Developments of an optical readout for imaging MPGDs

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on behalf of the GDD team

EP Detector Seminar - CERN - Friday 29th of April

Overview

Relevant mechanisms for the operation of gaseous detectors

Imaging applications of MPGDs outside high energy physics

Developments of the optical readout for MPGDs at CERN

Possible other applications

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Why gaseous detectors

Large dimensions (several m^2)

Not expensive (< 5 kCHF/m^2)

Good position resolution (<100 um)

Excellent time resolution (<5 ns and even 100 ps)

Radiation hard (10s year of LHC)

Low material budget (<0.01 X_0)

Compatible with magnetic field

Gas as active medium

Gas at RTP is not dense

Small amount of energy released

Few primary electron-ion pairs

Amplification is needed

Two possibilities: charge and light

Townsend mechanism

Externally applied electric field acts on electrons and ions (free to move) separating them.

On top of the random motion (diffusion) charges acquire energy and move *following* the field lines (drift).

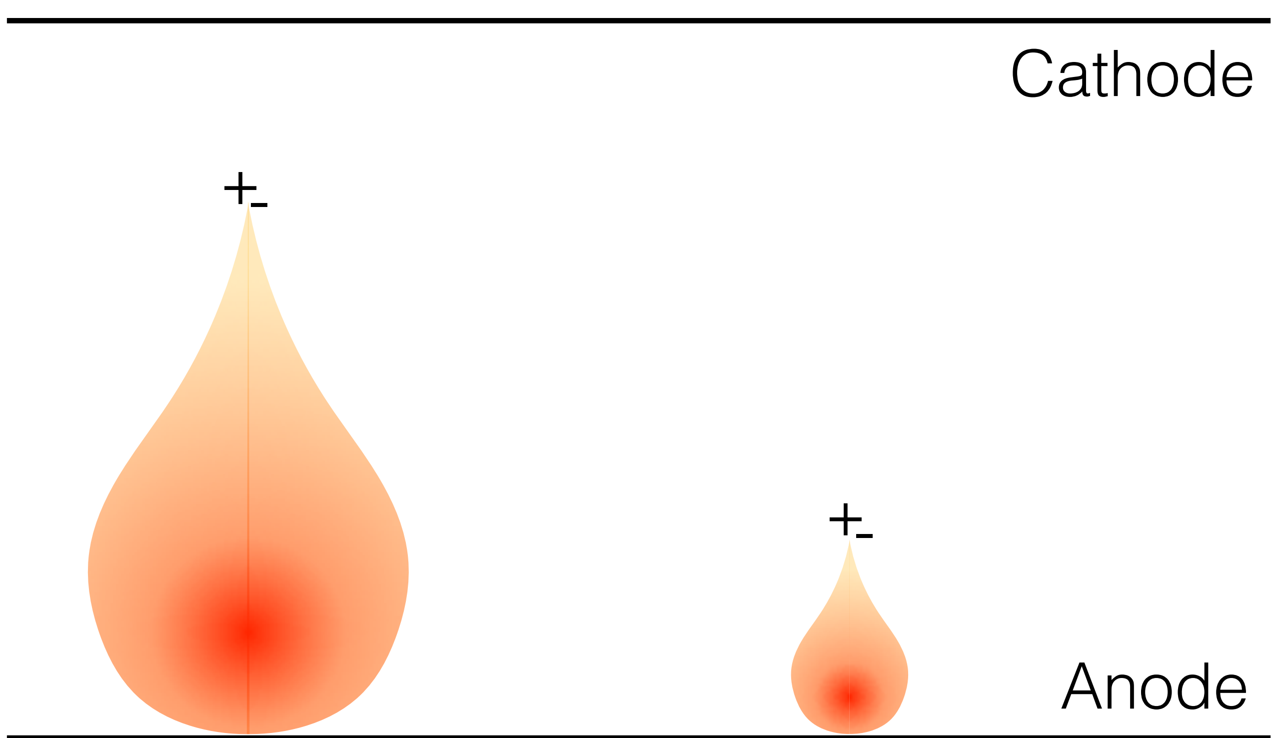
If the field is high enough, the energy gained by the electrons is sufficient to **further ionise** the gas.

Townsend avalanche

α: average number of electron ion pairs created by a single electron per unit path

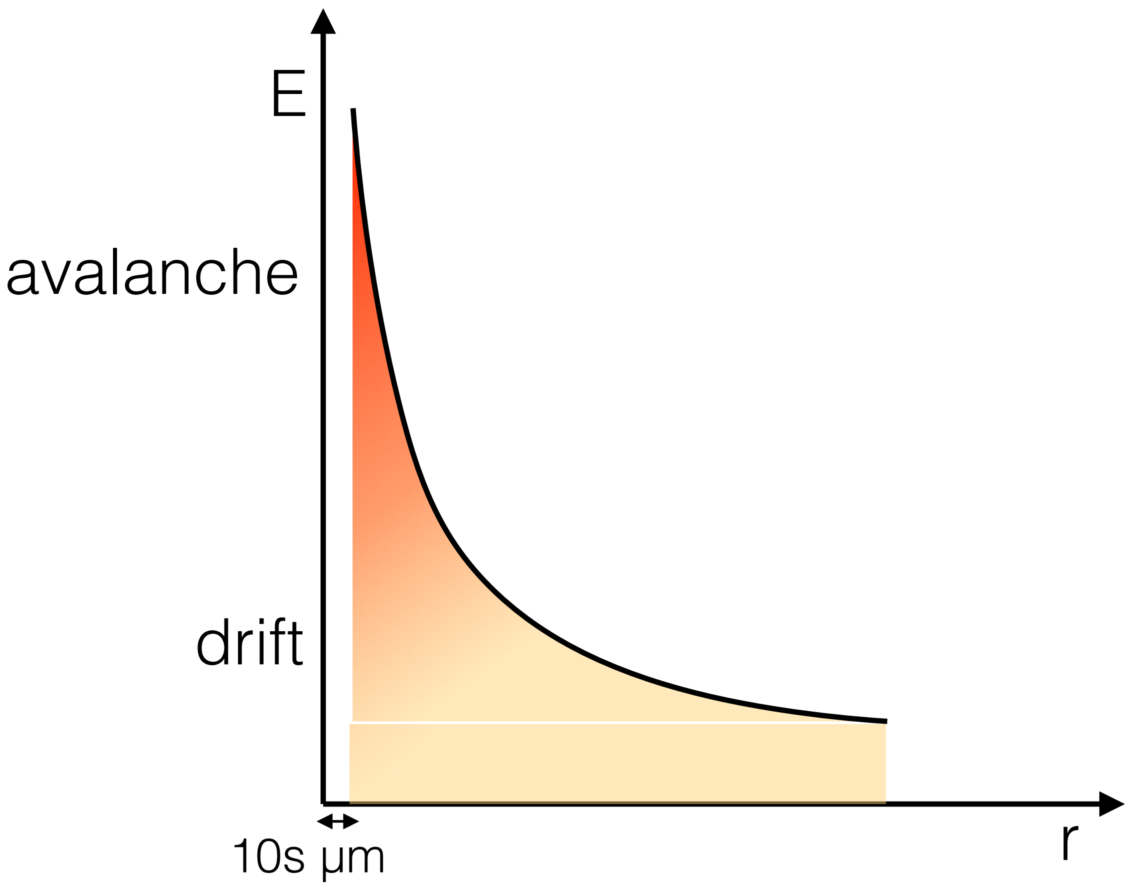
$$\frac{dn_e}{dx} = \alpha(E) \times n_e$$

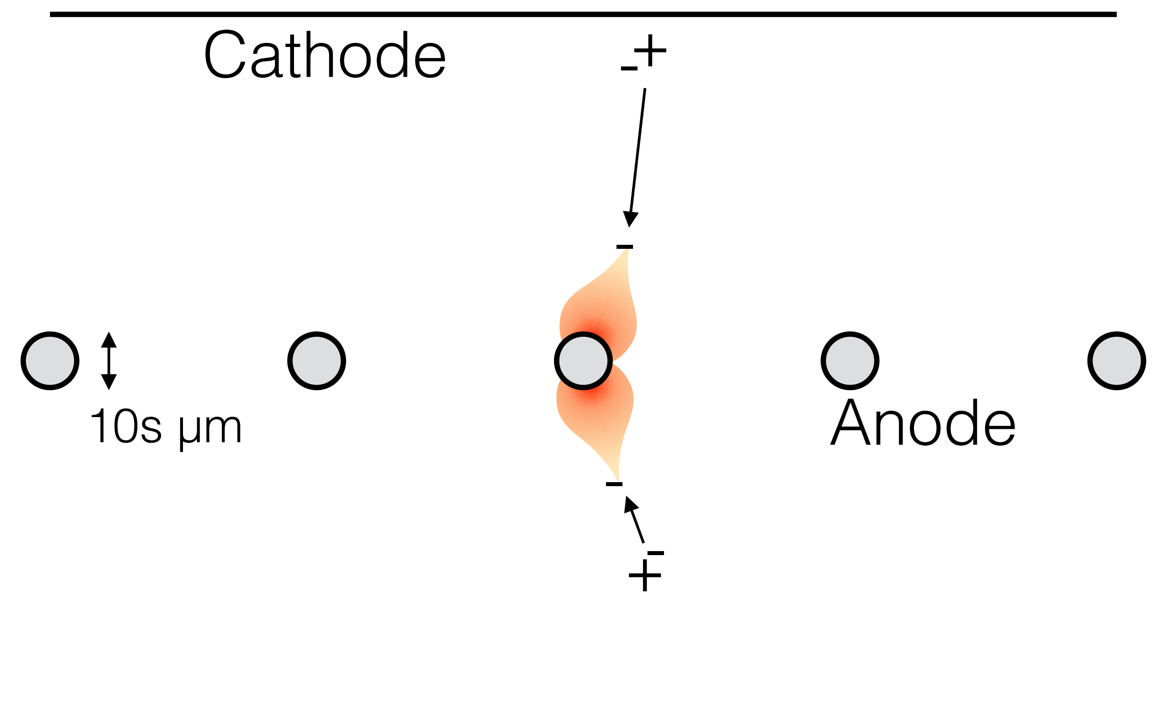
Avalanche increases ~exponentially in time, field and space



For a linear response od the detector, the amplification must be confined in a **small region**.

MWPC





The field is shaped by the **curvature** of the wire.
Several wires to allow the position resolution.

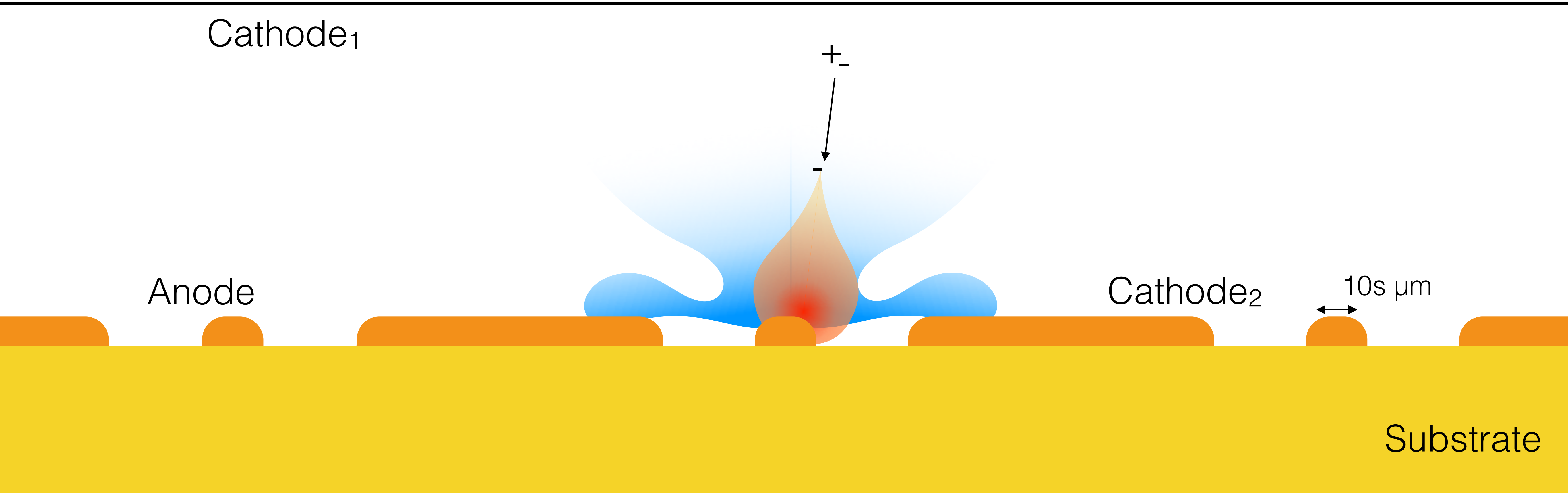
The field is sensitive to wire imperfections.
Slowly moving ions affect the rate capabilities.

Change of paradigm (I)

In order to evacuate the ionic charge fast, the cathode electrodes are placed in the **vicinity** of the anode electrodes:

Micro Pattern Gaseous Detectors.

MSGC



Ions are evacuated fast: better **rate capability**.
Finer anode pitch is possible: better **position resolution**.

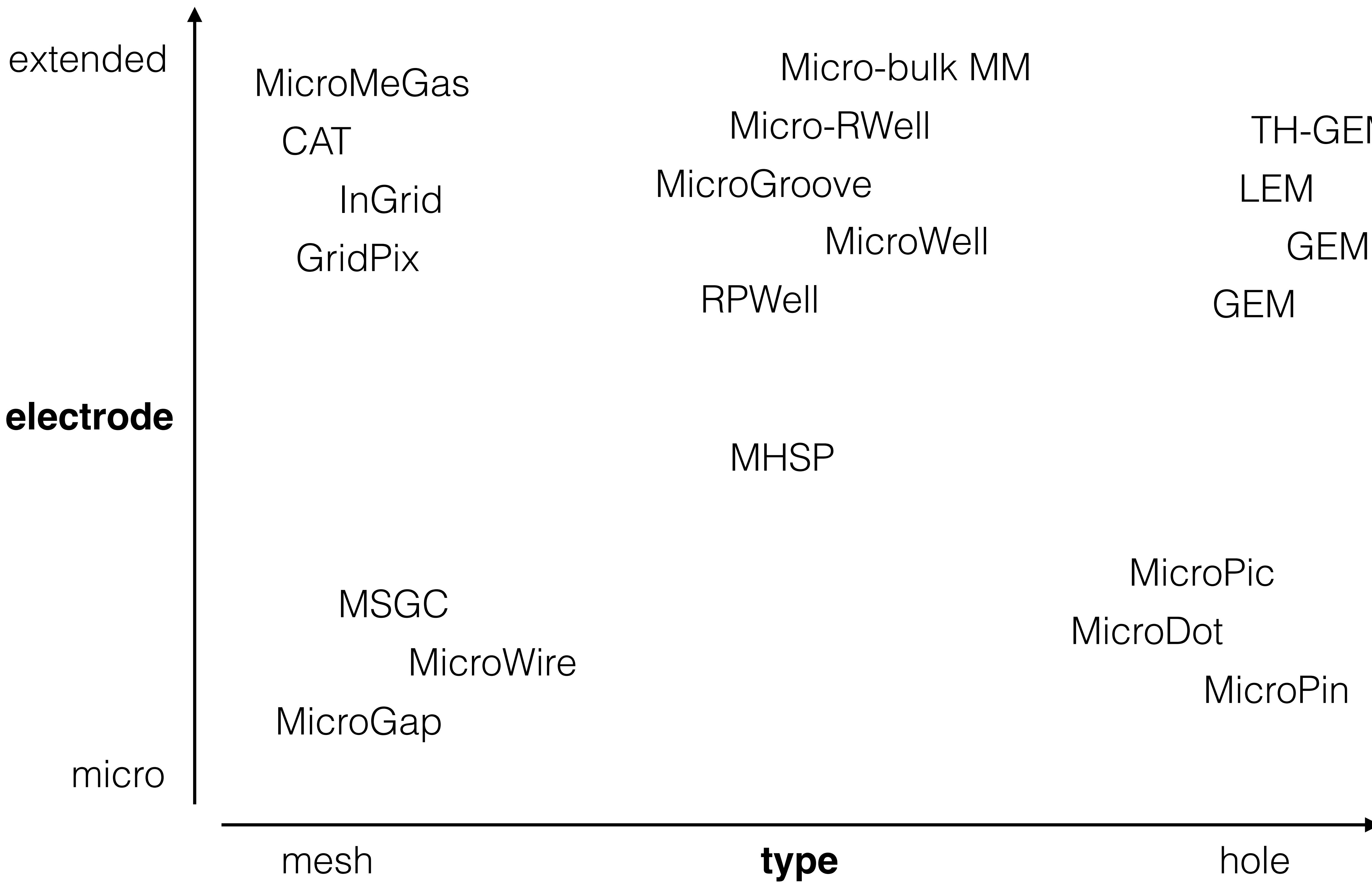
The dielectric substrate charges up, changing the field.
Close anode and cathode occasionally result in sparks.

Change of paradigm (II)

In order to reduce the effects of the discharges and the ageing, the electric field responsible for the amplification is shaped by **extended** electrodes.

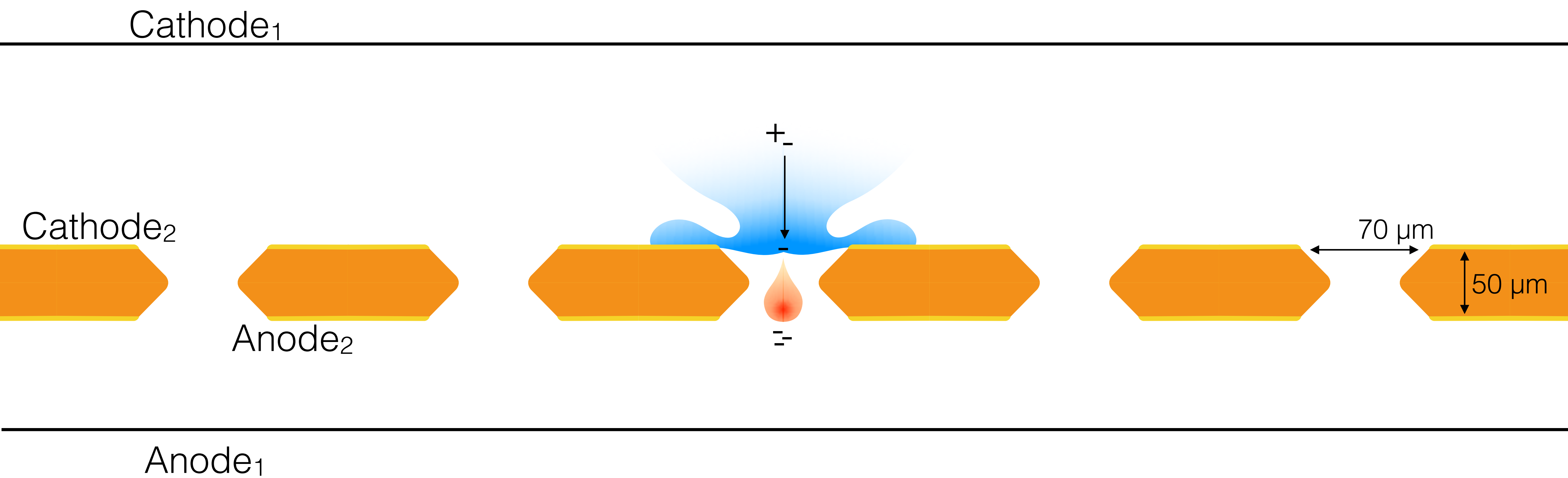
Non-exhaustive list

MPGDs: a rich variety



Sauli, 1997

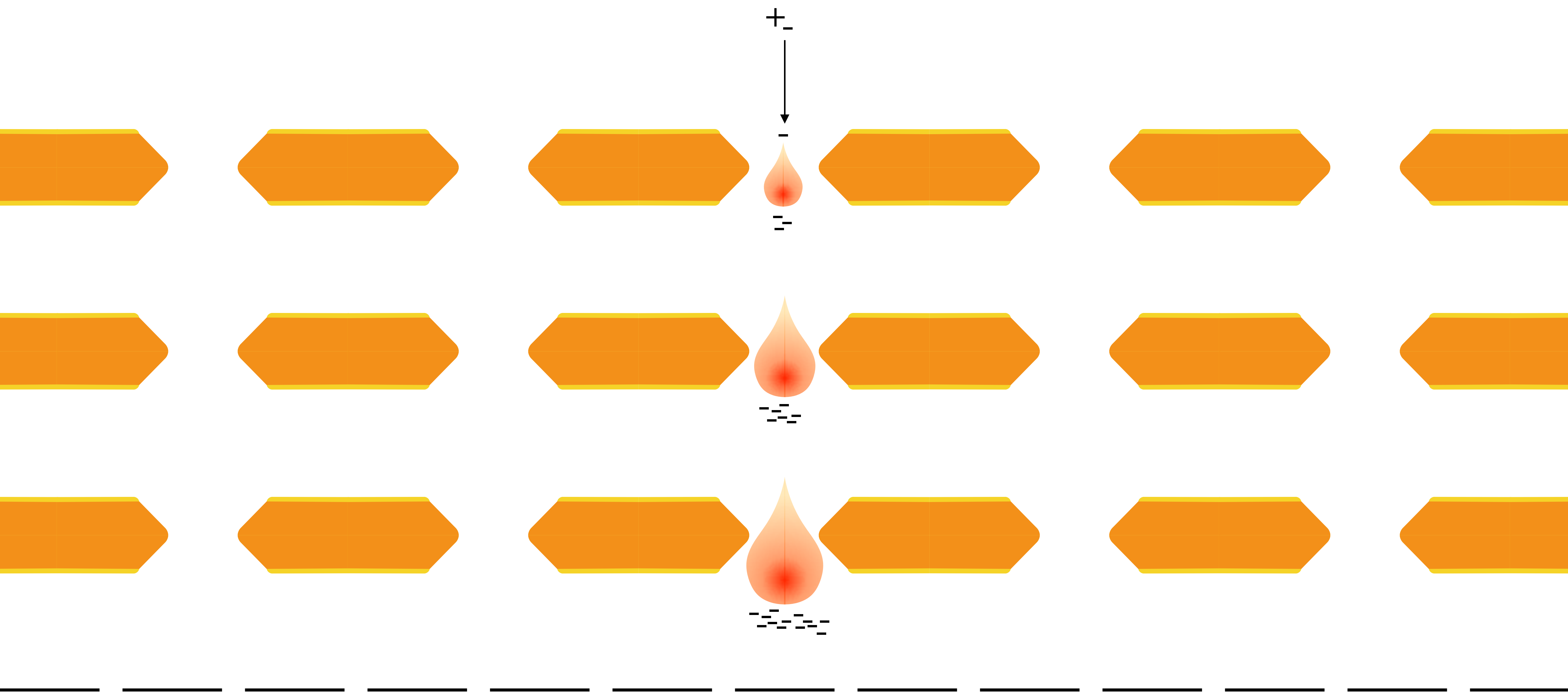
GEM



Amplified electrons available for **further** amplification

Sauli, 1997

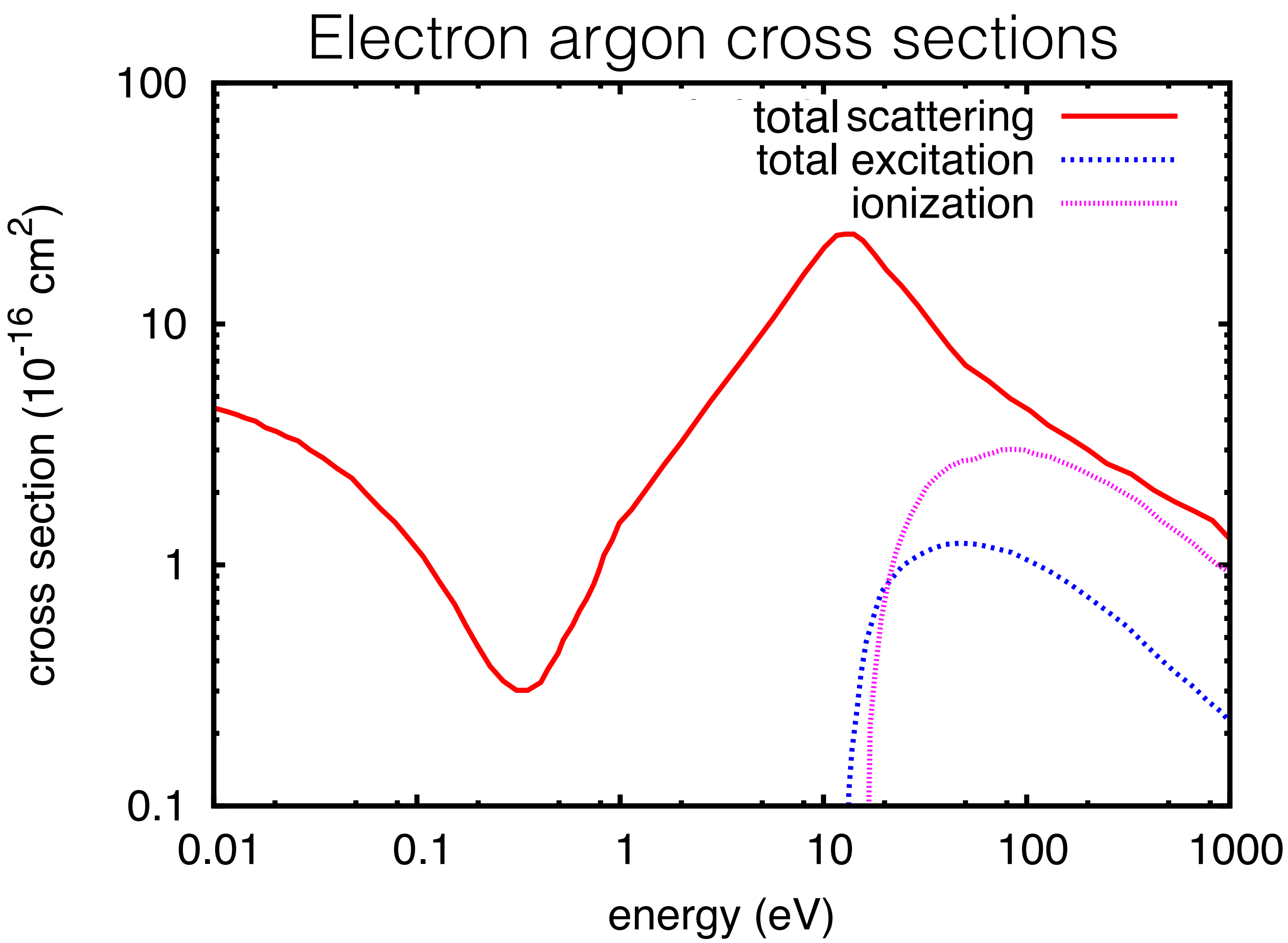
GEMs

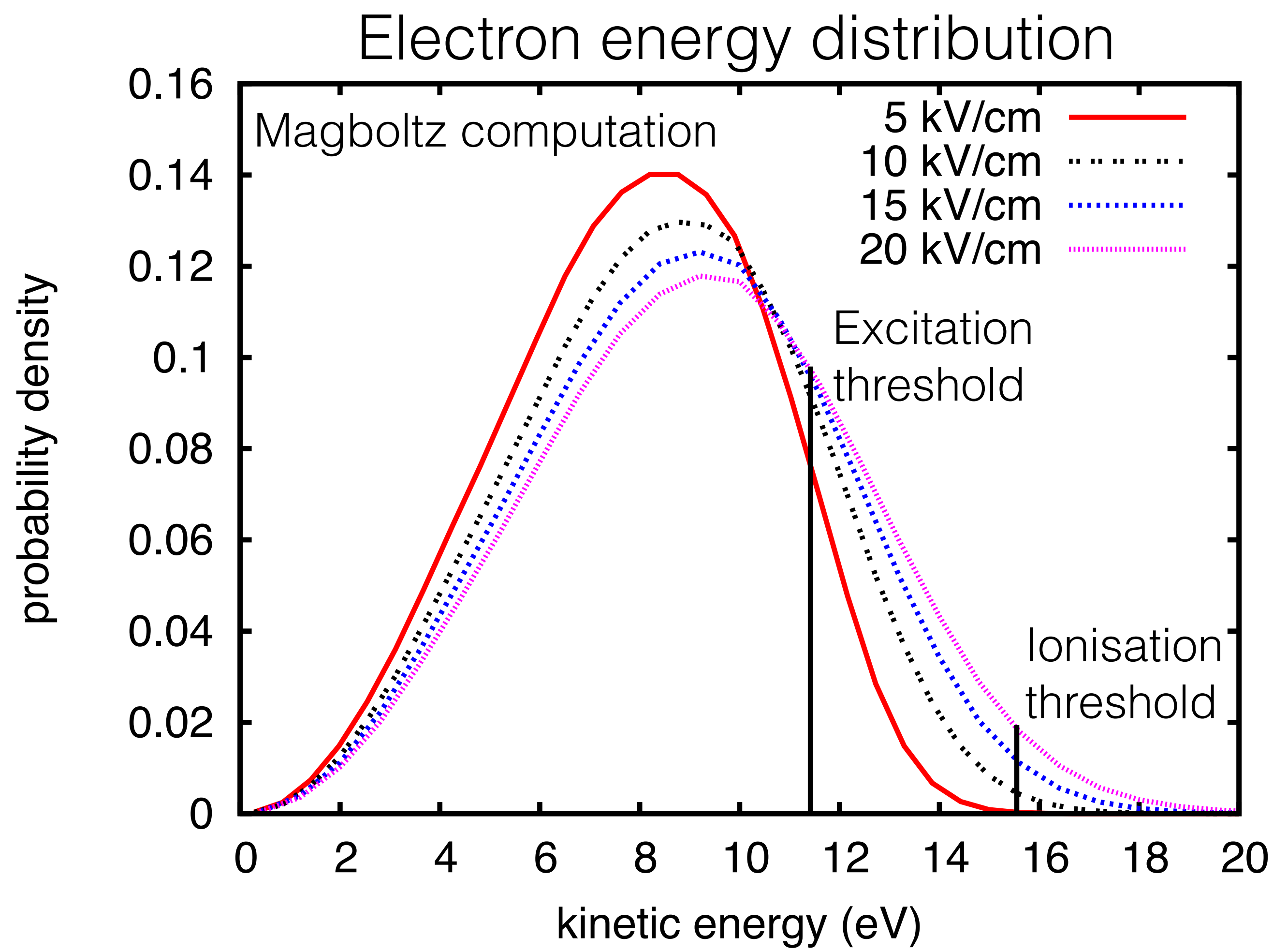


Push further the discharge limit: **larger** gain

Scintillation

Electrons in pure argon





Excitation happens at lower fields. It results in scintillation.
Electron and ion recombination may result in scintillation too.

Scintillation

Valid for all the rare gases

Simplified, but effective picture

$$R^* \to R + h\nu$$

Unlikely because of what follows

Vibrationally excited dimer

$$R^* + 2R \to R_2^{**} + R$$
$$R_2^{**} \to 2R + h\nu$$

First continuum:
relevant at low pressures

$$R_2^{**} + R \to R_2^* + R$$
$$R_2^* \to 2R + h\nu$$

Second continuum:
relevant at pressure >100mbar
Gas now transparent
(no rare gas molecules around)

Scintillation

Valid for all the rare gases

Often wavelength shifter are needed solid and/or gaseous

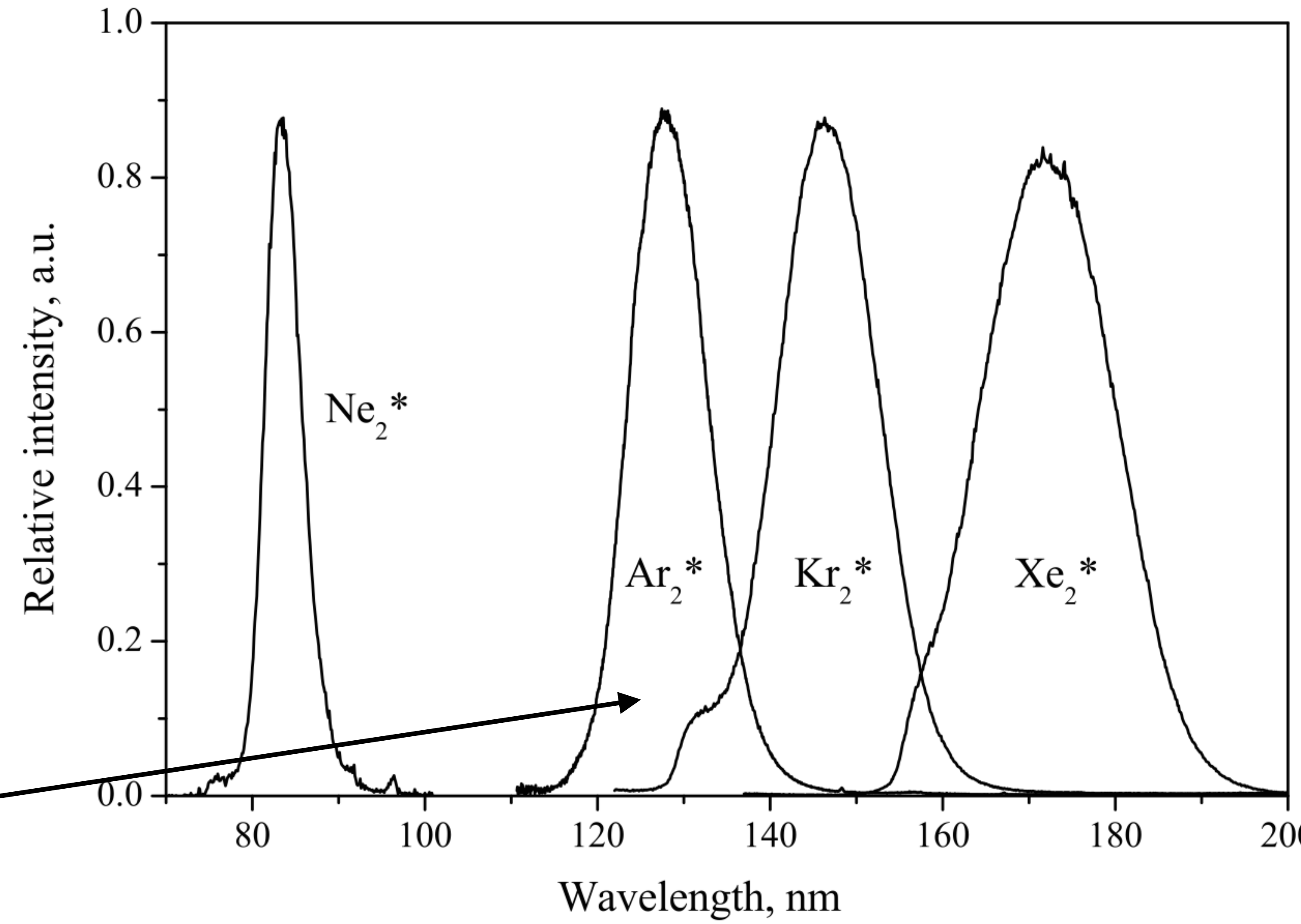
$$R^* \rightarrow R + h\nu$$

$$R^* + 2R \rightarrow R_2^{**} + R$$

$$R_2^{**} \rightarrow 2R + h\nu$$

$$R_2^{**} + R \rightarrow R_2^* + R$$

$$R_2^* \rightarrow 2R + h\nu$$



M. Hofmann (2012) PhD dissertation,
Technical University of Munich (and references)

Quencher and shifter

With the addition of molecules

Concurrent mechanism somewhere in the chain: *quencher* without and *shifter* with radiative emission.

$$R^* \rightarrow R + h\nu$$

Quencher/shifter

$$\cancel{R^* + 2R} \rightarrow R_2^{**} + R$$

$$\cancel{R_2^{**}} \rightarrow 2R + h\nu$$

E.g., adding a small amount of xenon into argon results in xenon scintillation.
Energy transfer (favoured) from argon to xenon.
Then the xenon chain is followed.

Quencher/shifter

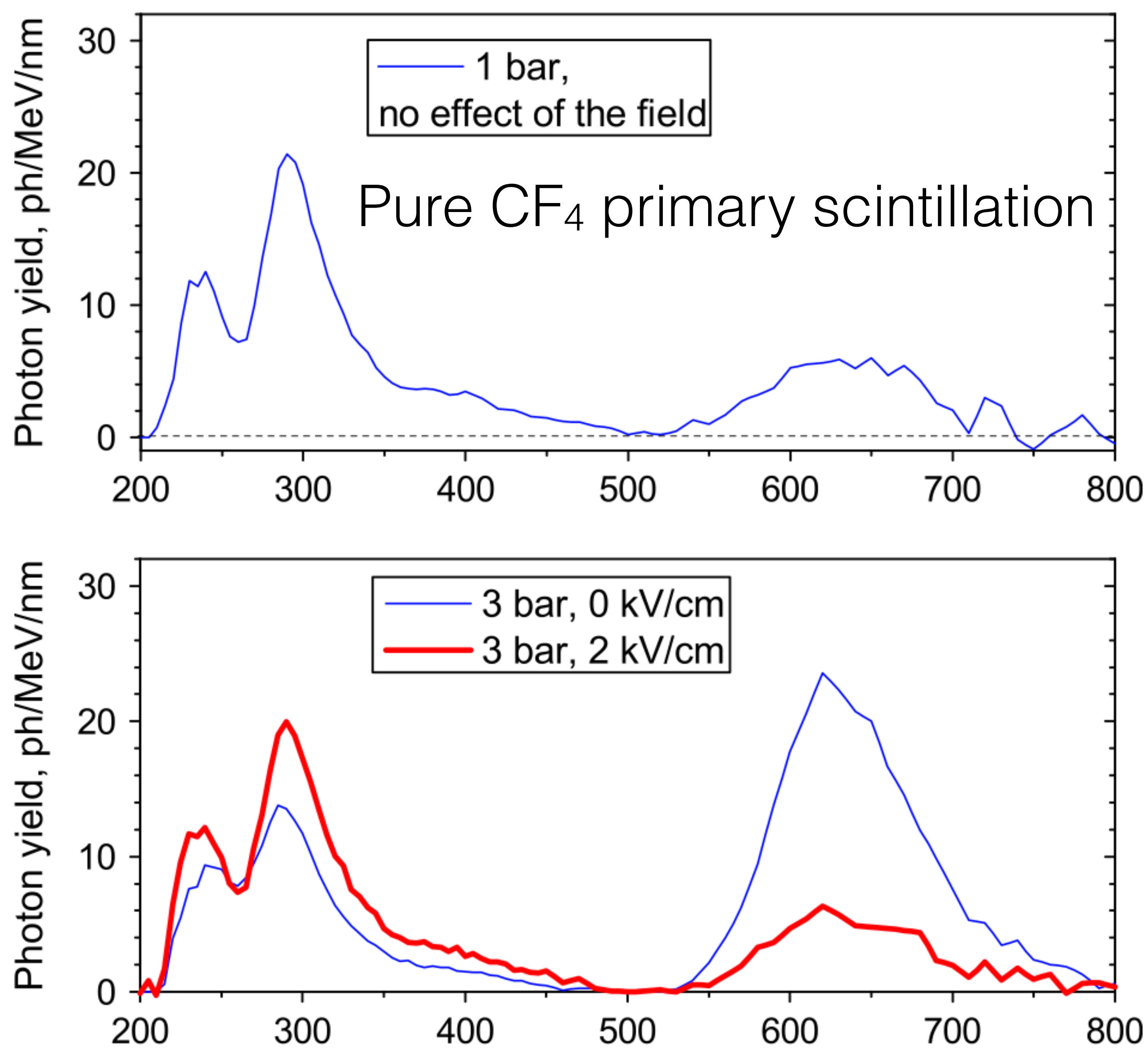
$$\cancel{R_2^{**} + R} \rightarrow R_2^* + R$$

$$\cancel{R_2^*} \rightarrow 2R + h\nu$$

Another form of quenching:
absorption (not transparent admixtures).

CF_4

Admixtures which provide useful scintillation (enough and near the visible range) are rare.



A. Morozov *et al.*, NIM A 628 (2011) 360

CF_4 is not transparent to the CF_4 de-excitation to ground.

What scintillates must be something else: (CF_3^*), CF_3^{+*} and CF_4^{+*}

Where to get the light from

Almost the same spectra

Primary	Electroluminescence	Avalanche
Excitation and ionisation produced by the particle interacting with the gas. Some dependance with the electric field.	Scintillation without charge amplification. Increase linearly with the field. Easy in pure noble gases.	Exponential scaling with the field. *Proportional* to the charge gain. The extreme is the visible spark.

If only CF_3^{+*} and CF_4^{+*} are the responsible of the scintillation, electroluminescence does not take place.
Certainly CF_3^{+*} and CF_4^{+*} are produced in avalanches, in fact avalanche scintillation present in CF_4 mixtures.

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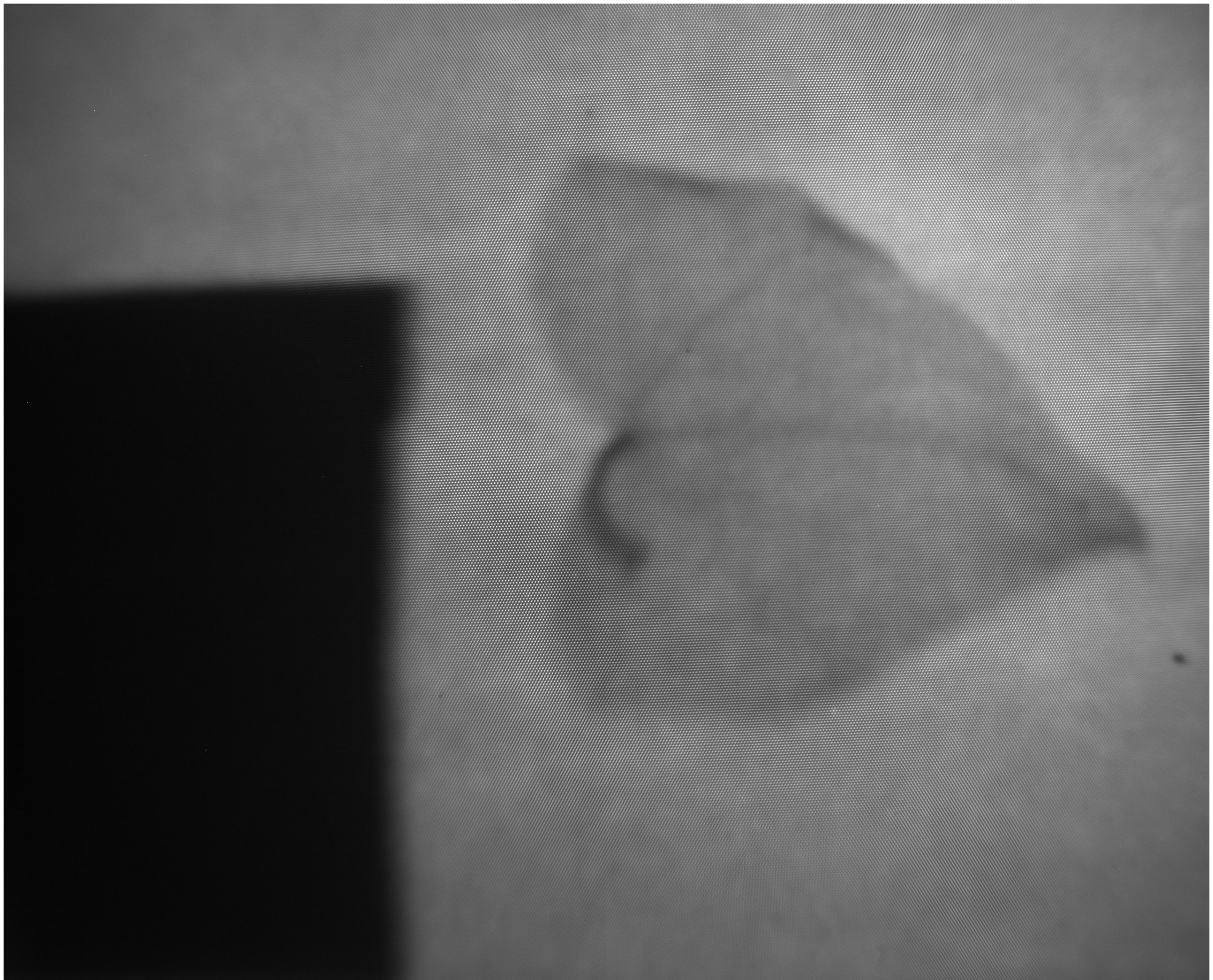
Imaging

Visual representation of an object (often, but not necessarily in spatial coordinates) using any of a variety of techniques.

When using a camera it's called photography.

Why imaging?



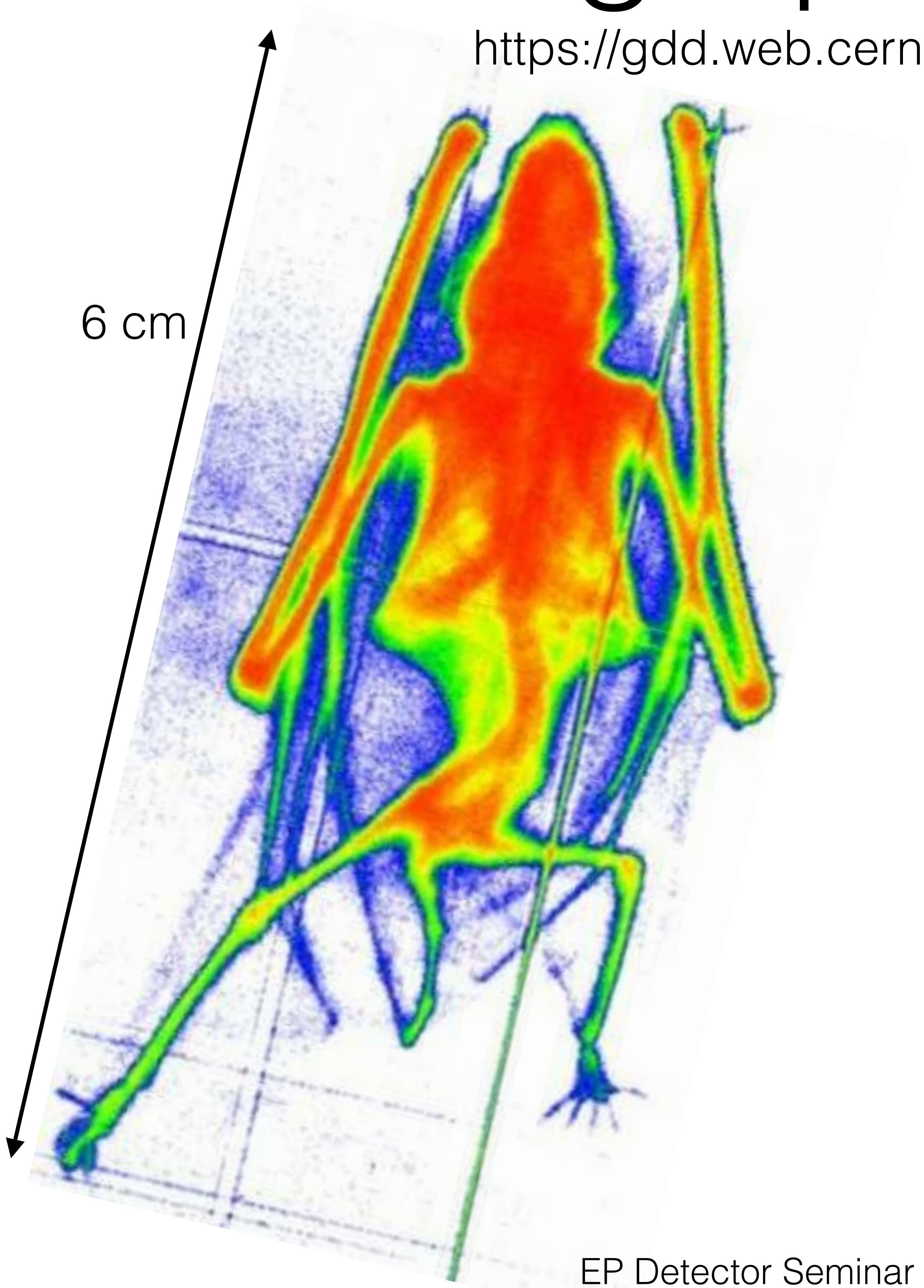
Sight

Our dominant sense:

- **Intuitive** handling of the data
- **Immediately** available information
- Visual learning fast and **effective**

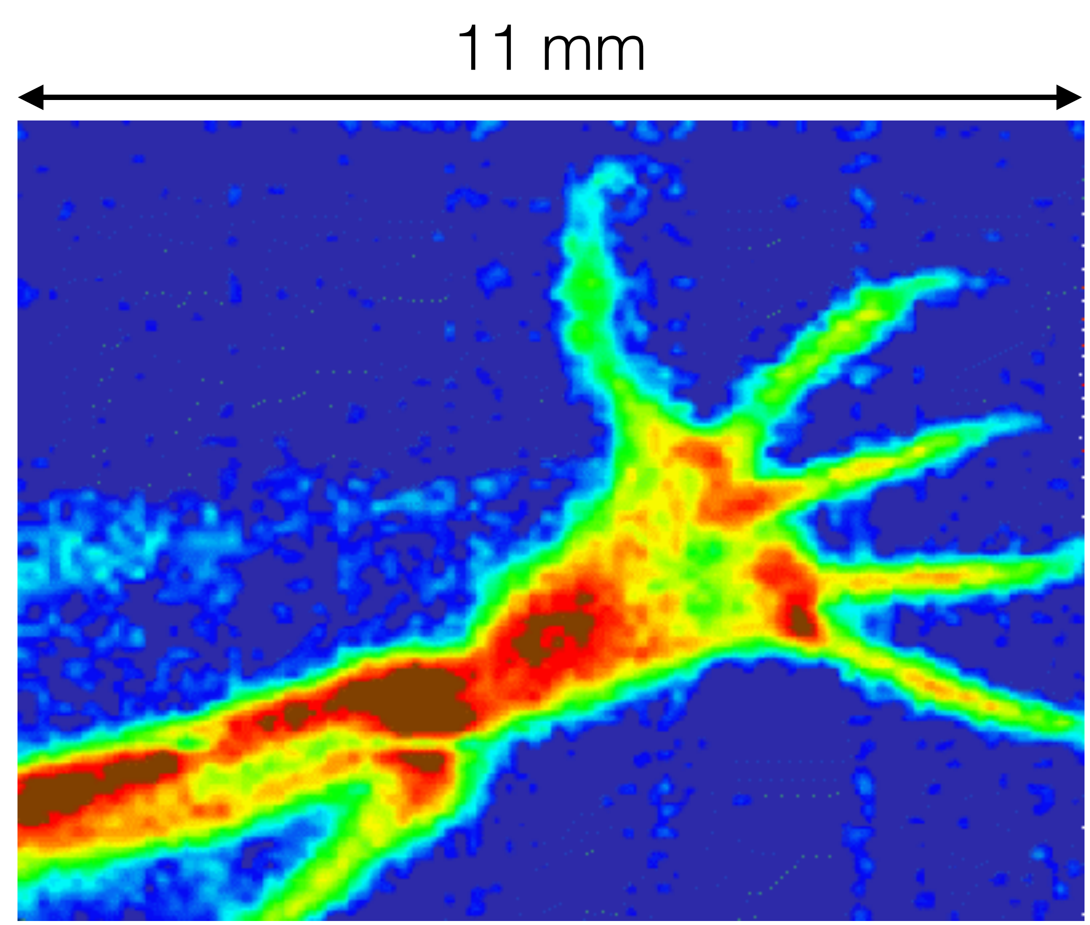
Radiography with GEMs

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



Demonstration application:
first radiography with GEMs of a small mammal.

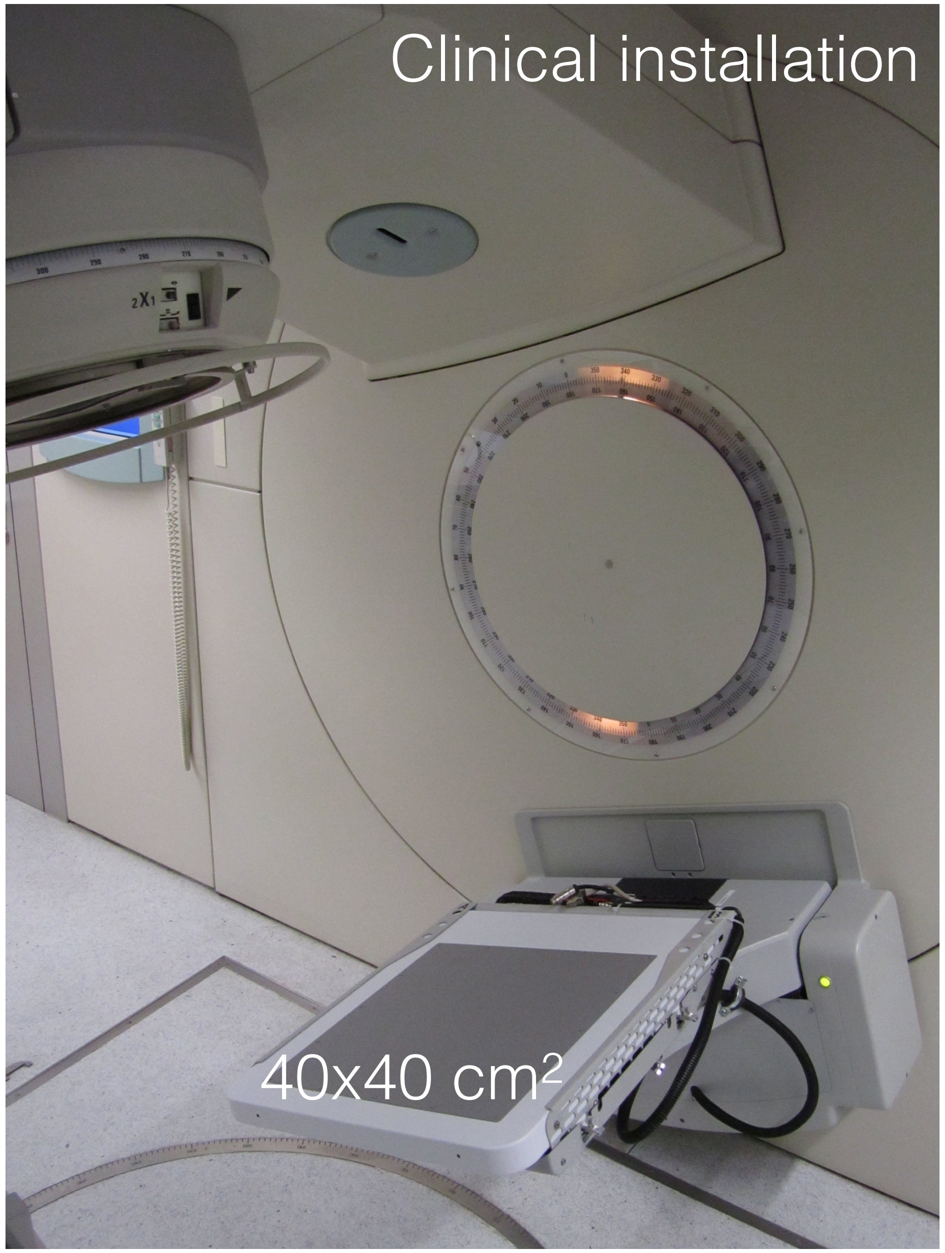
Cu X-ray and triple-GEM with X-Y readout.

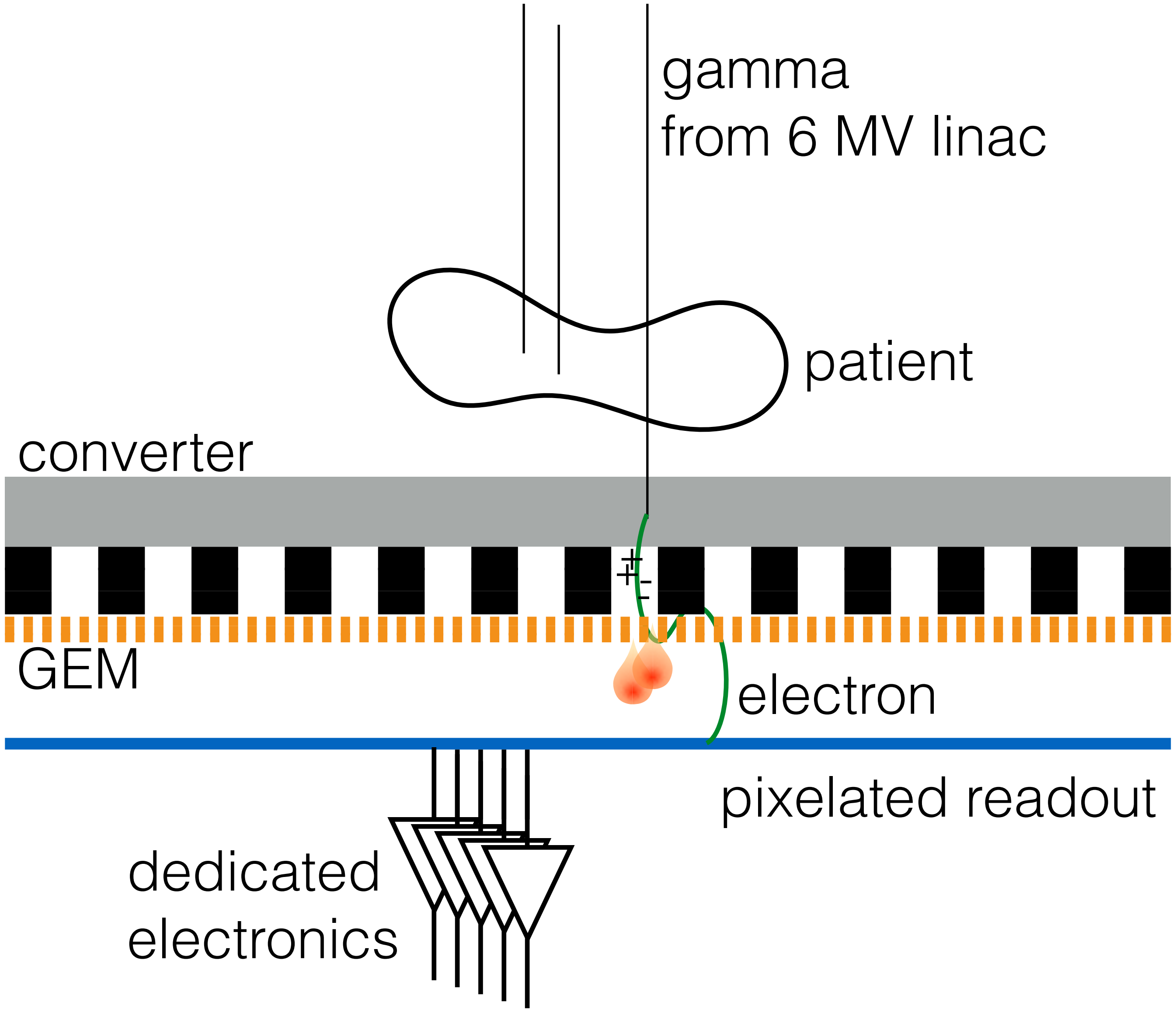


C-RAD GEMINI

Imaging applications in the radiotherapy treatment process

Increasing demand for better accuracy in monitoring the tumour position and movements.
Online verification of the actually delivered dose distribution.
Detectors exposed to high dose: radiation hard and ageing matters.

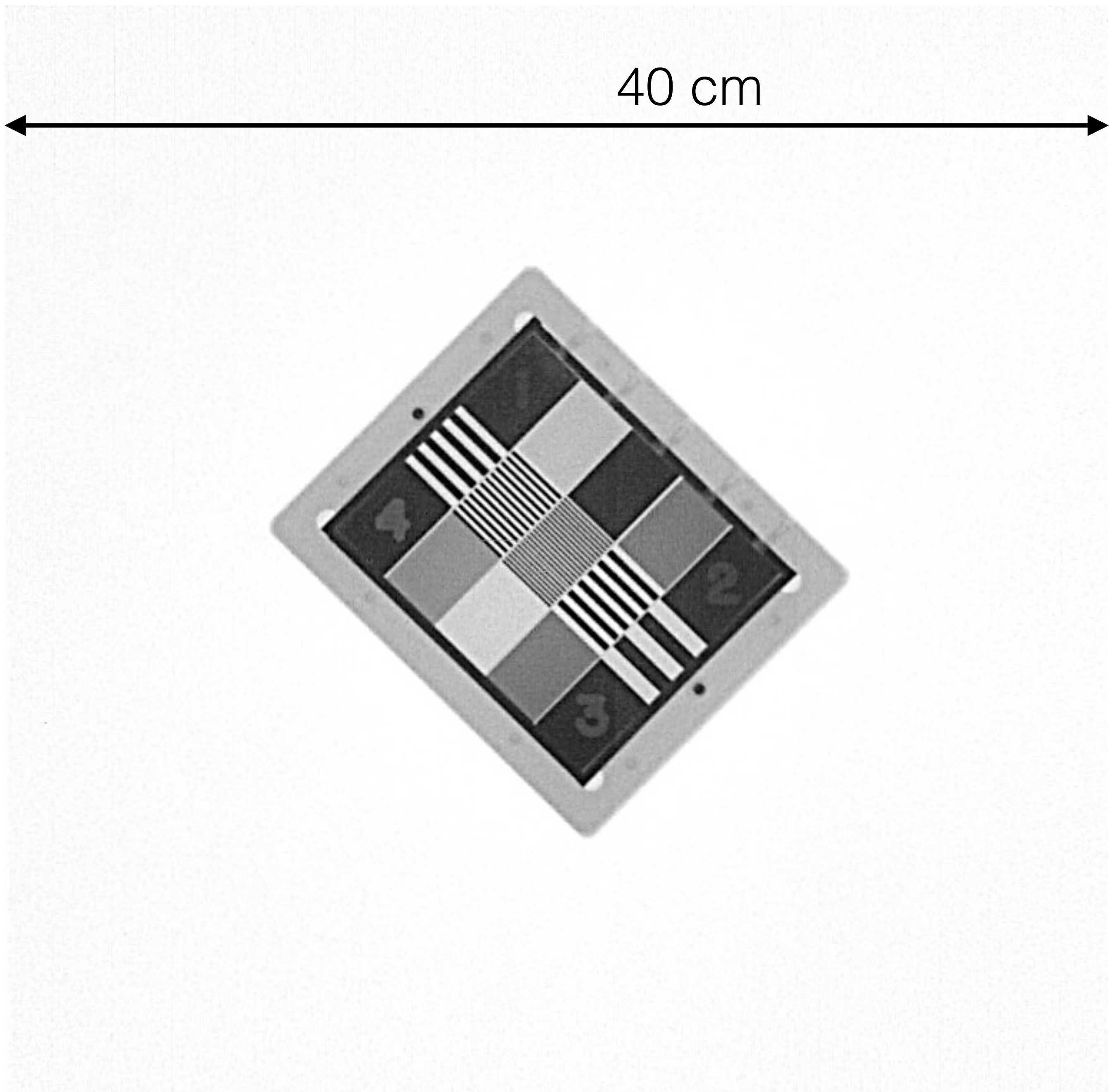




C-RAD GEMINI

6 MV linac, 1.5 MeV average gamma energy, 3 MU dose

QA object (resolution and contrast measure)

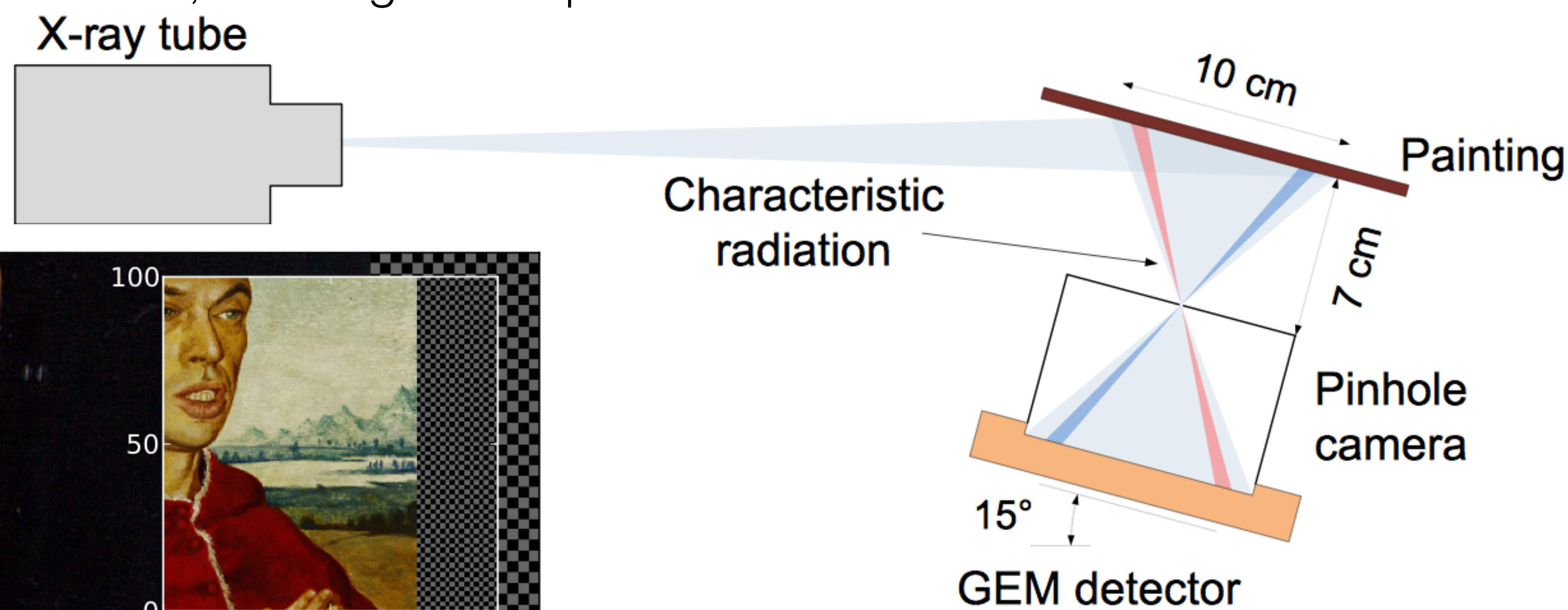


Pelvic phantom

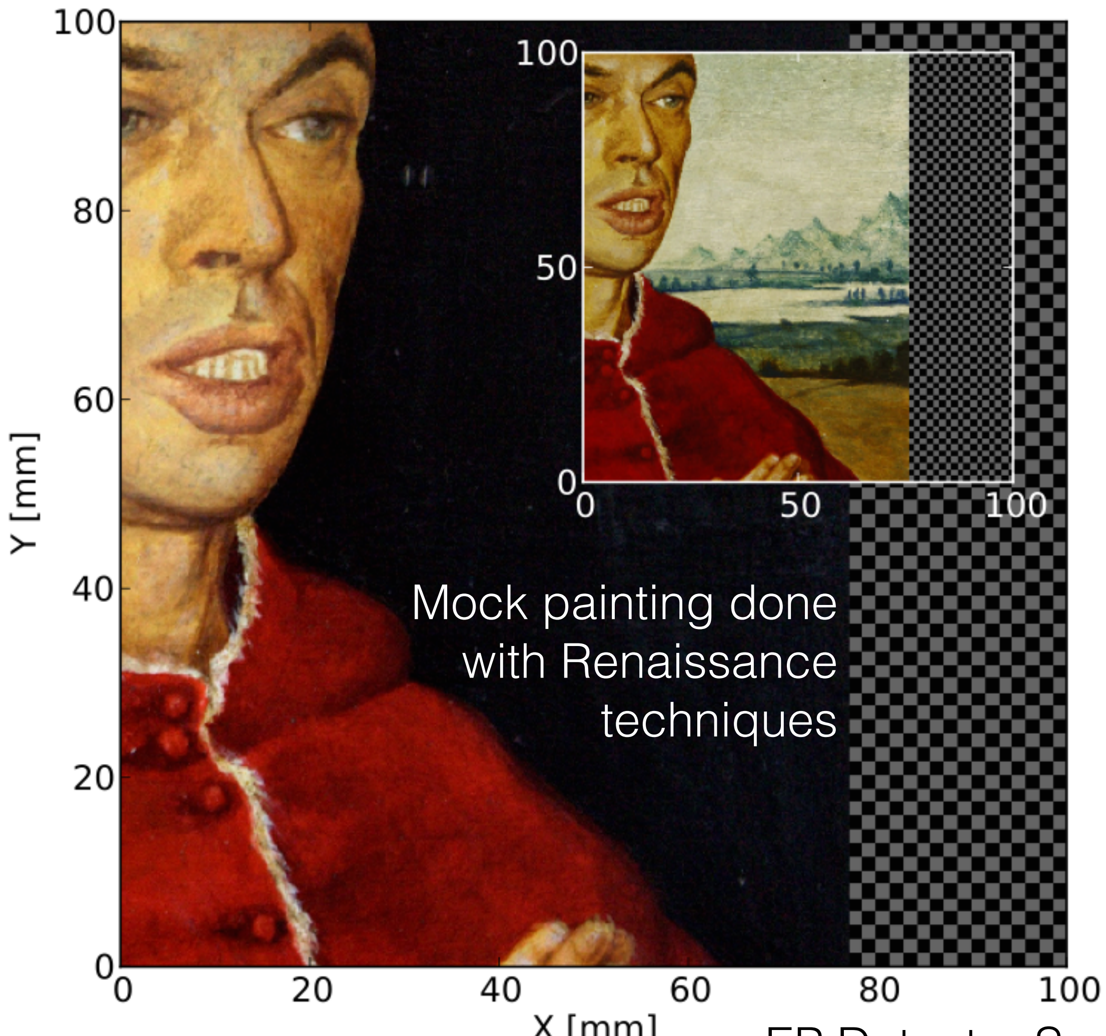
X-ray fluorescence

XRF imaging system for fast mapping of pigment distributions in cultural heritage paintings

Scanning XRF revealed a painting under Rembrandt's "An old man in military costume".
It took 19 days with an X-ray tube and 24 h with synchrotron radiation.
Scanning is detailed, but long and expensive.



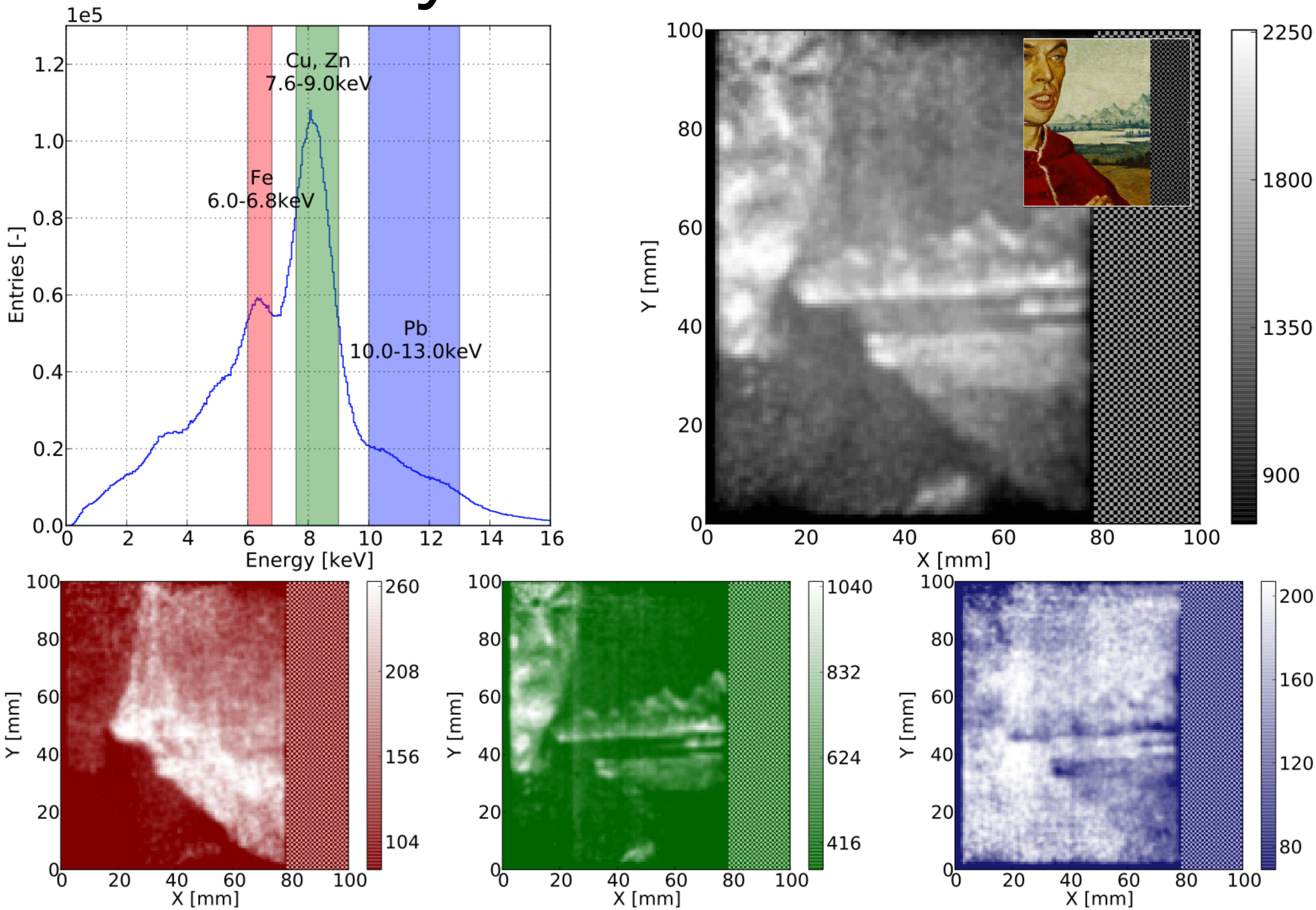
A. Zielińska, 2013 JINST 8 P10011



Position and energy sensitive method
No position scan required
The system can be brought to the museum

A. Zielińska, 2013 JINST 8 P10011

X-ray fluorescence



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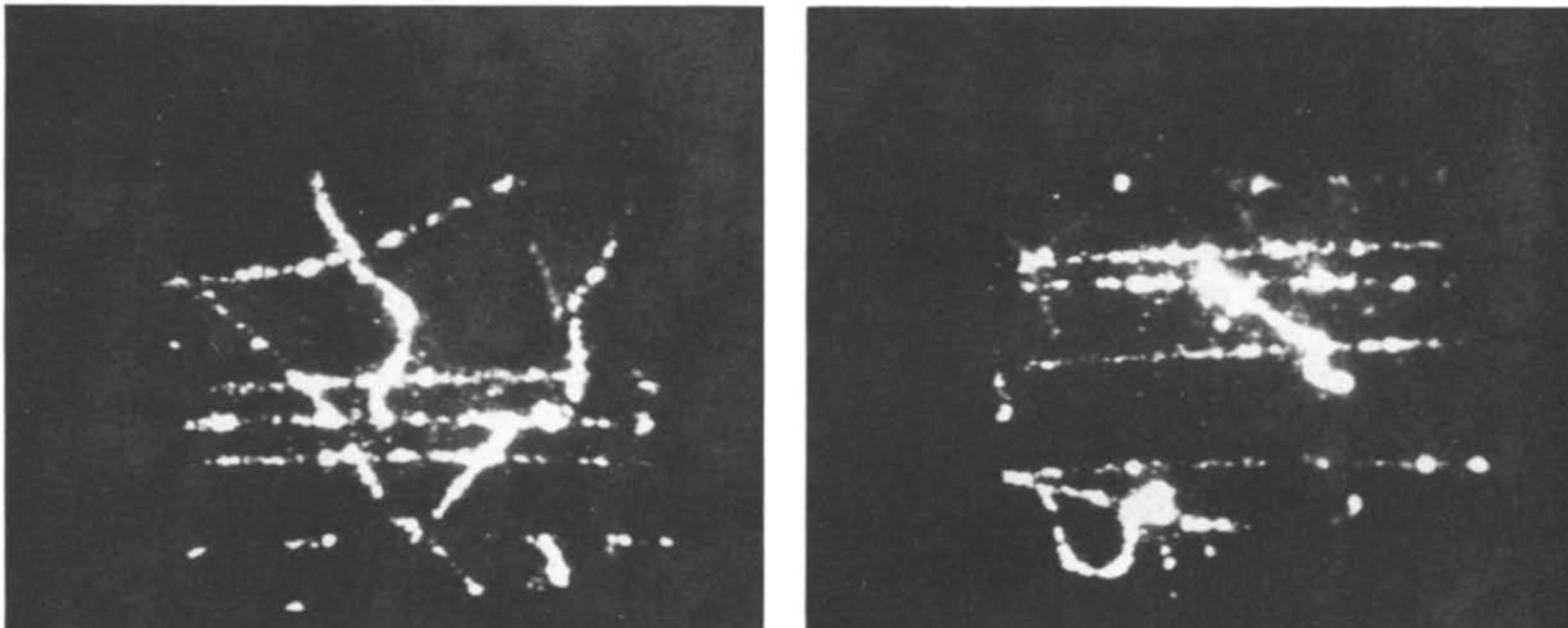
Optical readout

Record the light emitted during the Townsend avalanche with a camera: use the detector as a scintillating plate.

Only techniques are new

Parallel mesh chamber filled with $Ar/CH_4/TEA$ 80%/8%/2%
seen by an image intensifier and a camera

Muons and delta rays



G. Charpak *at al.*, NIM A258 (1987) 177

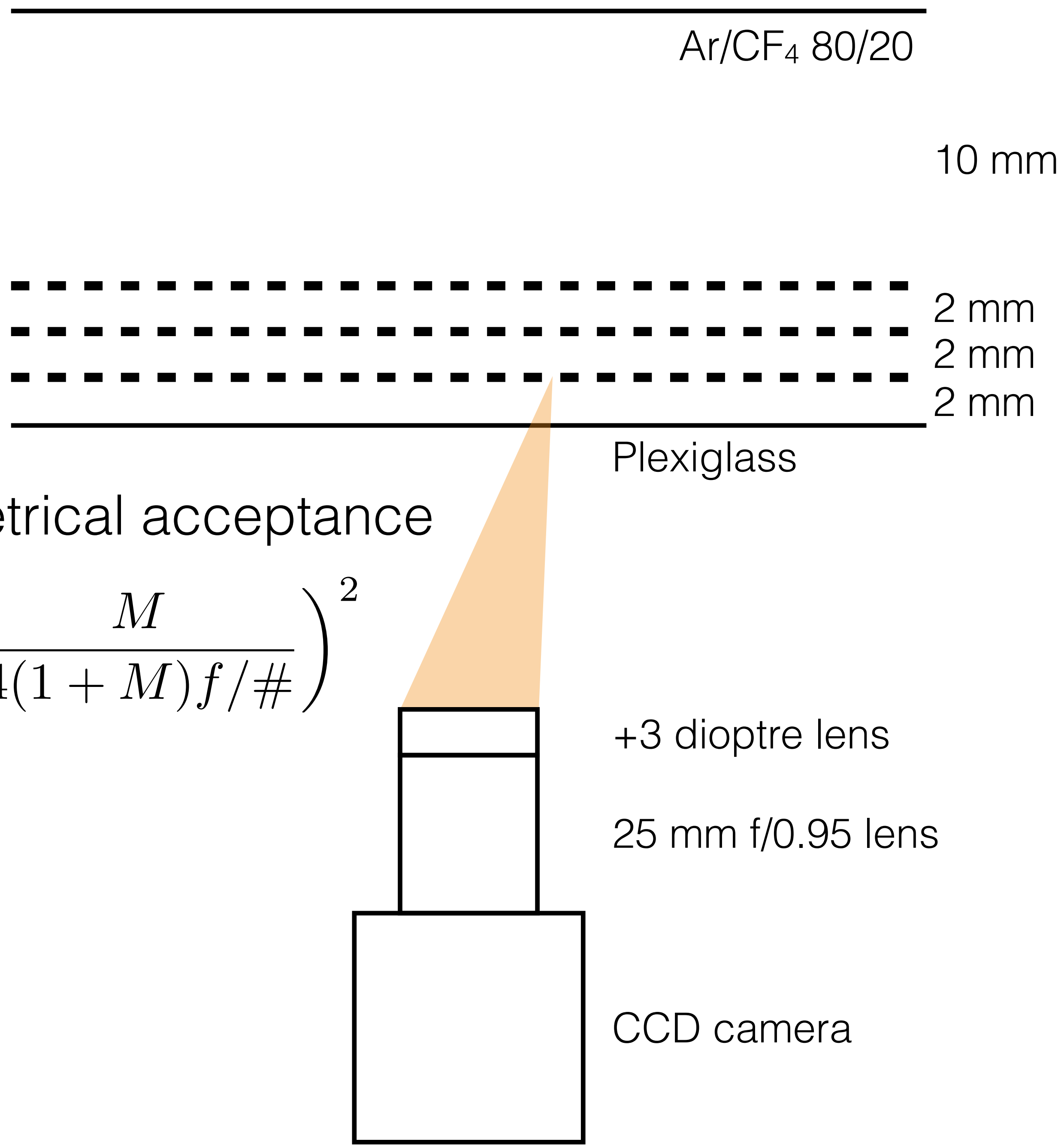
Advantages

Simplicity: like taking a picture

Robustness: as a device off-the-shelf

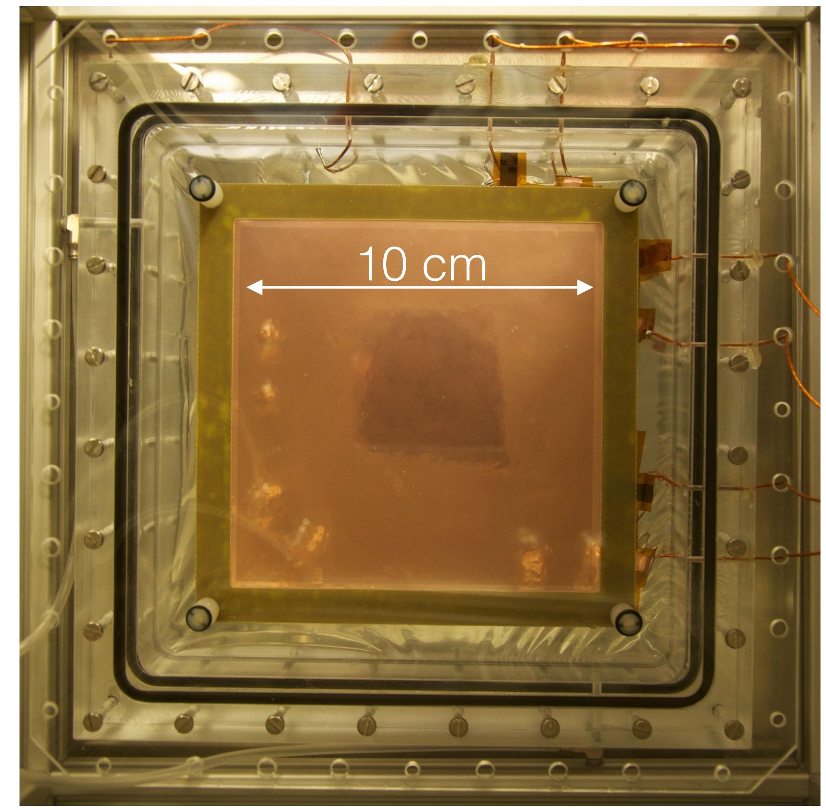
Versatility: several uses and environments

The setup



Geometrical acceptance

$$\Omega \approx \left(\frac{M}{4(1+M)f/\#} \right)^2$$



M = sensor size / image size

M ~ 0.1, $\Omega \sim 5\times10^{-4}$

This implies:
- large sensor
- low noise
- fast lens
- a lot of light

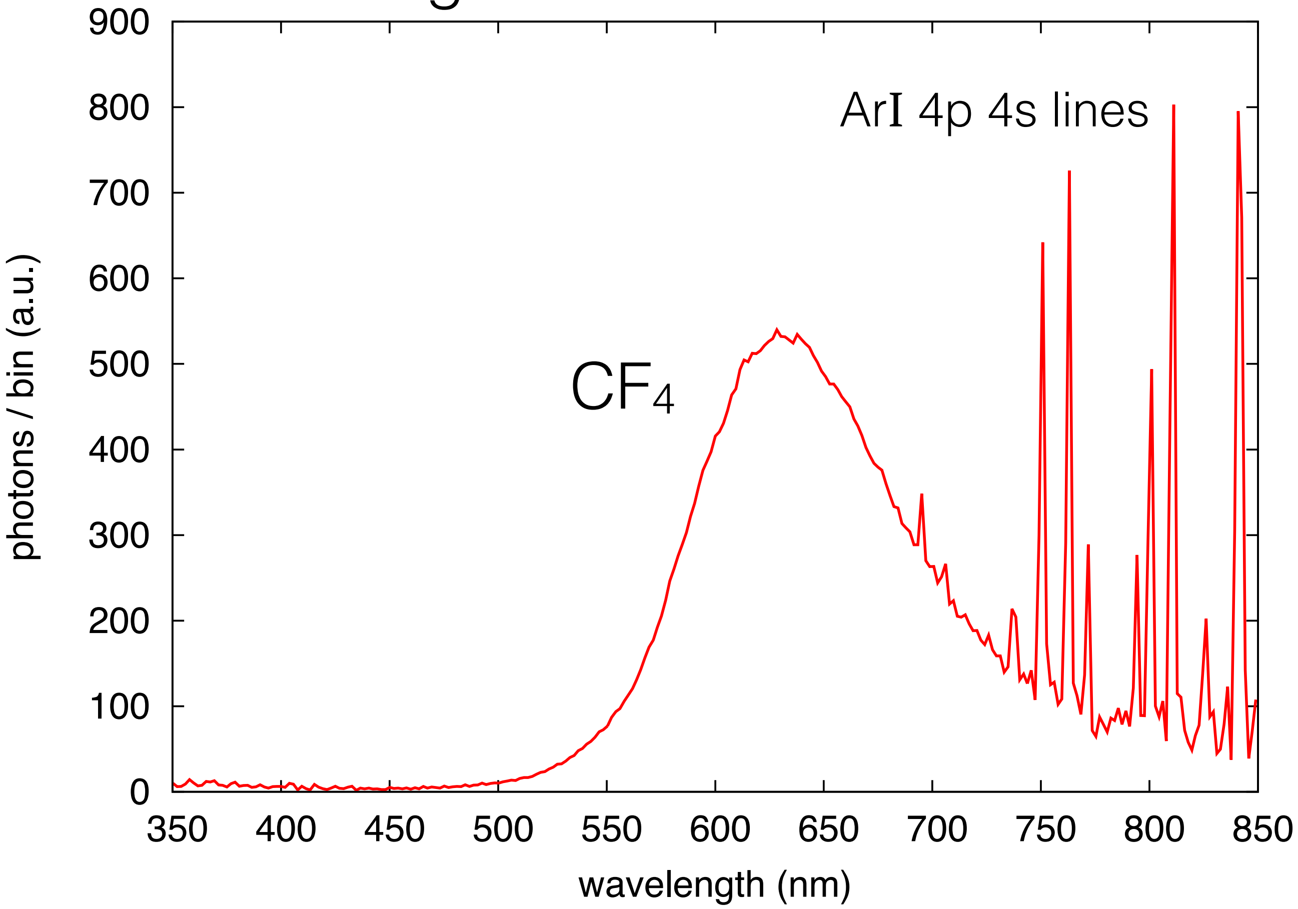
Camera and lens

QImaging Retiga R6
CCD: 2688x2200 4.54x4.54 um^2 pixels
ADC: 14 bit
rate: 6.9 fps (20fps with binning)
read noise: 5.7 e^- RMS
dark current: 0.0002 e^-/p/s @ -20^o C
trigger: external bulb + others

Navitar
focal length: 25 mm
aperture: f/0.95
Mount: C-Mount
Sensor type: 1'' format

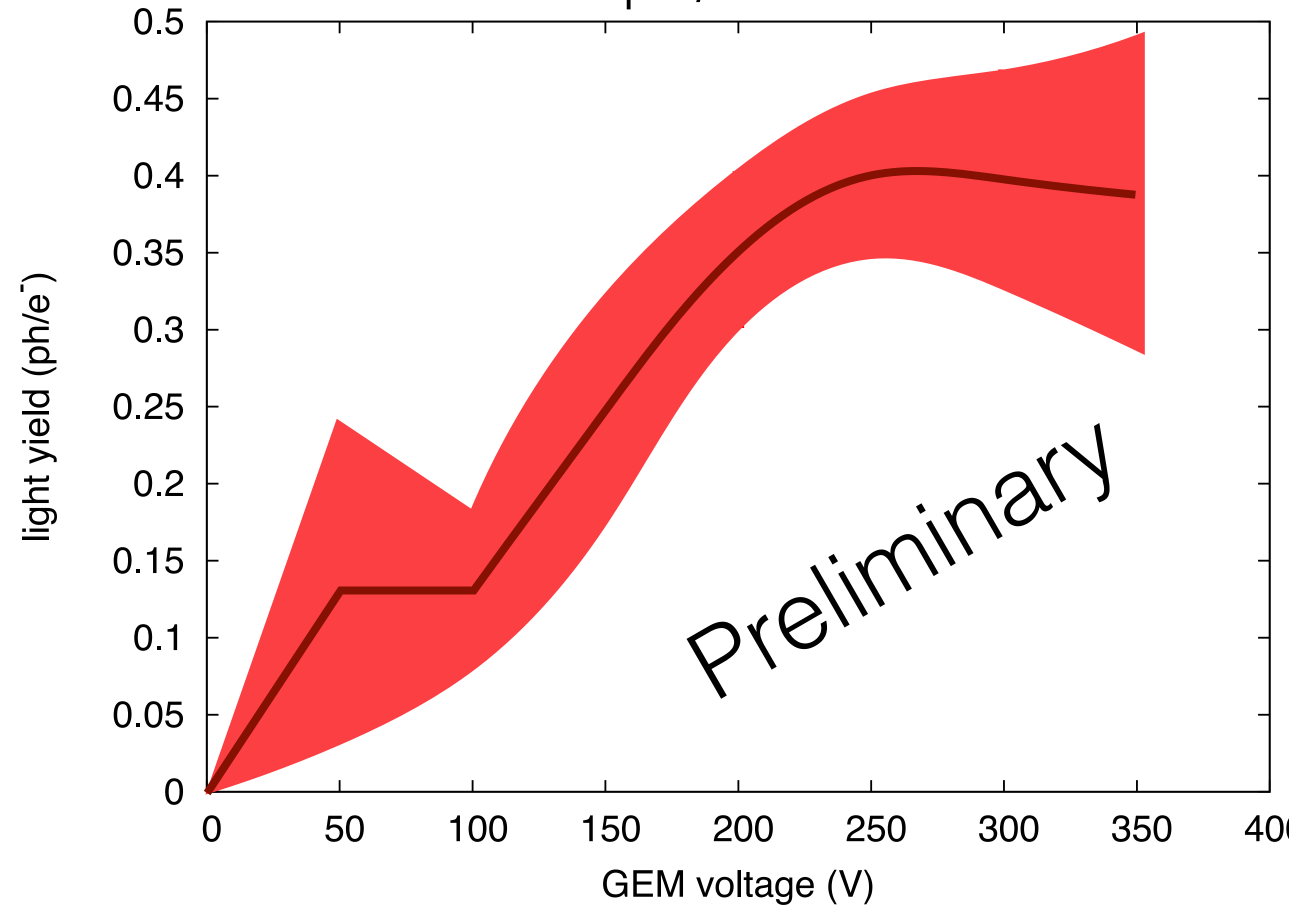
Ar/CF_4 80/20 scintillation

Plexiglass cuts below 400 nm



Nicely overlapping with CCD efficiency curve

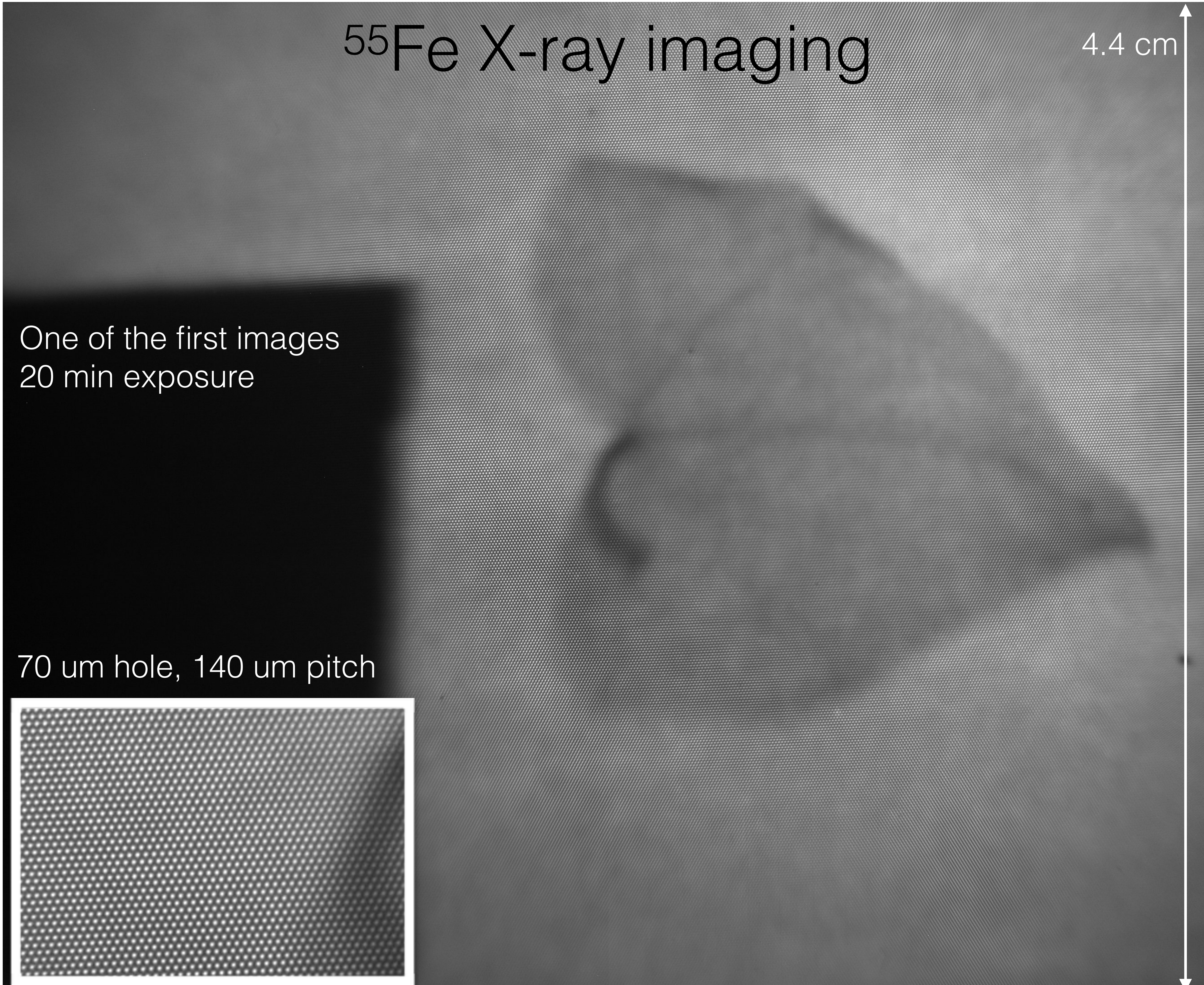
About 0.4 ph/e$^-$ in the visible



High charge gain -> high light gain

Light yield comparison
NaI: ~40 ph/keV
GEM at a gain of 10^5: ~10^6 ph/keV

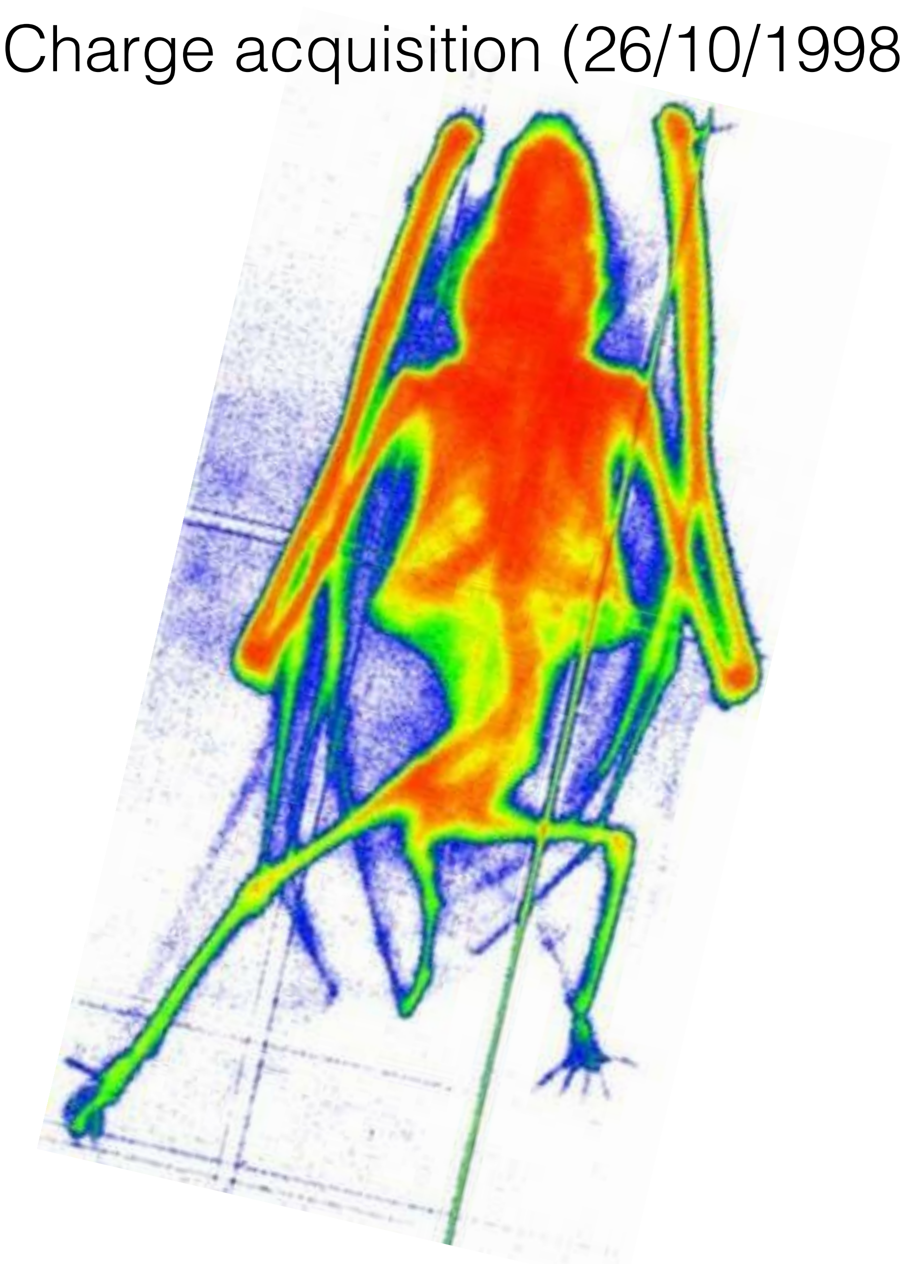
^{55}Fe X-ray imaging



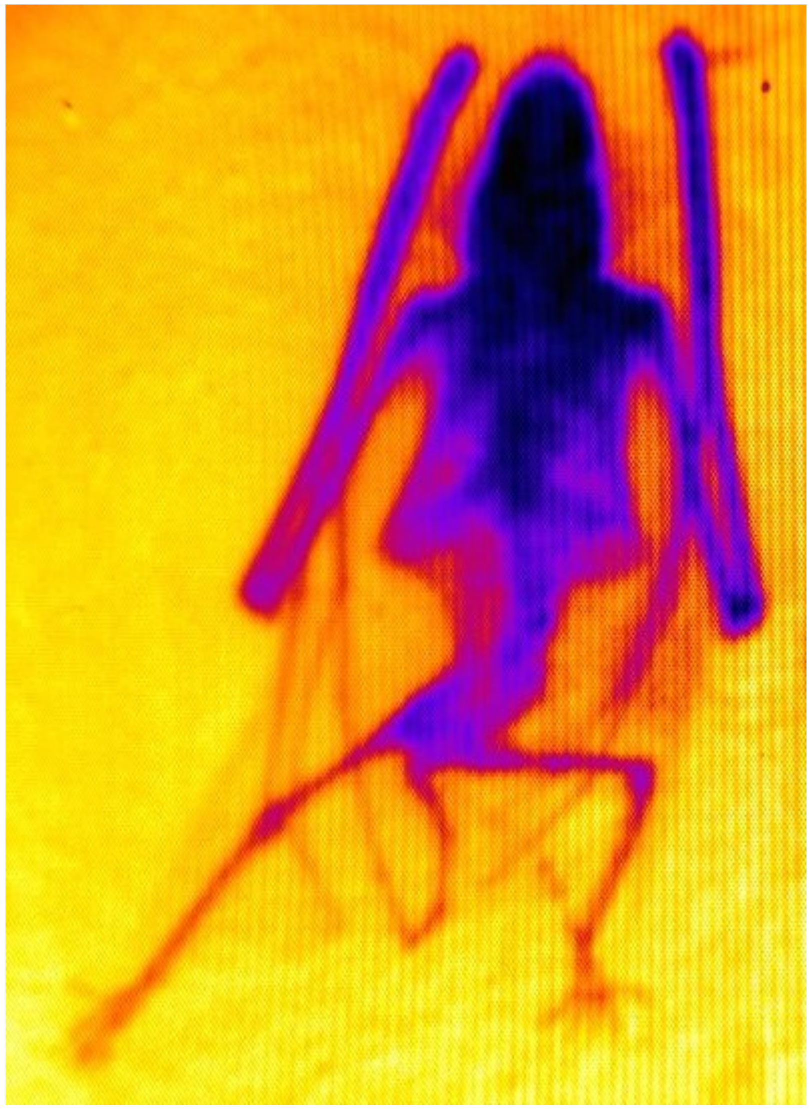
X-ray images

X-ray tube with W target at 20 kV - 40 kV at few mA

Charge acquisition (26/10/1998)



Light acquisition

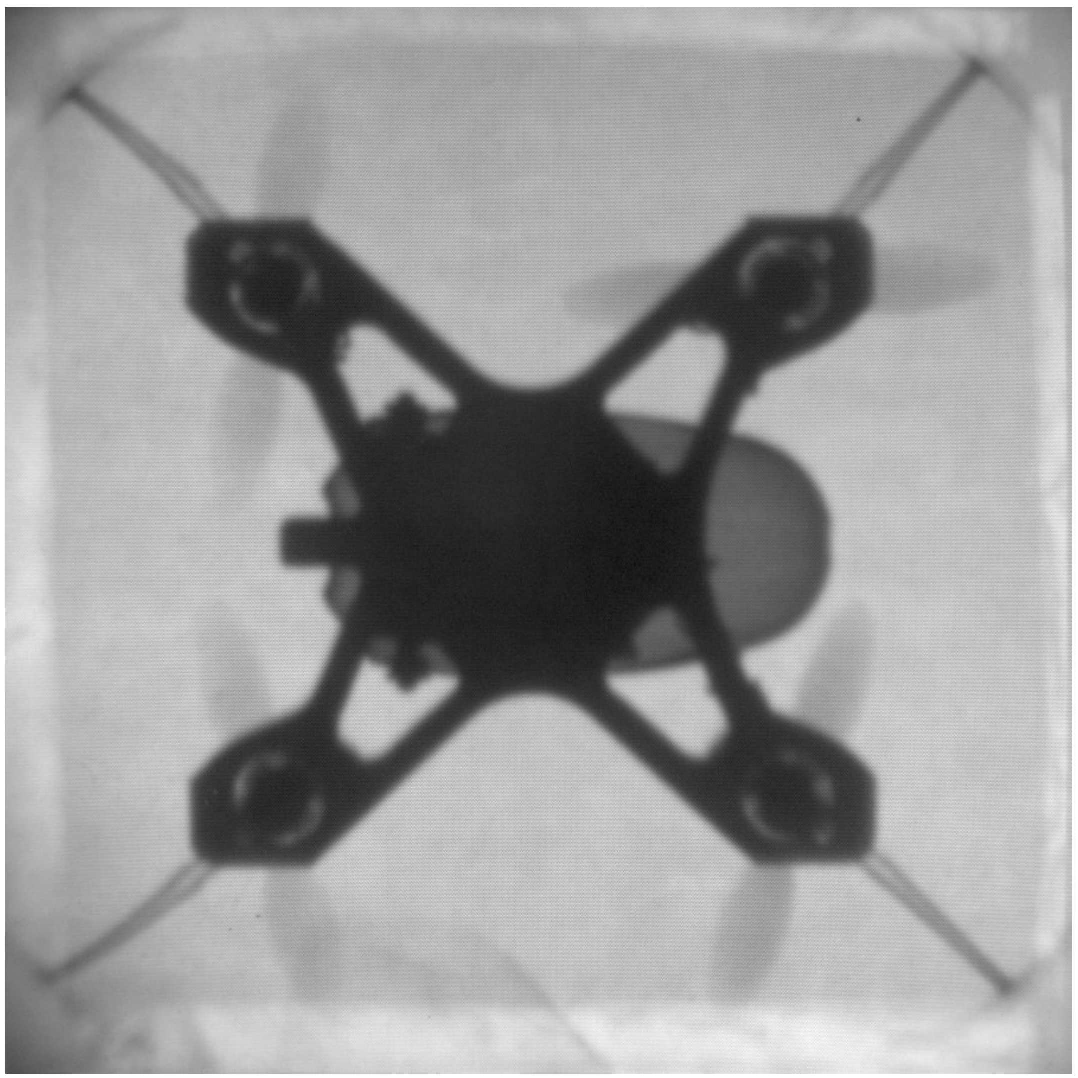


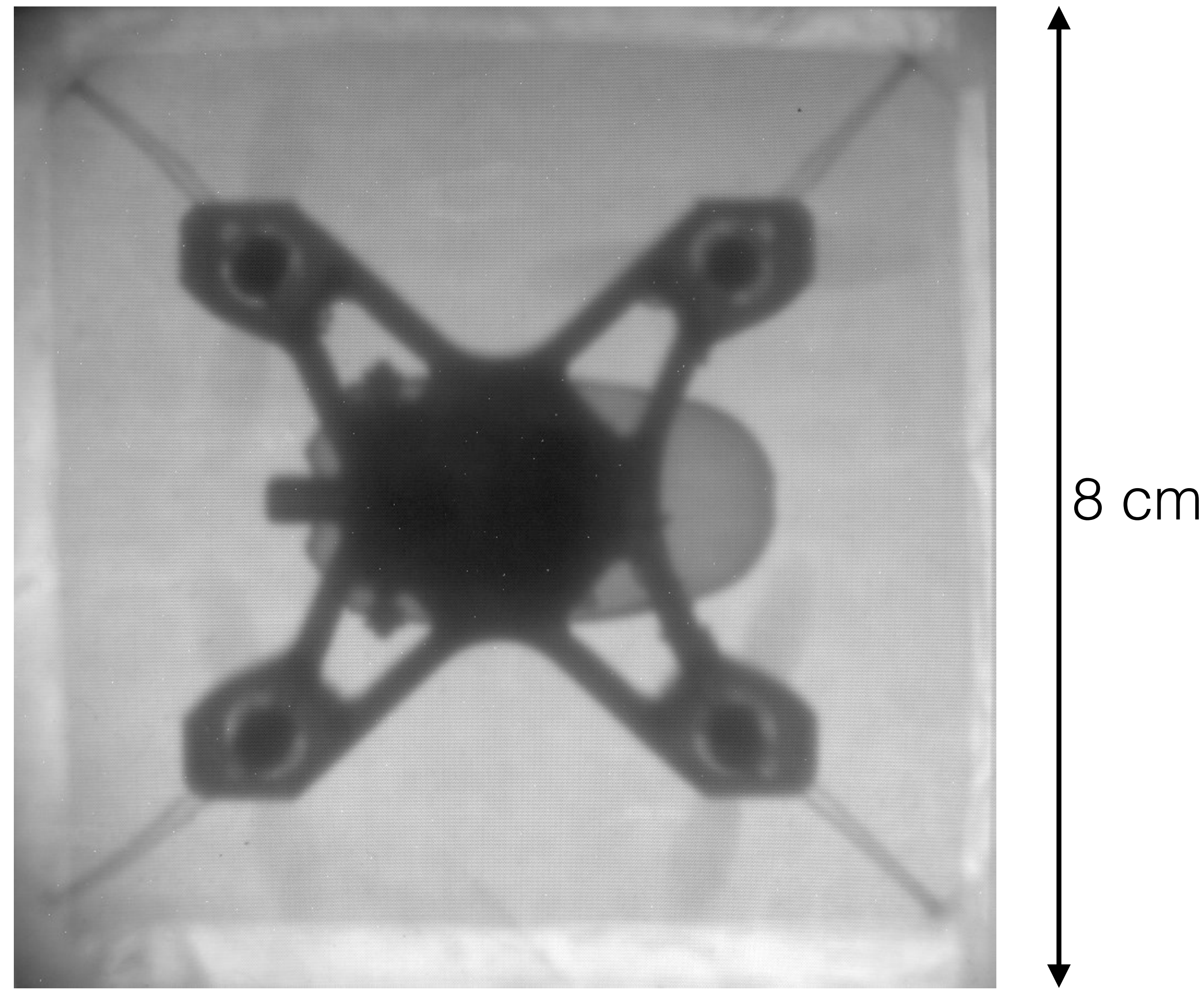
~7 cm

Raw data:
fast (<1 s) acquisition
and no processing time

X-ray images

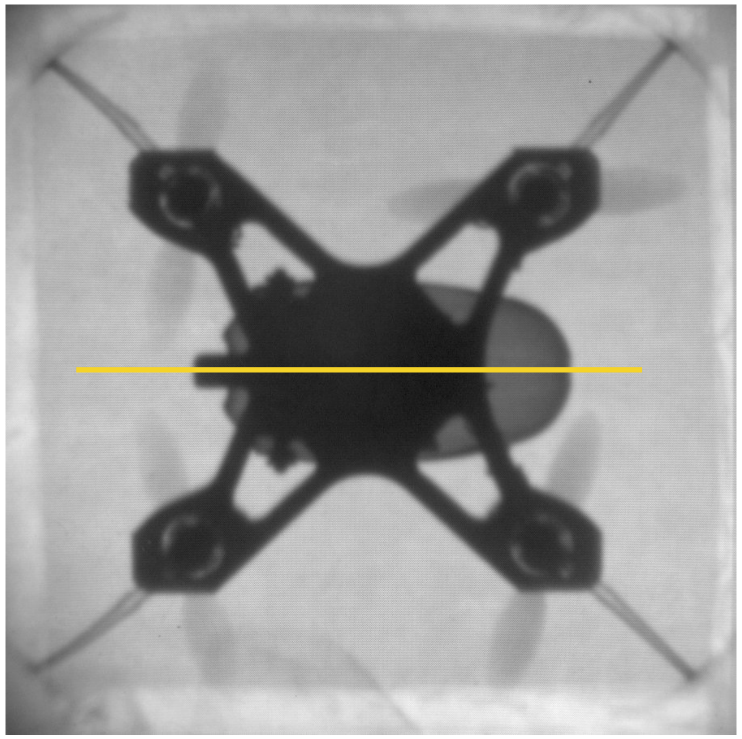
X-ray tube with W target

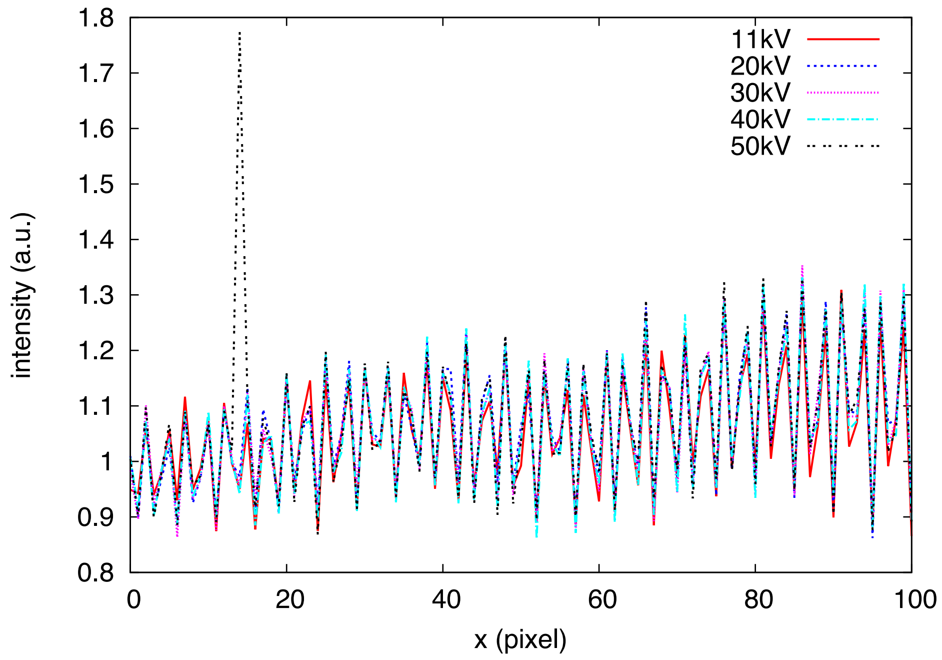


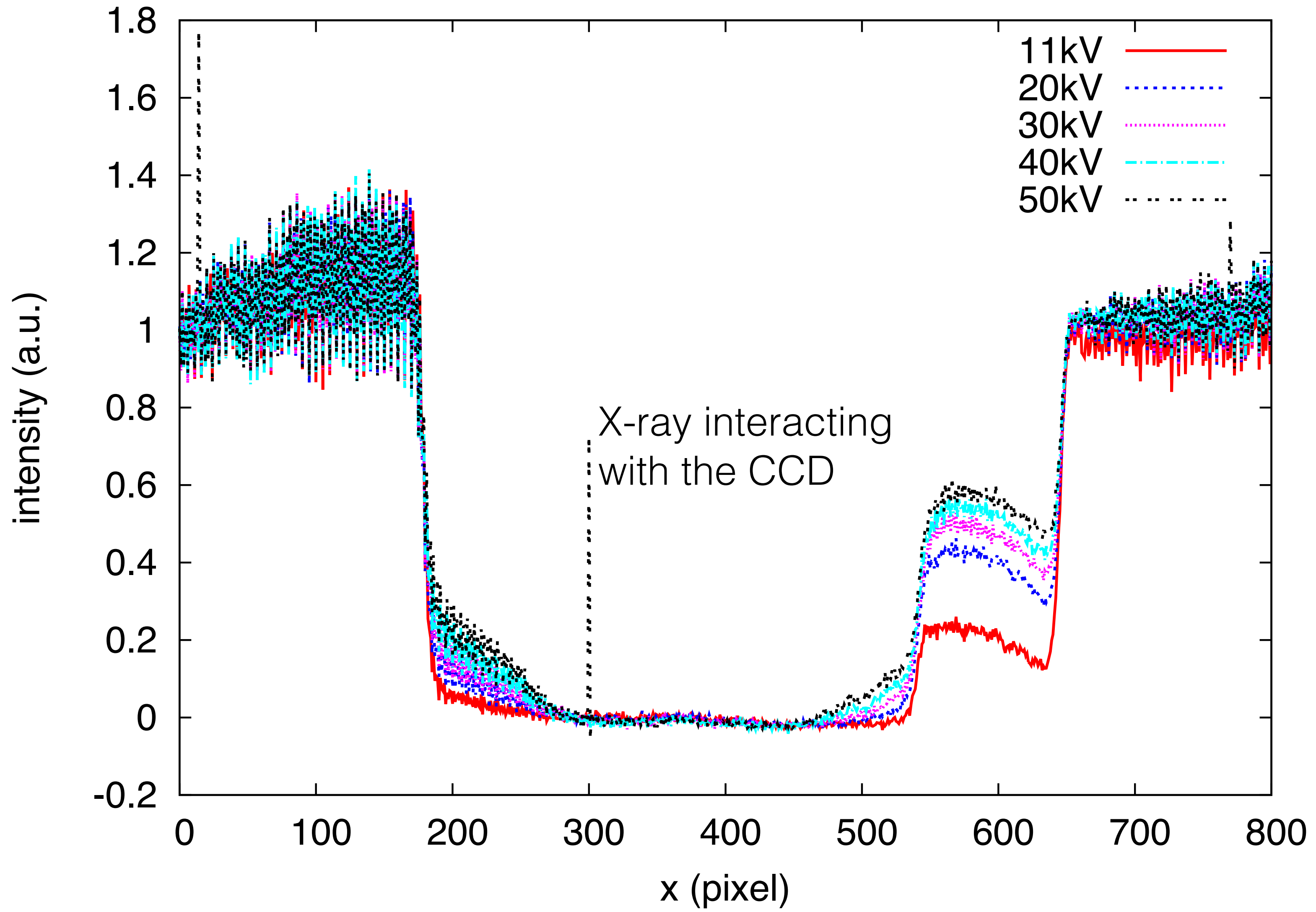


Straight out from the camera, no even the flat field correction

X-ray images







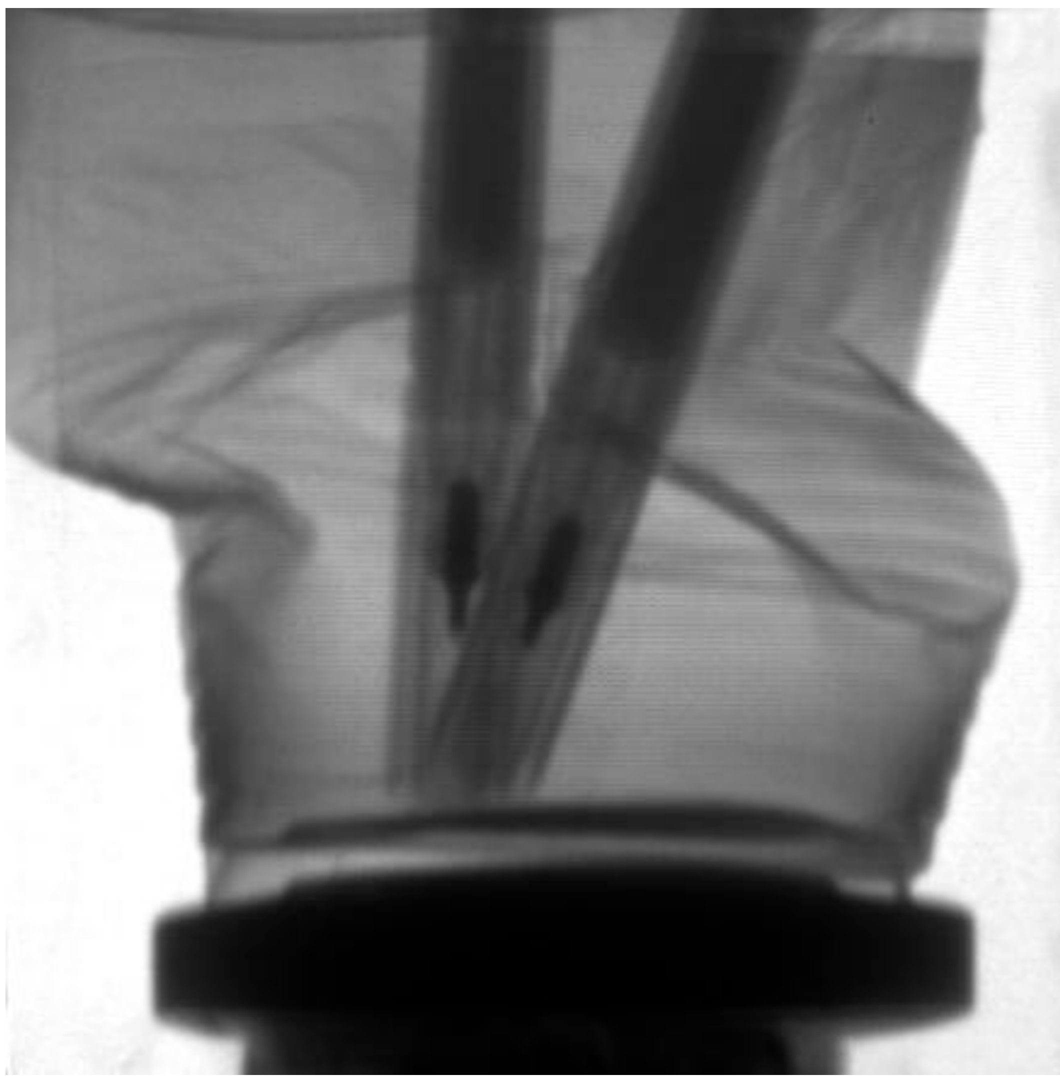
Increasing energy:
- Xray more penetrating
- Worse position resolution (larger charge cloud)

Fluoroscopy

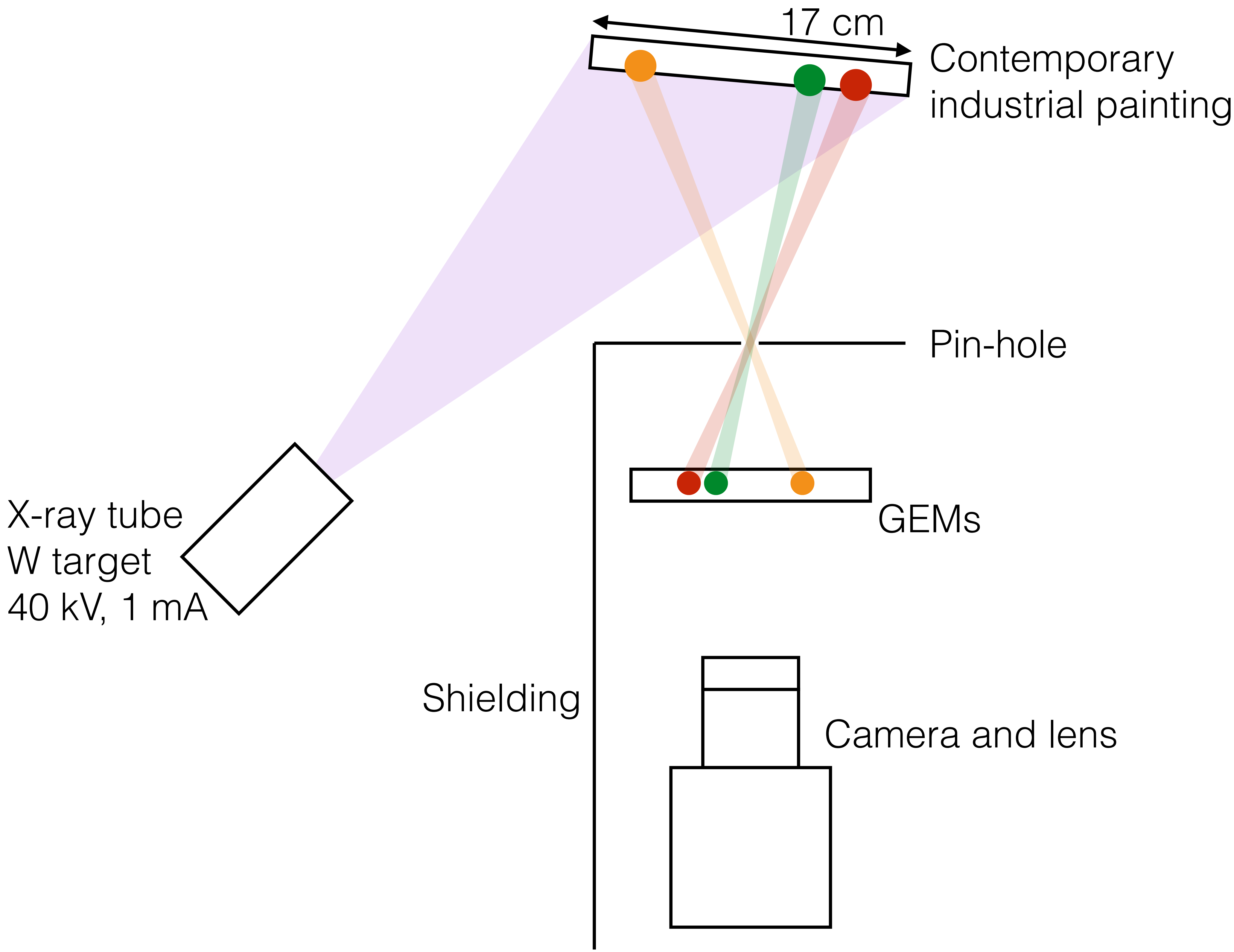
50 ms exposure
10 Hz acquisition

CT and 3D imaging

Image -> Sinograms -> Filtered Back Projection -> 3D image



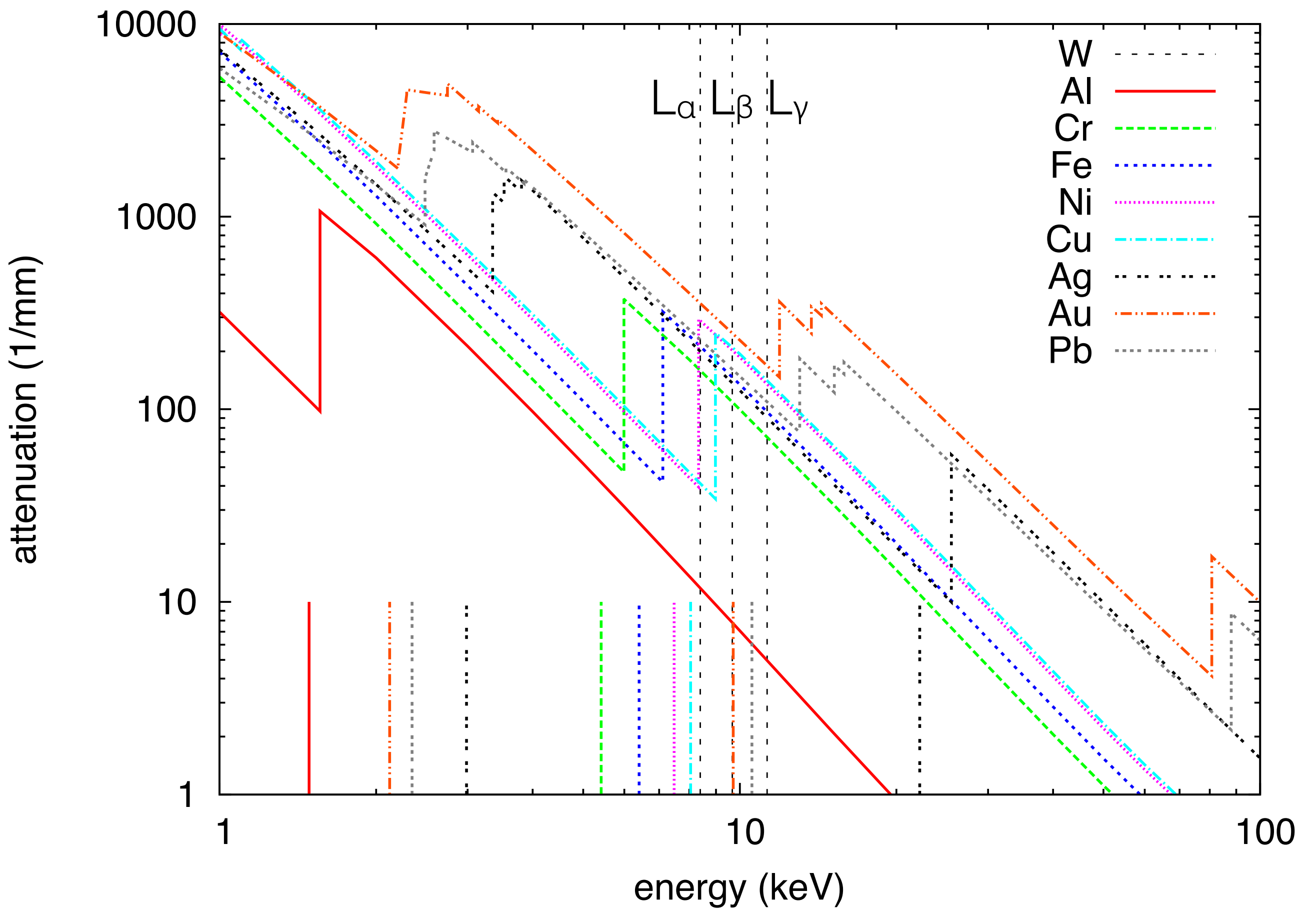
Fluorescence

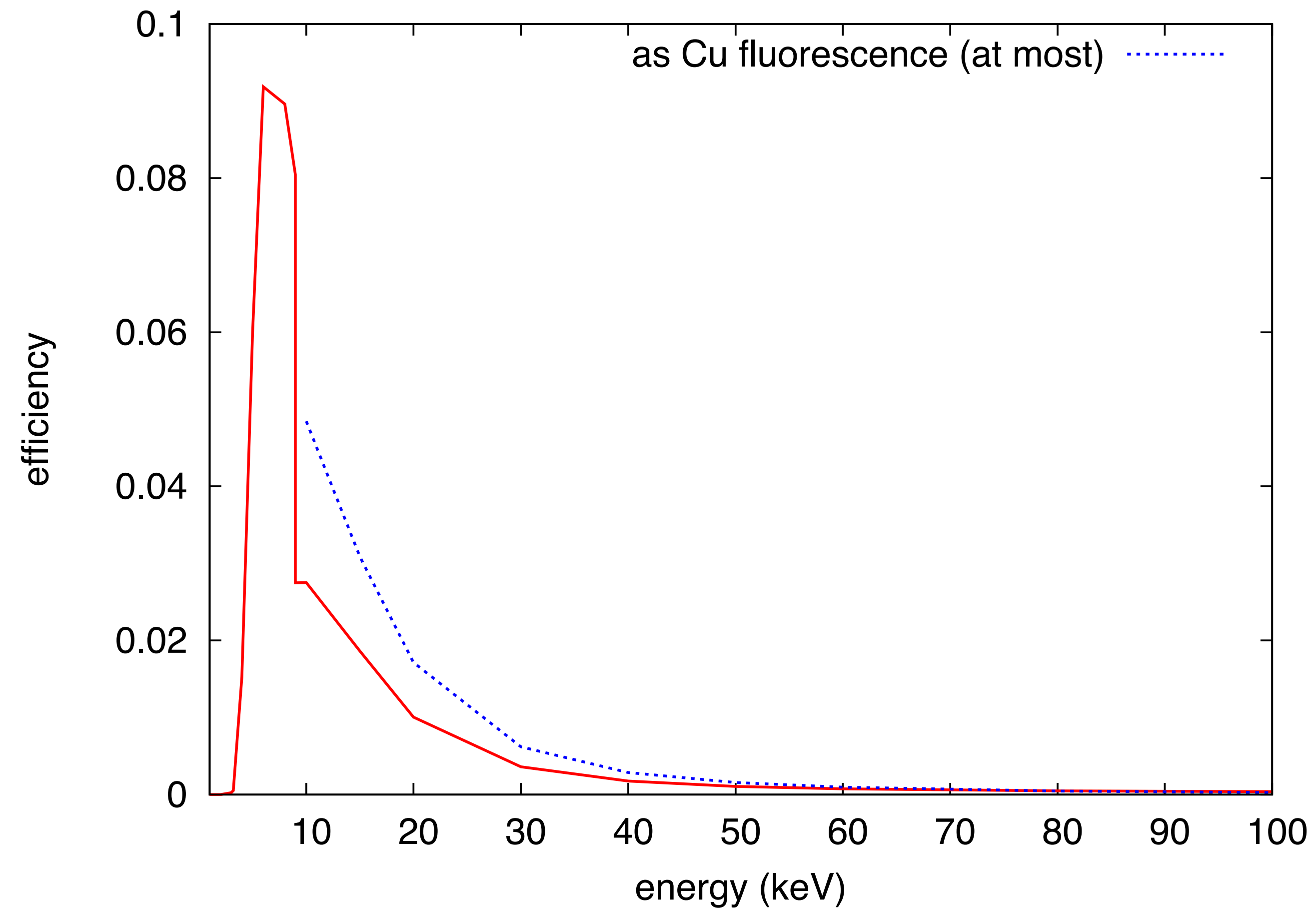


What should be expected

W target:
bremsstrahlung +
characteristic lines

Limiting factors (because not optimised):
- low energy -> window and cathode
- high energy -> gas



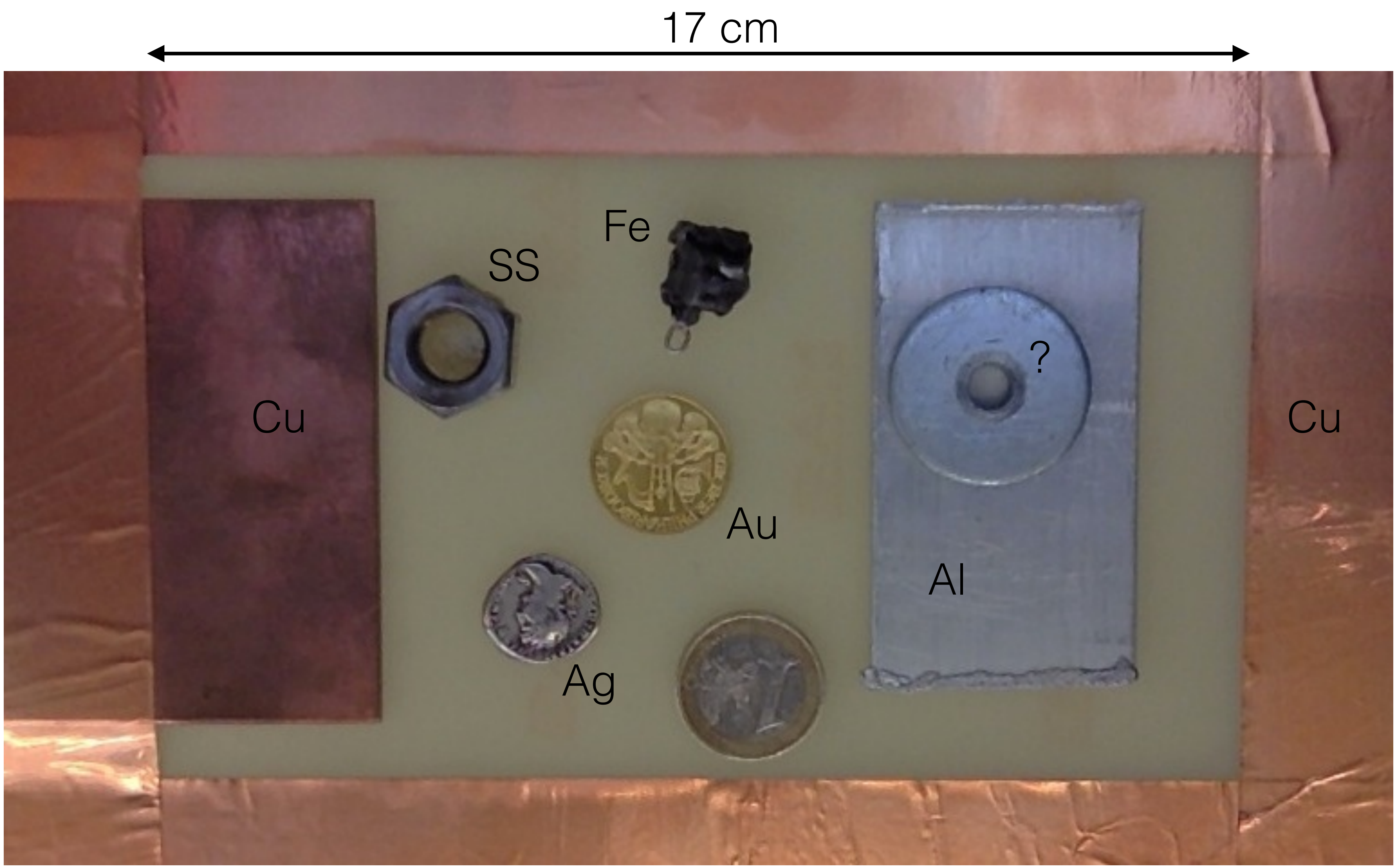


feasible:
Cr, Fe, Ni, Cu

difficult:
Au, Pb

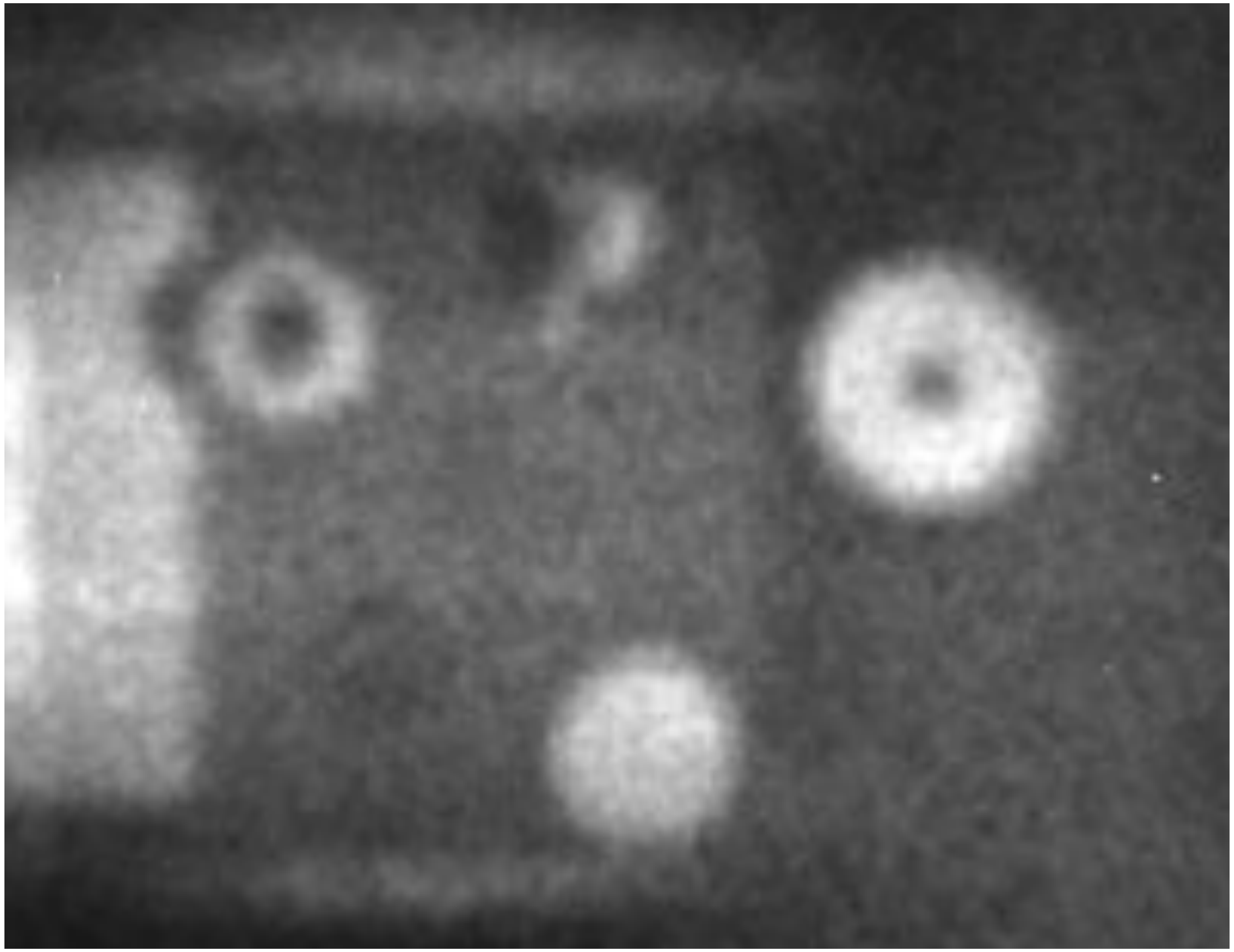
more difficult:
Al, Ag

The painting (visible)



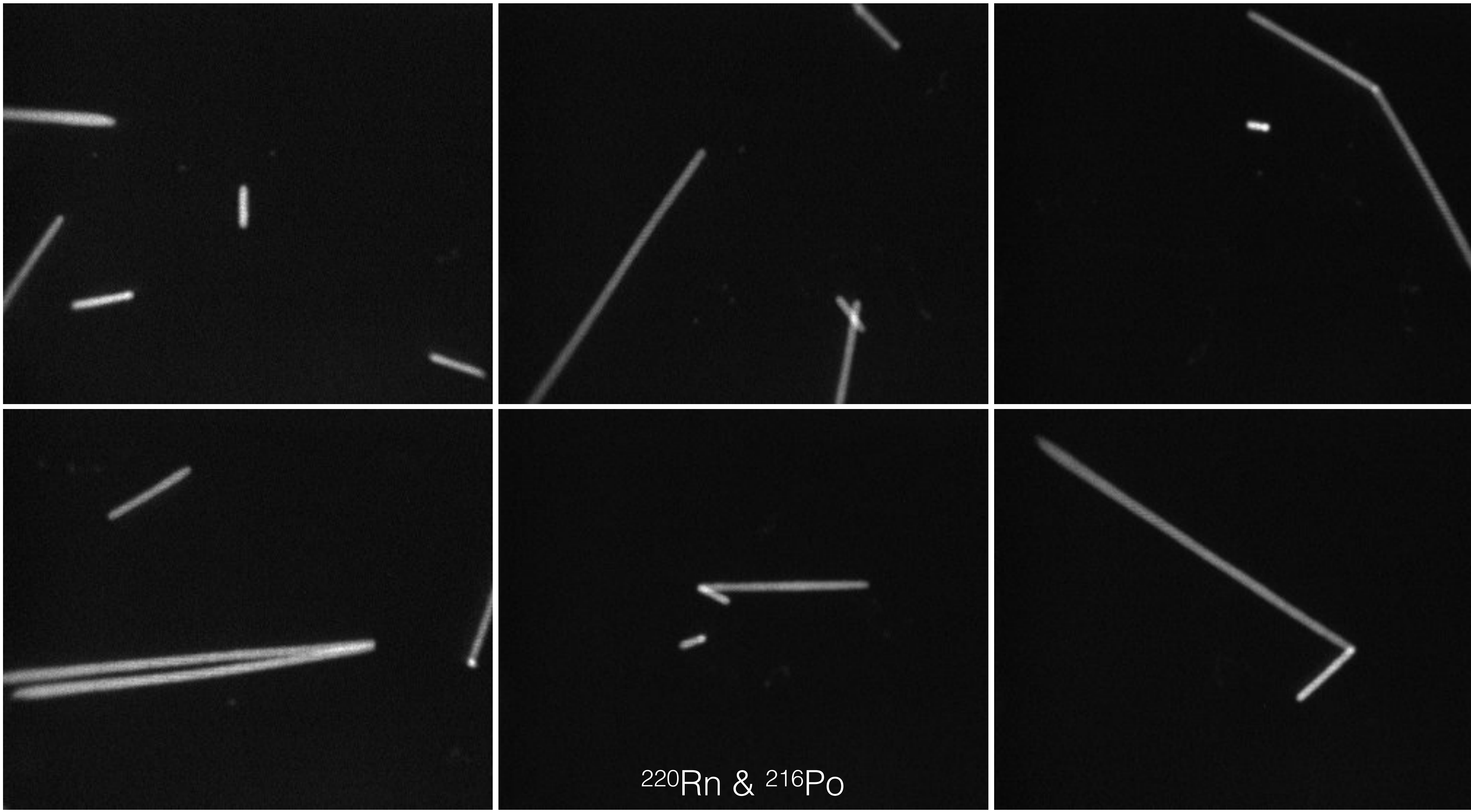
The painting (X-rays)

O(1 kHz) in 500 s exposure



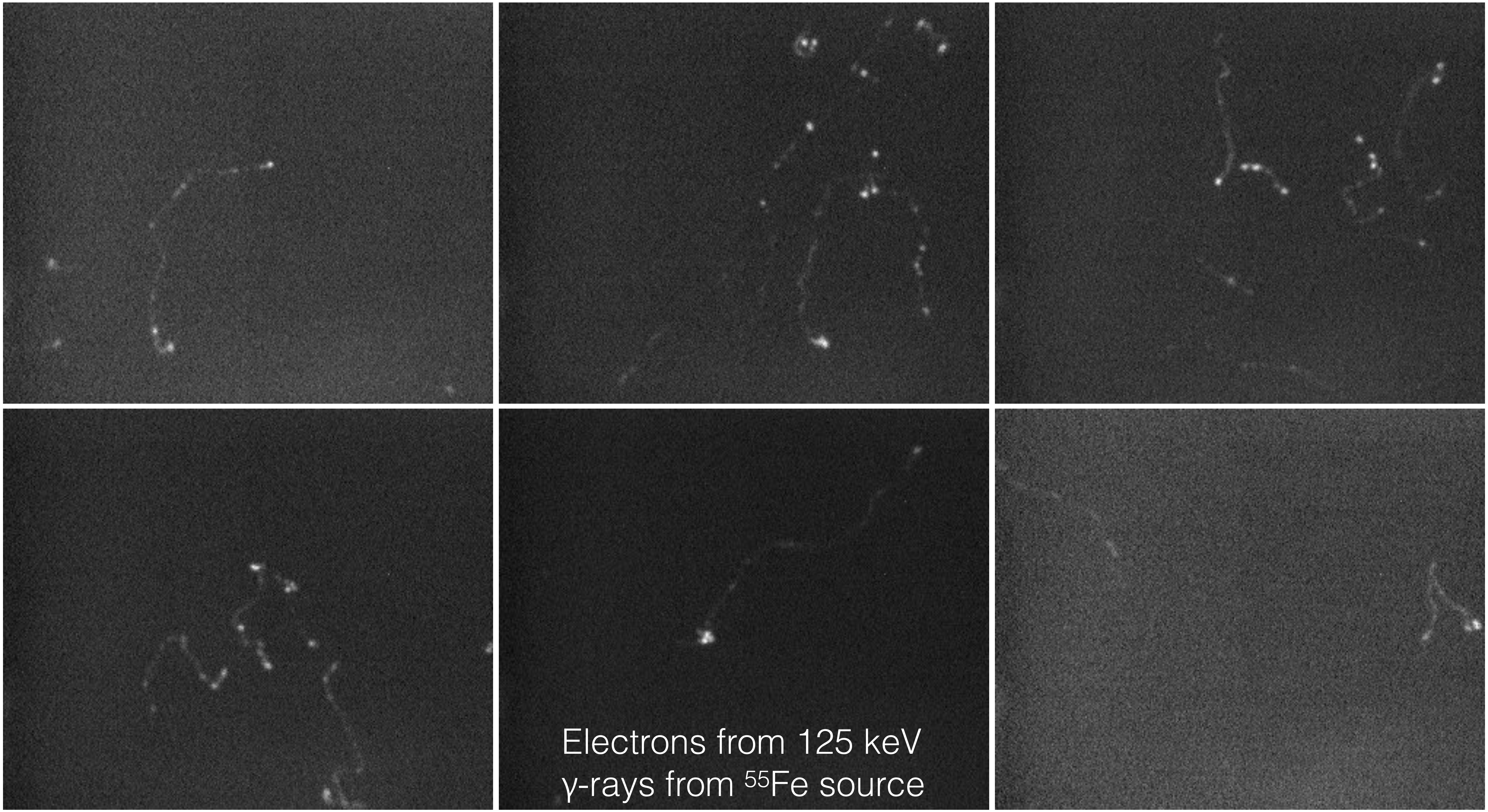
Event by event: alphas

Settable GEM gain: increasing it



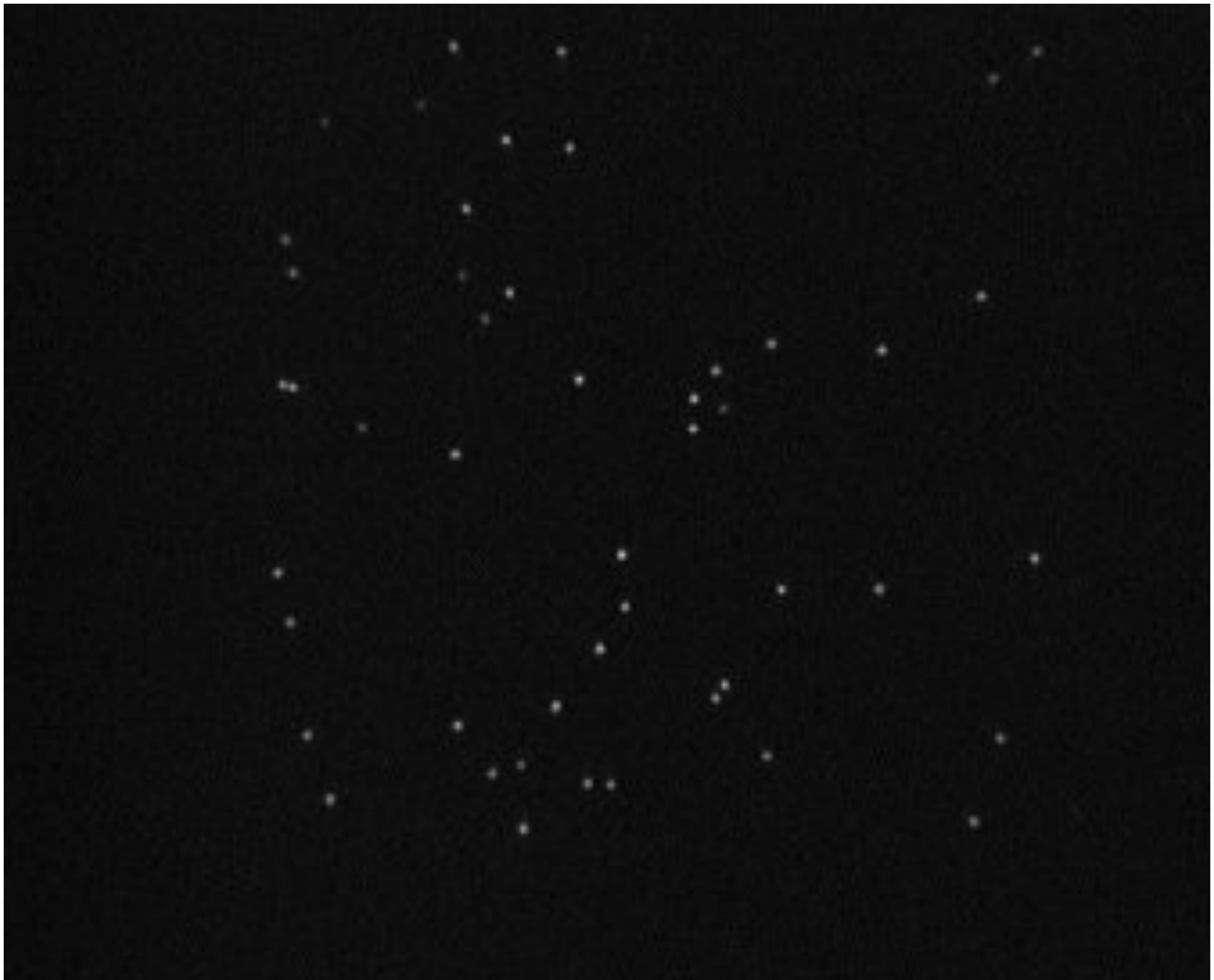
Event by event: electrons

Settable GEM gain: increasing it more

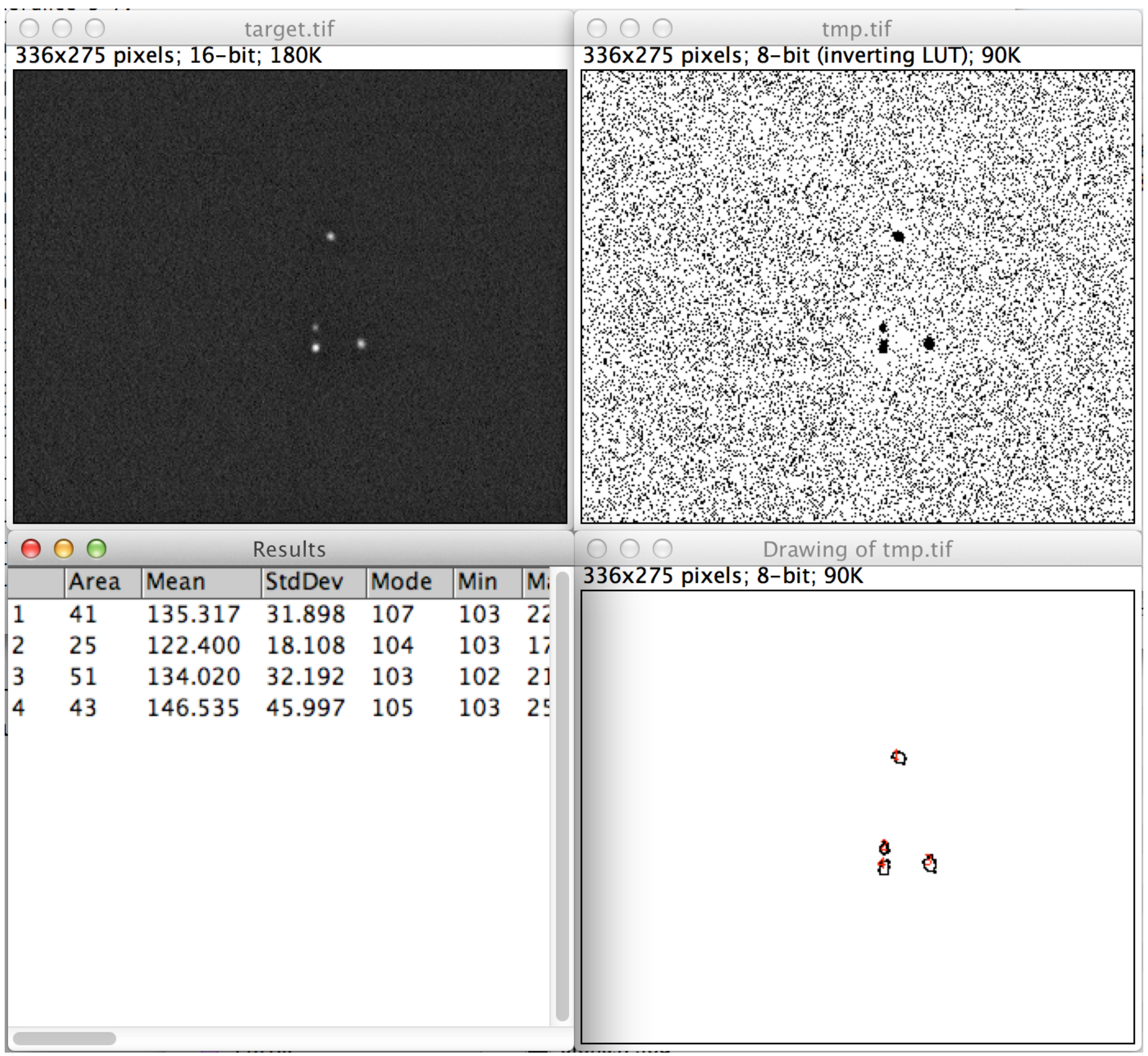


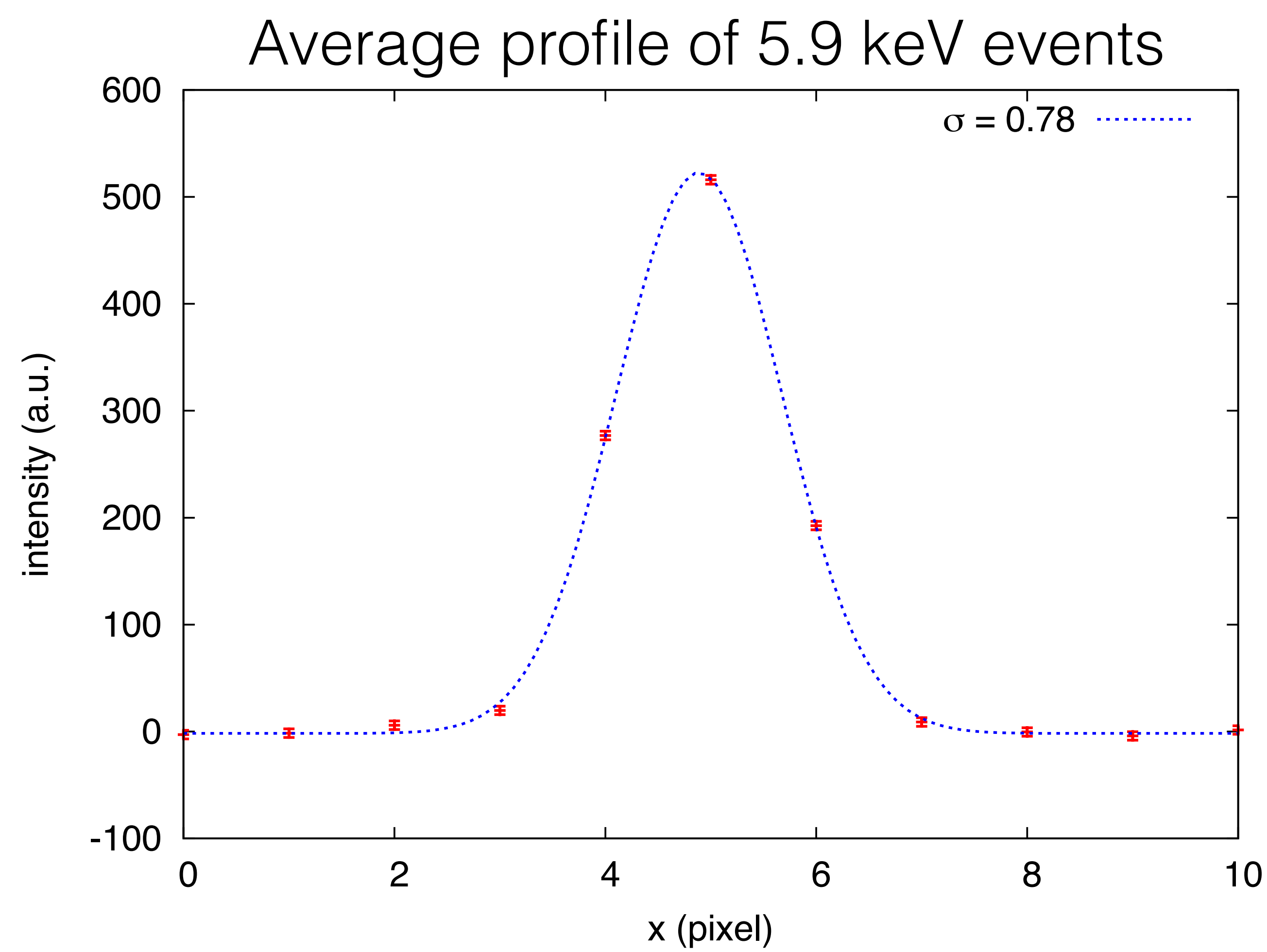
Event by event: X-rays

X-rays from ^{55}Fe source



Analysis of single clusters



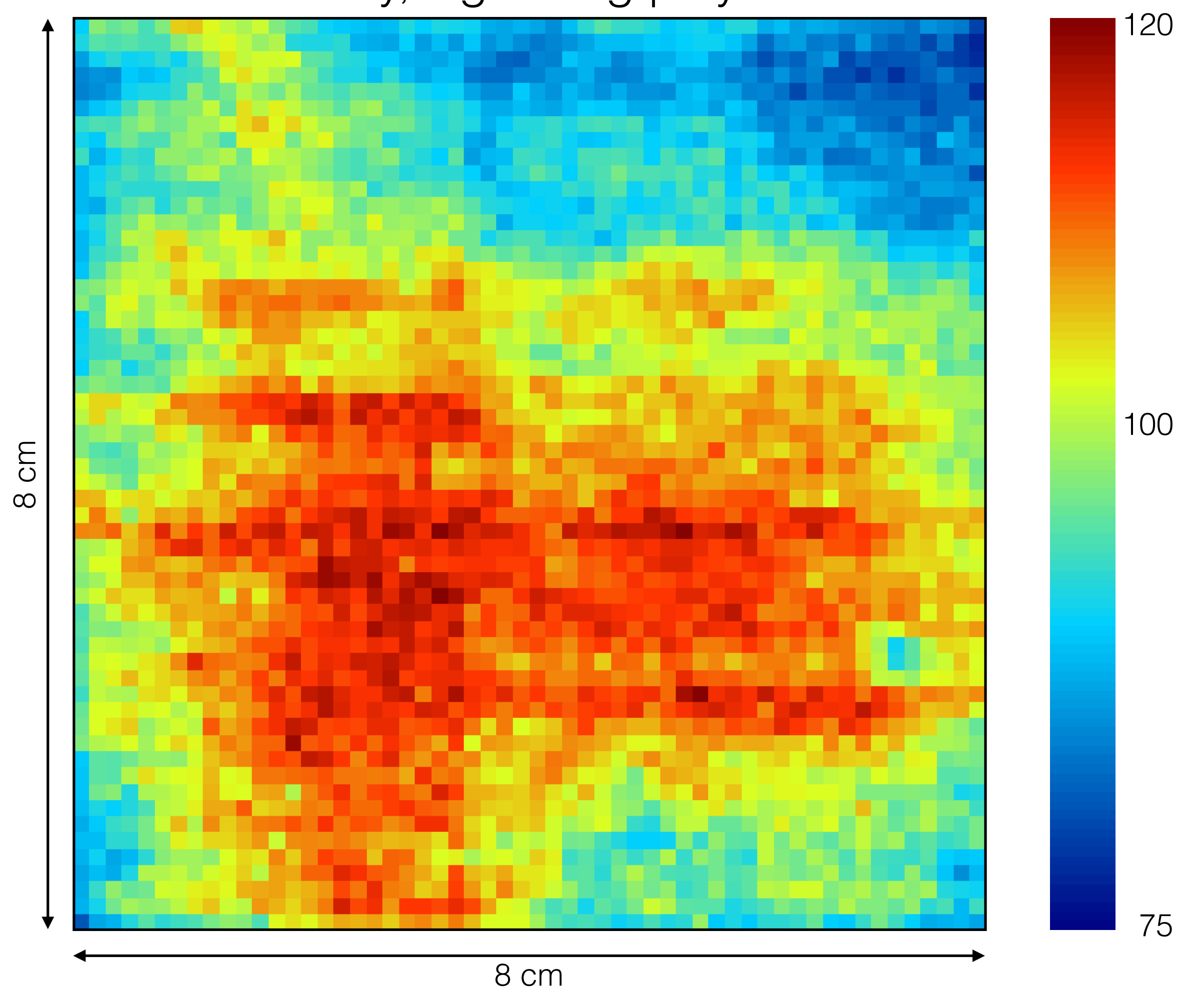


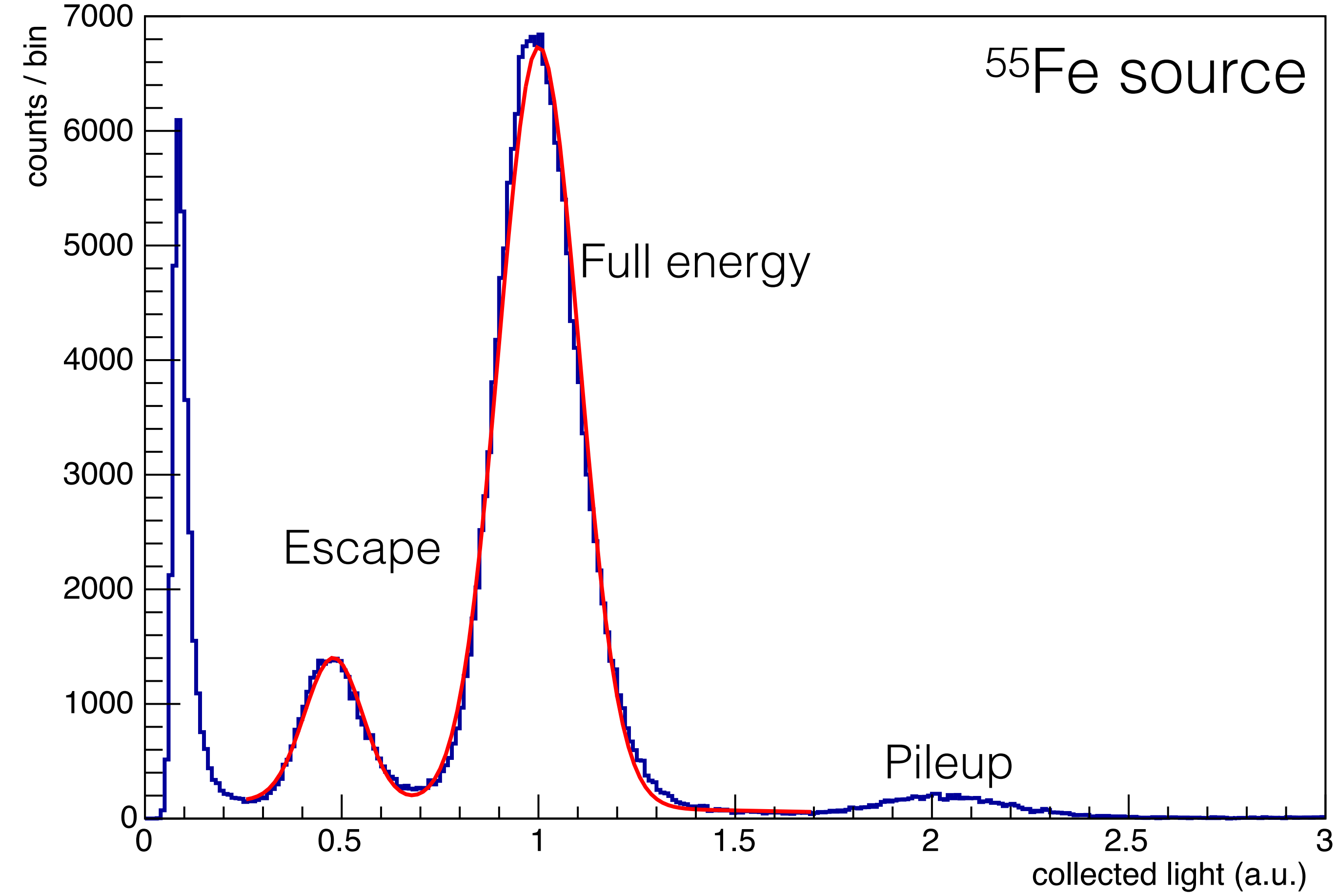
Spatial resolution in the limit of long exposure: 280 um for 1 cm drift and 5.9 keV X-rays. Dominated by e^- diffusion and cluster size.

Spatial resolution improves using the barycentre of the cluster

The spectrum
from CCD images

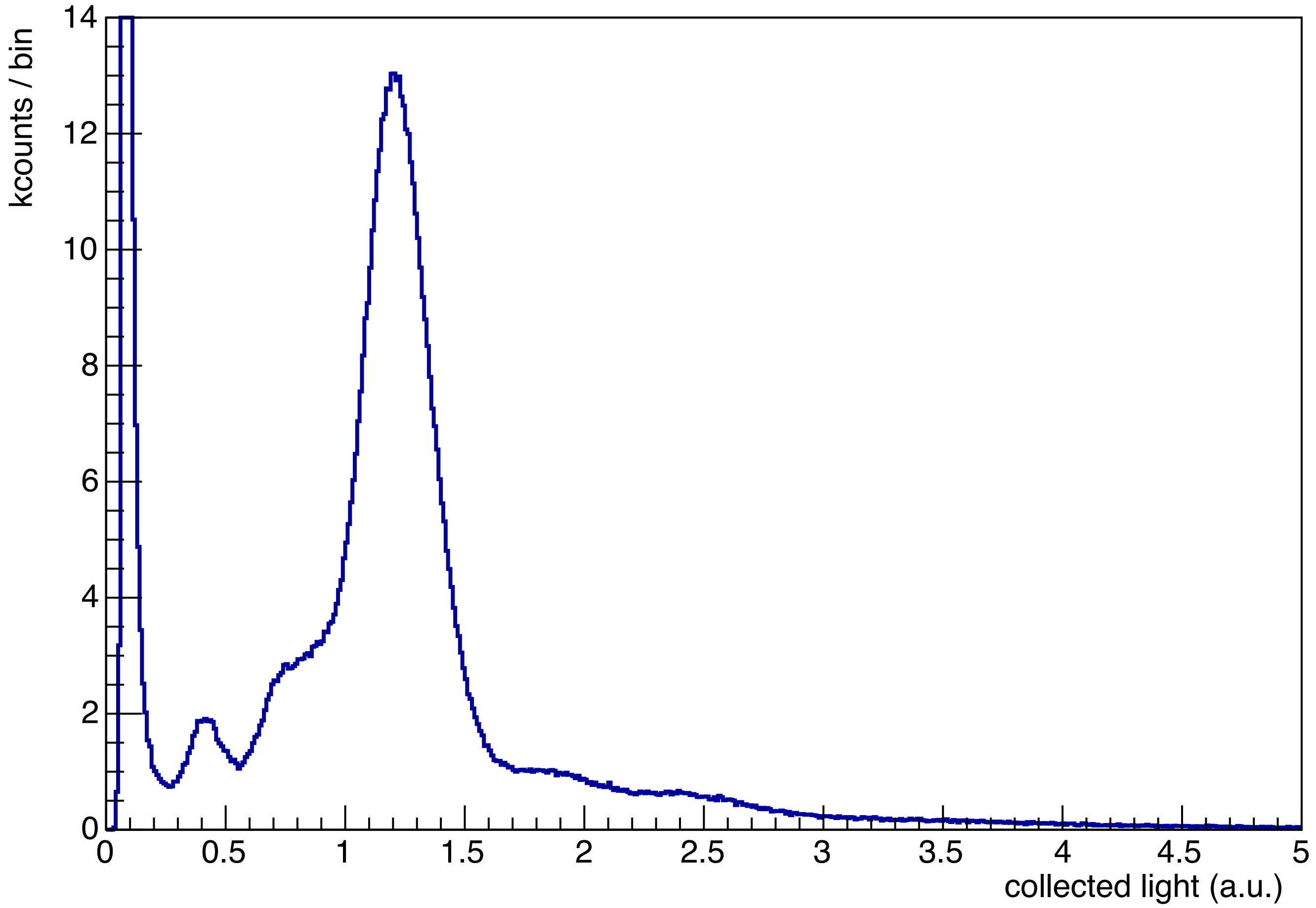
Gain uniformity, vignetting plays a role too

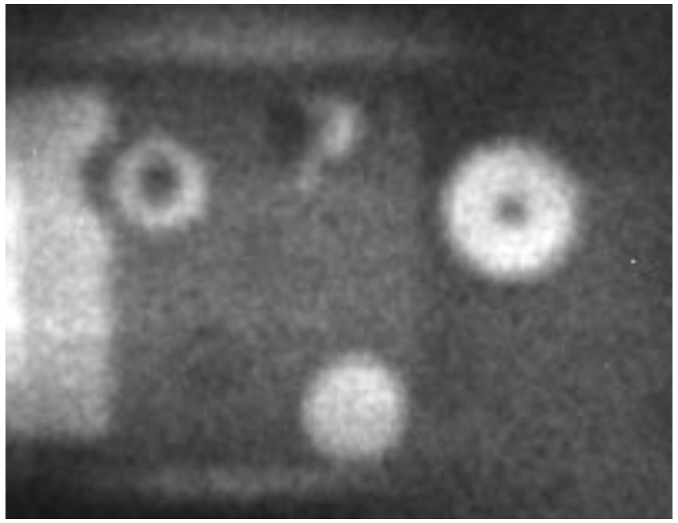


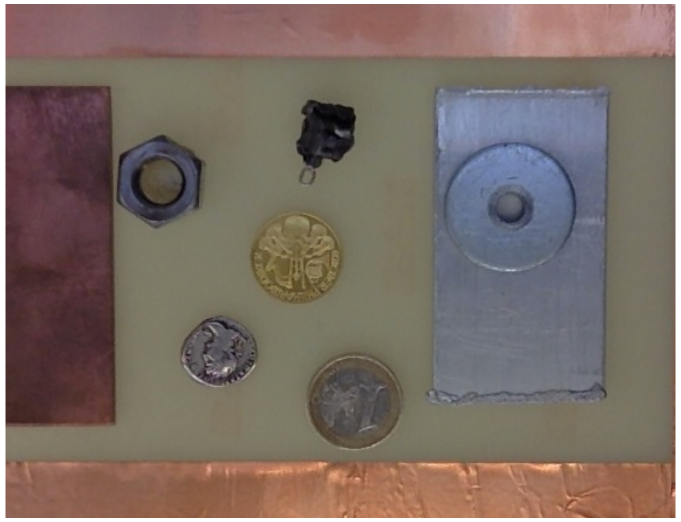


FWHM at 5.9 keV over 8x8 cm^2
~36% before gain uniformity correction
24.7% after gain uniformity correction

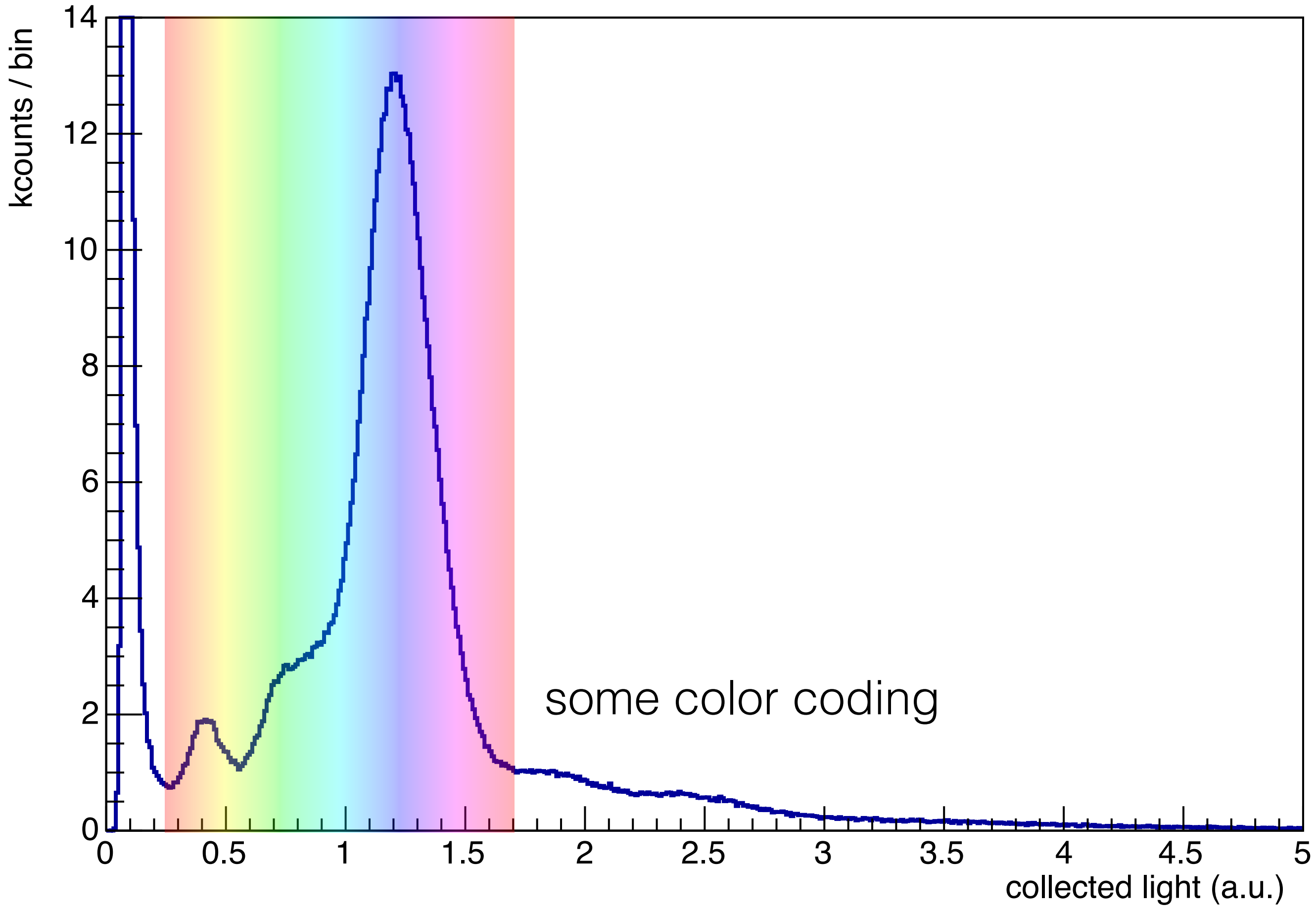
Fluorescence event by event

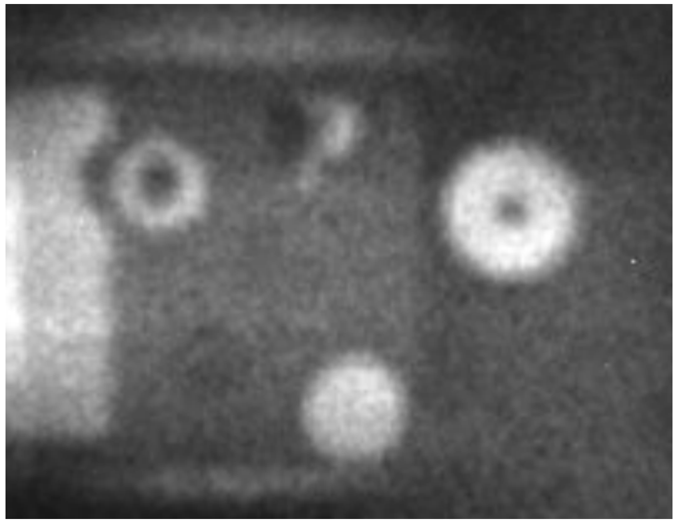


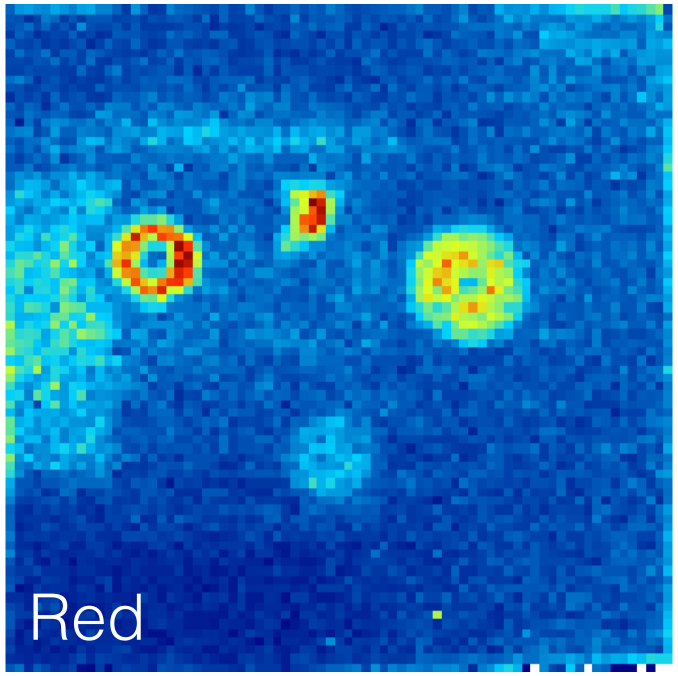


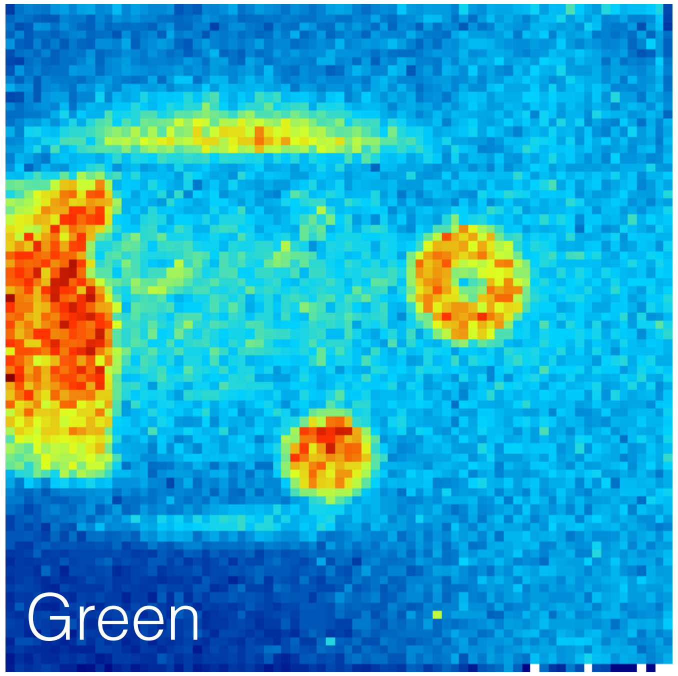


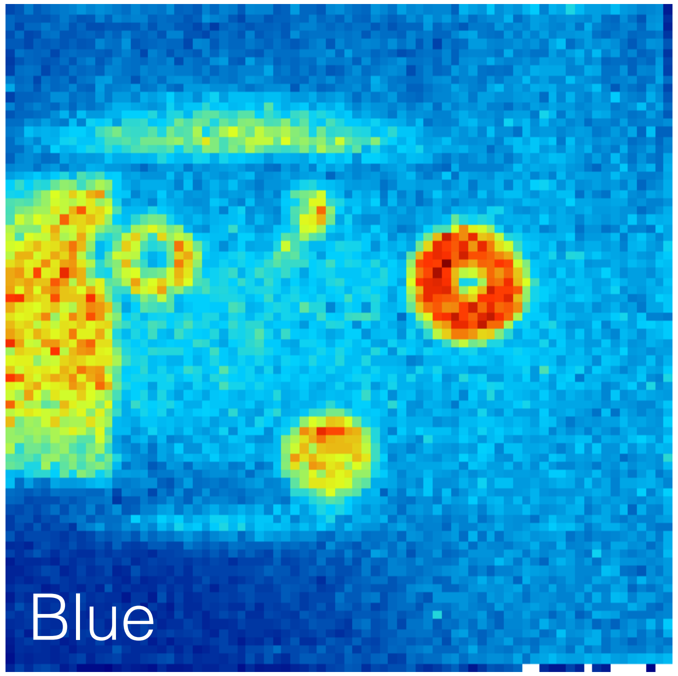
Fluorescence event by event



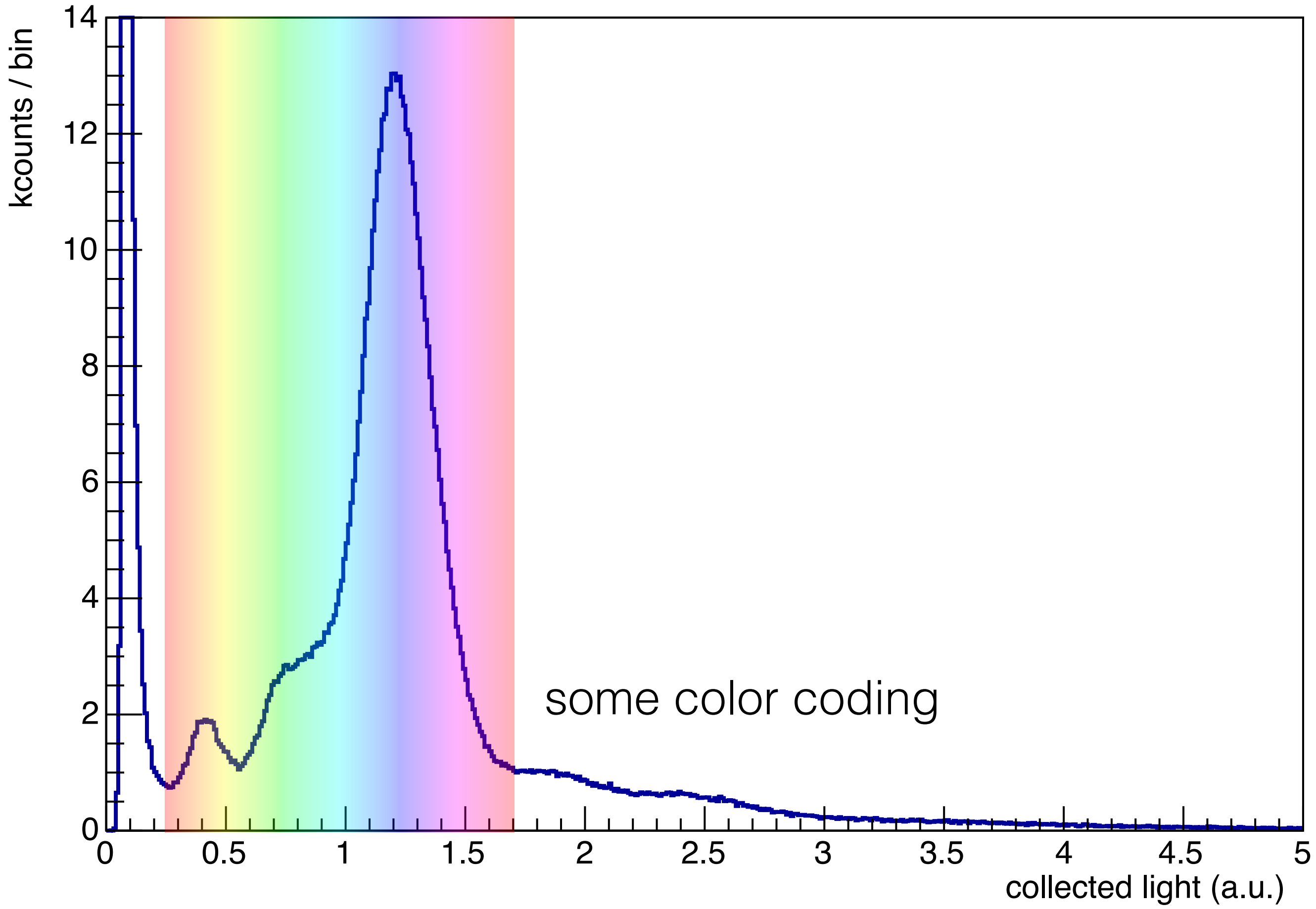


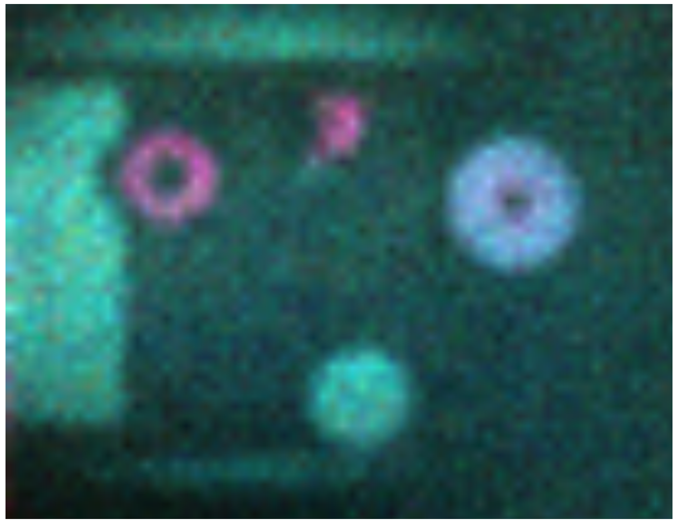


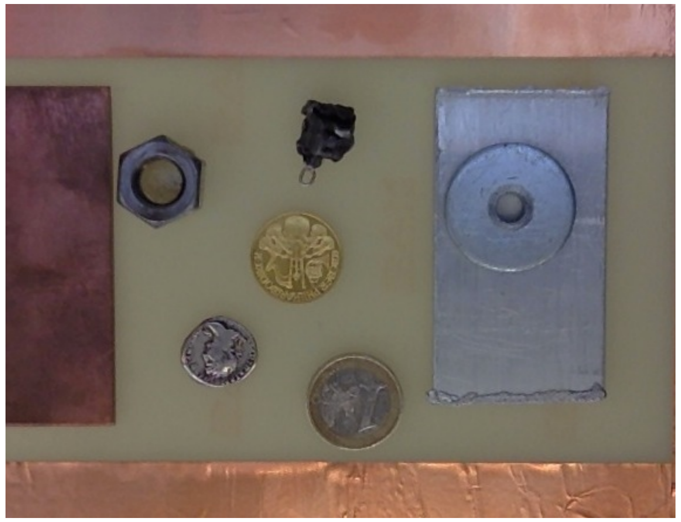




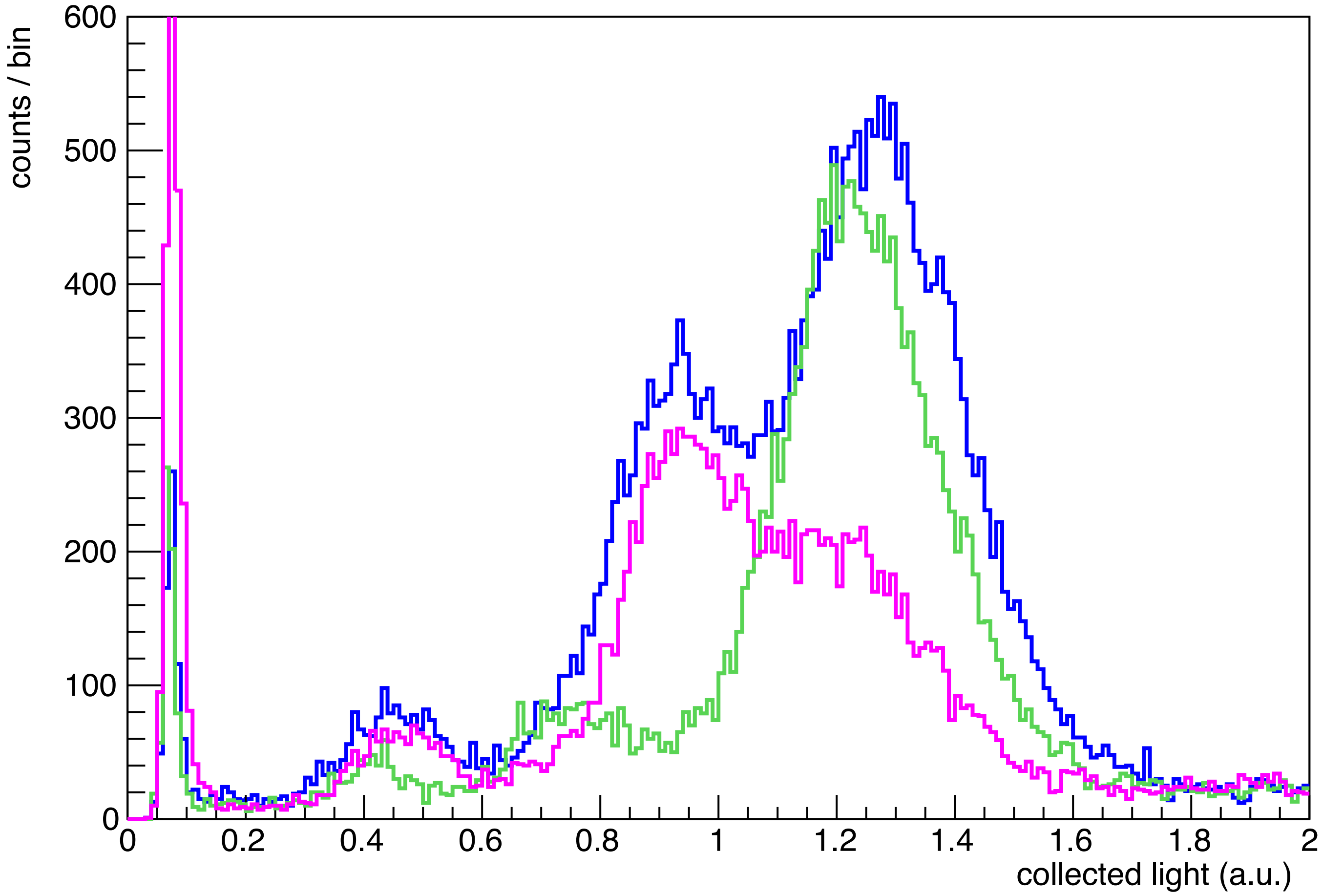
Fluorescence event by event

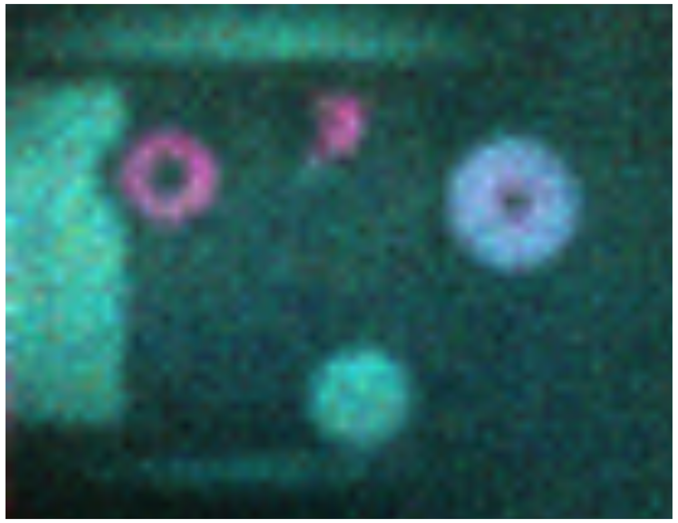


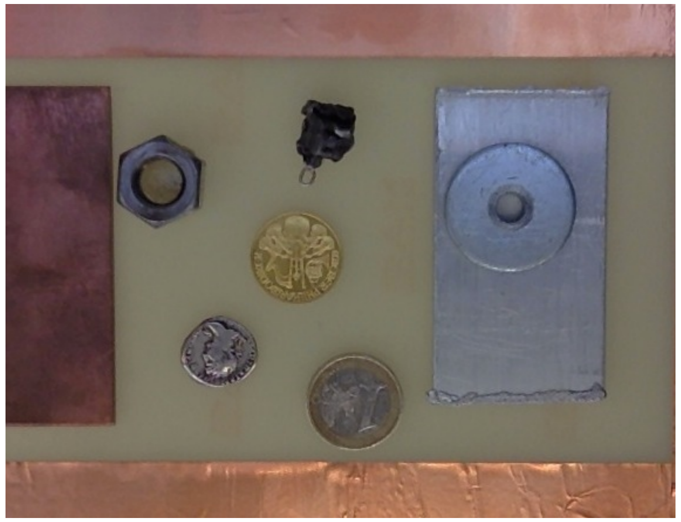




Fluorescence event by event







It’s Zinc

Overview

Relevant mechanisms for the operation of gaseous detectors

Imaging applications of MPGDs outside high energy physics

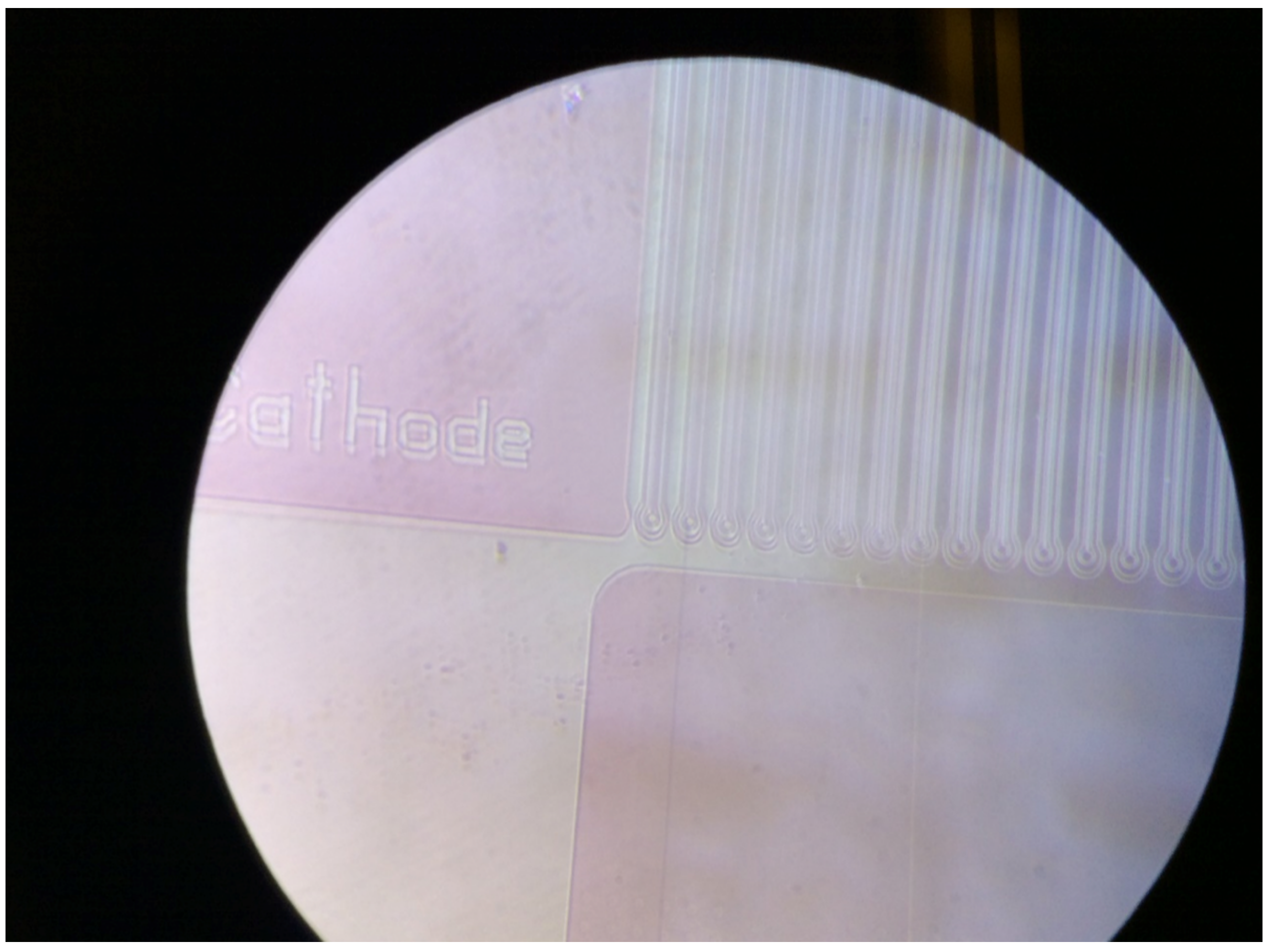
Developments of the optical readout for MPGDs at CERN

Possible other applications

Other kind of MPGDs?

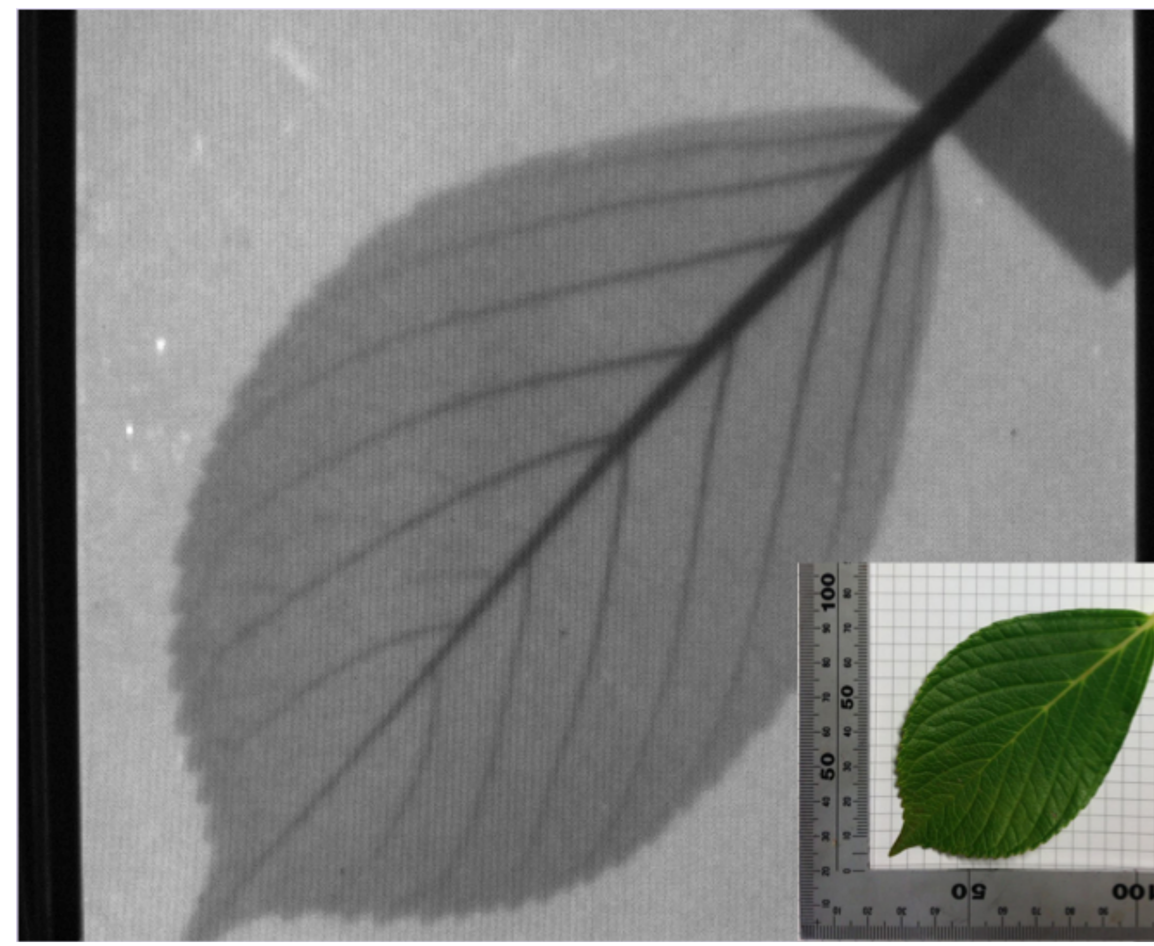
Developments not limited to triple GEMs

Transparent MSGC based on LCD technology



H. Takahashi, "Development of a transparent Single-grid-type MSGC based on LCD technology," MPGD2015

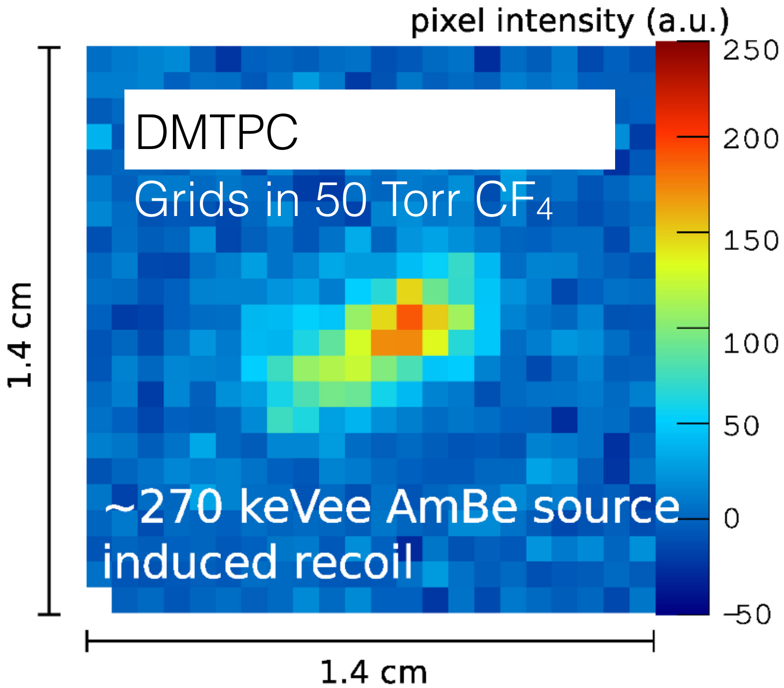
Scintillating glass THGEM



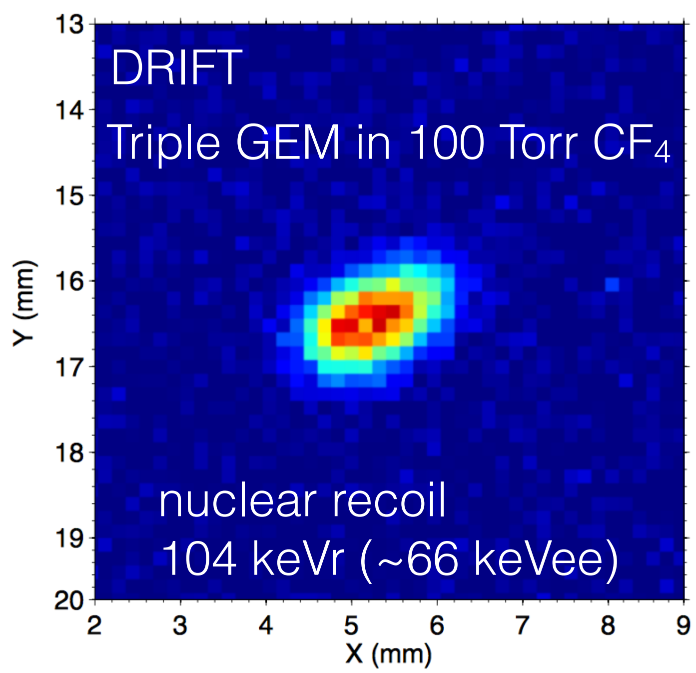
T. Fujiwara, "Development and application of Scintillating Glass-GEM detector," MPGD2015

TPC readout

Direction-Sensitive Dark Matter Searches with a low pressure CF_4 detector with optical readout.

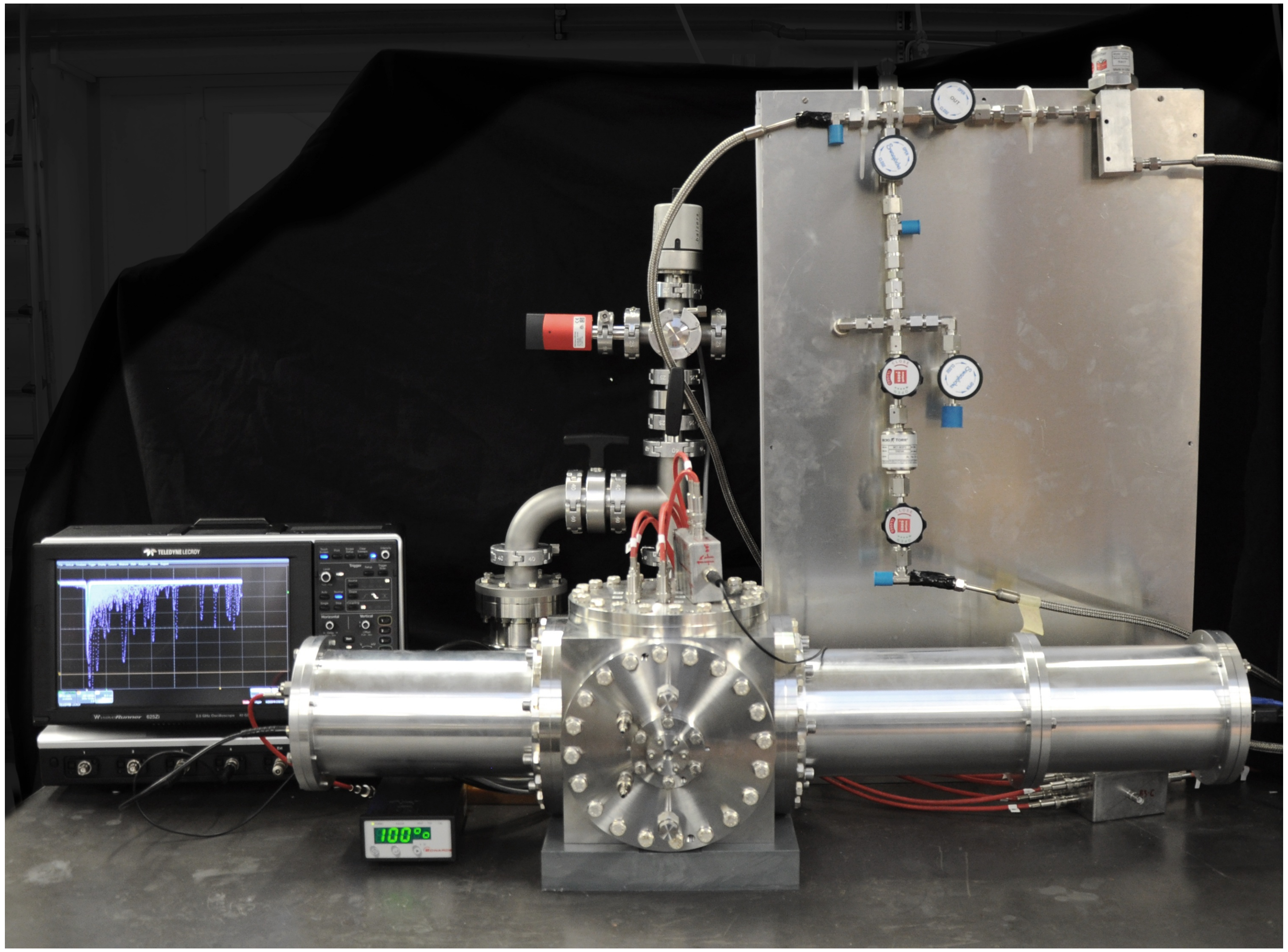


C. Deaconu *et al.*, Physics Procedia 61 (2015) 39



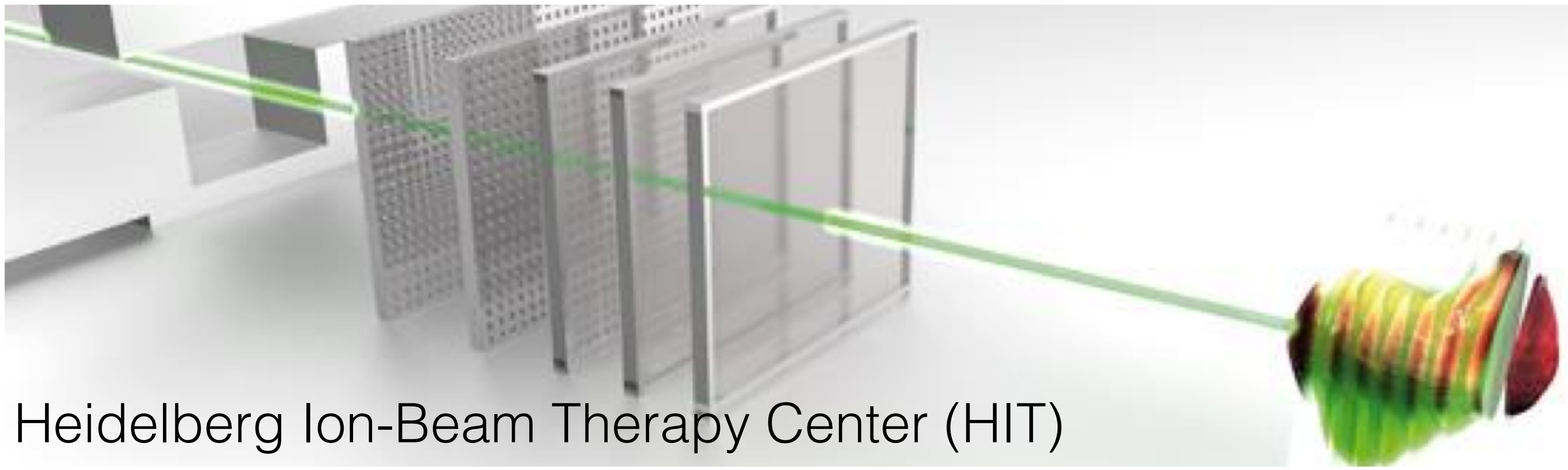
N. S. Phan *et al.*, arXiv:1510.02170

CERN/GDD development for studying scintillation in controlled conditions targeted to TPC readout with emphasis also on the primary scintillation.



Beam monitor

For instance for ion therapy beamlines



Heidelberg Ion-Beam Therapy Center (HIT)

B. Leverington private communication

Requirements

Fluxes: up to 10^9 Hz/beam size
Size: 32x42 cm^2
Material budget: <1.4 mm water equivalent
X and Y profiles + beam direction
Resolution: 200 um on the beam position
Readout rate: 4 kHz (challenging)
No deterioration in two years of operation
Beam shape (ellipticity) desired

Possible other application

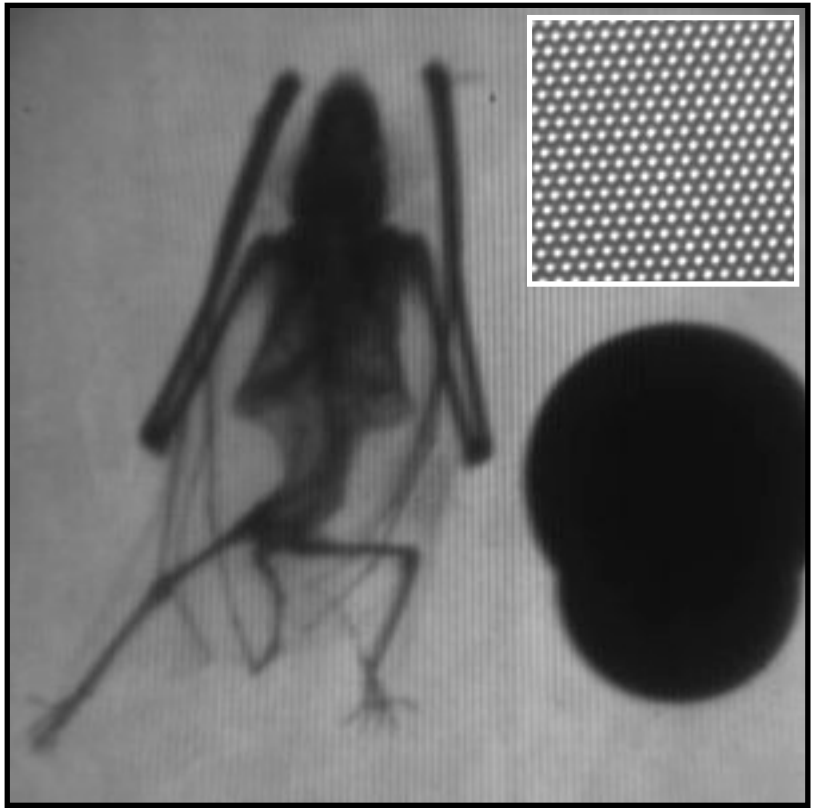
Crystallography

UV imaging

Neutron imaging

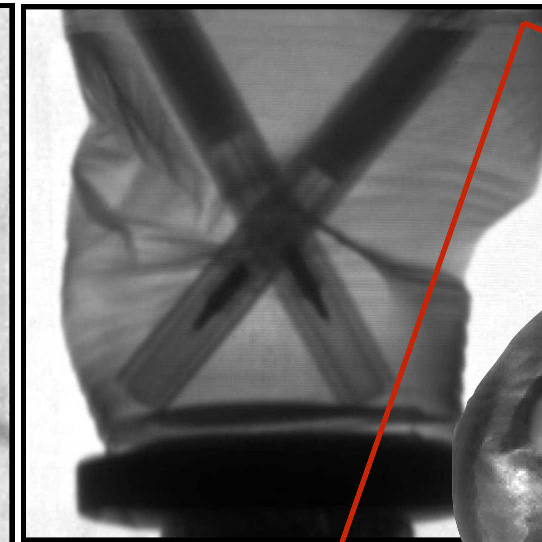
Gamma imaging

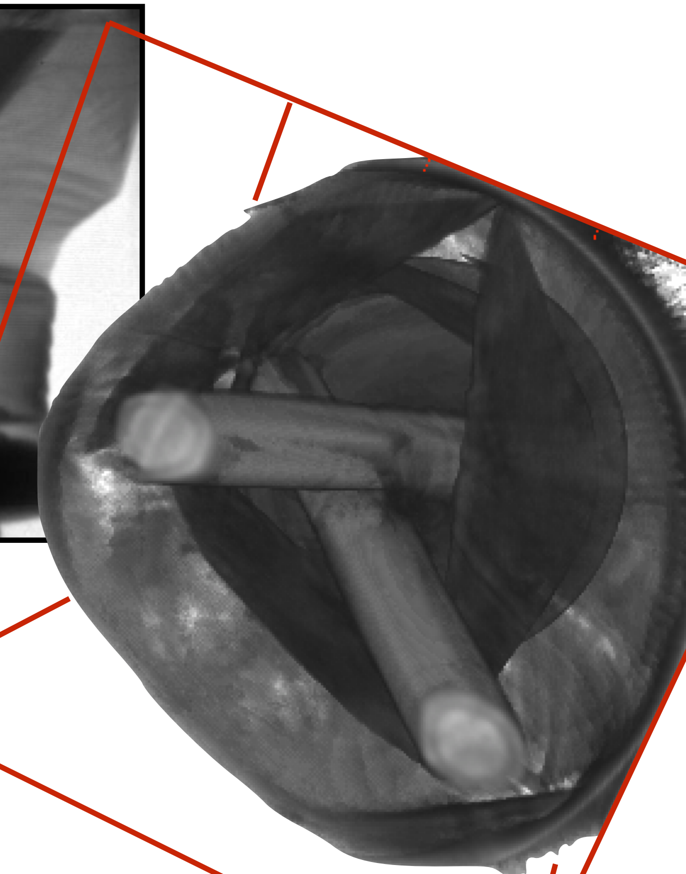
…



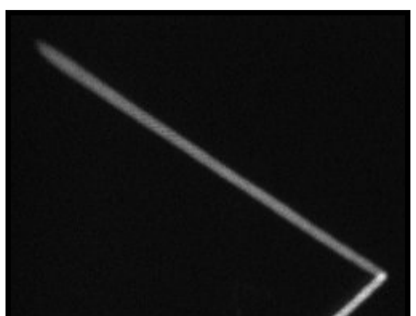
Radiography of a bat
and closeup of the GEM holes

Freeze-frame of an X-ray
movie of a flying drone

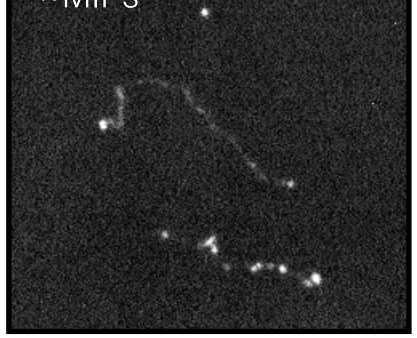




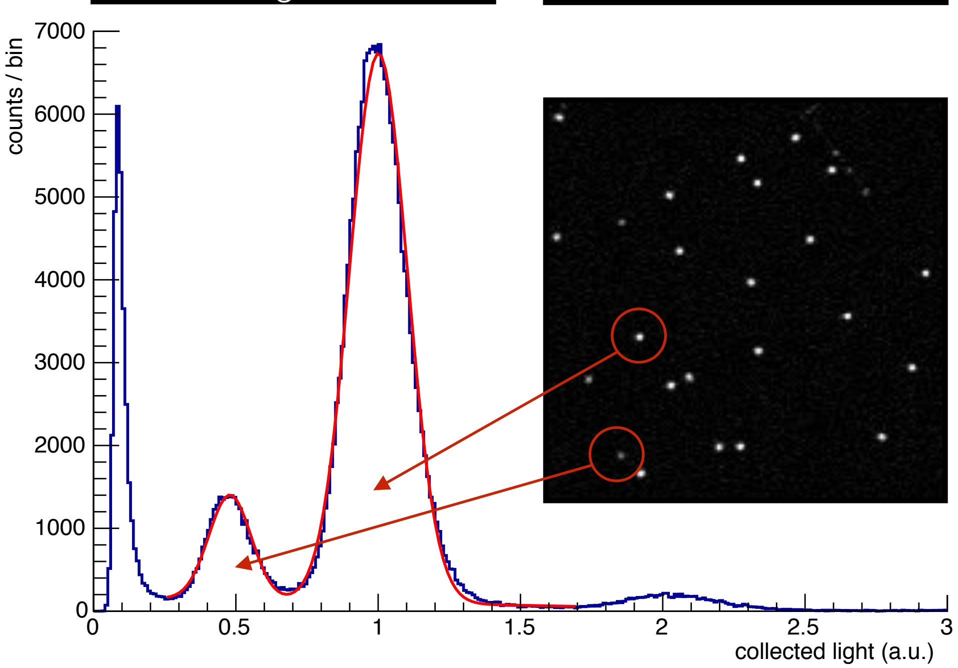
Radiography of a
crushed cup with pens and
its 3D tomographic reconstruction



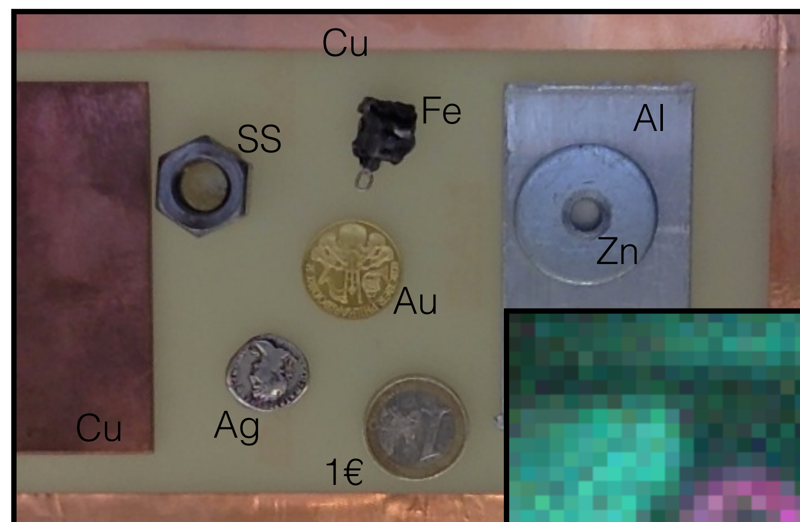
Alphas from ^{220}Rn decay
and its daughter ^{216}Po



O(100 keV) electrons
~MIPs



Single X-rays from ^{55}Fe
and the energy spectrum
extracted from the images



Visible picture of a *painting*
and its X-ray fluorescence image.
Different colours refer to different
materials (energy resolved)