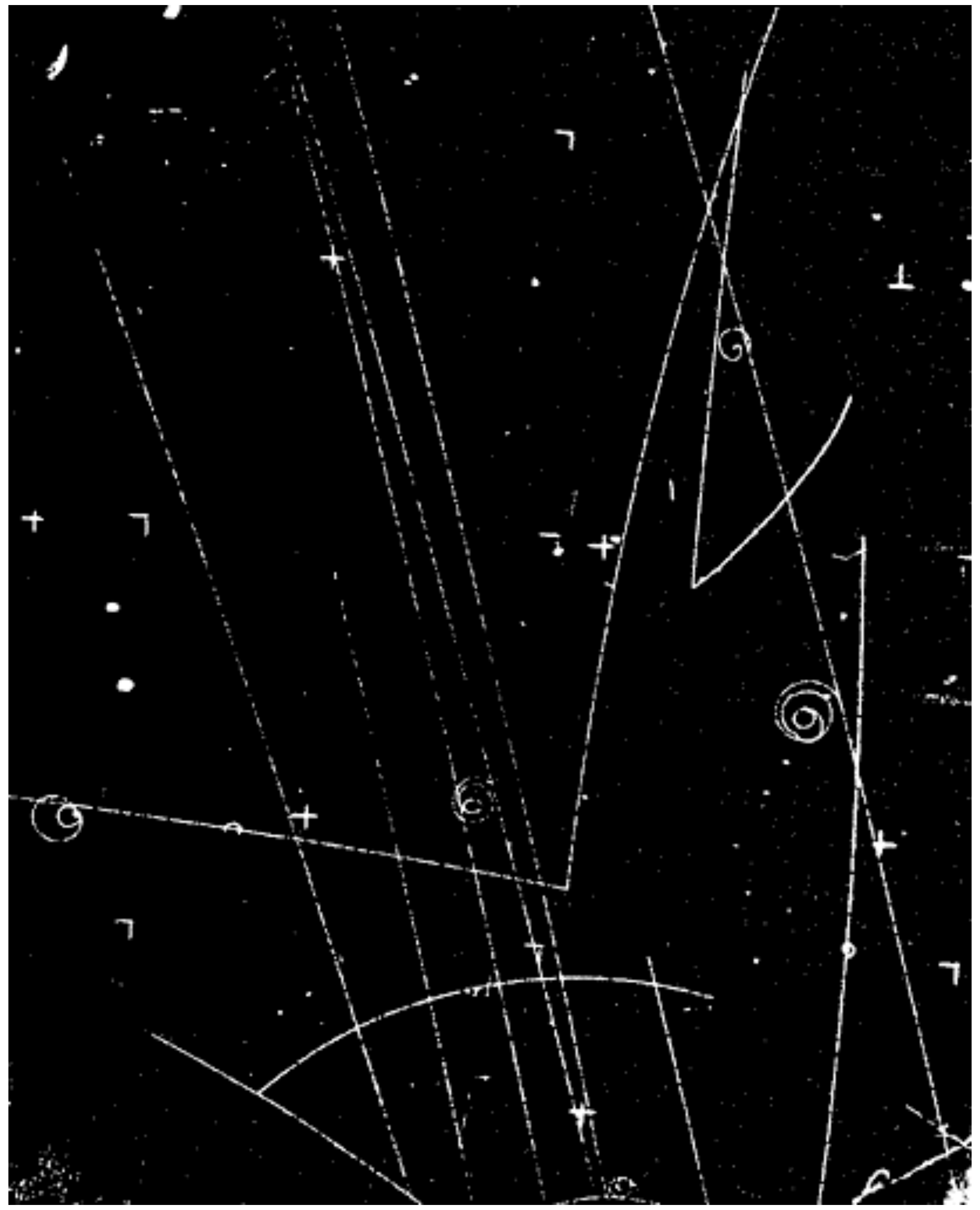
The optical readout options for cluster counting in dE/dx

F. M. Brunbauer (CERN GDD)

February 17, 2021 - RD51 Workshop on Gaseous Detector Contributions to PID

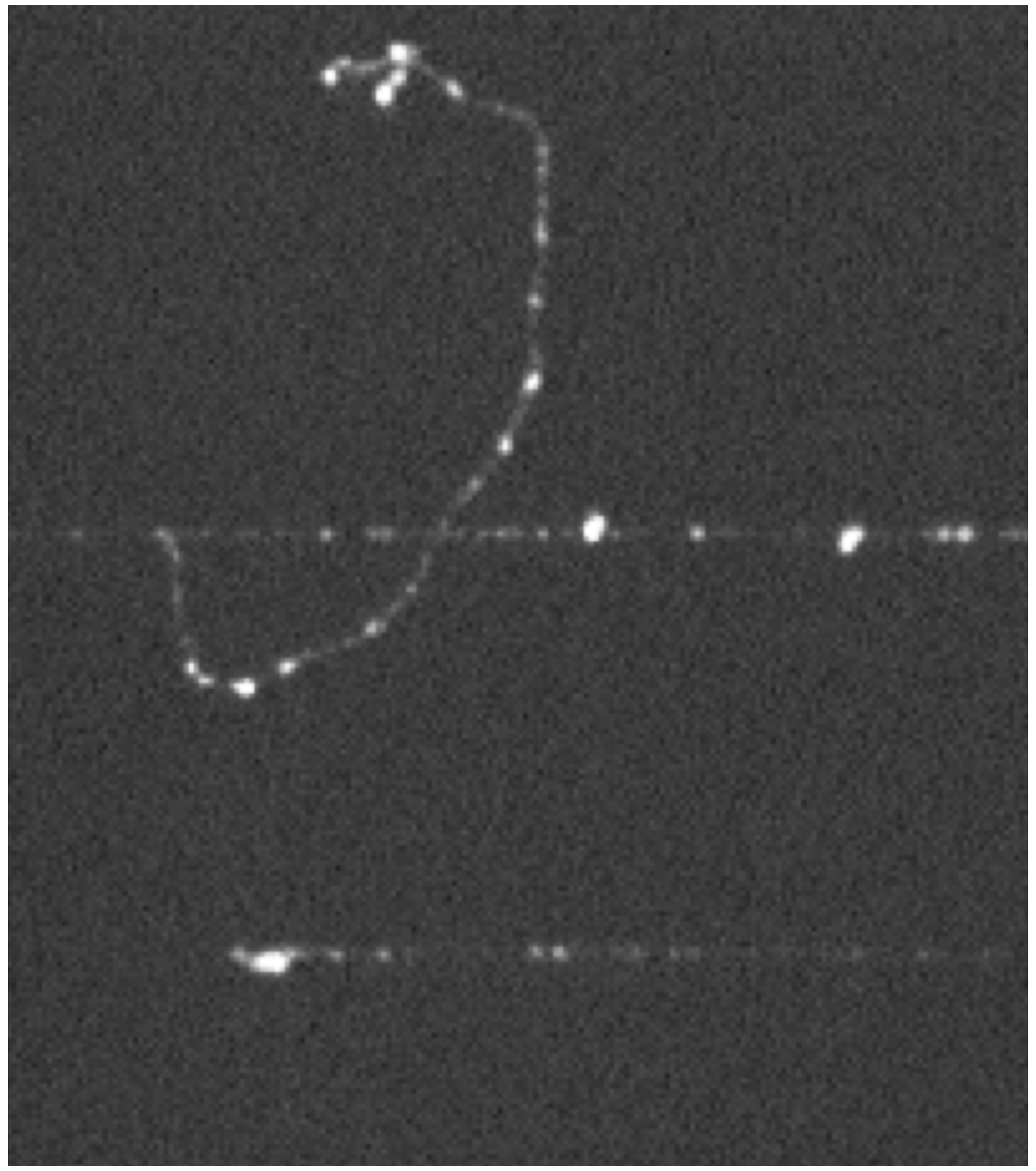
Optical readout for energy loss measurements

Bubble chamber



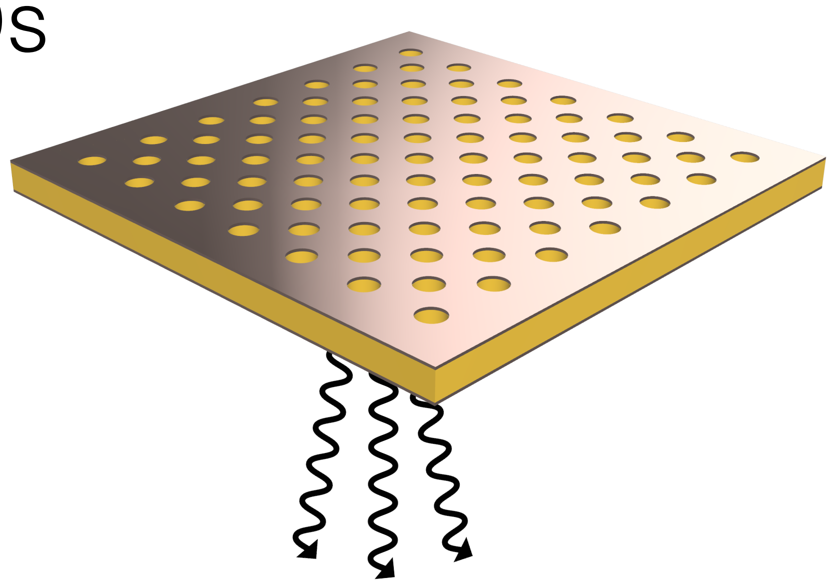
Interaction in a liquid hydrogen bubble chamber at the Berkeley Bevatron accelerator. http://www.hep.fsu.edu/~wahl/phy4822/expinfo/BC/bubchamber.html

Optical scintillation light readout

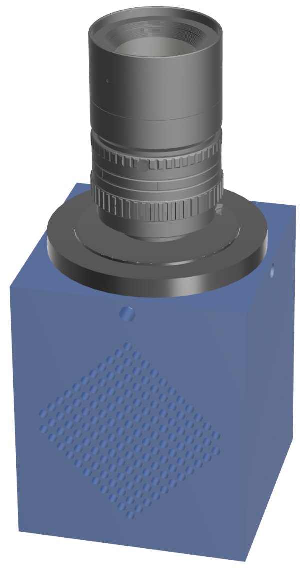


Muon tracks with δ-ray

Optical readout is an integrated imaging approach providing a 2D image of scintillation light emitted in MPGDs during avalanche multiplication.



State-of-the-art imaging sensors allow for high granularity pixellated readout with high sensitivity.



Track topologies on integrated images

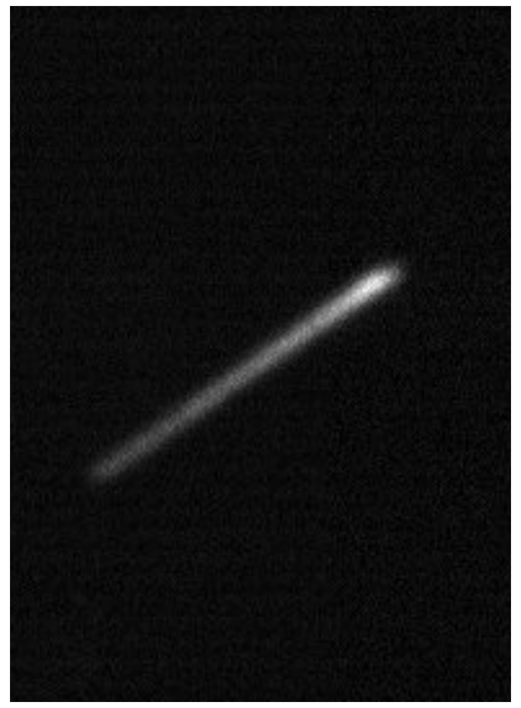
Topologies of events on integrated images allow intuitive classification and permit identification of tracks features such as δ-rays.

Energy loss profiles along tracks can display cluster structure or can be used for head-tail determination for 3D track reconstruction in optical TPCs.

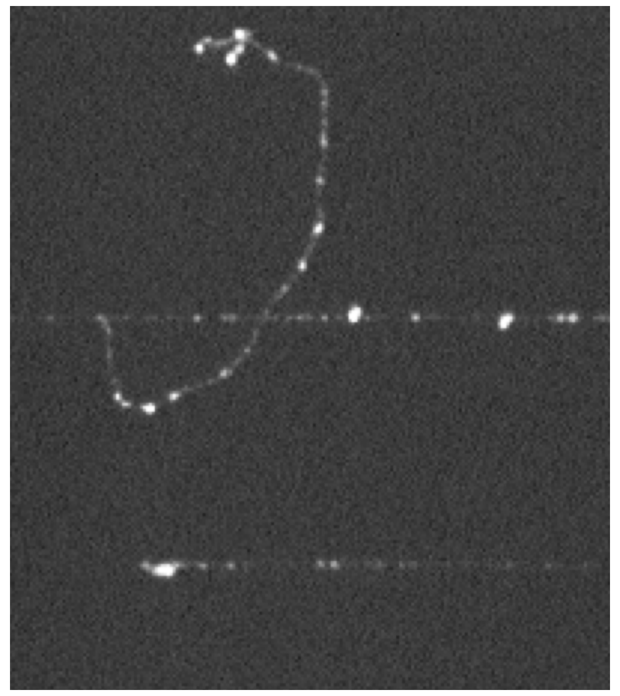
Pixel values and light density reflect energy loss along tracks.

Combination of topology and density for event classification.

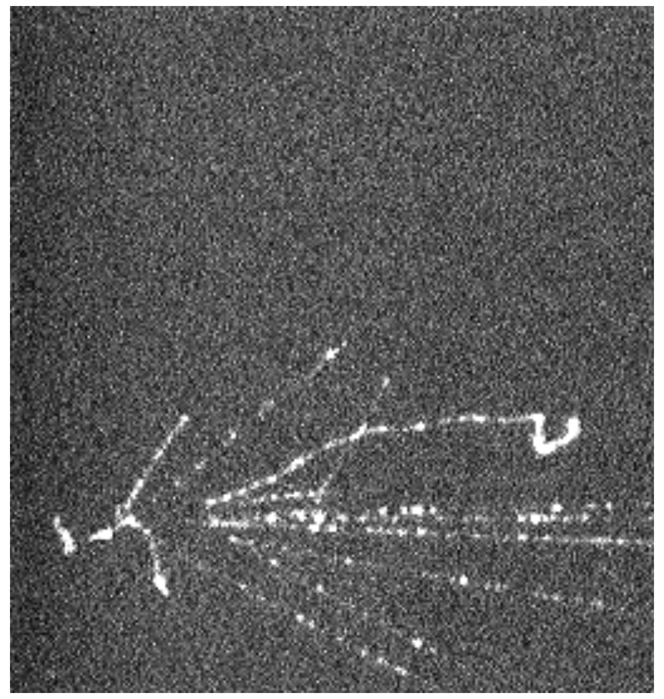
X-ray photons



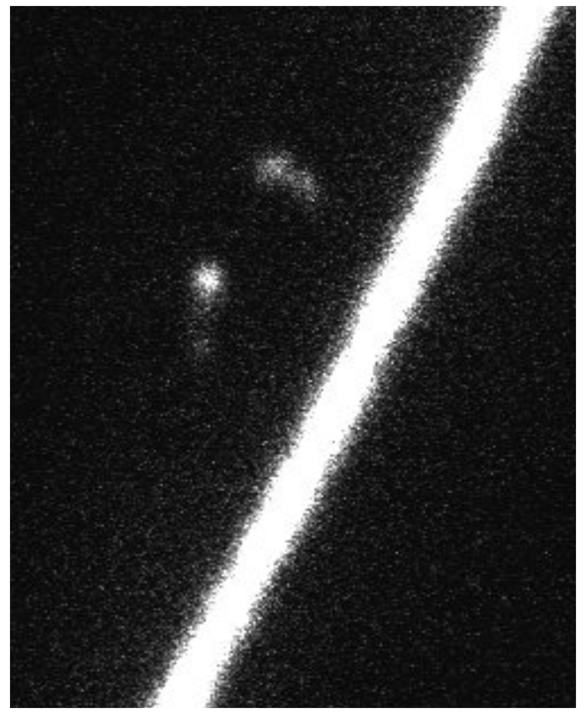
Alpha track



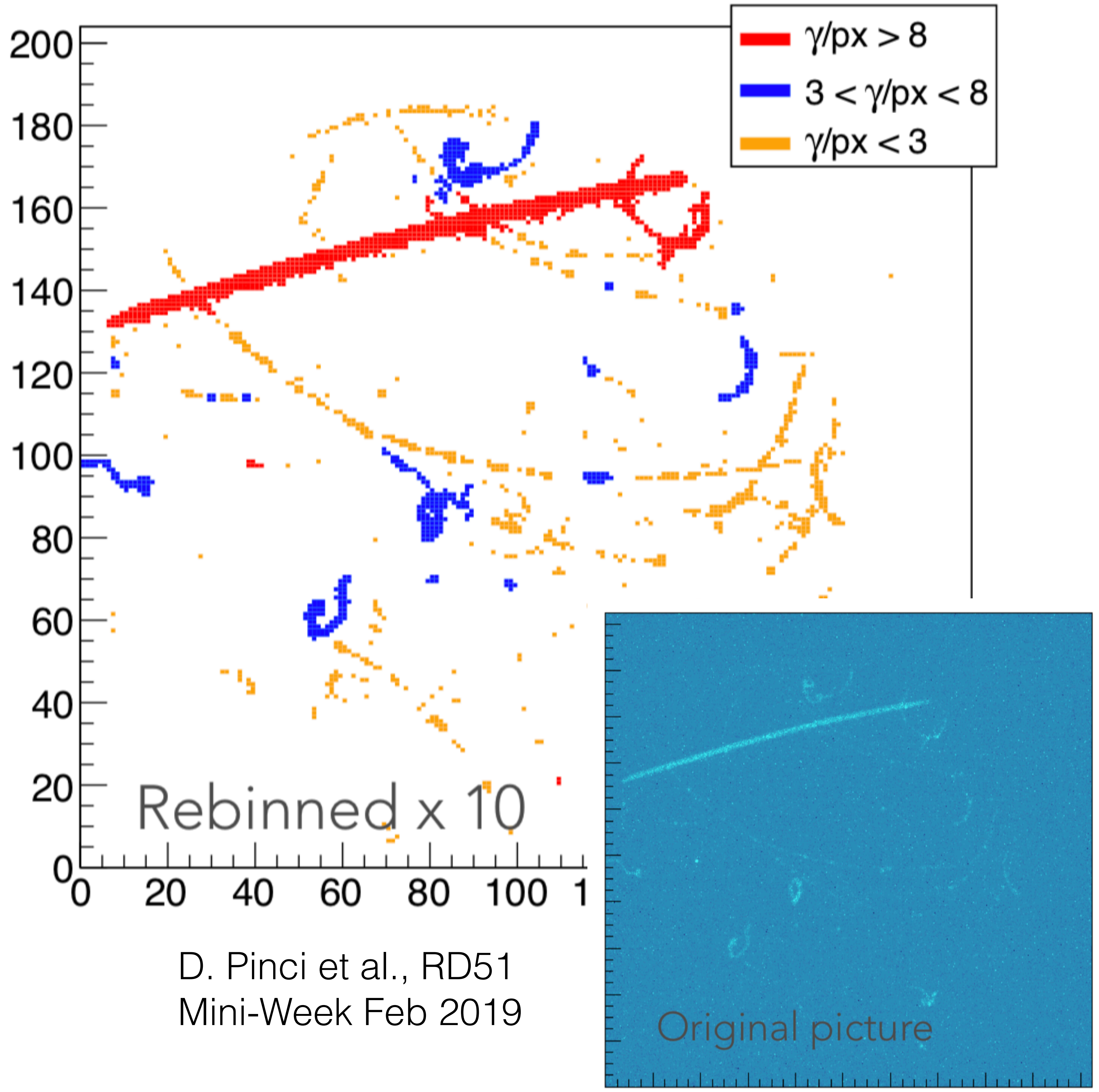
Muon tracks with δ-ray



Hadronic shower



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

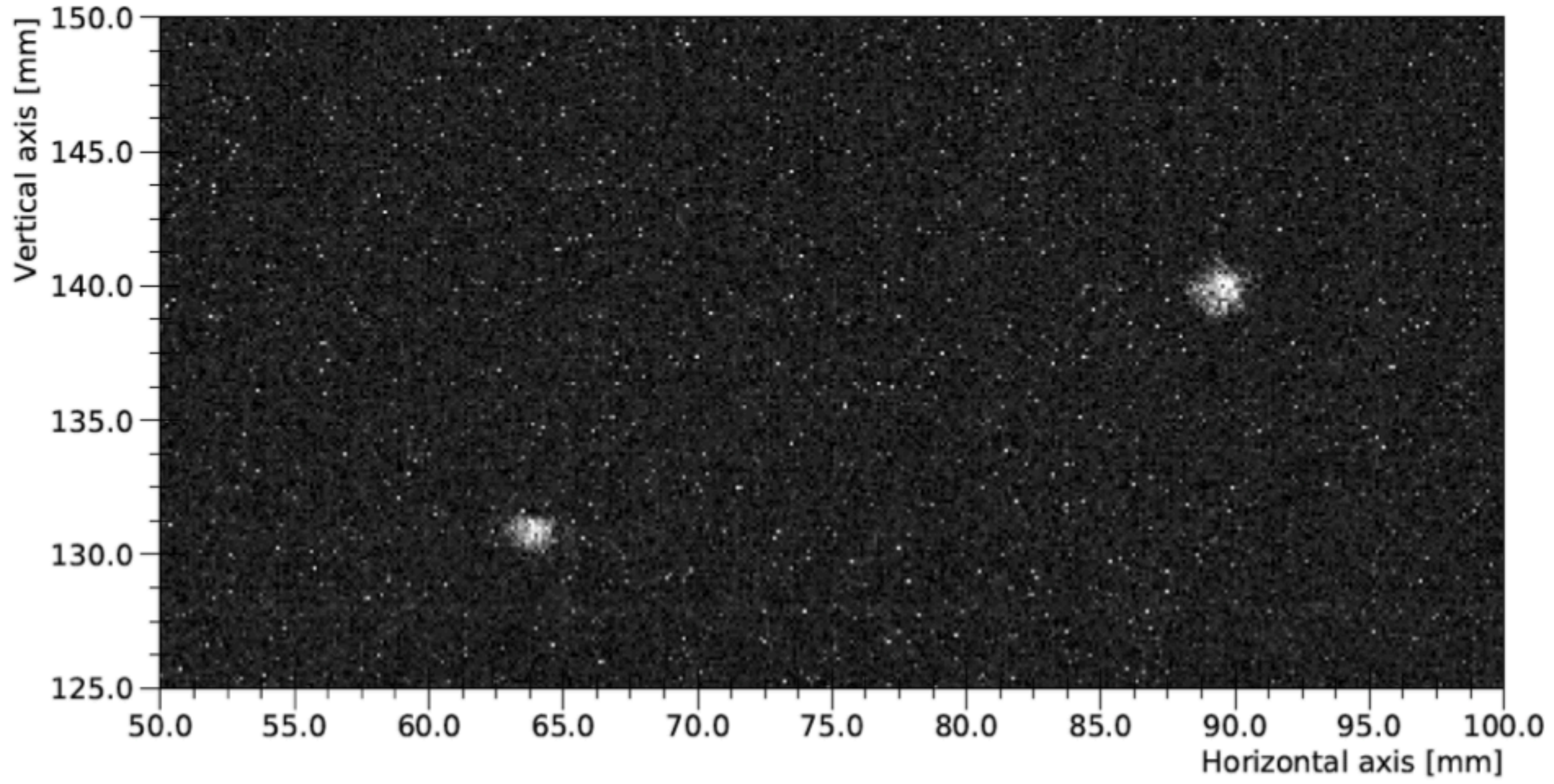


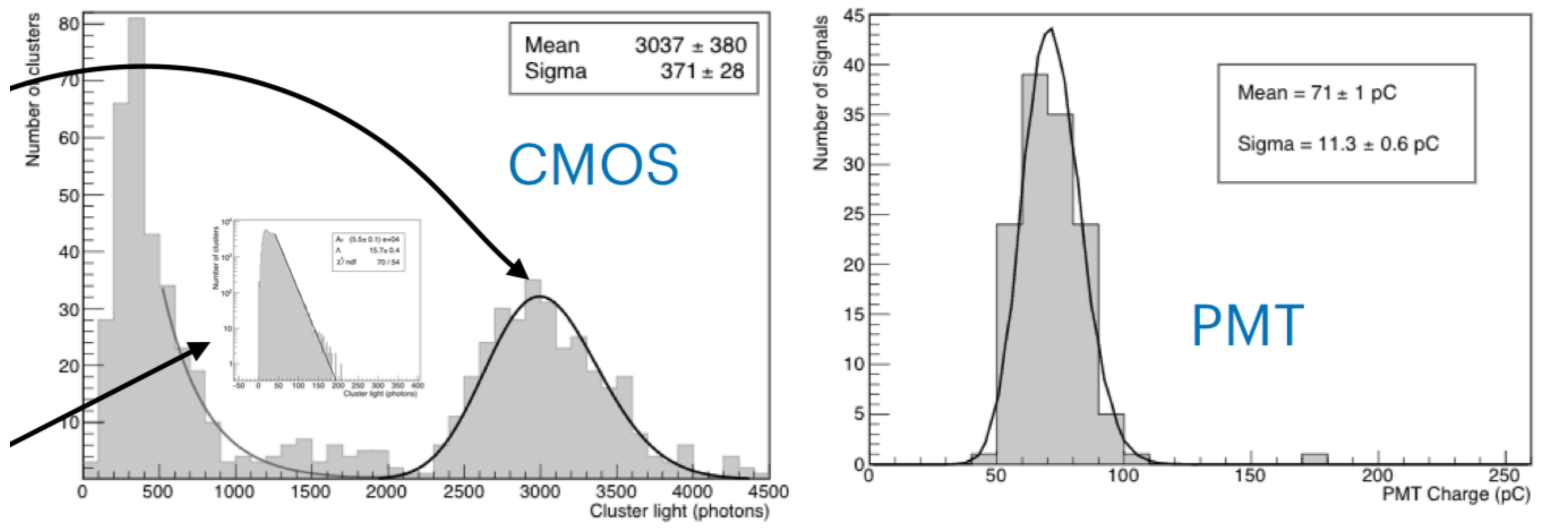
D. Pinci et al., RD51 Mini-Week Feb 2019

Energy determination with optical readout

Pixel values in images can be used to determine energy of events. Integrated pixel value intensities of individual events yield energy spectra with resolution comparable to electronically acquired spectra.

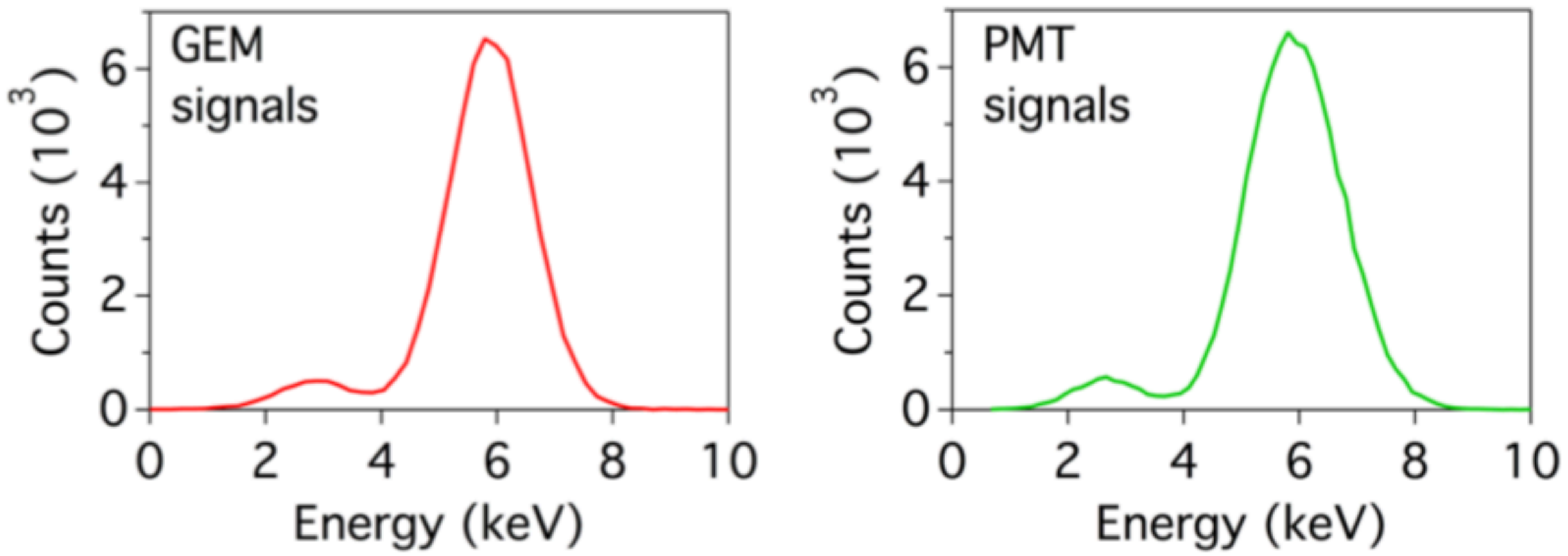
^{55}Fe photon events





D. Pinci et al., RD51 CM, 2020 https://indico.cern.ch/event/911950/contributions/3879503/attachments/2062895/3461258/pinci_CYGNO_RD51.pdf

Comparison of spectra recorded from charge and light signals



^{55}Fe energy resolution recorded with electronic and optical readout. A comparable energy resolution of 32% FWHM (at 5.9 keV, PMT) is achieved with optical readout.

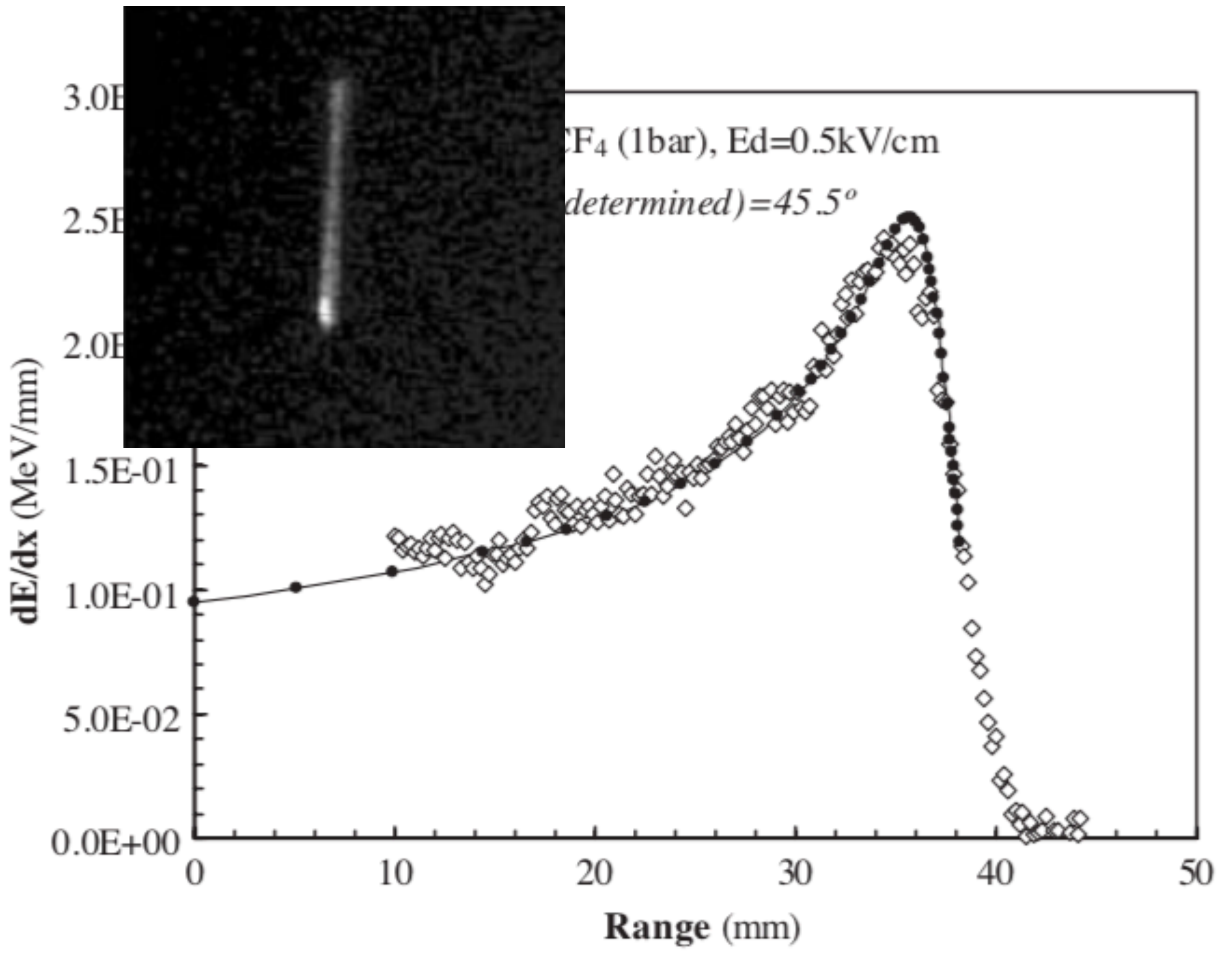
F.M. Brunbauer *et al* 2018 *JINST* **13** T02006 https://iopscience.iop.org/article/10.1088/1748-0221/13/02/T02006

Classical dE/dx information

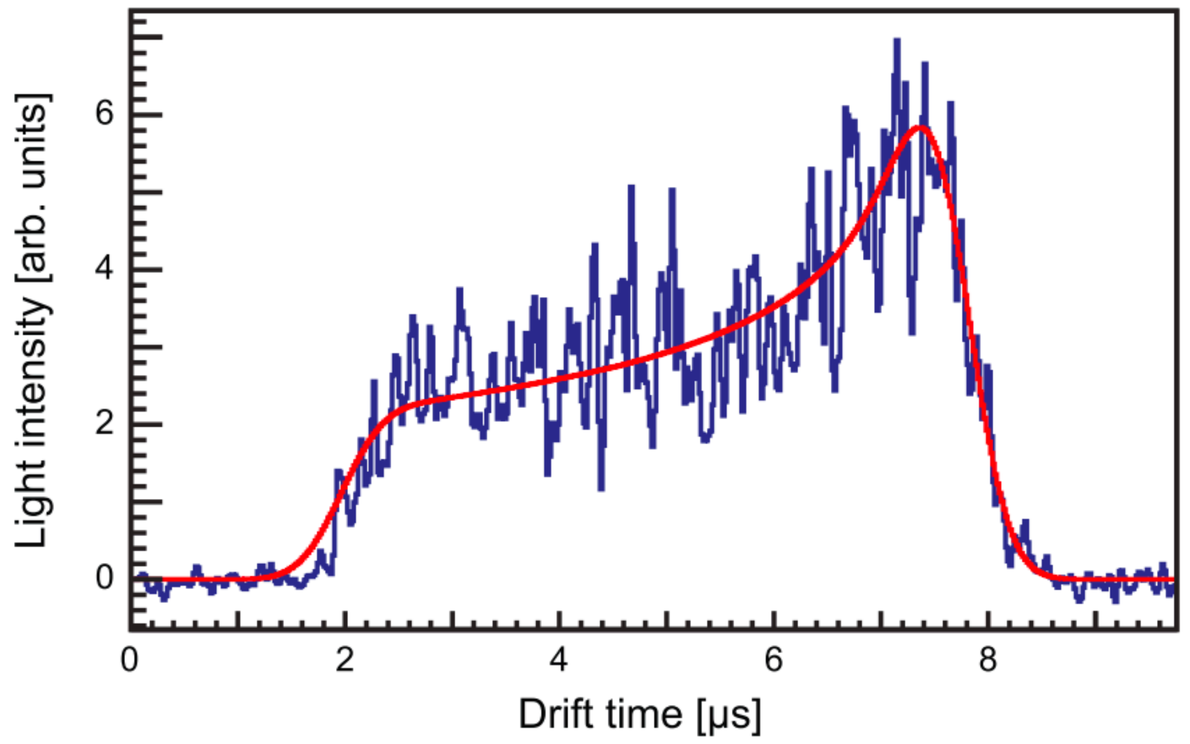
Line profiles across images yield energy loss profile along track. This is used in optical TPCs for orientation and can be used for total deposited dose measurements.

Accurate representation of deposited charge by recorded light intensity enables dose imaging and was demonstrated for proton beam monitoring and dose depth curve measurements with optically read out detectors.

Alpha track reconstruction

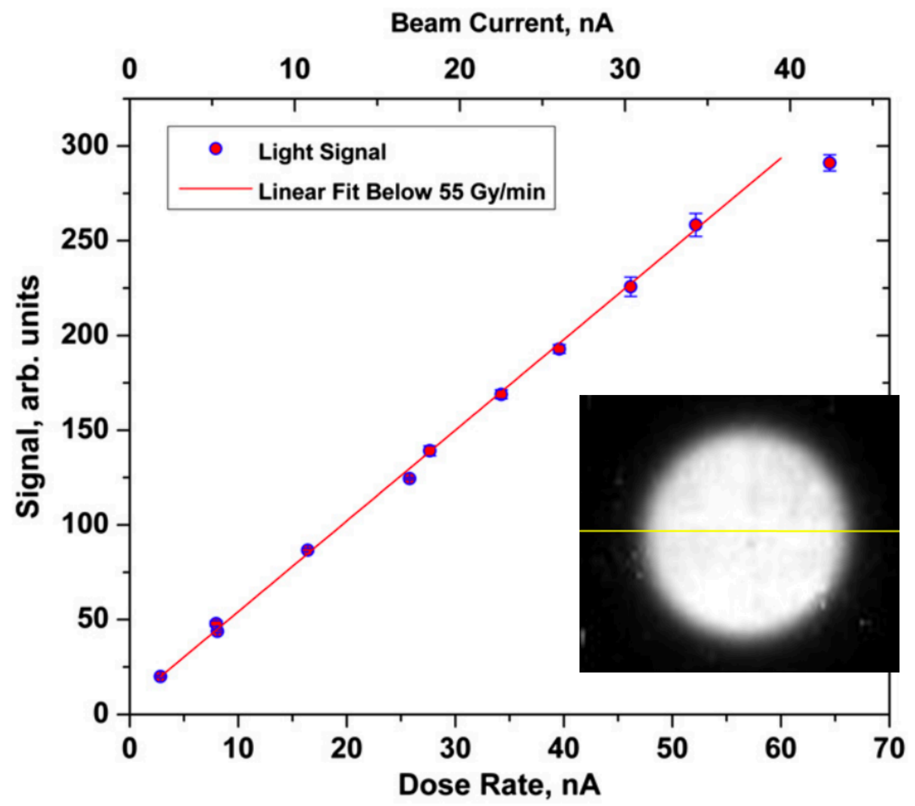


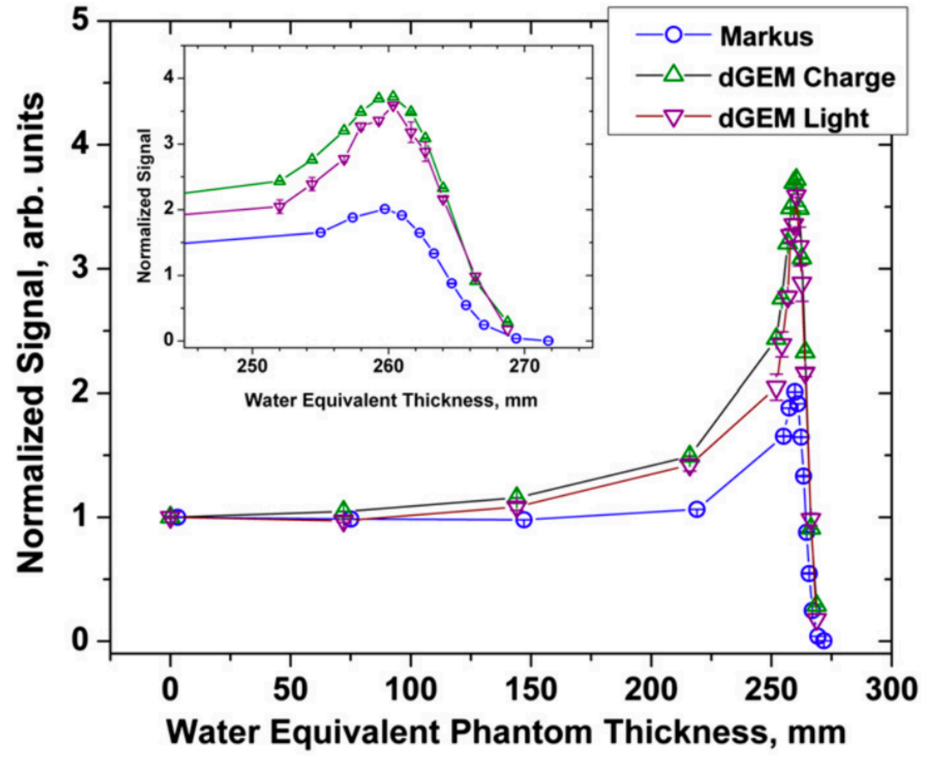
L.M.S. Margato et al., Performance of an optical readout GEM-based TPC, NIM A, 2004



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

Proton beam imaging and dose measurement

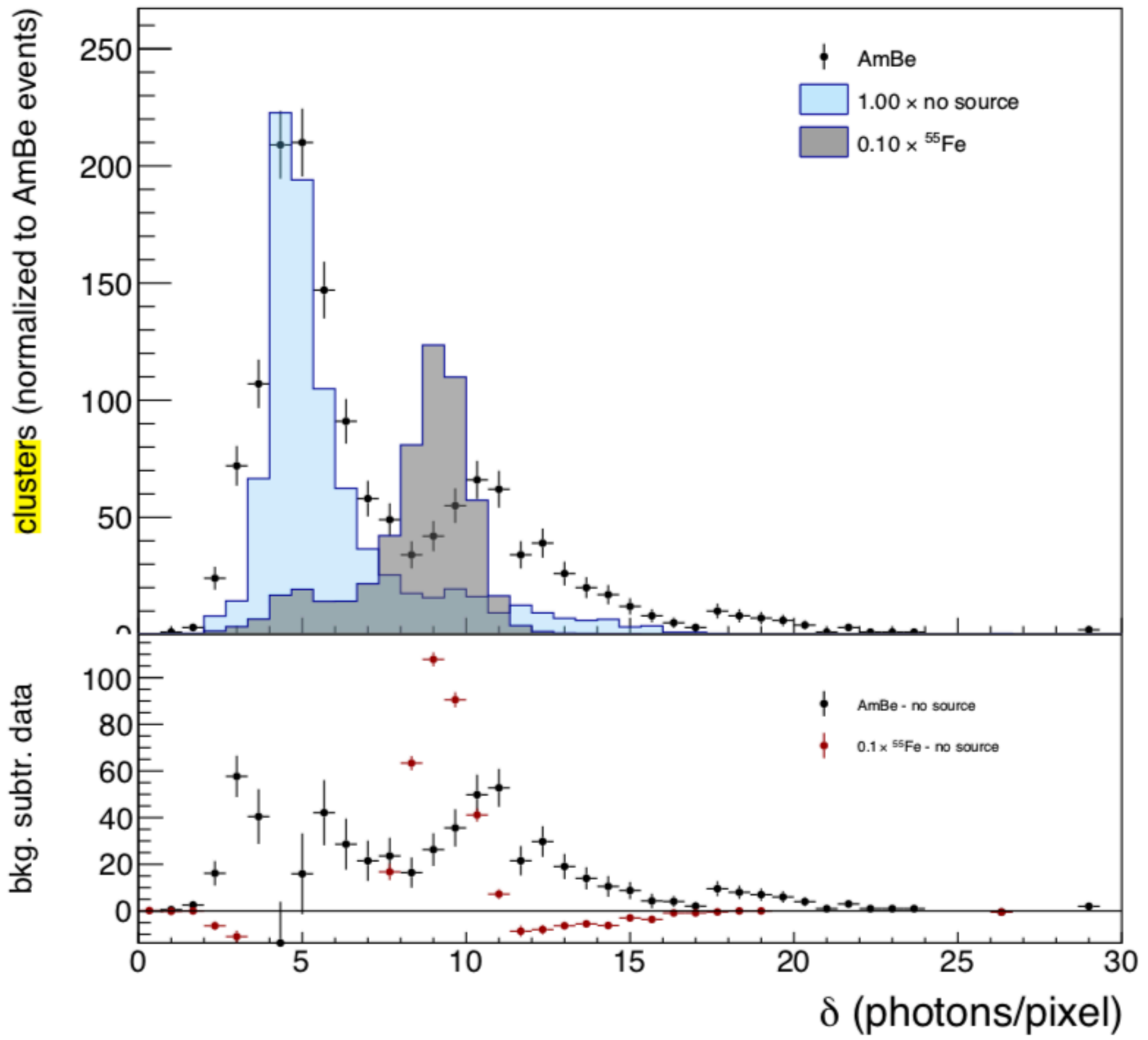




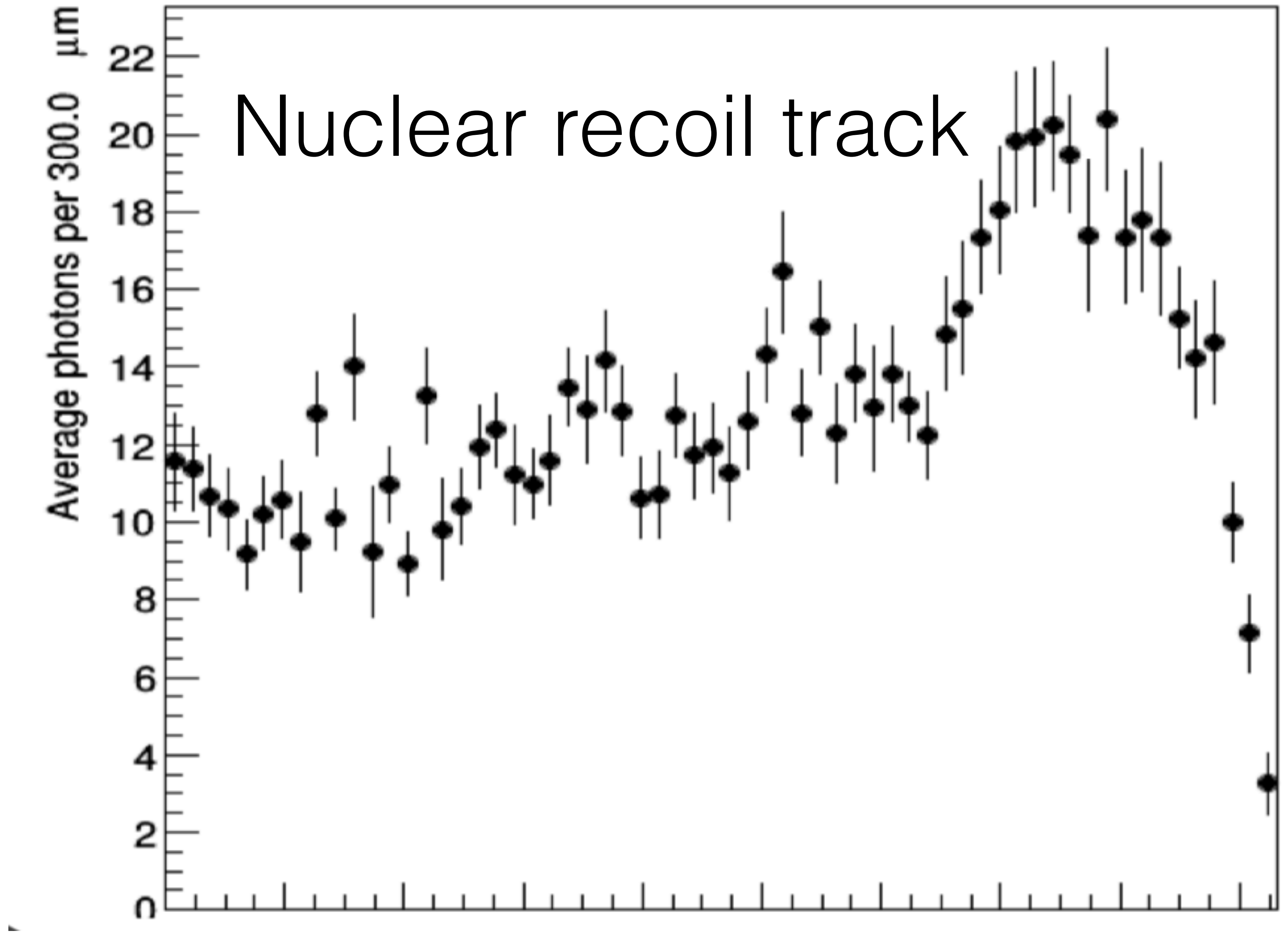
Klyachko et al. http://dx.doi.org/10.1016/j.nima.2010.07.019

Classical dE/dx information

Light density (e.g. pixel value per length) can be used to identify energy loss in profiles and classify tracks. Bragg peak allows for orientation of during reconstruction.



E Baracchini et al., arXiv:2007.12508v1 [physics.ins-det] 24 Jul 2020
https://arxiv.org/pdf/2007.12508.pdf

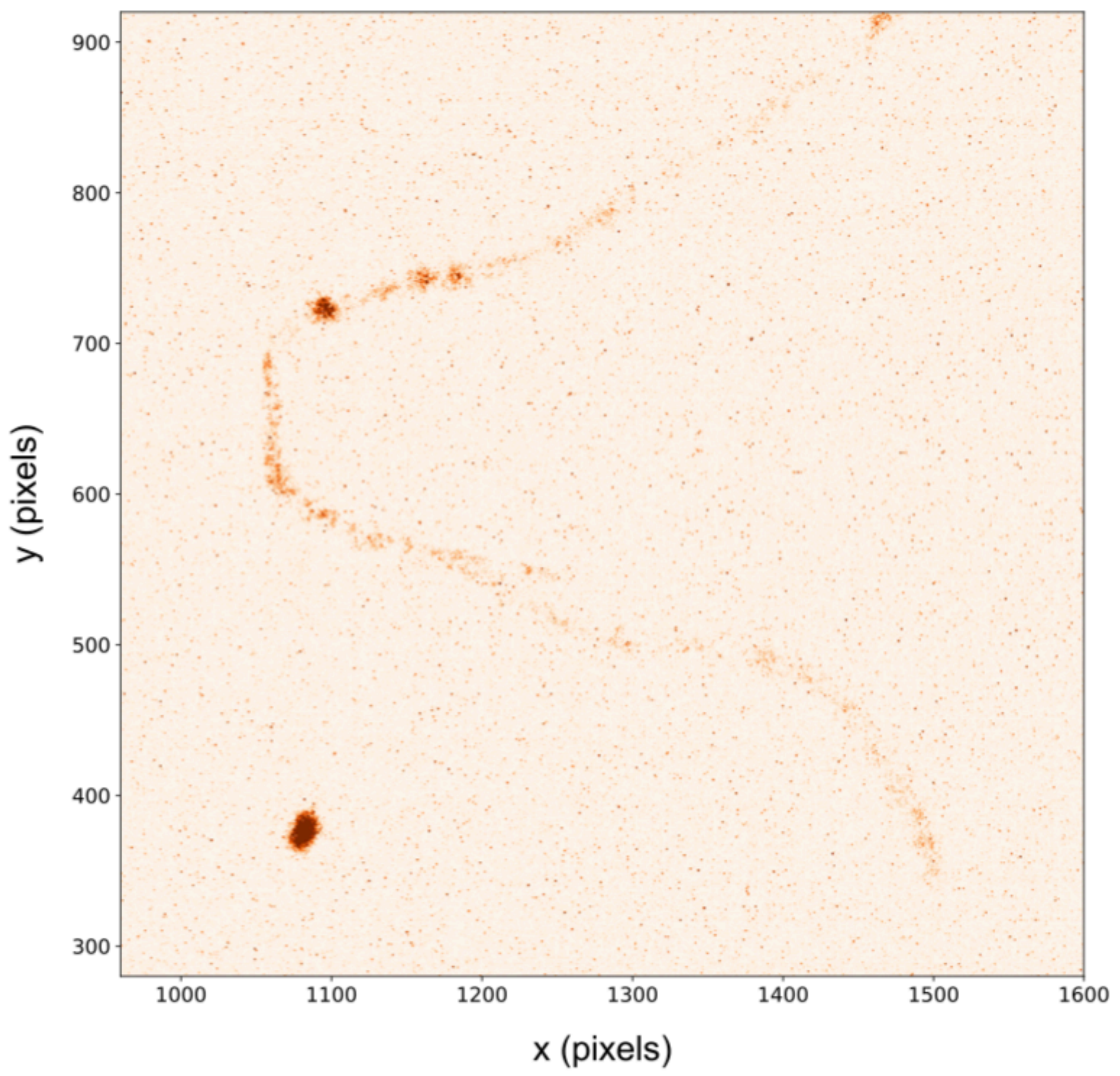


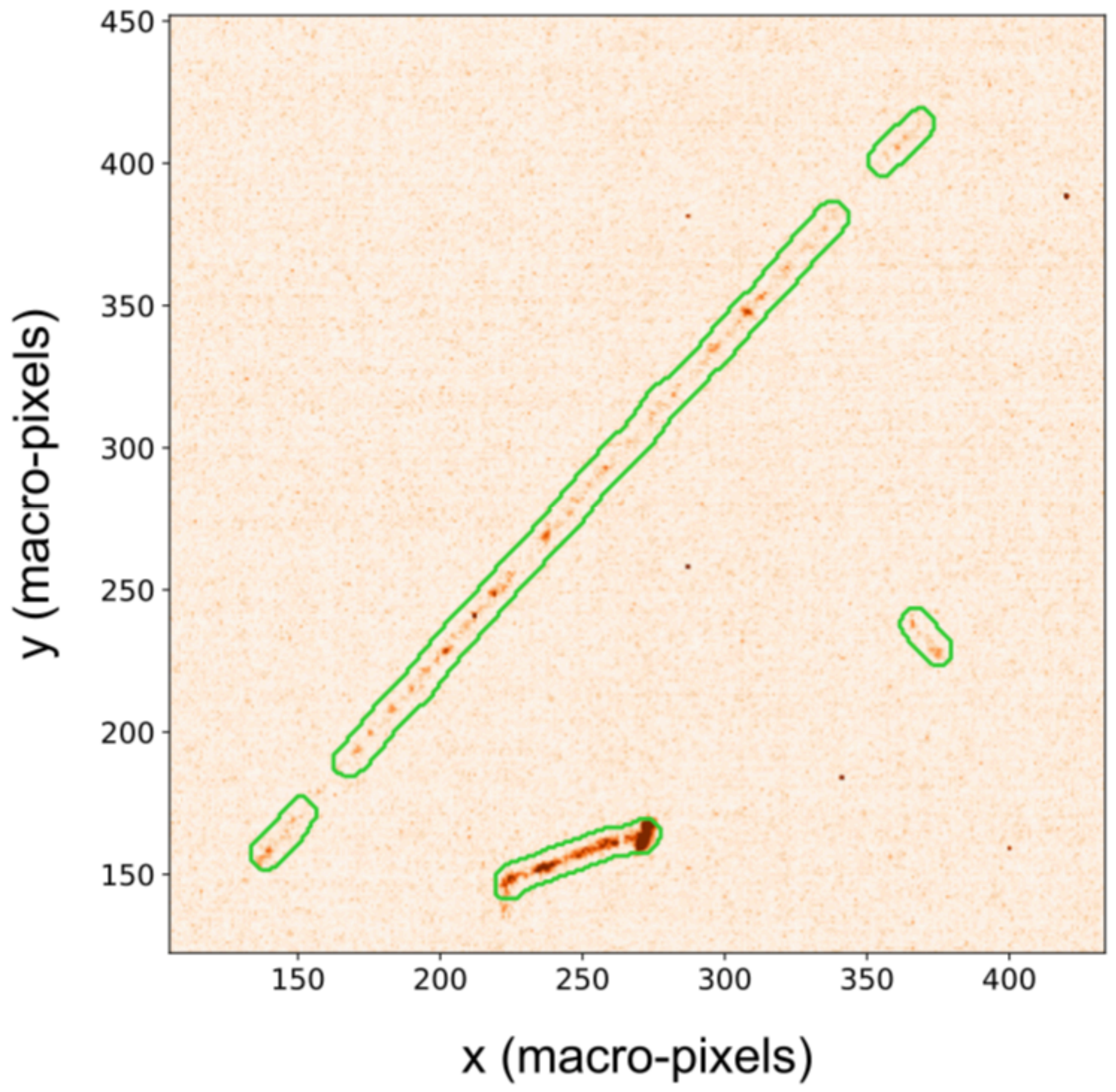
https://indico.cern.ch/event/782786/contributions/3283435/attachments/1790478/2916786/Cygno_RD51_Feb2019.pdf

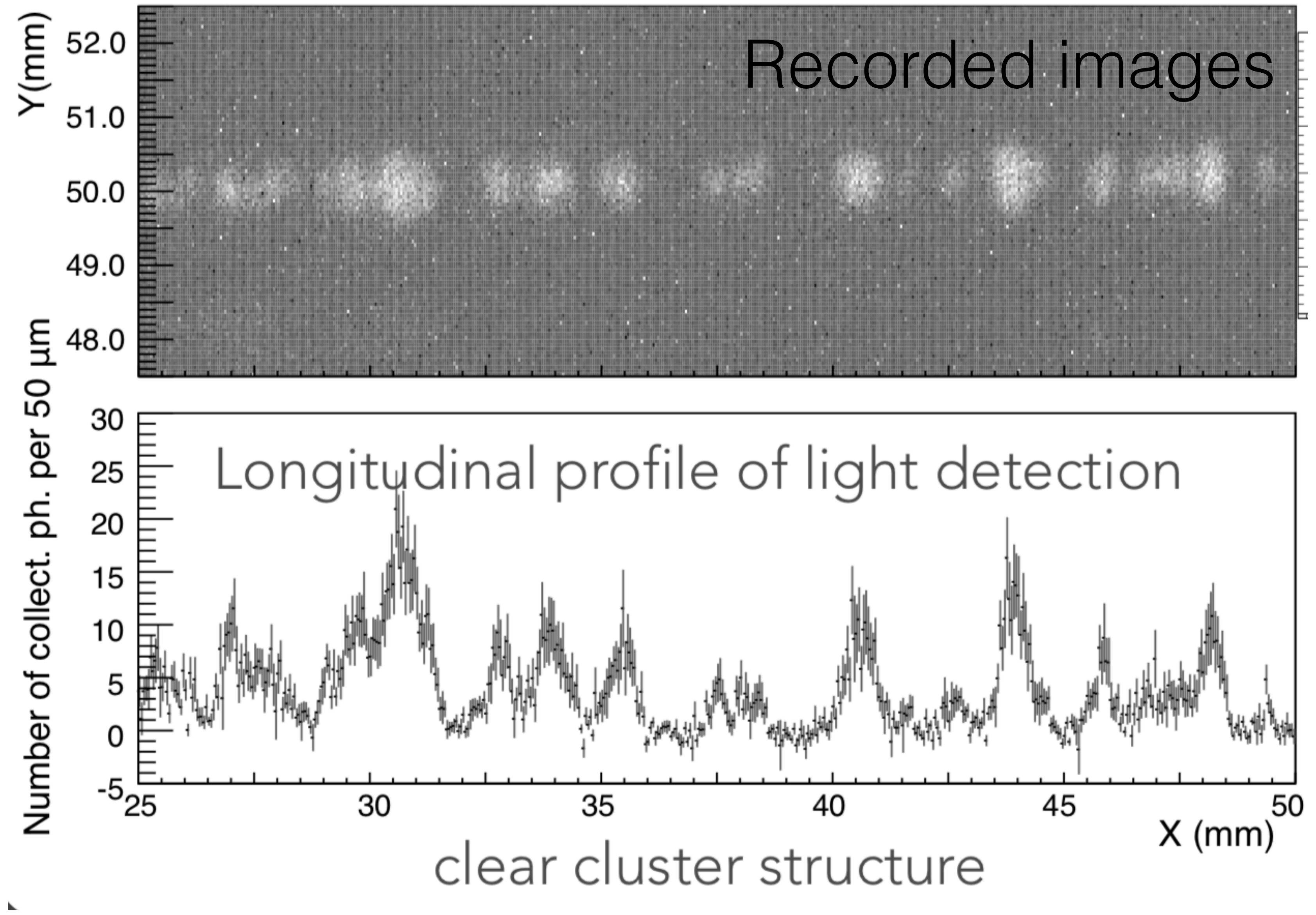
Cluster structure in optically read out images

Cluster structure clearly visible optically recorded **images** as well as in **PMT waveforms**.

Can be used for 3D reconstruction in optical TPCs by 2D images from camera with auxiliary timing information (e.g. from PMT).







E Baracchini et al., arXiv:2007.12508v1 [physics.ins-det] 24 Jul 2020
https://arxiv.org/pdf/2007.12508.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

Optical readout for cluster counting

Integrated read out approach taking advantage of state-of-the-art, commercially available image sensors.

Advantages of optical readout:

- **High granularity** pixellated readout with modern imaging sensors provides detailed track topology
- Adaptable to **large active areas** with suitable optics
- Insensitive to electronic noise

Disadvantages of optical readout:

- Need for **suitable gases** (CF_4) or wavelength-shifters
- Requires **high gain** due to low geometric acceptance
- Limited **frame rates**

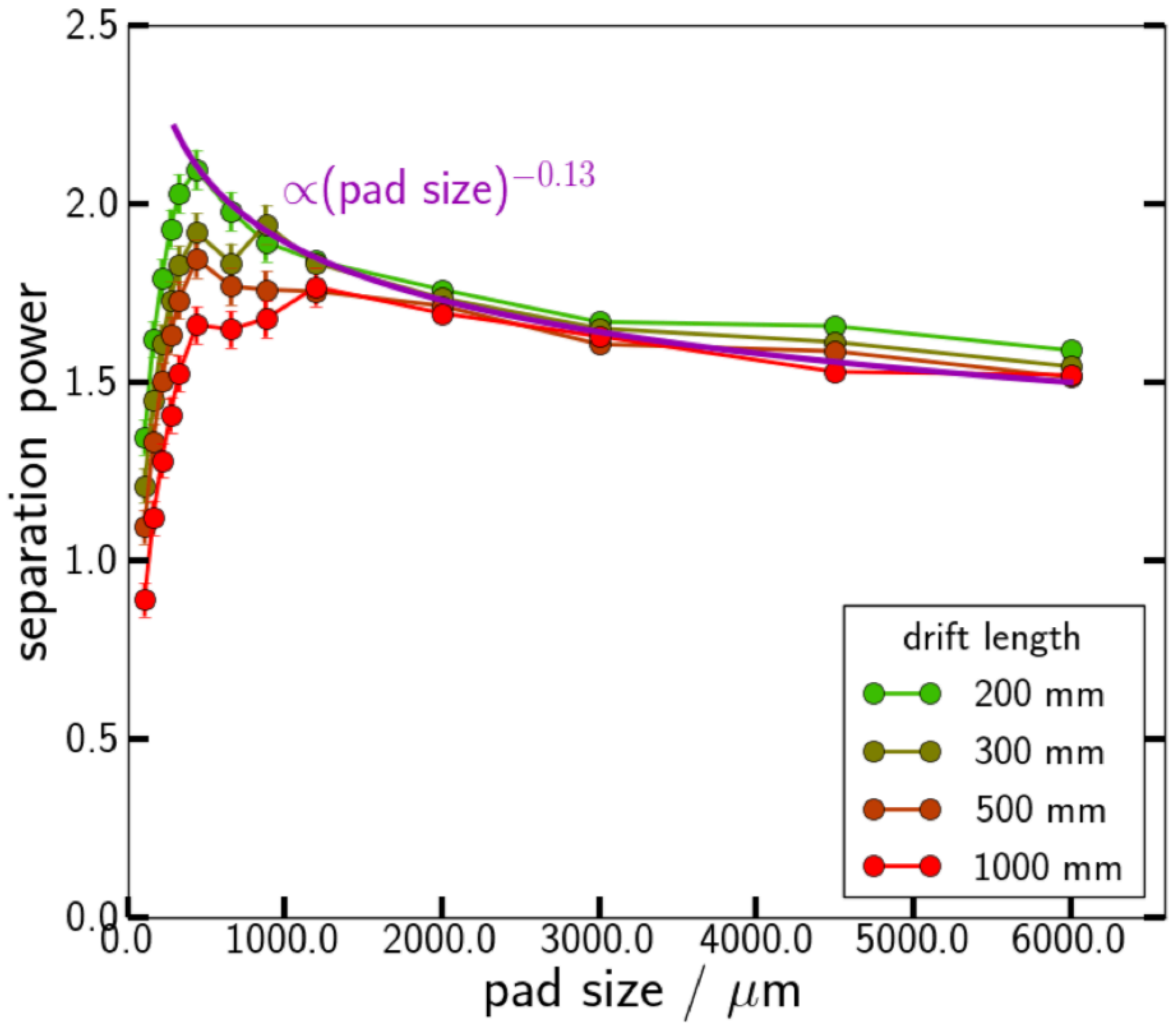
Optical readout for cluster counting

High readout granularity can enable cluster counting with superior dE/dx resolution compared integrated energy measurements.

Potential for “intuitive” 2D image acquisition with high pixel count compatible with cluster reconstruction with standard image processing techniques.

At the expense of additional complication and constraints concerning gas mixtures, detector geometry and operation.

Separation power between pions and kaons with GEM detector with pad-based electronic readout



$\sigma_{dE/dx} \propto L^{-0.34} \cdot N^{-0.13}$

L = total length of a track in the TPC volume

N = the number hits of that track

U. Einhaus, Studies on Particle Identification with dE/dx for the ILD TPC https://arxiv.org/pdf/1902.05519.pdf
M. Hauschild, dE/dx and Particle ID Performance with Cluster Counting http://ific.uv.es/~ilc/ECFA-GDE2006/

Challenges for cluster counting with optical readout

To exploit the advantages of optical read out for cluster counting, the readout system, detector geometry and operation parameters must be optimised to meet several challenges.

High granularity and cluster identification

- High-resolution image sensors with optimised effective pixel size
- Low/no sensor binning
- Low diffusion
- Low pressure

Maximise signal-to-noise ratio

- High gain and light yield
- Suitable gas mixtures

Particle identification

- Combination with classical energy measurement
- Using topological and energy information for classification

Camera options for optical readout

CCD cameras

QImaging Retiga R6, Thorlabs 8 MP Scientific CCD Cameras

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

Exemplary specifications

- 6 MP sensor (2688 x 2200)
- 4.54x4.54μm^2 pixels size
  - 10x10cm^2 active area: 45x45μm^2 on imaging plane
  - 50x50cm^2 active area: 227x227μm^2 on imaging plane
- 5.7 e- read noise
- 75% QE

sCMOS cameras

Hamamatsu ORCA-Fusion, Andor Zyla

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

Exemplary specifications

- 5.3 MP sensor (2304 x 2304)
- 6.5x6.5μm^2 pixels size
  - 10x10cm^2 active area: 43x43μm^2 on imaging plane
  - 50x50cm^2 active area: 217x217μm^2 on imaging plane
- 0.7 e- read noise
- 80% QE

EMCCD cameras

Hamamatsu ImageEM X2, ams technologies iXon

- **Limited resolution**
- **Internal gain, very high sensitivity**
- **≈tens Hz frame rate**

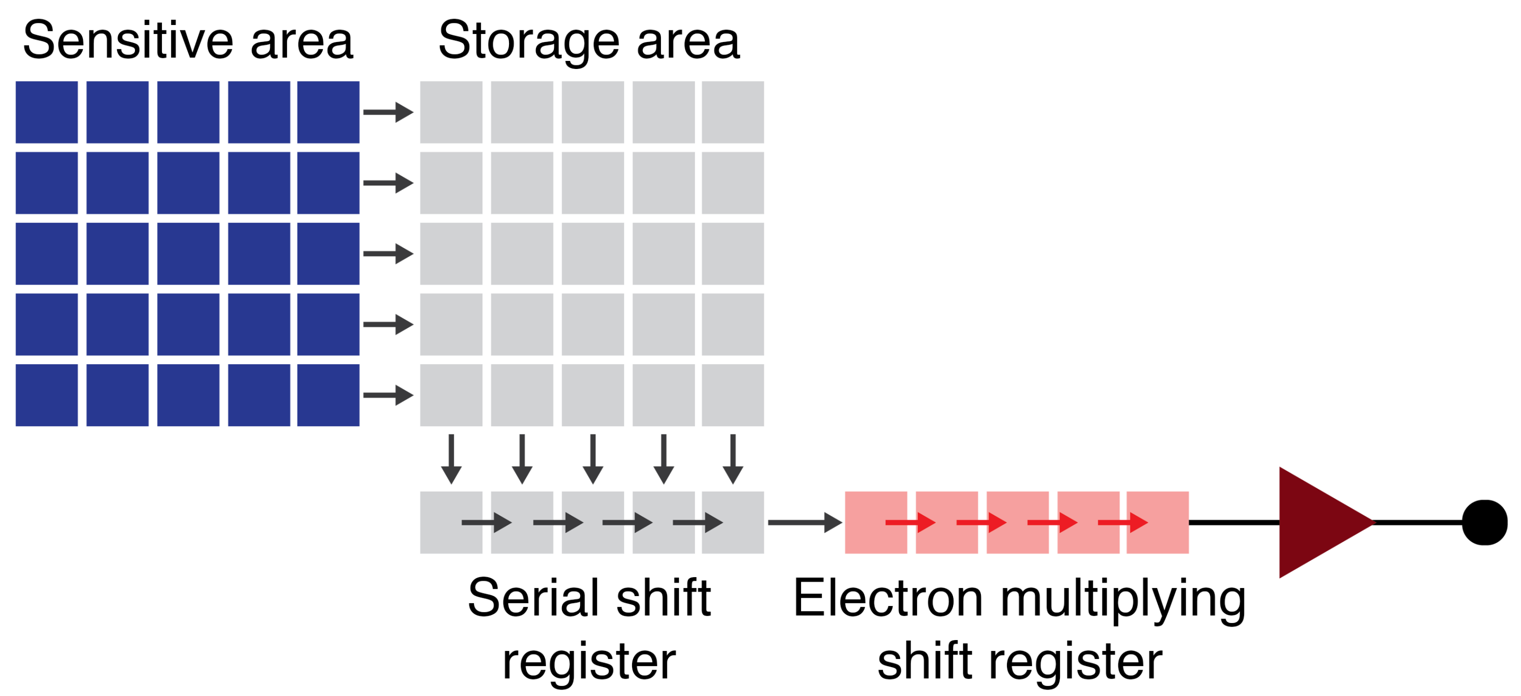
Exemplary specifications

- 1 MP sensor (1024x1024)
- 16x16μm^2 pixels size
  - 10x10cm^2 active area: 97x97μm^2 on imaging plane
  - 50x50cm^2 active area: 488x488μm^2 on imaging plane
- <1 e- read noise
- >90% QE

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.
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.



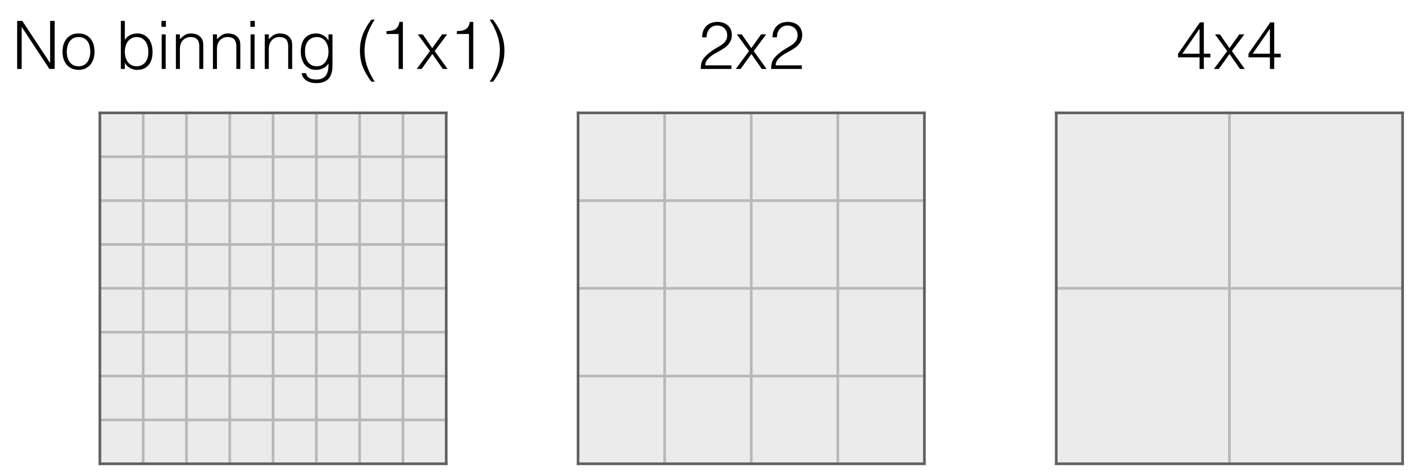
Binning increases the noise ratio by combining signal of N pixels together
Can be done in hardware (CCD) or in software (CMOS)

Hardware binning increases SNR with number of pixels N:

- Signal x N
- Readout noise constant

Software binning increases SNR only with √N

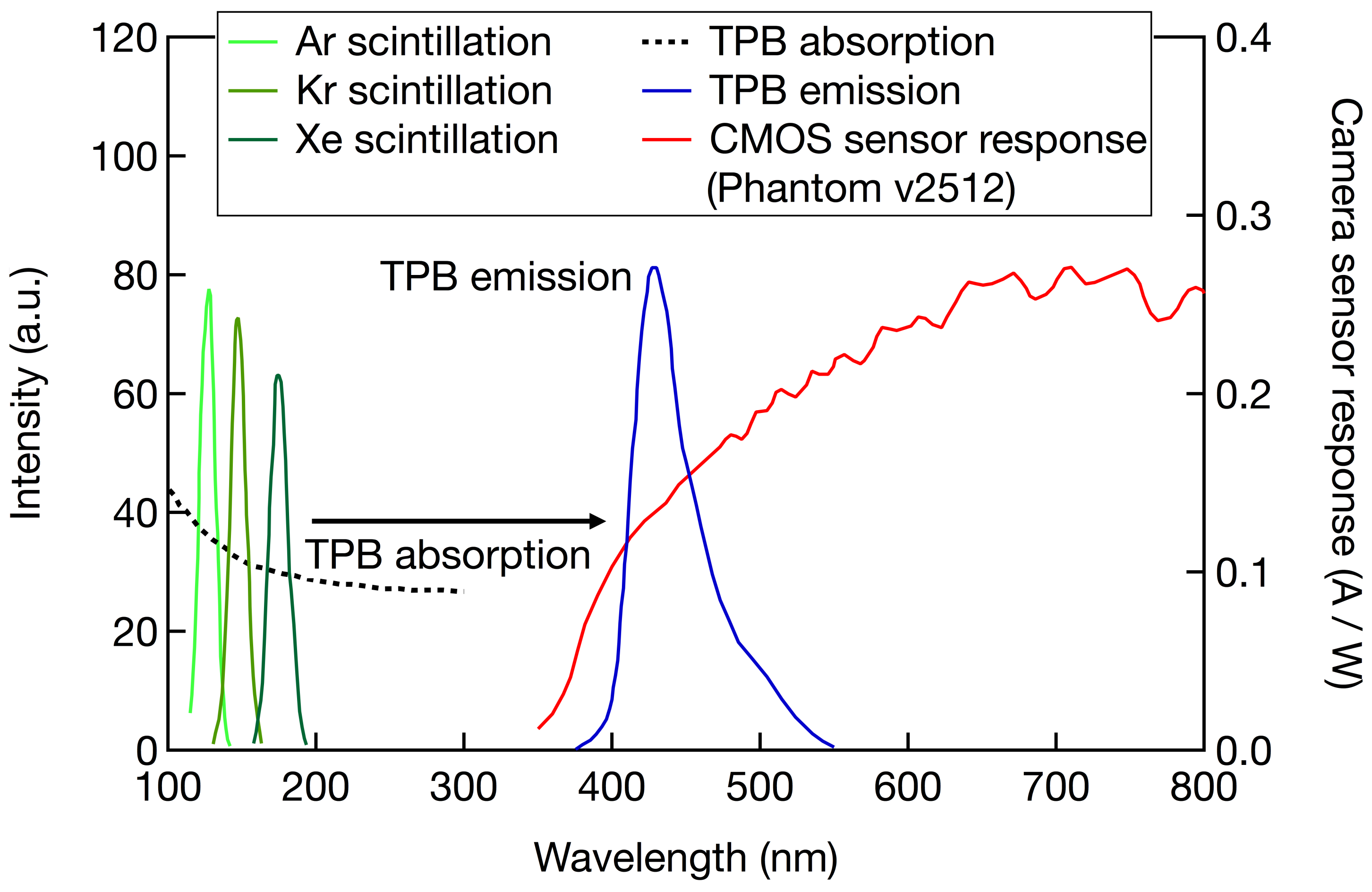
- Signal x N
- Readout noise x √N



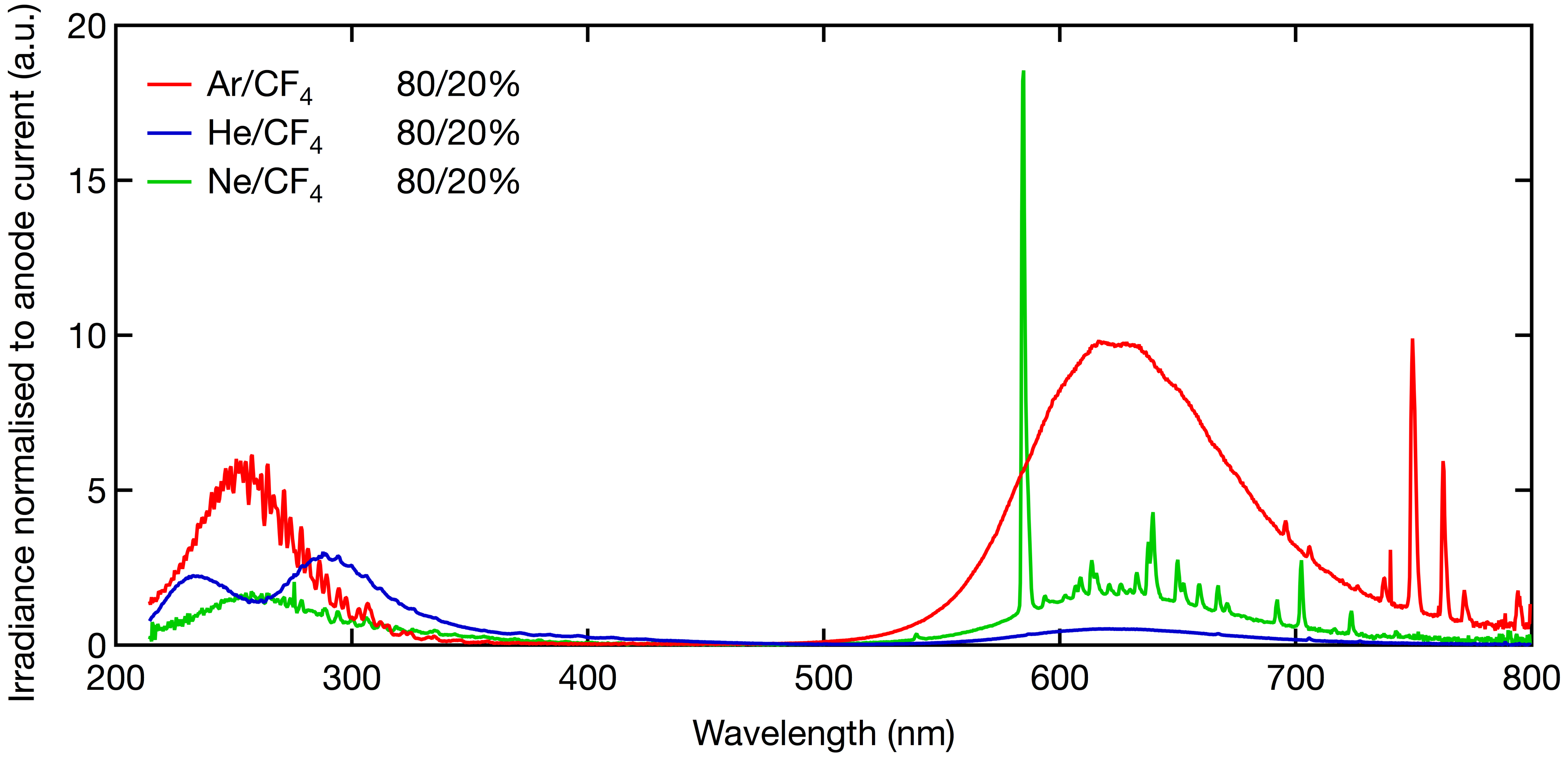
Scintillation spectra and sensor QE

The quantum efficiency of employed imaging sensors and the transmission of the optical system (windows, lenses) determined the part of the scintillation spectrum available for detection. The strong emission band of CF4-based mixtures in the visible range (around 600nm) is well-suited for conventional CCD and CMOS imaging sensors.

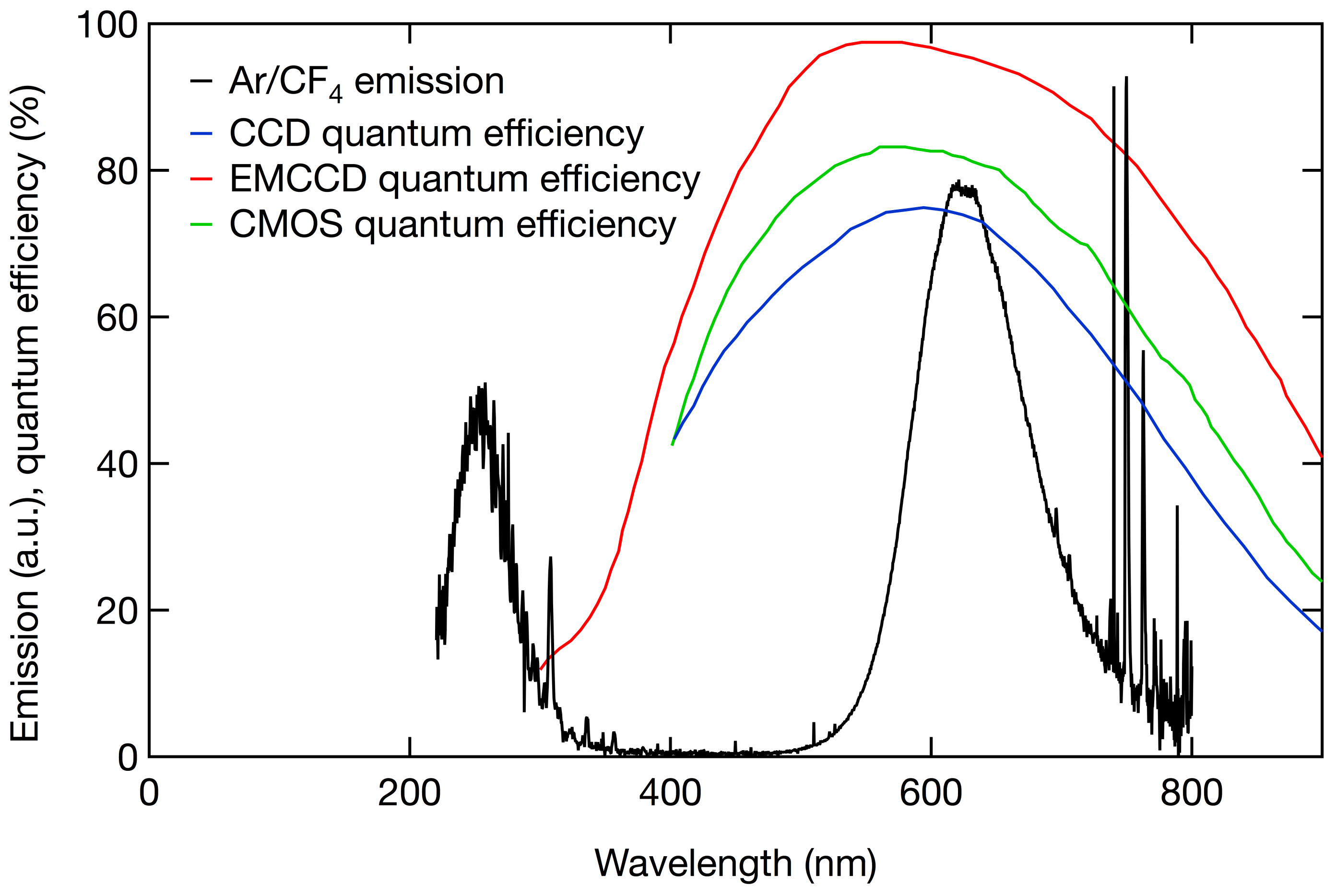
Wavelength shifting



Secondary scintillation spectra of mixtures with CF4



QE curves of cameras

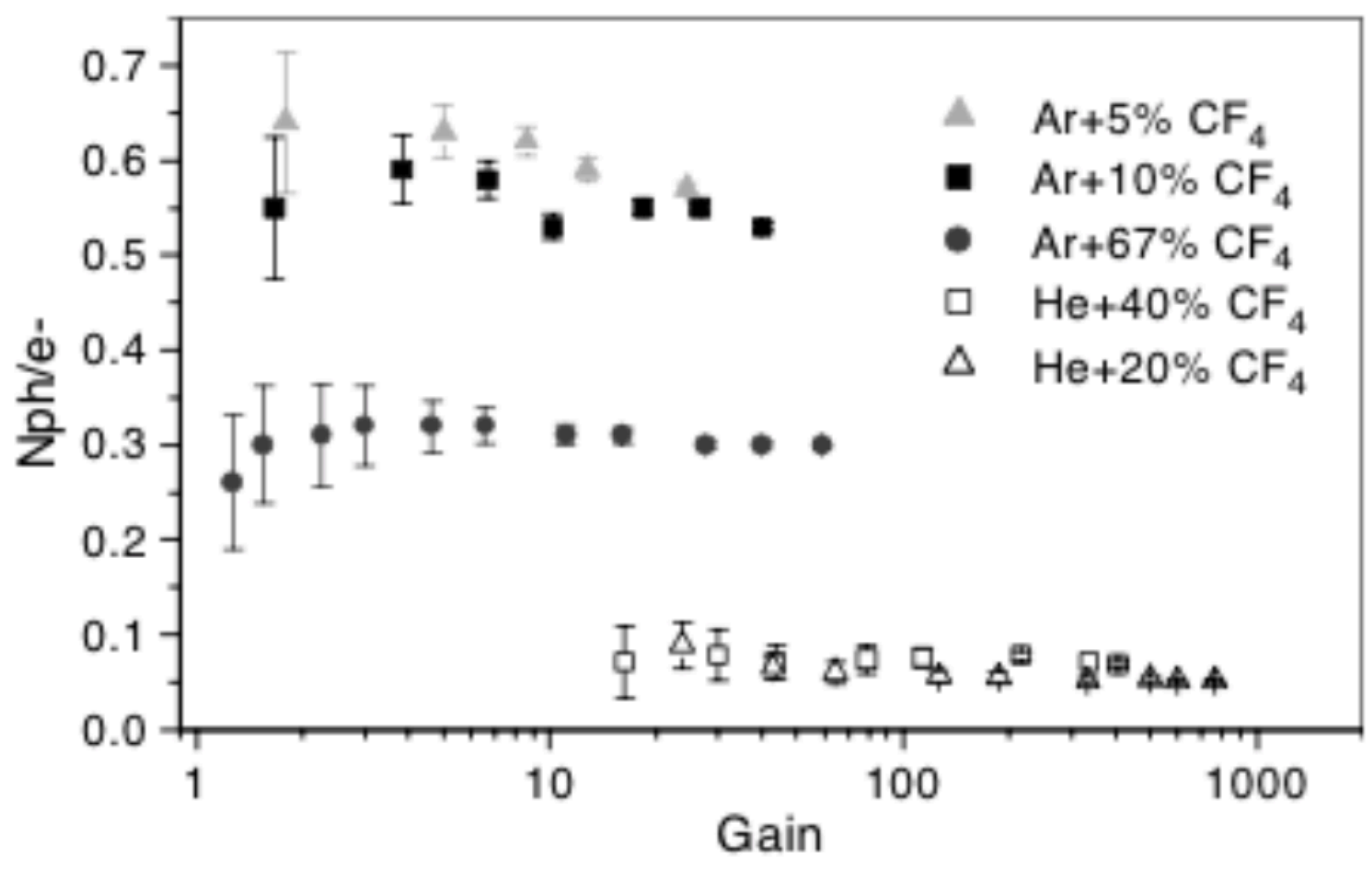


Light yield and achievable gain

The low geometric acceptance of optical readout with cameras requires a high secondary scintillation light intensity.

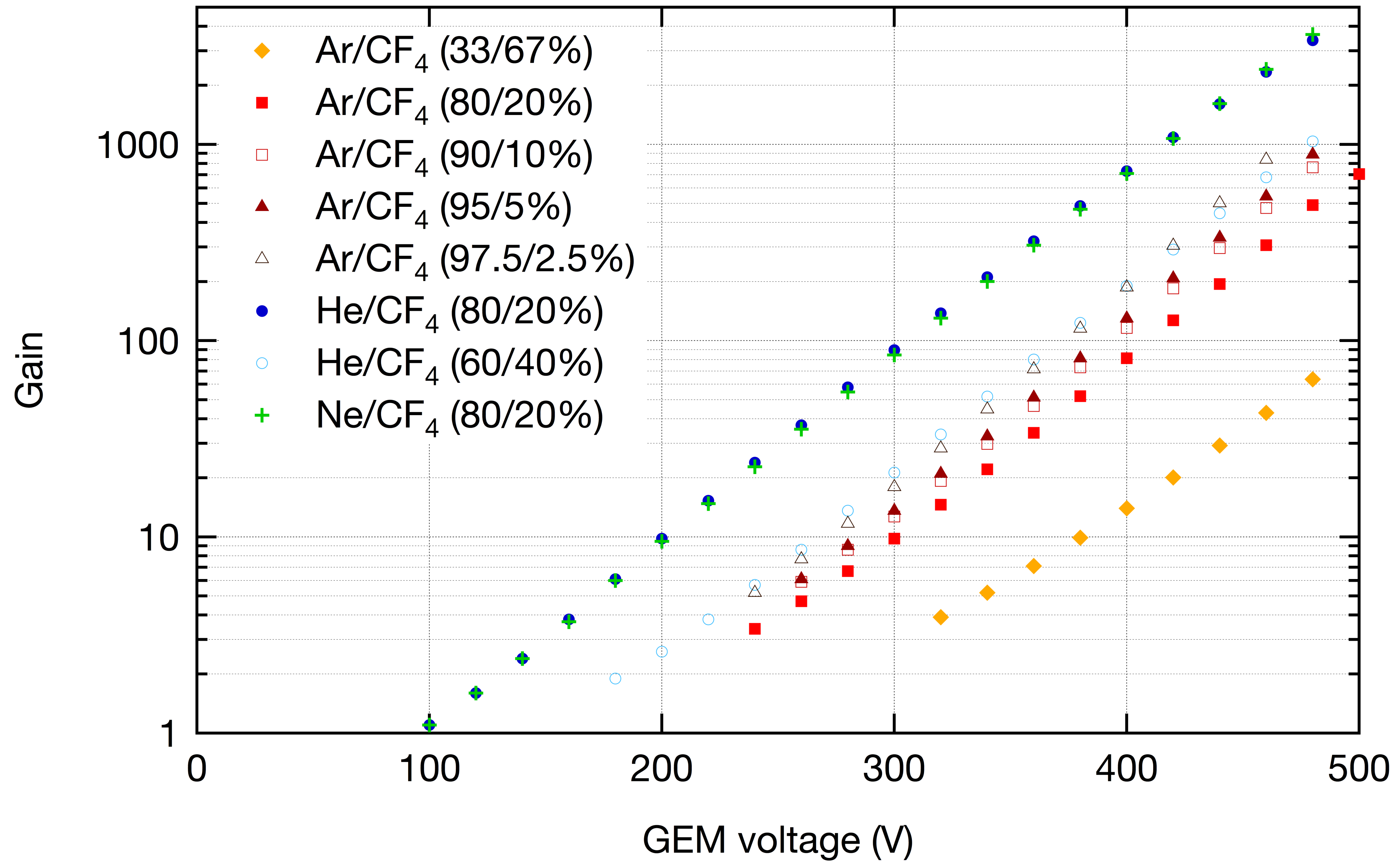
Light yield (ph/e) in the senstitive wavelength range as well as achievable gain determine maximum amount of photons available for detection.

Light yield (photons / electron)



Fraga et al. NIM A, 504, 003
https://doi.org/10.1016/S0168-9002(03)00758-7

Gain vs. voltage (single GEM)

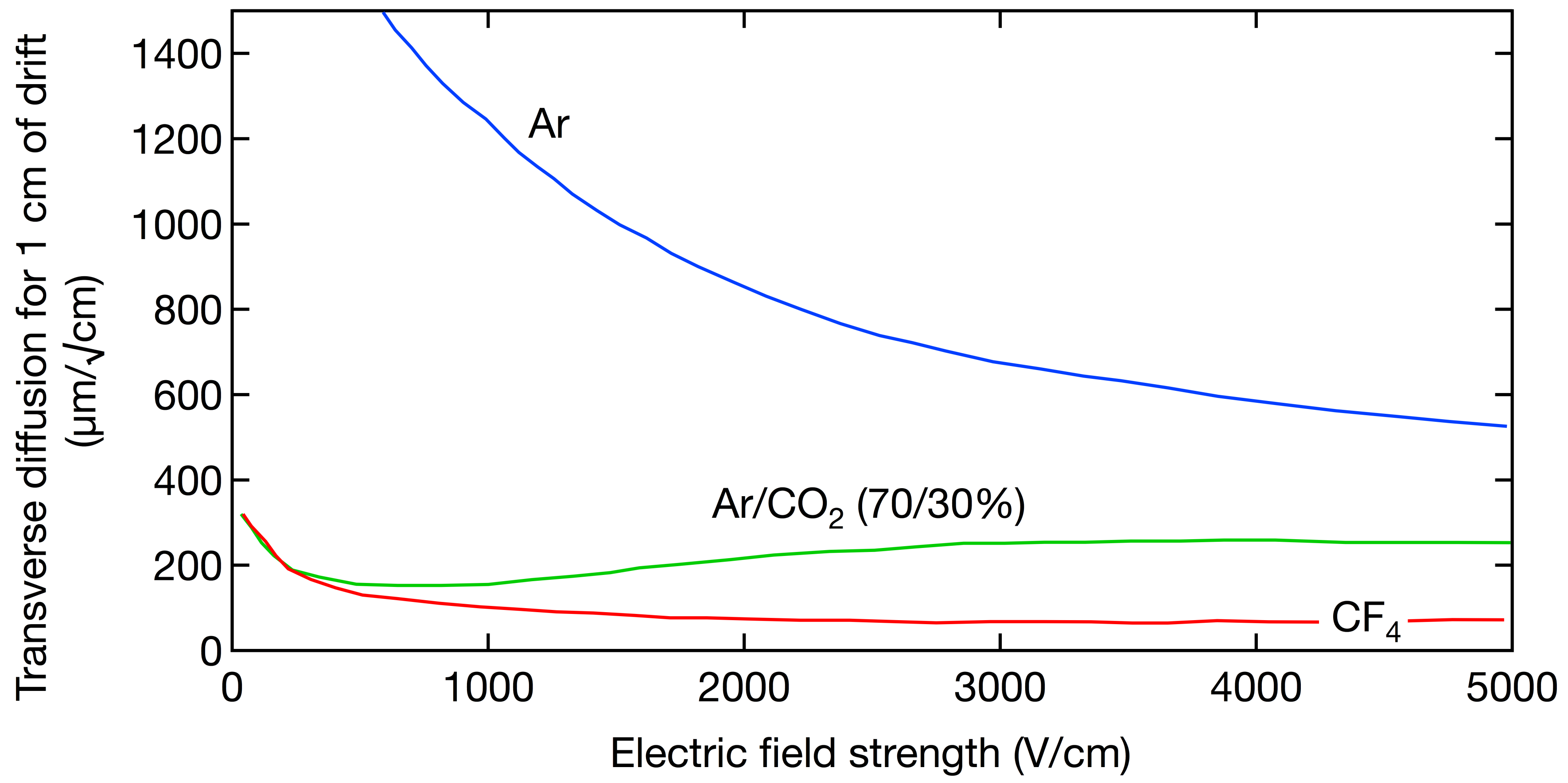


Diffusion

As integrated imaging approach, optical readout will provide a single image for a track. To differentiate clusters, transverse diffusion must remain low, imposing limits on drift distances and low pressure operation.

Negative ion drift may be promising for suppressing transverse diffusion even for long drift distances.

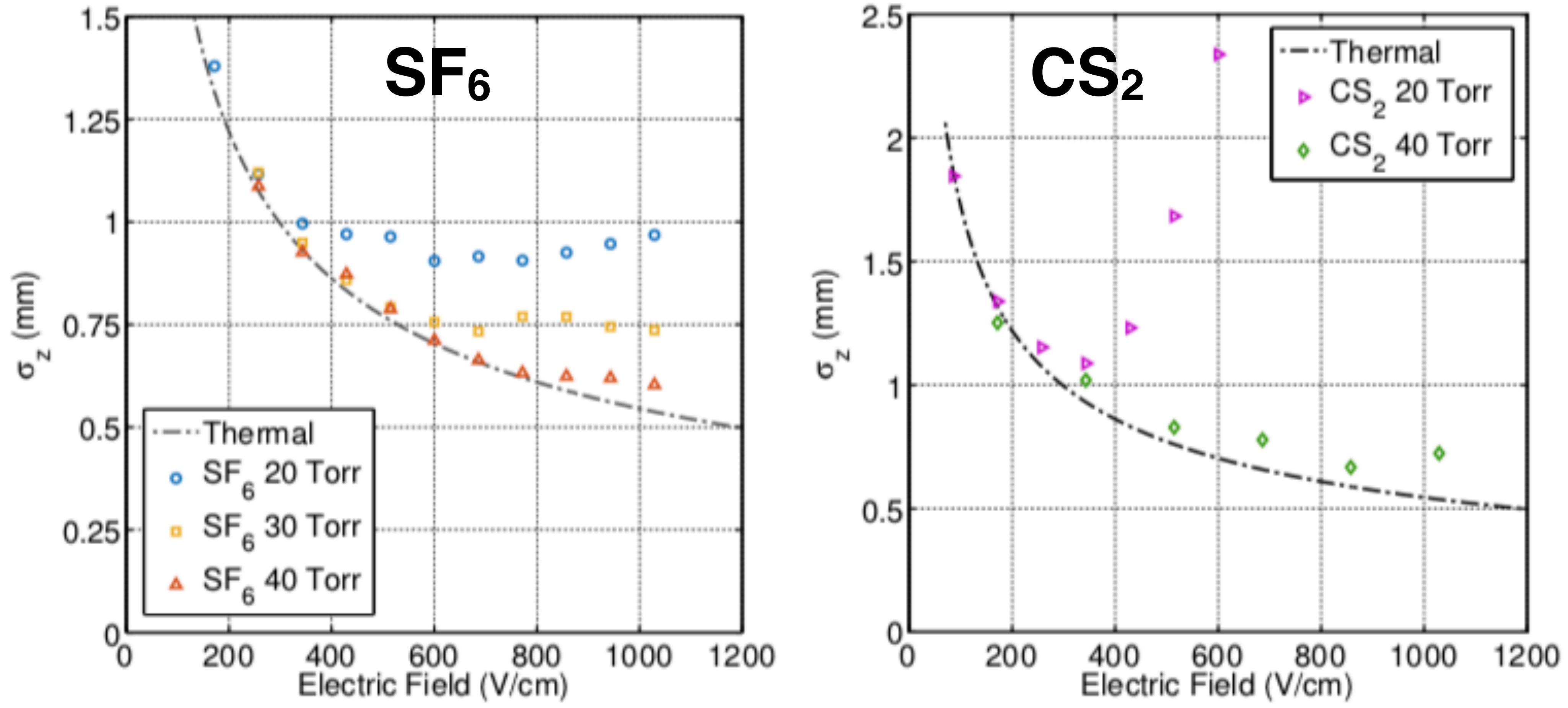
Low transverse diffusion of CF4



F. Sauli. Gaseous Radiation Detectors. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, Cambridge, 2014.

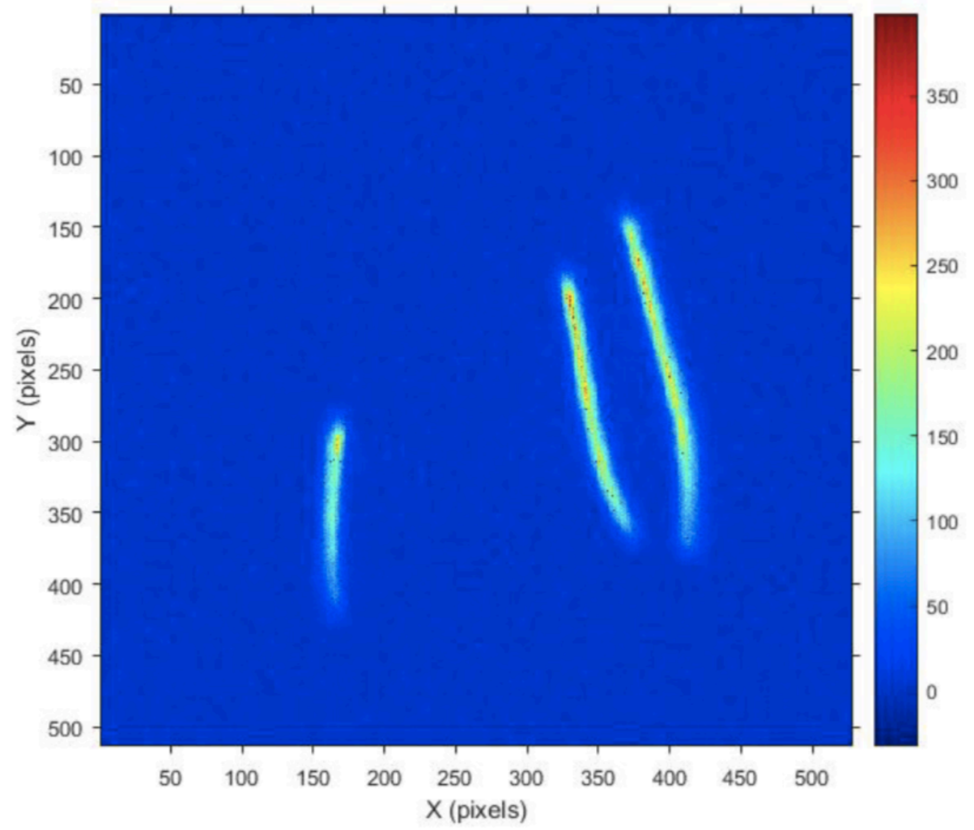
Negative ion drift:

low diffusion even for long drift distances

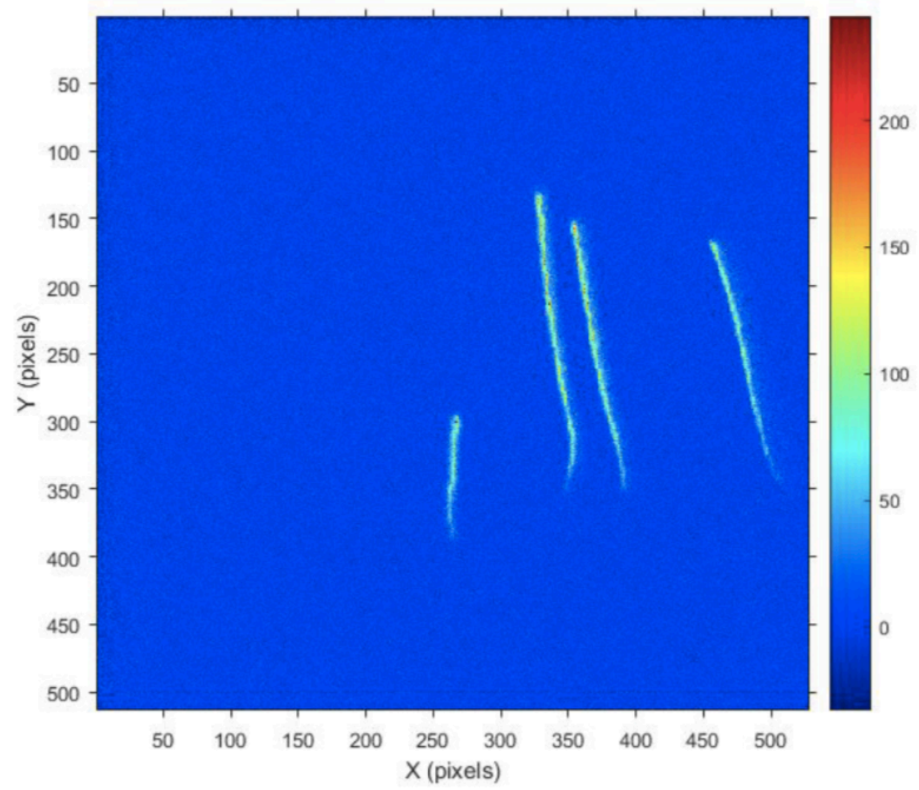


(a) SF_6 diffusion (b) CS_2 diffusion

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



150 Torr CF_4, **σ ~ 450 um**



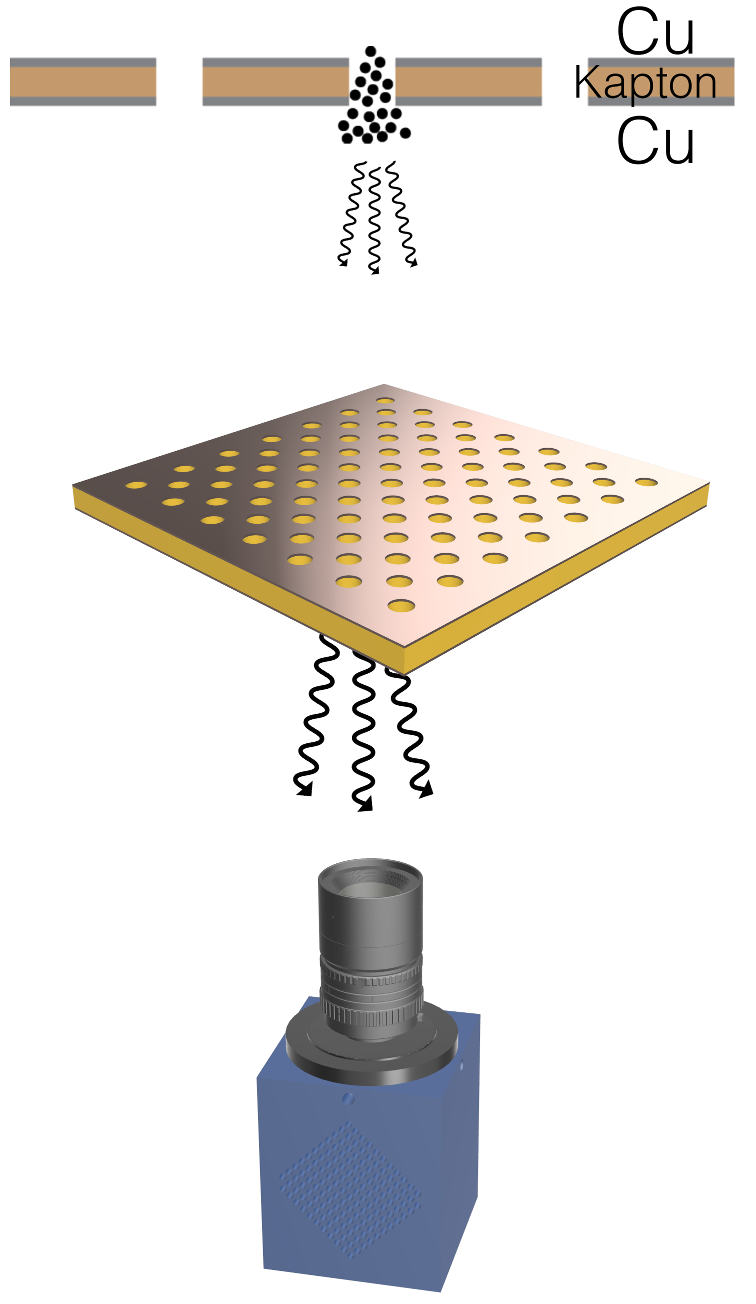
150 Torr CF_4 + 5.9 Torr CS_2, **σ ~ 150 um**

D. Loomba, UNM

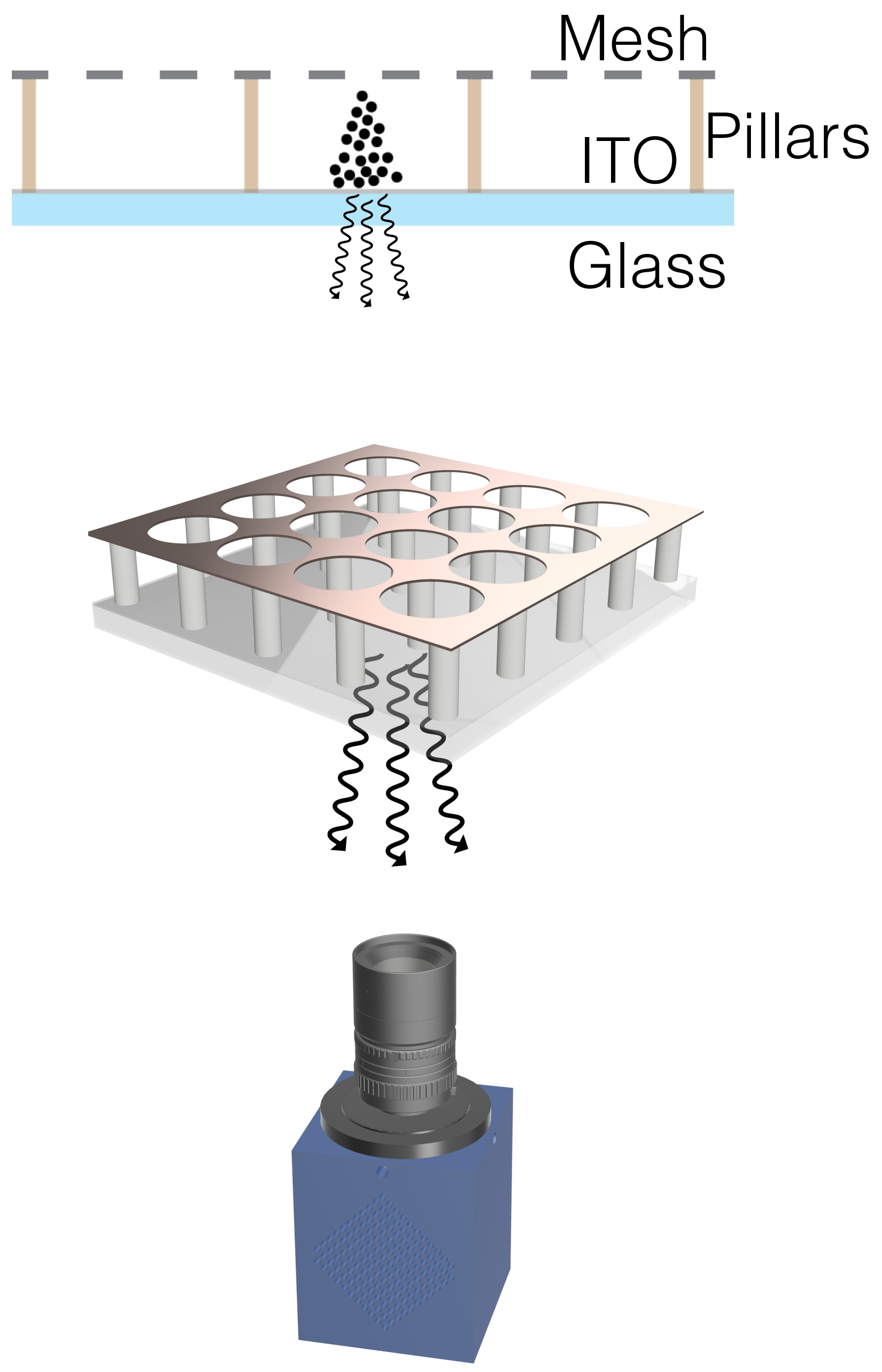
Optically read out MPGDs

Detector structure must achieve high gain while keeping diffusion to a minimum. Fewer amplification stages might be advantageous to mitigate diffusion in transfer gaps.

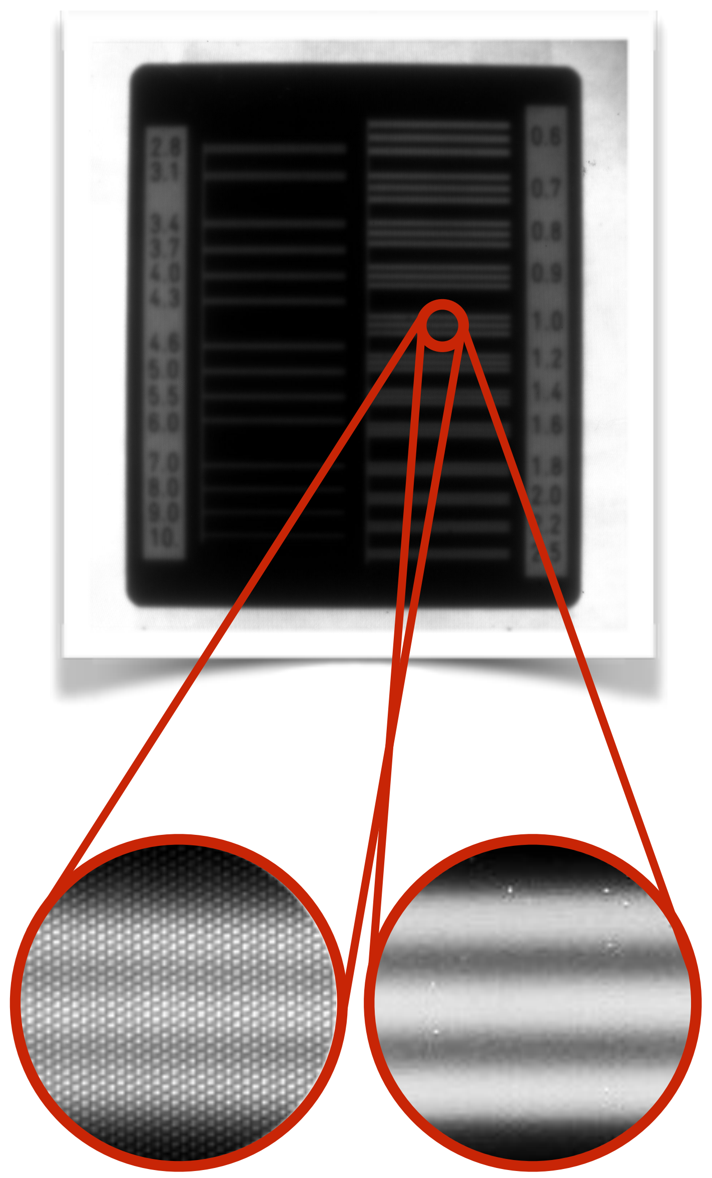
Gaseous Electron Multiplier (**GEM**)



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

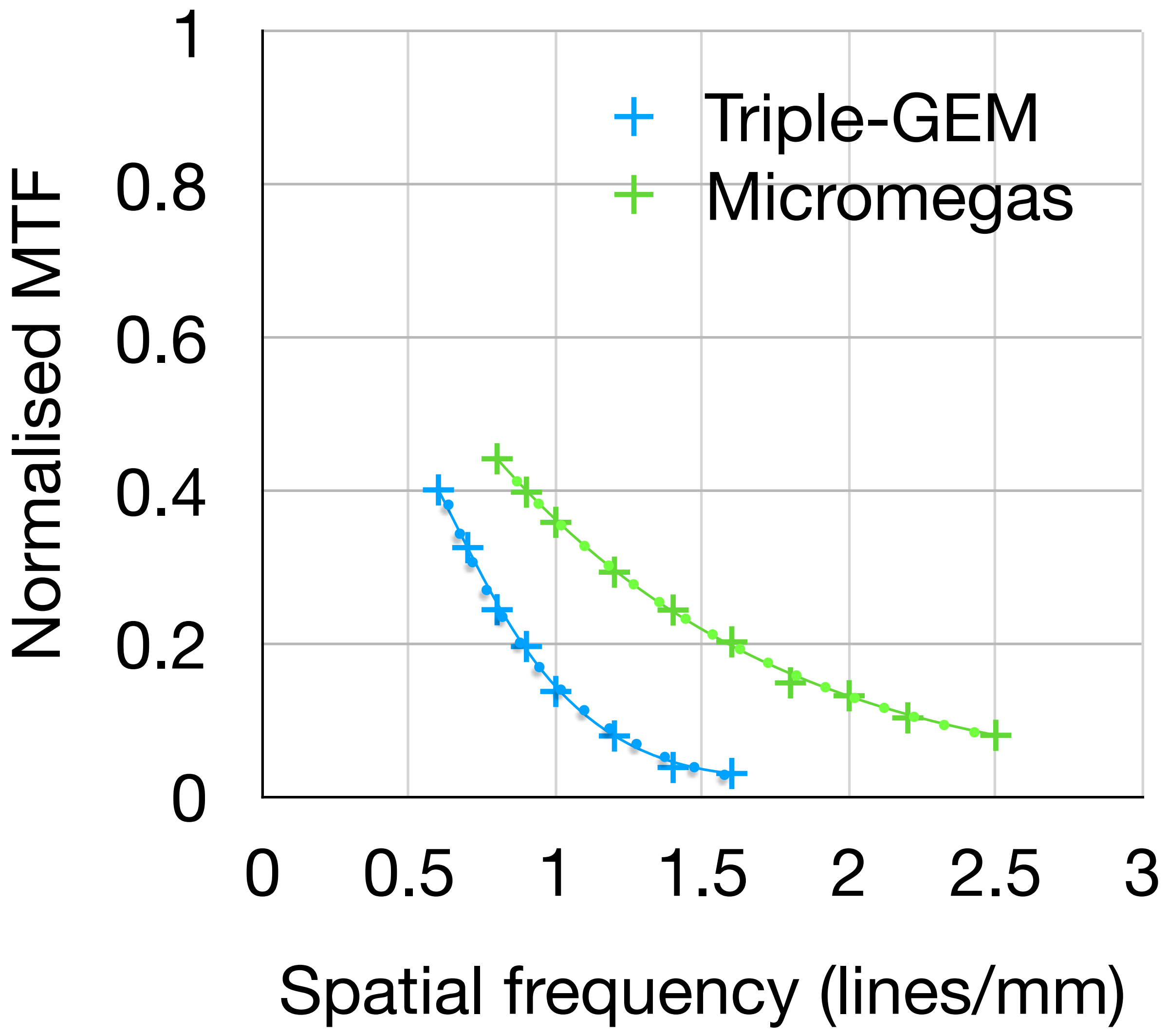


Larger diffusion in triple-GEM stack degrades spatial resolution compared to single-stage amplification in glass Micromegas.



Triple-GEM
Hole structure

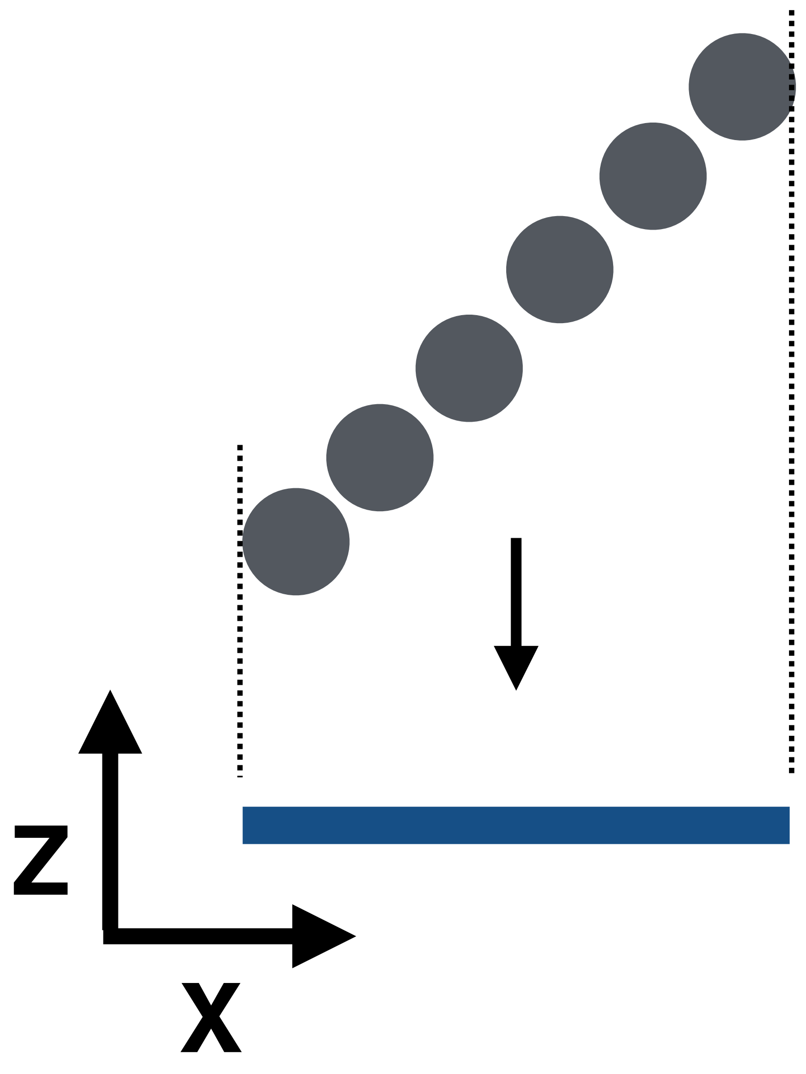
Micromegas
Uniform



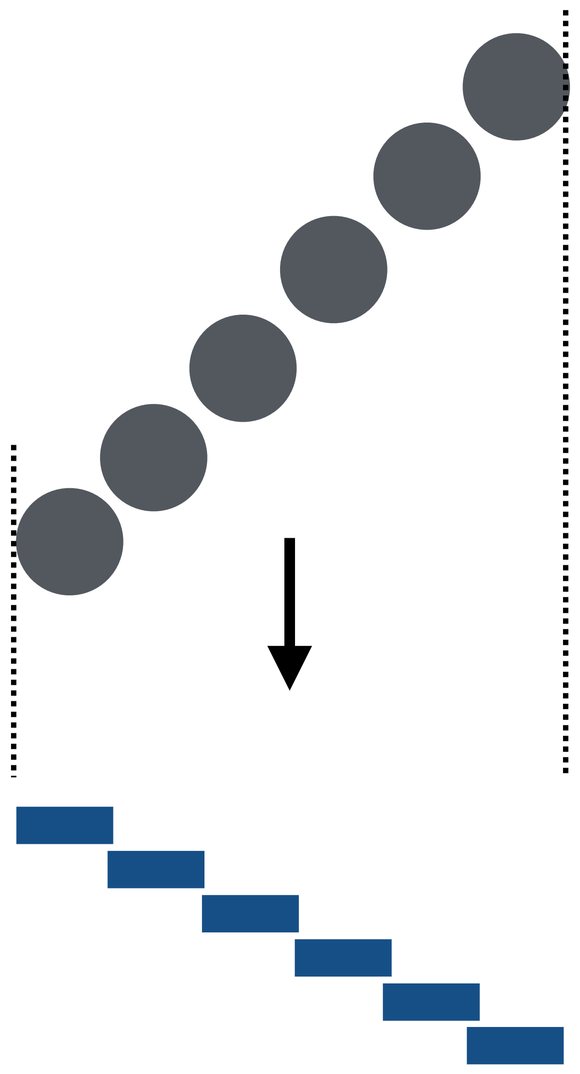
Hybrid readouts

Adding **depth information** from auxiliary charge readout or fast photon detectors can help to resolve clusters in **3D** and disentangle closely spaced structures in inclined tracks by.

Projection without z-information

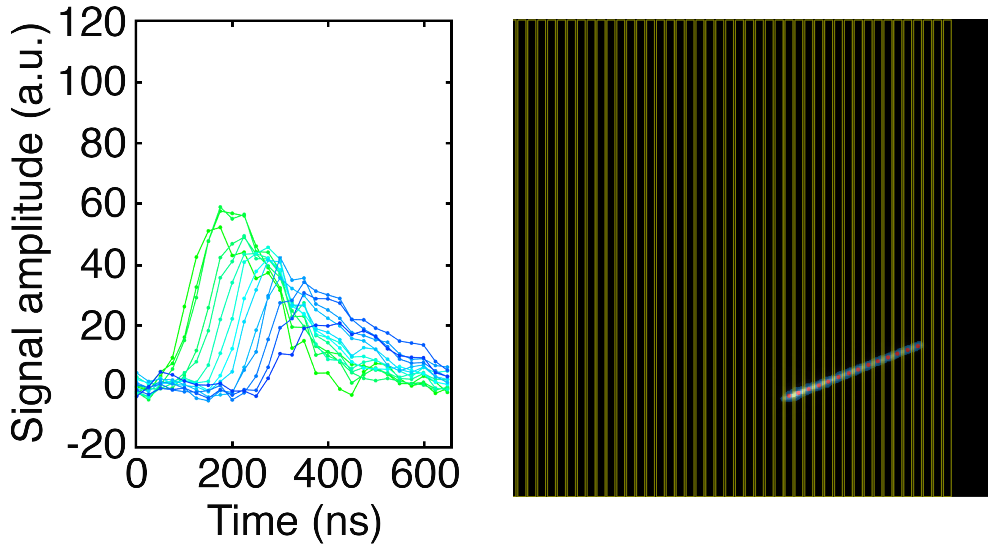


With drift time information



Charge + optical

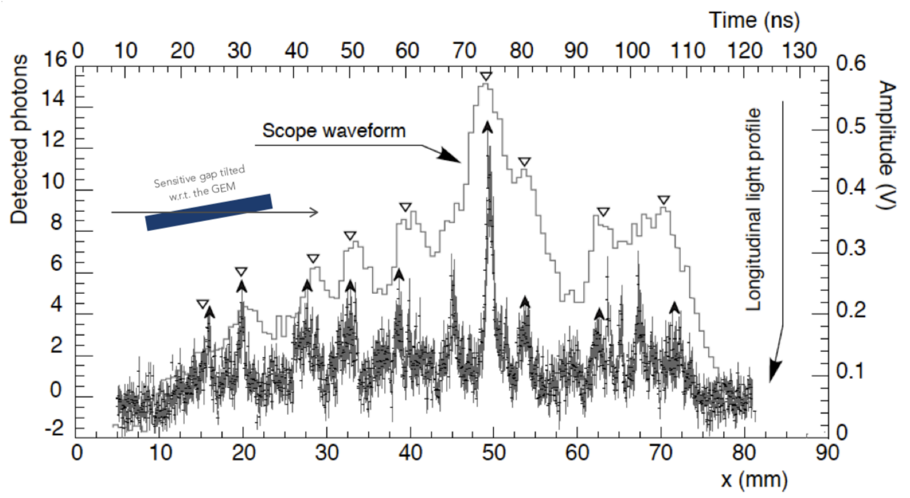
Signals from structured anode



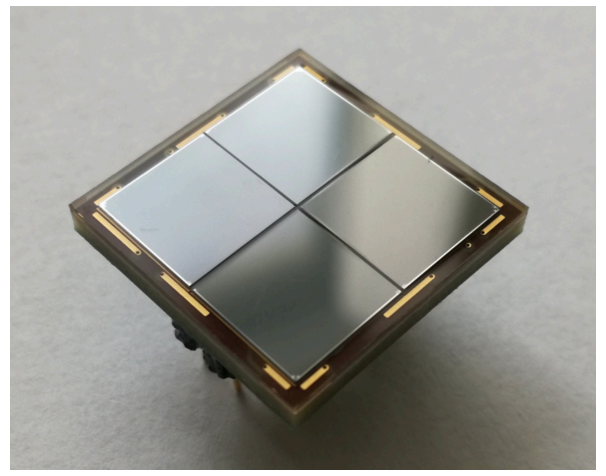
DOI: 10.1109/TNS.2018.2800775

Optical + optical

PMTs/ SiPMs / LG-SiPMs



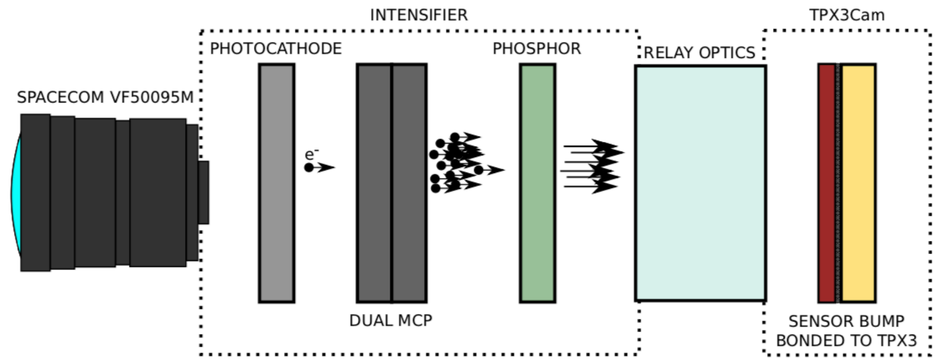
D. Pinci et al., CYGNO



A. Gola et al 2020 JINST 15 P12017

Fast optical

Ultra-fast cameras / Timepix cameras

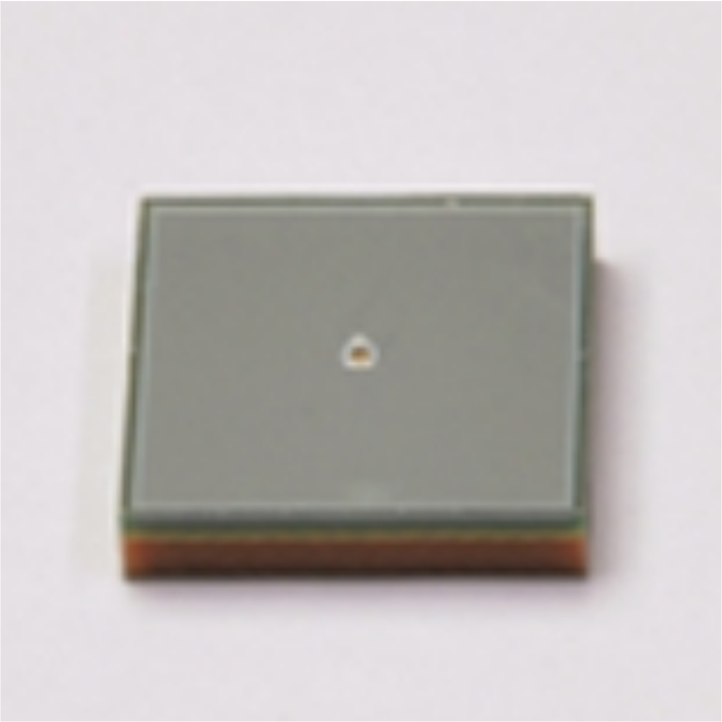


A. Roberts, ARIADNE, arXiv:1810.09955v3

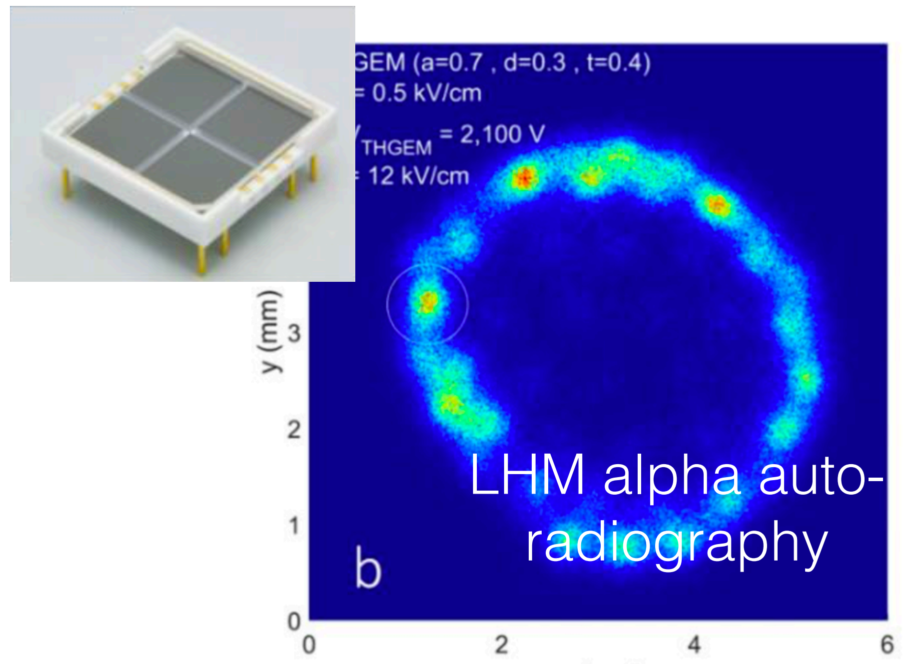
Ametek Phantom

Optical readout with SiPMs

Silicon Photomultipliers (SiPMs)



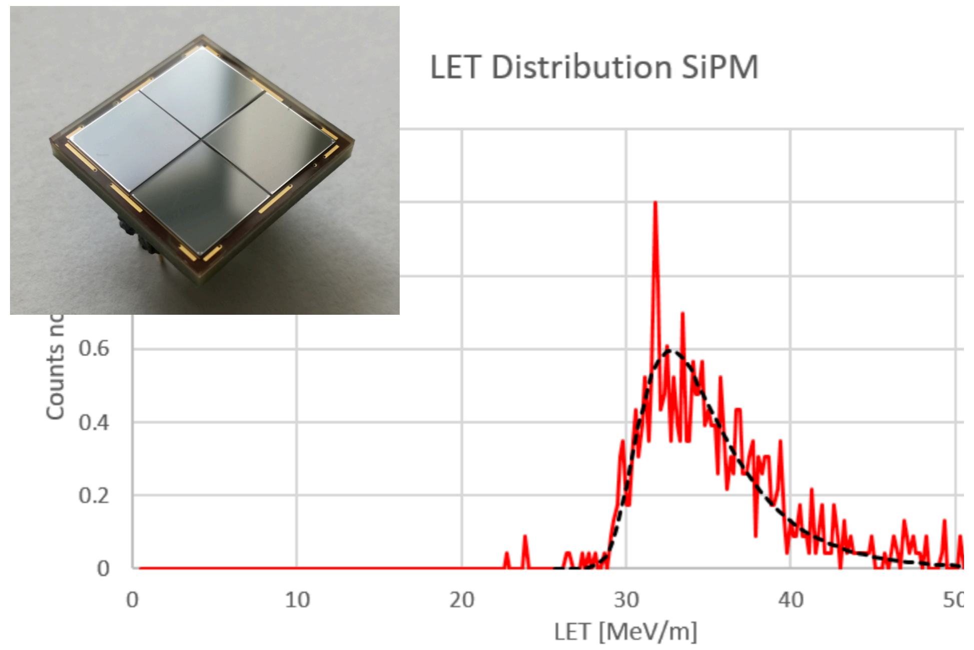
Hamamatsu SiPM

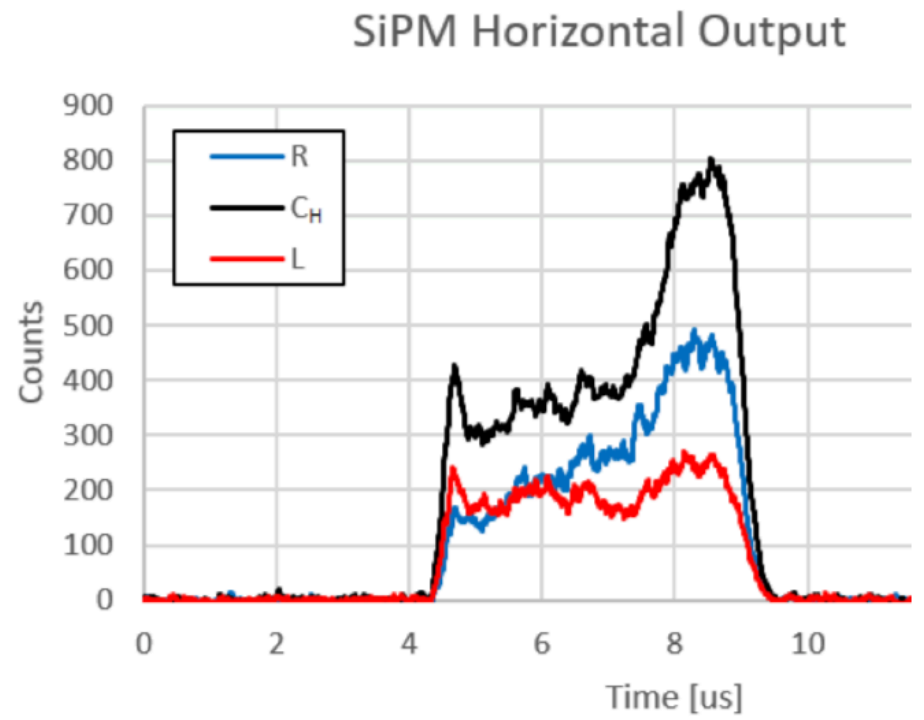


E. Erdal et al.. (2018). First Imaging Results of a Bubble-assisted Liquid Hole Multiplier with SiPM readout in Liquid Xenon.

- Arrays of SiPMs may be used to reconstruct clusters with sufficient resolution in low density media
- 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)





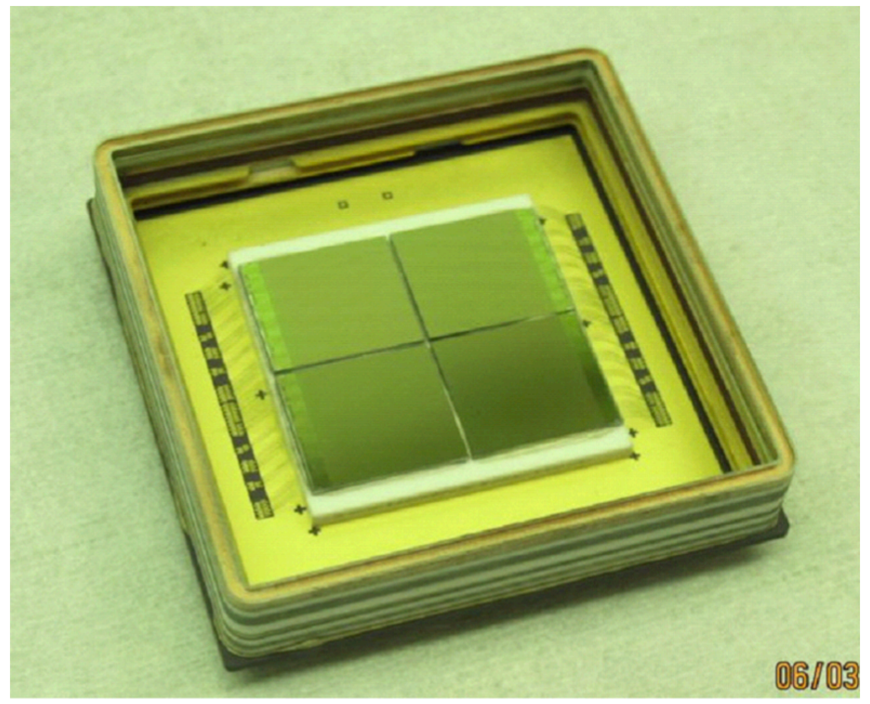
- Current in split in four outputs which allows to calculate x and y coordinates from continuous current signals
- Position resolution down to order of size of microcells (30µm)
- Fast response time of tens of ns
- Operated in low pressure CF_4 with THGEM

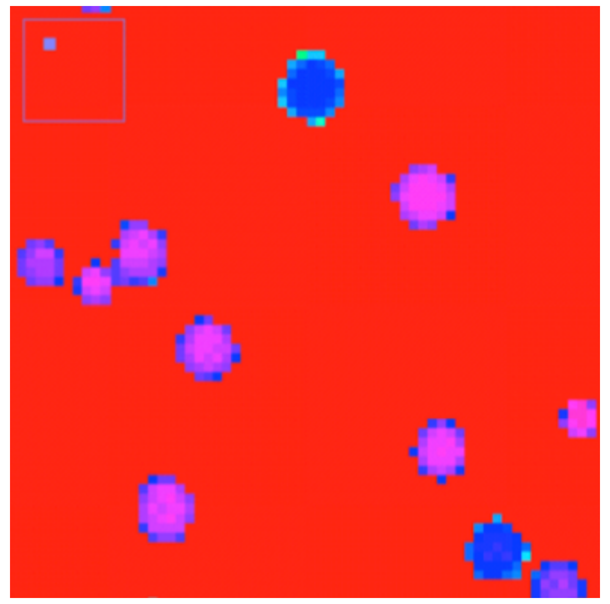
A. Gola et al 2020 JINST 15 P12017
https://doi.org/10.1088/1748-0221/15/12/P12017

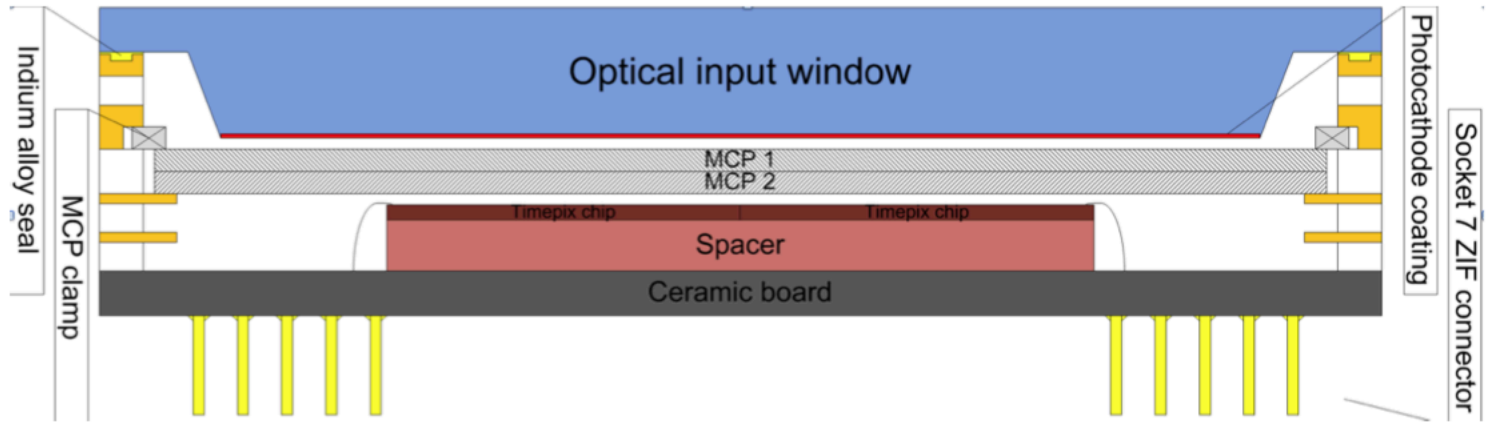
Timepix cameras

Timepix array with MCP and bi-alkali photocathode

Event counting with threshold or time of arrival recording





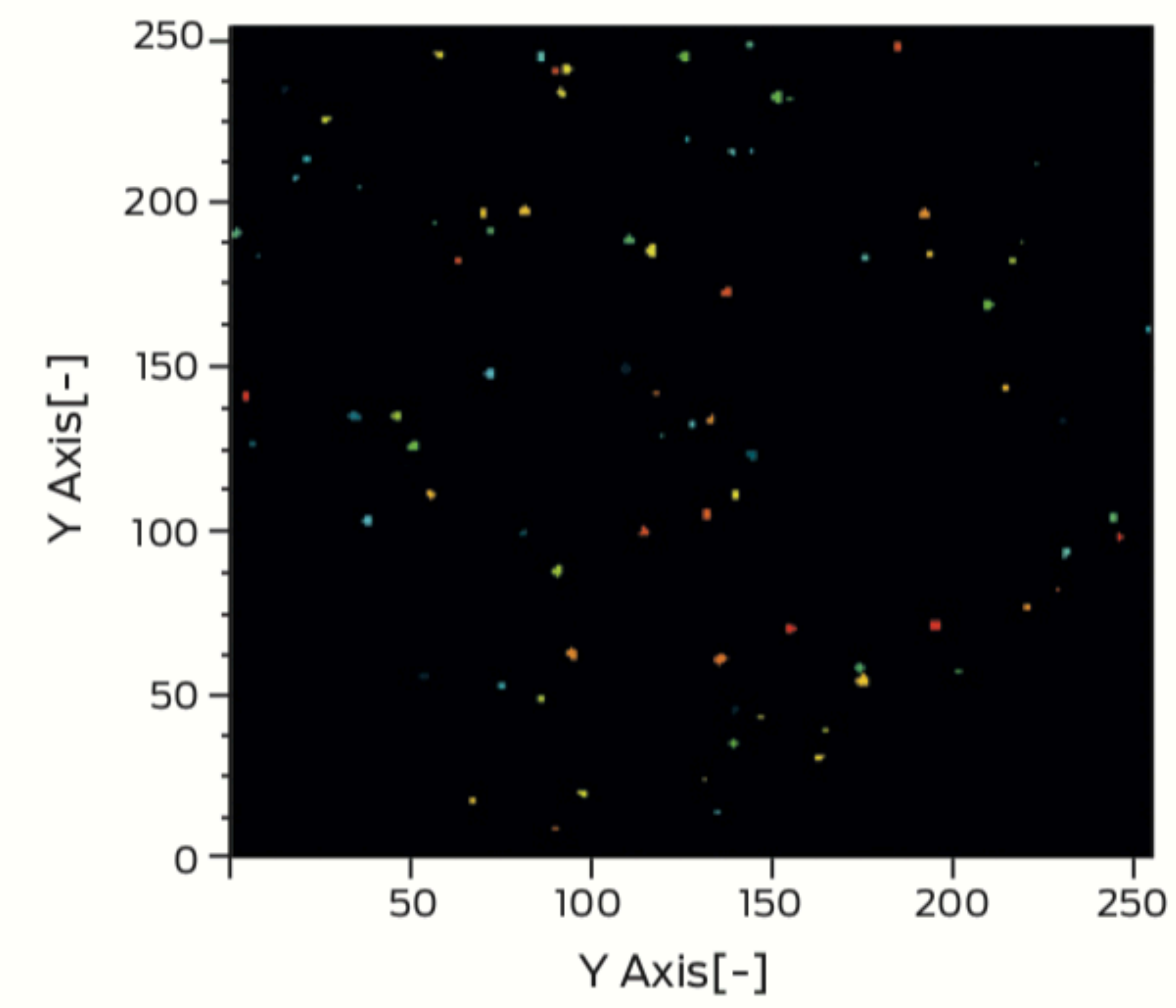


J Vallerga et al 2014 JINST 9 C05055

Timepix3 based optical camera with image intensifier

1.6ns timestamp resolution of single photon hits
Up to 80 Mhits/s rate

Commercially available

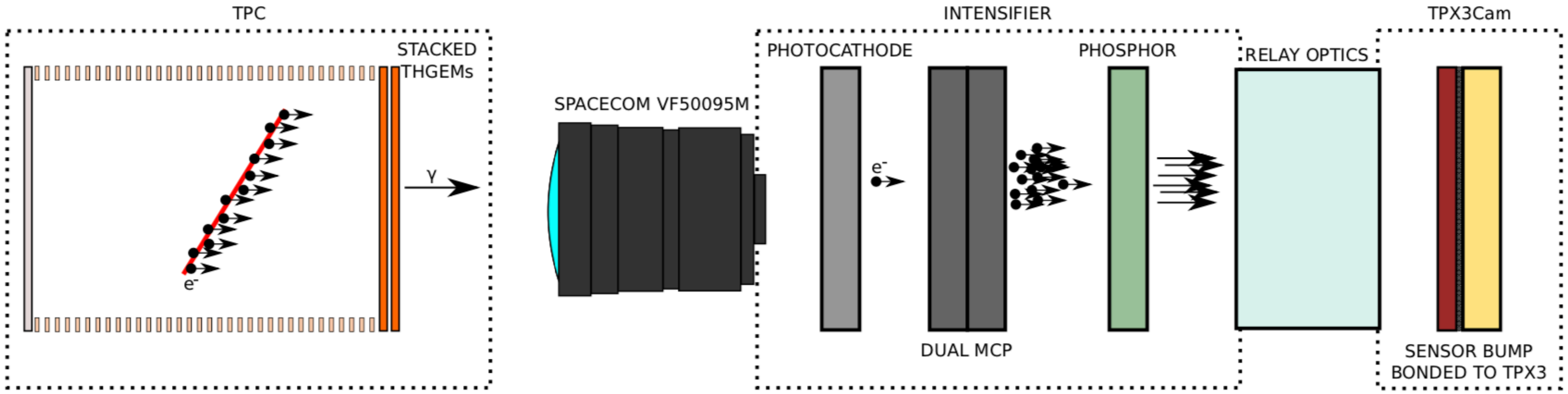


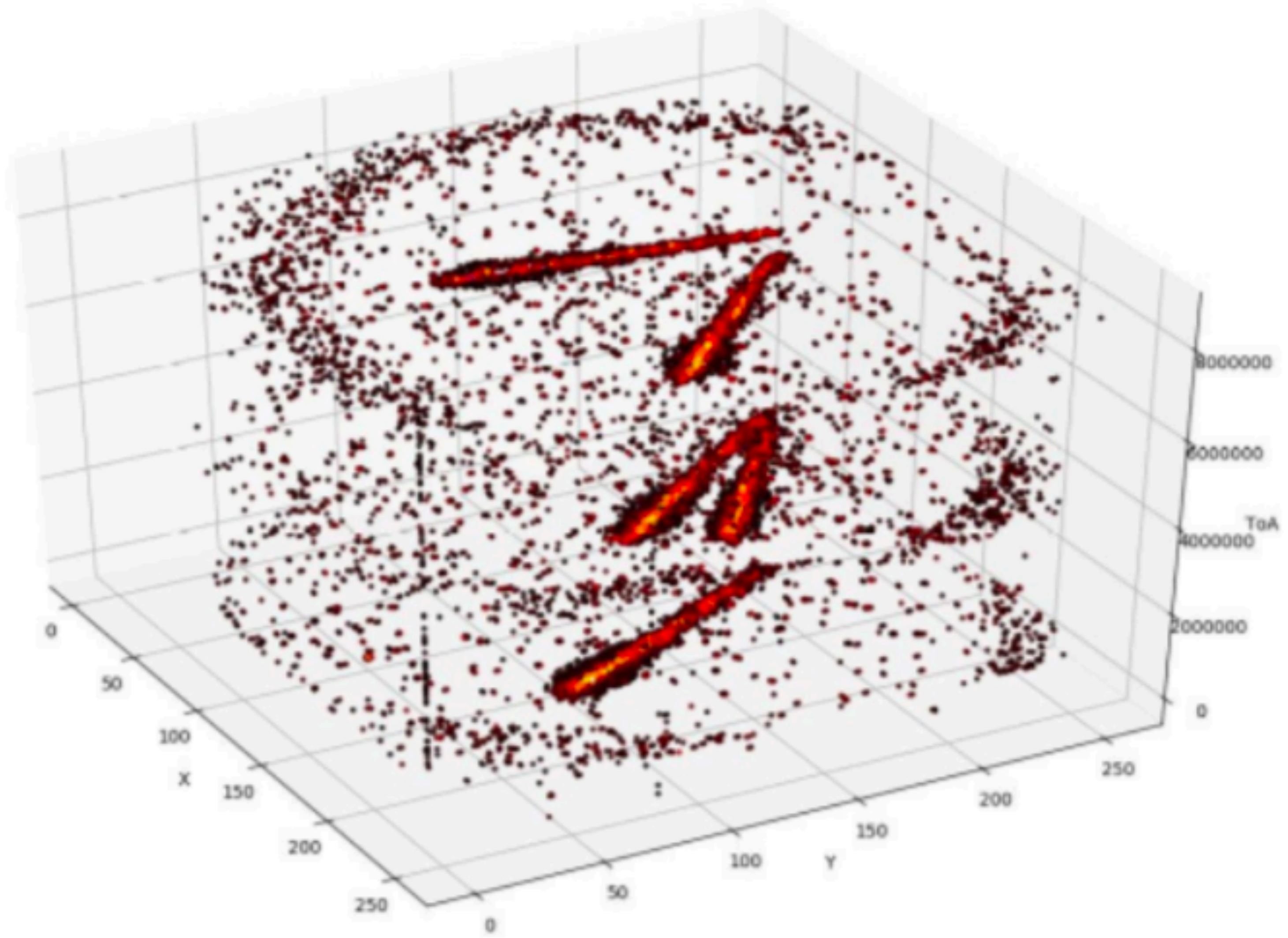
https://www.photonis.com/products/mantis3

Timepix cameras

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.





A. Roberts, ARIADNE, arXiv:1810.09955v3

Ultra-fast CMOS sensors

-

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

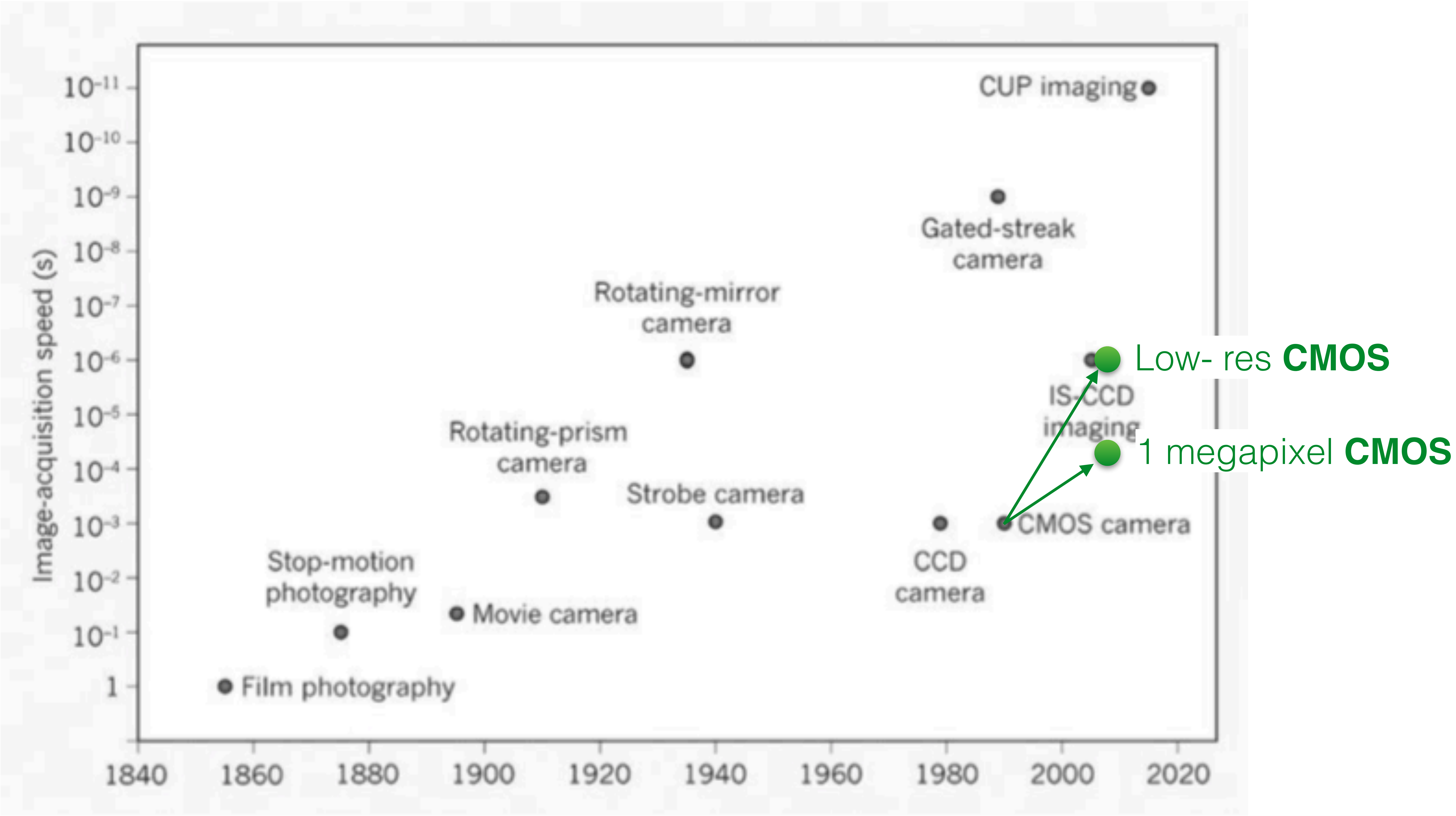
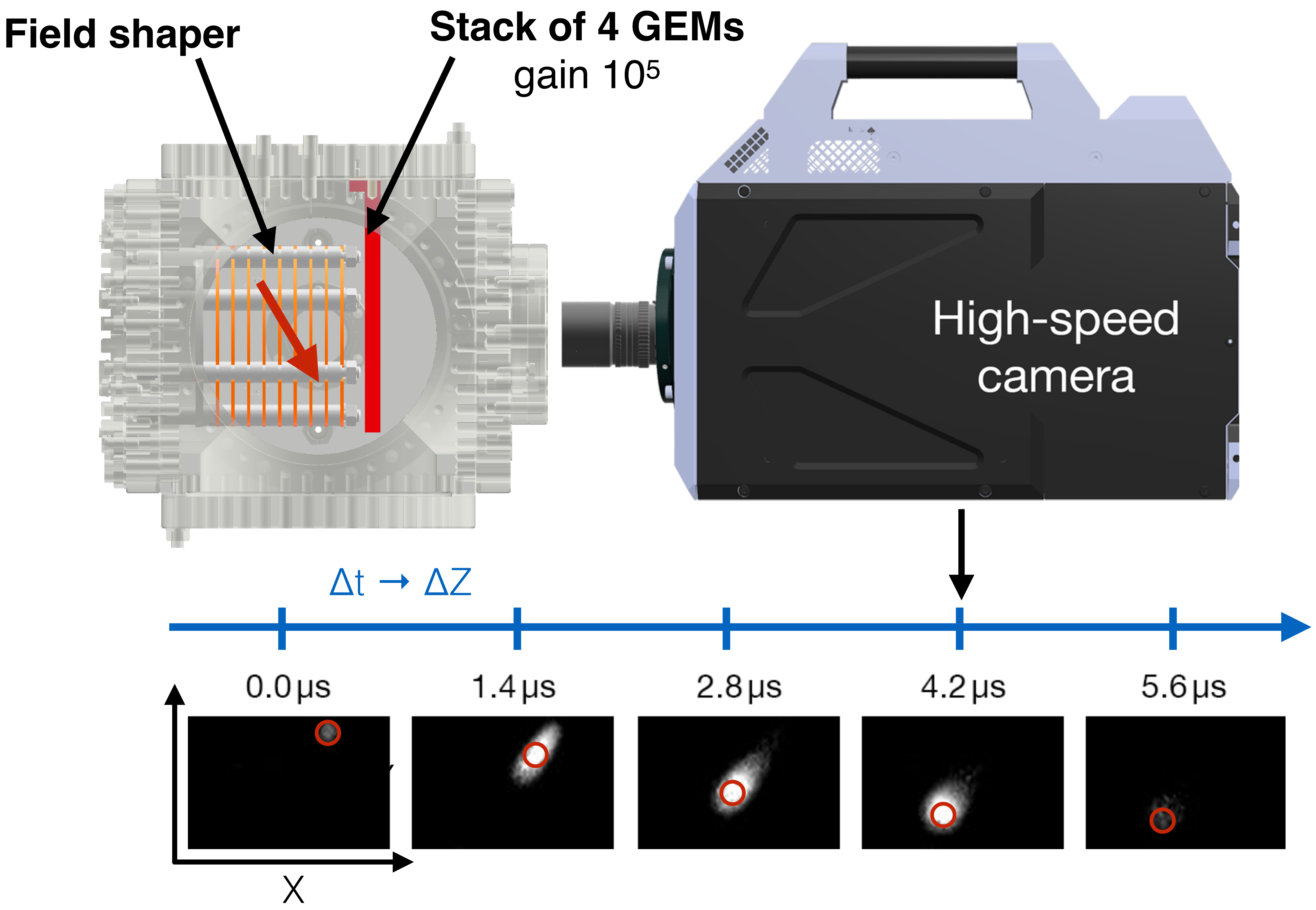


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

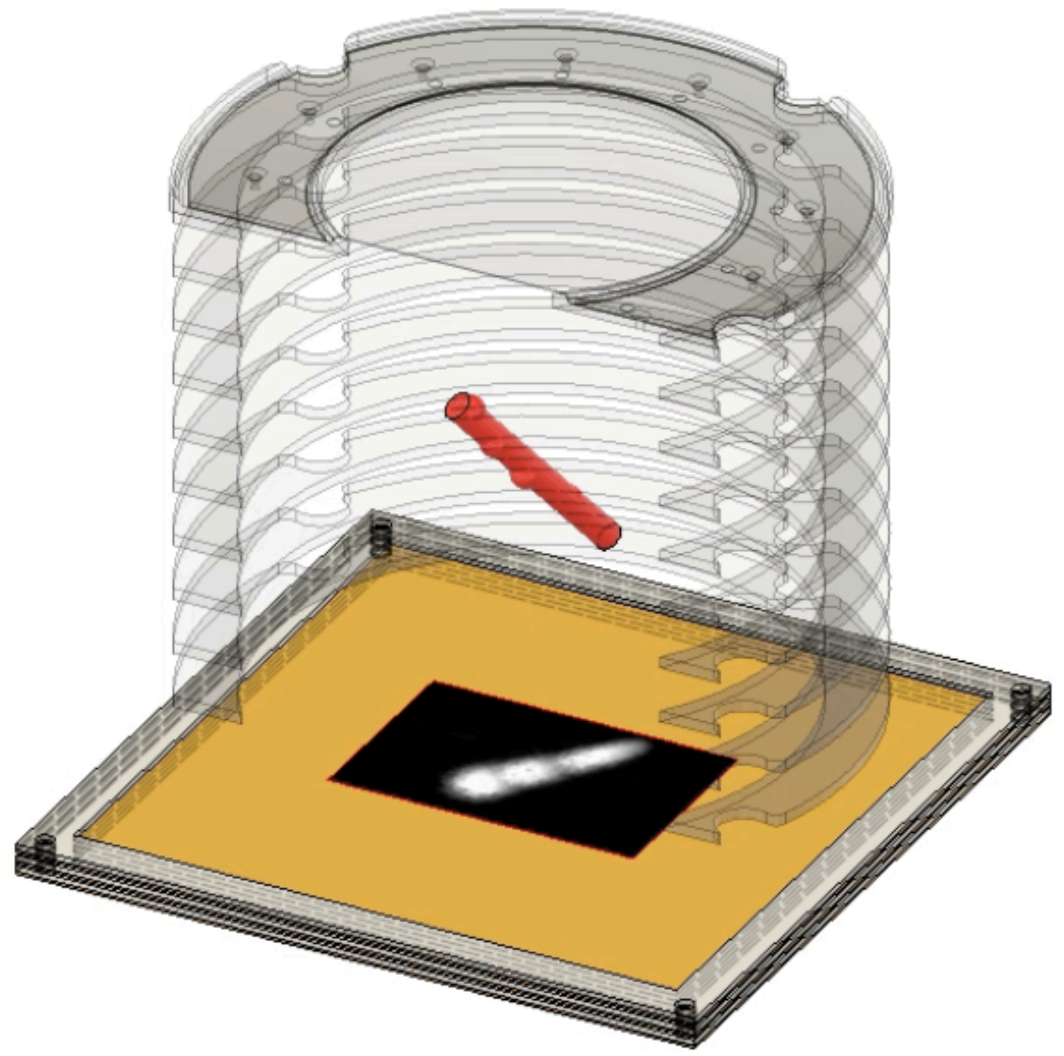
Phantom v2512

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

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

Summary

- Optically read out images contain **energy loss information** and **energy resolved imaging** as well as **track classification** based on integrated intensities or light density, respectively, have been demonstrated.

- To exploit high-granularity optical readout for dE/dx measurements with **cluster counting**, **high gain** and **light yield** must be achieved. This allows use high-pixel-count sensors with acceptable SNRs. Suitable gas mixtures for optical readout (CF4, WLS) are necessary.

- Photon detectors are promising candidates for **cluster counting** relying on **pixellated readout**.
- Fast photon detectors with single photon sensitivity (**SiPMs**, **Timepix cameras**) can be used to add **timing information** and permit 3D reconstruction and improved cluster reconstruction.