Optical readout of GEM-based TPCs:
ultra-fast optical readout and transparent readout anodes

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on behalf of the CERN EP-DT-DD GDD team

December 14, 2018 - 9th Symposium on large TPCs for low-energy rare event detection

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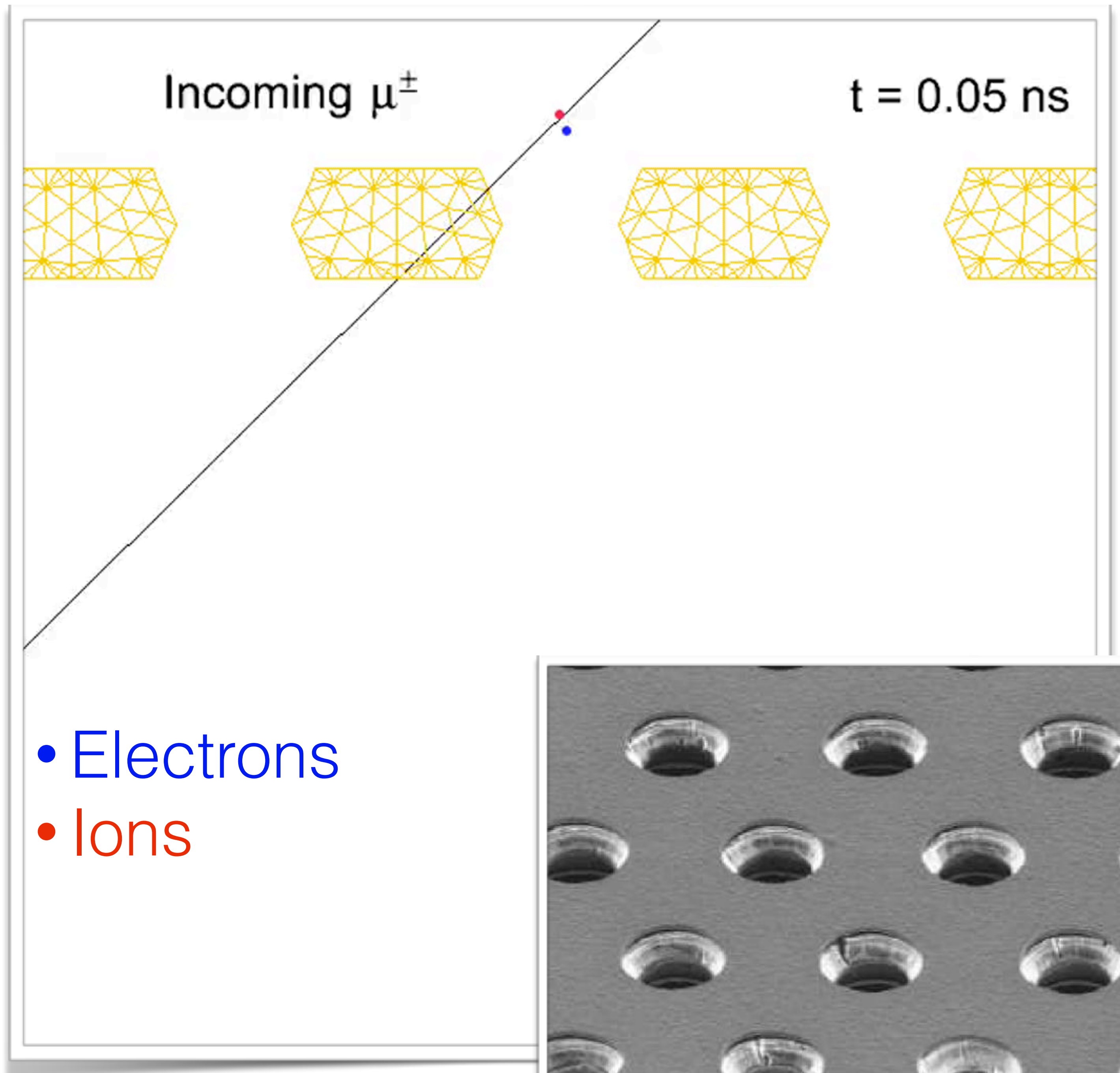
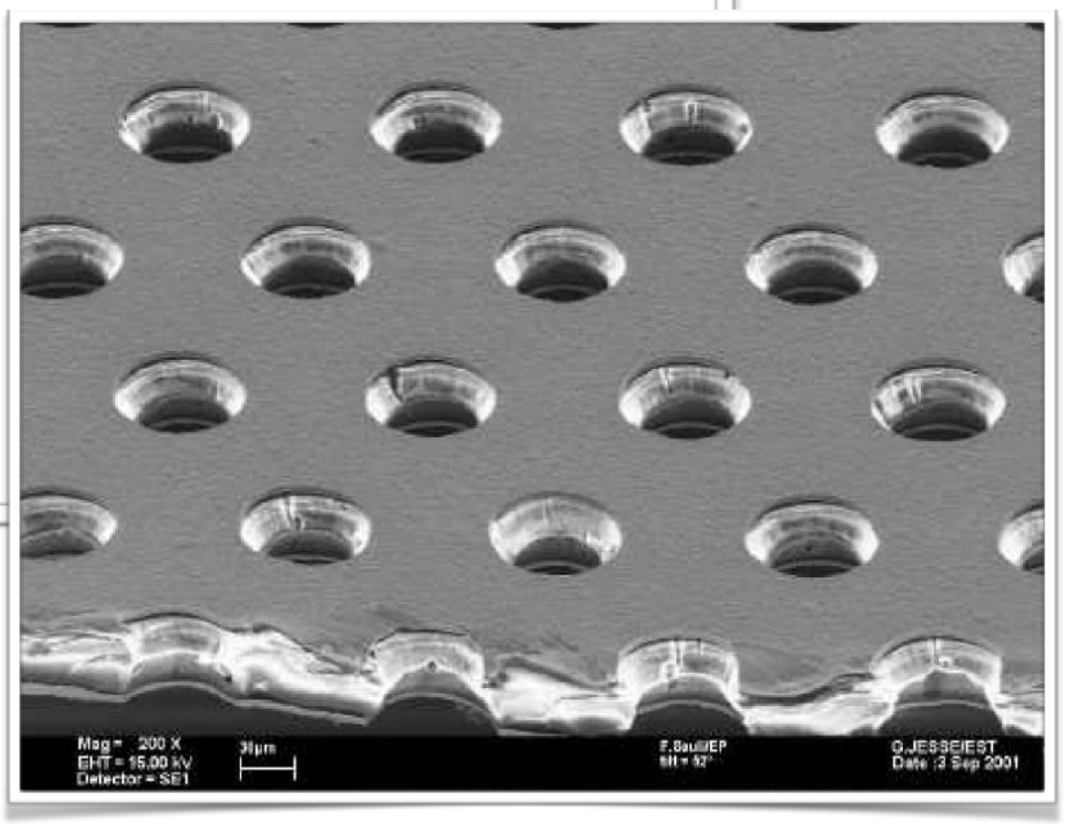
Optical readout of GEM-based detectors

Gaseous Electron Multipliers (**GEMs**) can be read out by recording secondary scintillation light emitted during electron avalanche multiplication with CCD or CMOS cameras.

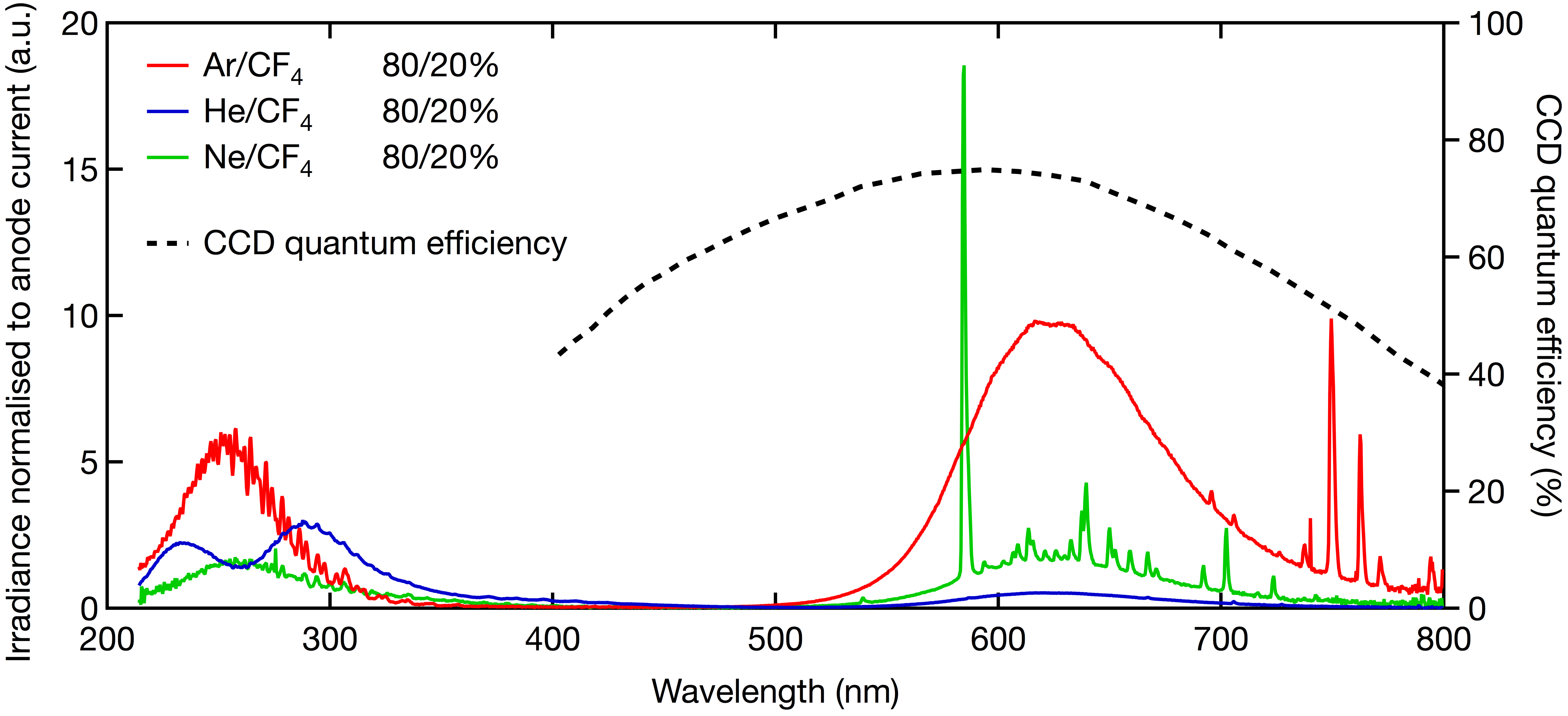
Avalanche multiplication in GEM





http://garfieldpp.web.cern.ch/garfieldpp/examples/gemgain/

Secondary scintillation spectra of gas mixtures containing CF_4



Schematics not drawn to scale

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

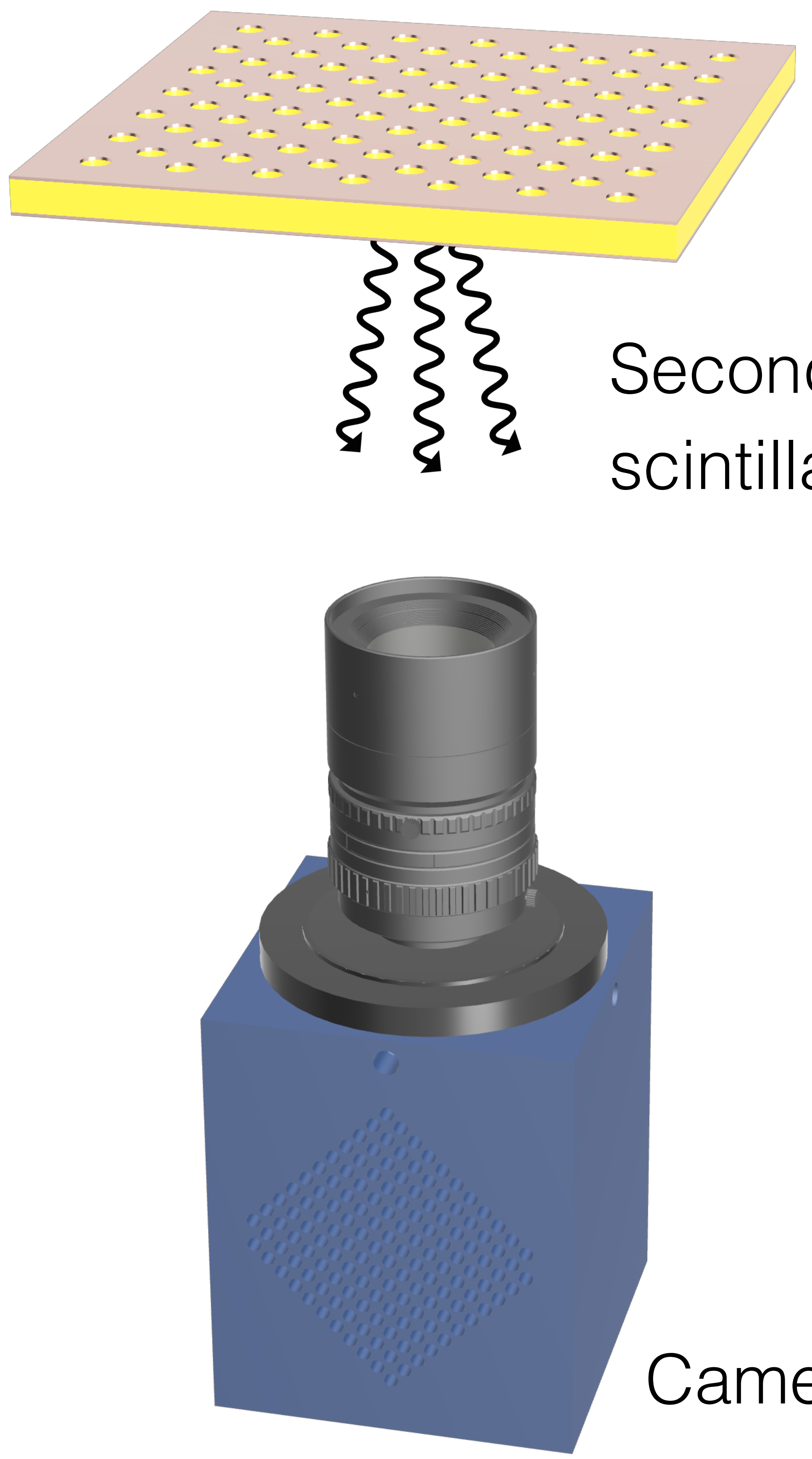
High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

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

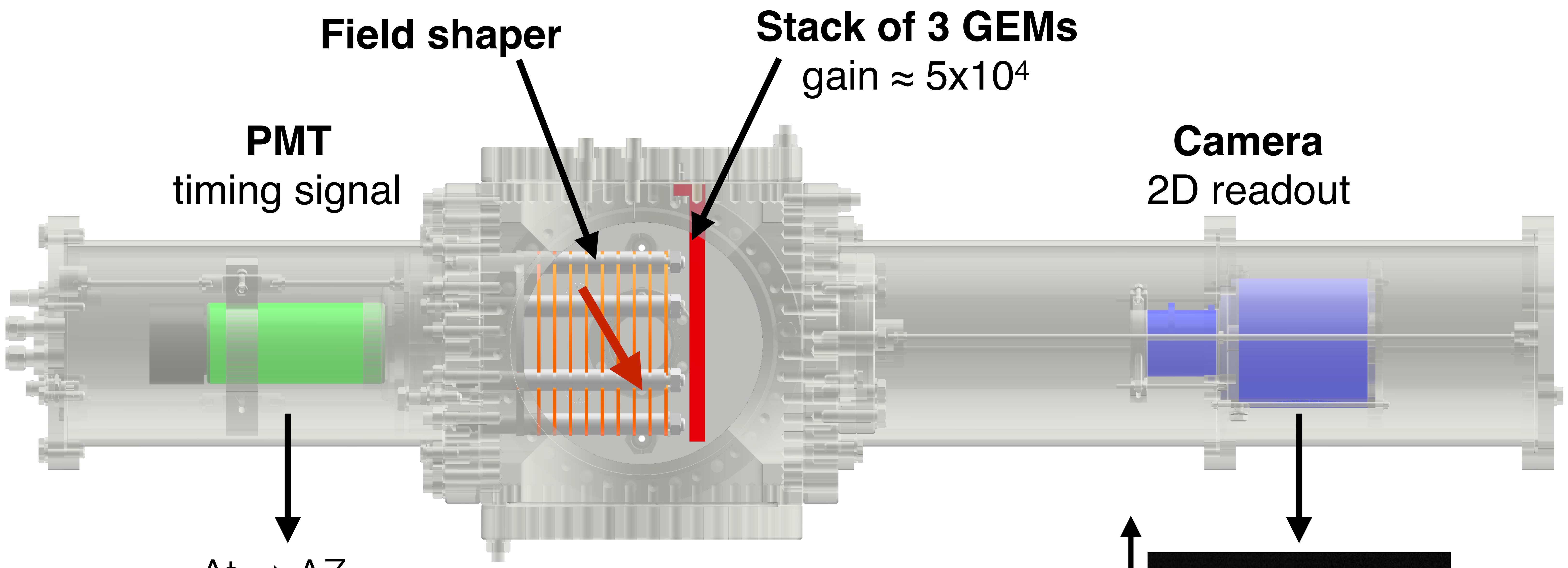


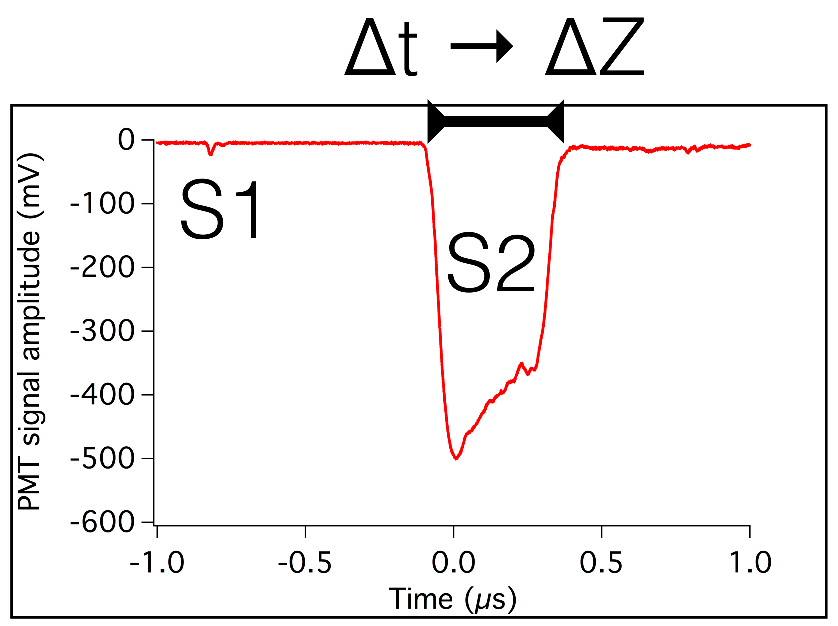
Schematics not drawn to scale

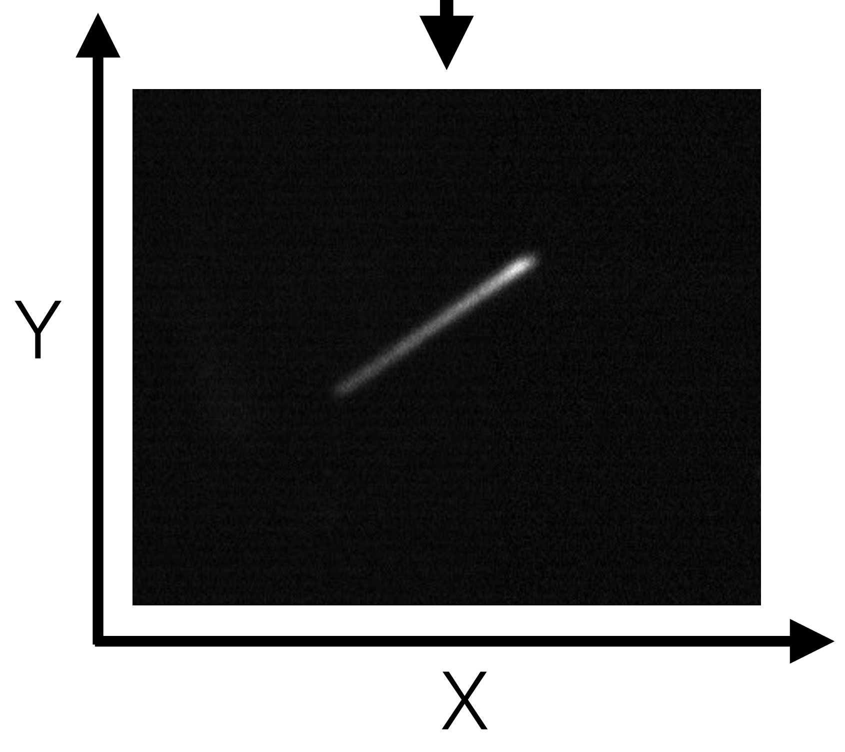
Transparent readout anodes

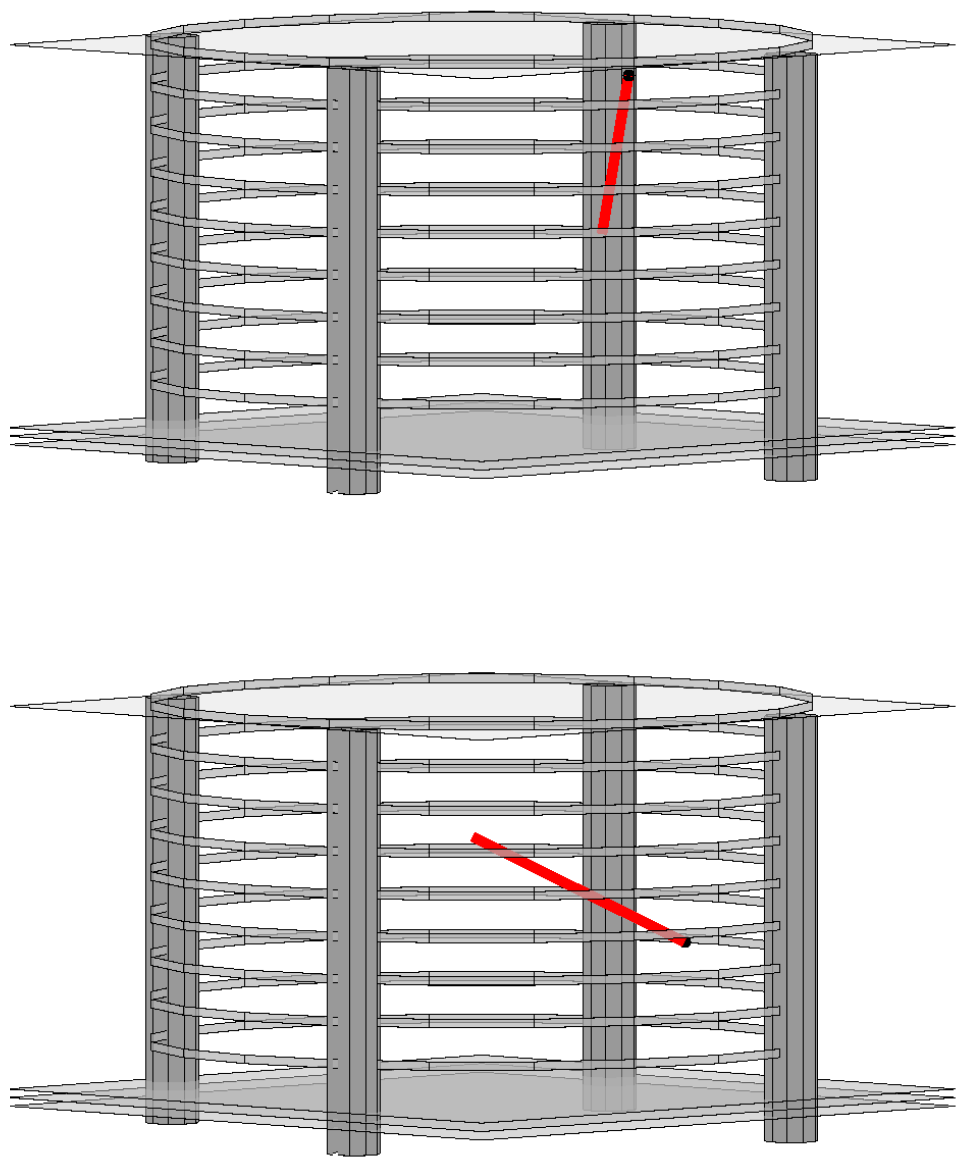
Combined optical and electronic readout

Optically read out TPC CCD + PMT

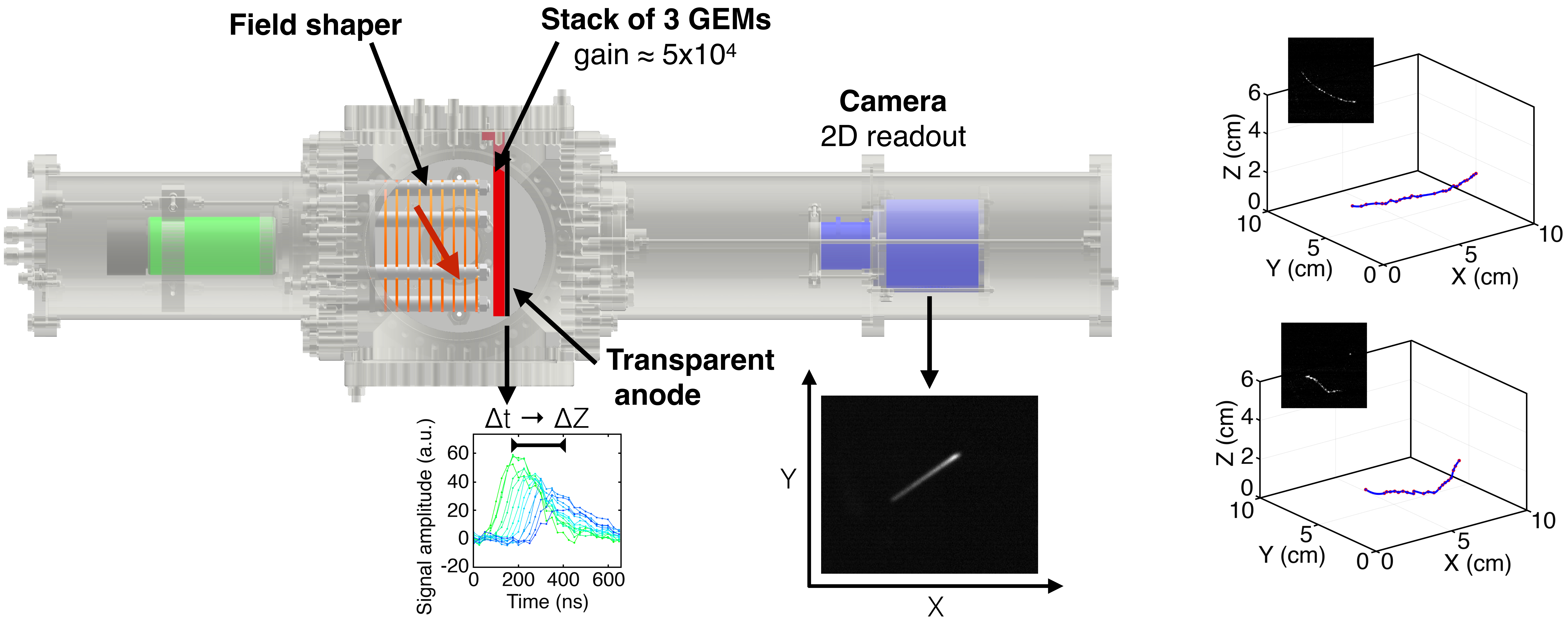








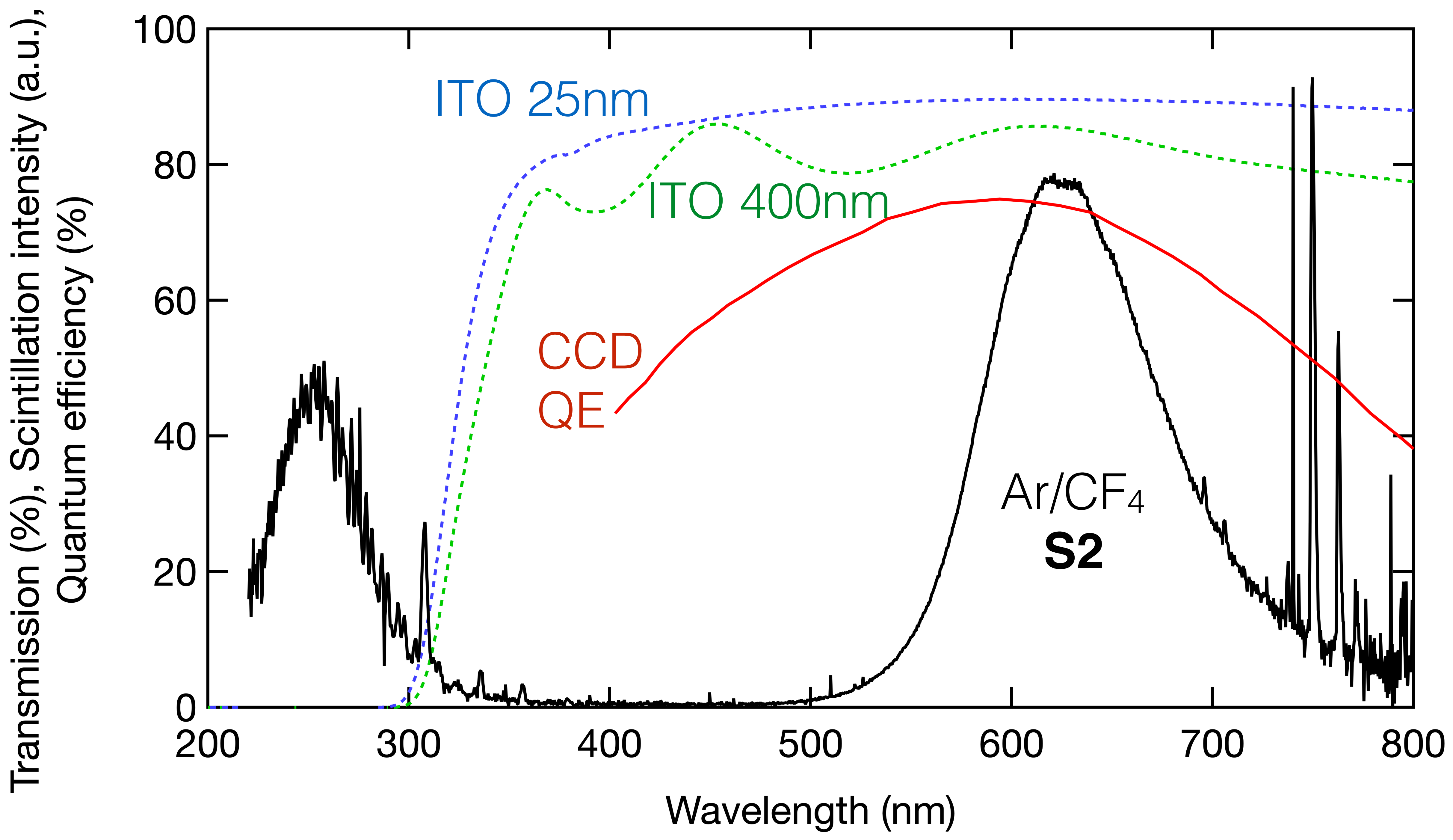
Optically read out TPC CCD + Electronic

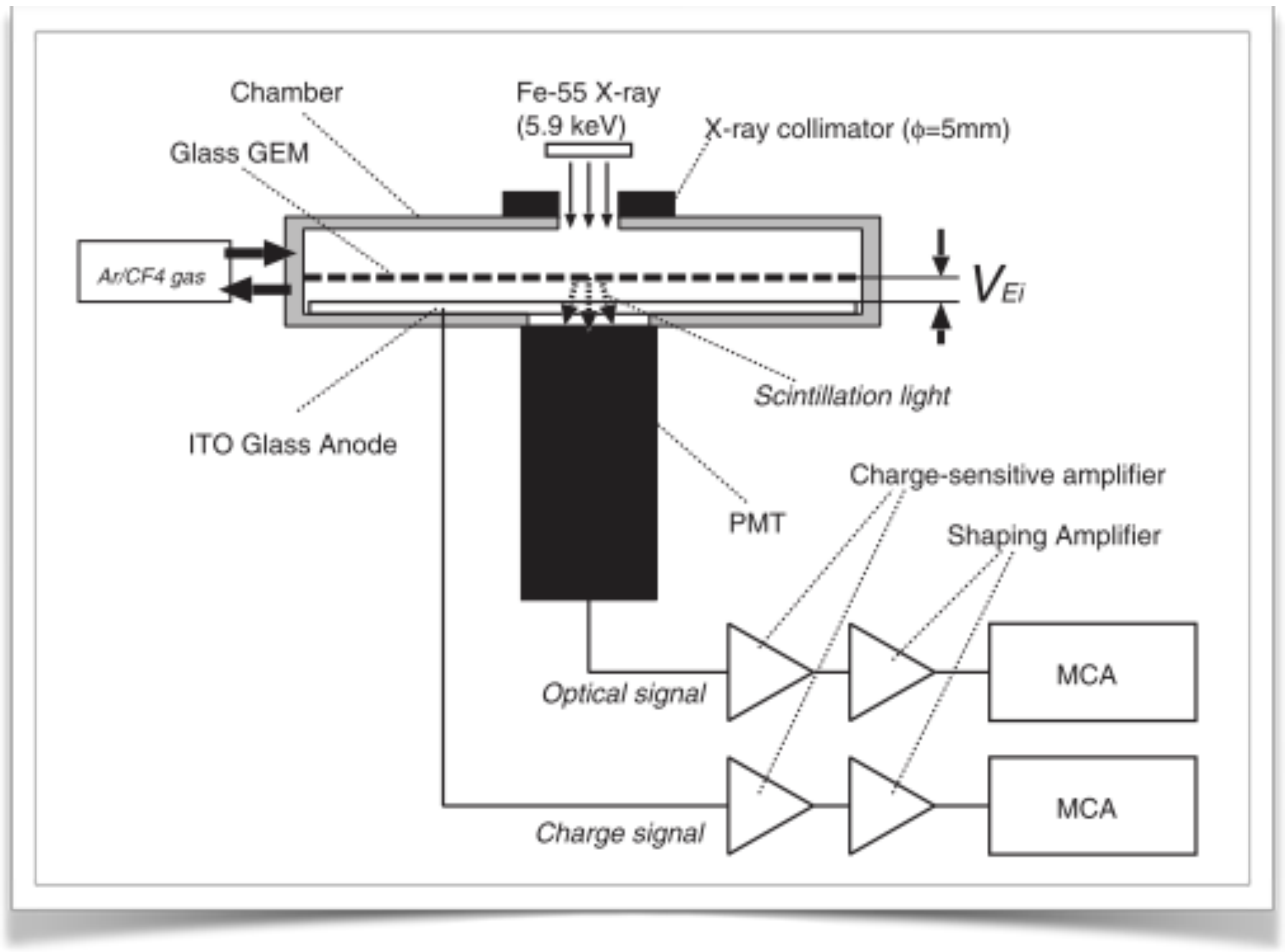


Schematics not drawn to scale

Indium tin oxide (ITO) for transparent anodes

- Optically transparent
- Electrically conductive
- Simple deposited of thin films by evaporation
- Can be etched in HCl

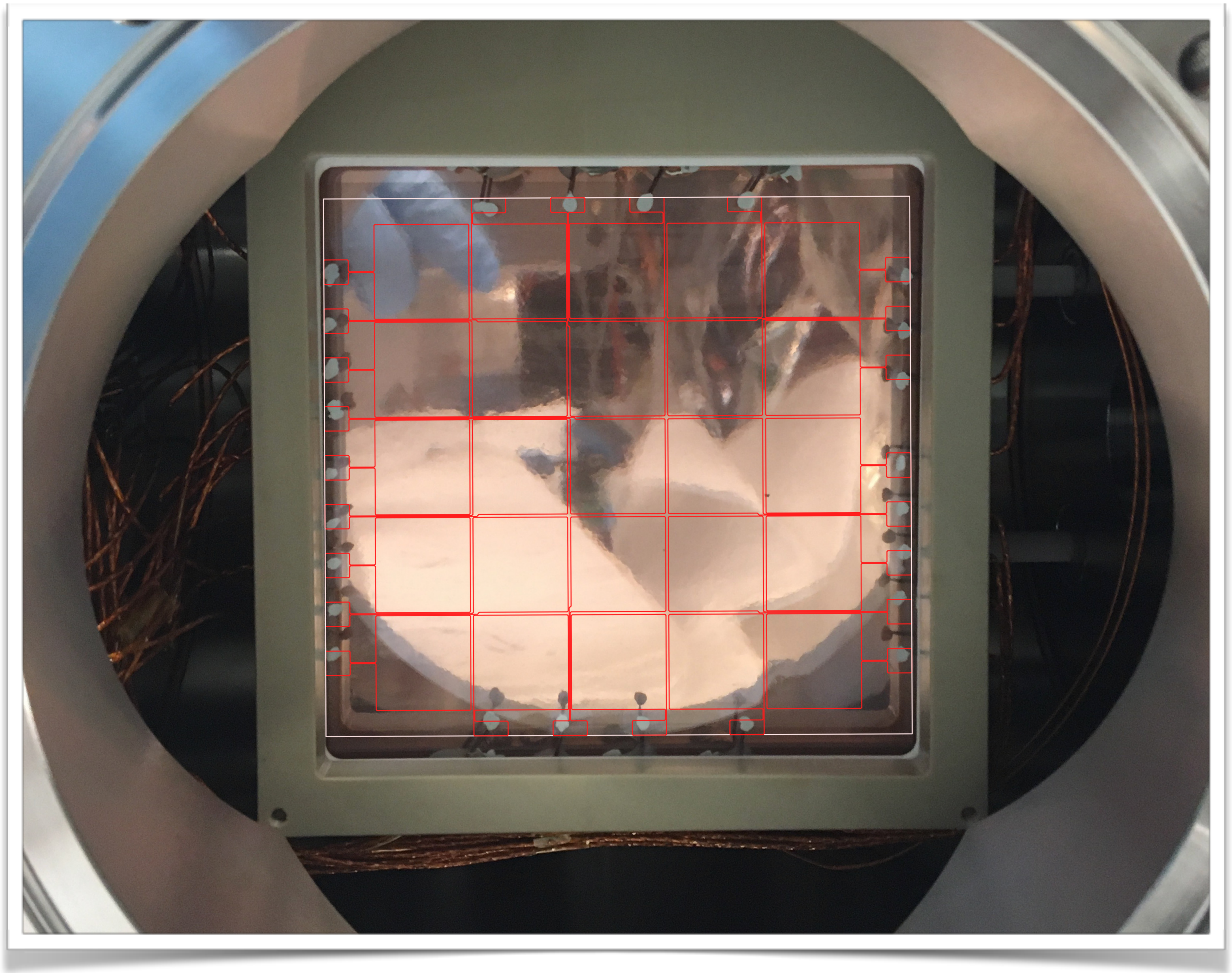




Used as transparent anode in optically read out detectors to collect energy spectra from charge signals

T. Fujiwara et al 2016 Jpn. J. Appl. Phys. **55** 106401

ITO pad anode



View into GEM-based TPC (10x10 cm^2 active area) as seen by camera with ITO pattern shown in red overlay

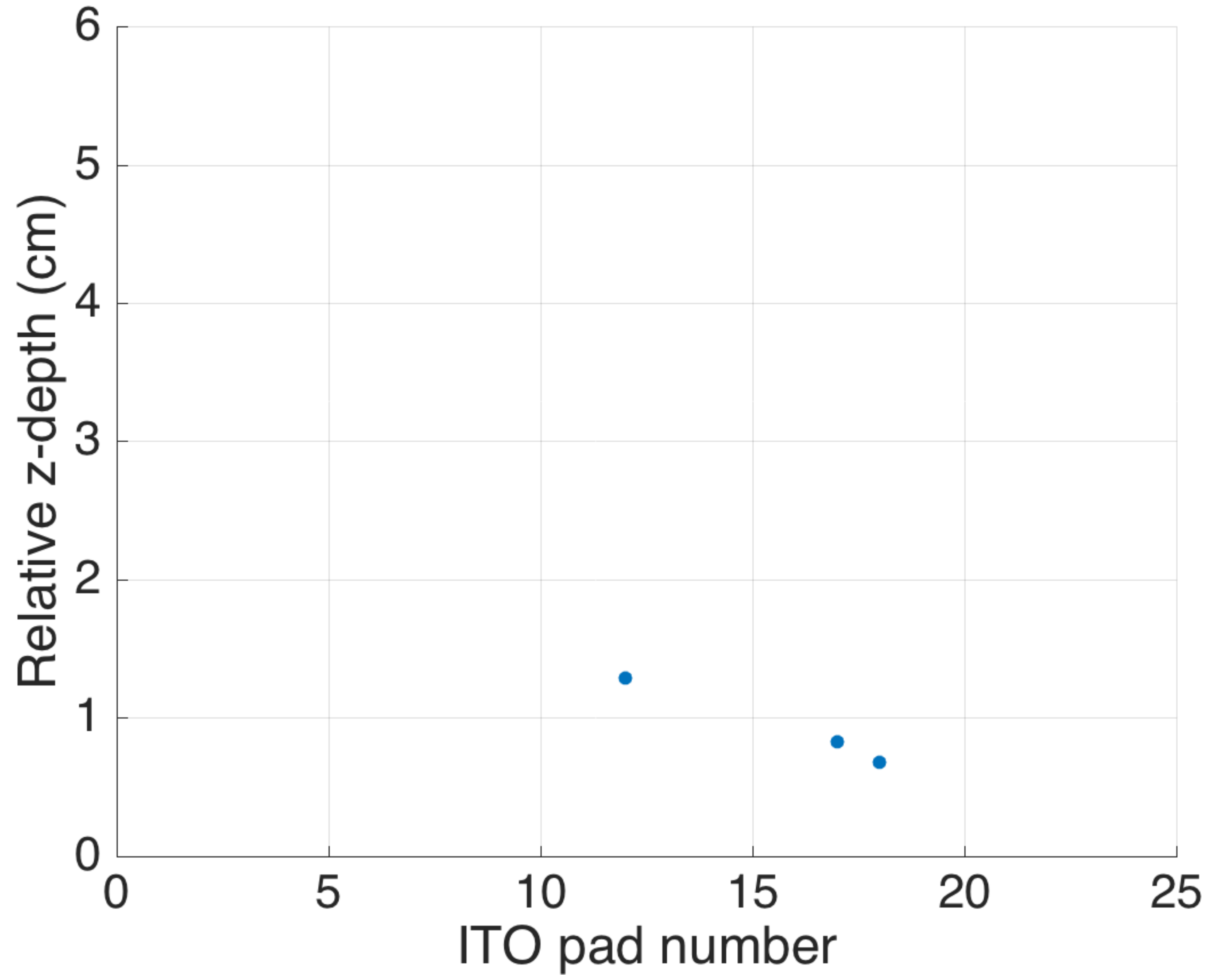
25 pads with 2x2 cm^2

25 nm ITO on 1.1 mm glass

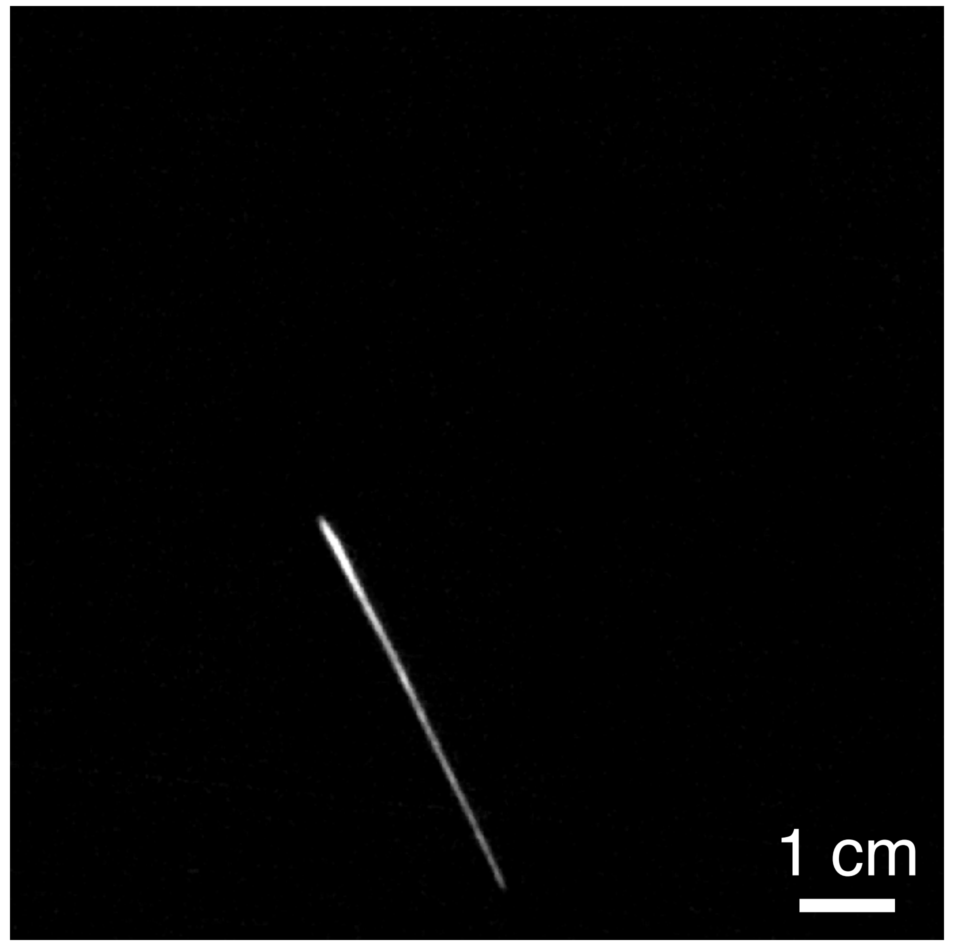
Structured by **direct laser lithography** and etching in HCl

Sheet resistance of 100 Ω/sq

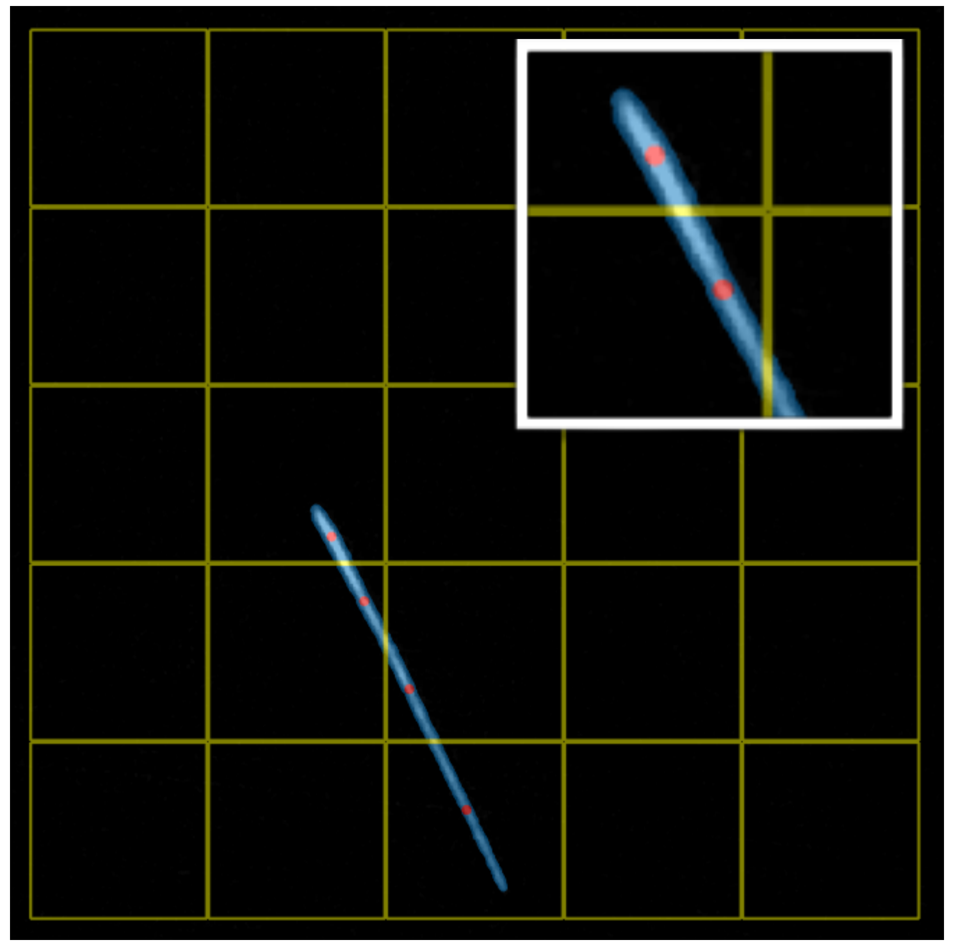
ITO pad anode + CCD images reconstruction



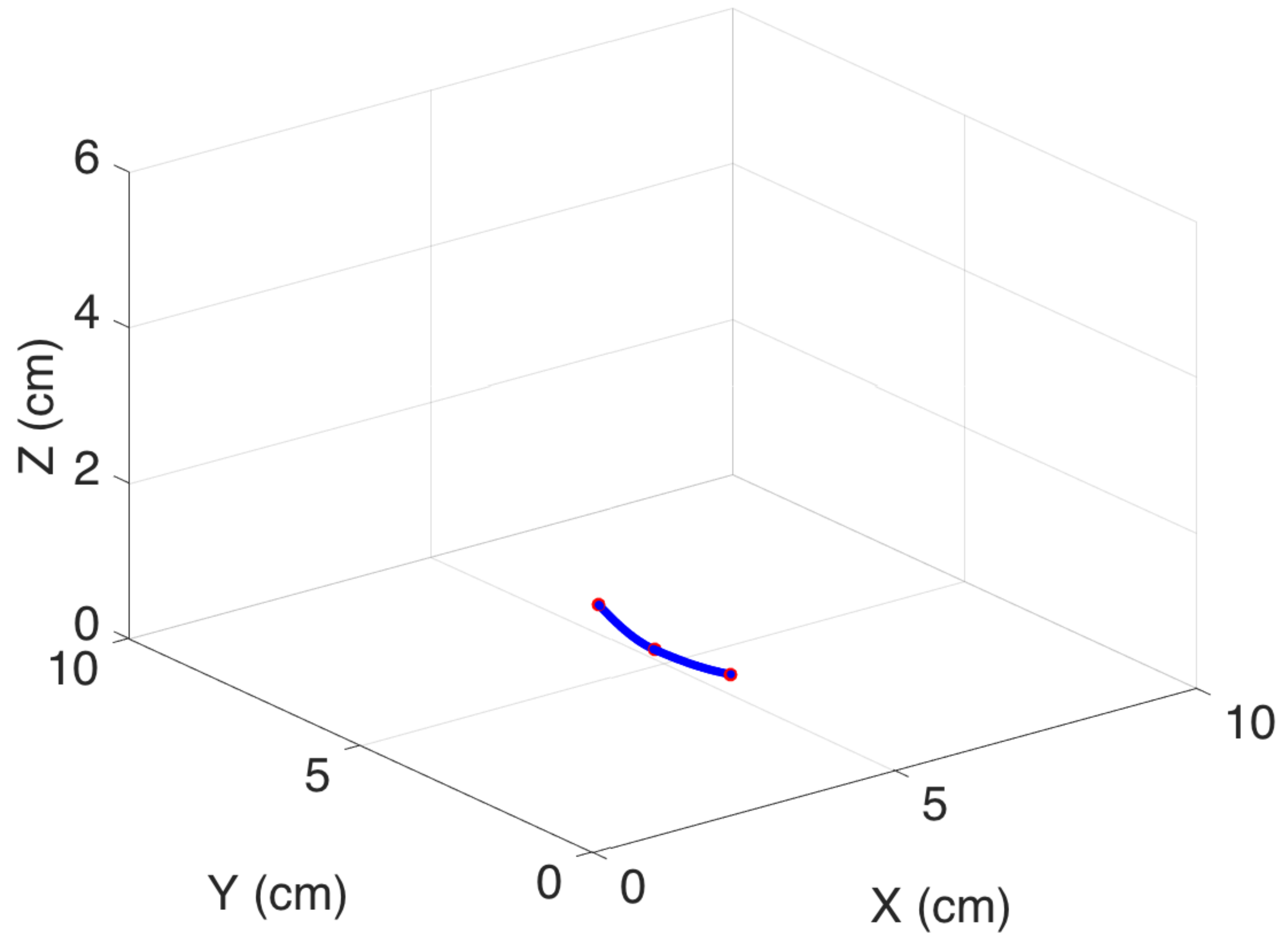
Depth information from pads



Raw image



Processed image with pad pattern overlay



3D reconstructed alpha track

Z-depth information is extracted from arrival times of electronic signals from ITO pads, image from camera is used to identify hit locations on pads (mean position of hit pixels in pad), 3D track points obtained from assigning depth information to each hit point, track from interpolation between points

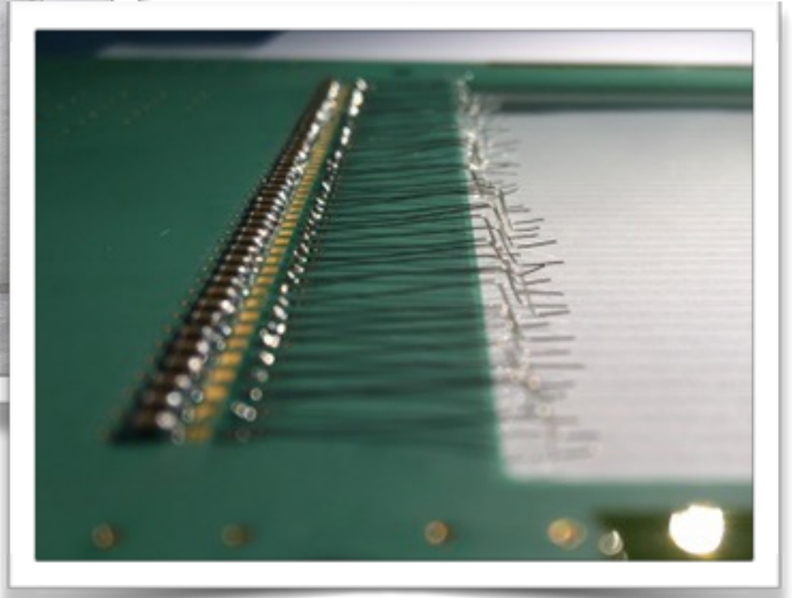
ITO strip anode

48 strips: 1.5 mm wide at 2 mm pitch

450 nm ITO on glass

Structured by direct laser lithography and etching in 32% HCl

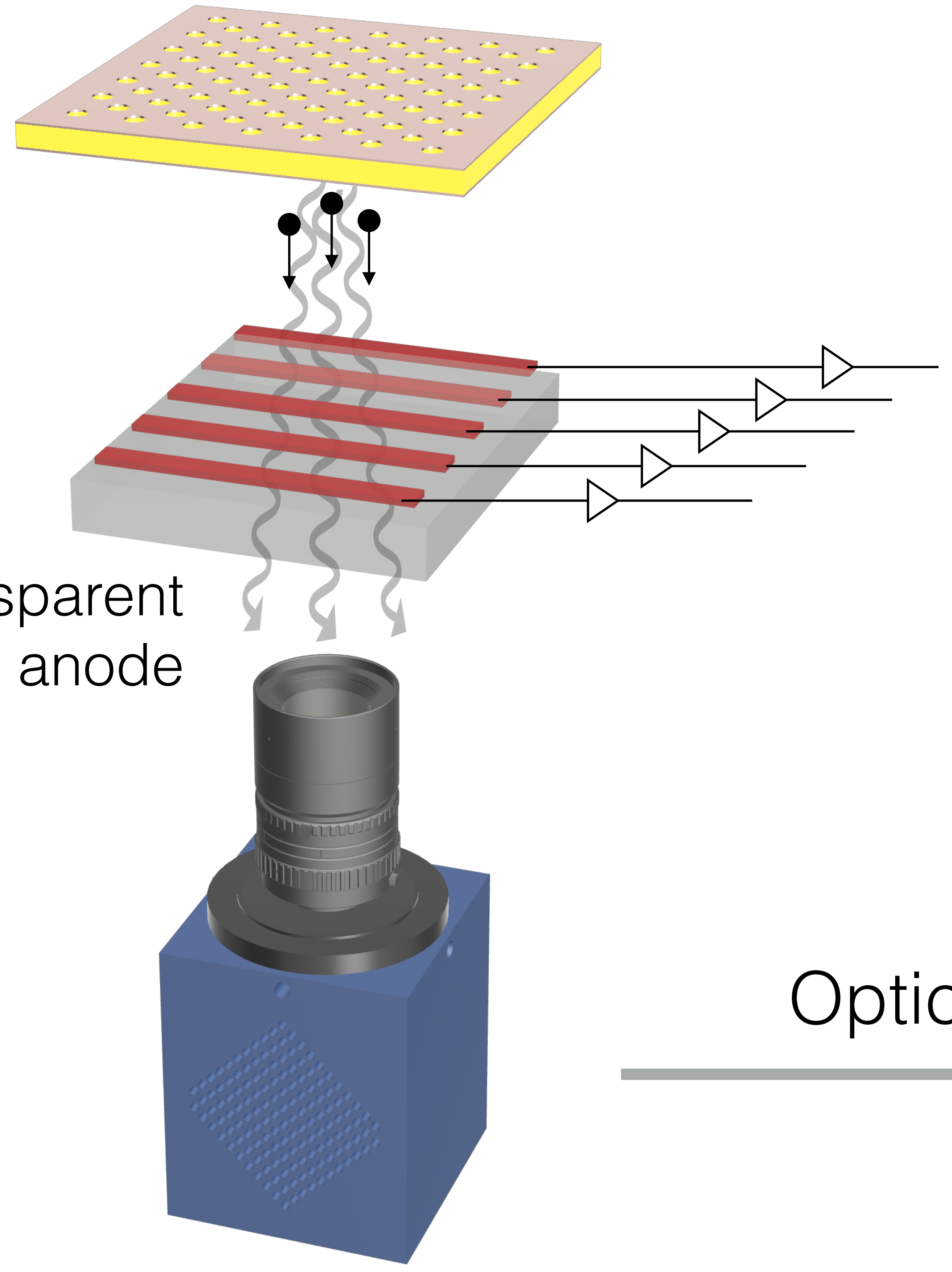
Sheet resistance of 4 Ω/sq results in resistance of ≈400 Ω across individual strips



Electronic readout of individual strips of ITO anode by **APV25 ASIC** and RD51 Scalable Readout System (SRS)

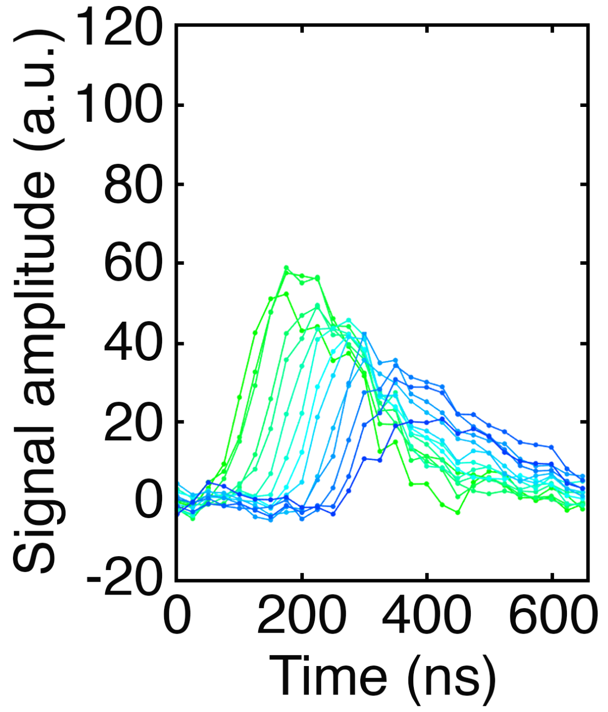
- 27 time bins with 25 ns width
- Triggered by PMT scintillation signal

Combined optical and electronic readout

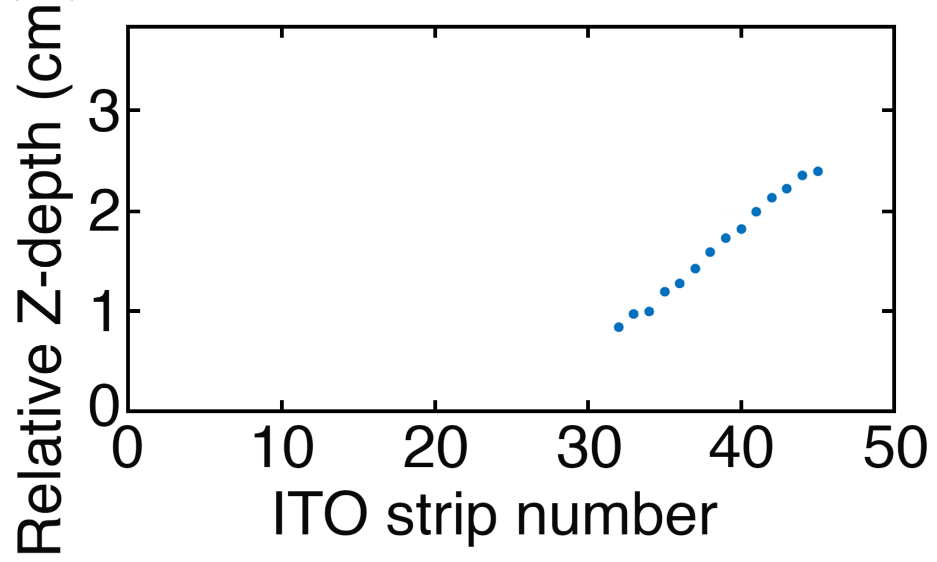


Transparent strip anode

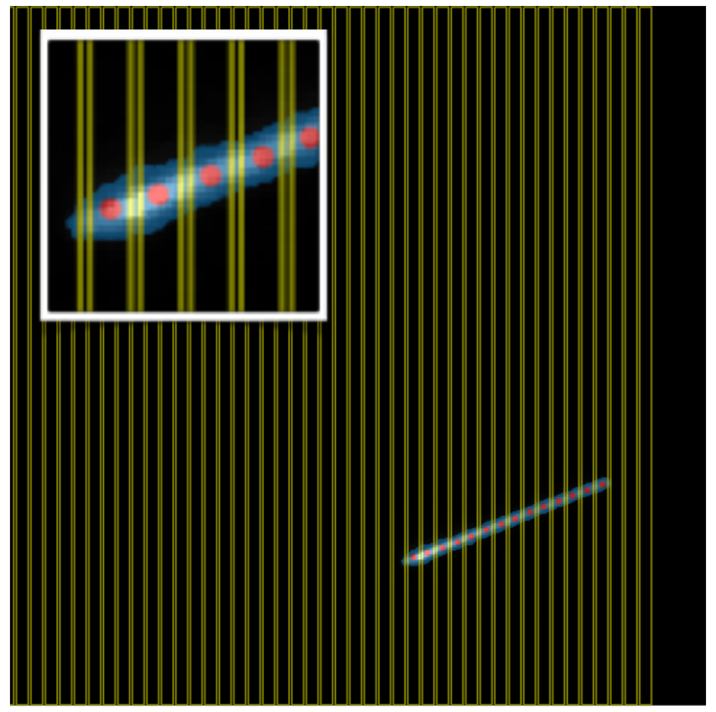
Electronic readout



Z depth information



Optical readout

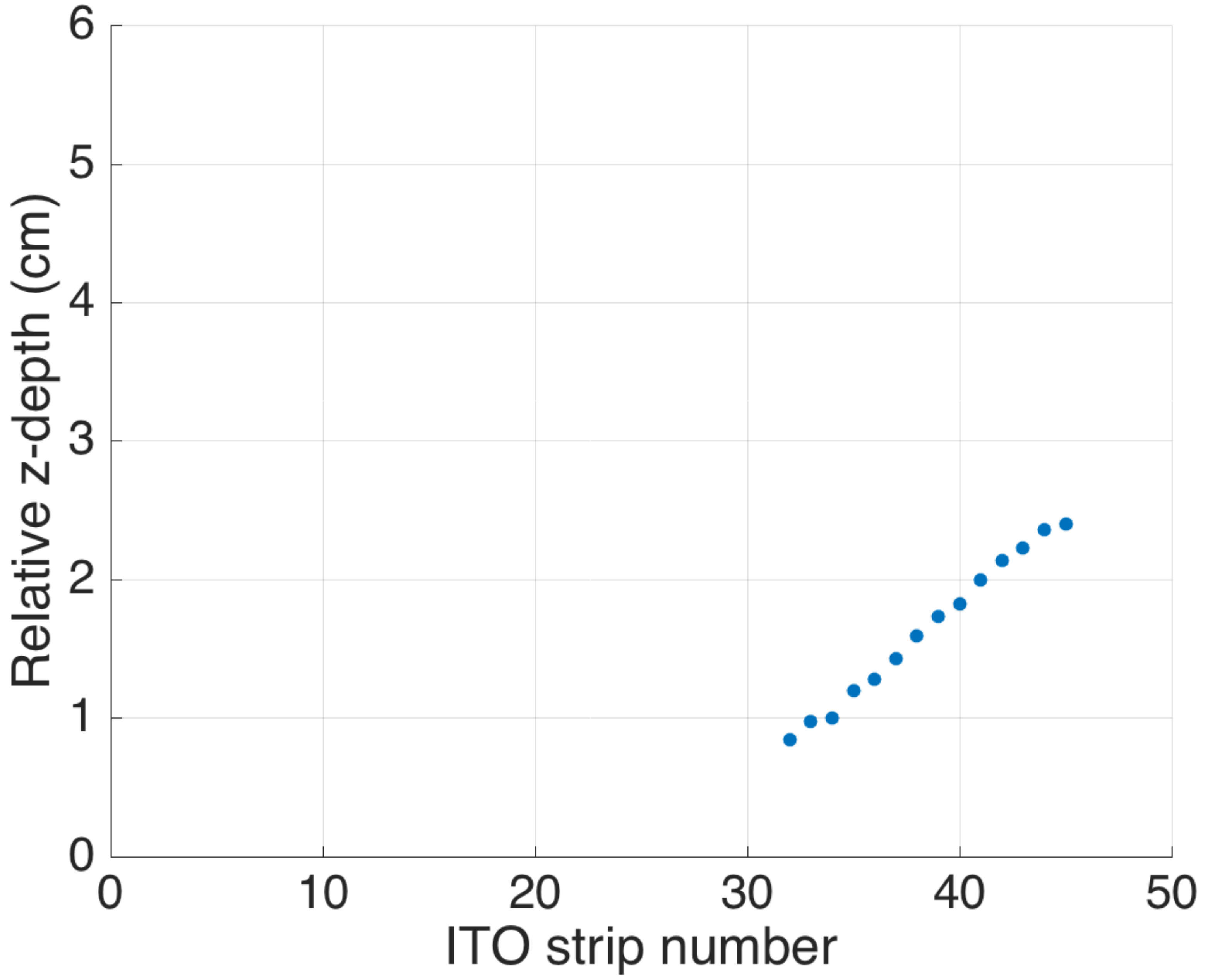


2D XY projection

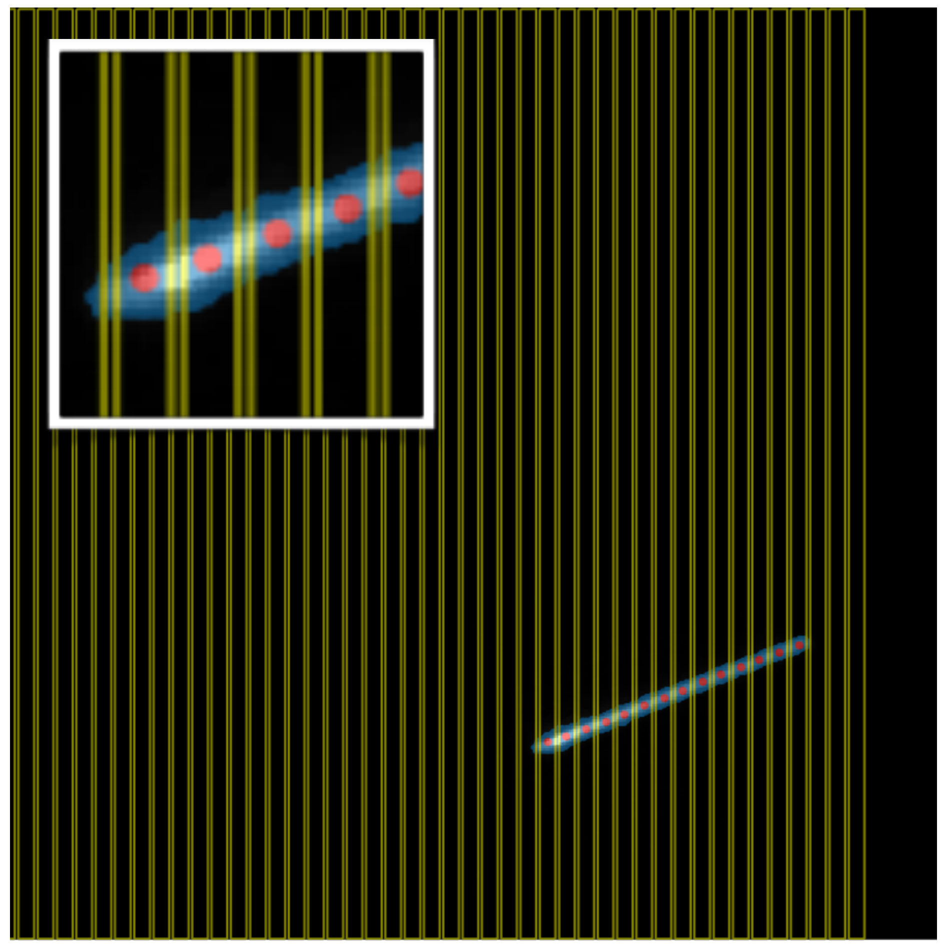
Schematics not drawn to scale

Combining Z with XY-information

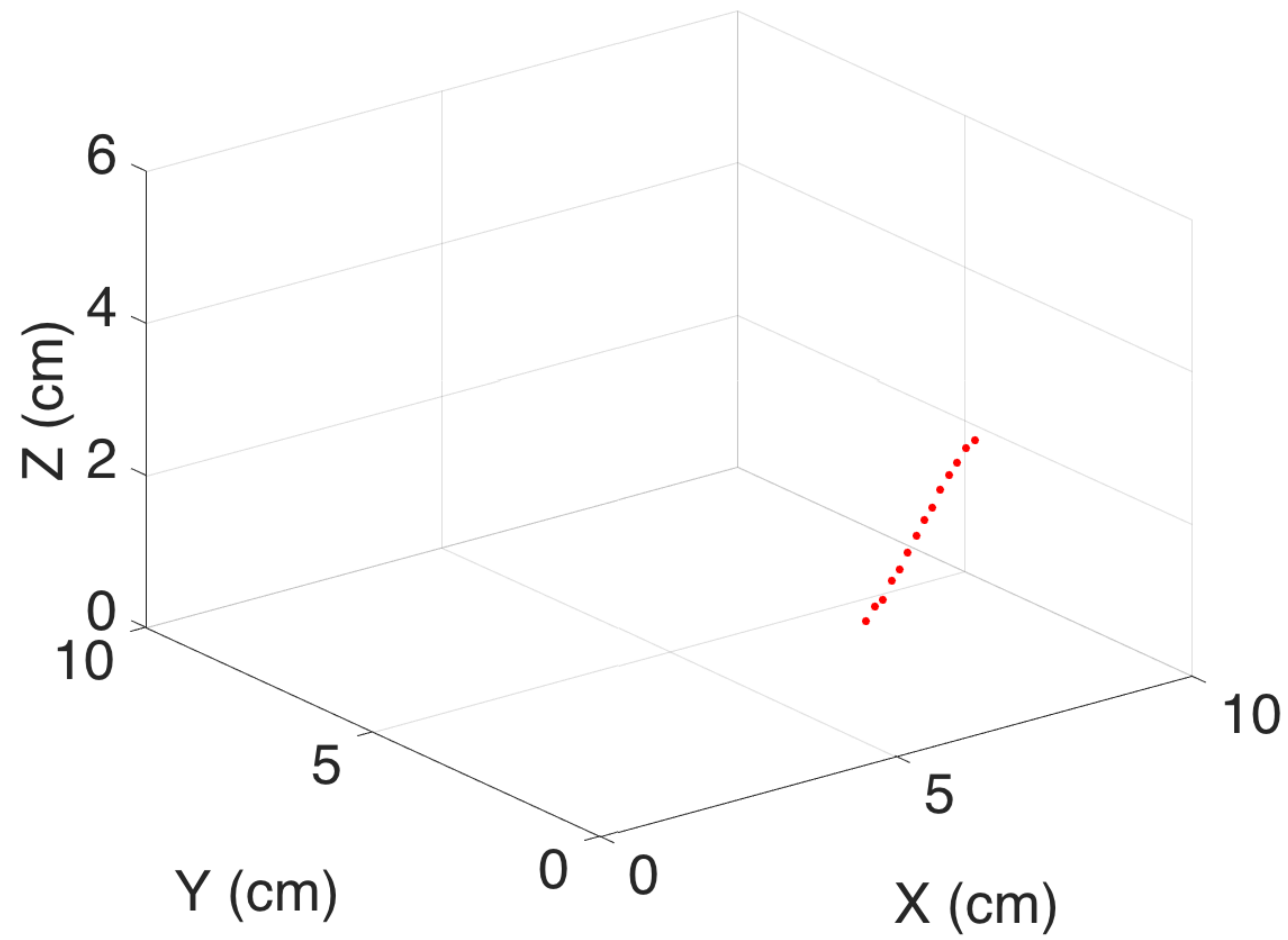
Relative Z depth information



XY projection



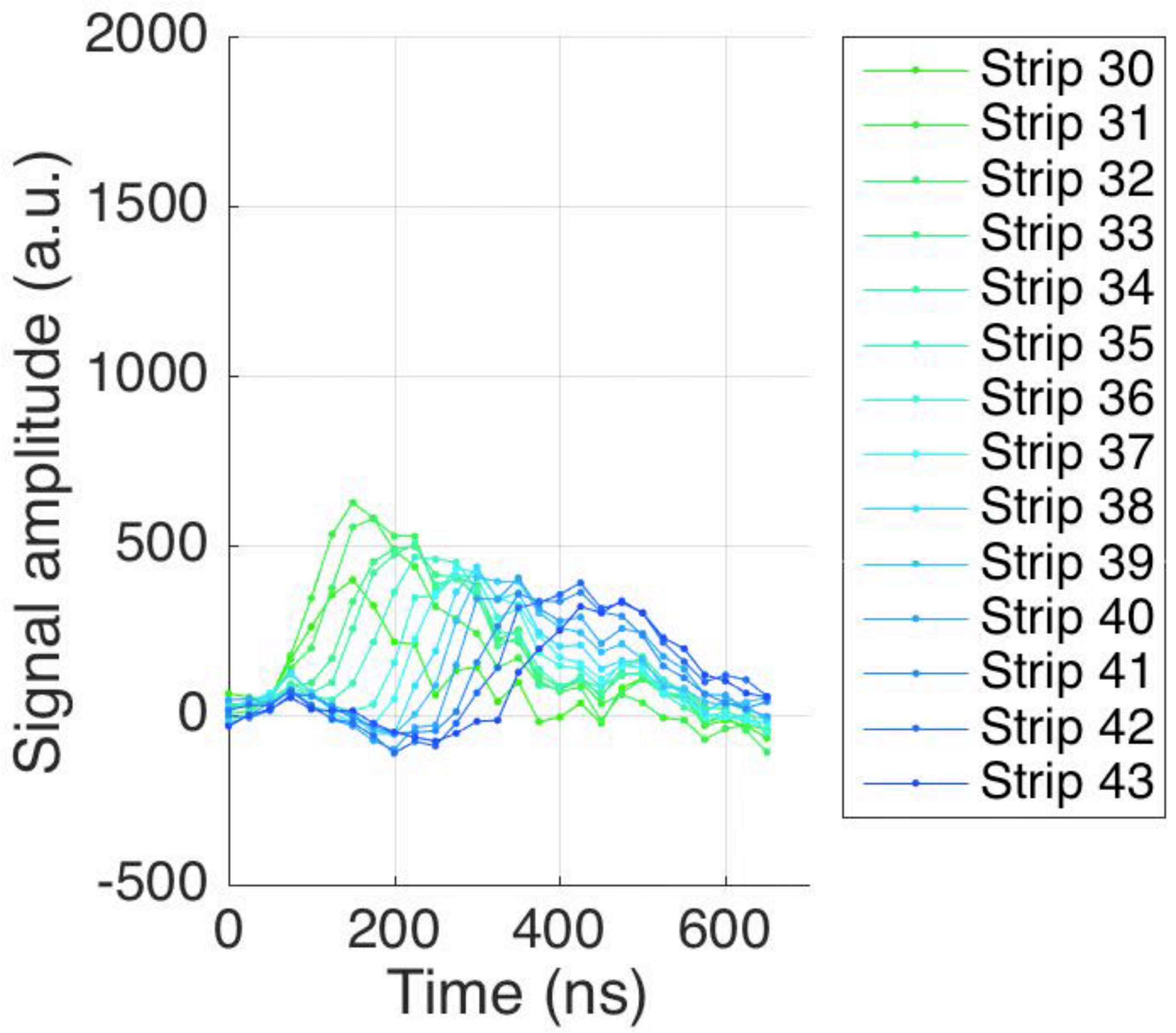
3D reconstruction



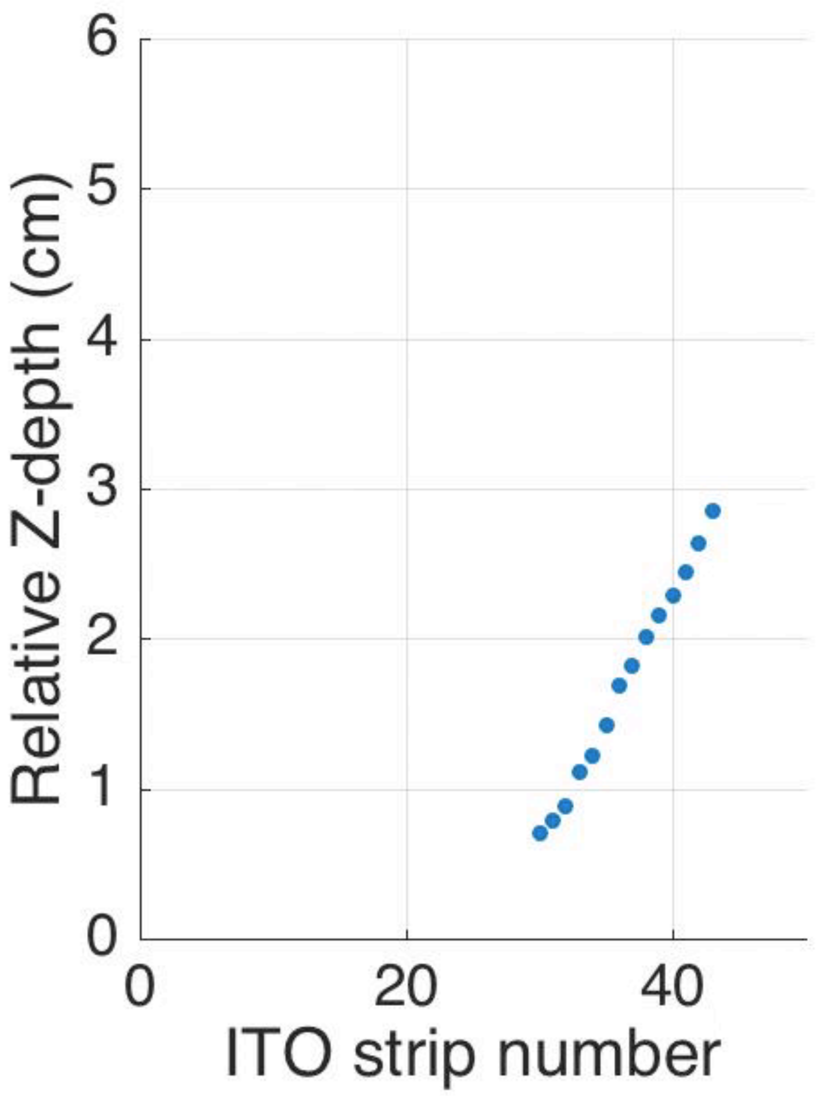
Relative depth information for each hit strip from electronic readout is combined with 2D positions of strip hits from optical readout to 3D track points

Reconstructed alpha tracks

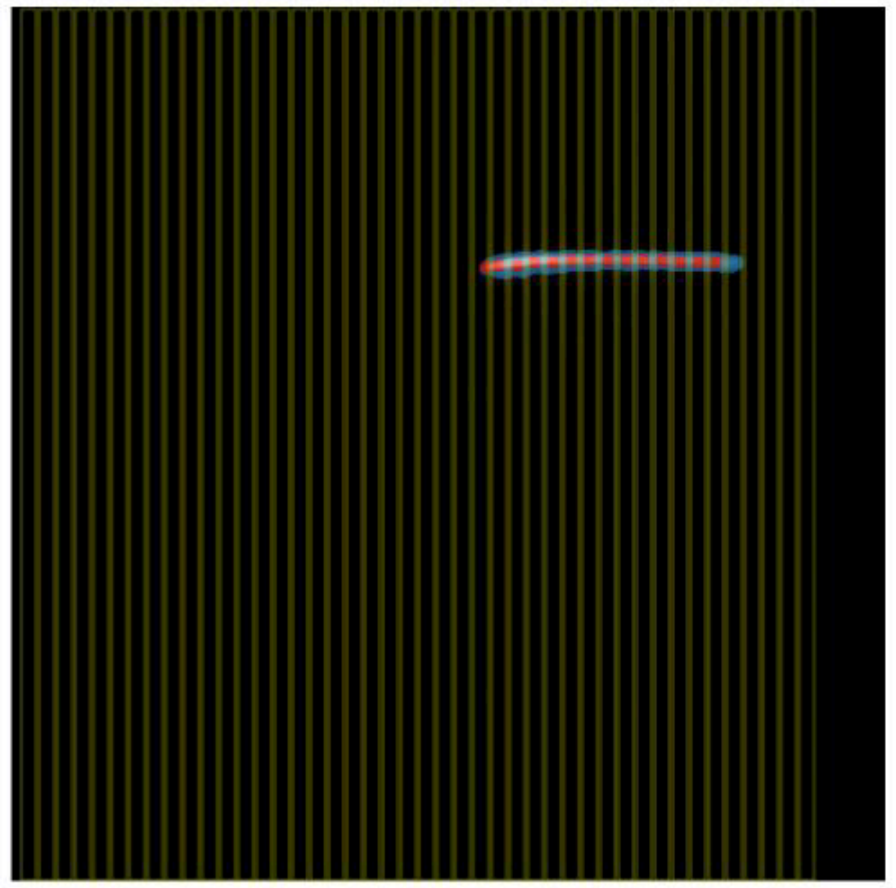
ITO strip signals



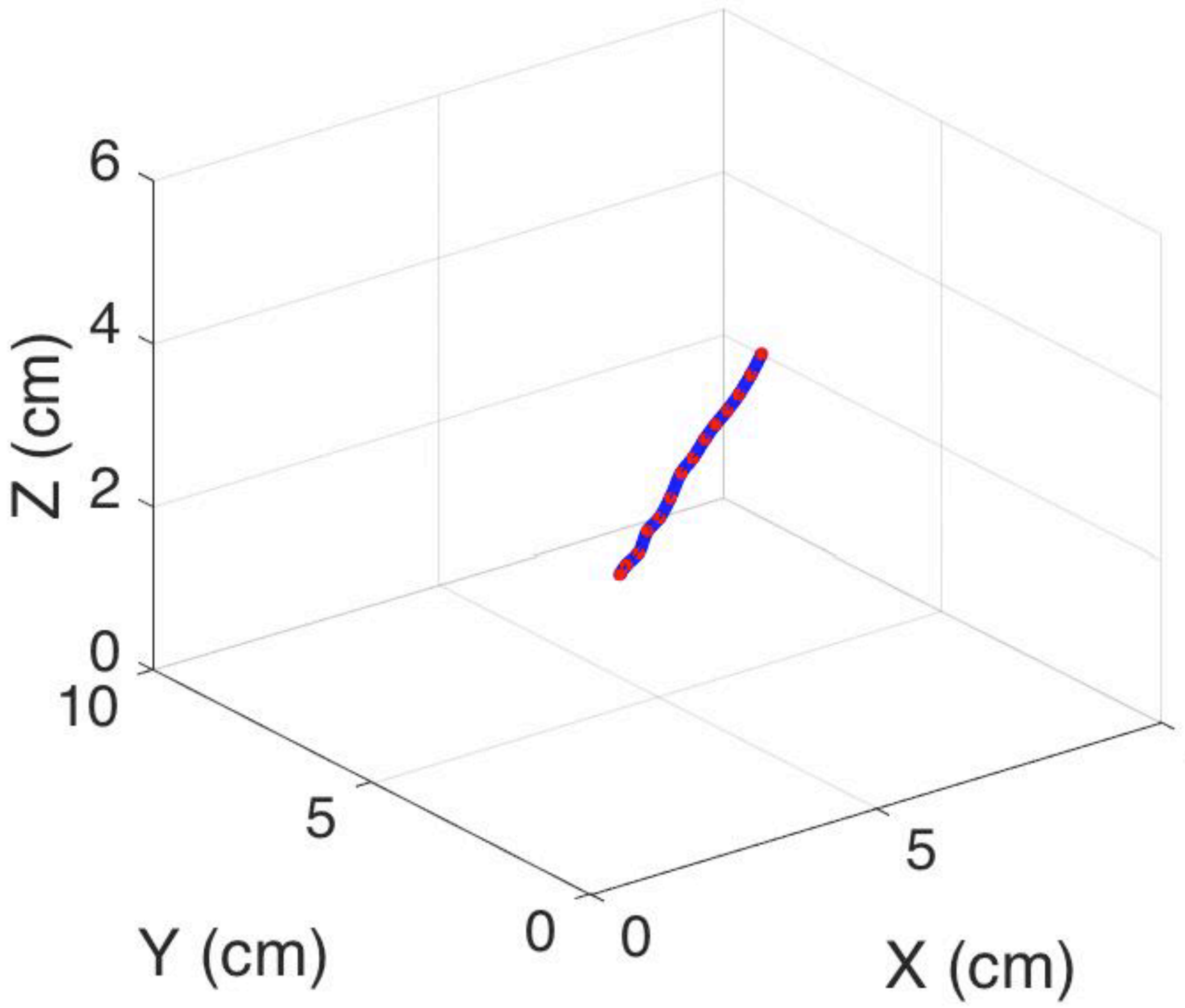
Depth information



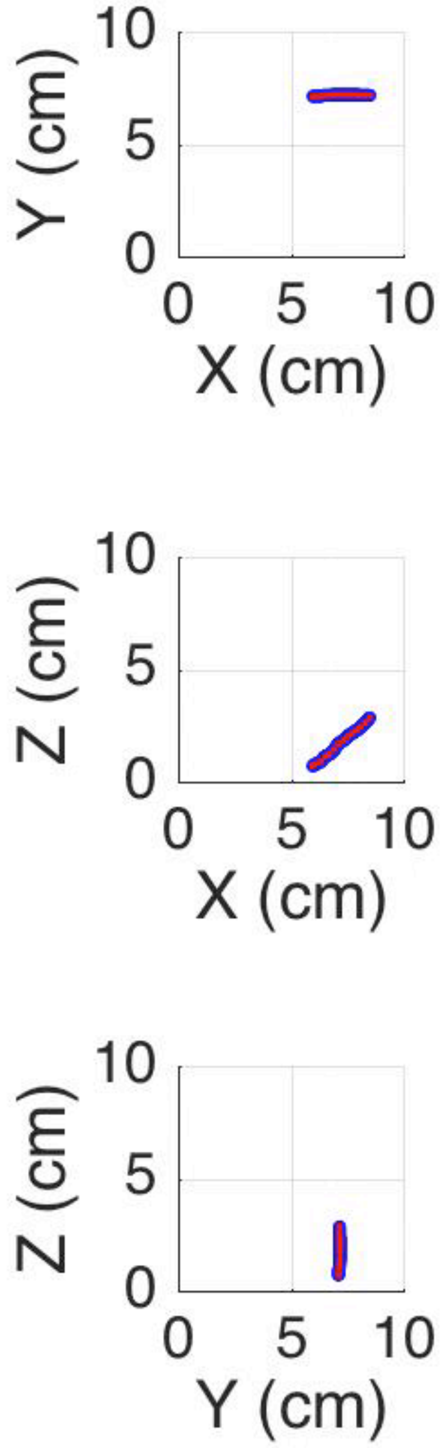
Camera image



3D track visualisation



Projections



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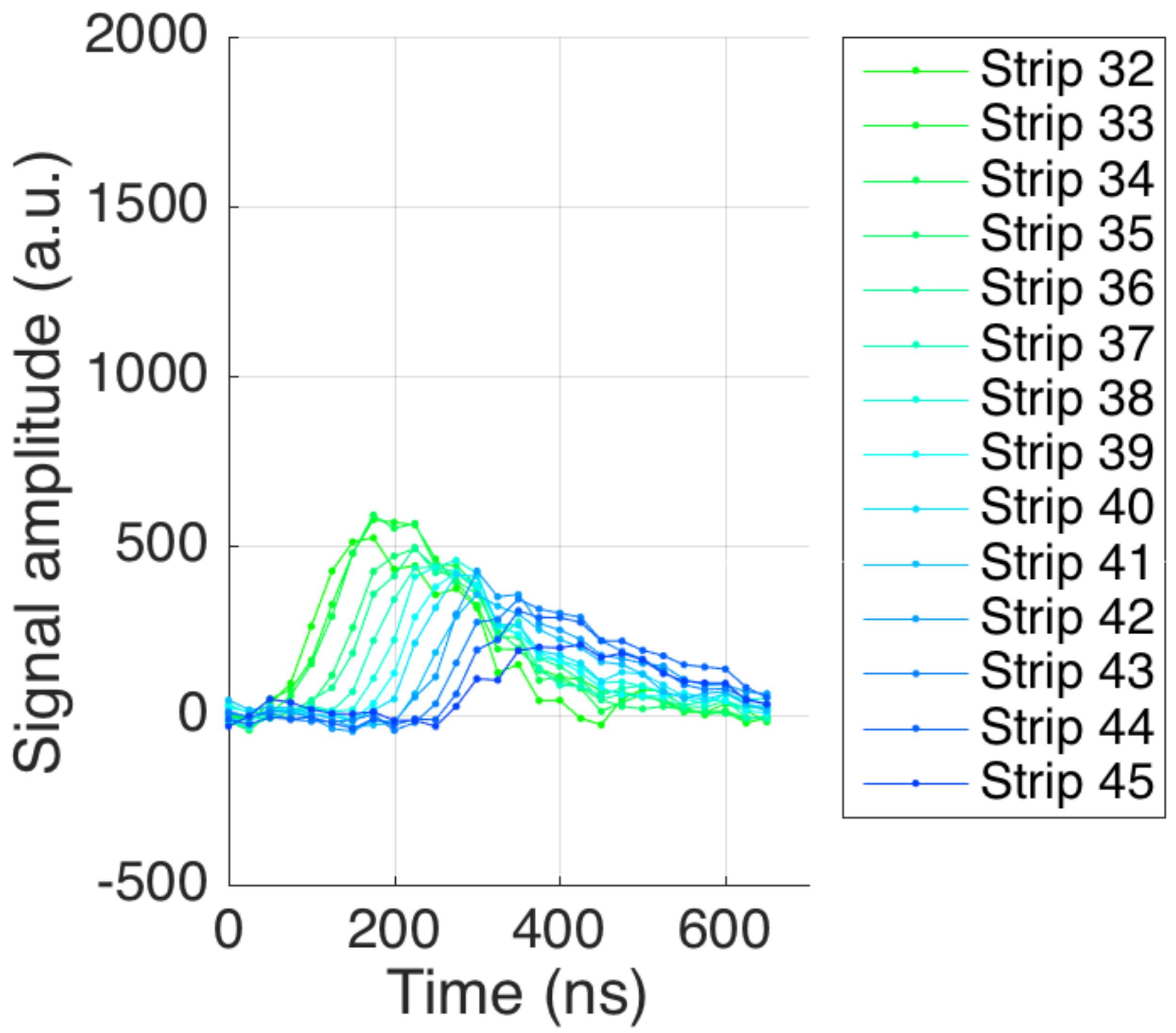

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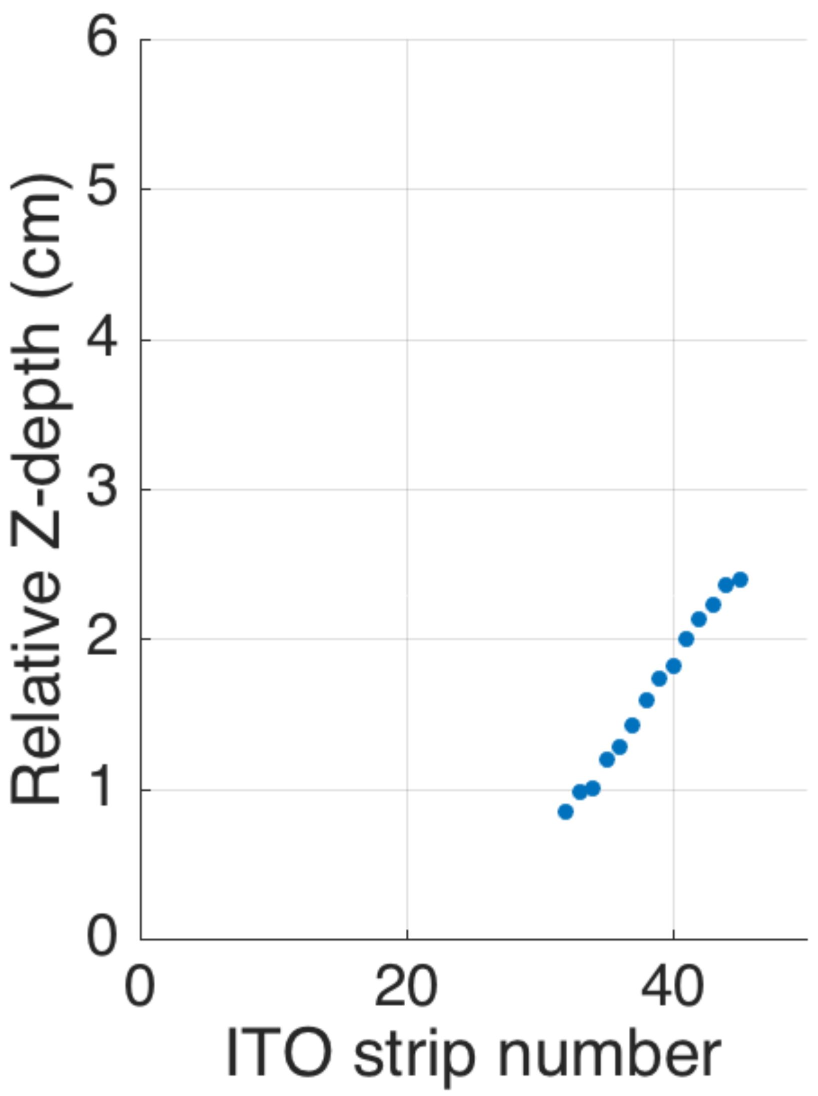

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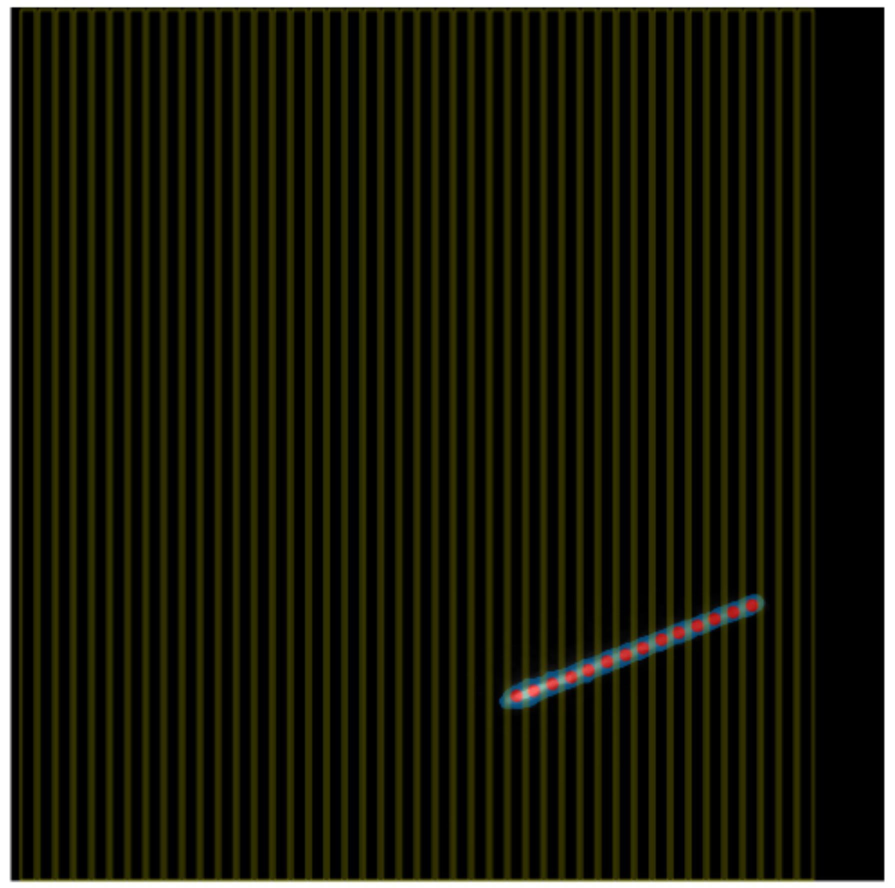

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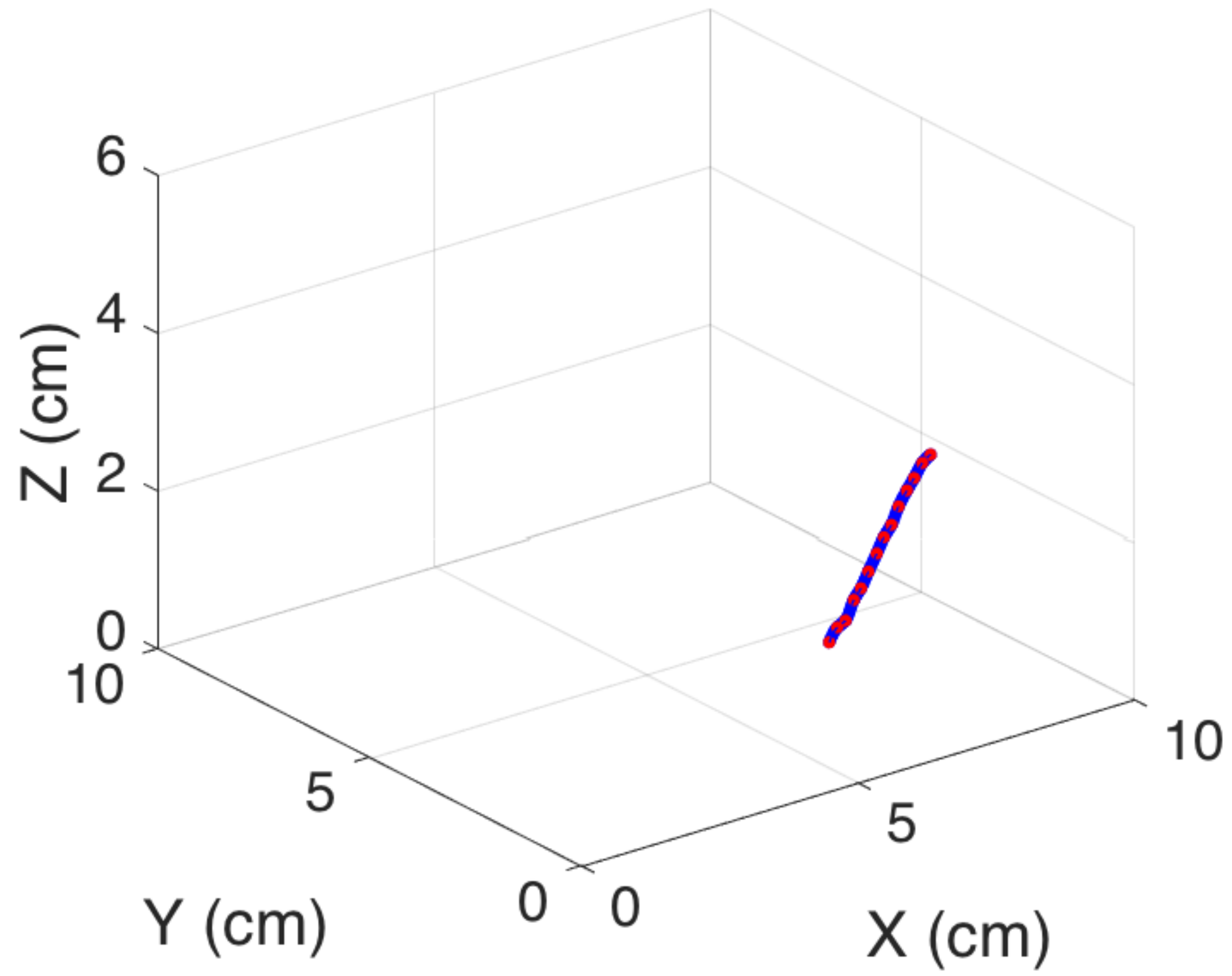

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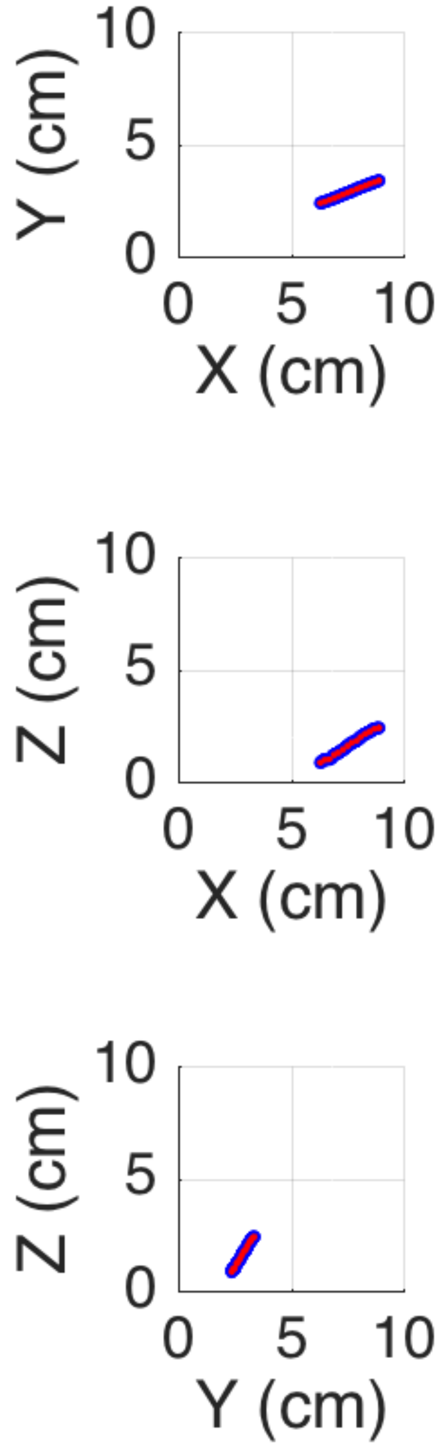
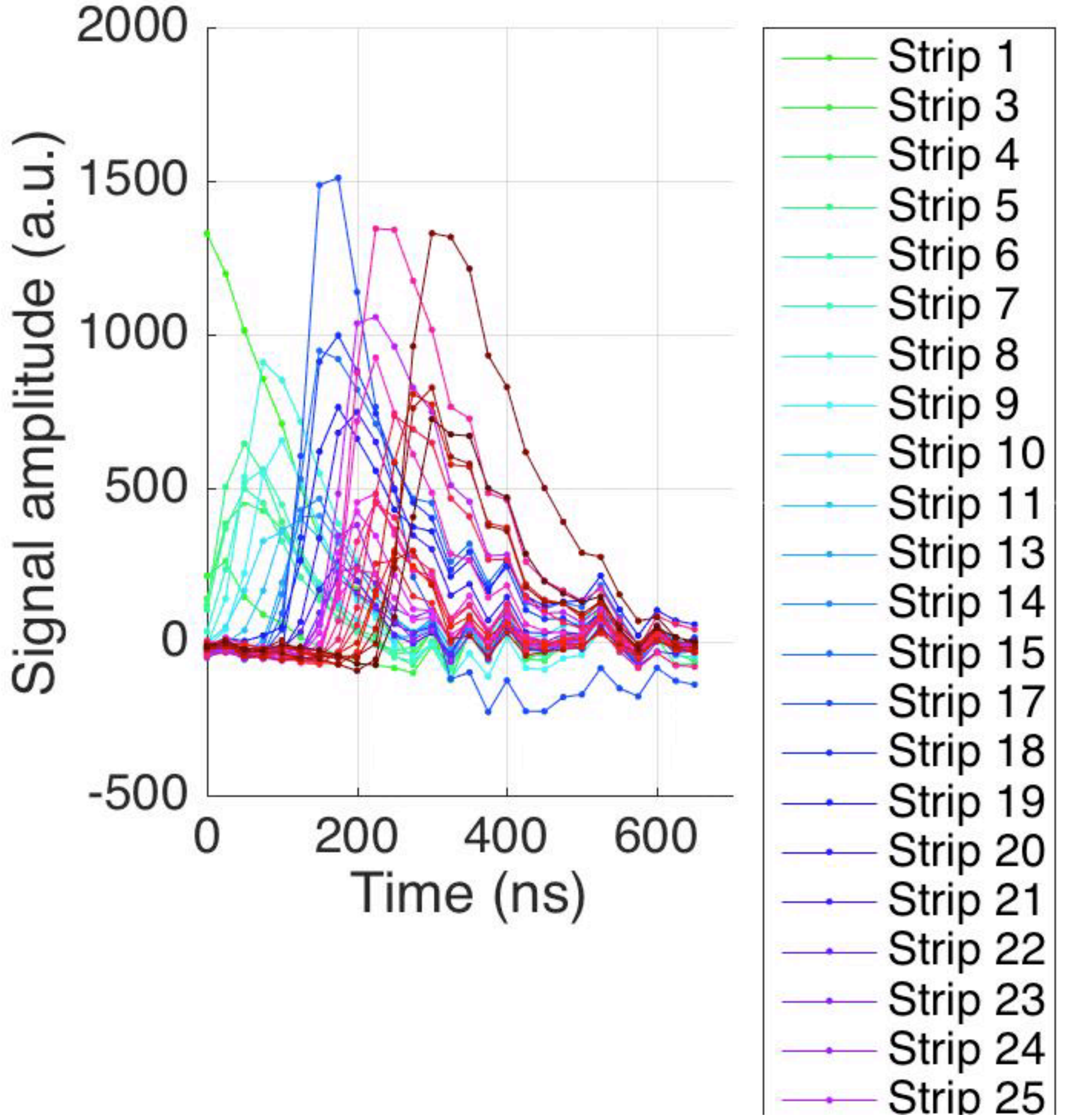
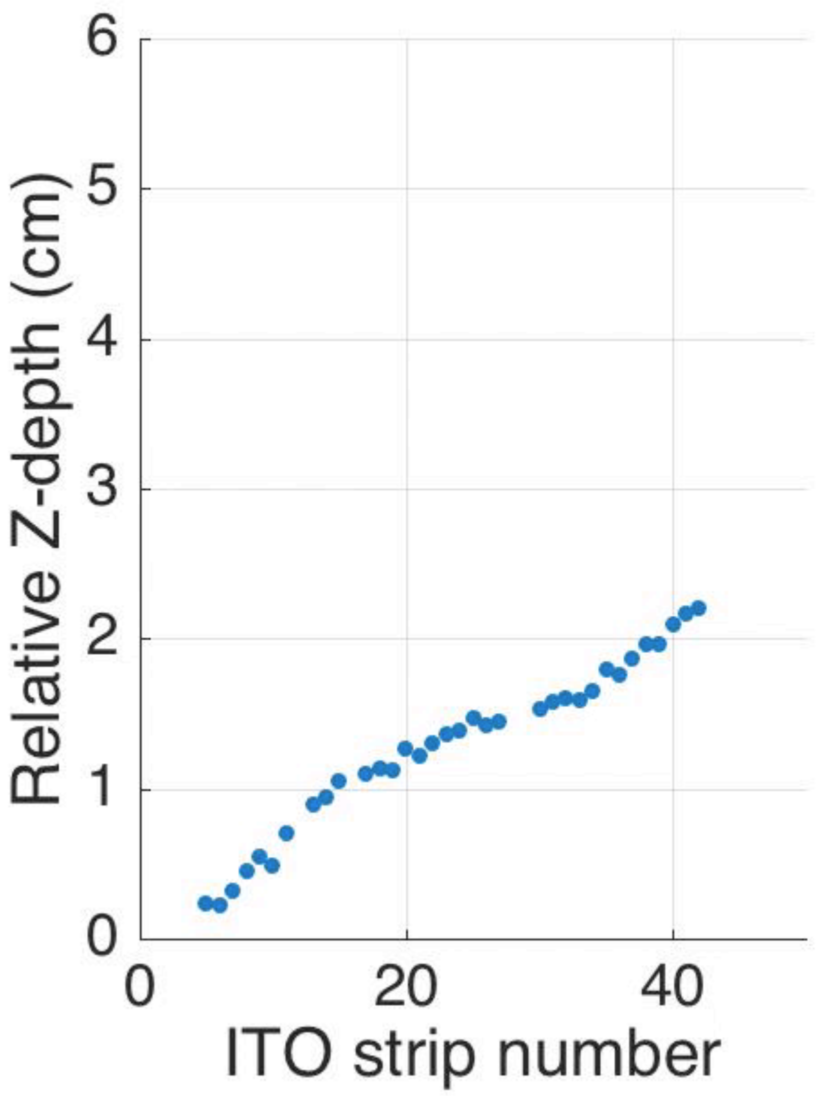


Reconstructed cosmic events

ITO strip signals



Depth information



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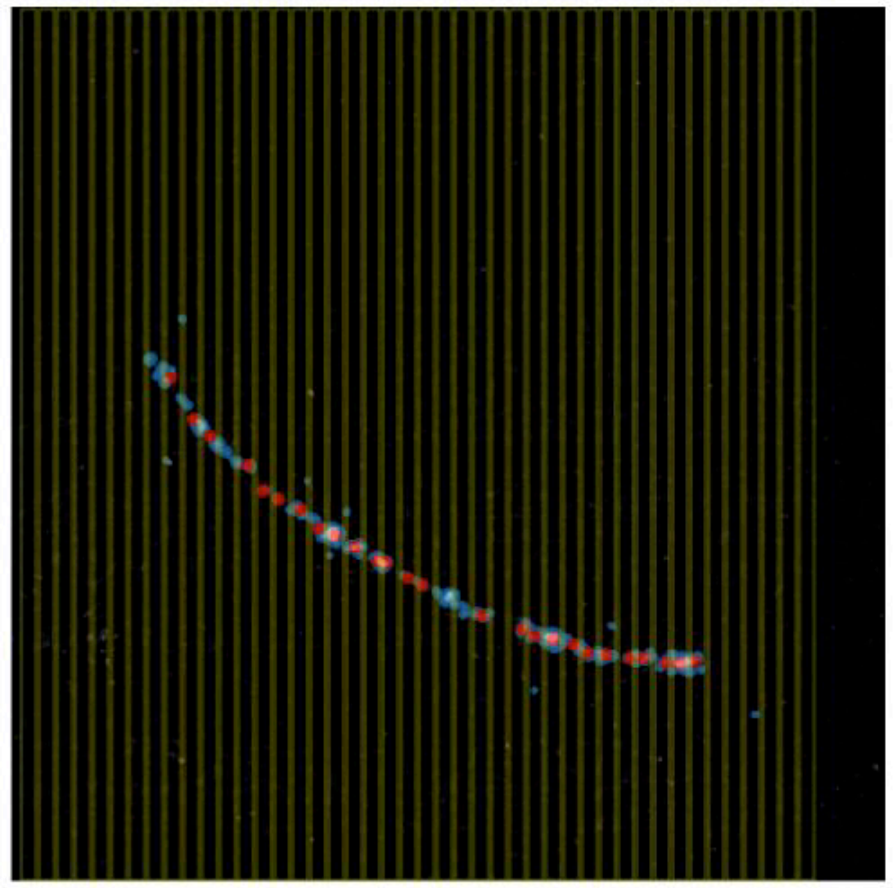

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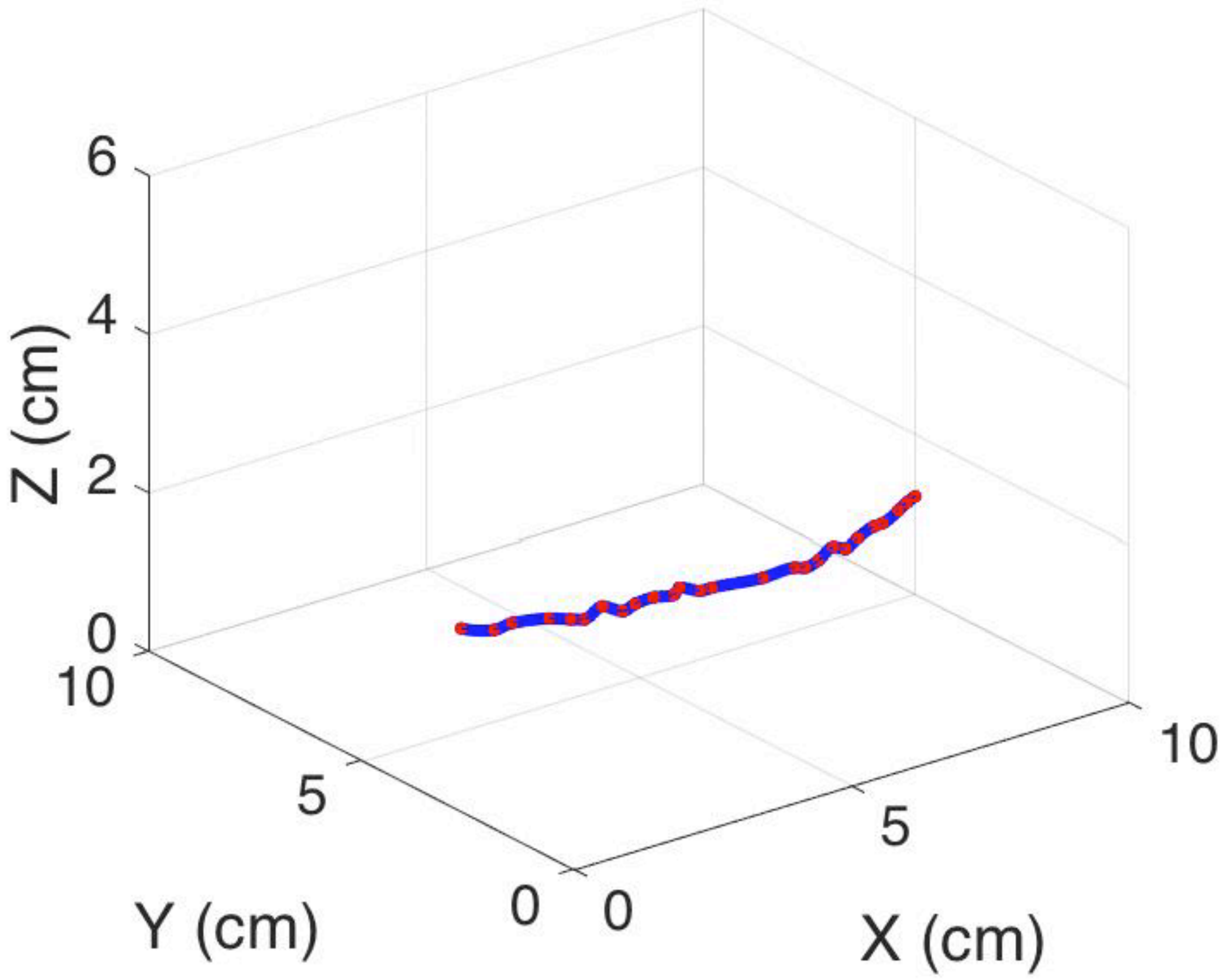

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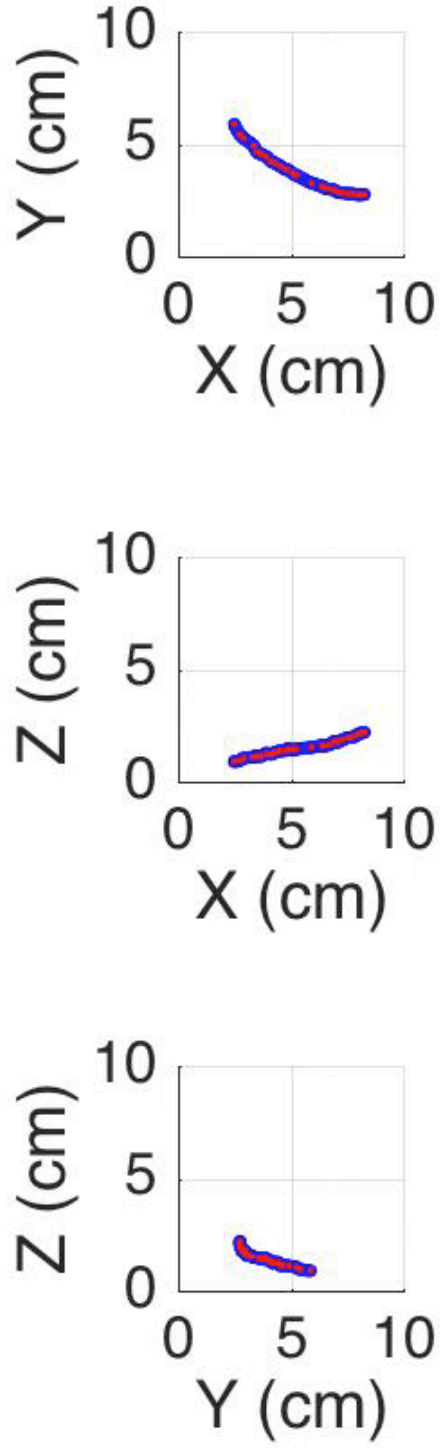

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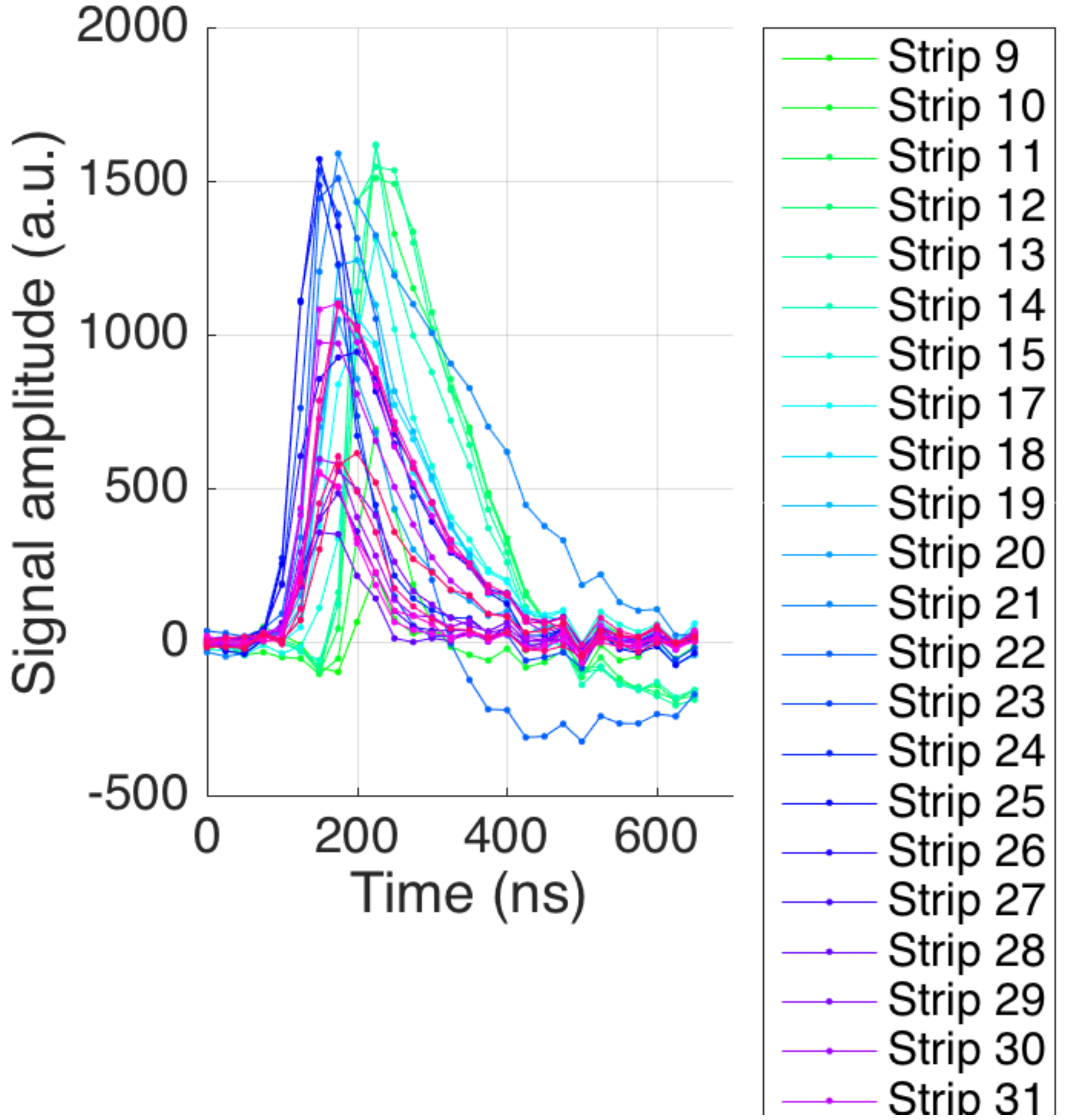

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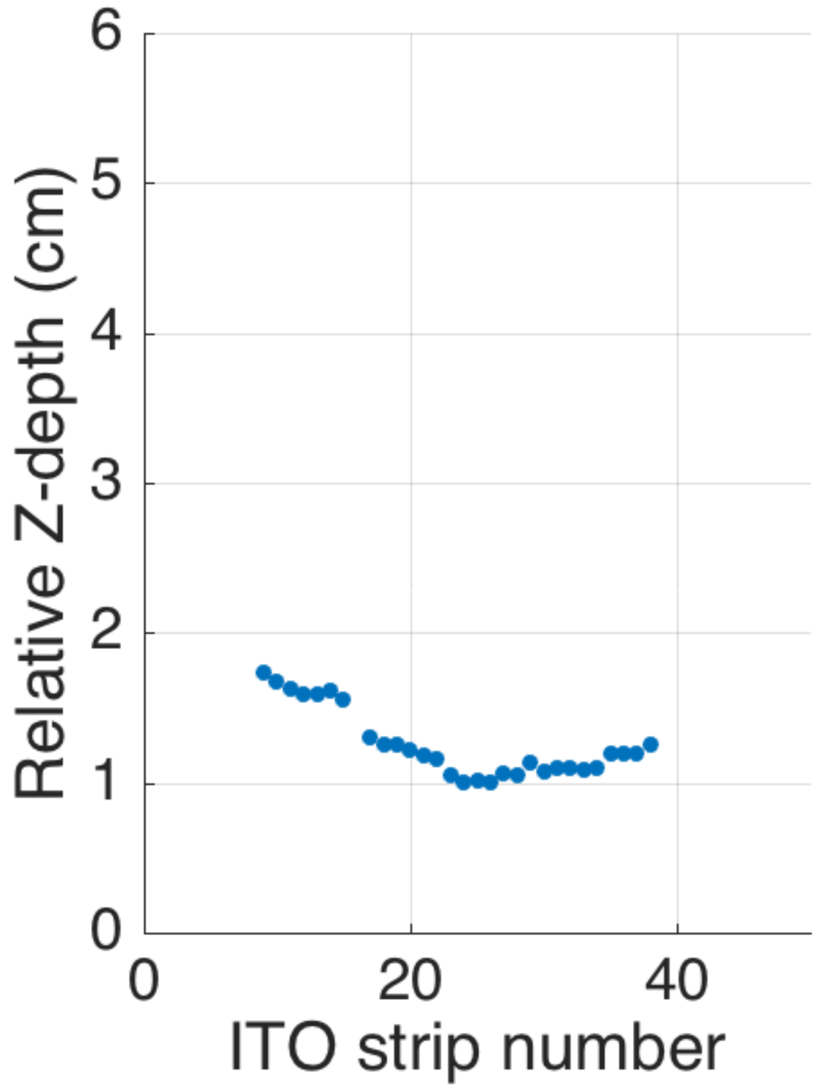

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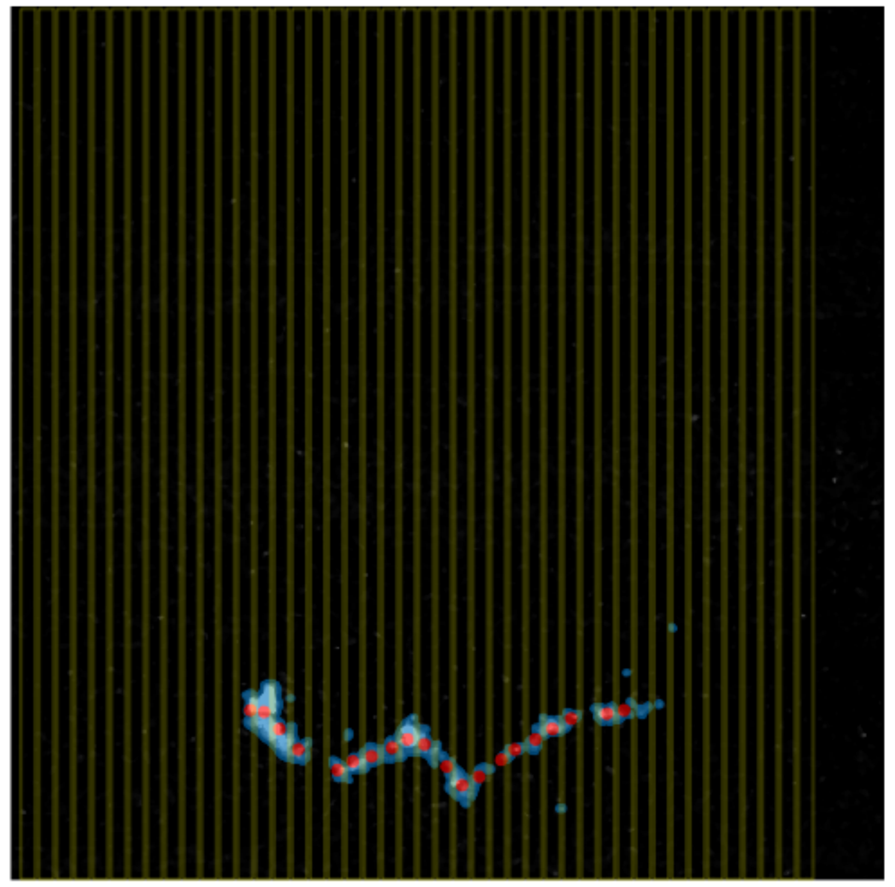

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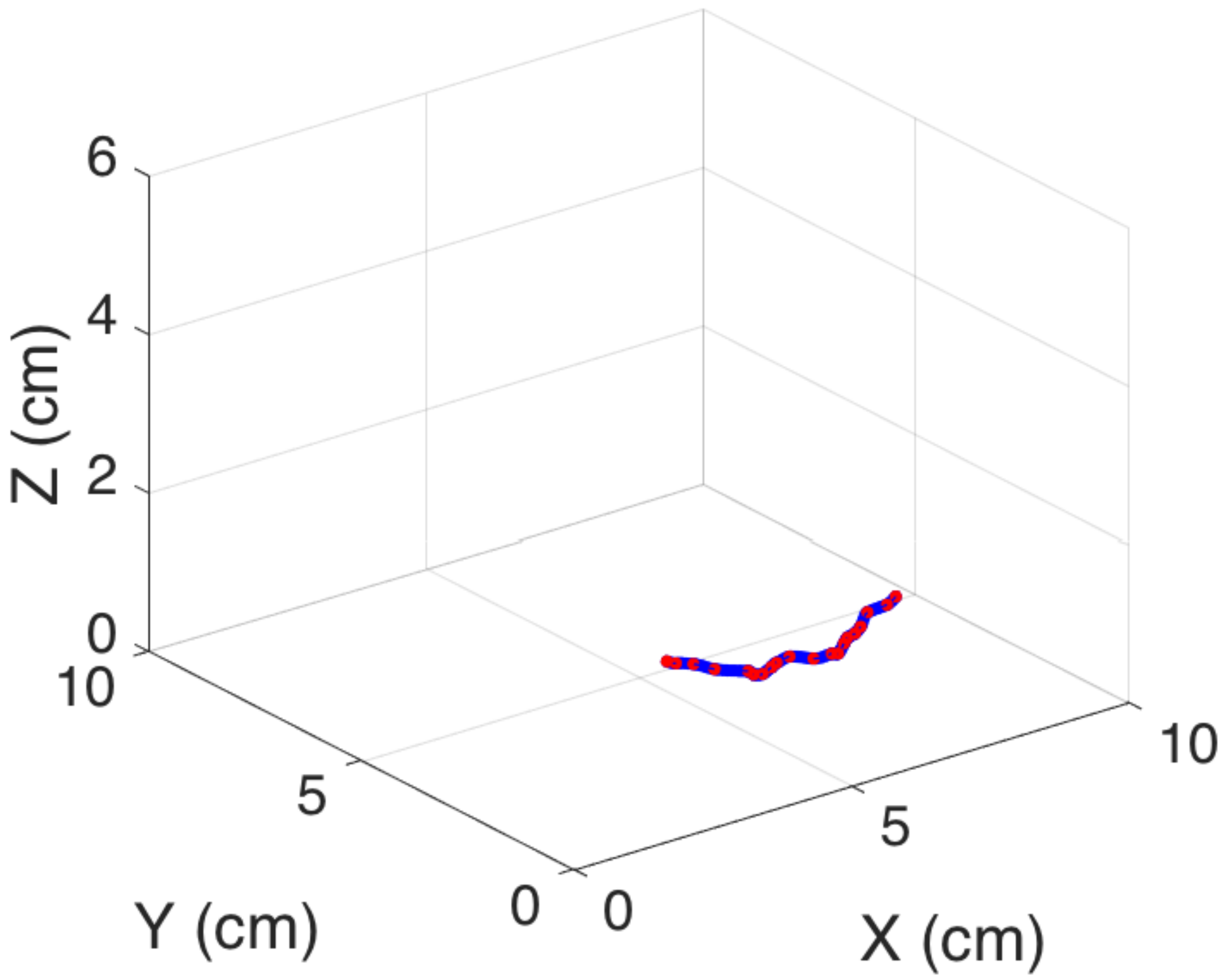

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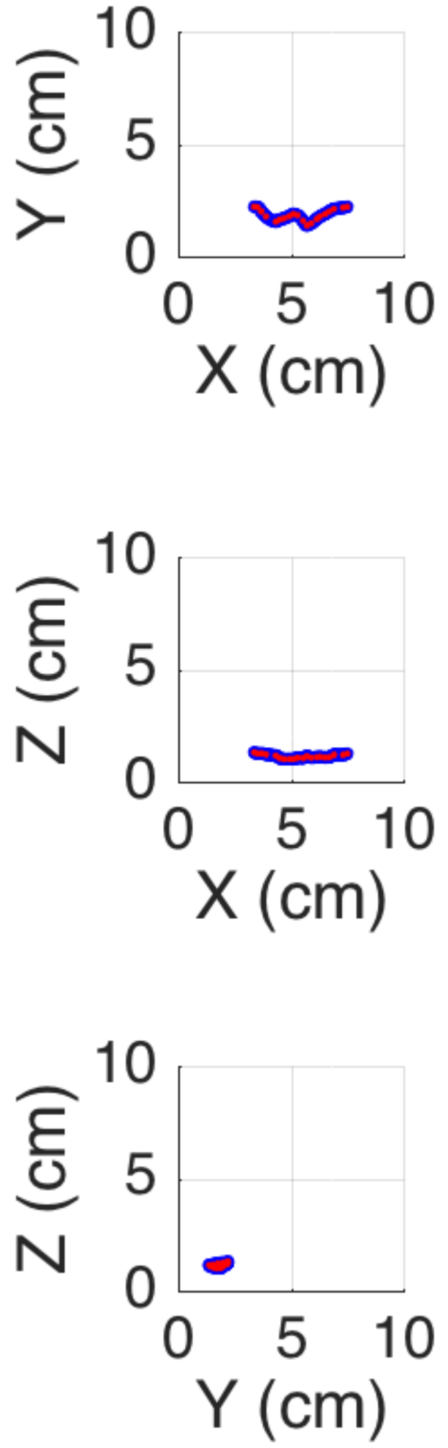

Optical TPC readout with

ultra-fast CMOS cameras

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

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

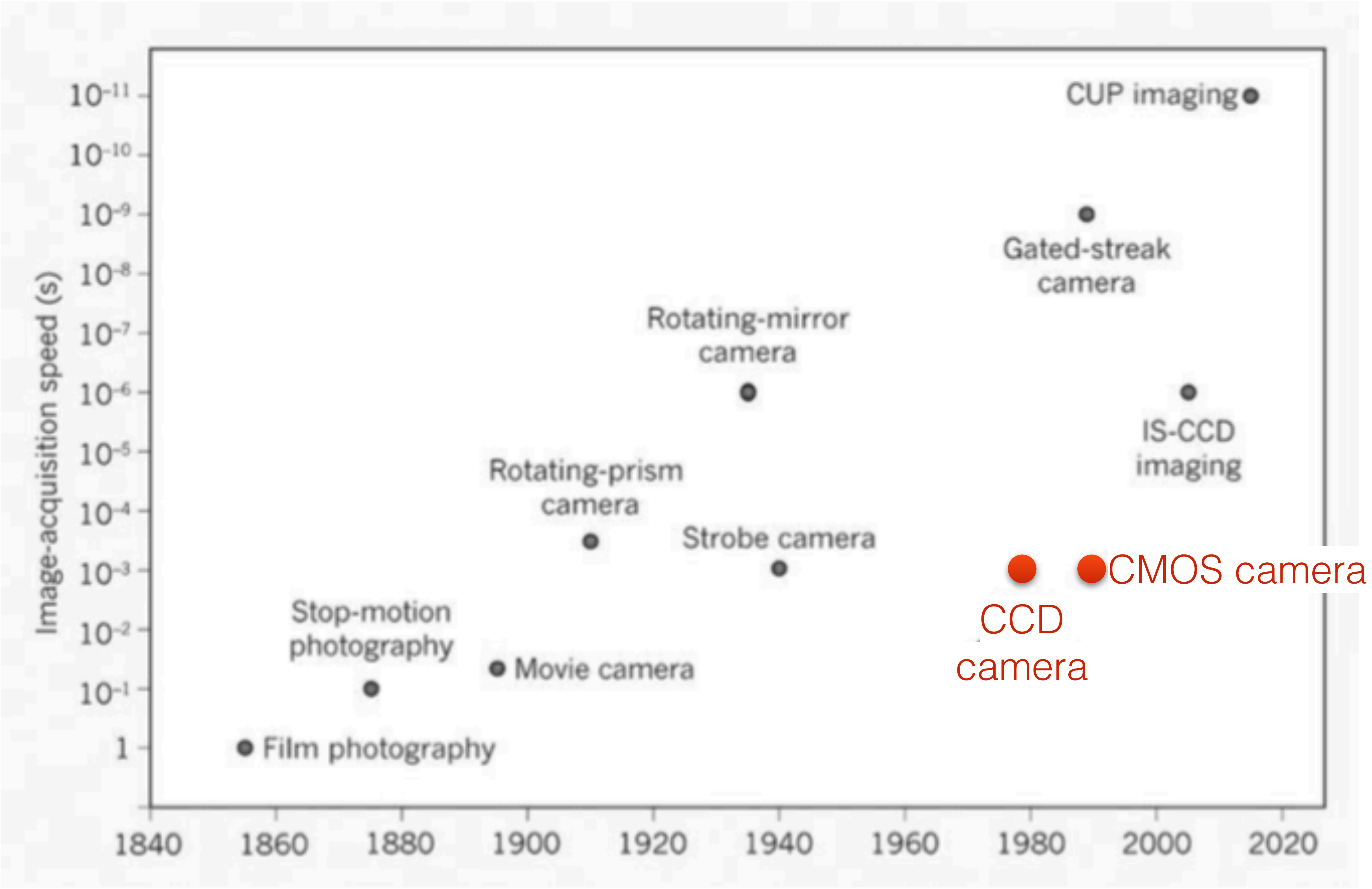

Image adapted from: B. Pogue, Nature 516 (2014) 46–47

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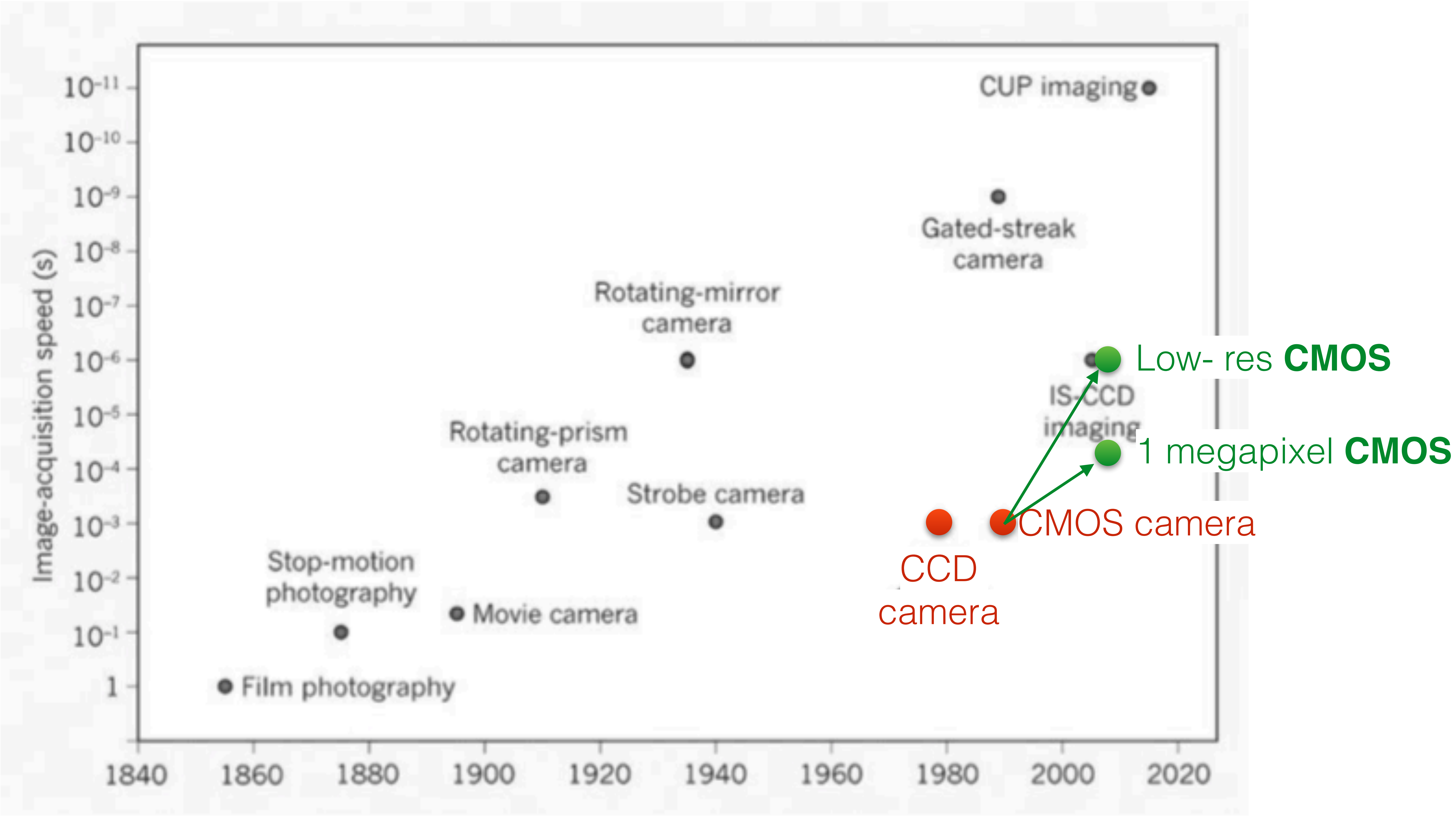

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Ultra-fast CMOS cameras

QImaging Retiga R6

- 6 MP **CCD**
- 7 Hz frame rate (6 MP)
- tens of Hz (lower resolution)
- 5.7 e- read noise

Hamamatsu ImagEM X2-1K EMCCD camera

- 1 megapixel **EMCCD** sensor
- 1200x EM gain
- 18.5 fps at 1024x1024
- 288 fps at 4x4 16px wide
- <1 e- readout noise

Ultra-fast CMOS cameras →

Photron FASTCAM SA-Z

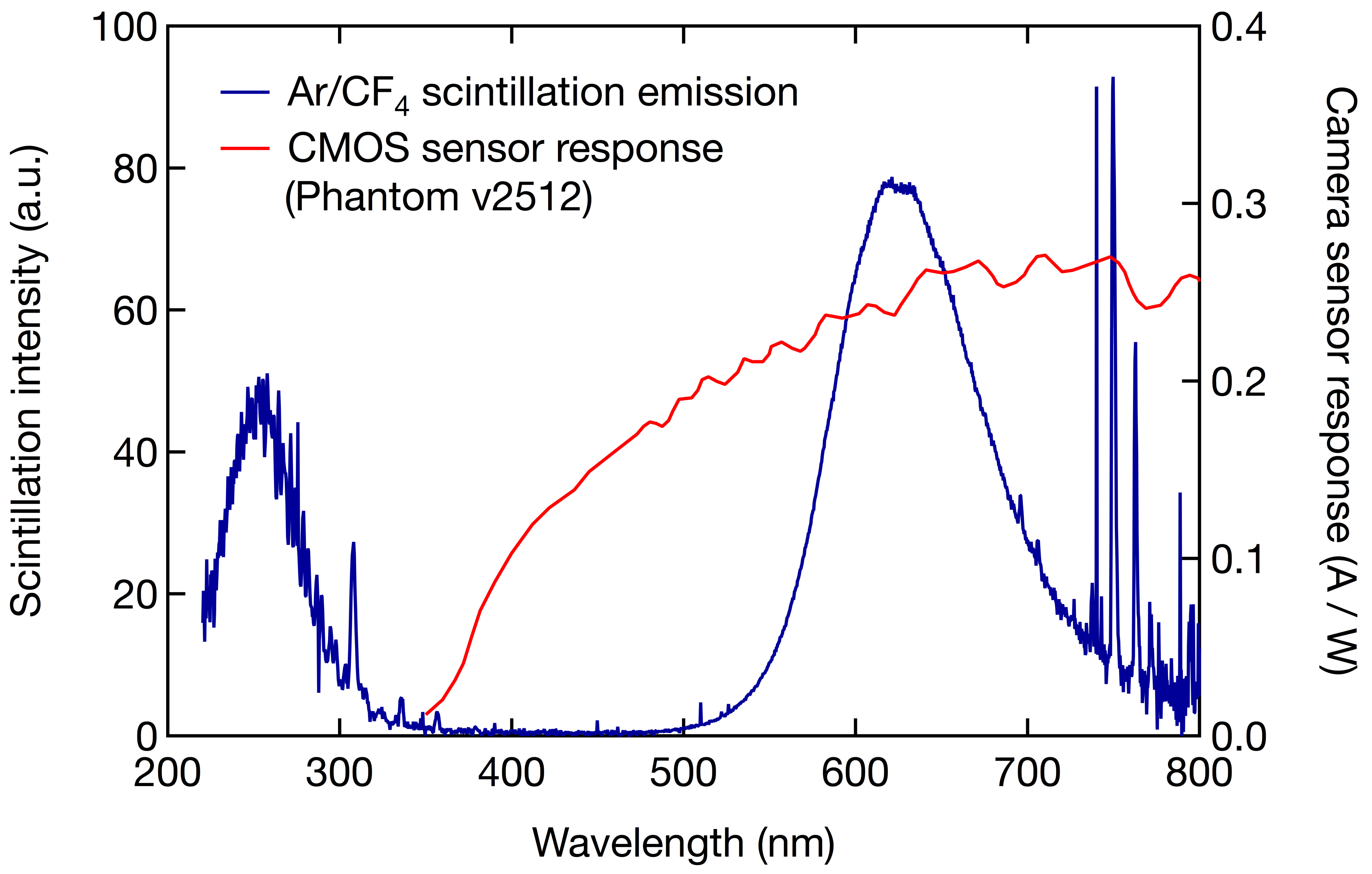
- 1 megapixel **CMOS** sensor
- 12 bit depth
- **20 kfps** at 1024x1024
- **2.1 Mfps** at 128x8
- ISO 50,000 sensitivity

Phantom v2512

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

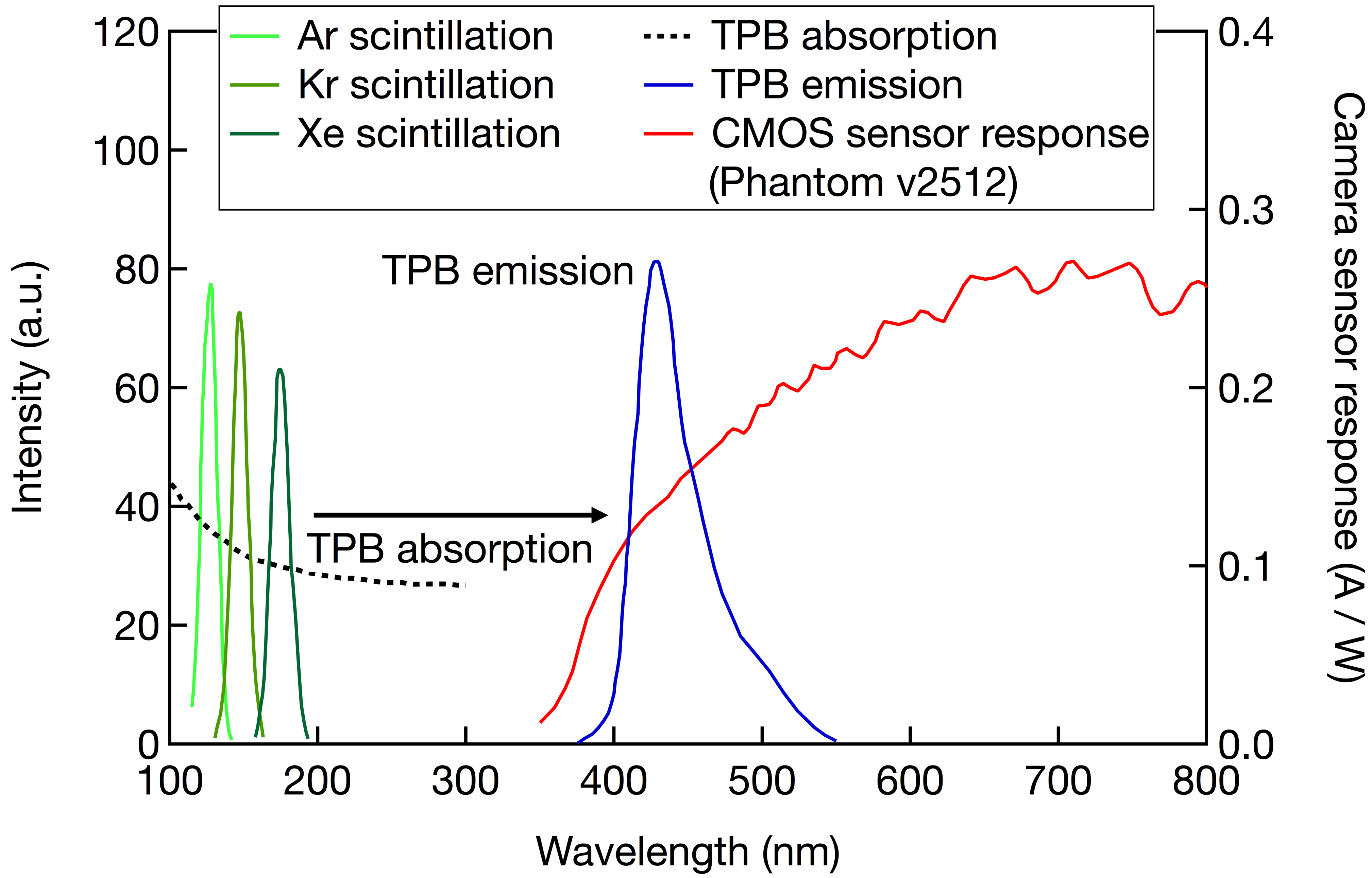
Optical readout scintillation spectra

Using CF_4-based gas mixtures



Ar/CF_4 gas mixtures feature ample visible scintillation light emission with a peak around **630 nm**

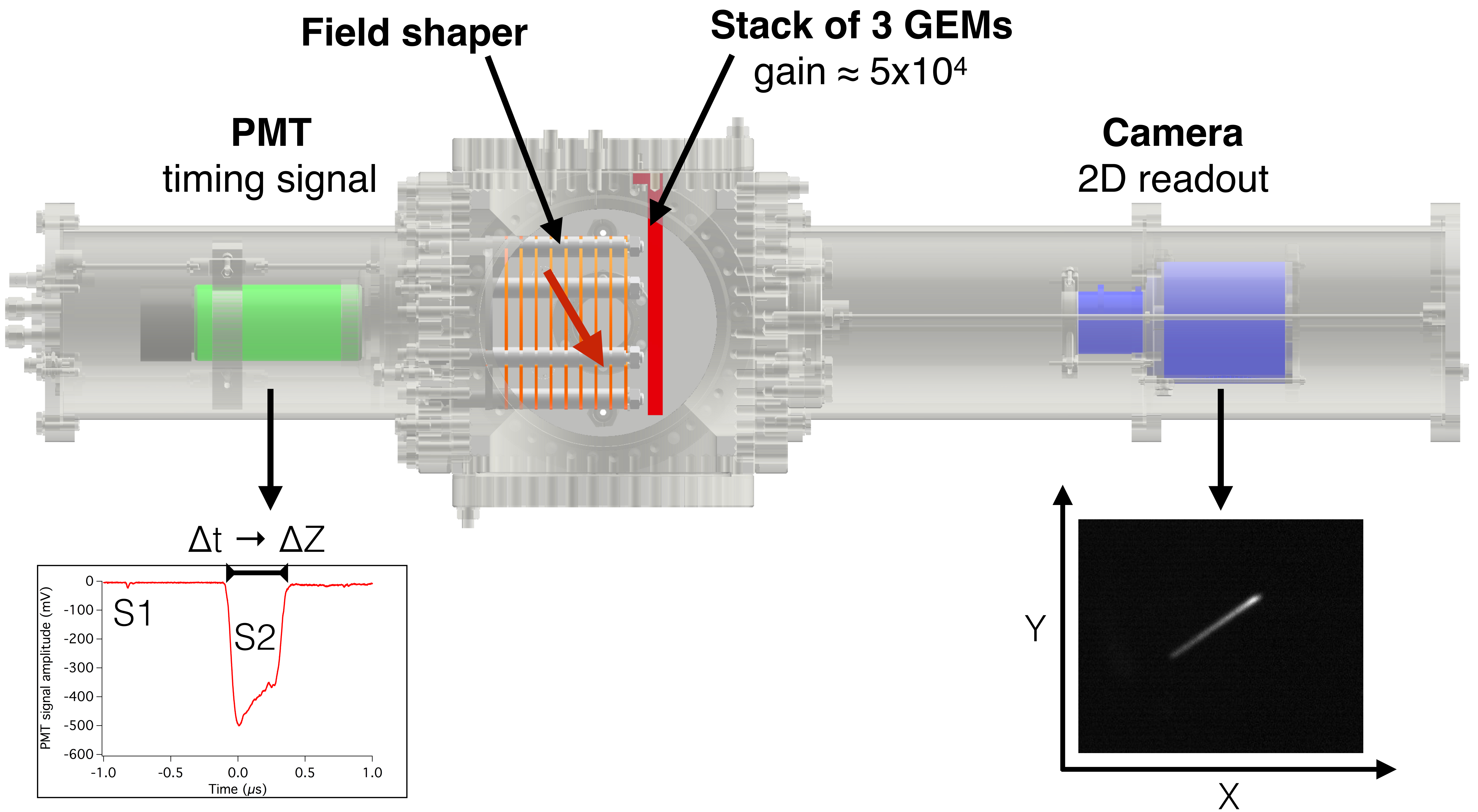
Using wavelength shifters



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

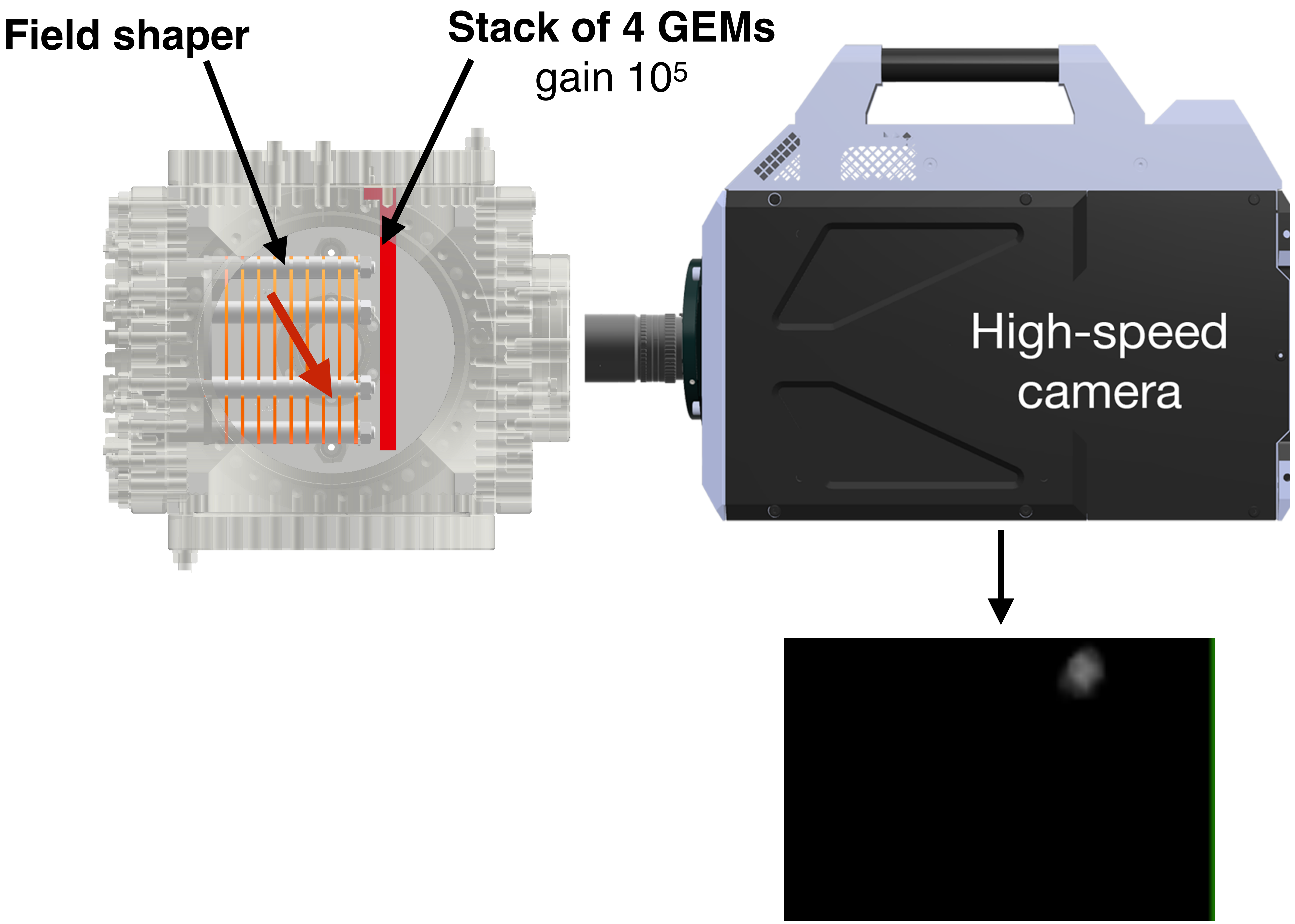
Wavelength shifters such as tetraphenyl butadiene (**TPB**) can be used to shift scintillation light spectrum to visible range with peak around **425 nm**

Optically read out TPC CCD + PMT



Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



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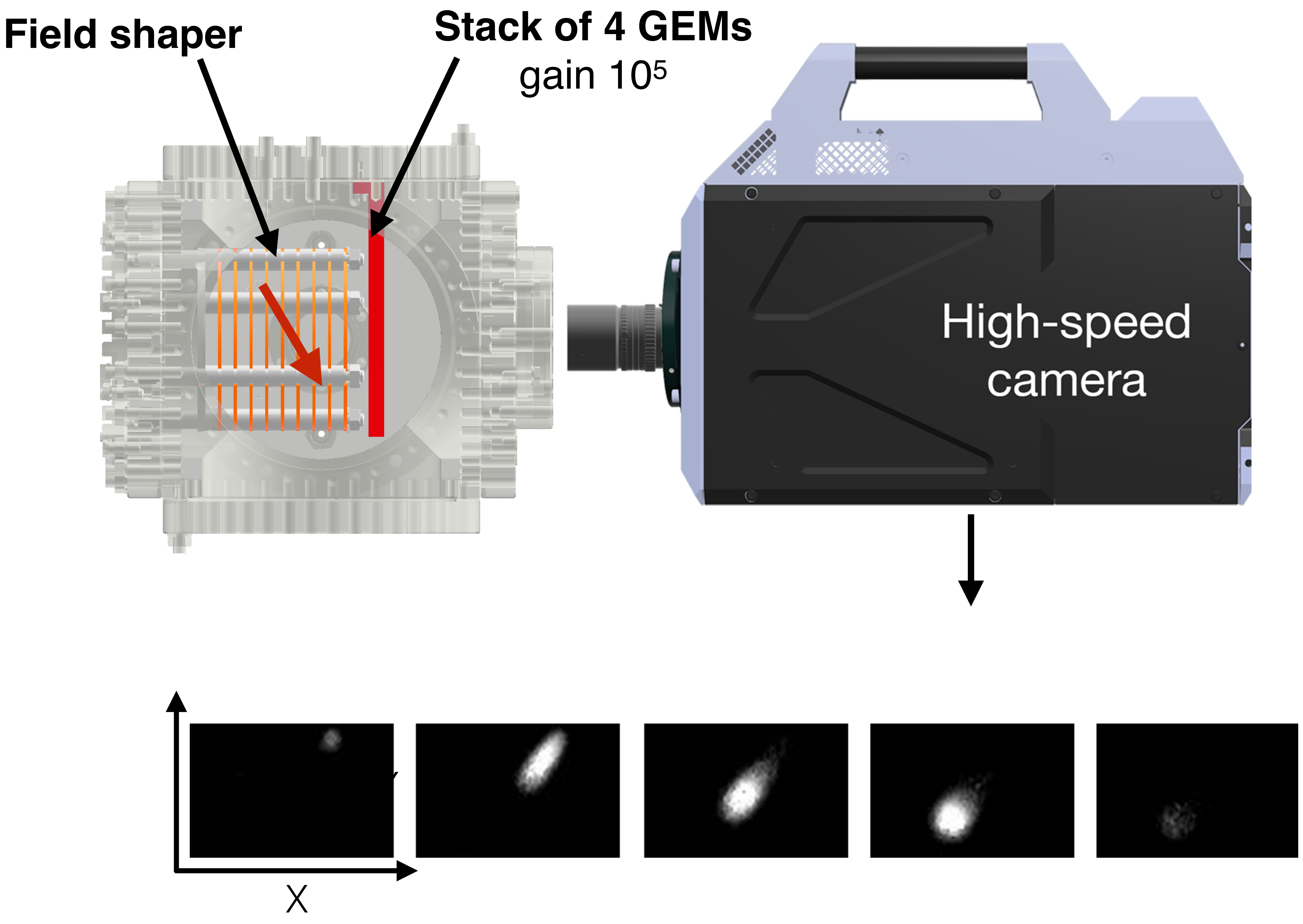

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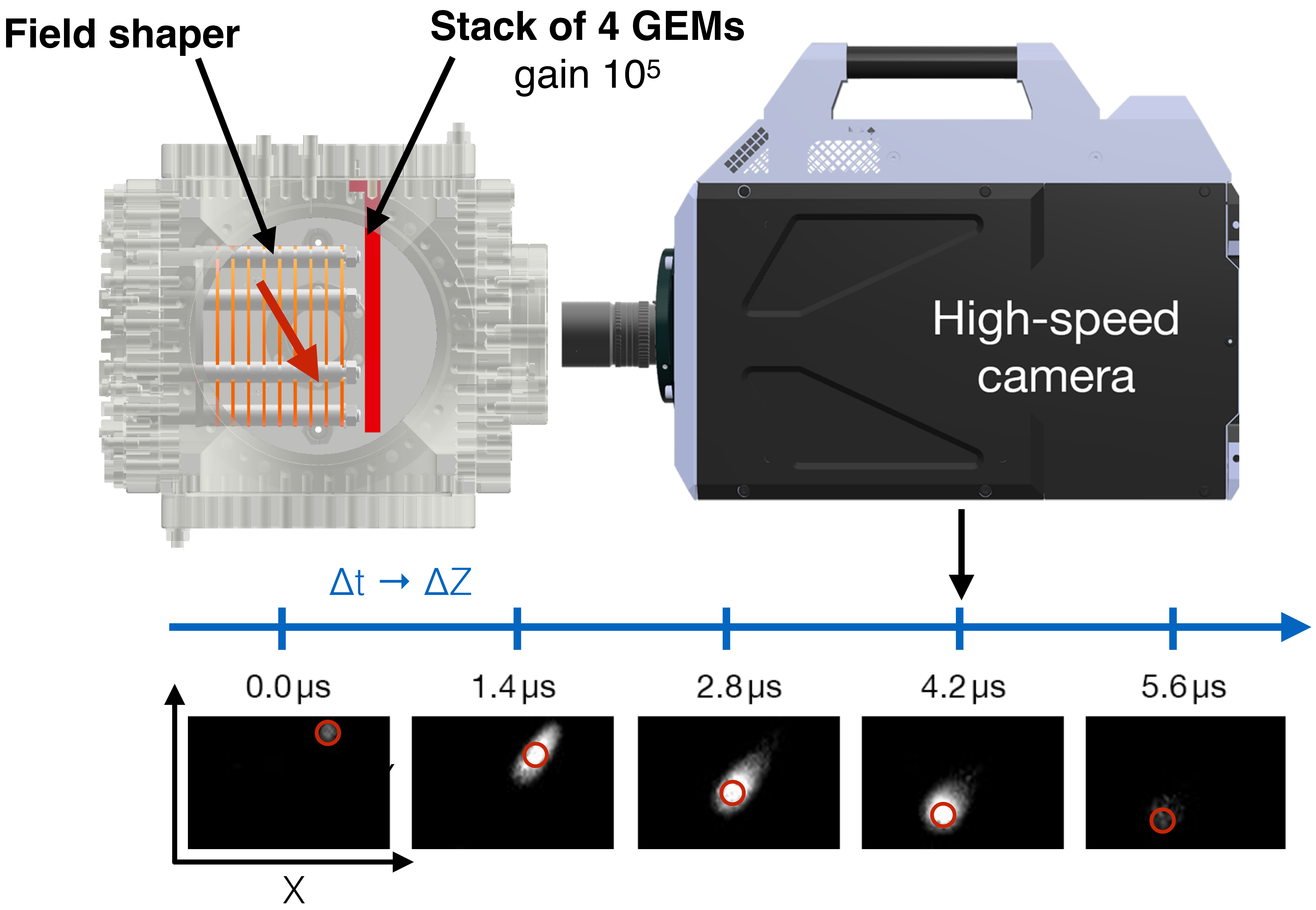
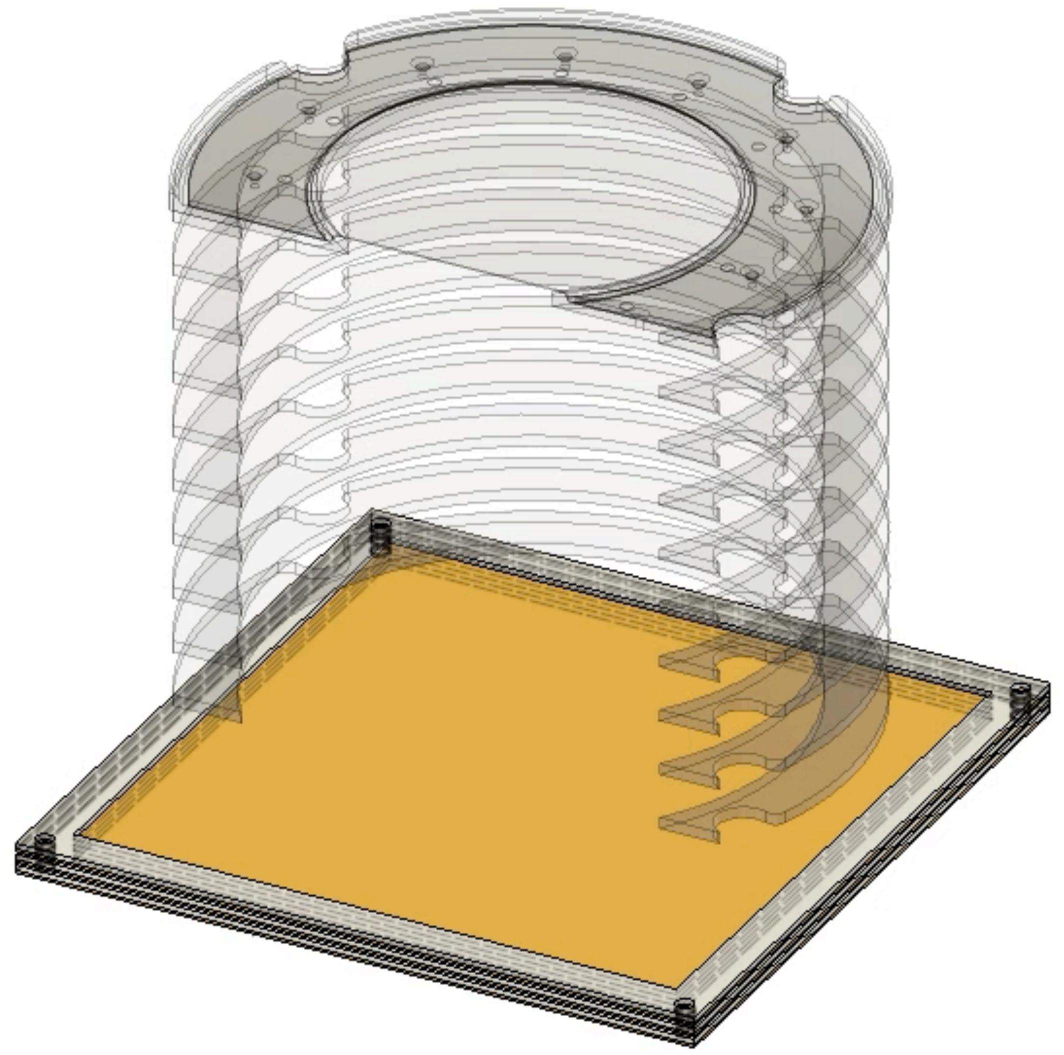
Optically read out TPC Ultra-fast CMOS



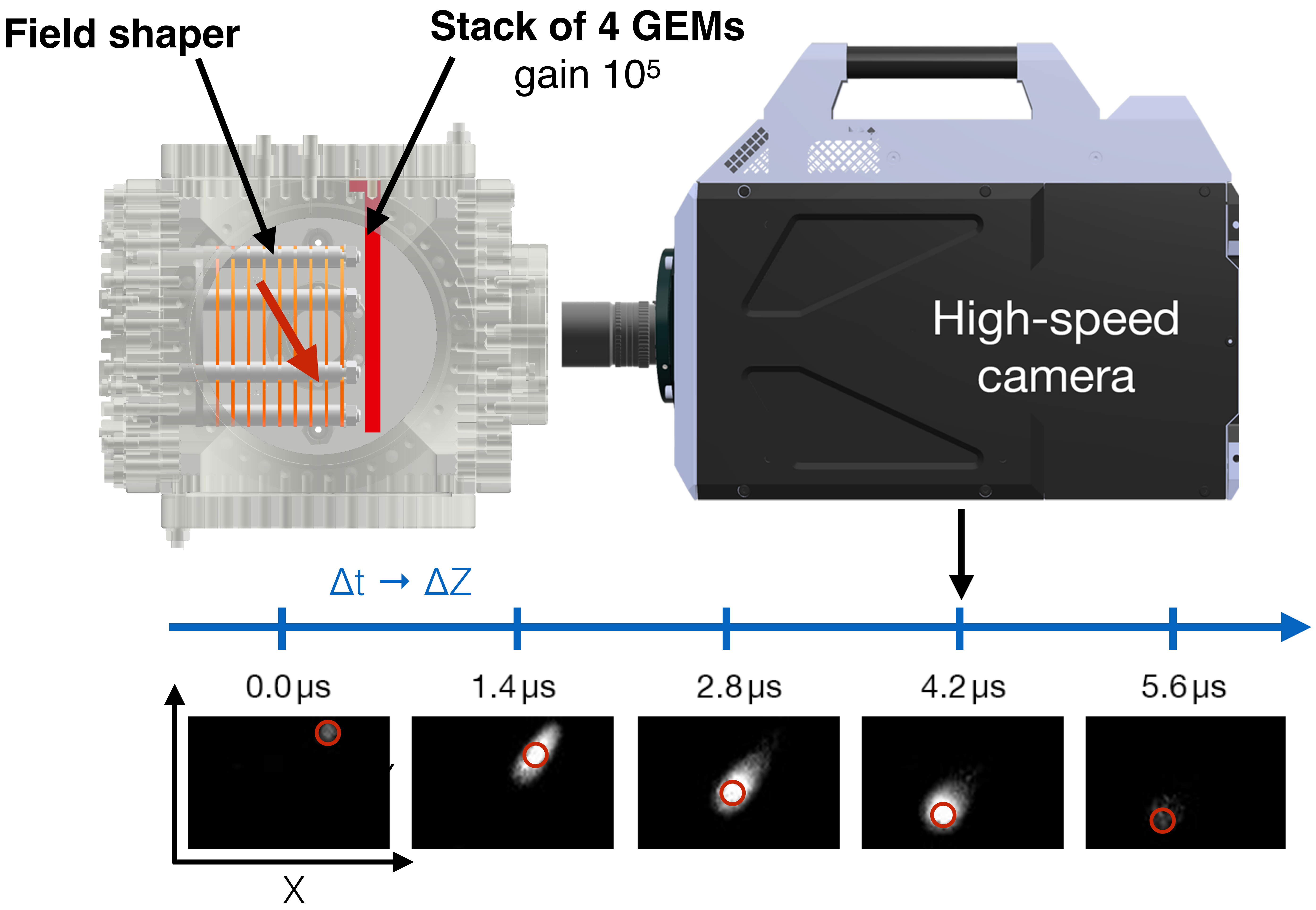
Recorded with 10 V/cm drift field corresponding to ≈0.5 cm/μs in Ar/CF_4



3D alpha track reconstruction (schematic)

Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



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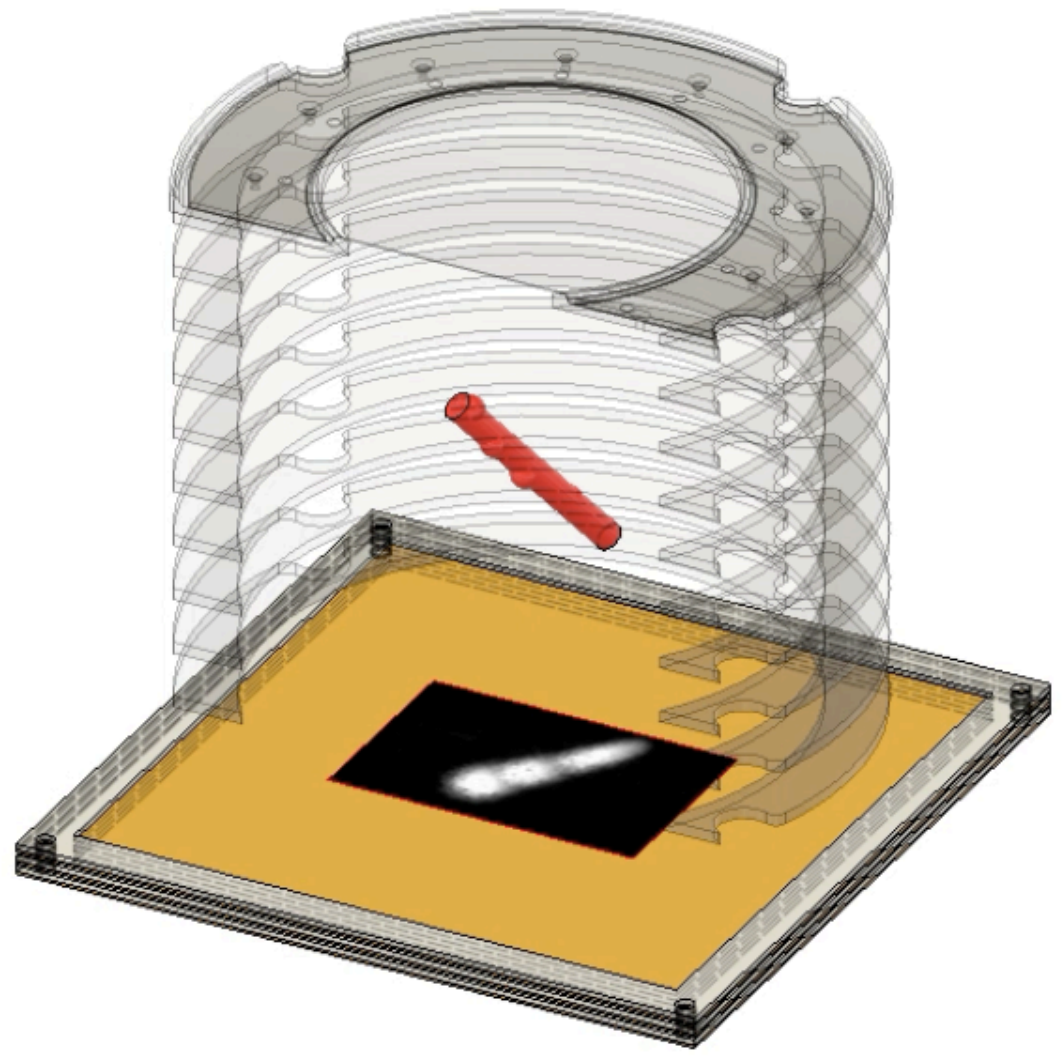

3D alpha track reconstruction (schematic)

Schematics not drawn to scale

Conclusions

3D track reconstruction in TPCs with **CCD or CMOS camera** used to readout scintillation light relies on S1 and S2 information from **PMT for Z-coordinate**.

Combined optical and electronic readout with **transparent, structured anodes** can be used for reconstruction of intricate particle tracks. This preserves advantage of **high-granularity pixelated readout** with cameras with the addition of **relative depth information** from electronic signals.

Ultra-fast CMOS cameras enable 3D track reconstruction from sequences images acquired with μs intervals without the need for extensive reconstruction algorithms.

While currently available **frame rates of Mfps** do not offer good depth resolution for gaseous electron-drift TPCs, they might be applicable for **LAr** or **LXe TPCs** or **negative-ion TPCs**.