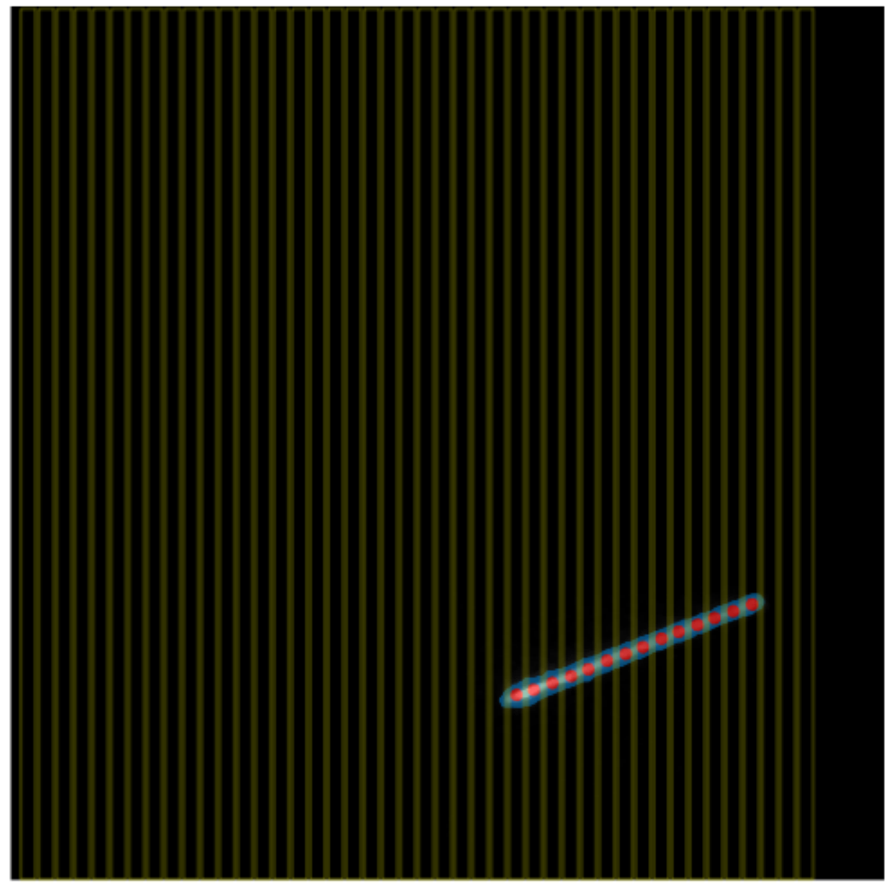
ITO strip signals



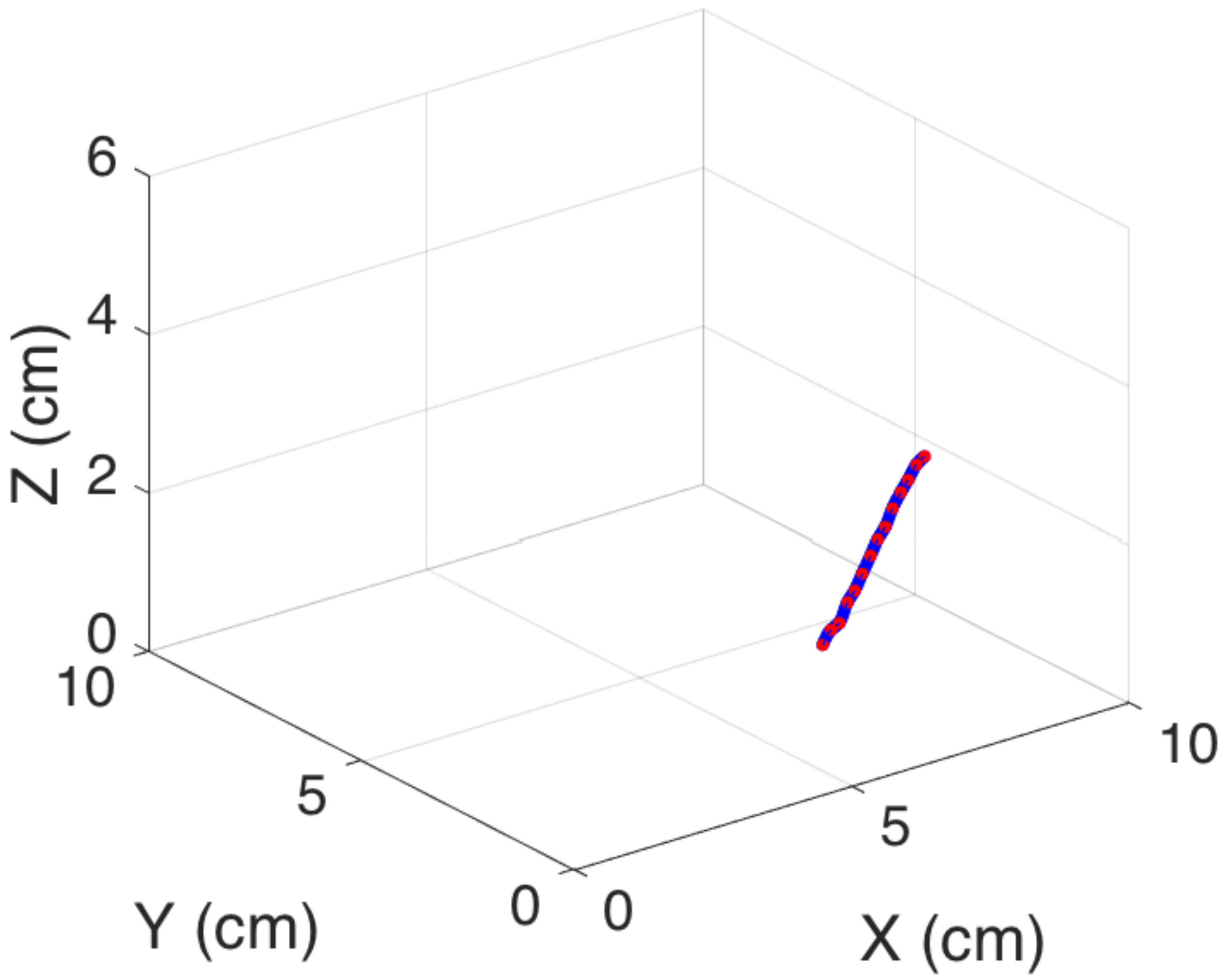
Depth information



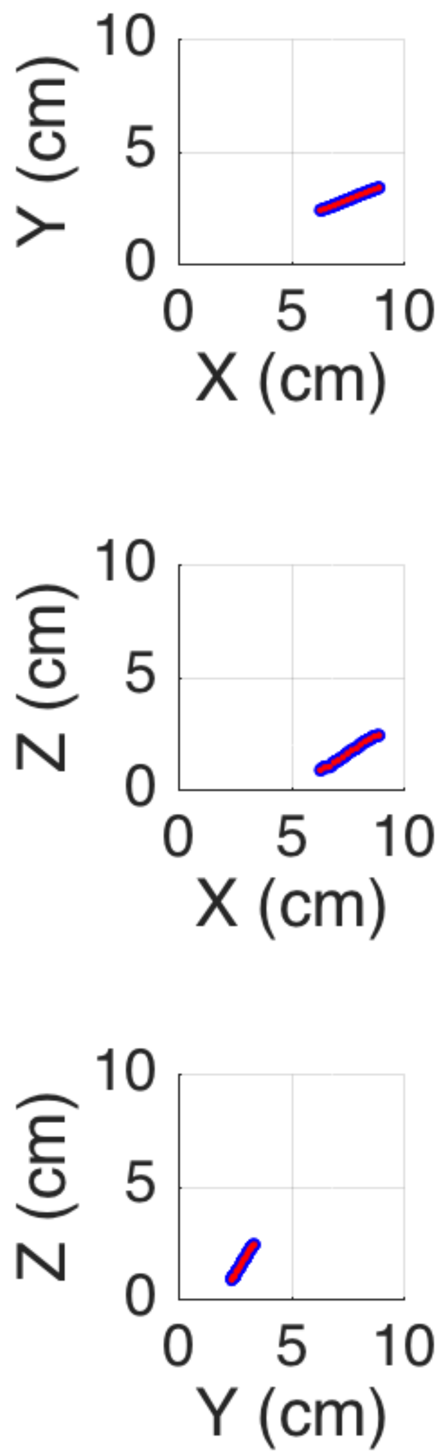
Camera image



3D track visualisation

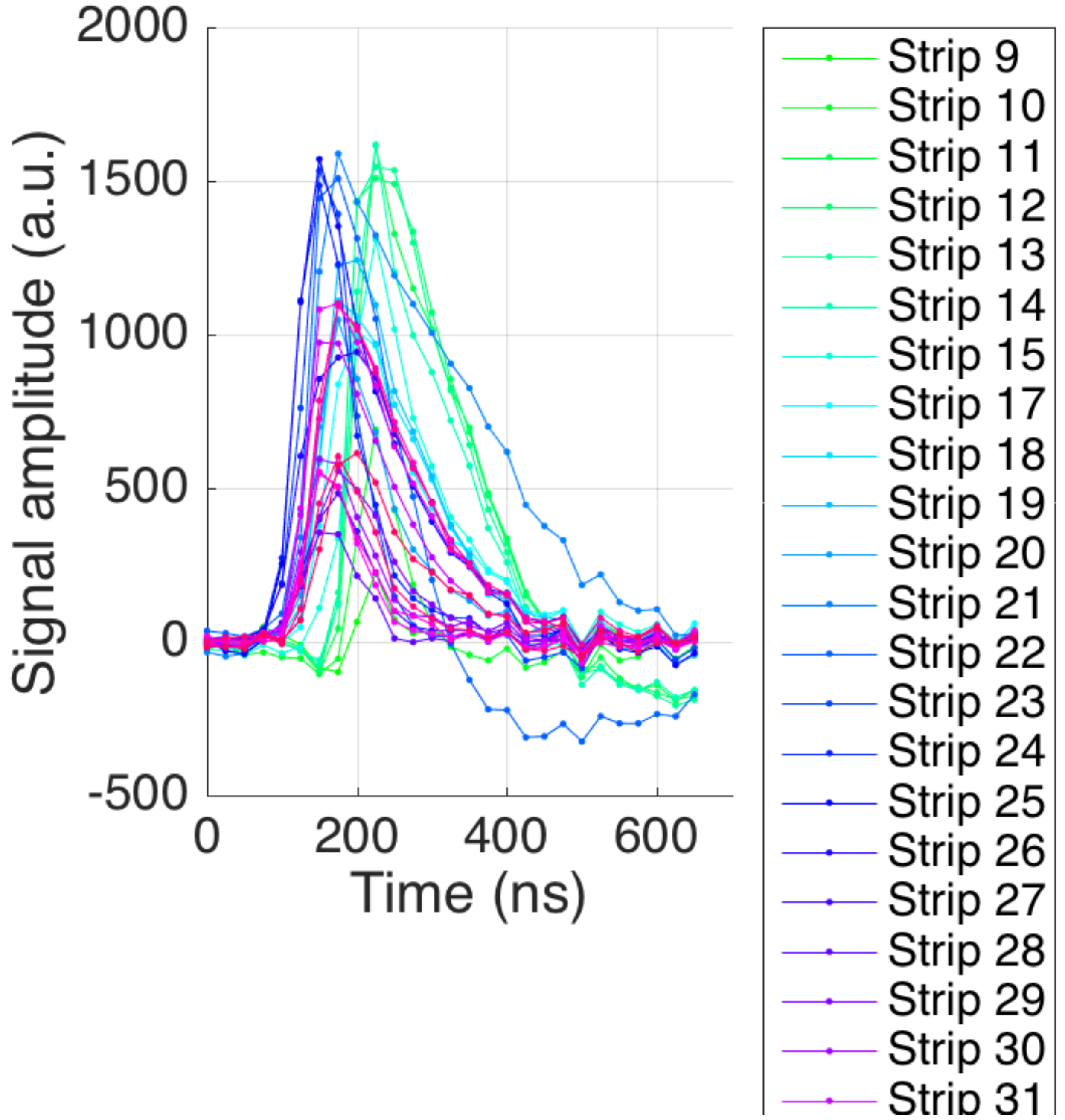


Projections

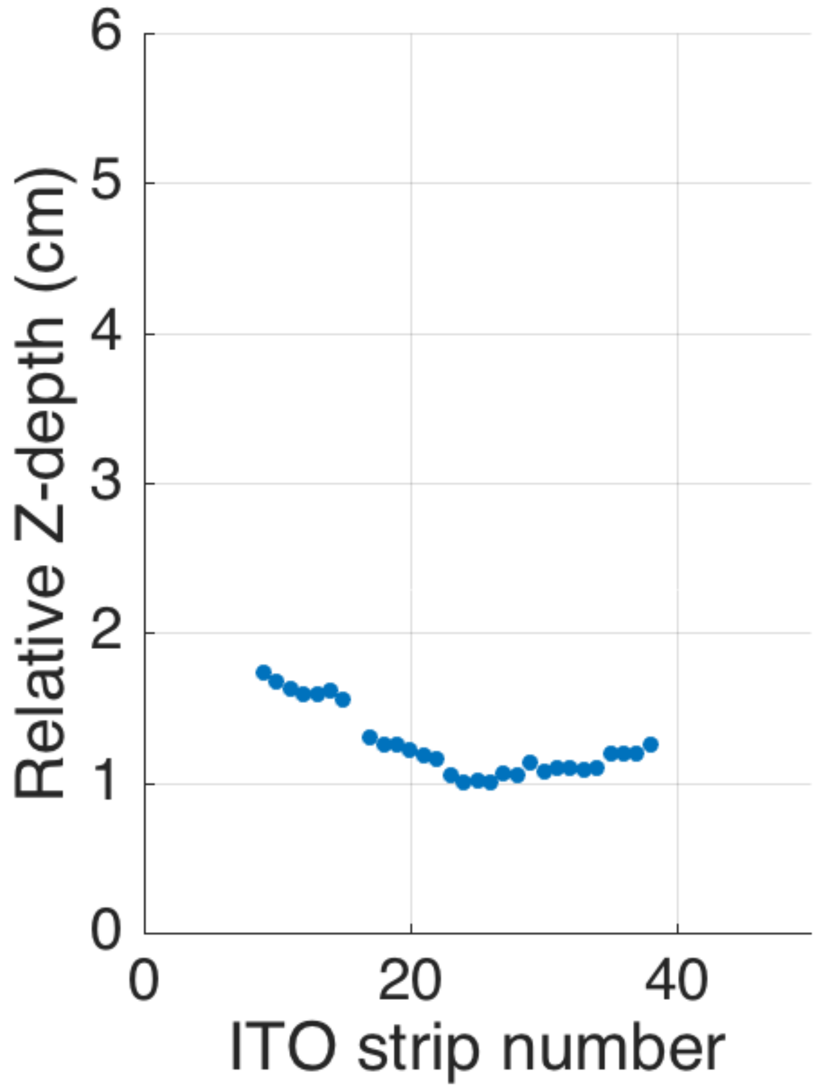


Reconstructed cosmic events

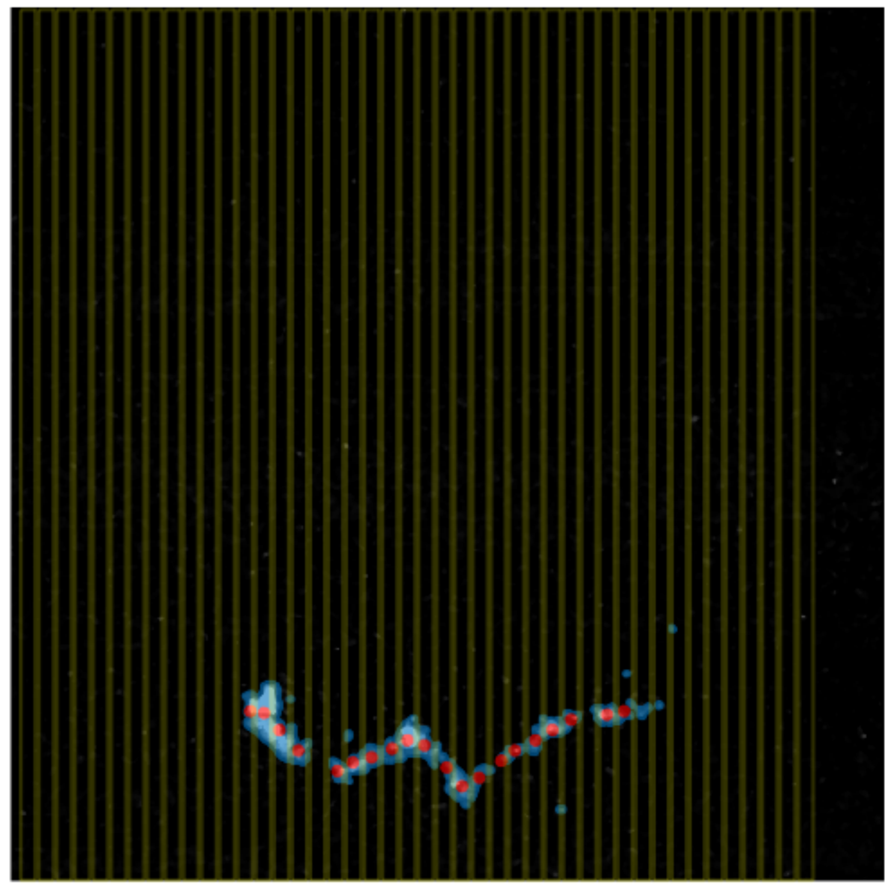
ITO strip signals



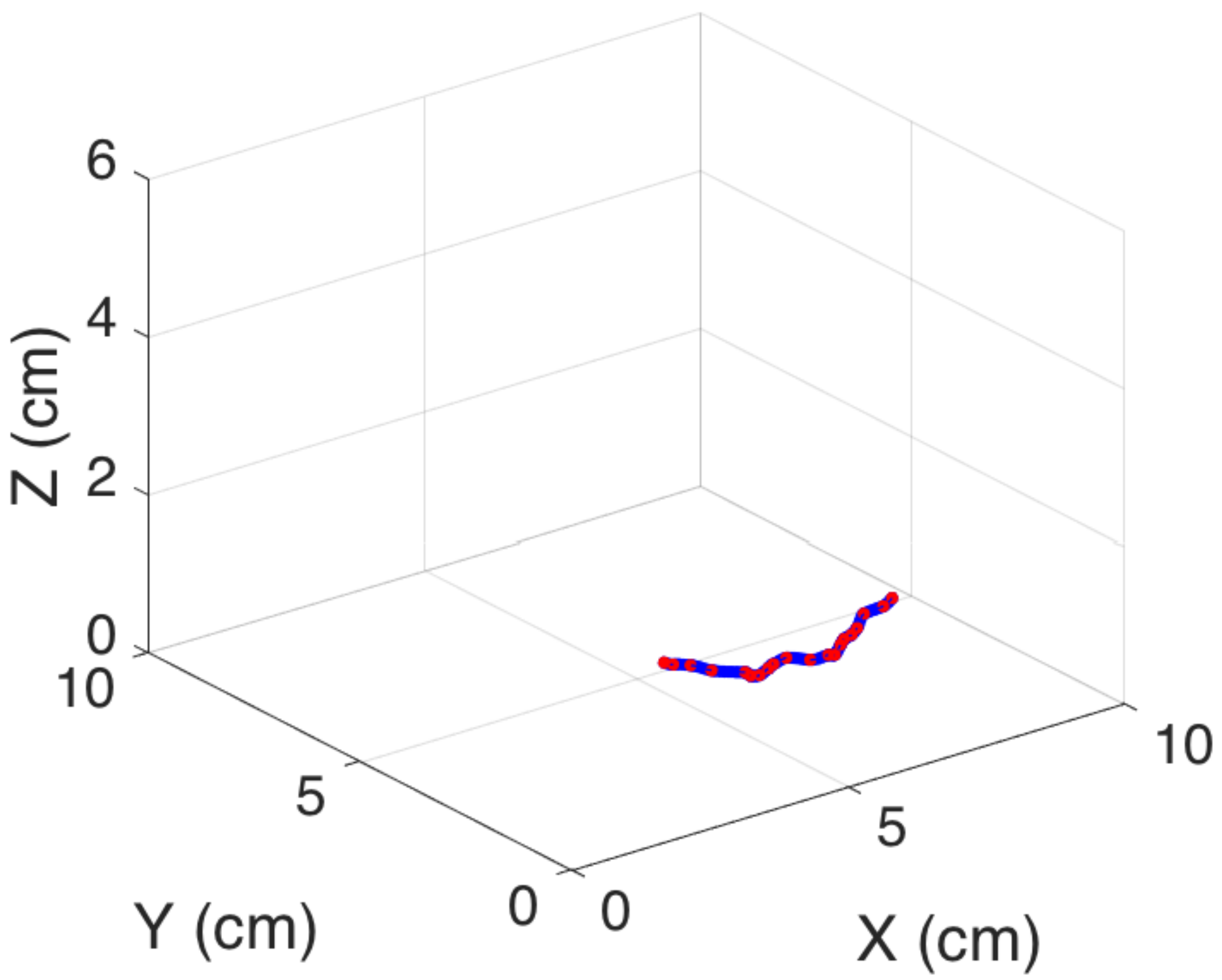
Depth information



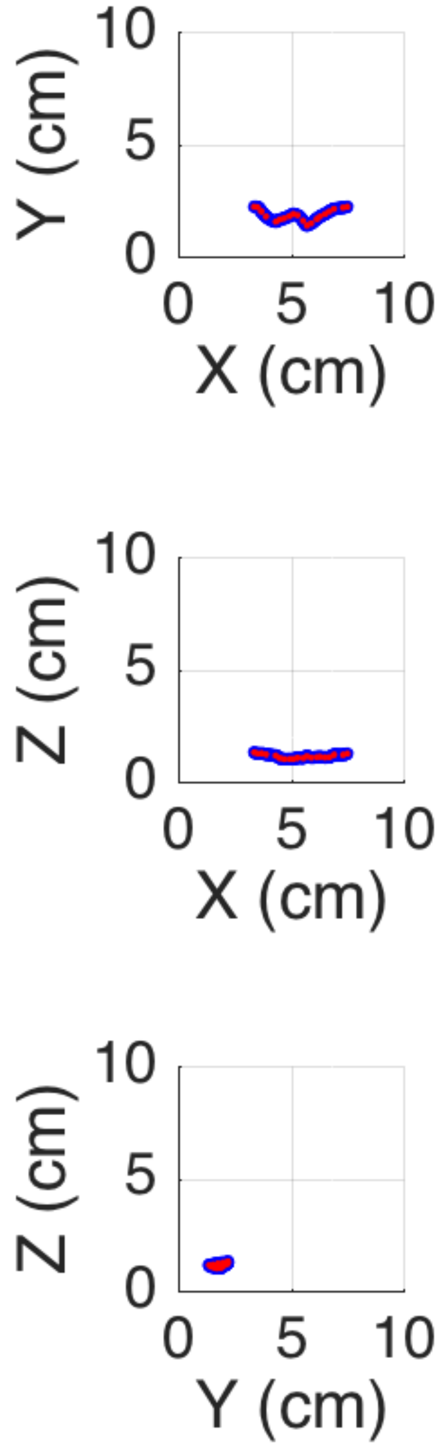
Camera image



3D track visualisation



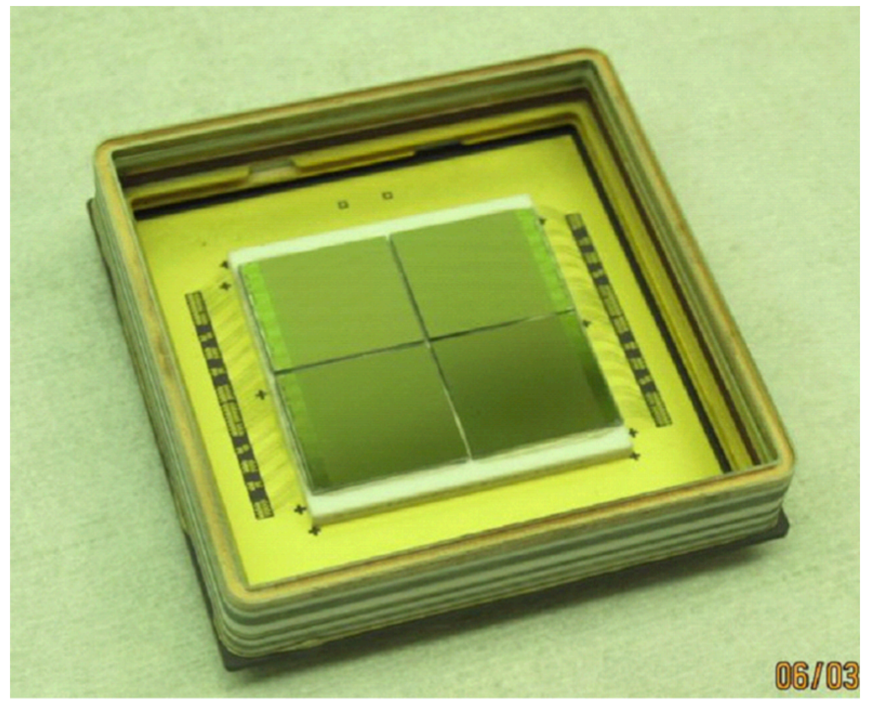
Projections

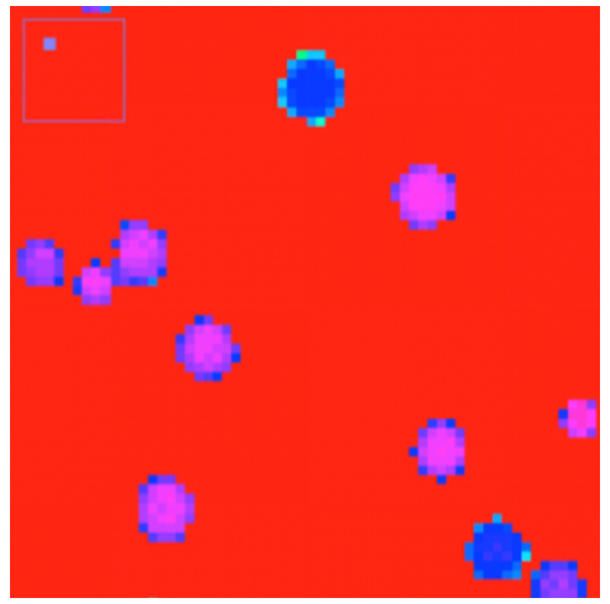


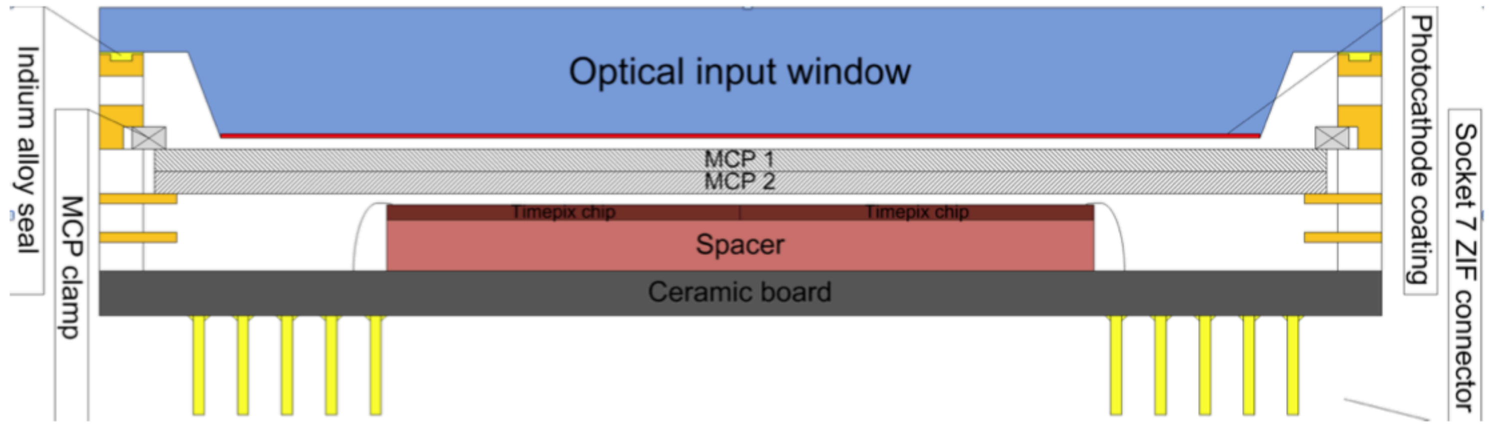
Timepix cameras

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

Event counting with threshold or time of arrival recording

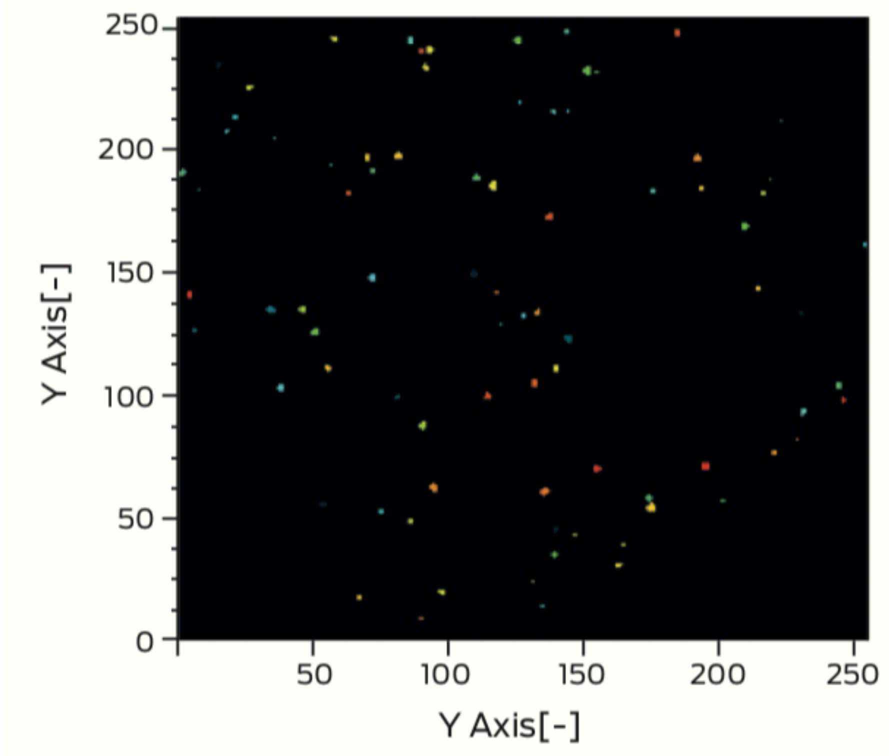


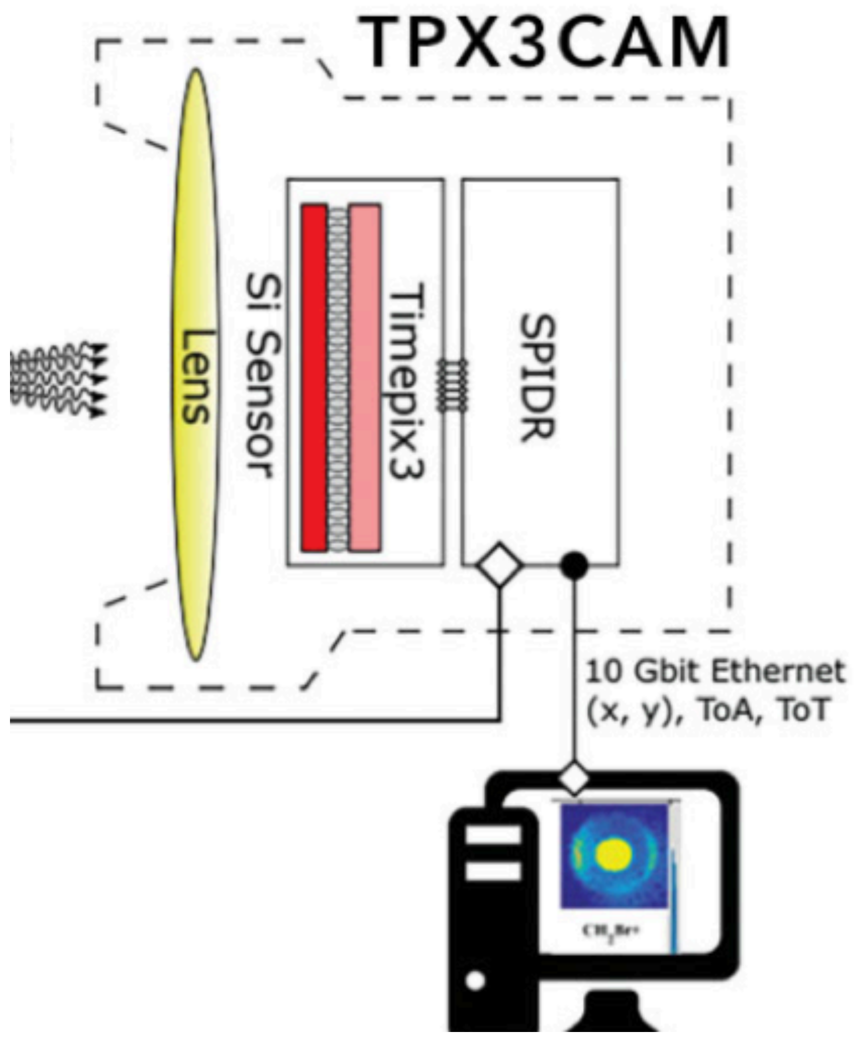




J Vallerga et al 2014 JINST 9 C05055
https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055/pdf

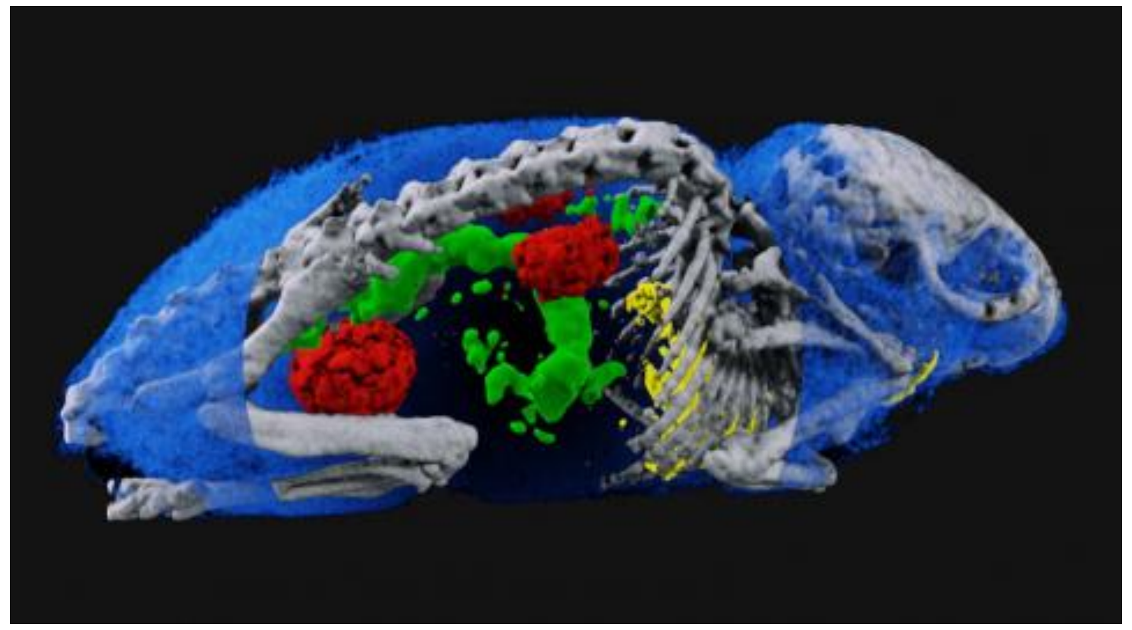
TPX3CAM
Optical detector for **time stamping** (1.6ns) of optical photons up to 80 Mhits/s rate.
Commercially available.





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

MARS bio imaging
Spectral imaging with Medipix3 chip
Can enable imaging of biochemical and physiological processes and increase efficiency of radiology procedures



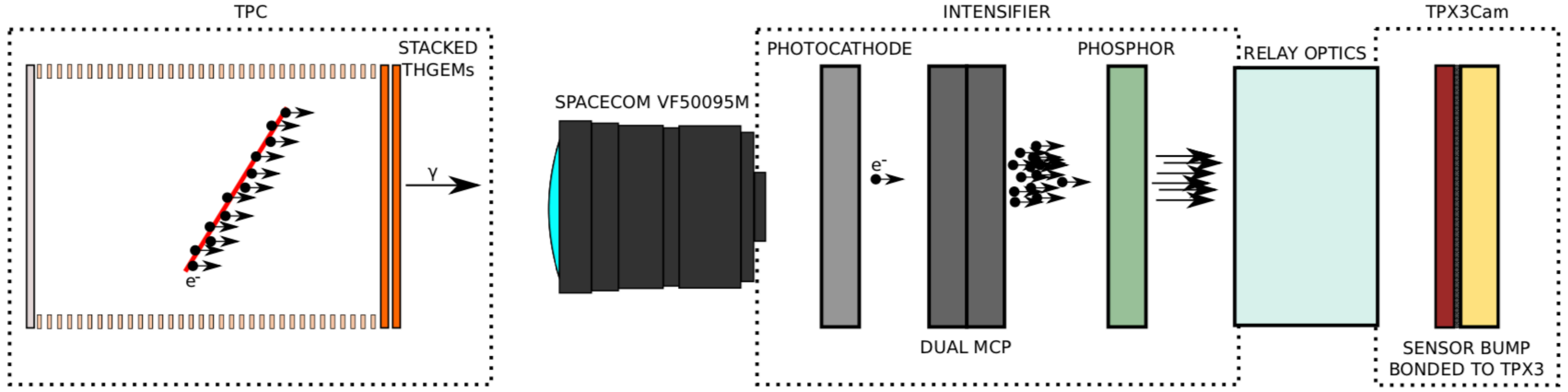
https://medipix.web.cern.ch/mars-bio-imaging

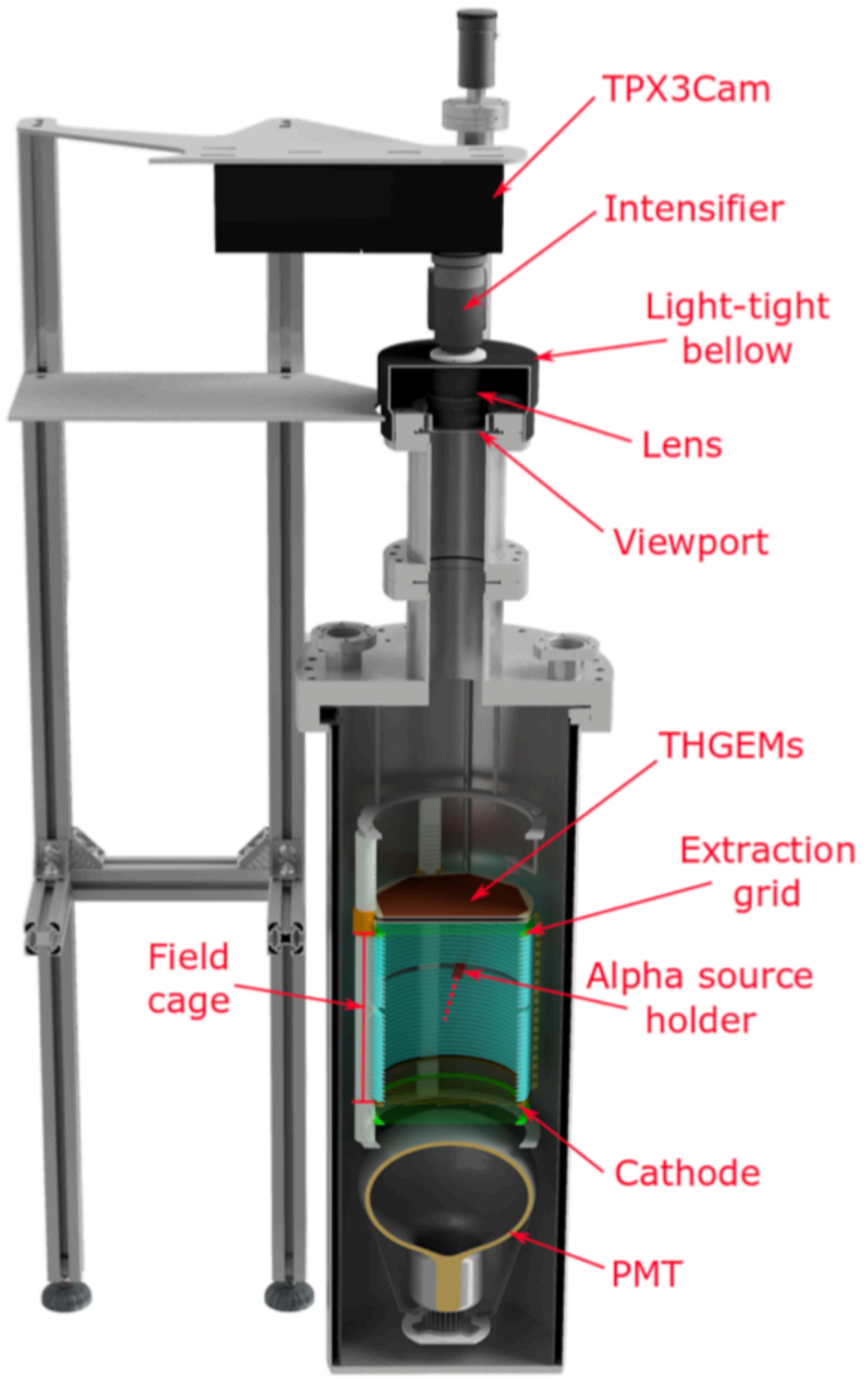
3D track reconstruction Intensified TPX3Cam

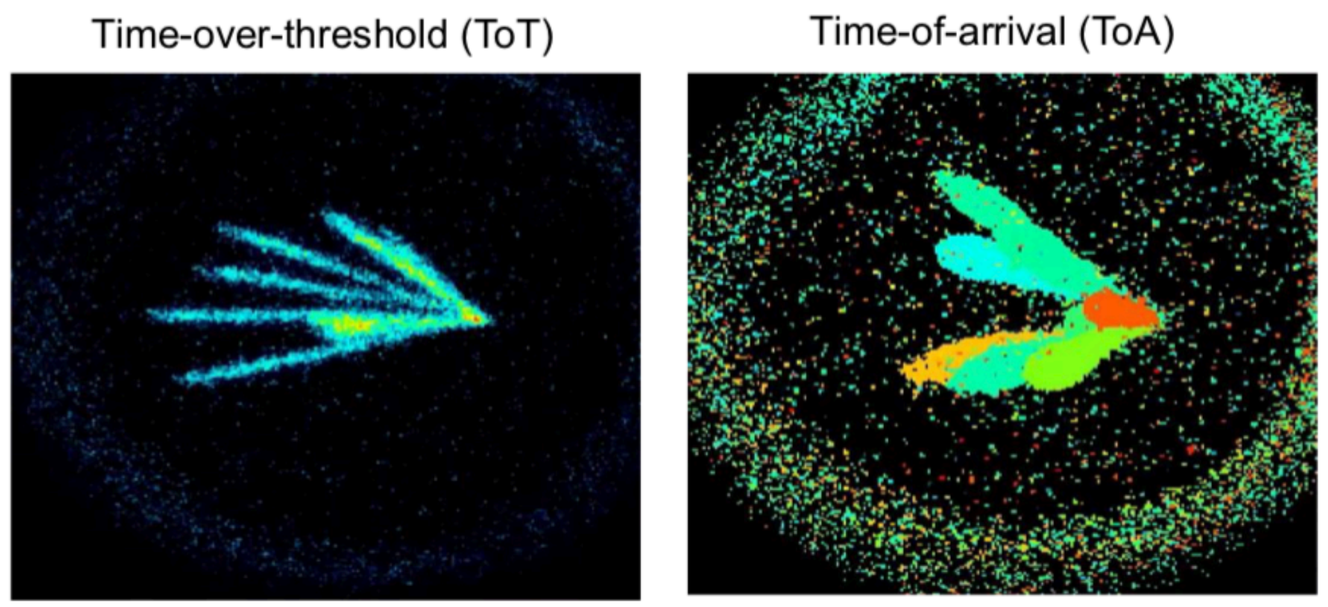
Readout of S2 scintillation in **dual phase TPC**

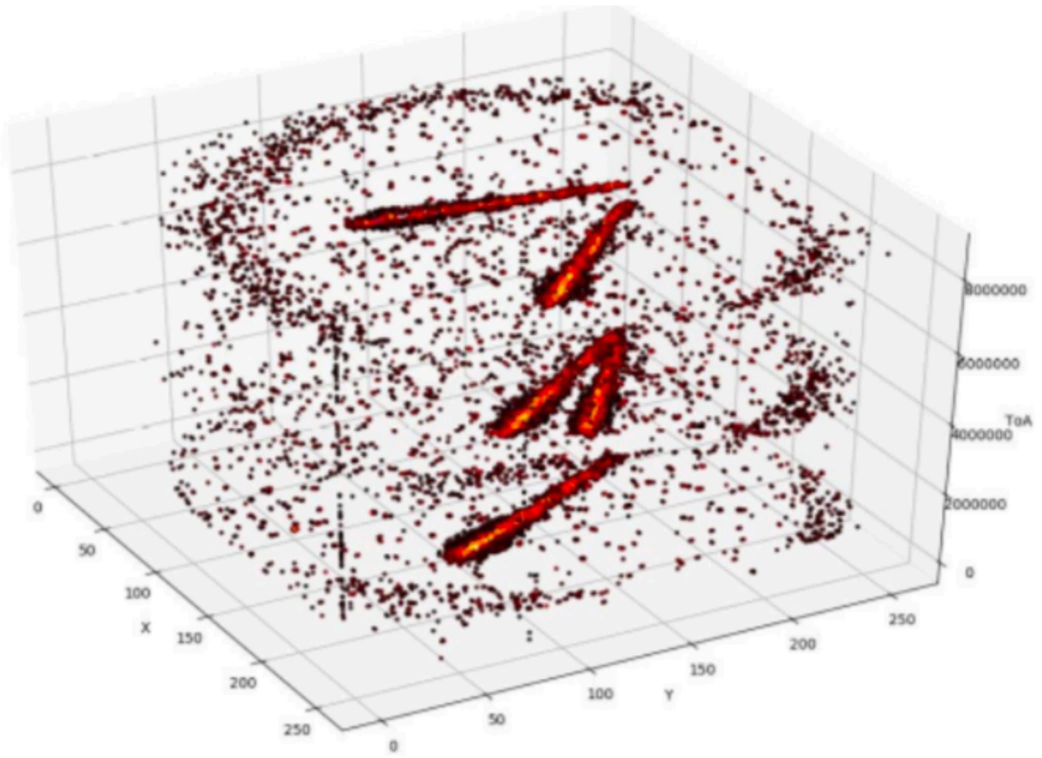
Light production with THGEM / GlassGEM in avalanche mode

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

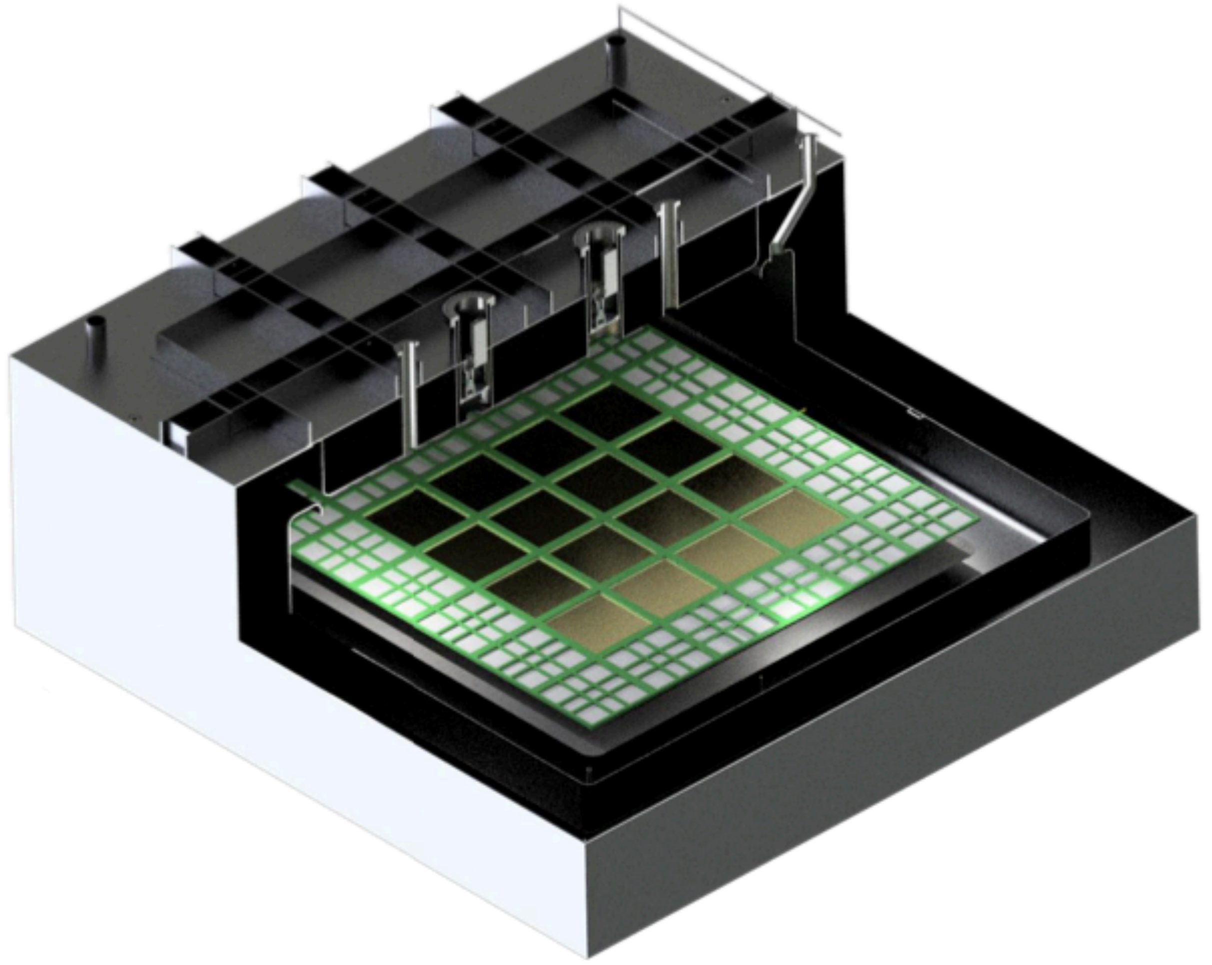








Next step: 2m x 2m test with large field of view and direct VUV imaging

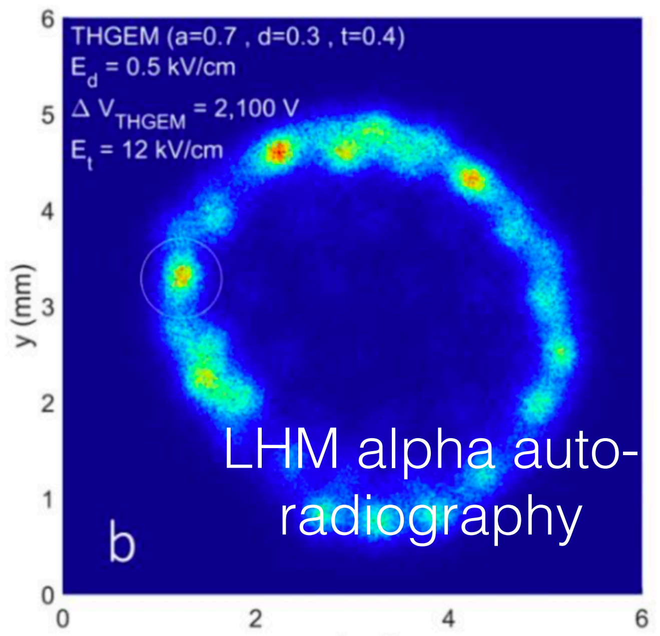


A. Roberts, ARIADNE, arXiv:1810.09955v3
https://indico.cern.ch/event/989298/contributions/4217751/attachments/2190565/3702236/RD51%20Optical%20readout.pdf

SiPM readout of MPGDs

- **Time resolution** and **single-photon sensitivity** of SiPMs makes them attractive for scintillation light readout of MPGDs
- May be used for timing as well as limited **position reconstruction** with **SiPM arrays**
- Requires matching of **scintillation light emission** characteristics (WL spectrum, time characteristics) with SiPM and associated readout electronics

Spatial resolution with SiPMs

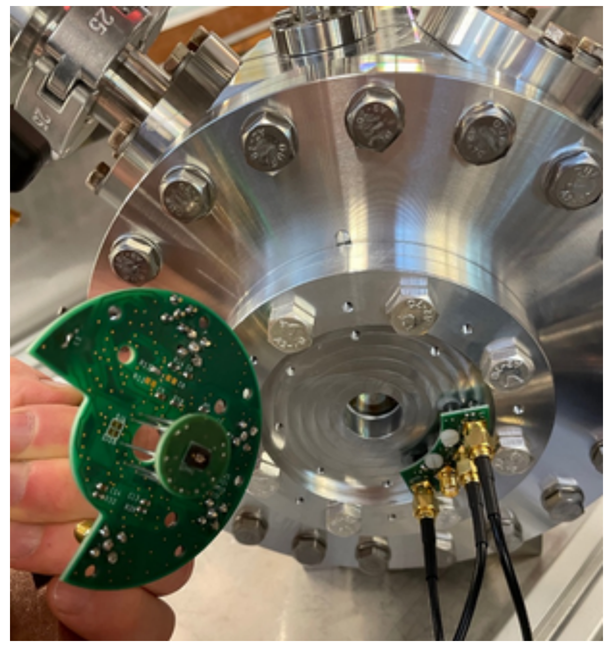


E. Erdal et al.. (2018). First Imaging Results of a Bubble-assisted Liquid Hole Multiplier with SiPM readout in Liquid Xenon.

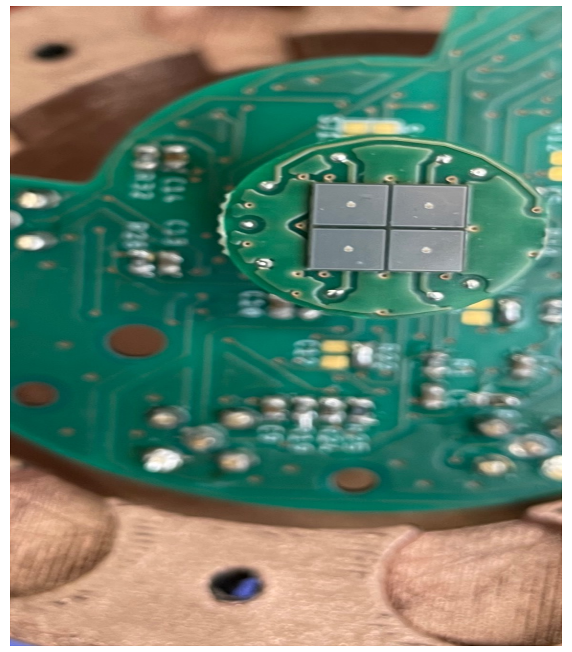
- Arrays of SiPMs to reconstruct clusters
- Fast timing response can enable operation in higher rate environments and 3D tracking with known t_0 timing signals

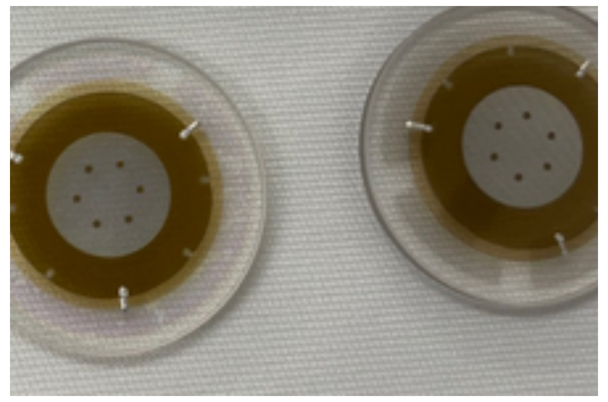
GlassMicromegas readout with SiPMs

Single channel SiPM

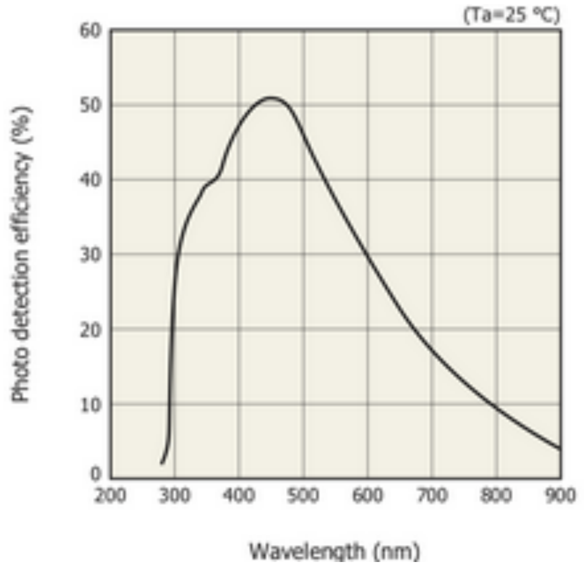


2x2 SiPM array

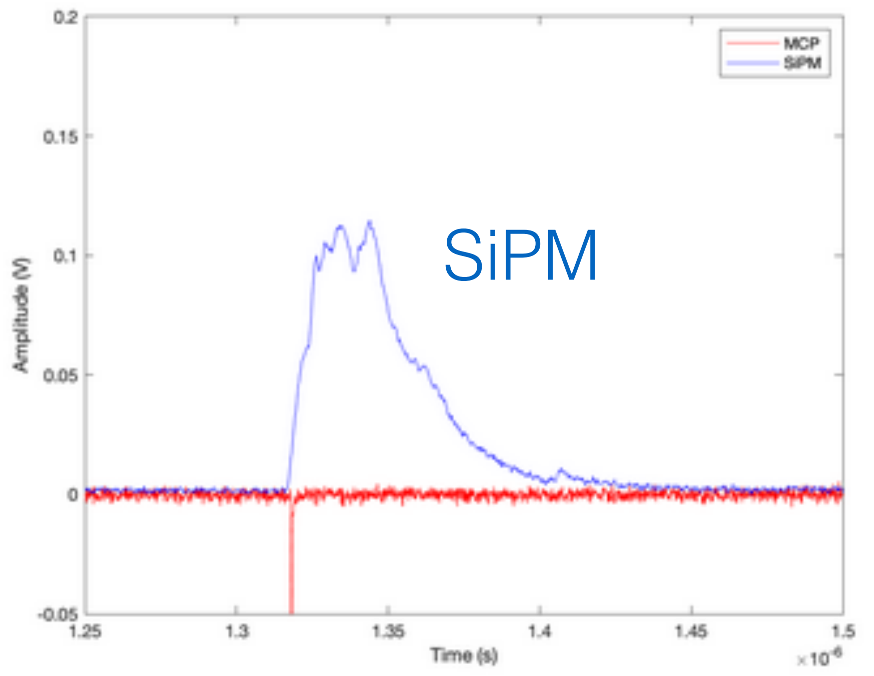




Optical MM with Cr/ ITO anode



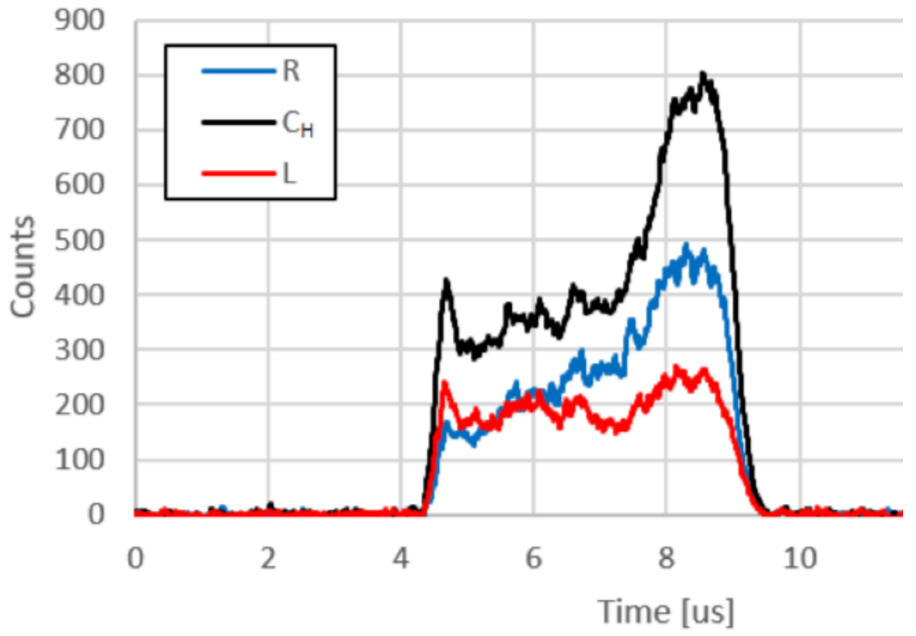
SiPM signal with sharp rising edge and sequential photon arrival



VIS-sensitive SiPM QE

https://www.hamamatsu.com/eu/en/product/type/S14160-4050HS/index.html

Linearly Graded Silicon Photomultipliers (LG-SiPMs)

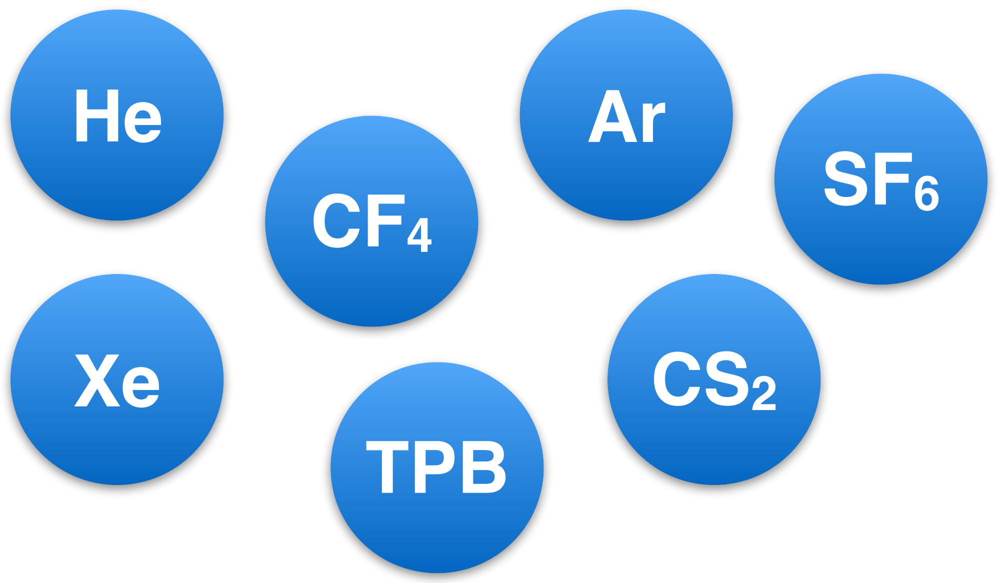


A. Gola et al 2020 JINST 15 P12017 https://doi.org/10.1088/1748-0221/15/12/P12017

- 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

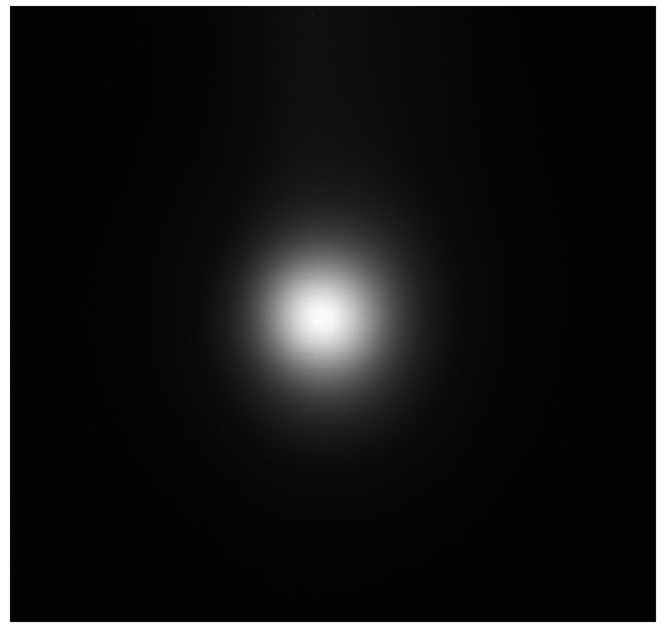
Challenges and summary

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



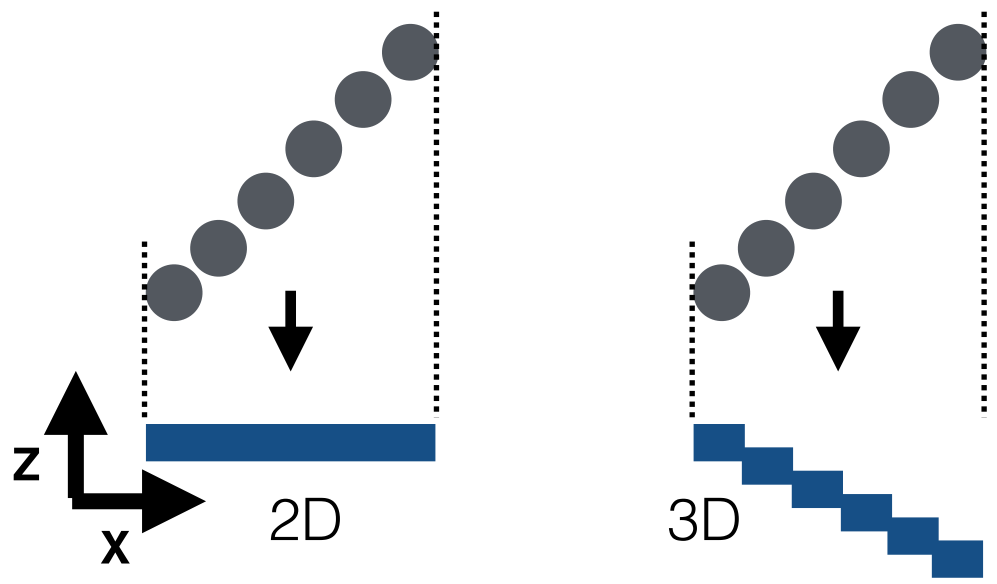
Sensor sensitivity: large sensors with low read noise, inherent amplification

Scintillation emission spectra
- **Gas choice** may be driven by physics and not ideal for imaging sensors
- Alternative gases, **WLS**
- Extended **VUV sensitivity** of imaging sensors



Beam monitoring and dose imaging
- Detailed beam position and profile with **pixellated readout**
- **Low material budget** detectors (gas + optics)
- **Real-time** beam monitoring and feedback with fast imaging sensors

Depth information with hybrid readout approaches:
- **Combined** optical+charge readout, PMT waveforms, **SiPMs arrays**? Ultra-fast imaging
- Readout **ASICs** with high timing resolution



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

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

Backup

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 reconstruction

Frame rates of typically **10s to 100s of fps** impose integrated imaging approach

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
- **Larger sensors** (larger pixels at high granularity) -> higher sensitivity
- **Low noise** (<1 e-) or amplification
- Extended **spectral sensitivity**

QImaging Retiga R6, Thorlabs 8 MP Scientific CCD Cameras

CCD cameras

- **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

Hamamatsu ORCA-Fusion, Andor Zyla

sCMOS cameras

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

Exemplary specifications

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

Hamamatsu ImageEM X2, ams technologies iXon

EMCCD cameras

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

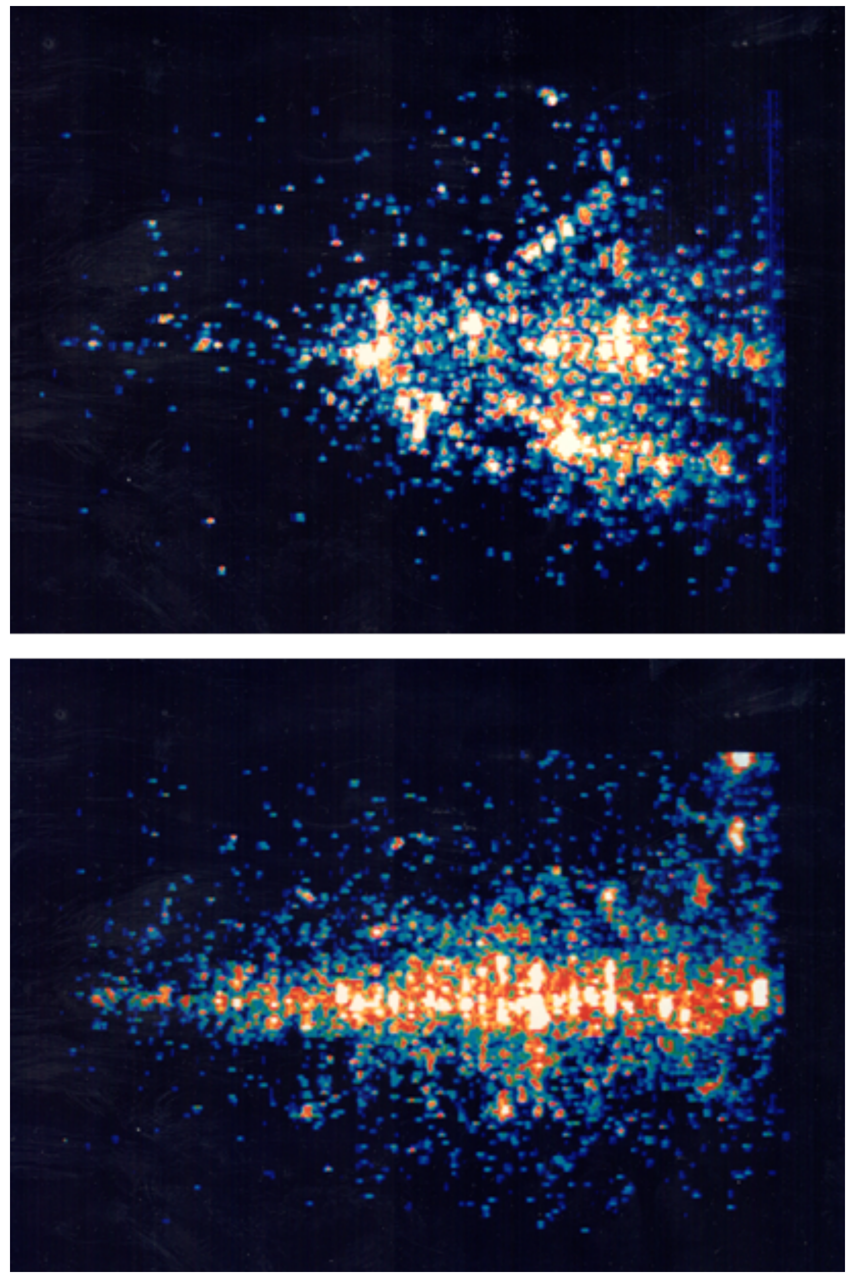
Exemplary specifications

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

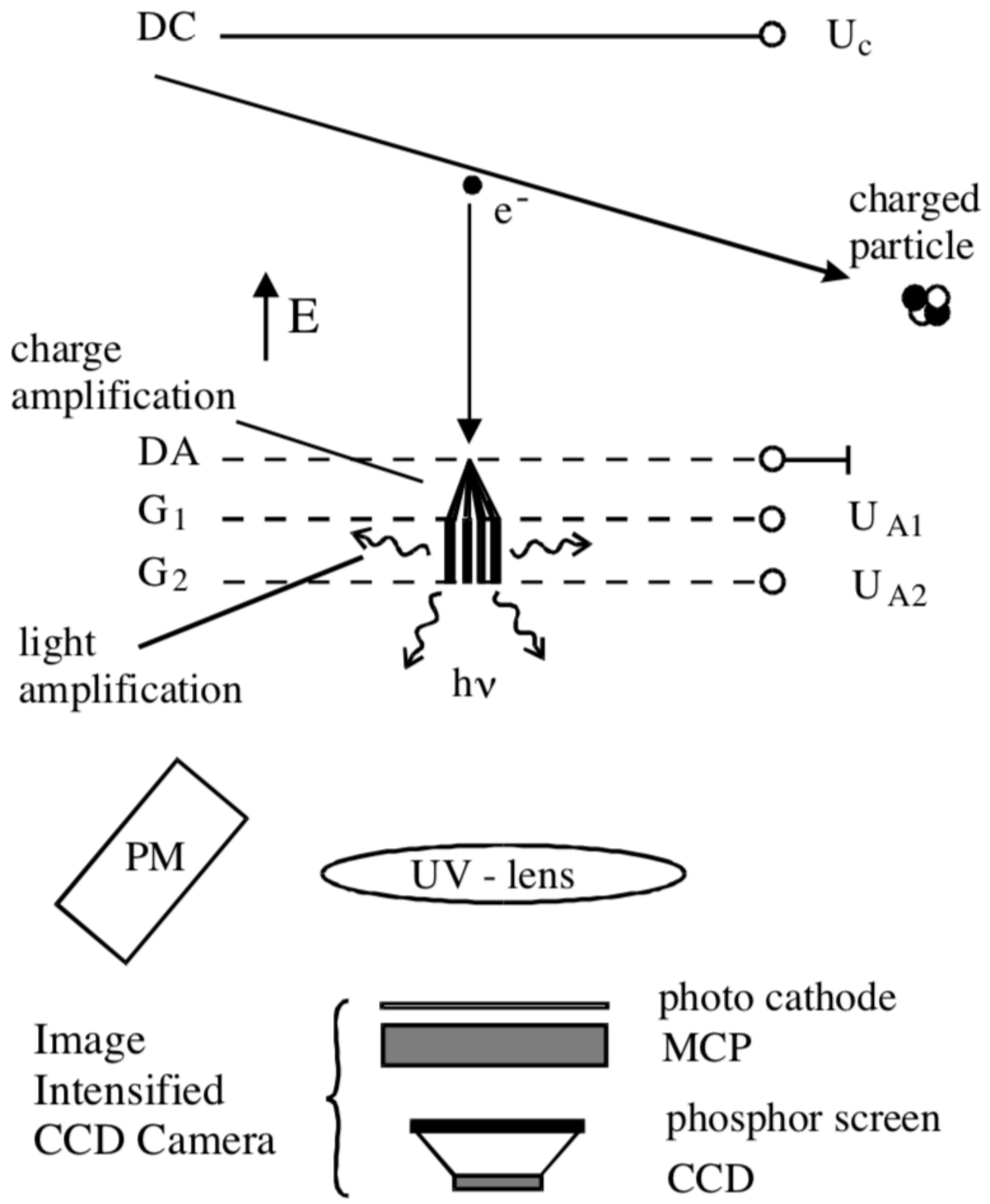
Optical TPCs

Long history of optically read out Time Projection Chambers

Detailed **2D projections** (energy loss, head/tail) from camera need **auxiliary timing** for 3D reconstruction

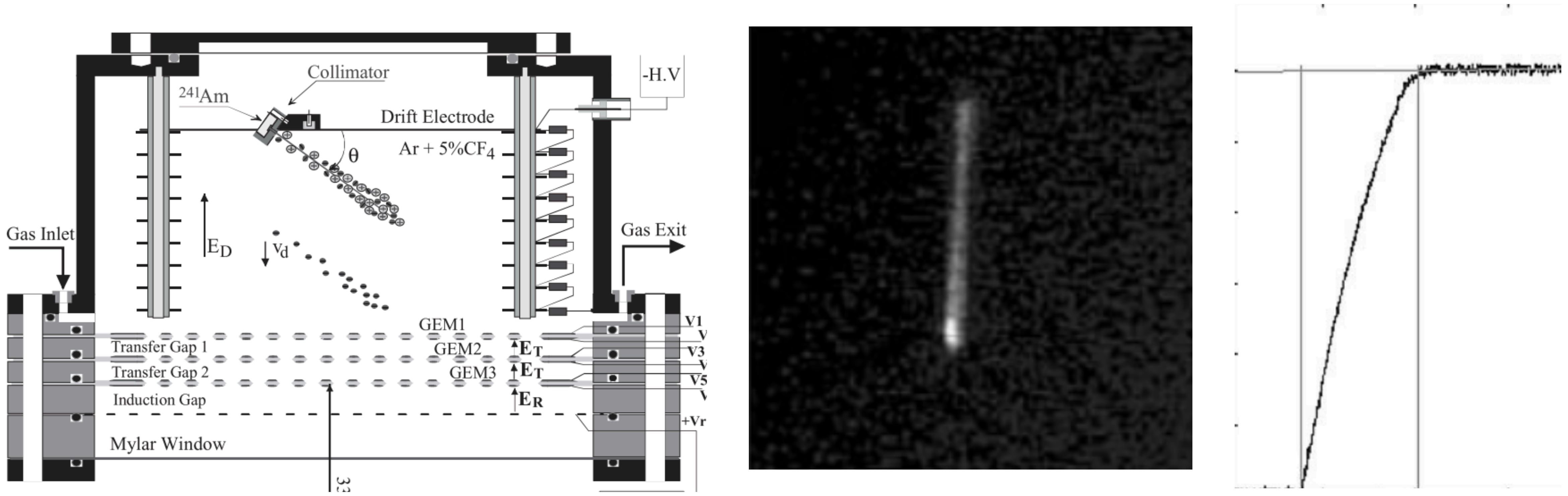


Fonte P., Breskin A., Charpak G., Dominik W. & Sauli F. (1989) NIM A. 283, 3, p. 658-664.



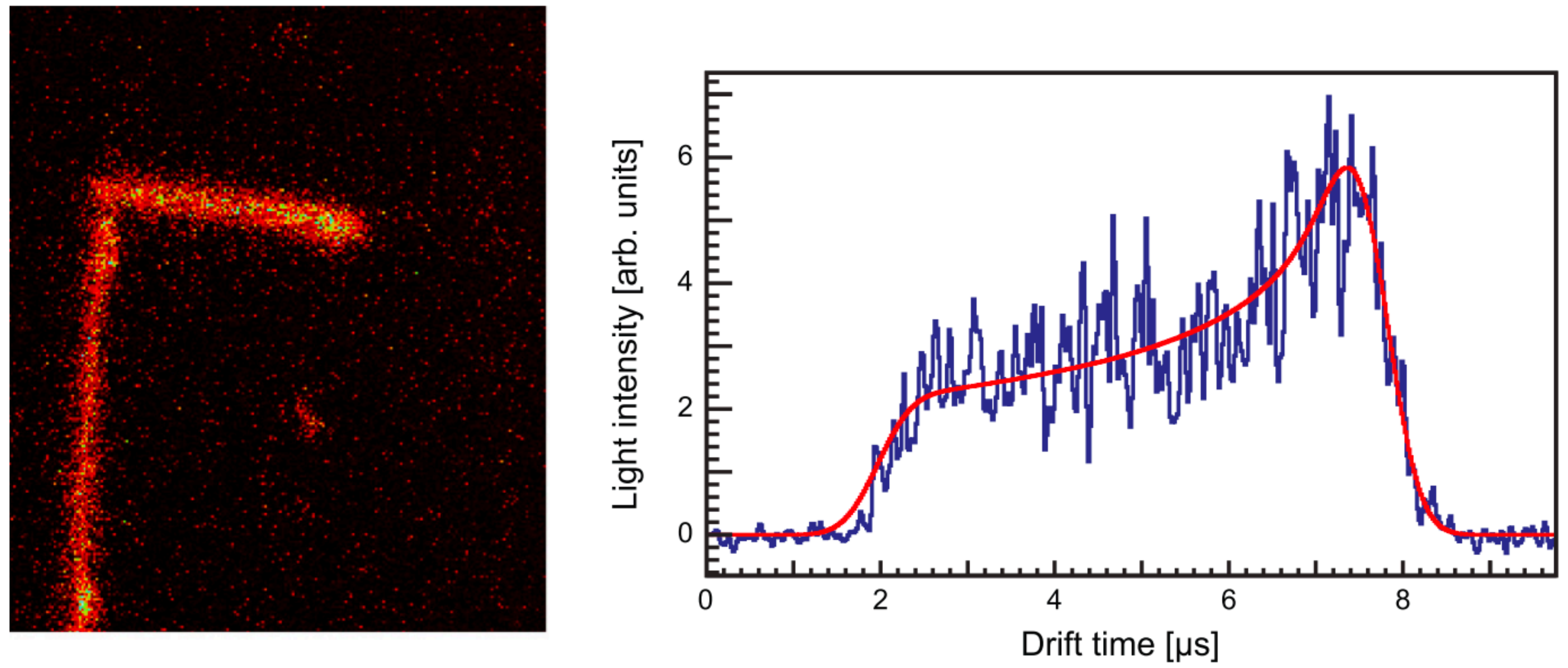
U. Titt et al. https://cds.cern.ch/record/800769/files/0410258.pdf

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



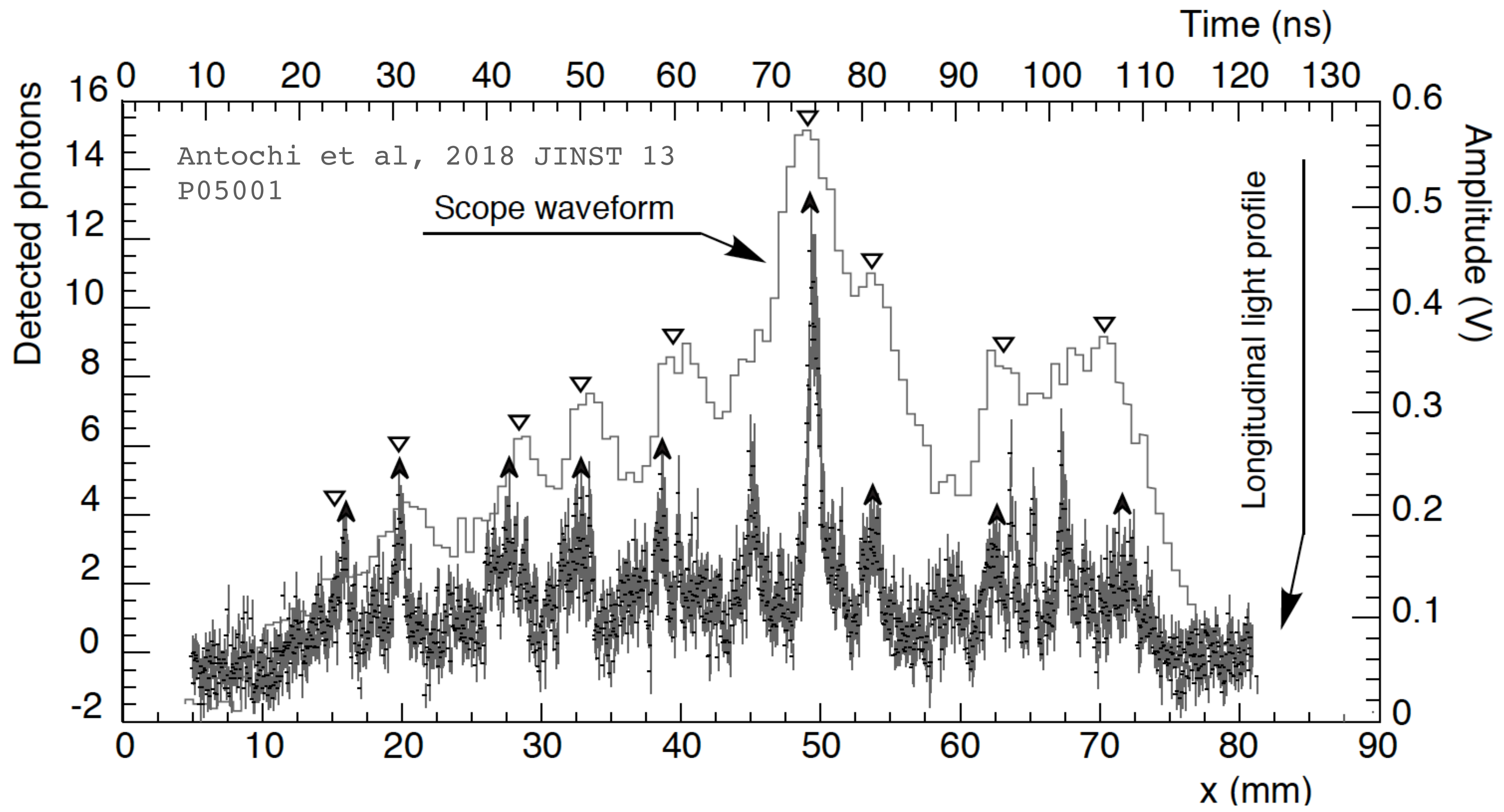
M. Pomorski et al. DOI: 10.1103/PhysRevC.90.014311

Depth reconstruction techniques

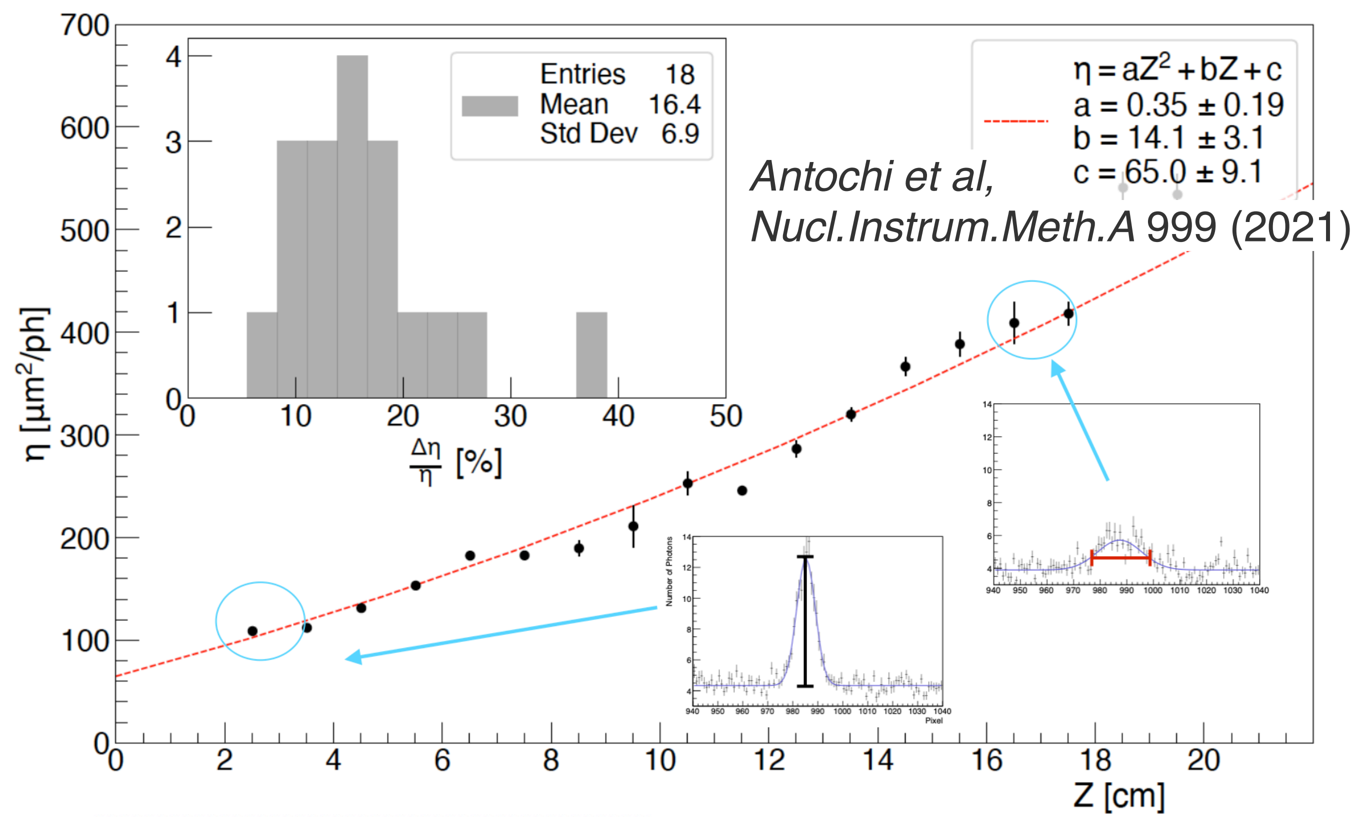
Fast drift velocity in CF4 mixtures (e.g. >10 cm/μs in Ar/CF4) make sub-mm scale depth resolution challenging

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

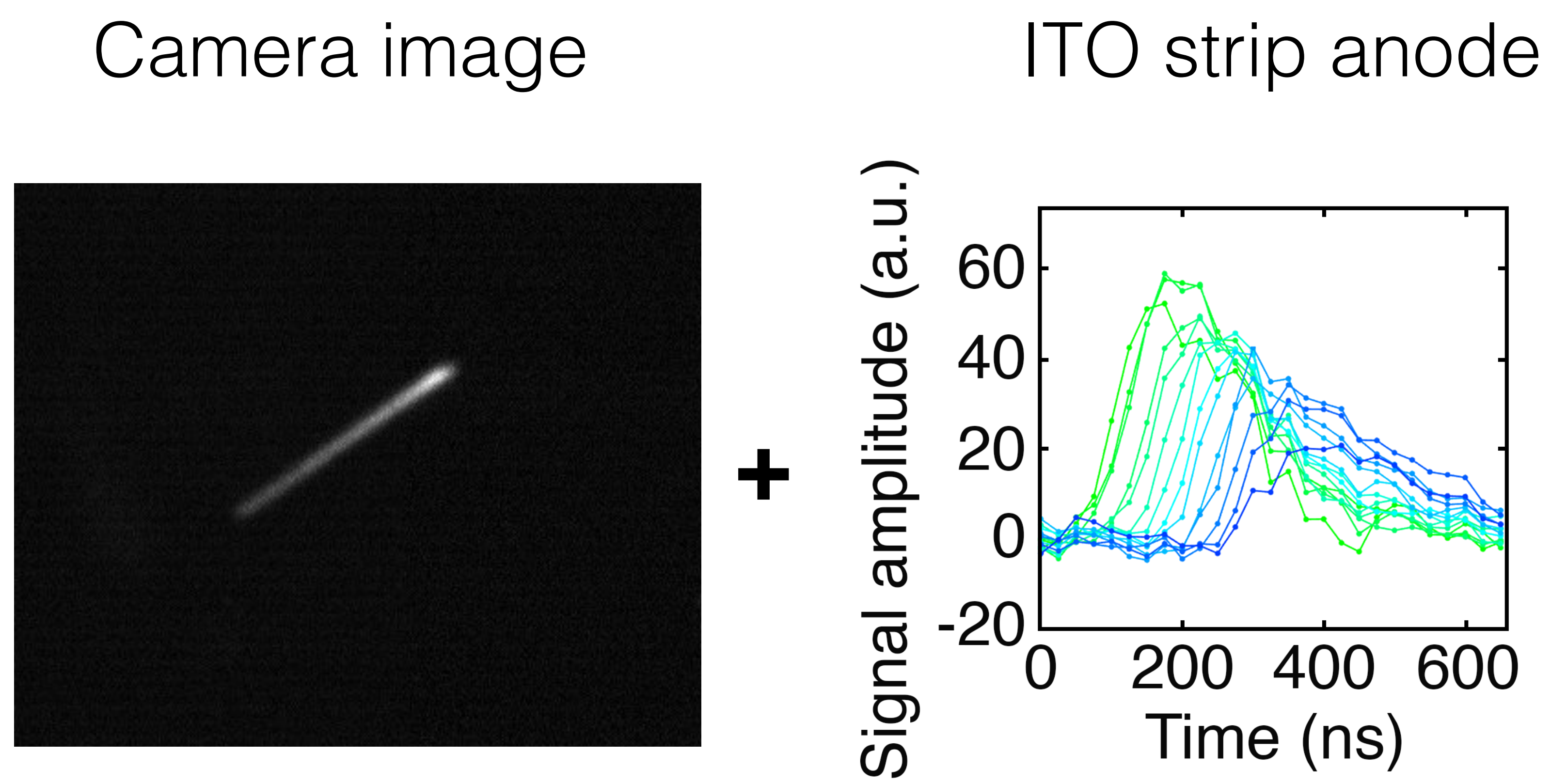
Matching of clusters in light intensity profile from image and in PMT waveforms for Z-determination



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

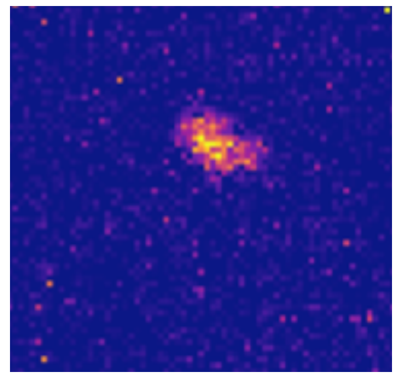
F. Brunbauer et al. 10.1109/TNS.2018.2800775

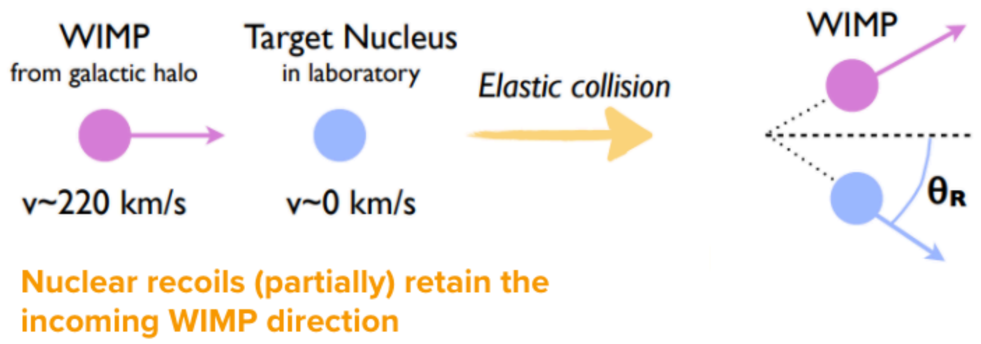
Optical TPCs

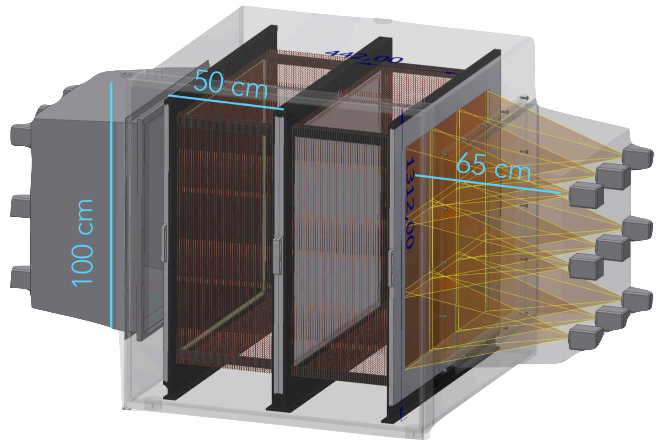
Atmospheric pressure Optical TPC

Rare event searches, directional dark matter

Triple GEM with **CMOS + PMT/SiPM** readout requiring low radioactivity background



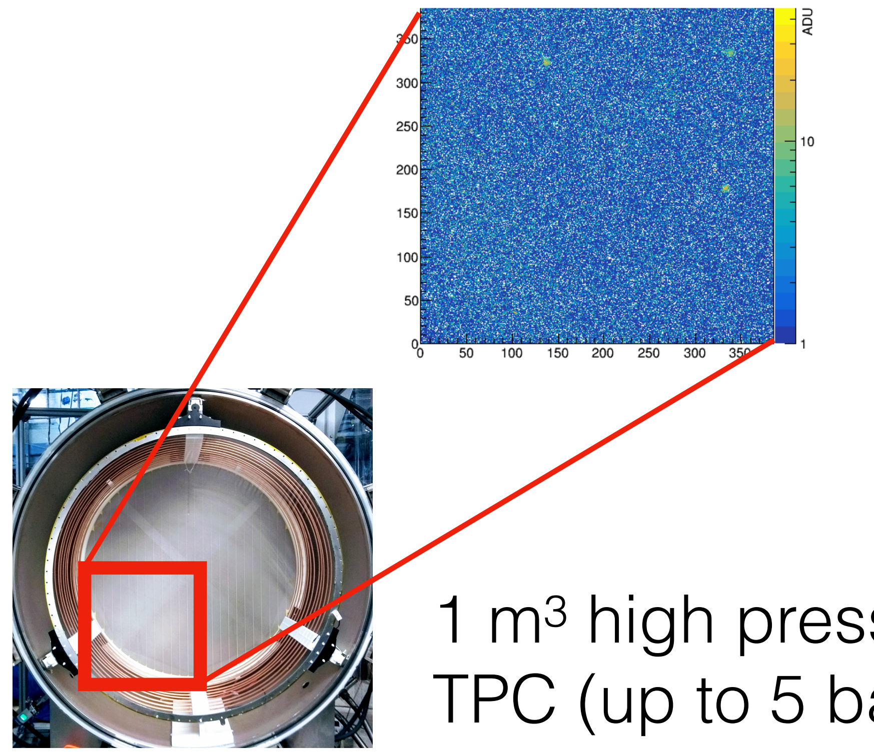




D. Pinci et al., CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search, MPGD 2019
https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf

High Pressure TPC

Towards a neutrino-nucleus cross section experiments



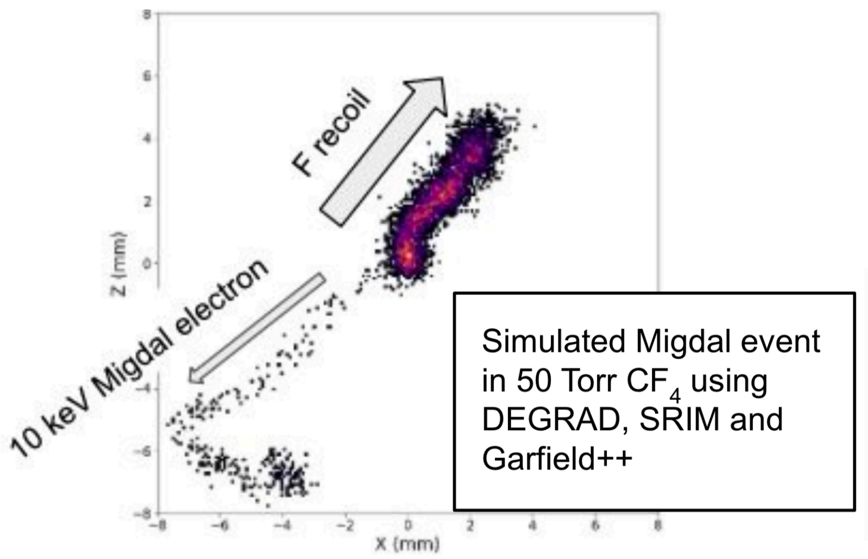
Stitched optical readout (4 CCD cameras) + **electronic signals** from meshes used for amplification

1 m³ high pressure TPC (up to 5 bar)

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

Low-pressure TPC with optical+electronic readout

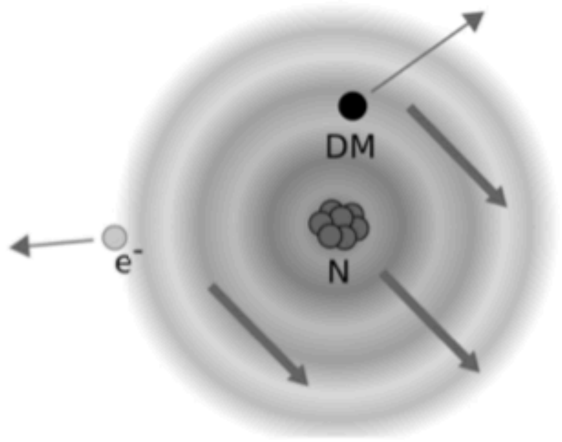
MIGDAL
Migdal In Galactic Dark mAtter expLoration



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

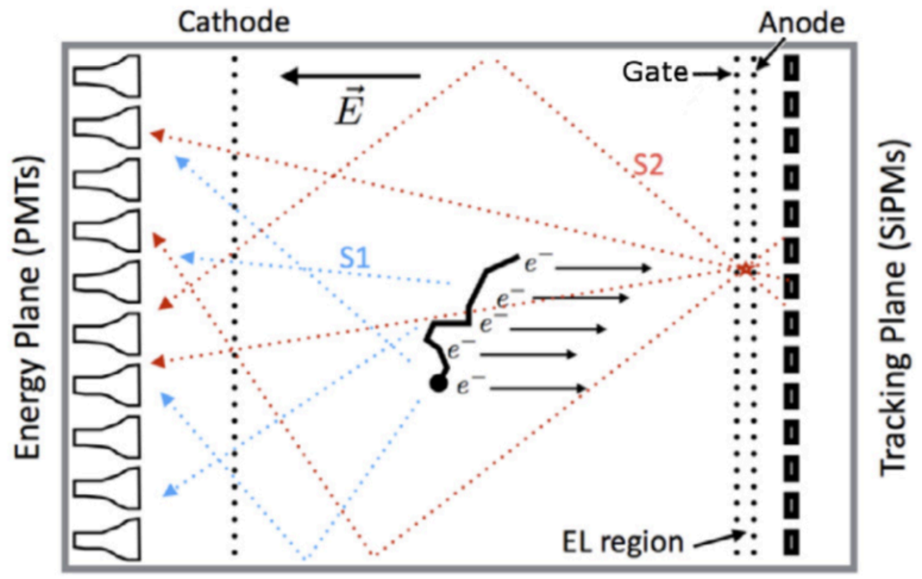
Migdal effect search in low-pressure CF_4 for DM searches in

CMOS + electronic readout of **transparent strip anode**



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

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

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

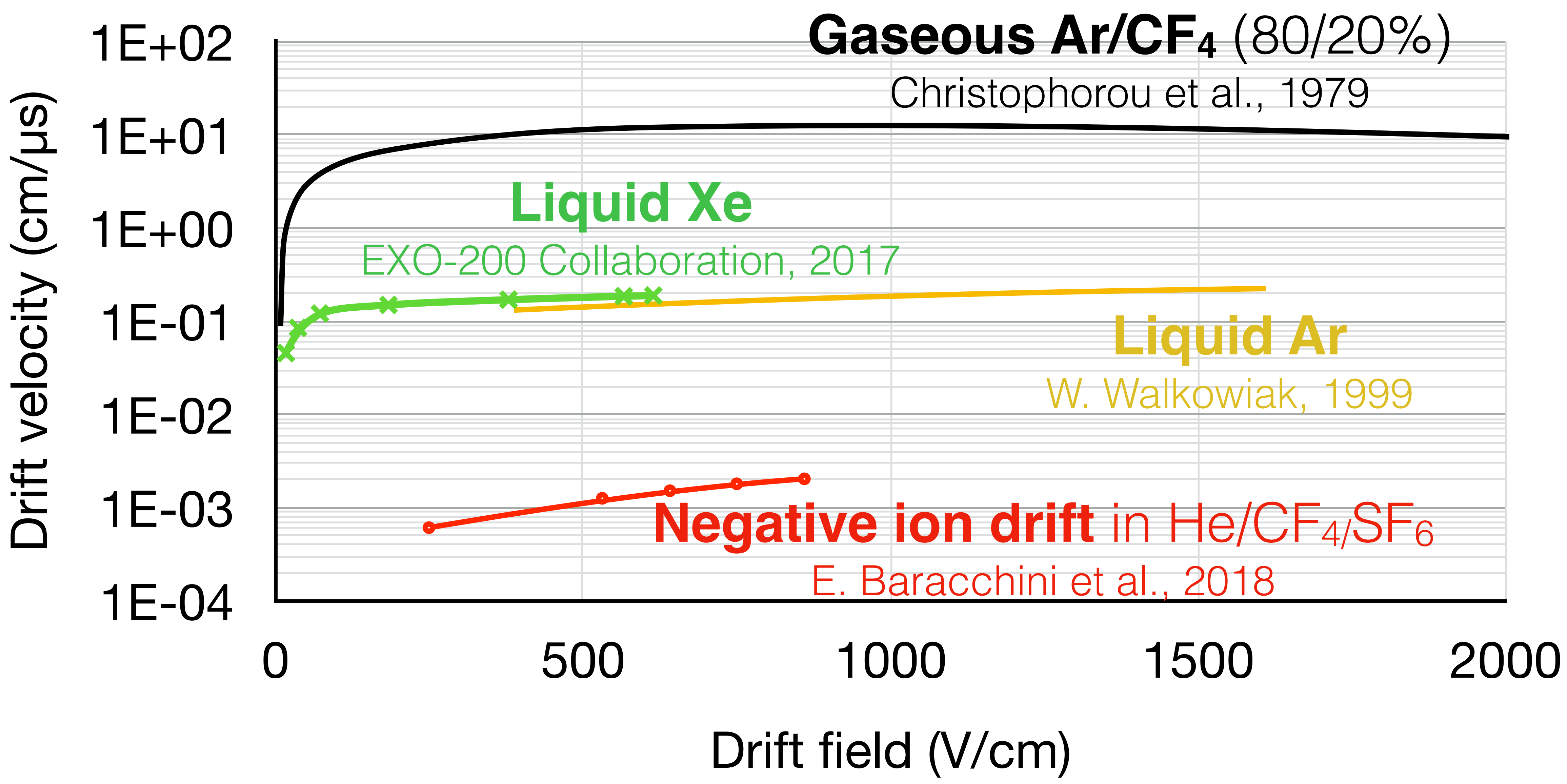
Negative ion TPCs

Negative ion drift may be promising for suppressing **transverse diffusion** down to thermal limits.

Very **low drift velocities** can allow for 3D reconstruction from image sequences recorded at kHz frame rates.

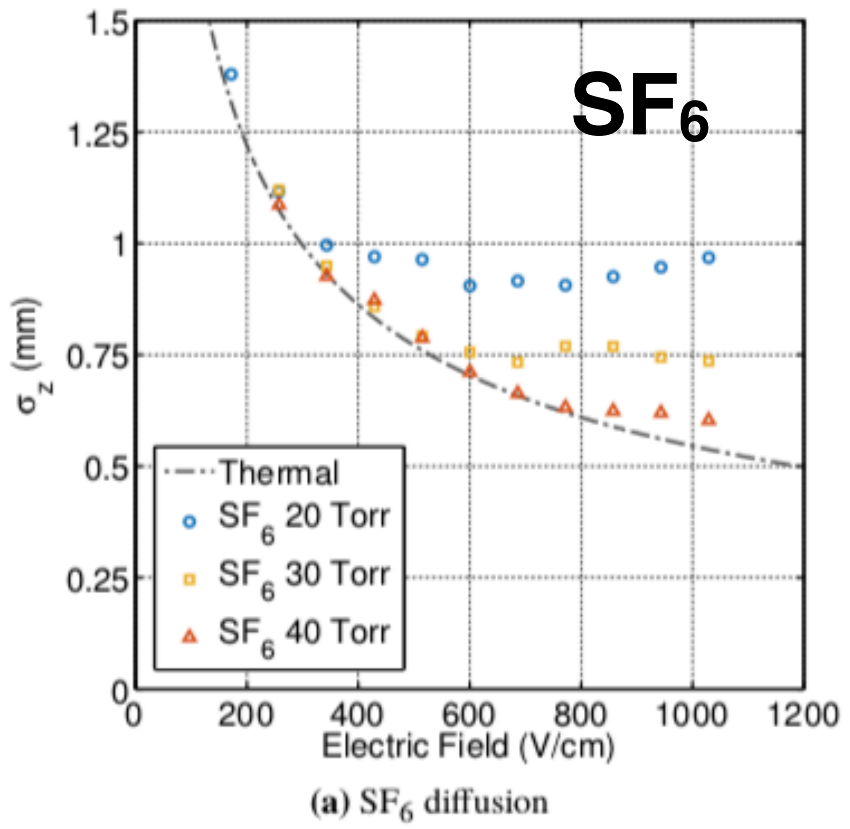
Negative ion mixtures strongly **suppress light yield** and achievable **gain**.

Alternative NI gas mixtures with suitable scintillation yield, **high-gain MPGD** geometries?



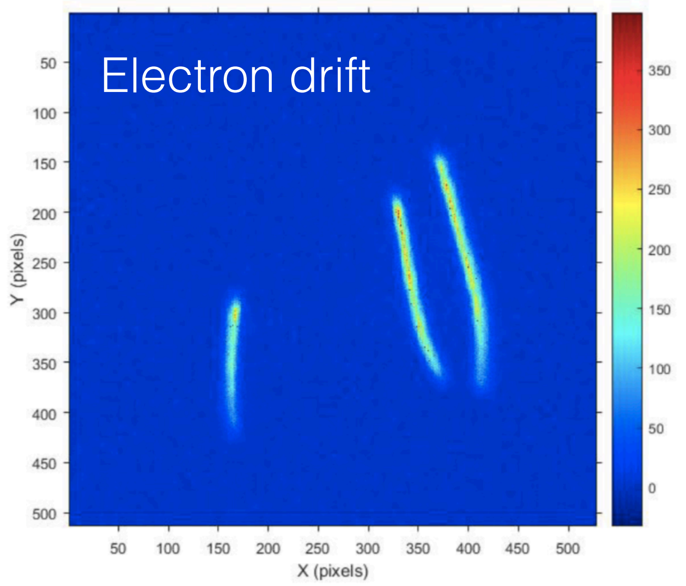
Low diffusion

approaching thermal limits

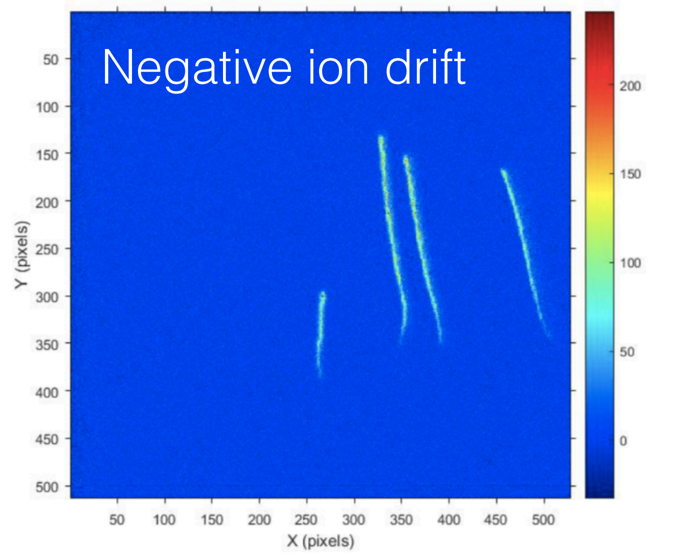


N.S. Phan et al 2017 JINST 12 P02012 https://doi.org/10.1088/1748-0221/12/02/P02012

NI Optical TPC



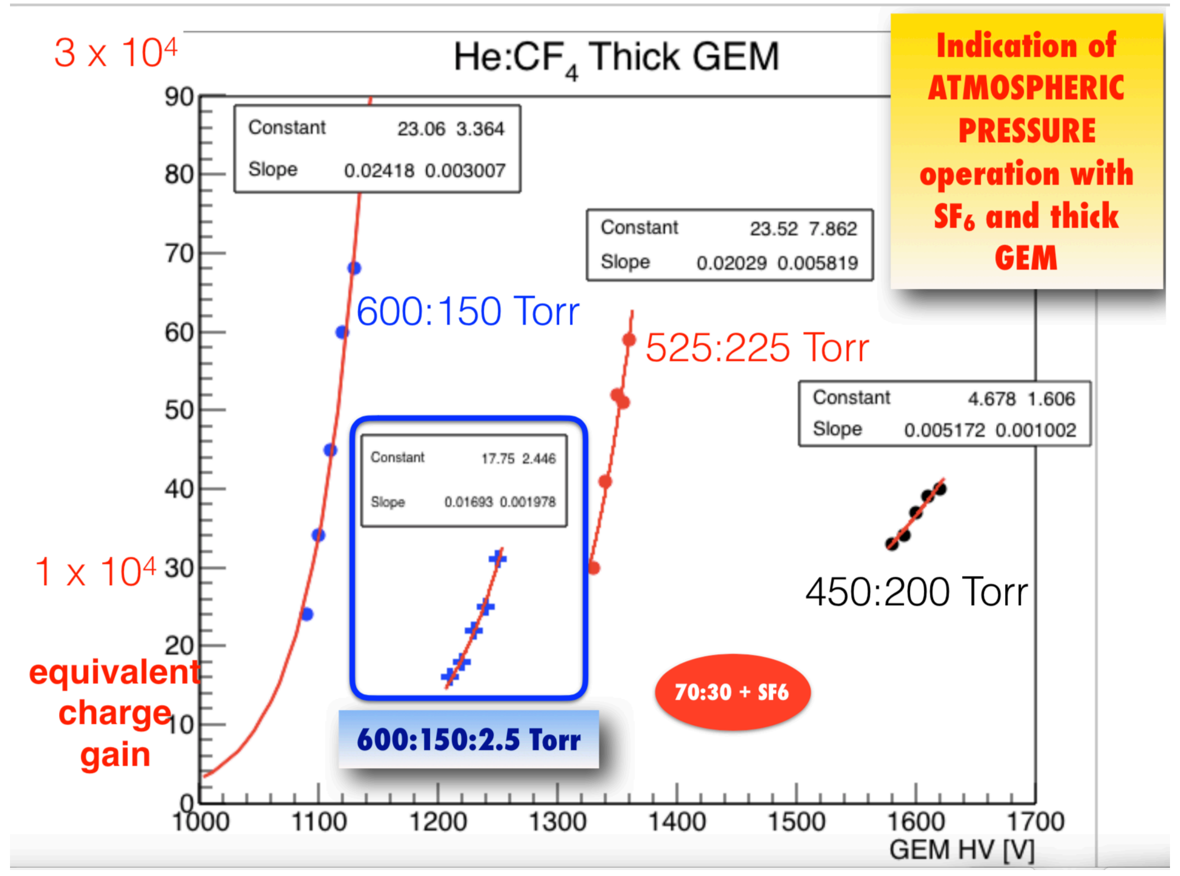
150 Torr CF_4, σ ~ 450 um



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

D. Loomba, UNM

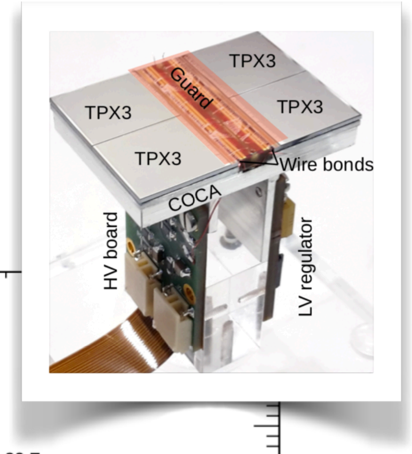
Gain demonstrated in atmospheric pressure He/CF4/SF6

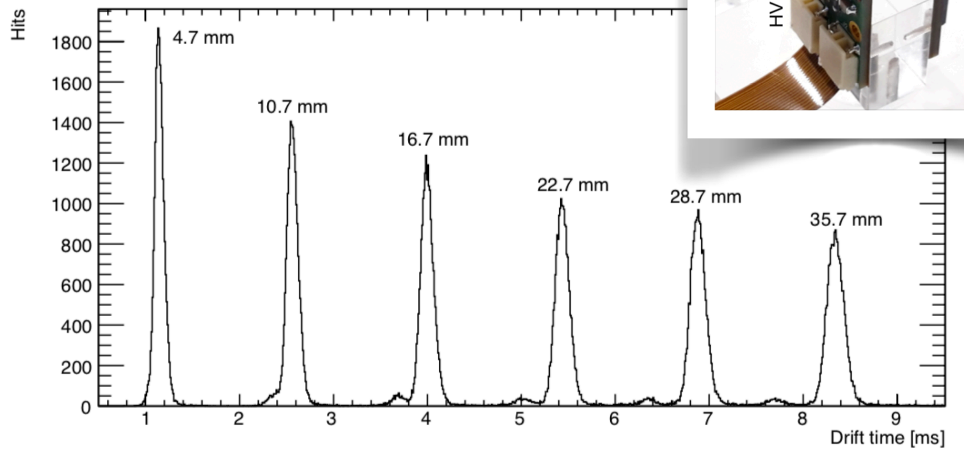


E. Baracchini et al., CYGNO INITIUM, ERC No 818744

GridPix NI TPC readout

1.6ns time resolution of Timepix3 for precise drift time measurements



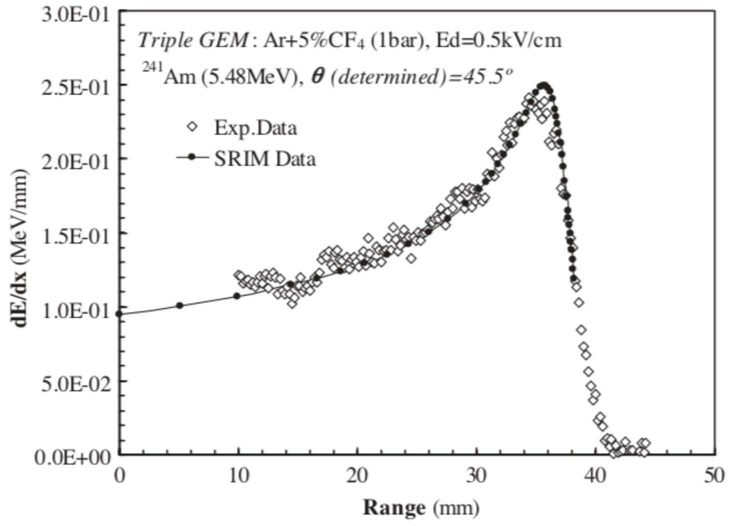


C. Ligtenberg et al., https://indico.nikhef.nl/event/2372/contributions/5576/subcontributions/225/attachments/2601/3036/NITPC_paper_v0612.pdf

Applications

Cluster counting for energy loss measurement

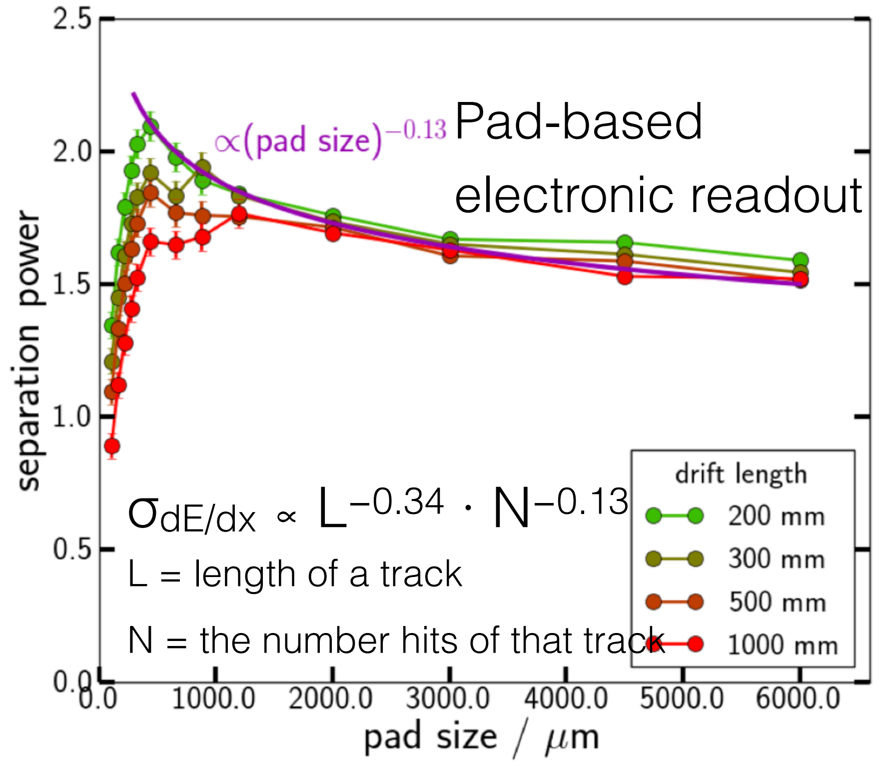
Classical energy loss measurement → **Cluster counting**



Energy loss represented by pixel value intensities e.g. alpha track energy loss profile

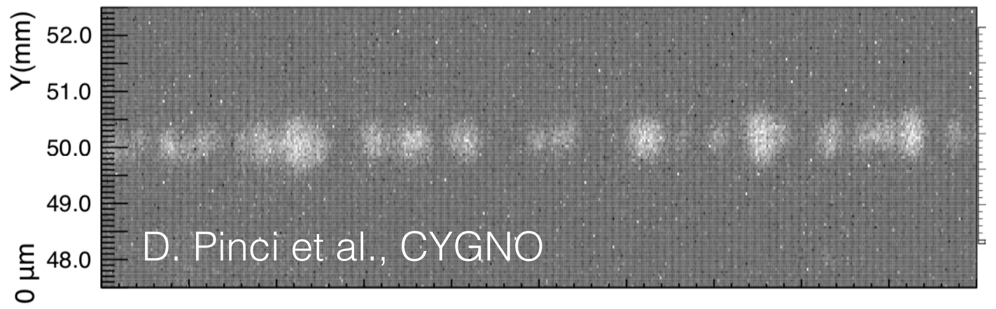
L.M.S. Margato et al., Performance of an optical readout GEM-based TPC, NIM A, 2004

Cluster counting may provide superior energy loss resolution



U. Einhaus, https://arxiv.org/pdf/1902.05519.pdf

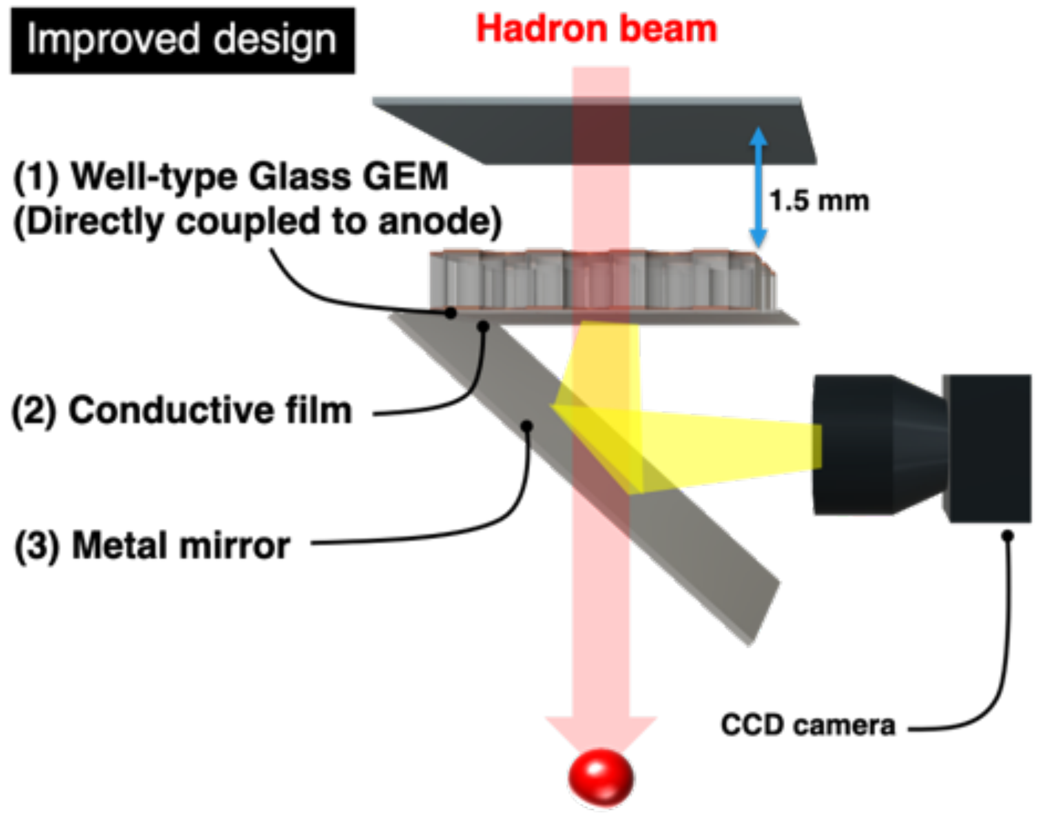
High granularity and **low diffusion** (NI, deconvolution?) required to distinguish clusters.

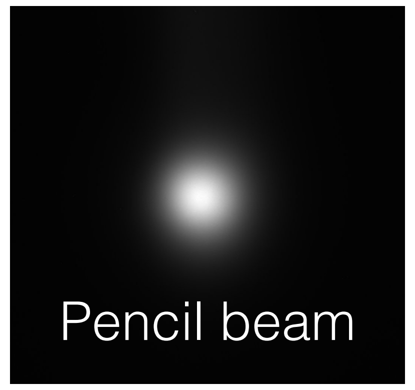


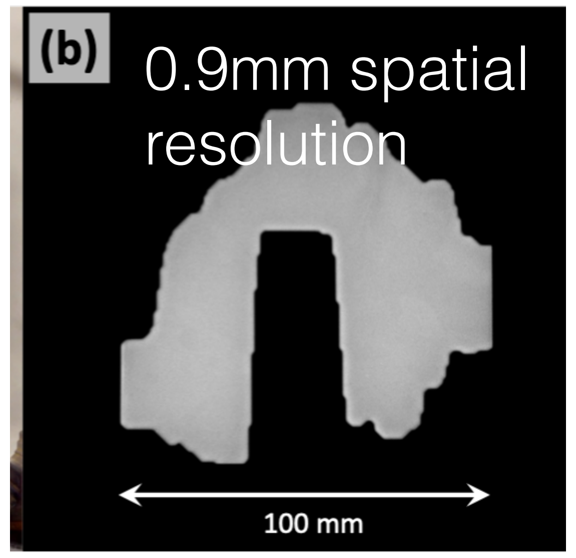
Cluster structure along electron track

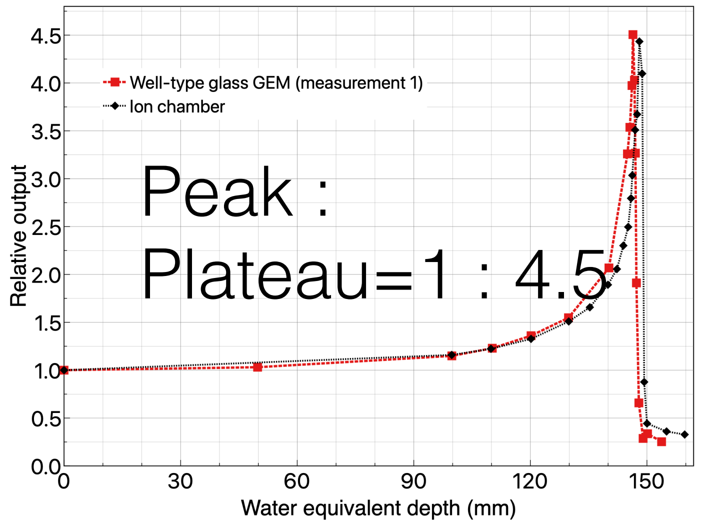
Dose imaging & beam monitoring

Beam monitoring & hadron/neutron therapy applications benefit from high **spatial resolution** and **high LET dose imaging** suitable for clinical proton/carbon beams ($2*10^9$ particles/sec)









T. Fujiwara, et al, Physica Medica (2021)

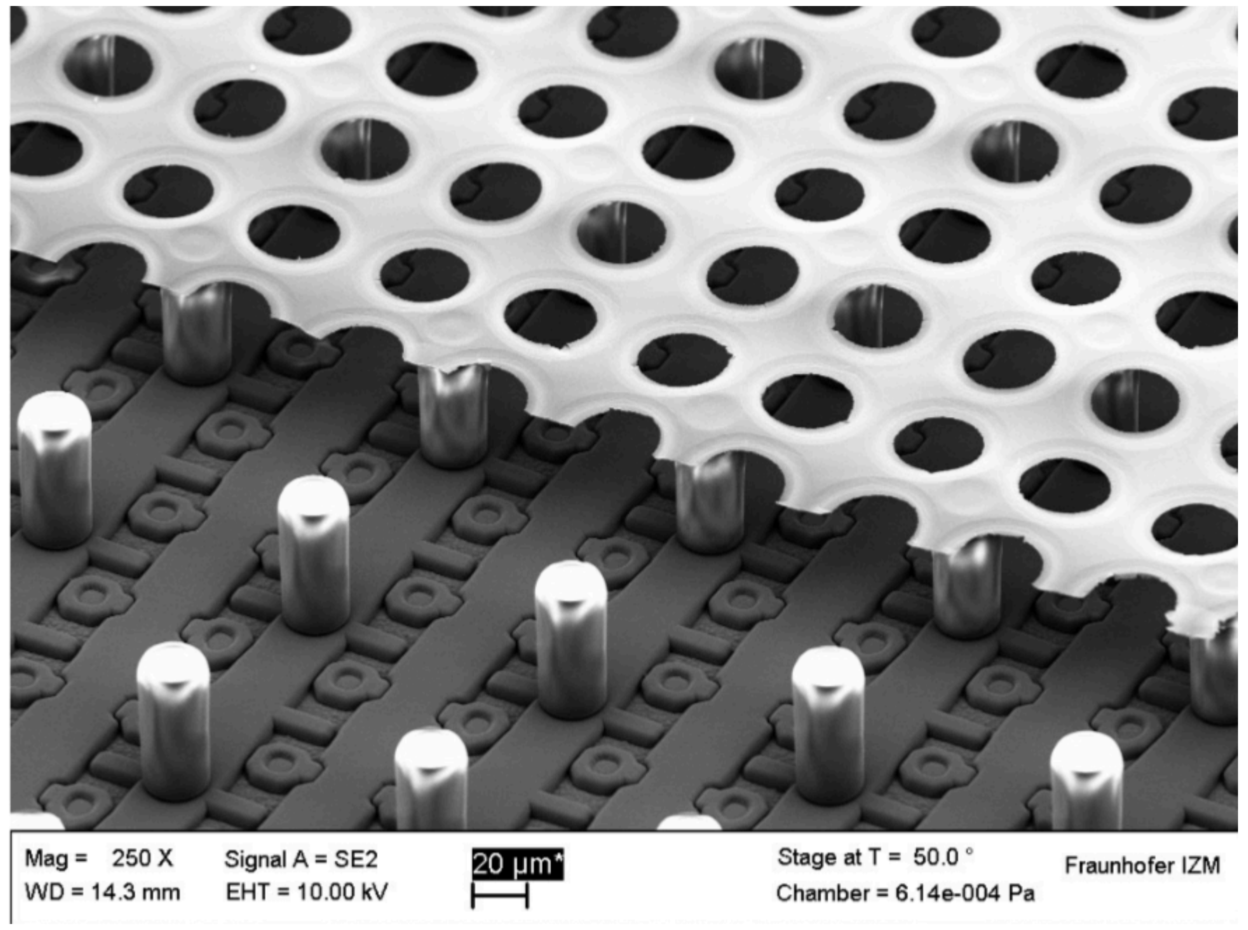
Moderate area coverage with high granularity and **high dynamic range**.

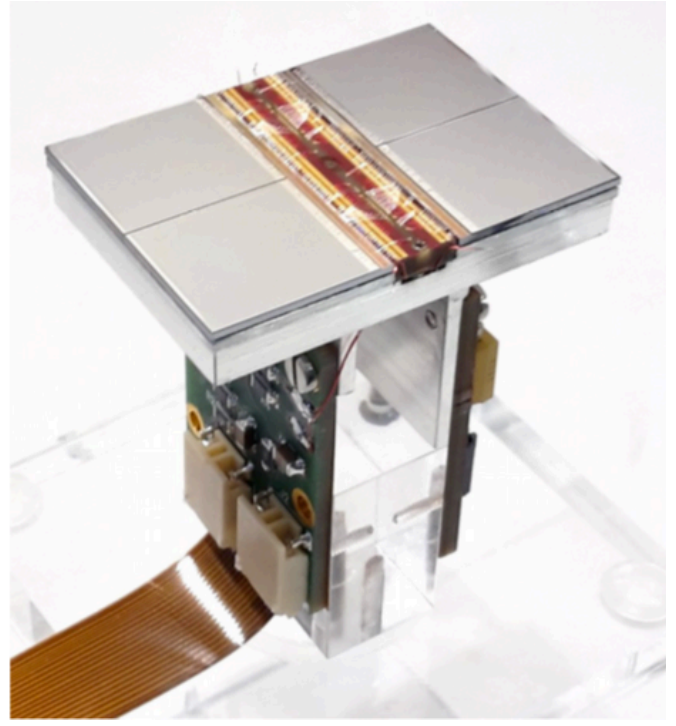
Radiation hardness of imaging sensors / readout ASICs and **frame rate** for **live feedback** applications?

GridPix

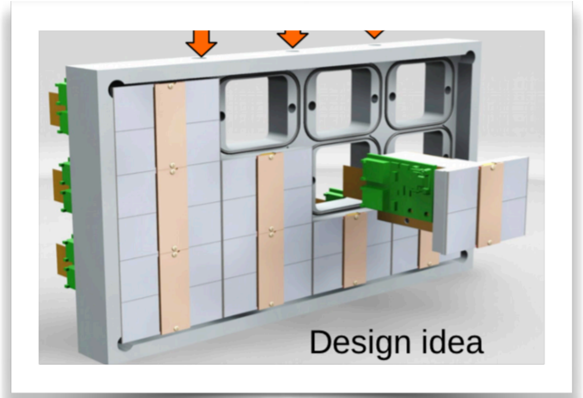
Micromegas on Timepix ASIC

- Bump-bond pads used for charge collection
- CMOS-ASIC designed by the Medipix collaboration
- GridPix based on Timepix 3:
  - 256 × 256 pixels with 55 × 55 μm² per pixel
  - Charge (ToT) and time (ToA) information with 1.56ns time resolution





QUAD module with fill factor of 68.9%

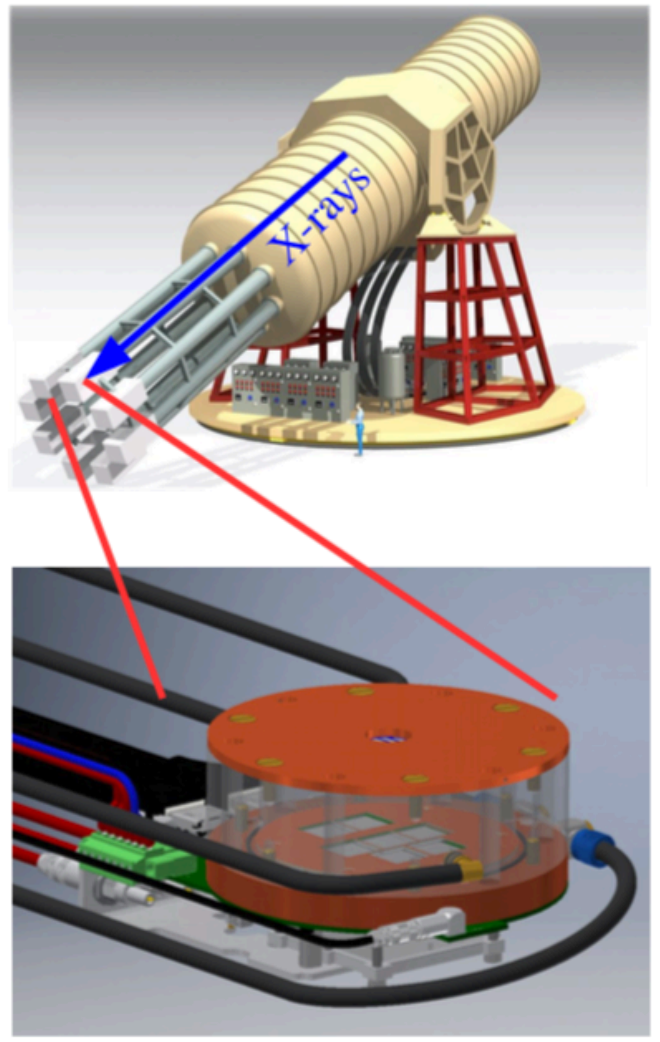


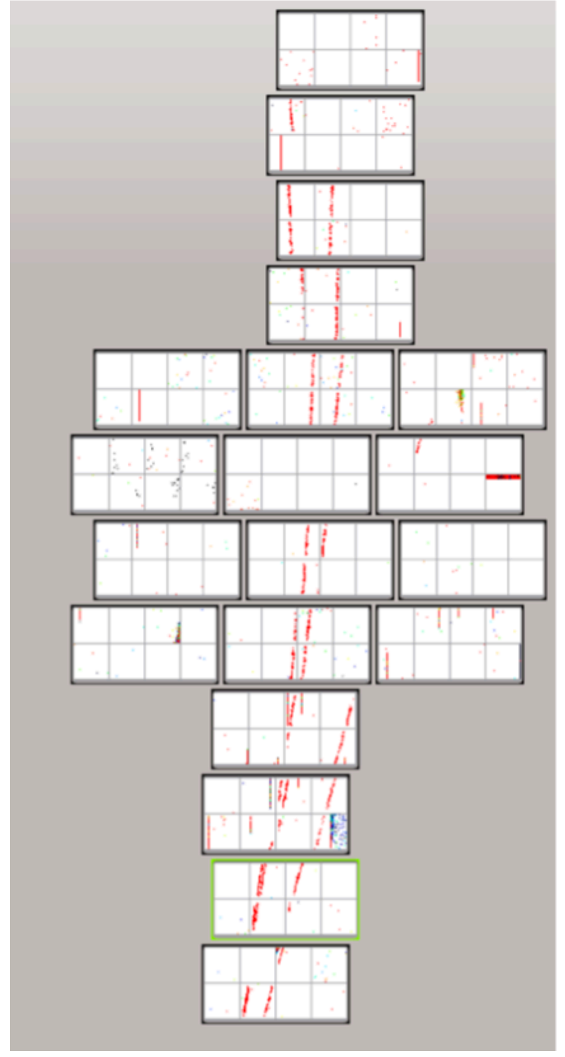
J. Kaminski et al.
NÌM A535 (2004) 506-510
NIM A845 (2017) 233-235

Proposed applications

IAXO/CAST: Low background, high spatial resolution, high energy resolution: σE/E=3.95%

ILD-TPC: To fulfil < 100μm spatial resolution and ≈ 5% dE/dx resolution with small pads for low occupancy





Applications for

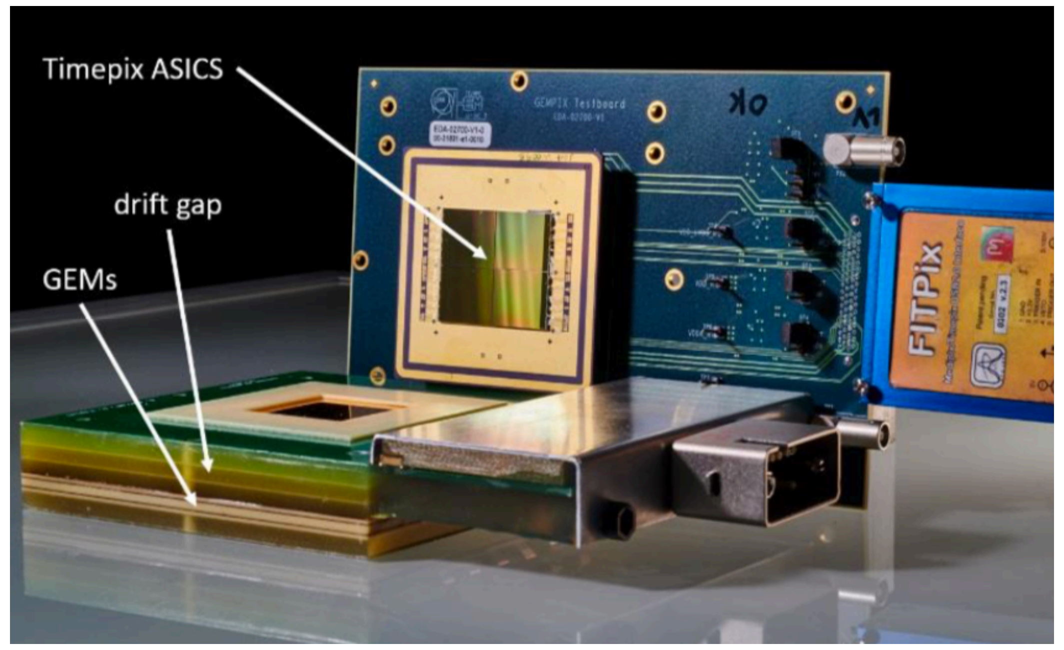
- Neutron TPCs
- X-ray Polarimetry
- Small area directional dark matter detectors

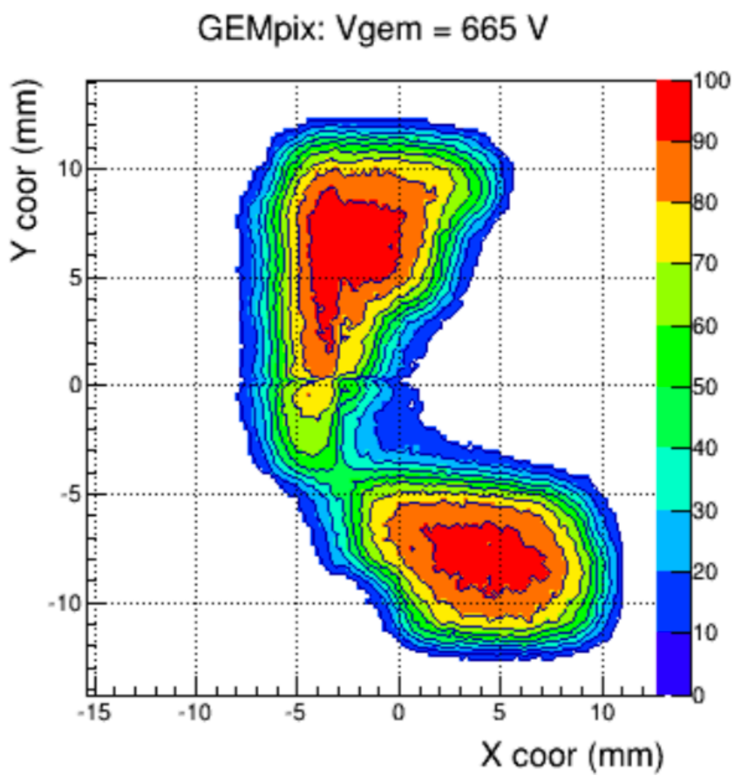
GEMGrid: InGrid on solid layer
TwinGrid: stacked grids
Timepix4?

GEMPix

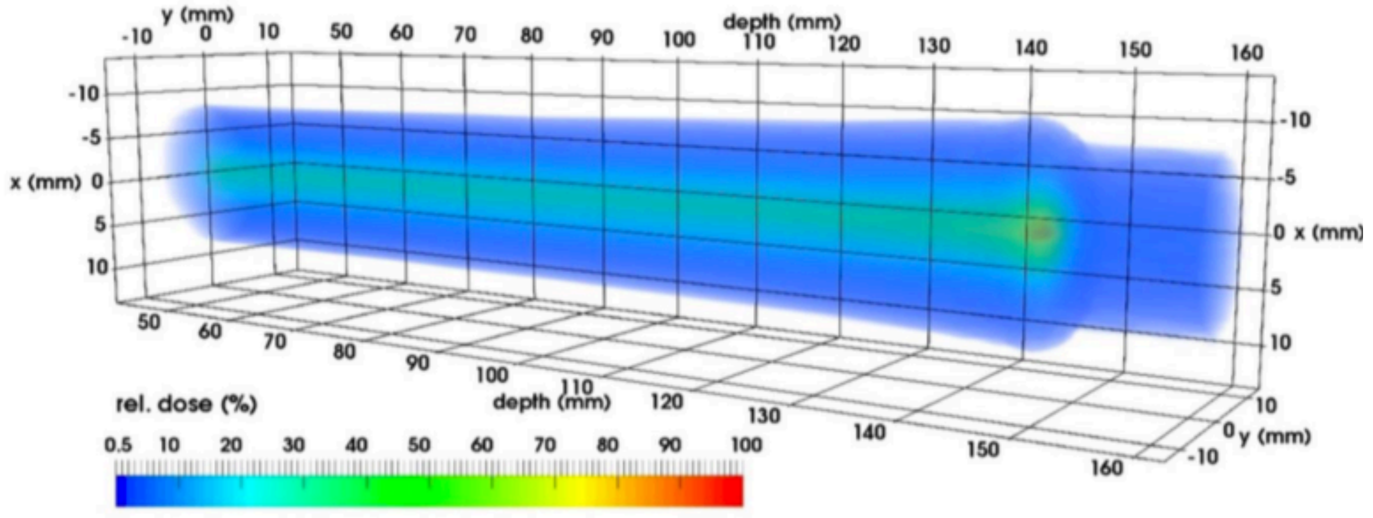
GEM + Timepix ASIC

- Four naked Timepix read out with FPGA-based FITPix
- **Dose distribution imaging**, beam profile measurements for **hadron therapy** and micro dosimetry are potential applications
- Limited in area (2.8 × 2.8 cm) by Timepix ASICs -> tiling with Timepix4 feasible

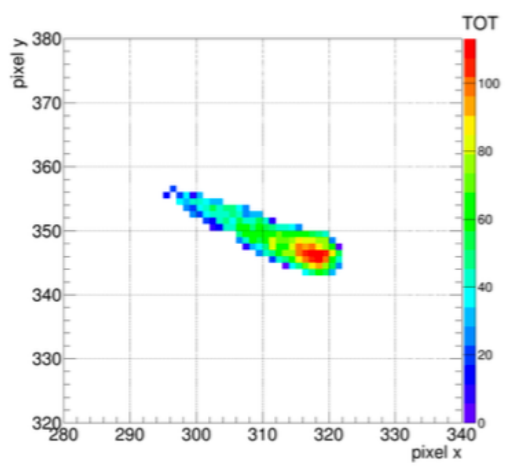




Dose distribution



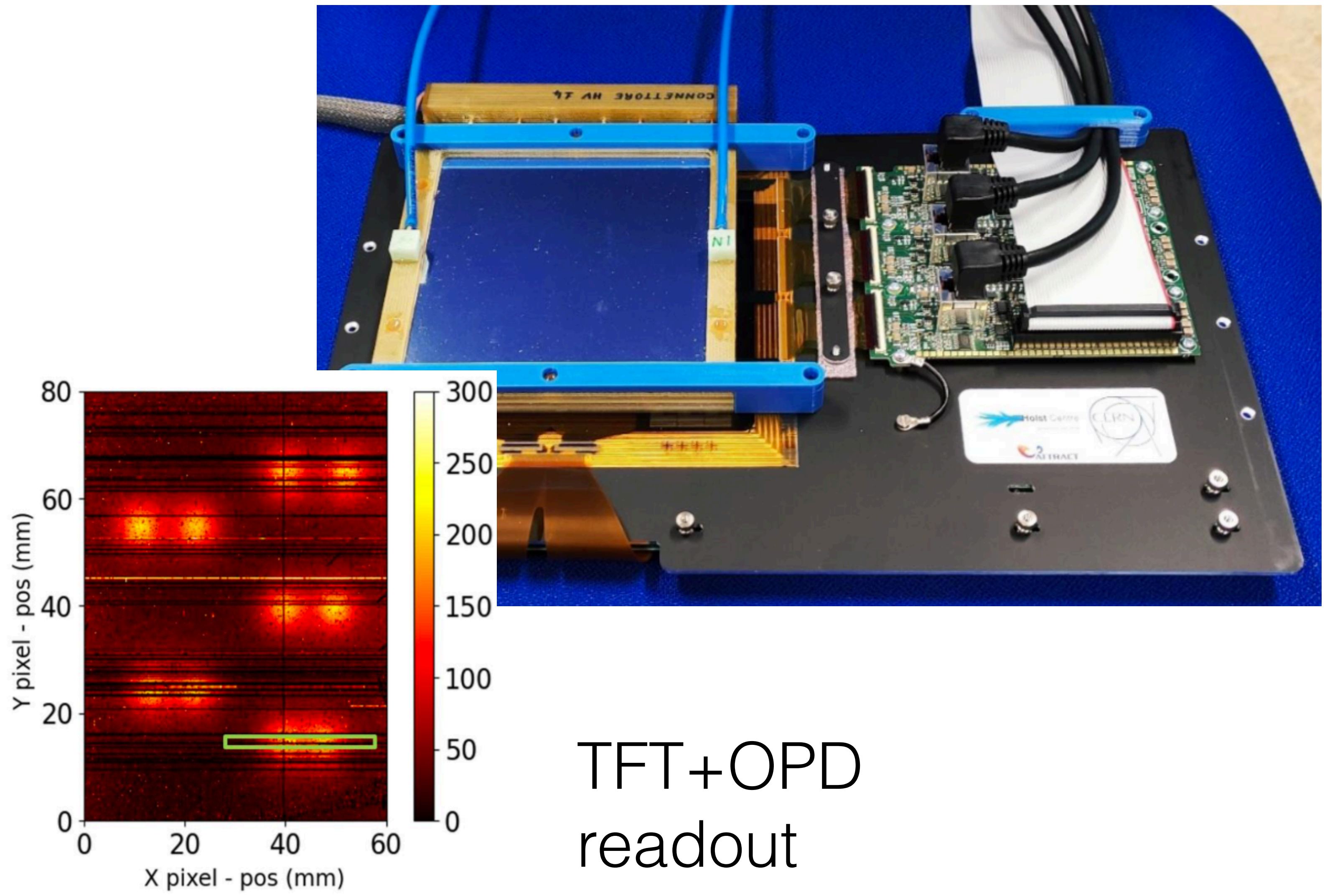
3D dose visualisation of carbon ion beam



Proton track

LaGEMPix

- **TFT backplane** compatible with scaling up to 20cm x 20cm but slow readout
- Optical readout: **optical photo detectors** (OPD) on top of TFT sensitive to scintillation light (poor resolution)
- Electronic readout: no OPD and direct charge readout from TFTs



TFT+OPD readout

J. Leidner et al. https://doi.org/10.3390/app11010440

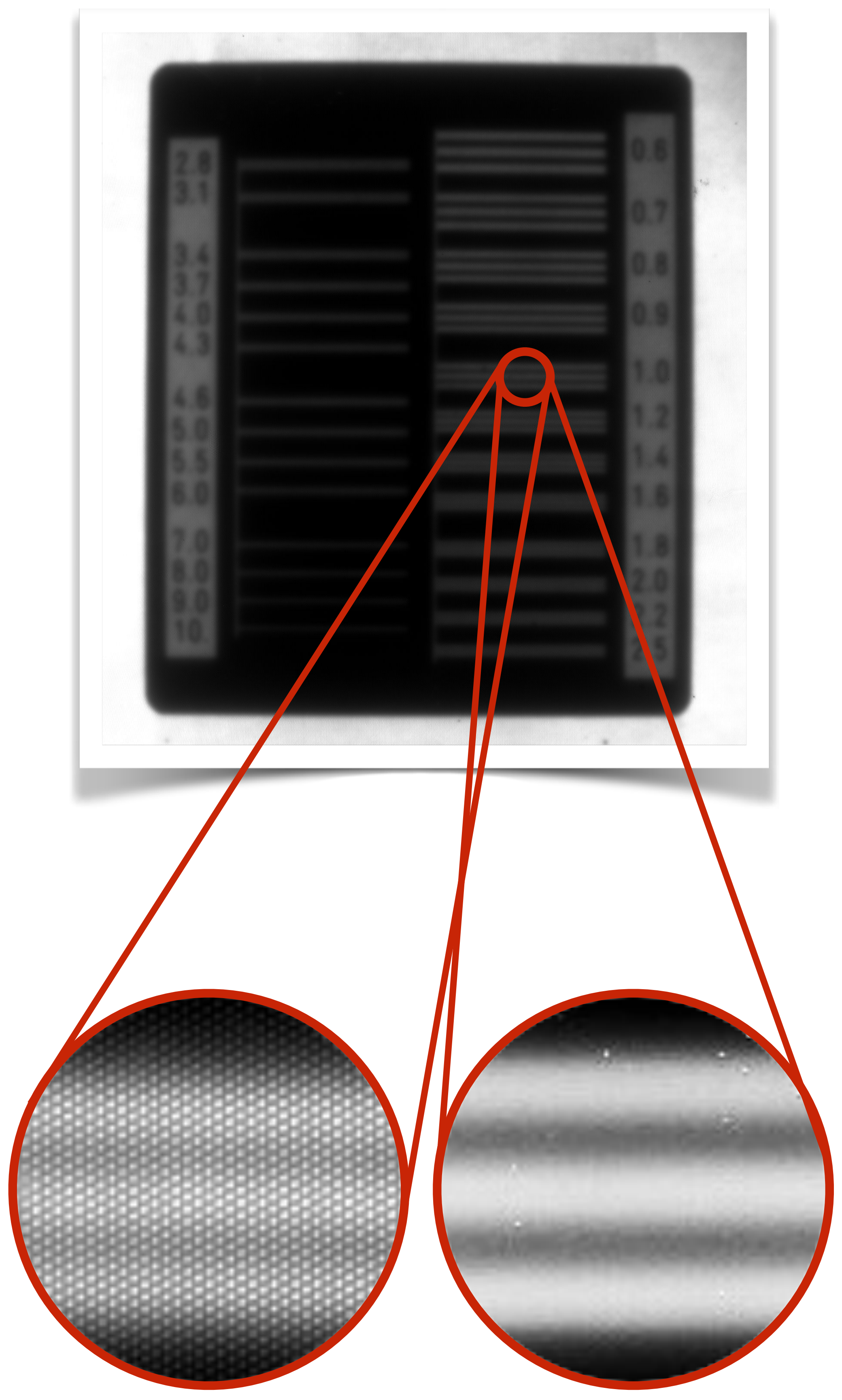
Spatial resolution comparison

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:

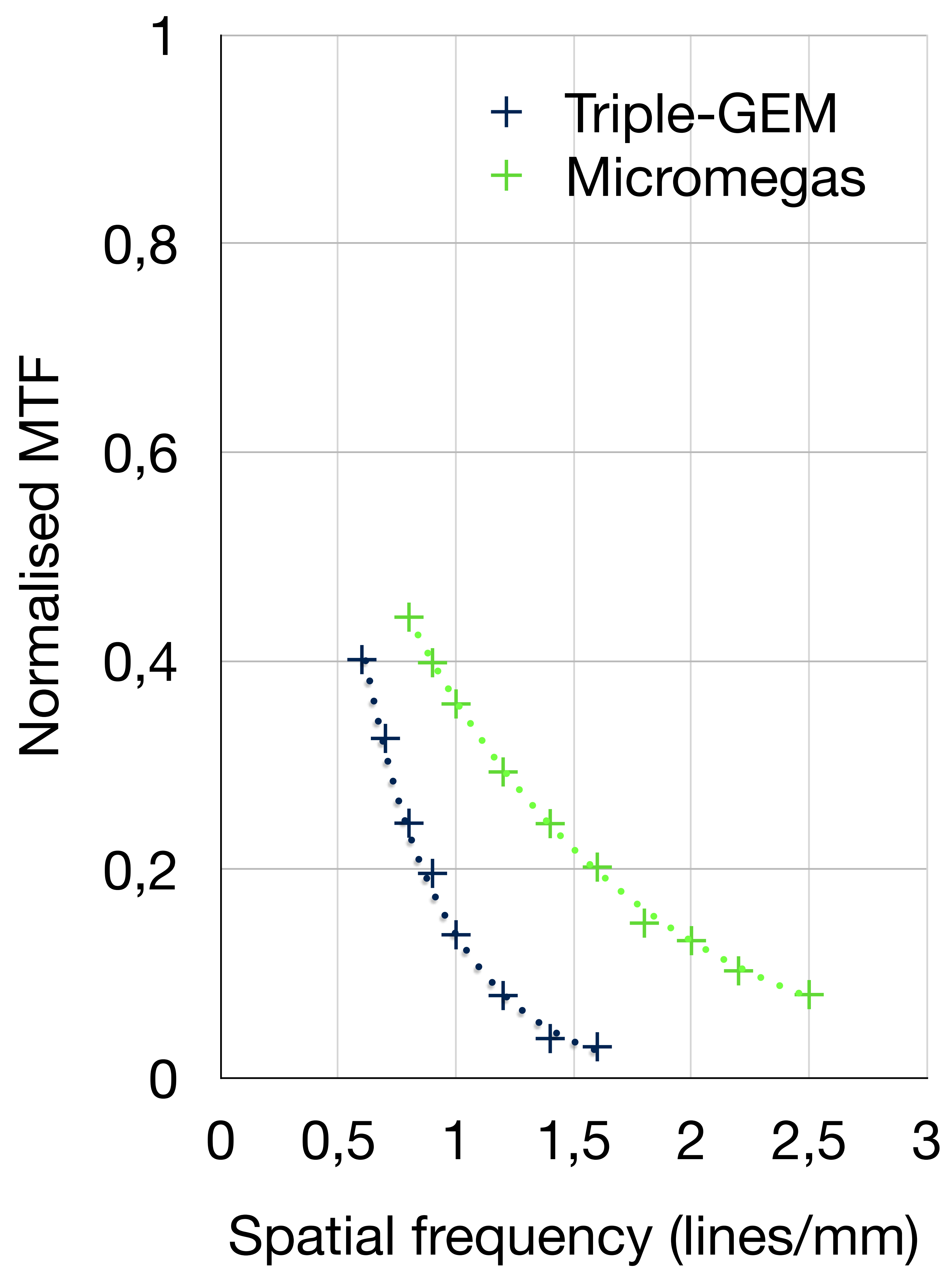
Triple-GEM: ≈**890 μm** (1.11 lines/mm)

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



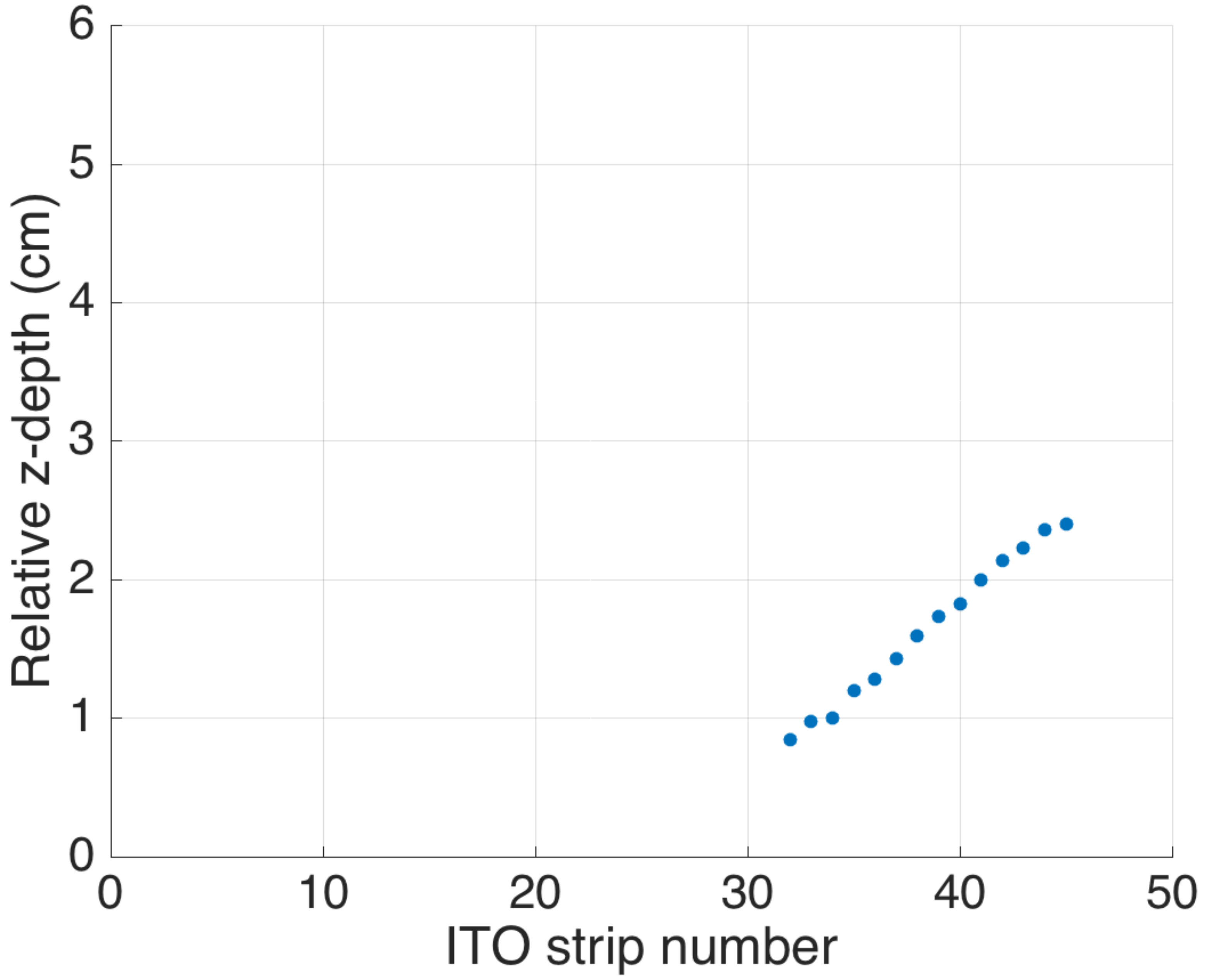
Triple-GEM
Hole structure

Micromegas
Uniform

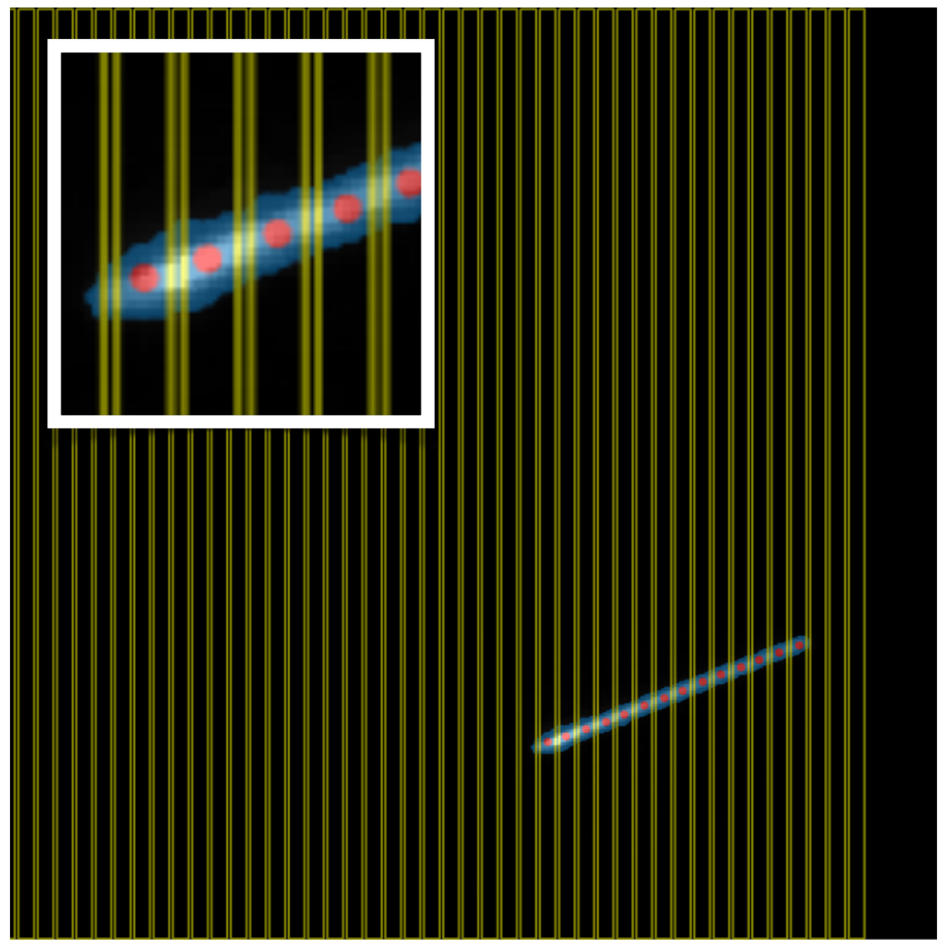


Combining Z with XY-information

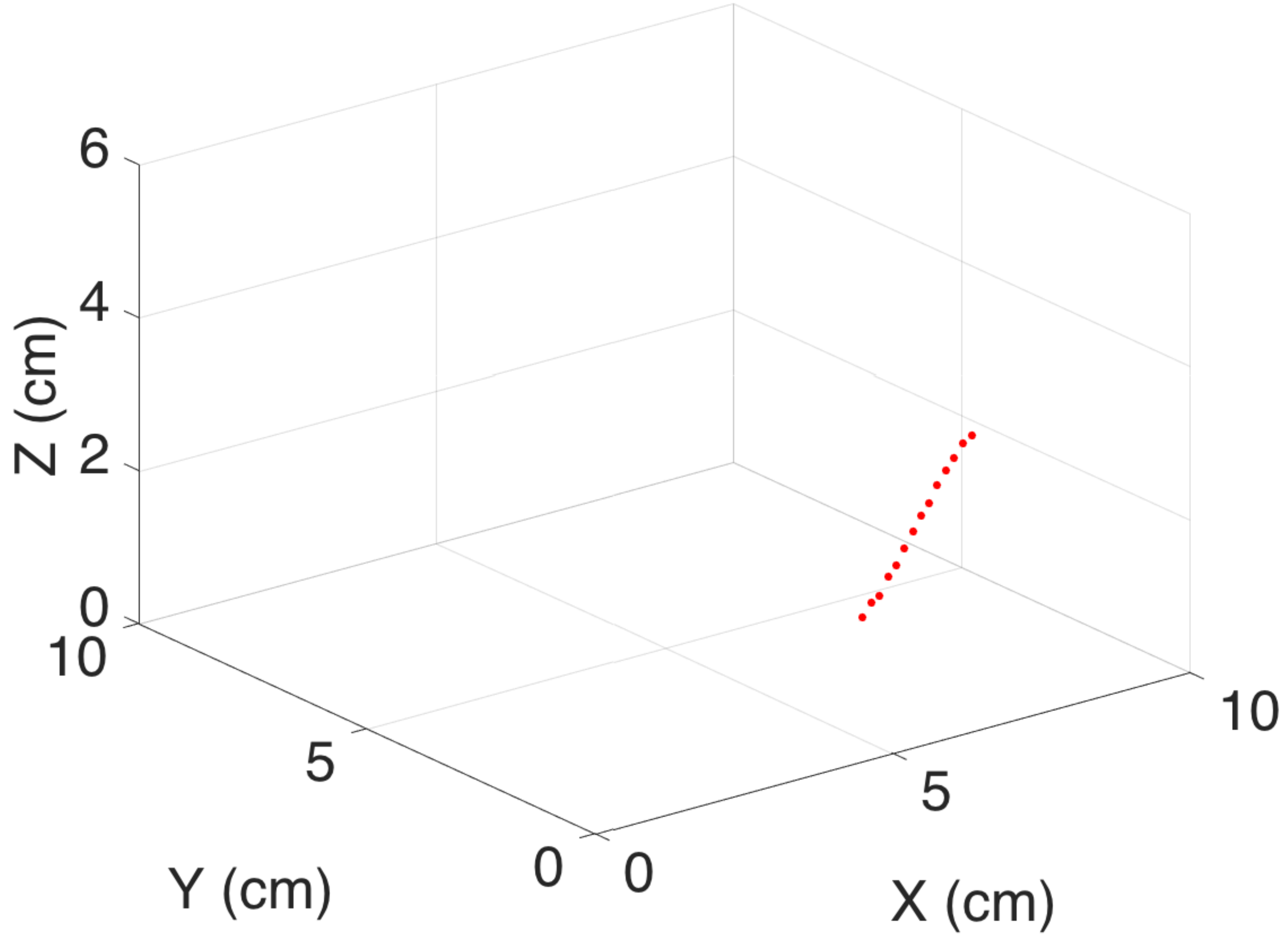
Relative Z depth information



XY projection



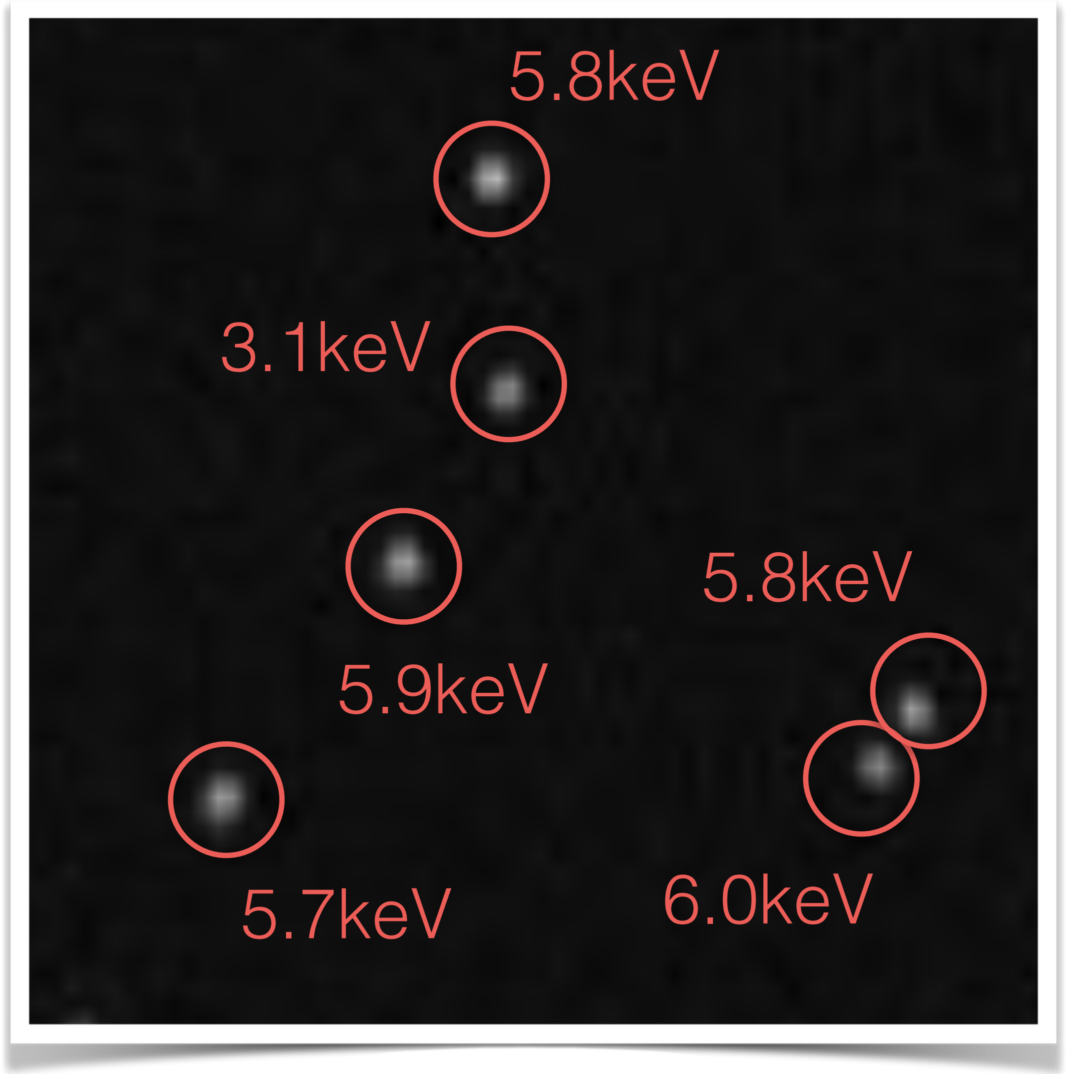
3D reconstruction



Relative depth information for each hit strip from electronic readout is combined with 2D positions of strip hits from optical readout to 3D track points

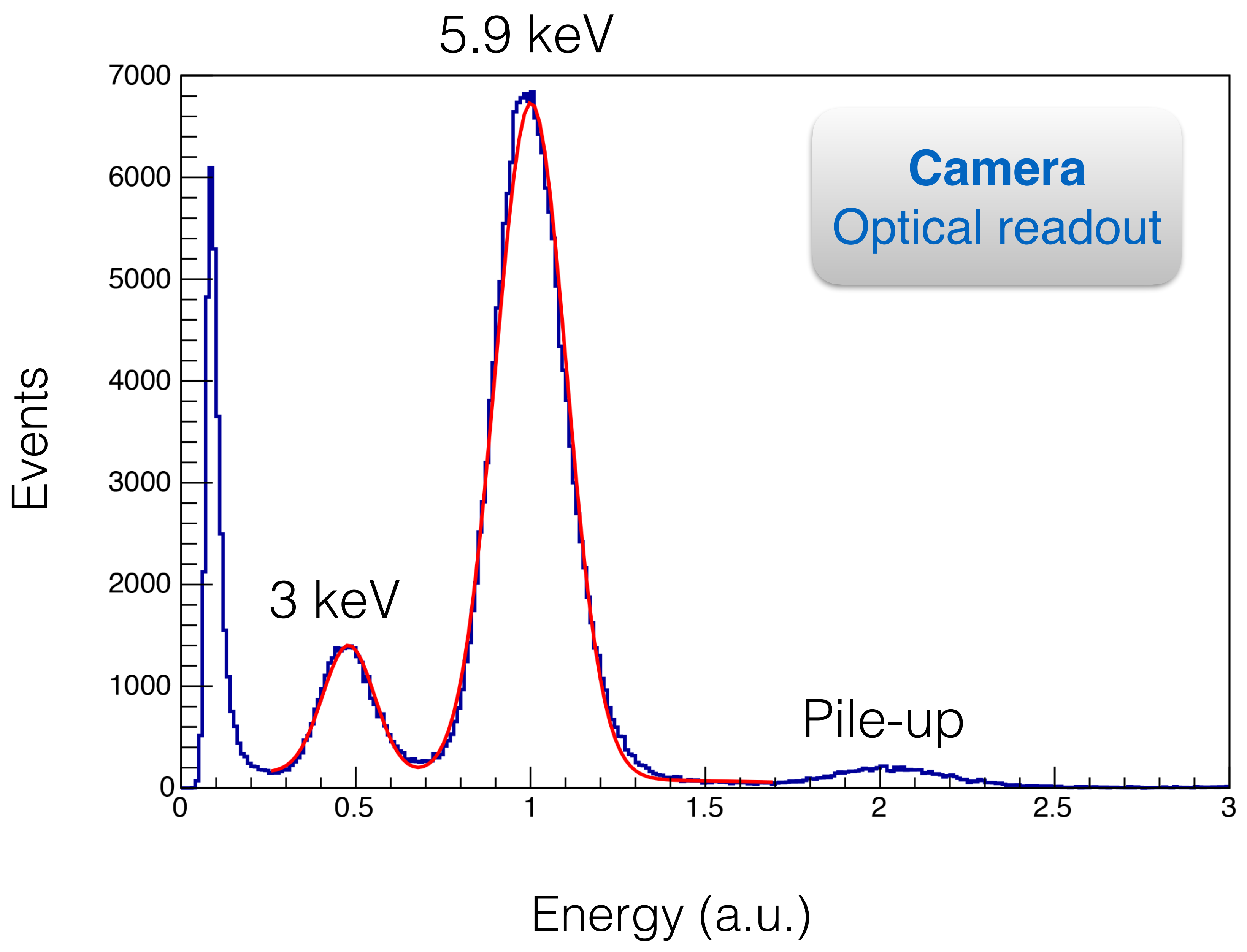
Energy-resolved imaging

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

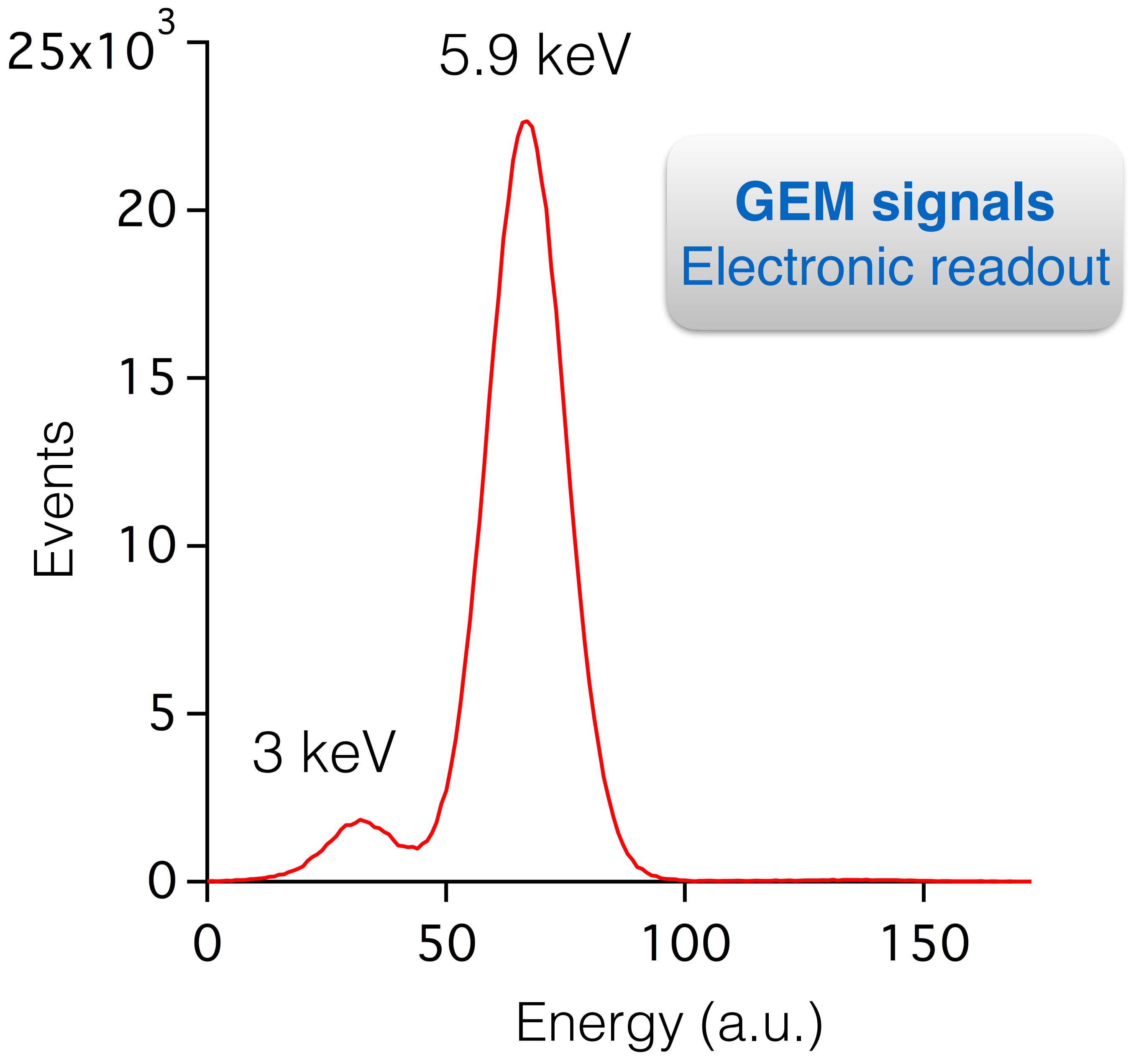


Brightness reflects deposited energy

Energy spectrum of ^{55}Fe source
Optical readout

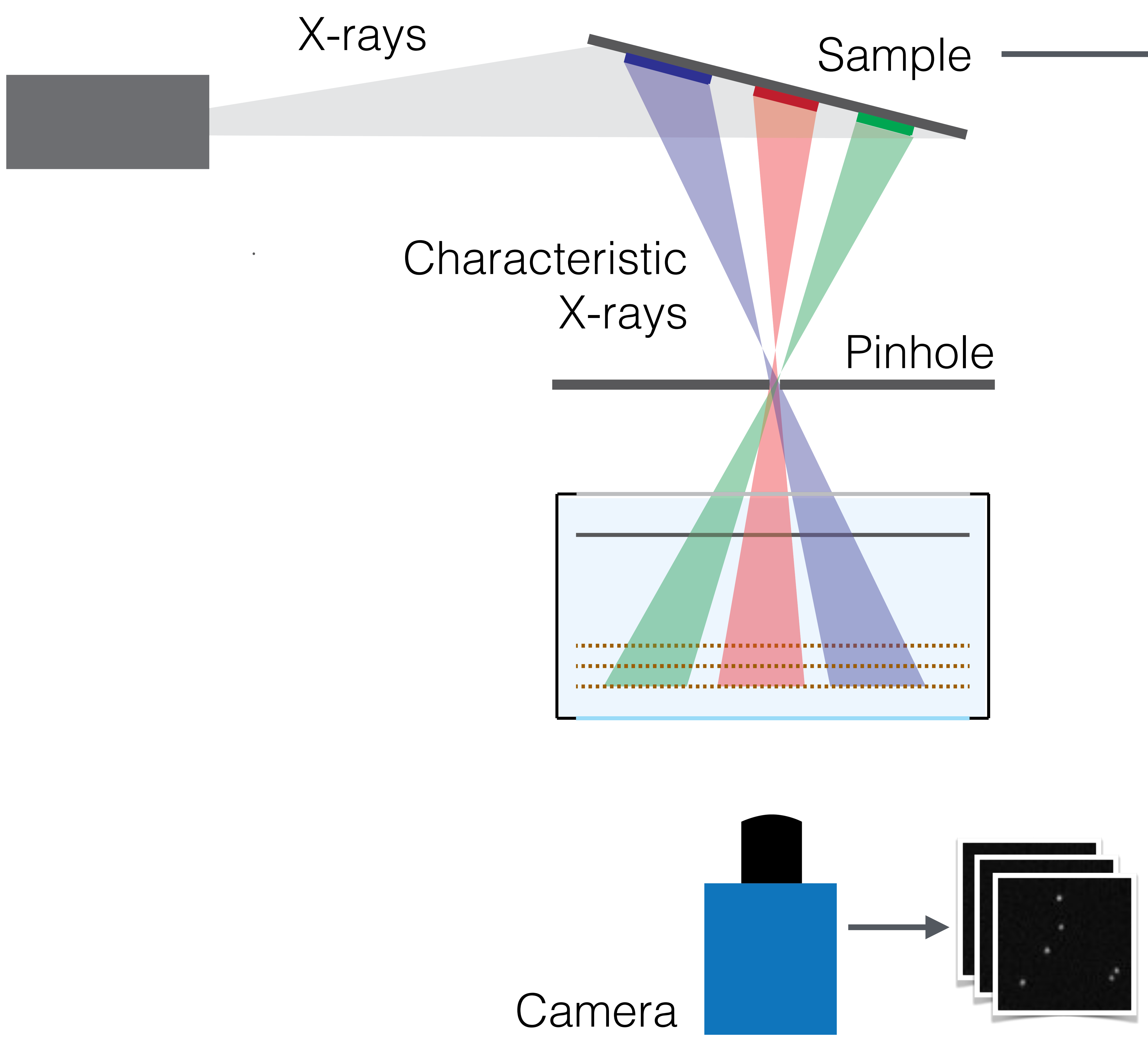


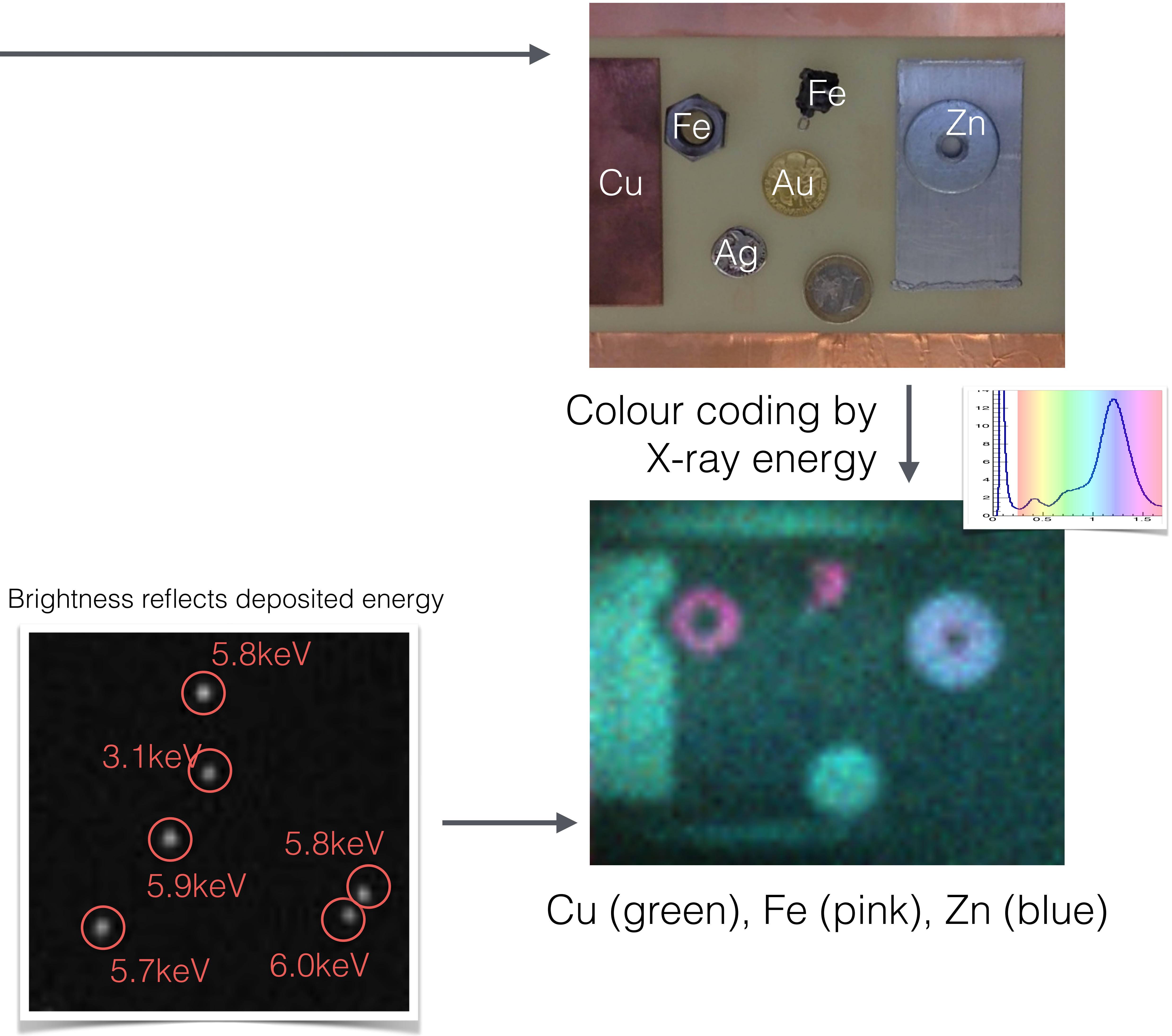
Energy spectrum of ^{55}Fe source
Electronic readout



Energy values are schematic and not to scale for illustration

Energy-resolved imaging: X-ray fluorescence





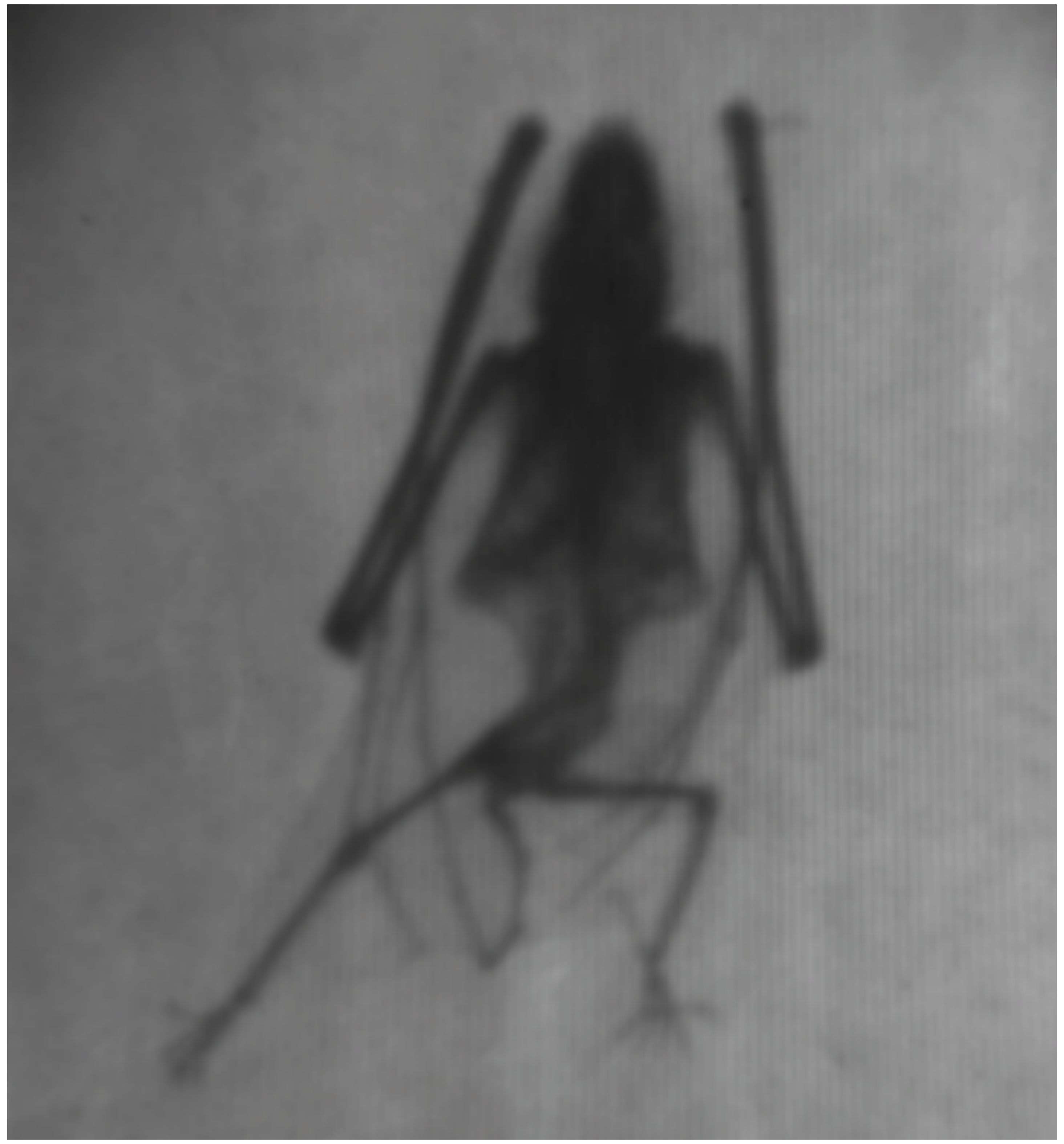
F.M. Brunbauer et al. JINST (13) 2018.

Schematics not drawn to scale

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

10 kV



20 kV

40 kV