Optical readout, novel readout electrodes, hybrids with ASICs

F. M. Brunbauer (CERN GDD)

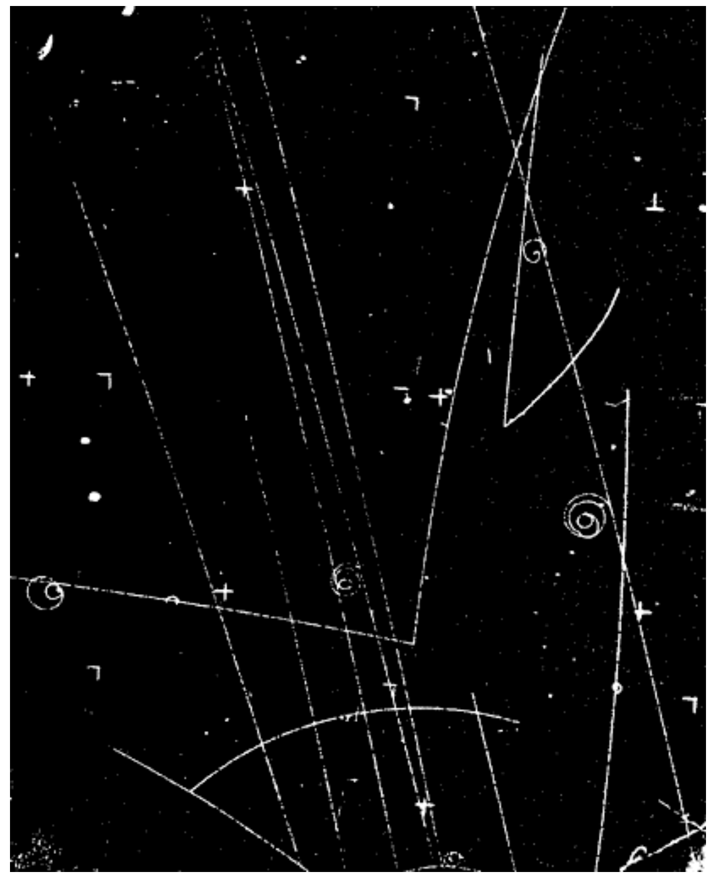
April 29, 2021 - ECFA Detector R&D Roadmap Symposium - TF1 Gaseous Detectors

Pixellated readout

High granularity pixellated sensors for detailed visualisation and reconstruction of particle tracks and imaging applications

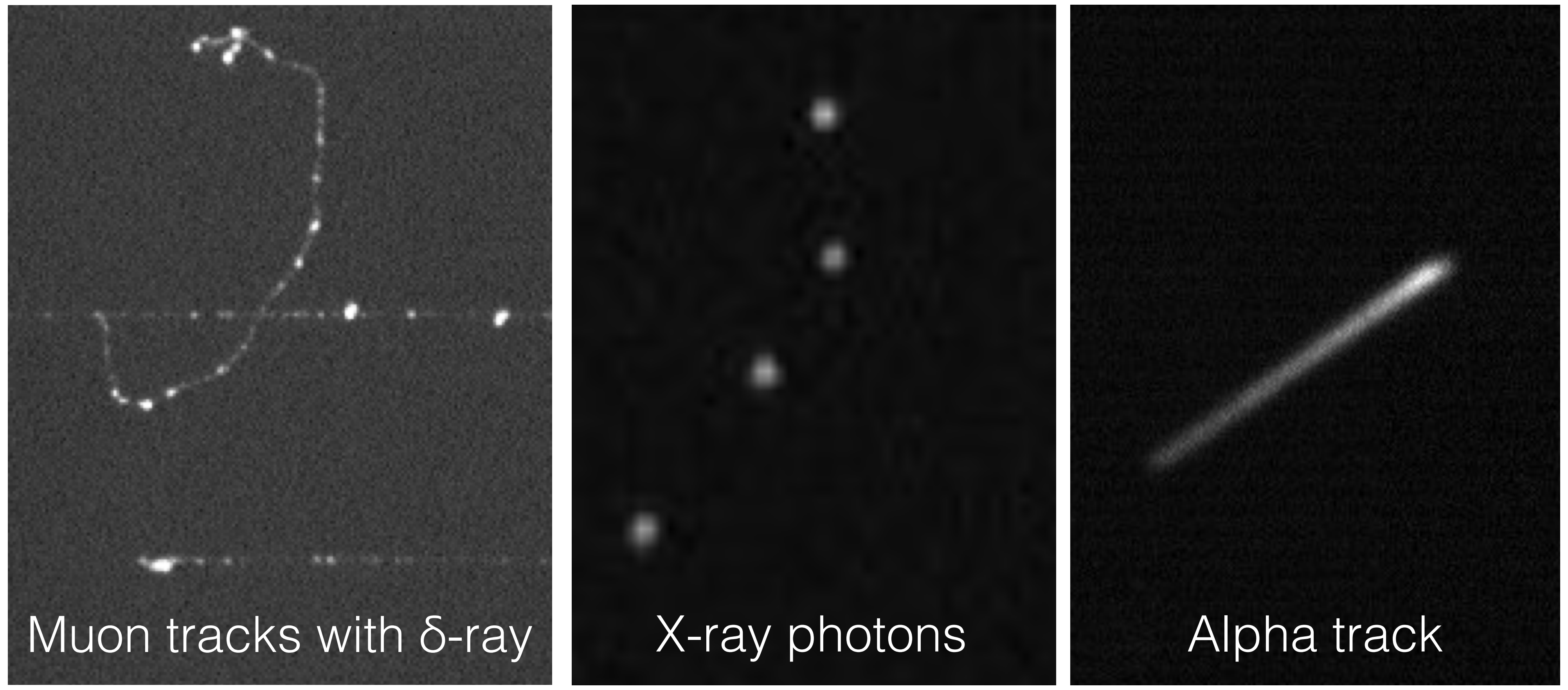
Taking advantage of state-of-the-art imaging sensors and readout ASICs

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



- **Optical readout with imaging sensors**
- **Hybrid readout (optical + electronic)**
- **Pixellated readout ASICs**

Requirements

Optimised matching of pixel size to amplification structure

High QE and low noise characteristics

Fast readout (frame-based / hit-based)

Thank you for all contributions, comments and discussions to E. Baracchini, A. Deisting, T. Fujiwara, H. van der Graaf, J. Kaminski, J. Leidner, D. Loomba, P. Majewski, F. Murtas, T. Papavangelou, D. Pinci, E. Pollacco, F. Resnati, … and many others!

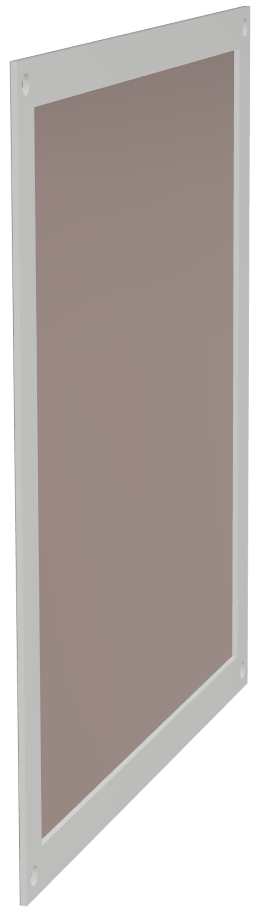
Optical readout

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)



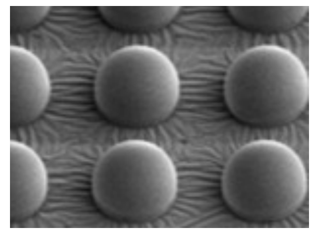
High gain MPGDs

Optics
(coupling)

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

photonis.com

szphoton.com



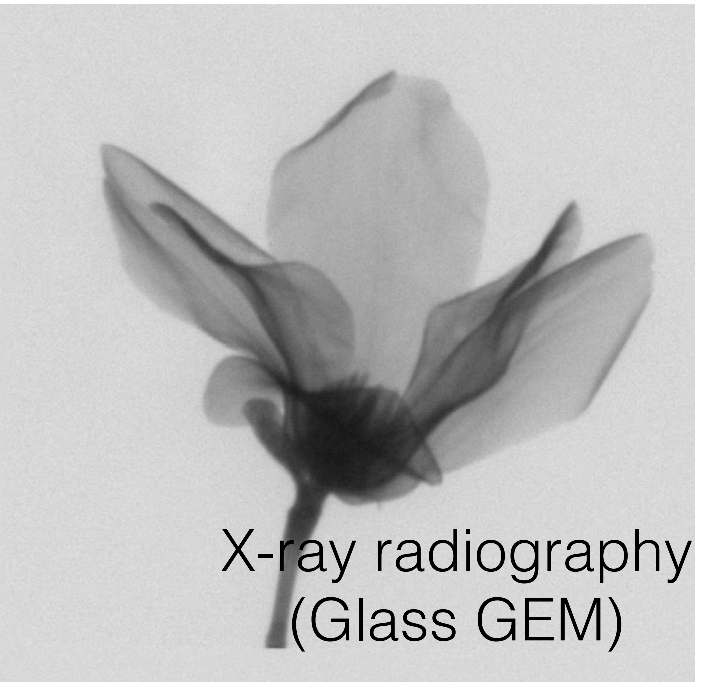
10.1016/j.apsusc.2018.01.253

Imaging sensor
(camera)

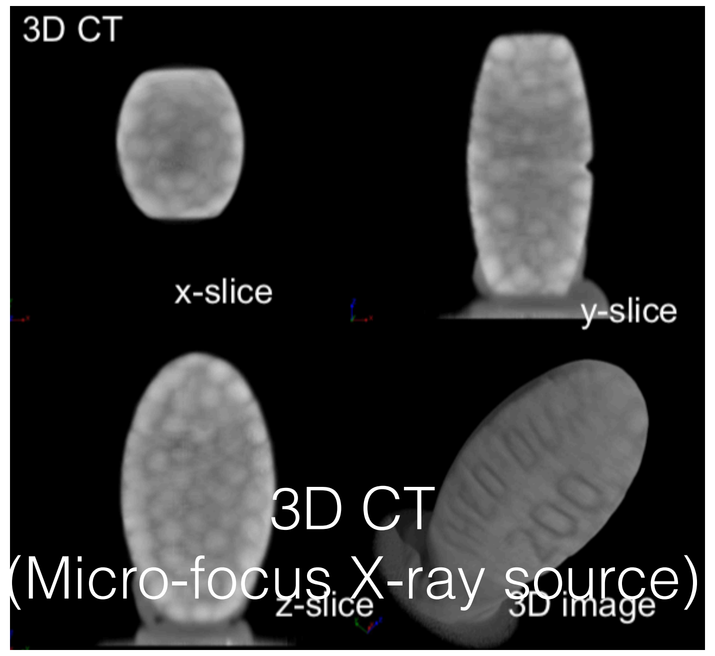
CCD, CMOS, ASICs

X-ray radiography
(Glass Micromegas)

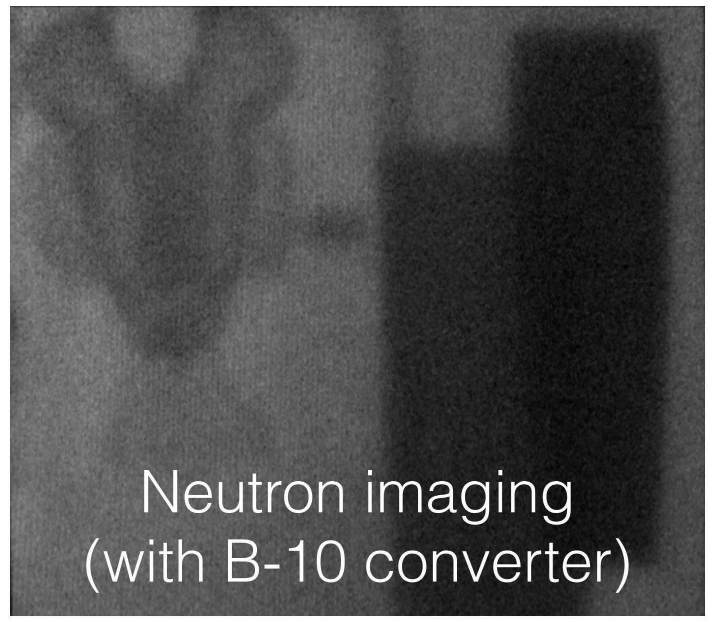
F. Brunbauer et al., Radiation imaging with glass Micromegas, https://doi.org/10.1016/j.nima.2019.163320



X-ray radiography
(Glass GEM)



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



Neutron imaging
(with B-10 converter)

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

Optically read out MPGDs

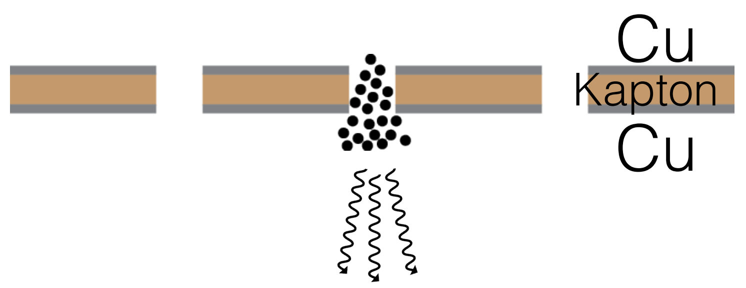
Different MPGD technologies have been used with optical readout for maximising spatial resolution (imaging), low pressure operation (glass GEM) and for detailed studies of detector physics.

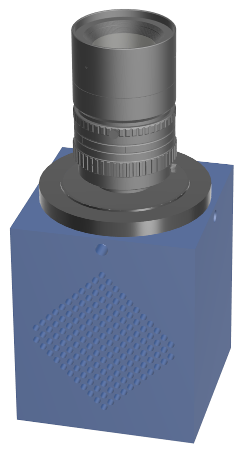
Integration on transparent substrate (ITO-coated glass) for optical light transmission.

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

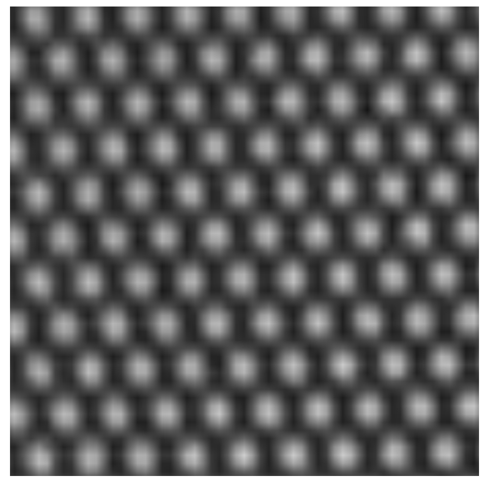
GEMs

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



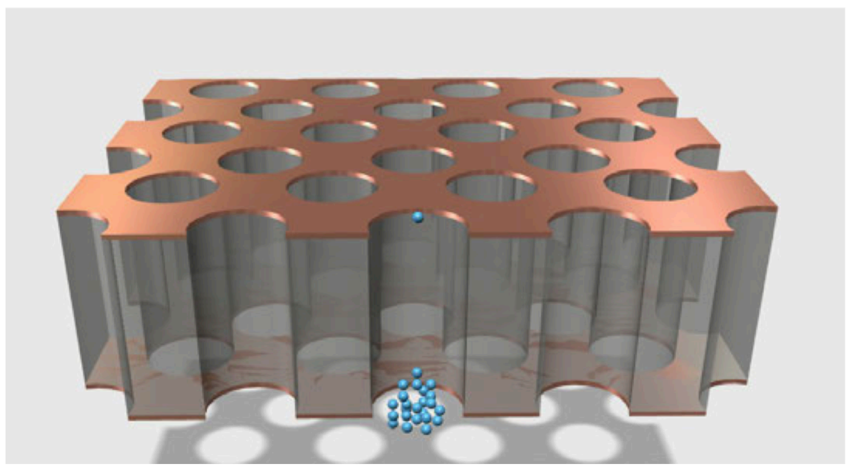


GEM holes
(140µm pitch)

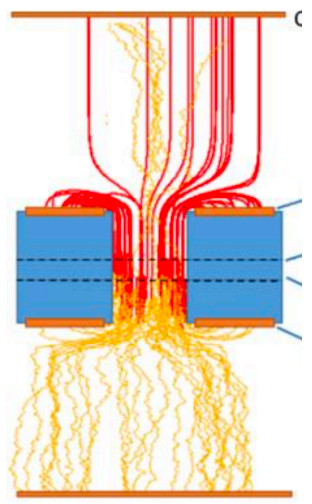


THGEMs

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



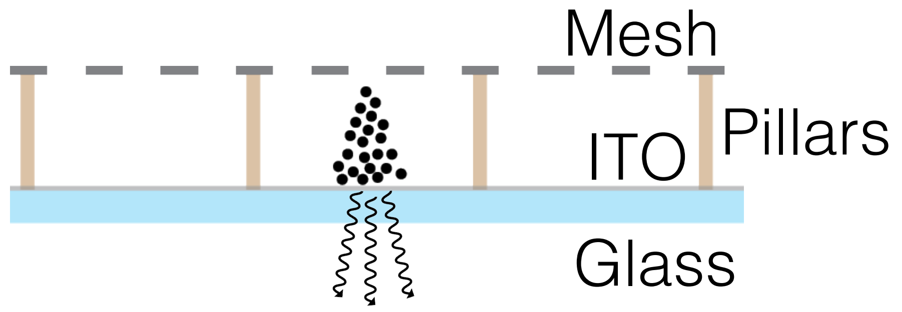
T. Fujiwara, MPGD2017

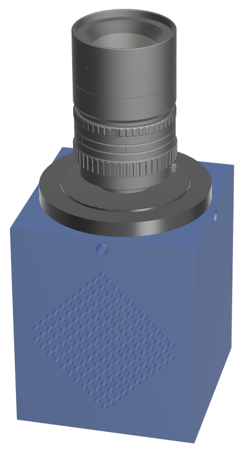


M. Cortesi, MPGD 2019

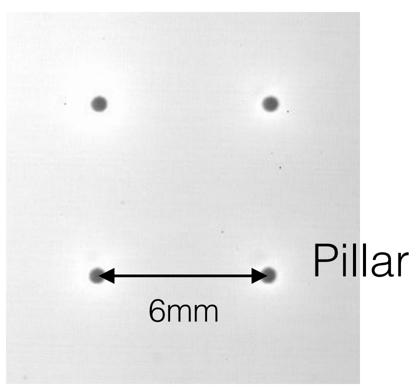
Glass Micromegas

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





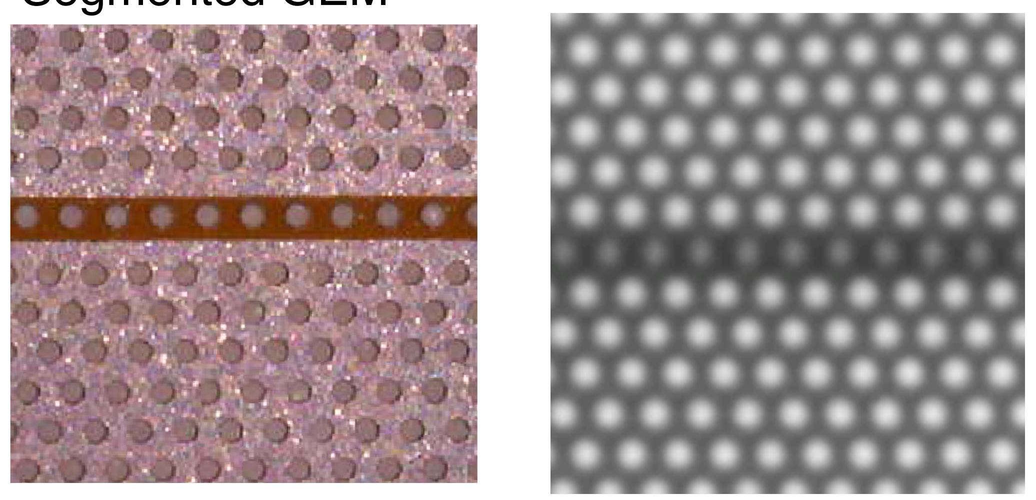
MM response

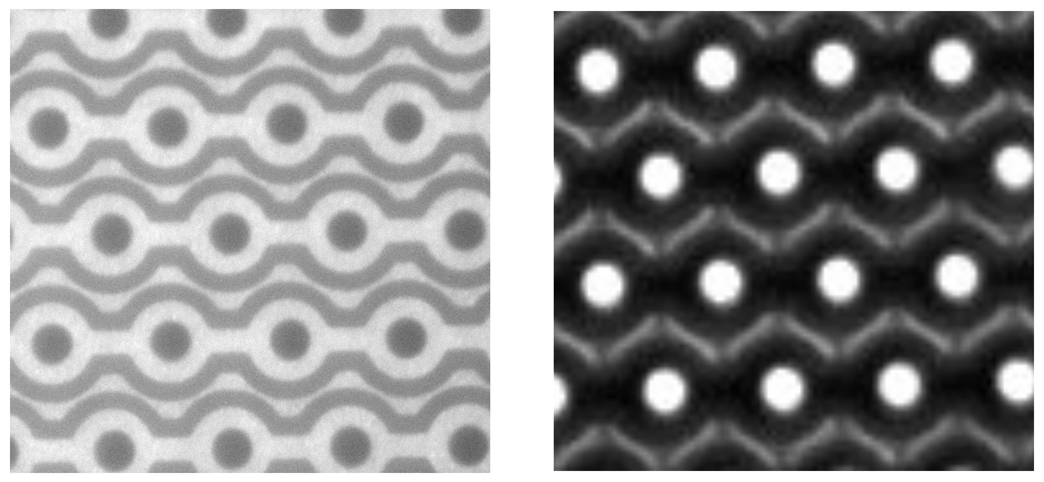


Glass substrates → other MPGDs

MPGD development and detector physics studies

Segmented GEM





THCOBRA

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

Scintillation spectra

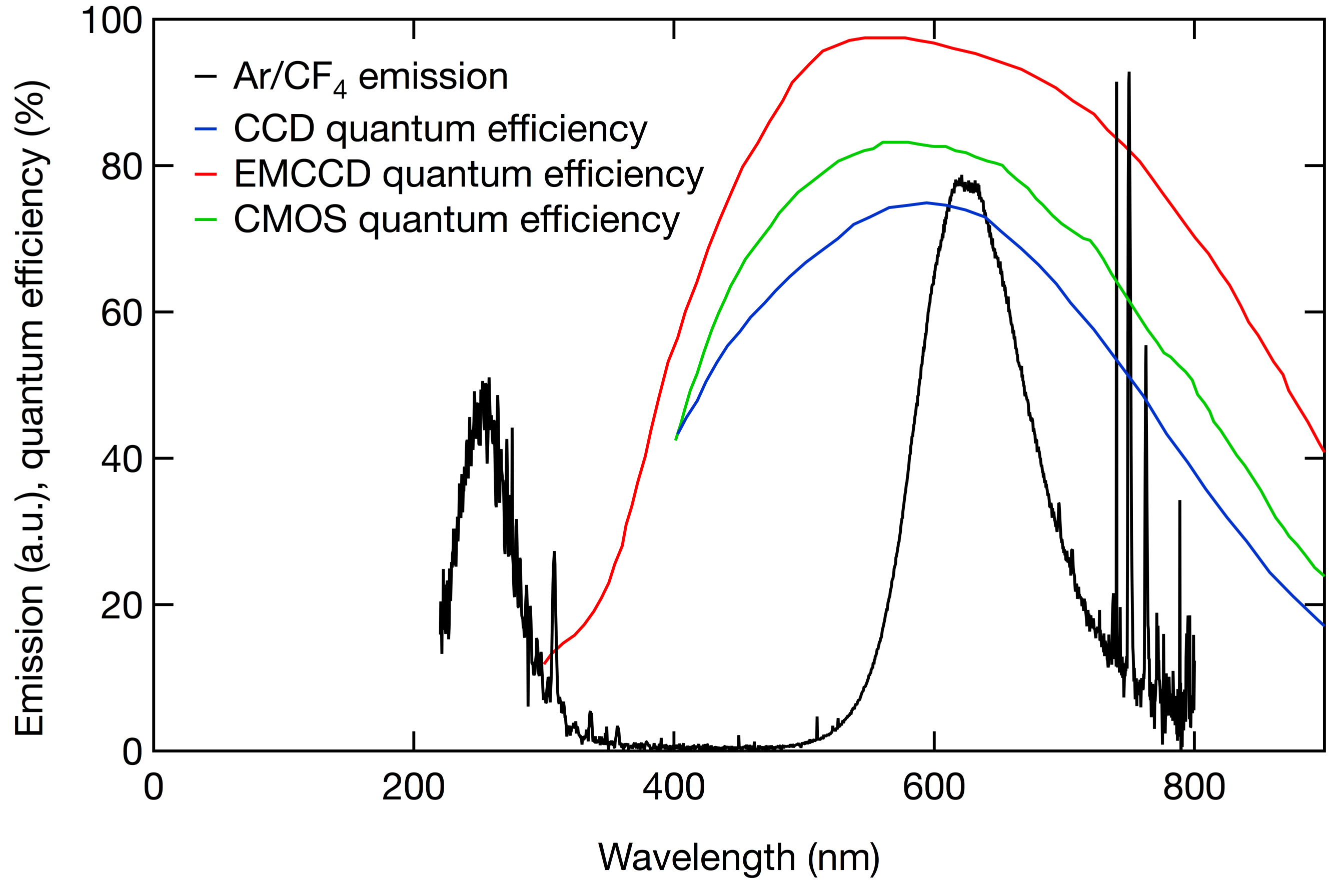
Reading out secondary scintillation light emitted during electron avalanche multiplication

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

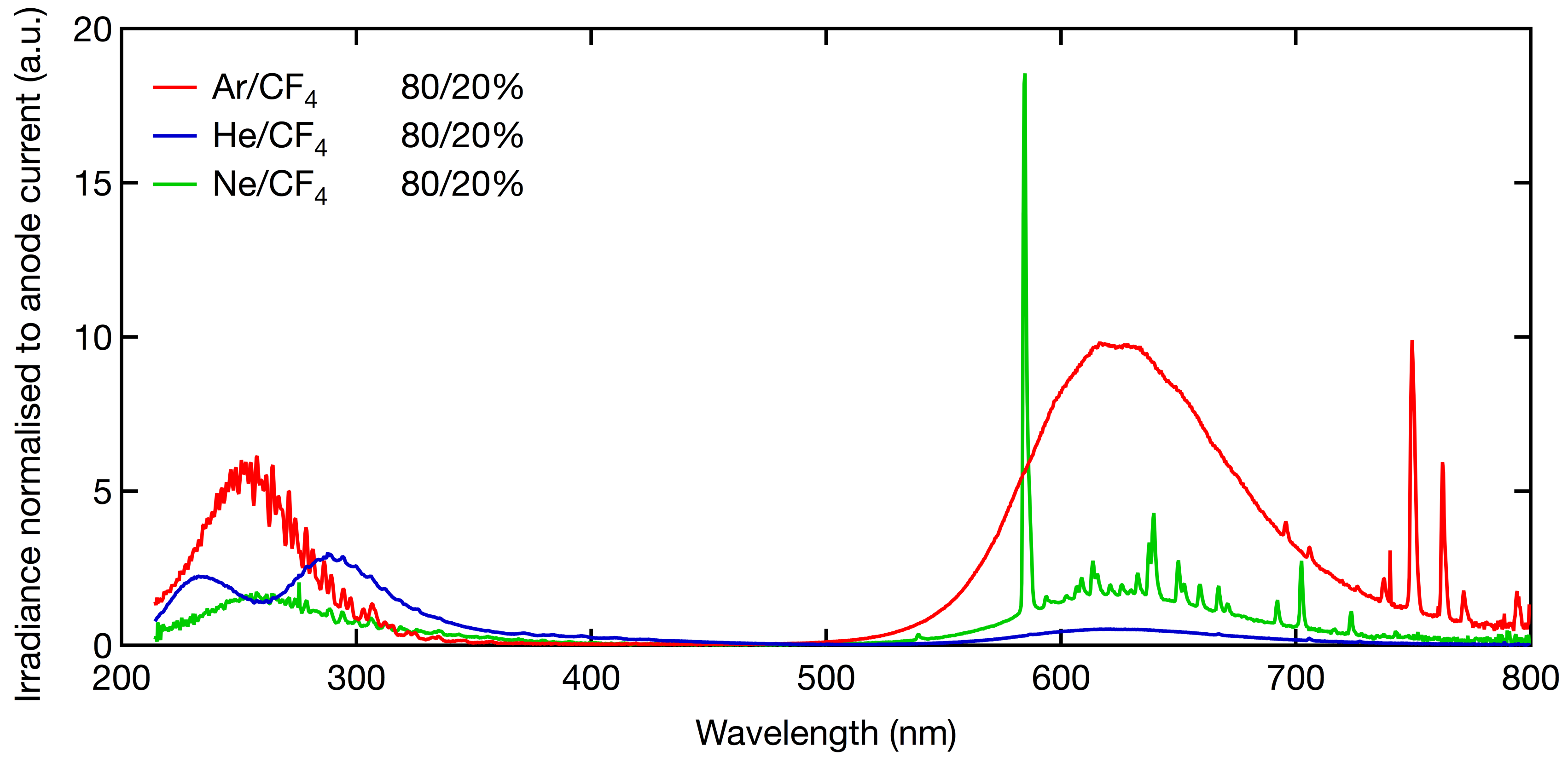
Alternative gases compatible with spectra sensitivity of imaging sensor?

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).

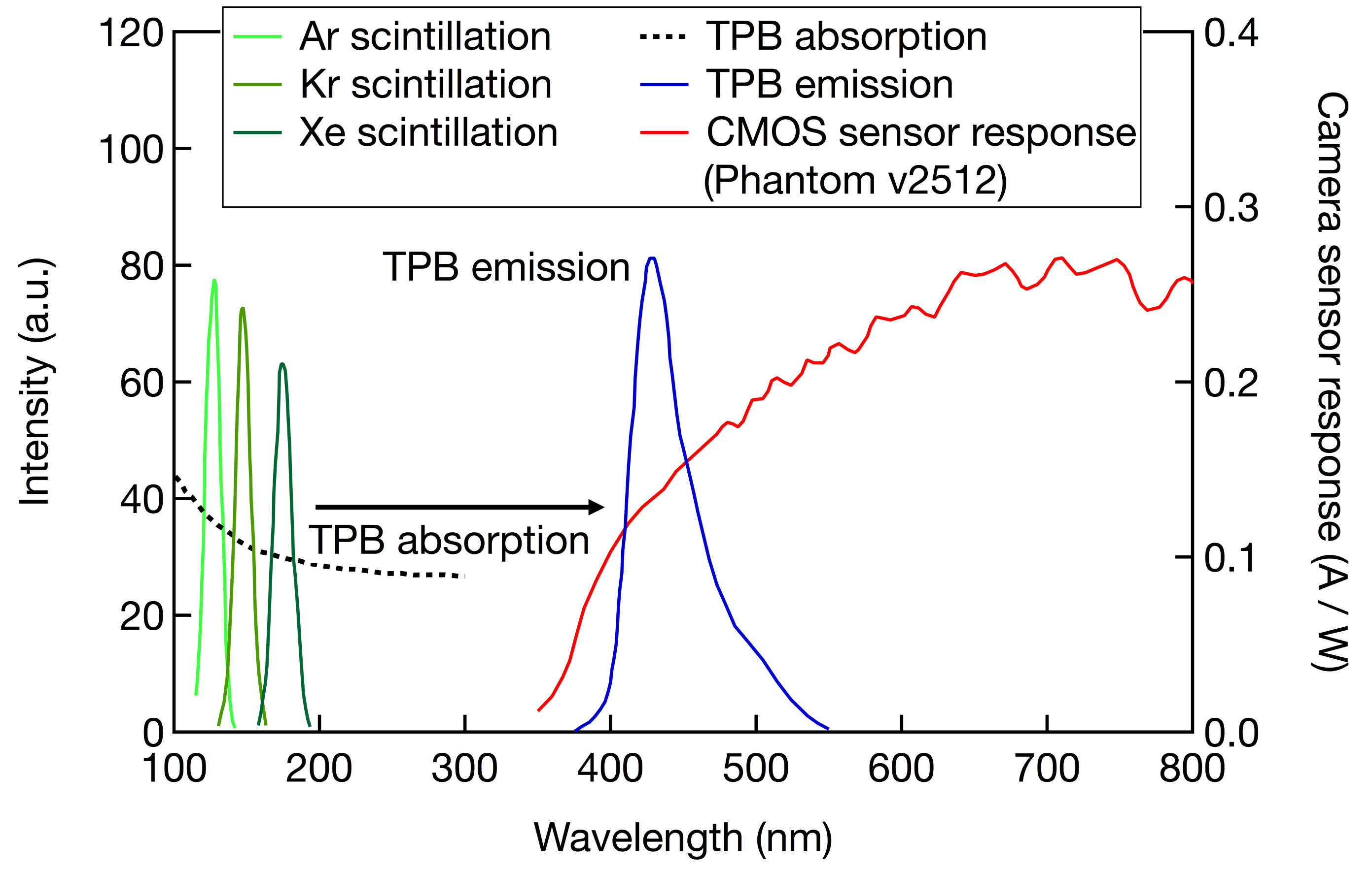
QE curves of cameras



Secondary scintillation spectra of mixtures with CF4



Wavelength shifting

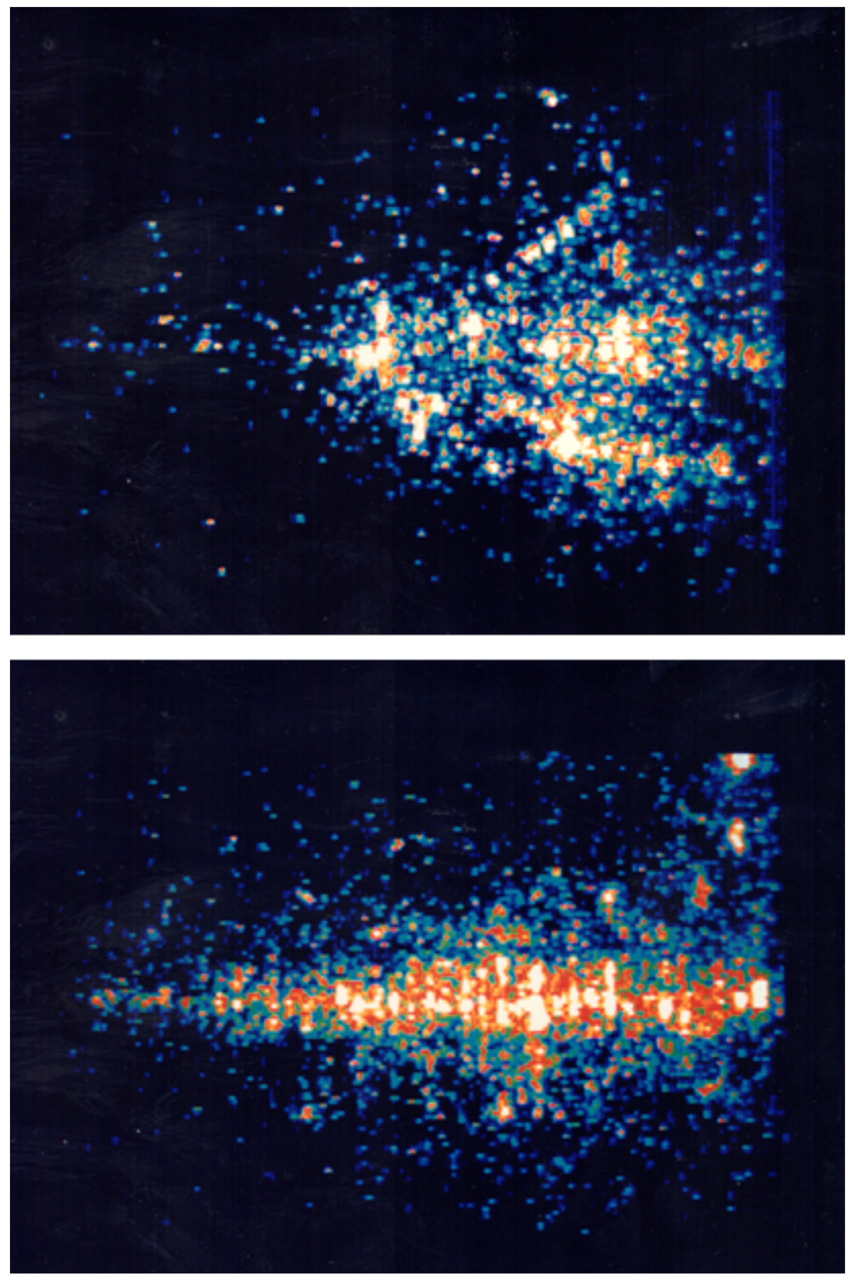


Optical TPCs

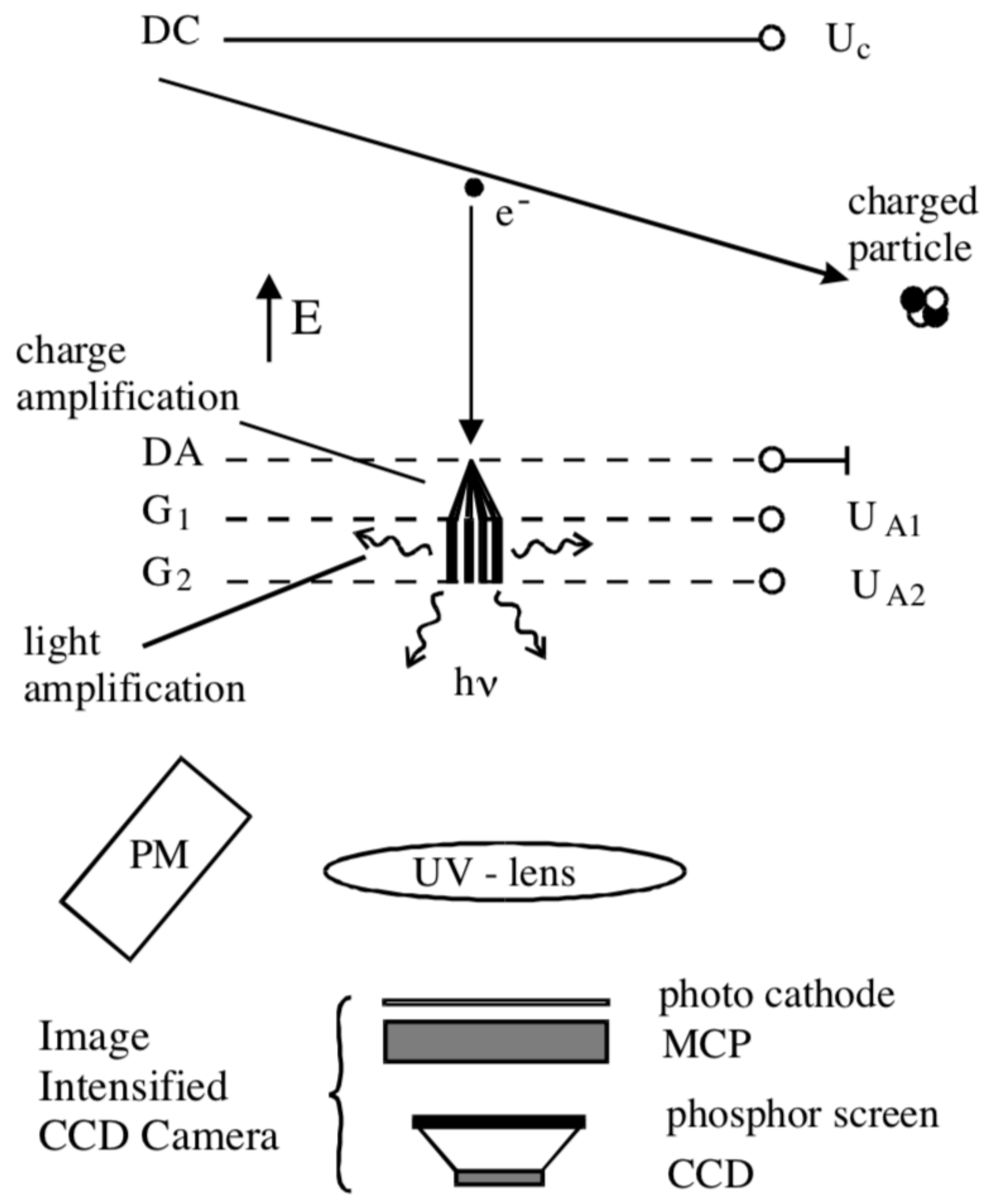
Long history of optically read out Time Projection Chambers

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

D. Gonzalez Diaz: [Recoil imaging for DM, neutrino, and BSM physics applications (TPCs variations, optical readout)]

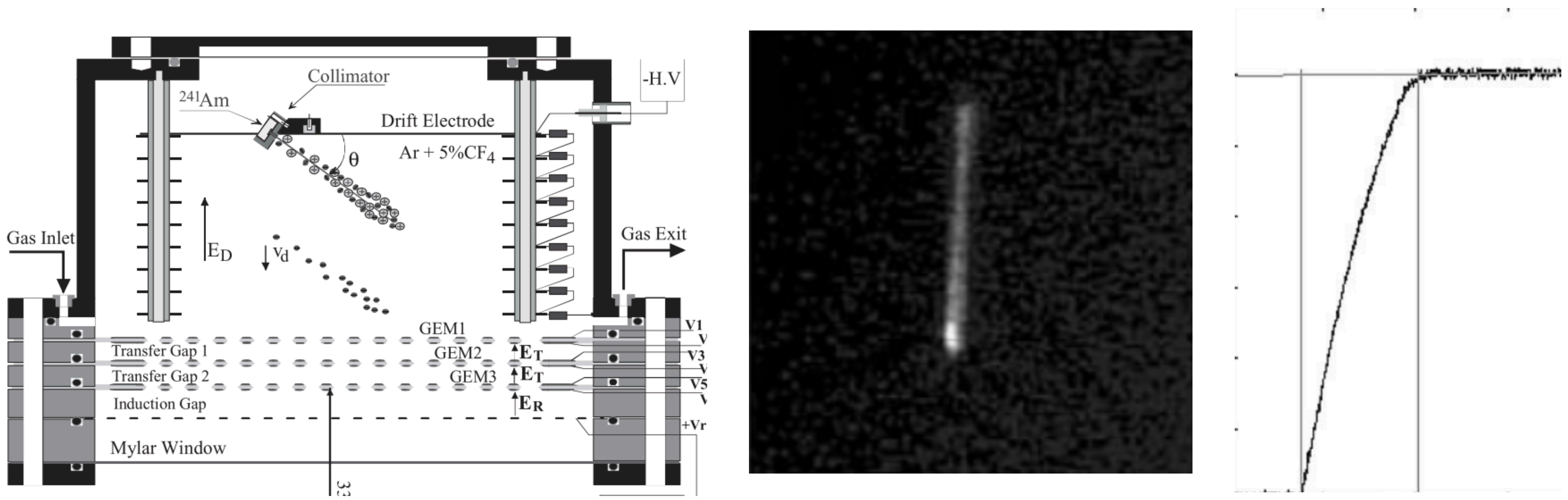


Fonte P., Breskin A., Charpak G., Dominik W. & Sauli F. (1989) NIM A. 283, 3, p. 658-664.



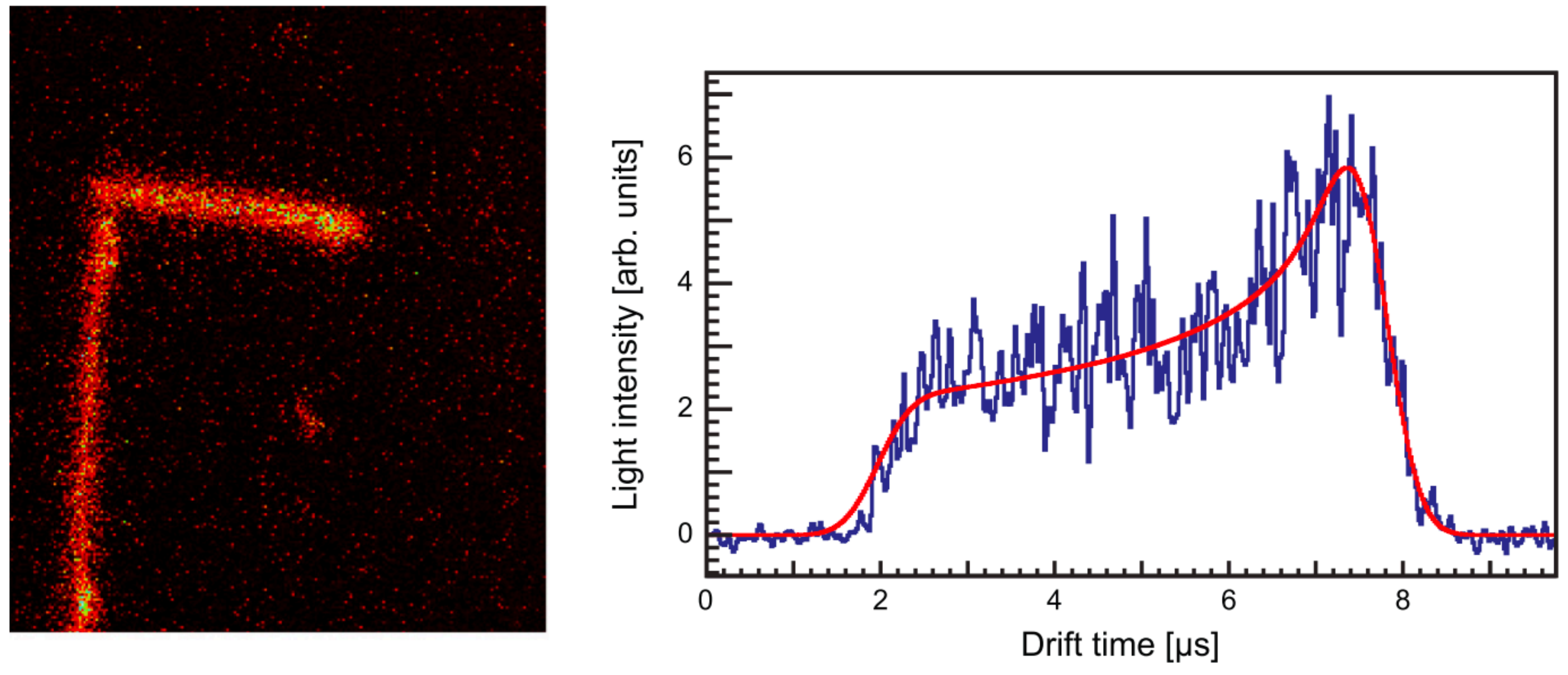
U. Titt et al. https://cds.cern.ch/record/800769/files/0410258.pdf

Z determination with PMT waveform



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

OTPC for proton spectroscopy



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

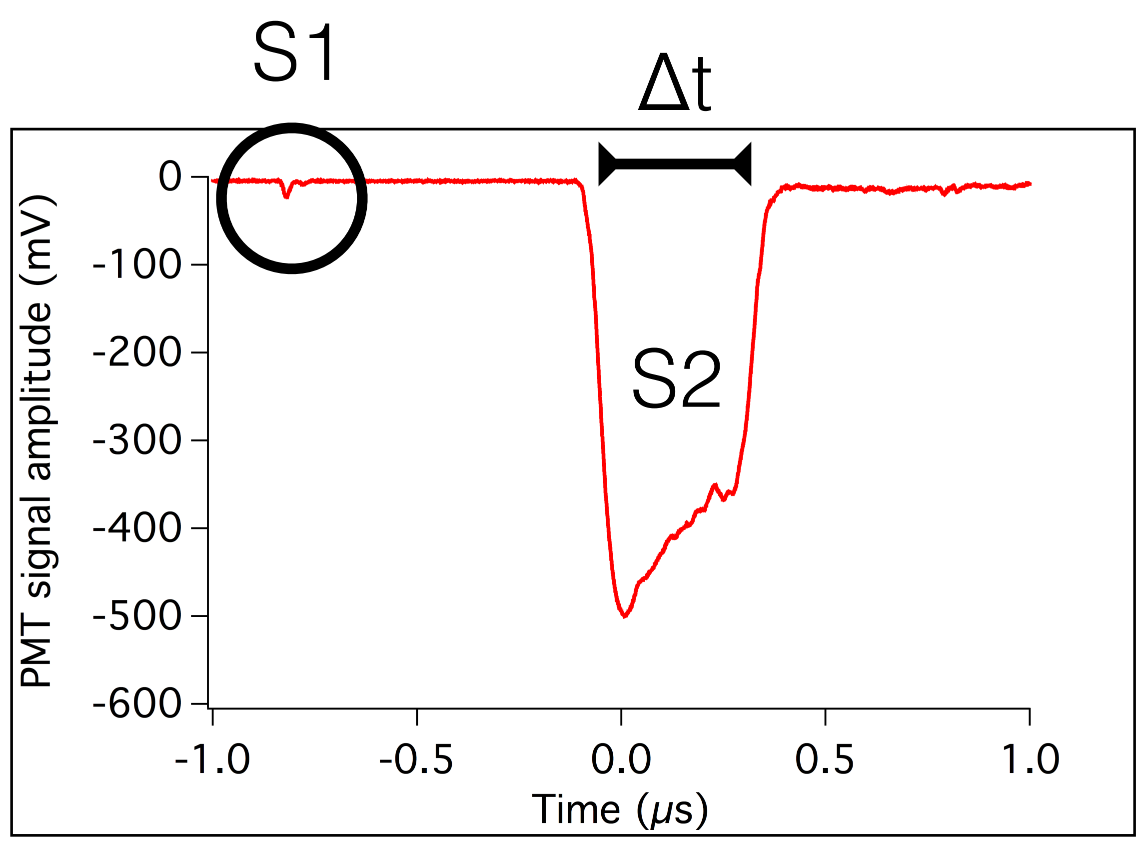
Depth reconstruction techniques

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

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

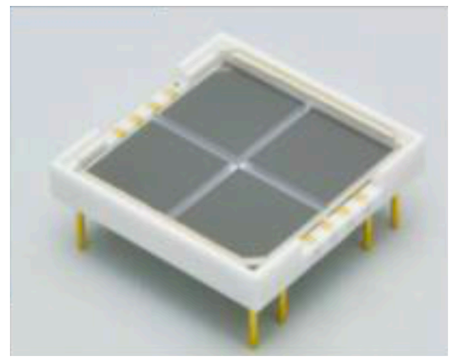
Photomultiplier Tubes (PMTs)

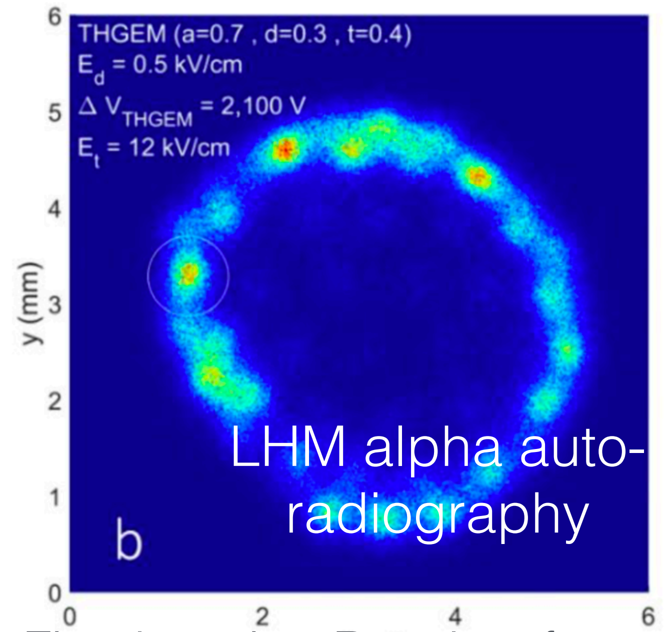
Hamamatsu R375 PMT



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

Silicon Photomultipliers (SiPMs)

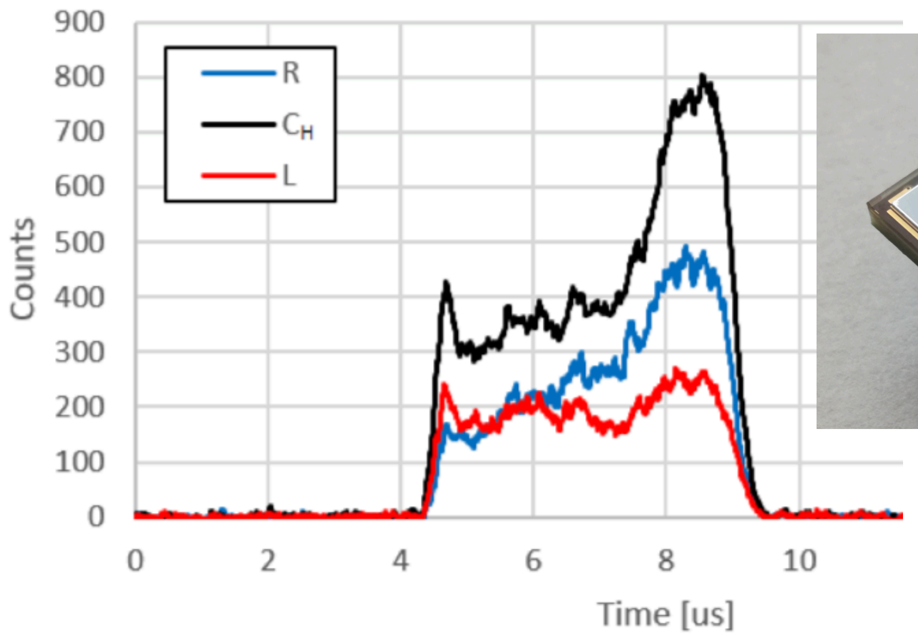


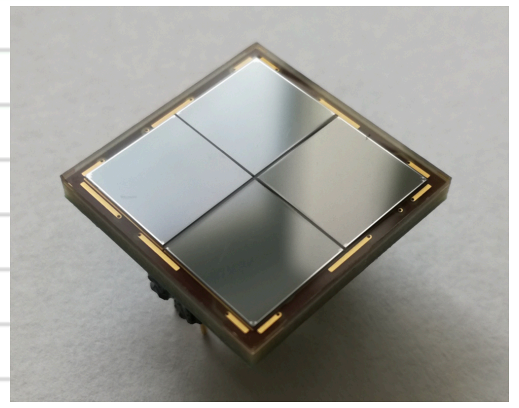


E. Erdal et al.. (2018). First Imaging Results of a Bubble-assisted Liquid Hole Multiplier with SiPM readout in Liquid Xenon.

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

Linearly Graded Silicon Photomultipliers (LG-SiPMs)





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

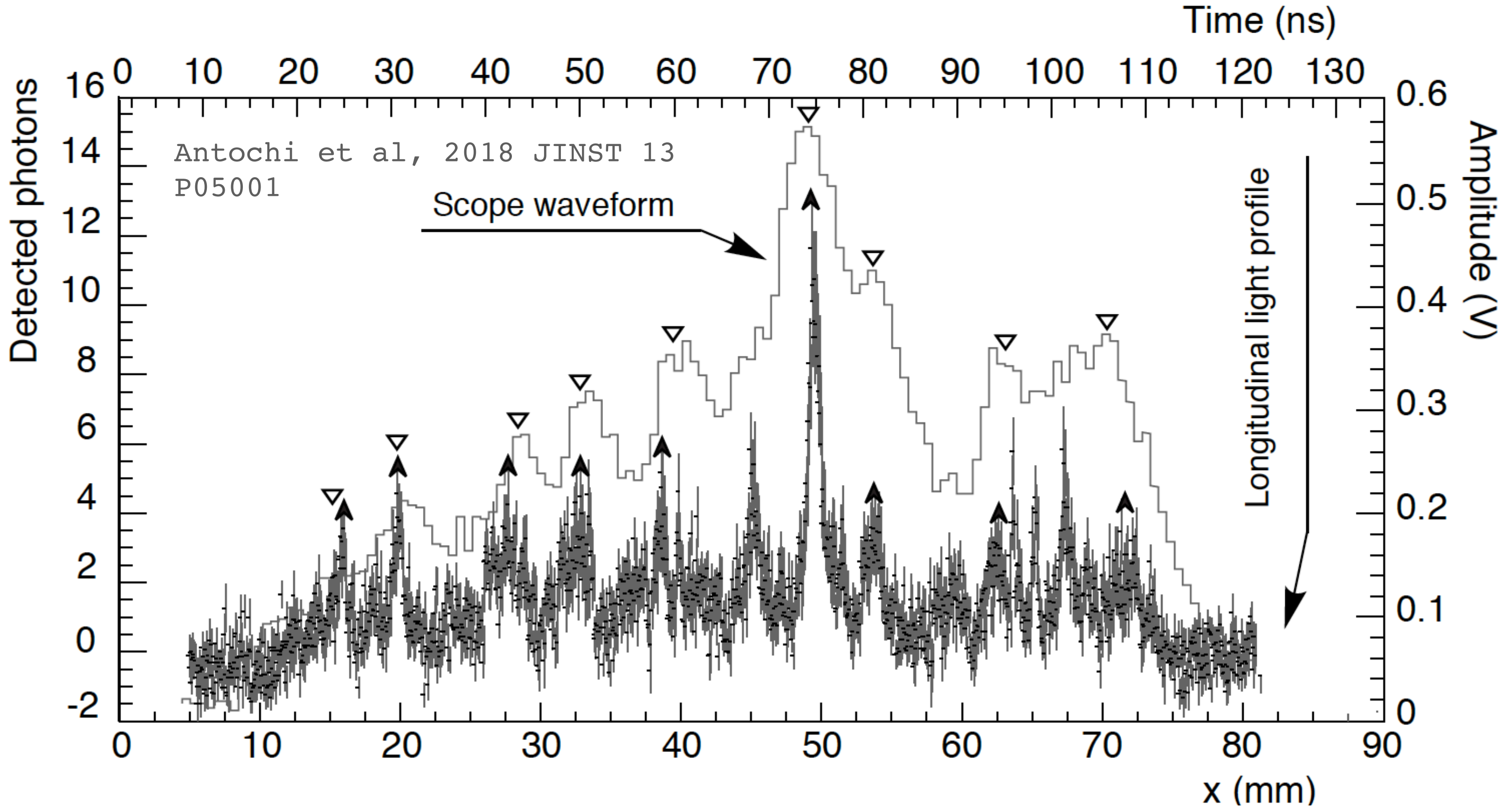
- Current split in four outputs to calculate x and y coordinates from current signals
- Position resolution down to order of size of microcells (30μm)
- Fast response time of tens of ns

Depth reconstruction techniques

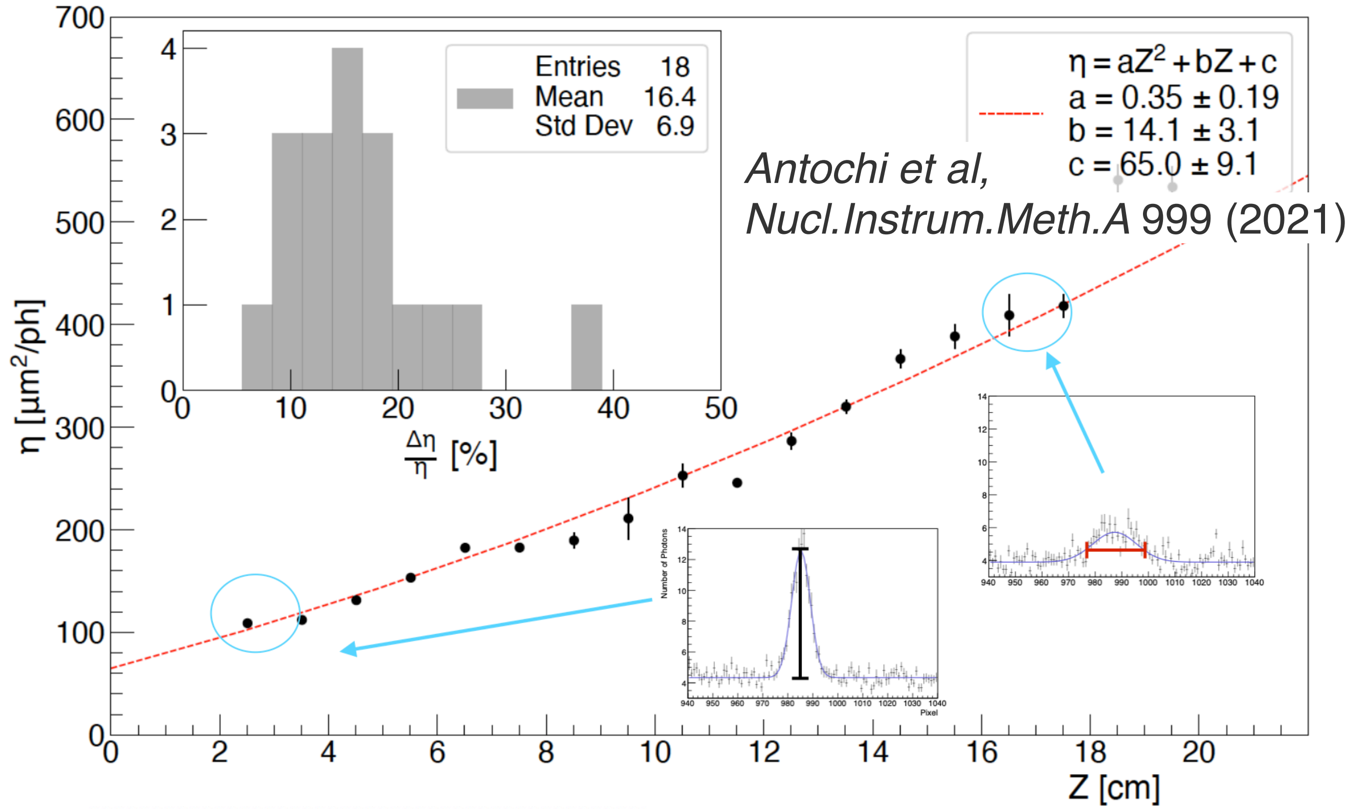
Fast drift velocity in CF4 mixtures (e.g. >10 cm/μs in Ar/CF4) make sub-mm scale depth resolution challenging

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

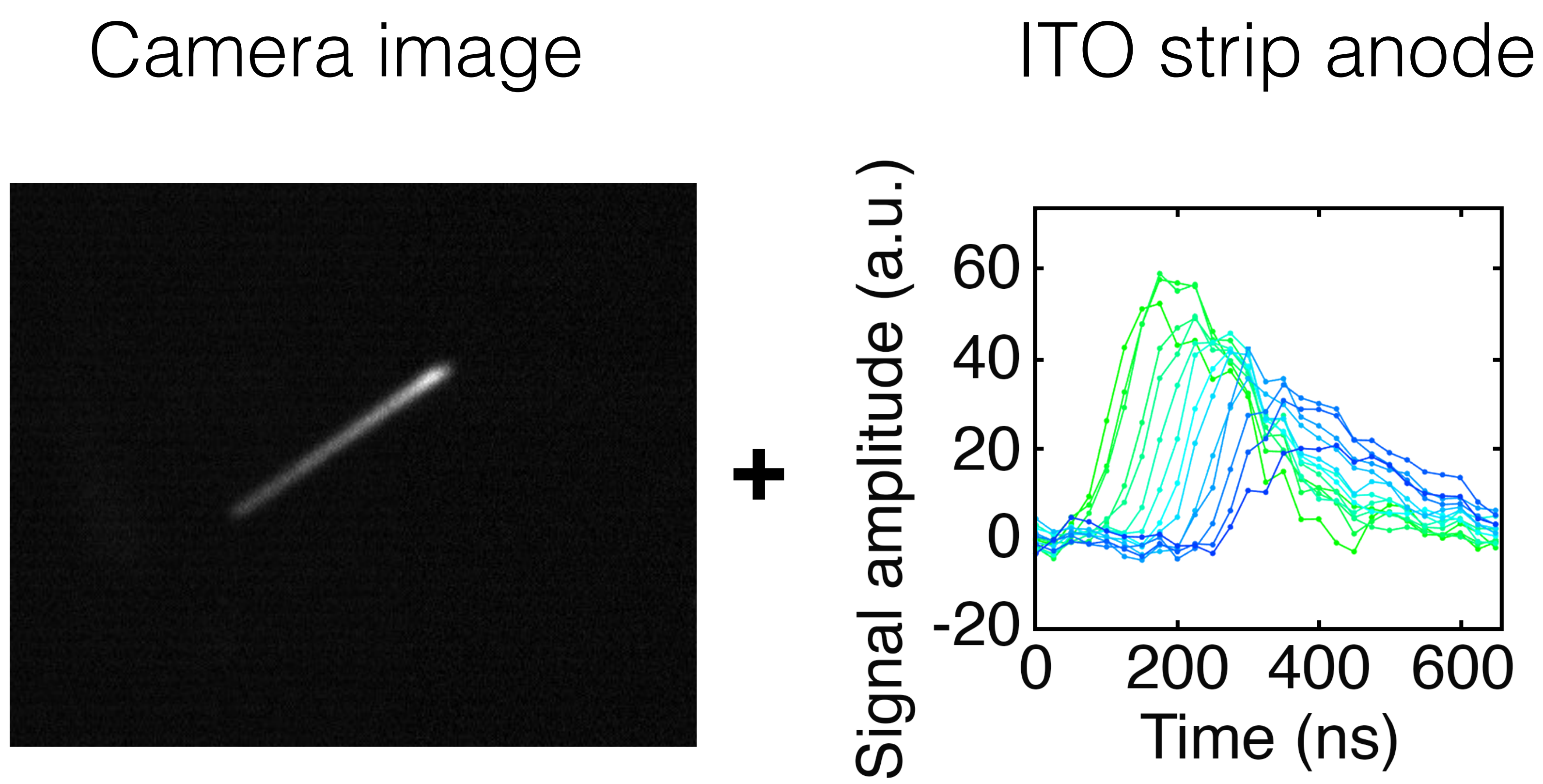
Matching of clusters in light intensity profile from image and in PMT waveforms for Z-determination



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

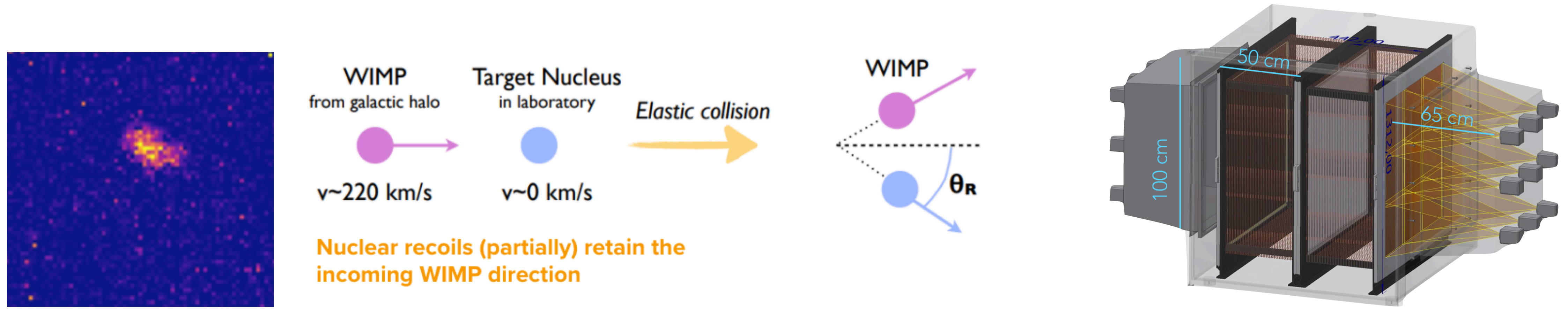
F. Brunbauer et al. 10.1109/TNS.2018.2800775

Optical TPCs

Atmospheric pressure Optical TPC

Rare event searches, directional dark matter

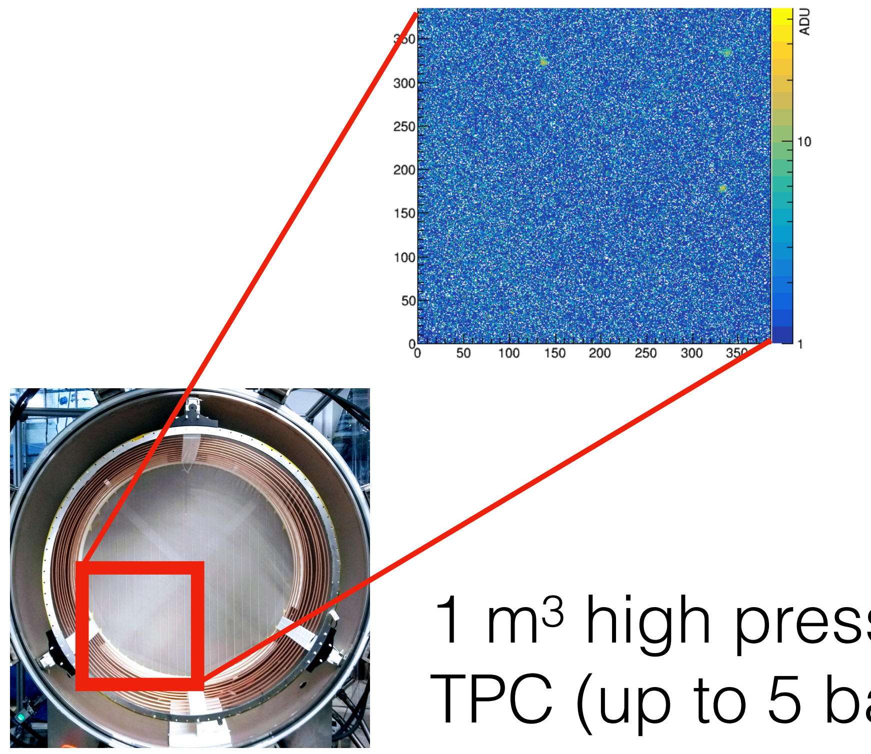
Triple GEM with **CMOS + PMT/SiPM** readout requiring low radioactivity background



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



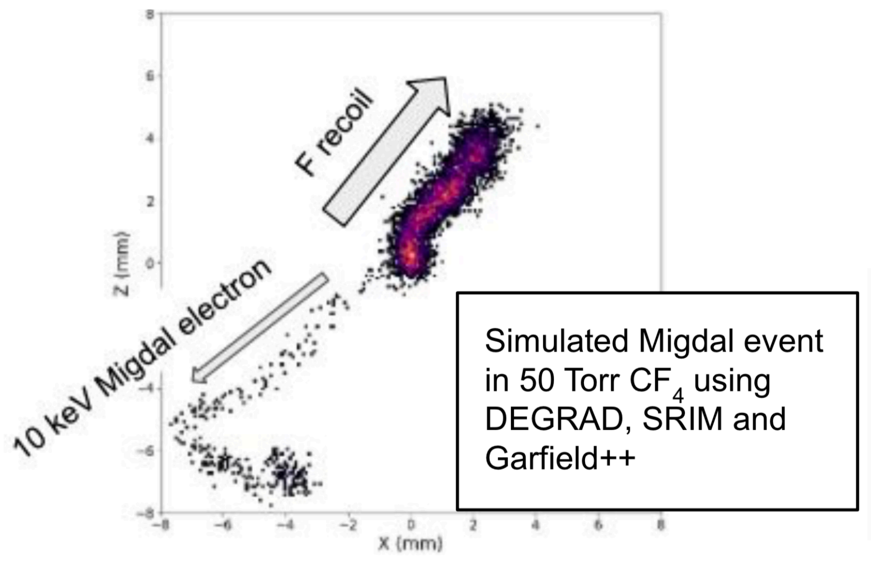
Stitched optical readout (4 CCD cameras) + **electronic signals** from meshes used for amplification

1 m^3 high pressure TPC (up to 5 bar)

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

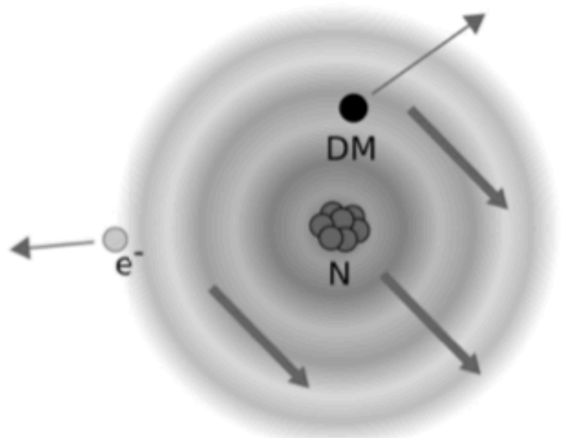
Low-pressure TPC with optical+electronic readout

MIGDAL
Migdal In Galactic Dark mAtter expLoration



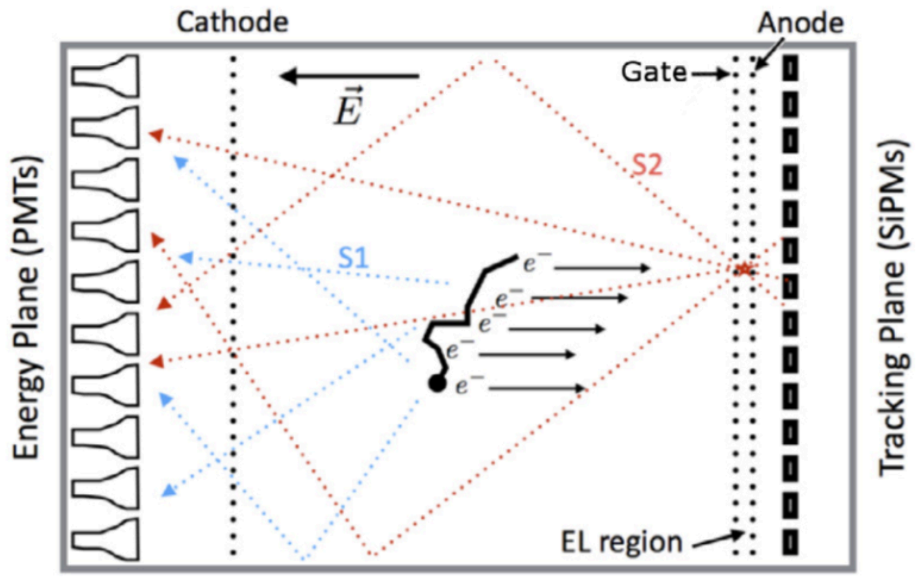
Migdal effect search in low-pressure CF_4 for DM searches in

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

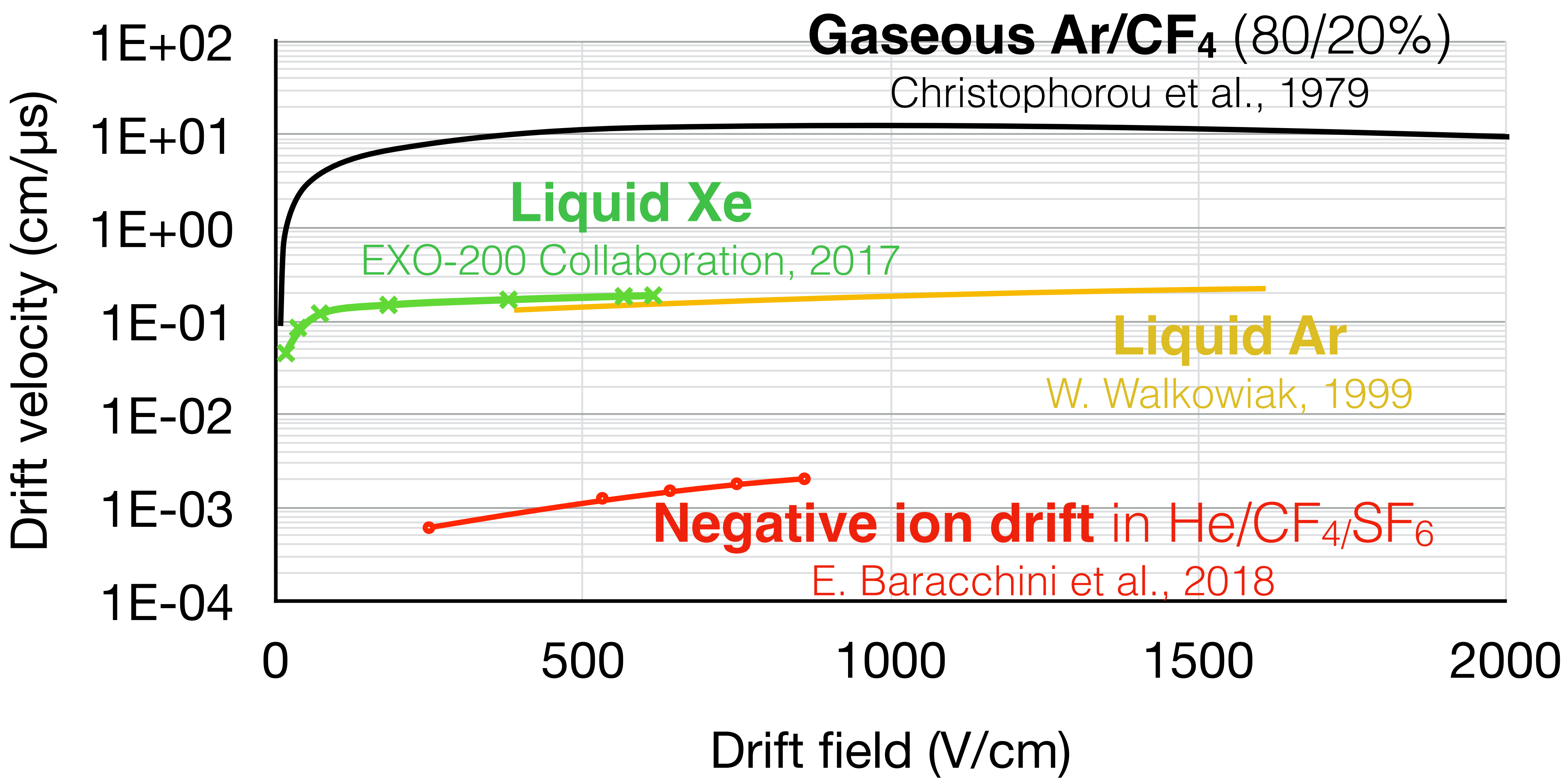
Negative ion TPCs

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.

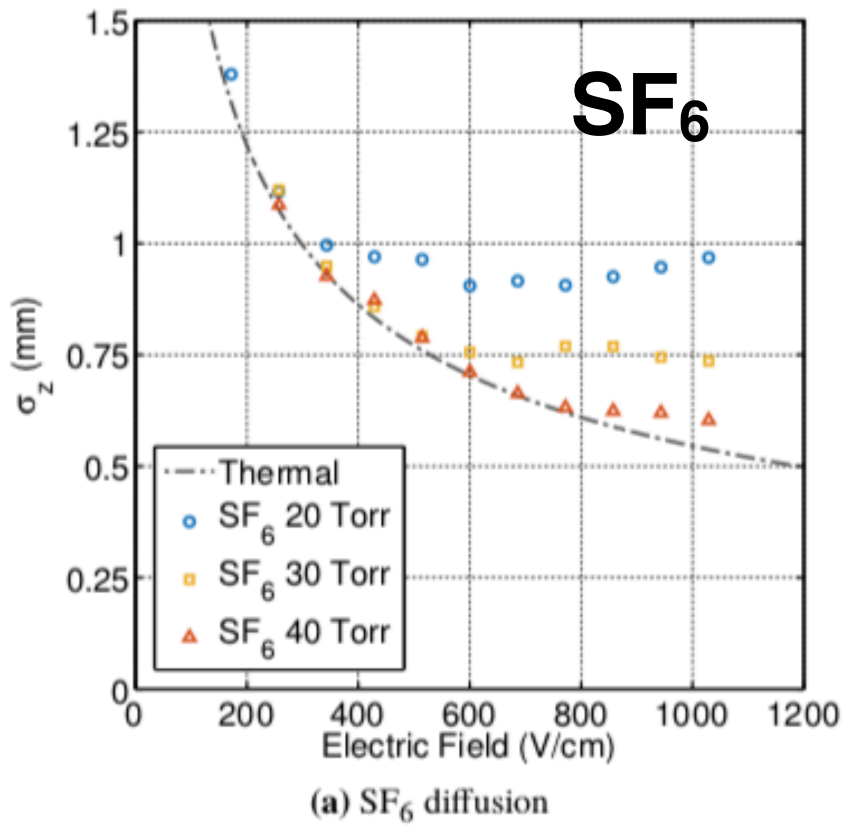
Negative ion mixtures strongly **suppress light yield** and achievable **gain**.

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



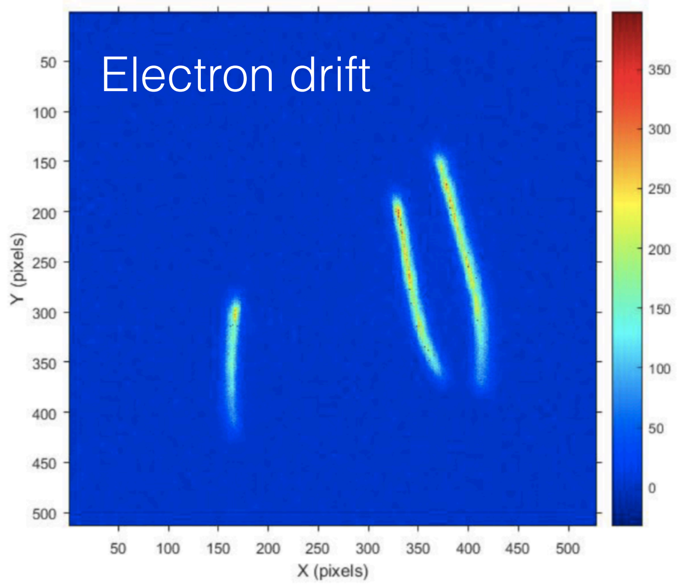
Low diffusion

approaching thermal limits

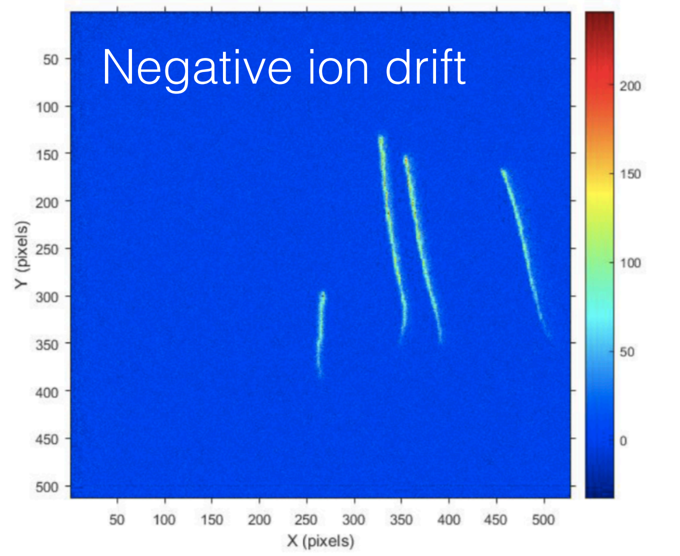


N.S. Phan et al 2017 JINST 12 P02012 https://doi.org/10.1088/1748-0221/12/02/P02012

NI Optical TPC



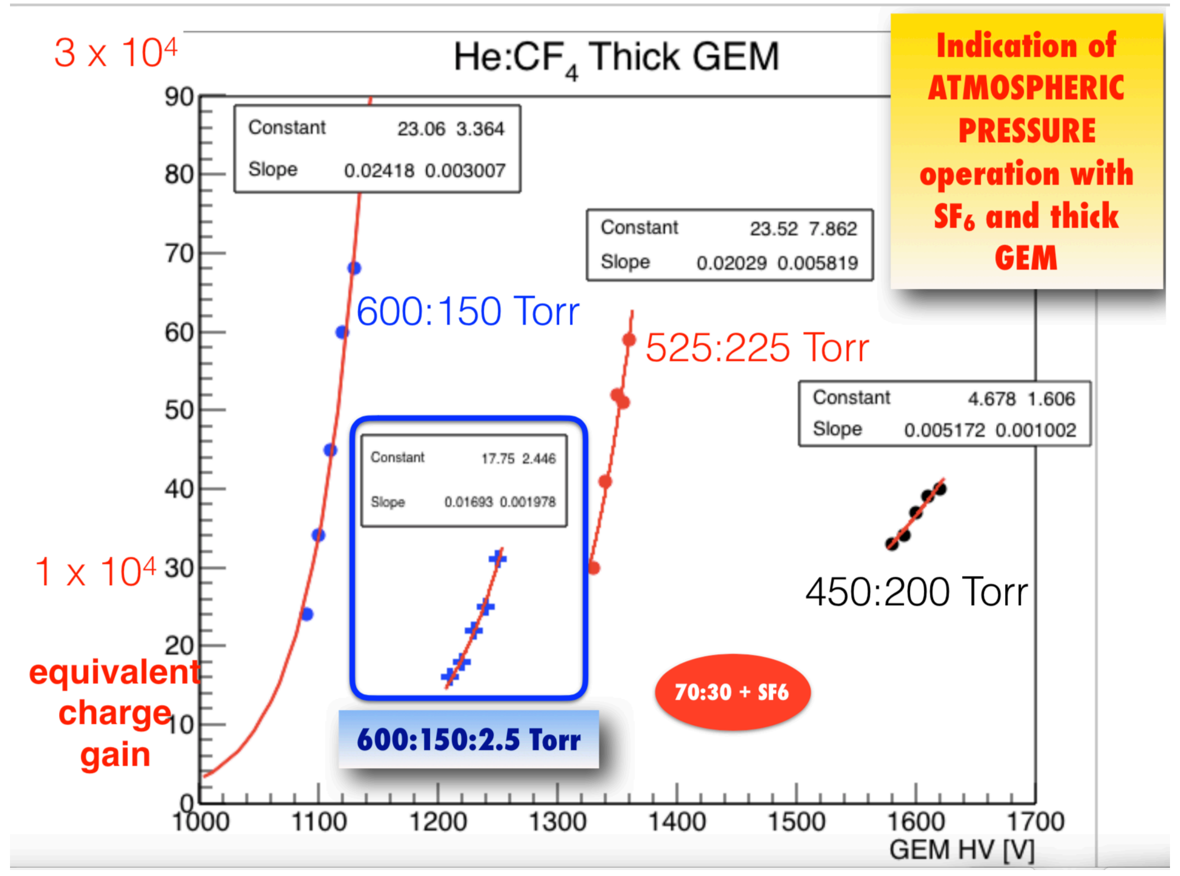
150 Torr CF_4, **σ ~ 450 um**



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

D. Loomba, UNM

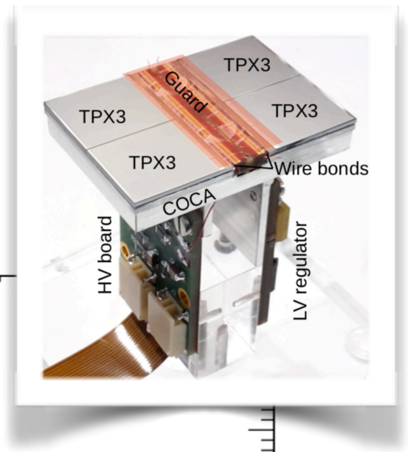
Gain demonstrated in atmospheric pressure He/CF4/SF6

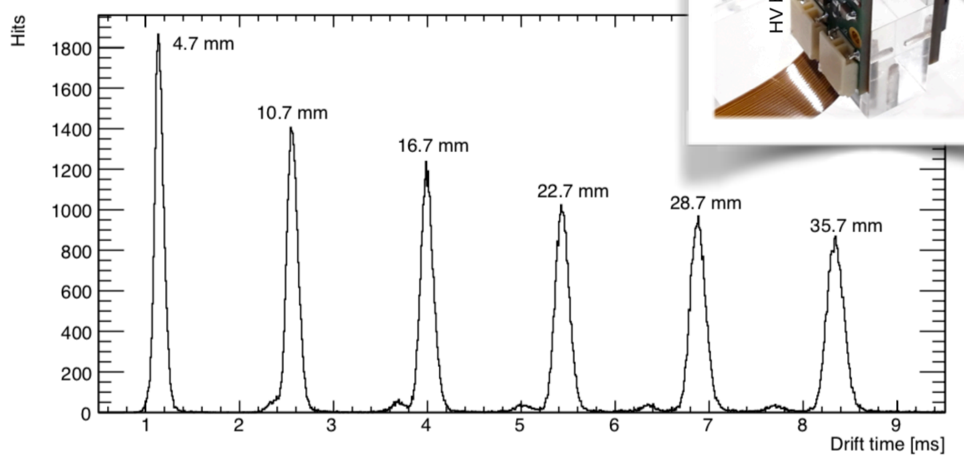


E. Baracchini et al., CYGNO INITIUM, ERC No 818744

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

Ultra-fast imaging sensors

High-speed CMOS sensors can deliver up to **1 million frames per second** at limited resolution. Can be used for rapid imaging (integrated imaging limited by incident radiation flux) and beam monitoring with active feedback.

Rapid radiation imaging or **beam monitoring** already feasible (kHz at megapixel resolution).

3D track reconstruction (NI?) requires lower read noise sensors and increased resolution at maximum frame rates.

Phantom v2512

- 1 megapixel **CMOS** sensor
- **25 kfps** at 1280 x 800
- **1 Mfps** at 128x32
- Higher read noise

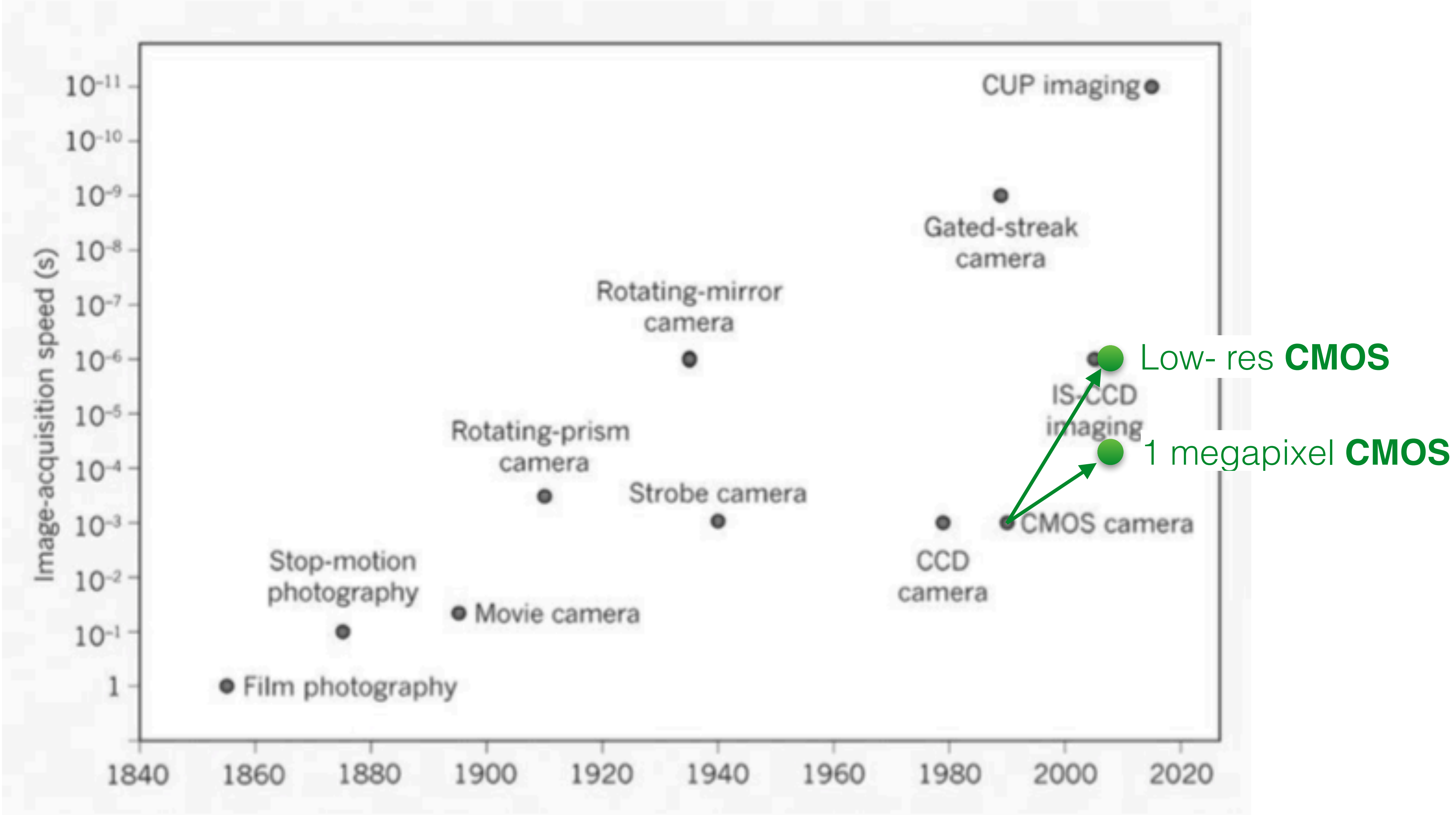
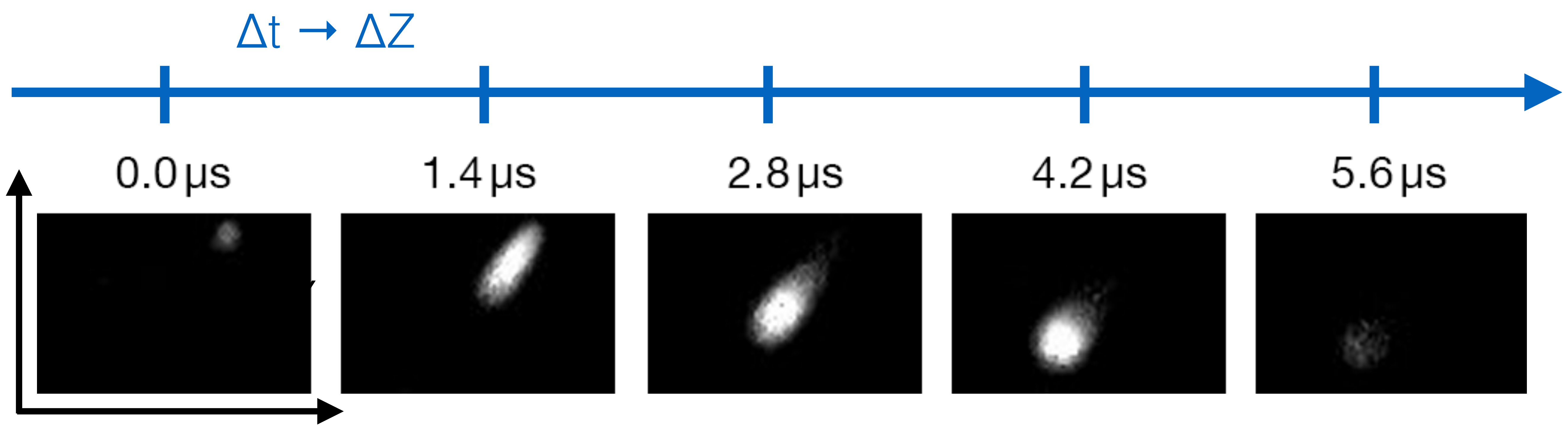


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

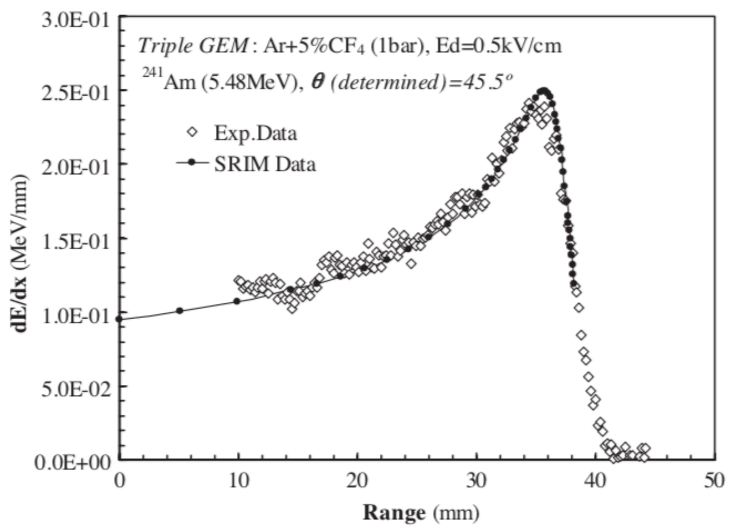
Sequence of images displaying alpha track segments in gaseous TPC recorded at 700 kHz.



Applications

Cluster counting for energy loss measurement

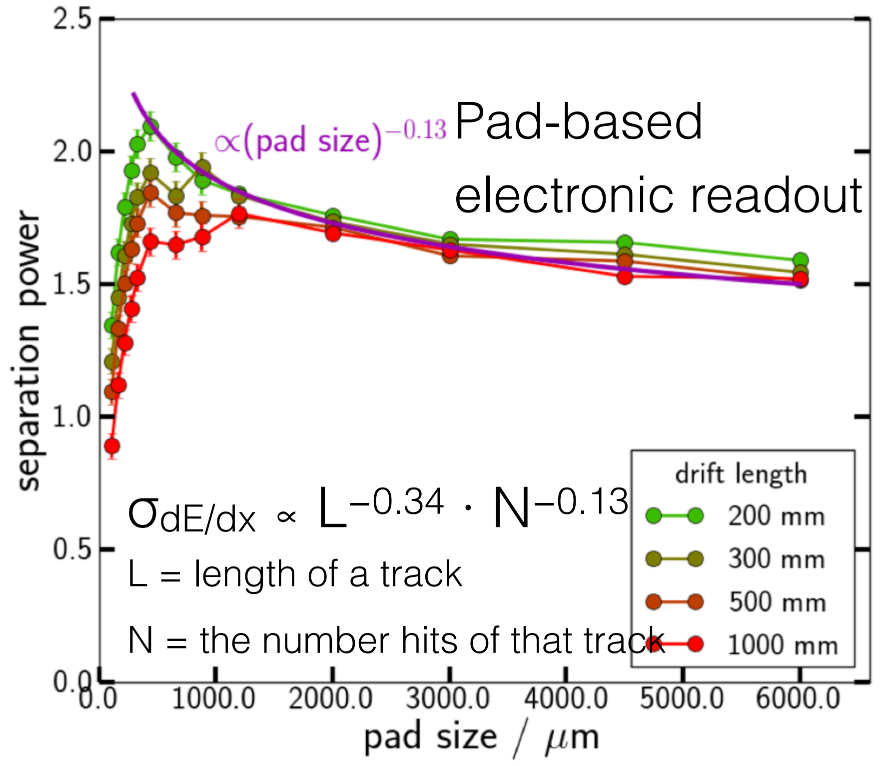
Classical energy loss measurement → **Cluster counting**



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

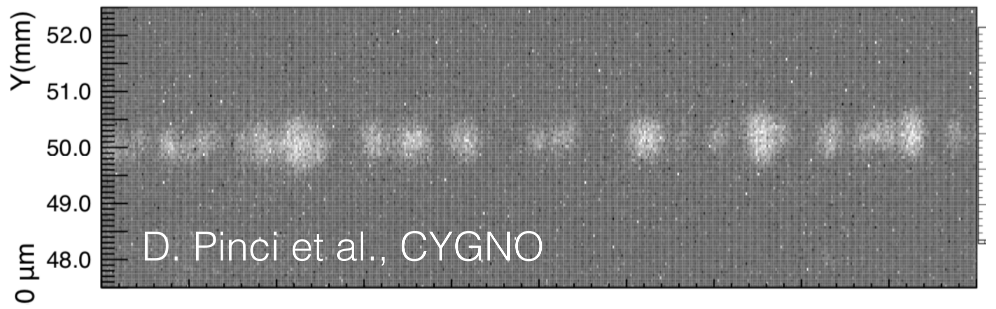
L.M.S. Margato et al., Performance of an optical readout GEM-based TPC, NIM A, 2004

Cluster counting may provide superior energy loss resolution



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

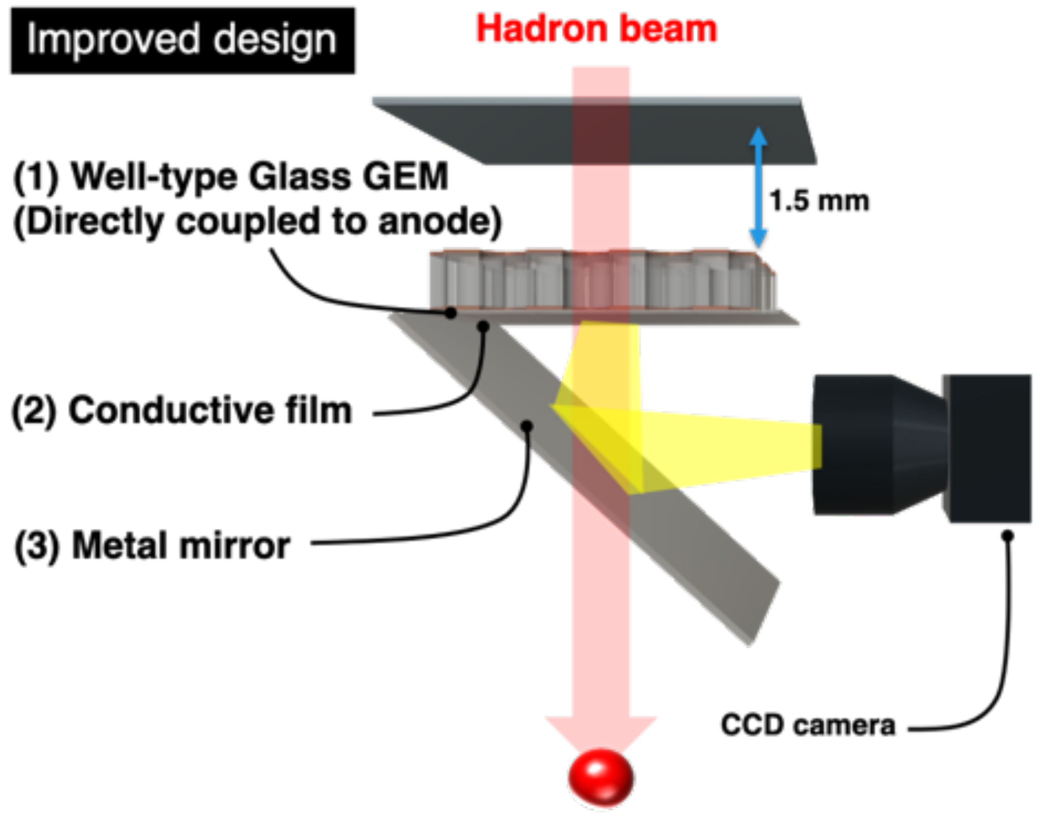
High granularity and **low diffusion** (NI, deconvolution?) required to distinguish clusters.



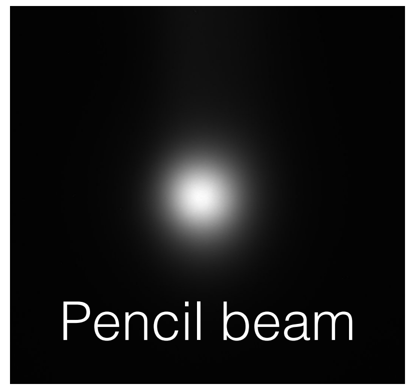
Cluster structure along electron track

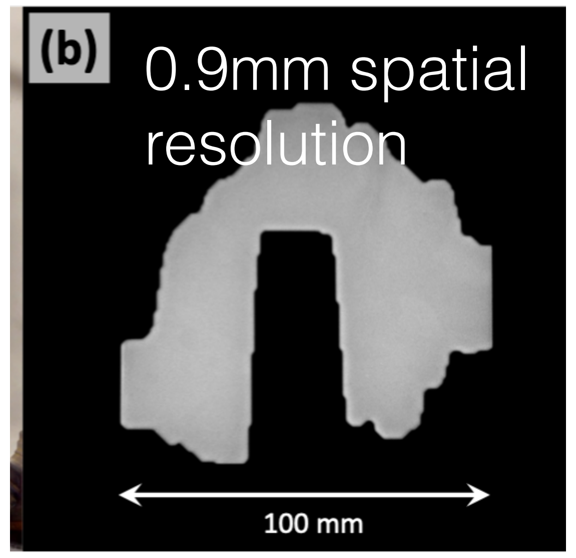
Dose imaging & beam monitoring

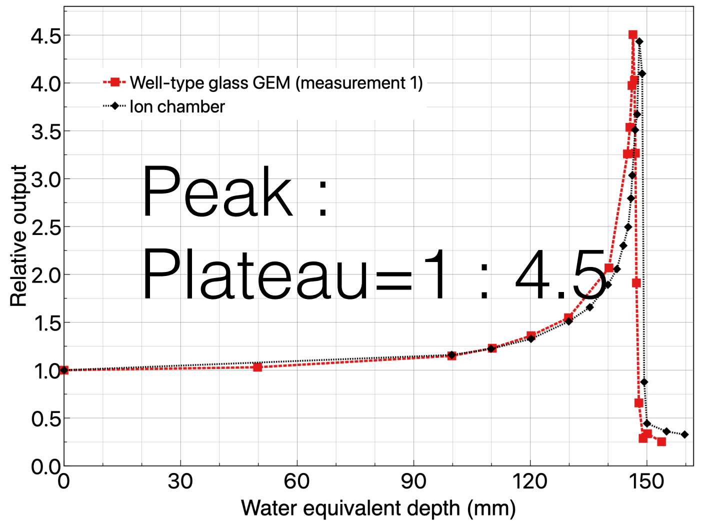
Beam monitoring & hadron/neutron therapy applications benefit from high **spatial resolution** and **high LET dose imaging** suitable for clinical proton/carbon beams ($2*10^9$ particles/sec)



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?

Timepix

Particle-tracker and **photon counting hybrid pixel detector** designed with the support of the Medipix collaboration

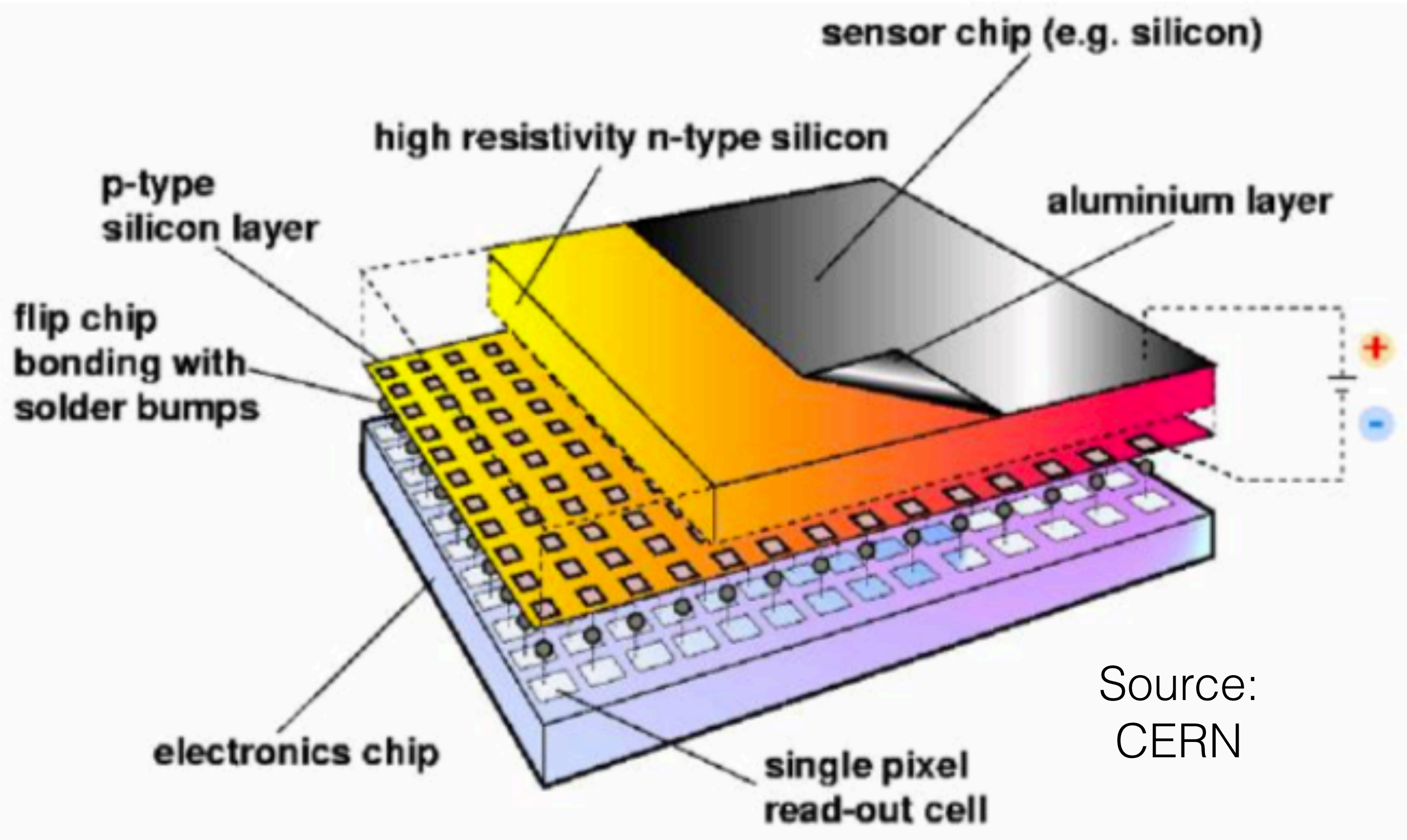
Basis for Timepix cameras, GridPix, GEMPix, …

Timepix 4:

- 4-side buttable, **data-driven** ASIC with 512x448 pixels
- **<200ps** timing resolution
- up to **11.8k fps** full-frame readout rate

Applications:

- High-rate pixel telescope
- Time-of-flight mass spectrometry
- Sub-pixel resolution imaging
- X-ray radiography at synchrotrons
- Neutron time-of-flight imaging
- Compton cameras
- Gamma and neutron imaging
- …



Source: CERN

			Timepix3 (2013)	Timepix4 (2019)
Technology			130nm – 8 metal	65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448 **3.5x**
Sensitive area			1.98 cm^2	**6.94 cm^2**
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit **33%**
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s** **8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)
		Max count rate	~0.82×10^9 hits/mm^2/s	~5×10^9 hits/mm^2/s **5x**
TOT energy resolution			< 2KeV	**< 1Kev** **2x**
TOA binning resolution			1.56ns	**195ps** **8x**
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz) **4x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps** (16x @10.24 Gbps) **32x**
Target global minimum threshold			<500 e^-	<500 e^-

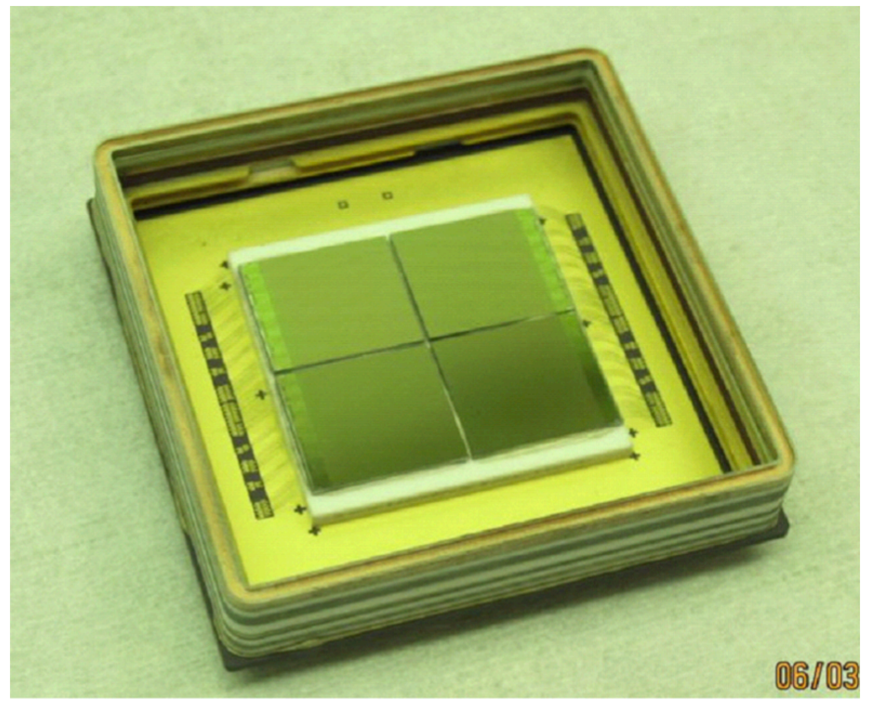
https://medipix.web.cern.ch/home

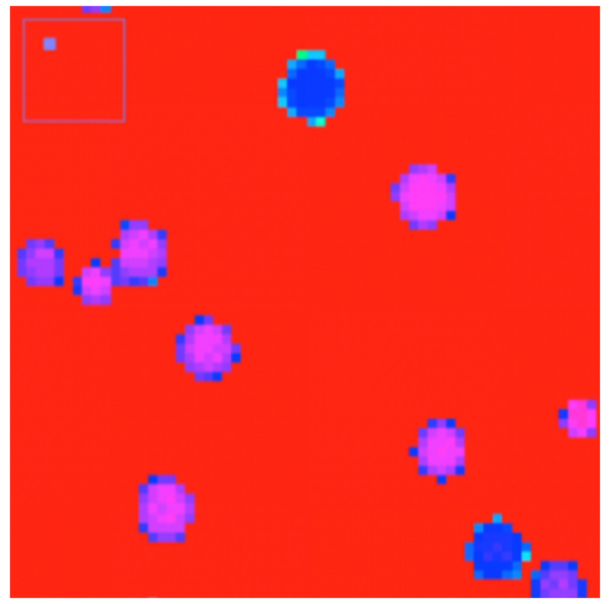
X. Llopart, Medipix4 Collaboration, https://indico.cern.ch/event/876275/contributions/3729426/attachments/1986038/3309319/Xavi_Timepix4_Muon.pdf

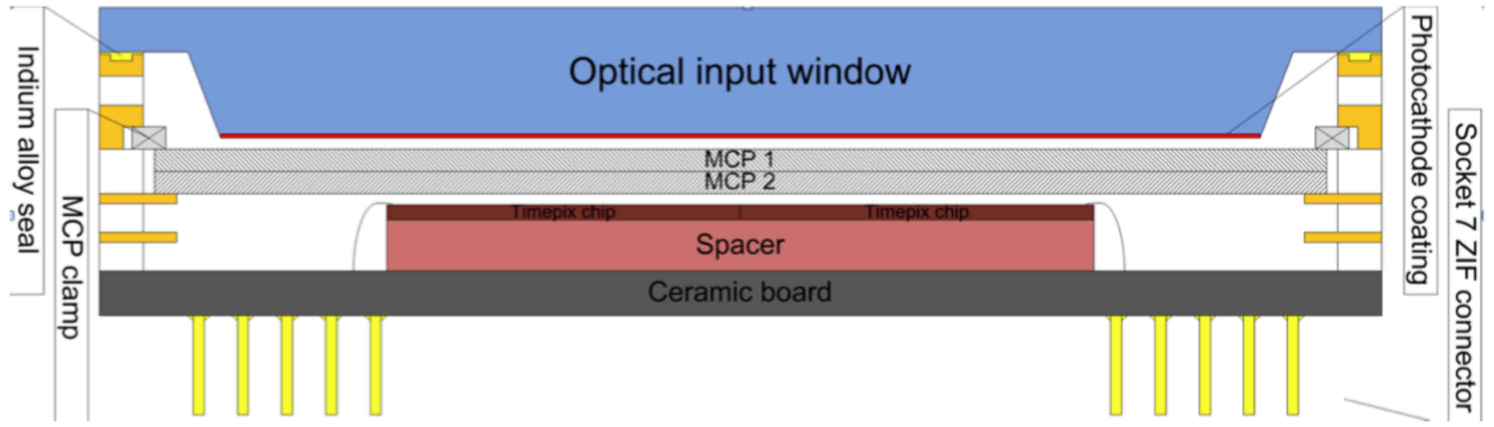
Timepix cameras

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

Event counting with threshold or time of arrival recording

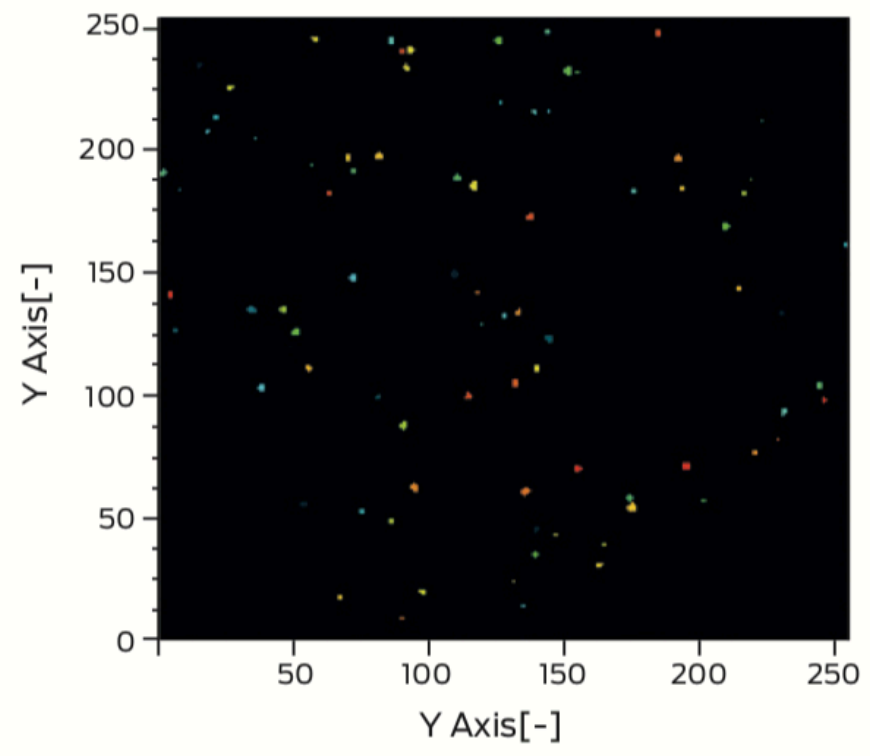


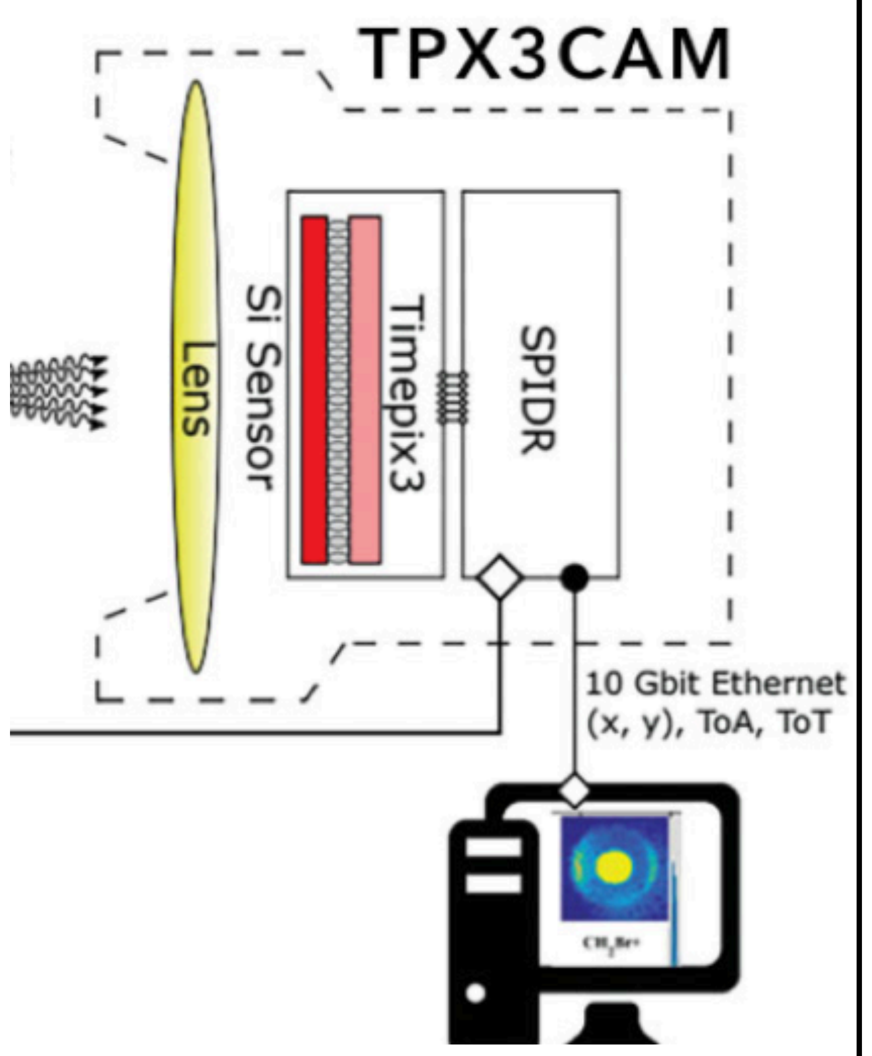




J Vallerga et al 2014 JINST 9 C05055
https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055/pdf

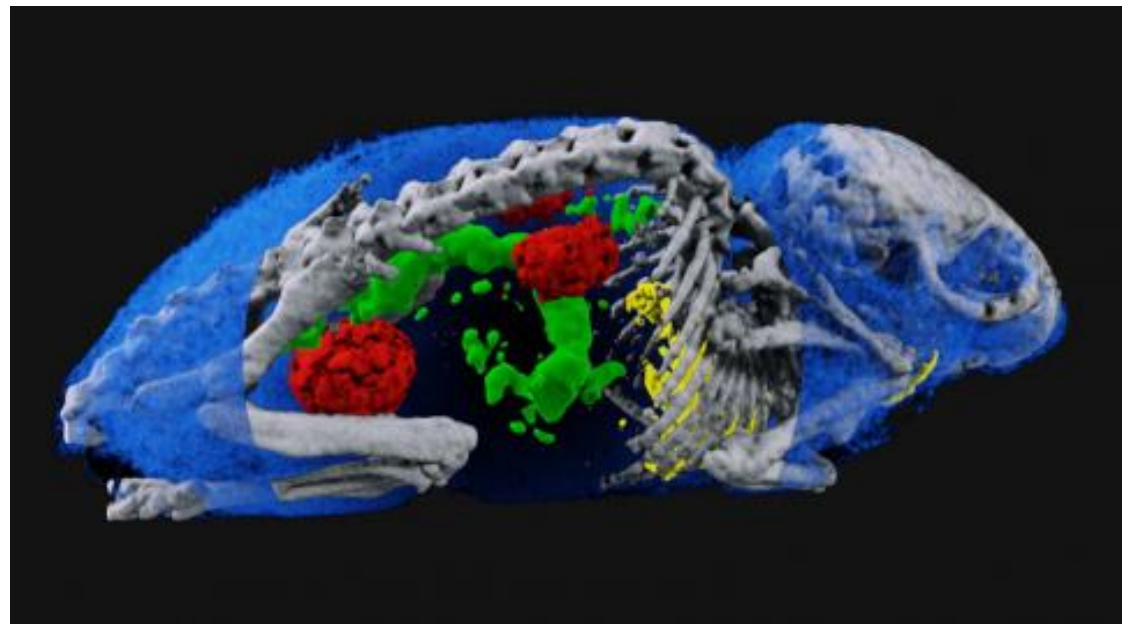
TPX3CAM
Optical detector for **time stamping** (1.6ns) of optical photons up to 80 Mhits/s rate.
Commercially available.





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



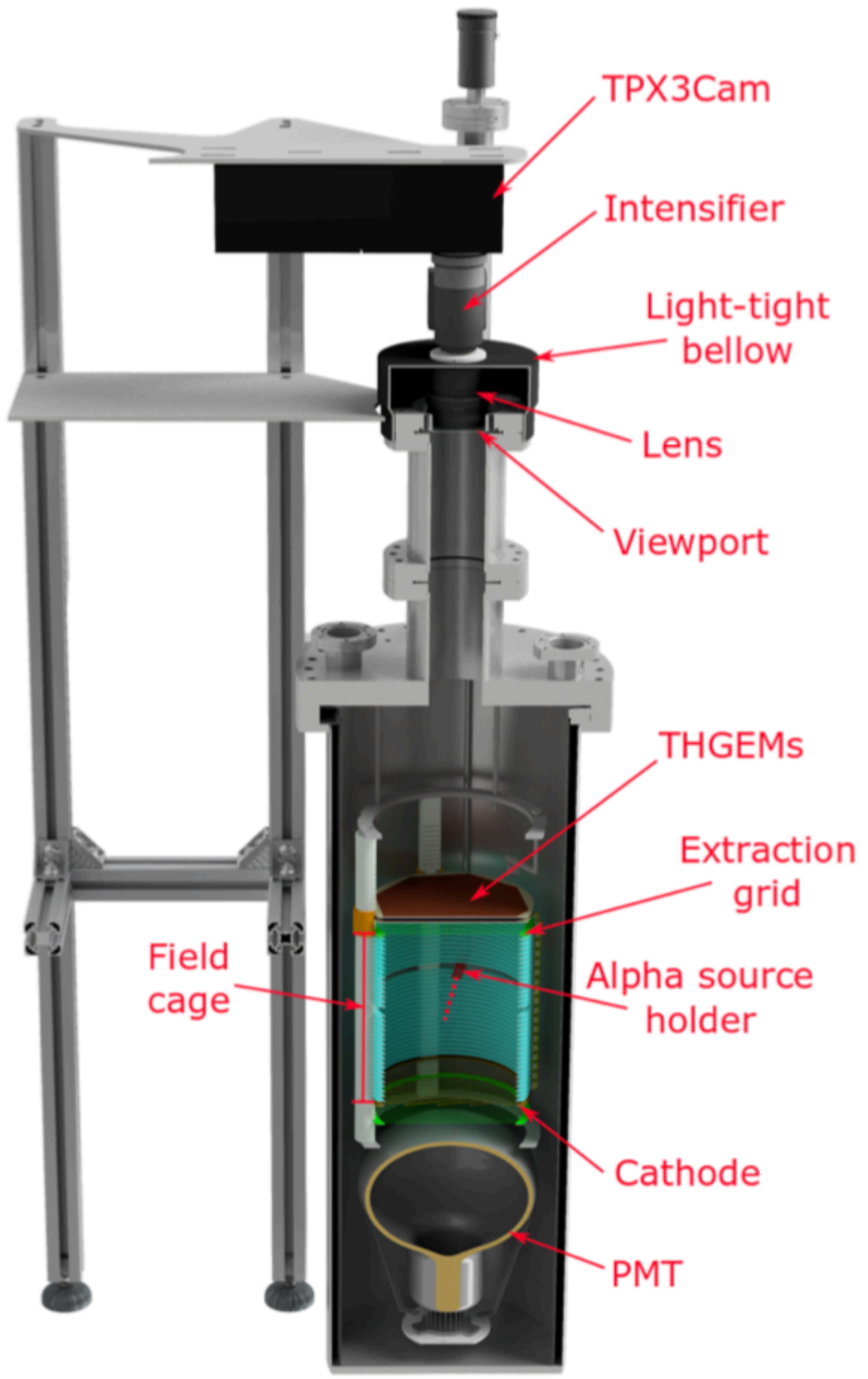
https://medipix.web.cern.ch/mars-bio-imaging

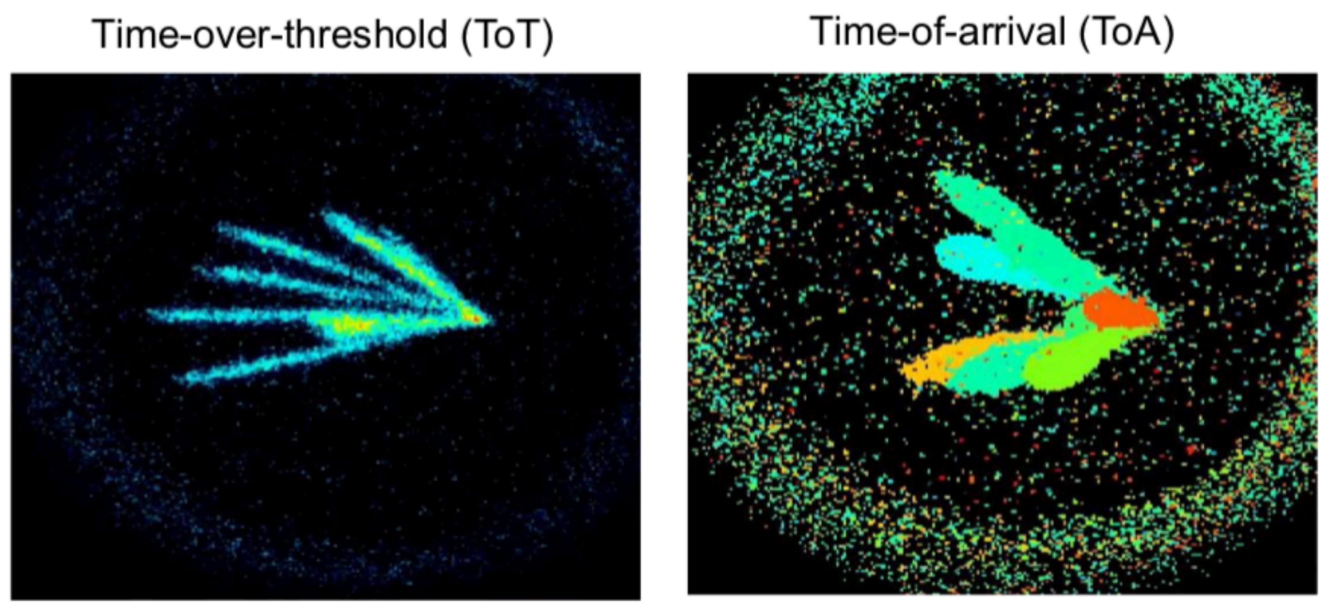
3D track reconstruction
Intensified TPX3Cam

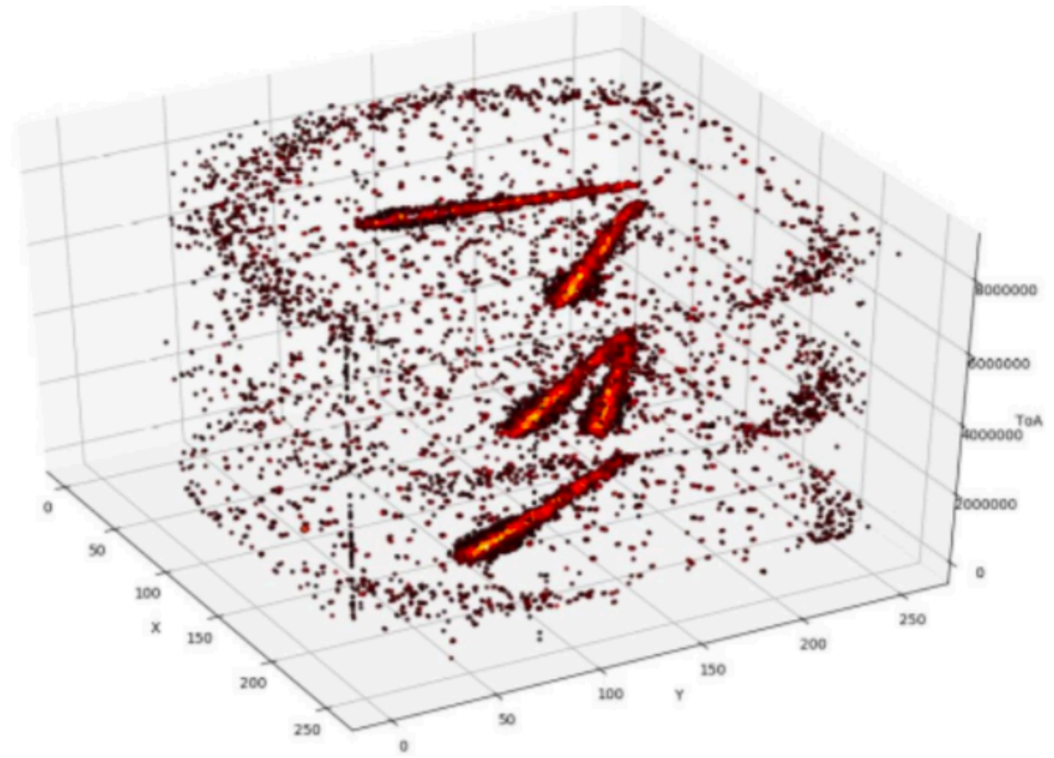
Readout of S2 scintillation in **dual phase TPC**

Light production with THGEM / GlassGEM in avalanche mode

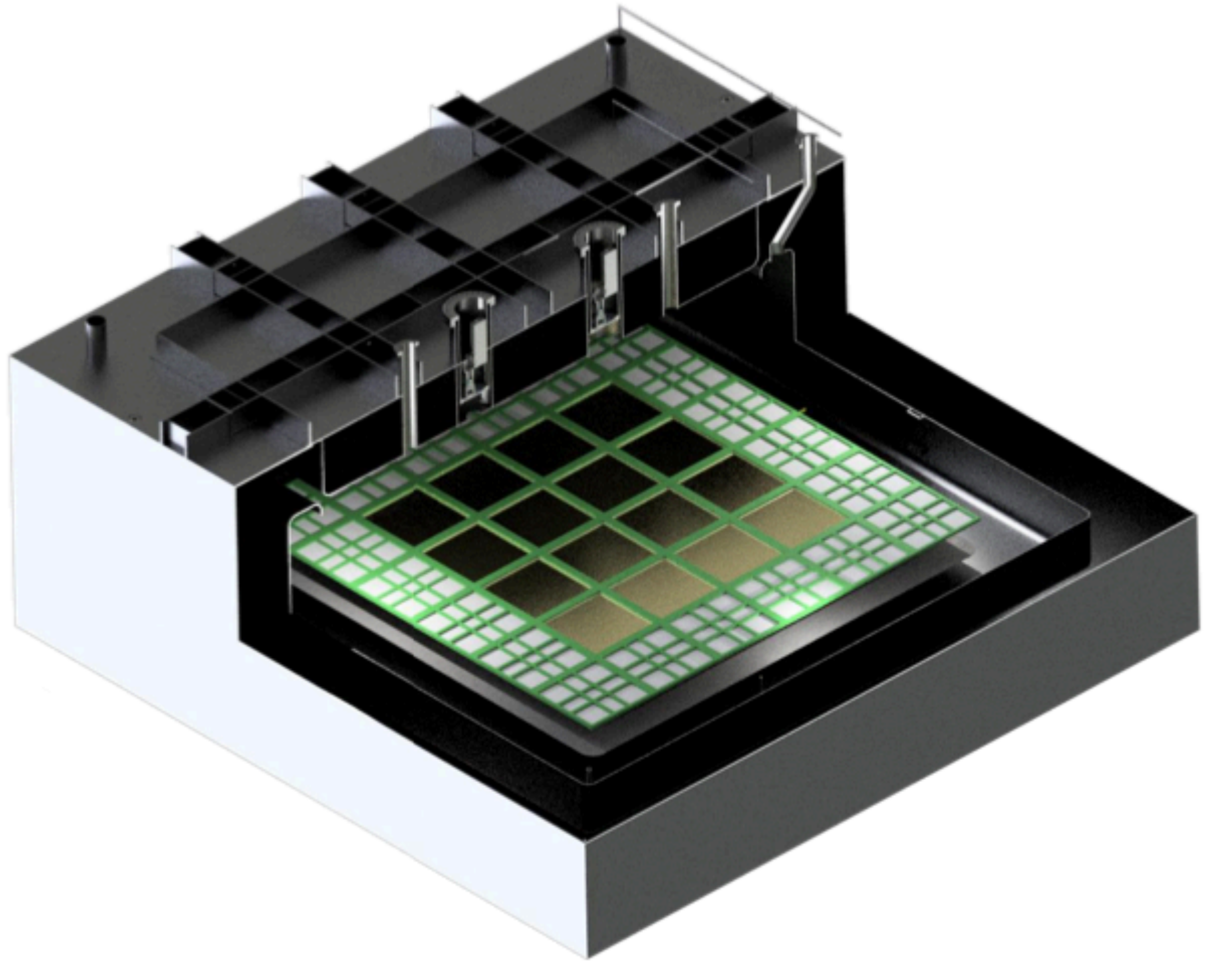
TPB wavelength shifter and VIS **photocathode** or **direct VUV imaging** with UV photocathode on intensifier

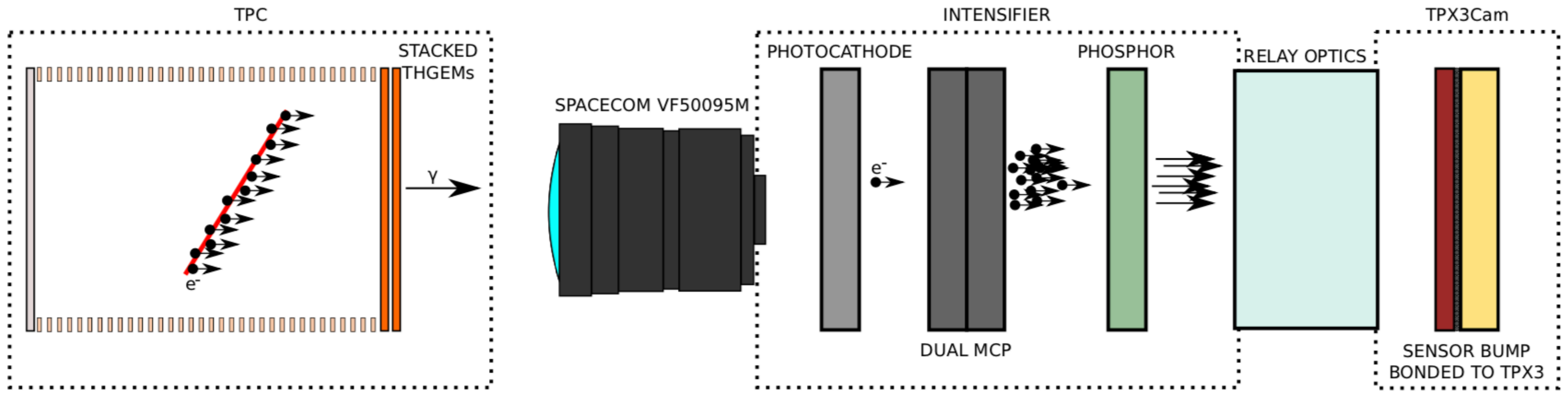






Next step: 2m x 2m test with large field of view and direct VUV imaging



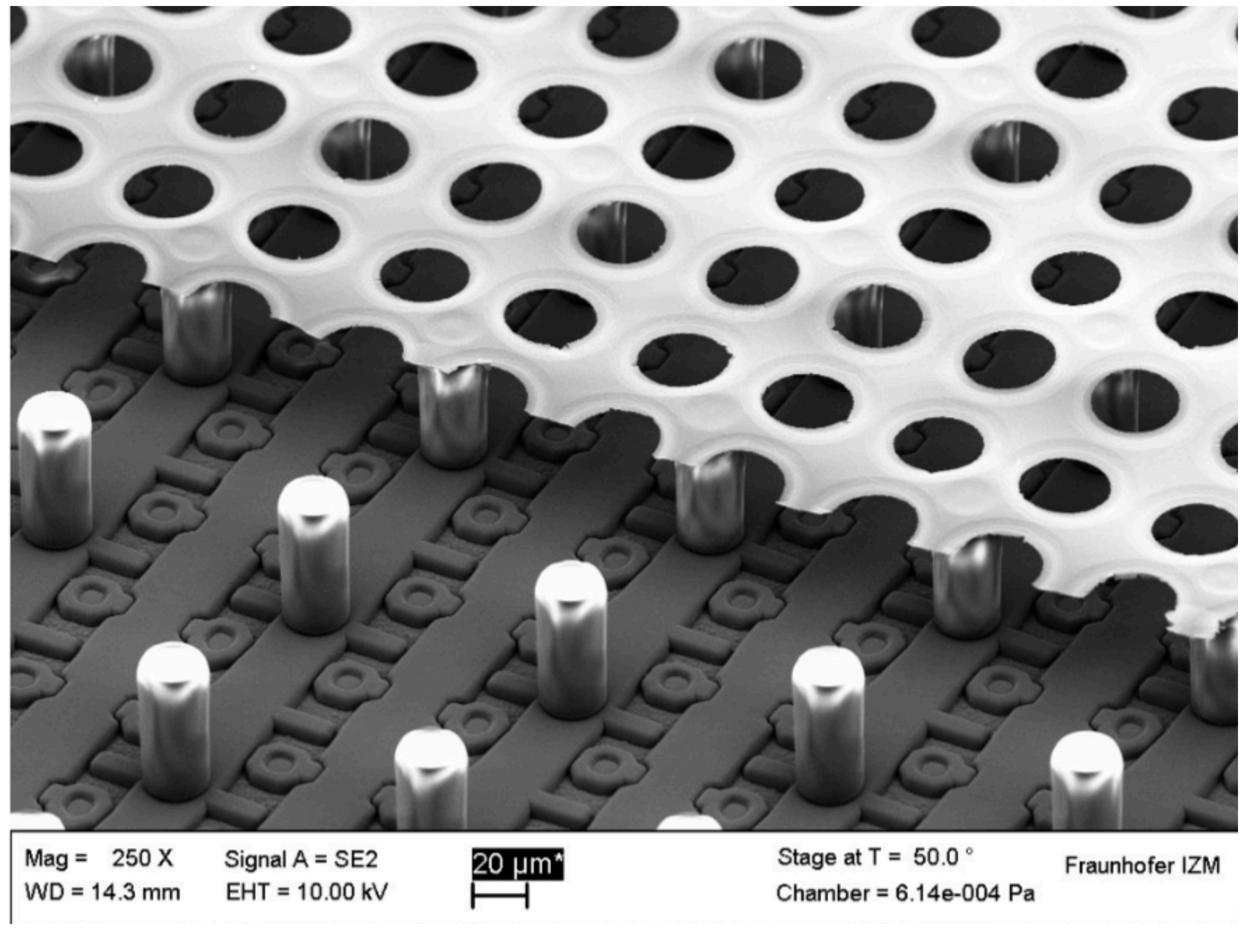


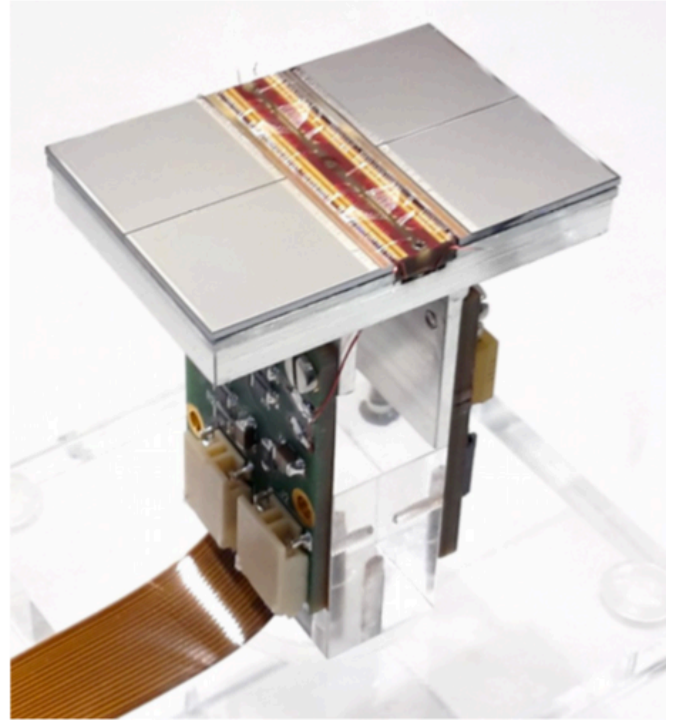
A. Roberts, ARIADNE, arXiv:1810.09955v3
https://indico.cern.ch/event/989298/contributions/4217751/attachments/2190565/3702236/RD51%20Optical%20readout.pdf

GridPix

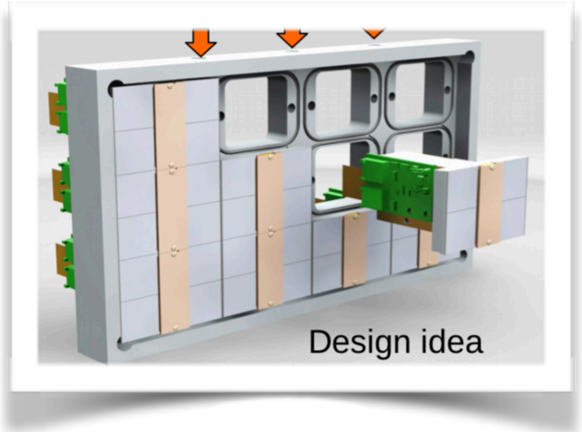
Micromegas on Timepix ASIC

- 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 μm^2 per pixel
  - Charge (ToT) and time (ToA) information with 1.56ns time resolution





QUAD module with fill factor of 68.9%

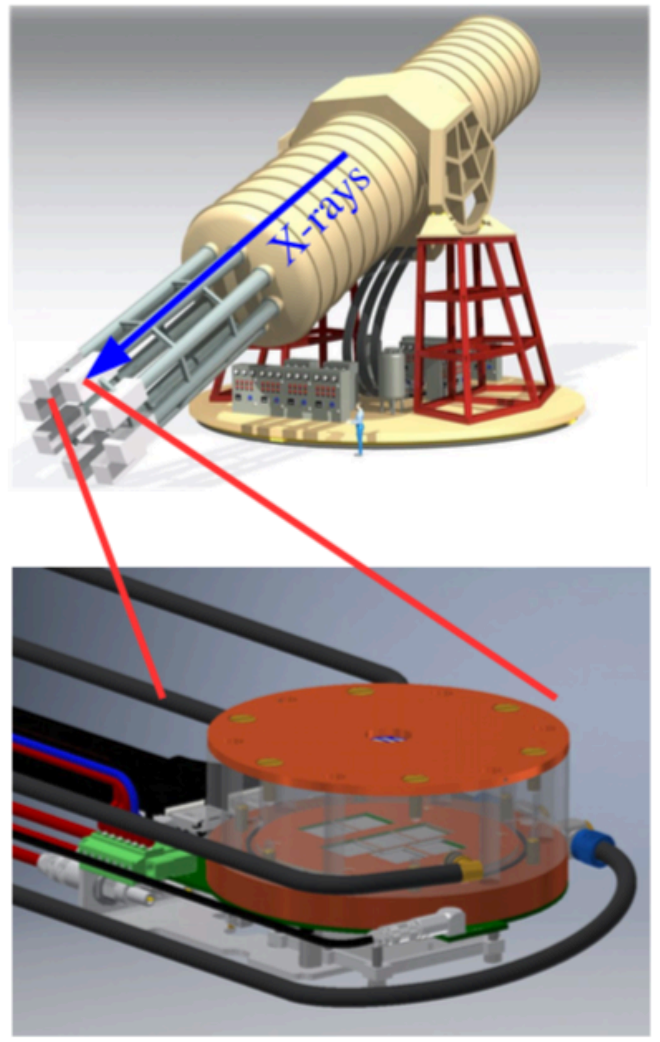


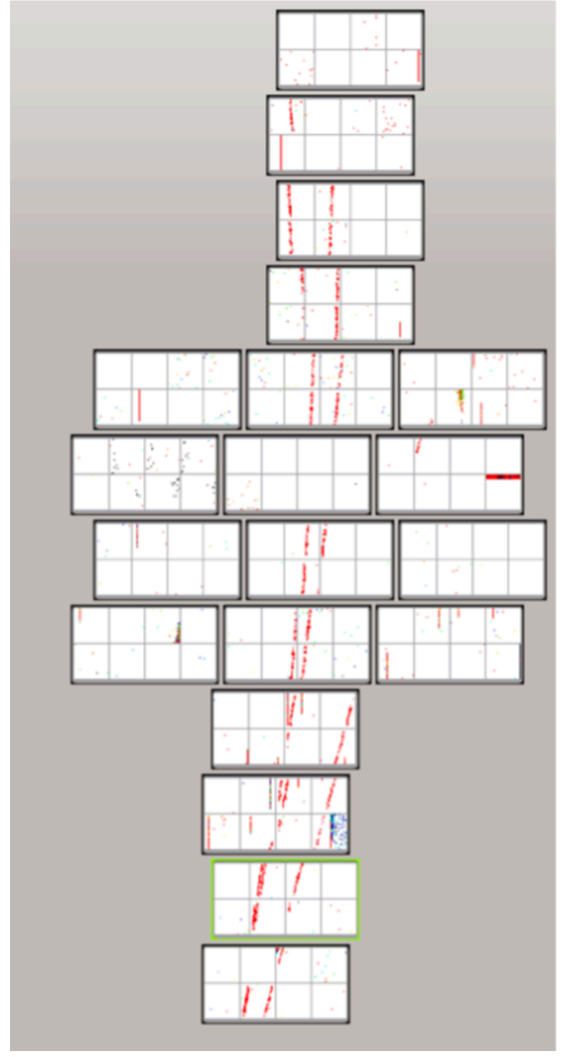
J. Kaminski et al.
NÌM A535 (2004) 506-510
NIM A845 (2017) 233-235

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

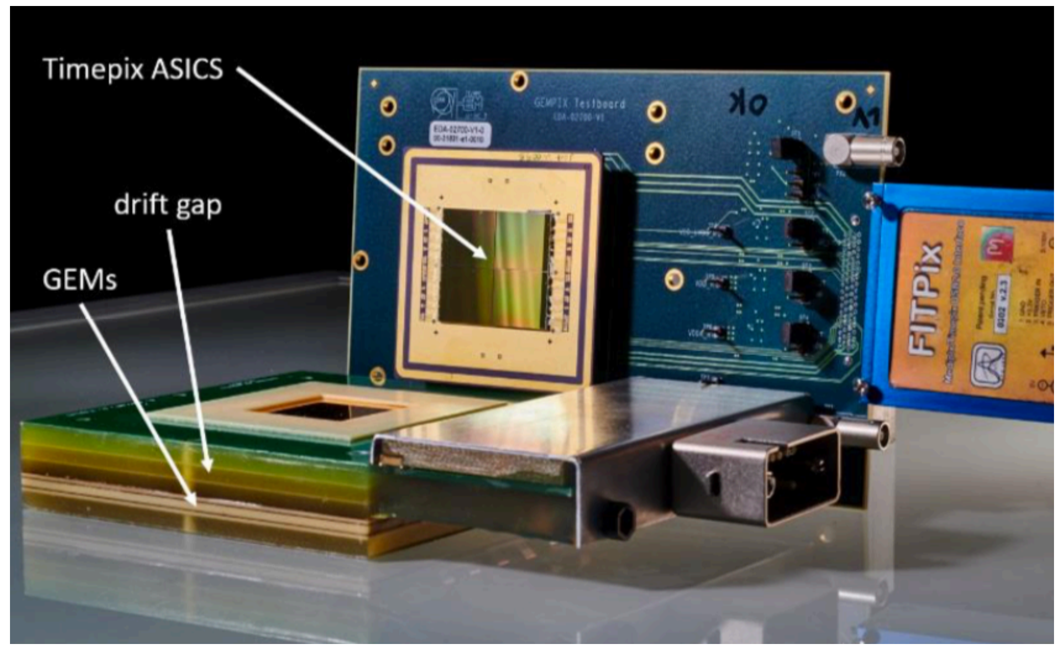
- Neutron TPCs
- X-ray Polarimetry
- Small area directional dark matter detectors

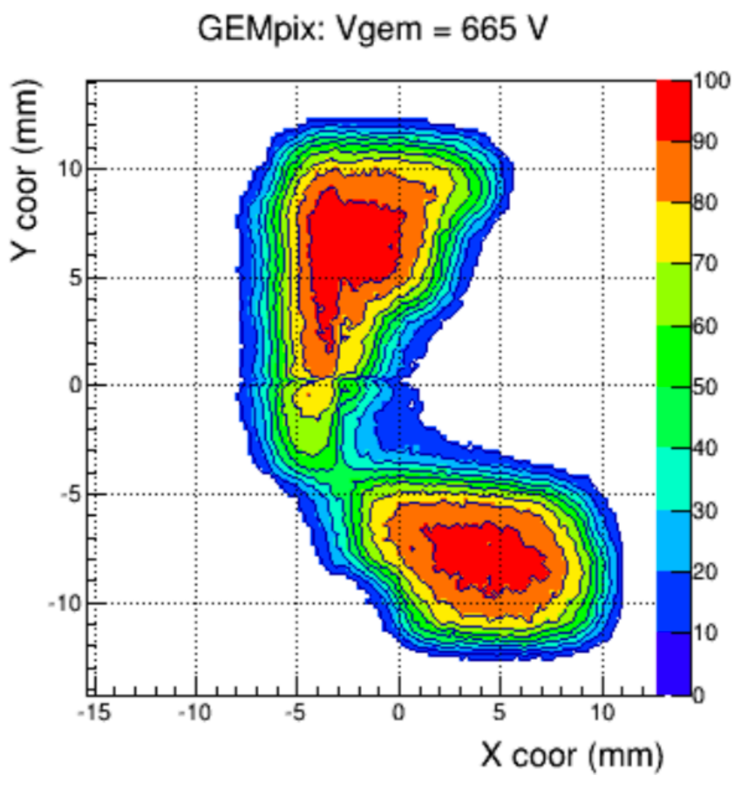
GEMGrid: InGrid on solid layer
TwinGrid: stacked grids
Timepix4?

GEMPix

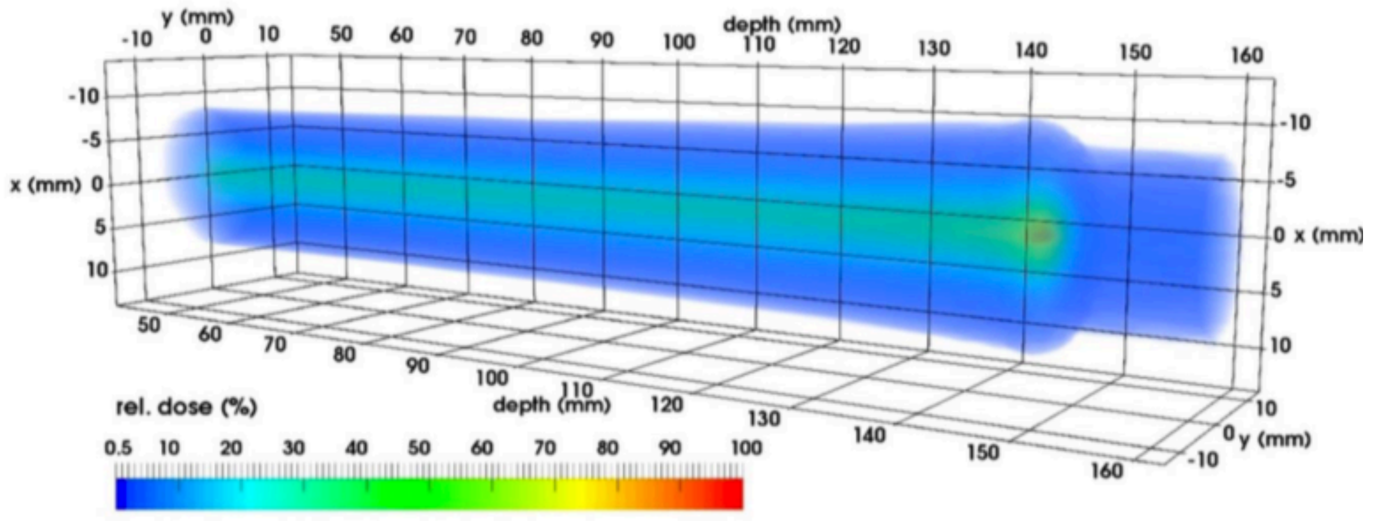
GEM + Timepix ASIC

- 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

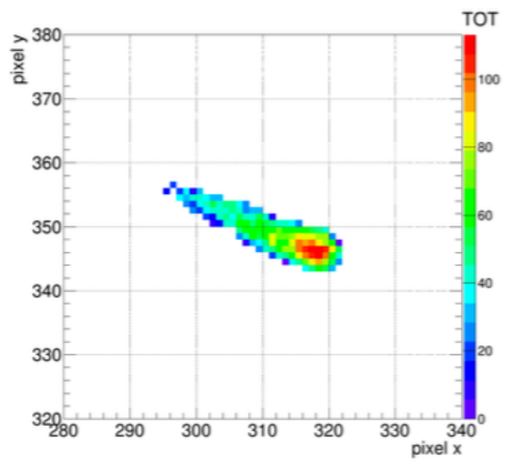




Dose distribution



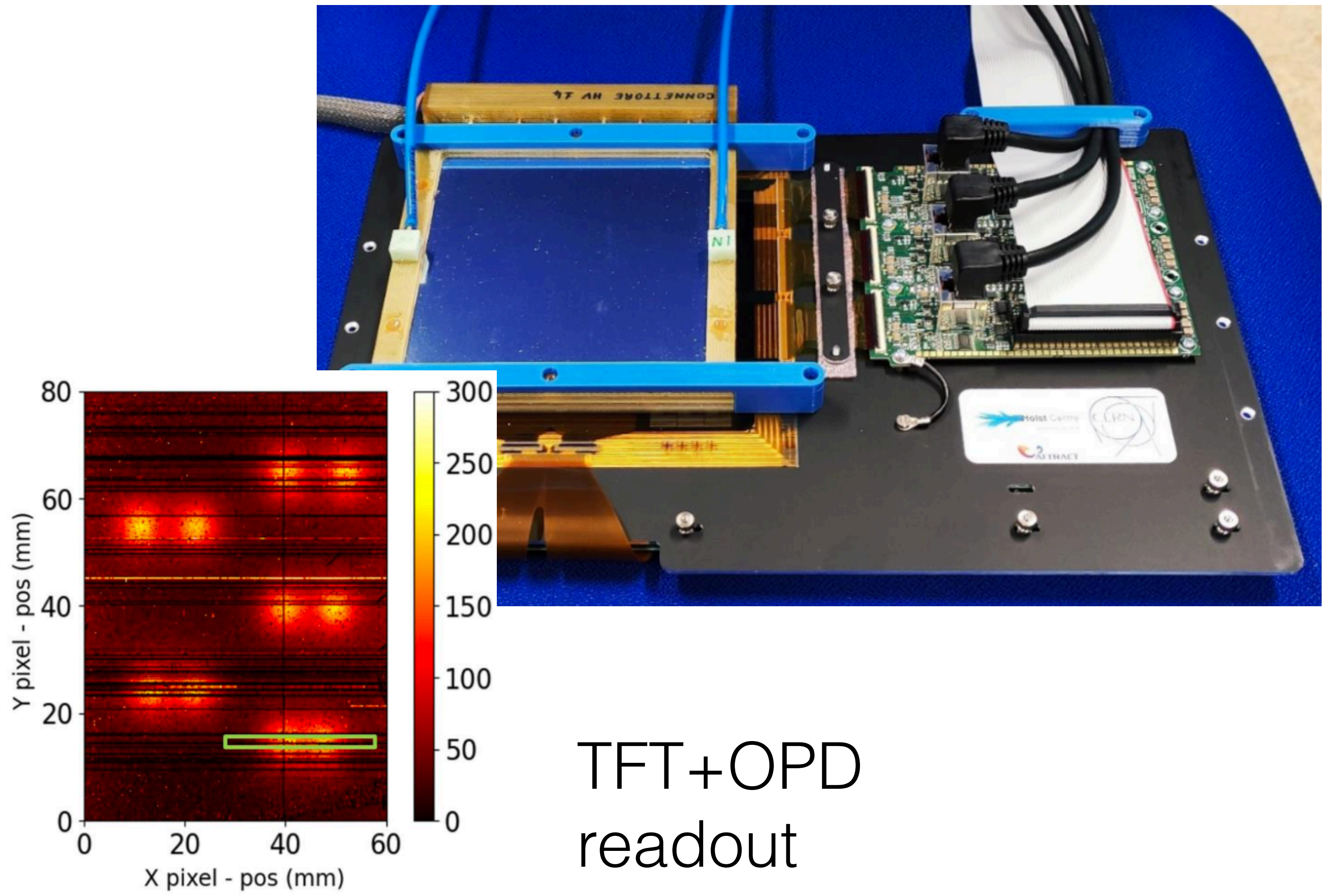
3D dose visualisation of carbon ion beam



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



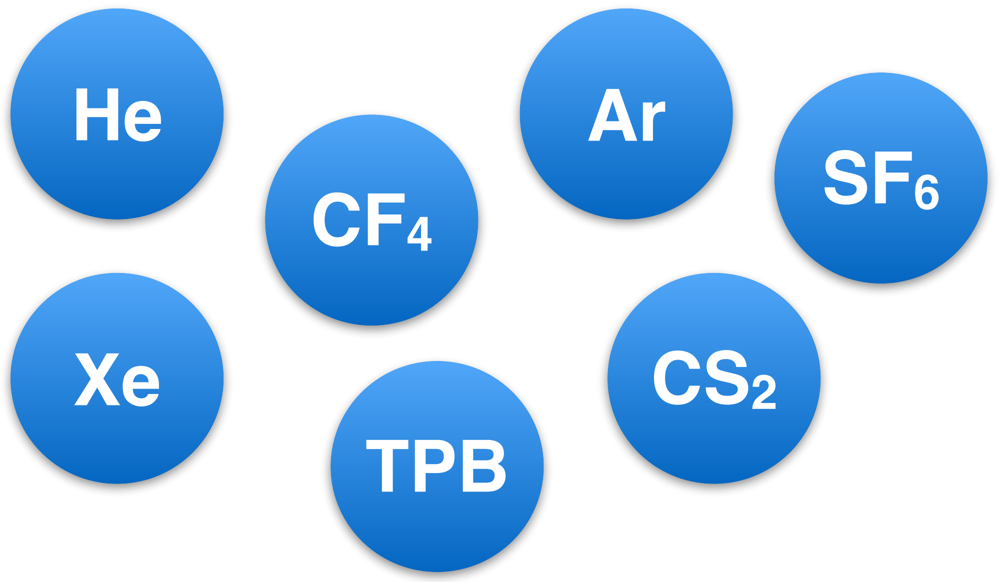
TFT+OPD readout

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

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

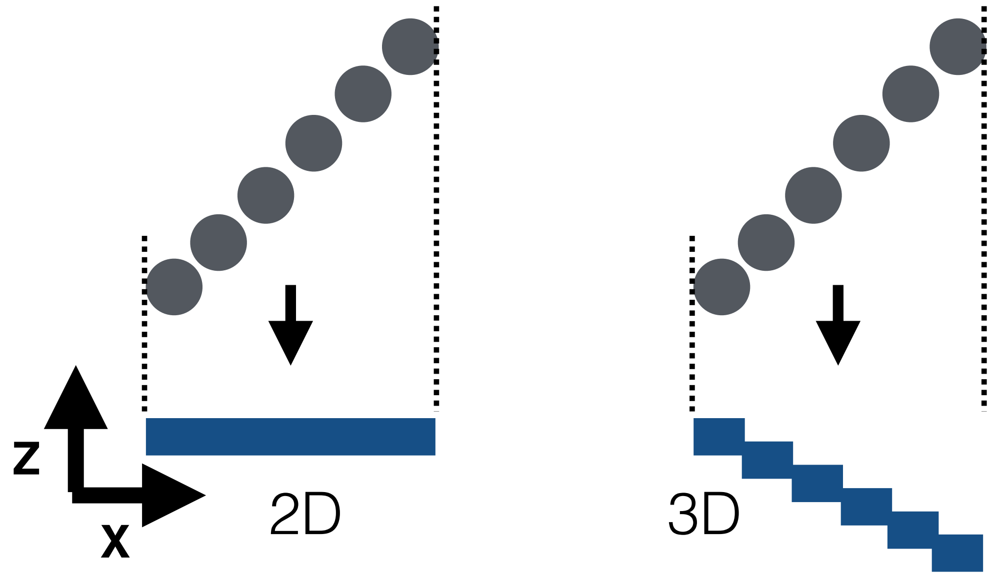


Scintillation emission spectra

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

Depth information in OTPCs

- **Combined** optical+charge readout, exploiting PMT waveforms, **SiPMs arrays**? Ultra-fast imaging?
- **Negative ion** TPCs for superior diffusion characteristics

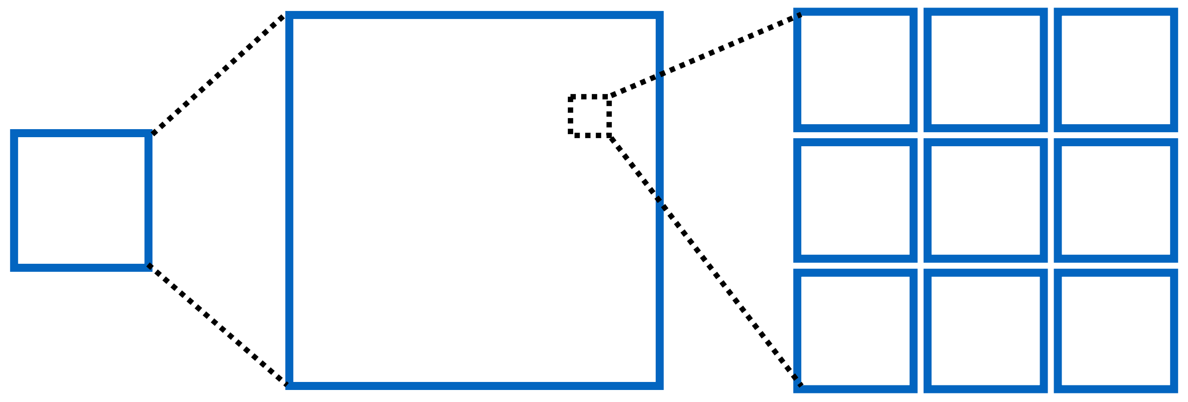


Readout speed

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

Equipping large areas

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



Radiation hardness of sensors

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

?