

Micro Pattern Gas Detector Optical Readout for Directional Dark Matter Searches

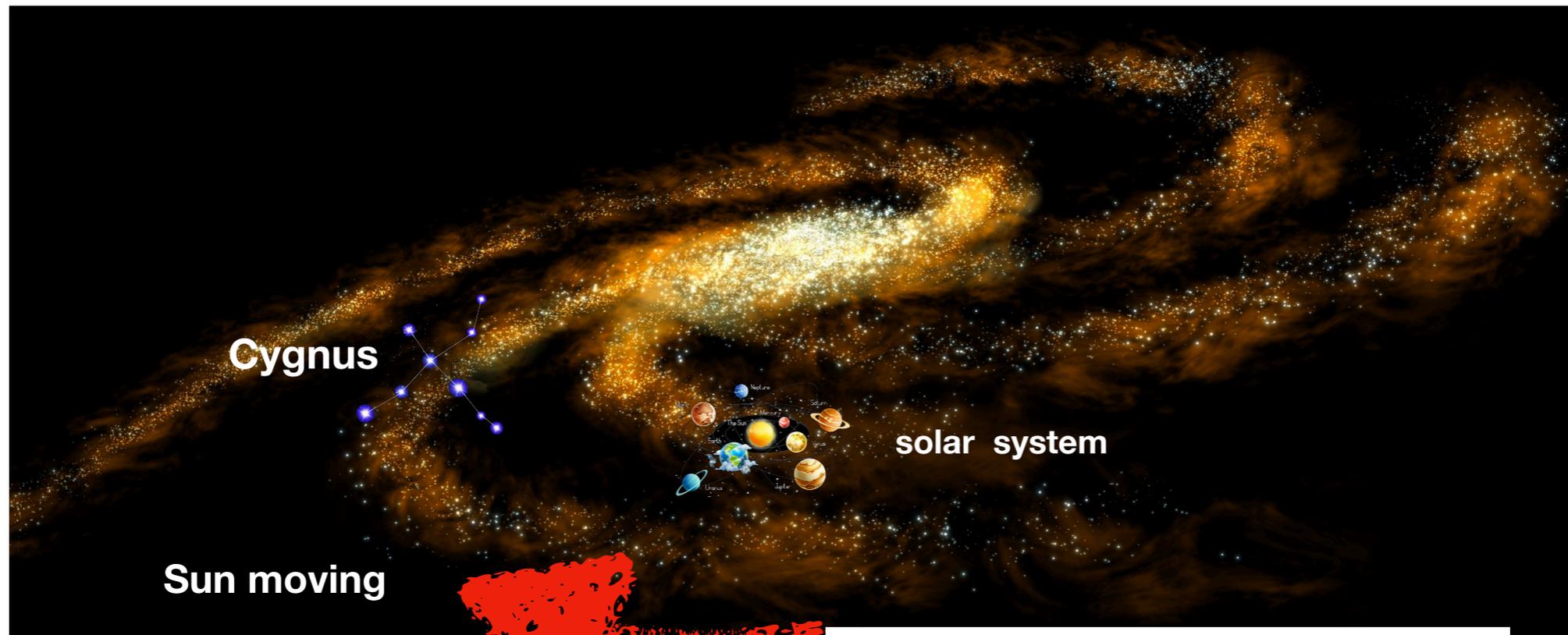
Gianluca Cavoto (Sapienza Univ. Roma & INFN)

VCI 2019

Outline

- ▶ The wind of dark matter (DM) particles
- ▶ A gas Time projection chamber for DM
- ▶ Light from triple-GEMs
- ▶ Prototype results
- ▶ Towards a low energy threshold
- ▶ Future plans

The dark matter wind in the Milky Way



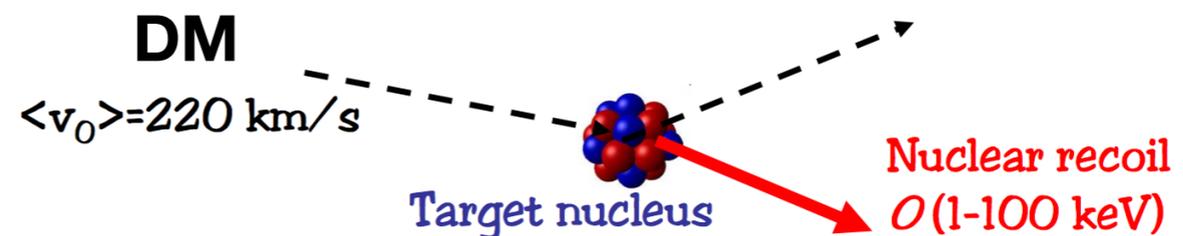
- ▶ We are all immersed in a halo of dark matter particles ($0.3 \text{ GeV}/\text{cm}^3$)
- ▶ $V_{\text{DM}} \sim 10^{-3} c$



Dark matter particles are appearing as coming from the Cygnus constellation

The direct dark matter search

- ▶ No idea how DM particles really interact with ordinary matter (if they do)
- ▶ Assume the basic model of elastic scattering: detect the **recoiling nucleus**



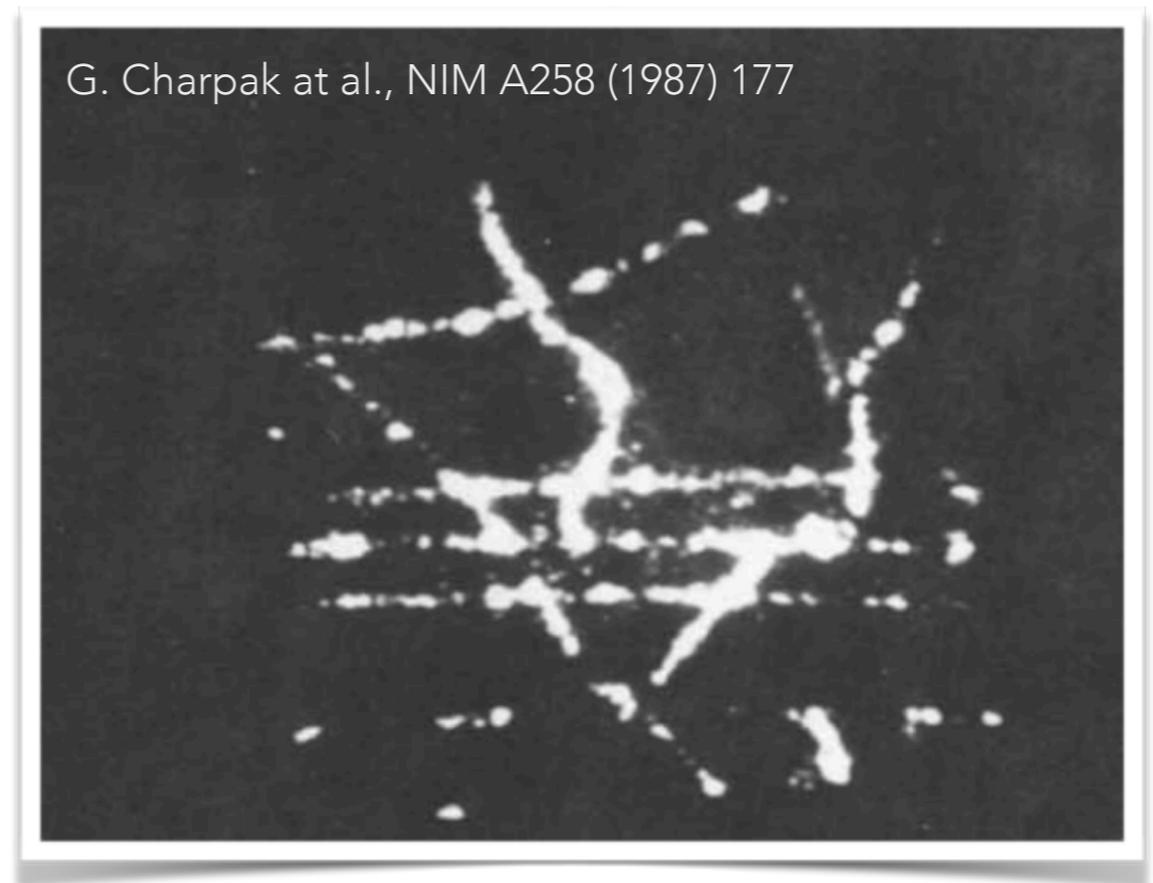
- ▶ Rate is **few** events/Kg/year
- ▶ Mass of the DM particles unknown, look at “light” DM (a **GeV** mass or even below)

*Energy release ($1/2Mv^2$) is **tiny** (as low as few keV)*

Idea: use **Time Projection gas Chamber** technique to “**image**” the nuclear recoil
Very **low** threshold, measuring the **shape** of the recoil (**background rejection**)
measuring the **direction** of the recoil (the DM wind)

Light readout of GEM in TPC

- ▶ Detect *light* from GEMs produced in the **multiplication** process close to the anode (instead of charge)



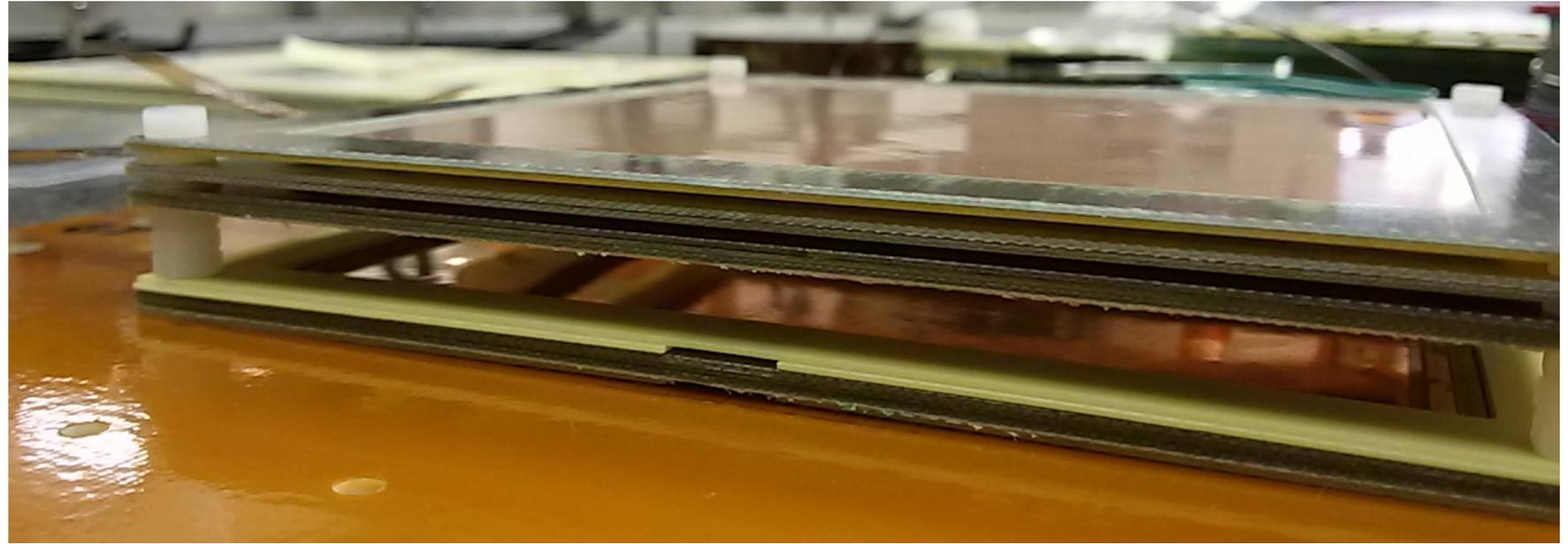
- optical **sensors**: high granularities, very low noise level and high sensitivity;
- optical **coupling**: sensor out of the sensitive volume (no HV operation hassle, lower gas contamination);
- system of **lenses**: large surfaces projected to small sensors.



An Optical ReAdout in GEM

Triple GEM (10x10 cm²)
with a 1 cm drift region

He/CF₄ (60/40) at
atmospheric pressure



Exceptional quantum efficiency
Over 70 %
at 600 nm

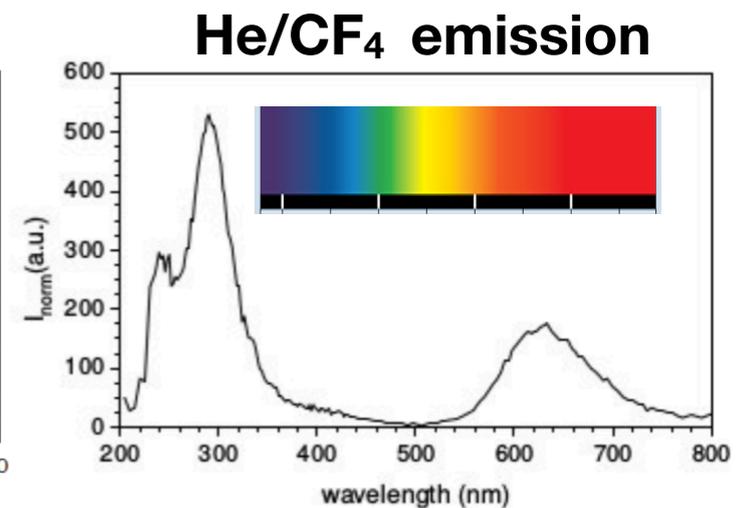
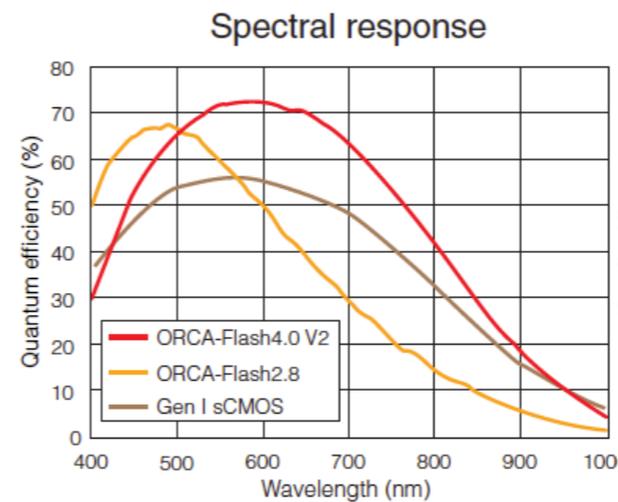
Low noise
1.0 electrons median 1.6 electrons rms
Standard scan at 100 frames/s

0.8 electrons median 1.4 electrons rms
Slow scan at 30 frames/s

High-speed readout
100 frames/s
Camera Link at 4.0 megapixels



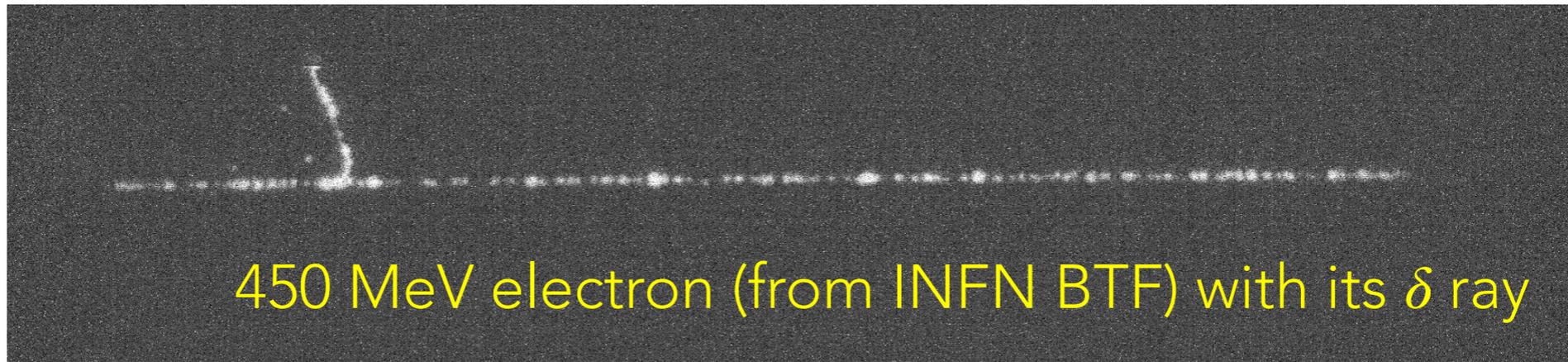
sCMOS sensors: very low noise and
4M pixels granularity and sensitivity



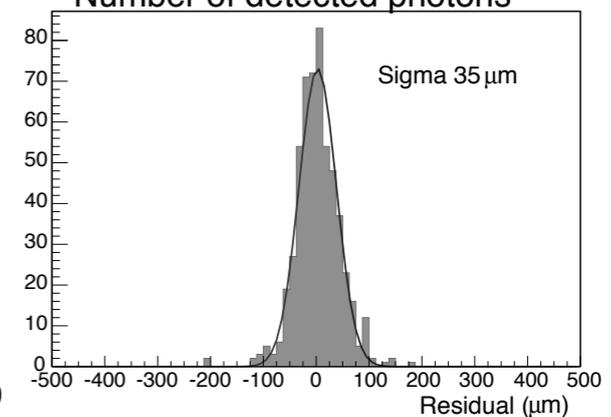
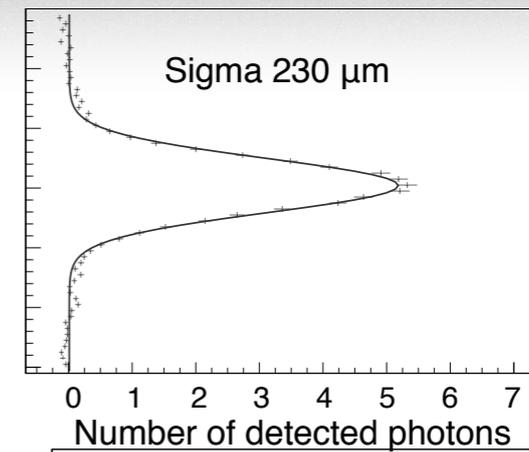
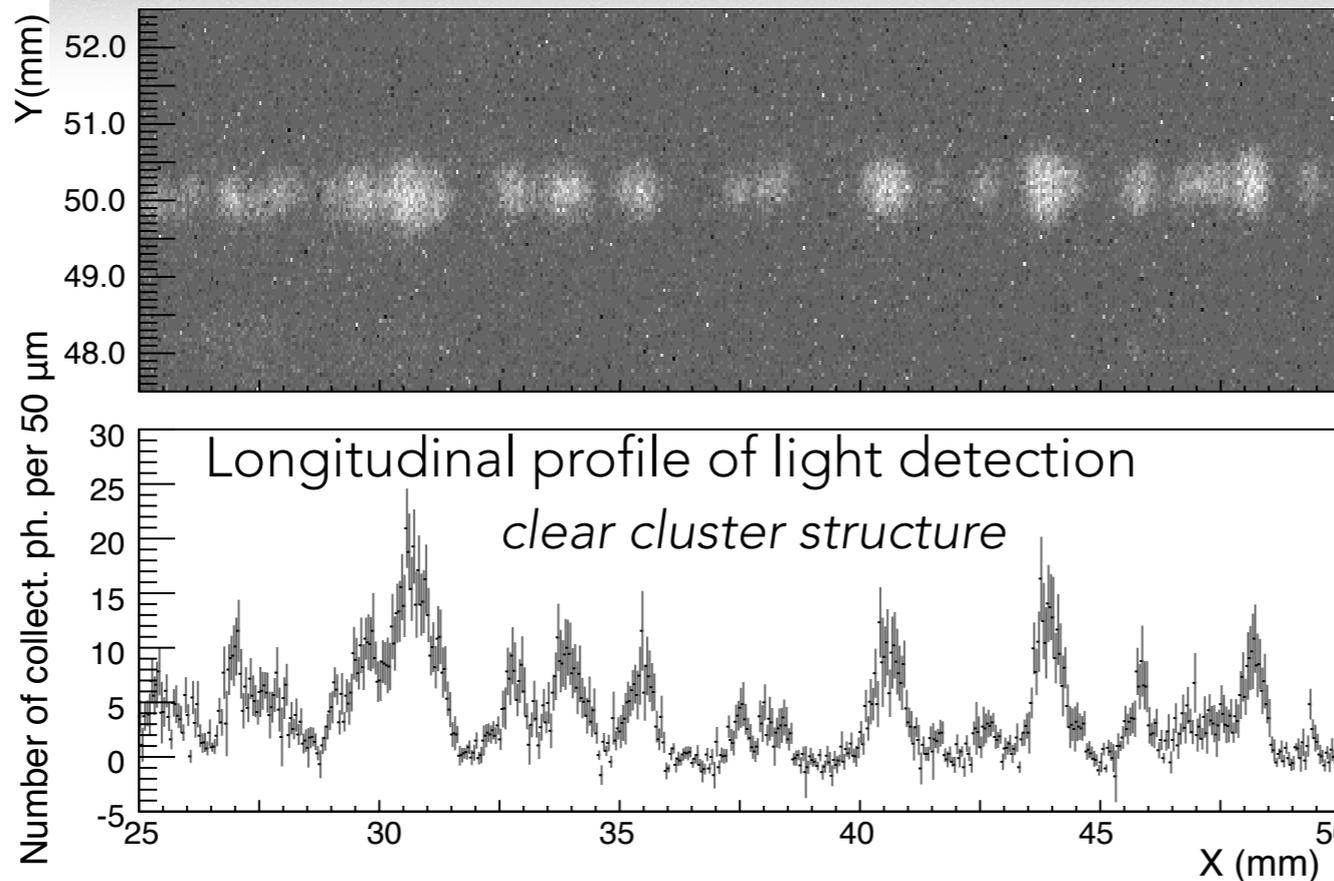
100 frames/s
6



Fast charged particle tracks



10-100 ms
long
sCMOS
camera
“exposures”

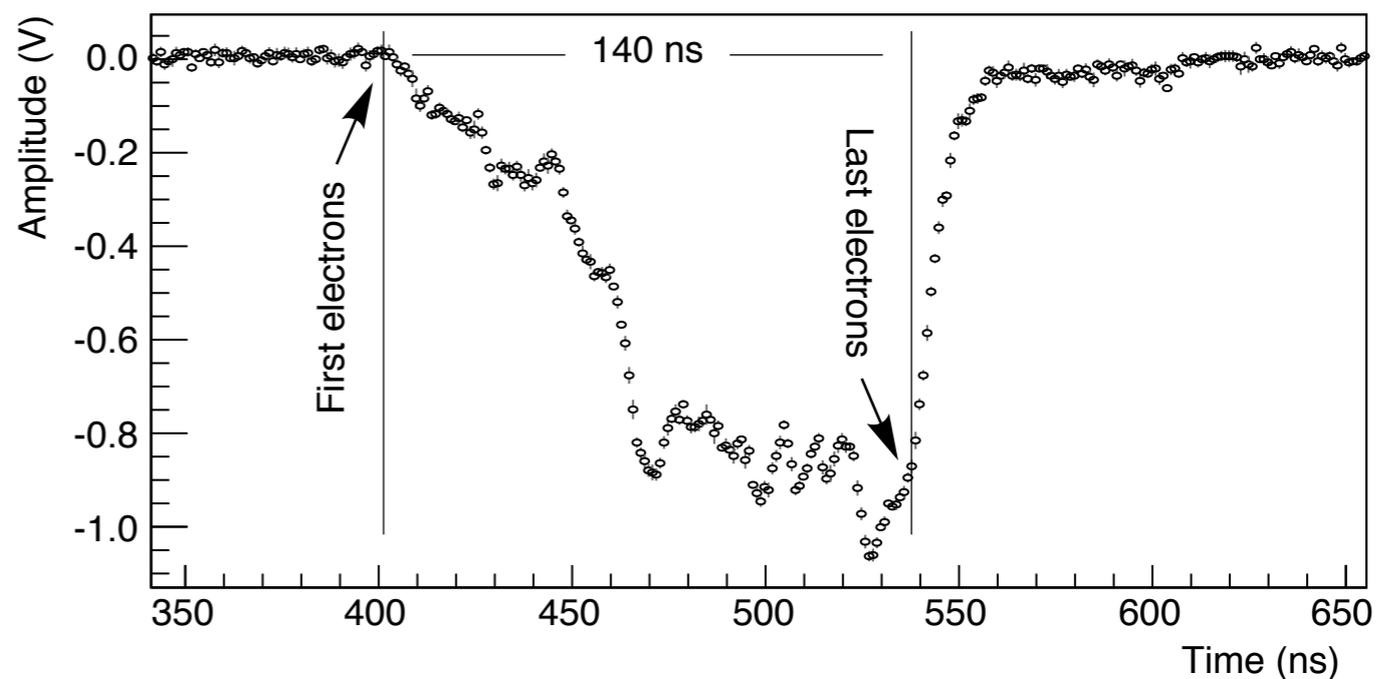
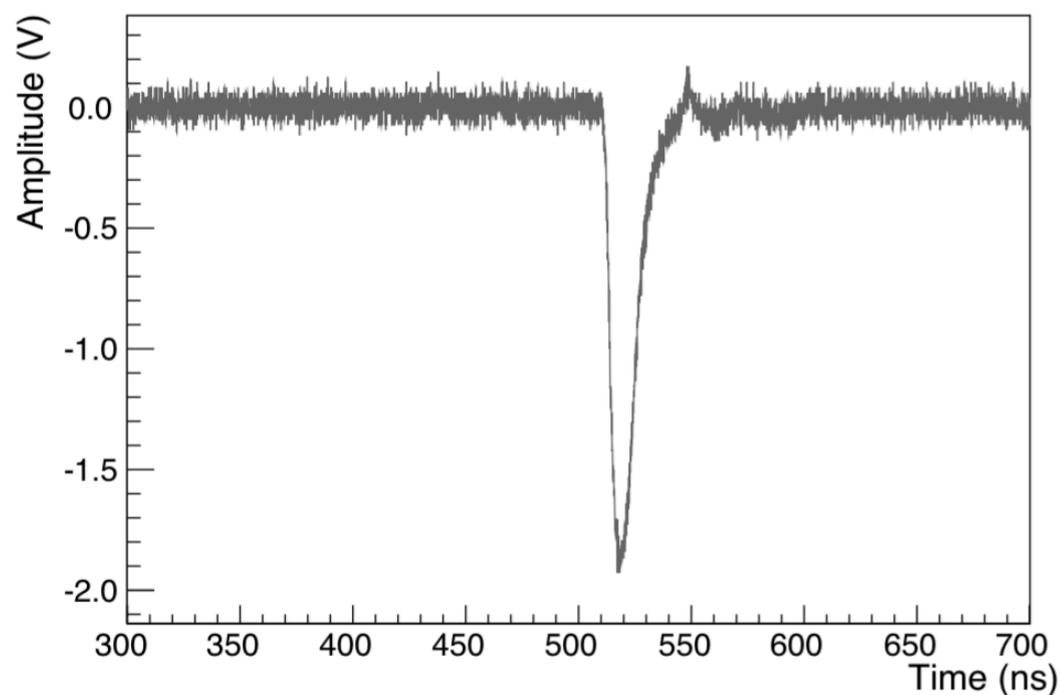
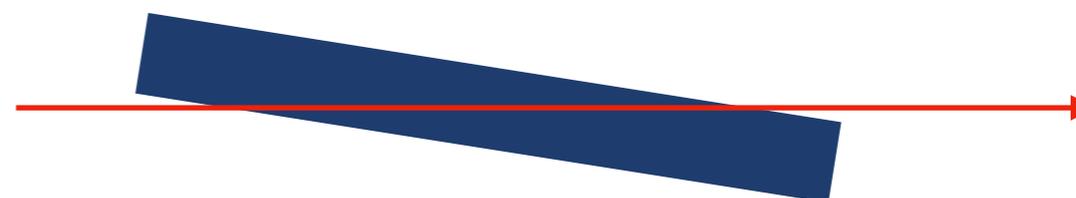


About 330 detected photons per track millimetre (for $V_{\text{GEM}} = 440\text{V}$),
i.e. 50 photons per primary electron (from Garfield).



Fast light readout (PMT)

Changing direction of the particle (with respect to the drift field lines)

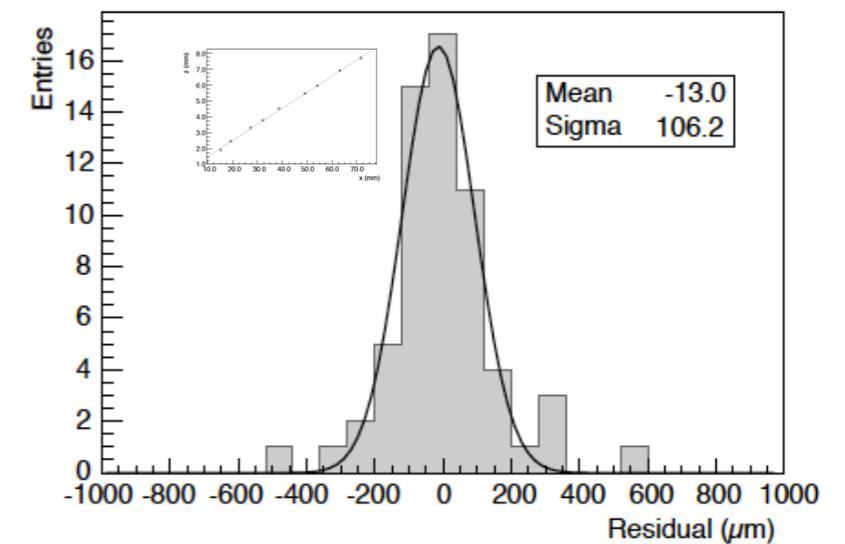
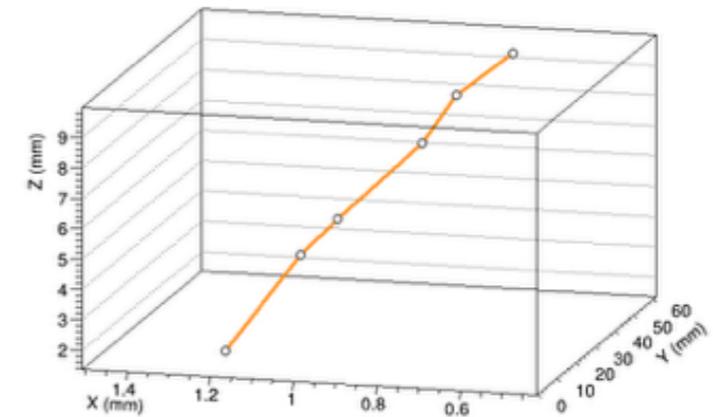
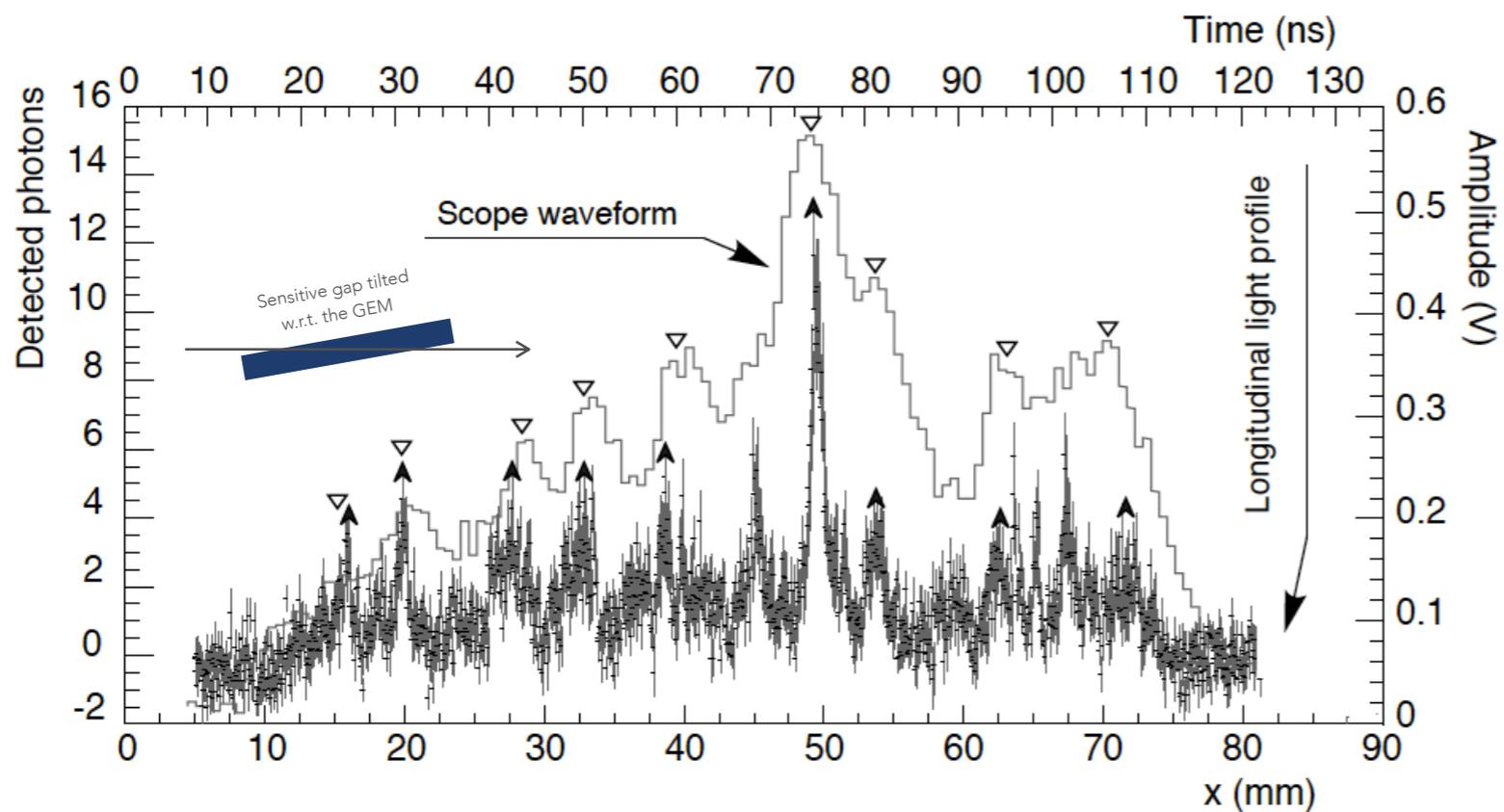


1 cm in 140 ns: drift velocity $7.2 \text{ cm}/\mu\text{s}$
(Garfield: $7.3 \text{ cm}/\mu\text{s}$)



Combined readout

Single cluster 3D position reconstruction:
light profile along the track (X, Y from sCMOS) and a fast waveform
(t from a PMT)



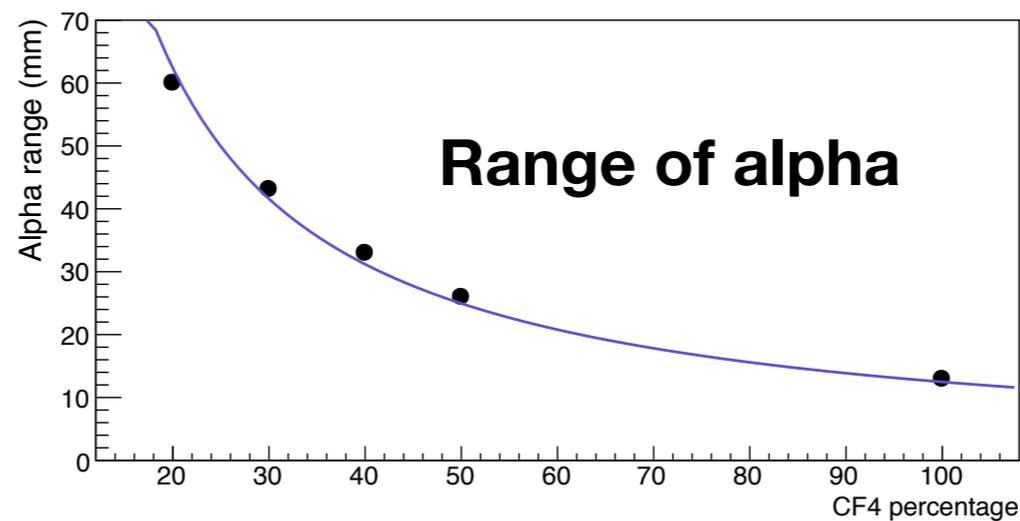
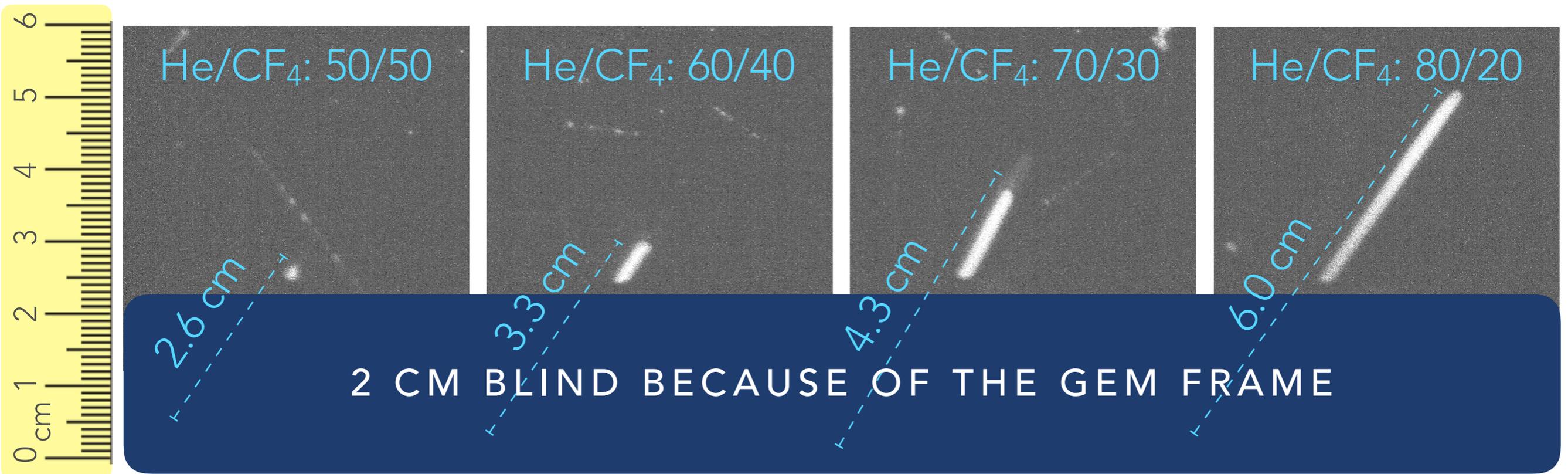
Residual distribution to a 3D fit: **100 μm** Z resolution



Alpha tracks

B. AZMOUN ET AL., 2010, IEEE TNS, VOL. 57, NO 4.

5.48 MeV alpha particles range in pure CF₄ : **13 mm**



Towards a DM detector

- ▶ Scale up to (much) **larger** volumes

CYGNUS-TPC project aims at building a multi-ton gas target for DM as various TPC detectors distributed in underground labs

- ▶ Explore **low** thresholds
 - ▶ Detect gamma-induced **electronic recoils** and neutron induced nuclear recoils, evaluate energy resolution
- ▶ Study **particle identification**
 - ▶ Exploit **pixel patterns** for discrimination
 - ▶ Novel technique for background suppression in DM searches !
- ▶ Eventually, determine **directional** capability
- ▶ and - for a real DM detector - use **low radioactivity** materials

The **CYGN0** 1m³ demonstrator

Atm. pressure He/CF₄ 60/40 (1.6 kg), two 50 cm drift regions divided by the cathode (drift field ~1 kV/cm)

Two anodes with a 3x3 triple-GEM's matrix each.

Each triple-GEM readout by:

- a sCMOS sensor (65 cm away from a transparent window)
- fast light detectors (PMT or SiPM).

*A total of $72 \cdot 10^6$
165 x 165 μm^2 pixels
on the GEM surface*

To be shielded from gamma rays and neutrons



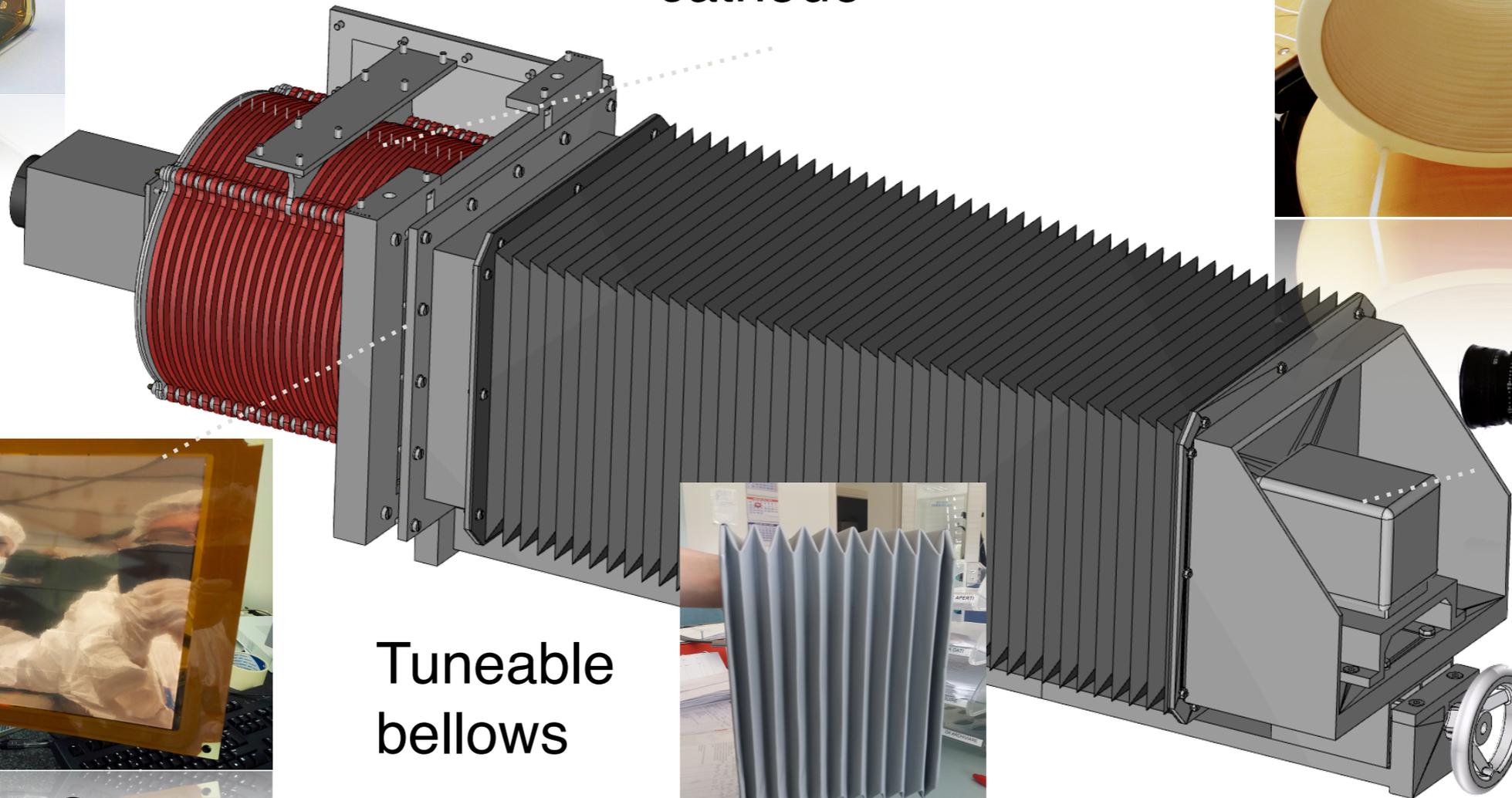
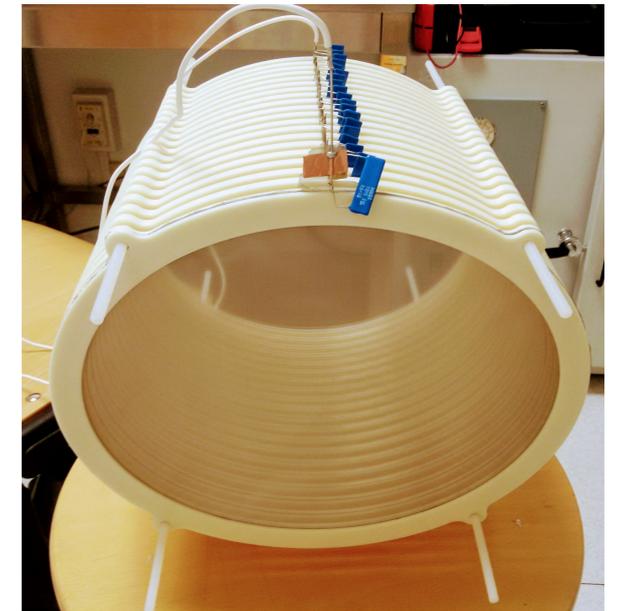
Large **E**lliptical **M**odule **O**ptically Readout

A 7 litre sensitive volume prototype (built in 2017)



7x7 cm² PMT

Elliptical field cage
with semi-transparent
cathode



Tuneable
bellows



sCMOS
camera

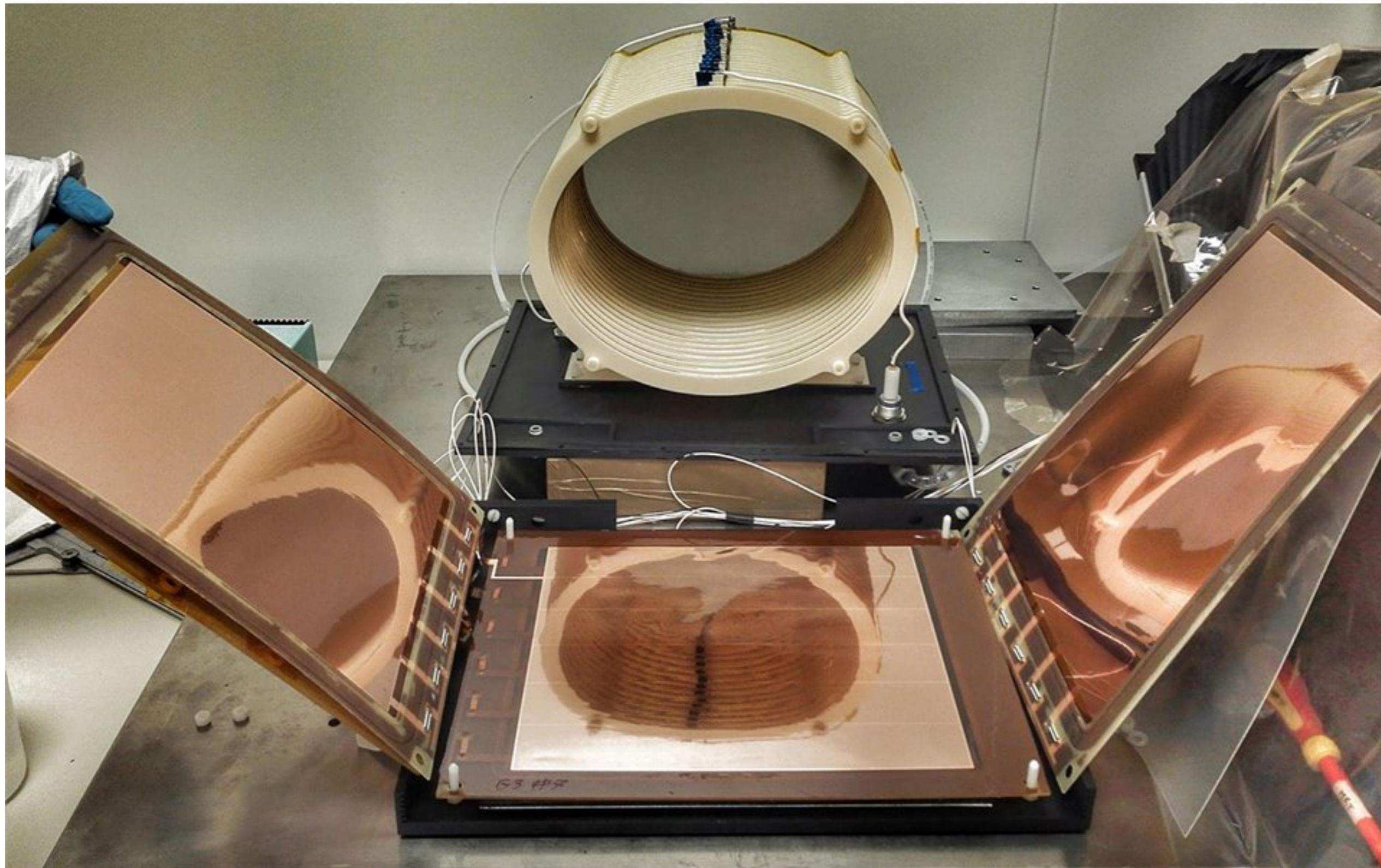


20x24 cm² GEMs



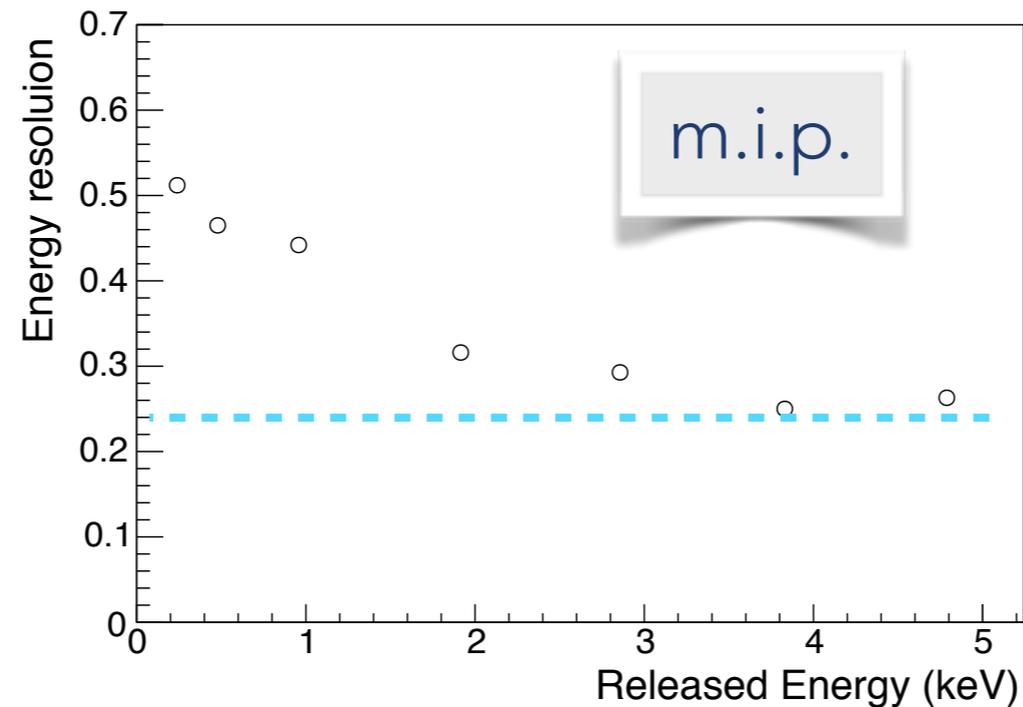
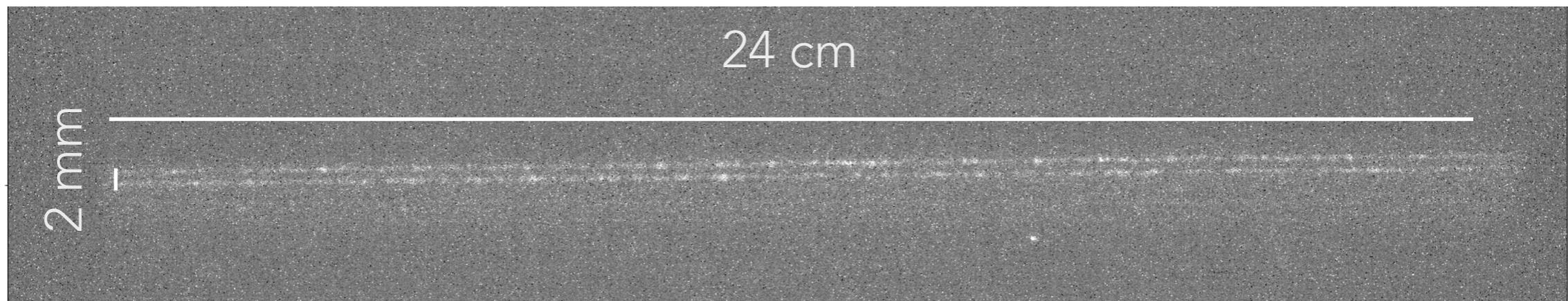


Exploded LEMOn





Energy resolution

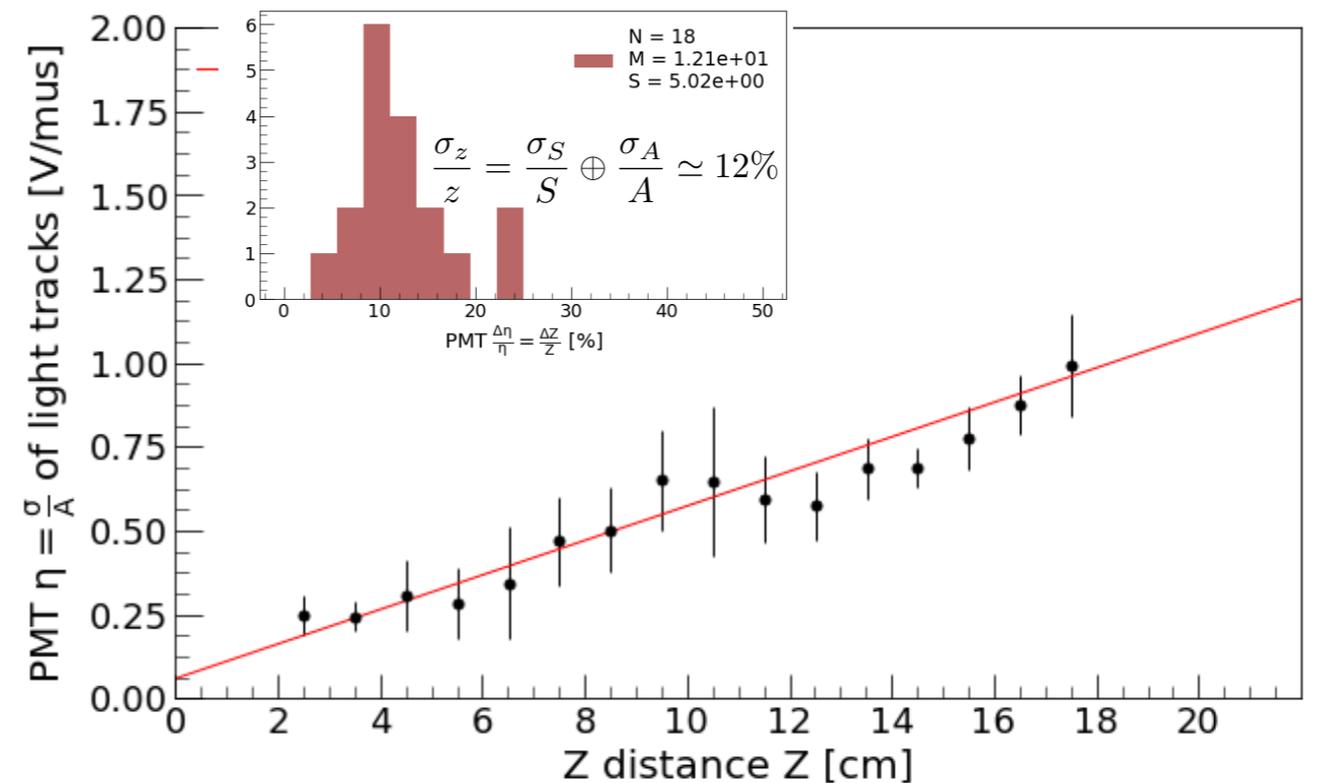
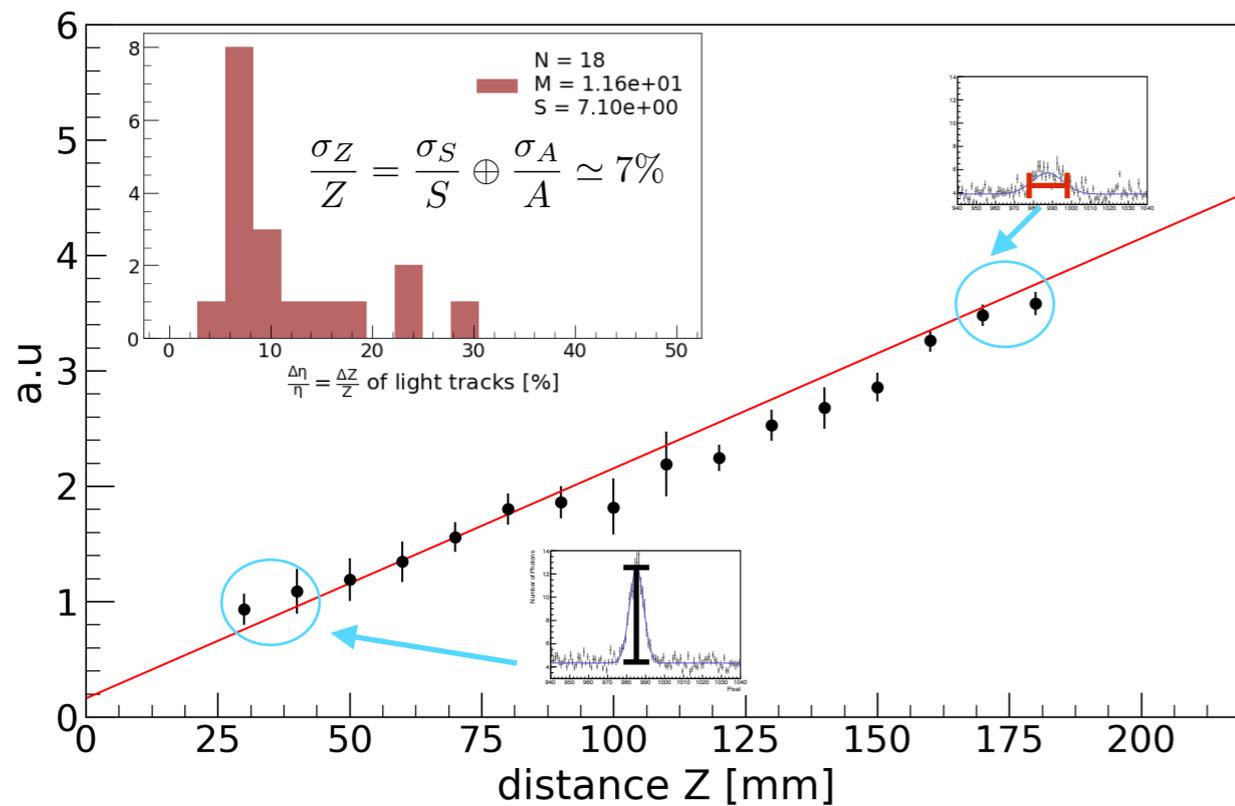


At 1 keV a resolution of 400-500 eV was measured
In the few keV region a relative resolution of **~25%** is achieved



Z resolution

- ▶ Using electron *diffusion*
- ▶ Light transverse profile (sCMOS) and PMT waveform: larger width and lower amplitude from z farther from the anode

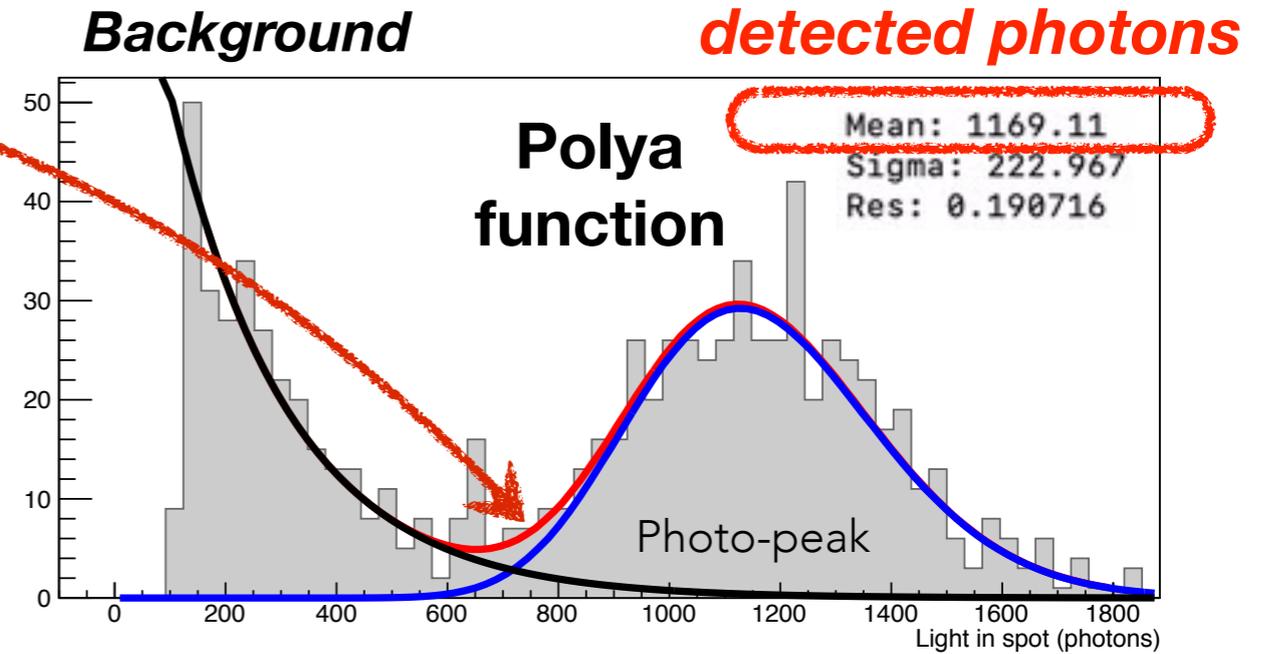
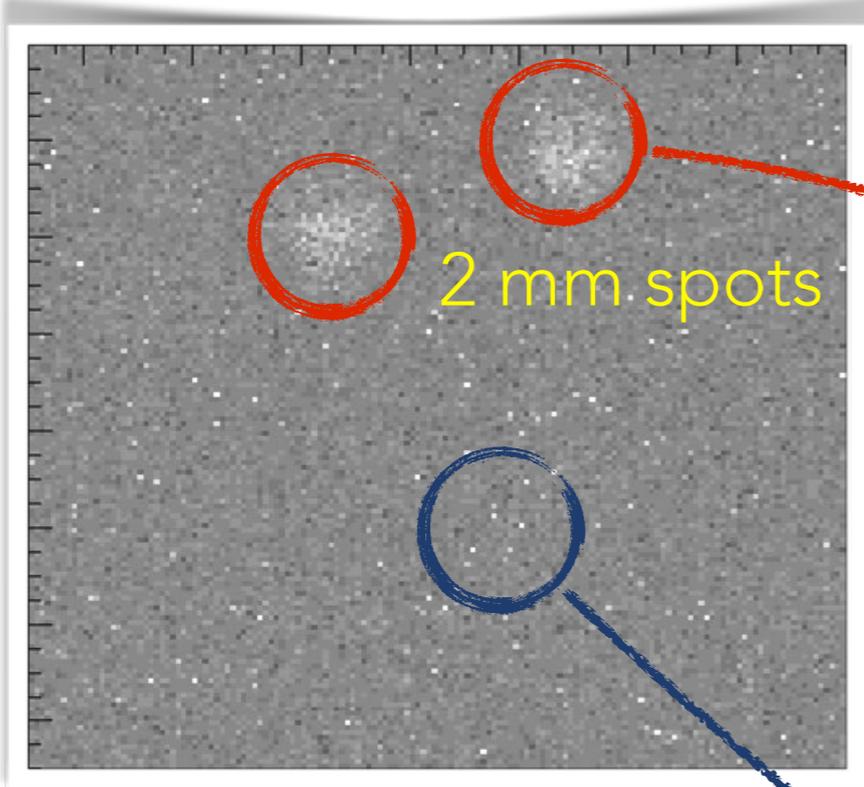
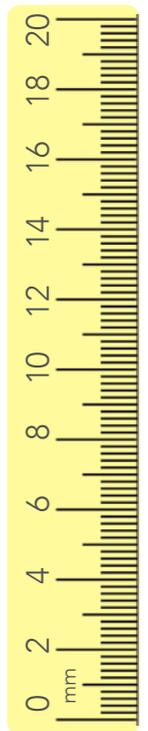


Both methods gives 10% precision: $\sigma_z \sim 2 \text{ cm} @ 20 \text{ cm}$



X-ray from ^{55}Fe

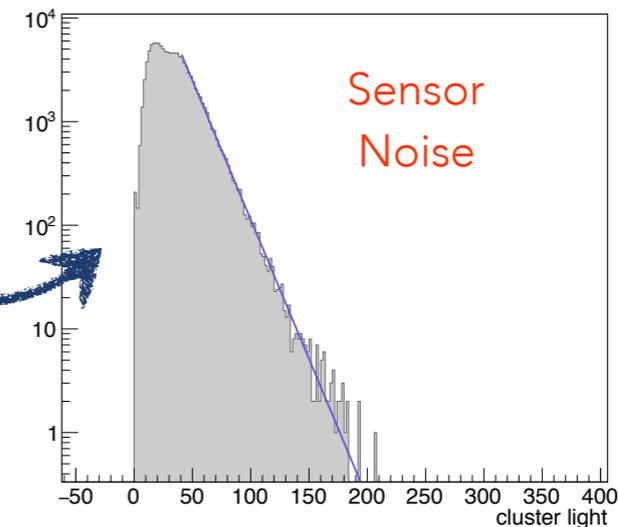
5.9 keV γ rays, source located 20 cm far from the anode (GEM).



1 photon detected every 5 eV

Exponential distribution for noise
(slope ~ 16 photons).

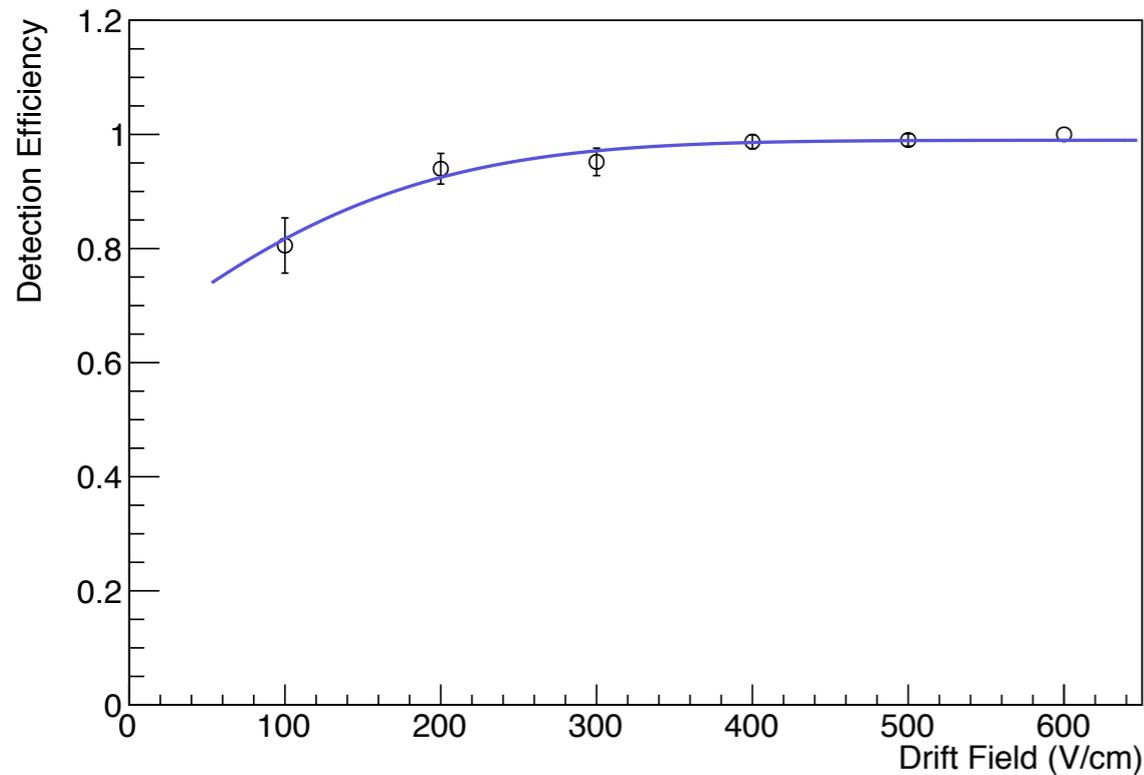
With 400 ph. threshold (2 keV) :
fake rate 10 events/year
per sCMOS sensor



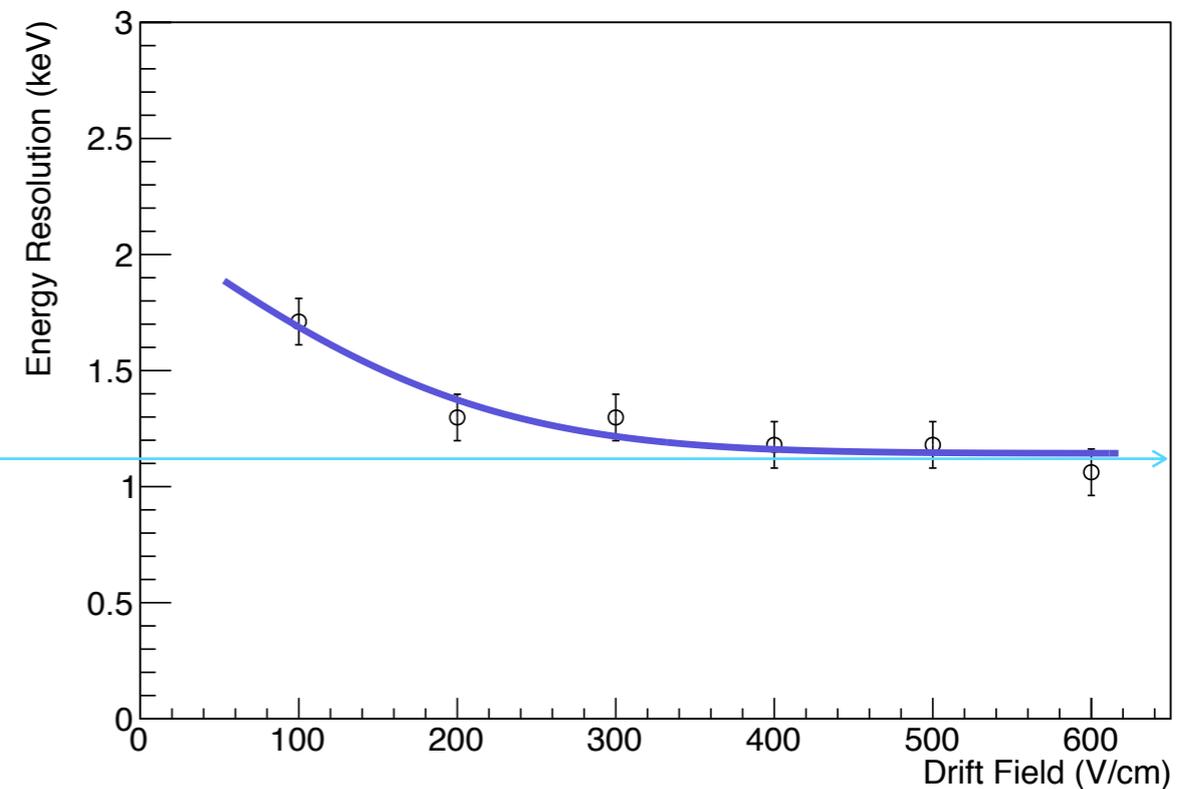


Efficiency and resolution at 5.9 keV

Drift field studies ($V_{\text{GEM}} = 460 \text{ V}$)



Number of detected clusters is plateau-ing already at 300 V/cm: fully efficient!



Energy resolution of $\sim 20\%$

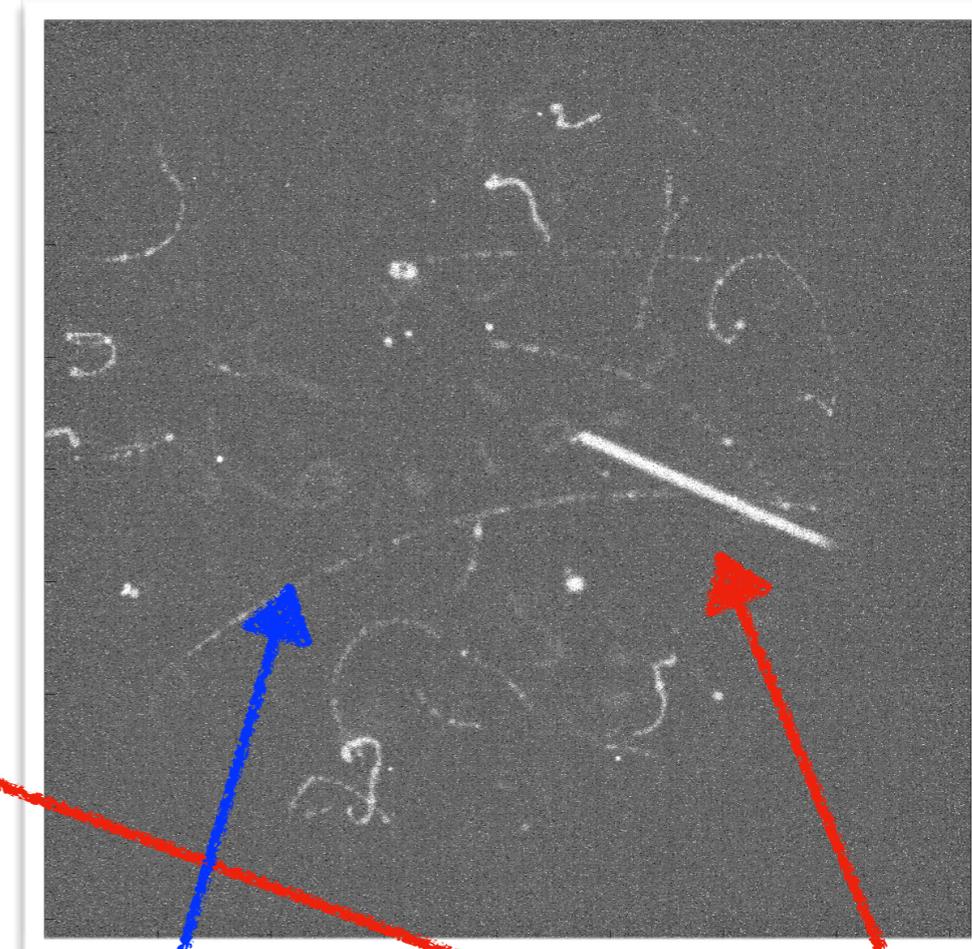
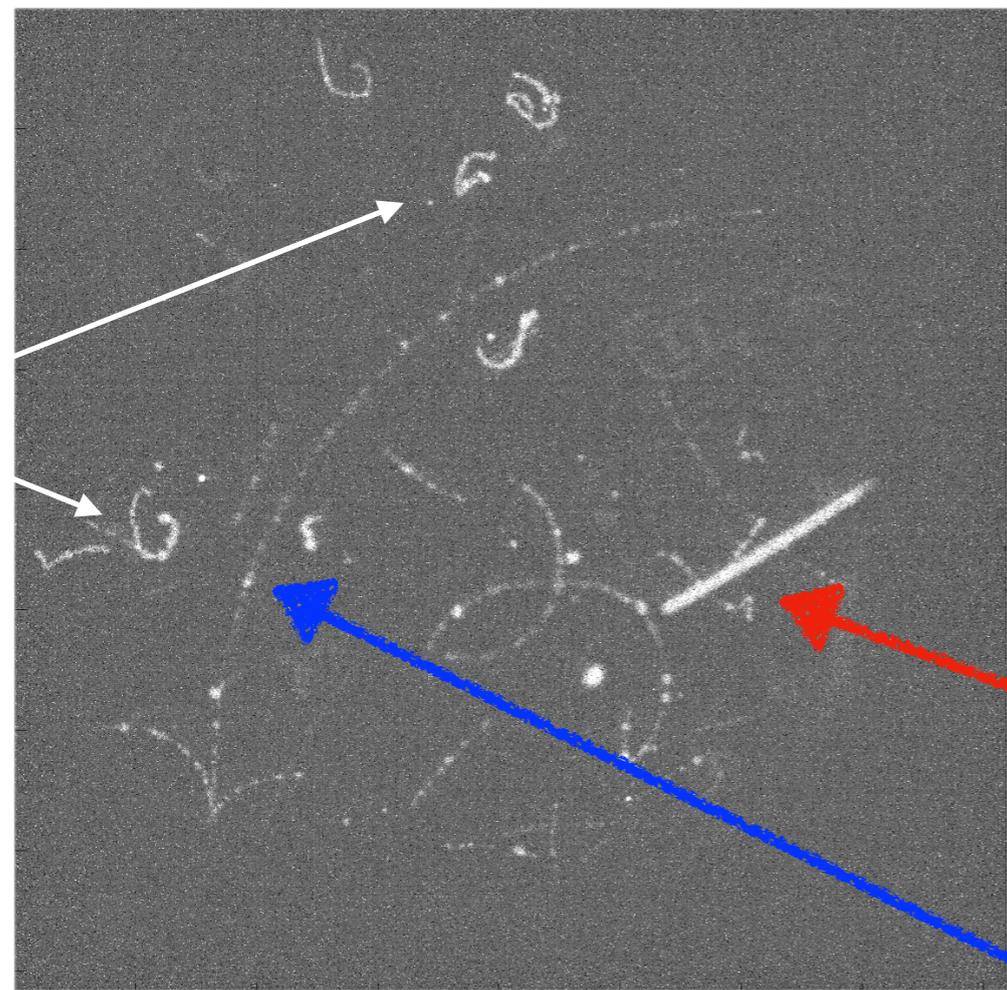
Operation with an energy threshold of 2 keV feasible



First studies with neutrons

- ▶ Expose ORANGE (1cm drift gap) to Am-Be source
 - ▶ 1-10 MeV **neutrons** along with 4 MeV and 60 keV **photons**
 - ▶ Both **electronic** and **nuclear** recoils in the same image.
 - ▶ Adding a 0.2 T **permanent magnet** to disentangle the three species

Low energy electrons (60 keV X rays)

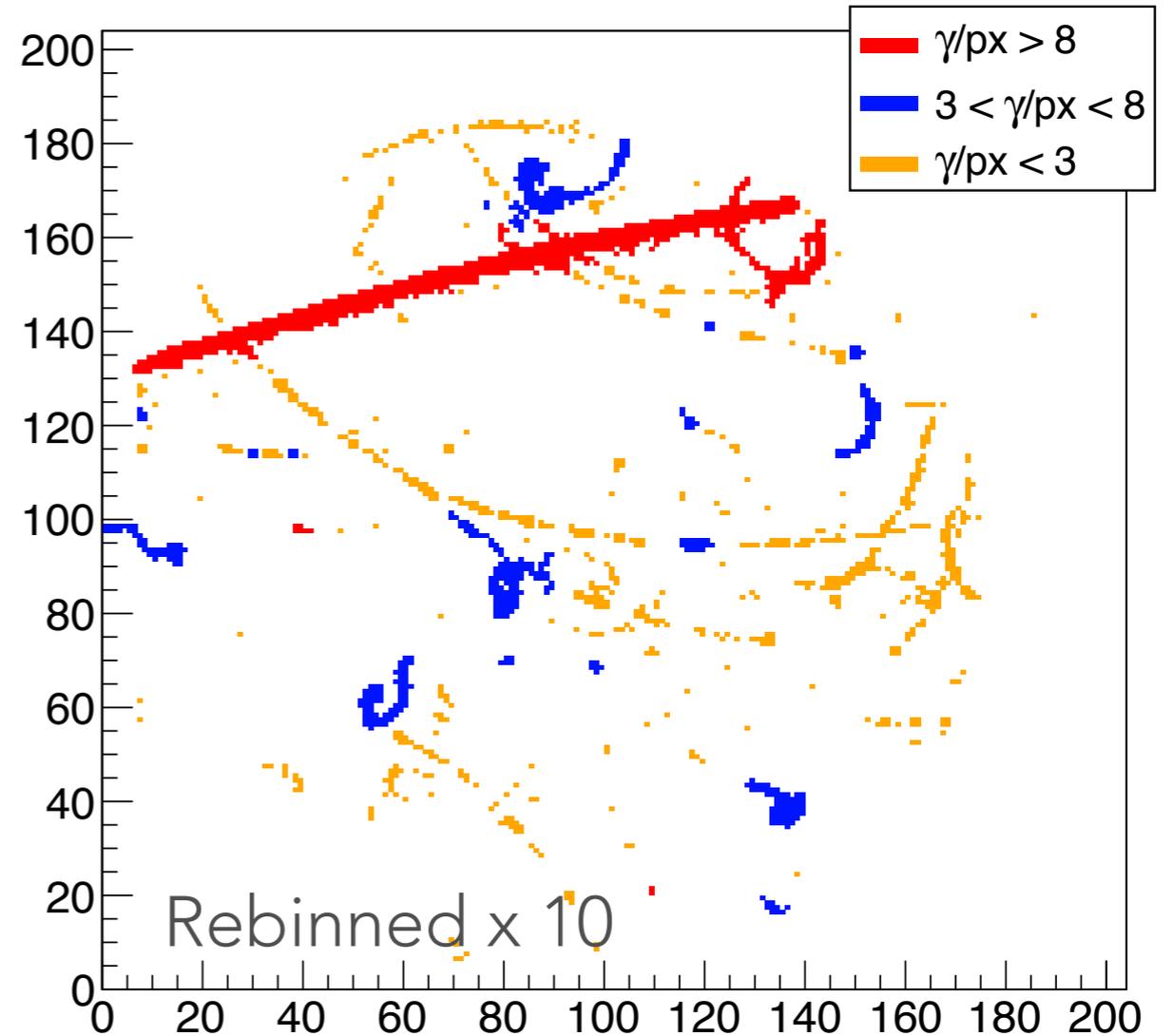
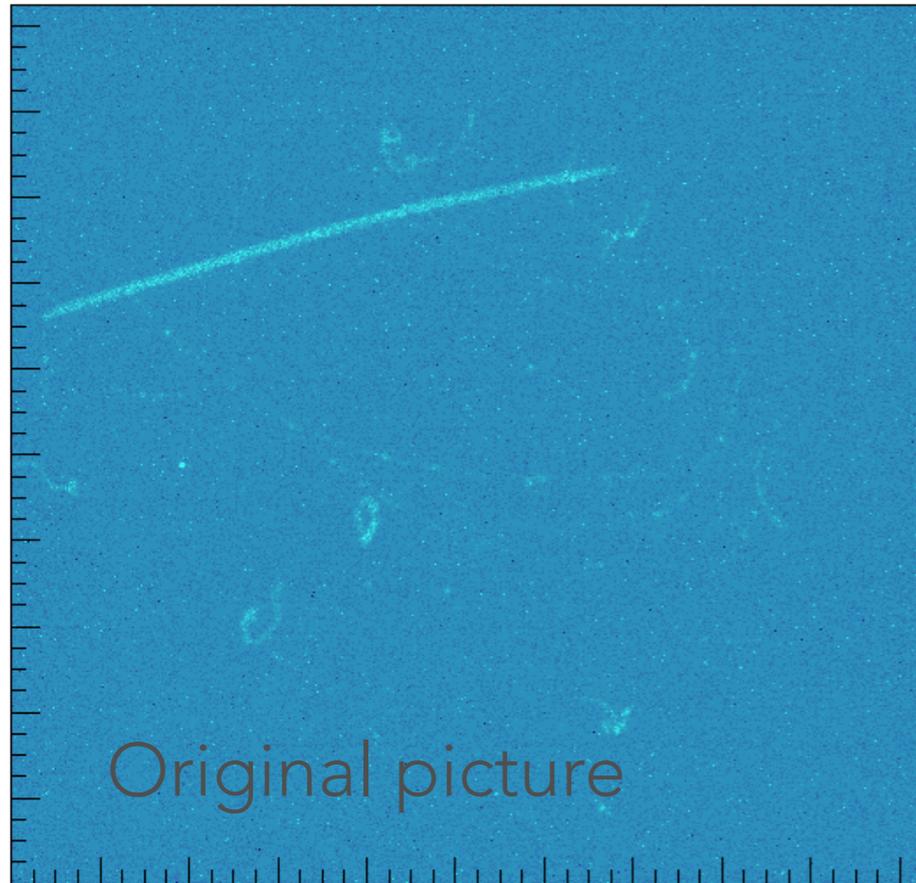


MeV electrons due to 4 MeV γ **Nuclear recoils**



Particle identification

Specific ionization: counting photons over 10 adjacent pixels

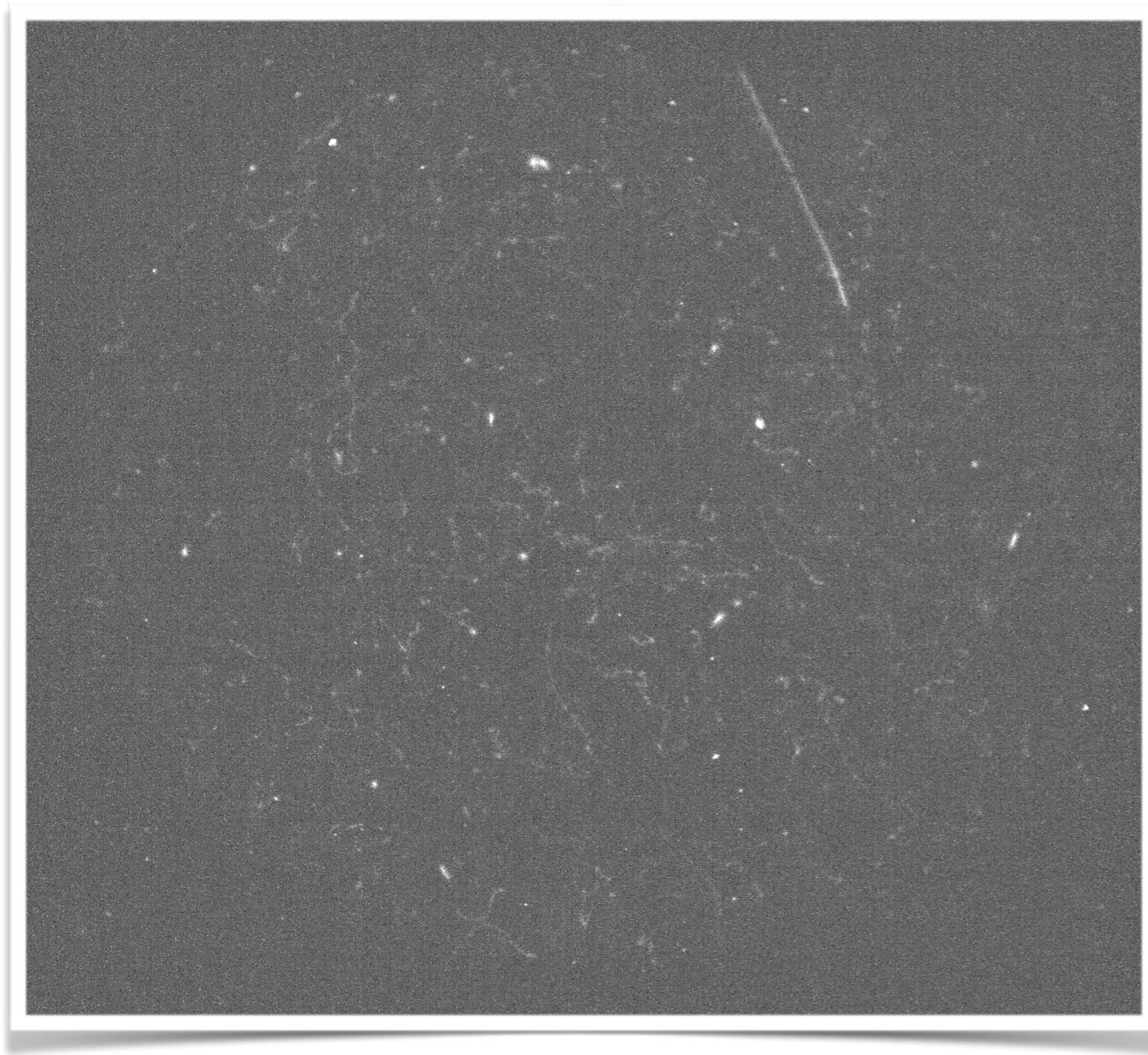


- ▶ Separation of the three species visible.

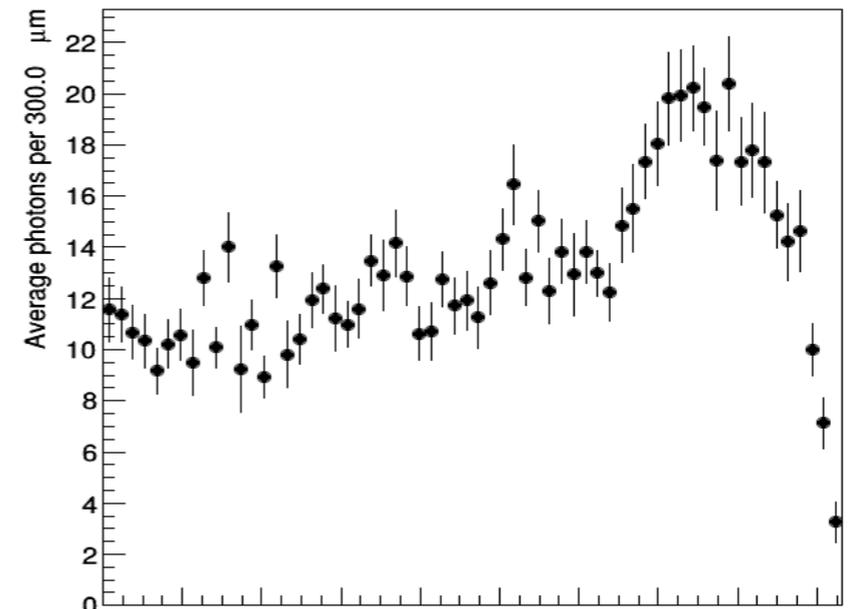


Monochromatic and parallel neutrons

- ▶ LEMOn (long drift gap) at 2.45 MeV neutrons at Frascati Neutron Gun facility (ENEA)



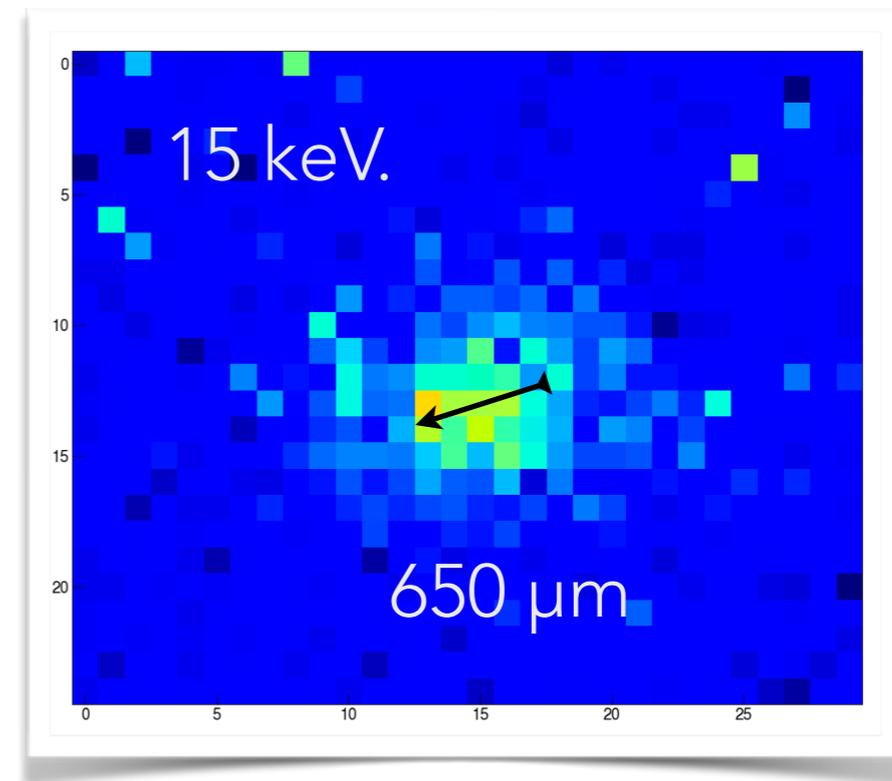
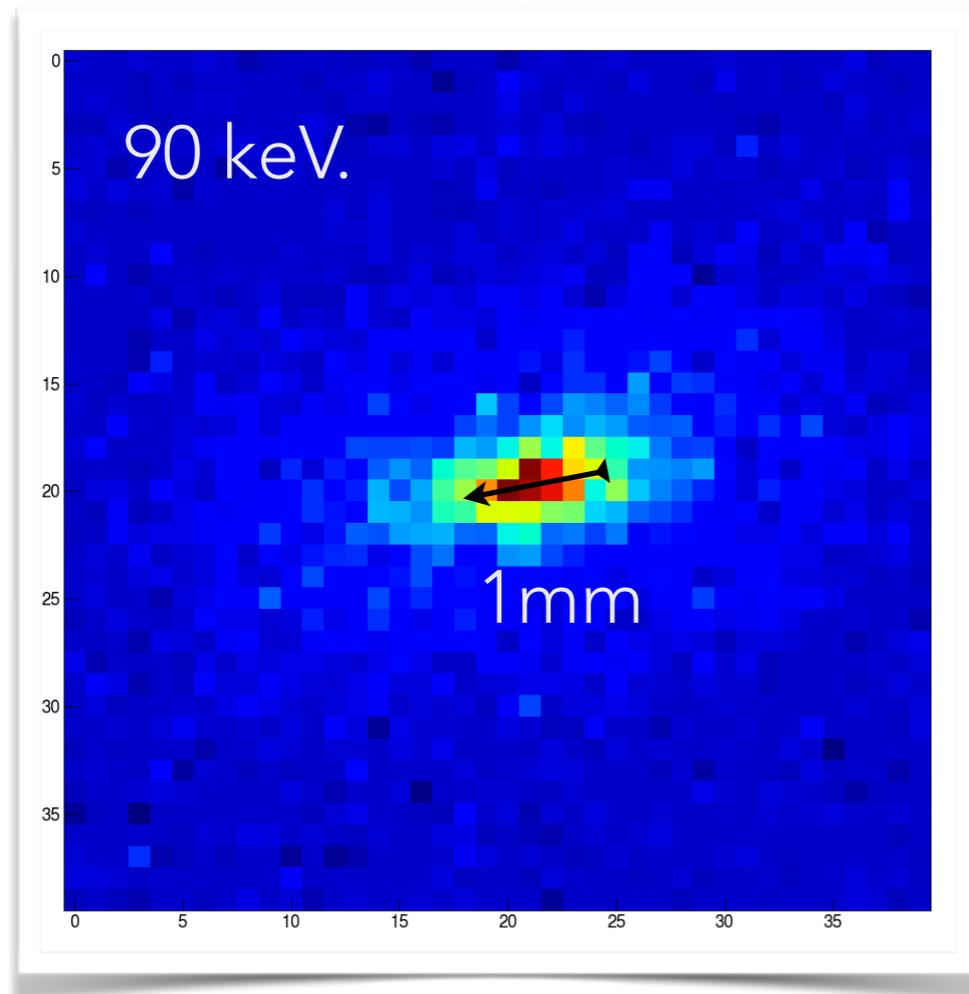
Nuclear recoils visible
(soft photons large background)



Light longitudinal profile



He nuclear recoil candidates



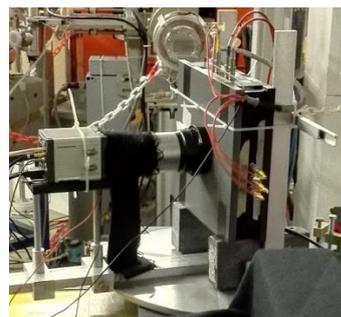
Direction and head/tail asymmetry still visible

Prospects

High resolution low noise (*albeit slow*) sCMOS camera look promising to readout light from GEM for (*low-rate*) DM applications.

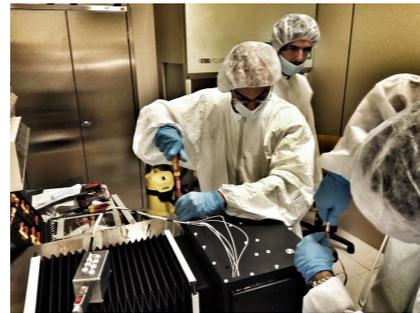
2018 @ ROMA1/LNF 2019 @ LNF 2020 @ LNF 2021 @ LNF 2022 @ LNGS ...

ORANGE



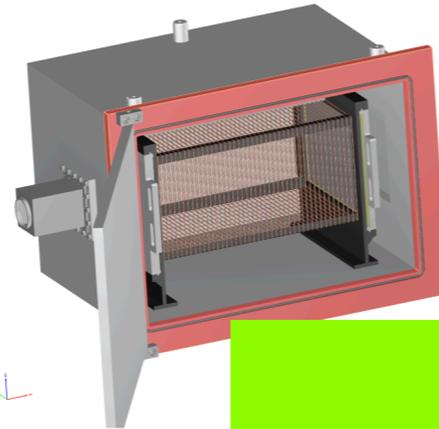
- OPT readout
- 1 cm drift

LEMON



- OPT readout
- 20 cm drift
- PID & tracking
- drift resolutions

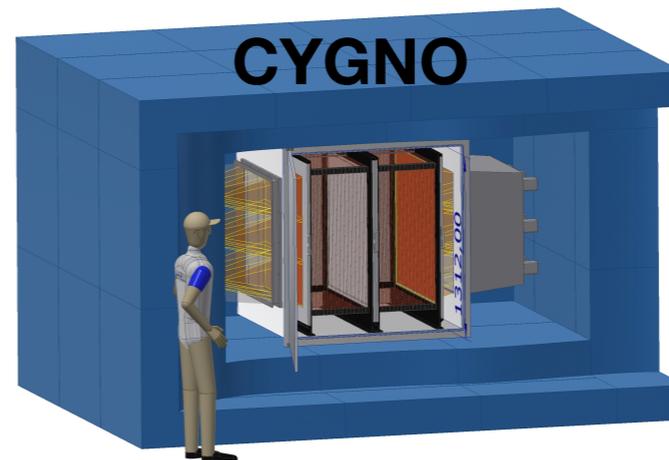
LIME



- 50 cm drift
- materials test
- gas

TDR

Construction & test



Installation & commissioning

- background
- materials test
- gas purification
- shielding
- stability
- scalability
- reliability

1 m³ demonstrator to be built in collaboration with INITIUM project (just funded with an ERC CoG)

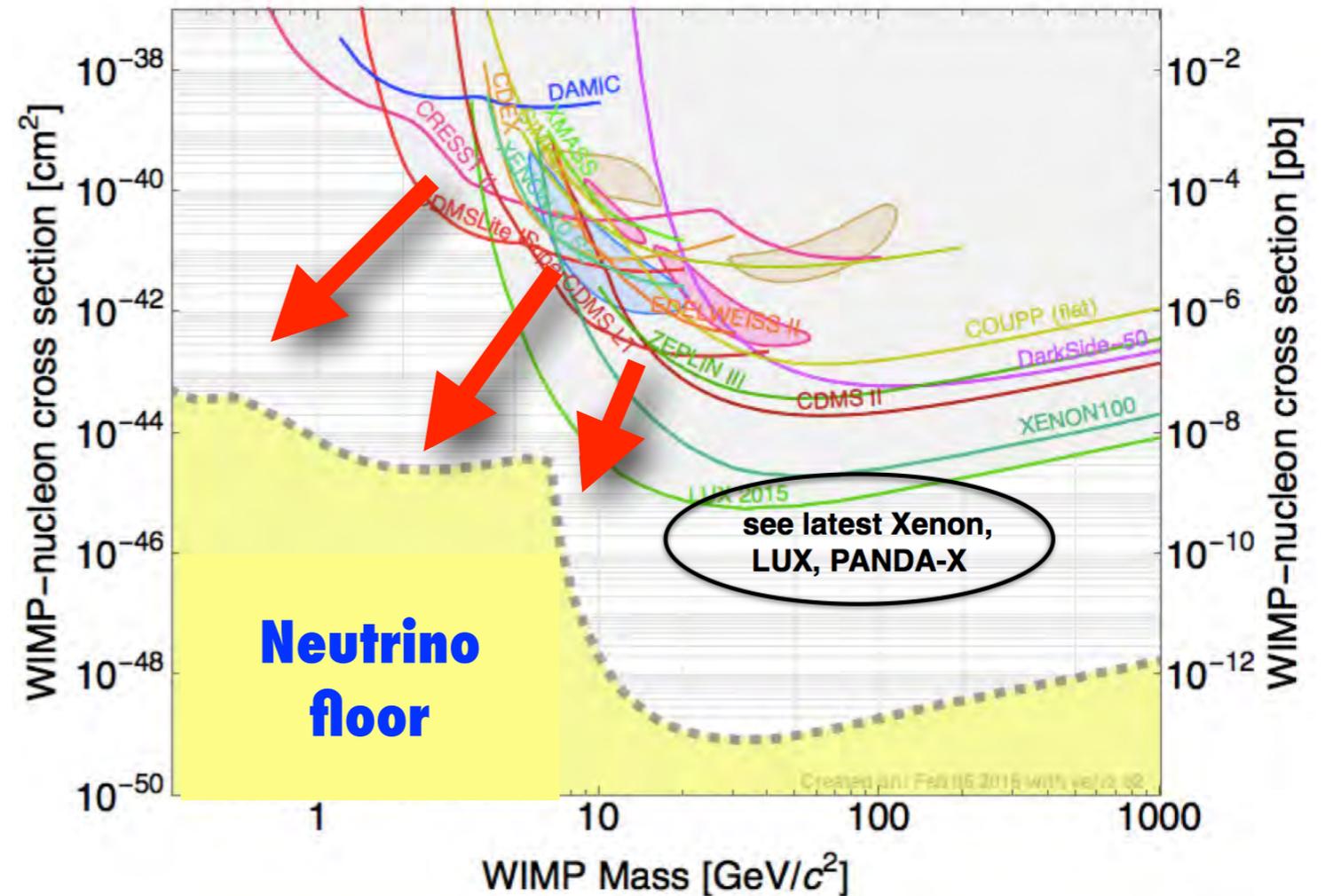
10-100 m³ CYGNUS



Back-up

Low mass WIMP

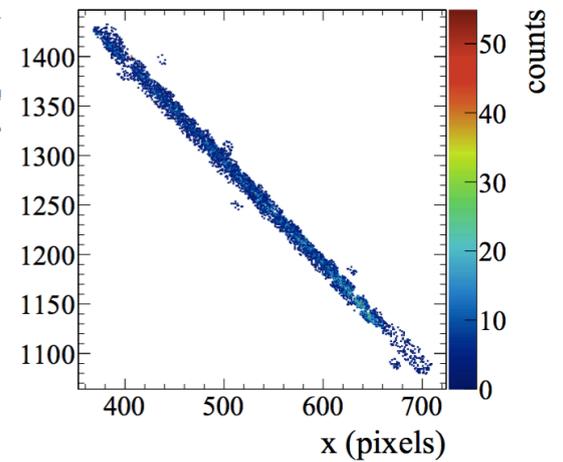
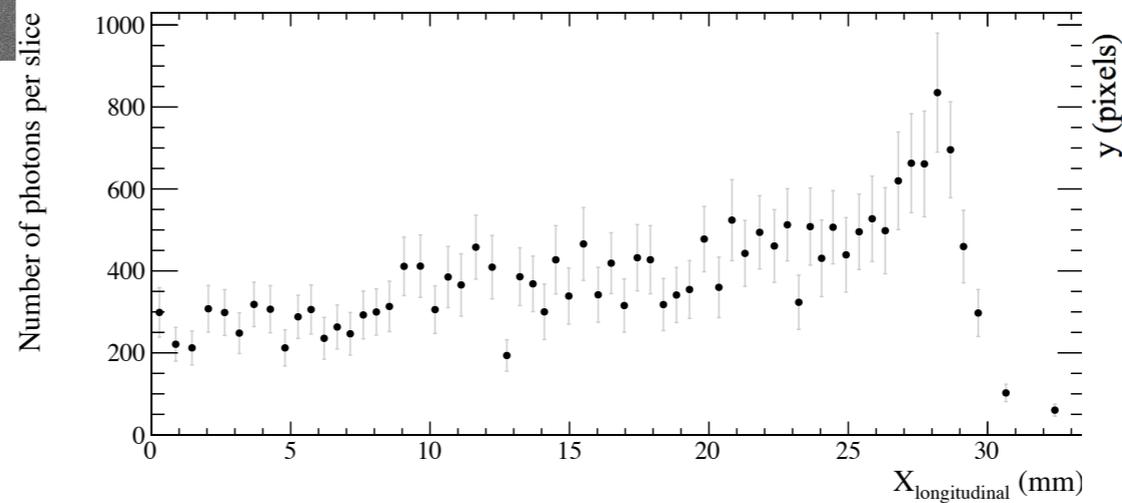
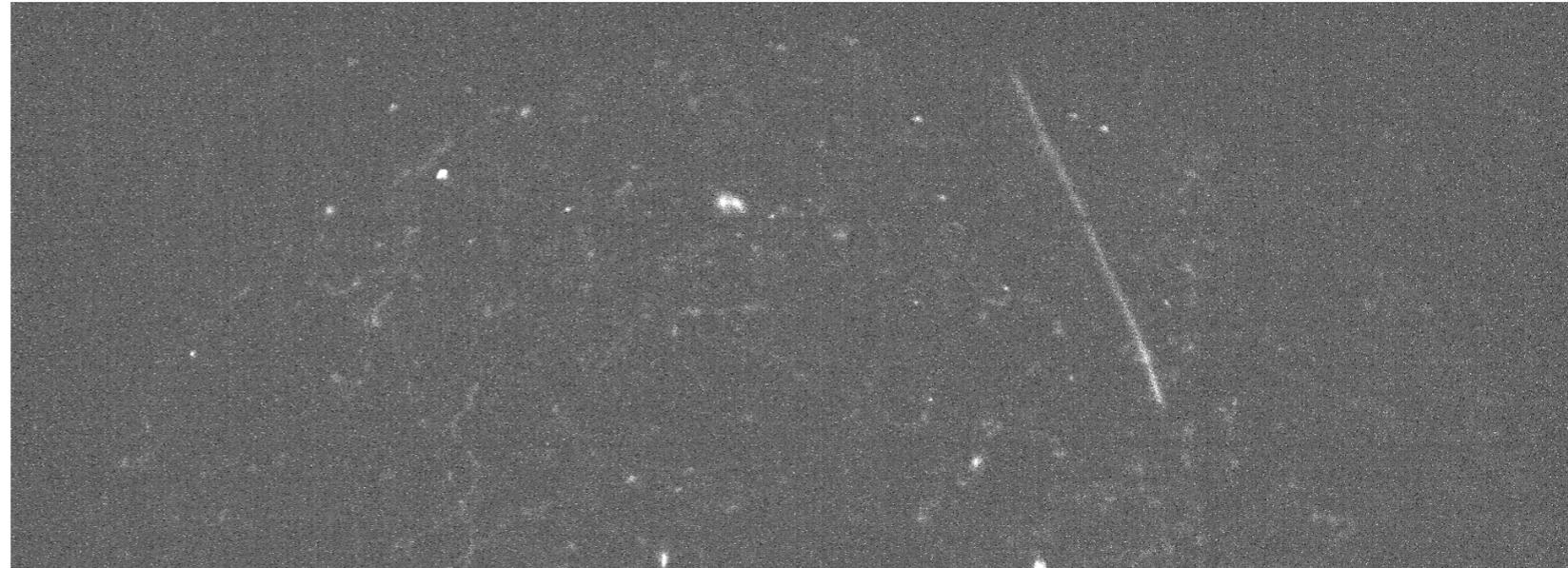
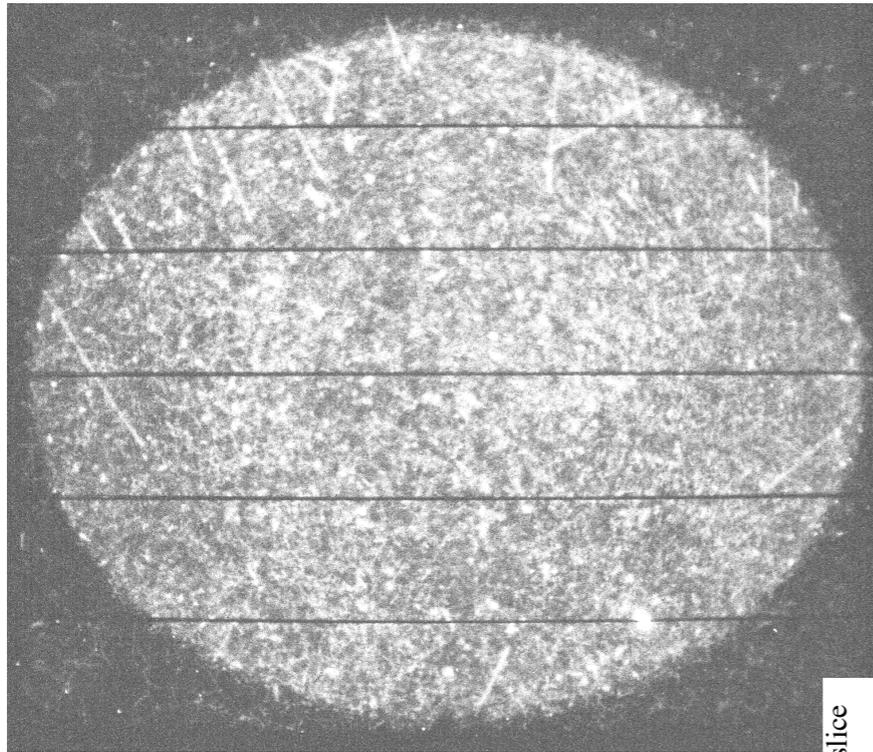
- ▶ Lowering **threshold** in cryogenic detectors
- ▶ Lowering **mass** of the target nucleus
- ▶ **Gamma rejection difficult at low WIMP masses: new techniques ?**



Bibliography

5s exposure @ 2.45 MeV neutrons
Frascati Neutron Generator

0.1s exposure @ 2.45 MeV neutrons
Frascati Neutron Generator



test beam 18-20 June 2018

(thanks to FNG)
Gianluca Cavoto

Diffusion of electrons

