Optical readout of MicroPattern Gaseous Detectors: developments and perspectives

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on behalf of the CERN GDD group

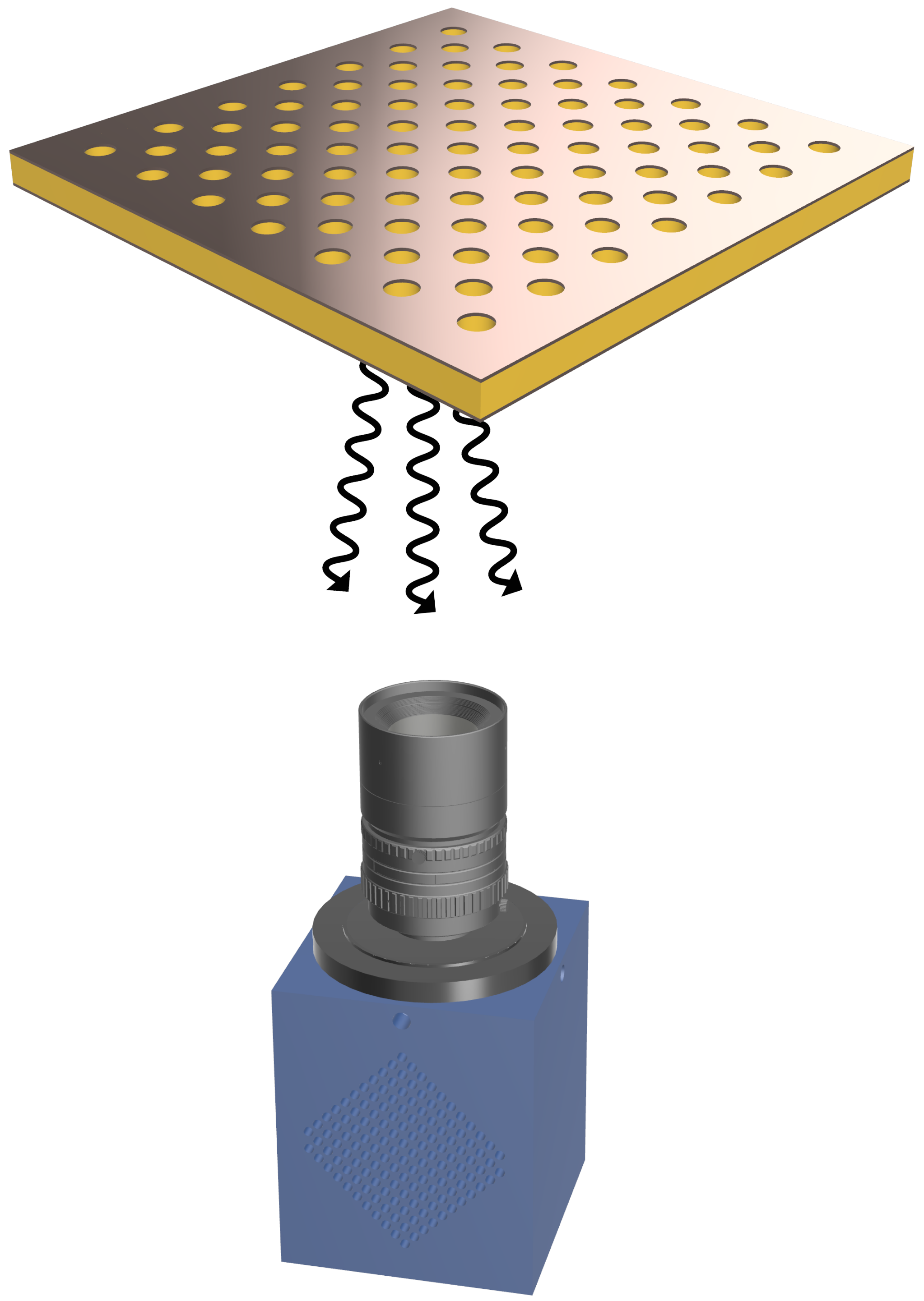
December 4, 2020 - Snowmass IF05 - MPGD topical group meeting

Optical readout of MPGDs

- Optical readout and imaging sensors

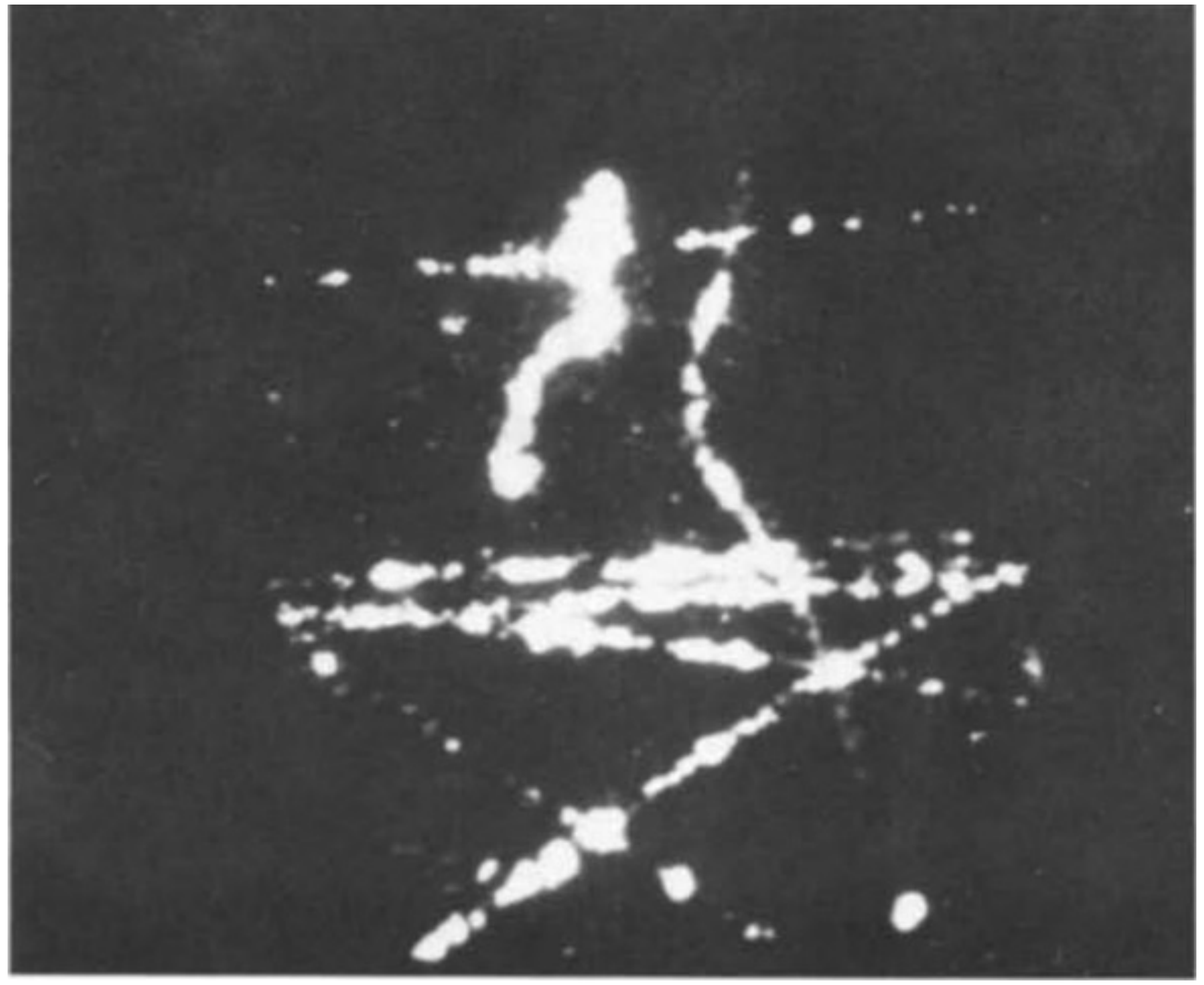
- Techniques and applications
  - Imaging
  - Track reconstruction in optical TPCs

- Perspectives for optical readout
  - SiPMs, LG-SiPMs, Timepix cameras
  - Ultra-fast CMOS sensors
  - Negative ion optical TPCs

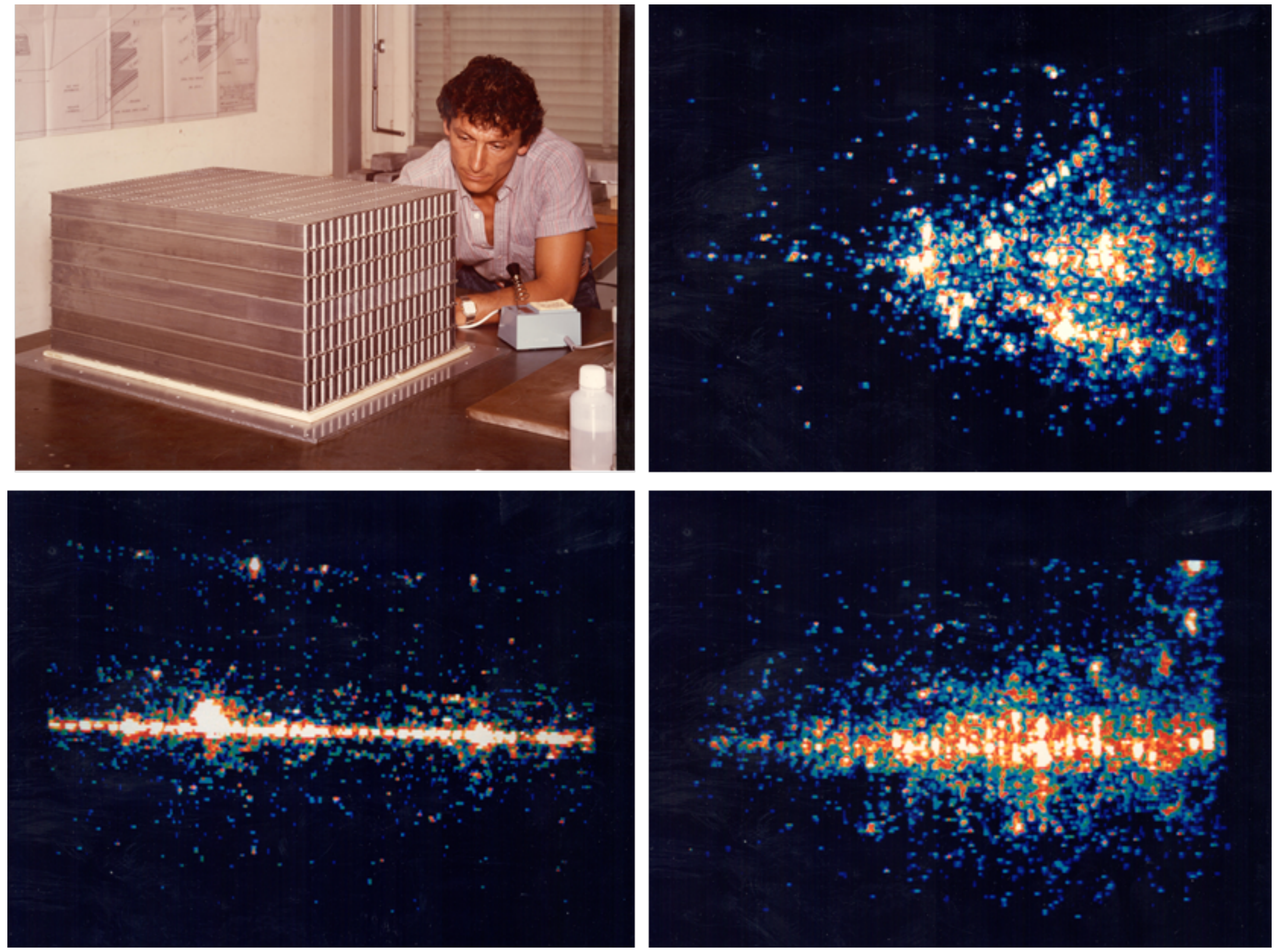


Optical readout

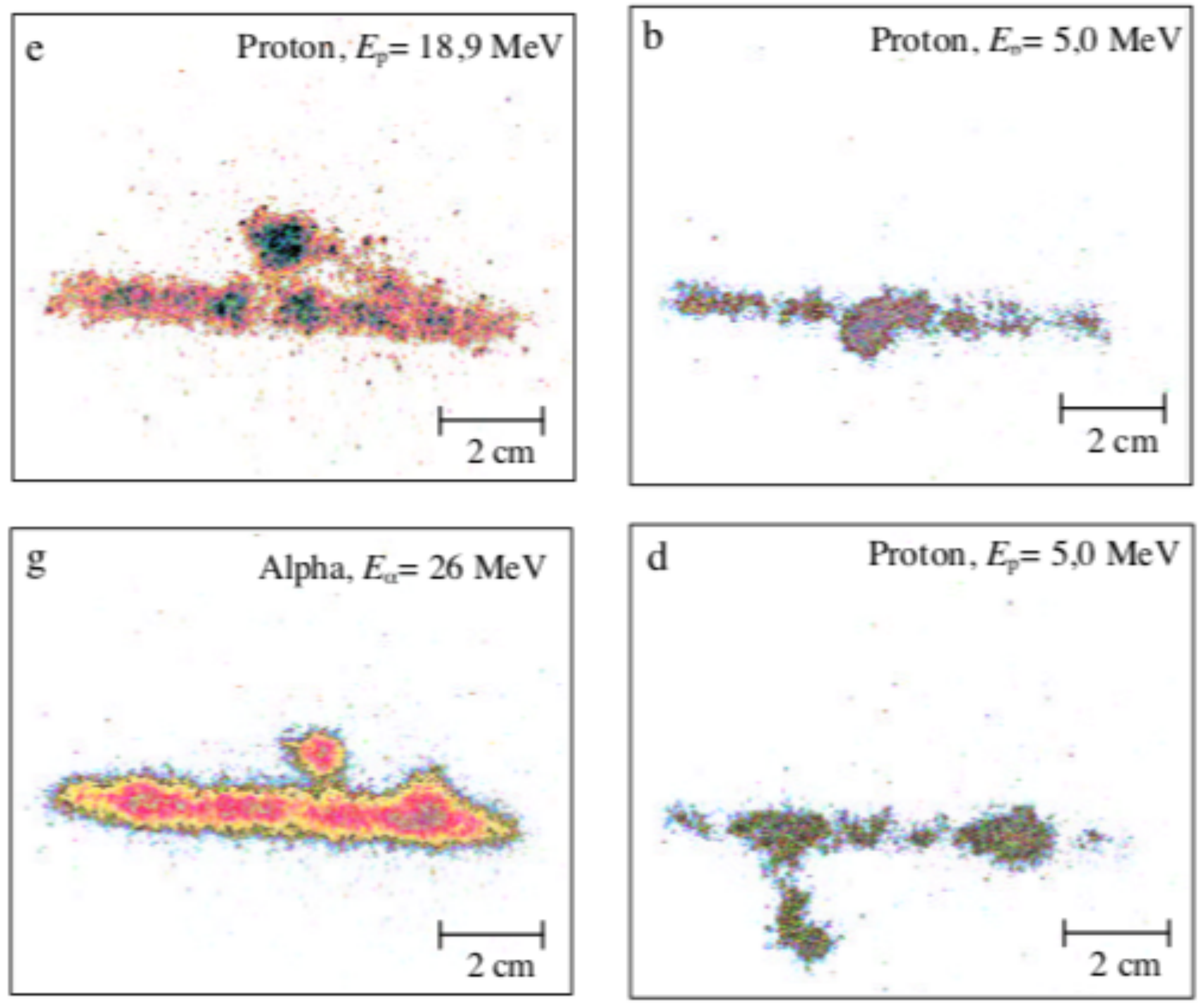
Early realisations of optical readout using TEA or wavelength shifters with parallel transparent meshes or plates show the potential of this integrated pixellated readout approach.



G.Charpak, J.P Fabre, F. Sauli, M. Suzuki and W. Dominik: **An optical proportional Continuously operating Avalanche Chamber**, NIMA258(1987)177.



Fonte P., Breskin A., Charpak G., Dominik W. & Sauli F. (1989) NIM A. 283, 3, p. 658-664. https://doi.org/10.1016/0168-9002(89)91436-8



Titt, U ; Breskin, Amos ; Chechik, R ; Dangendorf, V ; Schmidt-Böcking, H ; Schuhmacher, H, **A time projection chamber with optical readout for charged particle track structure imaging**, https://arxiv.org/pdf/physics/0410258.pdf, 2004

Optical readout of MPGDs

Recording **secondary scintillation** light emitted during electron avalanche multiplication in MPGDs.

High-granularity **pixelated readout** with state-of the art cameras offers high-spatial resolution and low noise specifications.

MPGDs allow for **high gain factors** and fine position resolution.

+

- High-granularity pixel readout
- Insensitive to electronic noise
- Intuitive integrated imaging
- Adaptable view with mirrors/optics

-

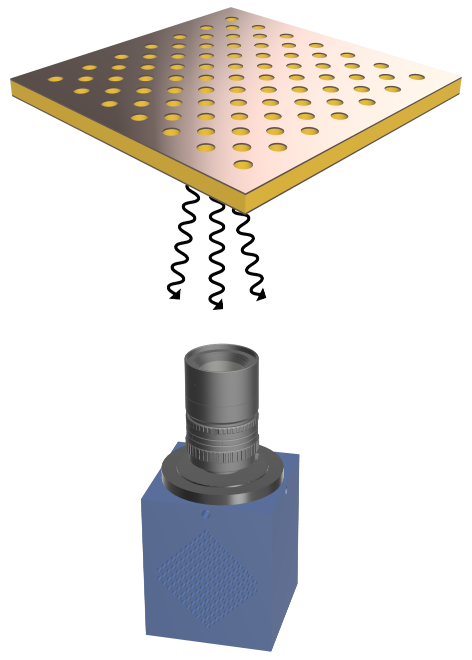
- Low frame rate capabilities
- High gain required
- Needs suitable gases or WL shifters
- Radiation hardness of image sensors

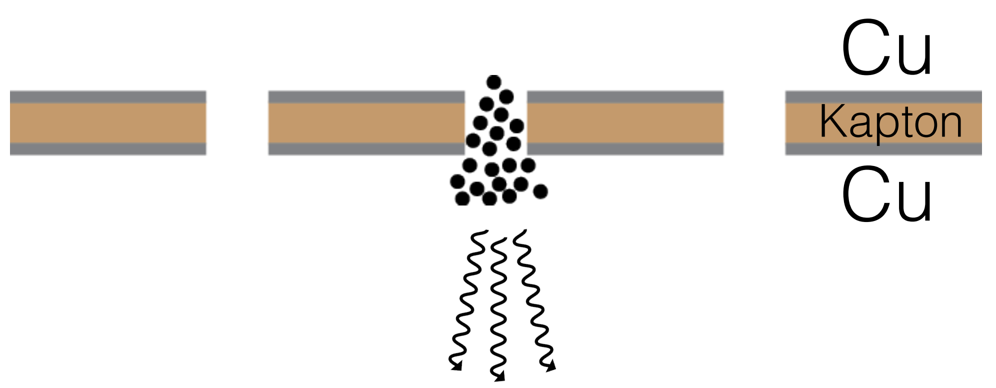
Optical readout of MPGDs

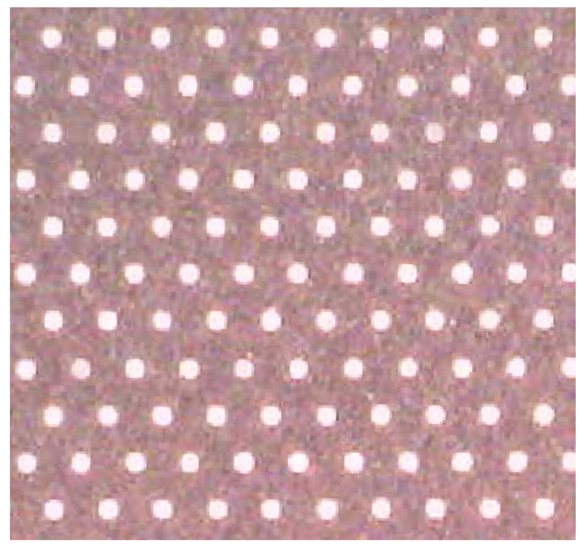
GEM / THGEM / GlassGEM

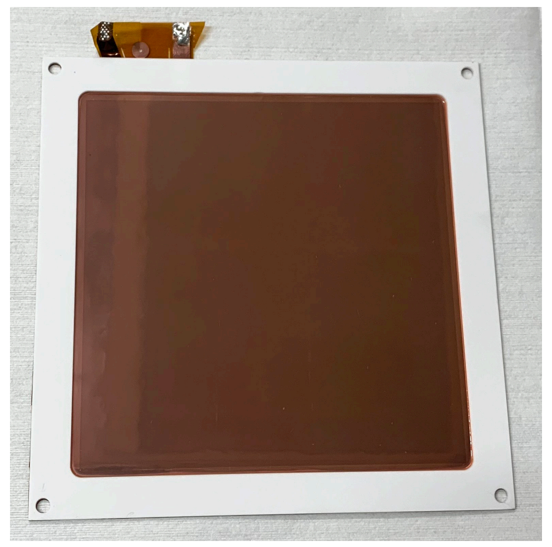
Open structure permitting light emitted during amplification in the GEM holes to be recorded by camera placed below.

High gains available with multi-GEM stacks.

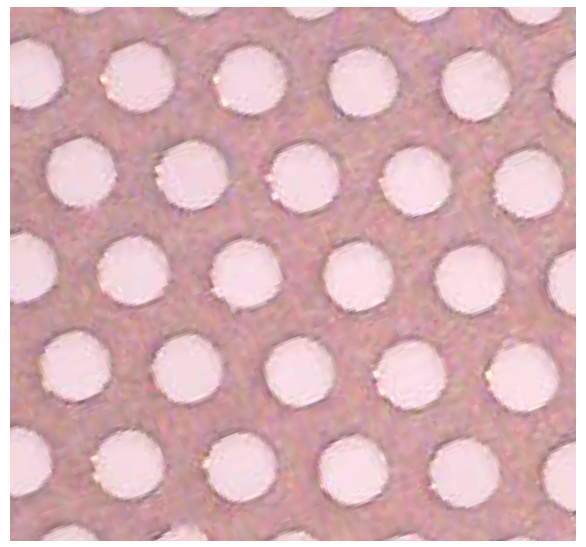








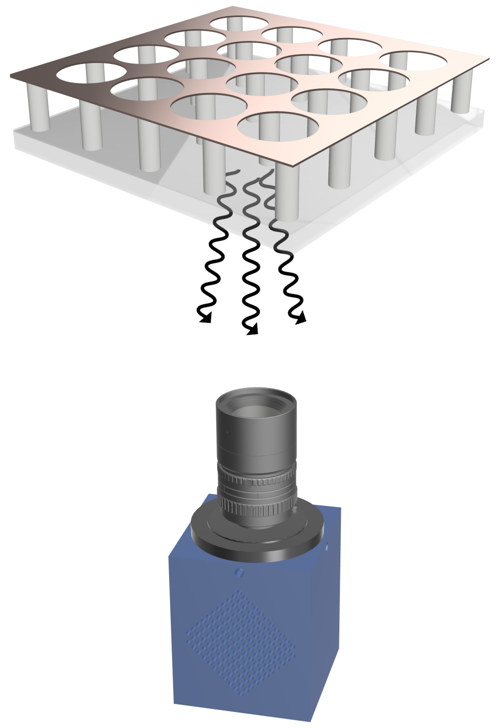
Thin GEM
70μm diameter holes
140μm pitch
50μm thick Kapton

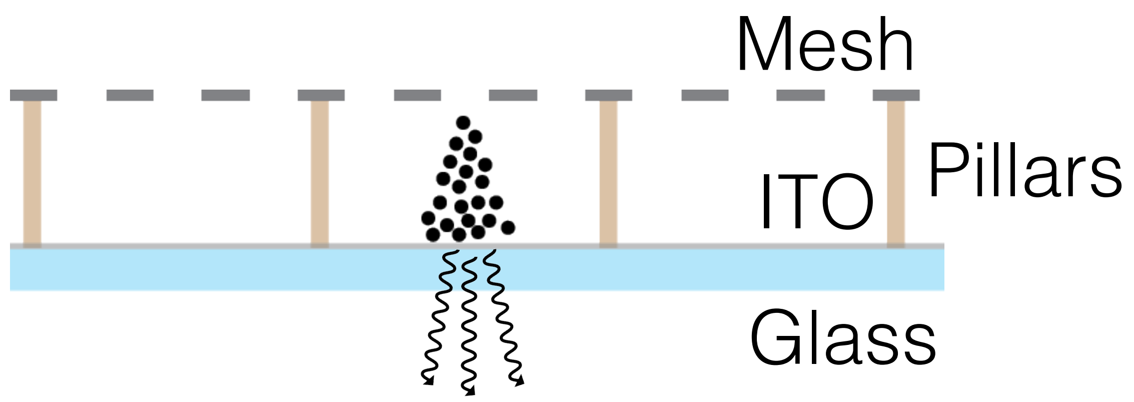


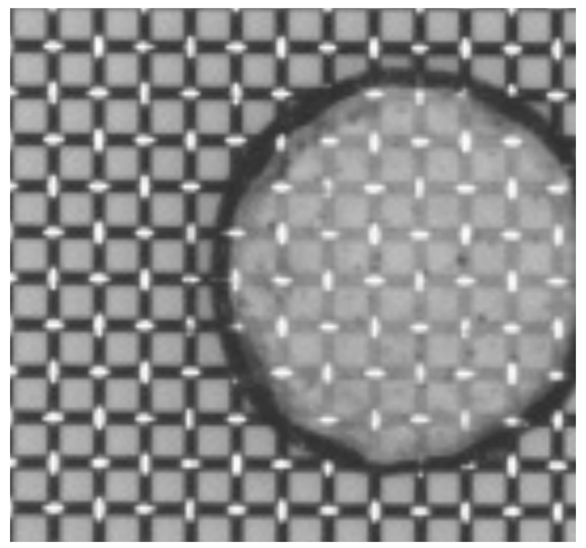
Glass GEM
160-180μm diameter holes
280μm pitch
570μm thick glass

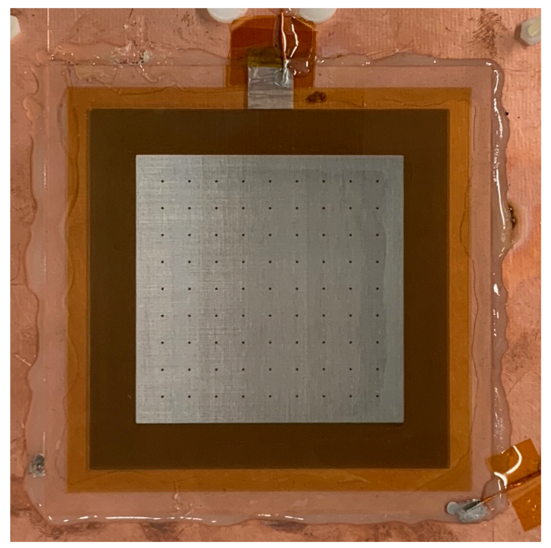
Glass Micromegas

Transparent substrate required to see light produced in amplification gap between mesh and anode. ITO-coated glass for conductive & transparent substrate.









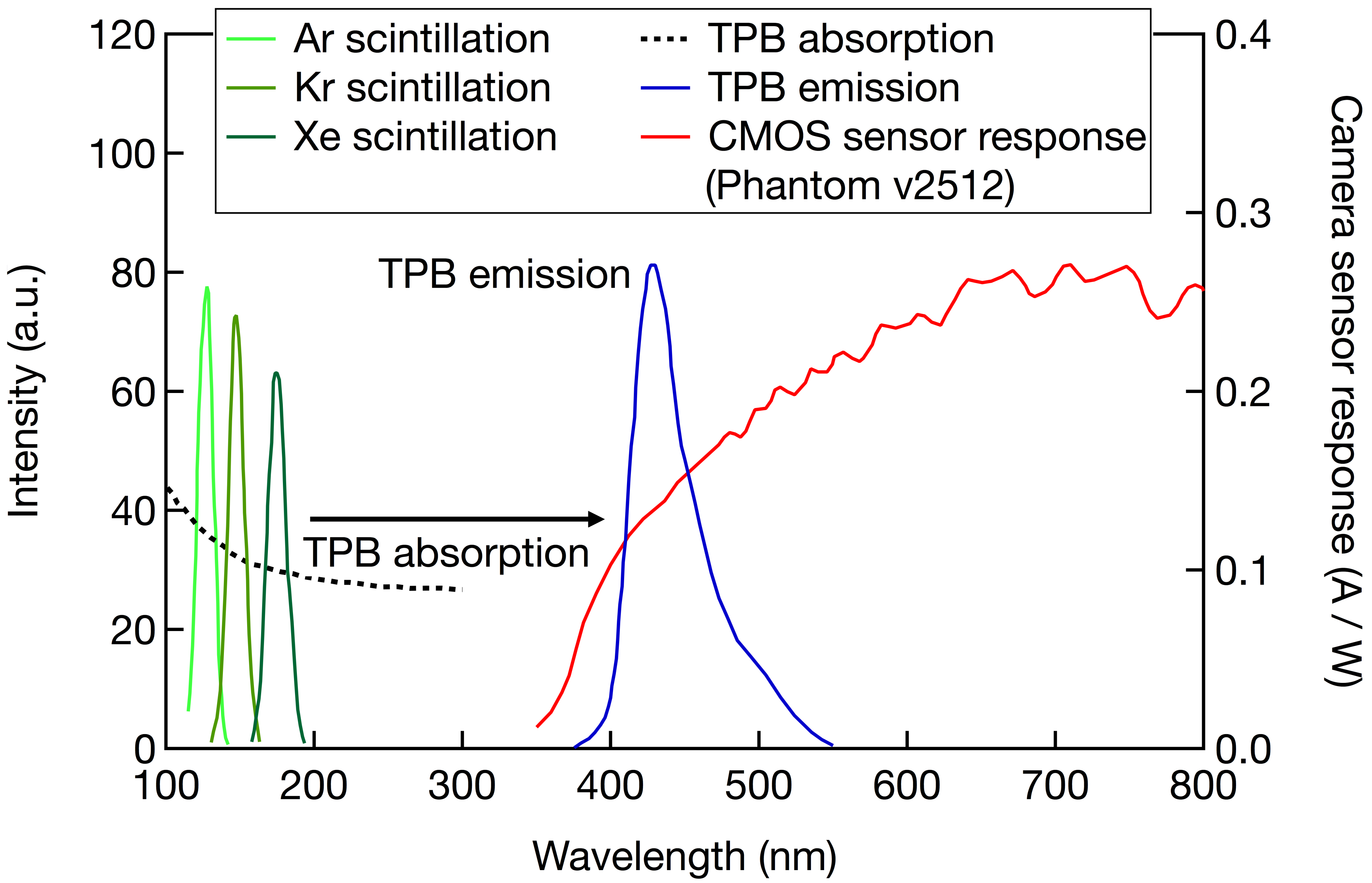
Bulk Micromegas
18/45 mesh
128μm thick amplification region

Optical readout of MPGDs

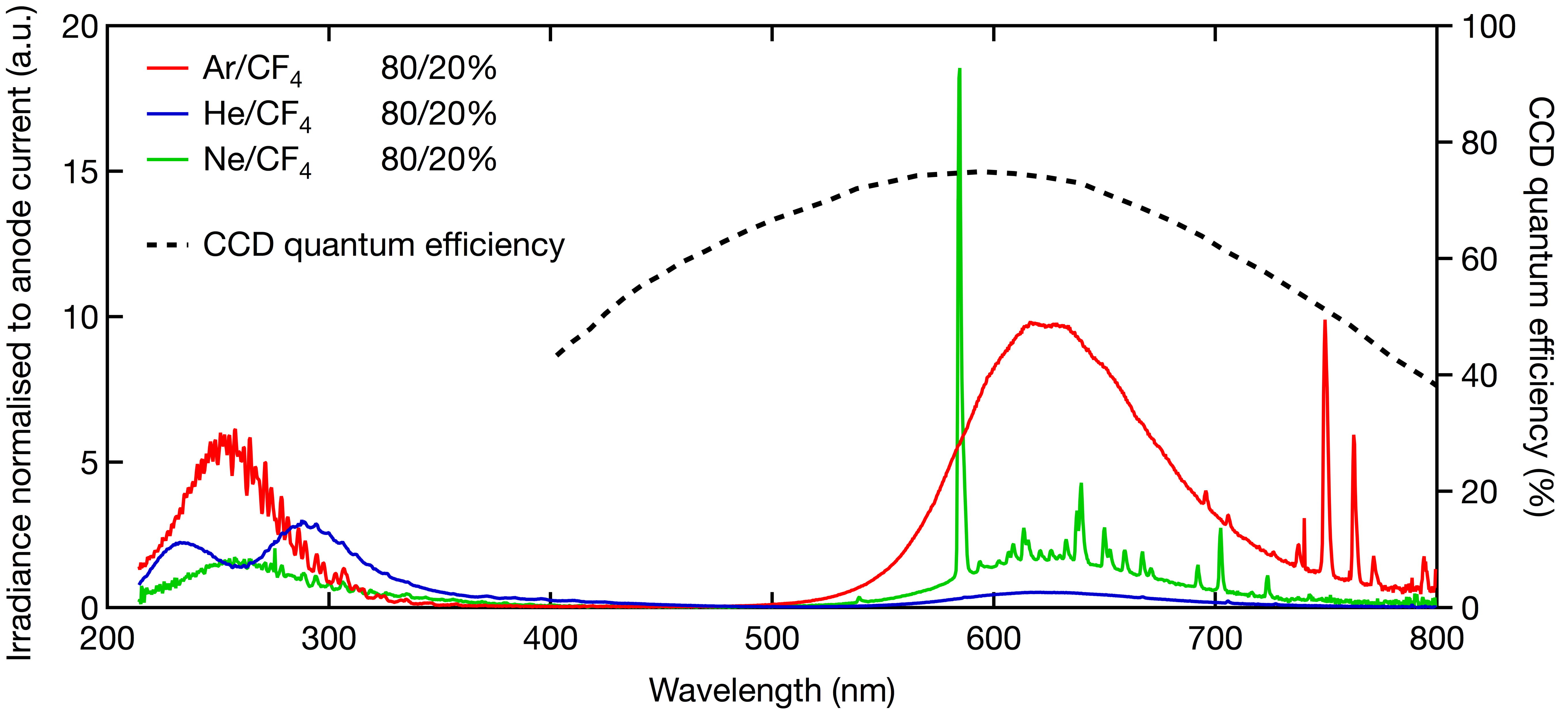
Secondary scintillation light spectrum must match the quantum efficiency of imaging sensors.

Using either (solid / gaseous) **wavelength shifters** or **CF_4**-based mixtures.

Wavelength shifting



Ar/He/Ne + CF_4



Optical readout cameras

Increasing sensitivity →

Ultra-fast CMOS cameras →

QImaging Retiga R6

- 6 MP **CCD** sensor
- 4.54µm x 4.54µm pixel size
- 7 Hz frame rate (6 MP)
- 5.7 e- read noise
- 75% QE

Hamamatsu ORCA-Fusion CMOS camera

- 5.3 MP **CMOS** sensor
- 6.5 µm x 6.5 µm pixels size
- 100 Hz frame rate
- 0.7 e- read noise
- 80% QE

Hamamatsu ImagEM X2-1K EMCCD camera

- 1 MP **EMCCD** sensor
- 16 µm x 16 µm pixels size
- 18.5 fps at 1024x1024
- **1200x EM gain**
- <1 e- readout noise
- >90% QE

Photron FASTCAM SA-Z

- 1 MP **CMOS** sensor
- 20 µm x 20 µm pixels size
- 20 kfps at 1024x1024
- **2.1 Mfps** at 128x8
- ISO 50,000 sensitivity
- 46% QE

Phantom v2512

- 1 megapixel **CMOS** sensor
- 28 µm x 28 µm pixels size
- 25 kfps at 1280 x 800
- **1 Mfps** at 128x32
- ISO 100,000 sensitivity
- 50% QE

Developments and applications

Imaging

Radiation event imaging

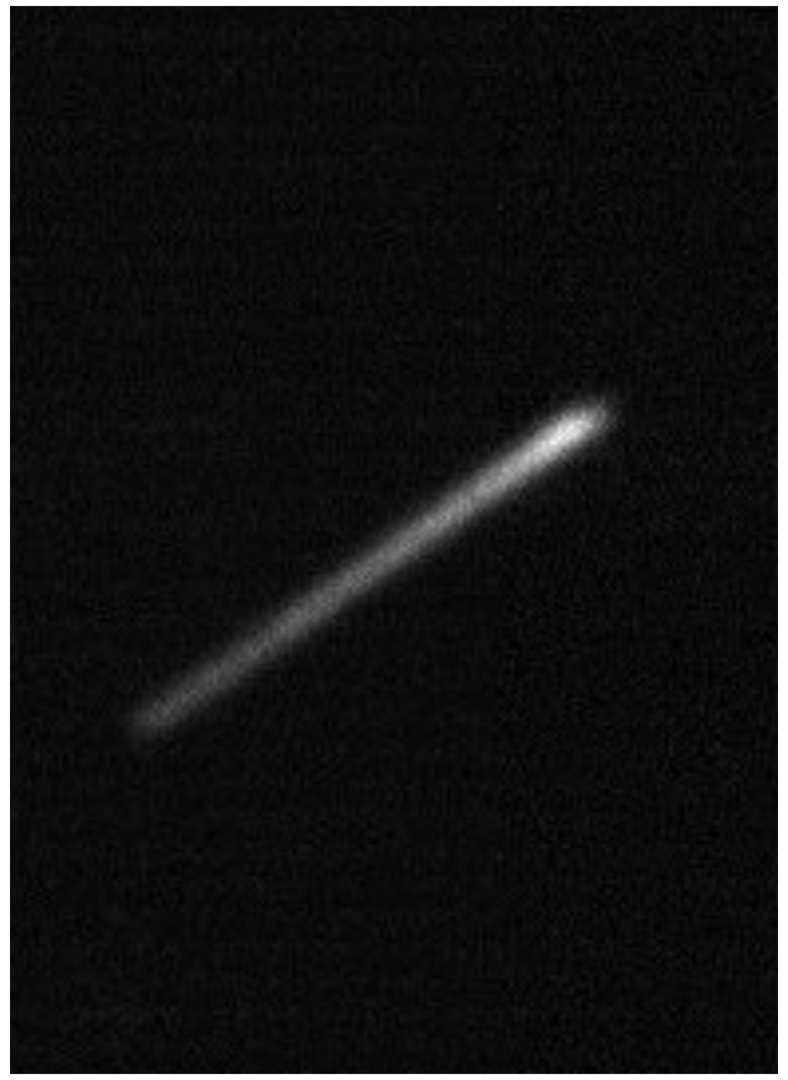
Images permit identification of individual interactions in active volume.

Track topology for head-tail determination. Pixel values and light density reflect **energy loss** along tracks.

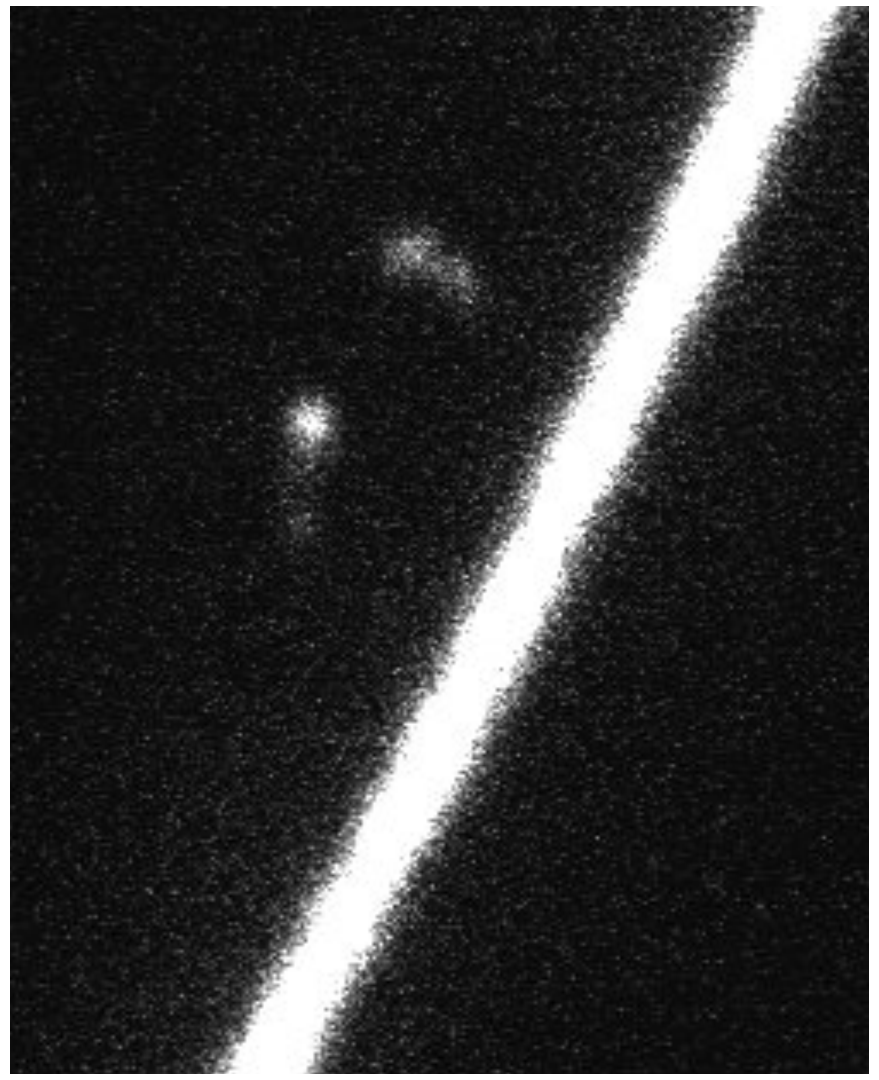
Combination of topology and density for event **classification**.

X-ray photons

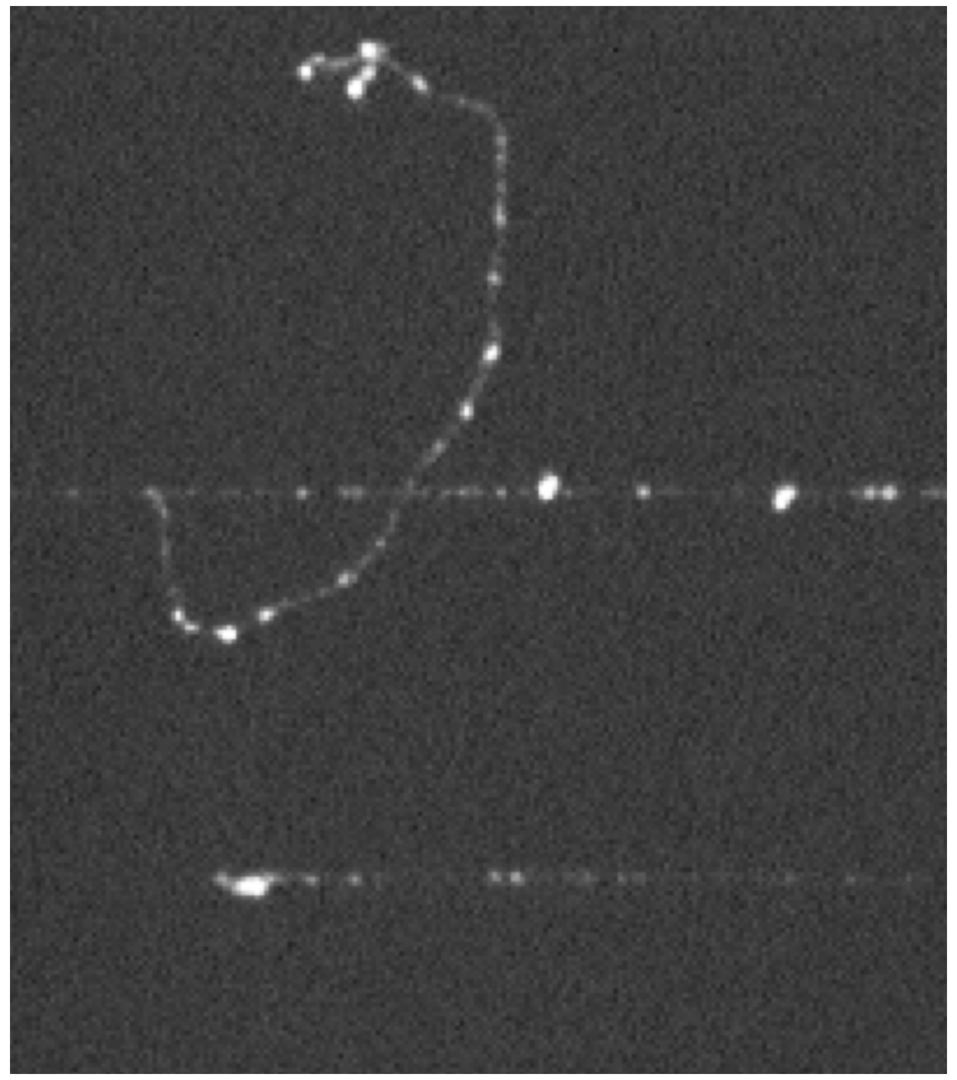
Alpha track



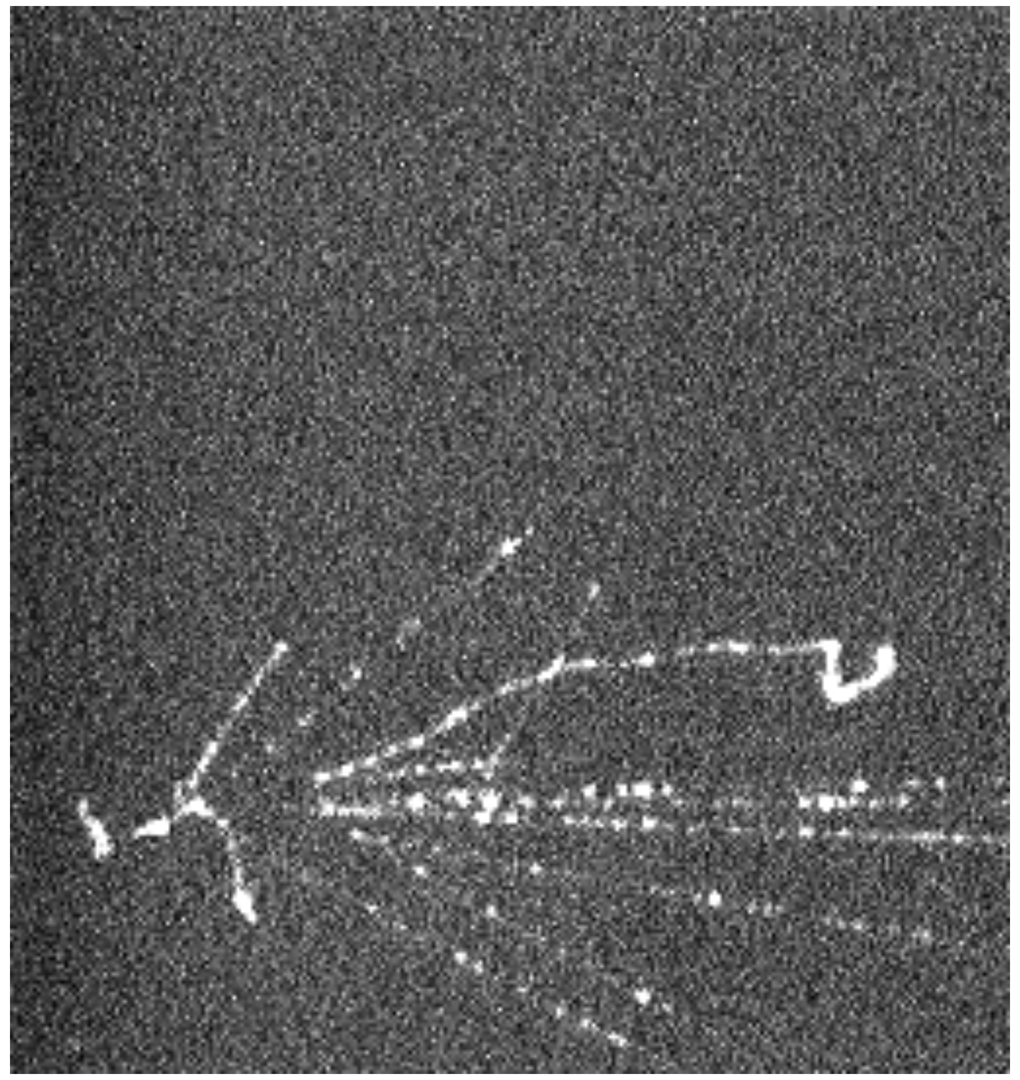
^{55}Fe X-rays & alpha at 50mbar



Muon tracks with δ-ray



Hadronic shower

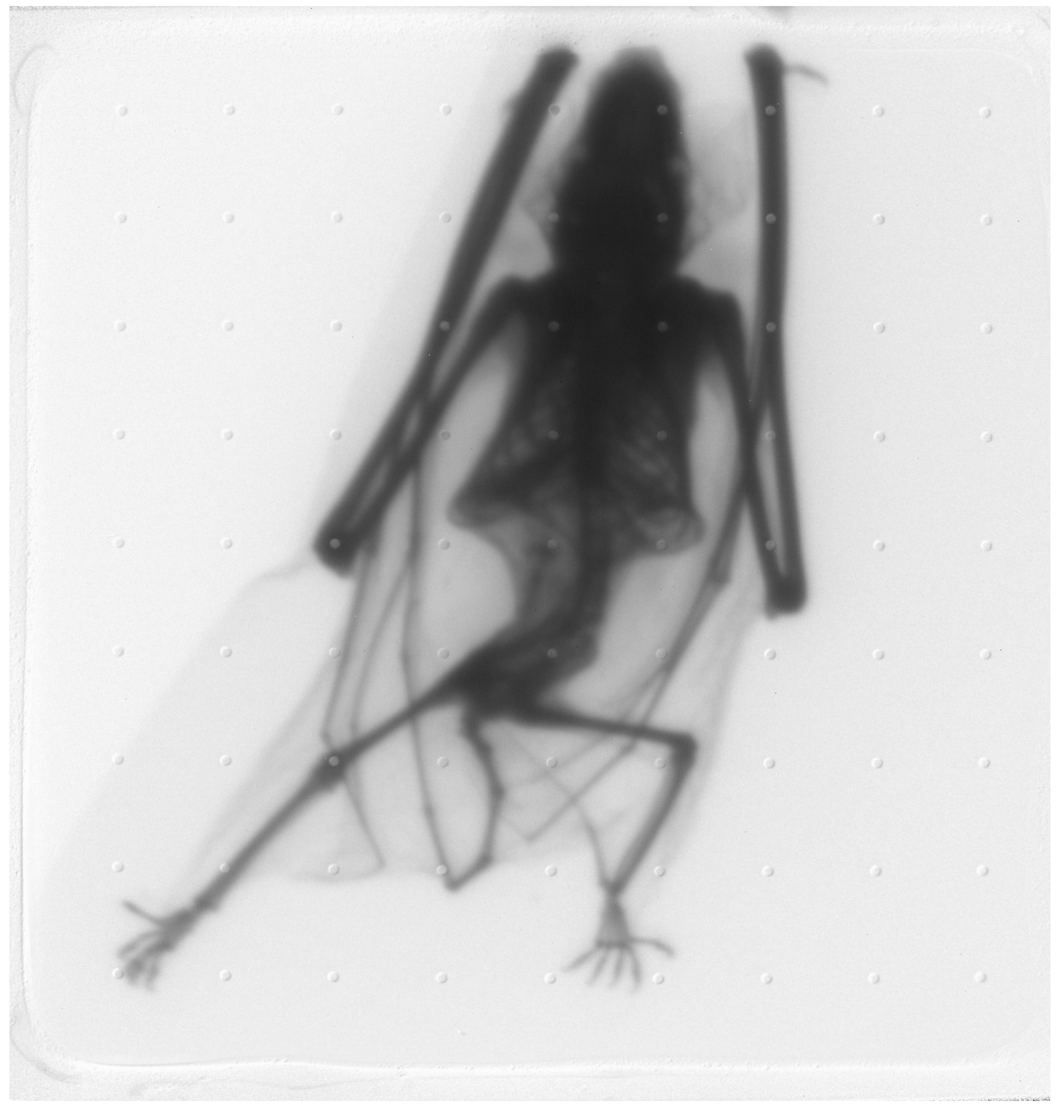


Radiography

Integrated imaging approach collects all light within exposure time **without deadtime**.
Image immediately available without need for reconstruction.

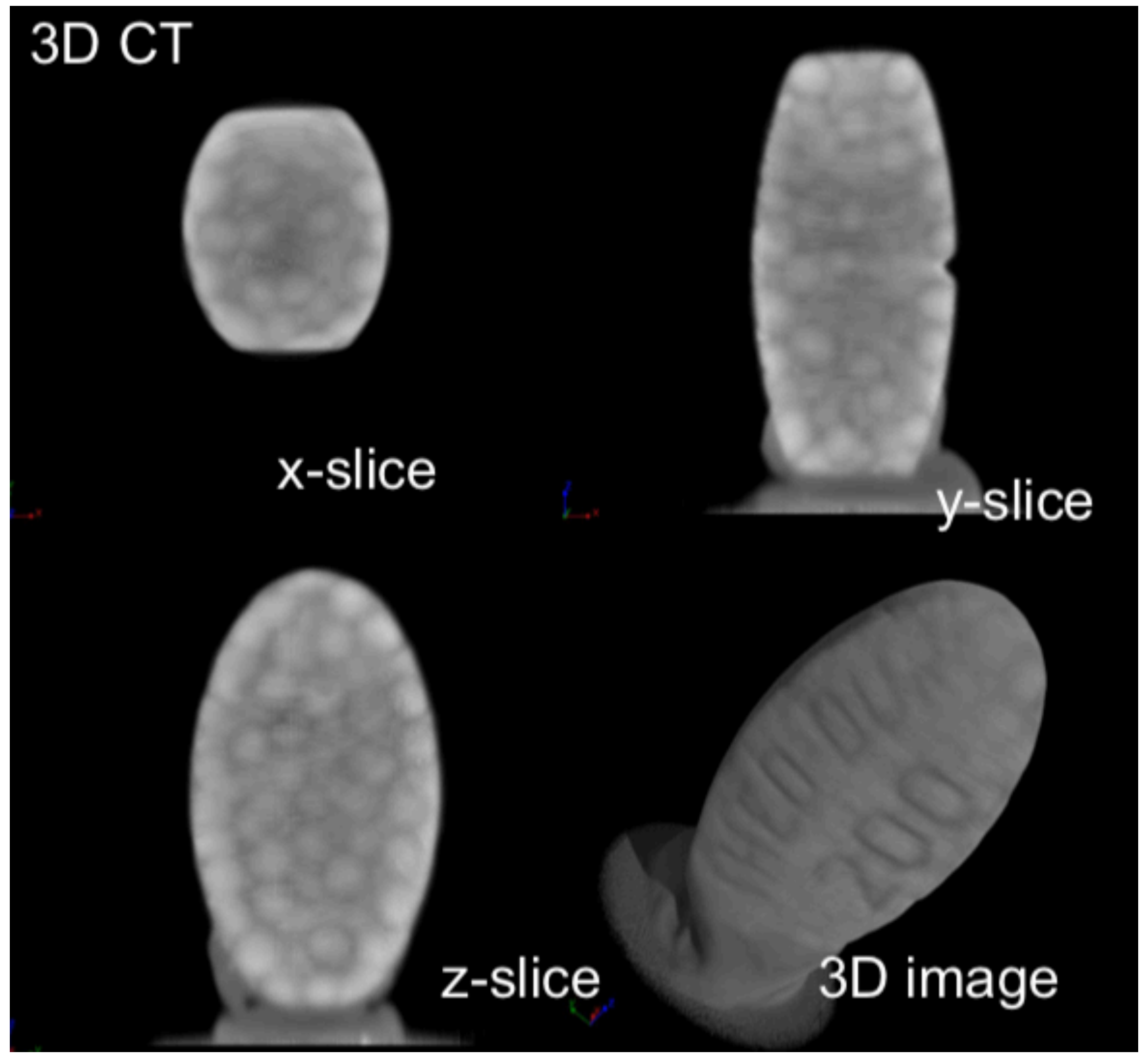
Tunable magnification with lenses to cover large detector areas.

X-ray radiography
(Glass Micromegas)

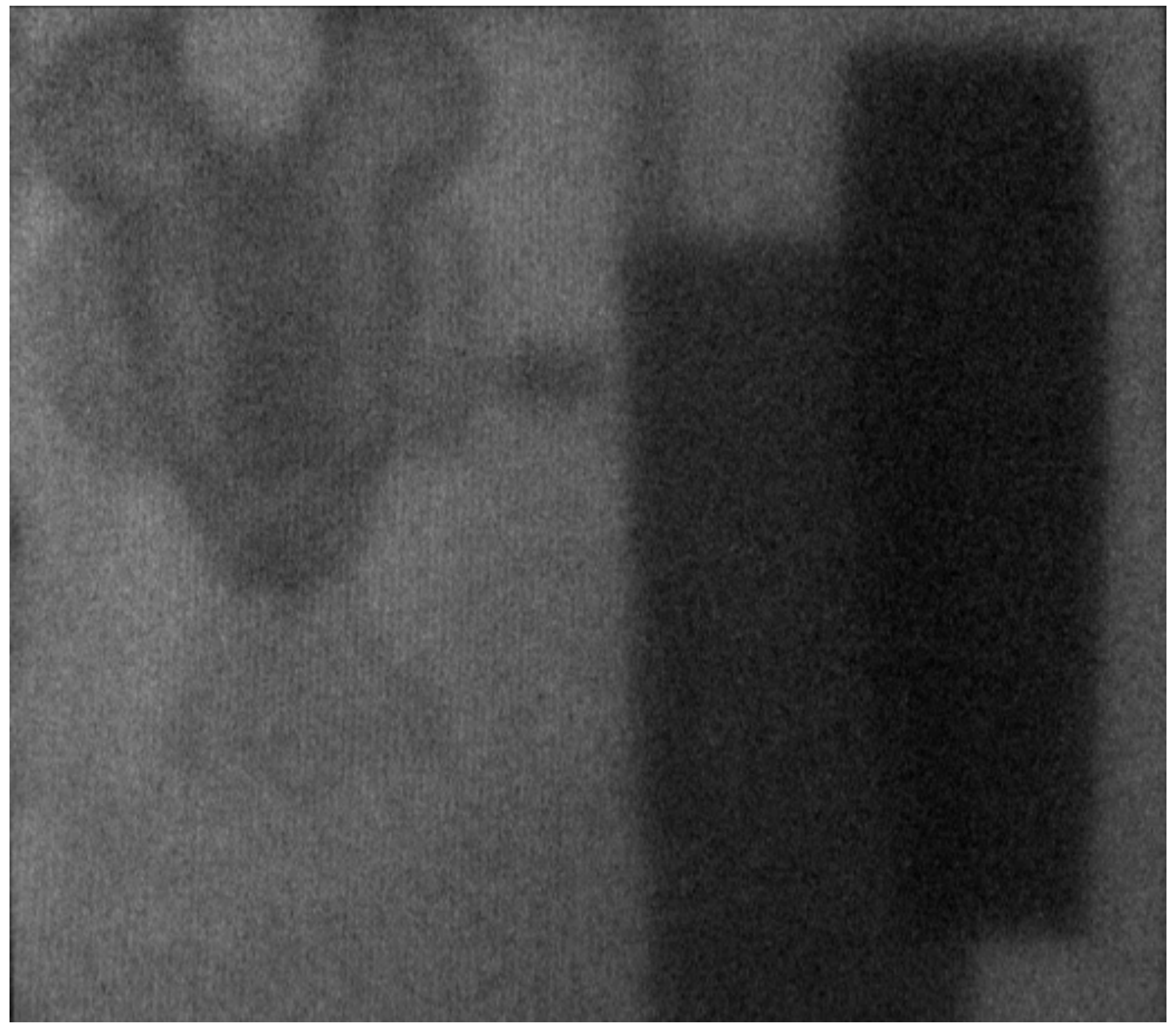


X-ray radiography
(Glass GEM)

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



Neutron imaging
(with B-10 converter)



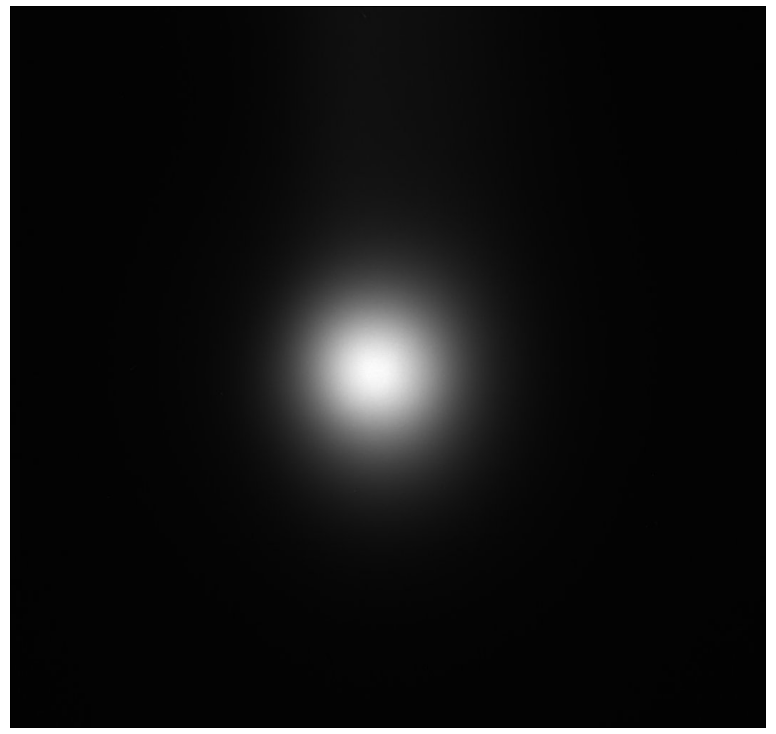
F. Brunbauer et al., Radiation imaging with glass Micromegas, https://doi.org/10.1016/j.nima.2019.163320

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

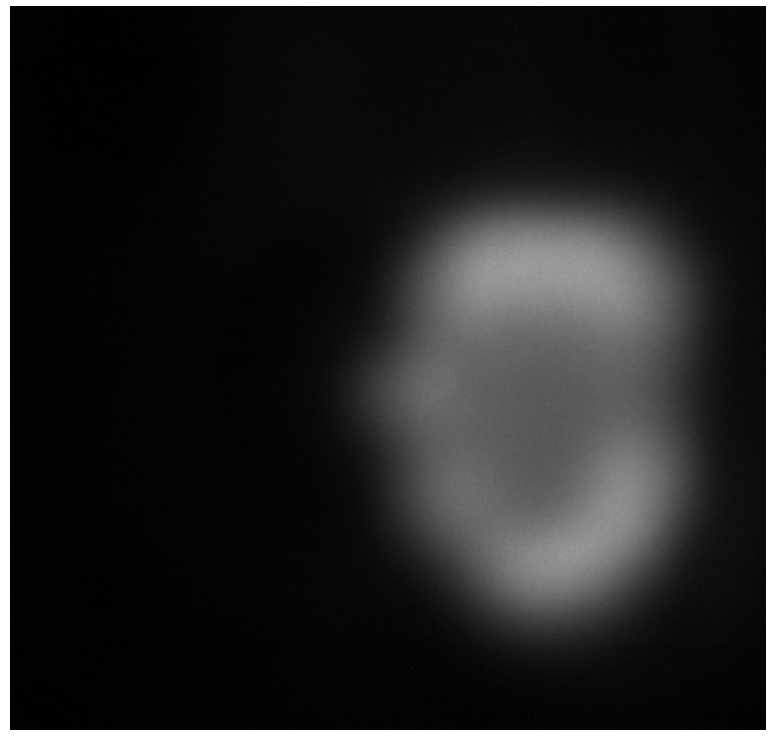
Dose imaging

2D distribution of **deposited dose** and **clinical proton beam** profiles can be recorded with optically read out GEM.

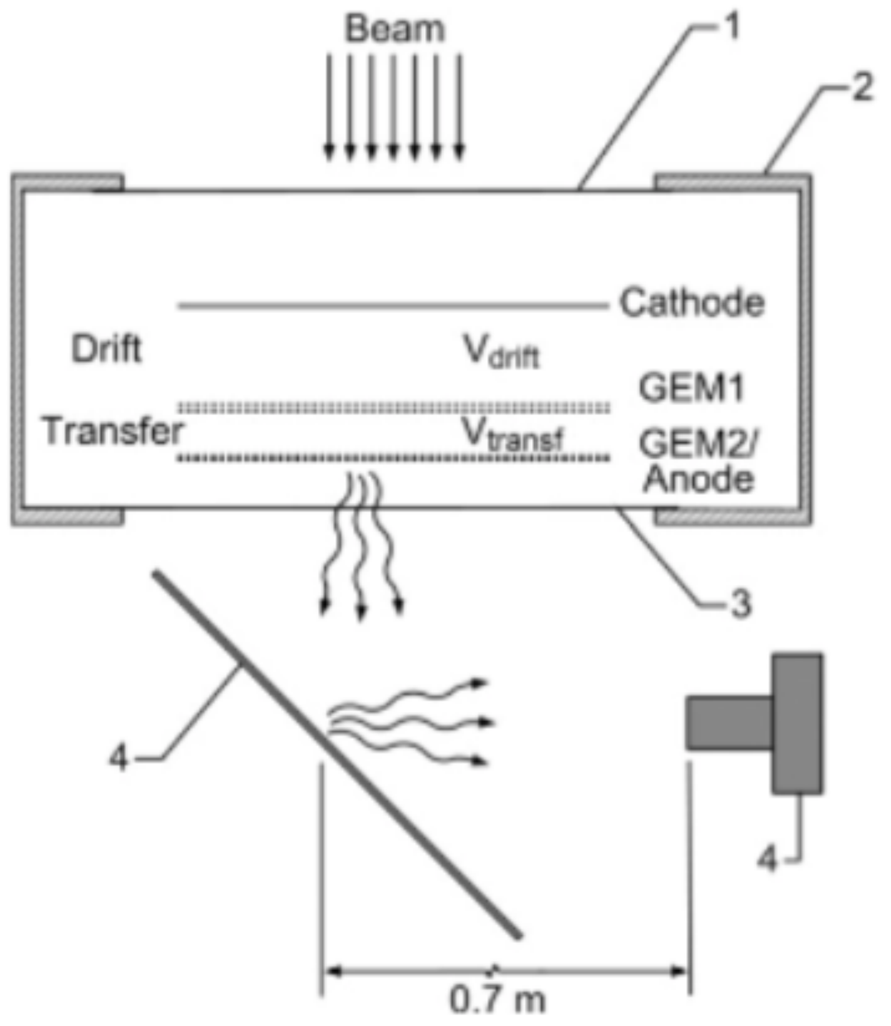
By coupling scintillation light to camera with mirror and using thin foil windows, beams can be monitored with **minimal attenuation** and low multiple scattering (low material budget beam monitor).

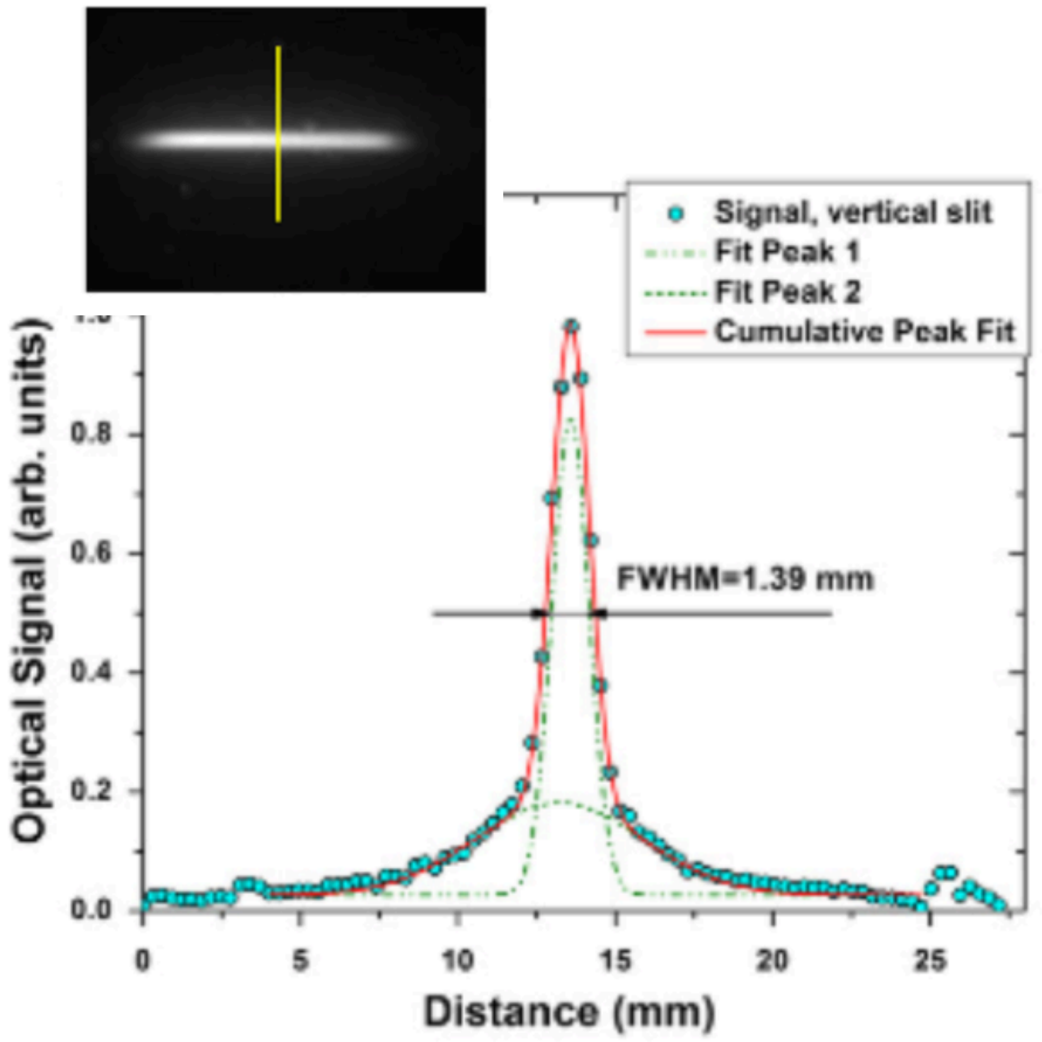


200 MeV pencil beam

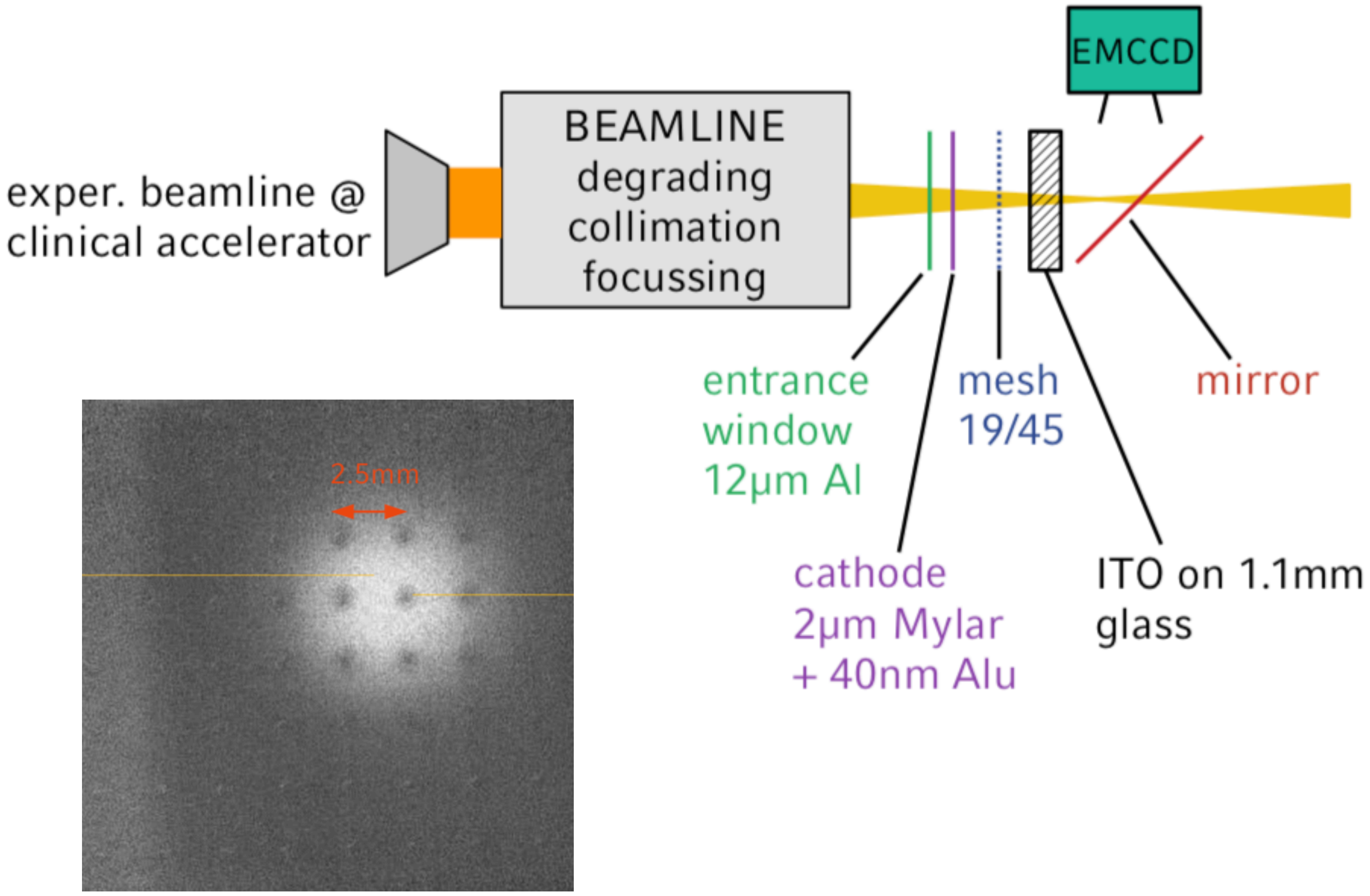


Treatment plan slice





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

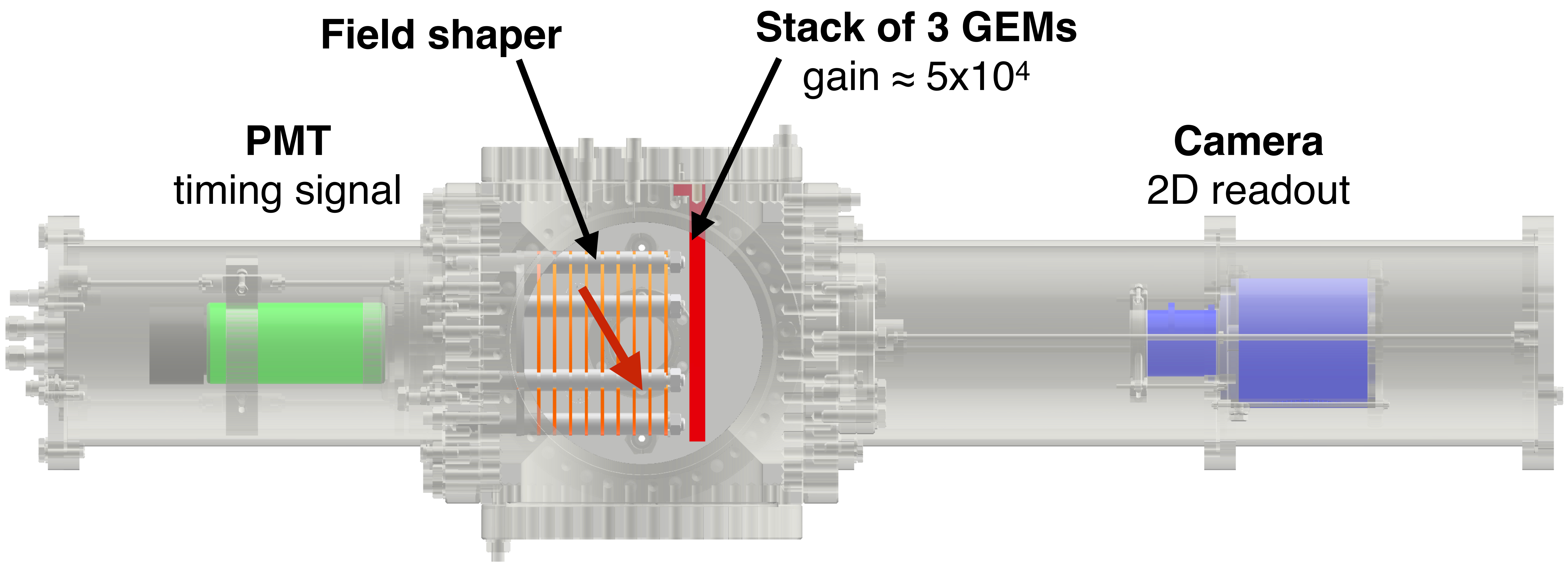


Jona Bortfeldt. RD51 Collaboration Meeting October 2020, https://indico.cern.ch/event/889369/contributions/4042751/attachments/2119709/3567276/bortfeldt_201009.pdf

Developments and applications

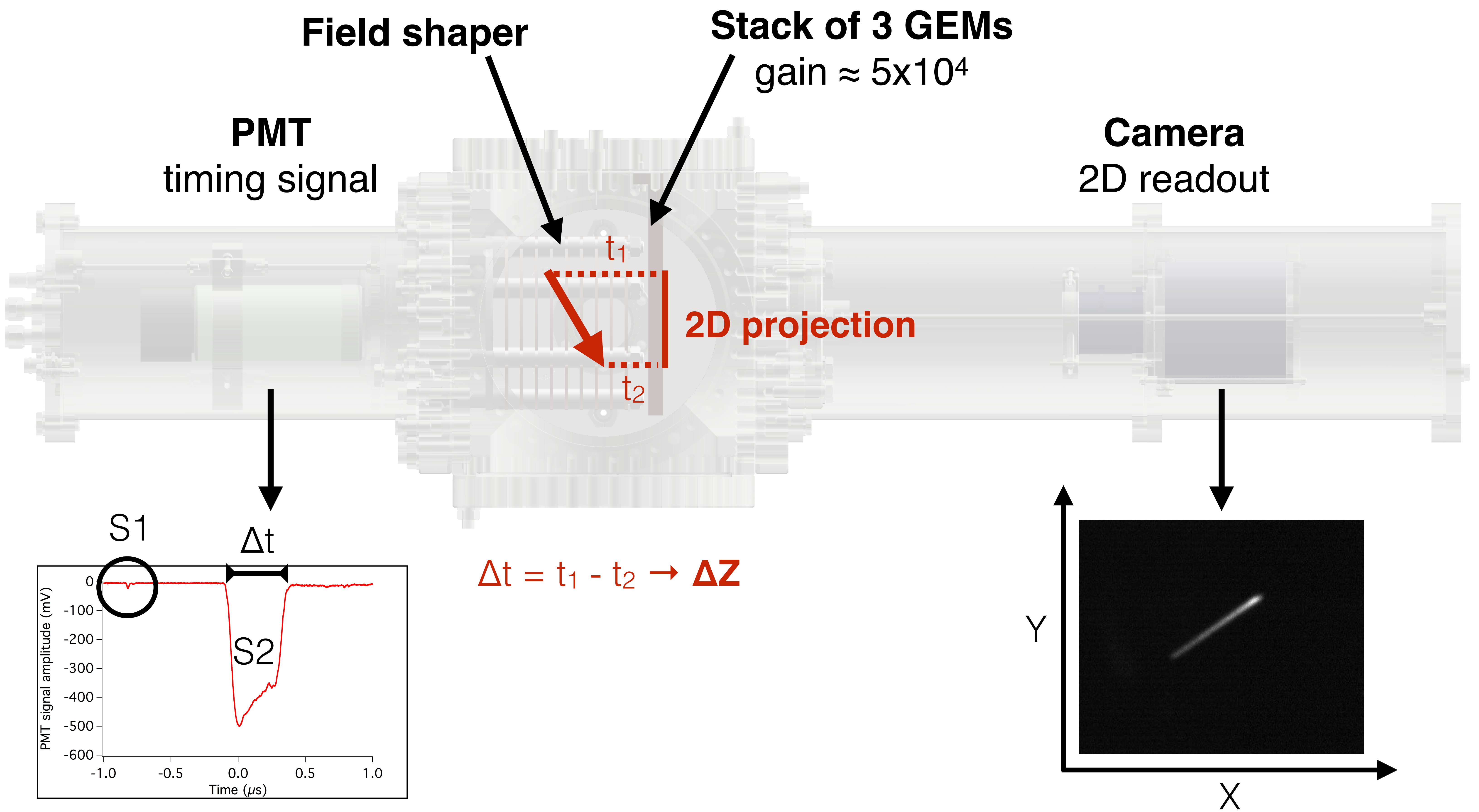
Track reconstruction in optical TPCs

Optically read out TPC Camera + PMT



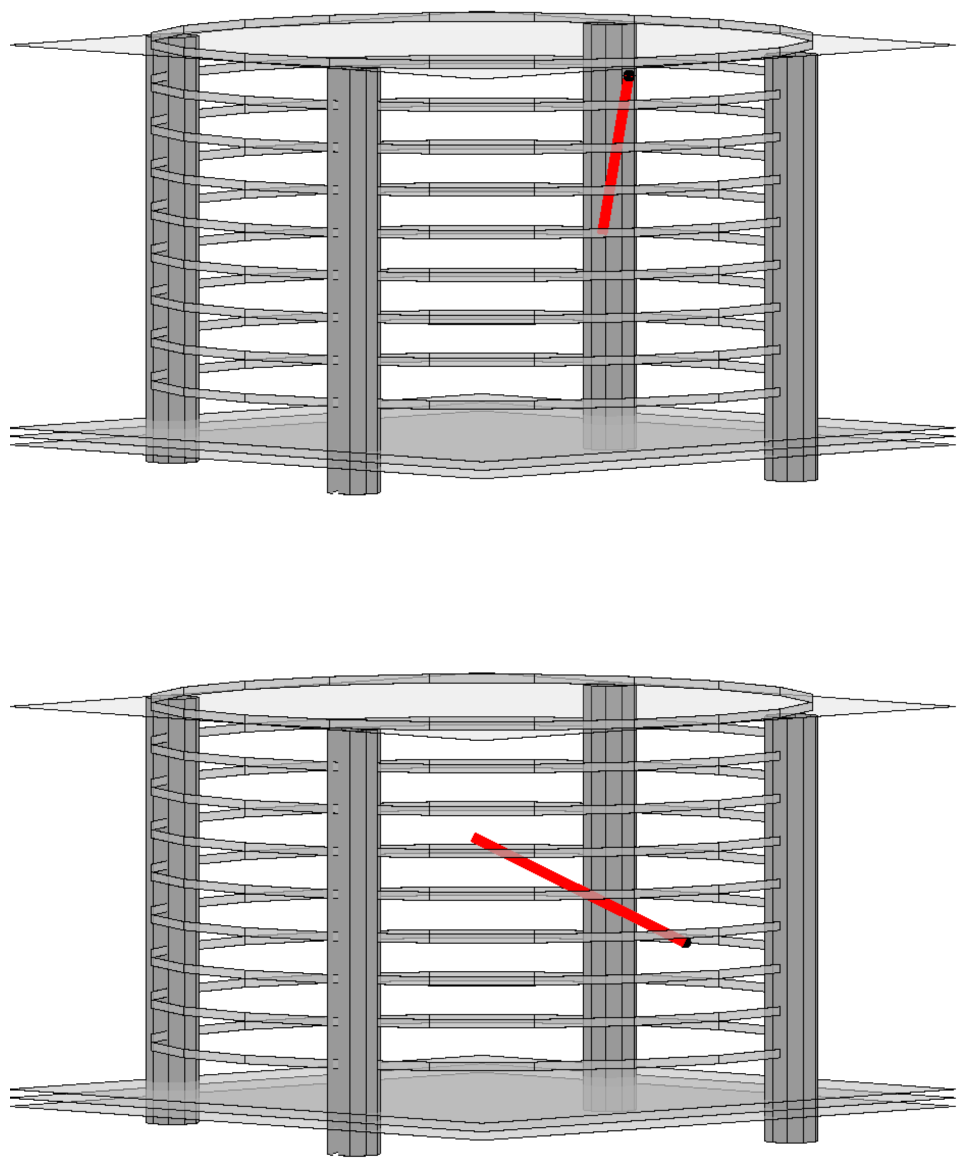
Schematics not drawn to scale

Optically read out TPC Camera + PMT



Primary scintillation **S1** for **fiducialization**

High granularity 2D projection

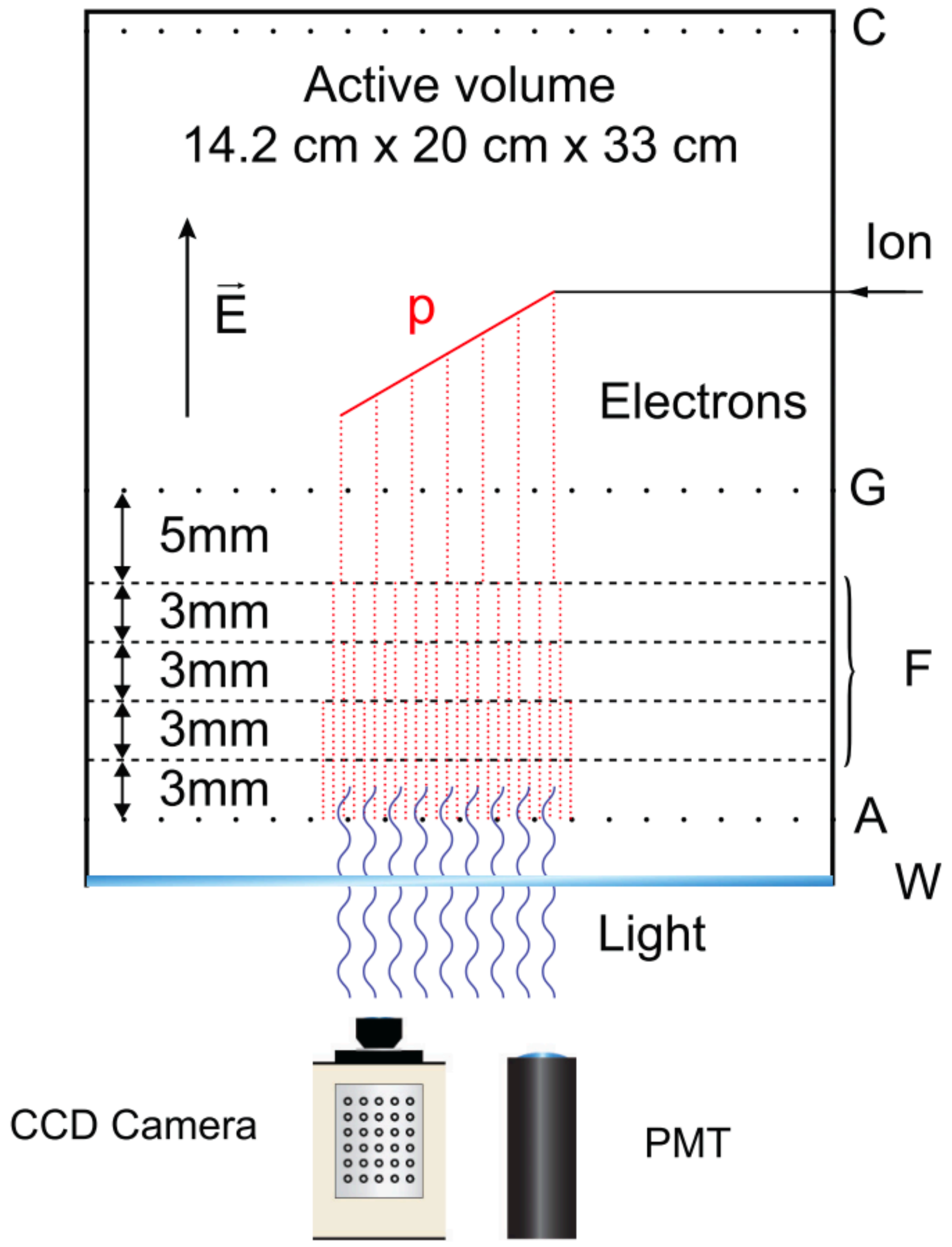


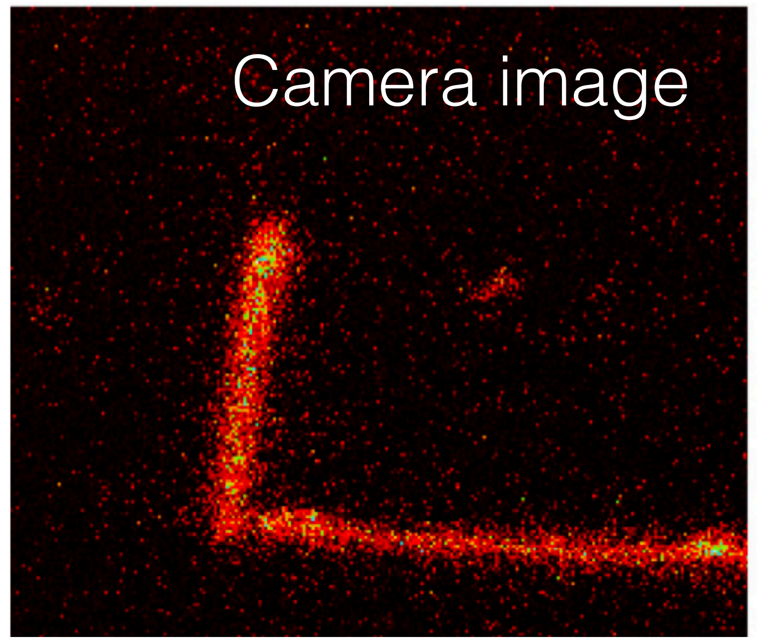
Schematics not drawn to scale

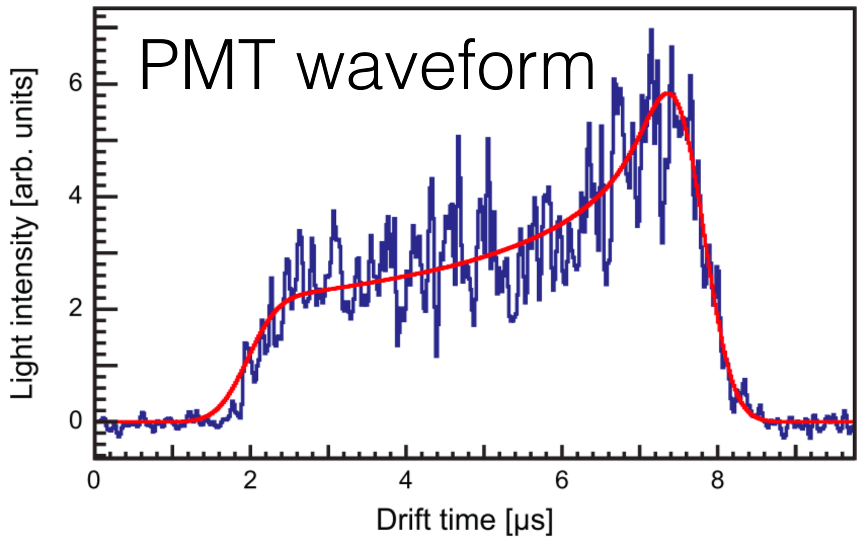
Optically read out TPC Camera + PMT

Decay spectroscopy of ^{48}Ni, ^{46}Fe and ^{44}Cr and instrumental in discovery of β-delayed three-proton (β3p) emission in the case of ^{45}Fe and ^{45}Cr.
Clean **reconstruction** and identification of events with **strong suppression of β background**.

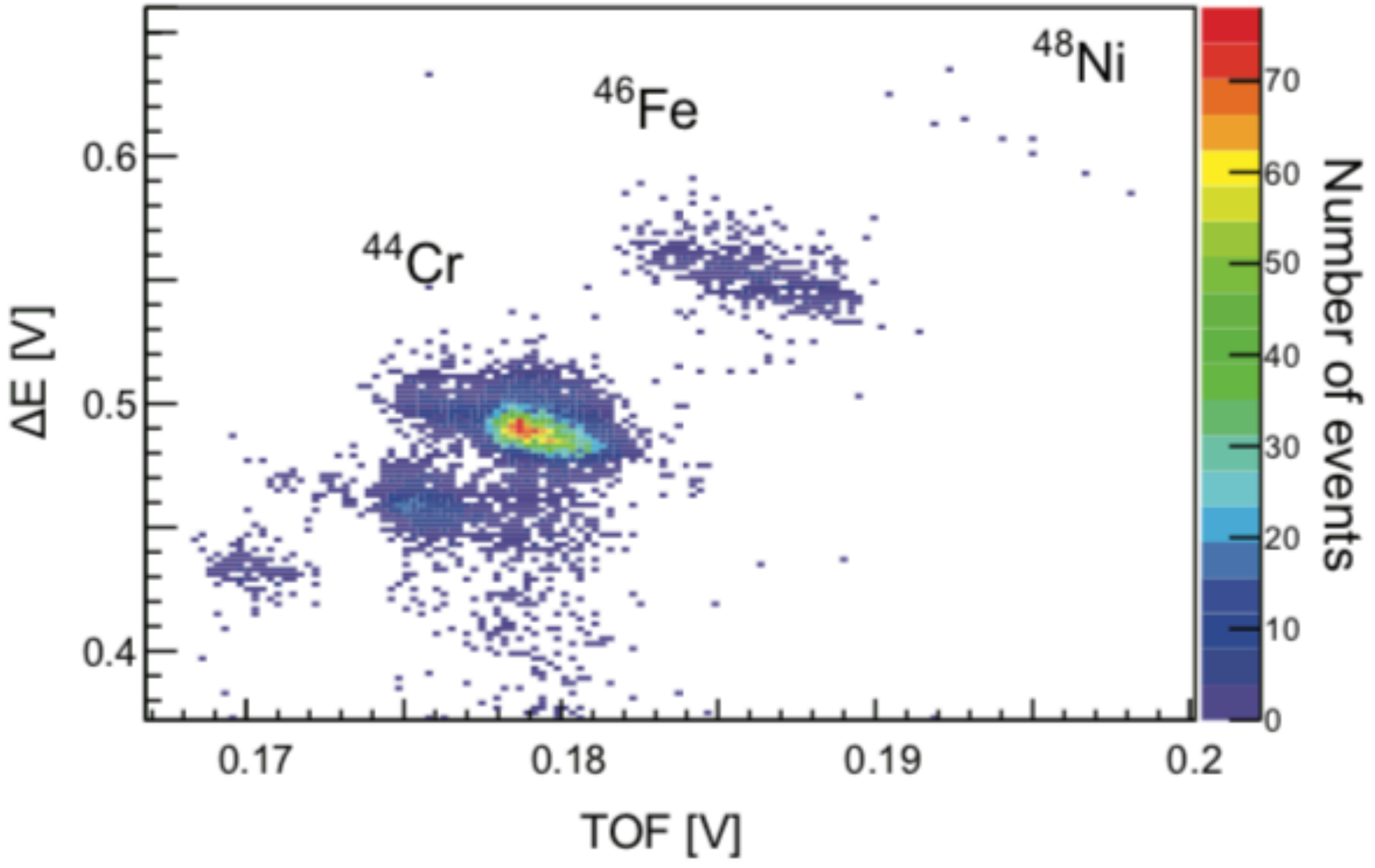
Optical TPM based on quad-GEM







Identification spectrum displaying ions under study

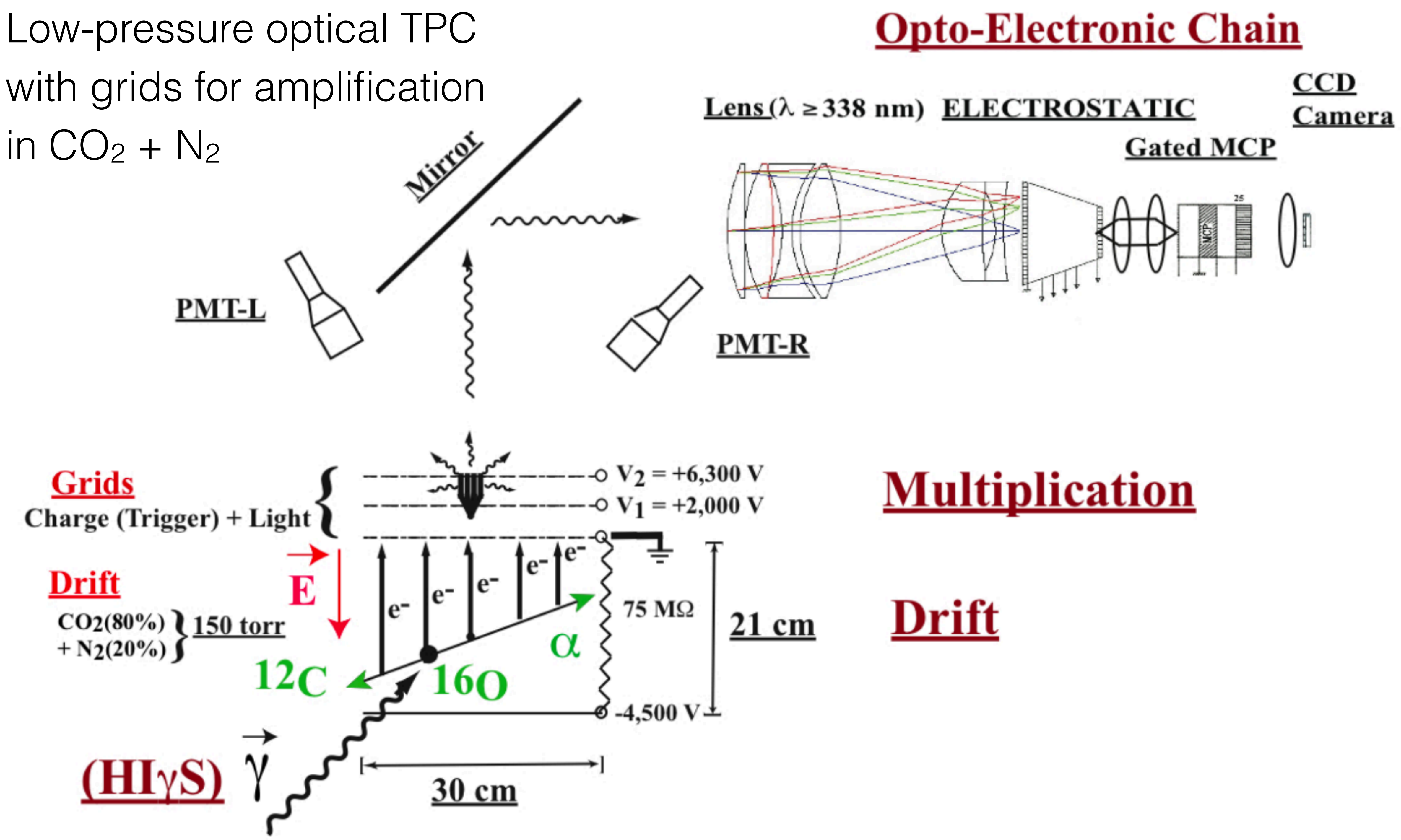


M. Pomorski et al. DOI: 10.1103/PhysRevC.90.014311 https://journals.aps.org/prc/pdf/10.1103/PhysRevC.90.014311

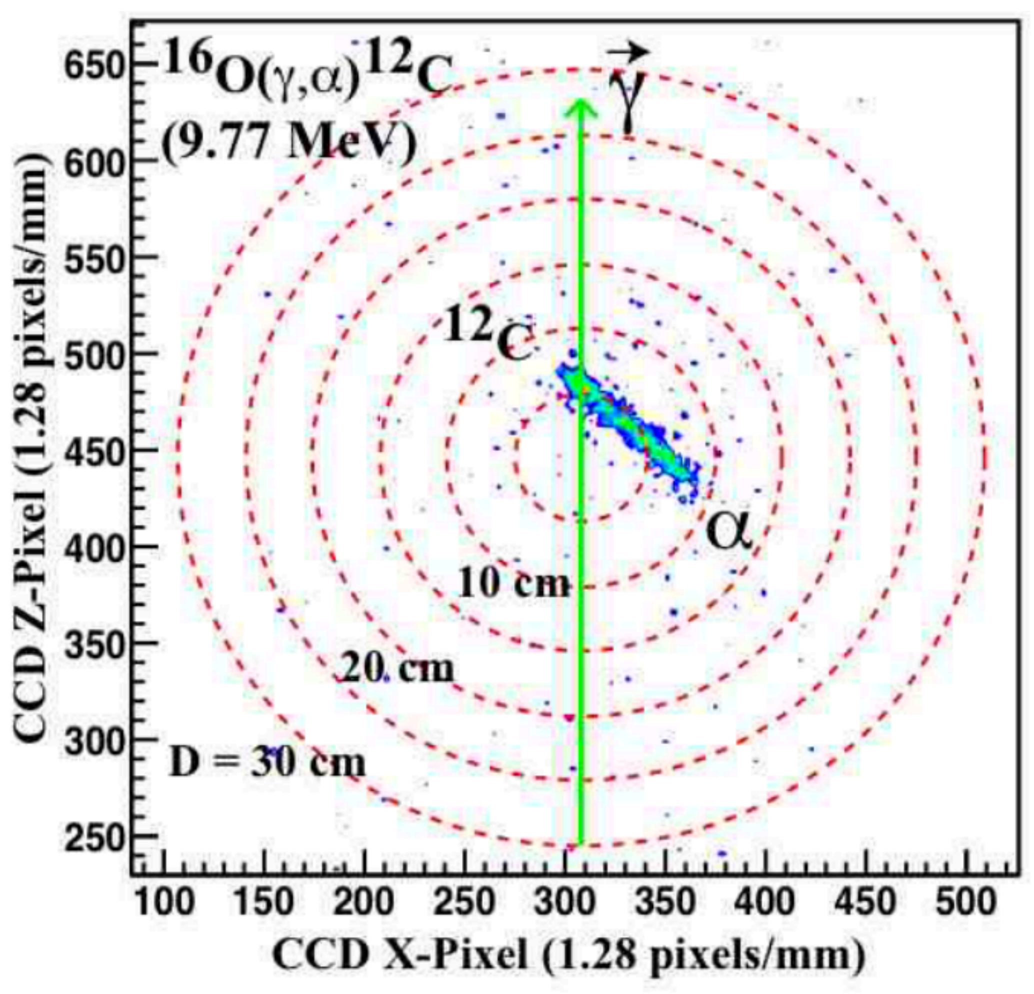
Optically read out TPC Camera + PMT

Study of the rate of formation of oxygen and carbon during the process of helium burning in intense gamma-ray beams. Exploit **energy loss profiles** in CCD images and PMT waveforms for accurate measurements of cross sections of nuclear reactions.
Identifying **^{12}C** and **^{16}O** with estimated accuracy of ±10% by dE/dx along the track and using track topology.

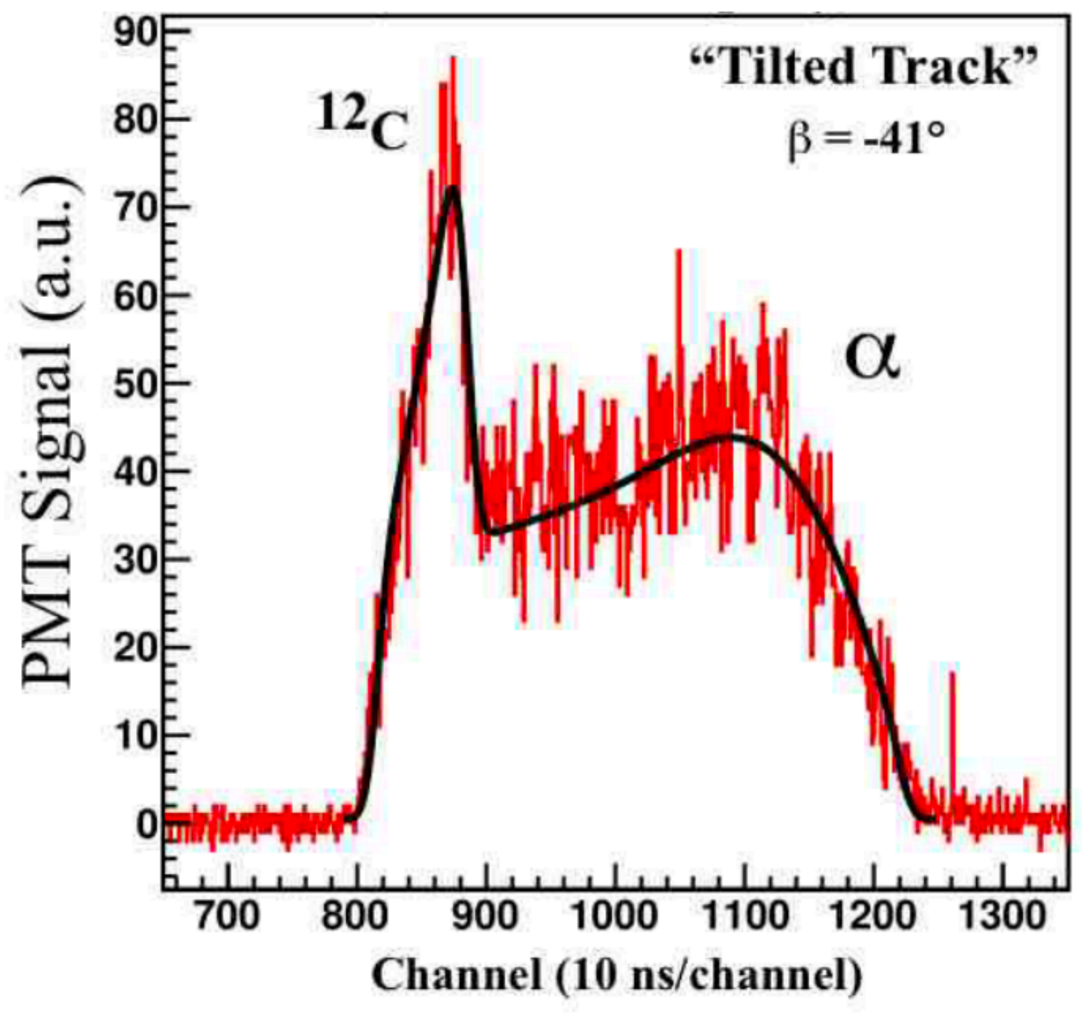
Low-pressure optical TPC with grids for amplification in CO_2 + N_2



CCD image



PMT waveform

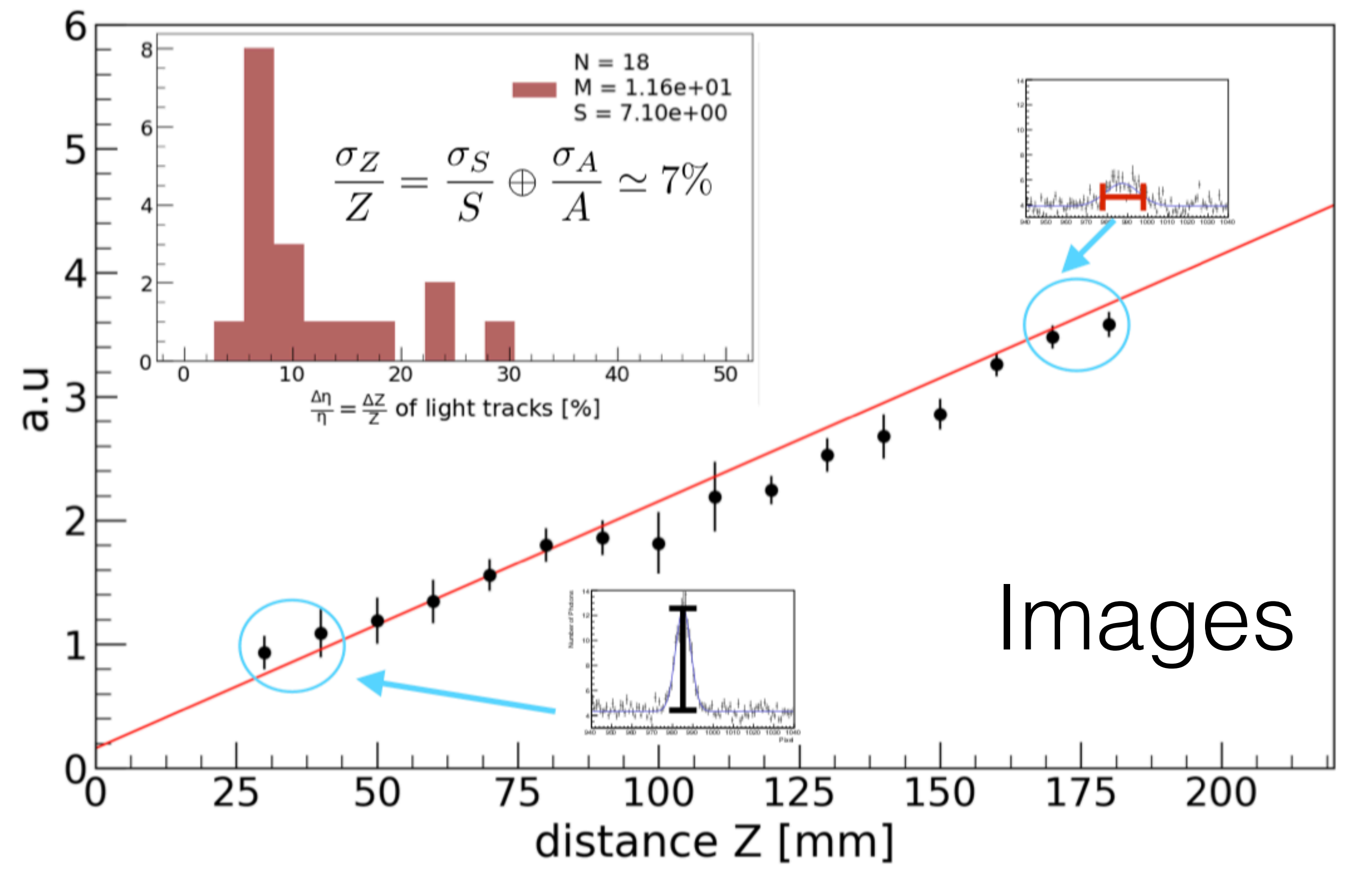


M Gai et al., An optical readout TPC (O-TPC) for studies in nuclear astrophysics with gamma-ray beams at HIγS1, DOI: 10.1088/1748-0221/5/12/P12004

3D reconstruction techniques: image + PMT

Extract depth from diffusion

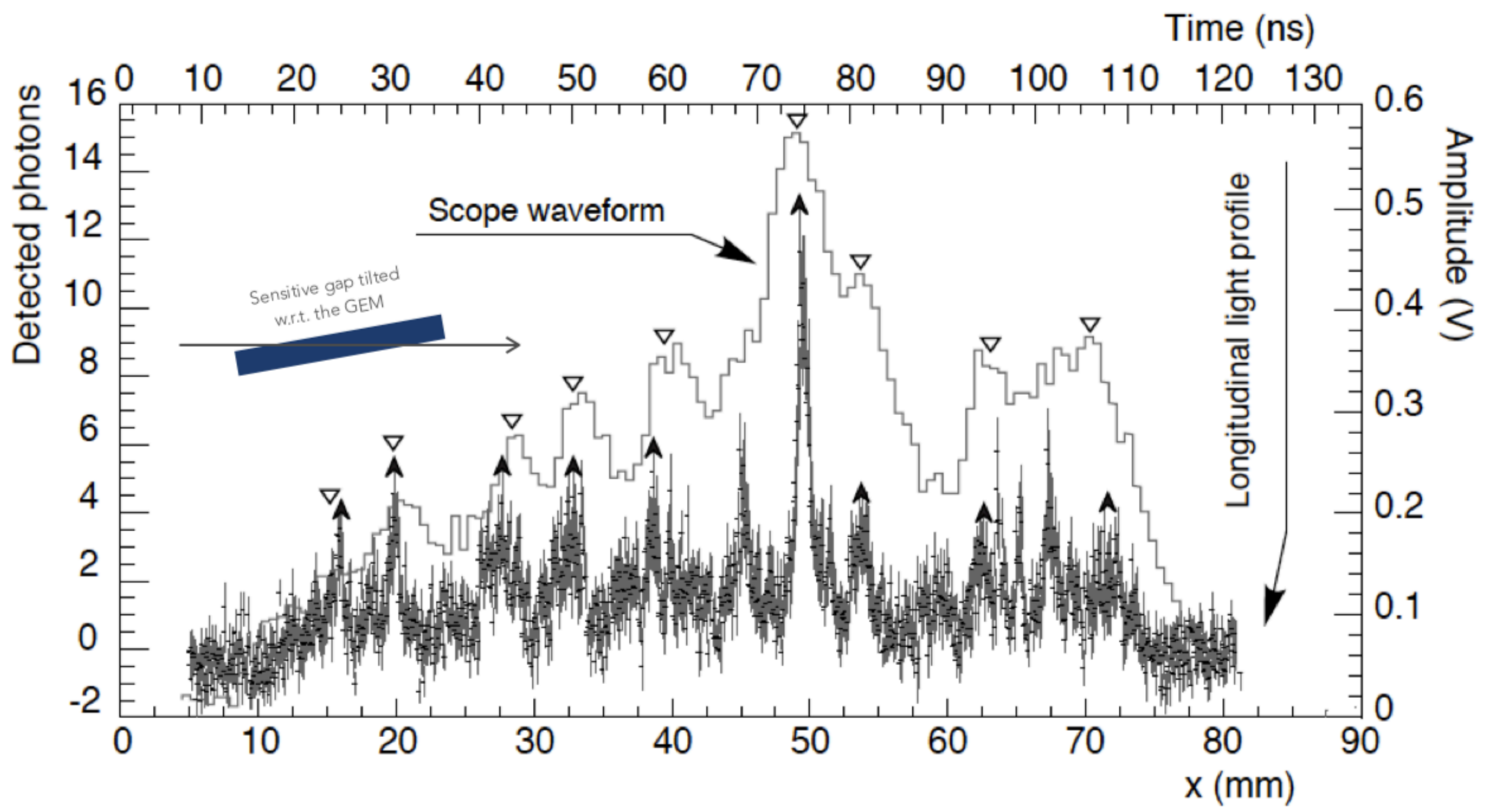
Amplitude and track width in images as well as from PMT waveforms can be used to determine depth
Achieves 10% precision: depth resolution of ~ **2 cm** for 20 cm drift

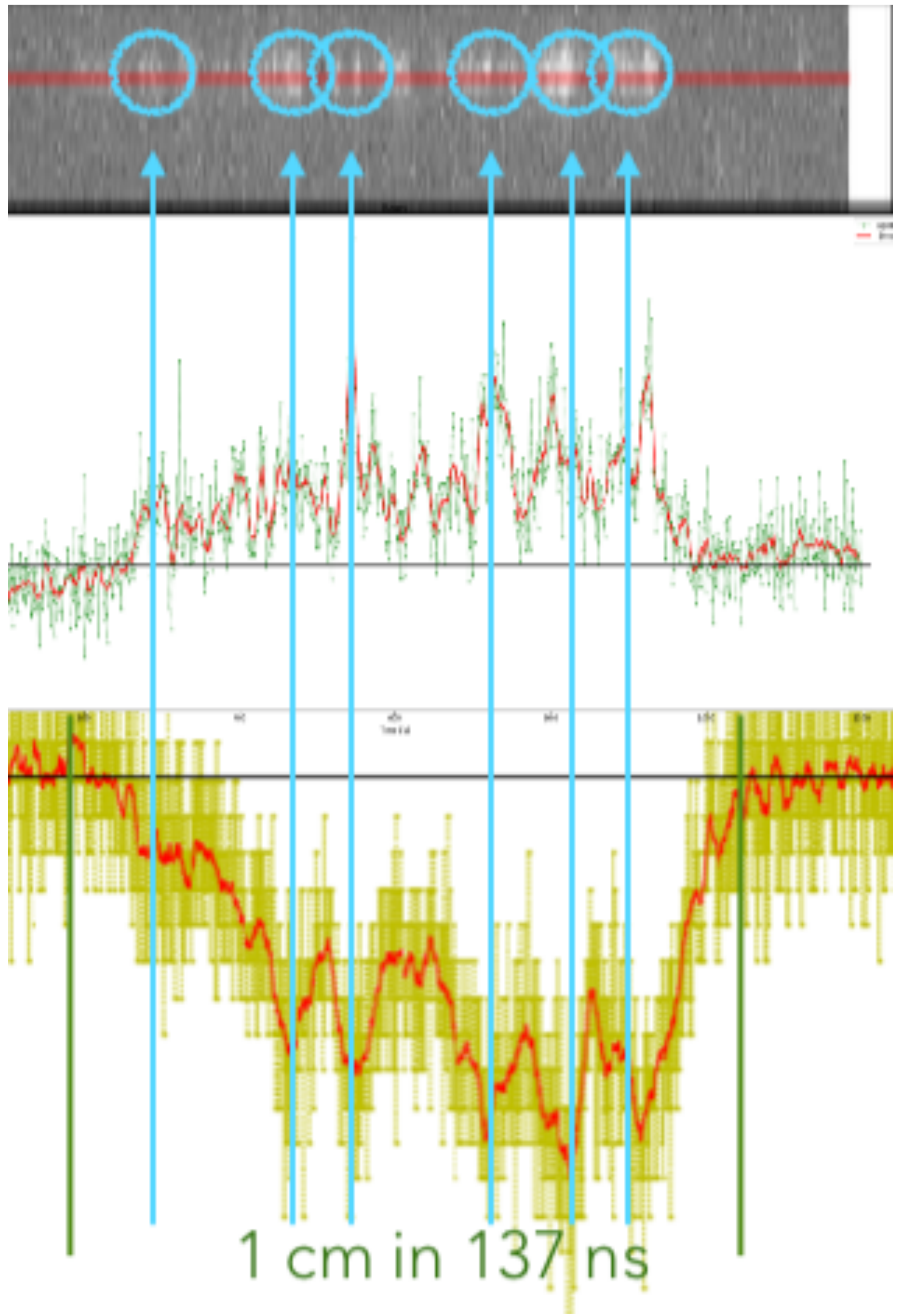


Matching clusters along track from images and PMT waveforms

Extracting timing information from PMT waveforms and assigning it to regions of tracks in acquired images by matching up cluster structure along tracks

Depth resolution of **100 μm** achieved (residual distribution after 3D fit)

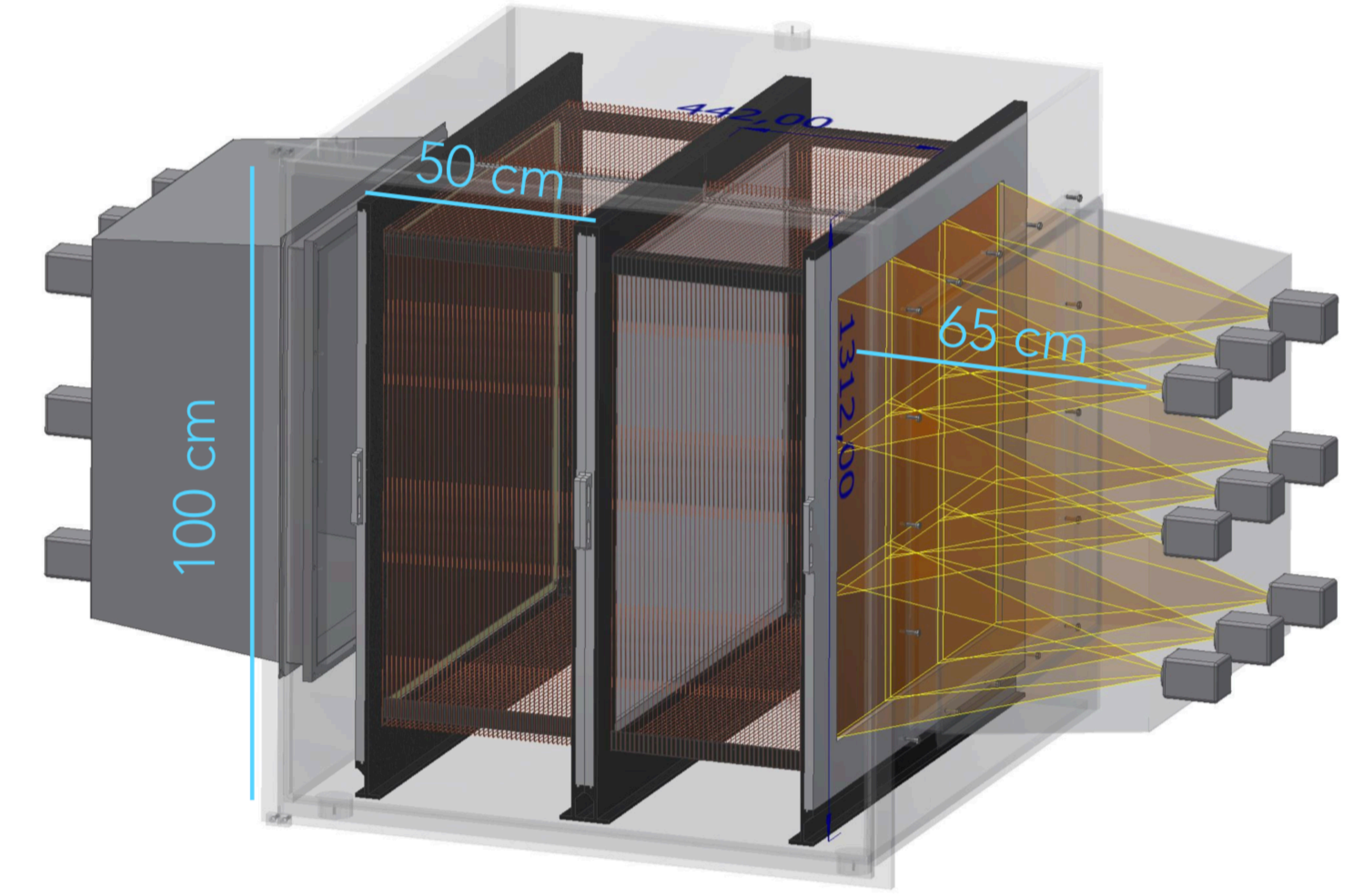


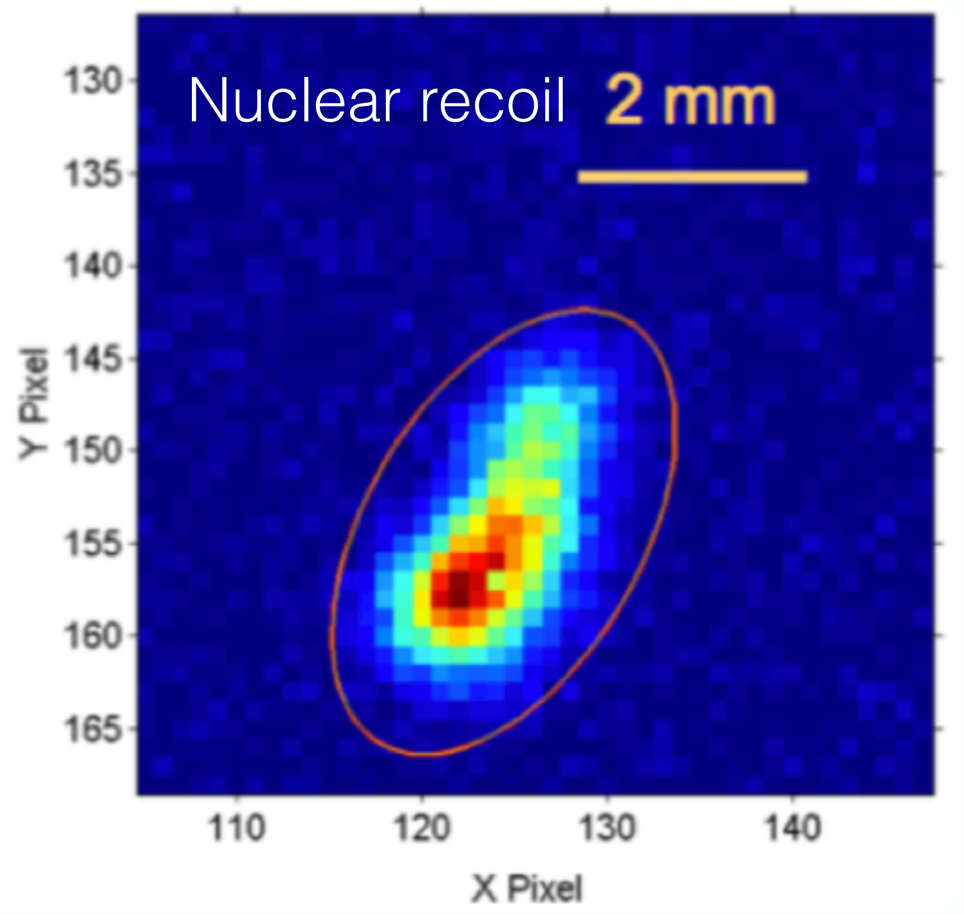


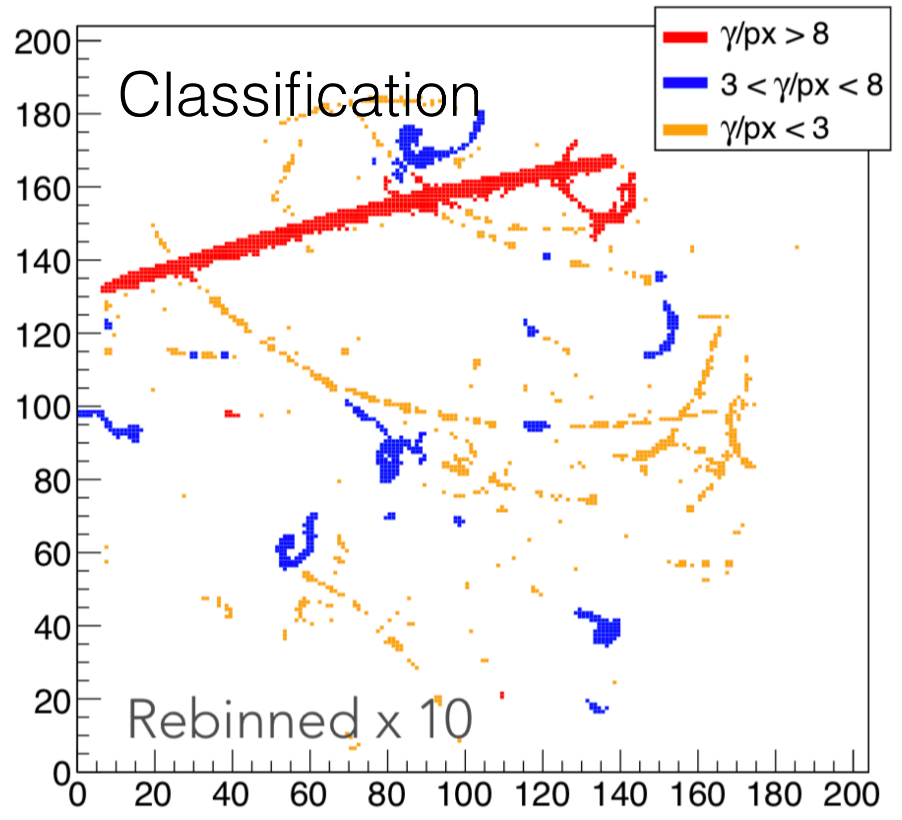
D. Pinci et al., CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search, MPGD 2019
https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf
D. Pinci et al., CYGNO project: a One Cubic Meter GEM-based Optically Readout TPC for Light Dark Matter Search, RD51 Mini-Week Feb 2019,
https://indico.cern.ch/event/782786/contributions/3283435/attachments/1790478/2916786/Cygno_RD51_Feb2019.pdf
https://indico.cern.ch/event/466934/contributions/2589340/attachments/1489348/2314797/EPS_2017_final.pdf

Optically read out TPC for Directional Dark Matter Search
CYGNO

- $1m^3$ gas volume read out with a 3x3 array of sCMOS cameras from each side
- Fast detectors (PMT or SiPM) for timing information
- Total of 72M readout pixels







D. Pinci et al., RD51 Mini-Week Feb 2019

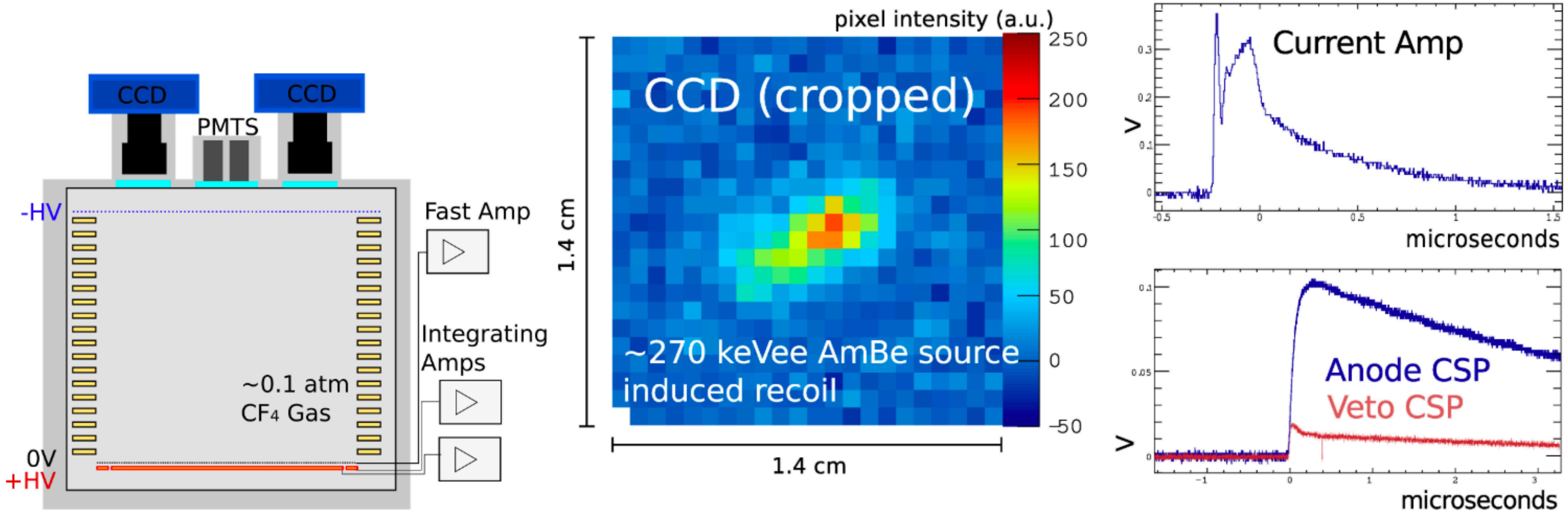
CYGNO: https://arxiv.org/pdf/1901.04190.pdf
D. Pinci et al., CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search, MPGD 2019
https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf

Dark Matter Time Projection Chamber
DMTPC

Exploit the expected **directional anisotropy** of dark matter velocities at Earth to observe dark matter induced recoils.

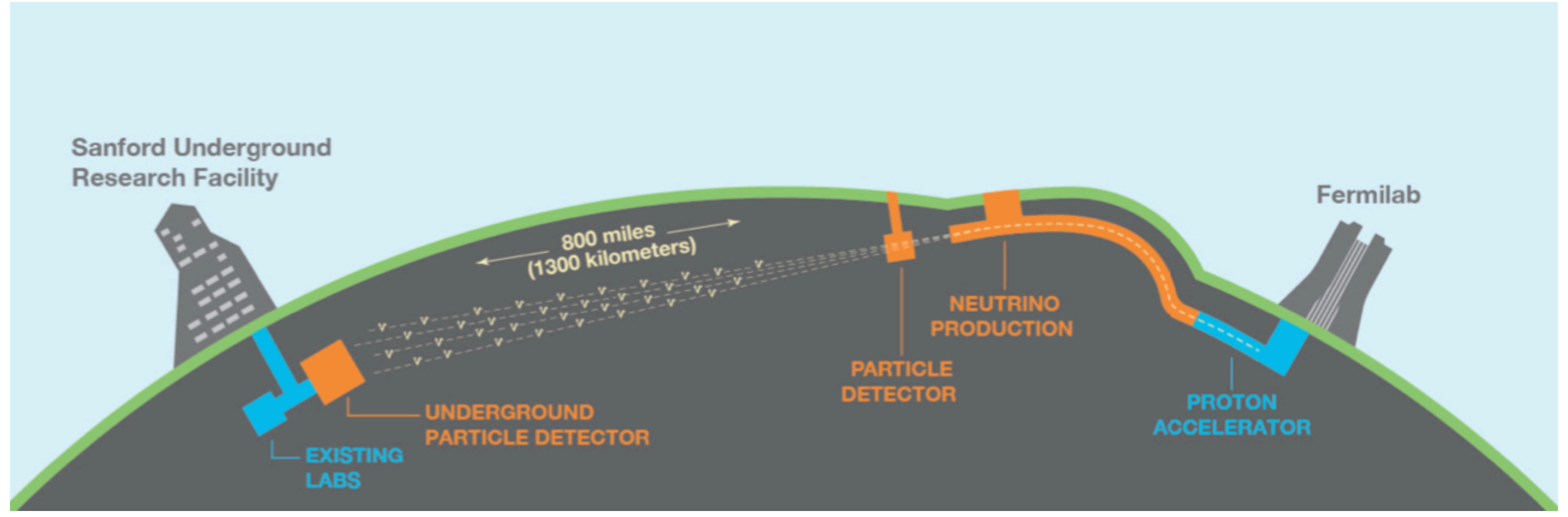
Measure energy and directions of nuclear recoils by using a **low-pressure CF_4** target.

CCD cameras used for 2D projection and **PMT/SiPM** used for time of arrival at micromesh amplification stage.
Rise time of electron peak used for Δz information and waveform analysis of induced anode signals provides information about track inclination



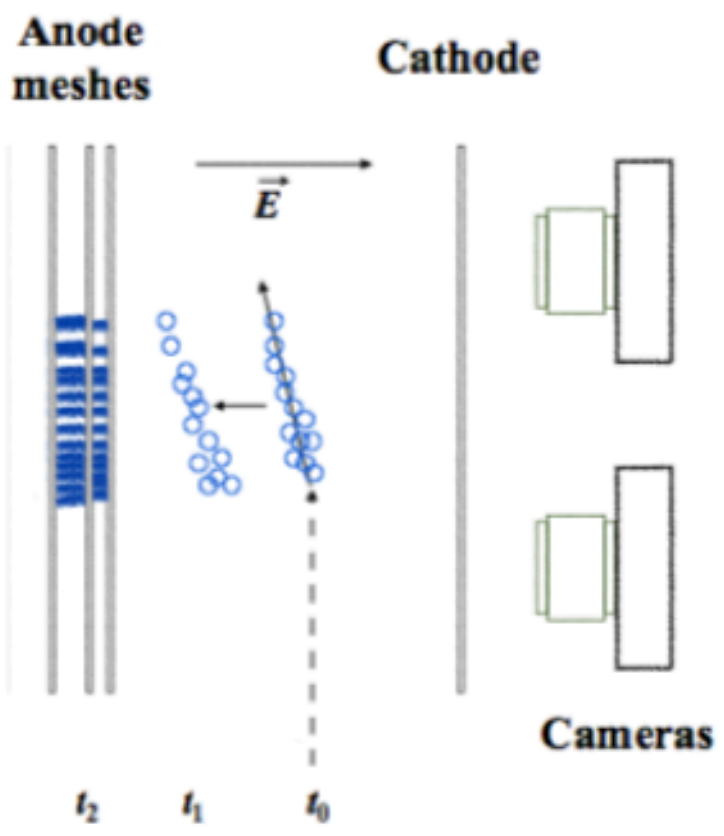
Cosmin Deaconu et al. / Physics Procedia 61 (2015) 39 – 44

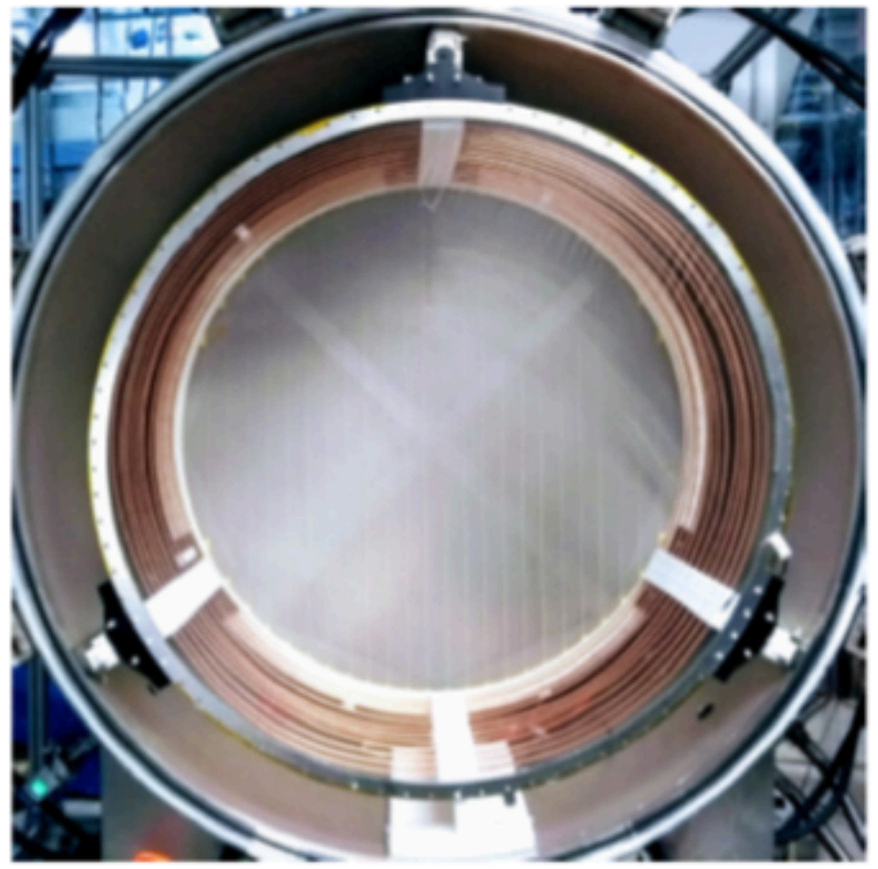
High Pressure Time Projection Chamber
HPTPC



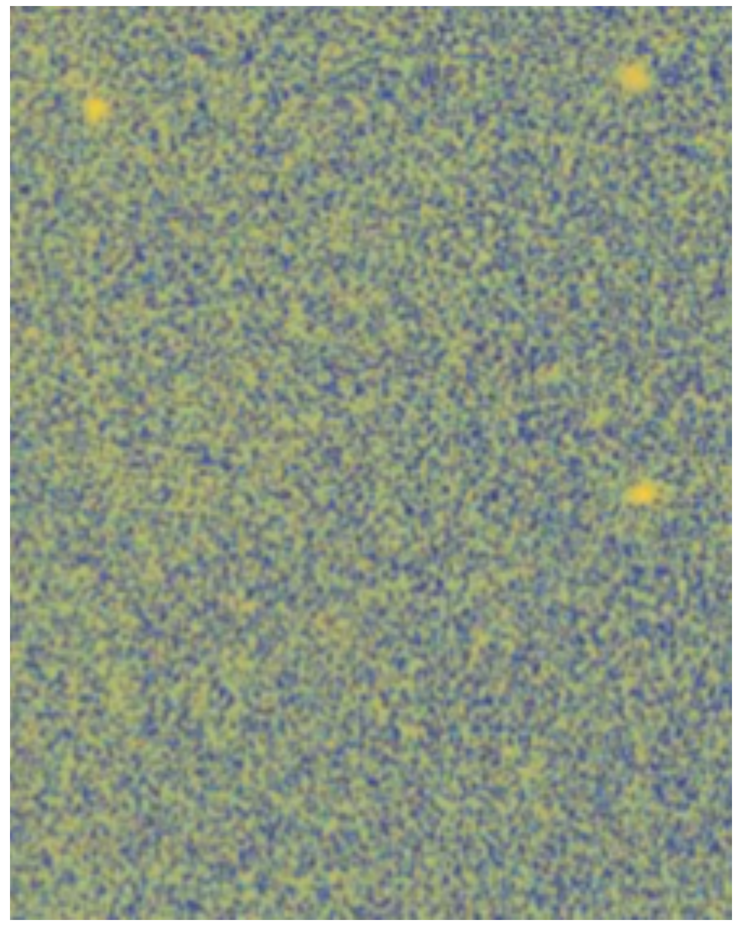
Part of reference design for Near Detector (ND) of DUNE and explored for upgrades of T2K and its successor Hyper-K.

High-pressure gas as **active target** to increase target mass and measure e.g. neutrino-nucleus scattering. Possibility of exchanging gas mixture allows for large range of scattering experiments.



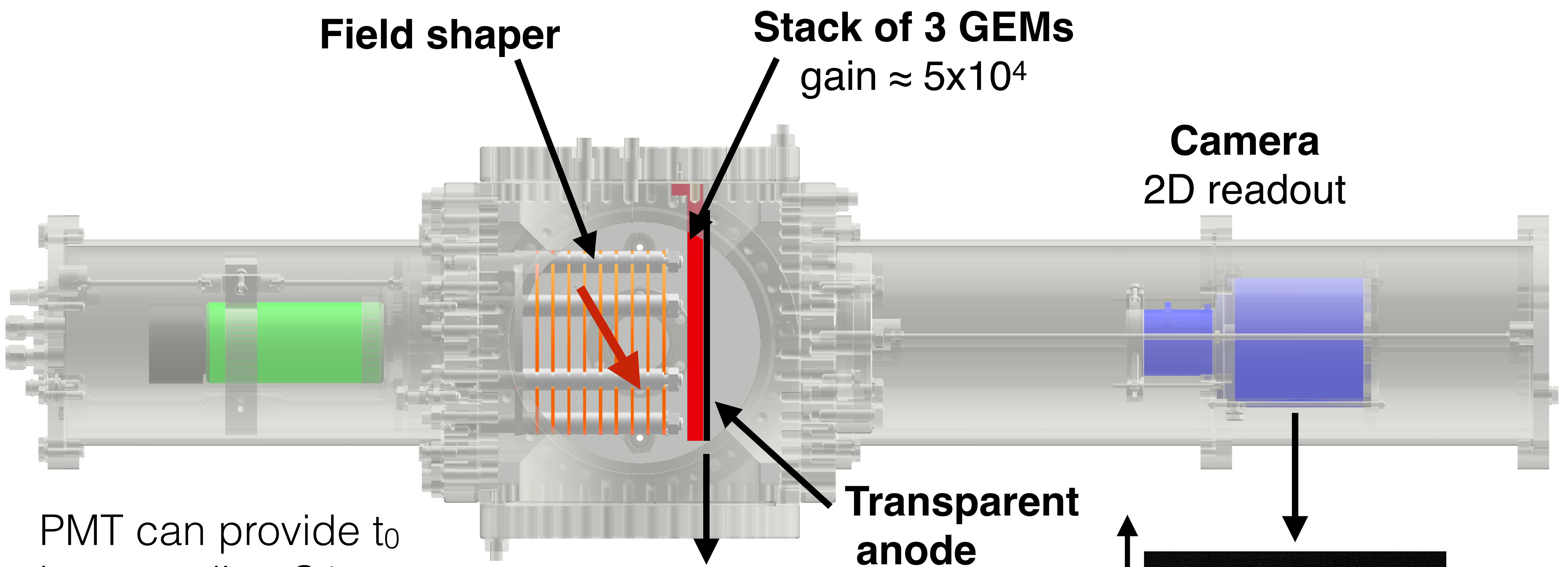


Four **CCD cameras** record 2D images with overlap for stitching.
Electrical signal recorded from anode meshes for energy spectra.

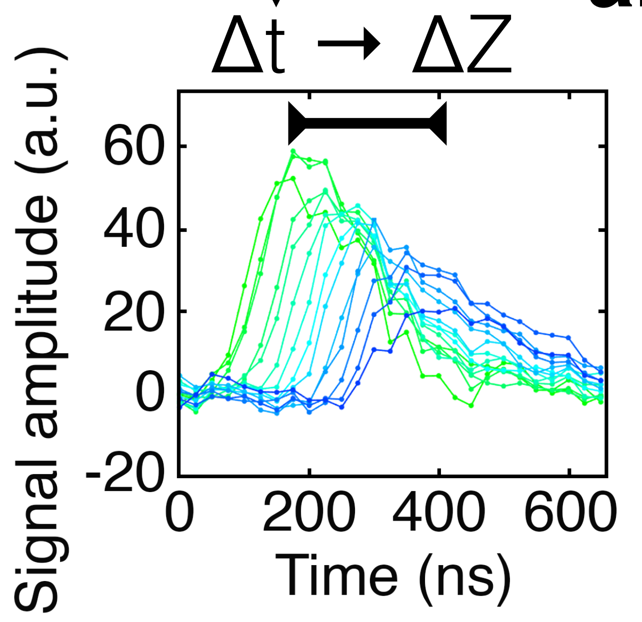


A. V. Waldron and A. Deisting, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9059848
http://www.hep.ph.ic.ac.uk/~awaldron/hptpc_20190731.pdf

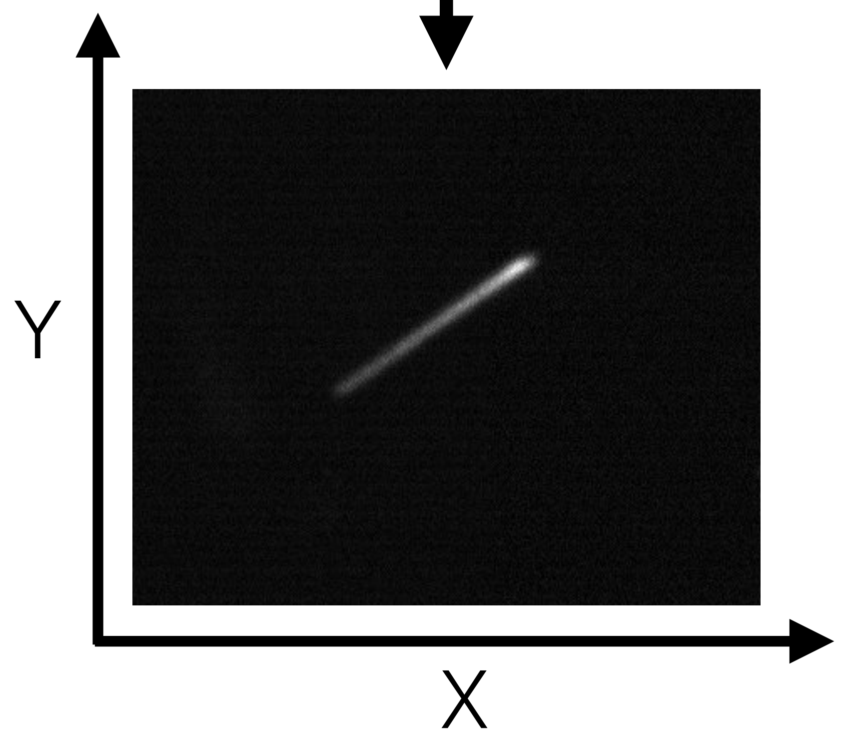
Optical + electronic readout



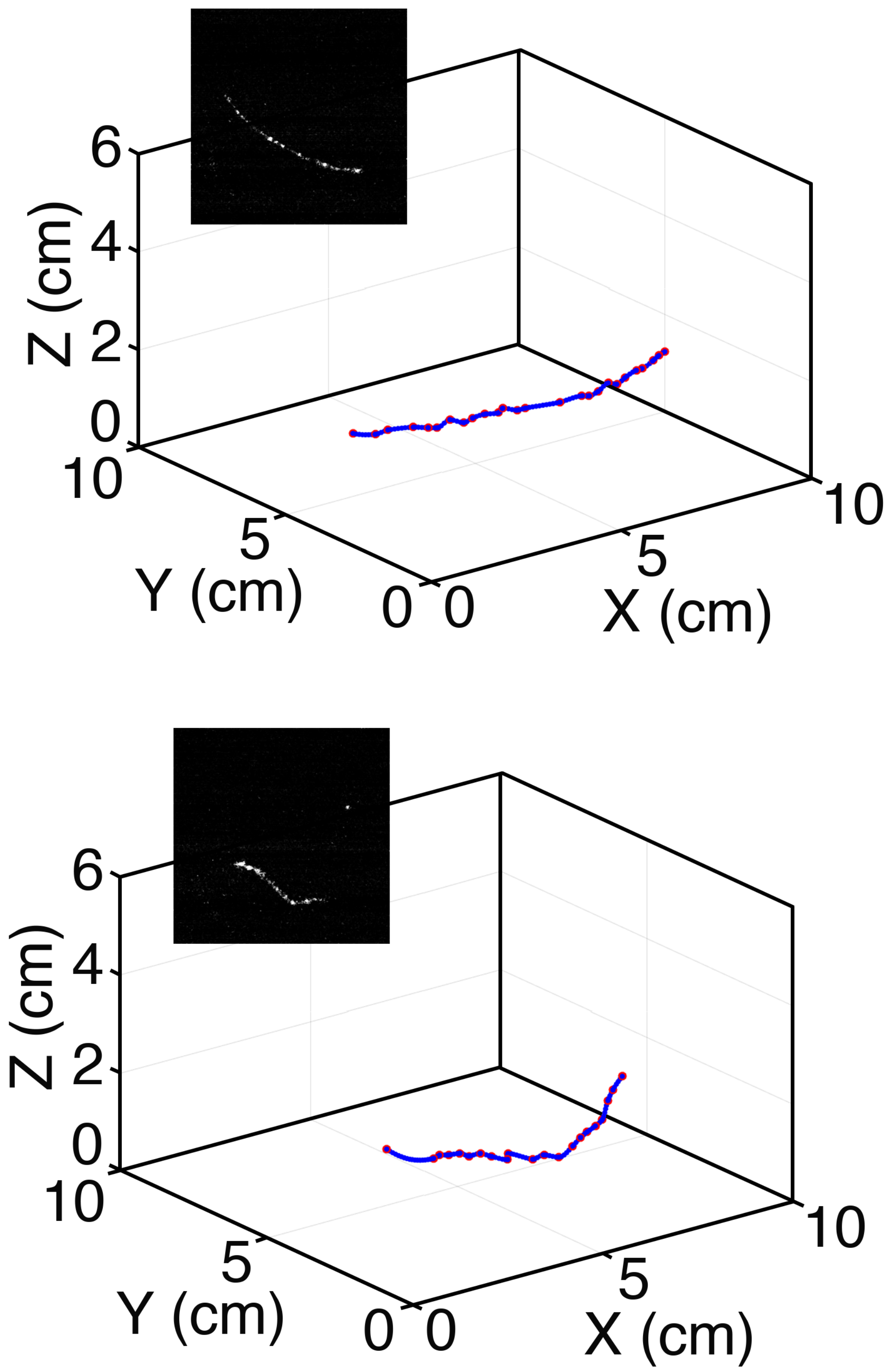
PMT can provide t_0 by recording S1



Drift times from anode



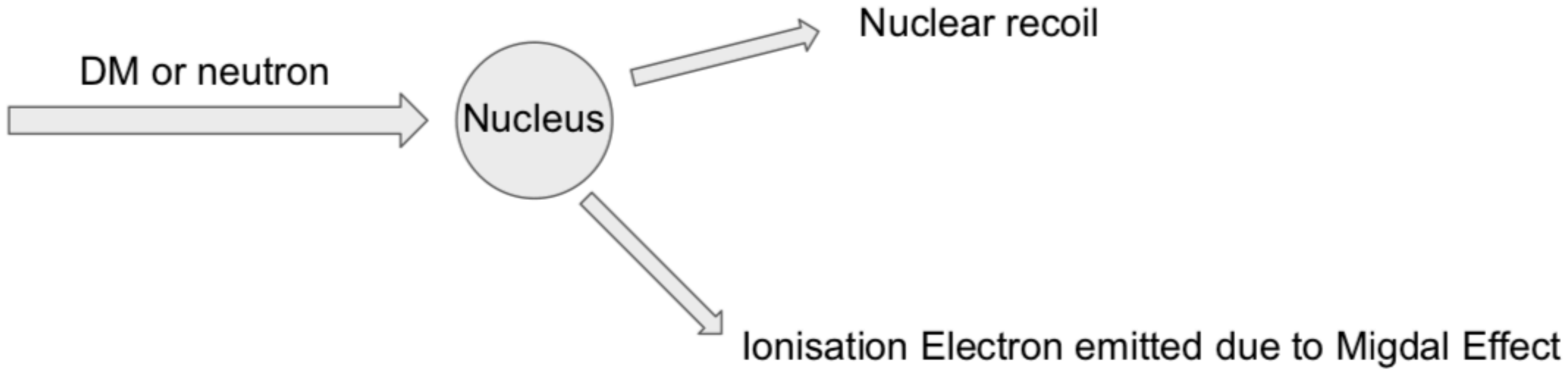
High granularity 2D projection

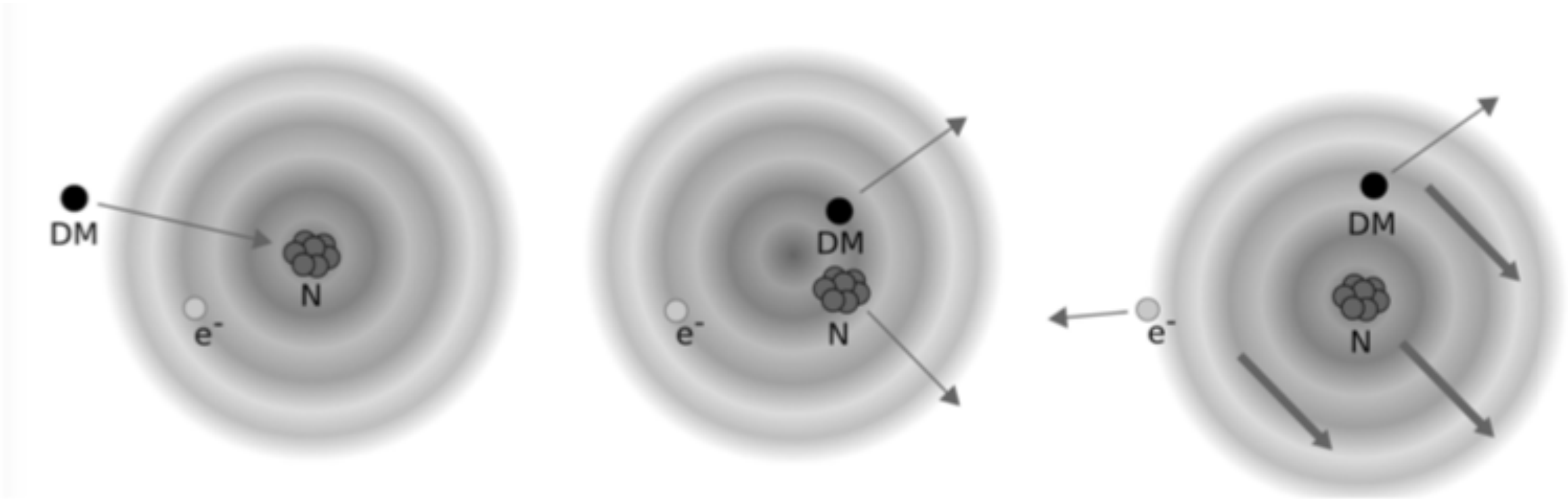


F. Brunbauer et al. IEEE TNS, VOL. 65, NO. 3, 2018
Schematics not drawn to scale

Low-pressure OTPC

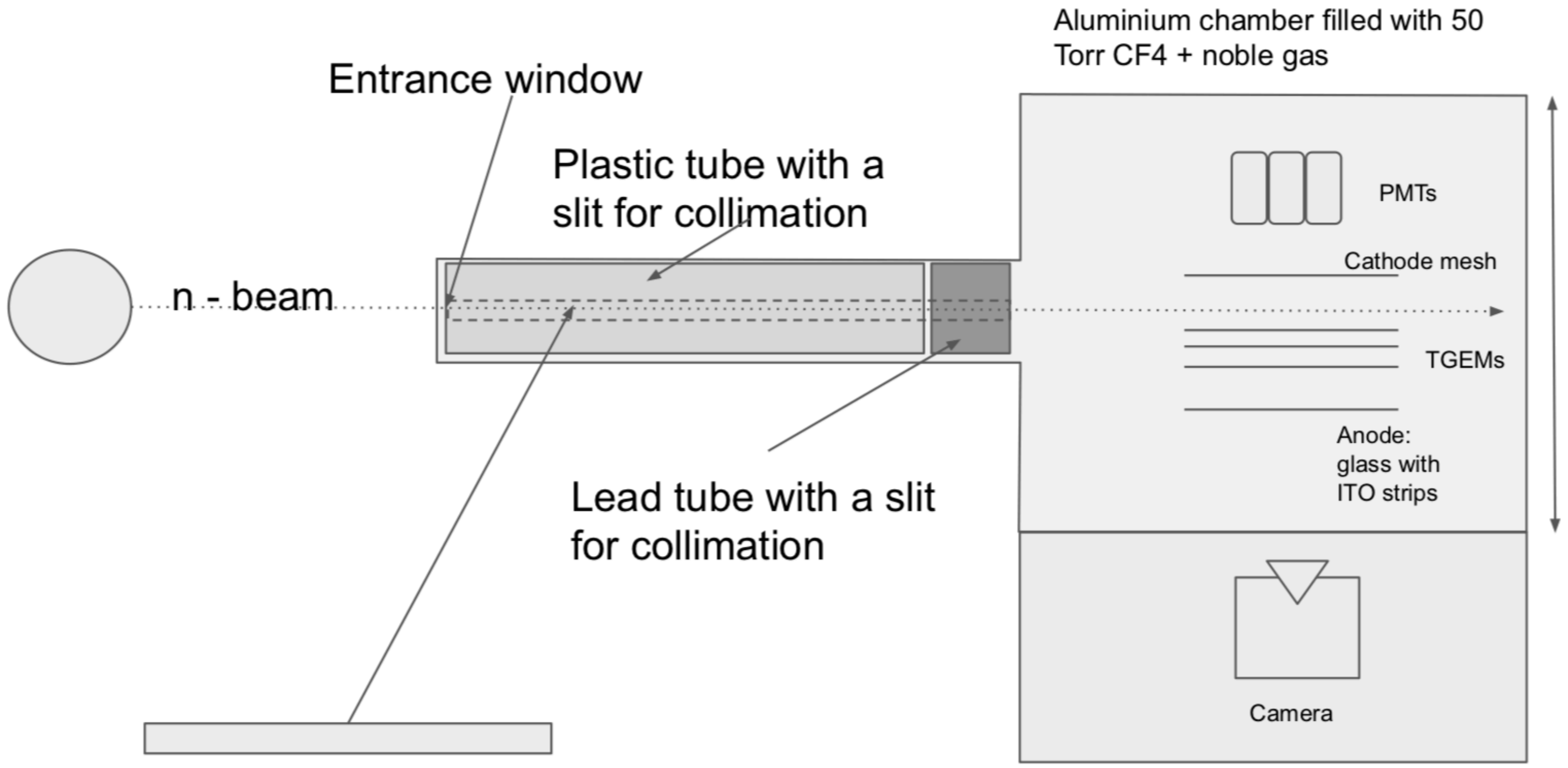
Migdal effect observation

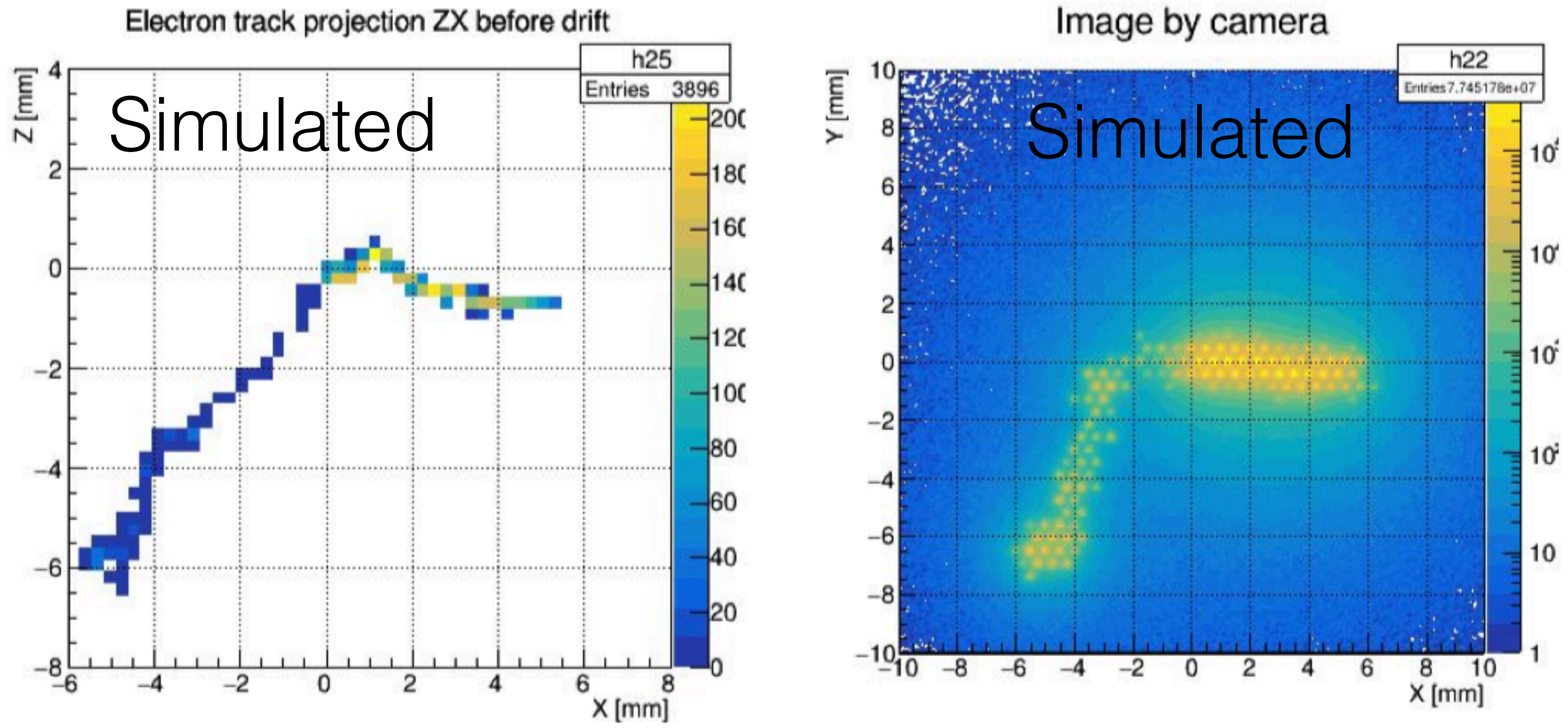




Observing simultaneous nuclear recoil and ionisation electron emitted due to **Migdal effect** can be used in **Dark Matter** searches for an extension of sensitivity in the low mass region.

Combining 2D image and strip ITO anode for **hybrid optical and electronic readout** for accurate 3D track reconstruction.





10 keV electron and 200 keV F ion in pure CF4

P. Majewski, RD51 mini-week Feb 2020

https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

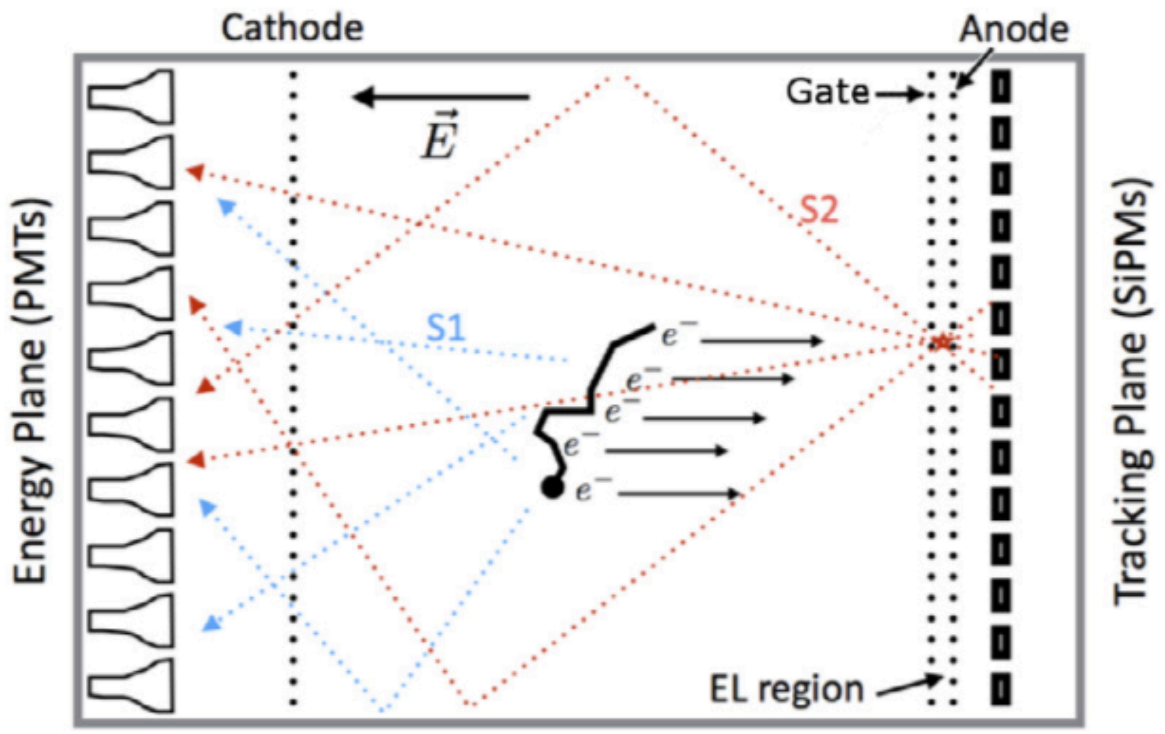
Perspectives for optical readout

SiPMs, LG-SiPMs, Timepix cameras

SiPMs, LG-SiPMs

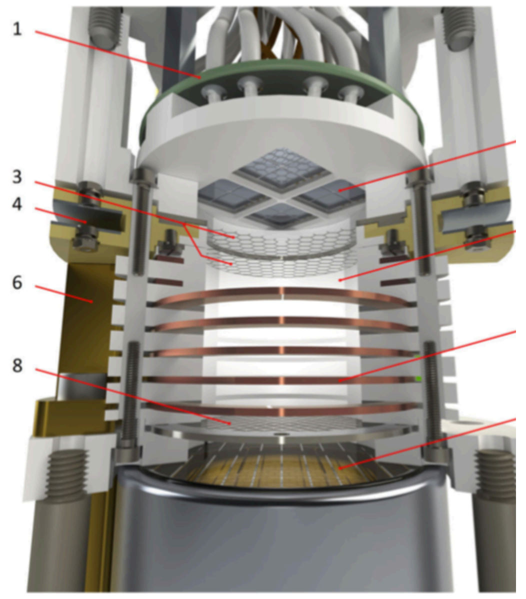
SiPMs

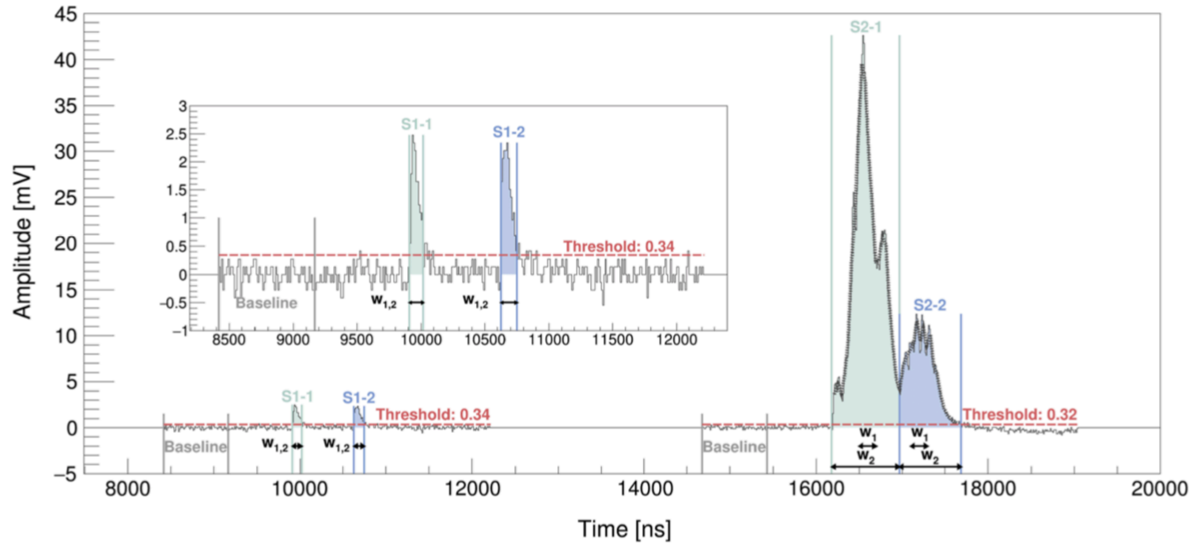
Time-slices of SiPM signals used to reconstruct hit locations as function of time.



NEXT TPC concept
SiPMs for tracking plane

Dual-phase xenon Xurich II TPC



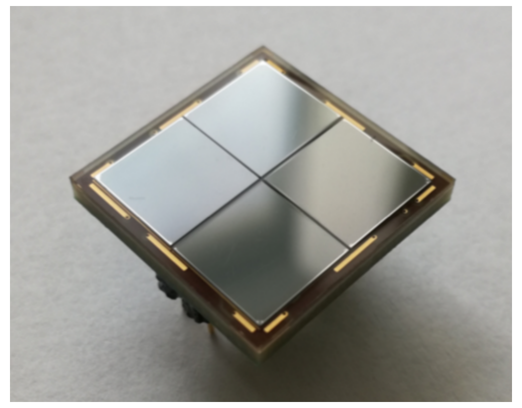


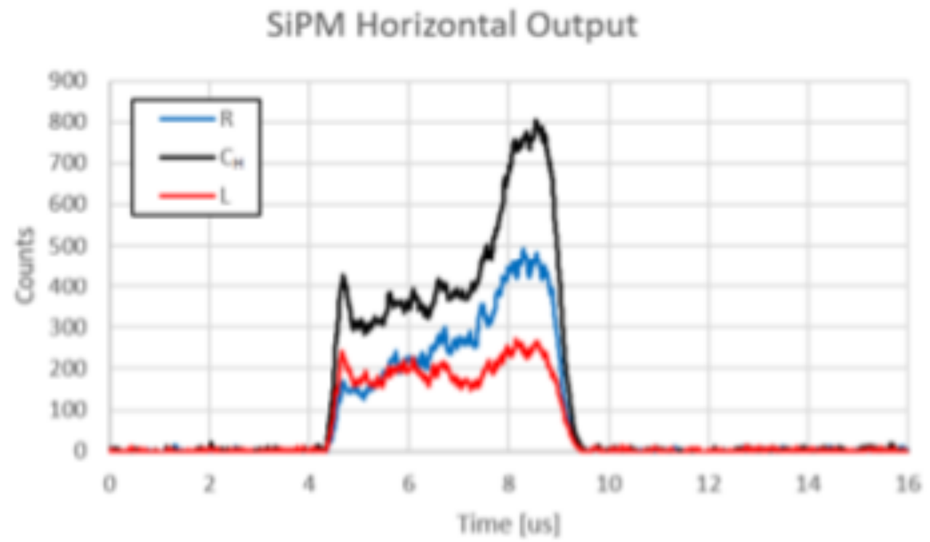
L. Arazi and NEXT collaboration, collaboration, NIM A 958 (2020) 162126

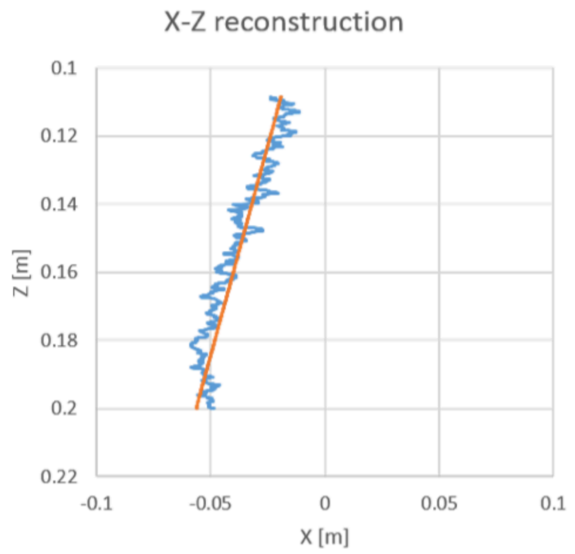
L. Baudis et al, https://doi.org/10.1140/epjc/s10052-020-8031-6

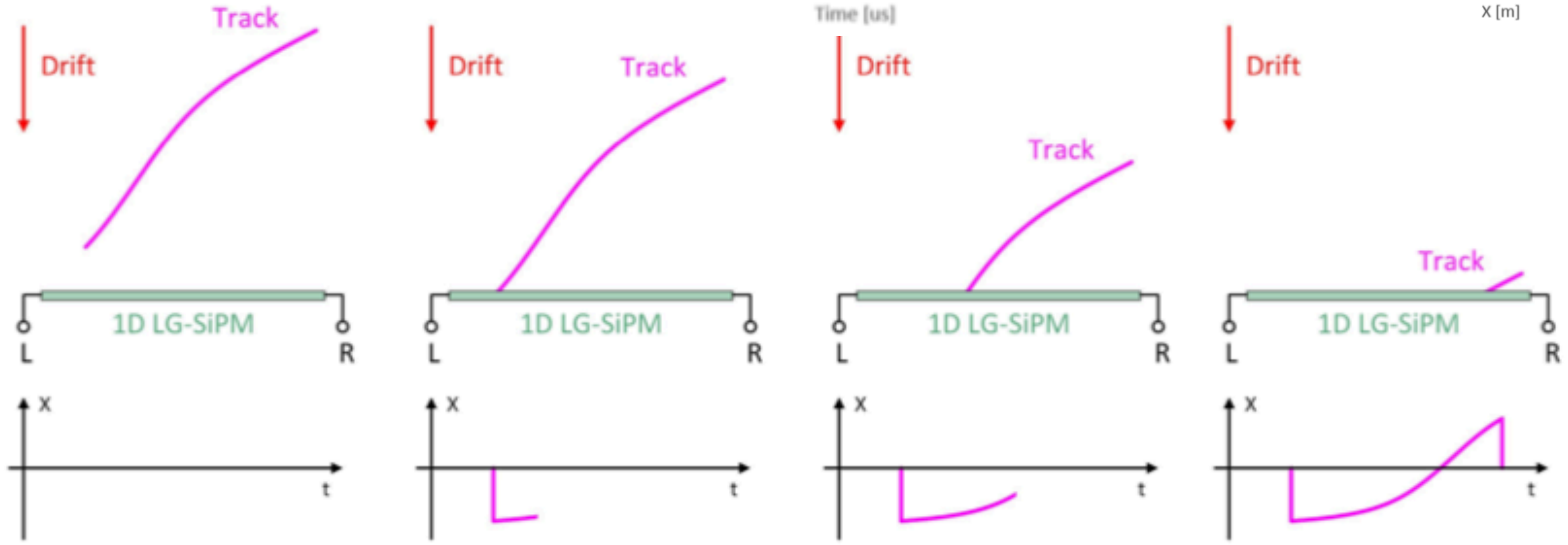
Linearly-graded SiPMs

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





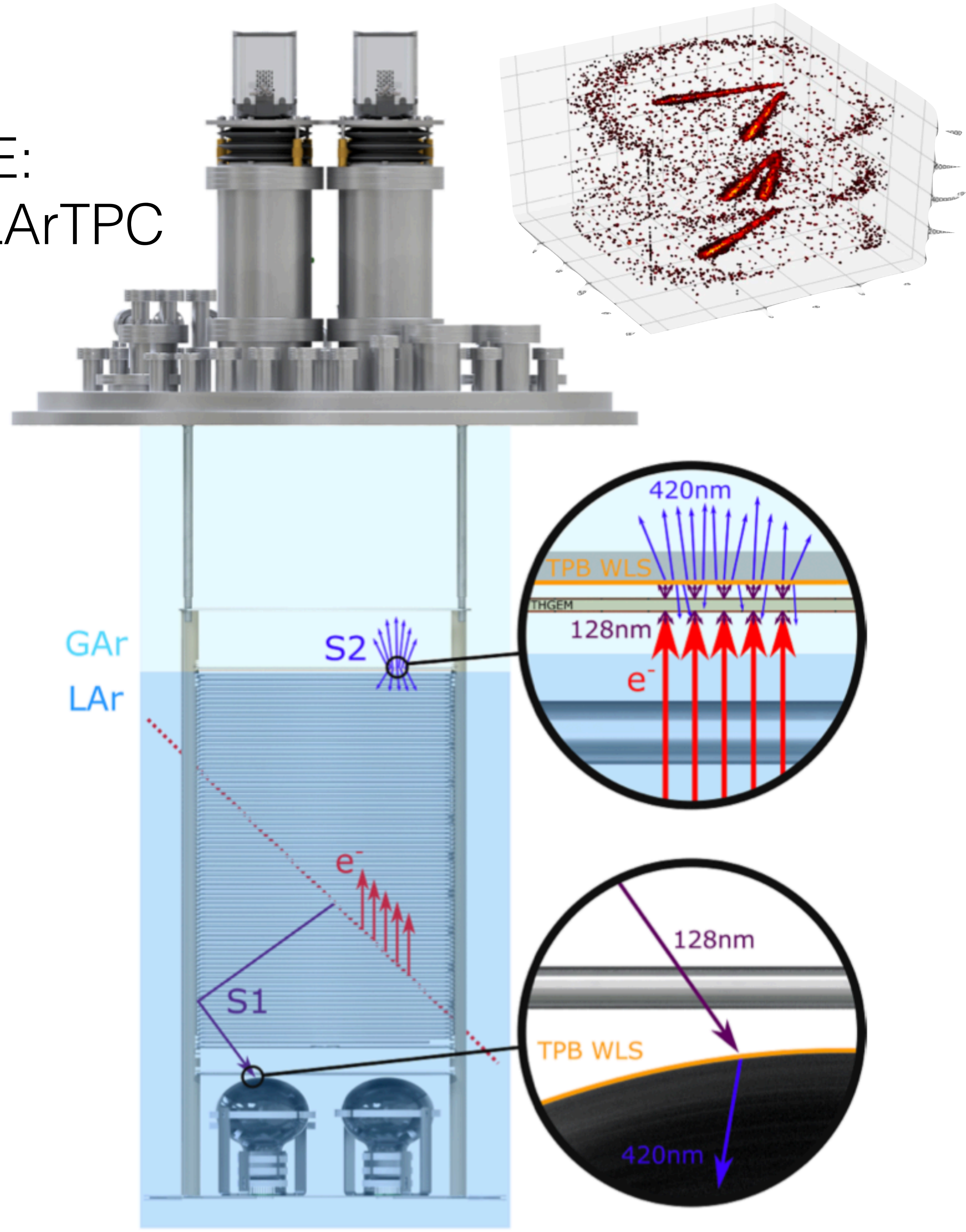




A. Gola et al, arXiv:2009.05086 [physics.ins-det]

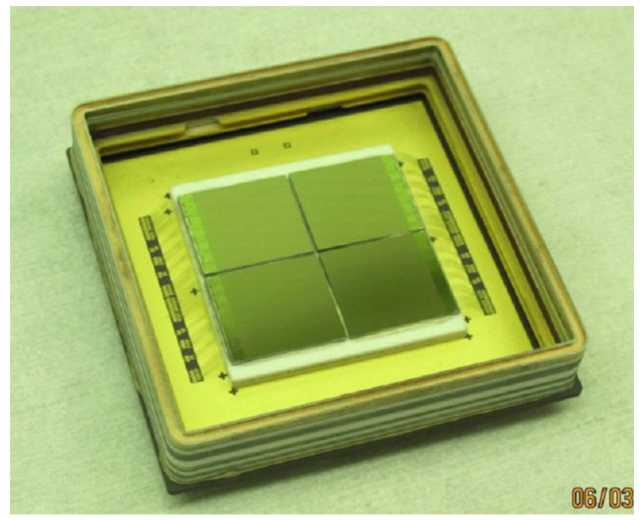
Timepix cameras

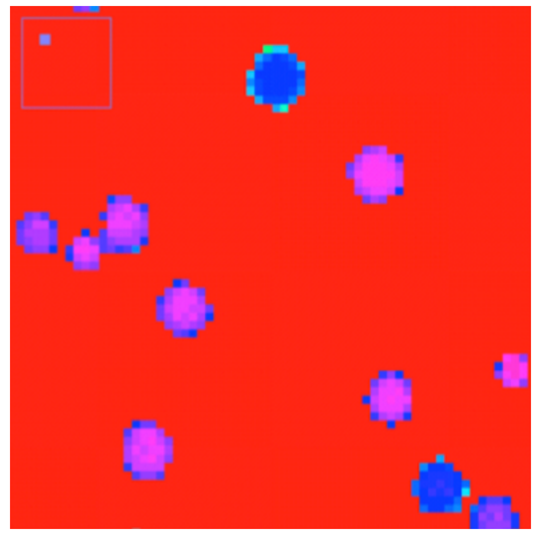
ARIADNE:
Optical LArTPC

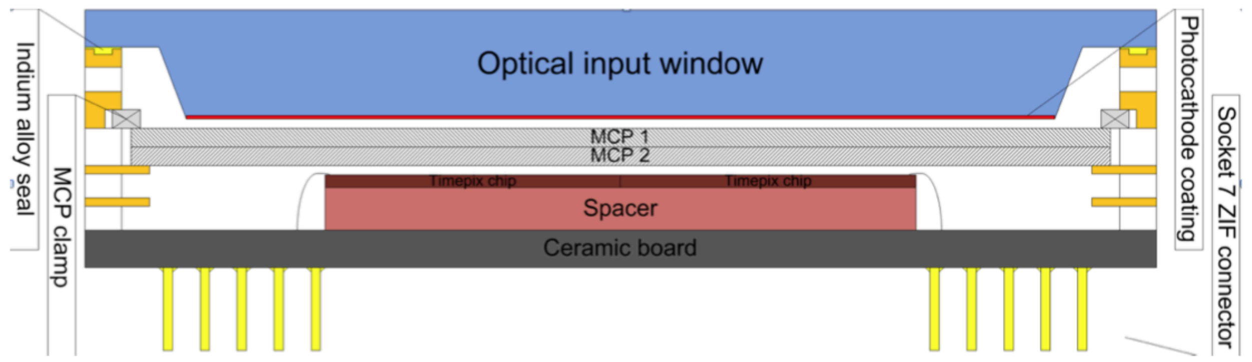


Timepix array with **MCP and bi-alkali photocathode**

Event counting with threshold or time of arrival recording



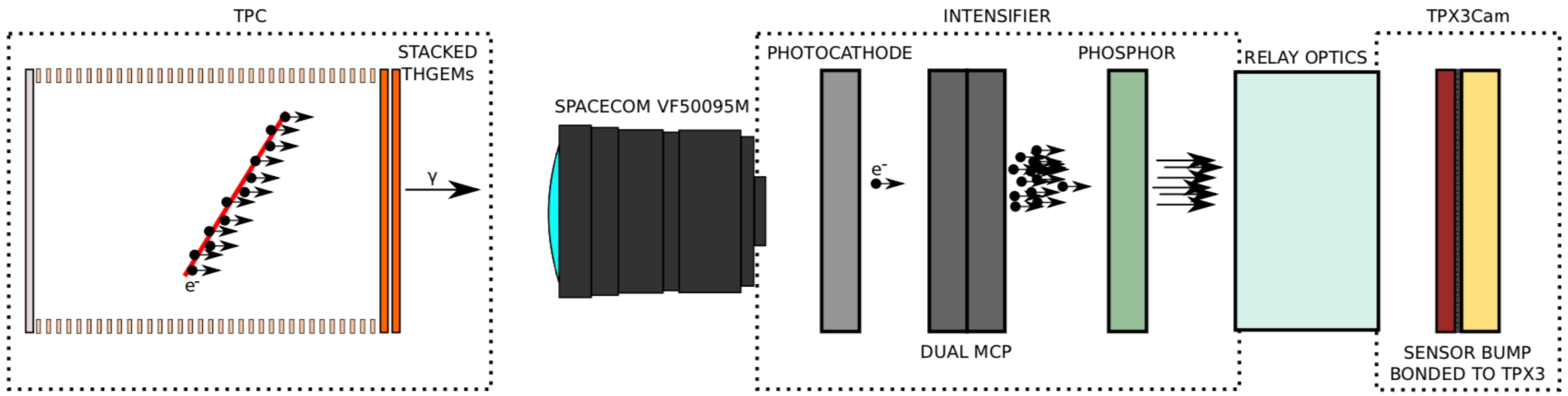




J Vallerga et al 2014 JINST 9 C05055

Image-intensified single-photon sensitive **Timepix3** camera provides time information with **1.6ns** timestamp resolution at a resolution of **256 x 256** pixels.

3D track reconstruction for alpha particles and cosmics has been demonstrated in **low pressure CF_4** with a double THGEM as amplification structure in a dual phase LAr TPC.



https://www.photonis.com/products/mantis3

A. Roberts, ARIADNE, arXiv:1810.09955v3
D. Hollywood *et al* 2020 *JINST* **15** P03003, https://iopscience.iop.org/article/10.1088/1748-0221/15/03/P03003/pdf

Perspectives for optical readout

Ultra-fast CMOS sensors

Ultra-fast CMOS sensors

-

- **Low frame rate capabilities**
- High gain required for good SNR
- Needs suitable gases or shifters
- Radiation hardness of image sensors

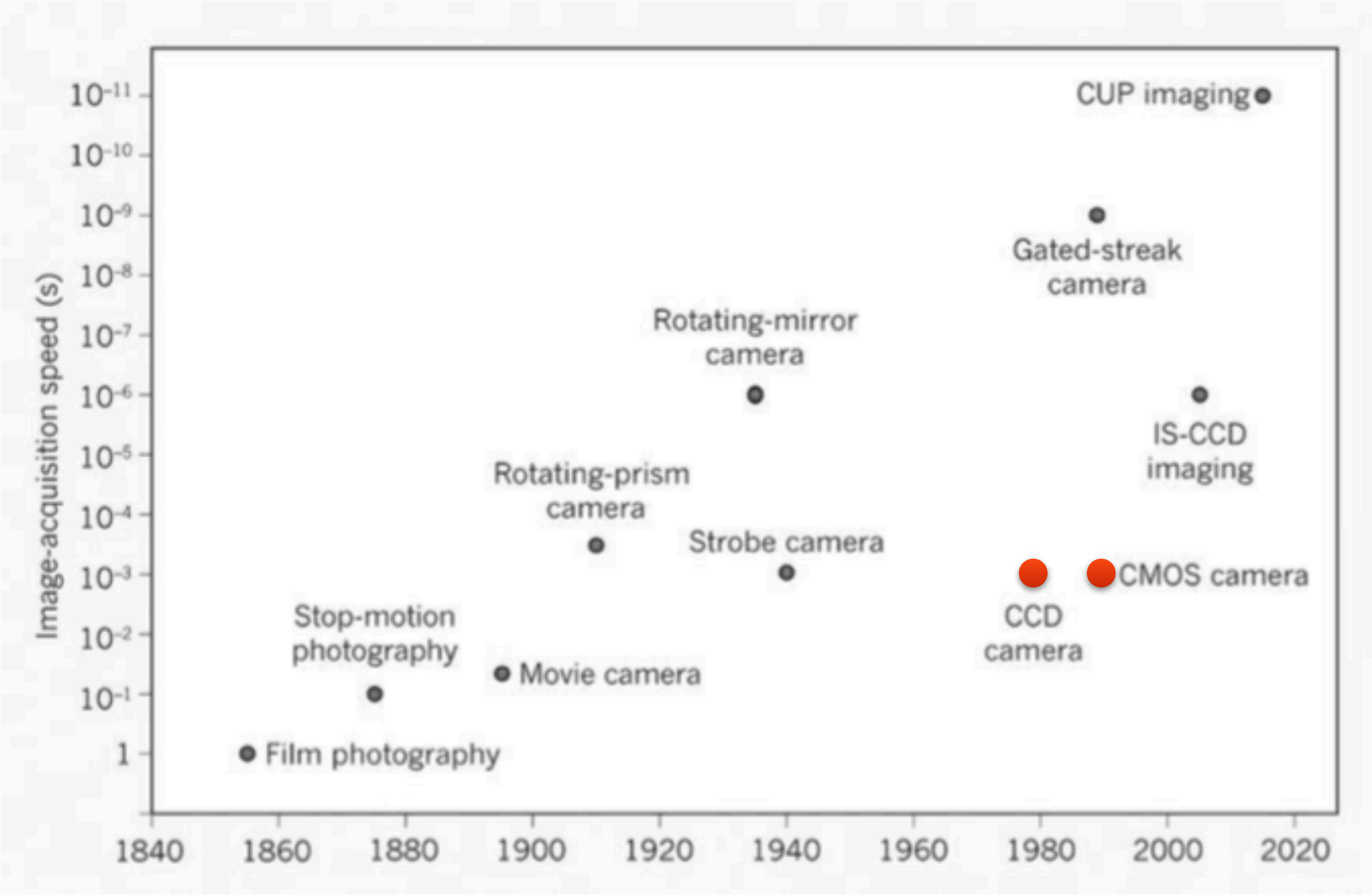


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Ultra-fast CMOS sensors

-

- **Low frame rate capabilities**
- High gain required for good SNR
- Needs suitable gases or shifters
- Radiation hardness of image sensors

Phantom v2512

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

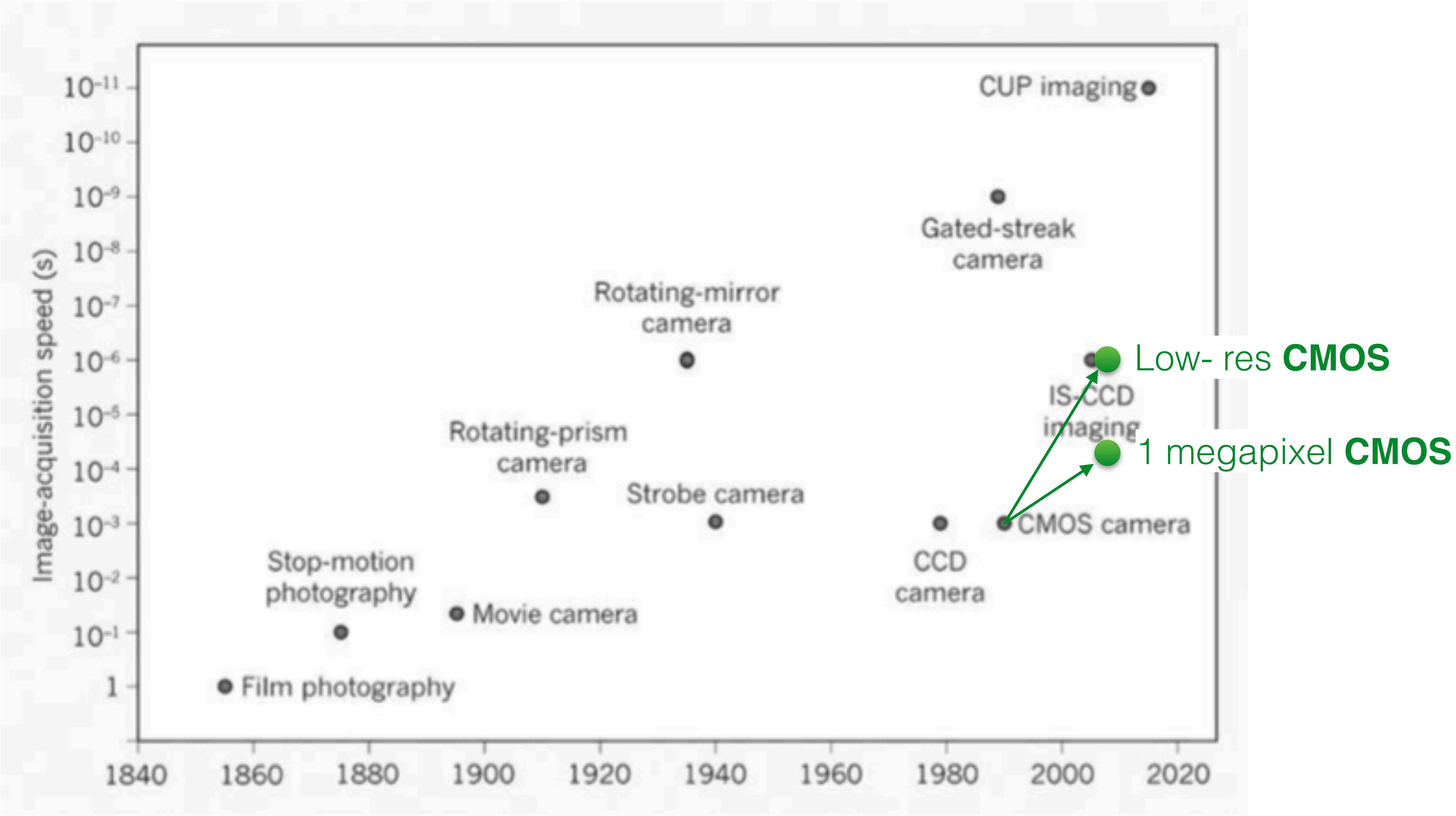
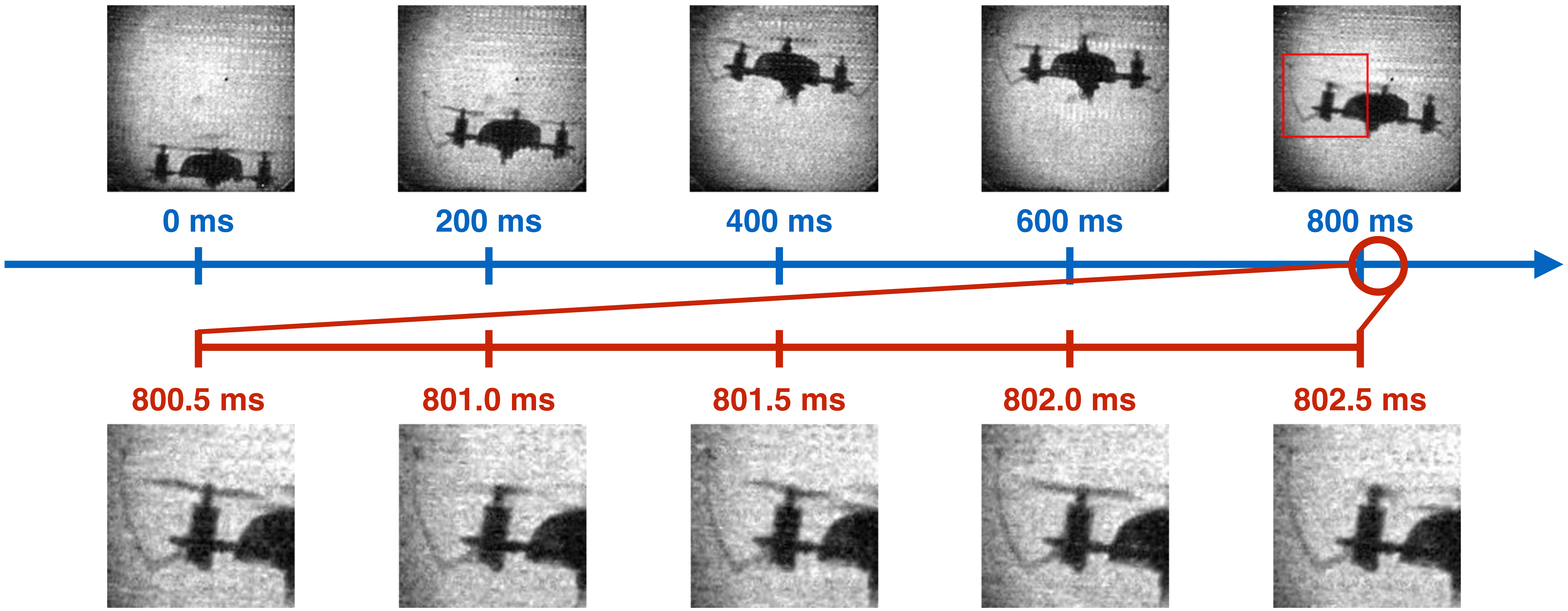


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Ultra-fast CMOS sensors

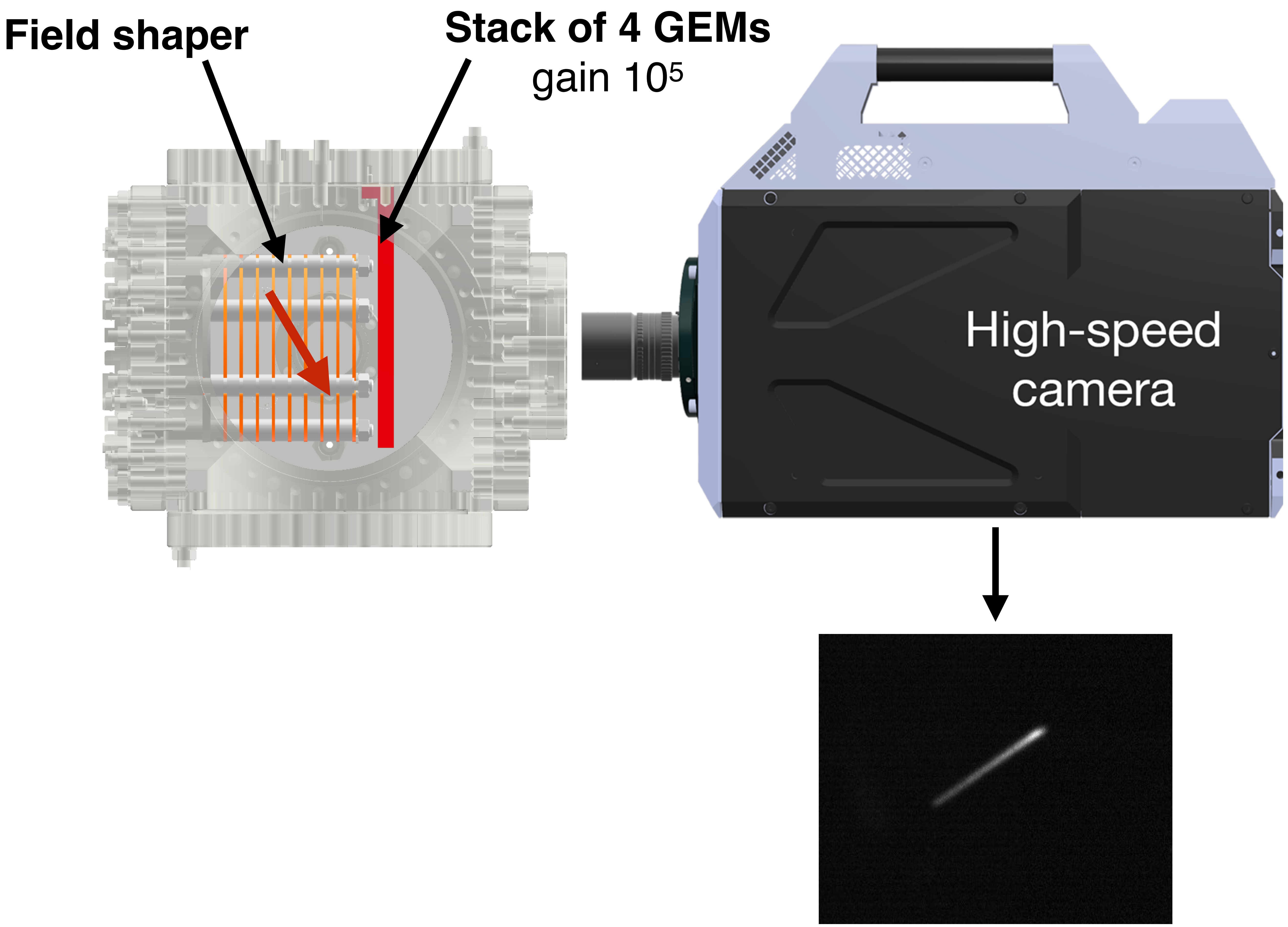
Ultra-fast cameras can be used for X-ray fluoroscopy imaging as well as single event reconstruction



Phantom v2512

Resolution	FPS
1280 x 800	25,700
1024 x 512	47,400
256 x 256	206,300
128 x 64	783,100
256 x 32	1,000,000

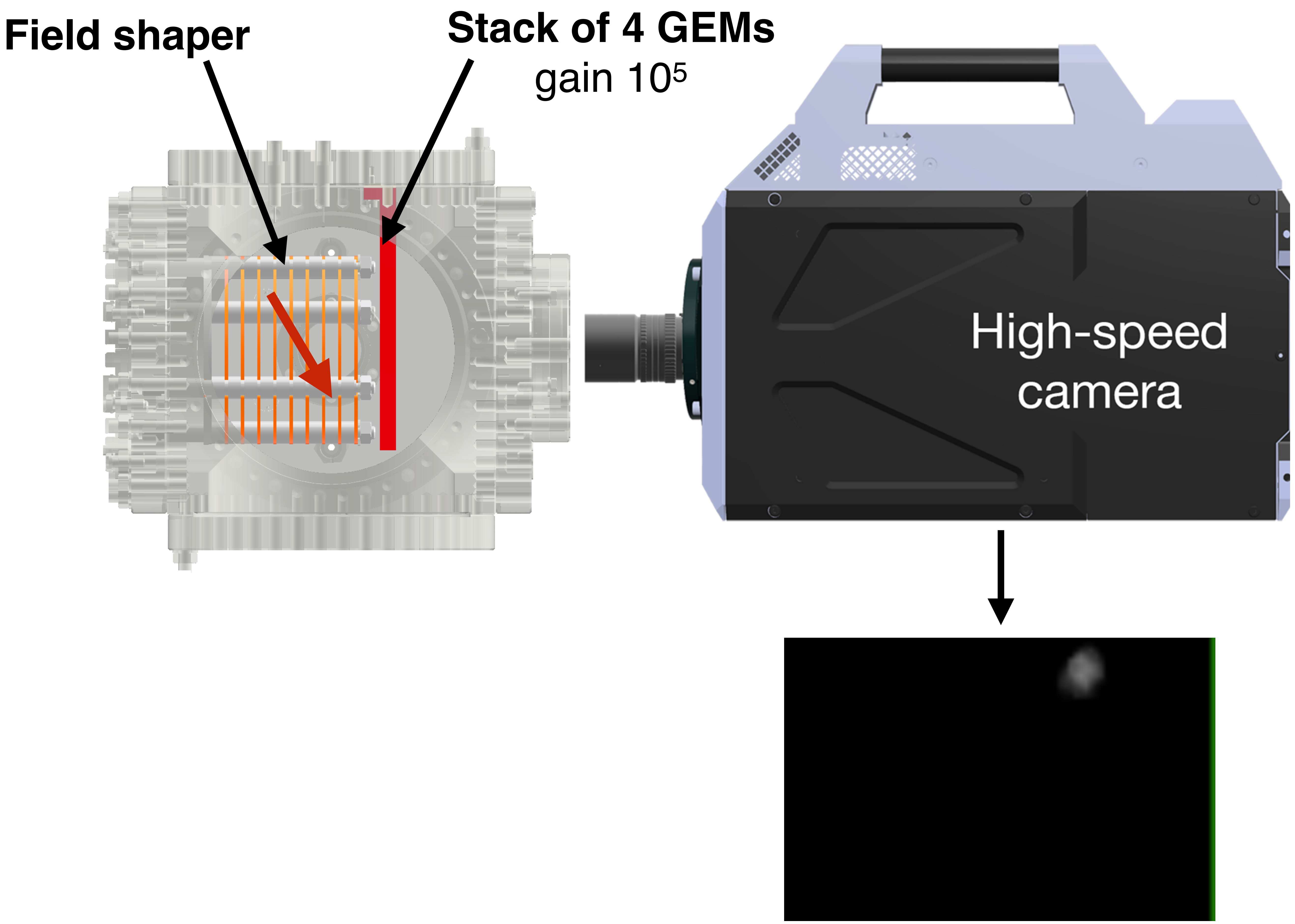
Optically read out TPC Ultra-fast CMOS



F. M. Brunbauer et al., IEEE NSS 2018

Schematics not drawn to scale

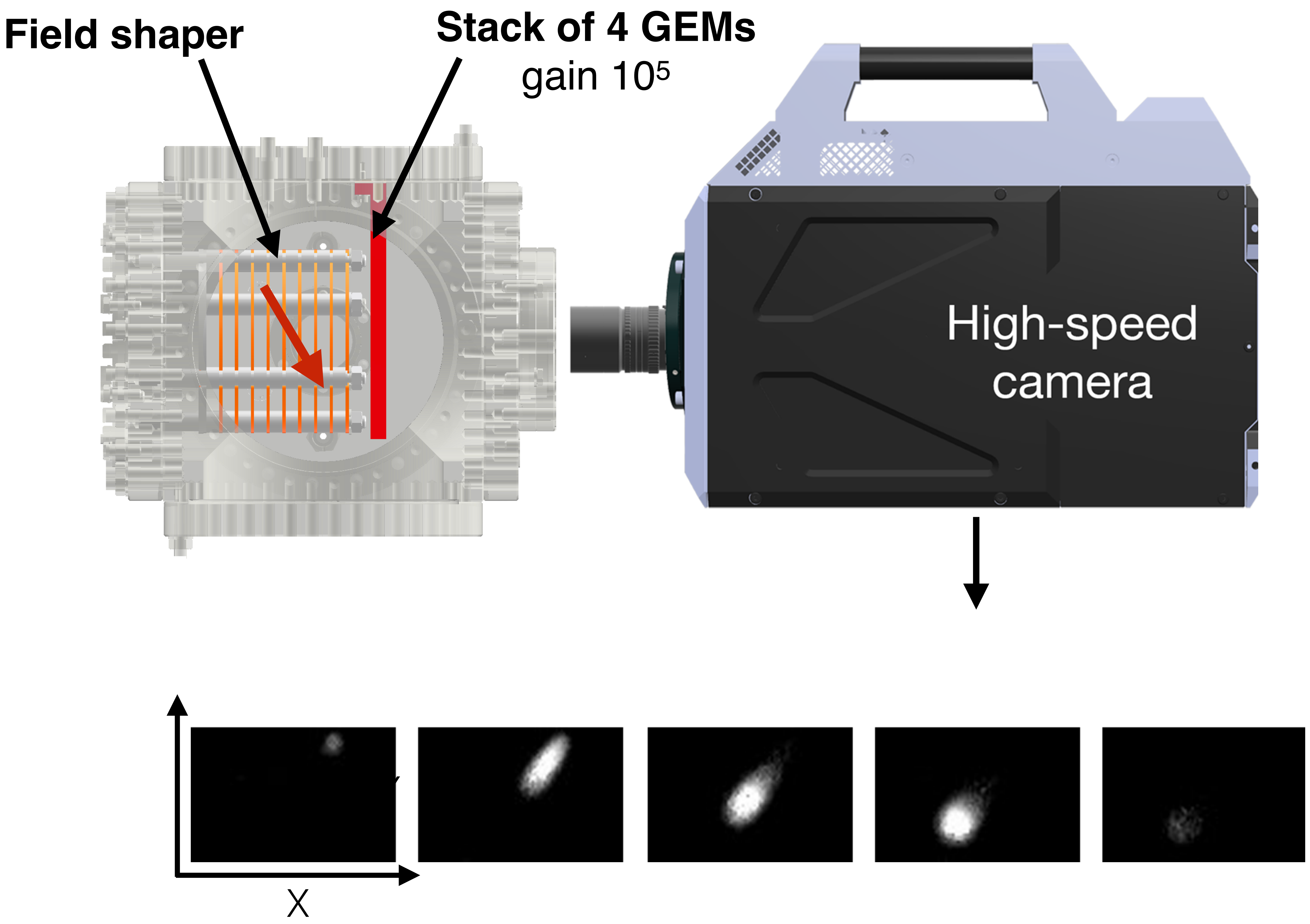
Optically read out TPC Ultra-fast CMOS



F. M. Brunbauer et al., IEEE NSS 2018

Schematics not drawn to scale

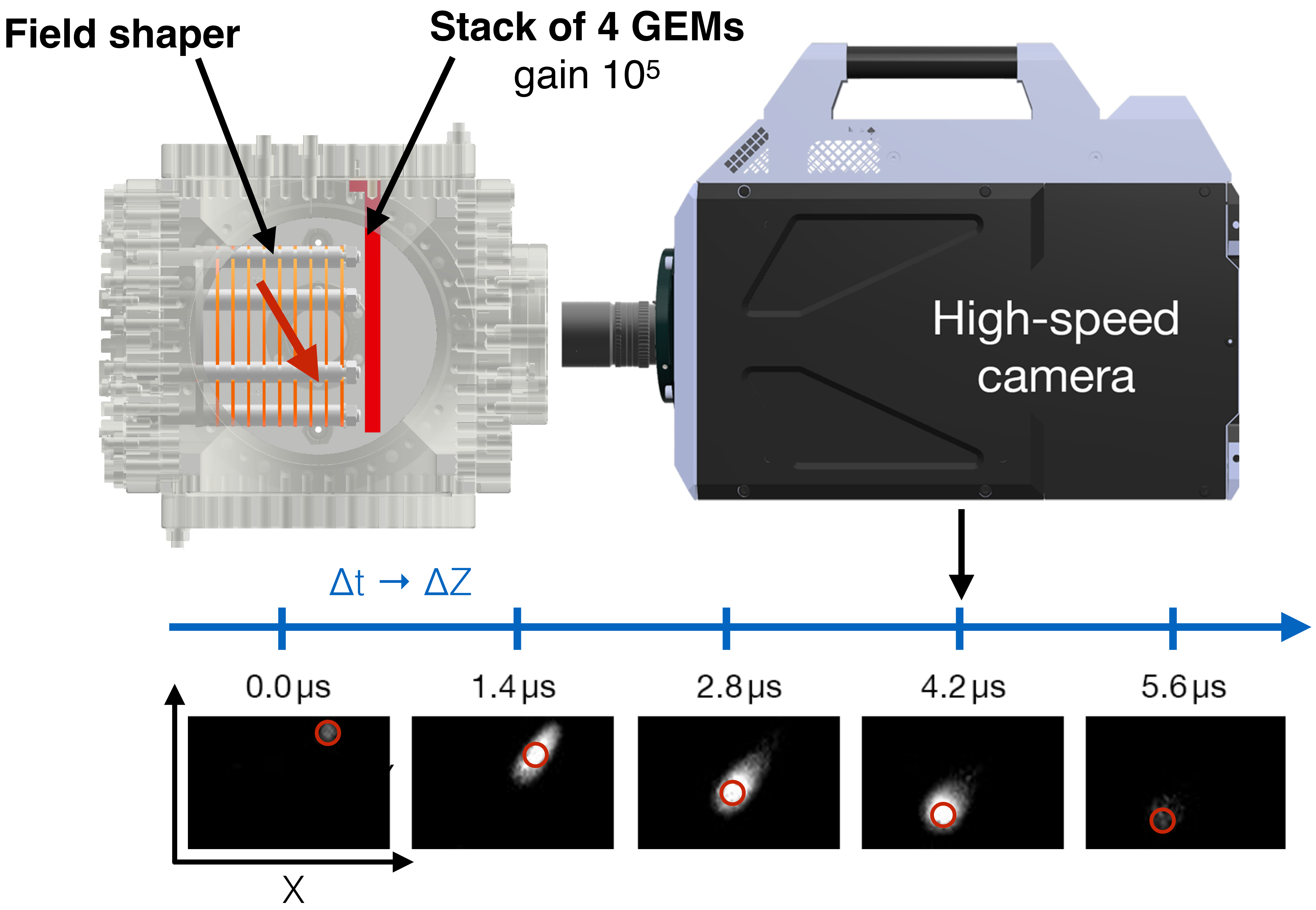
Optically read out TPC Ultra-fast CMOS



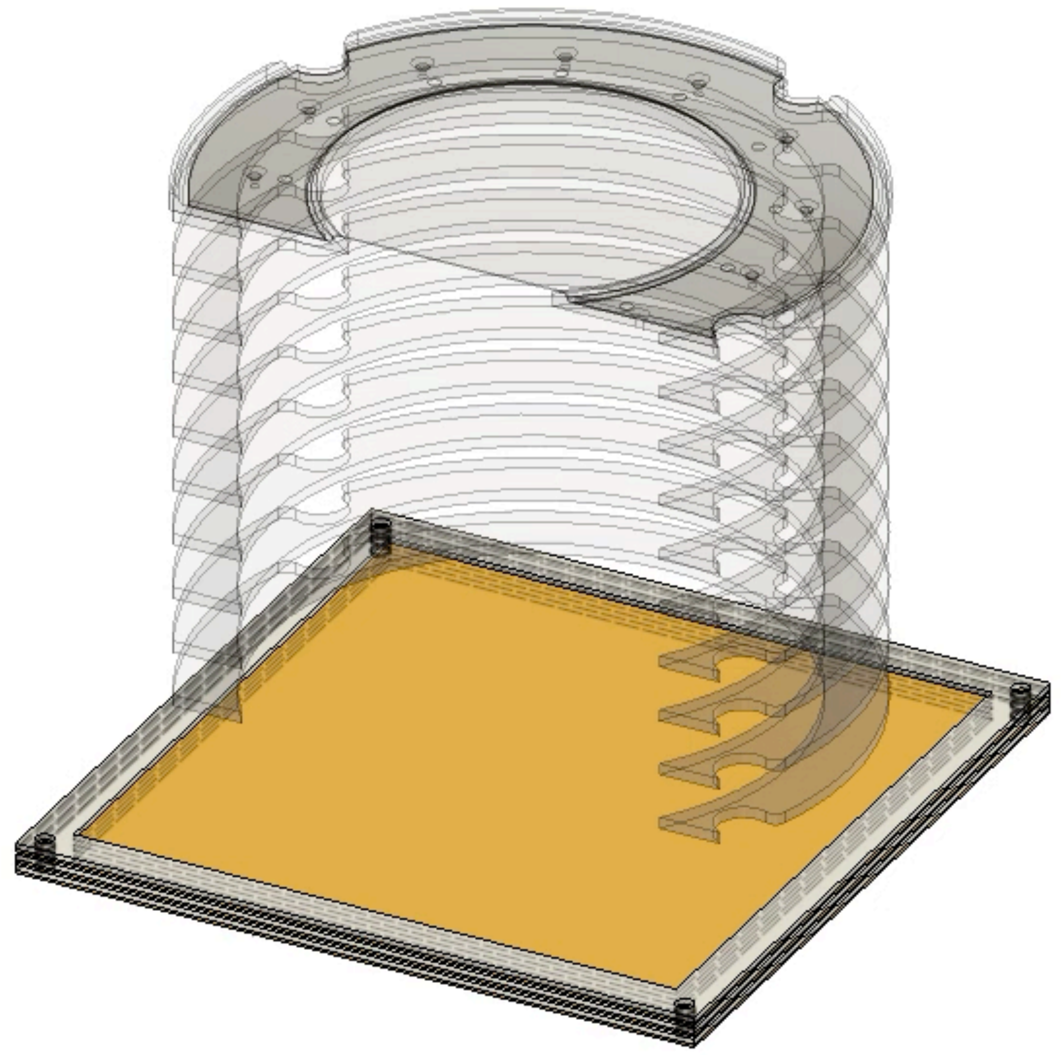
F. M. Brunbauer et al., IEEE NSS 2018

Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



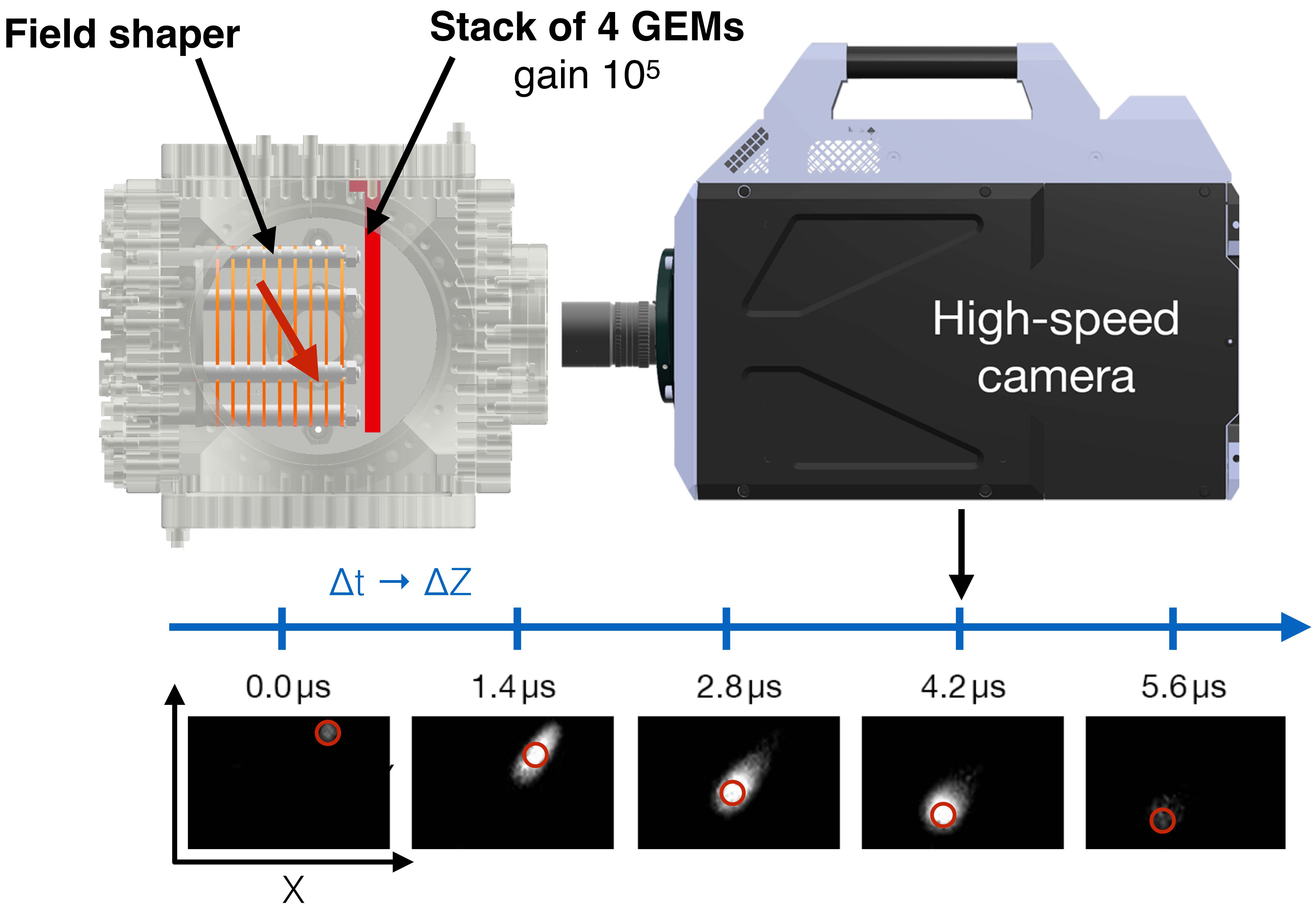
Recorded with 10 V/cm drift field corresponding to ≈0.5 cm/μs in Ar/CF_4



3D alpha track reconstruction (schematic)

Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



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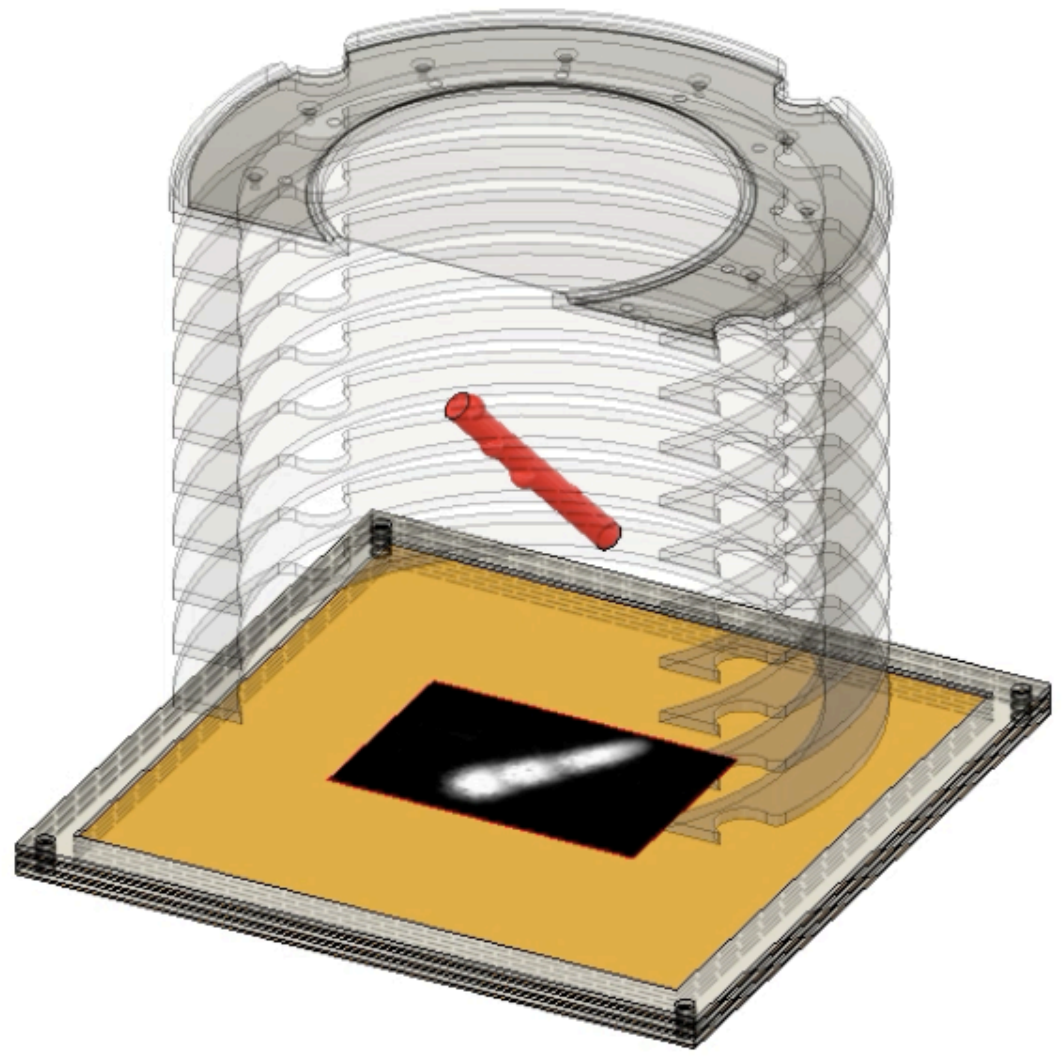


3D alpha track reconstruction (schematic)

Schematics not drawn to scale

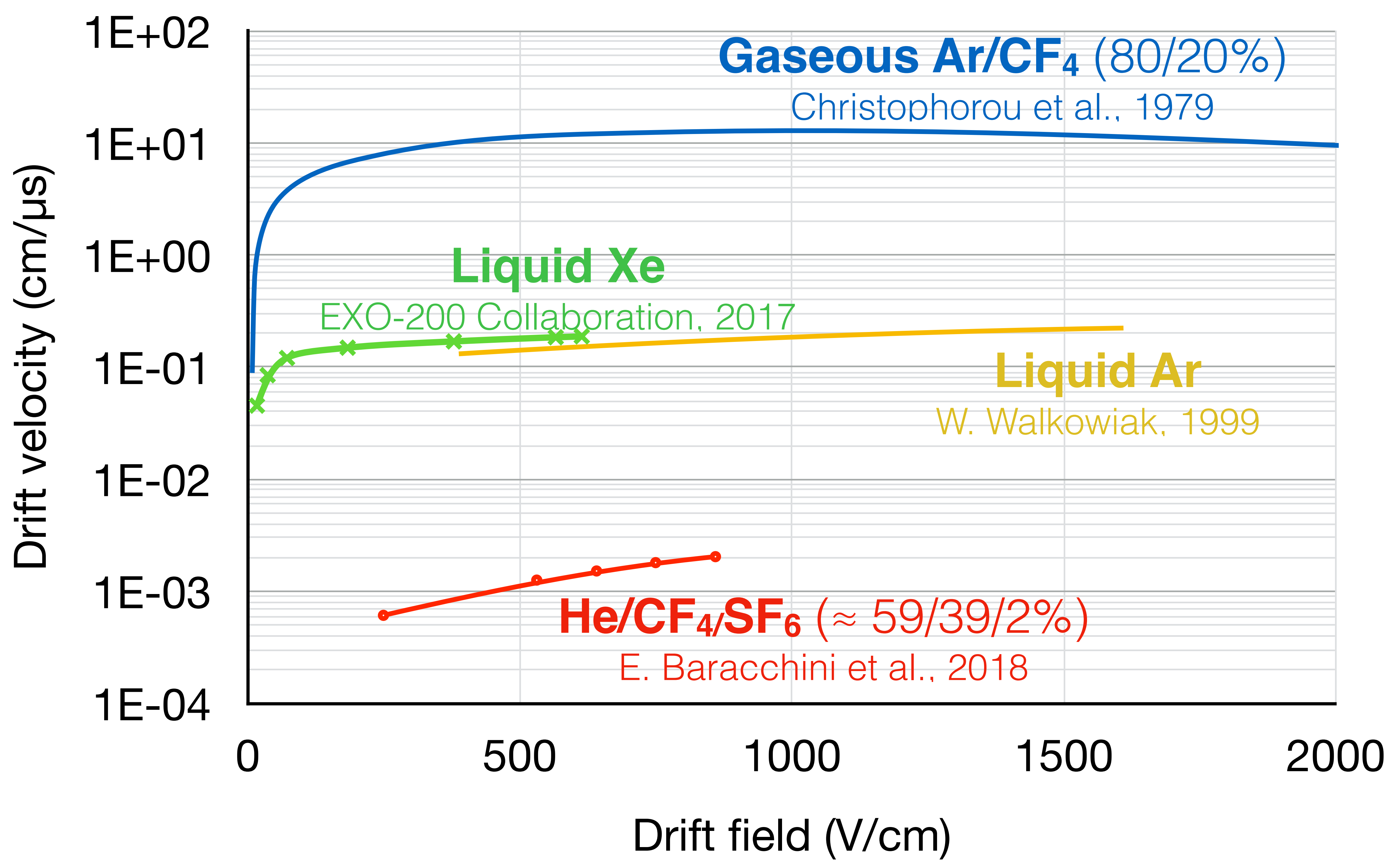
Perspectives for optical readout

Negative ion optical TPCs

Negative ion drift for optical TPCs

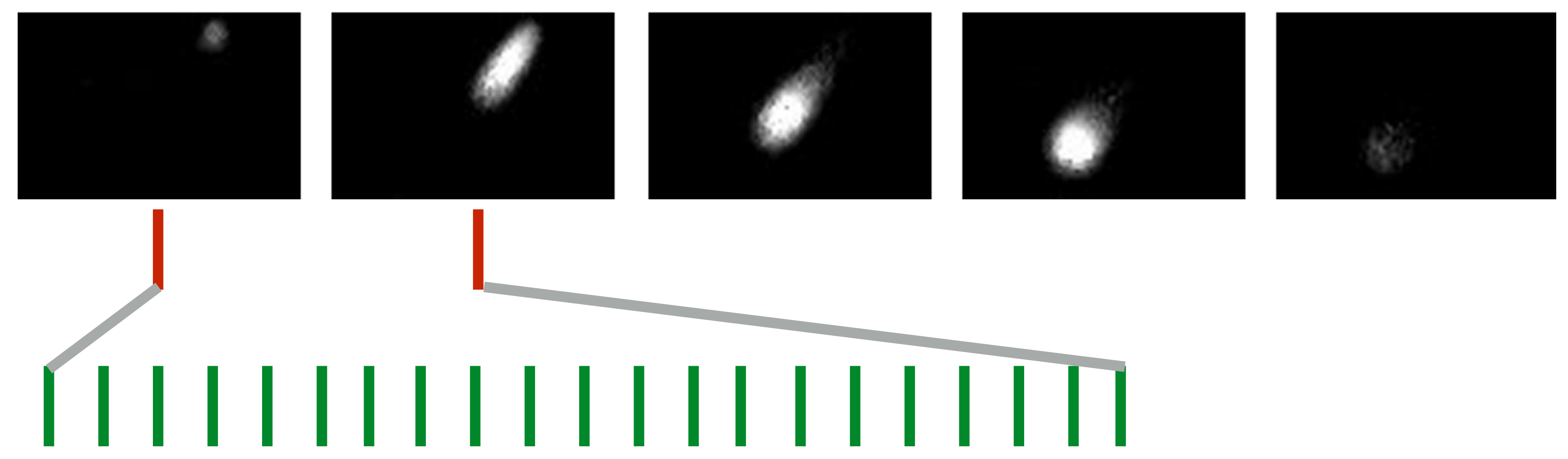
Low drift velocities

Negative ion drift can provide significantly slower drift velocities, which are ≈3 orders of magnitude slower than electron drift velocitites.
This may permit the recording of multiple frames at high resolution during negative ion drift time to achieve **depth resolution** well below millimetre scale.



Electron drift
5 mm/μs in Ar/CF_4
700 kFPS -> 1.4μs inter-frame time at 128x64 resolution
-> 7mm drift per frame

Negative ion drift
0.01 mm/μs in He/CF_4/SF_6
50 kFPS -> 20μs inter-frame time at 1024 x 512 resolution
-> 200μm drift per frame

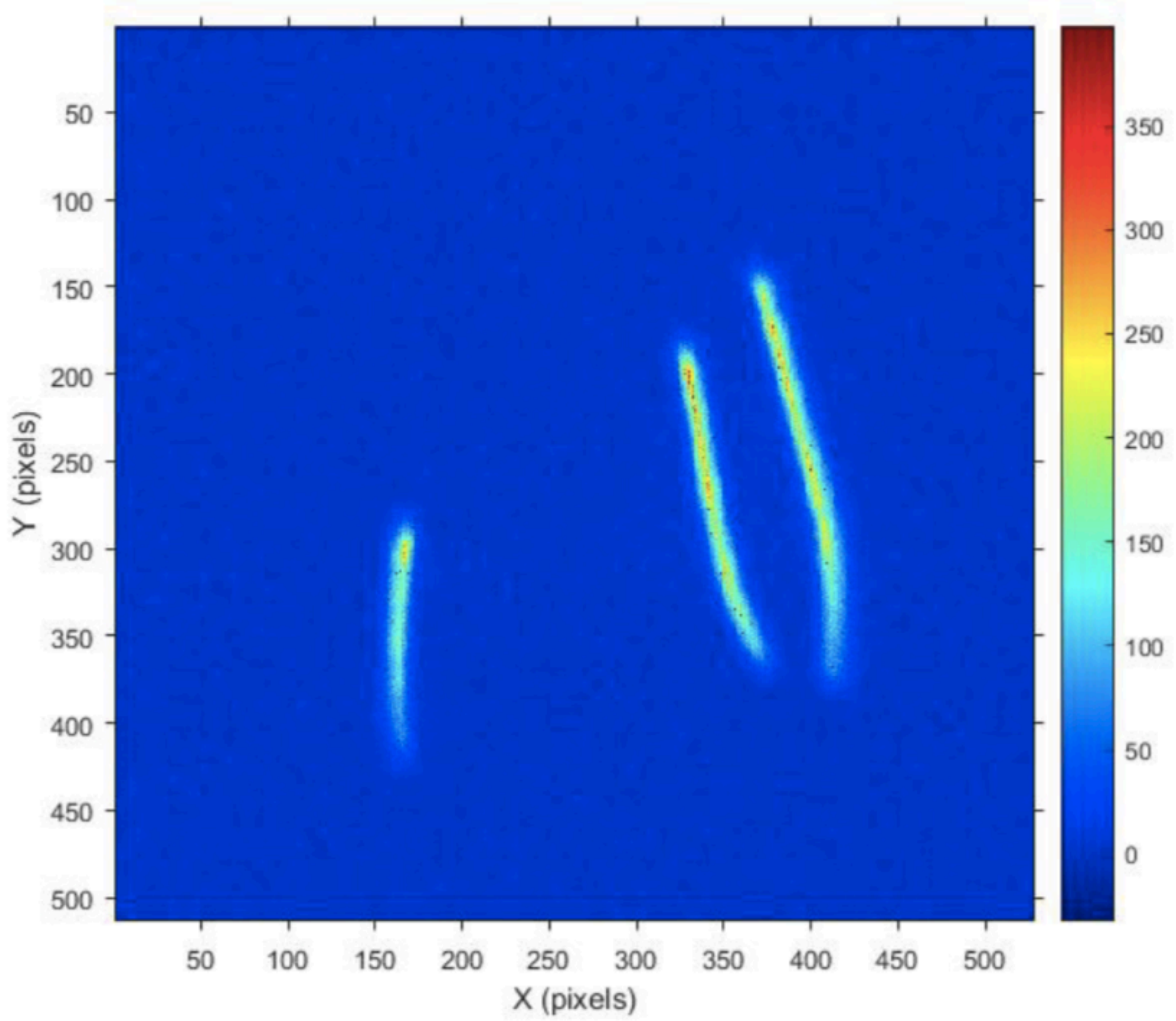


Negative ion drift for optical TPCs

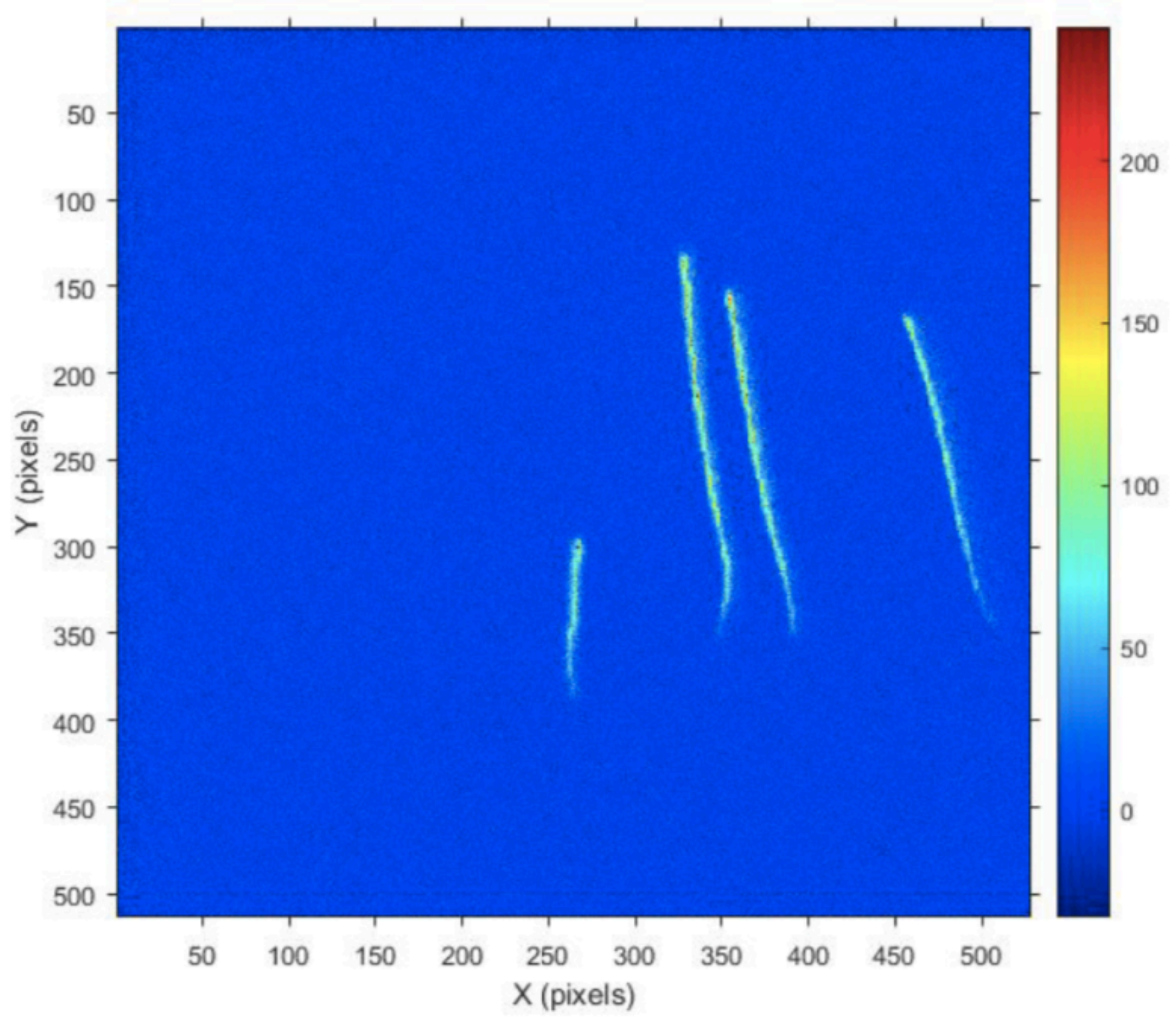
Low diffusion

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

May be exploited with high-pitch glass GEMs offering high gain at low pressure operation.

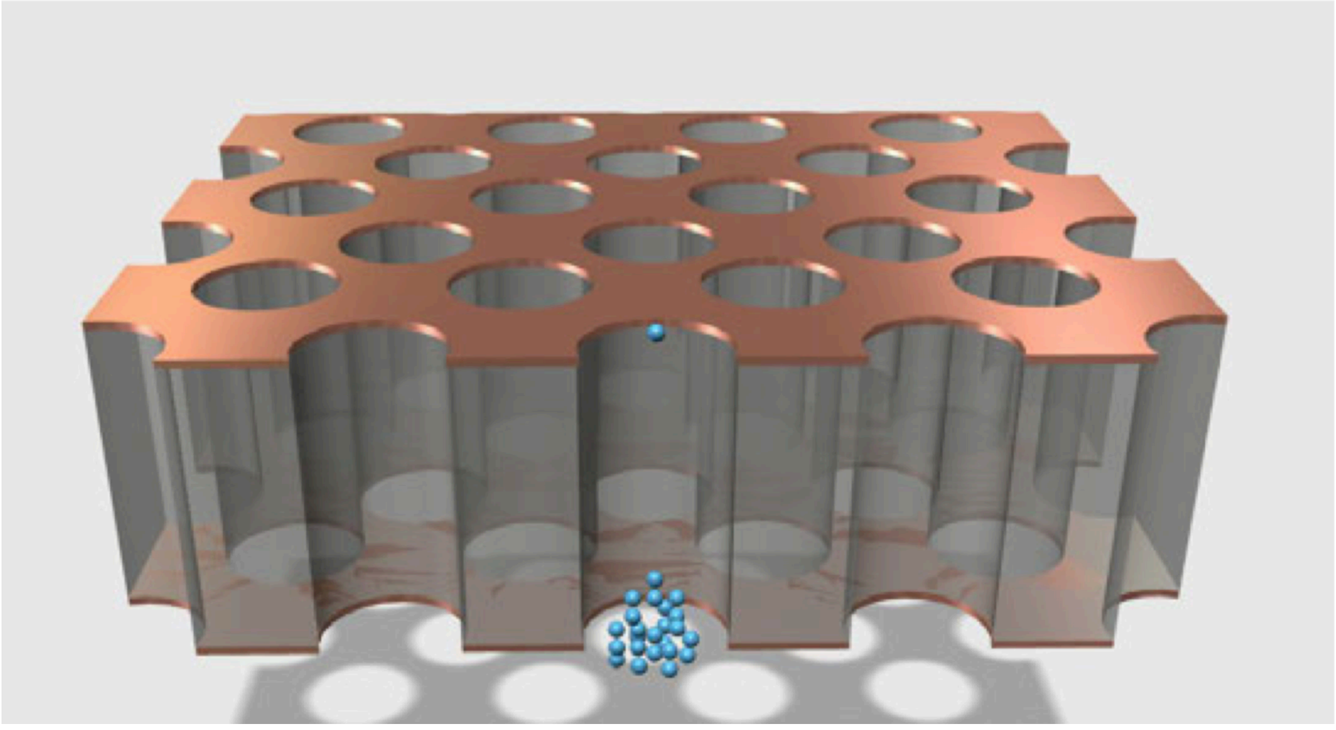


150 Torr CF_4, **$\sigma \sim 450$ um**



150 Torr $CF_4 + 5.9$ Torr CS_2, **$\sigma \sim 150$ um**

Glass GEMs for NI OTPCs



T. Fujiwara, MPGD2017

D. Loomba, UNM

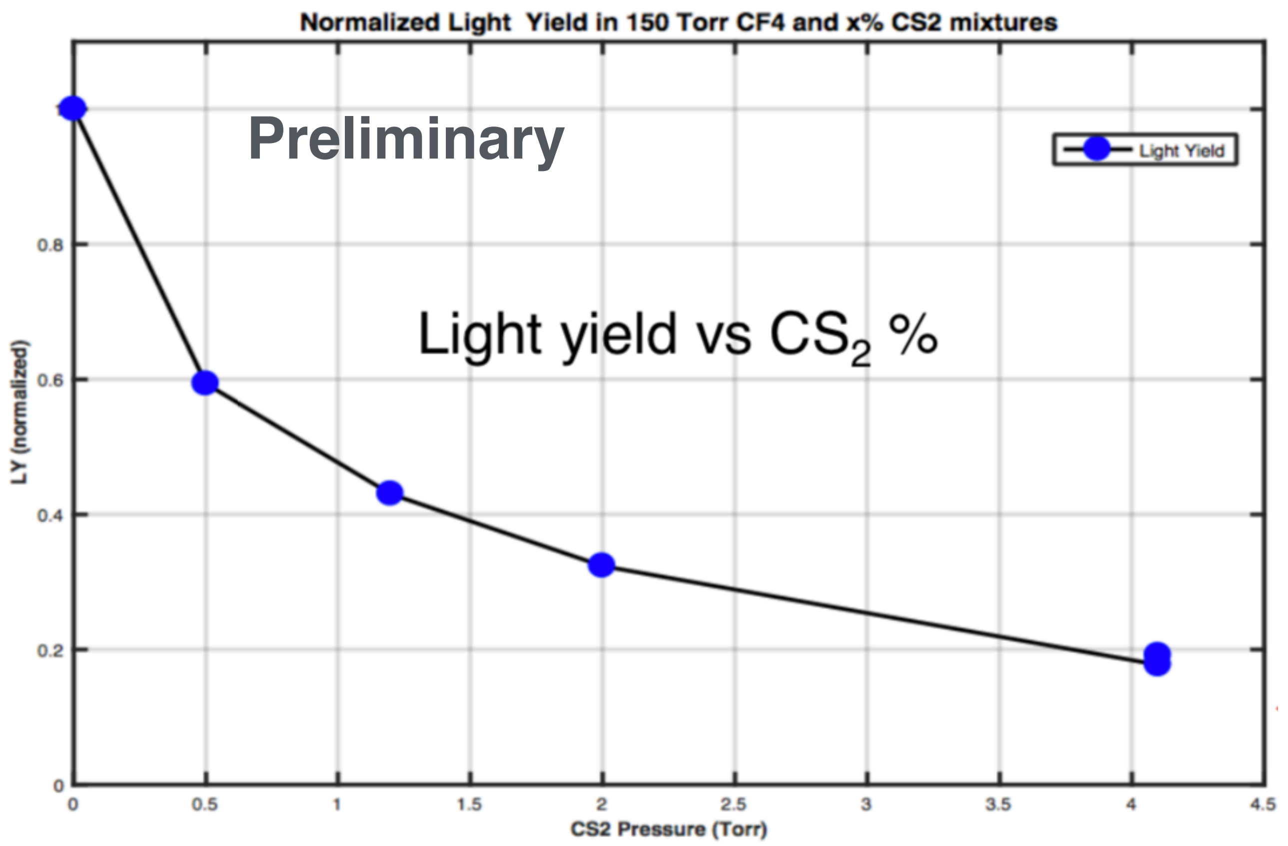
Negative ion drift for optical TPCs

Negative ion drift is very attractive for optical TPCs with superior resolution in all three coordinates:

- Suppressed diffusion to fully exploit high-granularity sensors
- Slow negative ion drift for excellent depth resolution

This comes with many challenges:

- Lower achievable gain
- Decreased light yield compared to electron drift gas mixtures
- Addition of electronegative ion gases such as SF_6 or CS_2
- Difficulties working with multi-stage amplification structures
- Effects of operating pressure on achievable gain



D. Loomba, UNM

Gas	Partial Pressure [Torr]
SF_6	75 ± 2
SF_6	100 ± 2
SF_6	150 ± 3
$He:CF_4:SF_6$	60 : 40 : 120 ± 4
$He:CF_4:SF_6$	360 : 240 : 10 ± 10
$Ar:CO_2:SF_6$	192 : 85 : 93 ± 7

E. Baracchini et al 2018 JINST 13 P04022

Conclusions

- Image sensors offer **high spatial resolution**, **flexibility** and adaptability for imaging applications and 3D track reconstruction in optical TPCs
- State-of-the-art CCD and CMOS sensors with low readout noise characteristics are used to record **secondary scintillation light** from MPGD-based amplification structures
- 2D information must be combined with depth information from fast **timing detectors** (PMTs, electronic readout, …) for 3D track reconstruction
- **Ultra-fast CMOS cameras** may be able to resolve drift time differences in image sequences recorded at tens of thousands of frames per second
- **Negative ion gas mixtures** are attractive for optical TPCs to fully exploit **superior diffusion** characteristics and very **low drift velocities**. Achievable gain and light yield in negative ion gas mixtures makes optical readout challenging.

Backup

Frame-based imaging sensors

Resolution: number of pixels available on sensor

Pixel size: sensitive area per cell, important for sensitivity

Quantum efficiency: response of sensor to incident photons

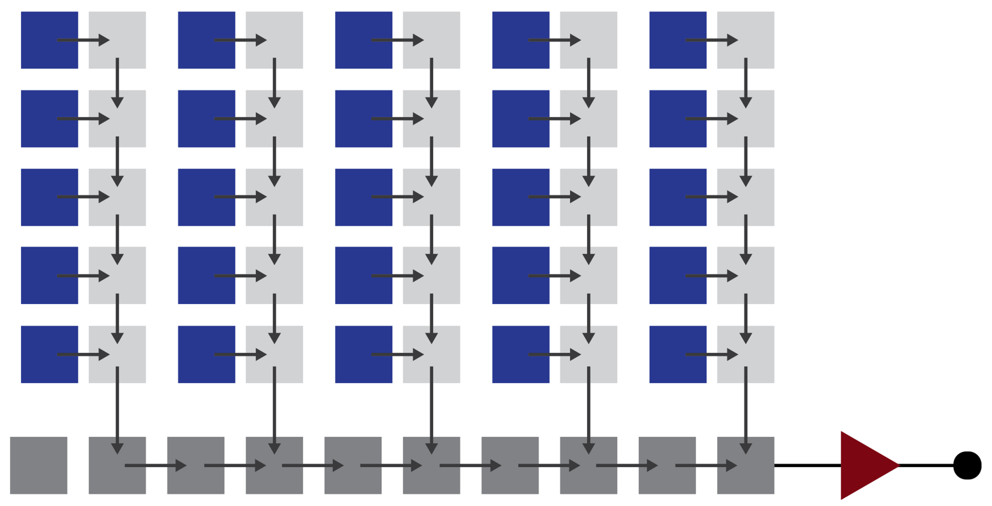
Well-depth: max. number of electrons per pixel -> dynamic range

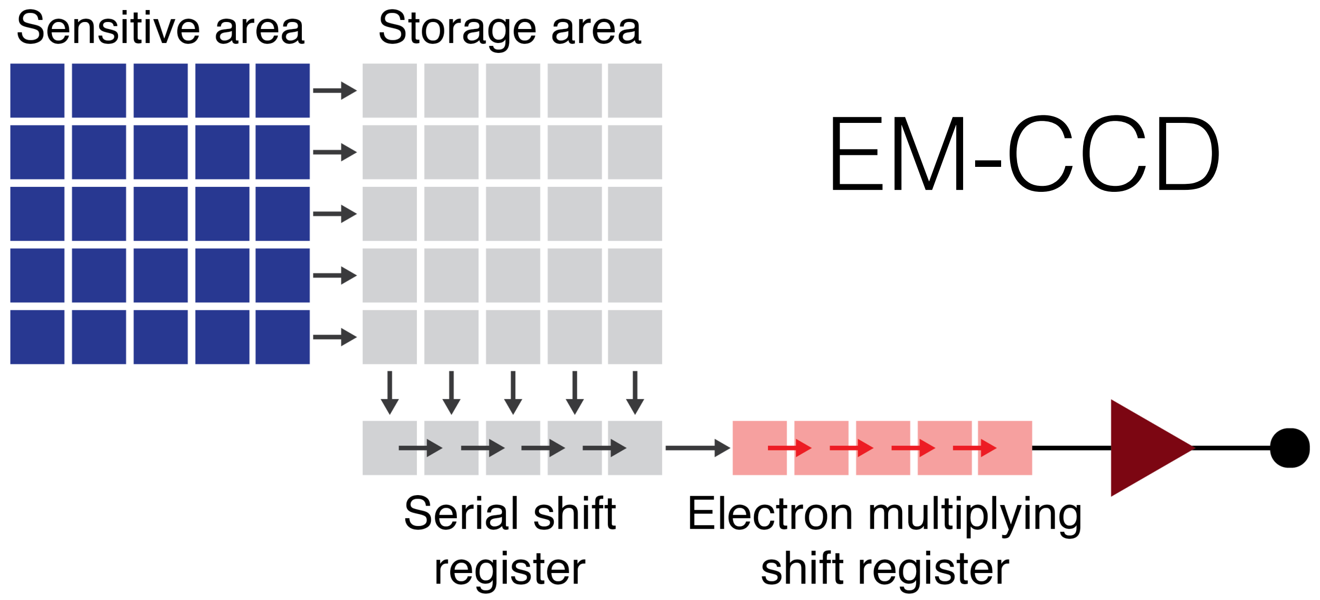
Readout noise: fixed noise in e- added during sensor readout, e.g. few e-

Dark noise: exposure-time dependent noise relevant for long exposures, e.g. 0.0009 e- / pixel /s

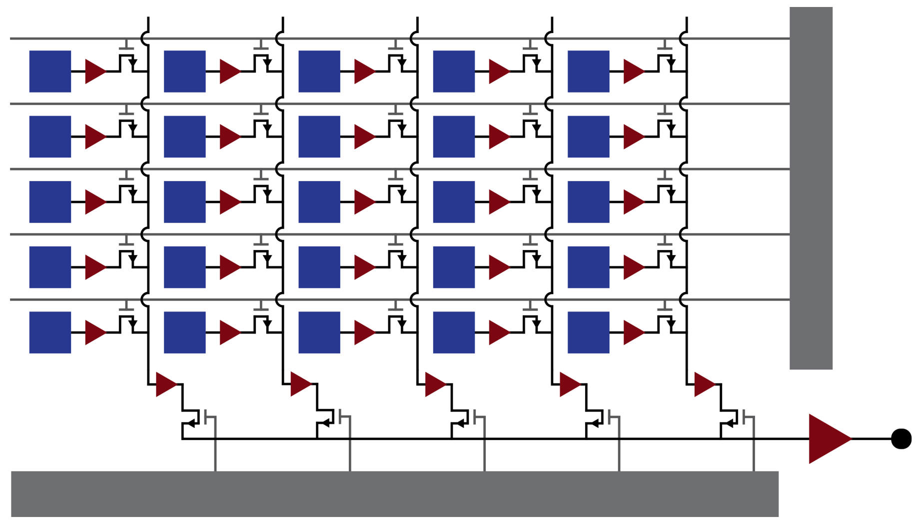
Frame rate: readout rate from sensor and digitisation electronics

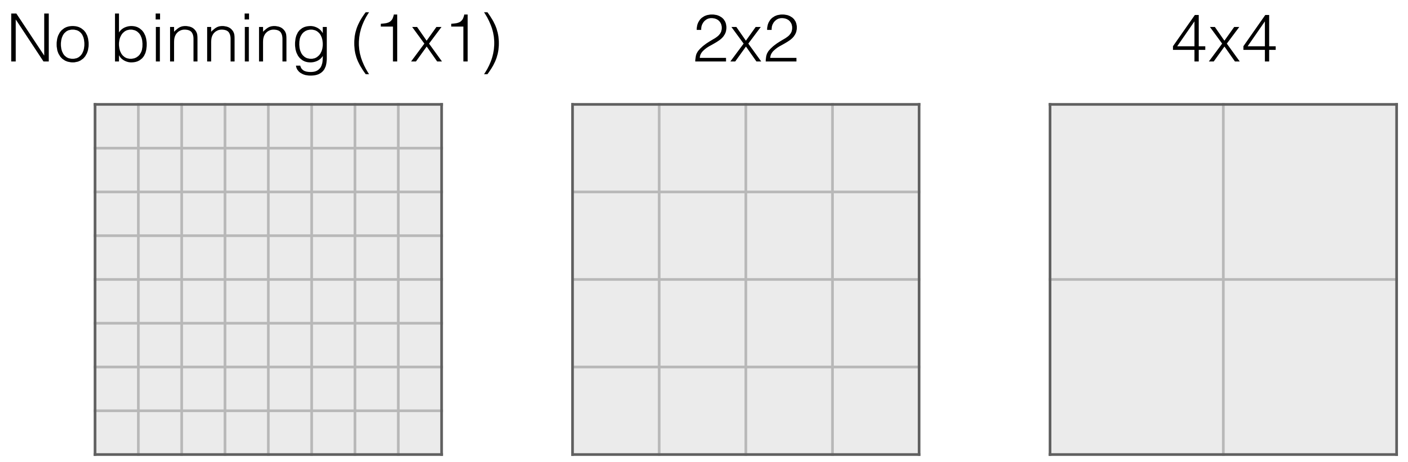
Binning: combination of pixels to larger “virtual” pixels to increase SNR, e.g. 2x2, 4x4


CCD

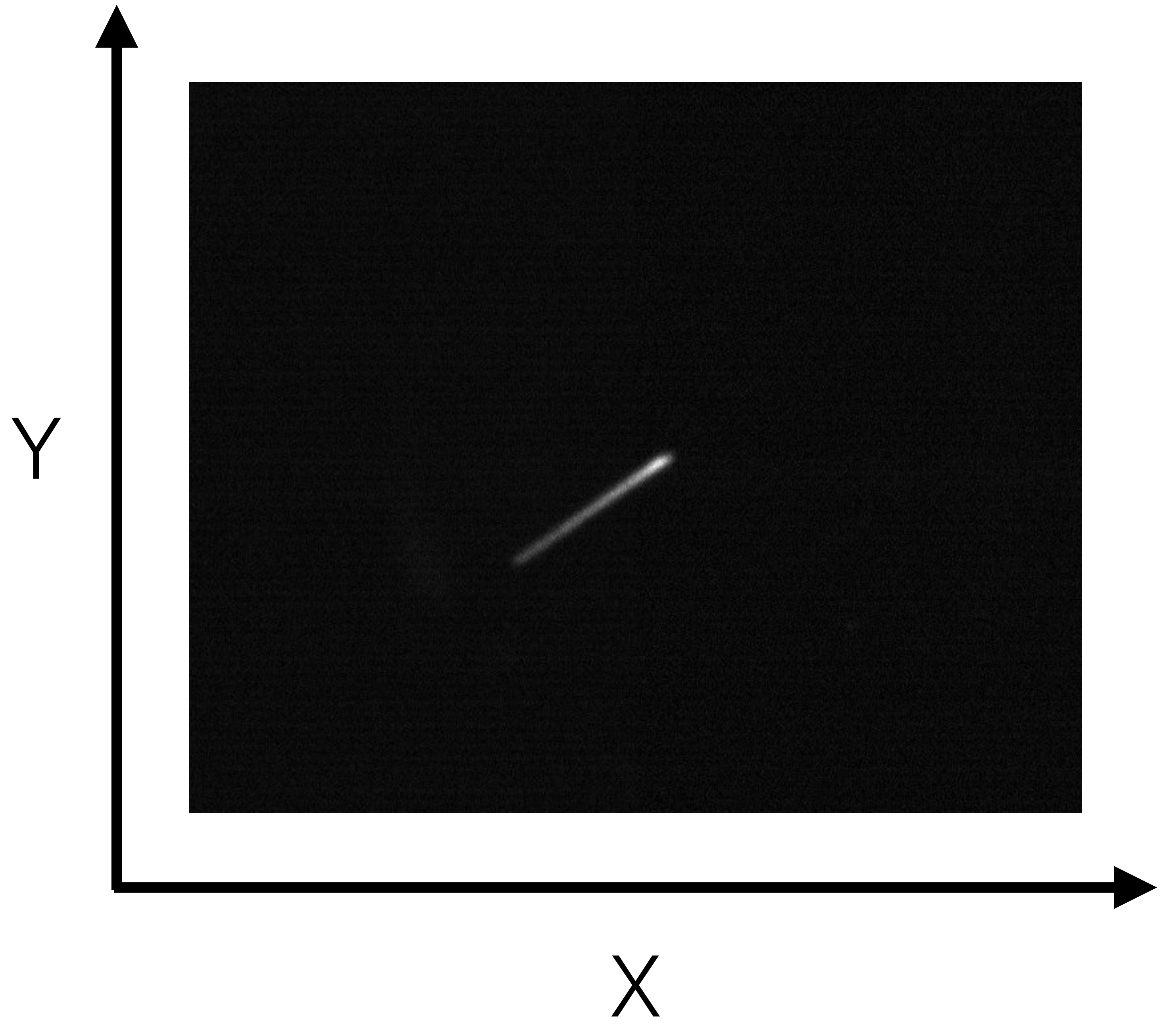


EM-CCD


CMOS



Optical readout of TPCs



2D projection

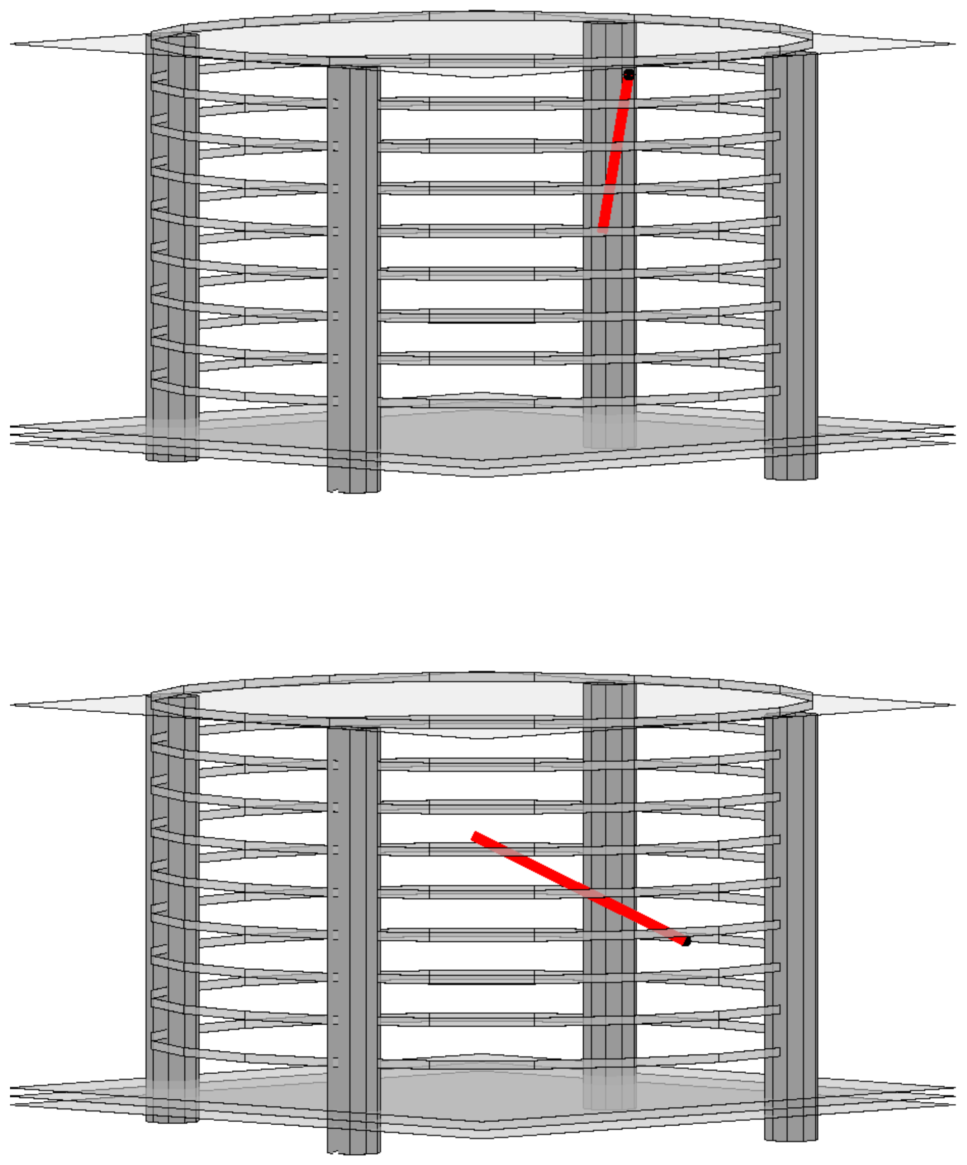
+

Camera + PMT

Camera + Electronic

Ultra-fast cameras?

Depth information

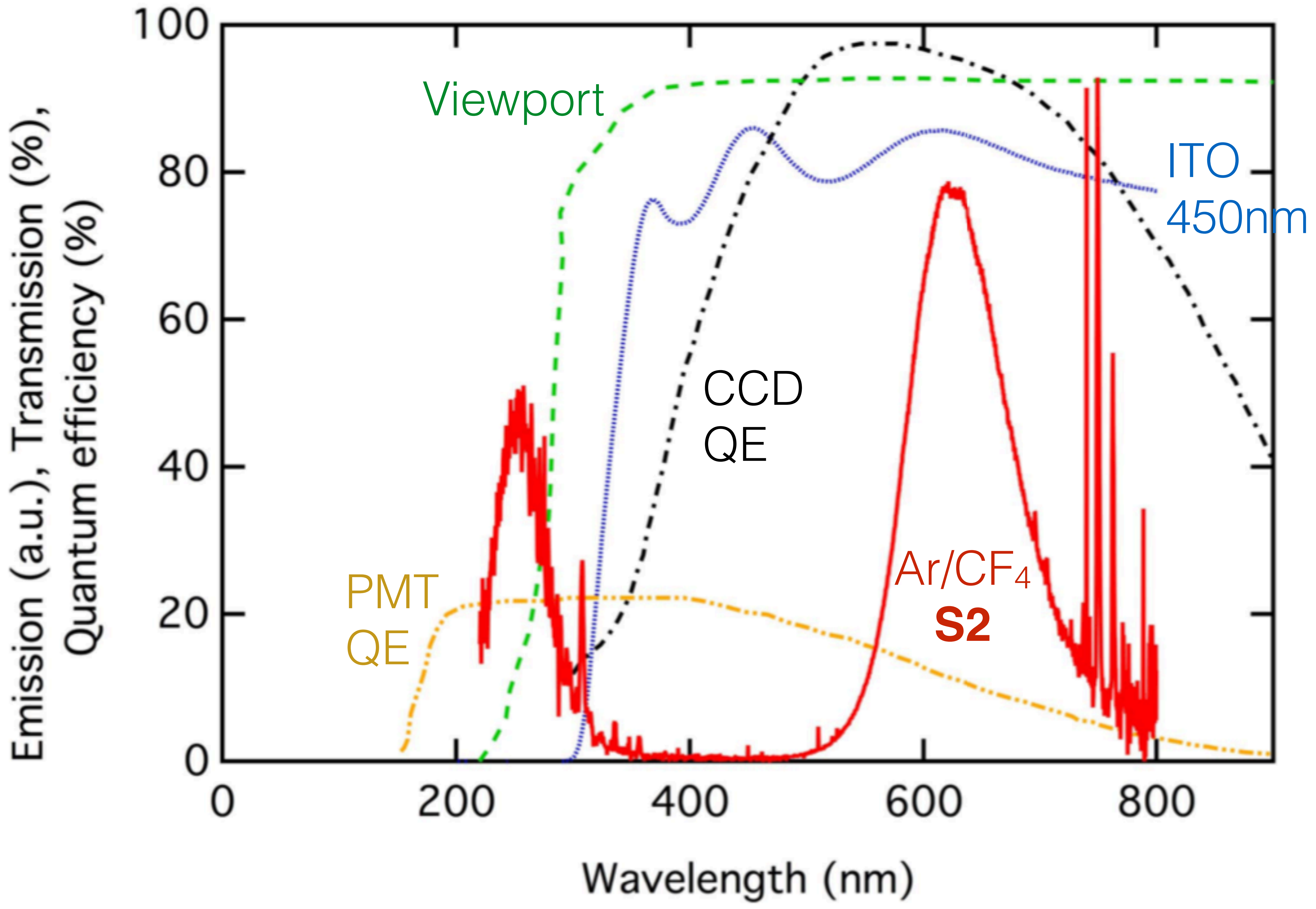


3D track reconstruction

Schematics not drawn to scale

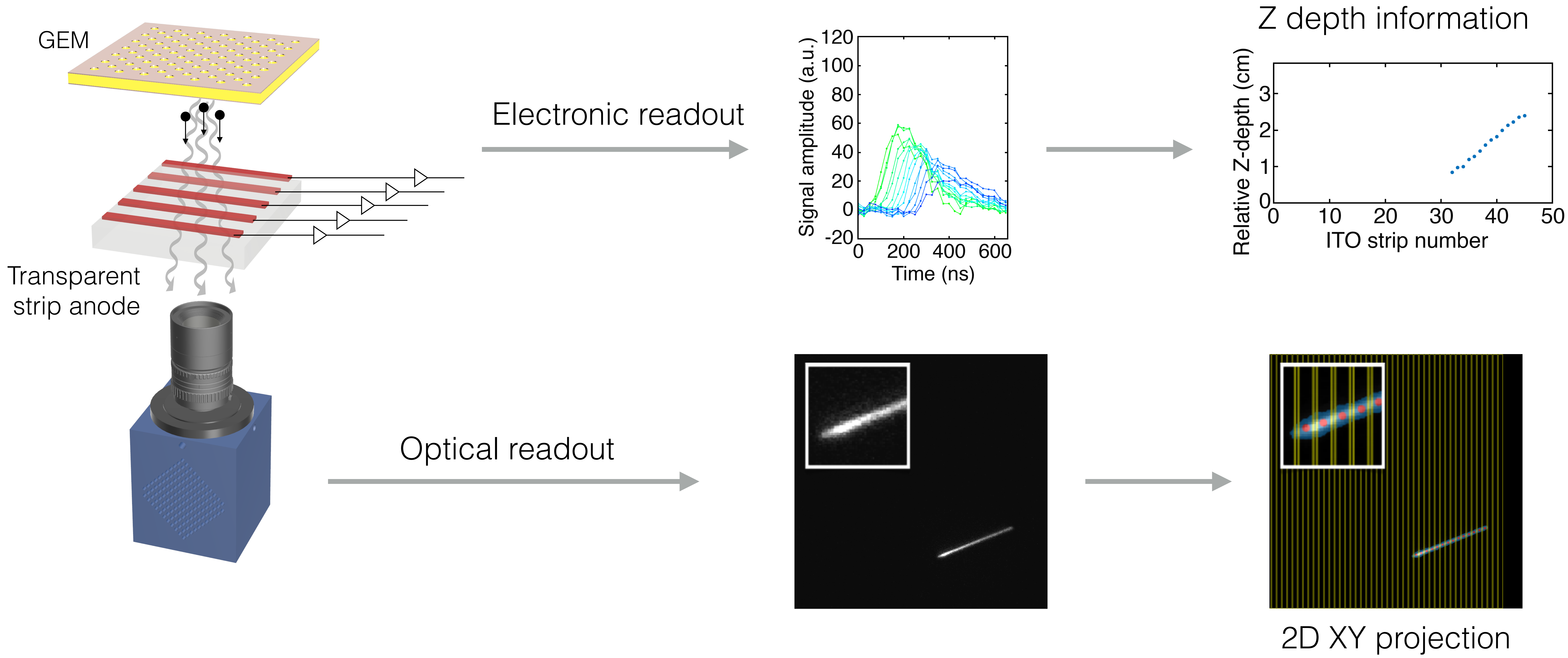
Indium tin oxide (ITO) for transparent anodes

Structured, conductive anode with good transparency



- 48 strips: 1.5 mm wide at 2 mm pitch
- 450 nm ITO on glass
- Structured by direct laser lithography and etching

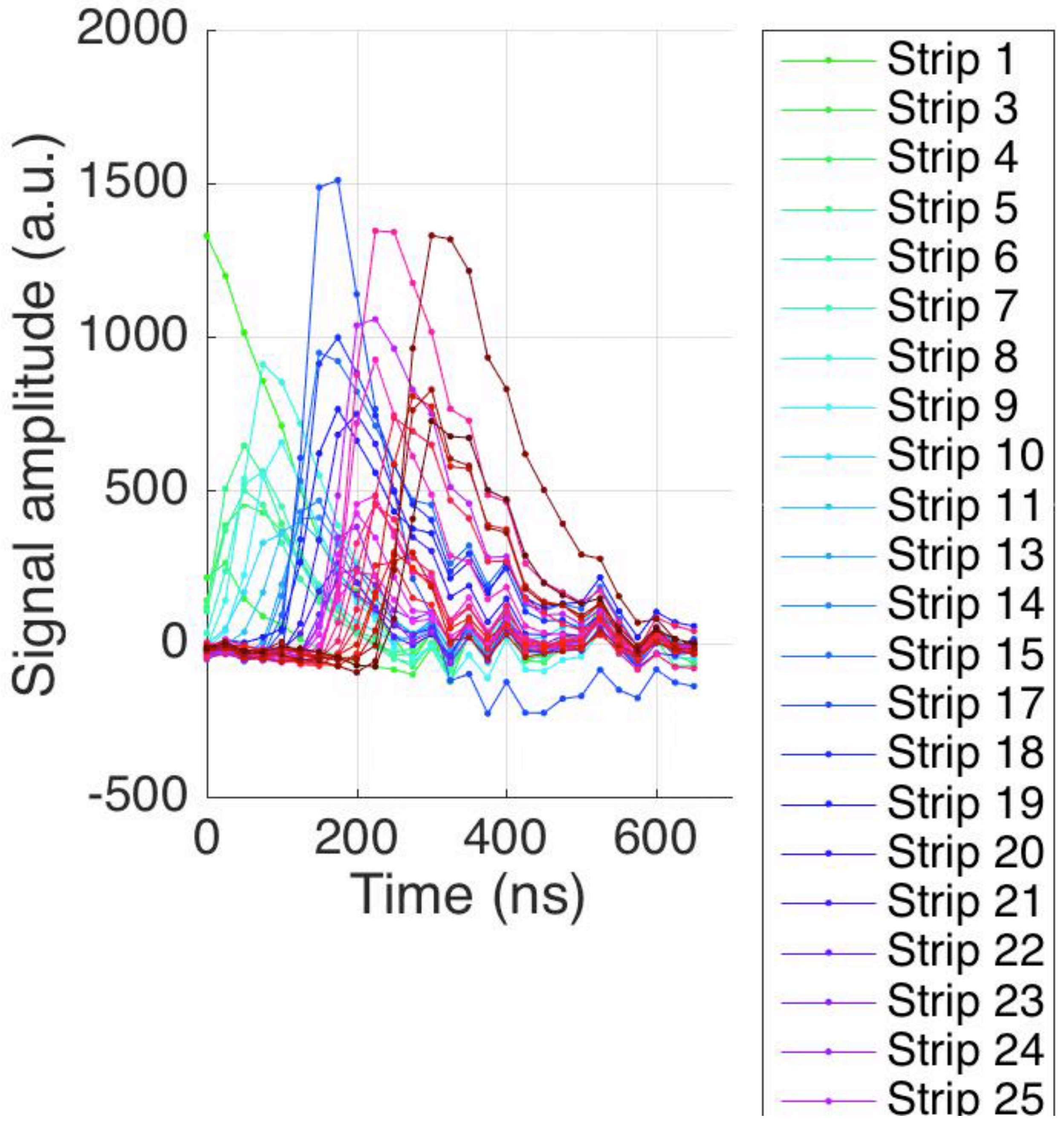
Optically read out TPC Camera + Electronic



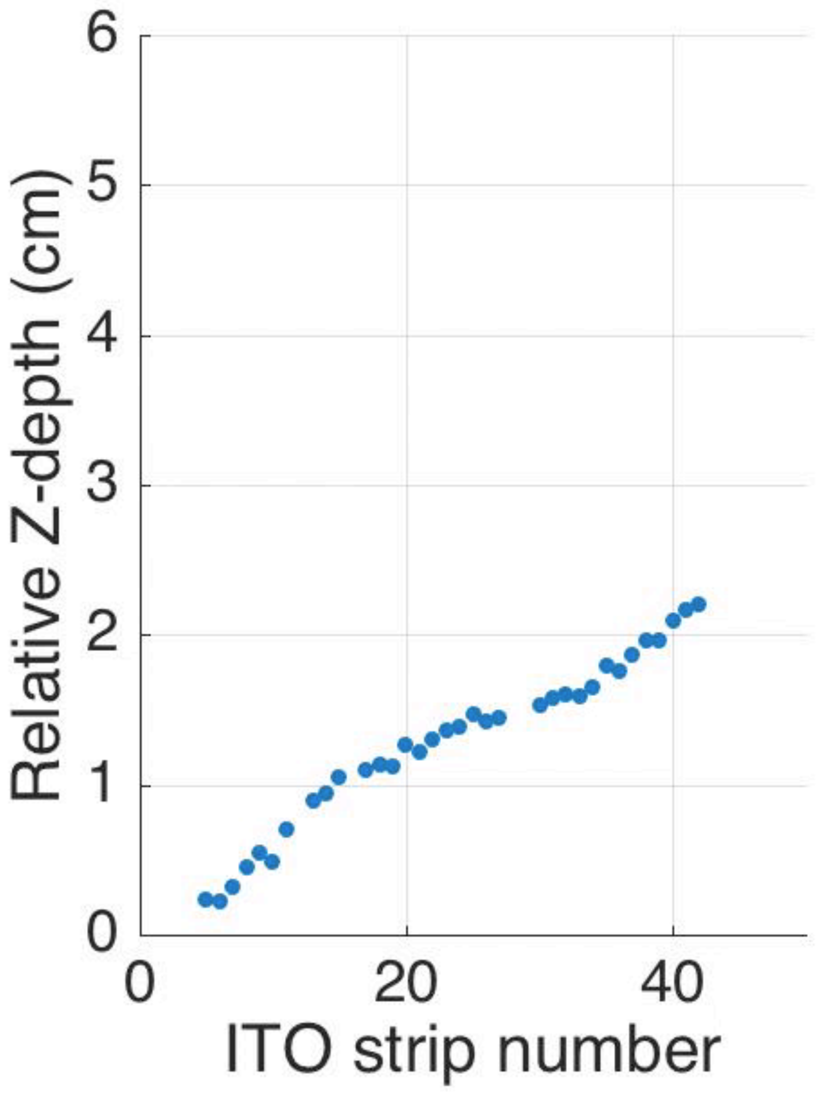
F. Brunbauer et al. IEEE TNS, VOL. 65, NO. 3, 2018
Schematics not drawn to scale

Optically read out TPC Camera + Electronic

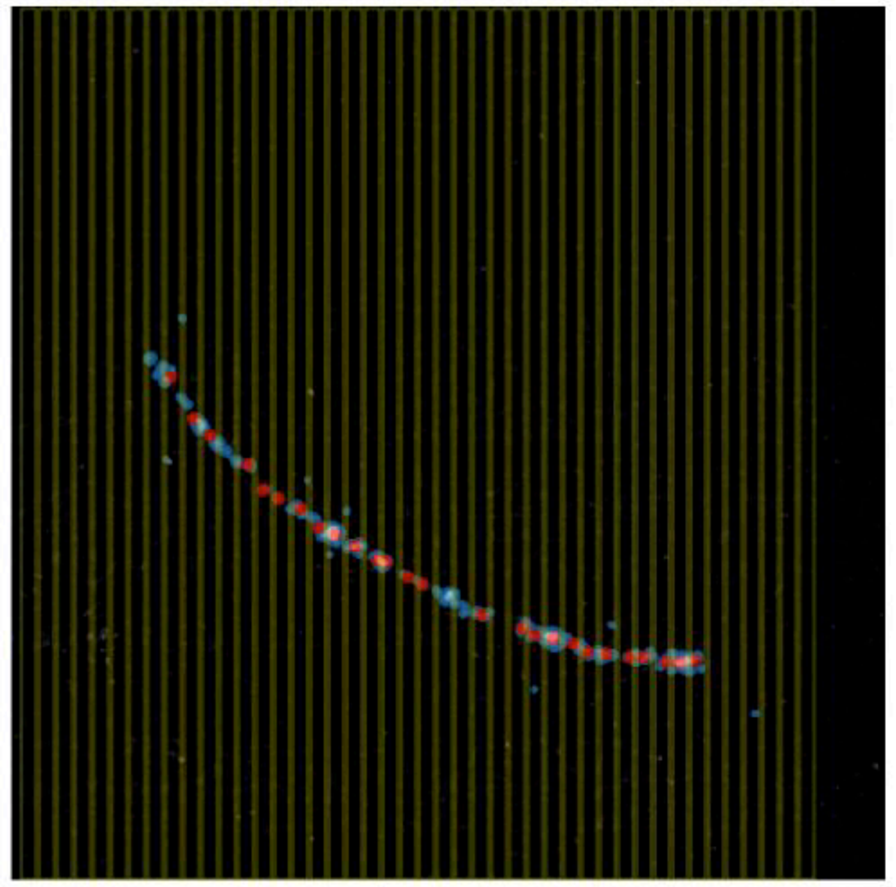
ITO strip signals



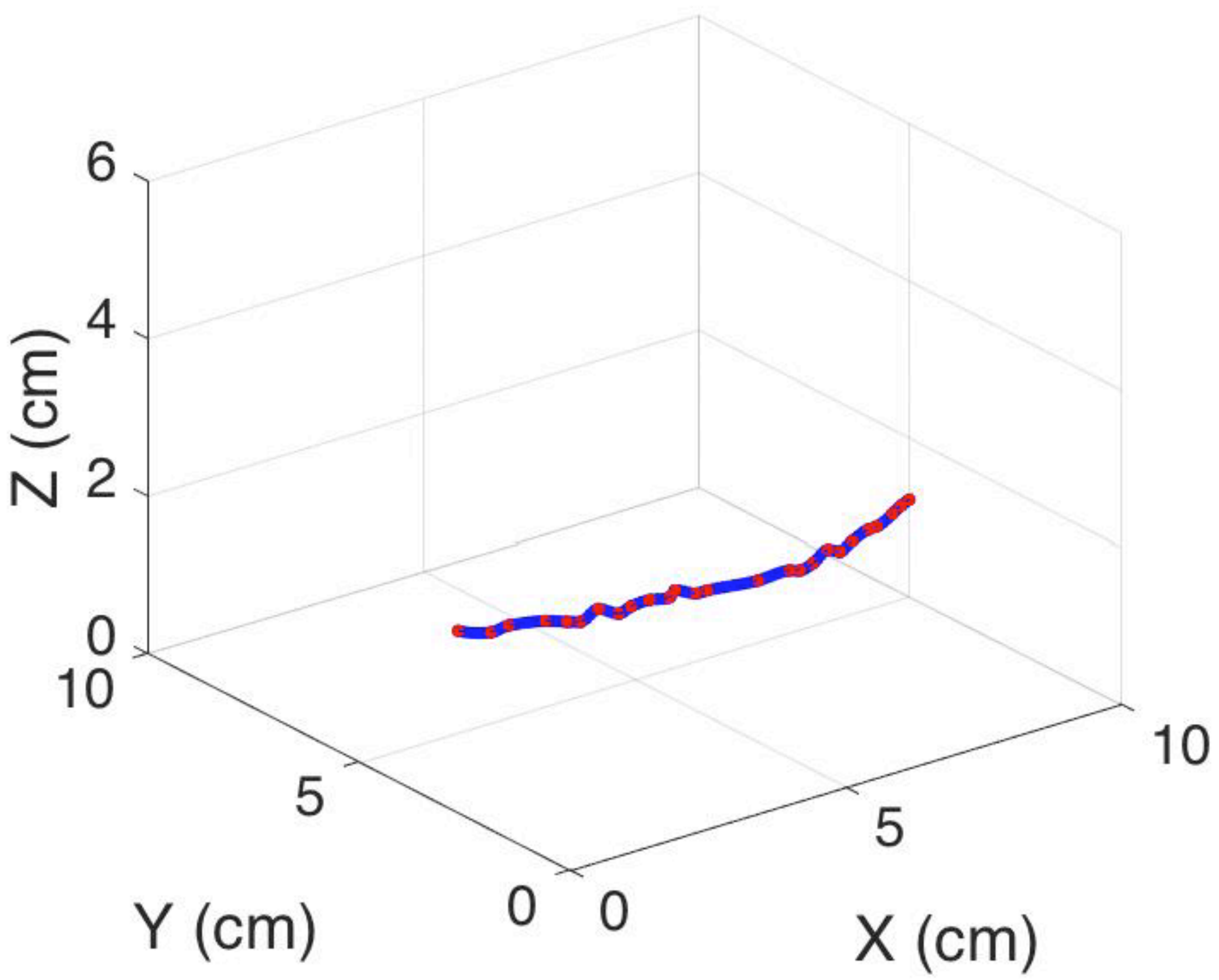
Depth information



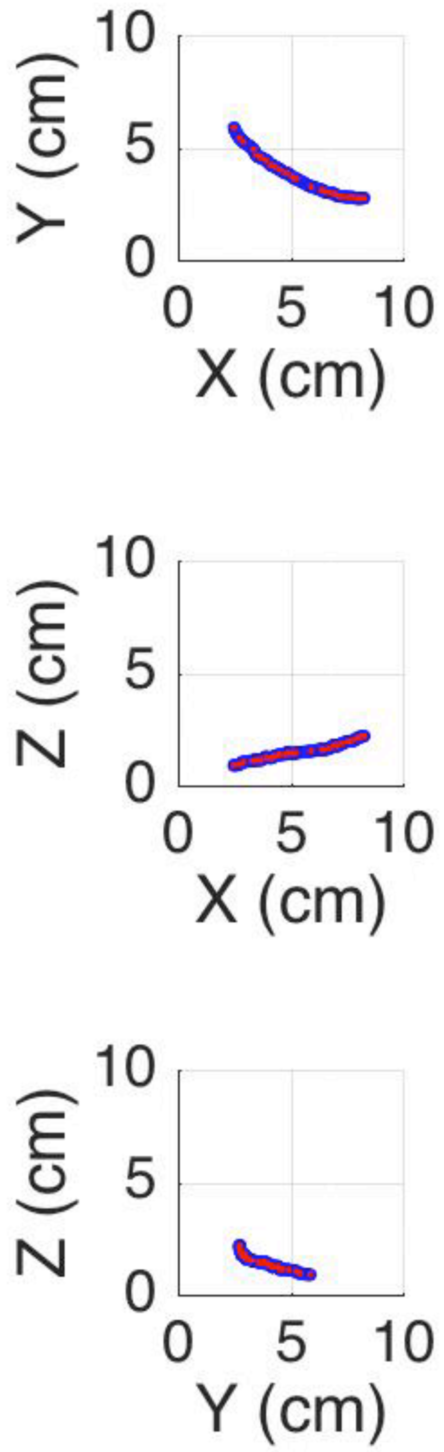
Camera image



3D track visualisation



Projections



F. Brunbauer et al. IEEE TNS, VOL. 65, NO. 3, 2018