CYGNO proposal

a CYGNus TPC module with Optical readout

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The CYGNUS collaboration

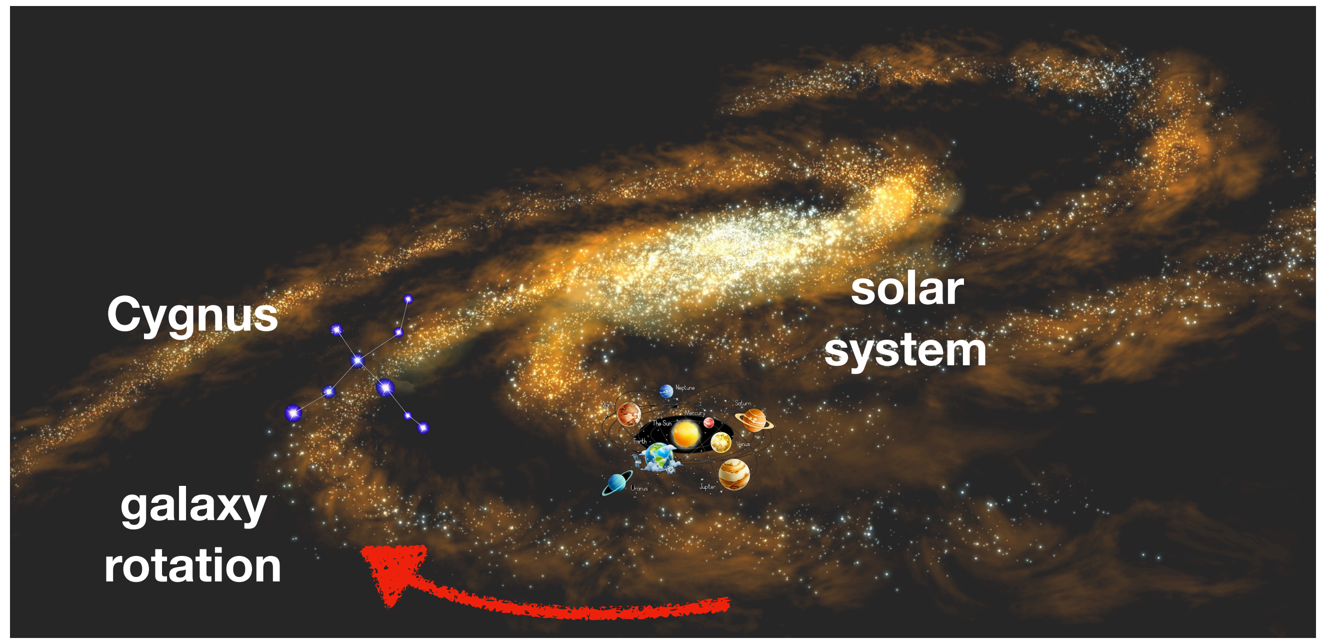
INFN LNF
Istituto Nazionale di Fisica Nucleare

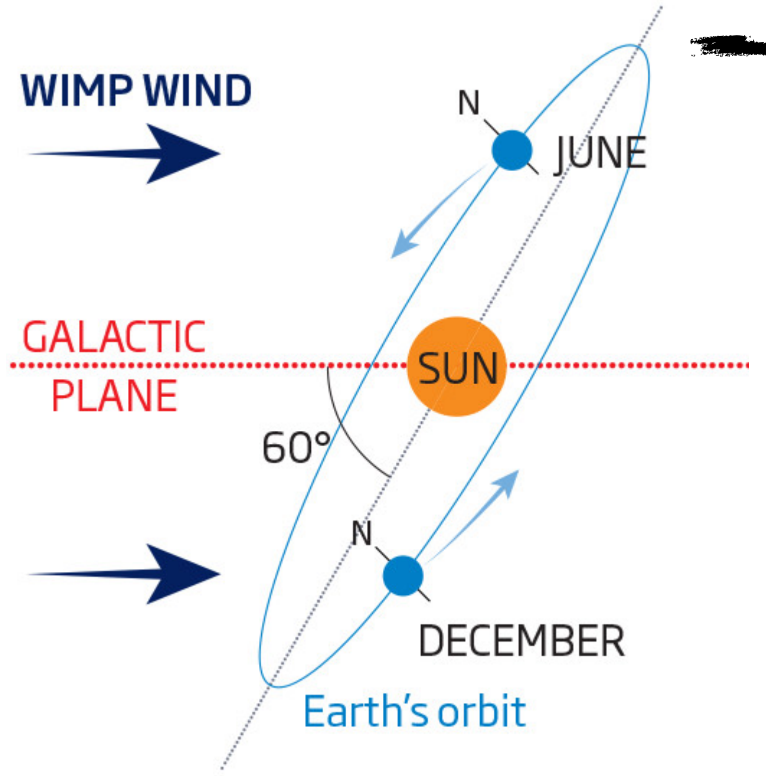
45 members from the US, UK, Japan, Italy, Spain, China, Australia

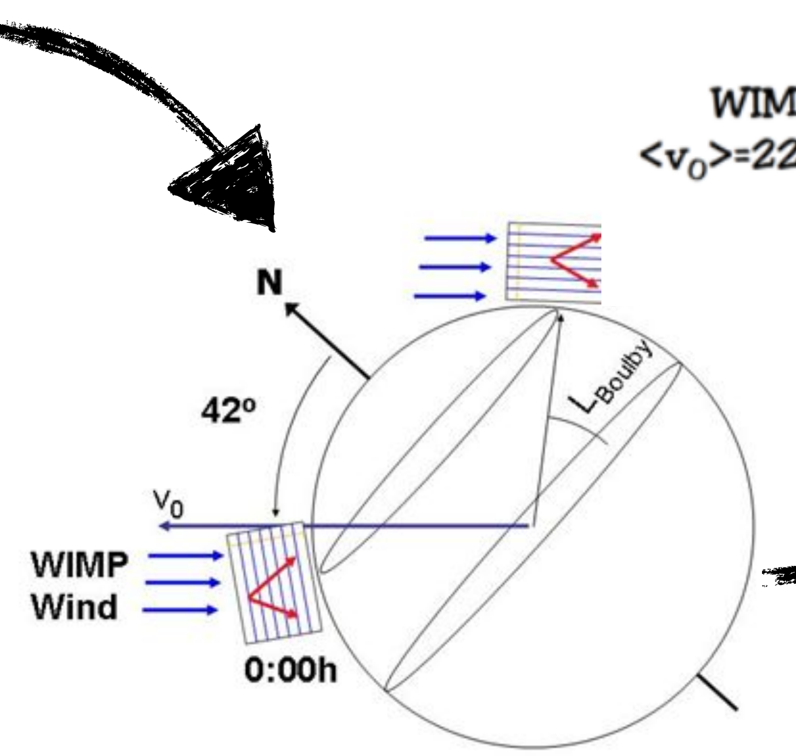
Galactic Nuclear Recoil Observatory
identify with **directional** sensitivity clear **dark matter** candidate and **coherent neutrino** scattering from the Sun and other sources

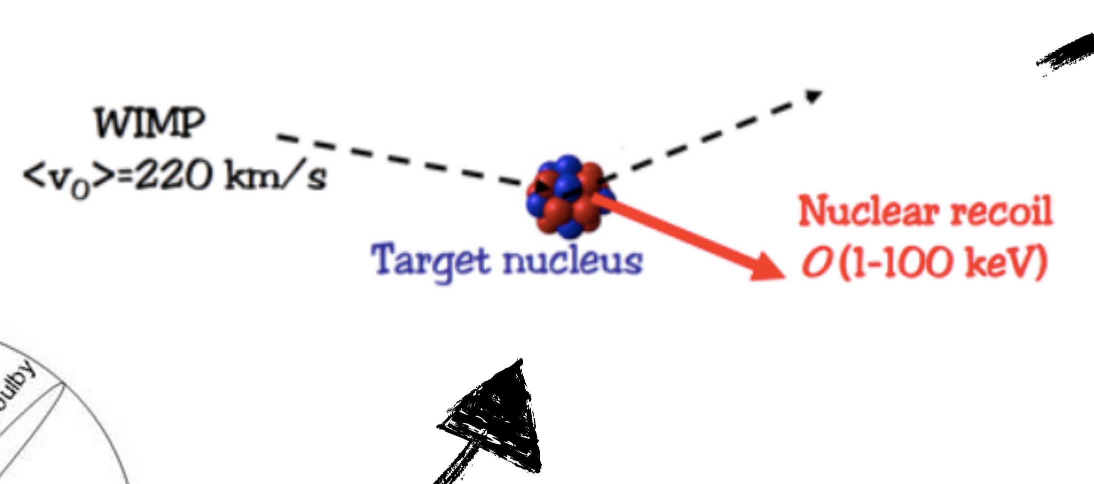
1. to establish the **science** case for CYGNUS, working with external experts as required
2. to establish the **feasibility** and **technology** choices for CYGNUS, coordinating R&D activities, resources and **joint publications** as necessary
3. to form an Institute **Board** including remit to prepare an organisational structure in readiness for launch of the collaboration
4. to write an **experiment LOI** as basis for formation of the collaboration based on (1-3)
5. to launch and follow the **international collaboration**

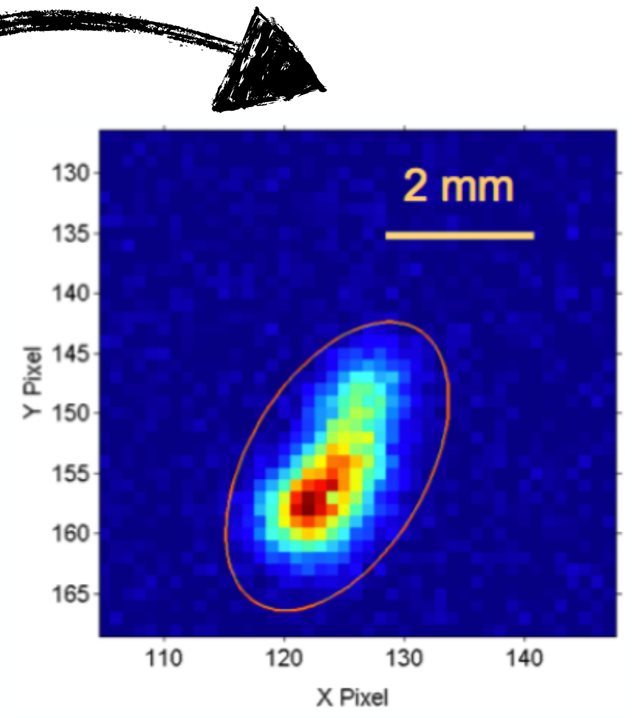
CYGNUS collaboration objective

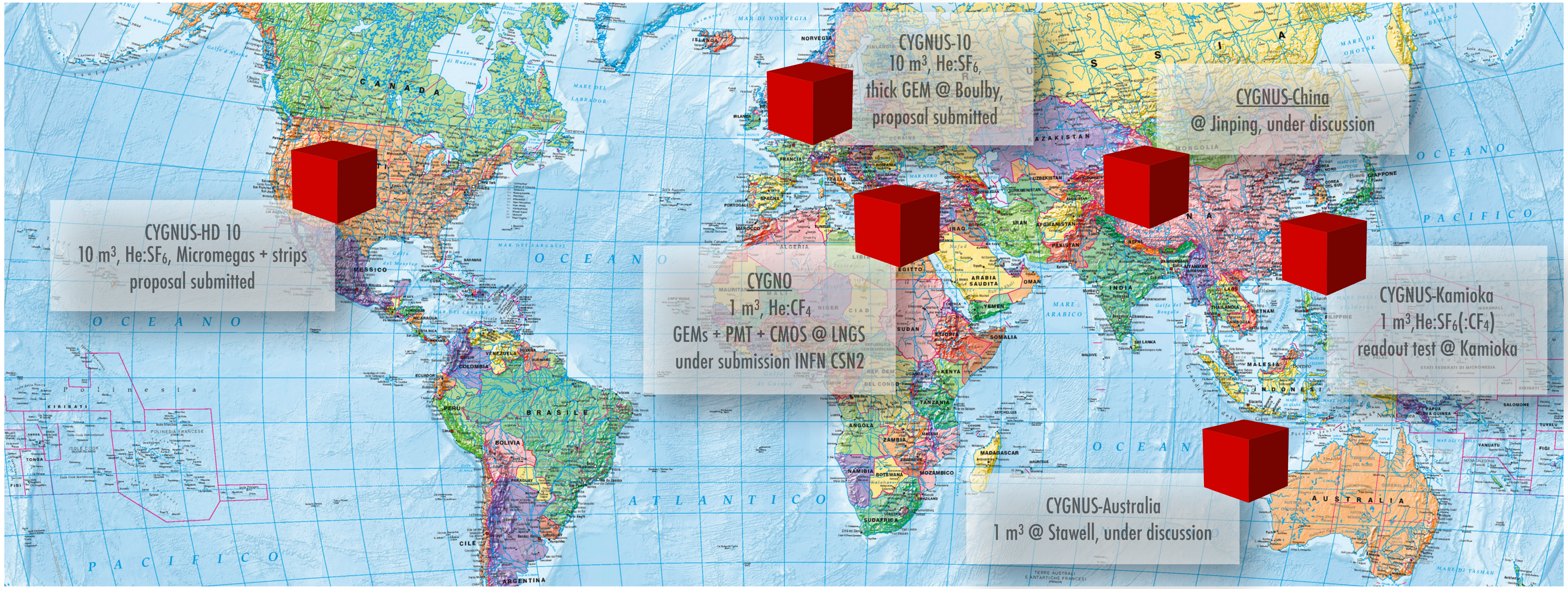






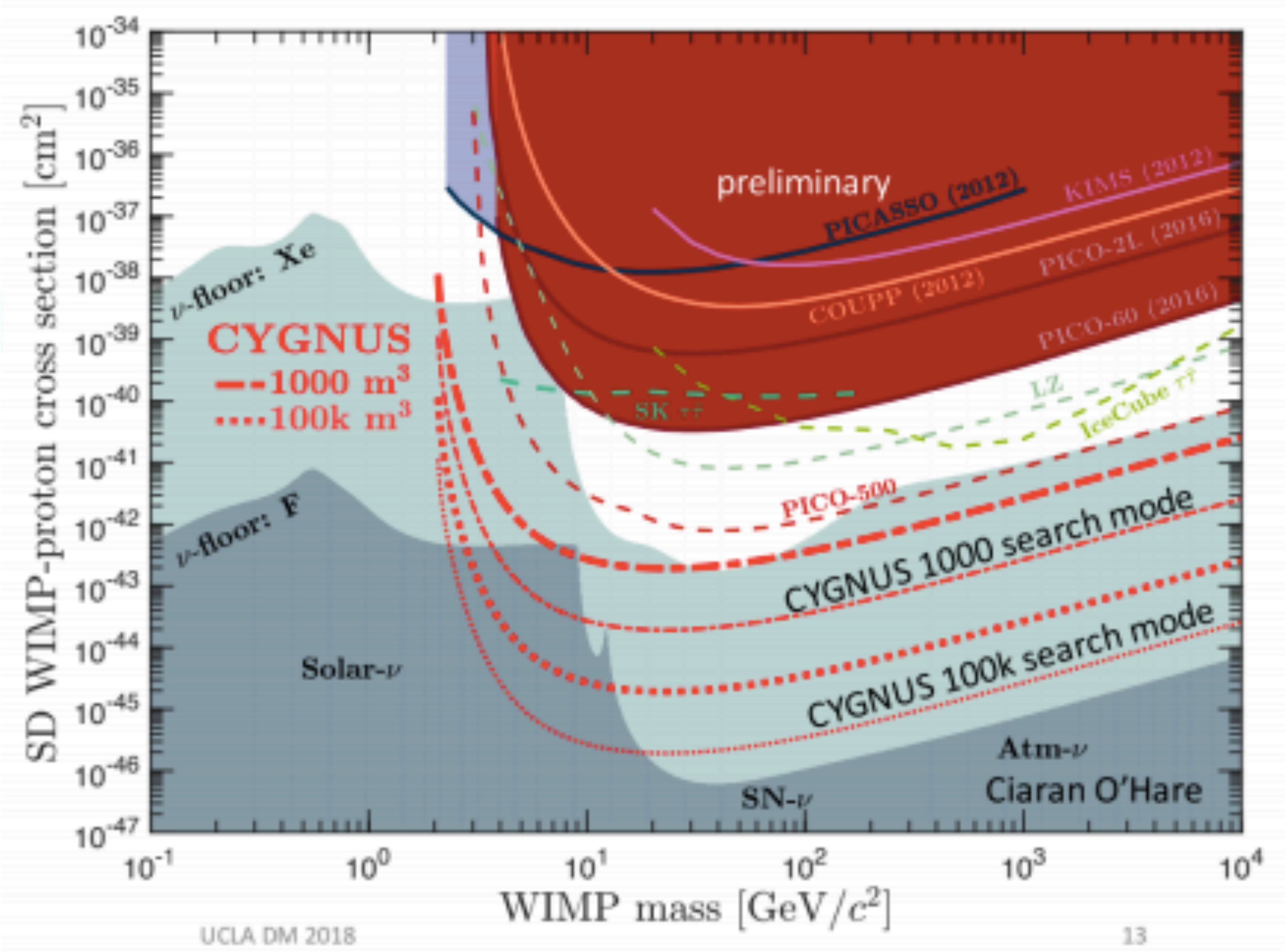


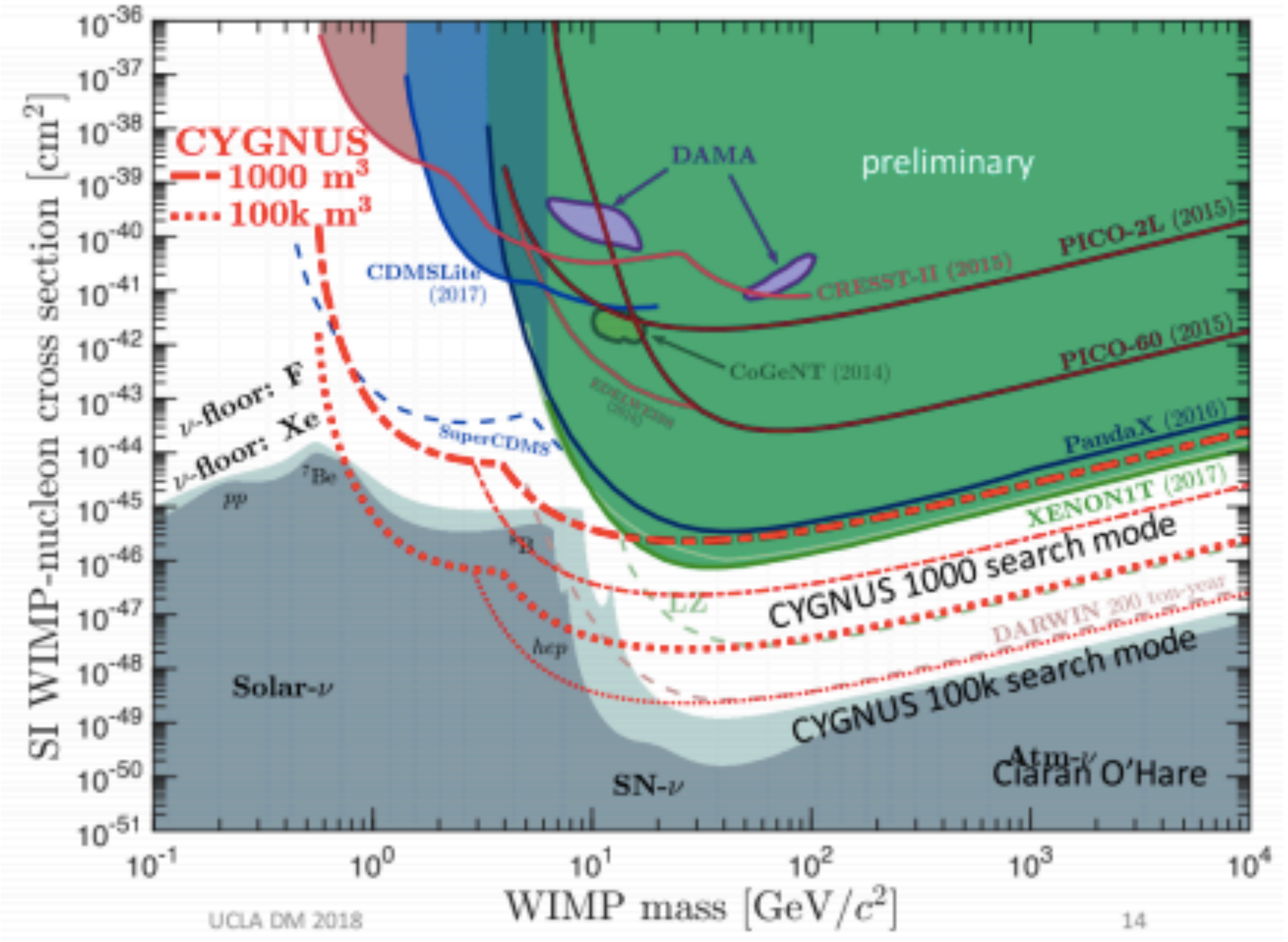




The CYGNUS TPC challenging to goal

Sven Vahsen

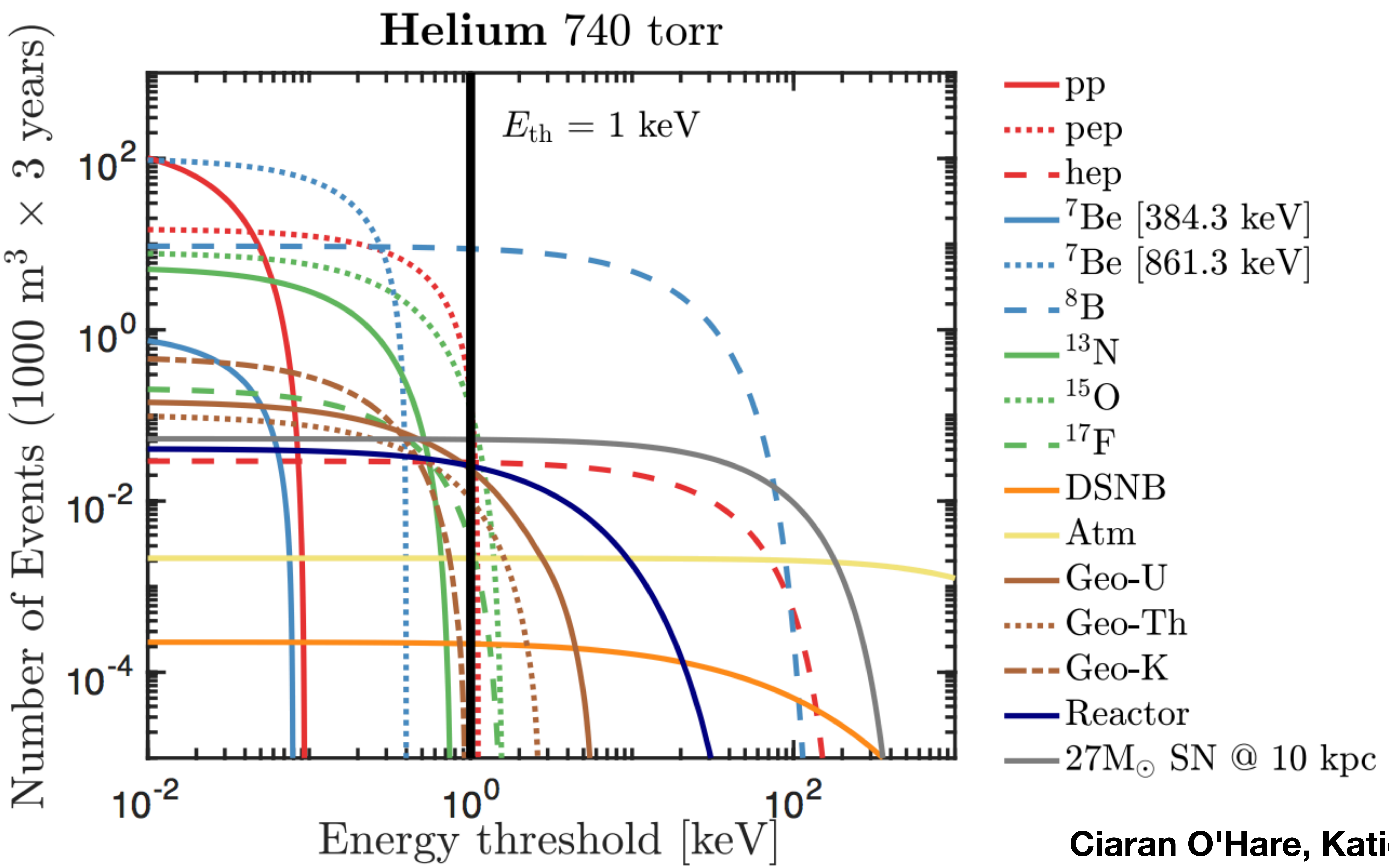




- **Energy threshold 1 keVee**
- **Target mass 100-1000 kg (F, He)**
- **Zero neutron background**
  - no steel (vacuum) vessel (acrylic?)
  - ceramics; almost no internal electronics
- **x, y, z fiducialisation and radon rejection**
  - either negative ion drift or other technique
  - material selection and scrubbing is not enough
- **Gamma discrimination below 10 keVee**
- **Directional sensitivity**

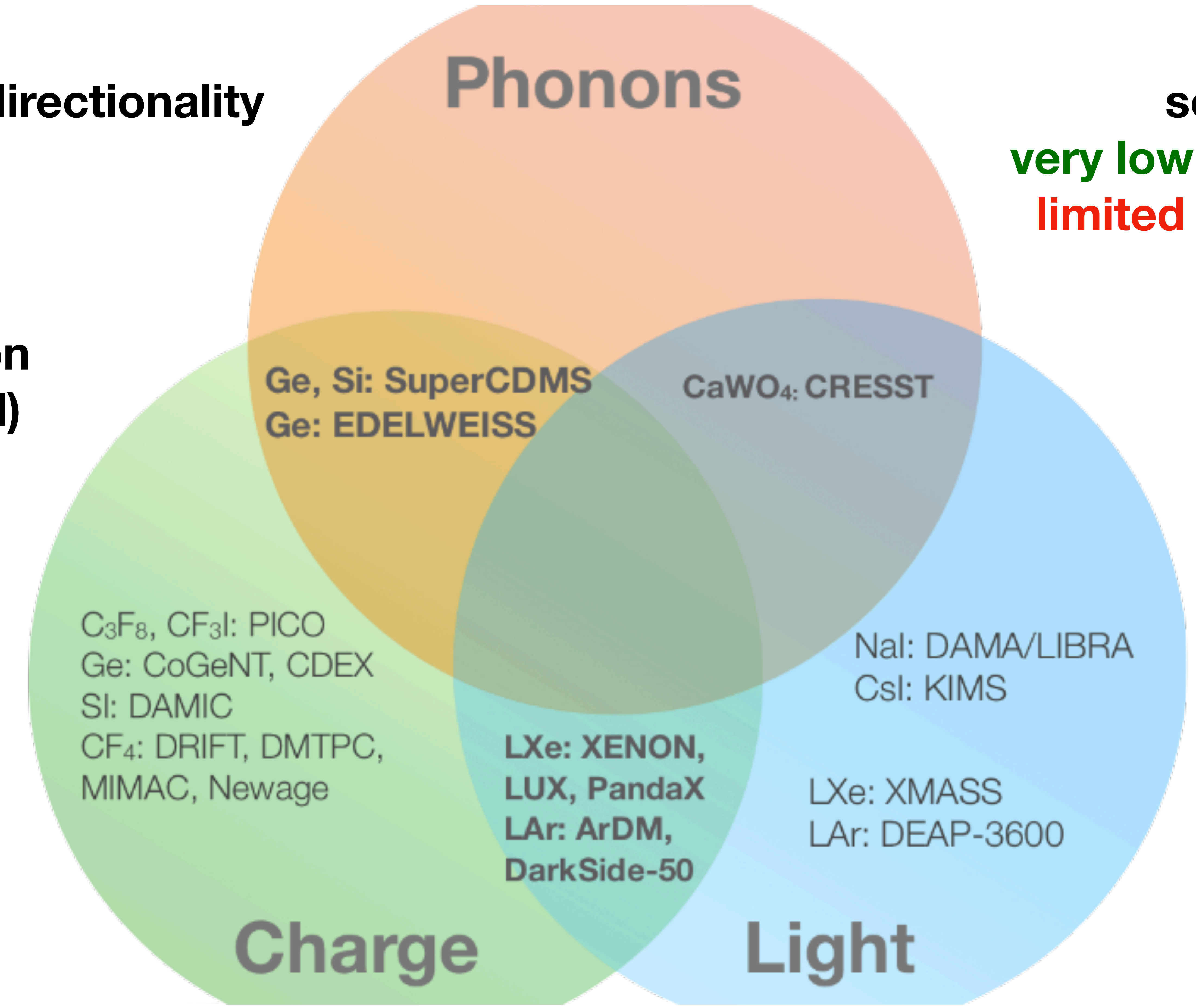
…approaching the neutrino floor

very preliminary estimation for CYGNUS HeSF6



Ciaran O'Hare, Katie Mack

DM detection strategy



directionality

particle Identification
(signal, background)

gassous
low (KeV) threshold
ideas to increase
sensitivity and scalability

solid, cryogenic
very low (10-100 eV) threshold
limited mass and scalability

liquid, cryogenic
medium (MeV) threshold
high sensibility and
scalability

picture M. Messina

Why gaseous TPC?

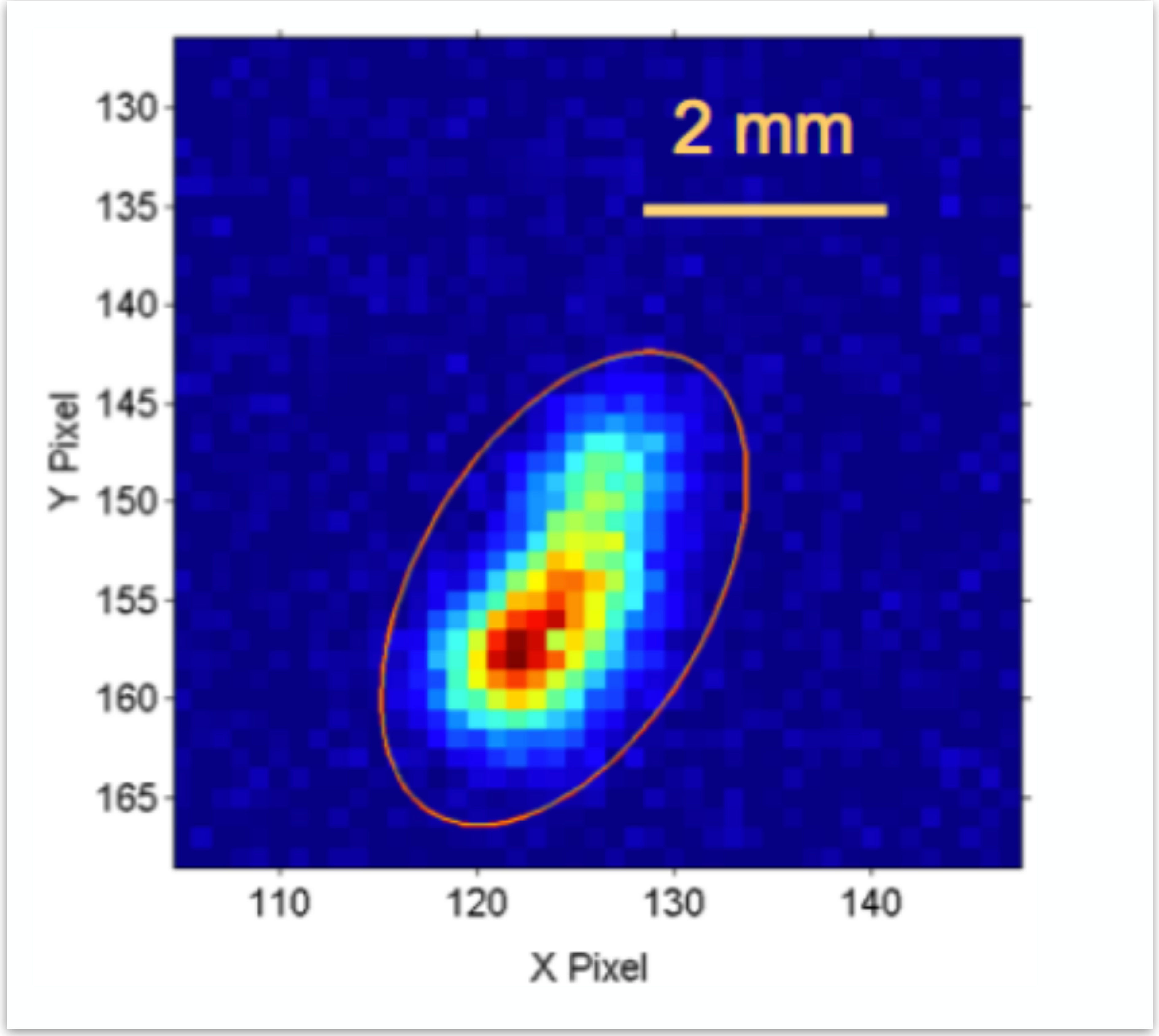
Time Projection Chambers provide:

- 3D tracking (position and direction);
- total released energy measurement;
- dE/dx profile (pid, head-tail);
- reduced readout channel number;

gas represents an interesting target:

- nuclei free path can be **long** enough to be reconstructed;
- **low mass** gases allow an efficient momentum transfer from light DM;

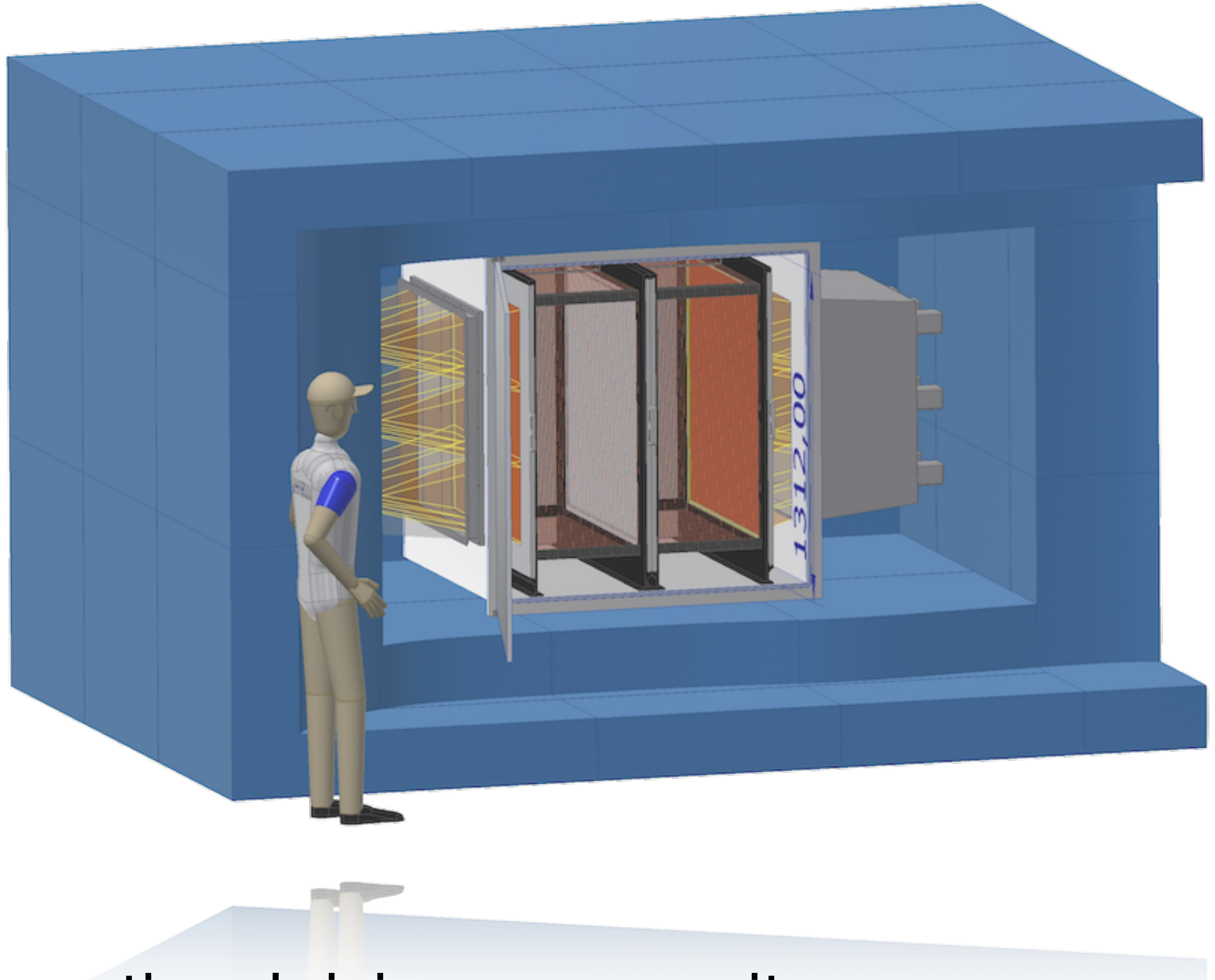
Nuclear recoil in gas



- avalanche mechanism allows a **sensitivity** to single primary electrons (i.e. energy release of 30-40 eV);

CYGNO: a CYGNUs Collaboration 1 m^3 Module with Optical Readout for Directional Dark Matter Search

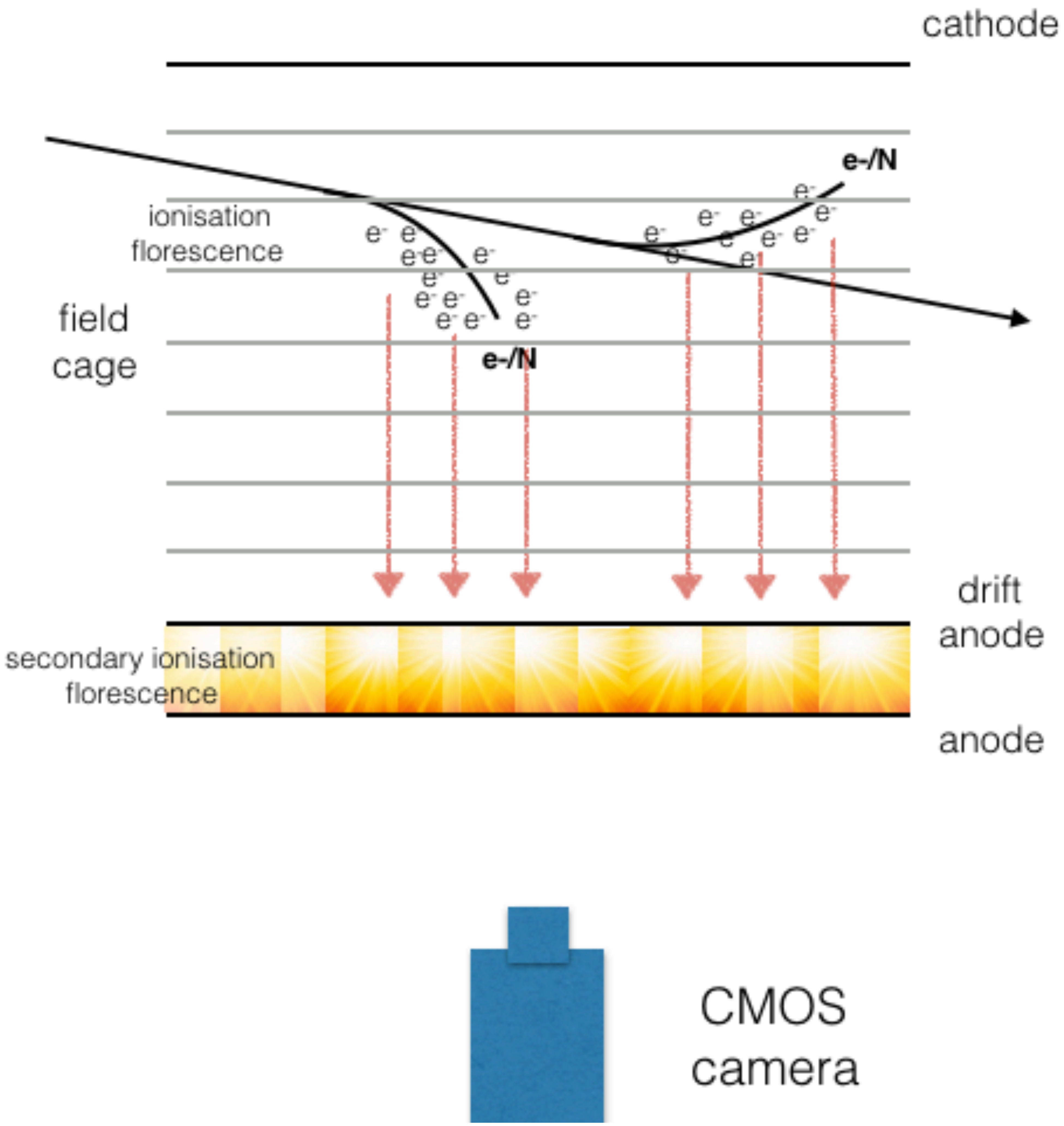
- **objectives:**
  - demonstrating the validity of technology
  - understanding noise and background due to radioactivity
  - performing neutron LNGS flux measurements and contribute to directional dark matter upper limit measurements with a different systematics



… and moreover participating to a new international rising community for sub GeV DM candidate measurement

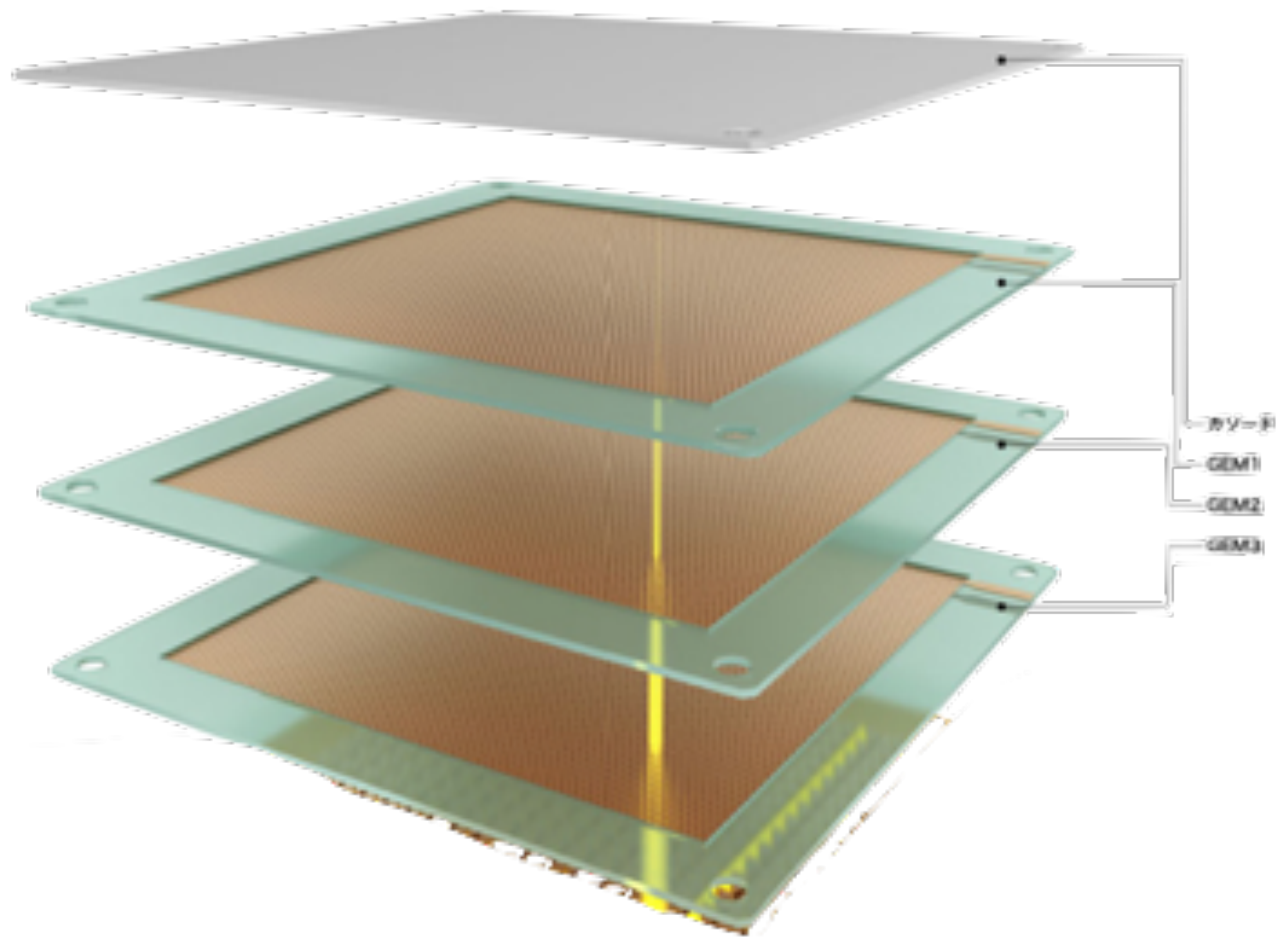
The CYGNO demonstrator strategy

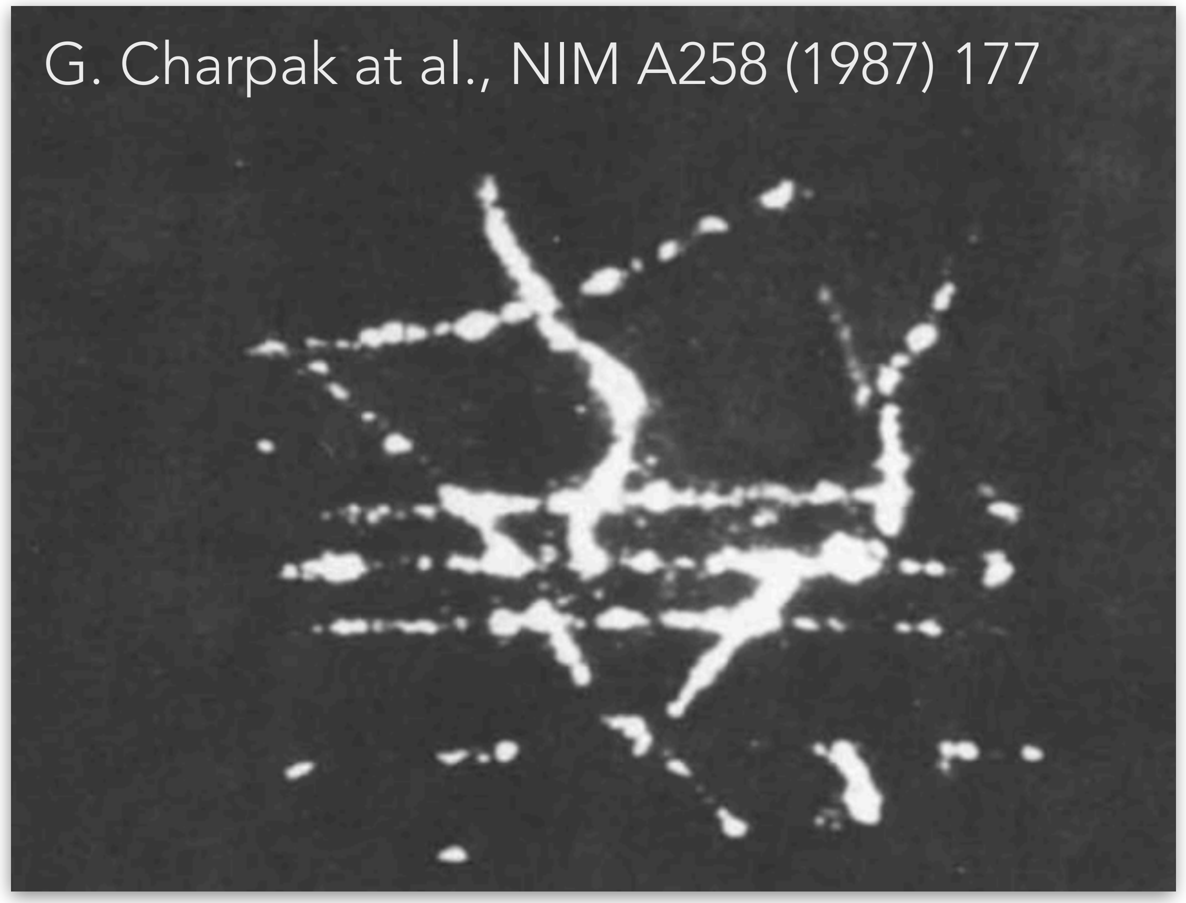
- **high granularity (CMOS+PMT) optical read out:**
  - threshold
  - discrimination
  - directionality;
  - x, y, (z) fiducialisation
  - electronics decoupling
- **atmospheric pressure He gas mixture:**
  - low target density (low threshold)



Optical Read Out

Multiple GEM structures can be used to share the gain and make more stable detectors.




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

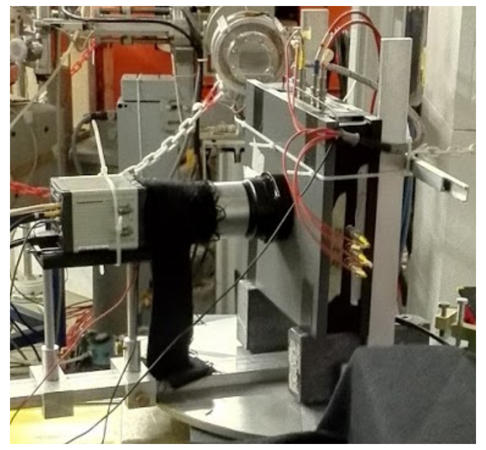
During the multiplication process, photons are produced along with electrons by the gas through atomic and molecular de-excitation;

- **optical sensors** are able to provide **high granularities** along with very **low noise** level and **high sensitivity**;
- **optical coupling** allows to keep sensor out of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable **lens** allow to acquire **large surfaces with small sensors**;

CYGNO Roadmap @ LNGS

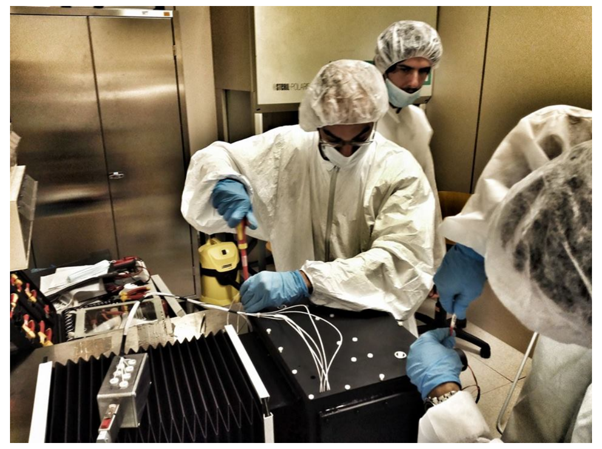
	2018	2019	2020	2021	2022	…
@ ROMA1/LNF	@ LNF	@ LNF	@ LNF	@ LNGS		
		TDR	Construction & test	Installation & data taking		

ORANGE



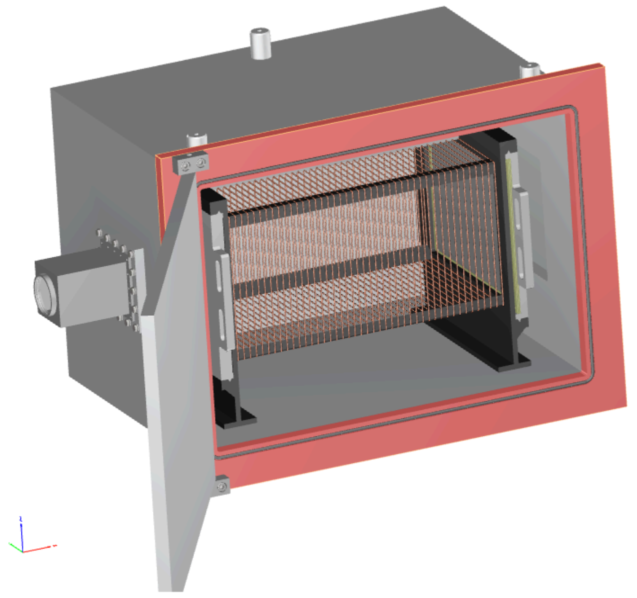
- OPT readout
- 1 cm drift
- 0 resolution

LEMON



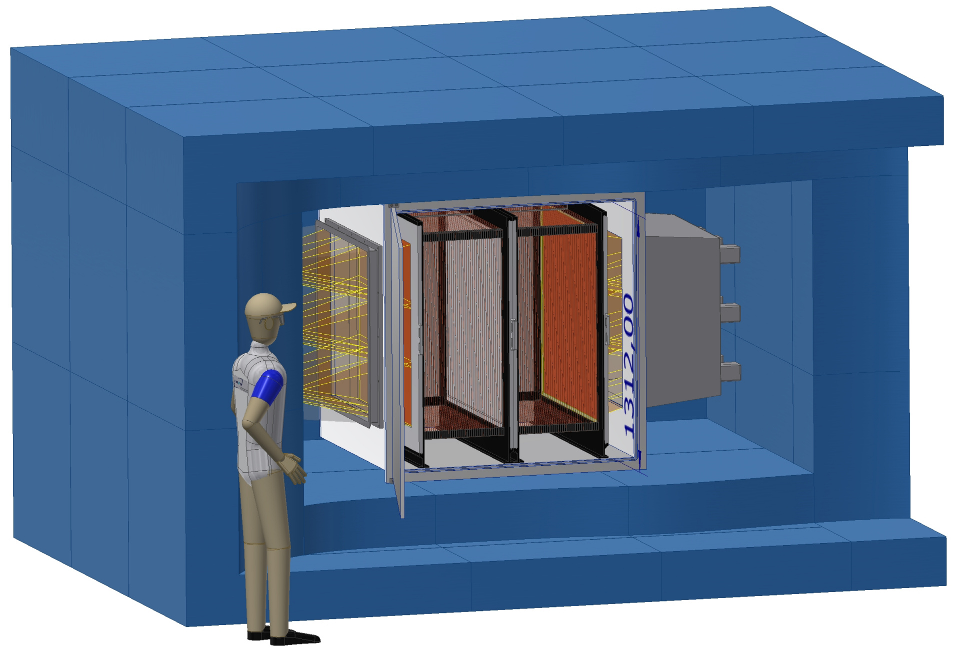
- OPT readout
- 3D printing
- 20 cm drift
- PID
- tracking
- drift resolutions

LIME



- …
- 50 cm drift
- drift scaling
- materials test
- gas

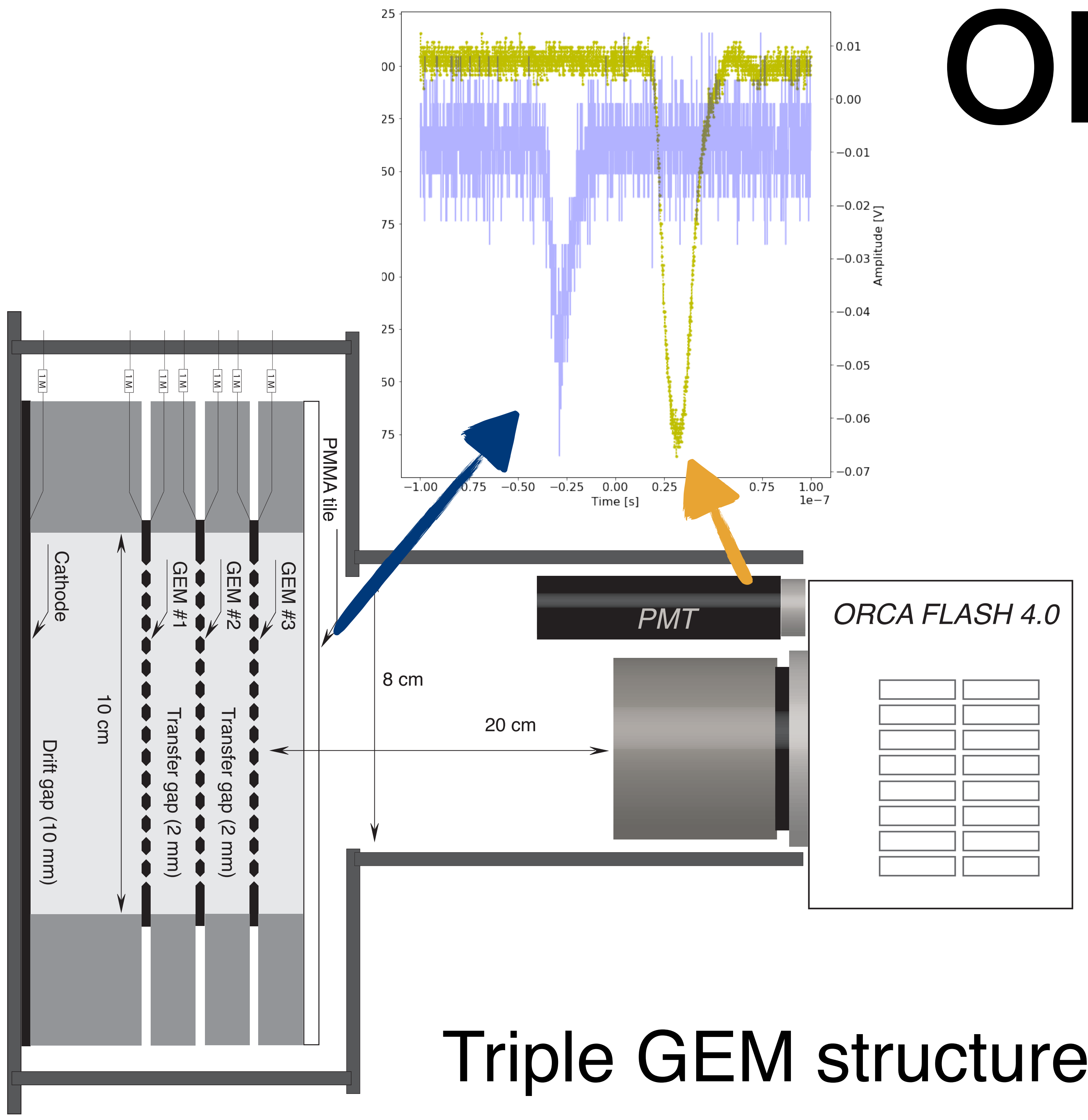
CYGNO "demonstrator"

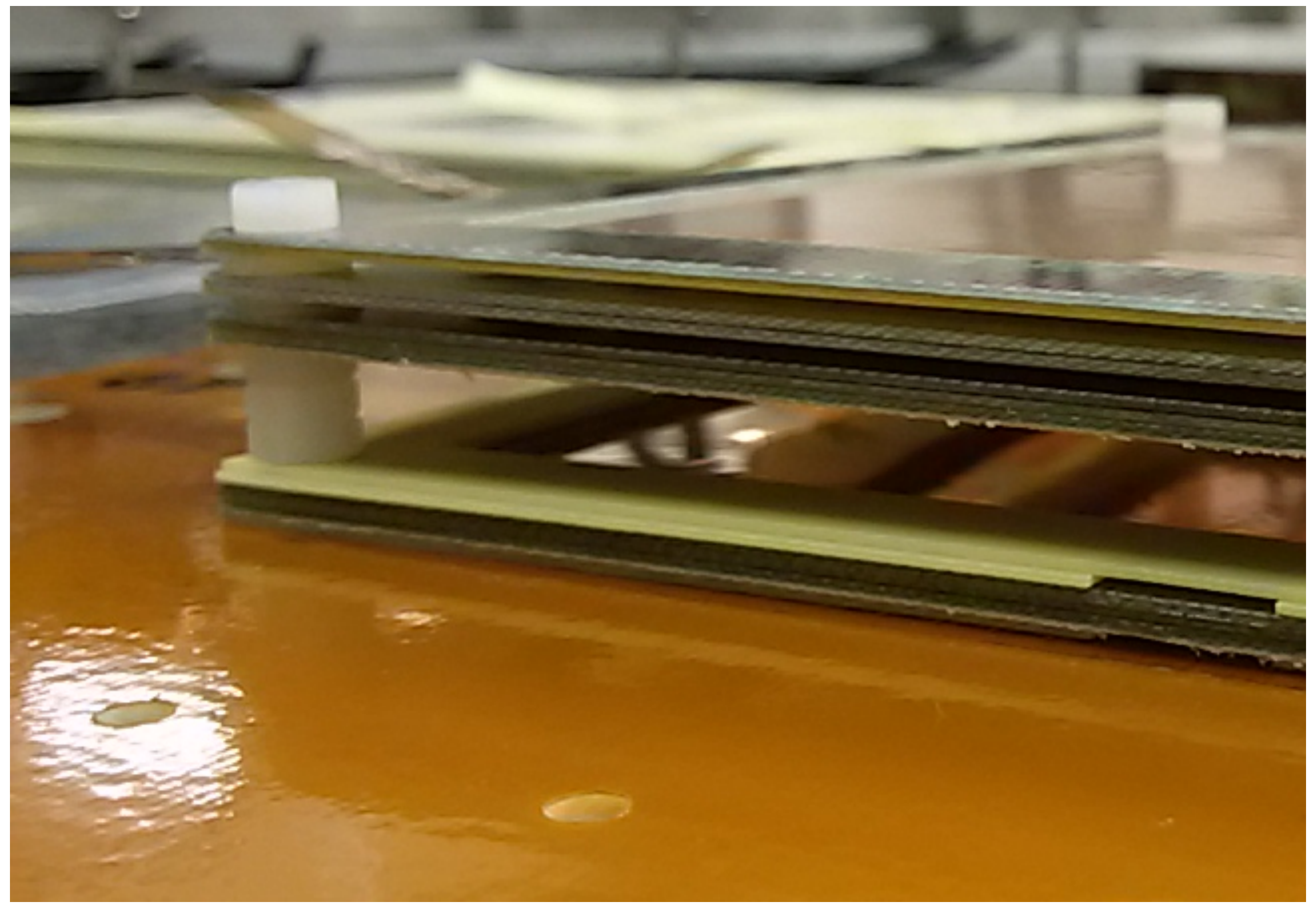


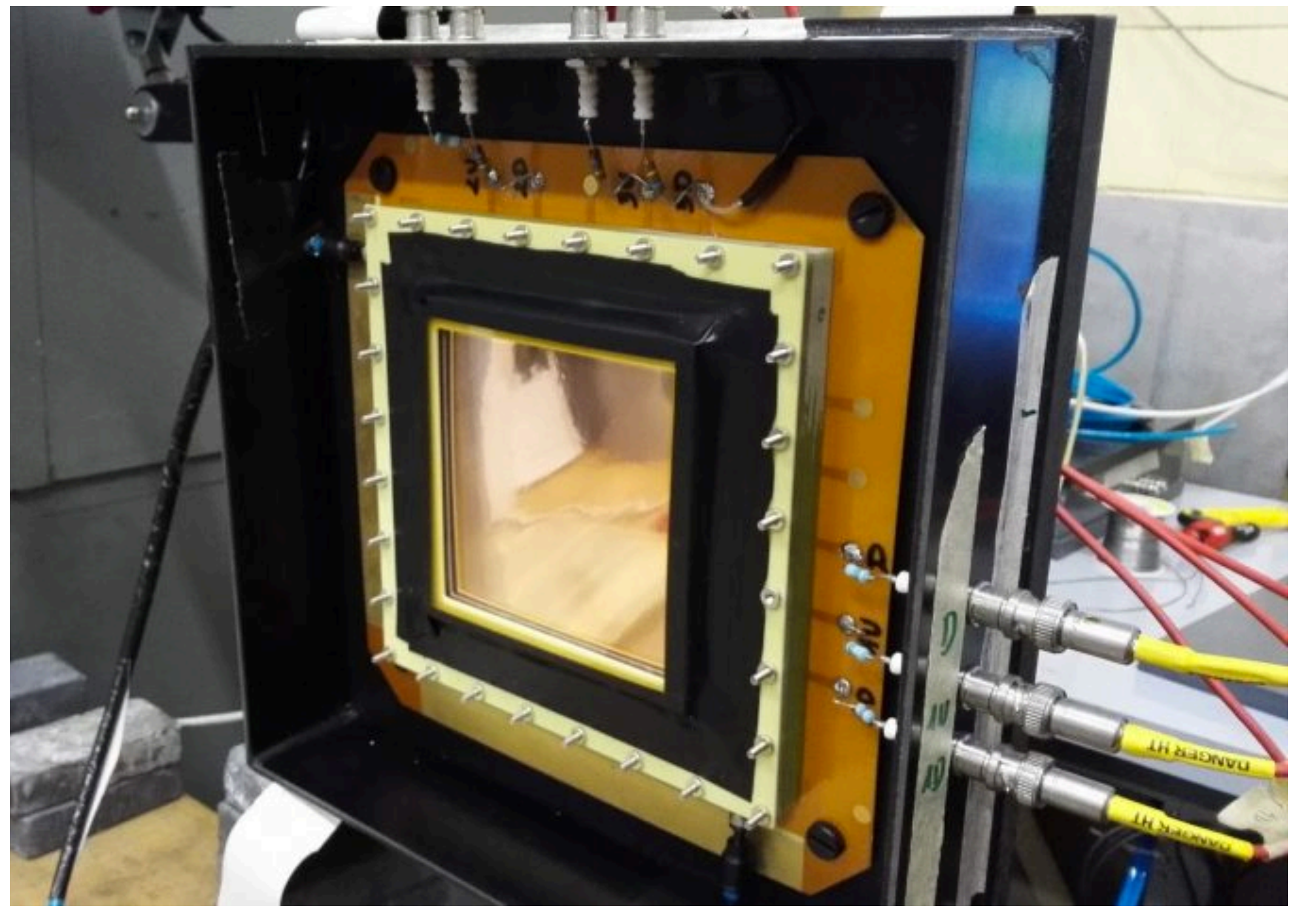
- …
- background
- materials test
- gas purification
- shielding
- stability
- scalability
- reliability

CYGNUS 100-1000 m^3

ORAnGE prototype

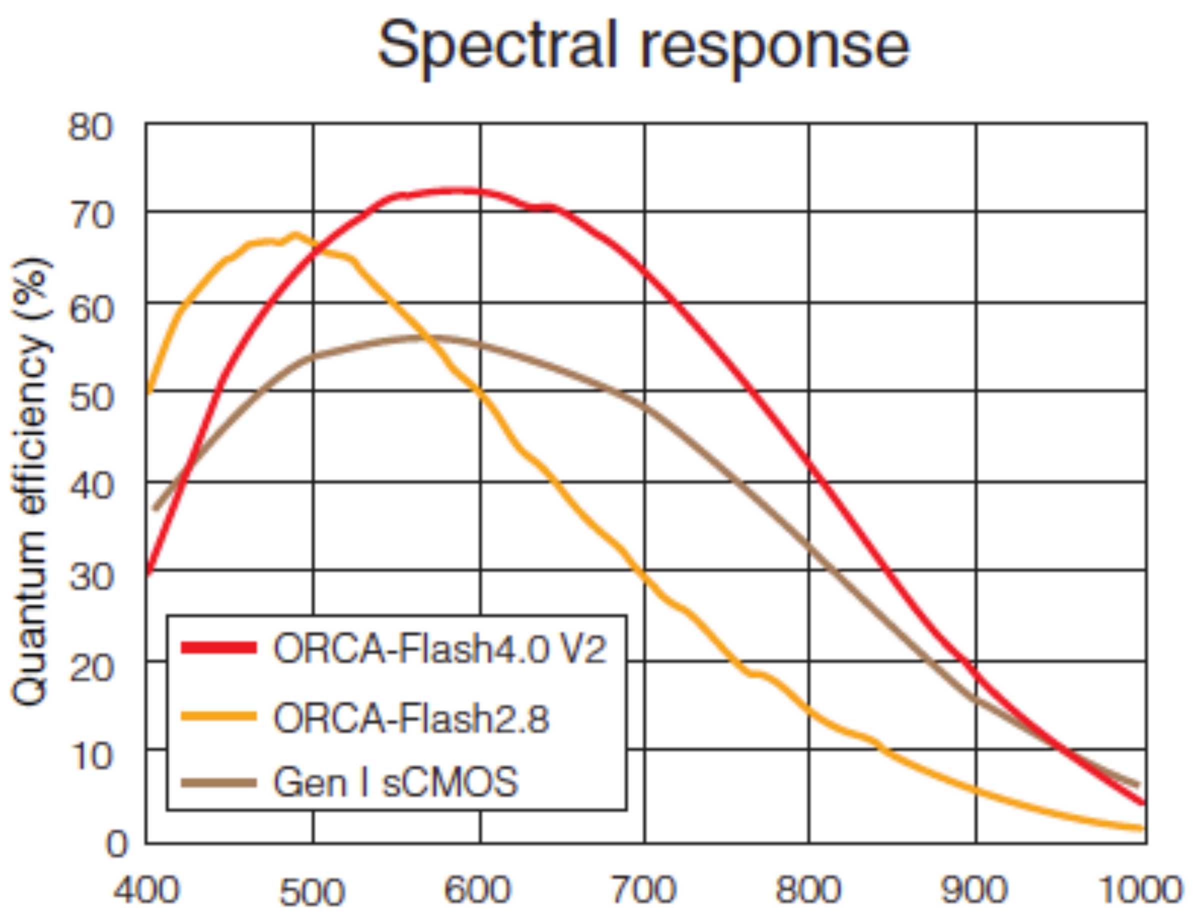


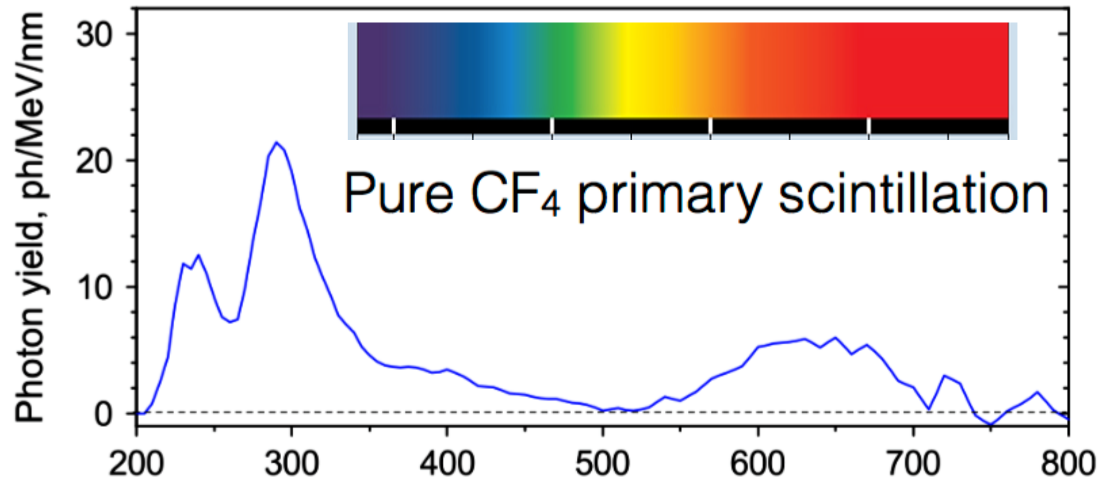




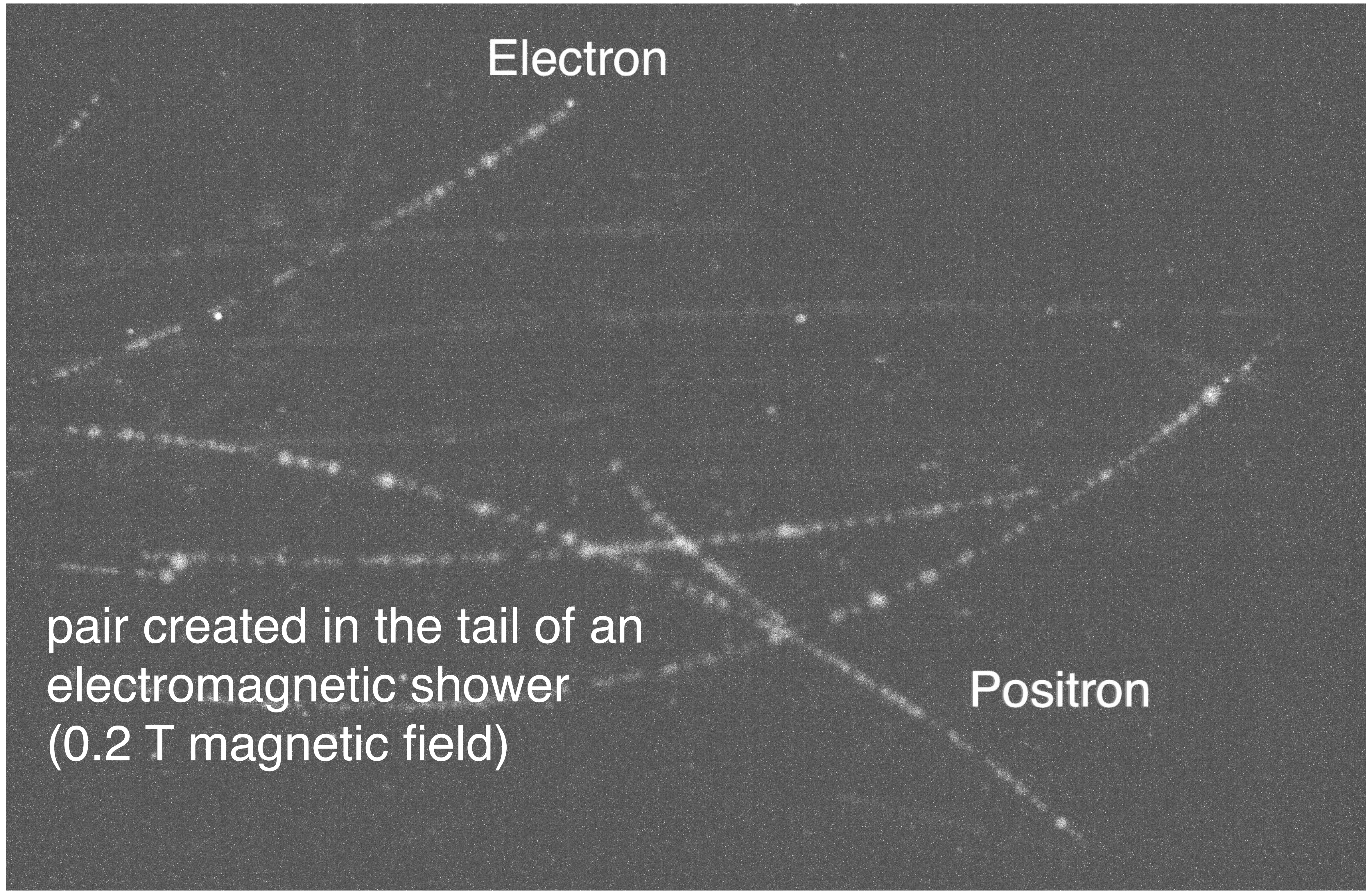
Triple GEM structure (10x10 cm²) with 1 cm sensitive gap.

He/CF_4 (60/40) mixture



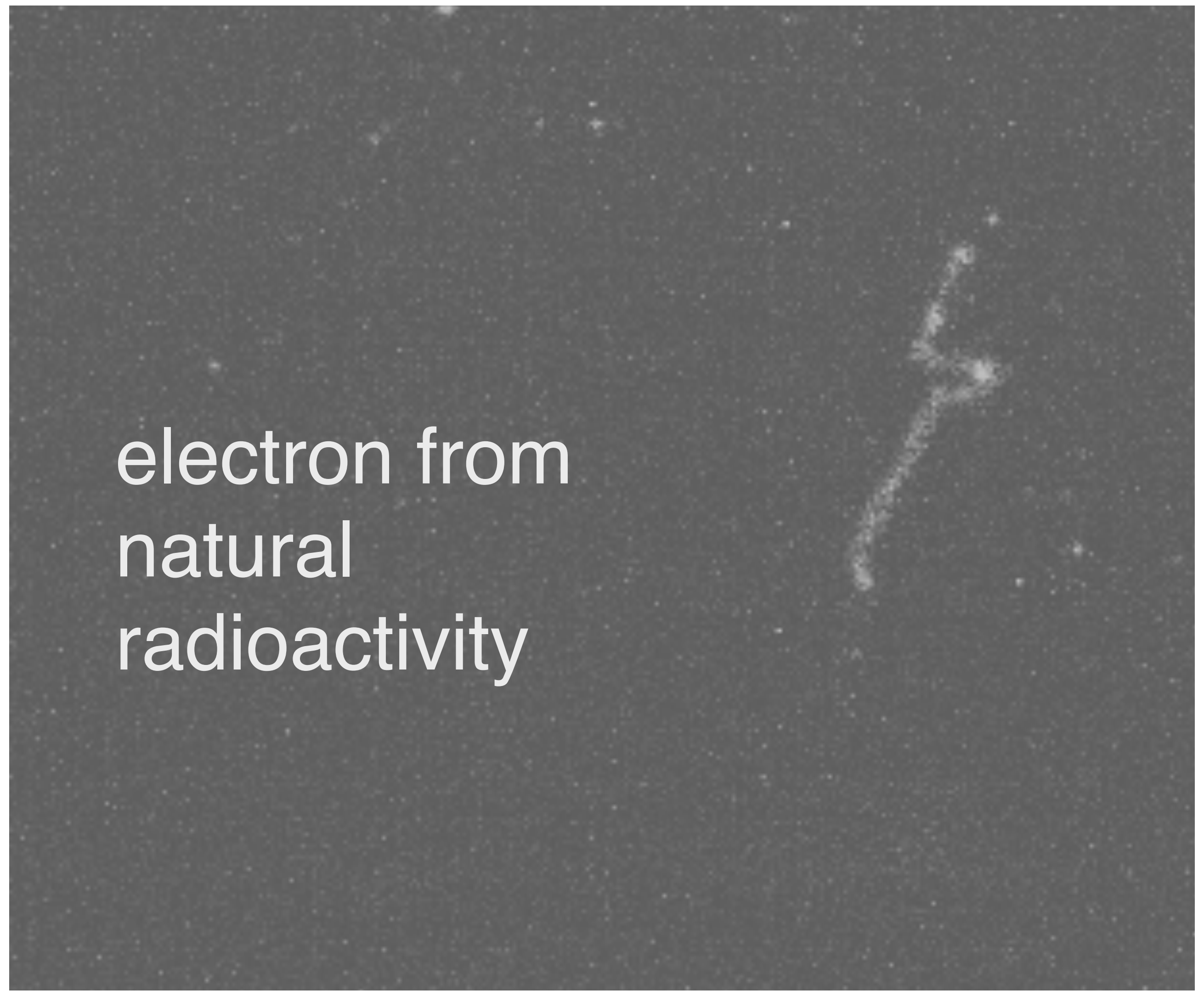


CMOS: low noise; high granularity (2048×2048 pixel / 125×125 μm²) and high sensitivity equipped with optics f/0.95-25 mm

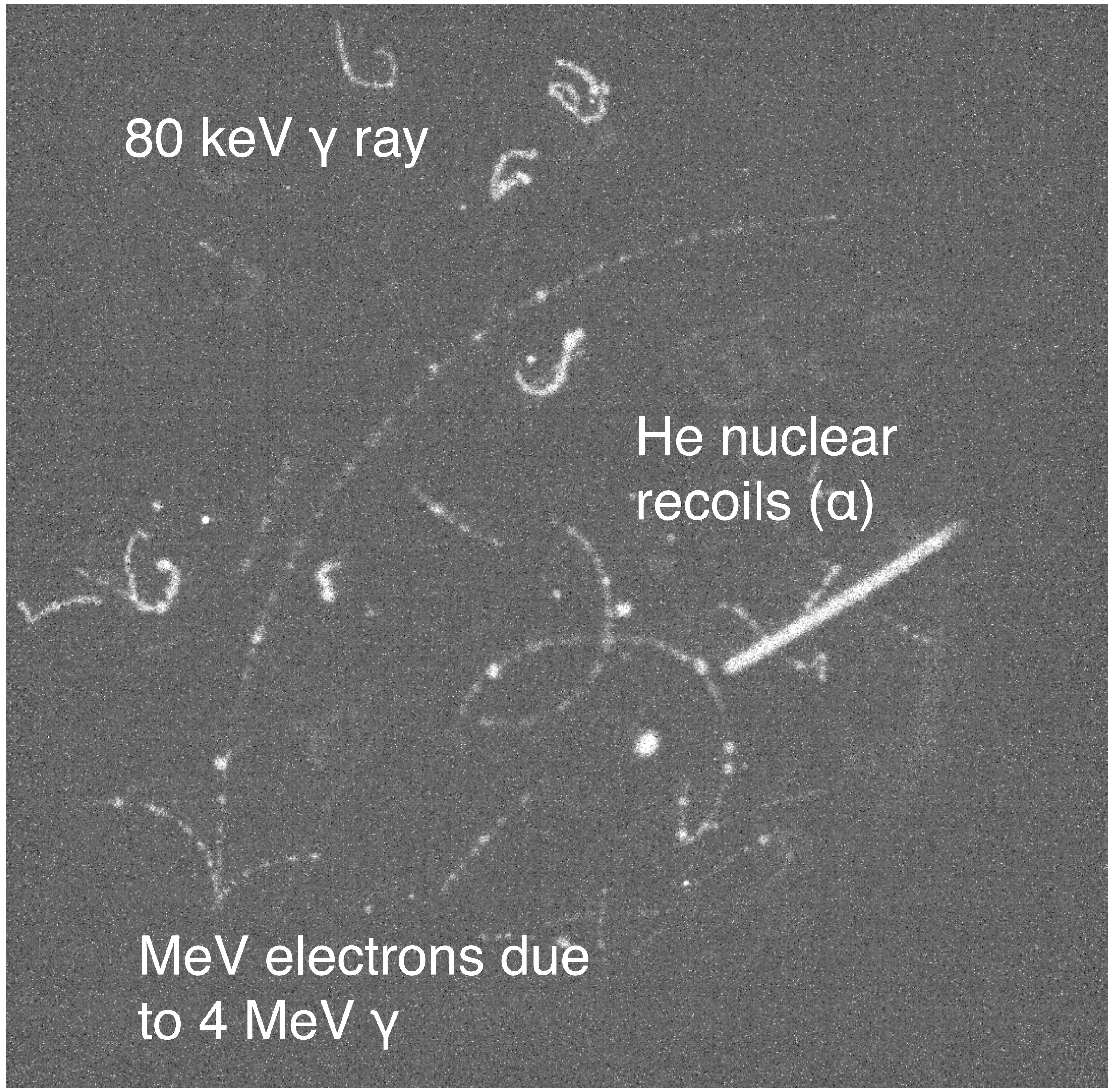


(thanks to Frascati Beam
Test Facility BTF)

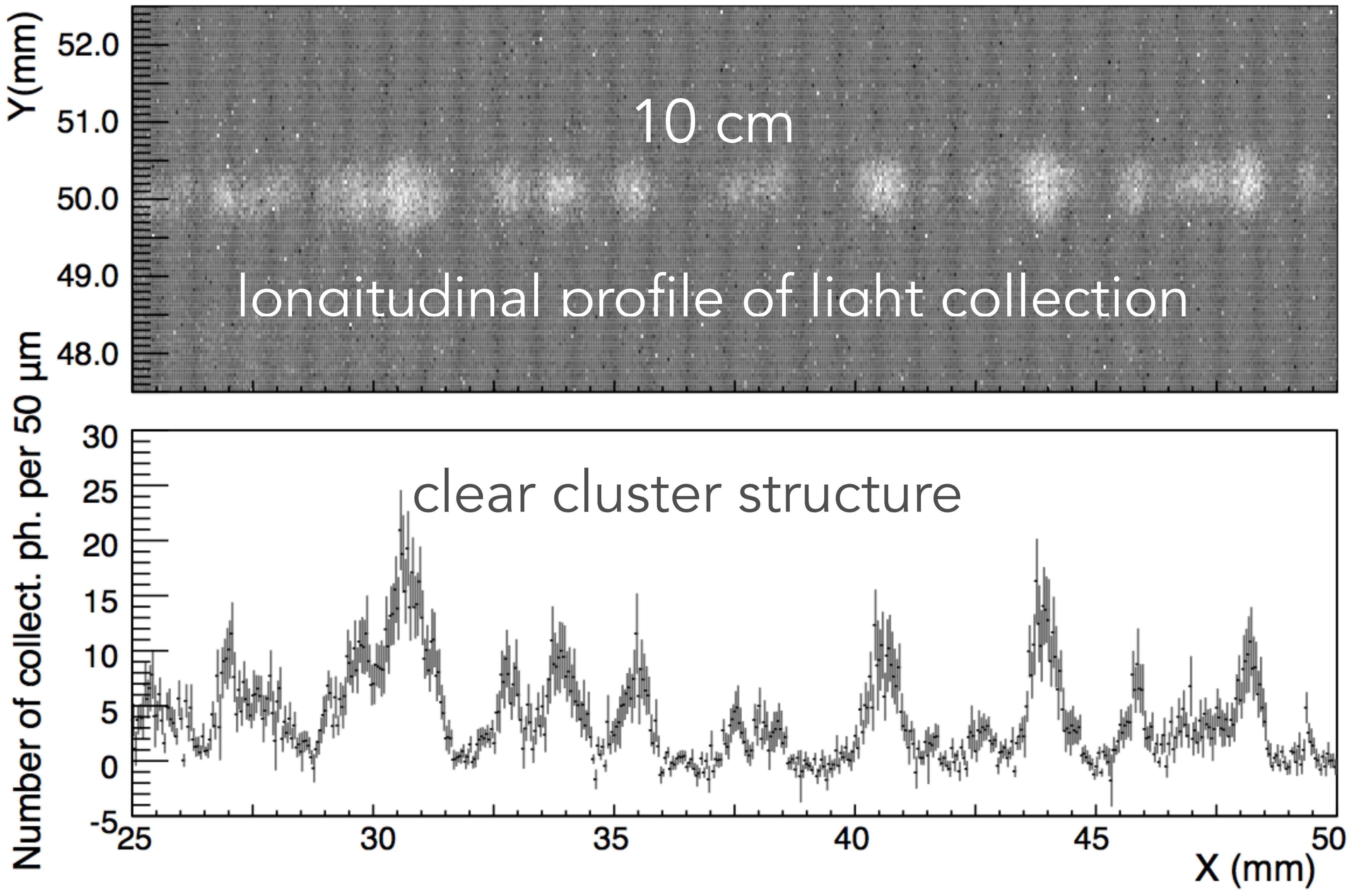
AmBe Neutron source
(thanks to FISMEL)

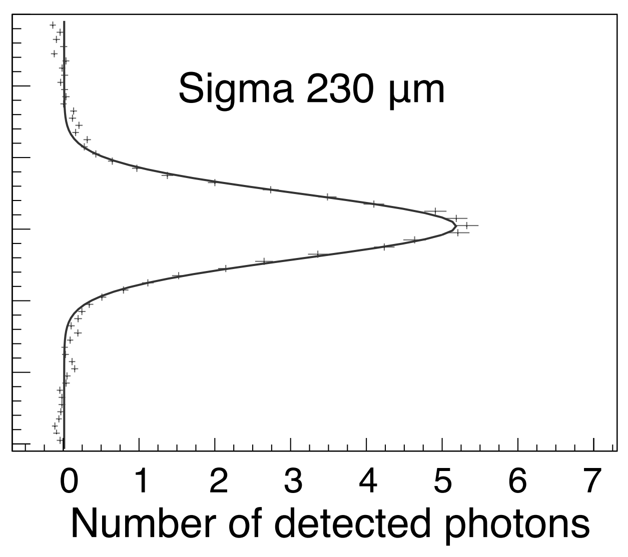


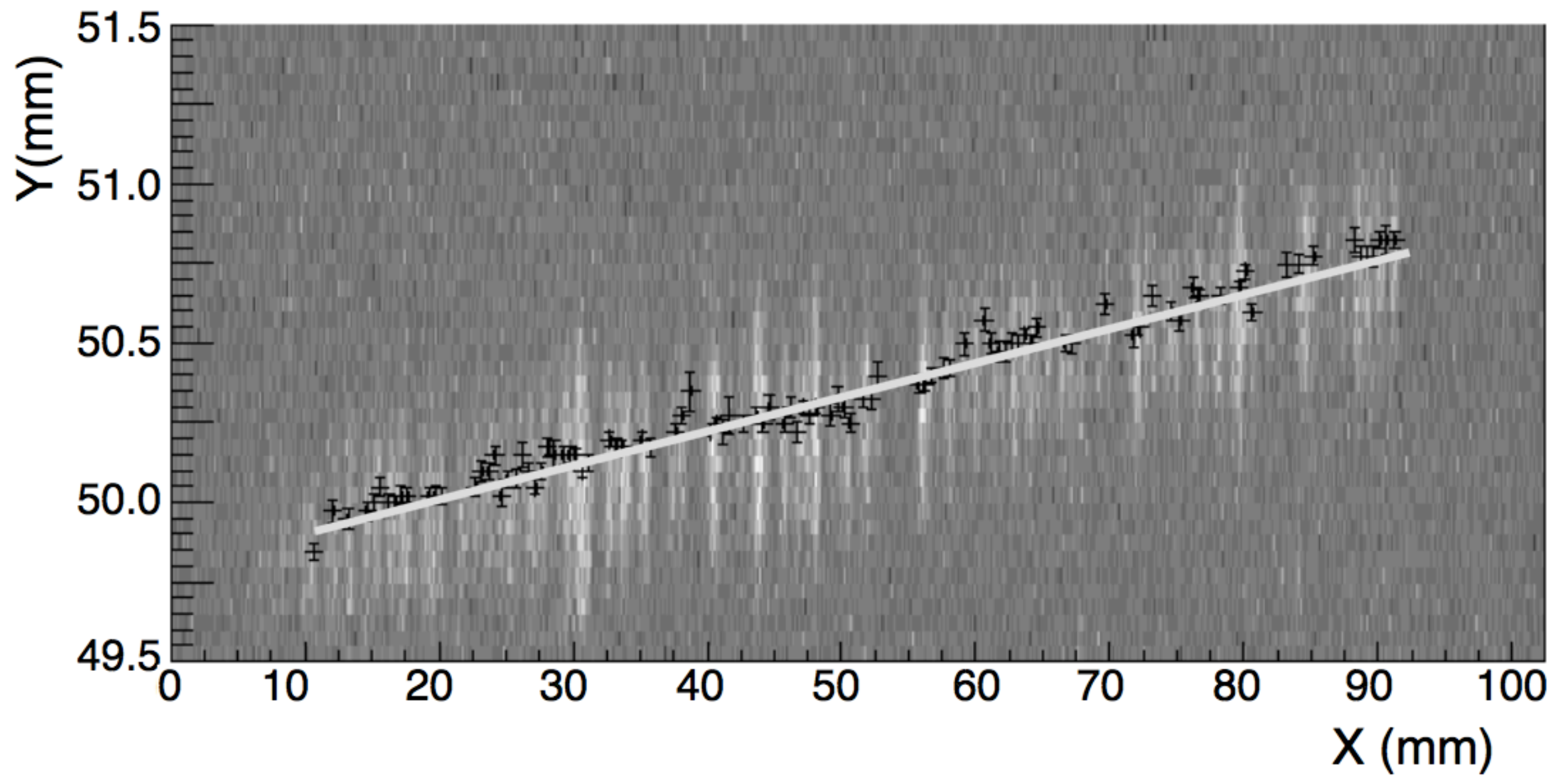
(thanks to nature…)

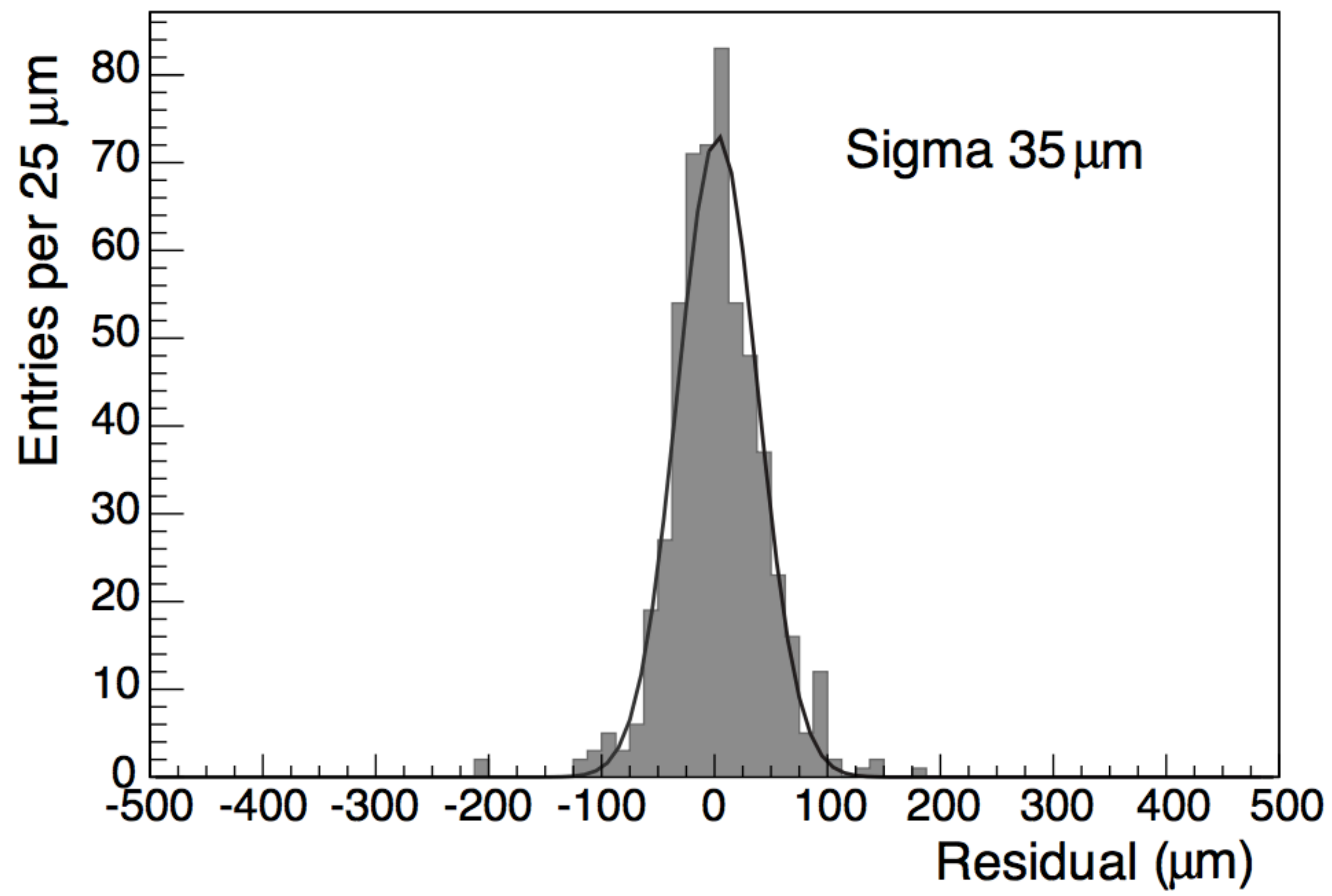


XY resolution in ORAnGE



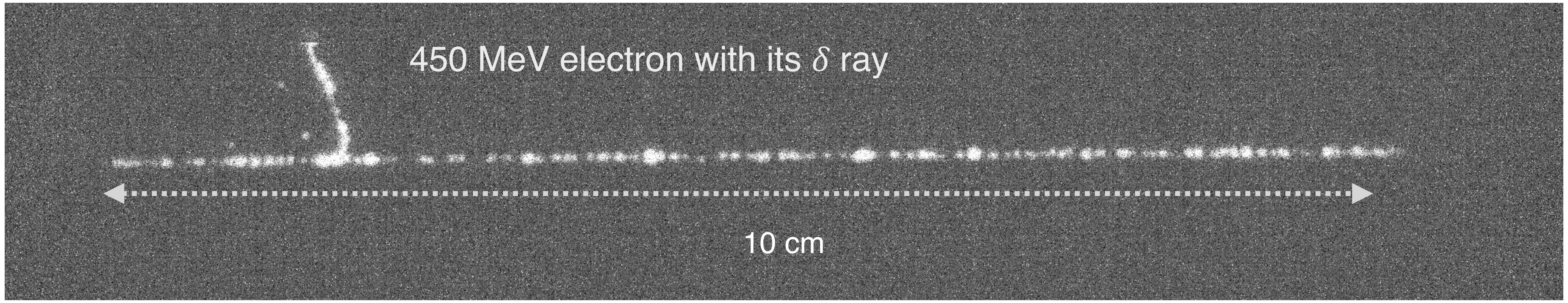




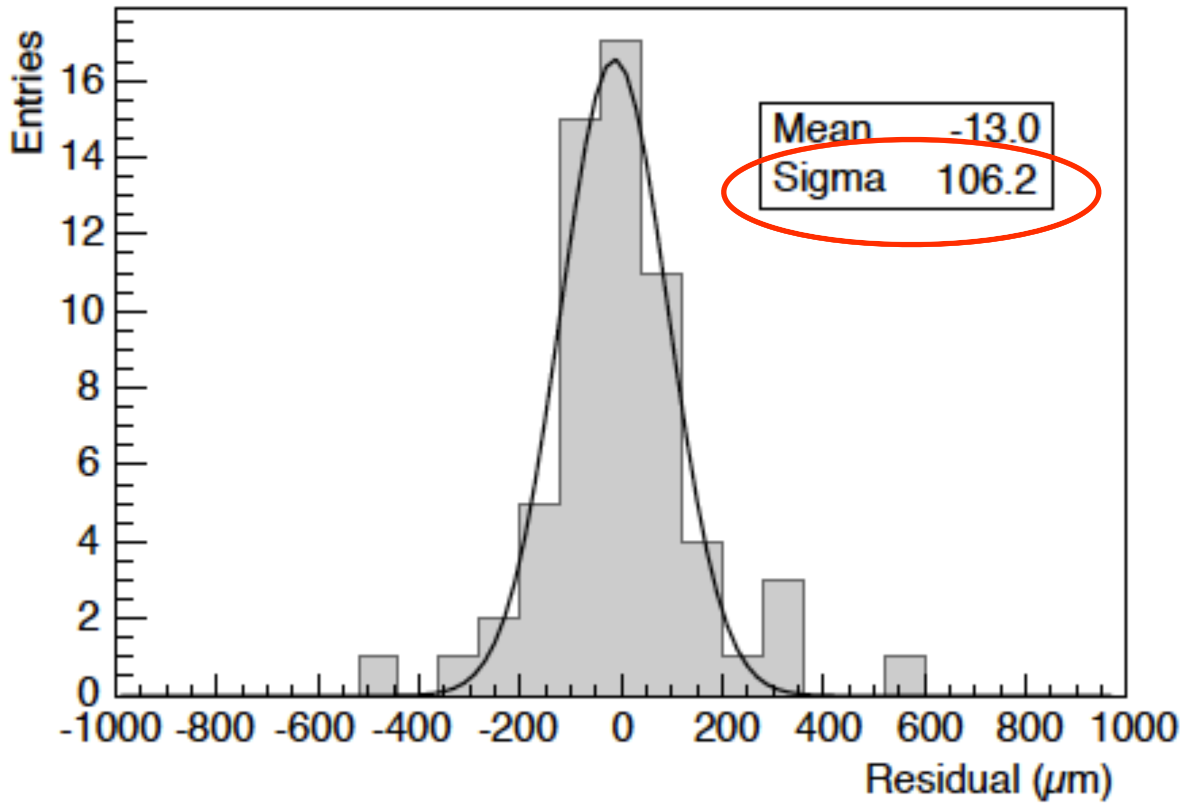


About 330 detected photons per track millimetre
(for VGEM = 440V), i.e. 230 eV released in gas (from Garfield).
XY resolution = 35 μm

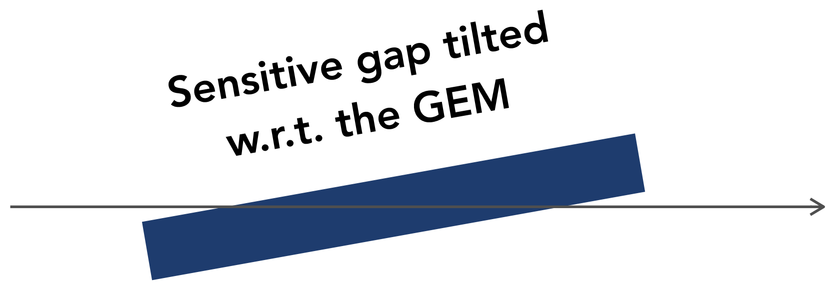
Z resolution in ORAnGE

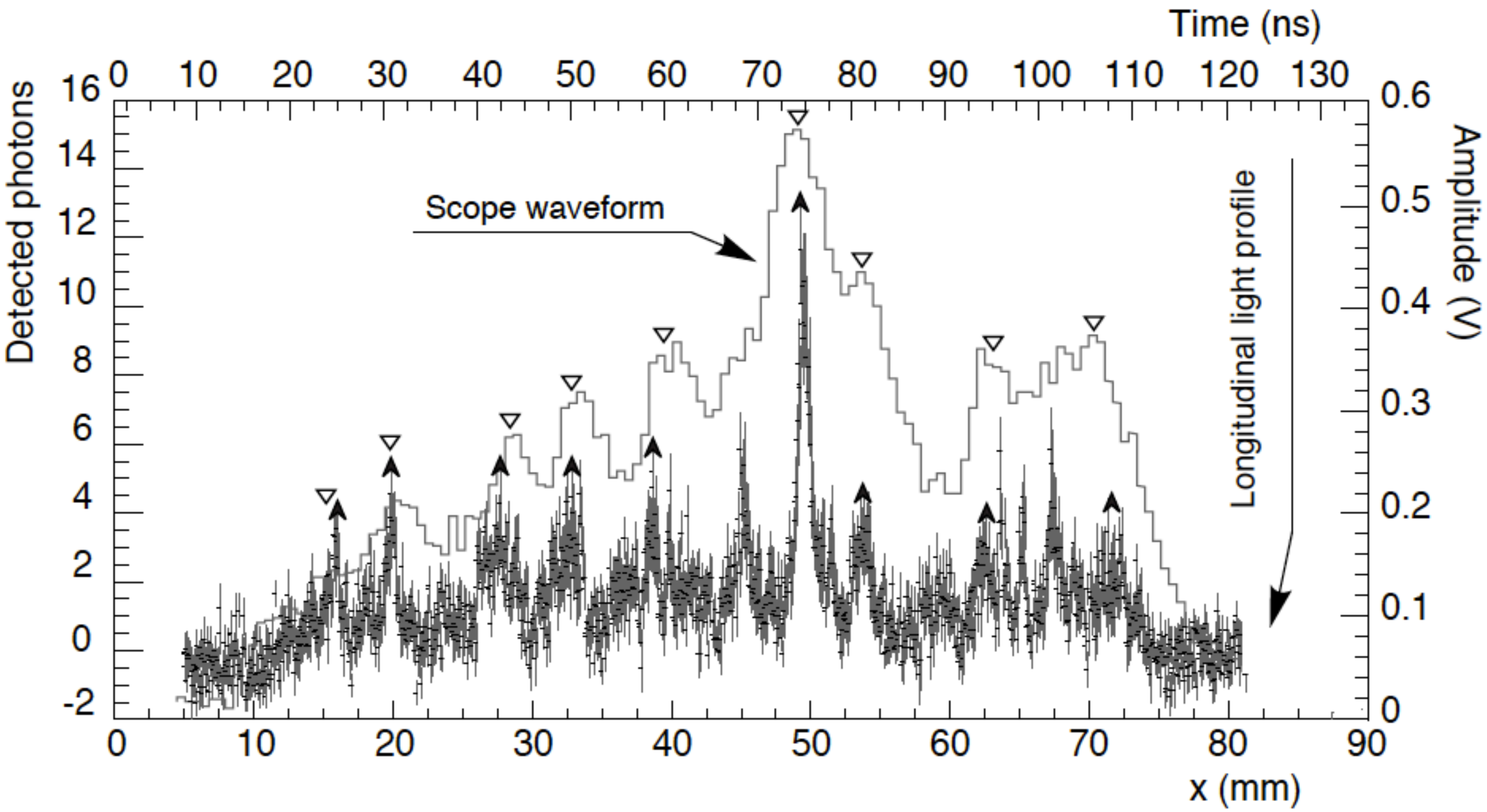


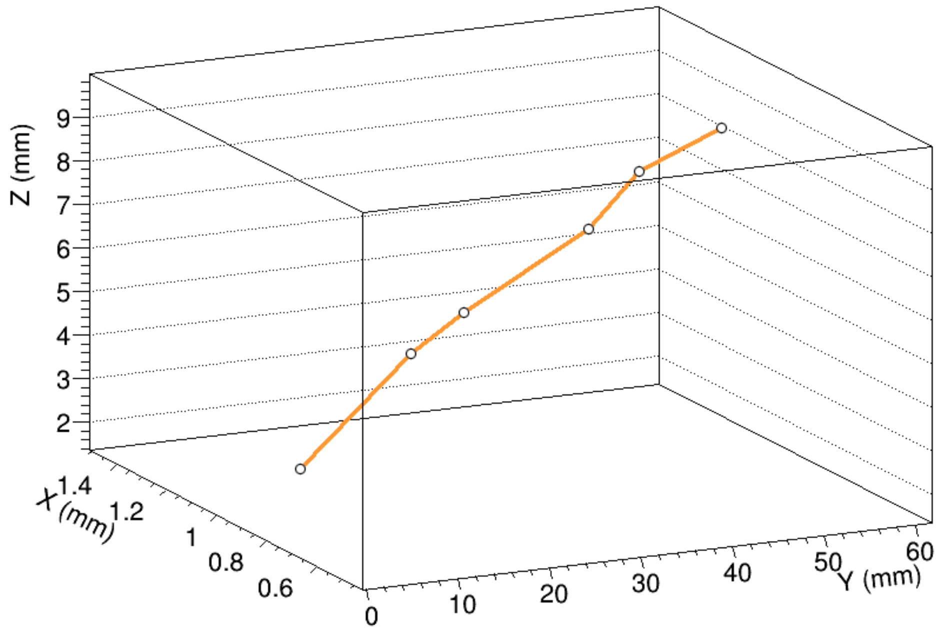
Z resolution



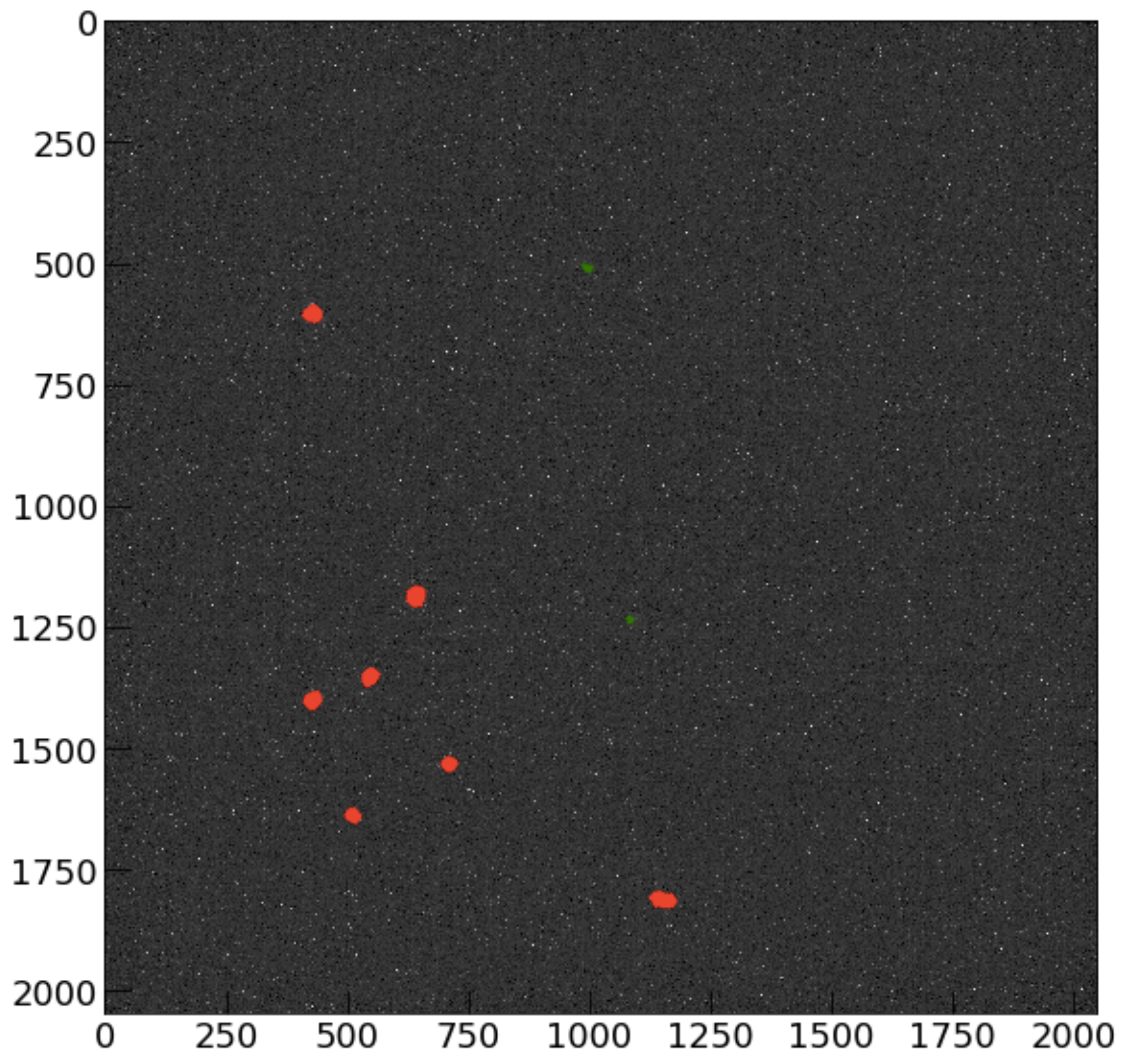
combined OPT readout PMT+CMOS

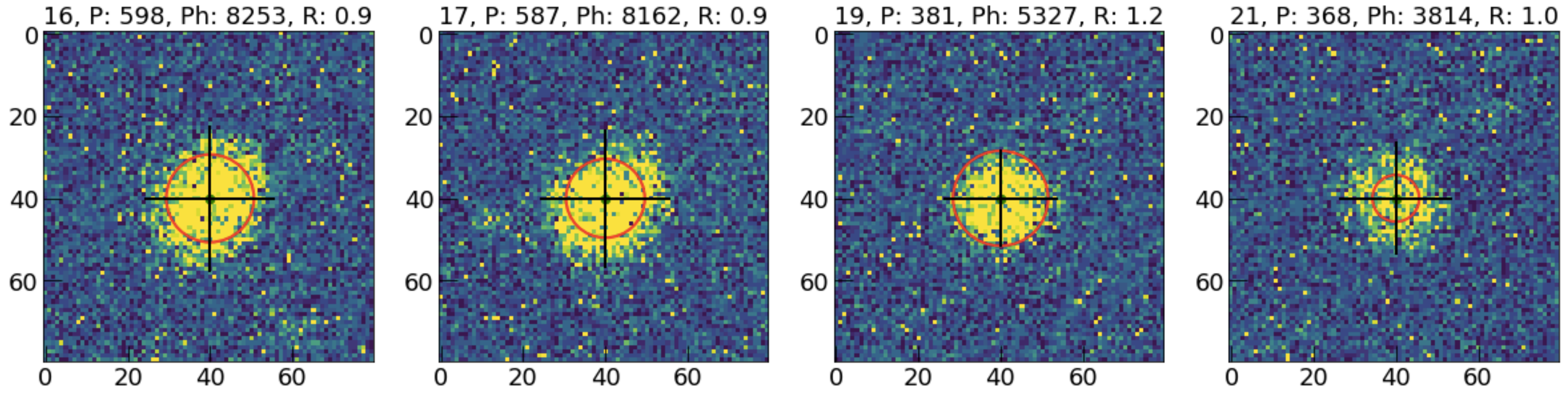


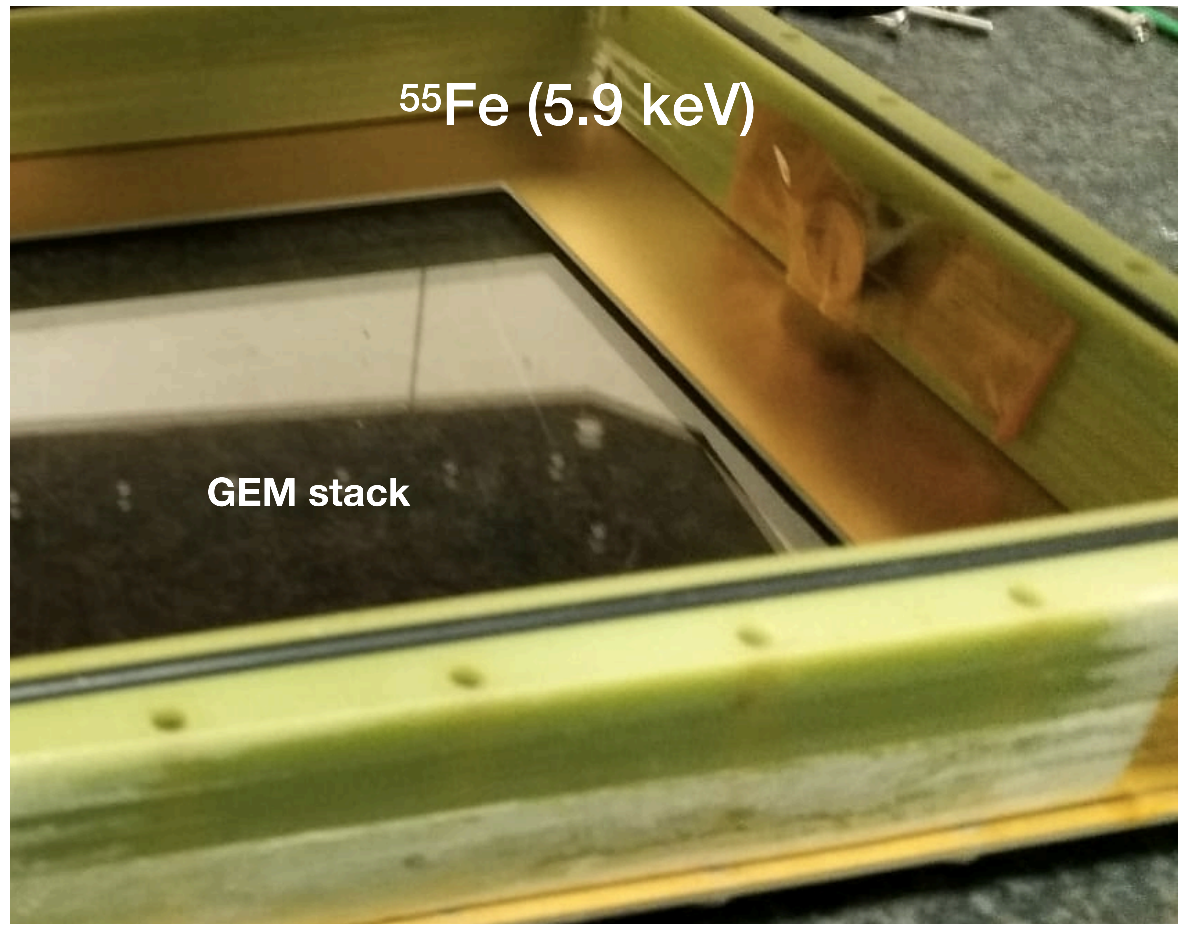


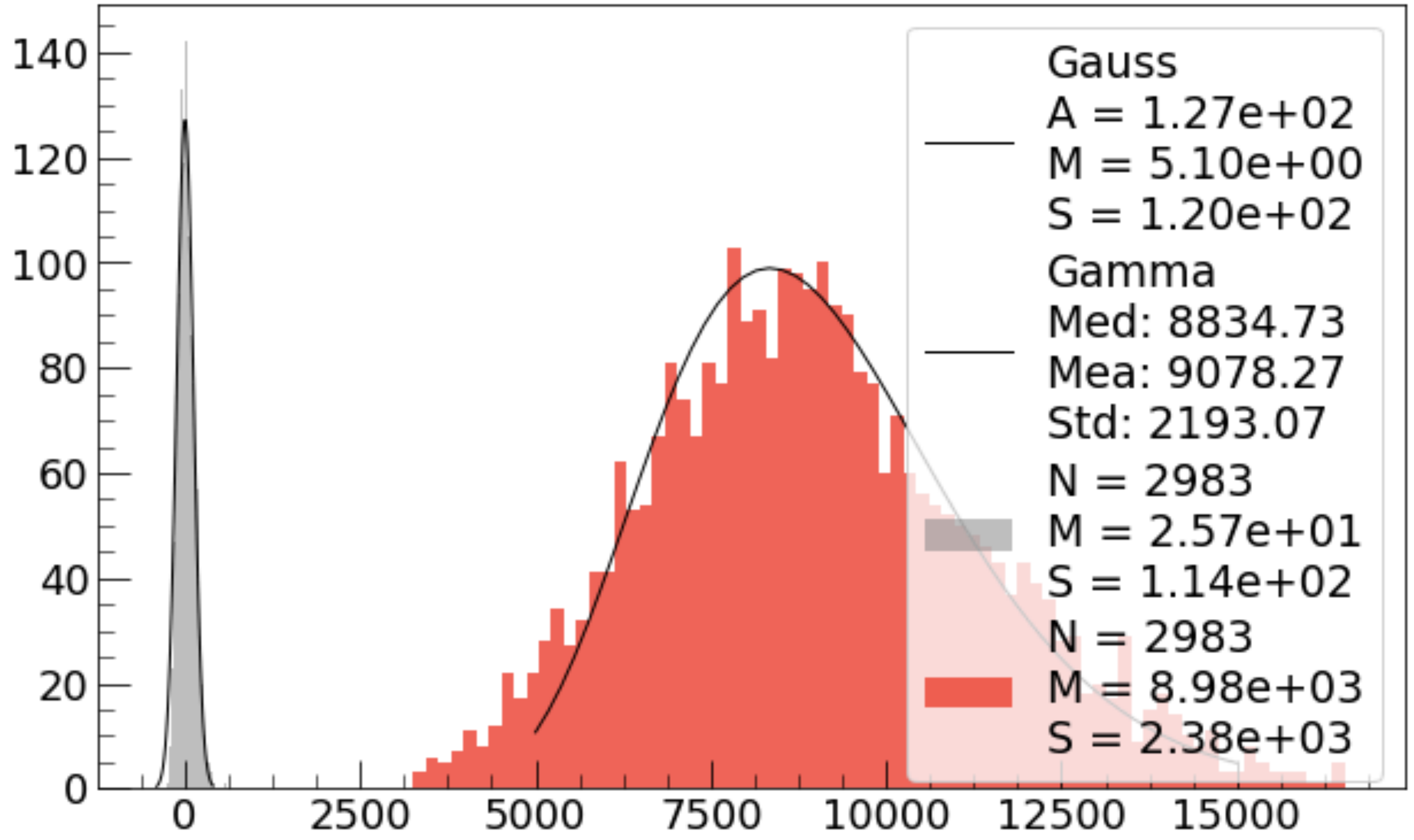


Energy resolution ^{55}Fe (5.9 keV)









9078 ph / 5900 eV
–> **1.5 ph/eV**.

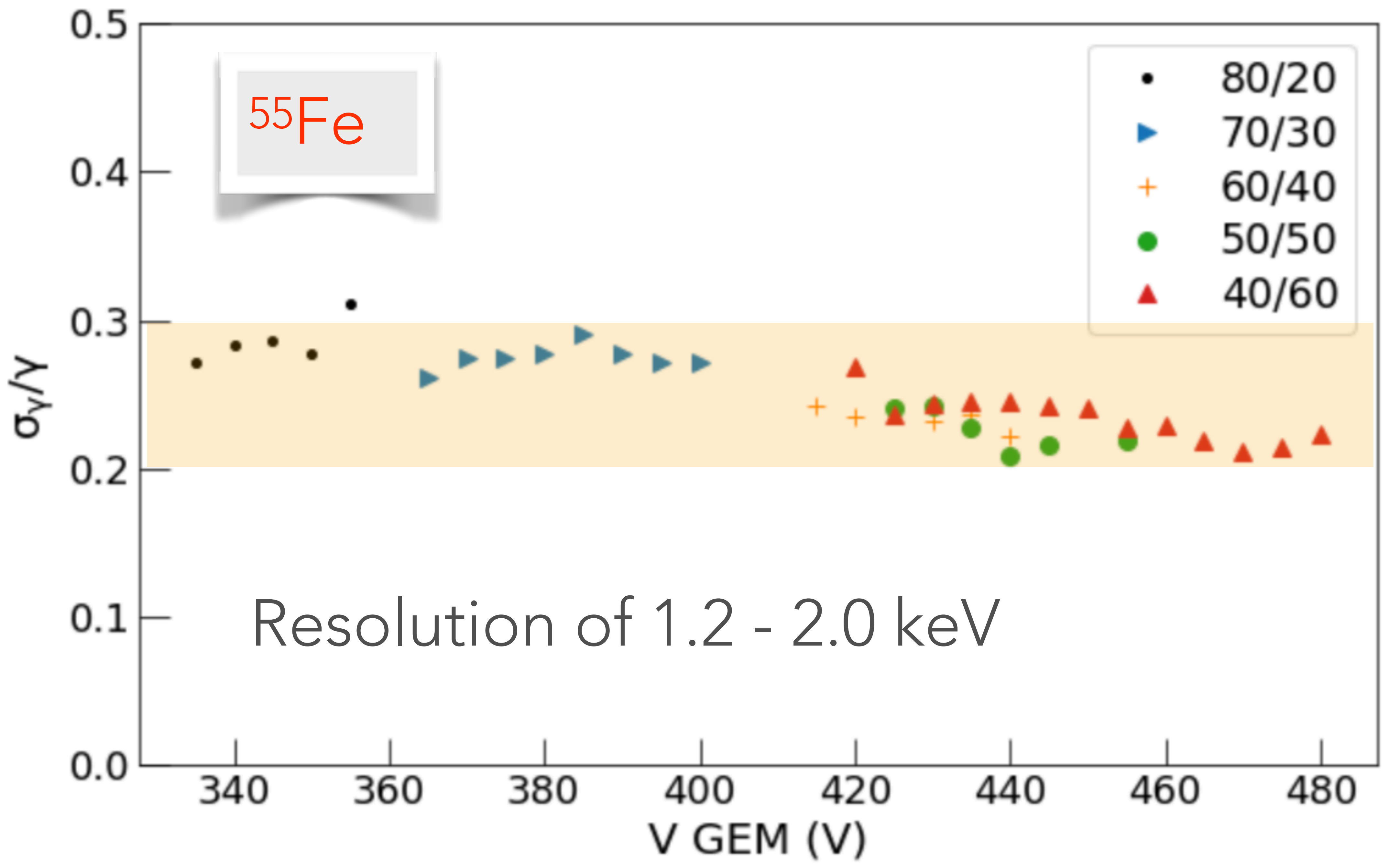
pedestal jitter 120 ph
@ 5 sigma **600 ph**
—> 600/1.5 —> **Th = 400 eV**

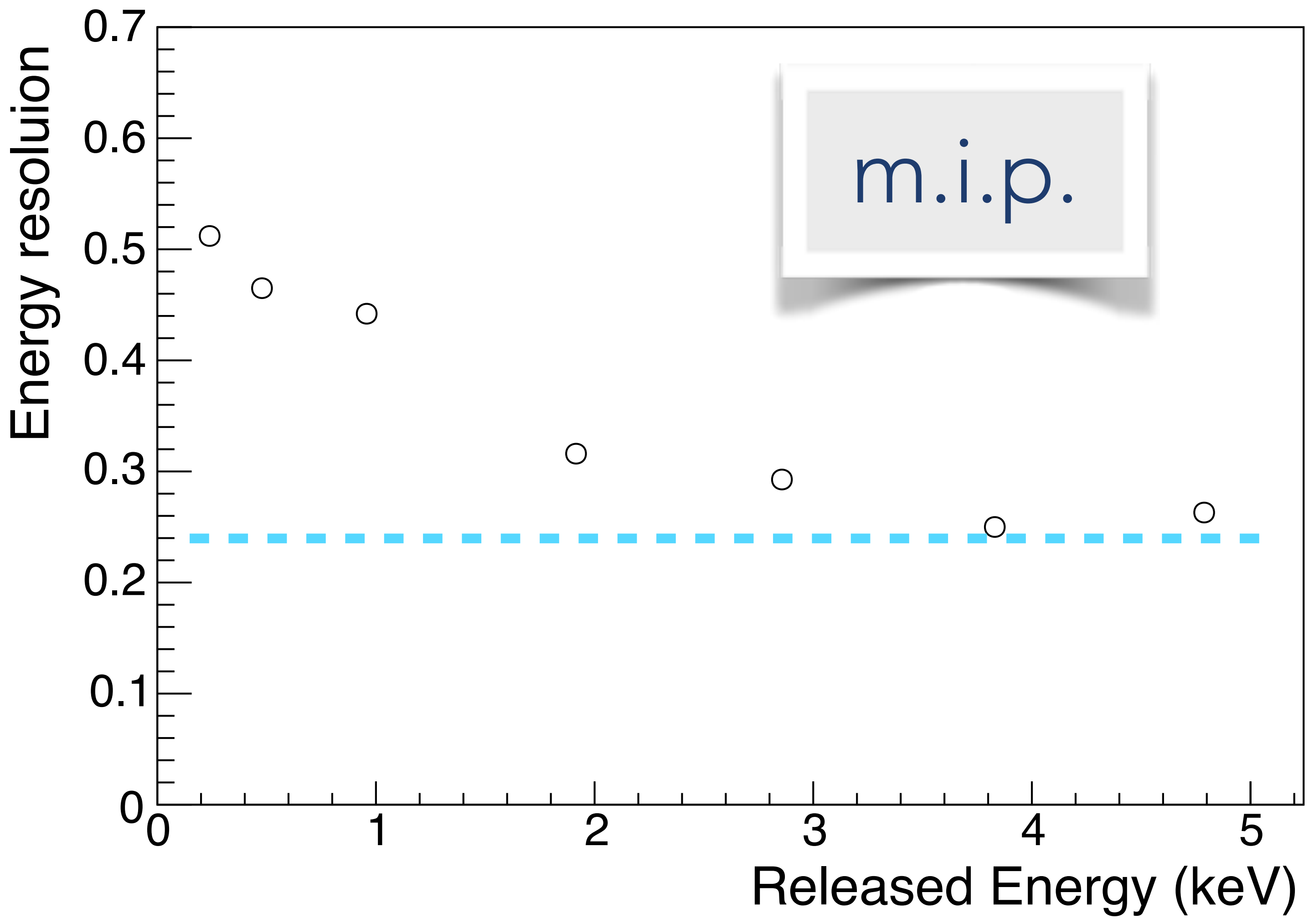
(pedestal based on average of the run within Fe source in the detector)

Energy resolution ~ **24% ~ 1.5 keV**

Energy resolution ^{55}Fe (5.9 keV)

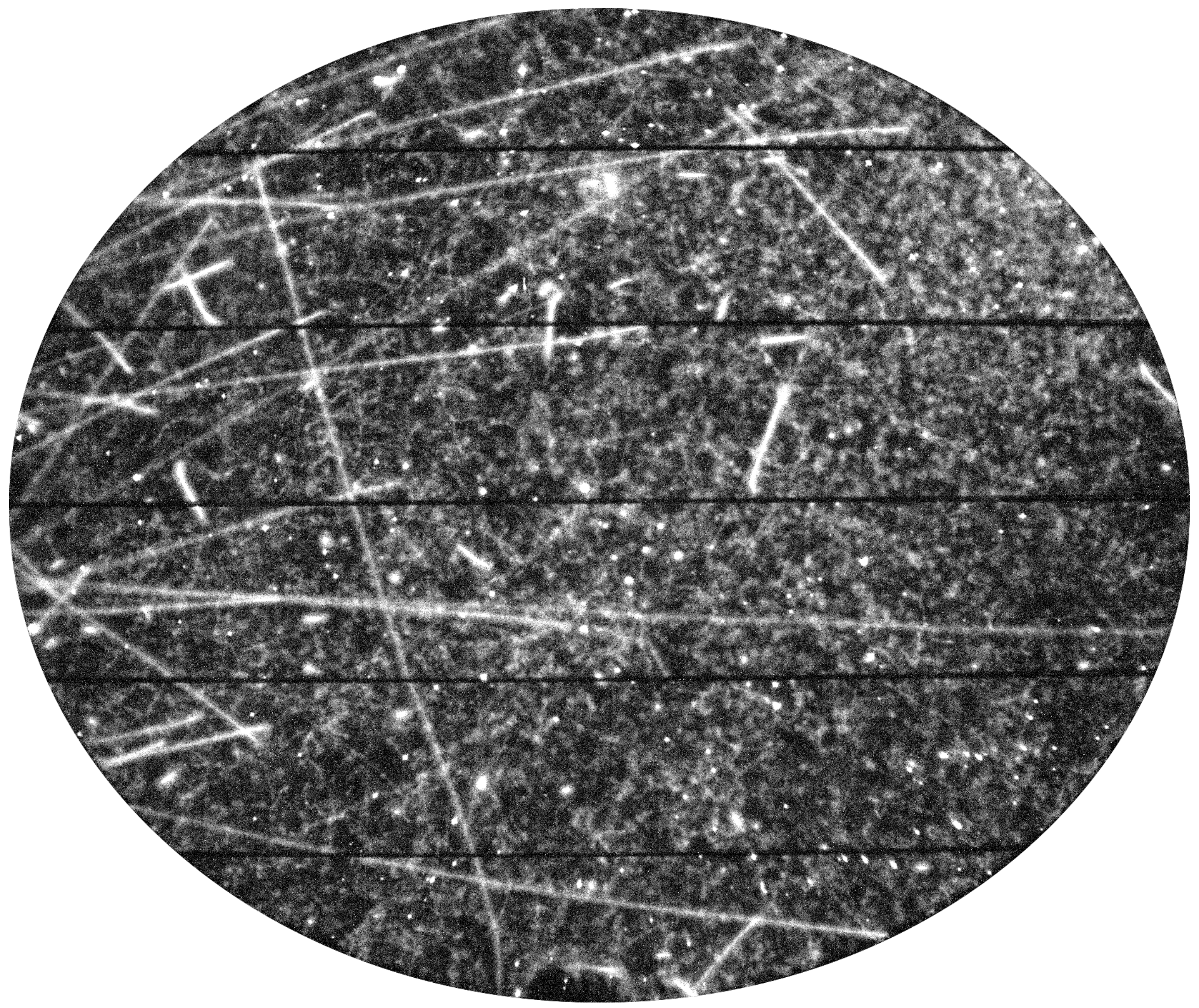
An energy resolution between 20% and 30% is achieved for releases of 5.9 keV;

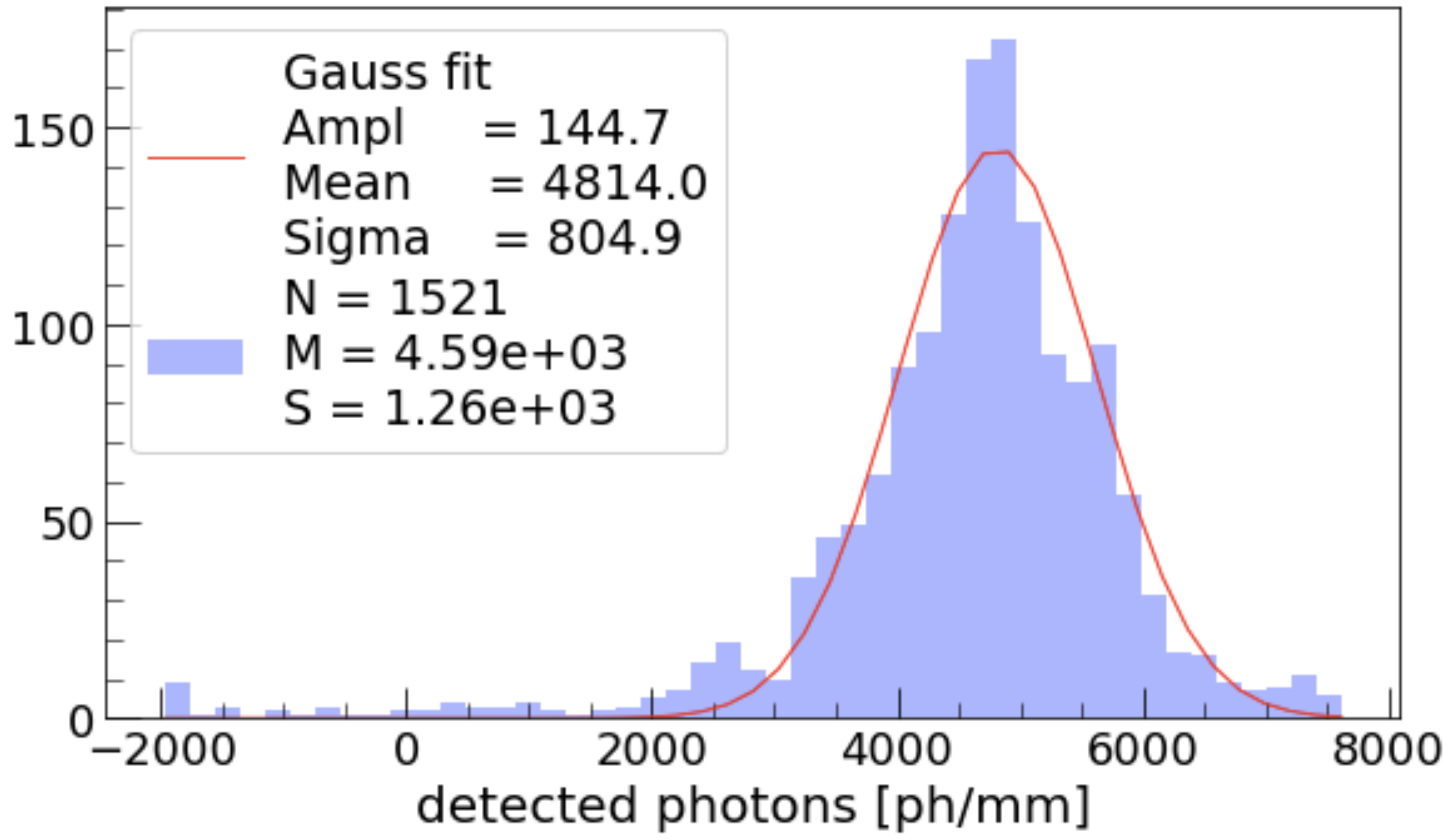




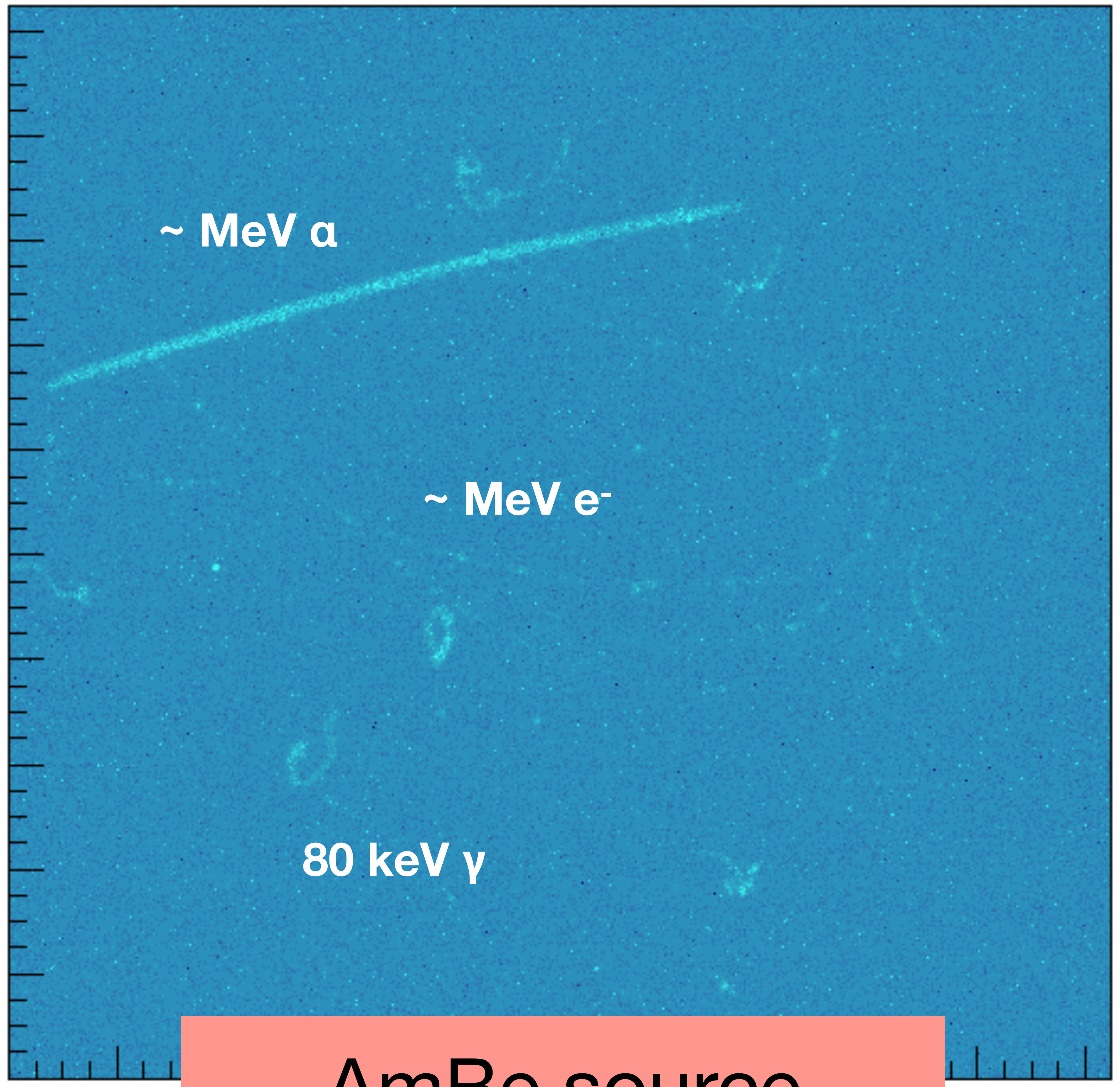
With 60/40 at 440 V, a resolution of 1.3 keV was measured for ^{55}Fe signals;
For 1 keV energy releases a resolution of hundreds of eV is achieved.

PID performances

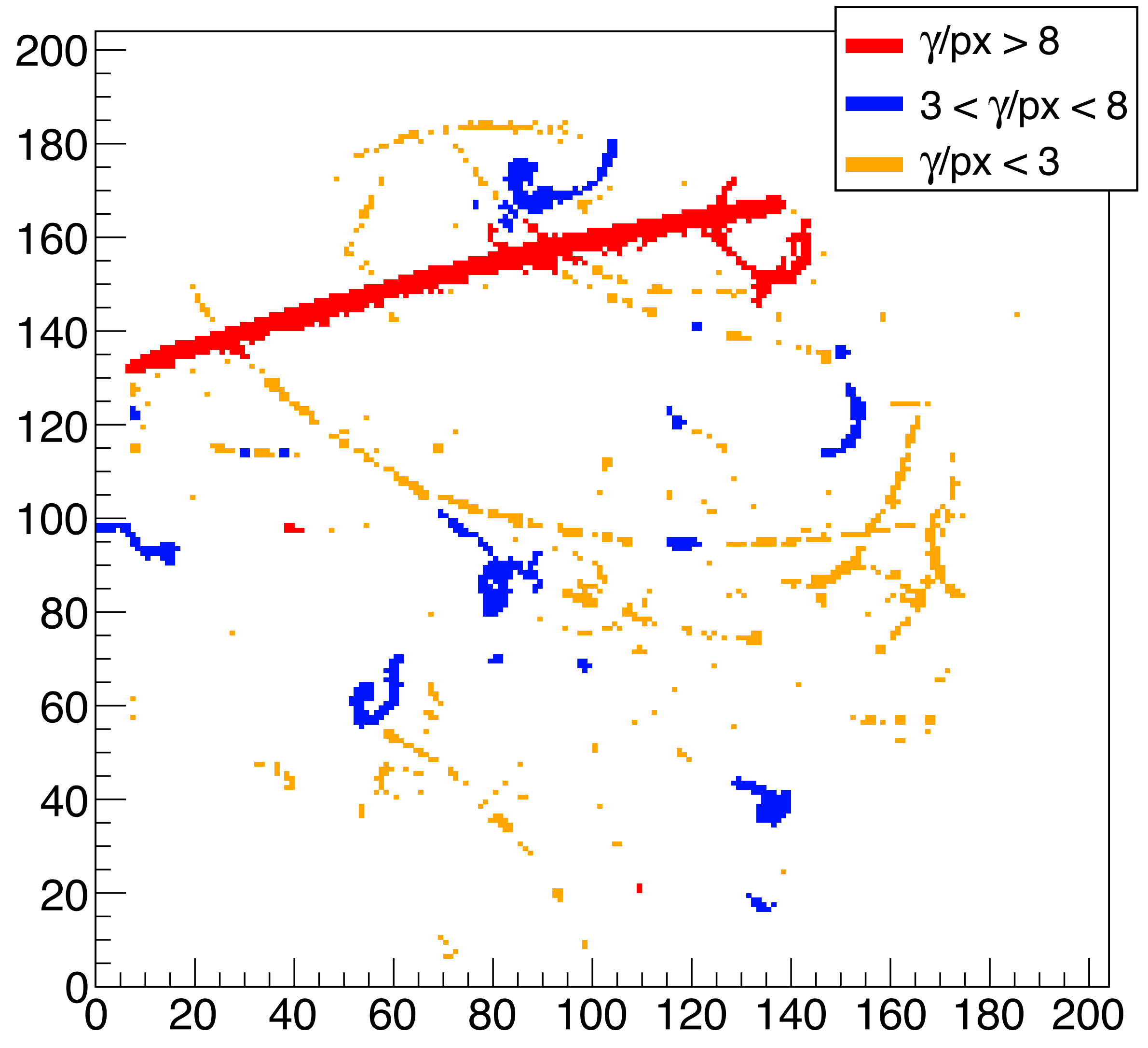


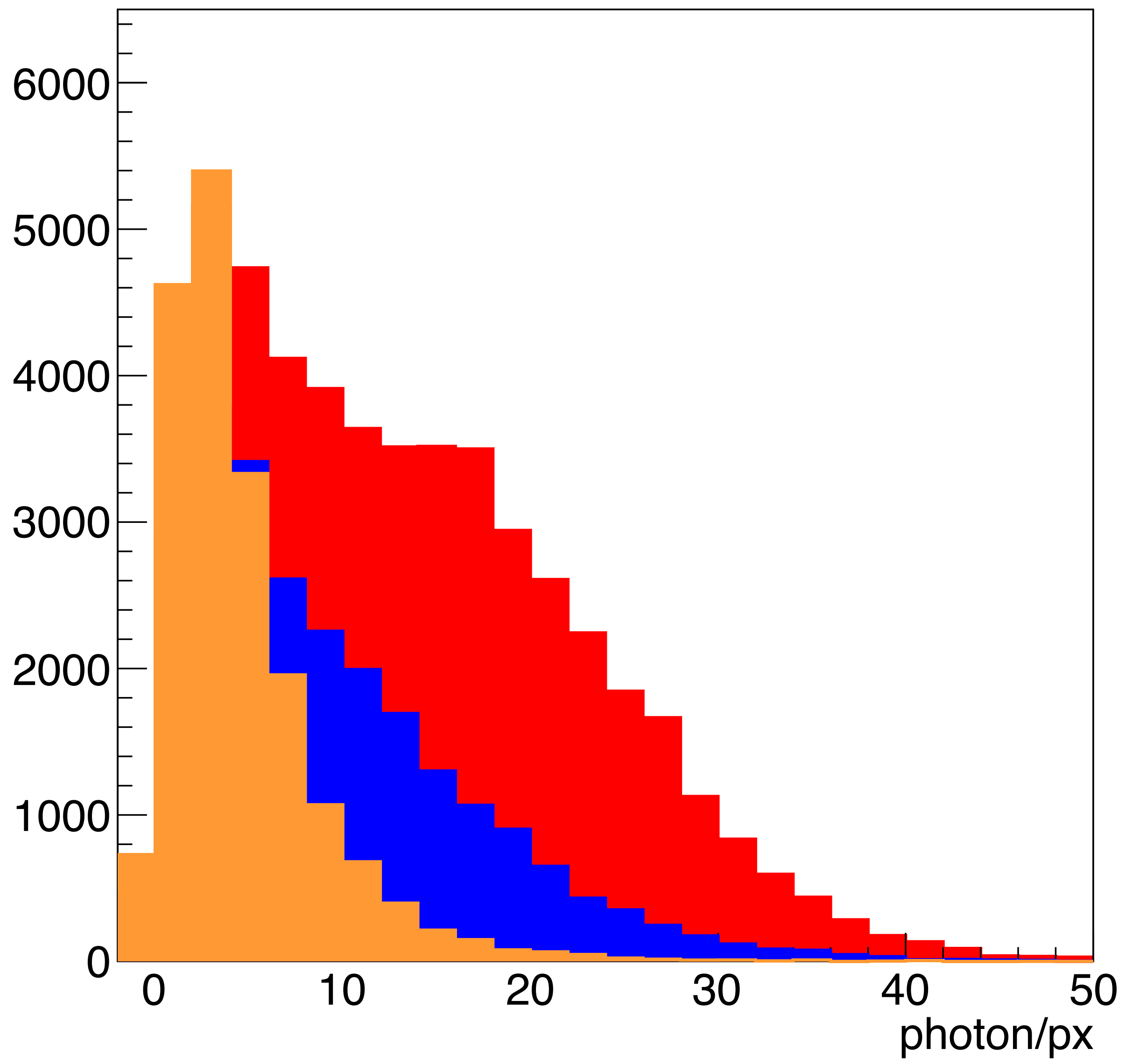


4000 ph/mm (~ 4 times mips)



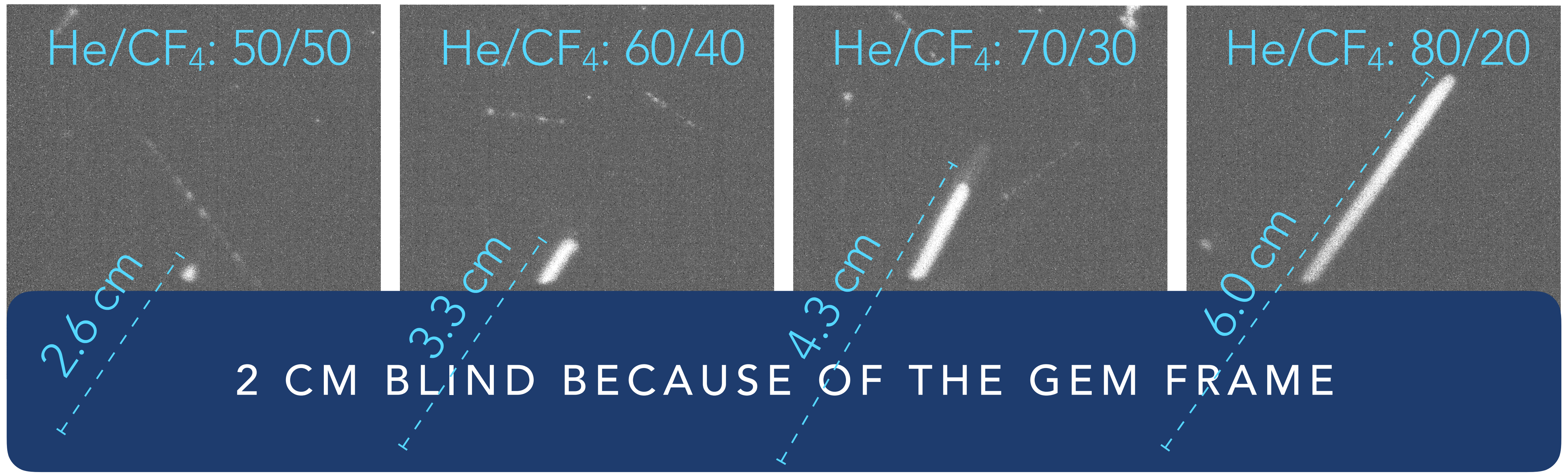
AmBe source

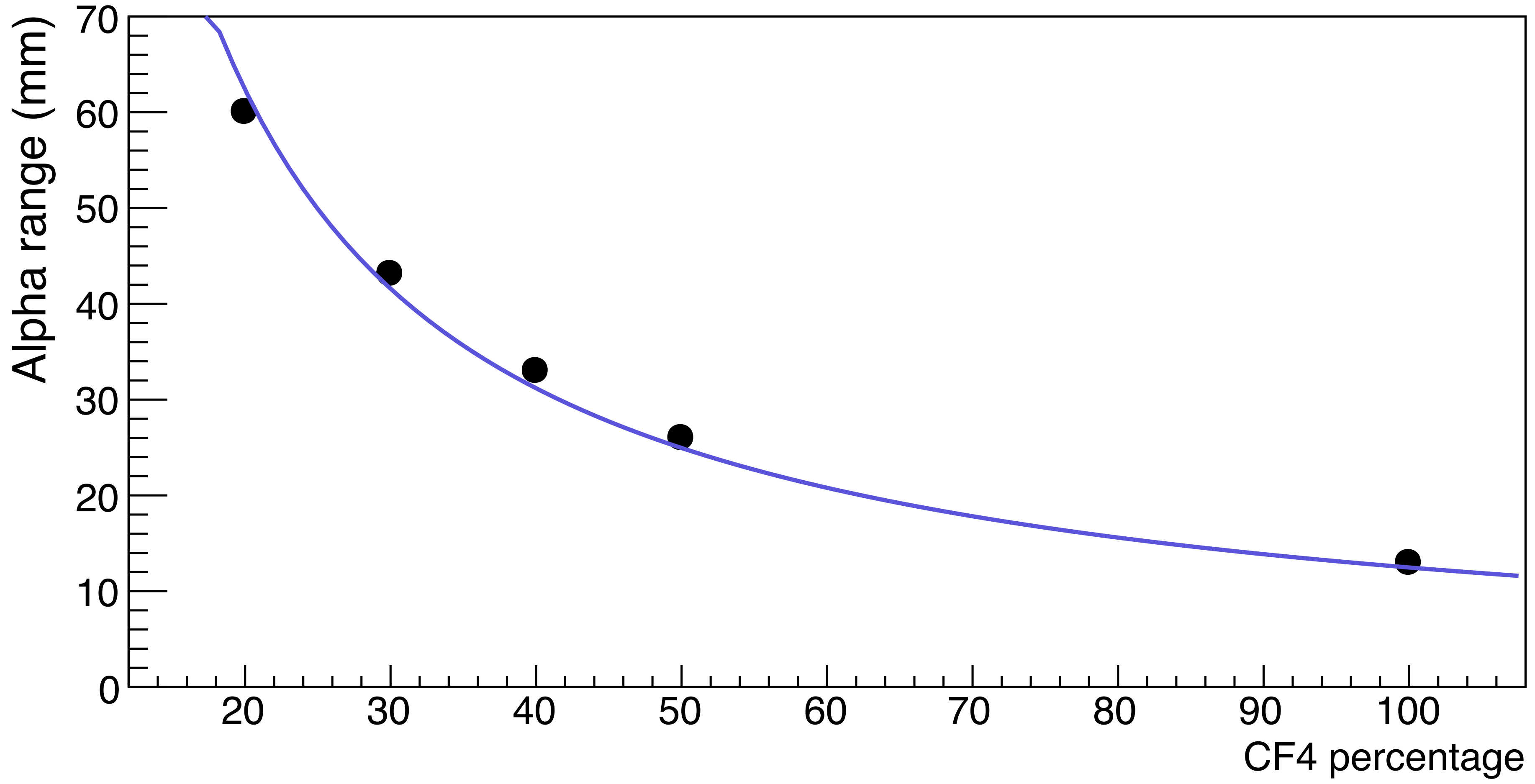




Range and recoil energy released

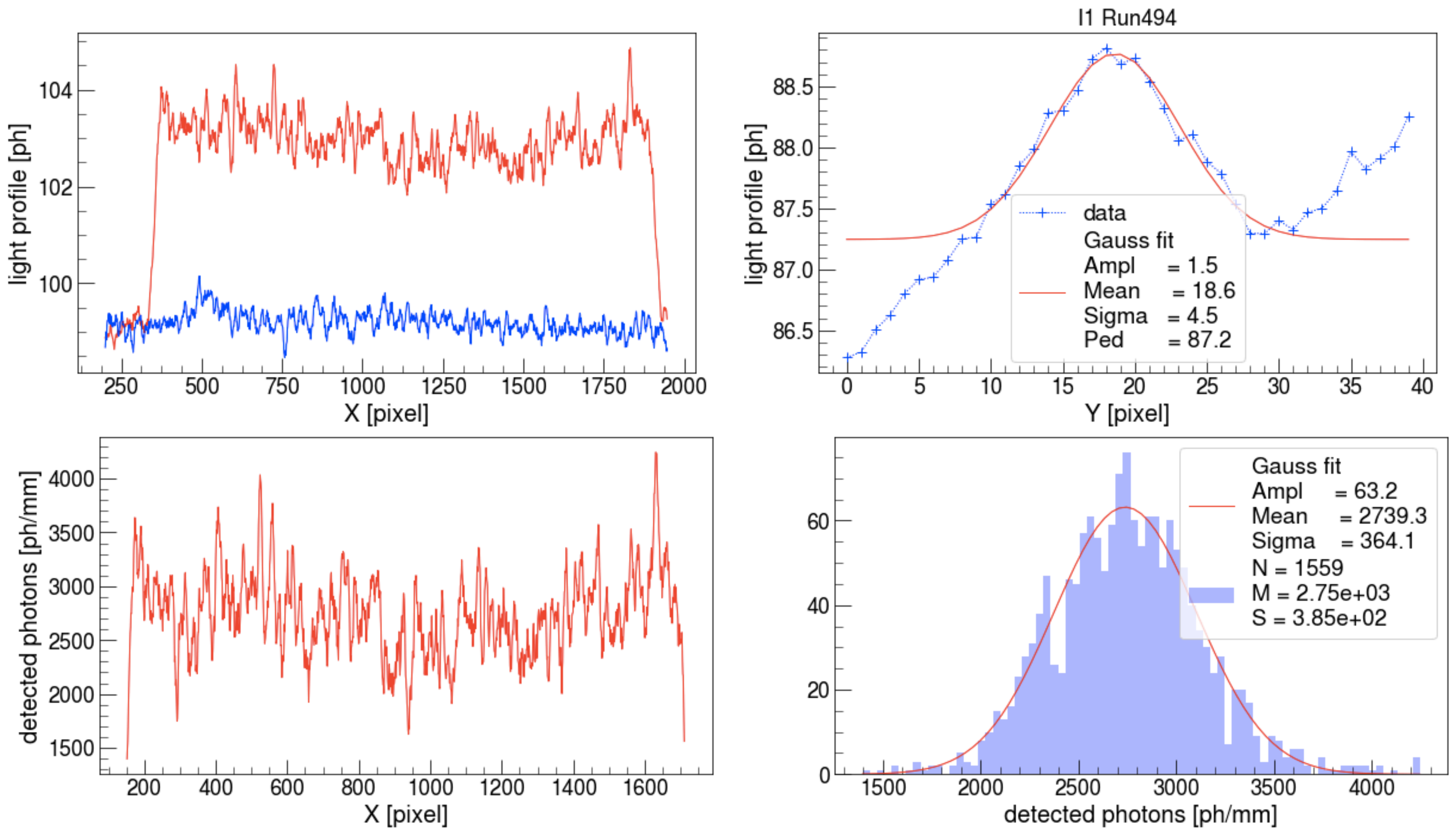
alpha particles path in He gas detector prototype

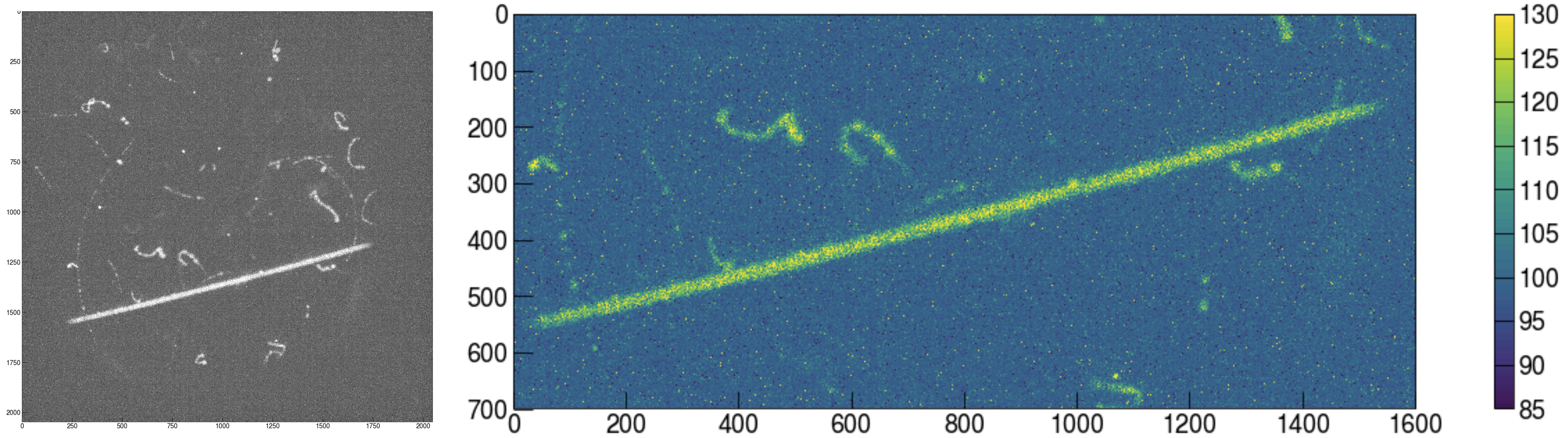




alpha range seems to be “determined” only by CF_4 and to decrease linearly with its amount

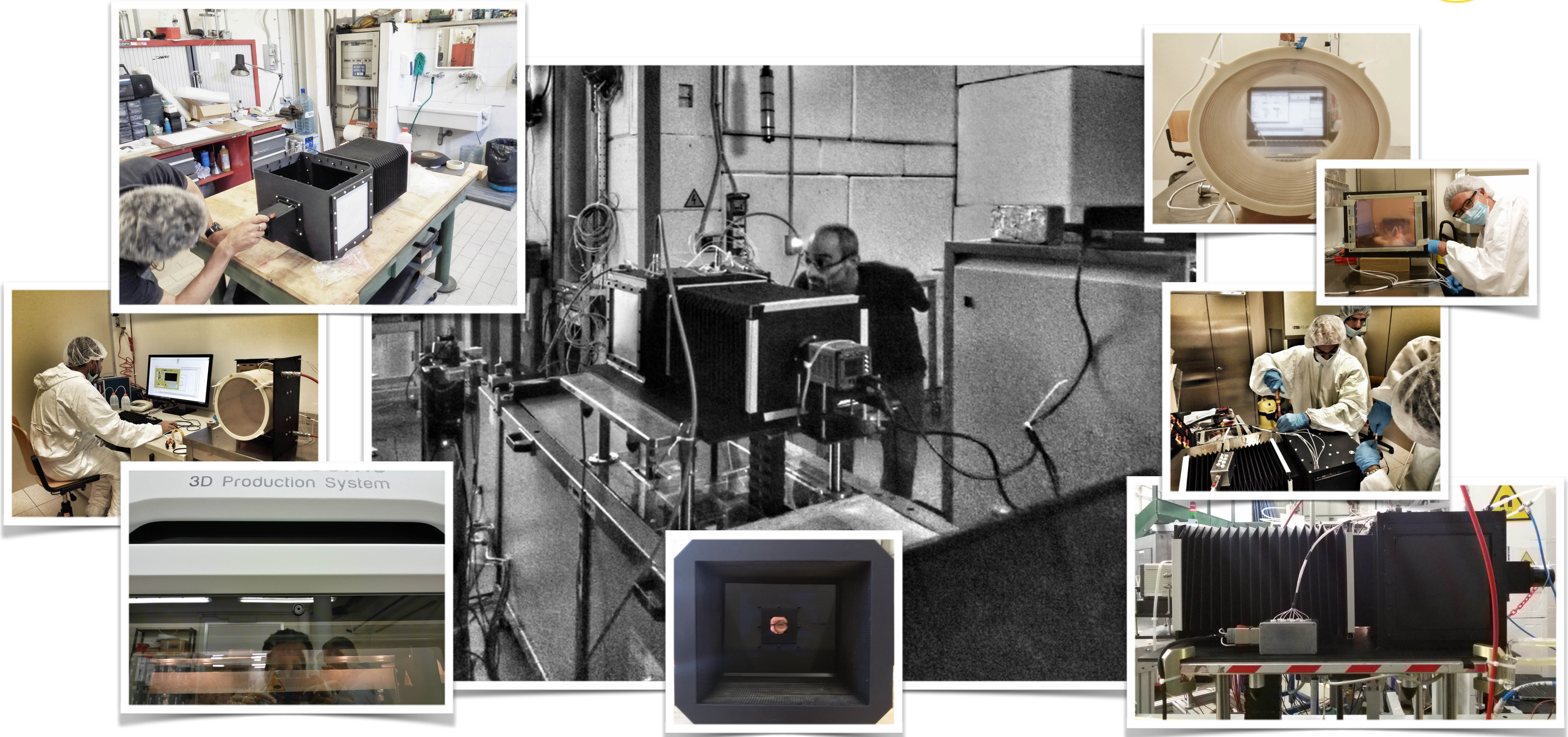
AmBe Orange GEM 440/2kVcm - drift 1kV/cm - 2000 ms





2740 [ph/mm] / 1.5 [ph/eV] —> 1.7 keV/mm (55 μm resolution)

LEMOn prototype

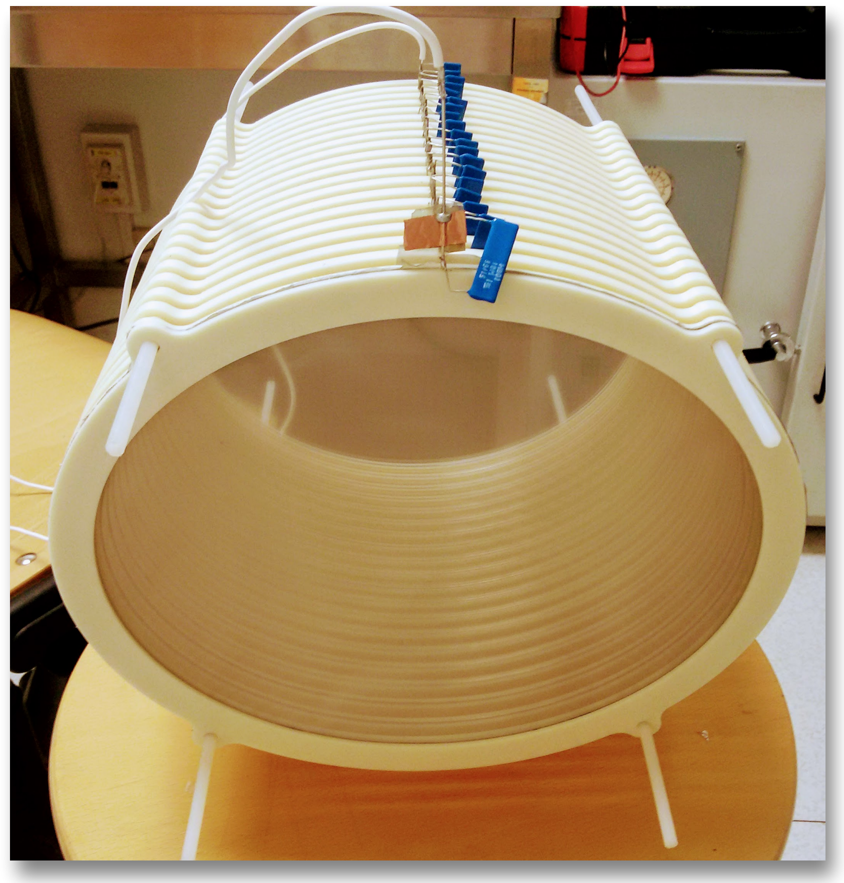


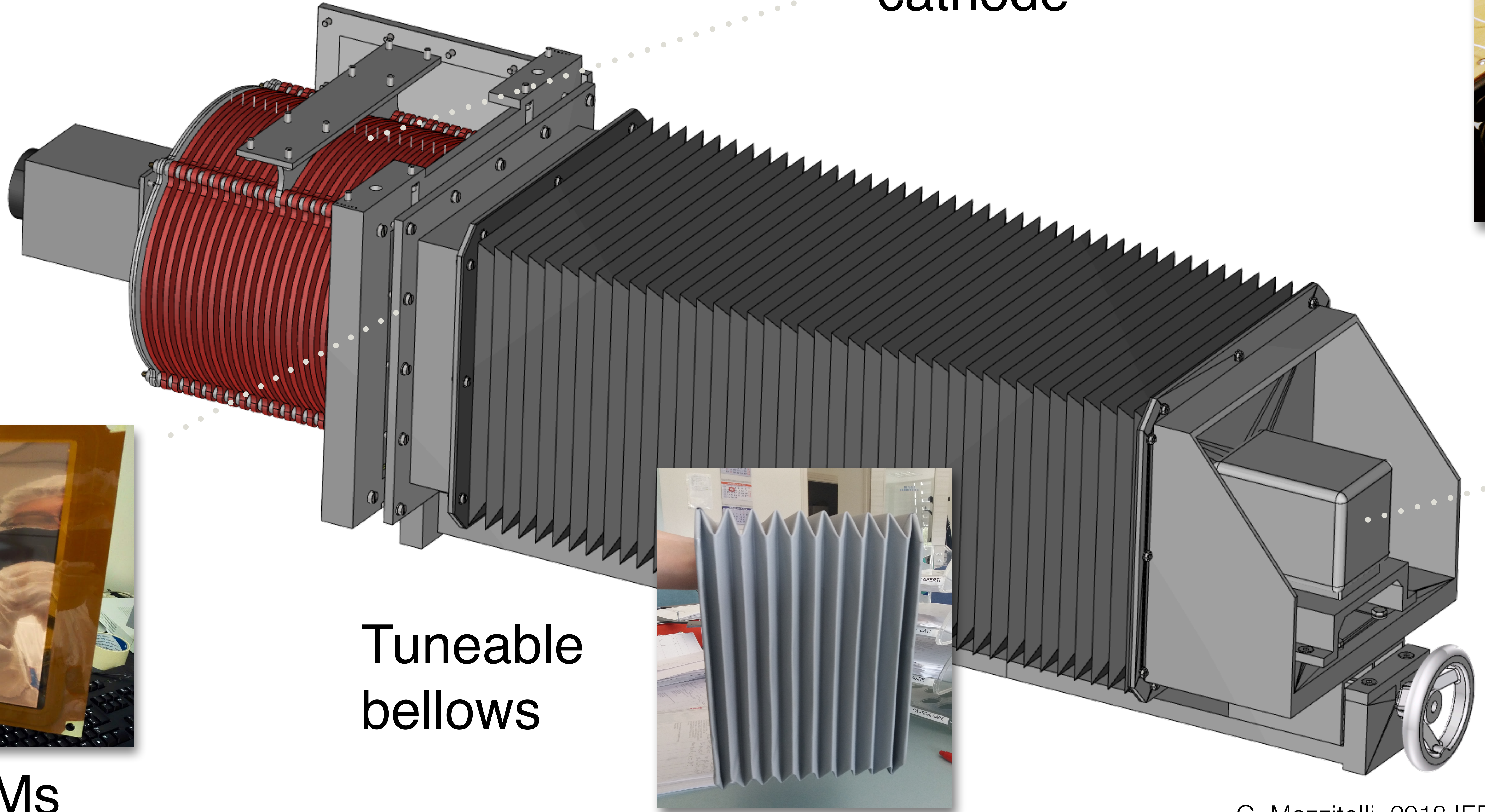
LEMOn prototype design

A new prototype with 7 litre sensitive volume (LEMOn: Large Elliptical Module Optically readout) was built in 2017 tested on electron beam in July.

7x7 cm^2 PMT

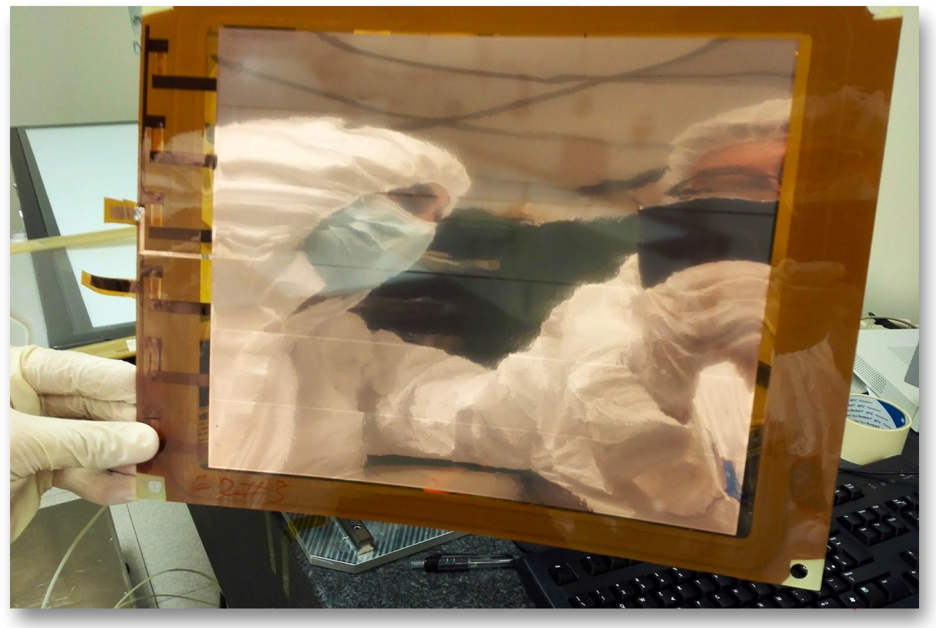
Elliptical field cage with semi-transparent cathode



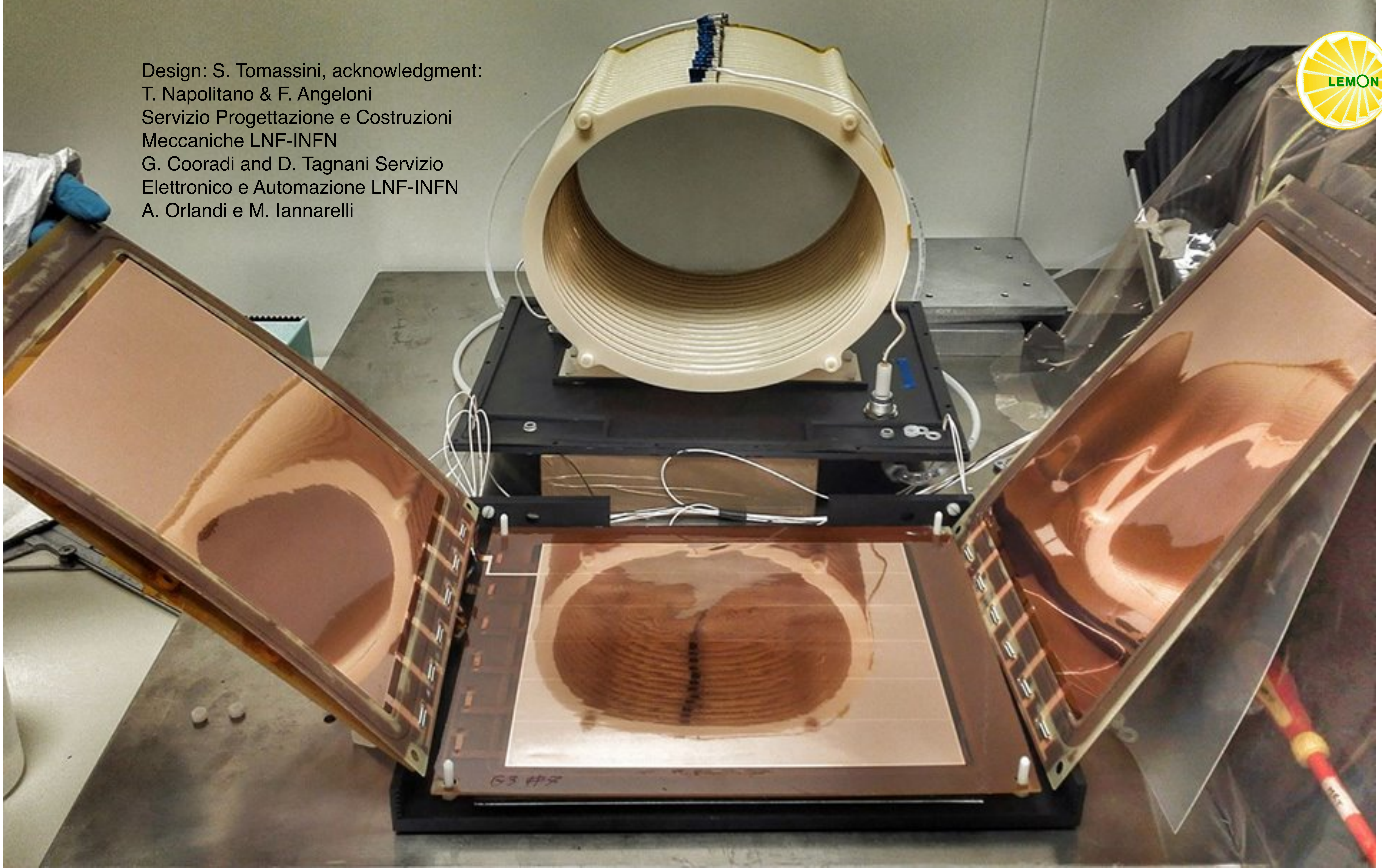


CMOS camera

Tuneable bellows

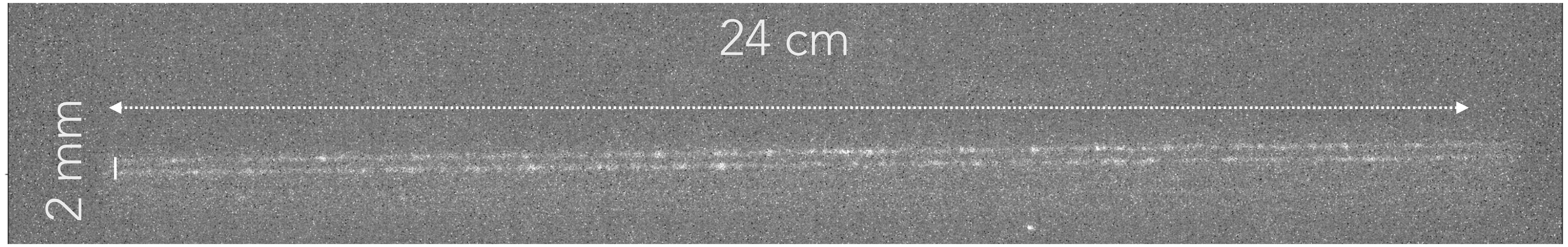


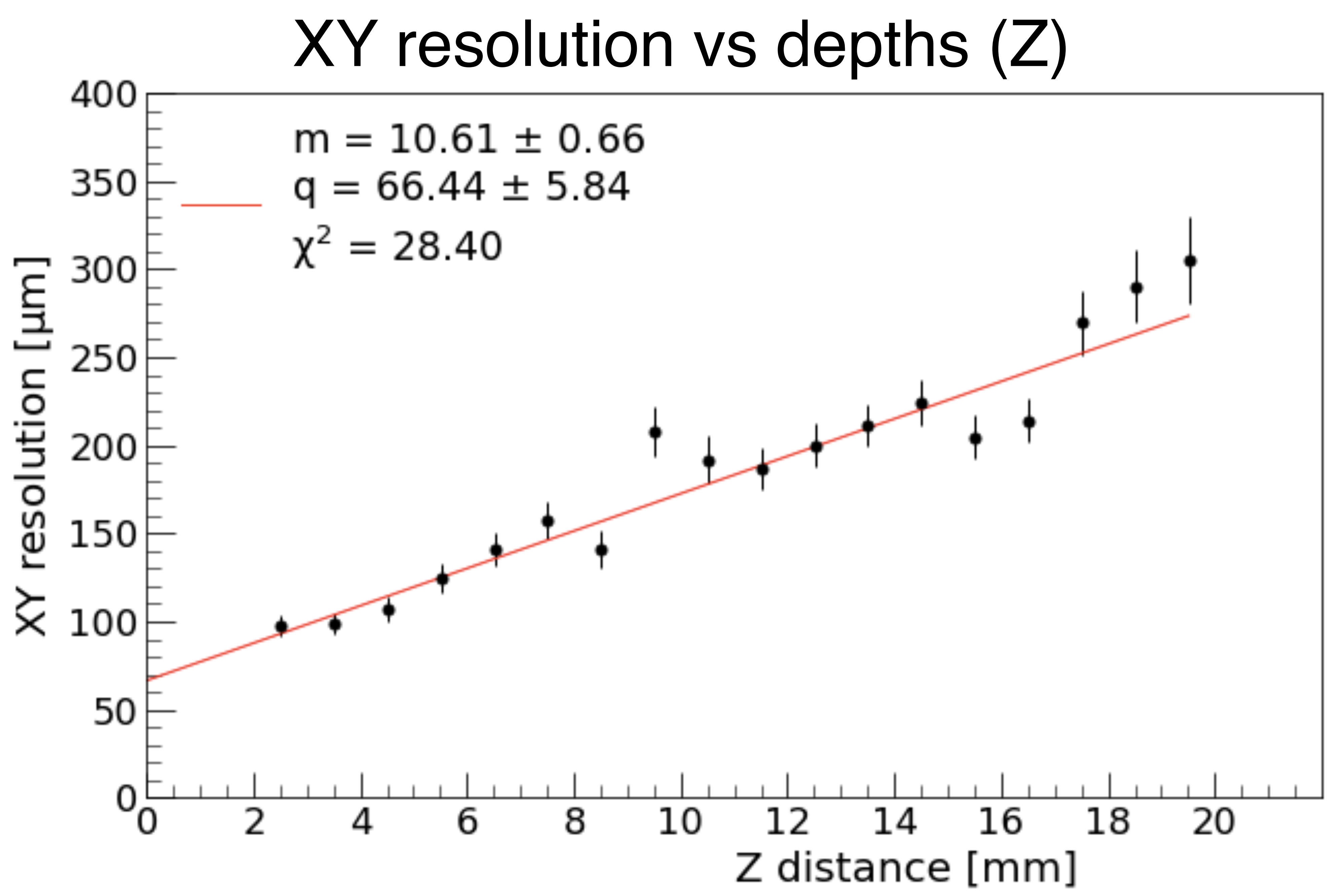
20x24 cm^2 GEMs



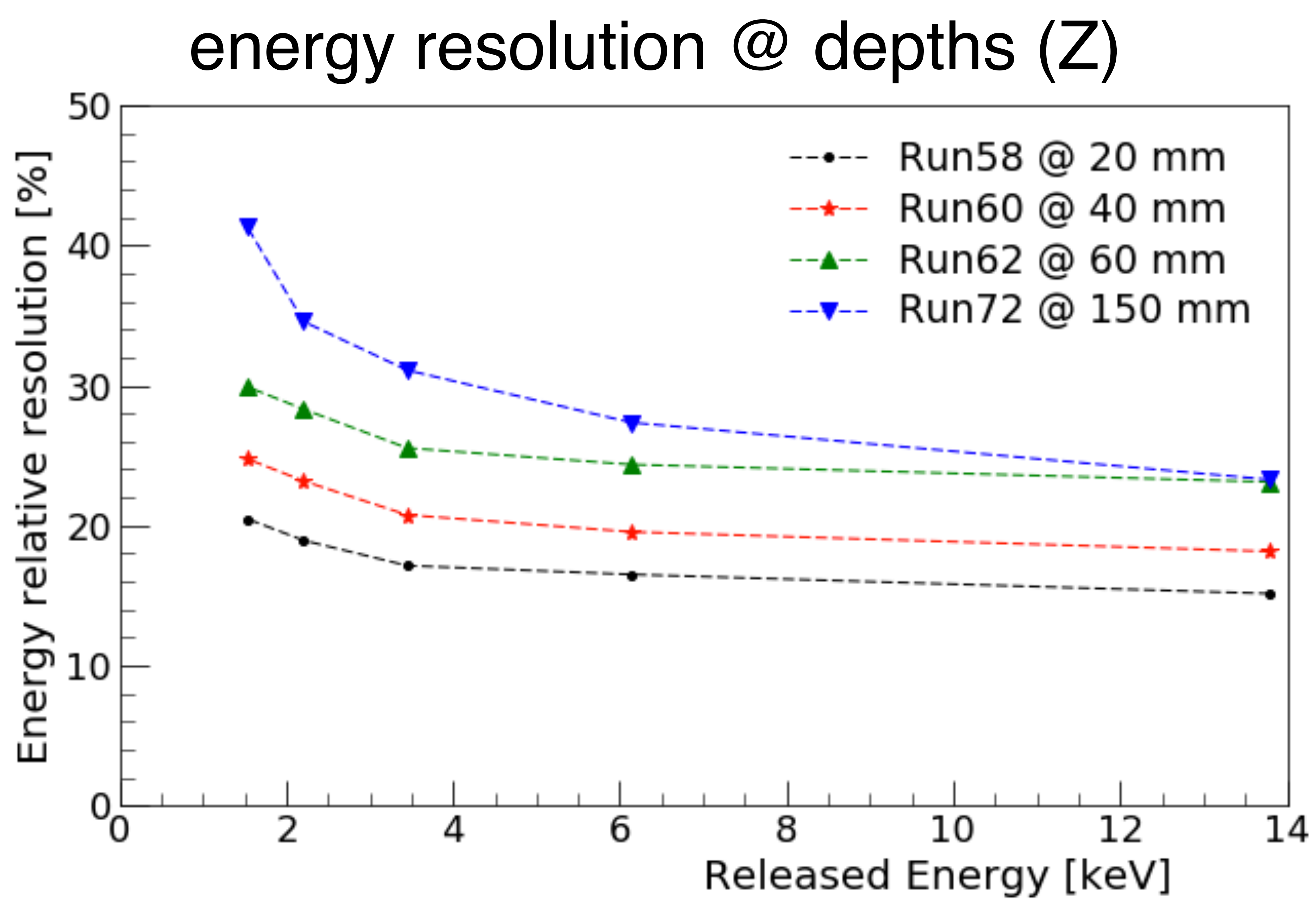
Design: S. Tomassini, acknowledgment:
T. Napolitano & F. Angeloni
Servizio Progettazione e Costruzioni
Meccaniche LNF-INFN
G. Cooradi and D. Tagnani Servizio
Elettronico e Automazione LNF-INFN
A. Orlandi e M. Iannarelli

XY and energy resolution



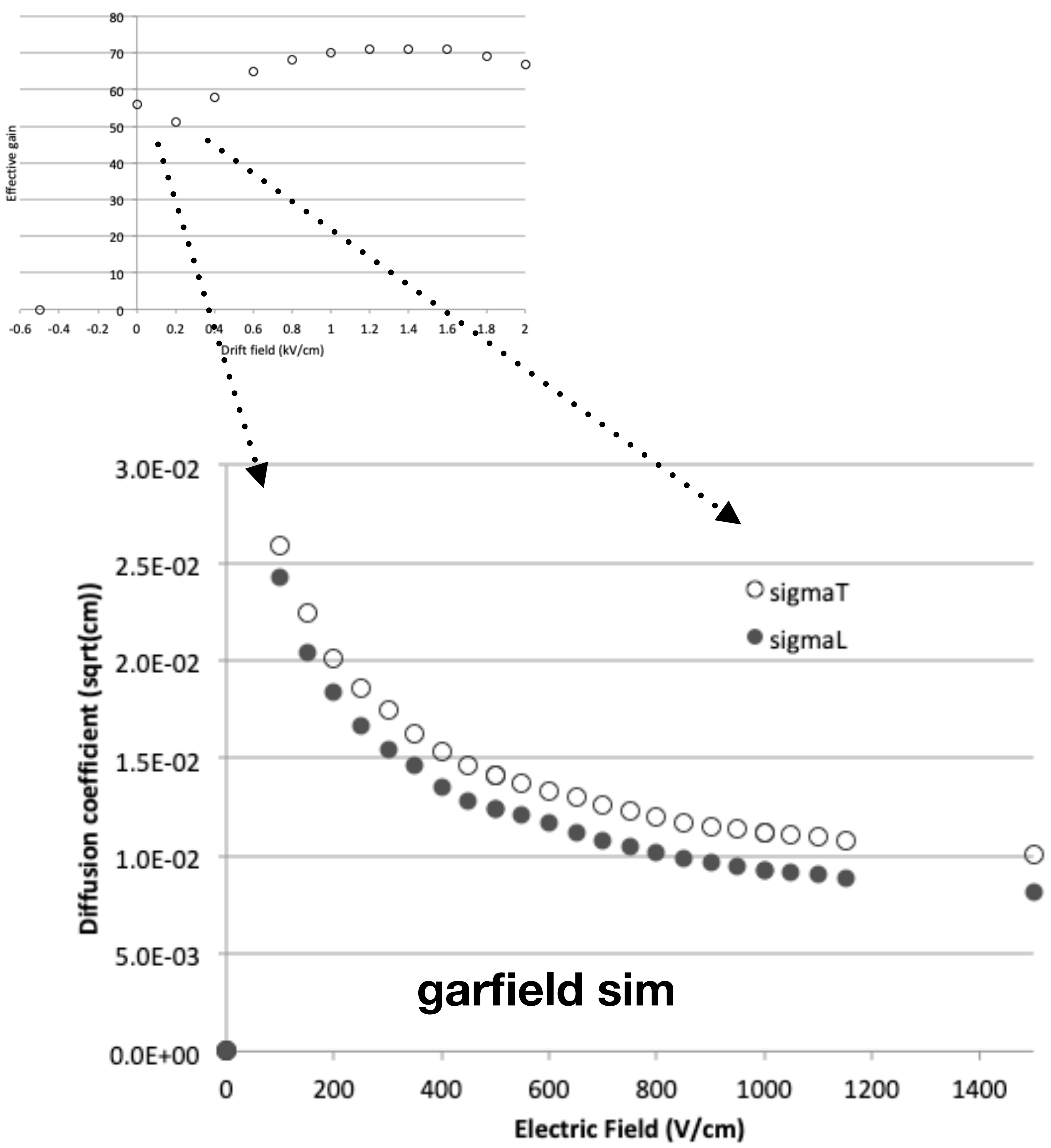


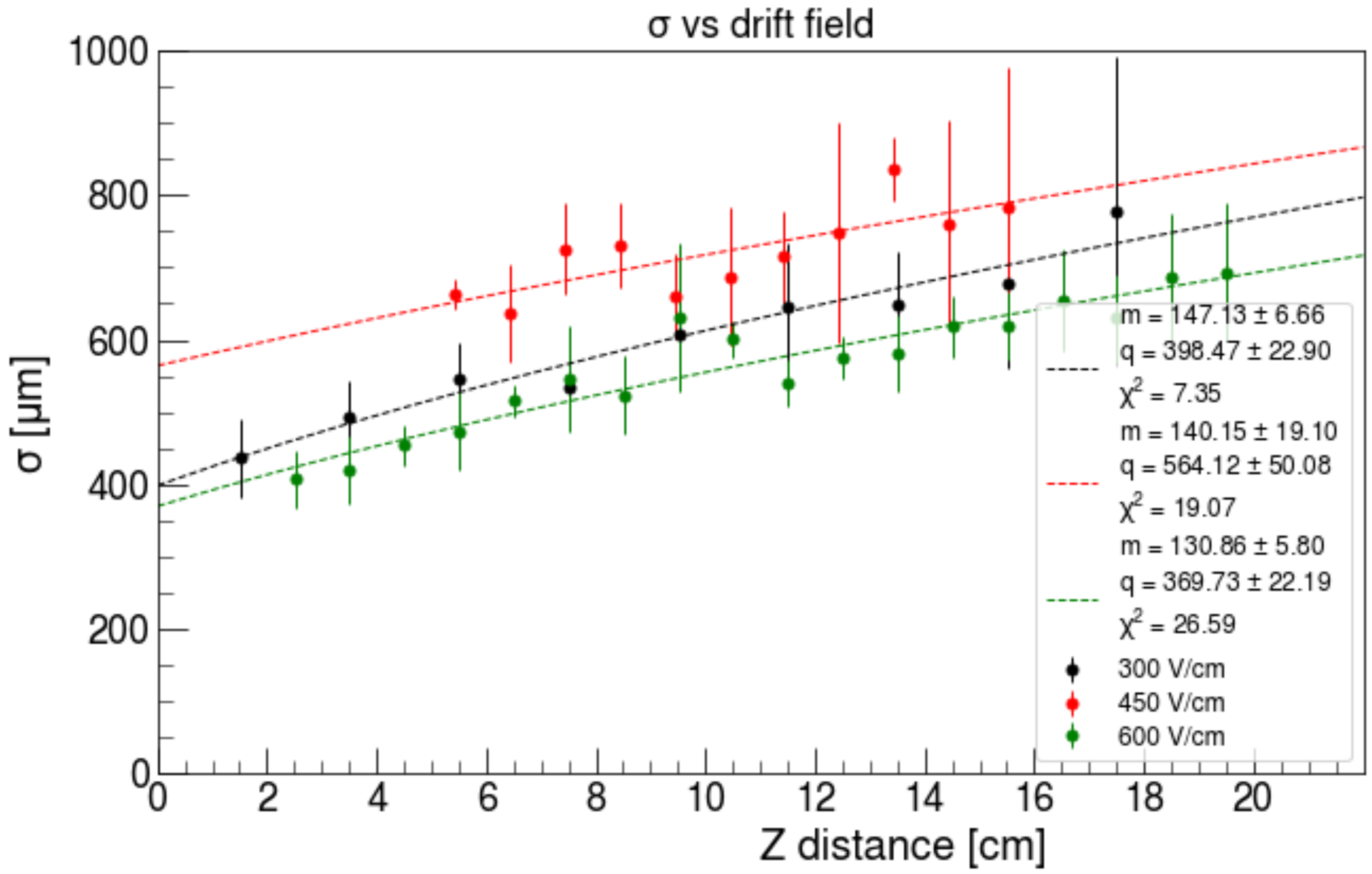
resolution obtained with a drift field to 0.6kV



in the few keV region a relative resolution of 20%-30% is achieved

diffusion in HeCF4 for electrons

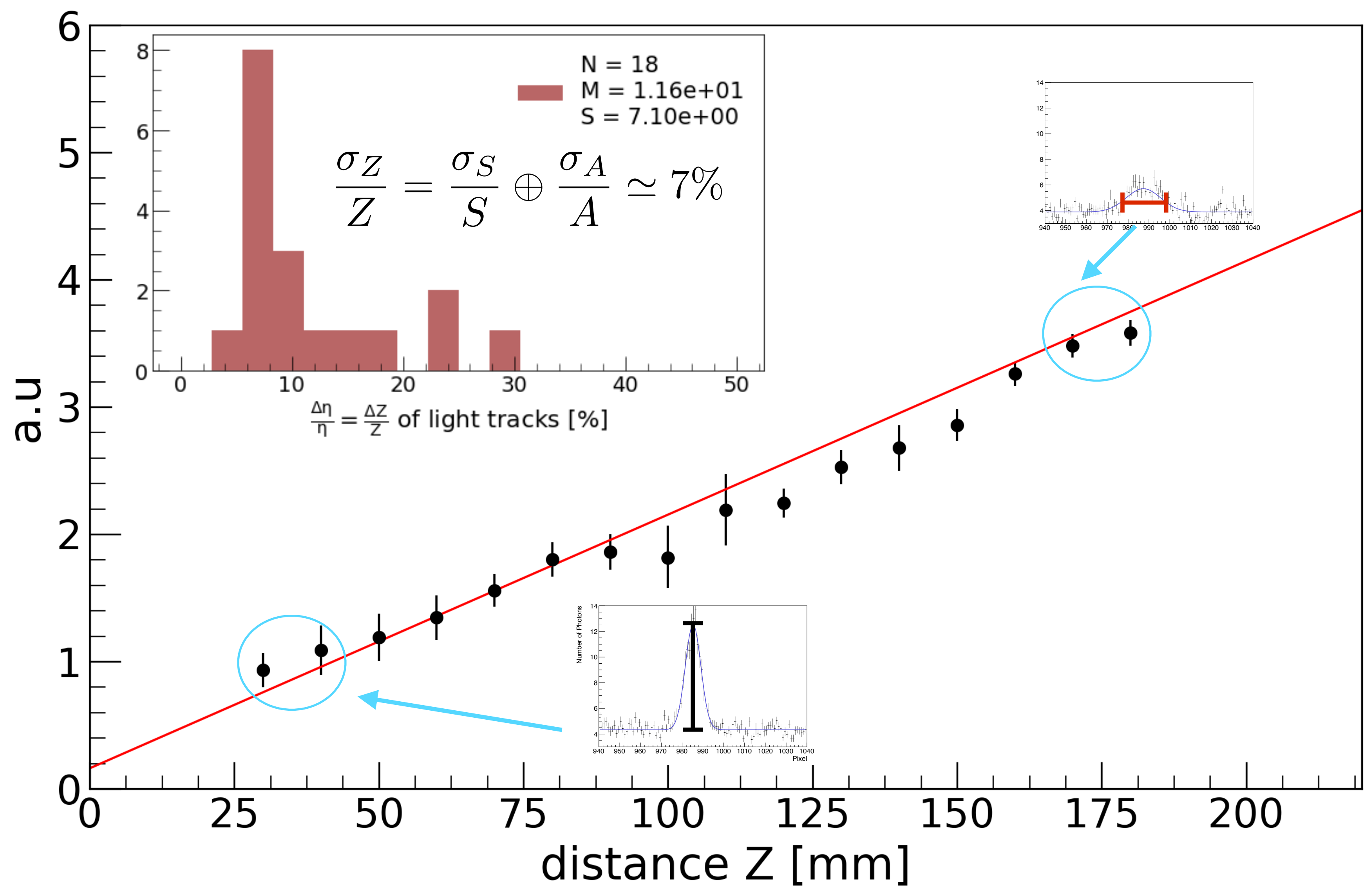


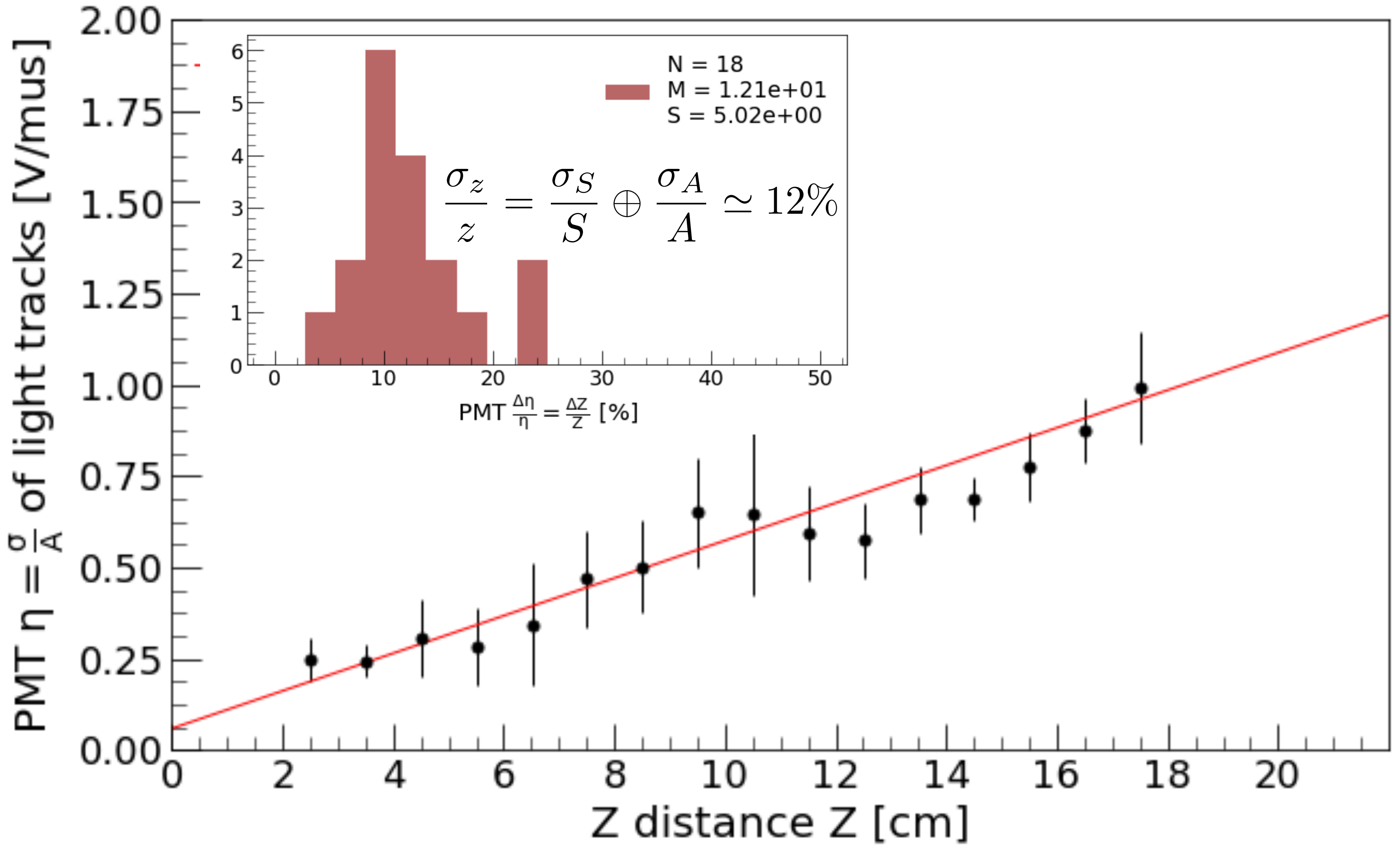


LEMON data @ Frascati BTF

Z resolution in LEMOn

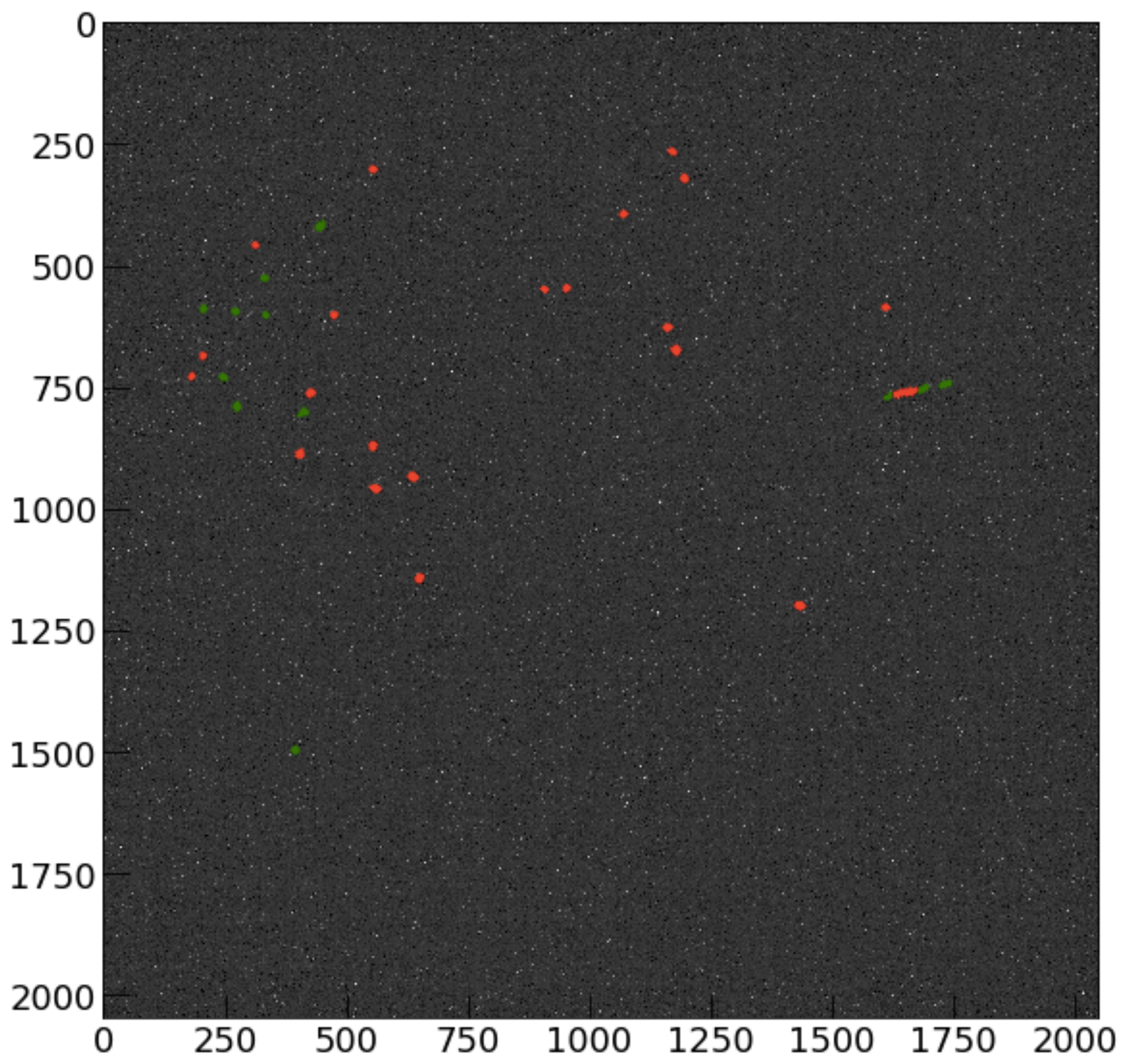
Electron diffusion in the drift gap can be exploited to evaluate the Z of the event. The transverse light profile and the PMT signal waveform are expected to become lower and larger as long as the event is far from the GEM;
Since the amplitude (A) decreases and the width (S) increases with Z, their ratio η = S/A increases (independently from the amount of produced light);

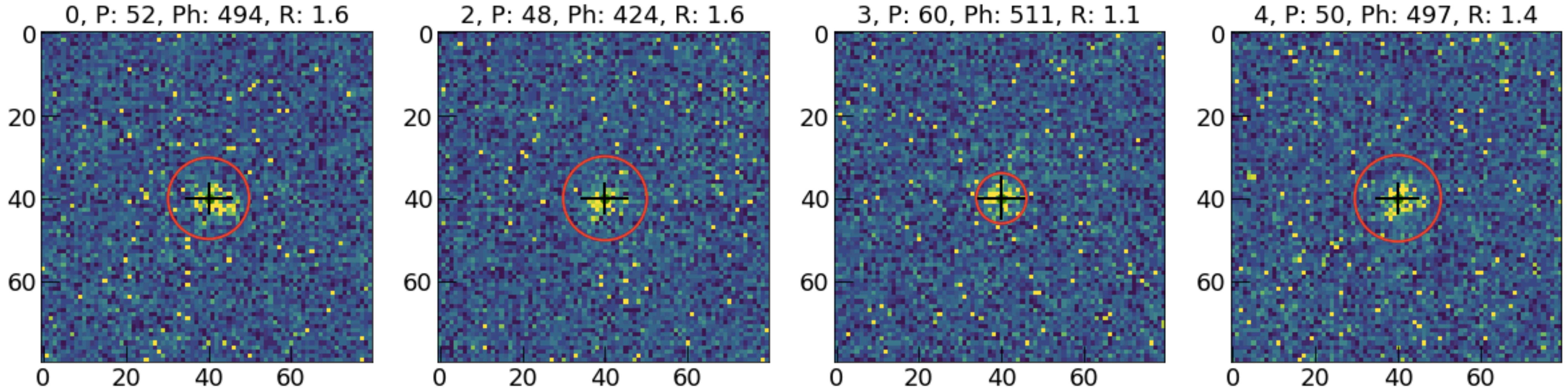


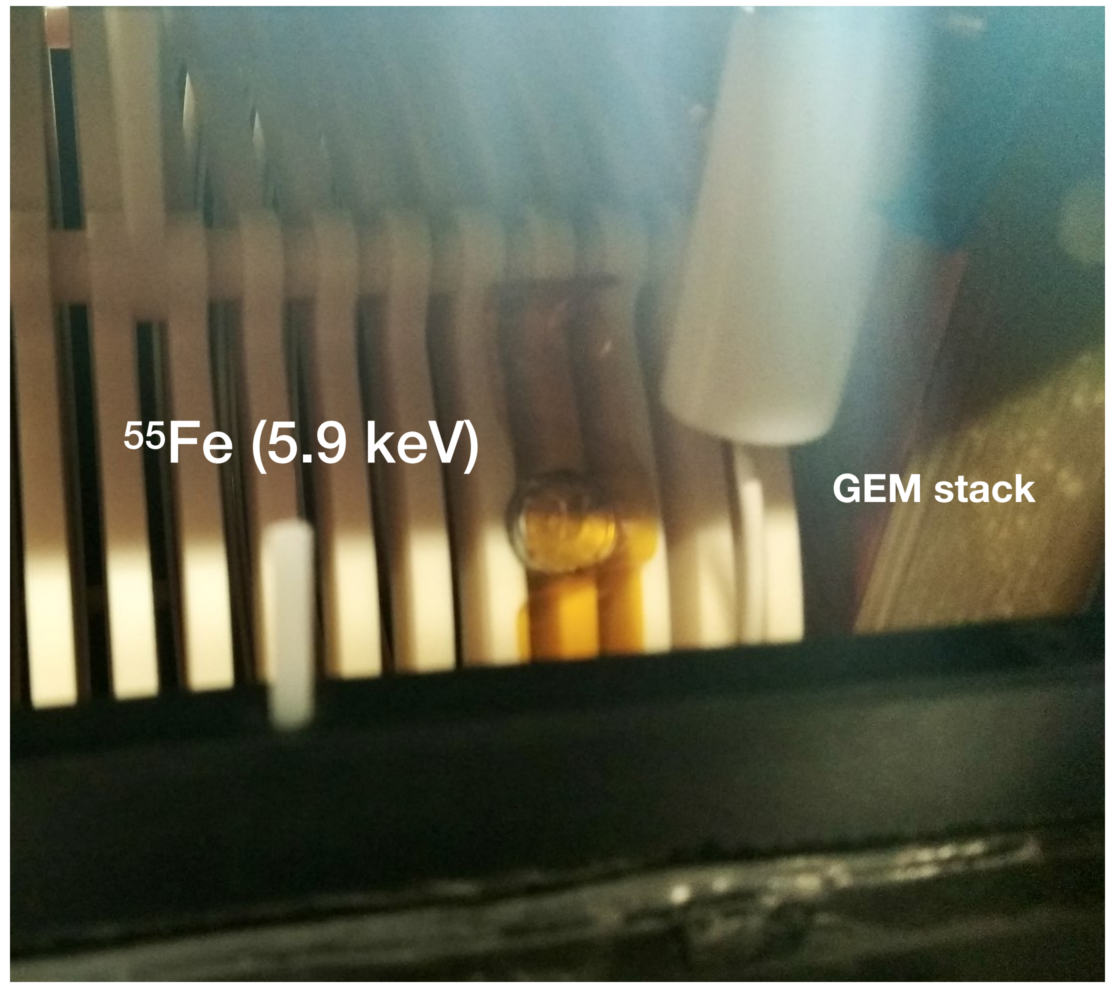


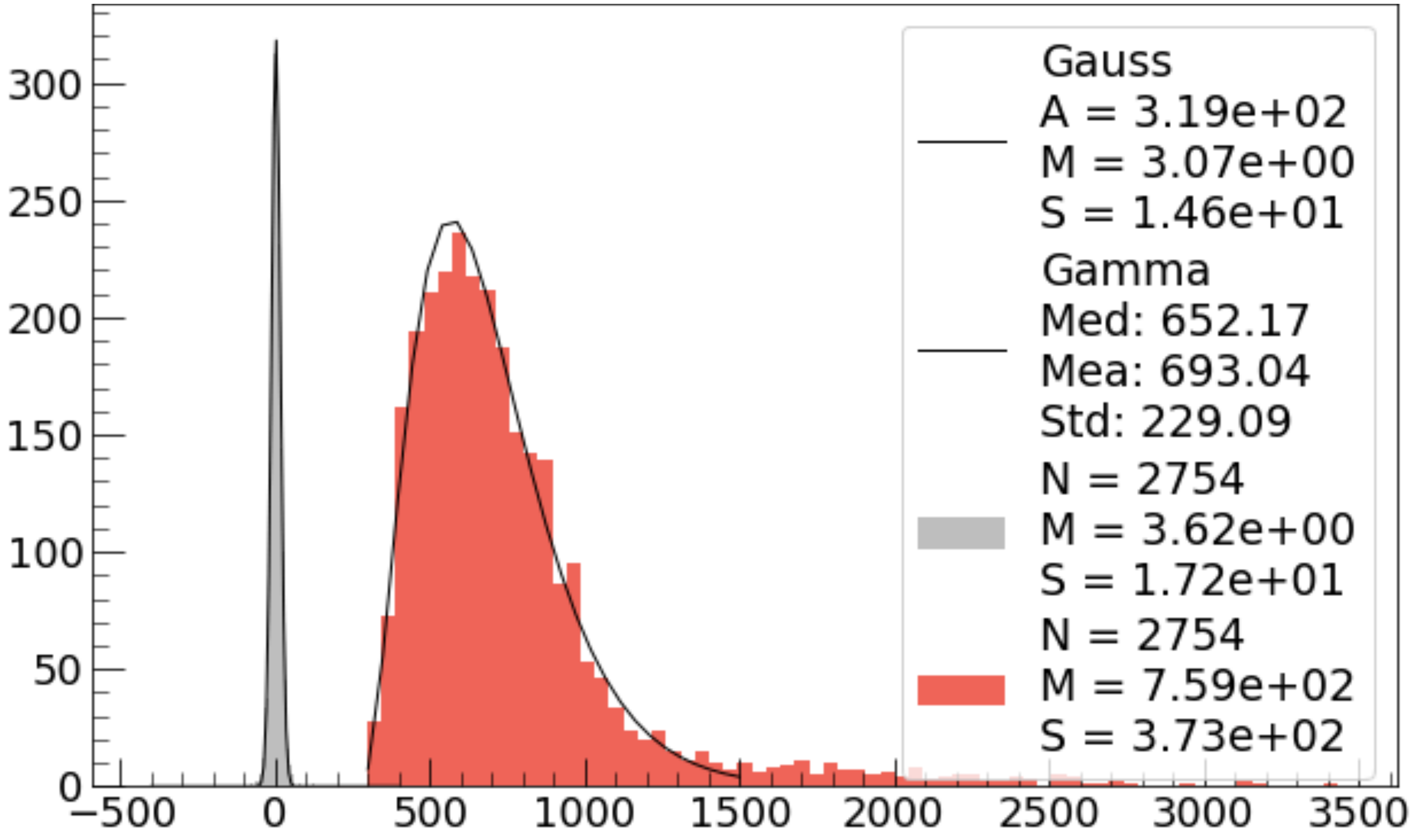
both methods gives 10% precision: σz ~ 2 cm @ 20 cm

Energy resolution ^{55}Fe (5.9 keV)









693 ph / 5900 eV
–> **0.12 ph/eV**.

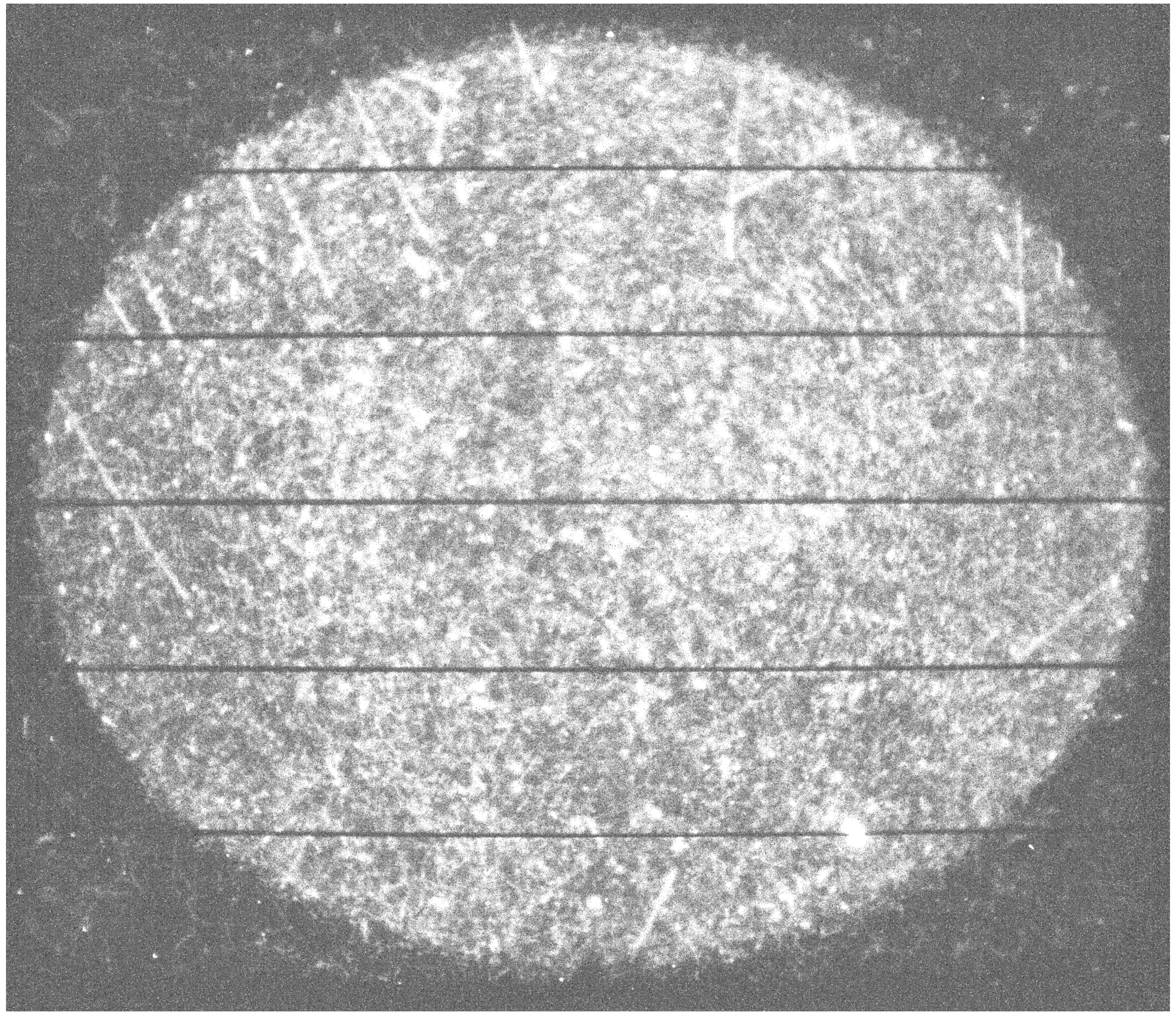
pedestal jitter 15 ph
@ 5 sigma **75 ph**
—> 75/0.12 —> **Th = 625 eV**

(pedestal based on average of the run within Fe source in the detector)

Energy resolution ~ **33% ~ 2 keV**

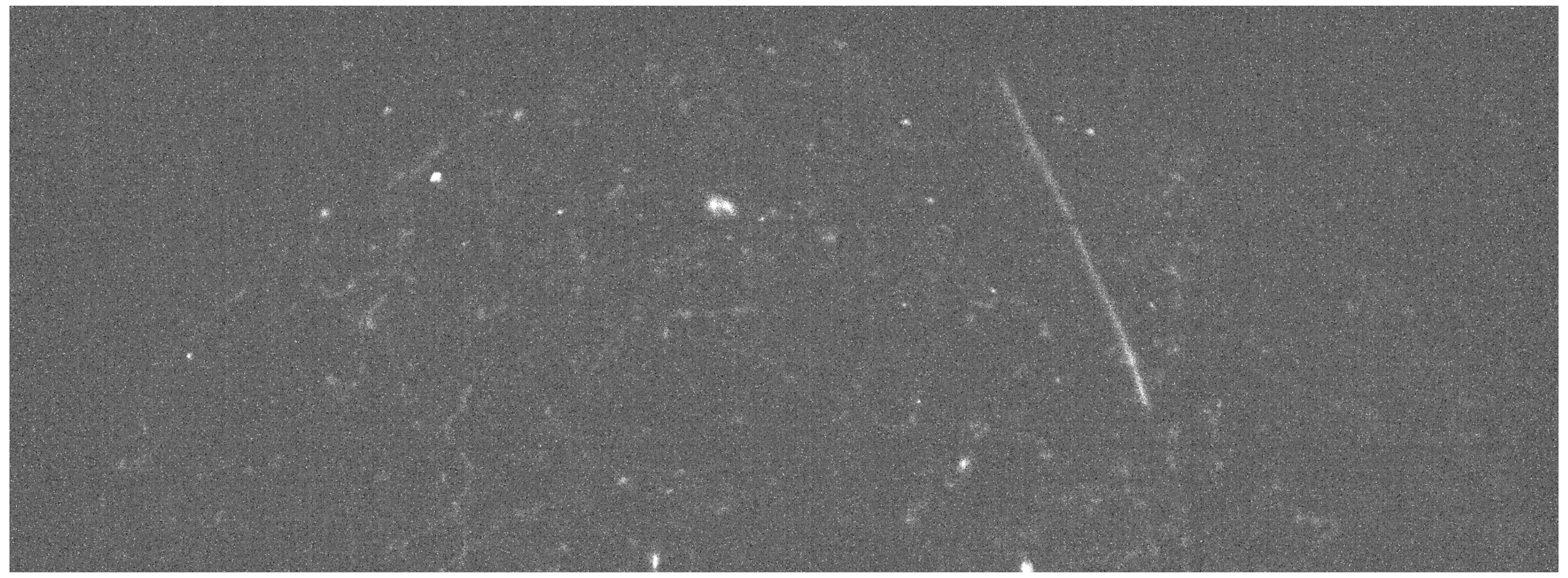
LEMOn @ ENEA FNG

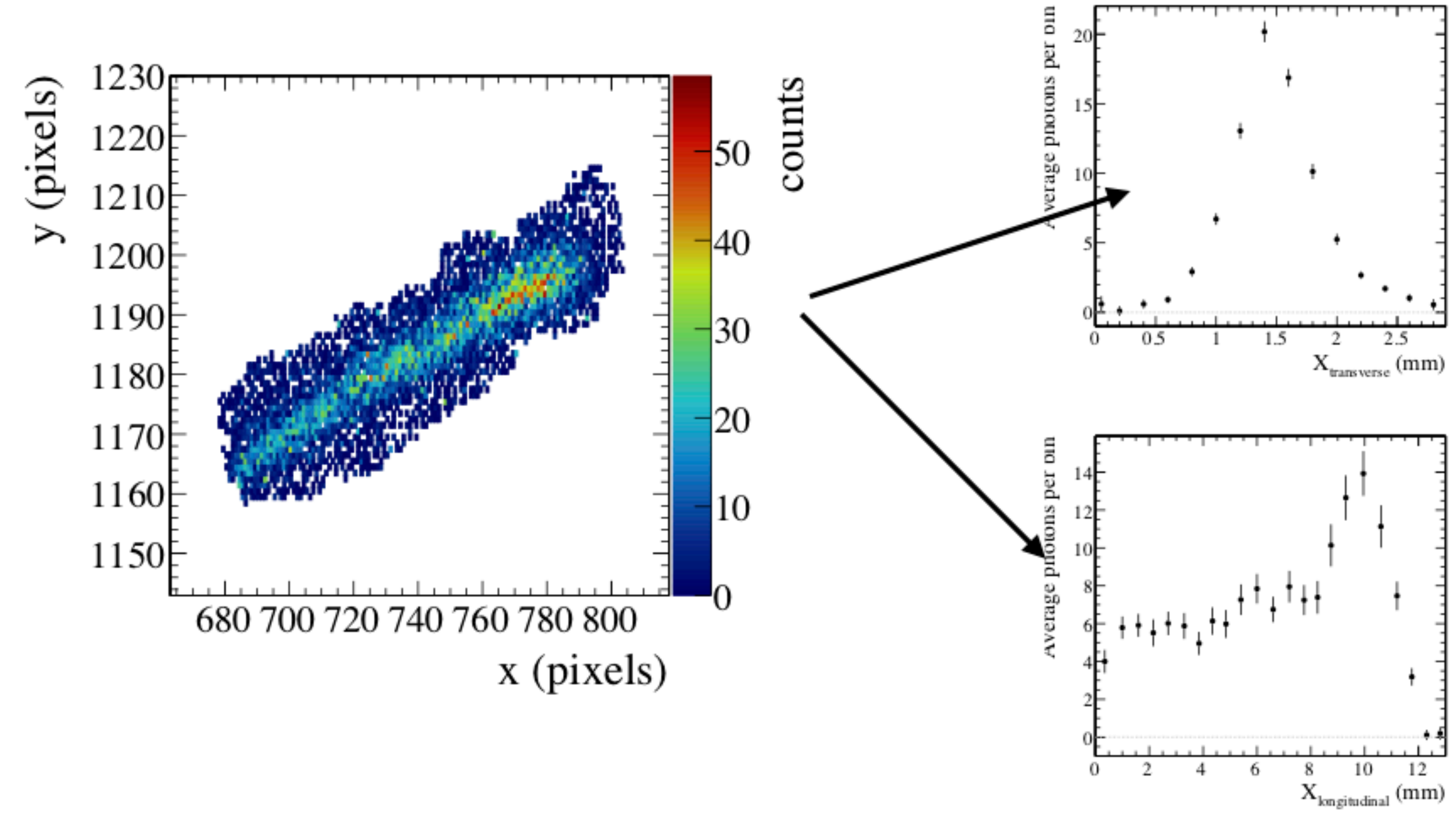
5s exposure @ 2.45 MeV neutrons
Frascati Neutron Generator



test beam 18-20 June 2018
(tanks to FNG)

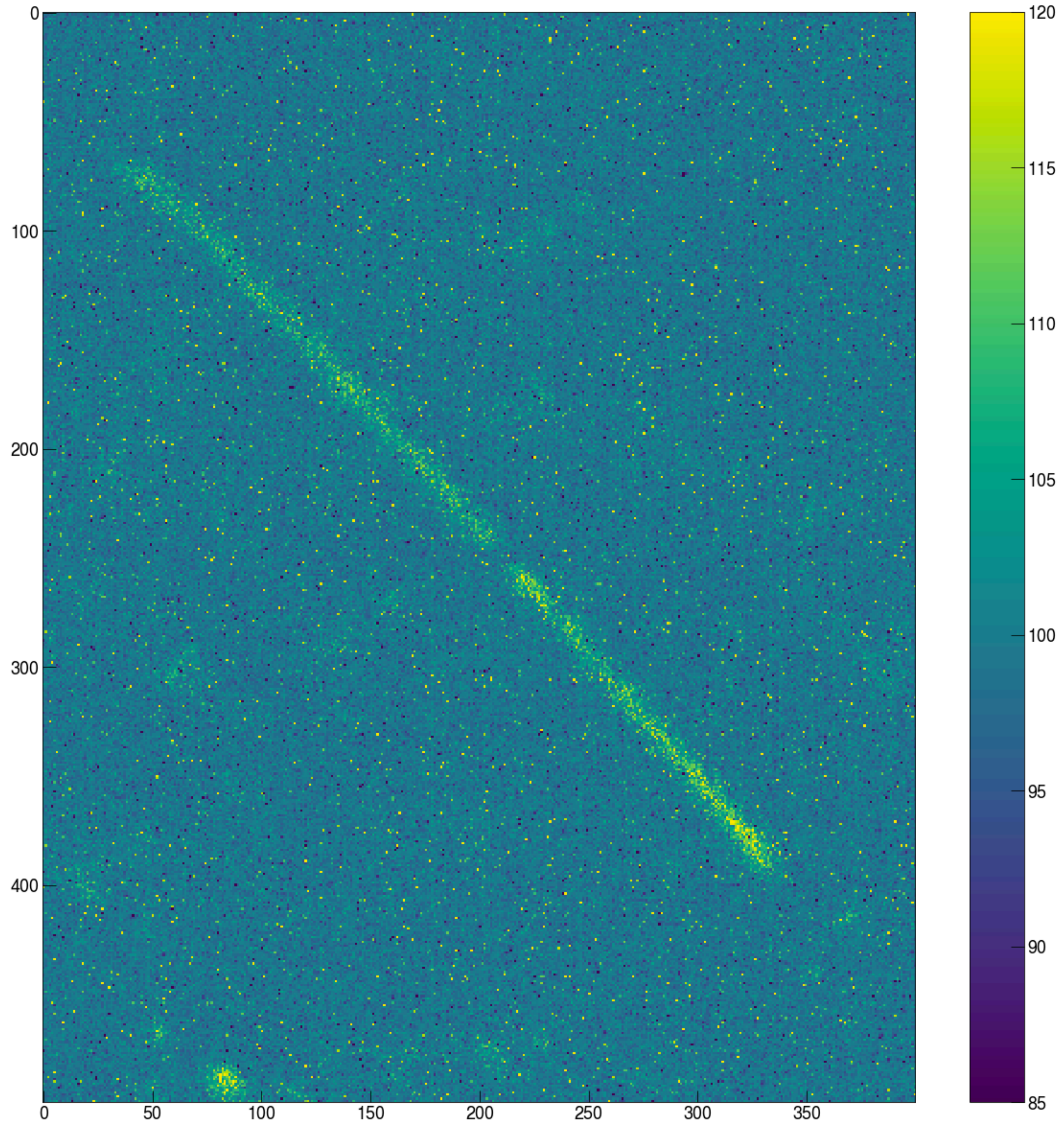
0.1s exposure @ 2.45 MeV neutrons
Frascati Neutron Generator



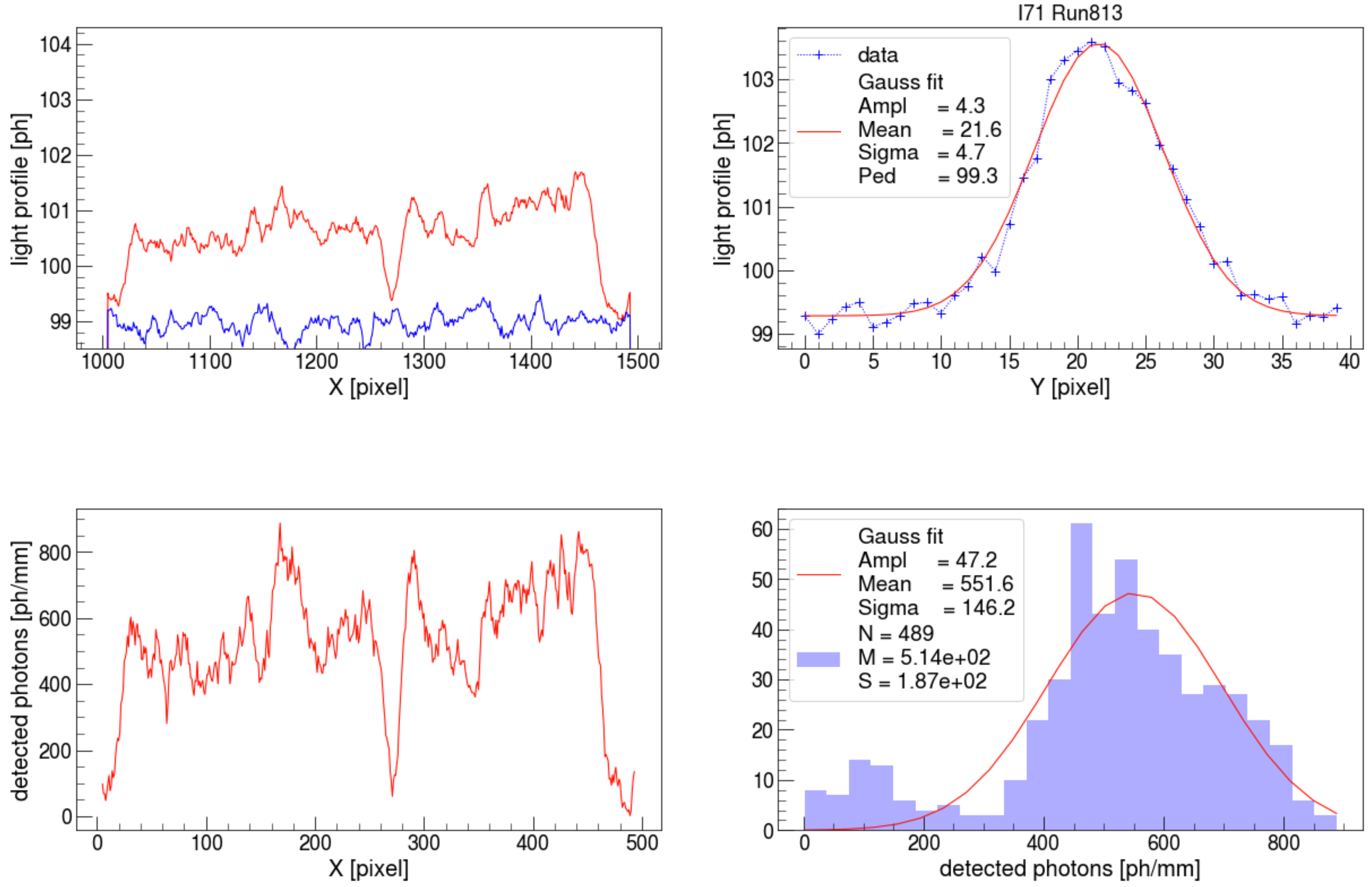


Longitudinal light profile shows a typical Bragg peak shape

LEMOn @ ENEA FNG



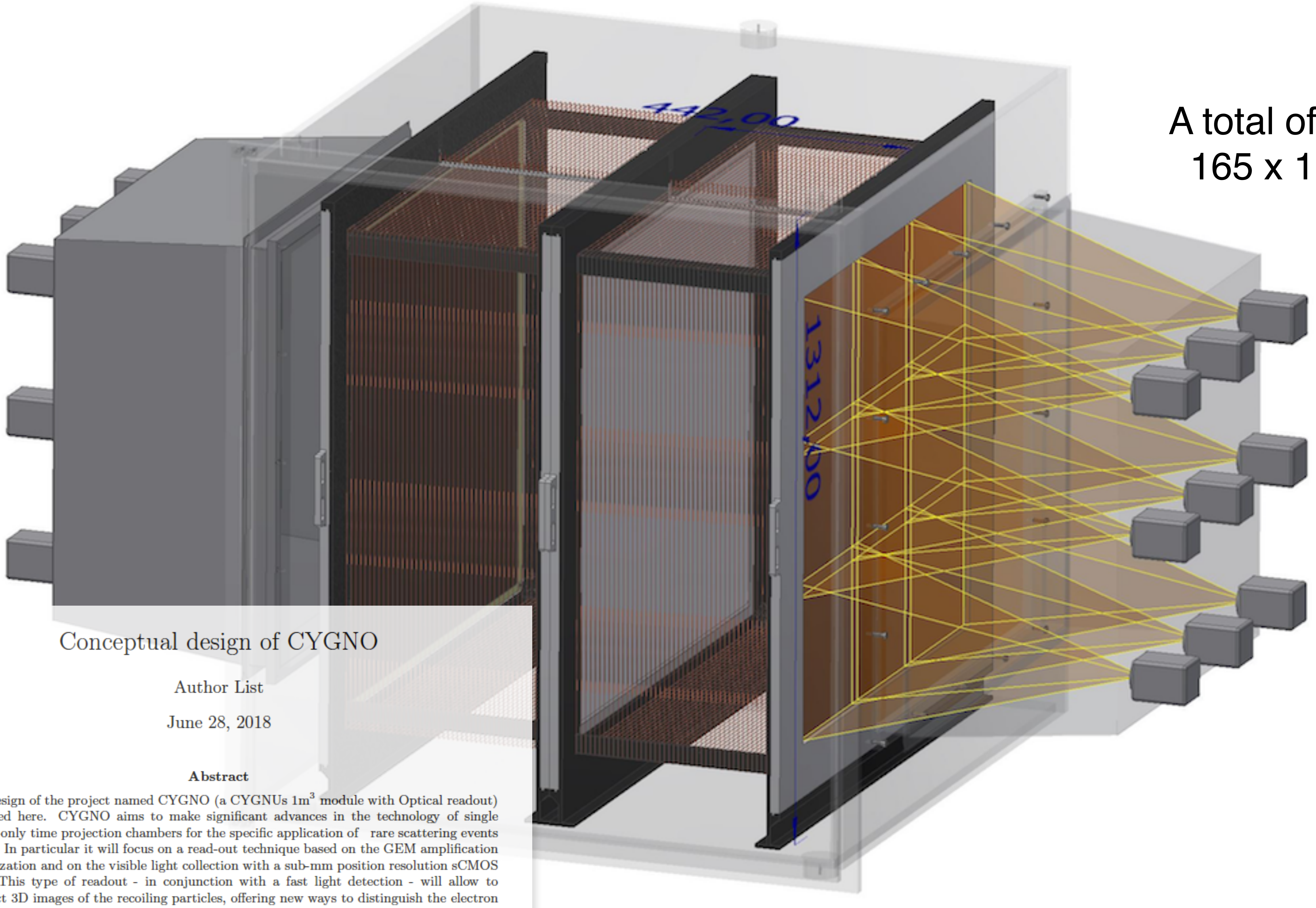
GEM 440V/2kVcm - drift 0.6kV/cm - 100 ms



550 [ph/mm] / 0.06 [ph/eV] —> 9.2 keV/mm (125 µm resolution)

~ 0.575 MeV recoil He energy

CYGNO Detector



A total of 72 10^6 readout
165 x 165 μm^2 pixels.

18 cameras monitoring
330*330 mm each
with **160 mµ** resolution
and a sensitivity of
~ **1 ph / 20 eV** released in gas

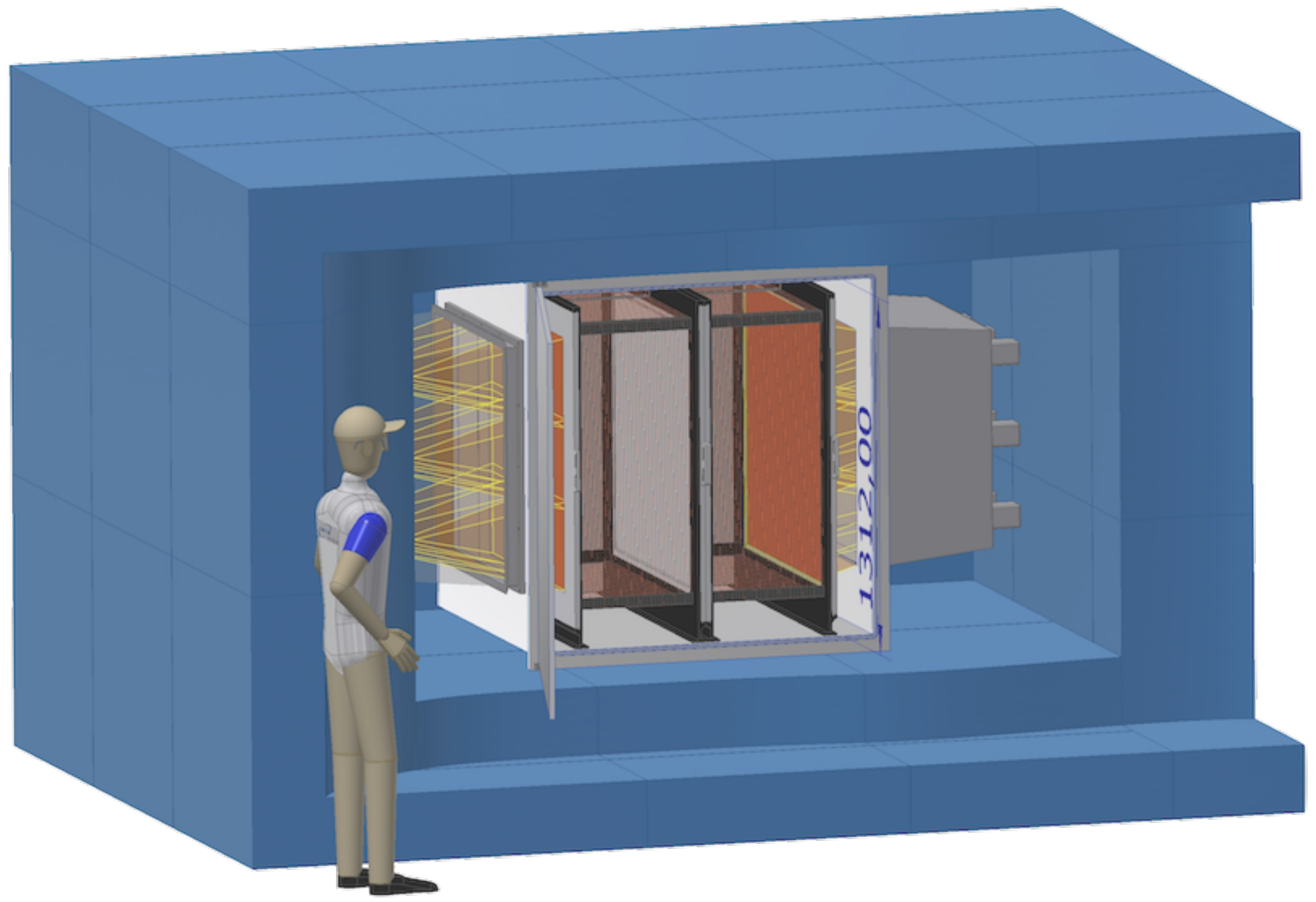
Conceptual design of CYGNO

Author List

June 28, 2018

Abstract

The design of the project named CYGNO (a CYGNUs $1m^3$ module with Optical readout) is described here. CYGNO aims to make significant advances in the technology of single phase gas-only time projection chambers for the specific application of rare scattering events detection. In particular it will focus on a read-out technique based on the GEM amplification of the ionization and on the visible light collection with a sub-mm position resolution sCMOS camera. This type of readout - in conjunction with a fast light detection - will allow to reconstruct 3D images of the recoiling particles, offering new ways to distinguish the electron and nuclear recoils. The final goal is to deliver a high resolution 1 cubic meter detector for underground neutron flux measurements that - with proper shielding and accurate choice of the materials - can be a prototype for a dark matter (DM) detector. The recoil direction resolution is also being investigated as a further tool to reject background in the detection of Galactic DM particles. This project is part of the world-wide effort of the CYGNUS collaboration to define an optimal DM detection scheme sensitive to DM direction, towards a one-ton gas TPC nuclear recoils observatory.



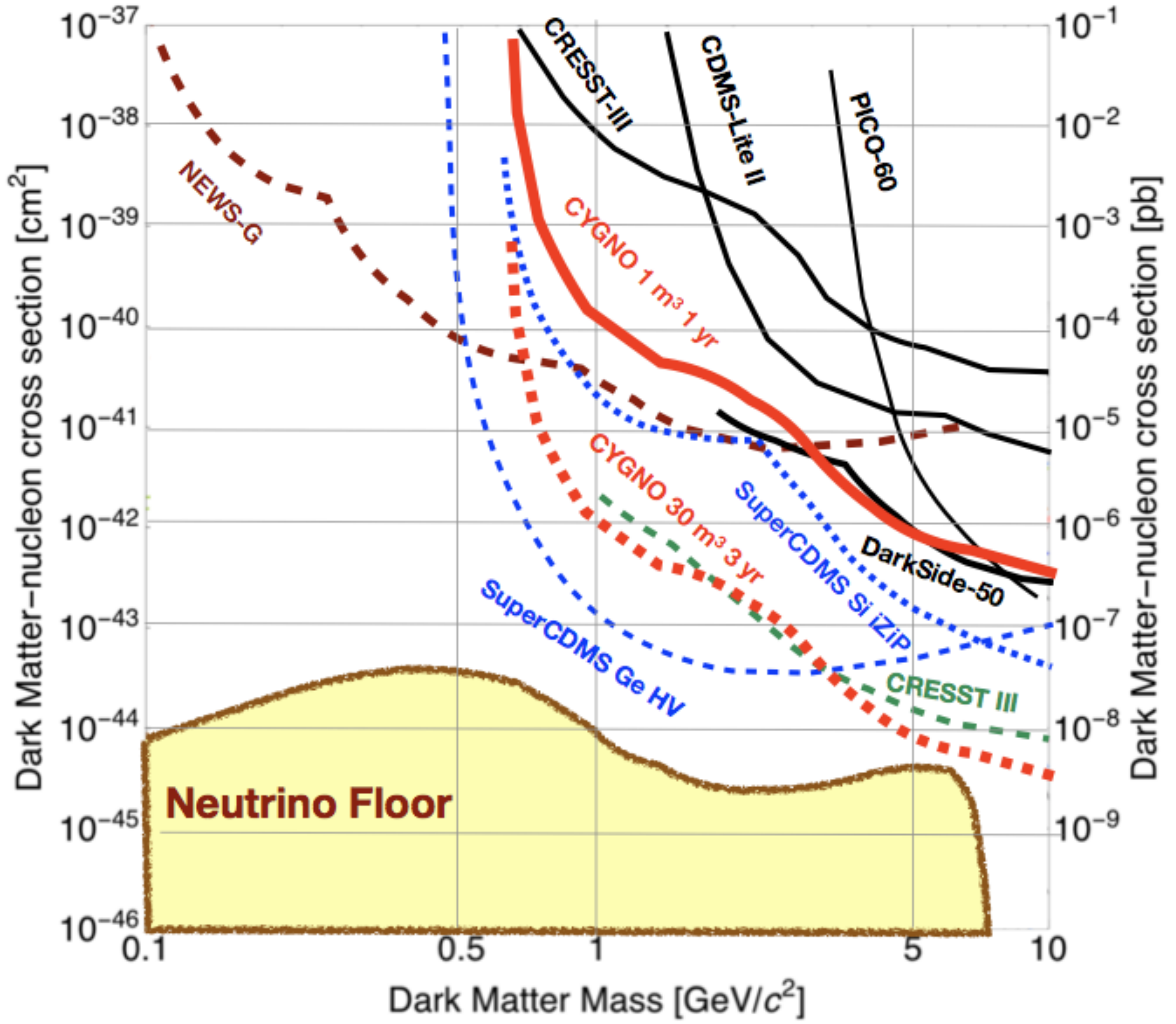
CYGNO Physics

a 1.6kg-1m³ of HeCF4 with a threshold of few 1keVe could exploit some interesting area in sub GeV DM search, but before that, CYGNO have to dimostrate with an emerging technology a full compression of: **background; materials; gas purification; stability; scalability and reliability**

E interval (eV)	Thermal Neutron Flux ($10^{-6}cm^{-2}s^{-1}$) Ref. [21]	Ref. [22]	Ref. [23]	Ref. [24]
0 - 0.05	5.3 ± 0.9	1.08 ± 0.02 (1.07 ± 0.05)	0.54 ± 0.13	0.32 ± 0.09
0.05 - 1000		1.84 ± 0.20 (1.99 ± 0.05)		

Table 2: Thermal and epithermal (top) and fast (bottom) neutron flux measurements at the Gran Sasso laboratory reported by different authors. In analyzing their experimental data with Monte Carlo simulations, Belli et al. [22] have used two different hypothetical spectra: flat, and flat plus a Watt fission spectrum. This leads to the upper and lower data sets shown for ref.[22] respectively.

E interval (MeV)	Fast Neutron Flux ($10^{-6}cm^{-2}s^{-1}$) Ref. [25]	Ref. [26]	Ref. [22]	Ref. [21]	Ref. [27]	Ref. [28]
0.1 – 1			0.54±0.01 (0.53±0.08)			2.56±0.27
1 – 2.5		0.14±0.12				
2.5 – 3		0.13±0.04	0.27±0.14 (0.18±0.04)			
3 – 5	0.78±0.3			3.0±0.8	0.09±0.06	
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)			
10 – 15		$(0.4 \pm 0.4) \cdot 10^{-3}$	$(0.6 \pm 0.2) \cdot 10^{-3}$ ($(0.7 \pm 0.2) \cdot 10^{-3}$)			
15 – 25			$(0.5 \pm 0.3) \cdot 10^{-6}$ ($(0.1 \pm 0.3) \cdot 10^{-6}$)			

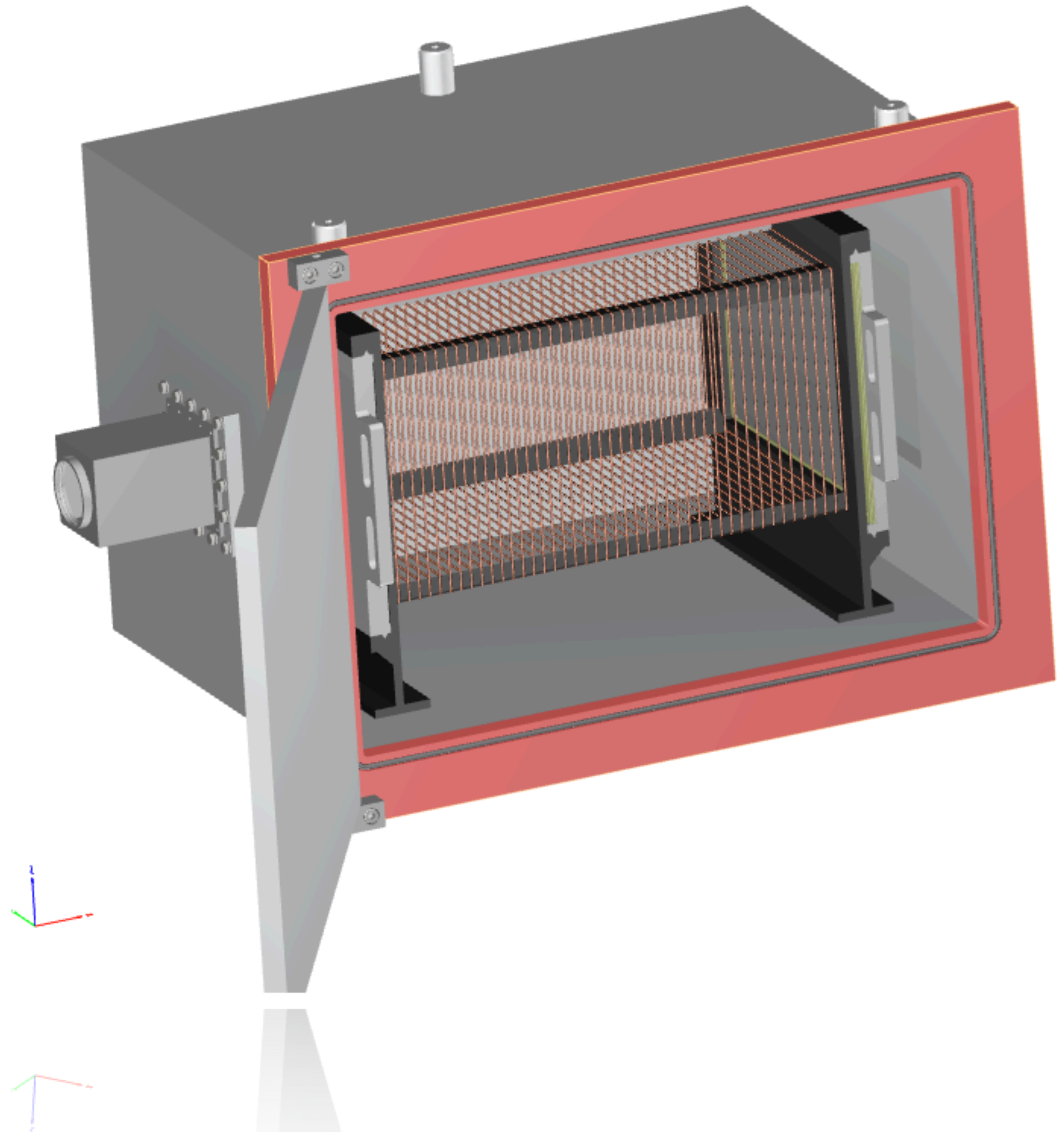


on the other hand CYGNO can provide a low noise **seasonal measurement of the neutron flux** intensity and spectrum at LNGS, presently highly desirable in order to check the current results and to **reduce the experimental errors.**

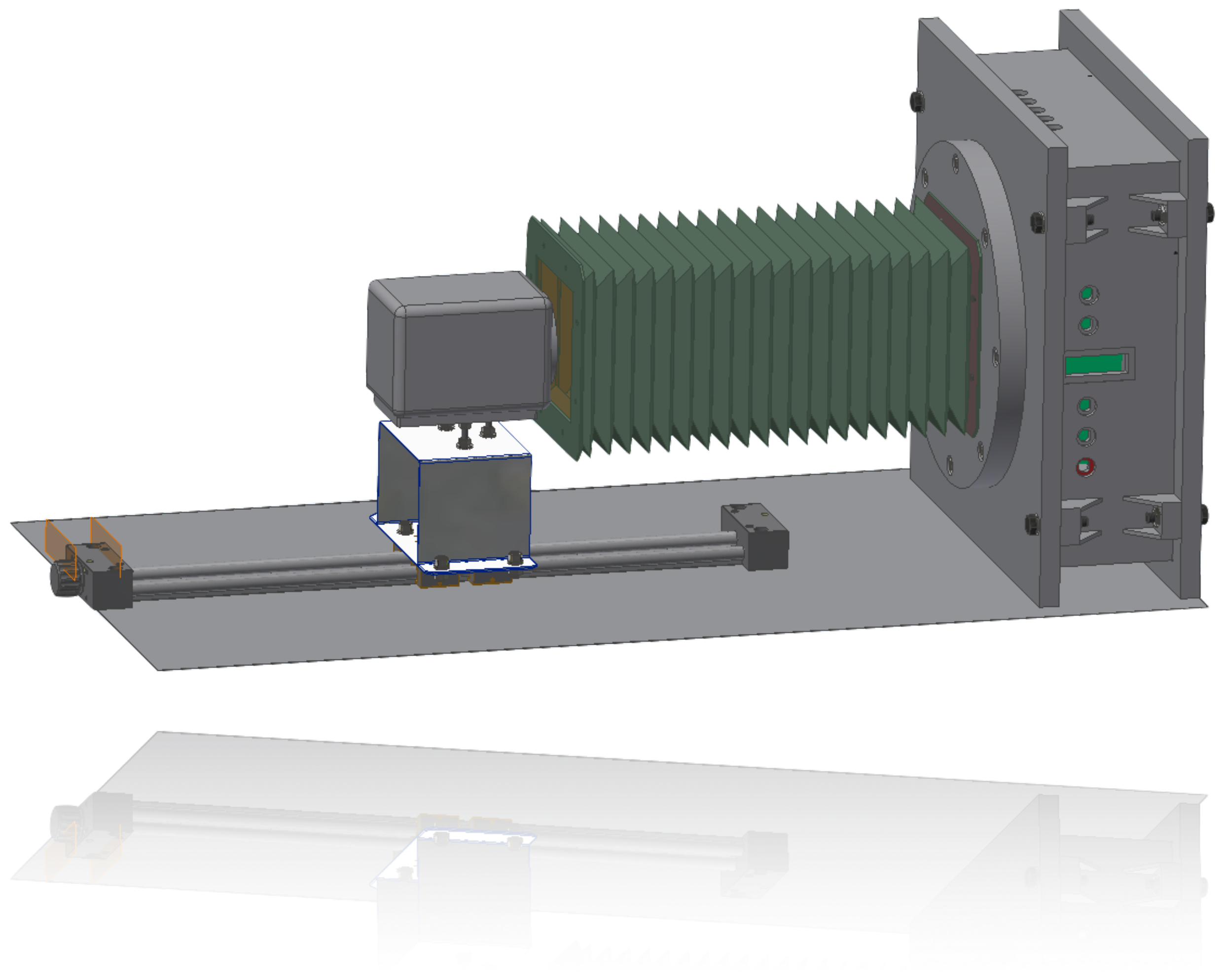
in the meantime… LIME & MANGO

LIME: Long Imaging ModulE

- **50 cm** long drift gap, 25 litre sensitive volume
- studied material choice
- performing a detailed study, minimisation and simulation of **radioactive background**;
- **gas** re-circulation and purification.
- optimisation of **PMT/SiPM** readout and trigger.
- HV Test



F. Rosatelli & S. Tomassini



MANGO - Multipurpose Apparatus for Negative ion studies with GEM and Optical readout

- 5 cm drift gap
- THGEM test
- 4 GEM test (lower HV with the same gain)
- **Negative Ion test**

Conclusion 1/2

- TPC based on **optically readout GEM** demonstrated very interesting performance:
  - X-Y resolution around 100 μm;
  - 20%-30% precision on the evaluation of released energy already in the keV range;
  - effect of electron diffusion can be exploited to determine the track depth with a 12% uncertainty;

- use of a **PMT** for a combined allows:
  - the 3D reconstruction of single clusters with 100 μm resolution;
  - a concurrent evaluation of the event Z with 12% uncertainty;
  - detection of light produced by the particle crossing to get the t0 of the event.

- **tracking and PID** looks to be very promising tools to lower the energy threshold and identify signal respect to background

Conclusions 2/2

- The international community CYGNUS is studying and promoting a third class of Dark Matter and neutrino detector able to explore the **keV region**, taking in to account the **directionality** of the signals and exploiting the PID characteristic to **identify background**;

- 1 m^3 prototypes has been funded around the world, and CYGNO is the one investigating the possibility to realise a **very high spatial and energy resolution** detector exploring the **optical readout** performance;

- CYGNO demonstrator has a sensitivity on the paper already of interest for Dark Matter and Neutron Flux measurements, with the aim to open a roadmap to 30-100 m^3 where physics is very interesting and competitive.

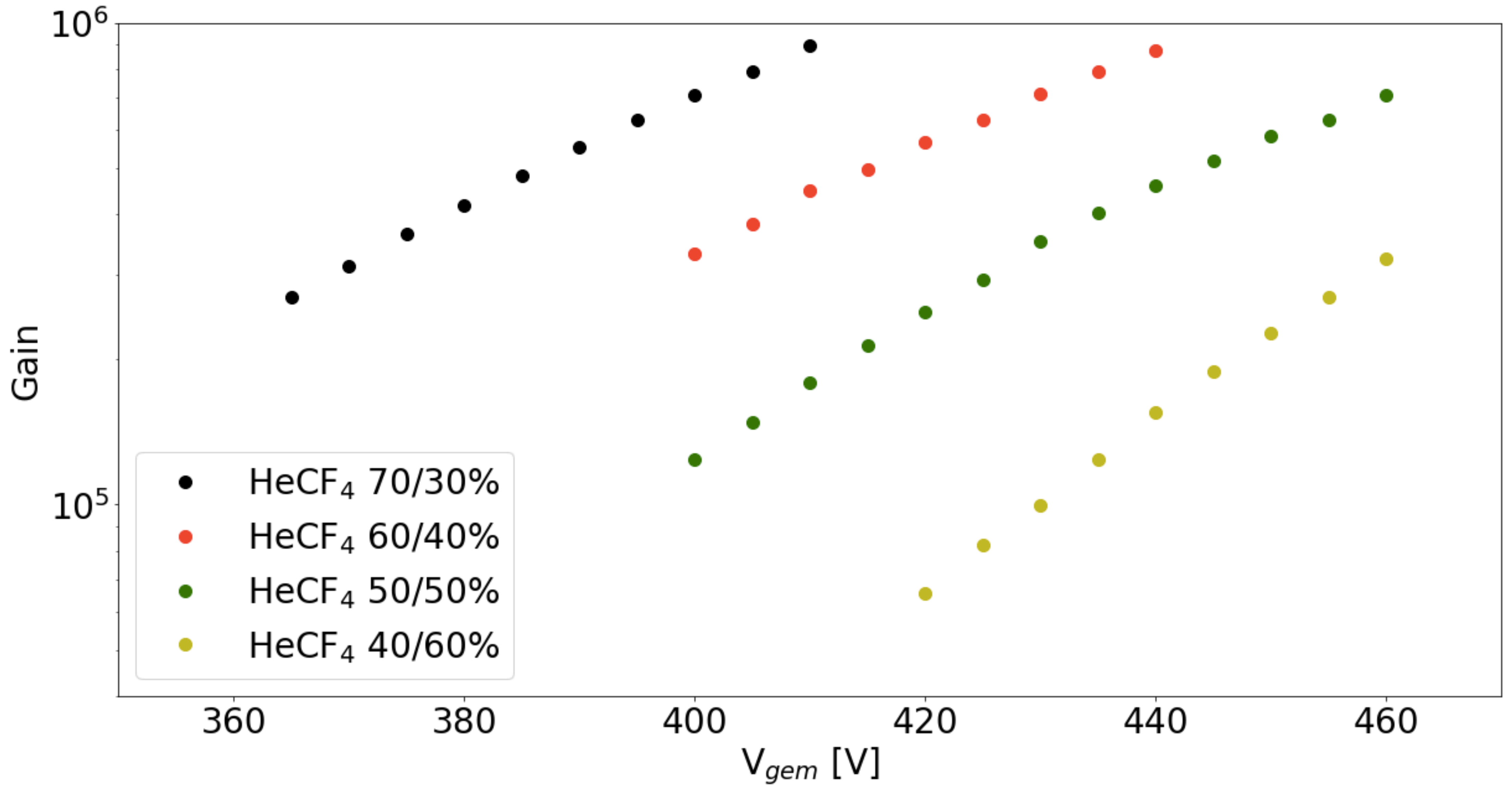
CYGNUS (CYGNO) Collaboration

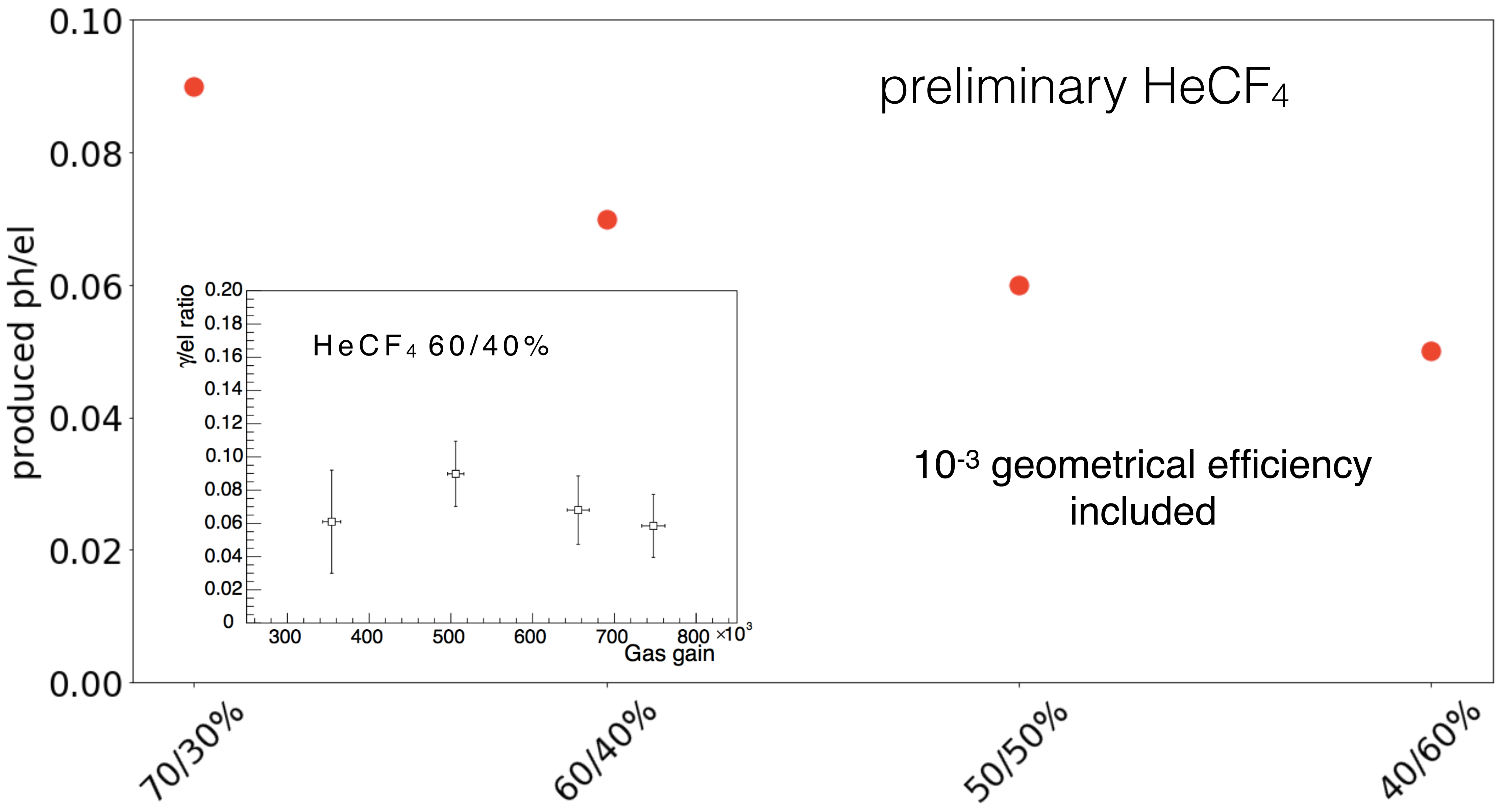
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati (RM), Italy; Gran Sasso Science Institute, L'Aquila, Italy; Sapienza Università di Roma, Dipartimento di Fisica, Rome, Italy; Australian National University, ACT, Canberra, Australia; Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Rome, Italy; University of Sheffield, Sheffield, United Kingdom; University of New Mexico, Albuquerque, New Mexico, United States of America; Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Rome, Italy; University of Hawaii, Honolulu, Hawaii, United States of America; Kobe University, Kobe, Japan; Istituto Nazionale di Fisica Nucleare, Sezione di Roma TRE, Rome, Italy; ENEA, Frascati, Frascati (RM), Italy; Università di Roma TRE, Dipartimento di Matematica e Fisica, Rome, Italy; Sapienza Università di Roma, Dipartimento di Ingegneria Chimica Materiali Ambiente, Rome, Italy; Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, L'Aquila, Italy

“spare”

–Johnny Appleseed

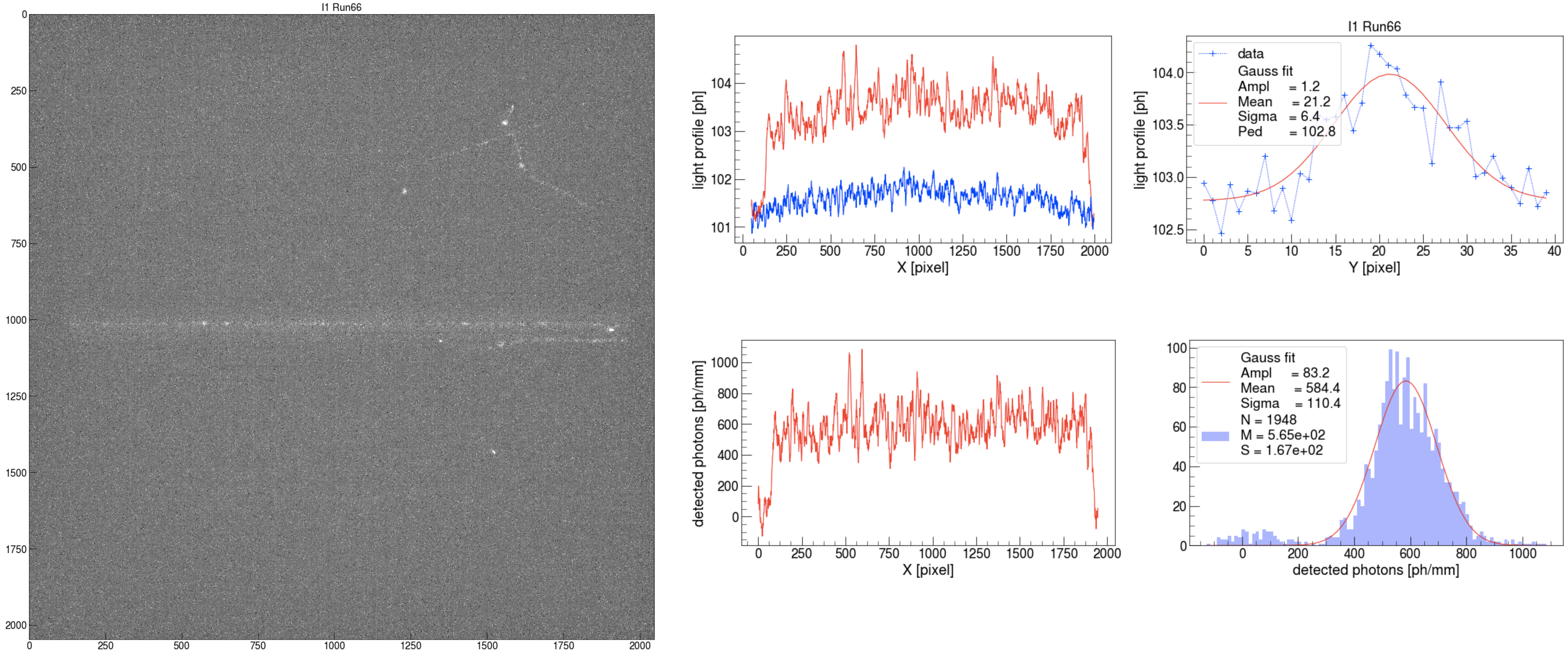
Electrical and light GAIN



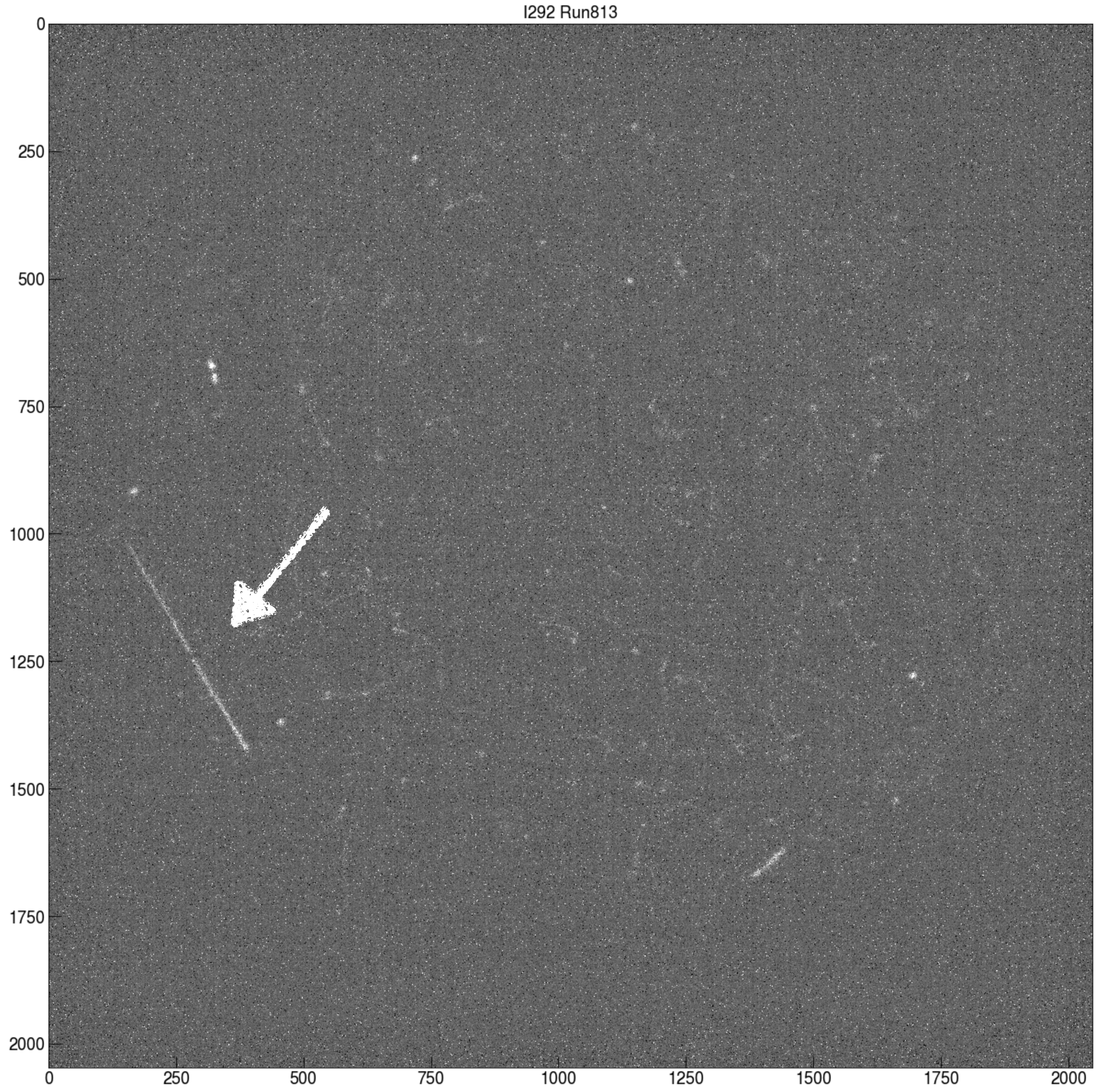


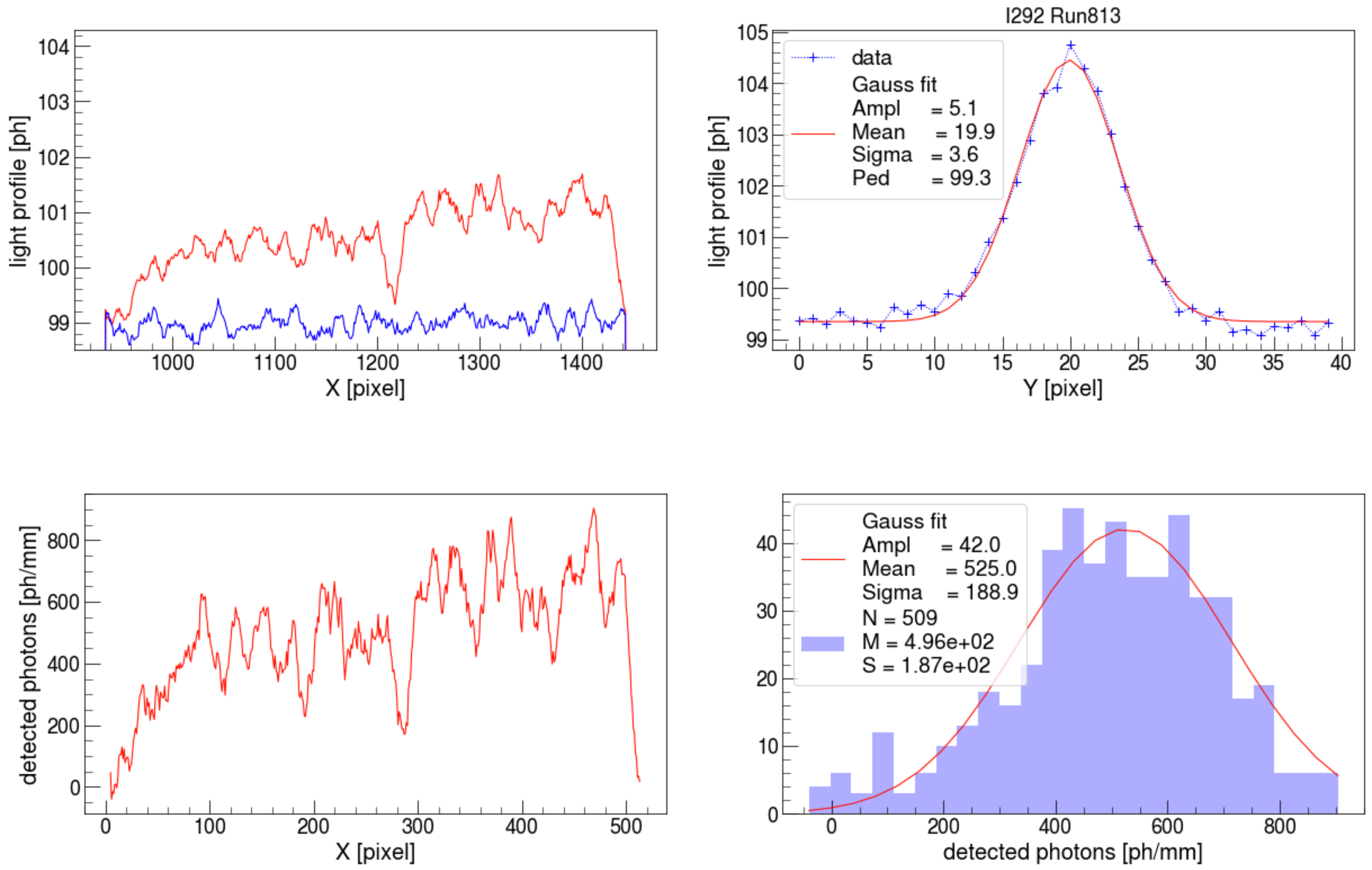
about 0.07 photons produced by secondary electron in the GEM shower

MIP LEMON
GEM 455V(?)/2kVcm - drift 0.6kV/cm - 30 ms

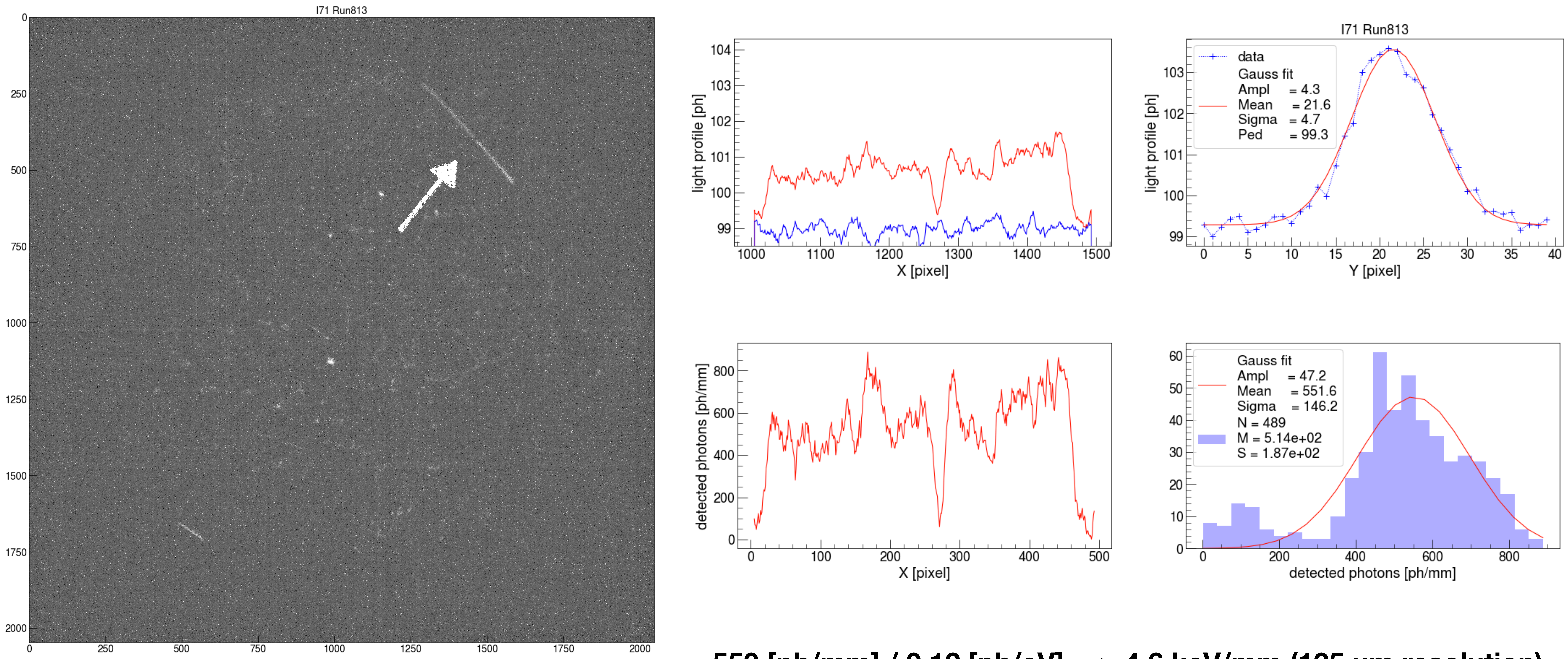


FNG LEMON
GEM 440V/2kVcm - drift 0.6kV/cm - 100 ms





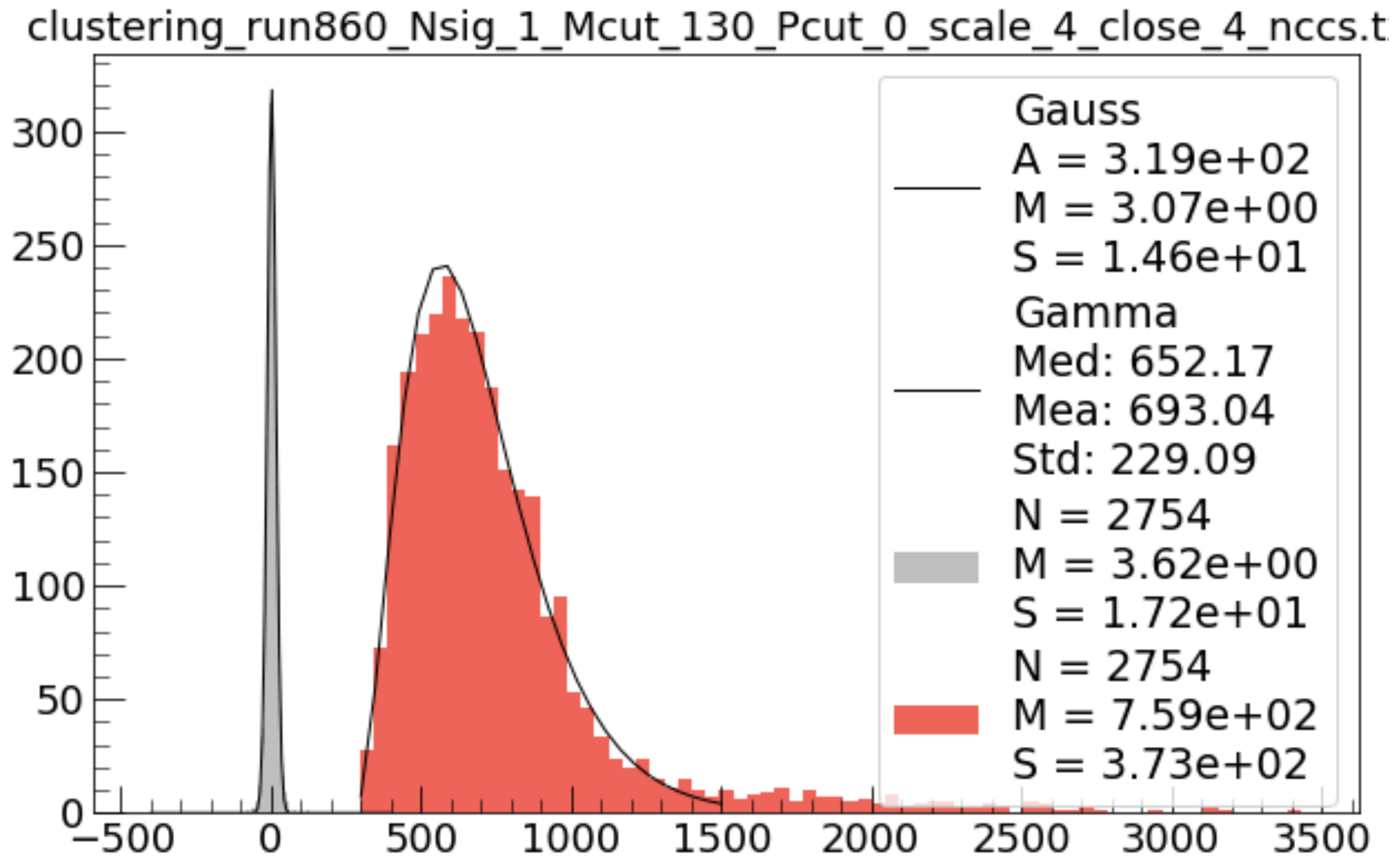
FNG LEMON
GEM 440V/2kVcm - drift 0.6kV/cm - 100 ms



550 [ph/mm] / 0.12 [ph/eV] —> 4.6 keV/mm (125 µm resolution)

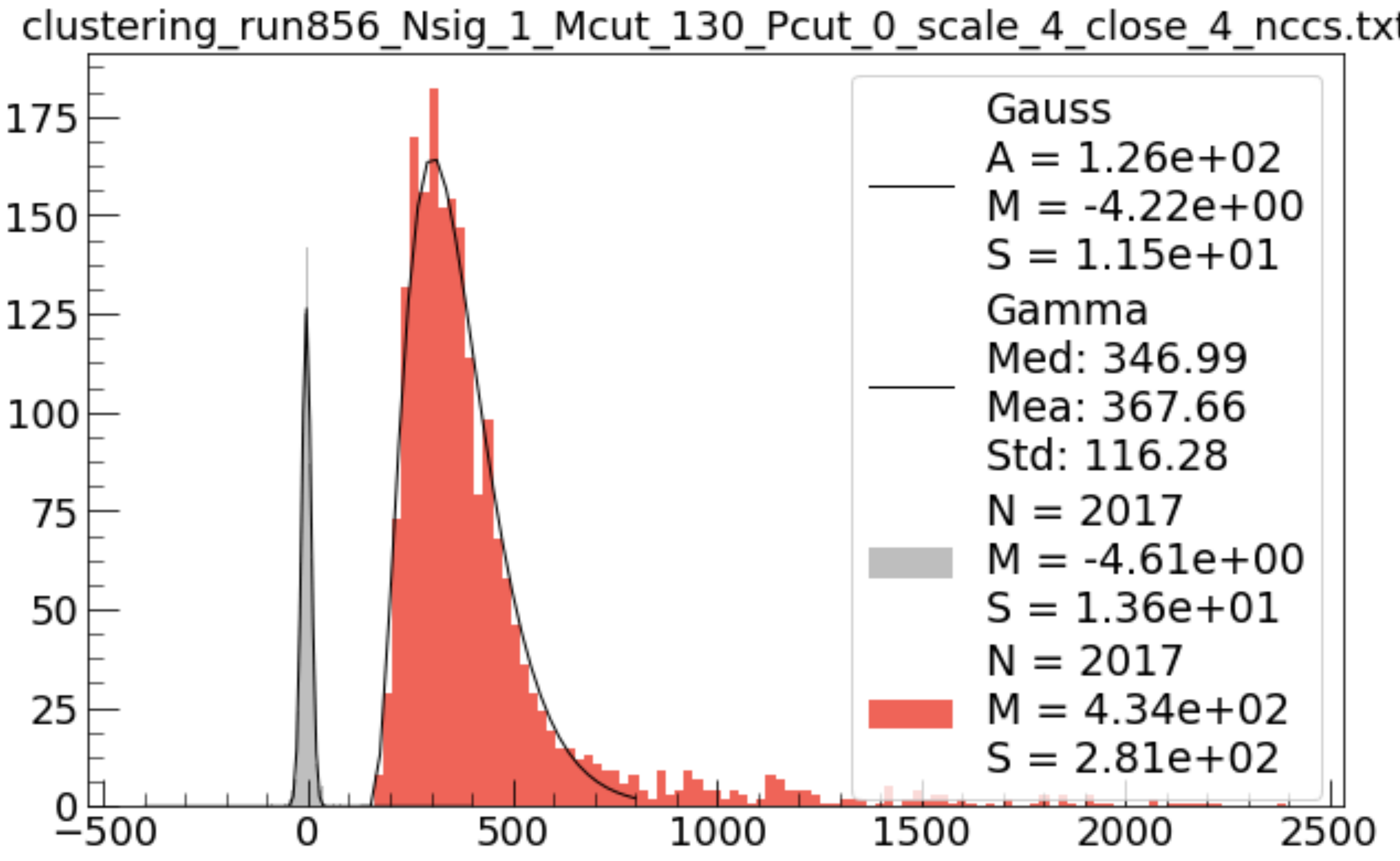
Fe @ 440 for FNG comparison

LEMON - 460 - 0.6kV



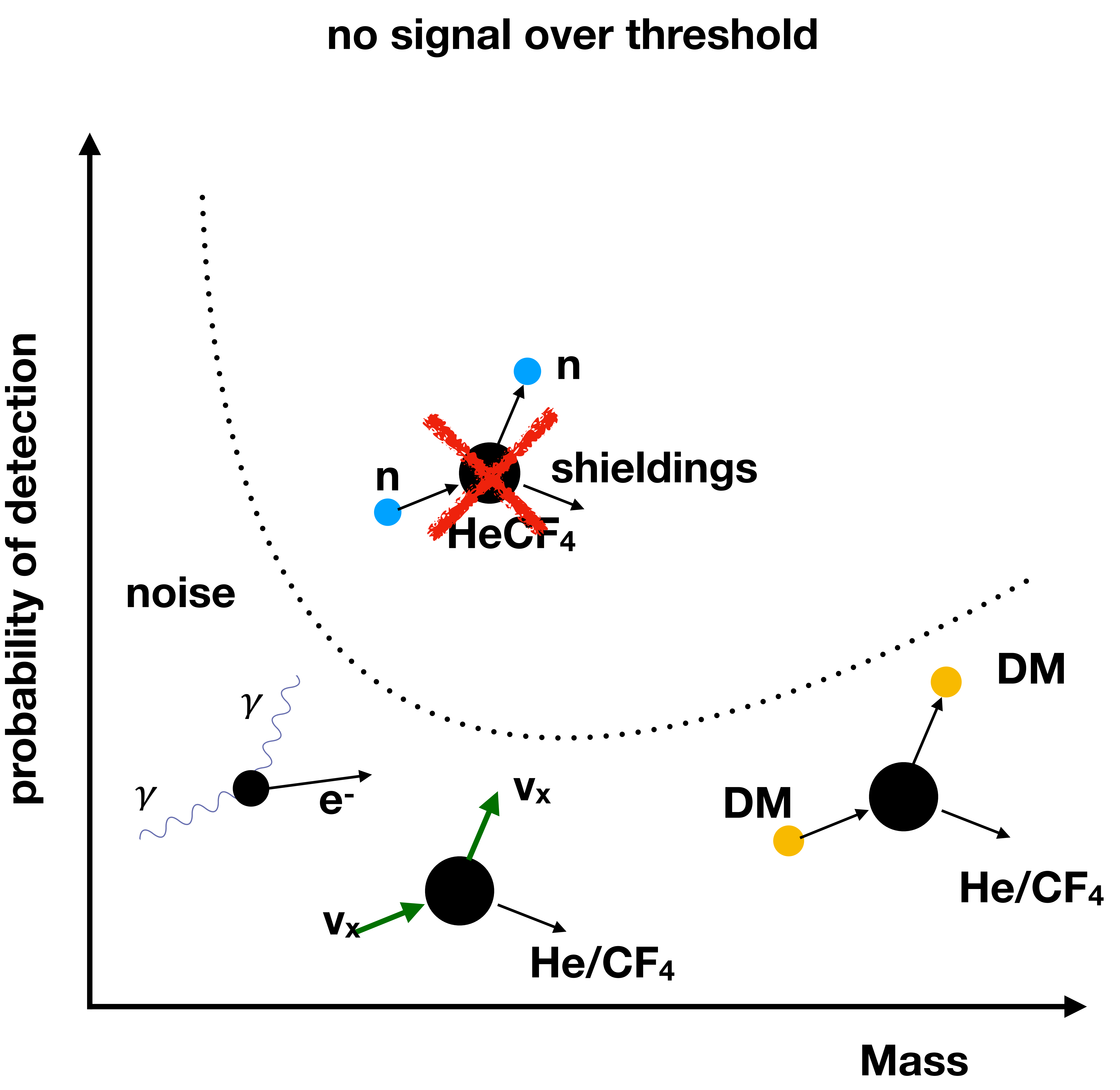
693 ph / 5900 eV
–> **0.12 ph/eV**.

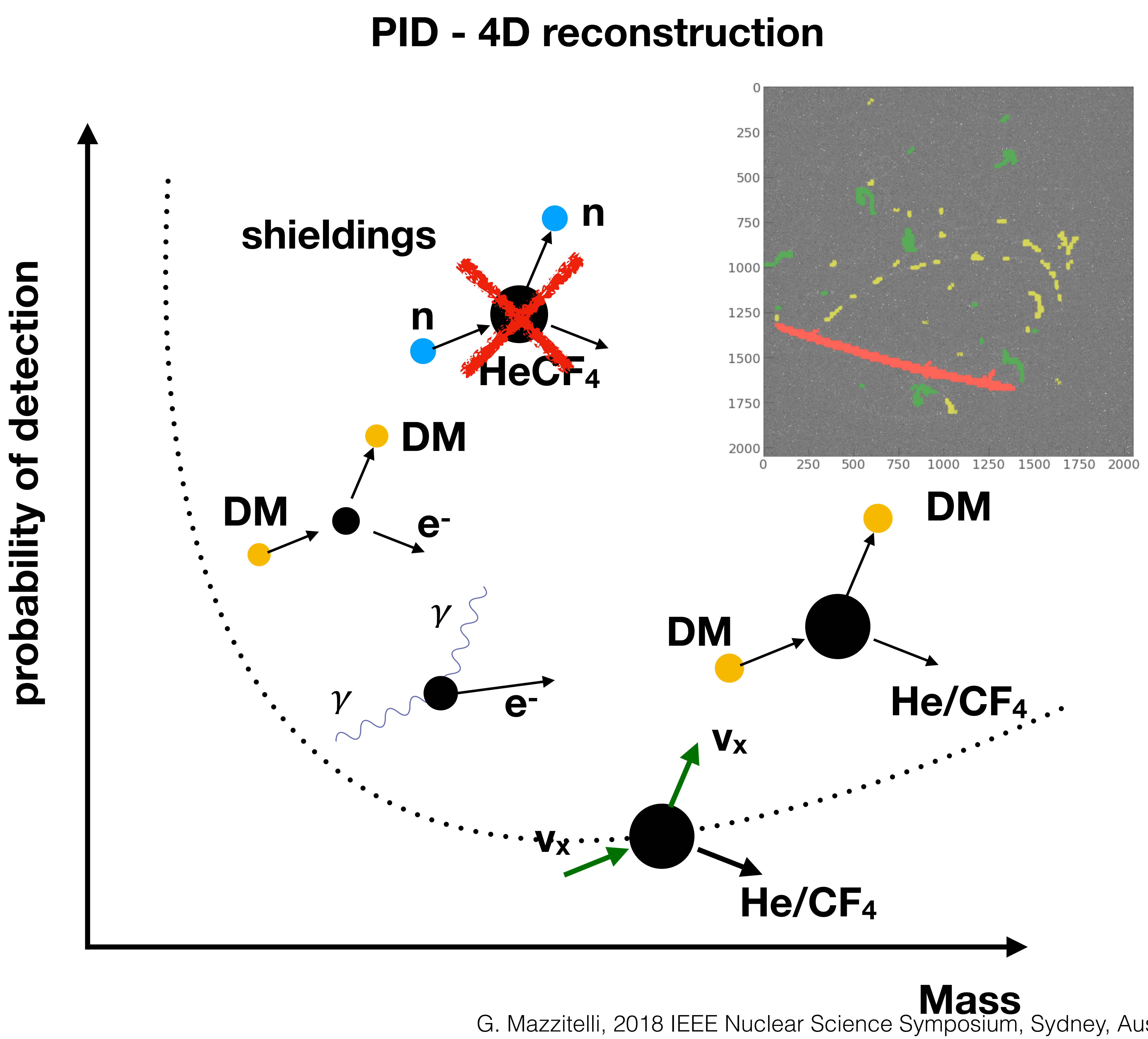
LEMON - 440 - 0.6kV



367 ph / 5900 eV
–> **0.06 ph/eV**.

Detection vs Identification





G. Mazzitelli, 2018 IEEE Nuclear Science Symposium, Sydney, Australia