A low radioactivity He:CF_4 TPC with optical readout for the CYGNO experiment

ICRM-LLRMT 2022, LNGS 2-6 May 2022

Andrea Messina - Sapienza Università di Roma & INFN Roma1
on behalf of:

F. D. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, A. Cortez, R. J. de Cruz Roque, I. A. Costa, E. Dané, E. Di Marco, G.Grilli di Cortona, G. D'Imperio, G. Dho, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, H. P. Lima Júnior, G. Maccarrone, R. D. P. Mano, M. Marafini, G. Mazzitelli, A. G. Mc Lean, A. Messina, M. L. Migliorini, C.M.B. Monteiro, R. A. Nóbrega, A. Orlandi, I. F. Pains, E. Paoletti, L. Passamonti, F. Petrucci, S. Pelosi, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, F. Rosatelli, A. Russo, J.M.F. dos Santos, G. Saviano, A. da Silva Lopes Júnior, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli

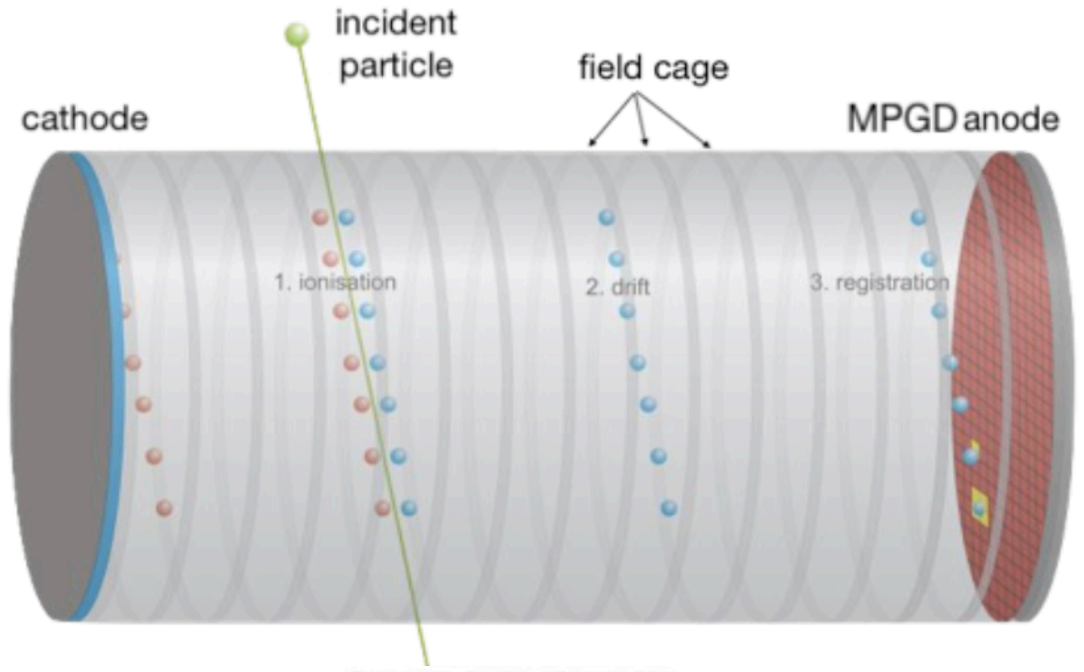
in synergy with erc INITIUM
funded from ERC in Horizon 2020 program (grant agreement 818744)

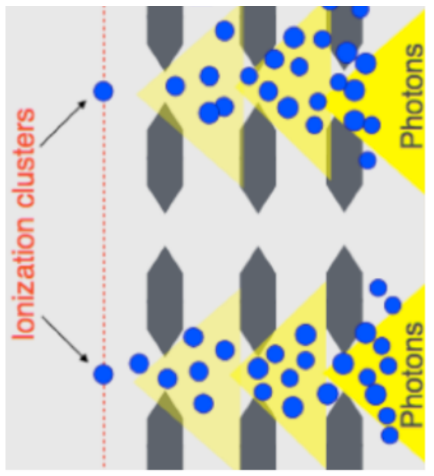
The CYGNO project:

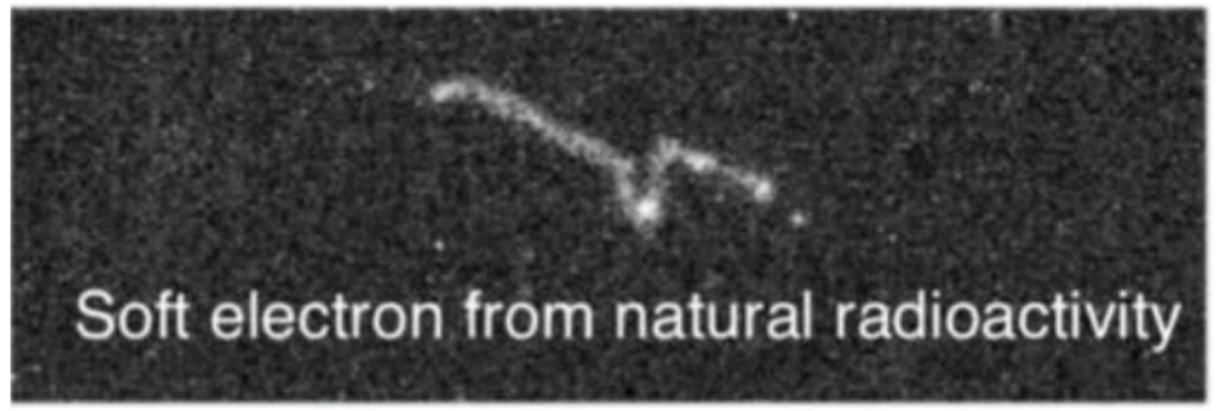
- **Aiming at** a large detector for high precision 3D tracking of rare low energy nuclear recoils (keV)

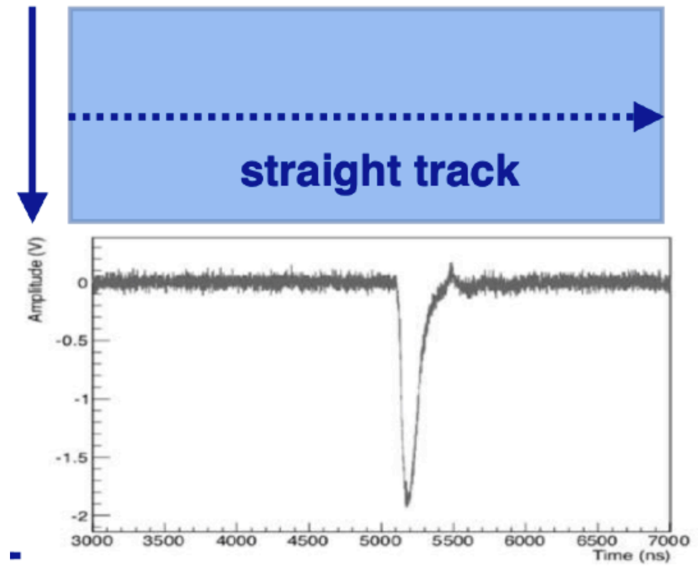
- **Experimental challenges**: rate O(evt/kg/y), background rejection, and energy threshold (keV)

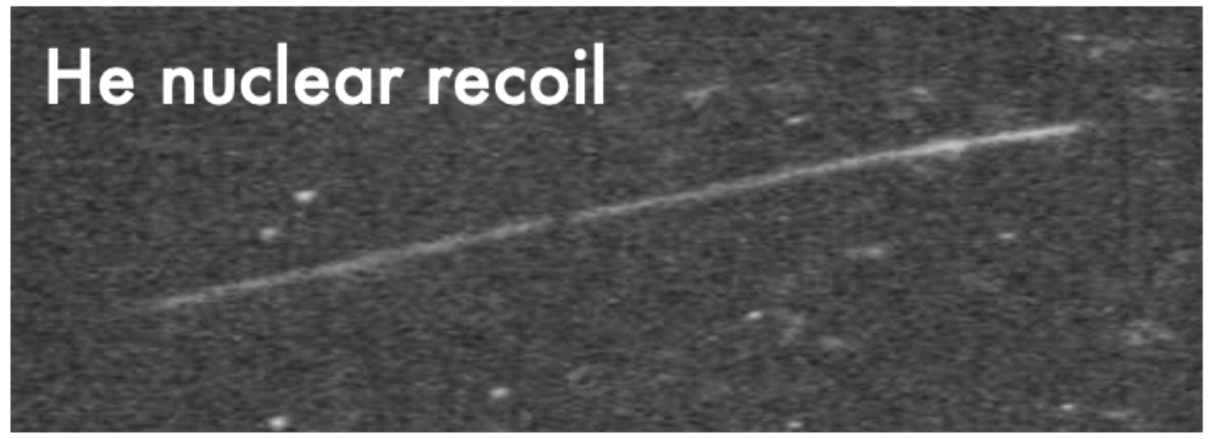
- **Strategy:** photograph nuclear recoil in a He:CF_4 (1 atm) TPC with a GEM amplification stage
  - 3D tracking: position, direction, and fiducialization, total released energy, dE/dx (head/tail)
  - **optical sensors**: high granularity, very low noise, and high sensitivity
  - **optical coupling**: sensors outside the sensitive volume, acquire large surfaces with small sensors

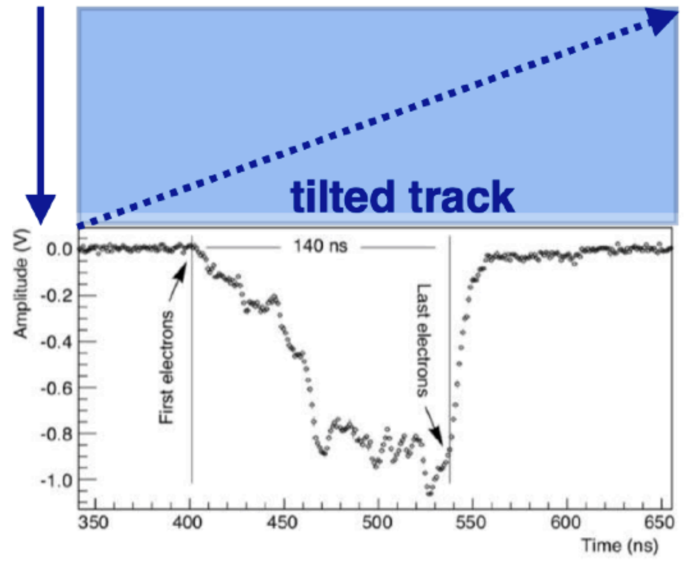








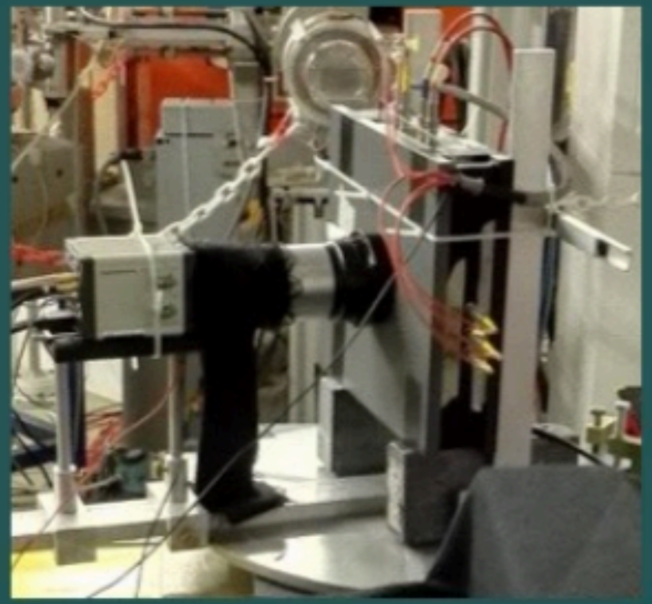
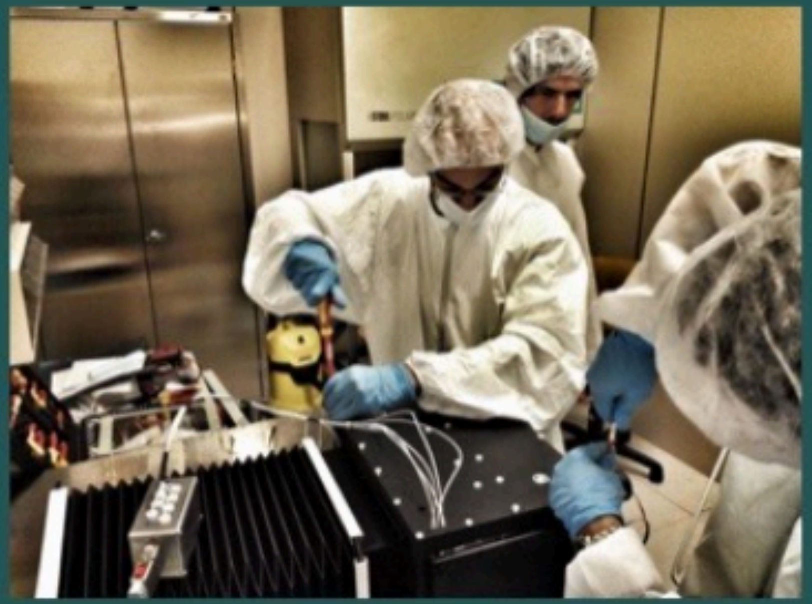




CYGNO timeline

PHASE 0: R&D and prototypes

2015/16 ROMA1	2017/18 LNF	2019/21 LNF/LNGS
ORANGE	LEMON	LIME


- 1 cm drift

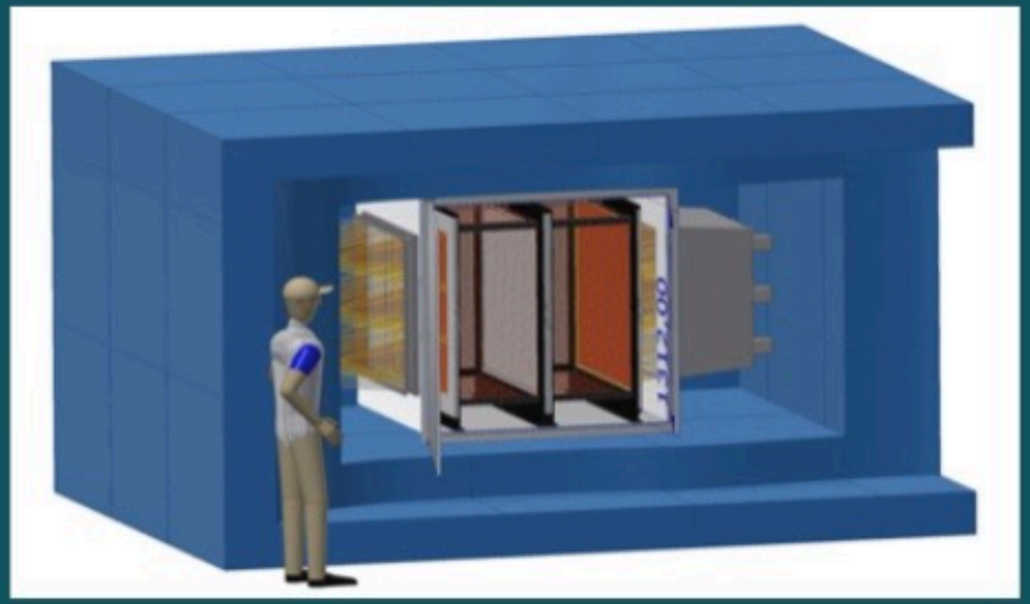
- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding

PHASE 1: 1 m³ Demonstrator

2022/25 LNF/LNGS

CYGNO_01

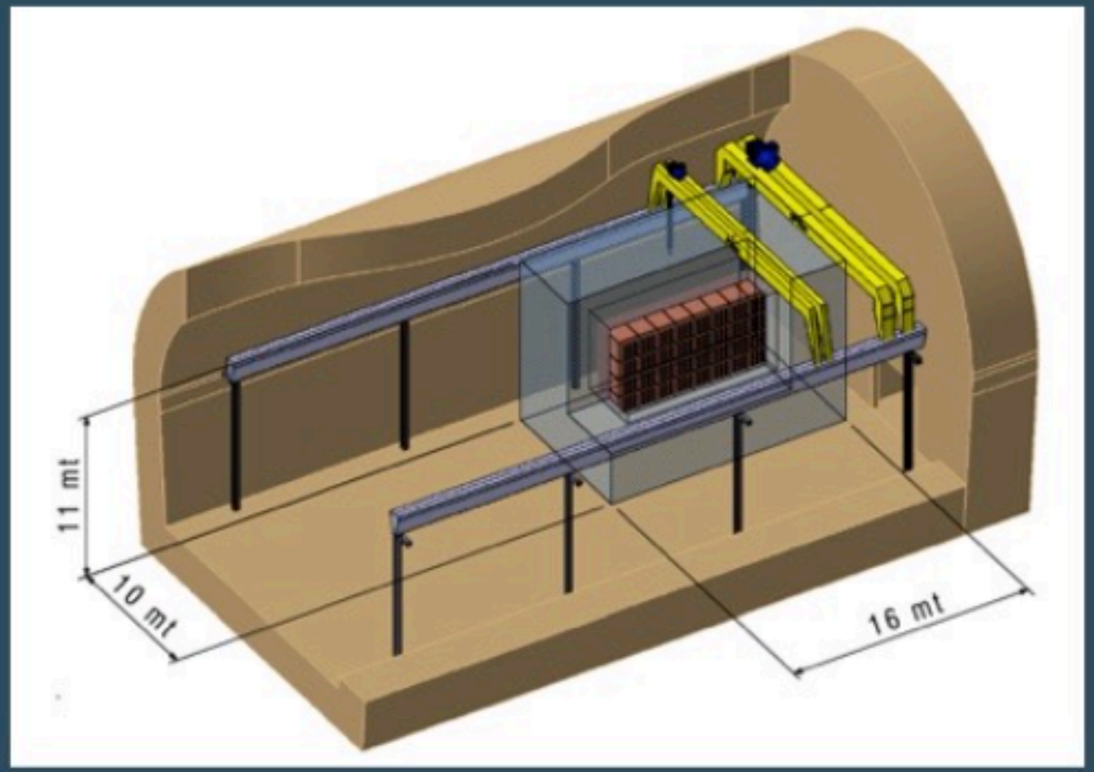


- background
- materials test, gas purification
- scalability

PHASE 2: 30 m³ Experiment

2026.. LNGS

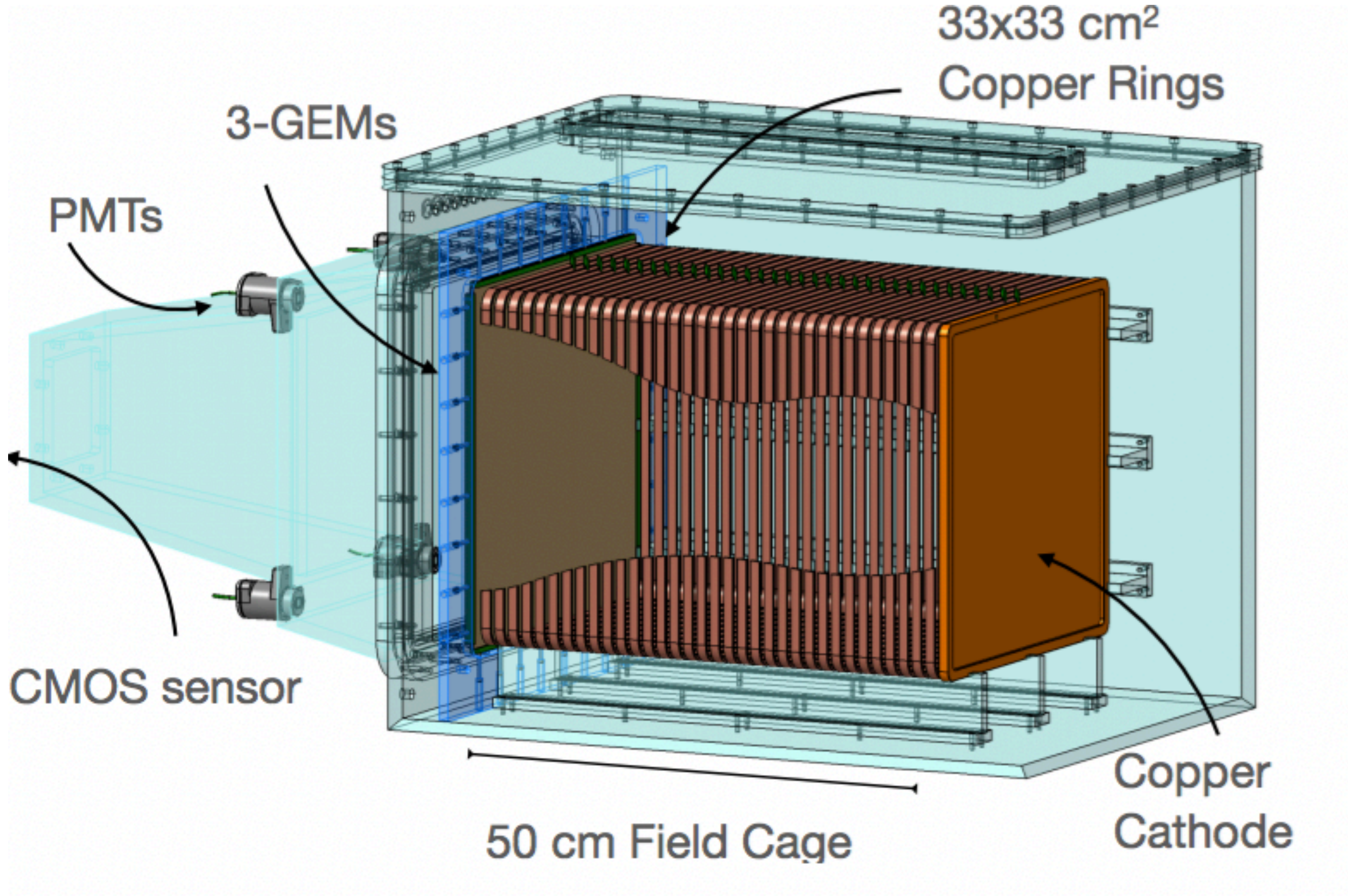
CYGNO_30

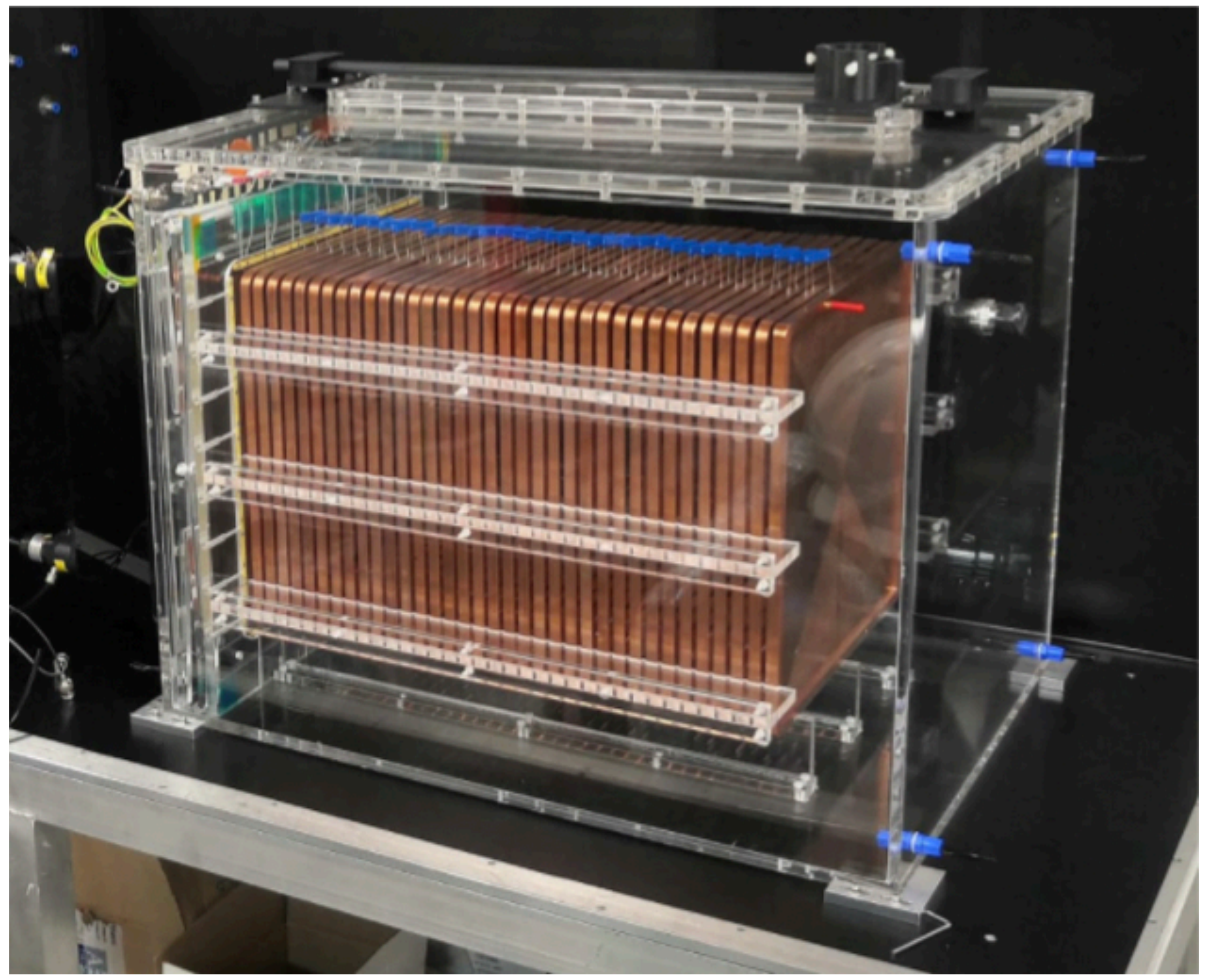


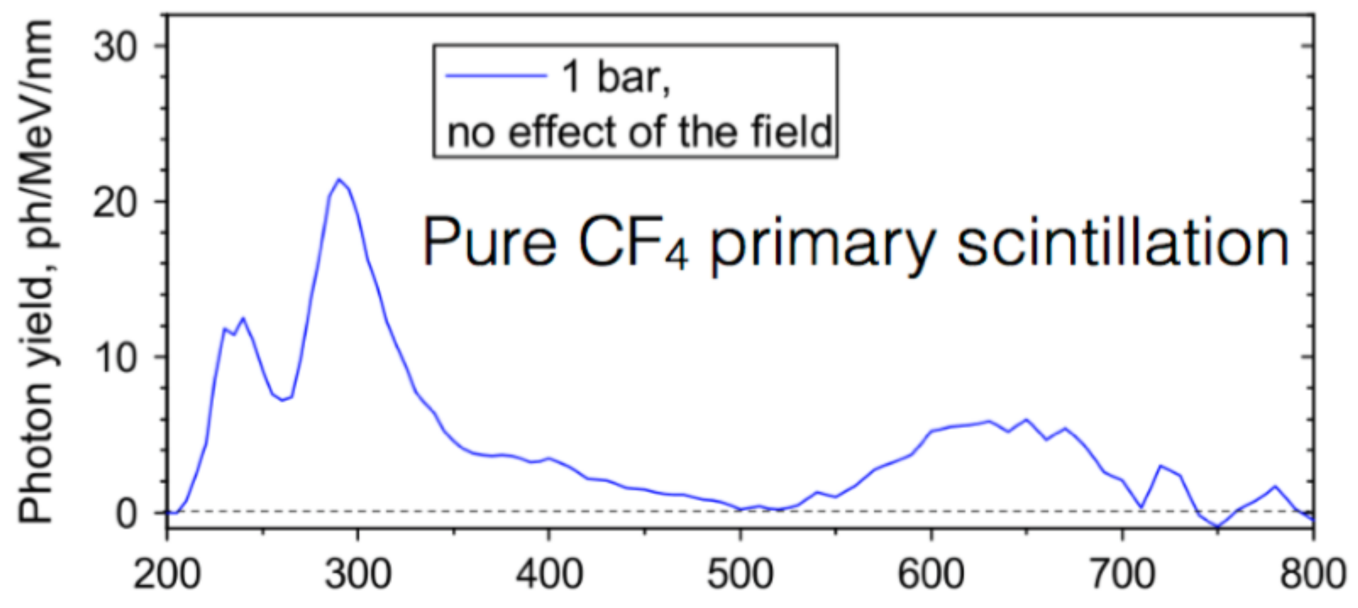
- Physics research

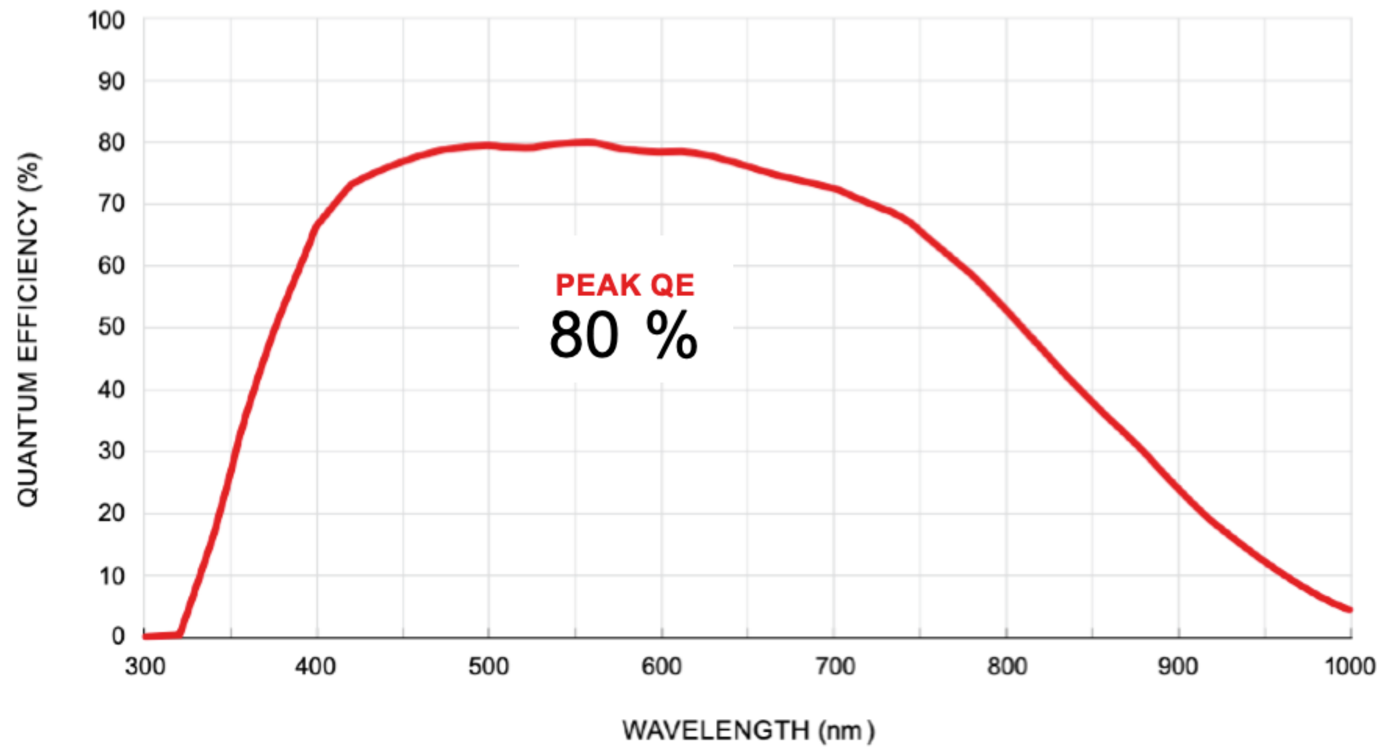
Instruments 6 (2022) 1, 6   JINST 15 (2020) P10001   JINST 15 (2020) 12, T12003
2019 JINST 14 P07011   JINST 15 (2020) P08018
NIM A 999 (2021) 165209   Measur.Sci.Tech. 32 (2021) 2, 025902

CYGNO PHASE 0: Lime prototype

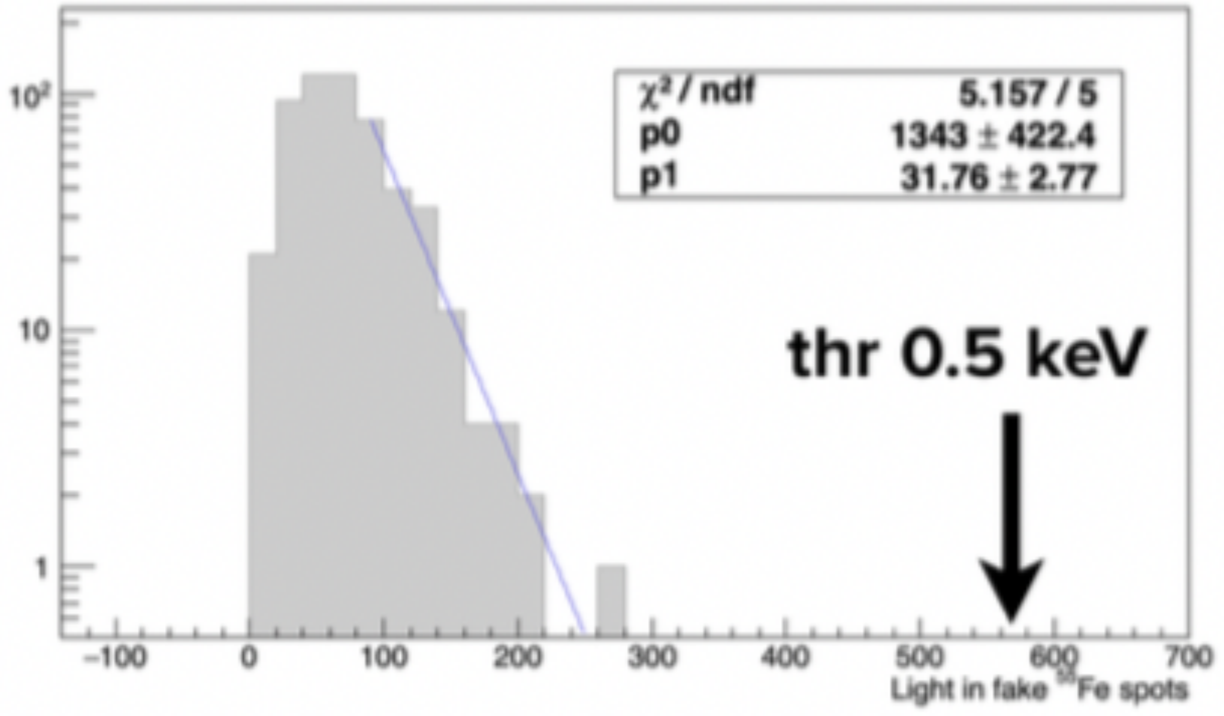








- He:CF_4 (1 atm)
- copper ring field cage, 50 cm drift
- 1 sCMOS sensor + 4 PMT
- 3 GEMs for a 33 x 33 cm^2 sensitive area
- acrylic vessel, aluminium faraday cage



1 keV = 1200 photons

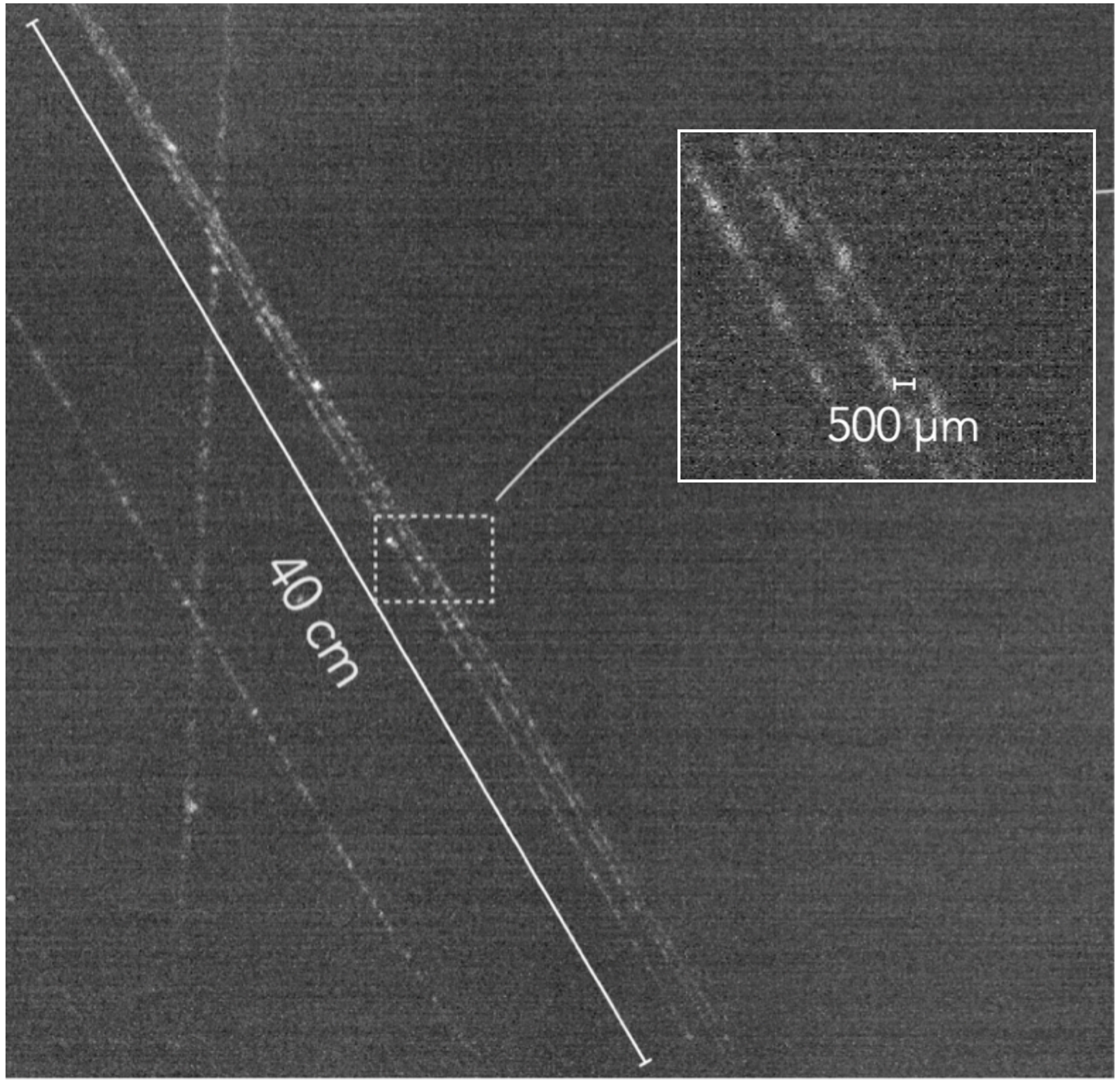
ORCA-Fusion

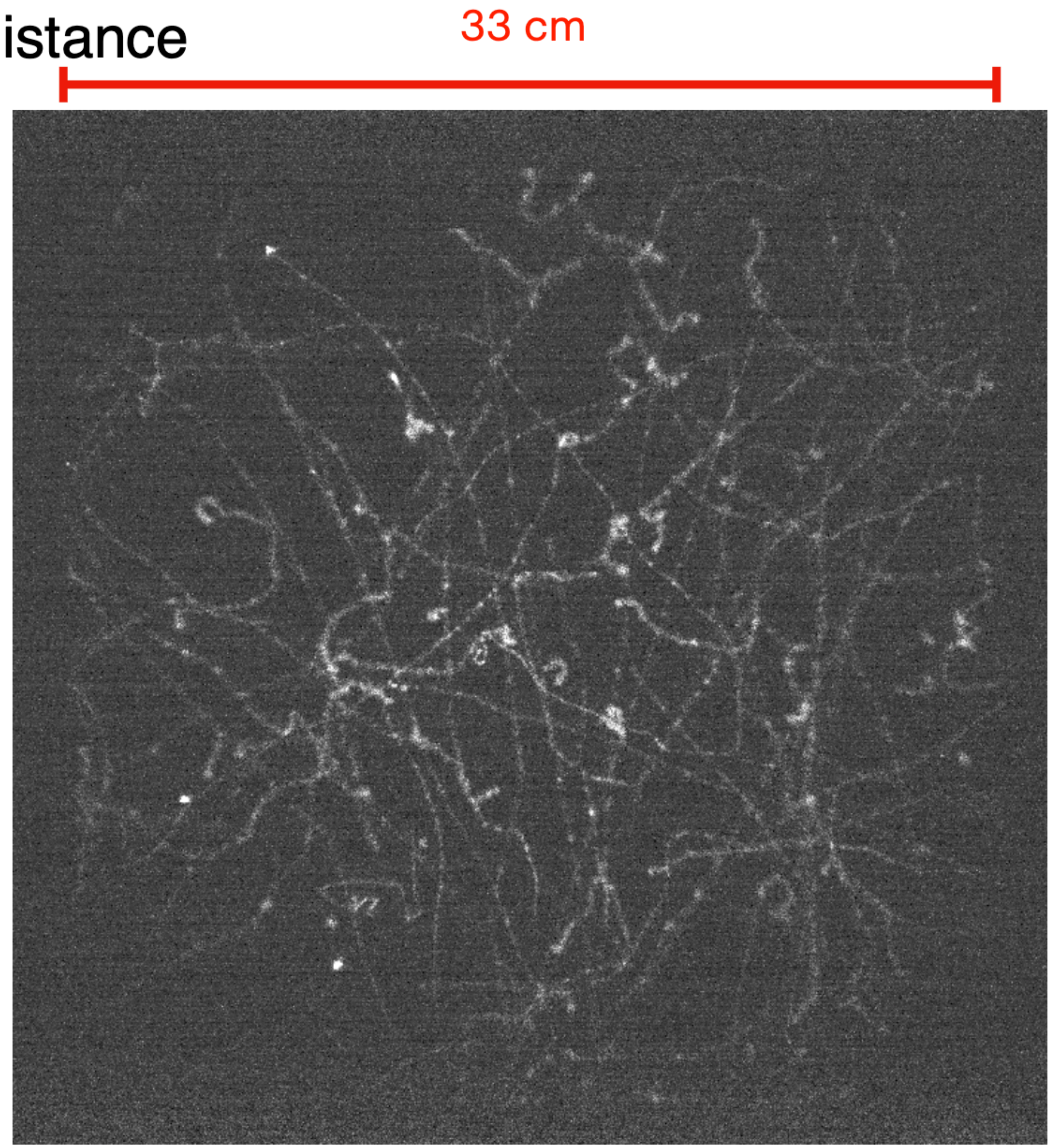
HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan

Overground images

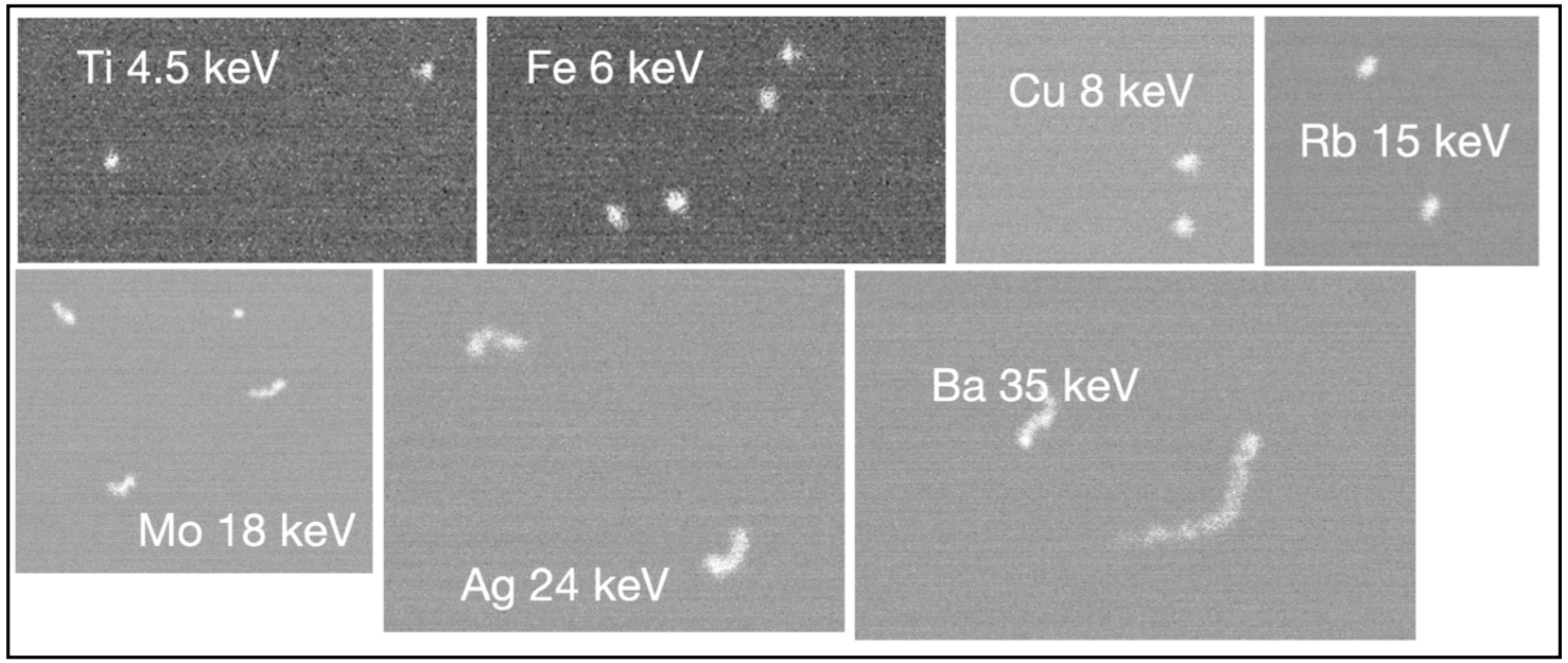
- 2D projection of over the 50 cm drift distance

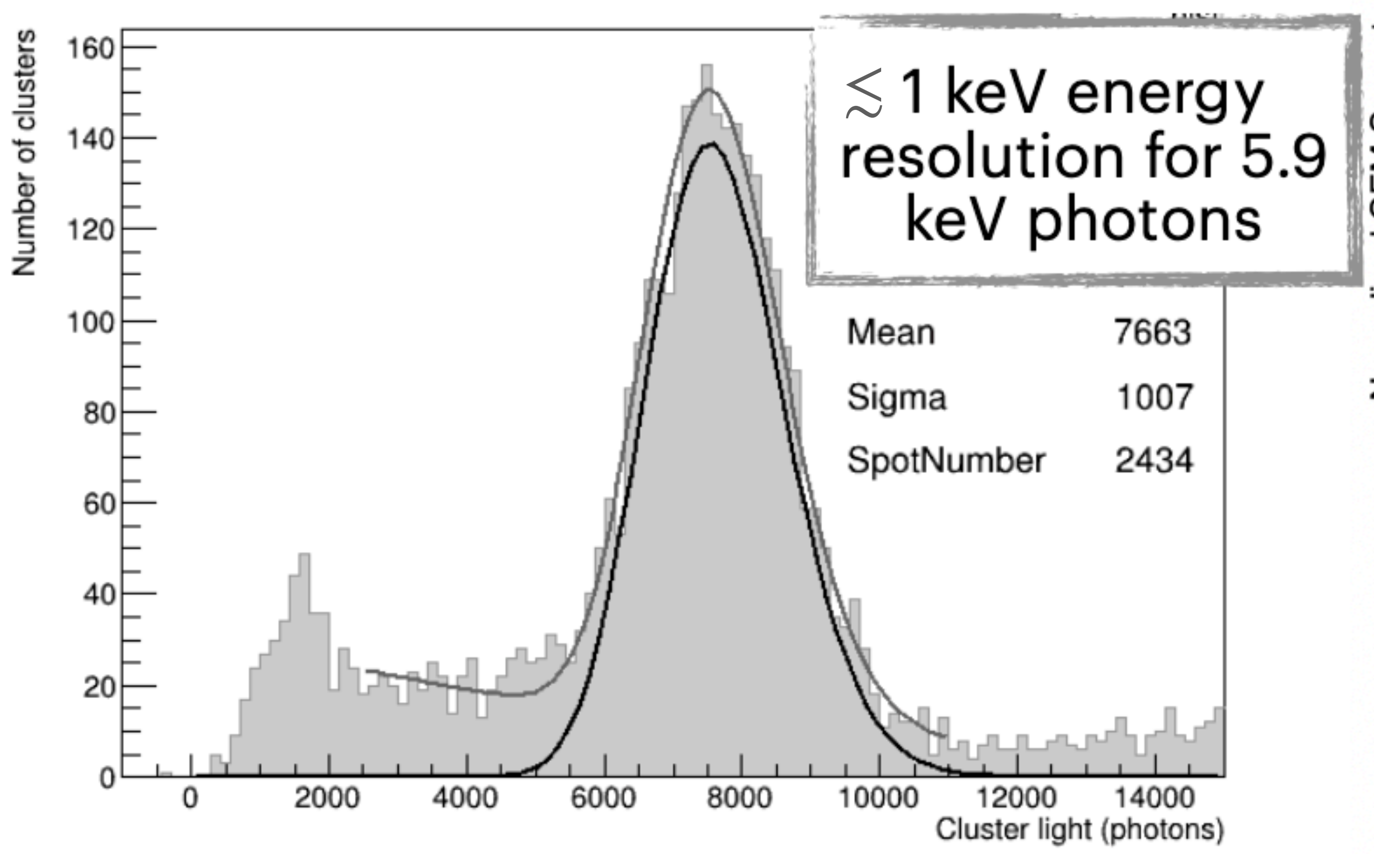


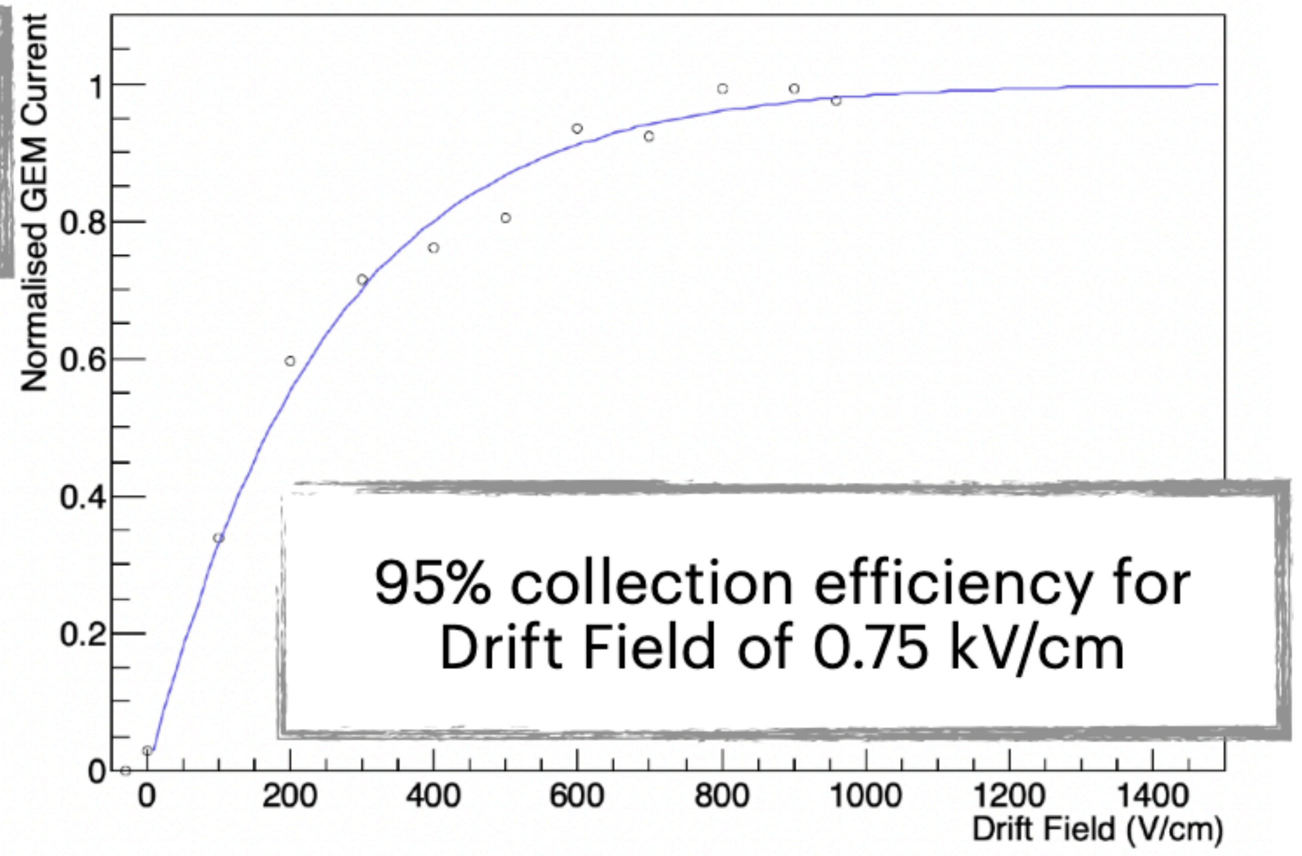


- Cosmic ray and radioactivity clearly visible (no shielding)

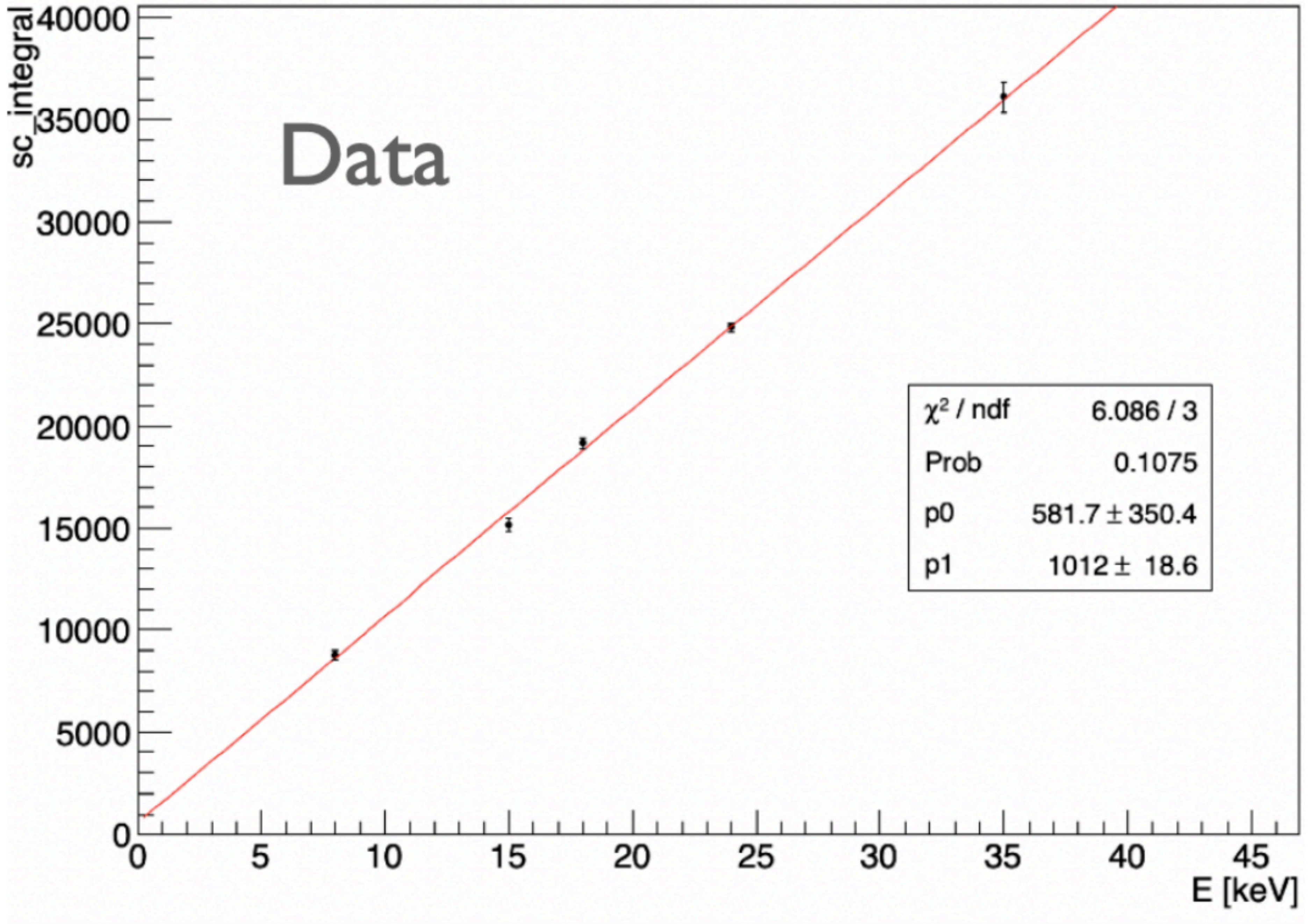
Energy response







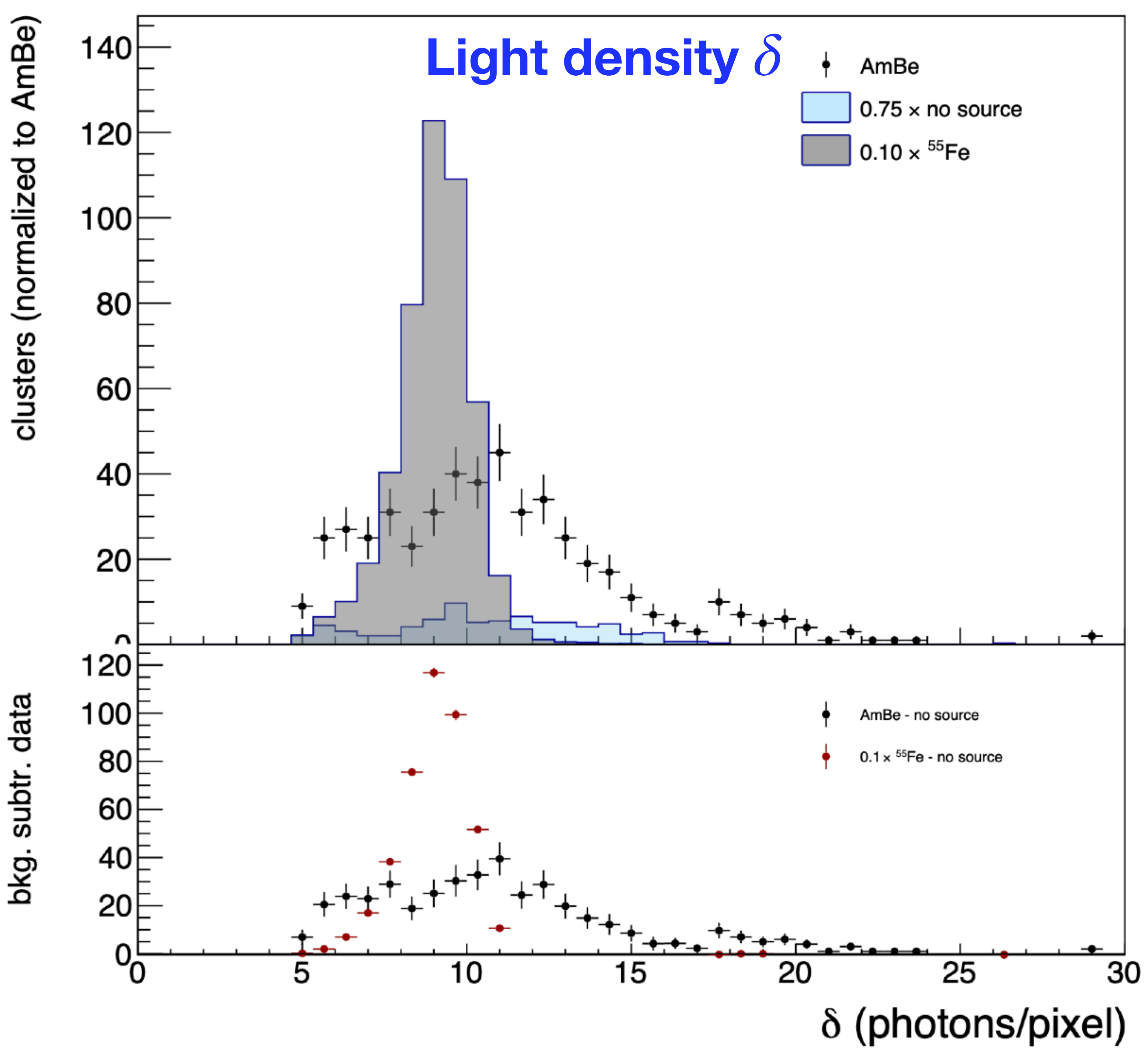
while below 10 keV signals are spot-like, electrons with larger energies travel in gas.

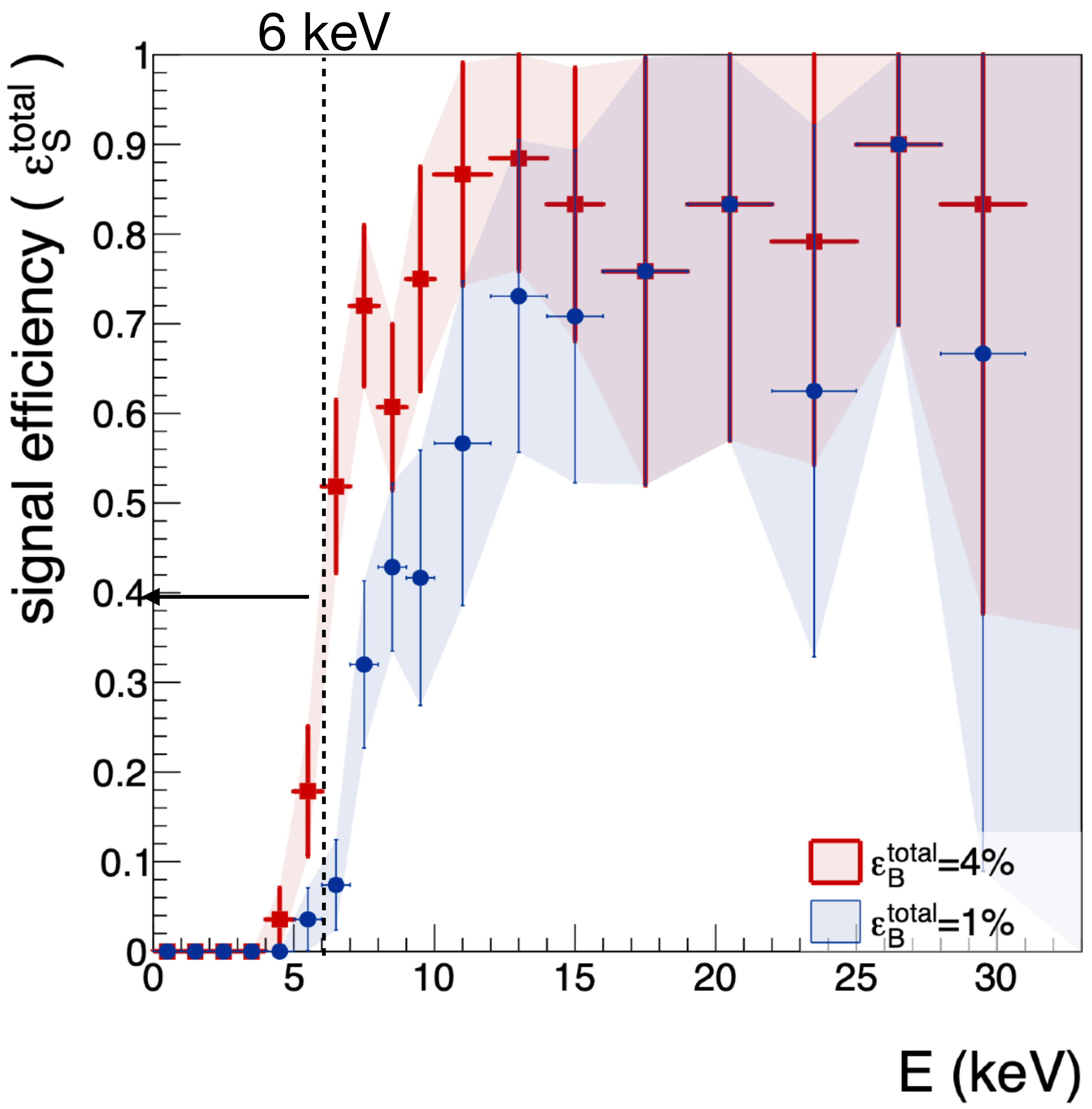


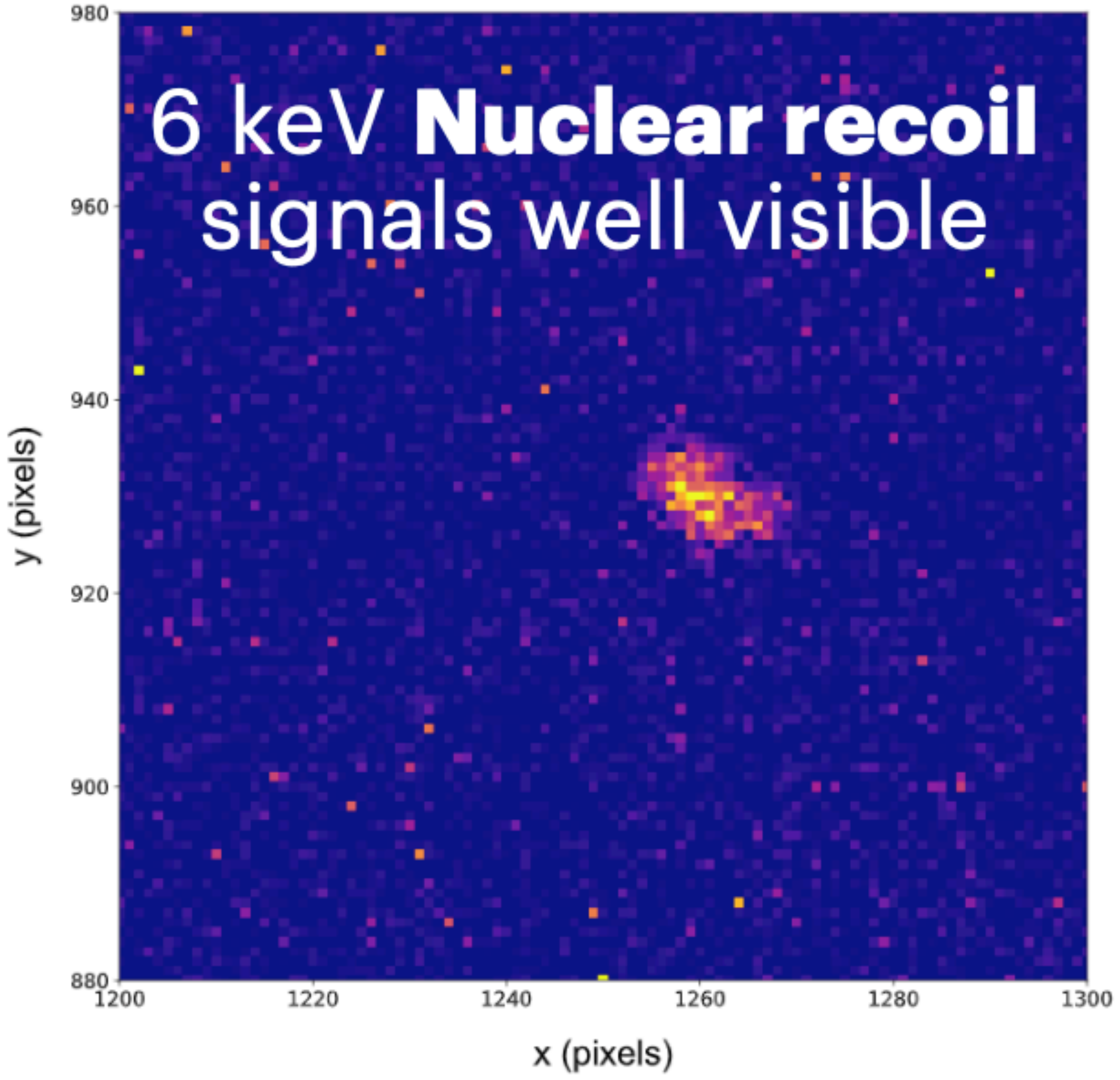
good linearity **response in the energy** range 4.5 keV - 45 keV

Energy resolution of 15% at 5.9 keVee with sCMOS and PMT

Response to low energy nuclear recoils



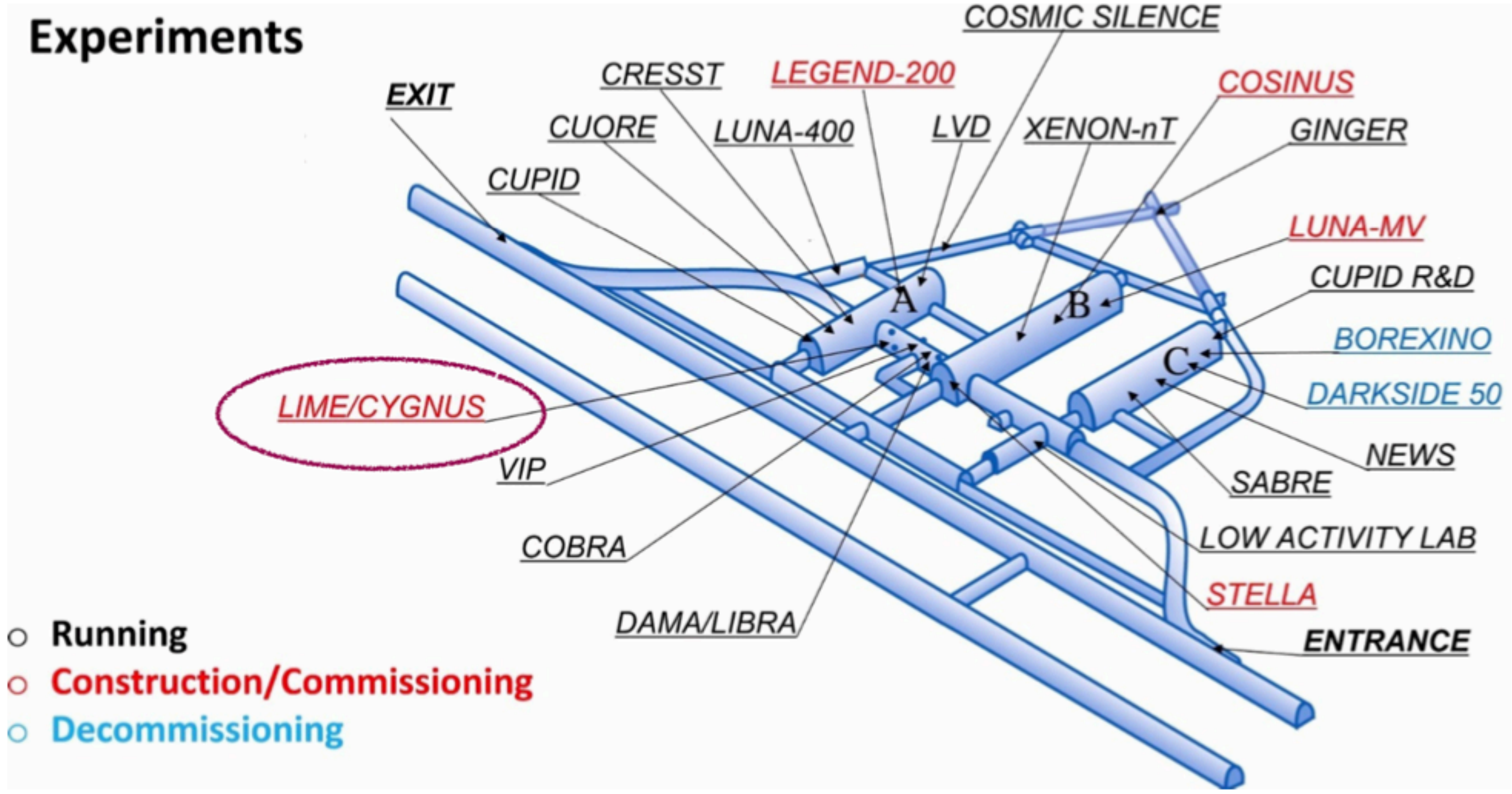




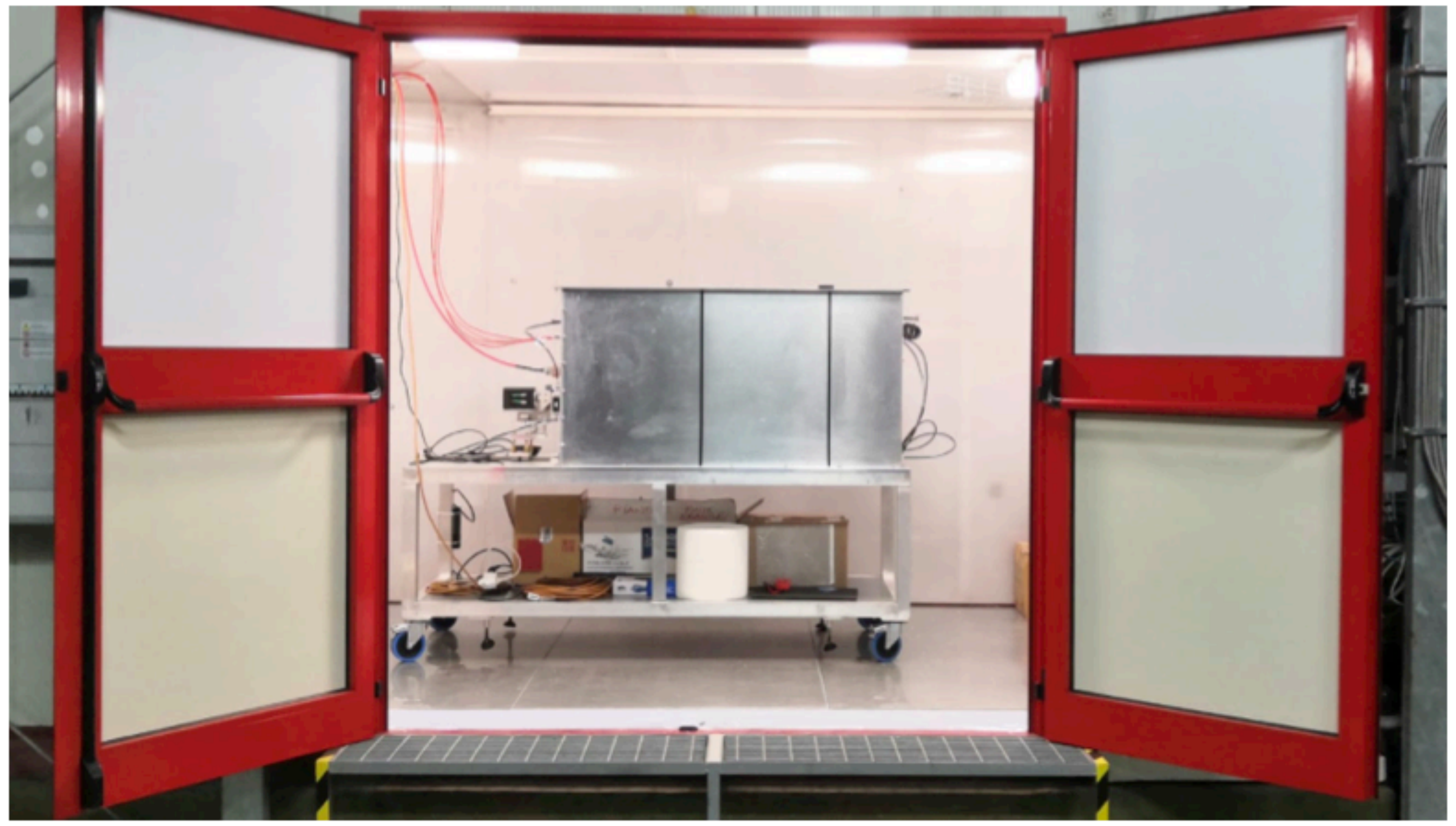
40% nuclear recoil efficiency at 6 keV_{ee} with 96% rejection against ^{55}Fe

CYGNO PHASE 0: LIME underground installation

HV, VME and NIM crate

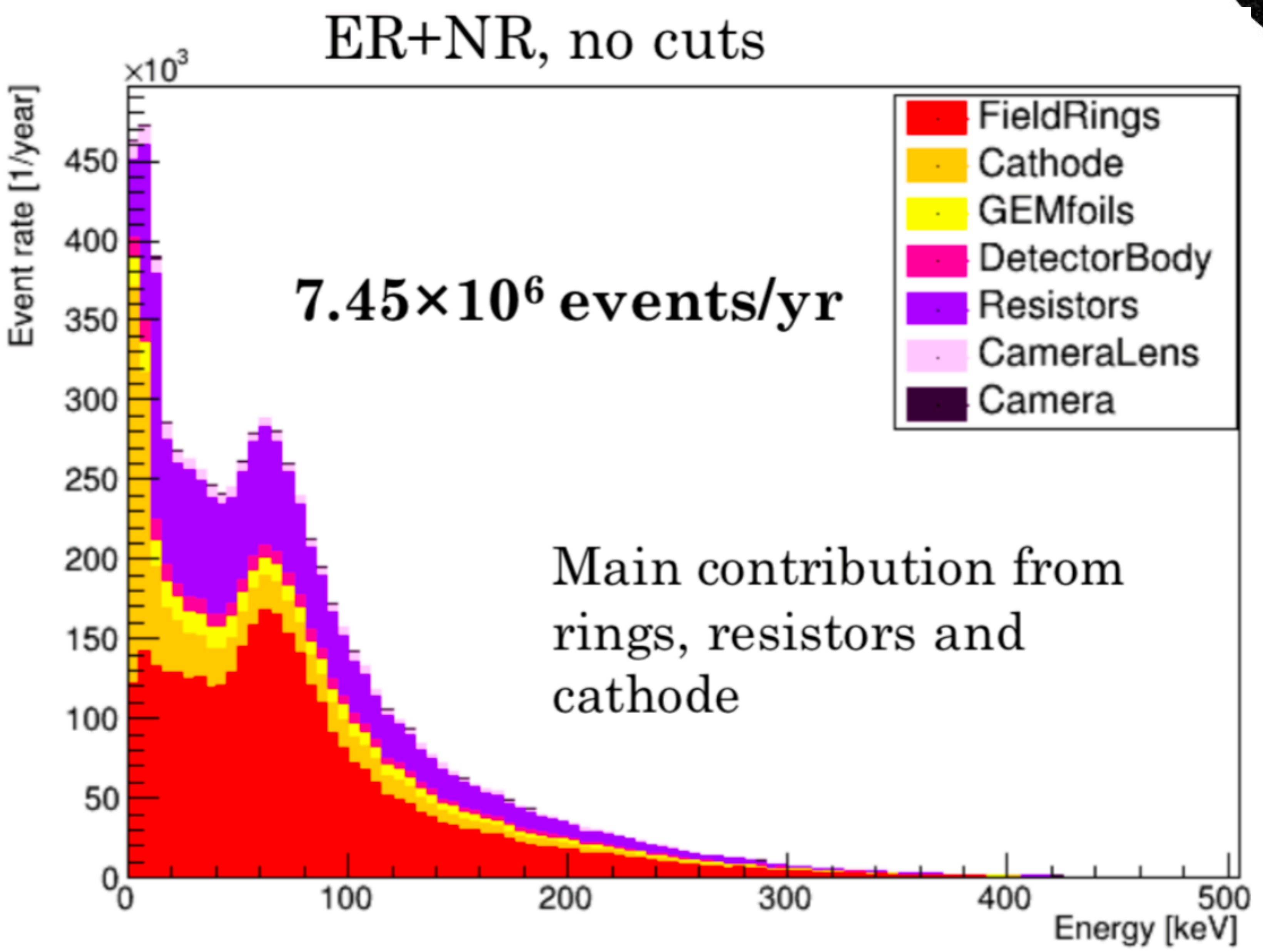


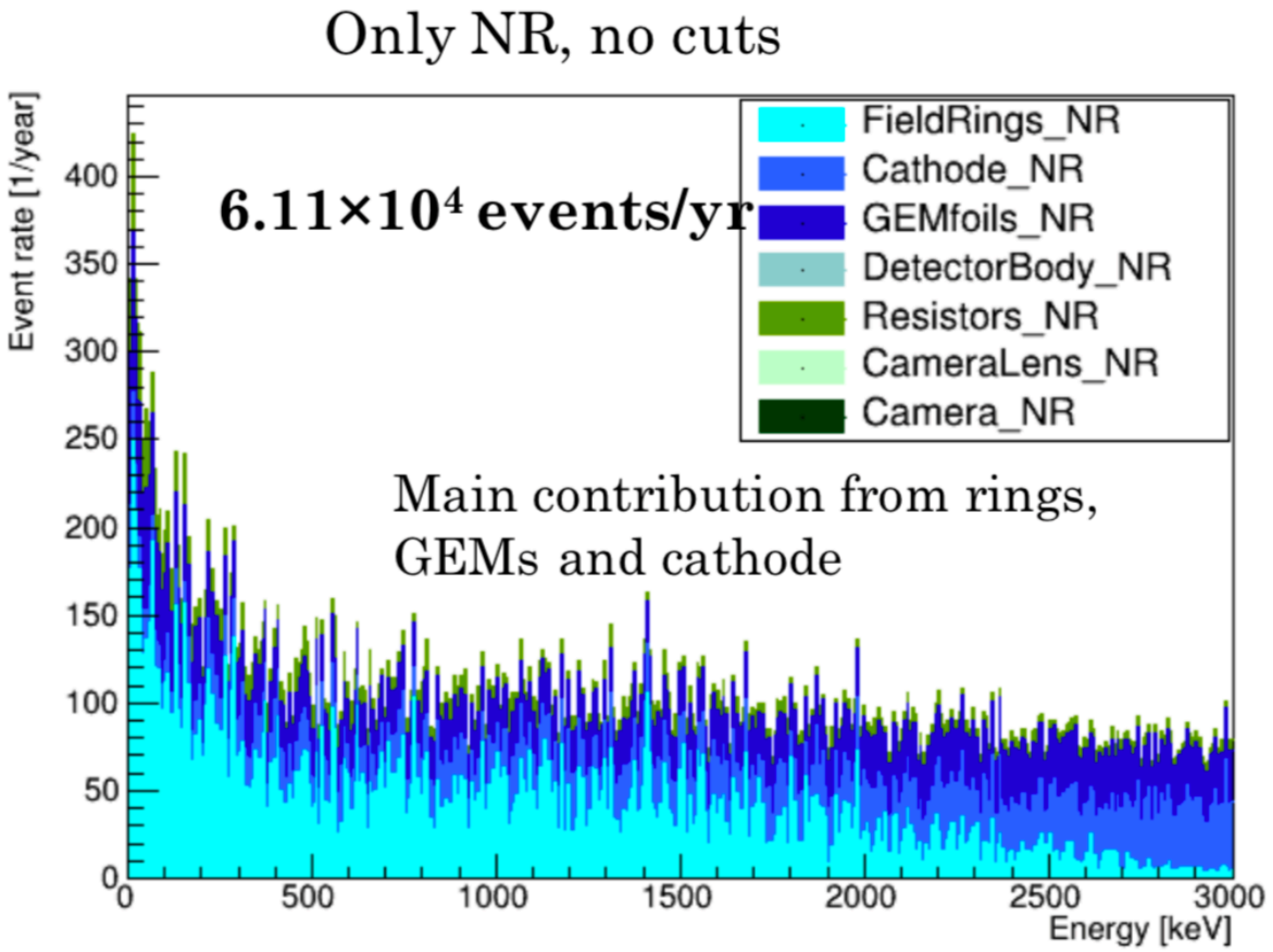
DAQ, services PC and temporary network



Internal background simulation

- Natural radioactivity from decay chains of ^{232}Th, ^{238}U, ^{235}U, …
- Activity of all the main components of LIME was measured underground by M. Laubenstain @ LNGS
- Main contribution from rings, resistors and cathode
- Internal bkg can be reduced by 96% (99%) for ER (NR) with fiducial cuts



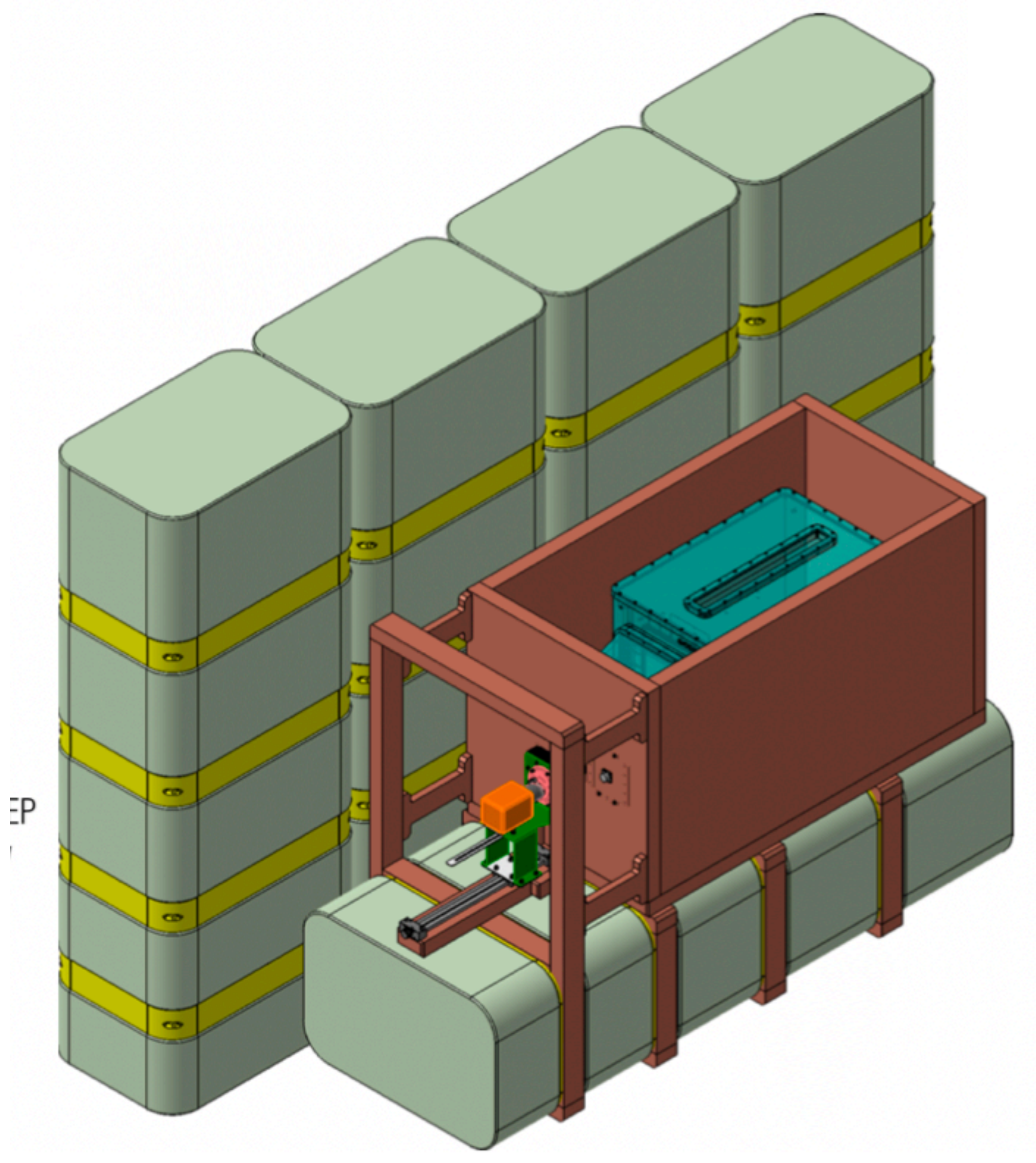


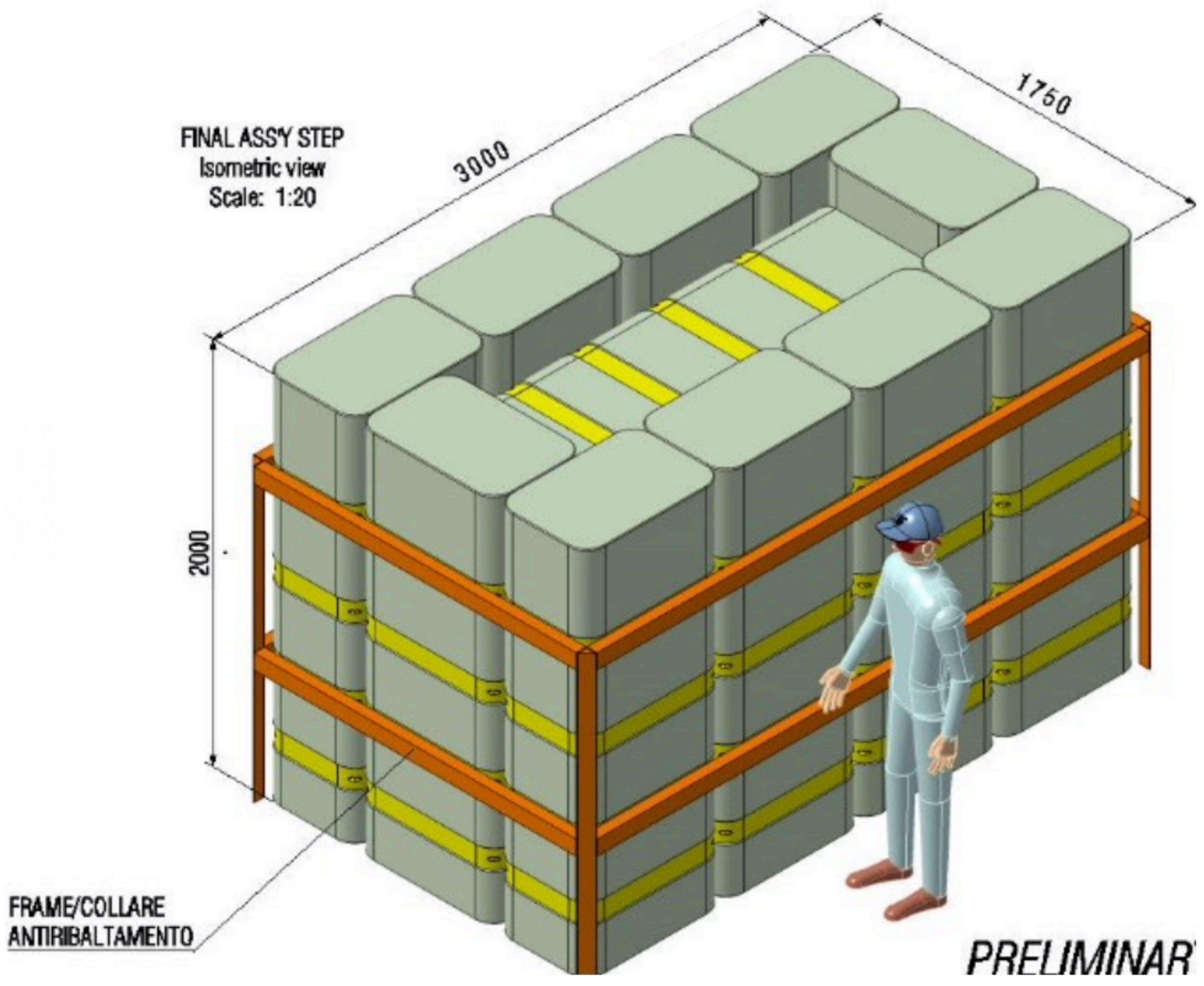
Component	^{238}U (^{234m}Pa)	^{238}U (^{226}Ra)	^{235}U	^{232}Th (^{228}Ra)	^{232}Th (^{228}Th)	^{40}K
Camera body [Bq/pc]	7	1.8	0.4	2.1	2.1	1.9
Camera lens [Bq/pc]	0.9	0.41	0.031	0.08	0.08	11
GEM foil [Bq/m^2]	<0.104	0.004	<0.002	<0.004	<0.002	<0.045
Acrylic [Bq/kg]		0.003		0.005	0.004	0.035

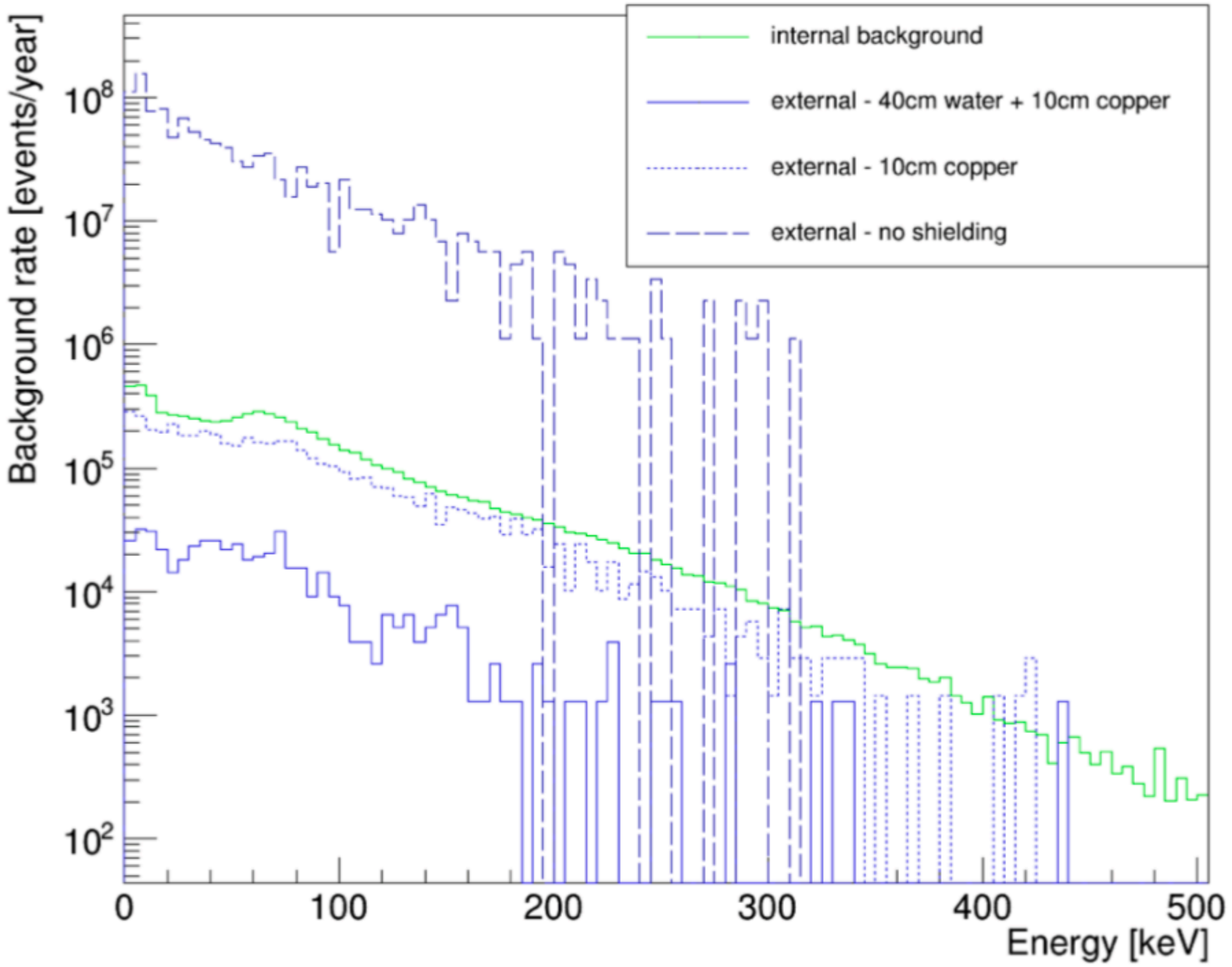
CYGNO PHASE 0: underground campaign

- Shielding: 10 cm of copper and 40 cm of water
- Validation of Monte Carlo simulation and shielding
- Measure neutron flux in the 1-100 keV range (expect 200 NR from neutron in 4 months)

Shielding	Internal [ev/yr] (1-20 keV)	External* [ev/yr] (1-20 keV)
No shield	$1.5344(7)\times10^{6}$	$4.061(8)\times10^{8}$
5cm copper	$1.5344(7)\times10^{6}$	$1.90(2)\times10^{7}$
10cm copper	$1.5344(7)\times10^{6}$	$1.024(2)\times10^{6}$
40cm water + 10cm copper	$1.5344(7)\times10^{6}$	$2.46(1)\times10^{5}$

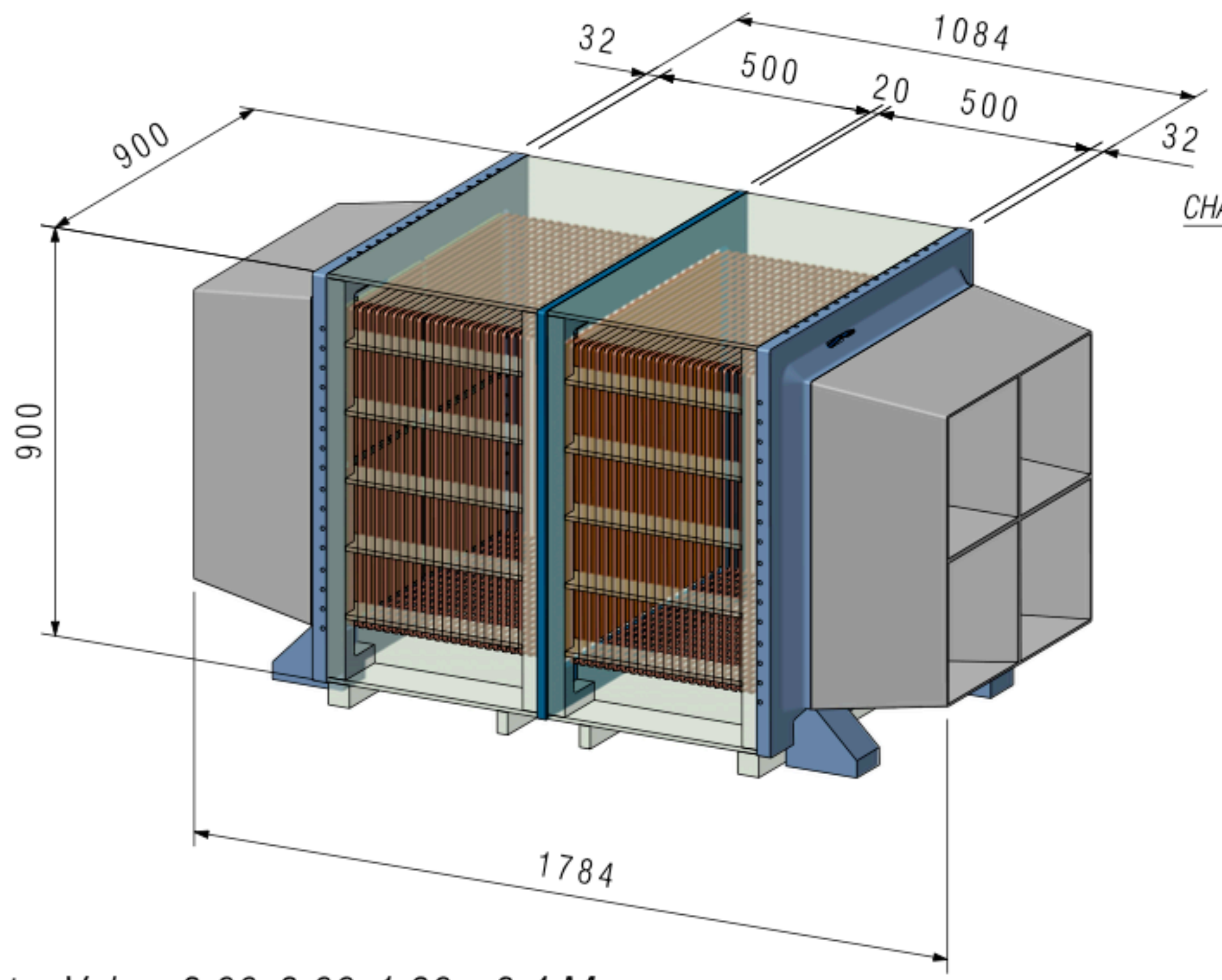




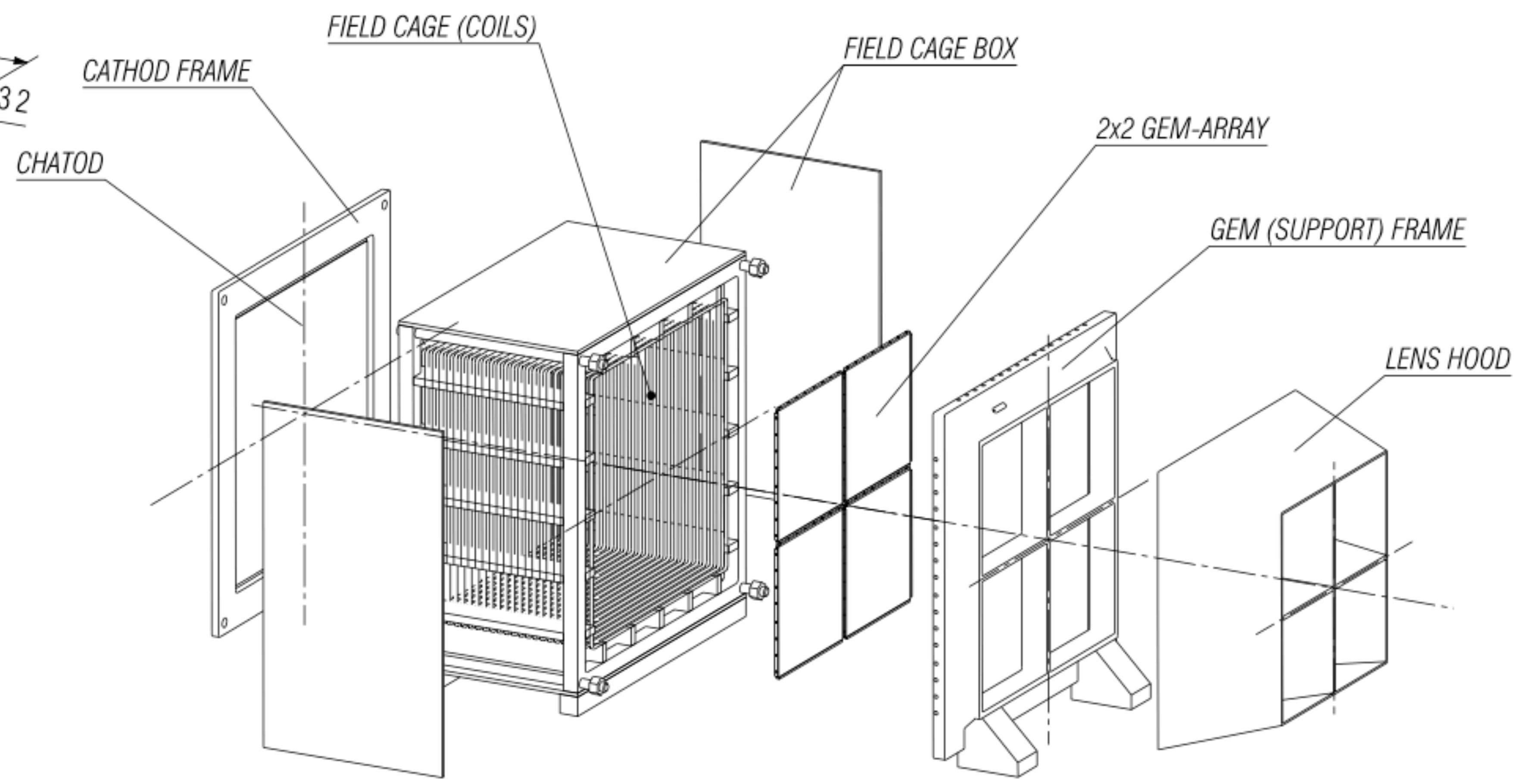


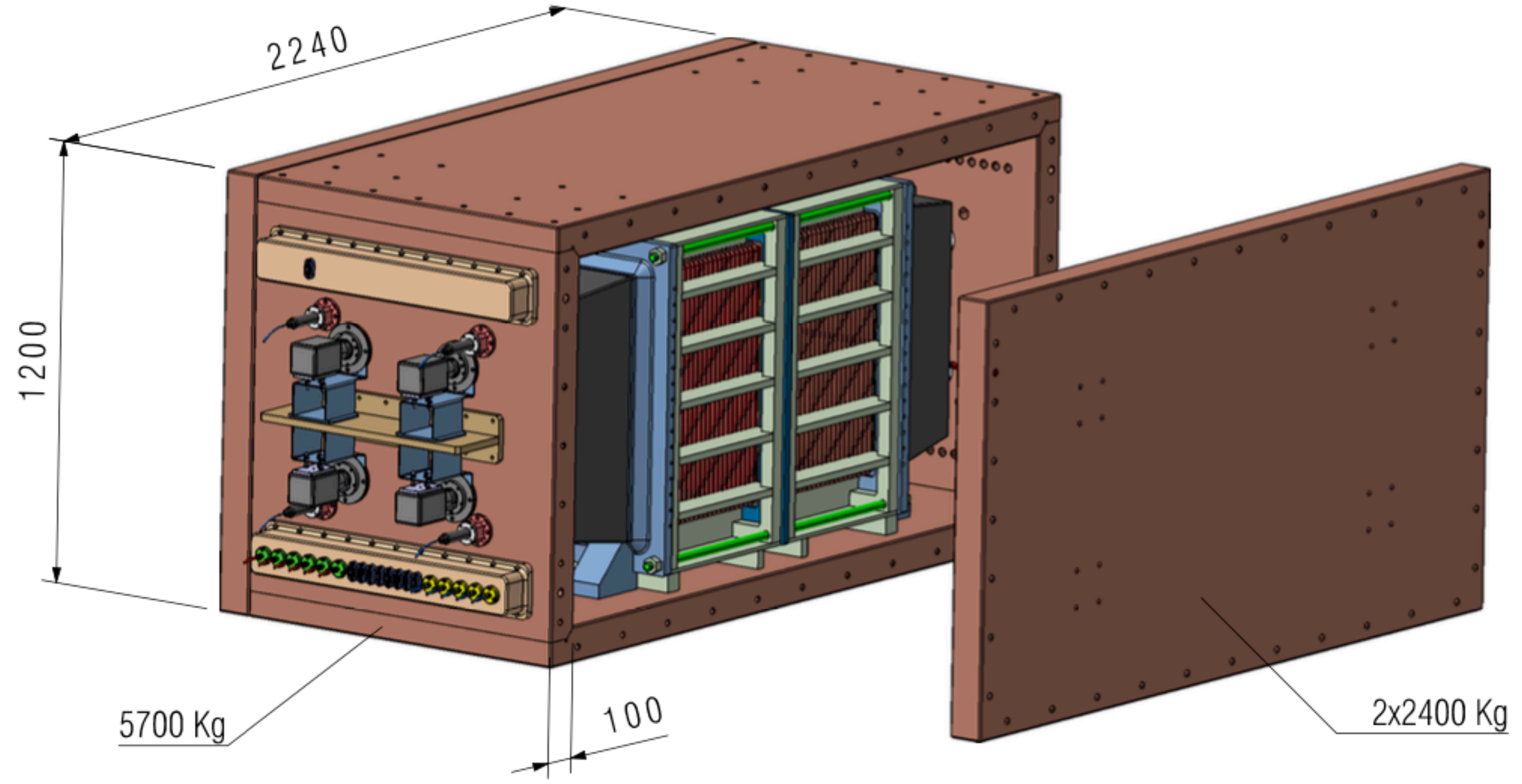
PHASE 1: CYGNO_04 preliminary design

- 2 field cages with a common cathode closed by 2 matrices of 2x2 GEMs.
- Each GEM is readout by a module identical to LIME.
- low radioactivity PMMA vessel.
- Enclosed by 10 cm Cu + 110 cm water.



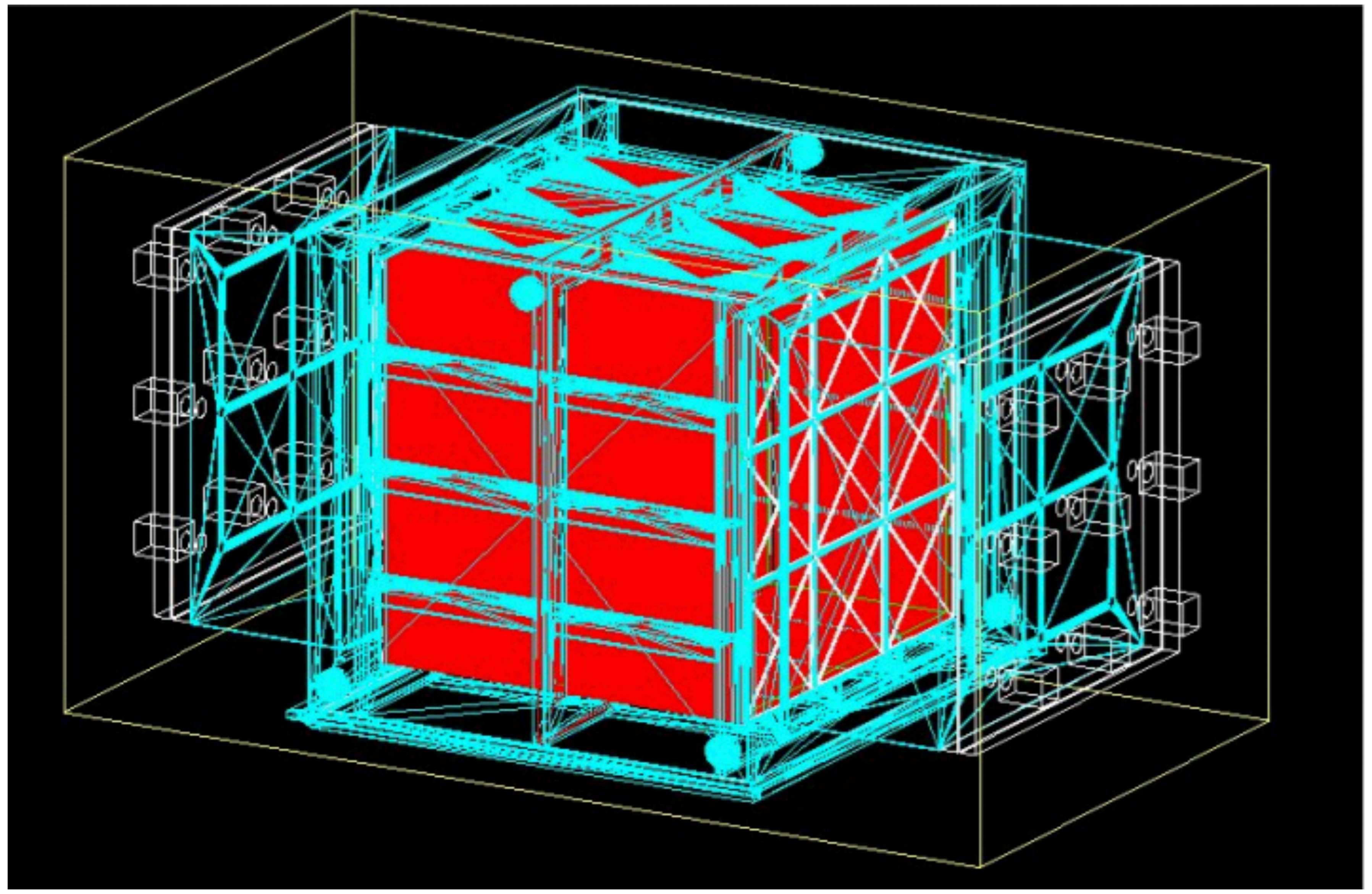
Detector Vol = 0.66x0.66x1.03=0.4 Mc



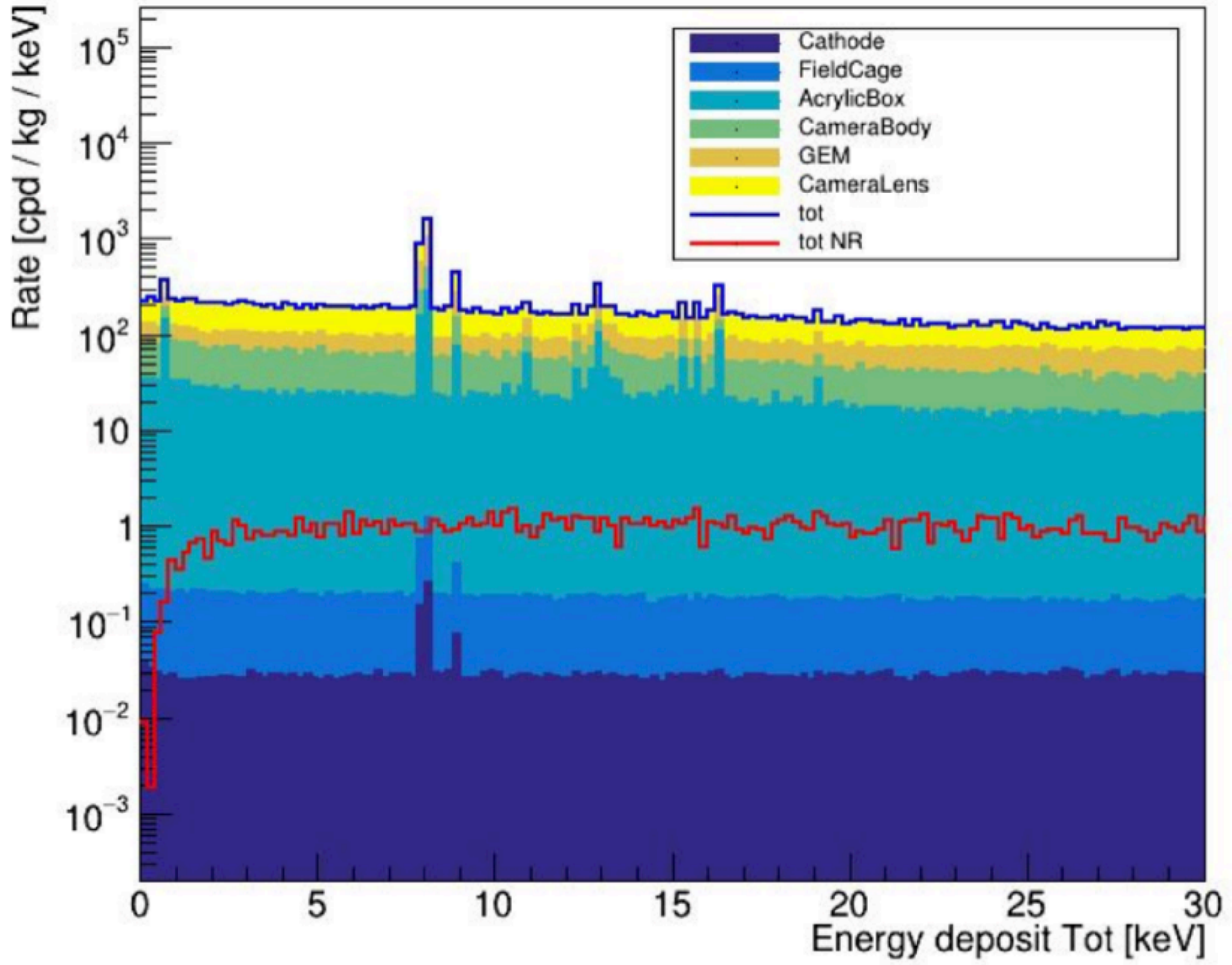


Designed at LNF and to be installed at LNGS

PHASE 1: CYGNO_04 backgrounds

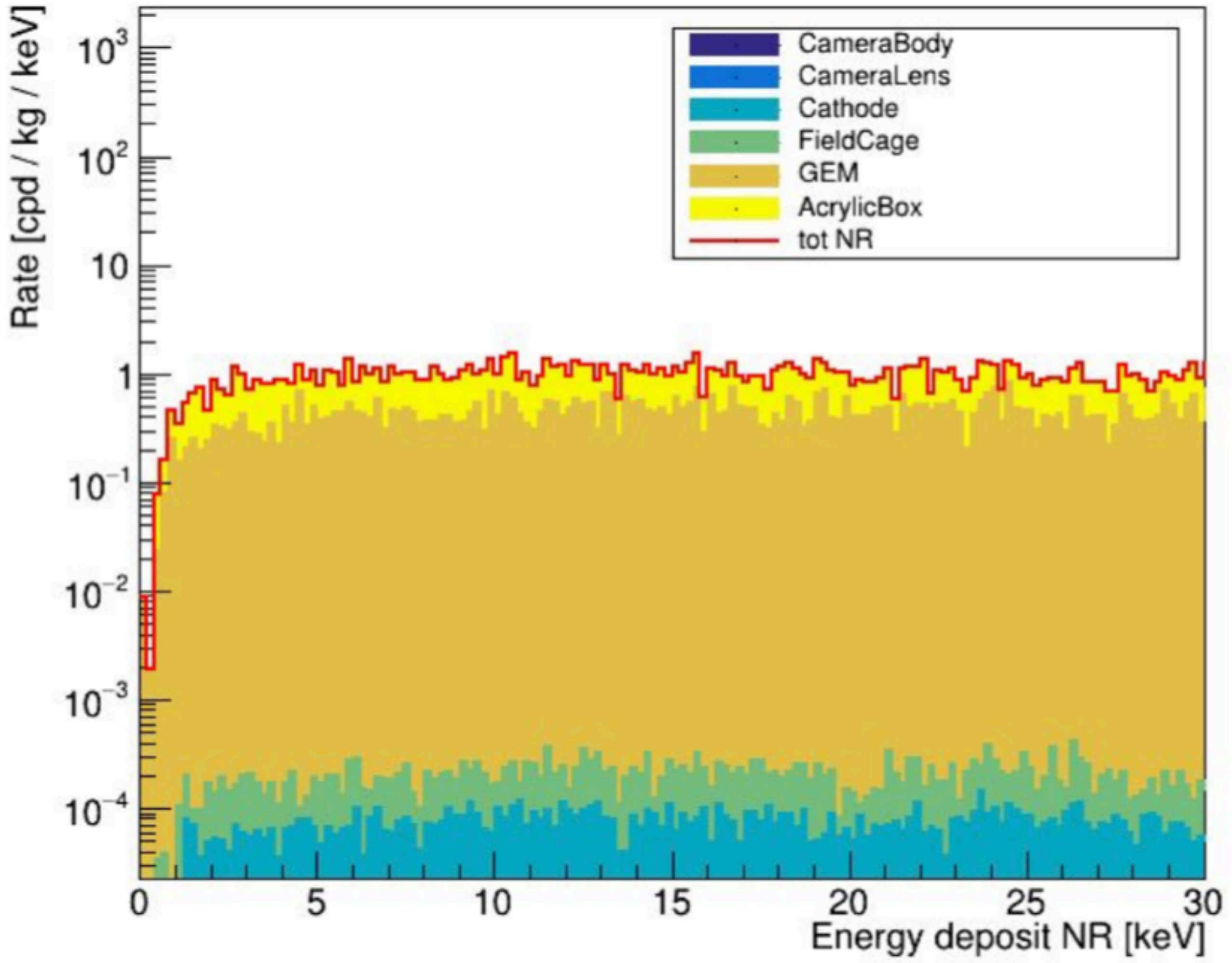


- CYGNO_04: ER rate [1-20] keV = 4.9x10^{5} cts/yr



Internal ER background

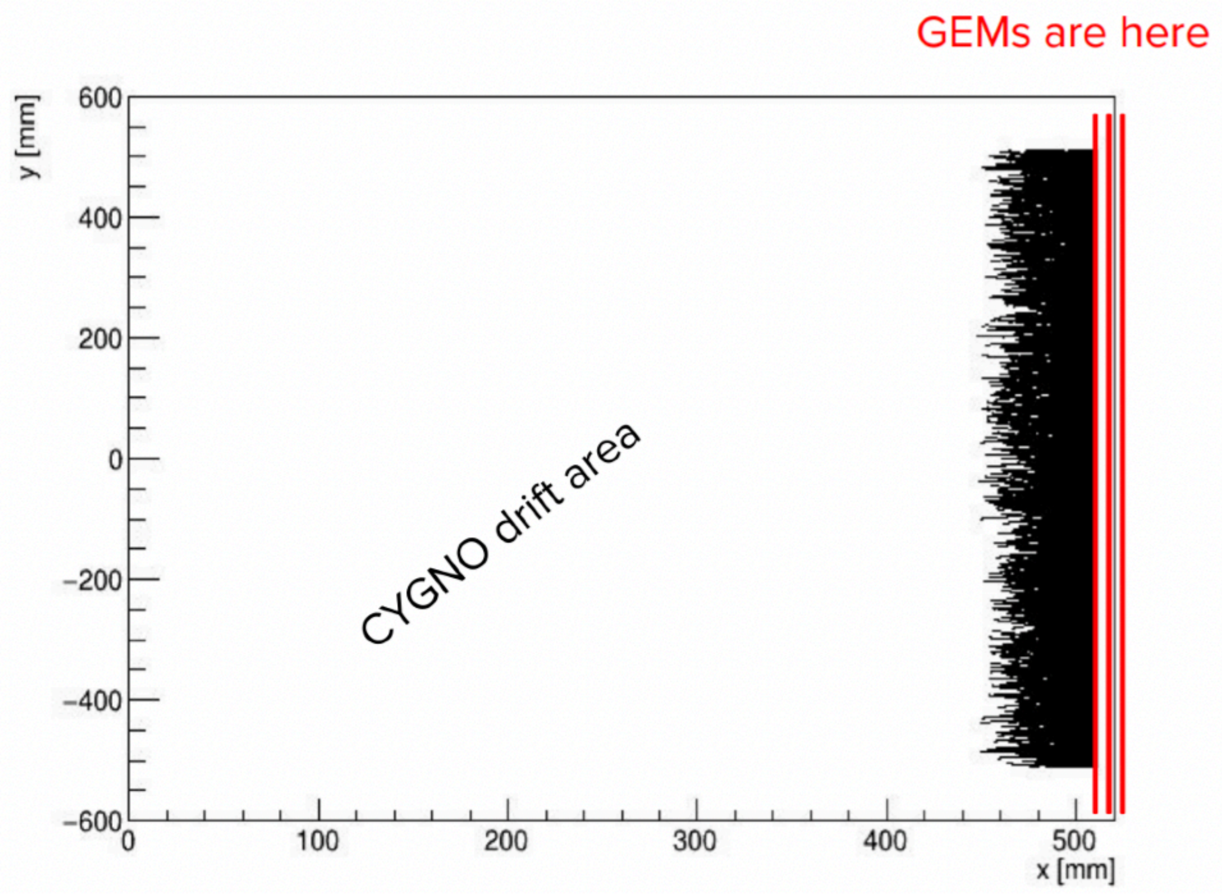
- CYGNO_04: NR rate [1-20] keV = 2.6x10^{3} cts/y



Internal NR background

Full background simulation for 1 m3 detector

- NR: mostly from GEMs / vessel reducible with fiduacal cuts
- Low radioactivity GEMs at CERN following T-Rex R&D
- ER: working in close contact with producing companies to reduce the radioactivity of the sCMOS sensor and lens

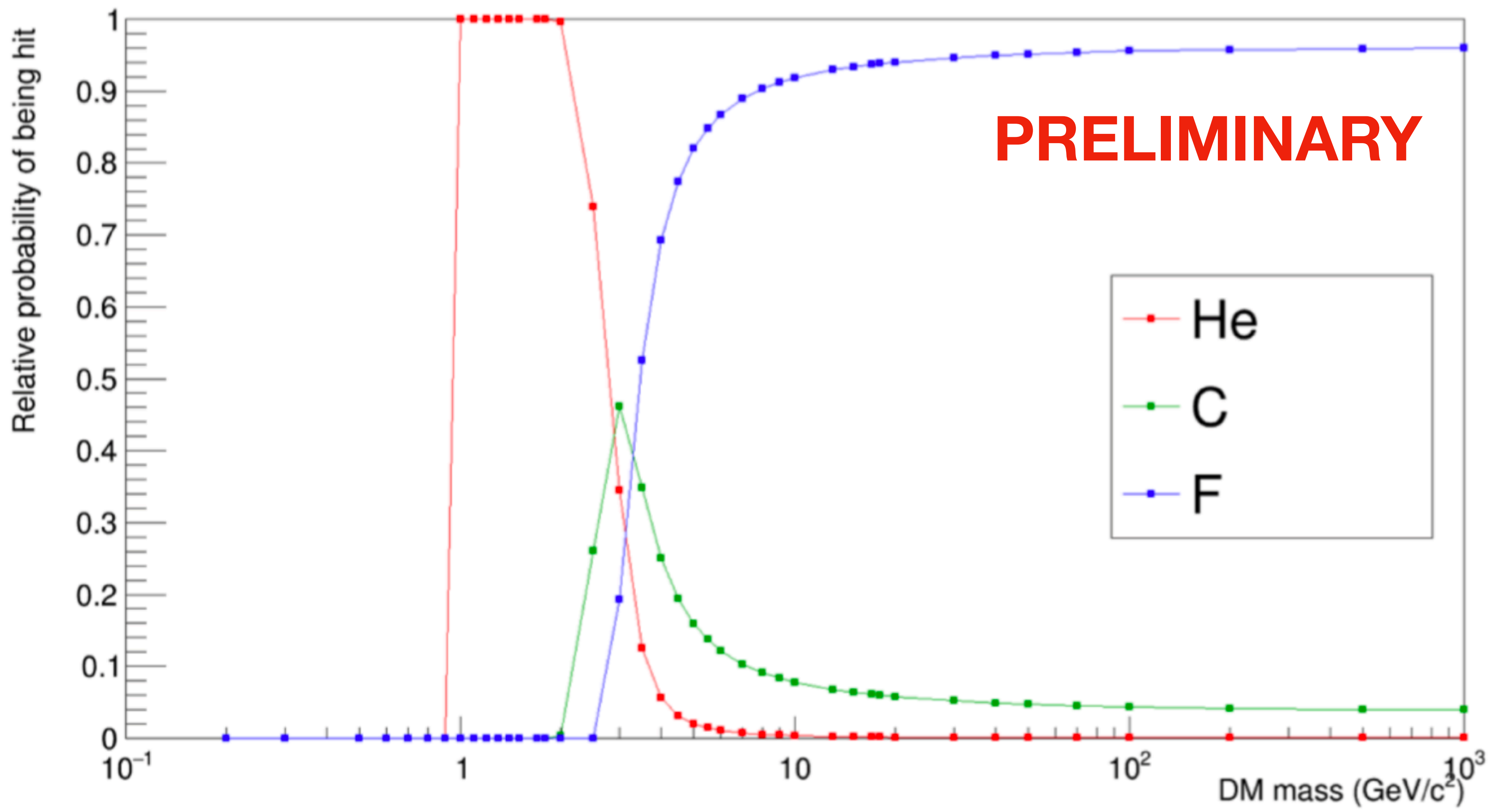


PHASE 2: The CYGNO experiment 30 m^3

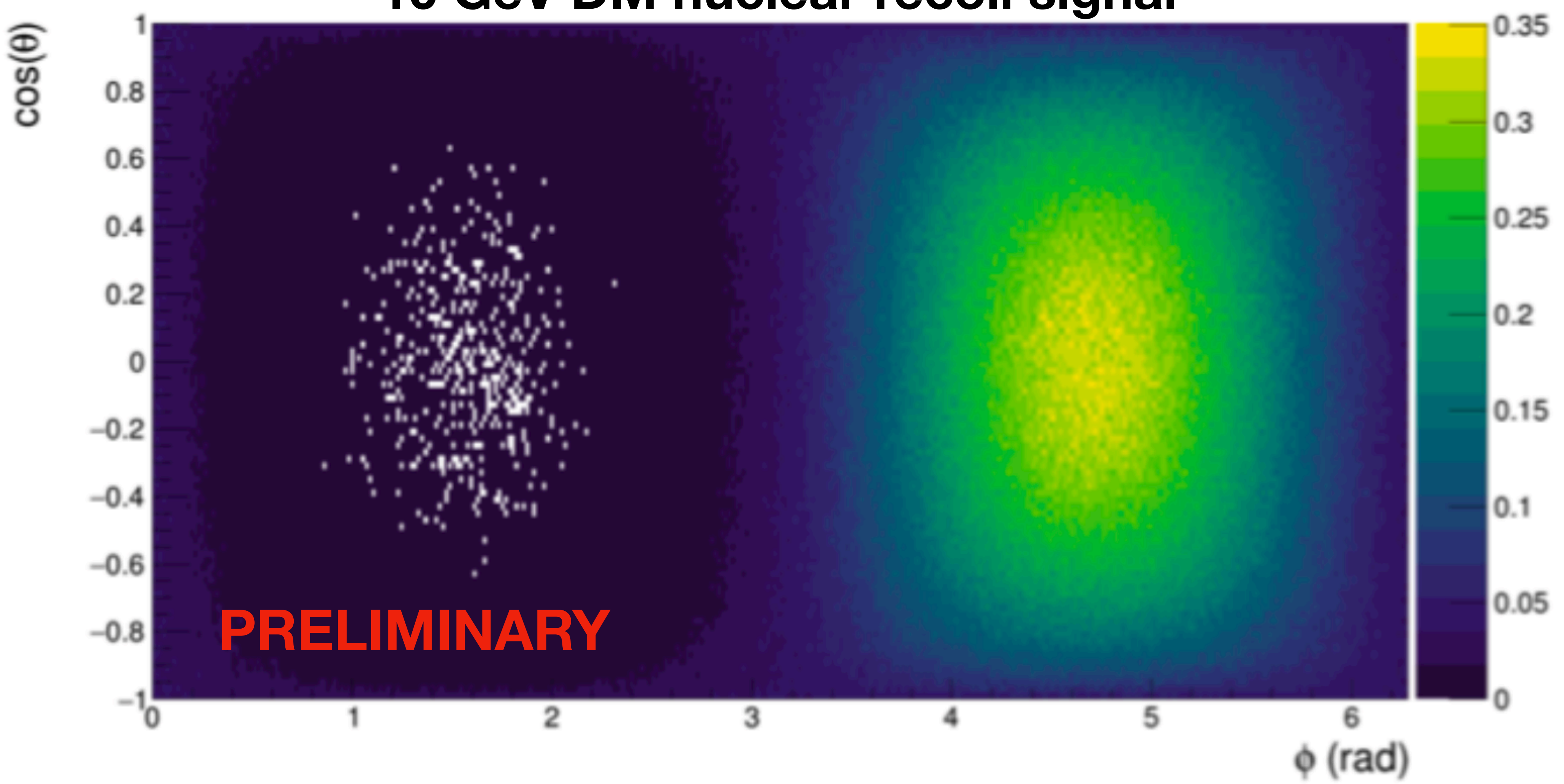
Searching for low mass DM

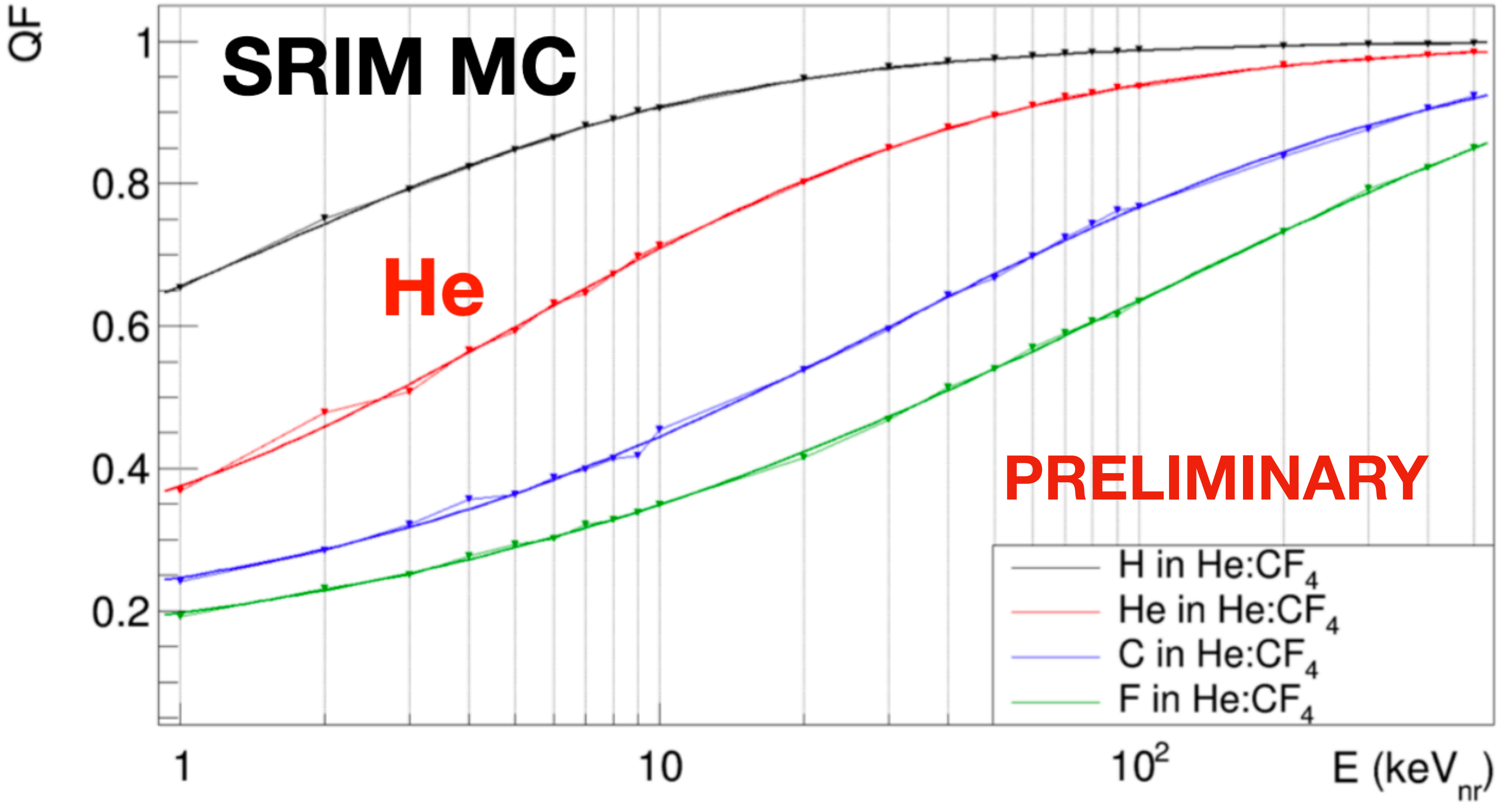
- **Use 1(0.5) keVee threshold**
- **QF evaluated with SRIM**
- **Angular distribution as discriminating information**
  - full head/tail recognition
  - 30 deg. resolution
- **Various scenarios with different background levels**
  - isotropic distribution

relative probability to detect a NR at 1 keV



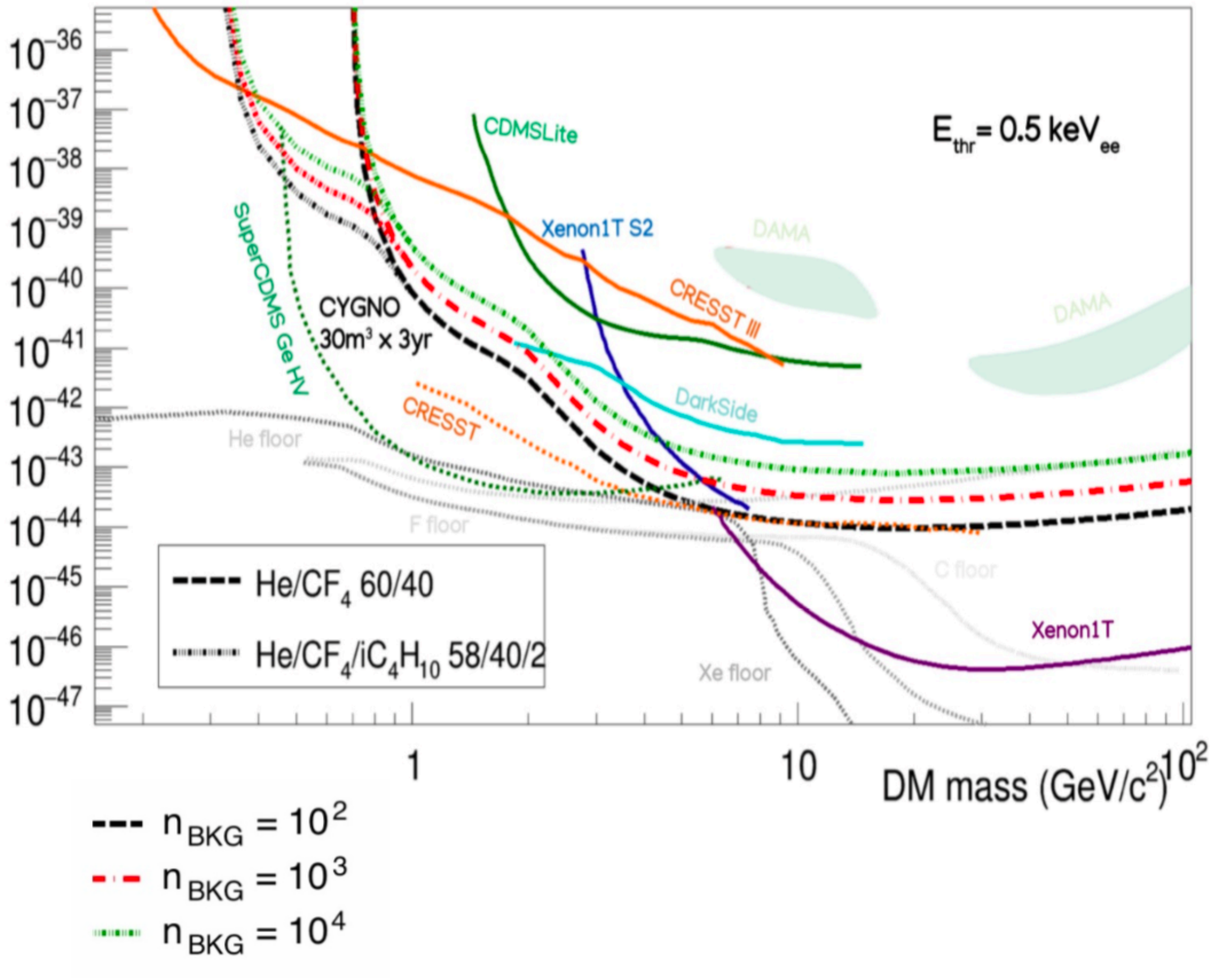
10 GeV DM nuclear recoil signal



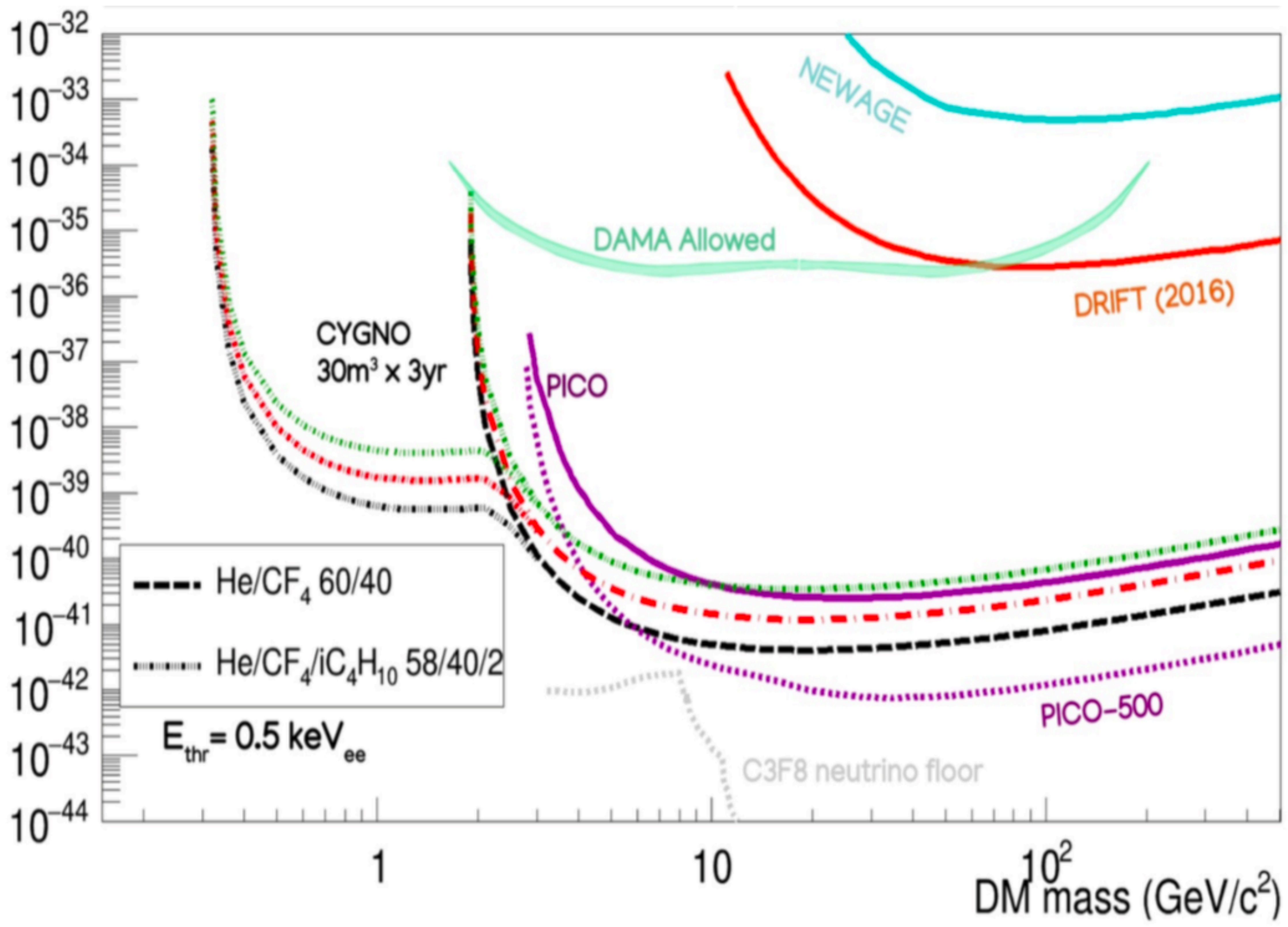


PHASE 2: The CYGNO experiment 30 m^3
Searching for low mass DM

Spin Independent



Spin Dependent



New R&D activities

Minimise internal radioactivity

- Develop custom sCMOS sensor
- Realisation of custom lens with large aperture & low radioactivity

Gas studies

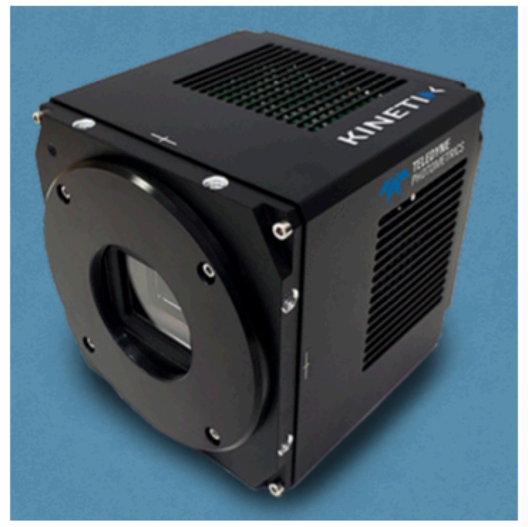
- adding isobutane
- First demonstration of a **very good light** yield from with C_4H_{10}
- Work on eco-friendly gas mixture as substitute for CF_4

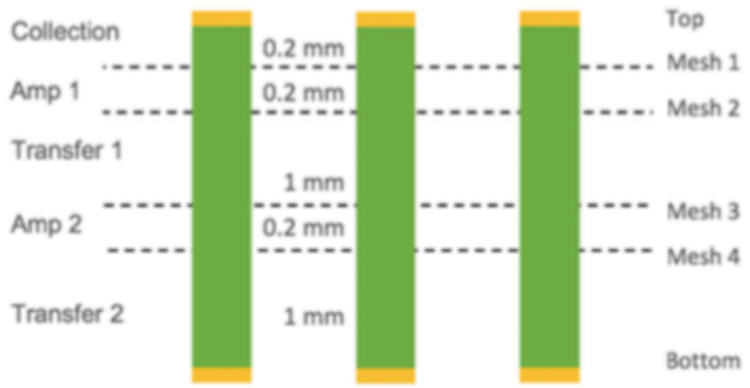
Negative ion drift

(financed by ERC INITIUM GA 818744)

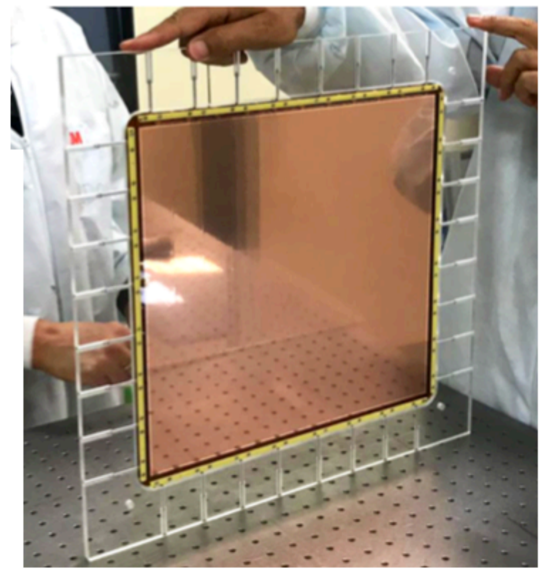
- Add SF_6 to produce **negative ions** drift resulting in **better fiducialization**
- First encouraging results at nearly **atmospheric pressure**

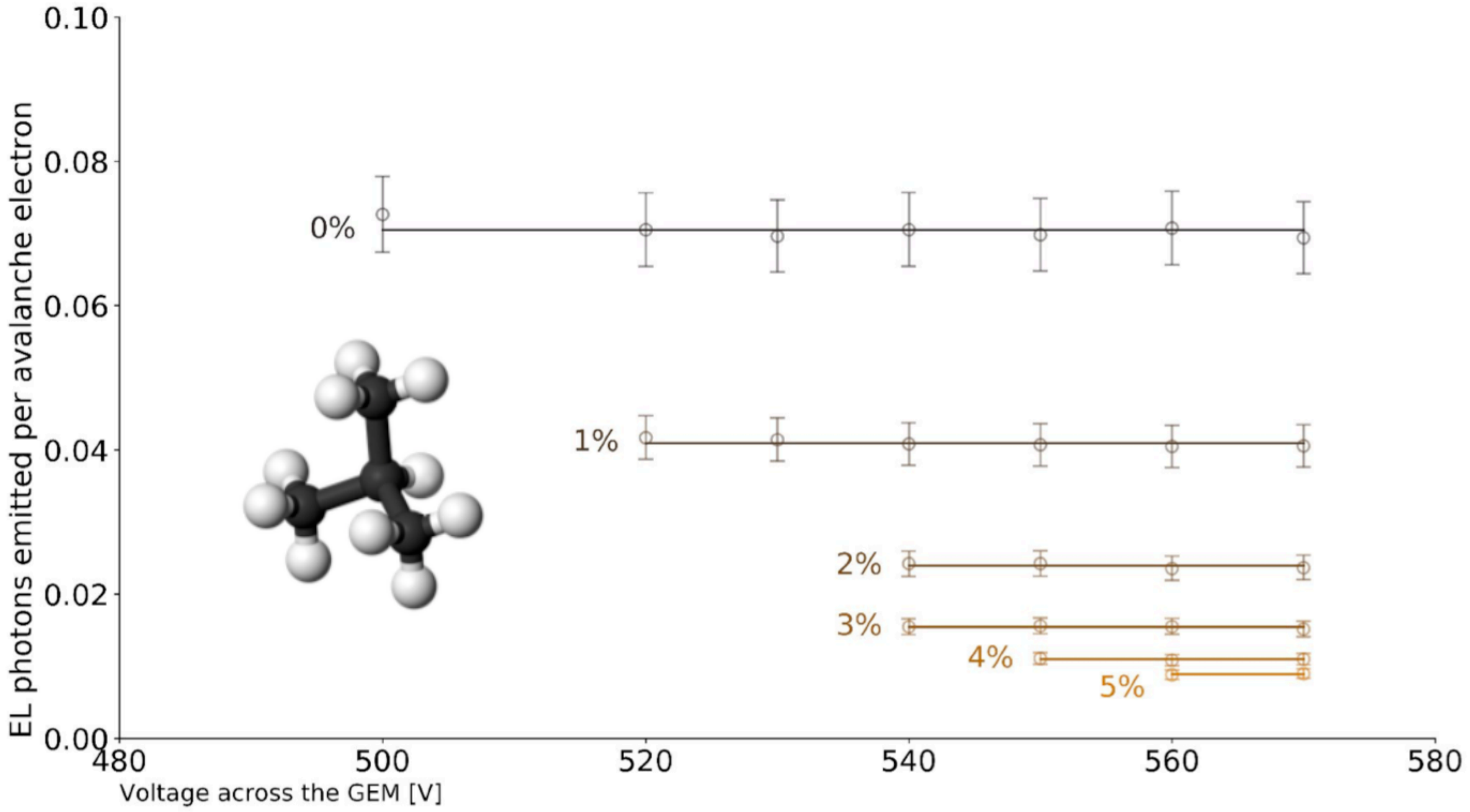
JINST 13 (2018) 04, P04022

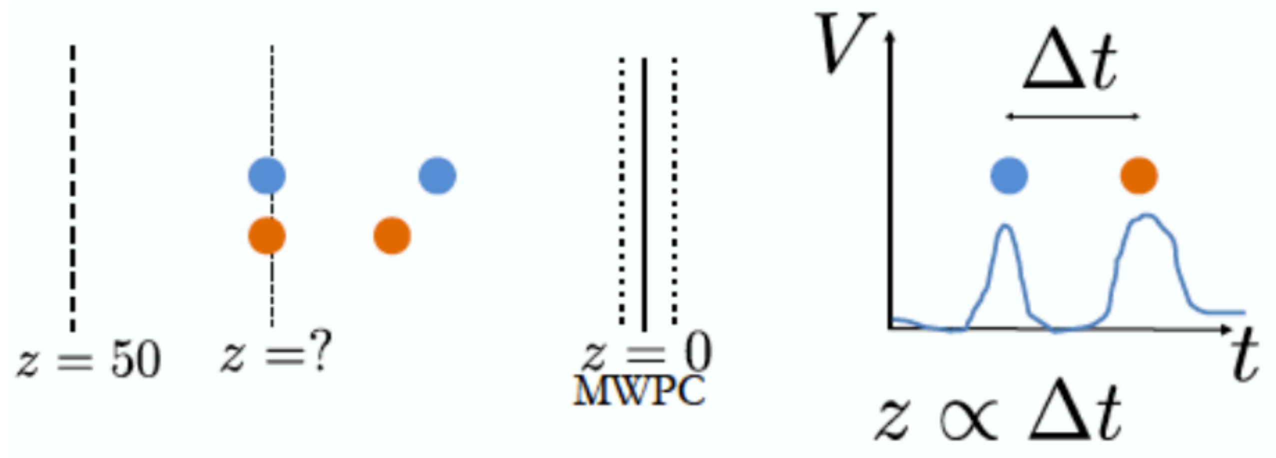




(a) Cross-section of the MMThGEM detector with the field names (left), plane names (right) and the gap widths (centre-left)



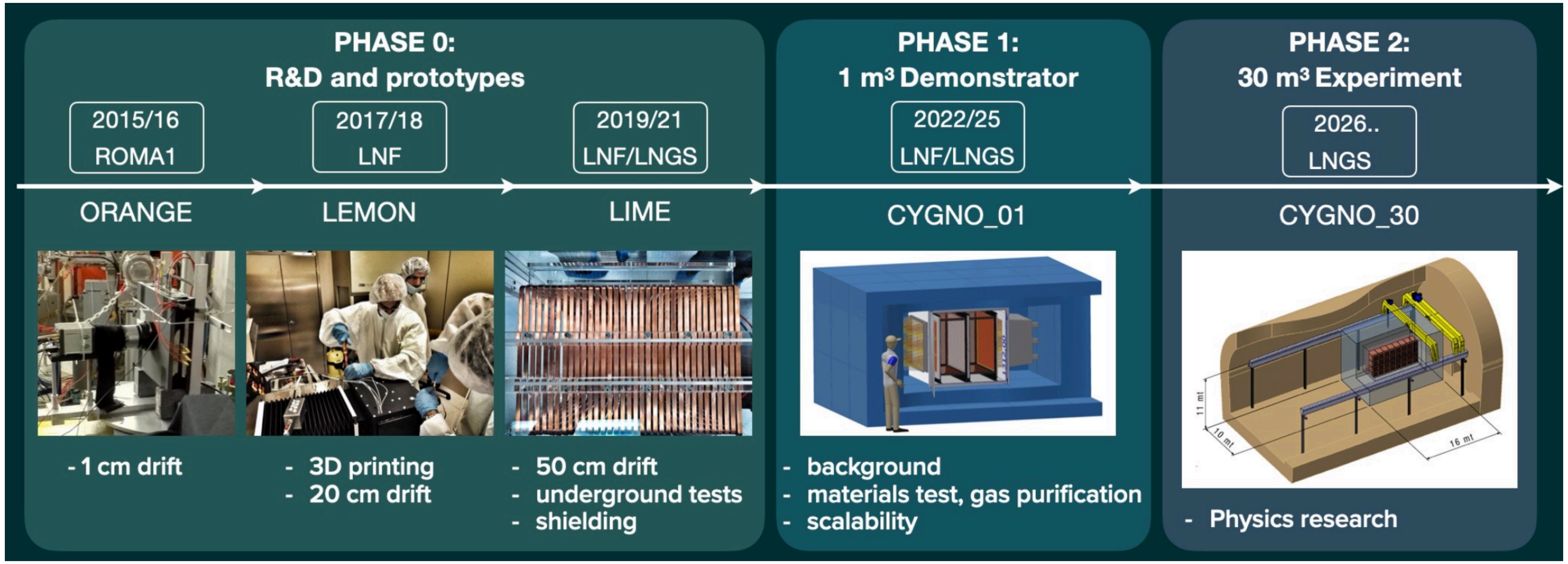




Summary

The CYGNO collaboration is developing a **He:CF_4 TPC with optical readout**

- **CYGNO PHASE 0** commissioned overground: very good detector stability, energy and position resolution;
- **CYGNO PHASE 0 installed underground at LNGS:** measure neutron flux, validate the background model, shielding configuration;
- **CYGNO PHASE 1:** construct and operate a CYGNO demonstrator to pave the road for a larger apparatus for Dark Matter search.



Acknowledgements

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

CYGNO Project is funded by INFN.

Thank you!

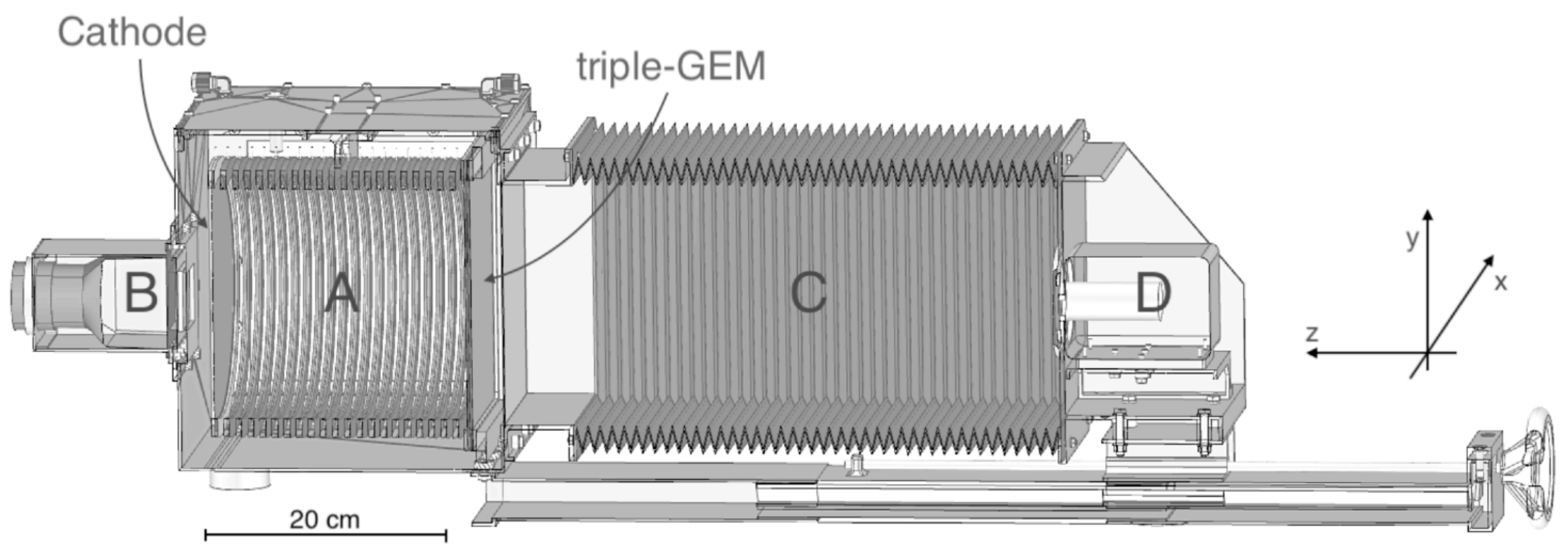
The CYGNO collaboration:

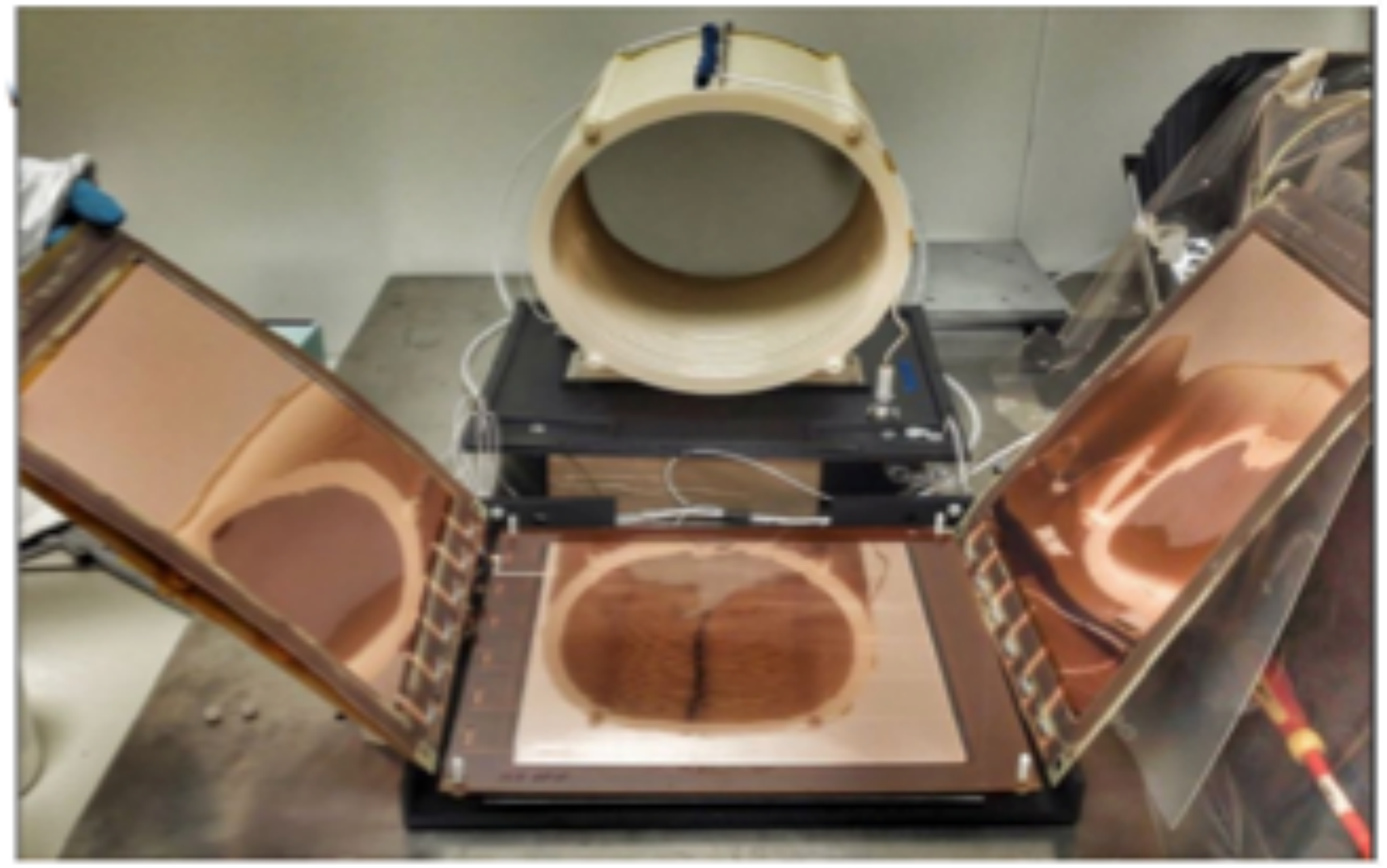
F. D. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, A. Cortez, R. J. de Cruz Roque, I. A. Costa, E. Dané, E. Di Marco, G.Grilli di Cortona, G. D'Imperio, G. Dho, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, H. P. Lima Júnior, G. Maccarrone, R. D. P. Mano, M. Marafini, G. Mazzitelli, A. G. Mc Lean, A. Messina, M. L. Migliorini, C.M.B. Monteiro, R. A. Nóbrega, A. Orlandi, I. F. Pains, E. Paoletti, L. Passamonti, F. Petrucci, S. Pelosi, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, F. Rosatelli, A. Russo, J.M.F. dos Santos, G. Saviano, A. da Silva Lopes Júnior, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli

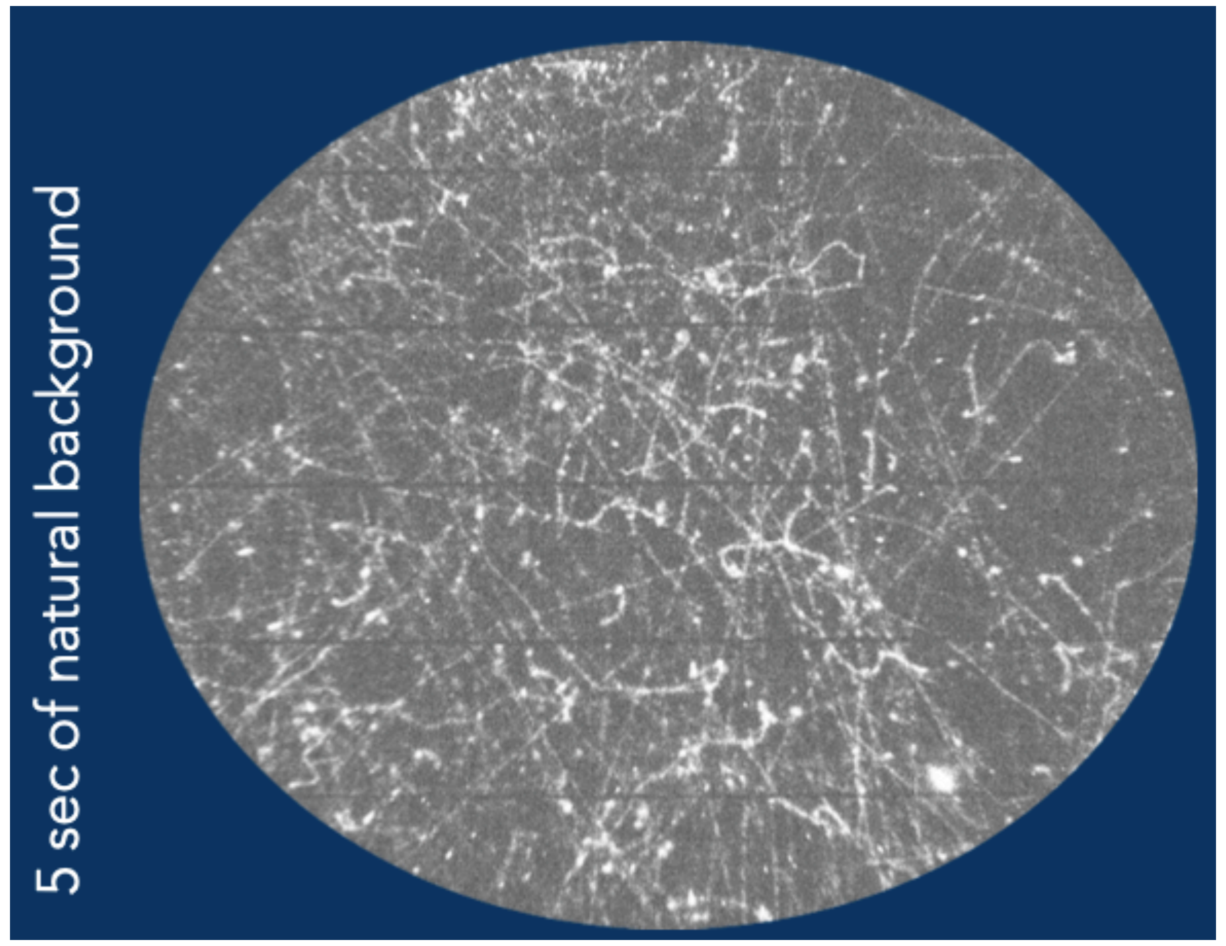
LEMOn prototype

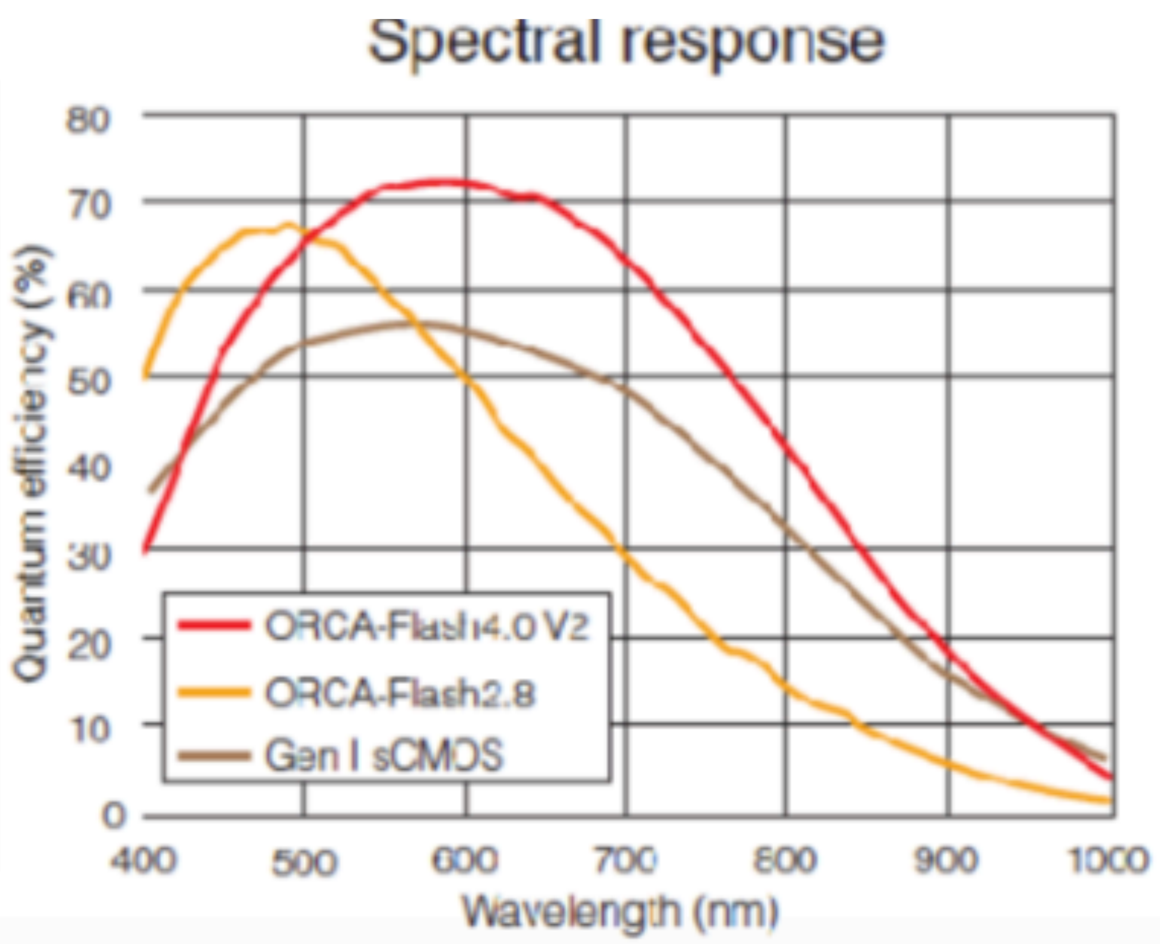
JINST 15 (2020) P10001

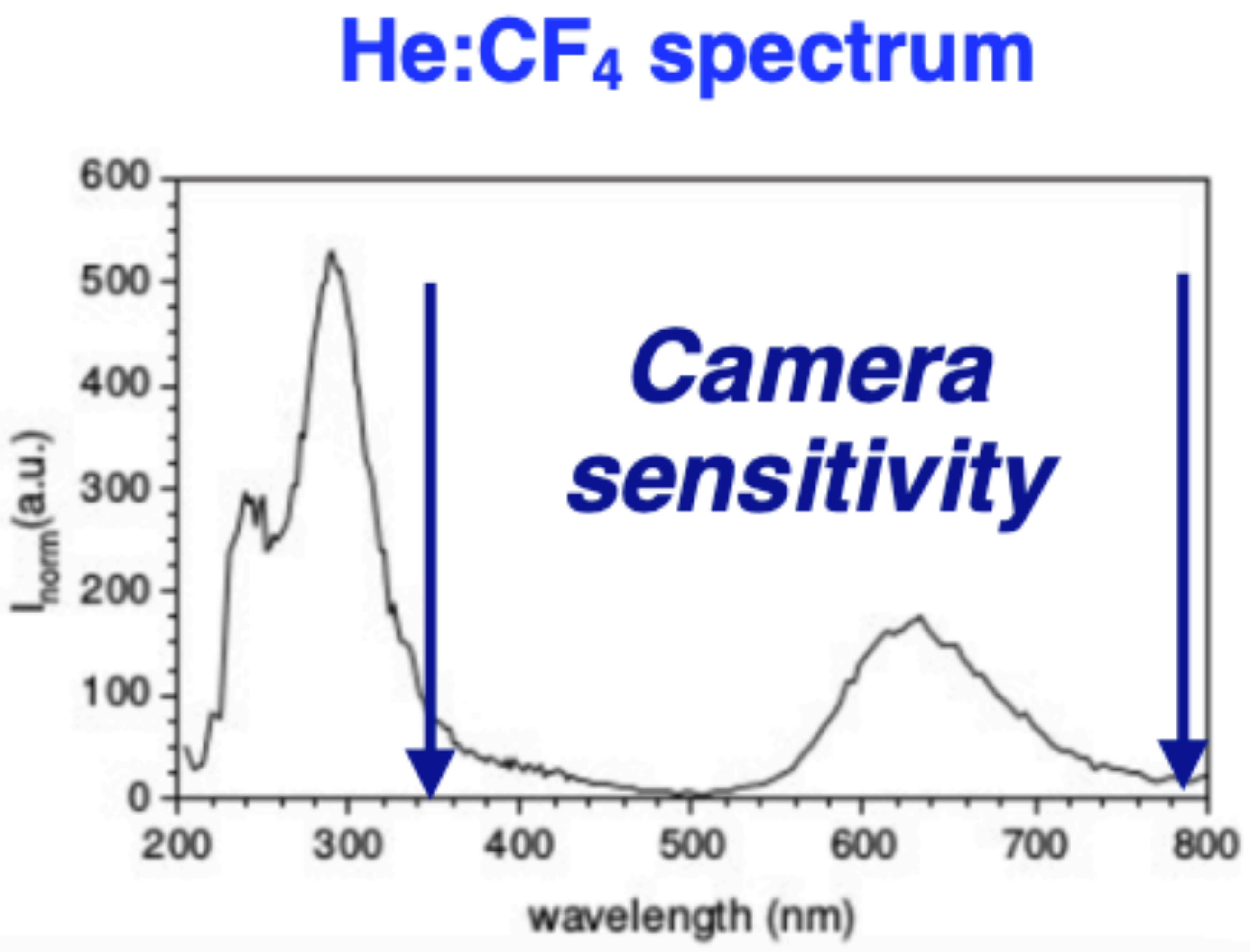
- **24 x 24 cm^2 readout area**
- **20 cm drift**
- **1 sCMOS + 1 PMT**





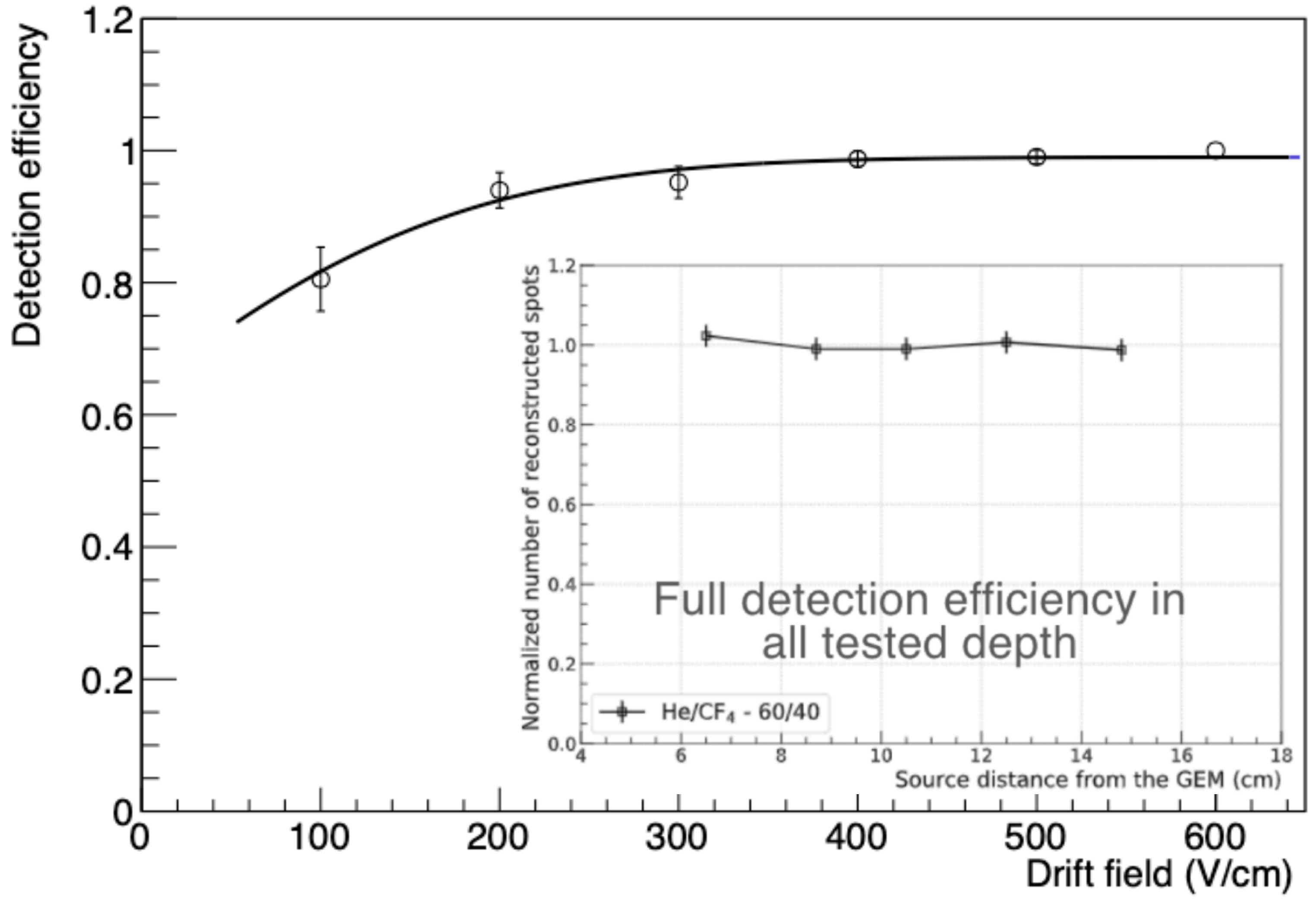


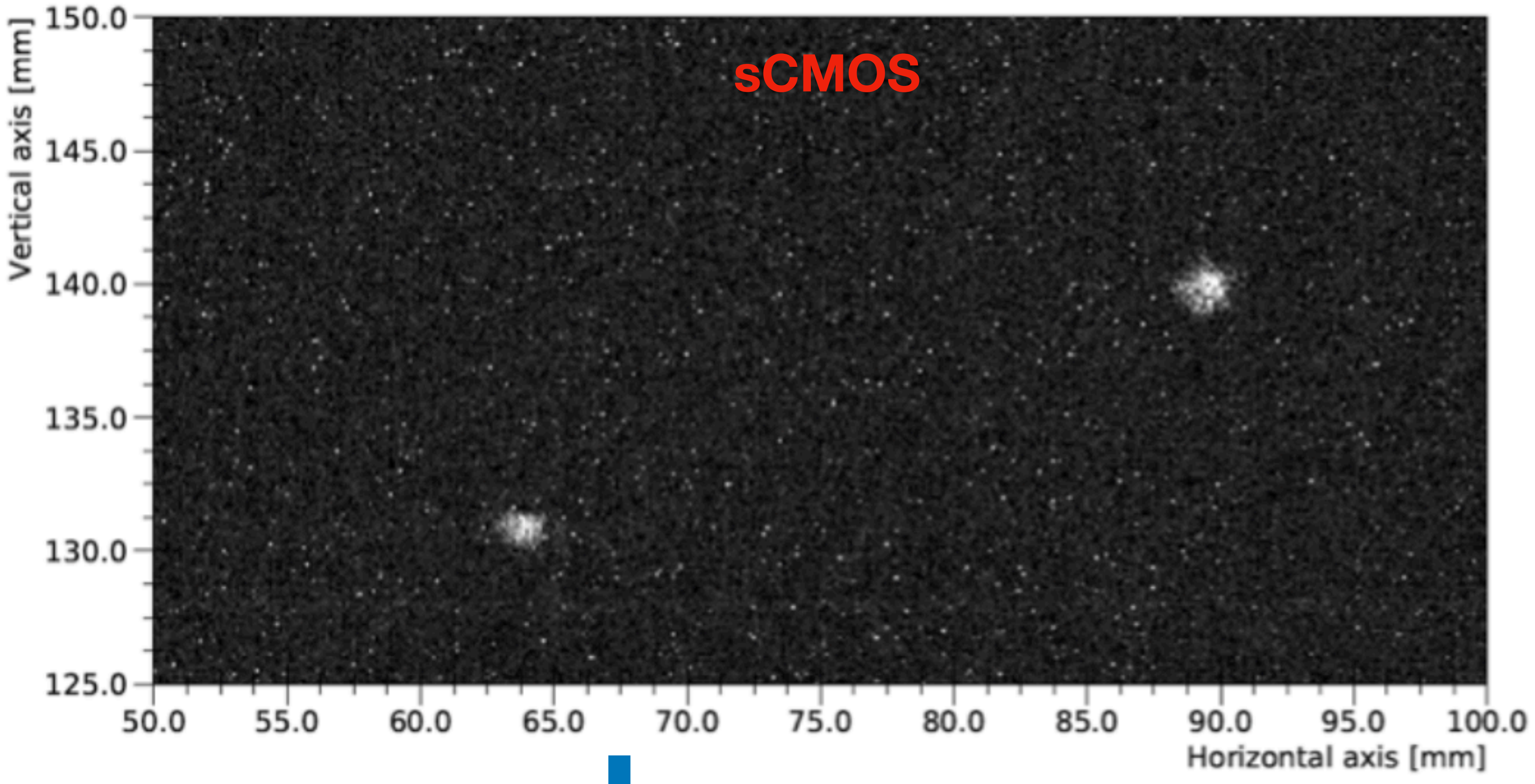


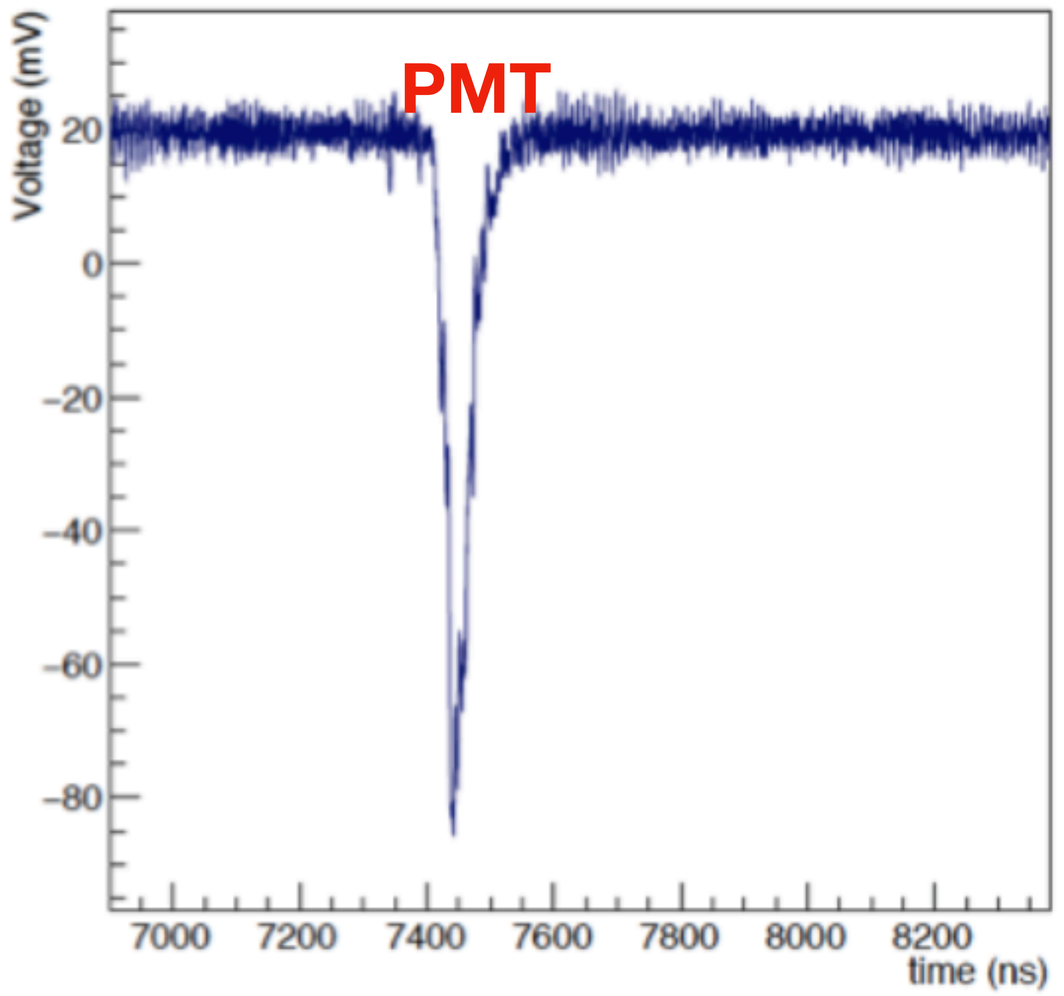


Response to ^{55}Fe X-rays: energy resolution and threshold

JINST 15 (2020) P10001 2019 JINST 14 P07011

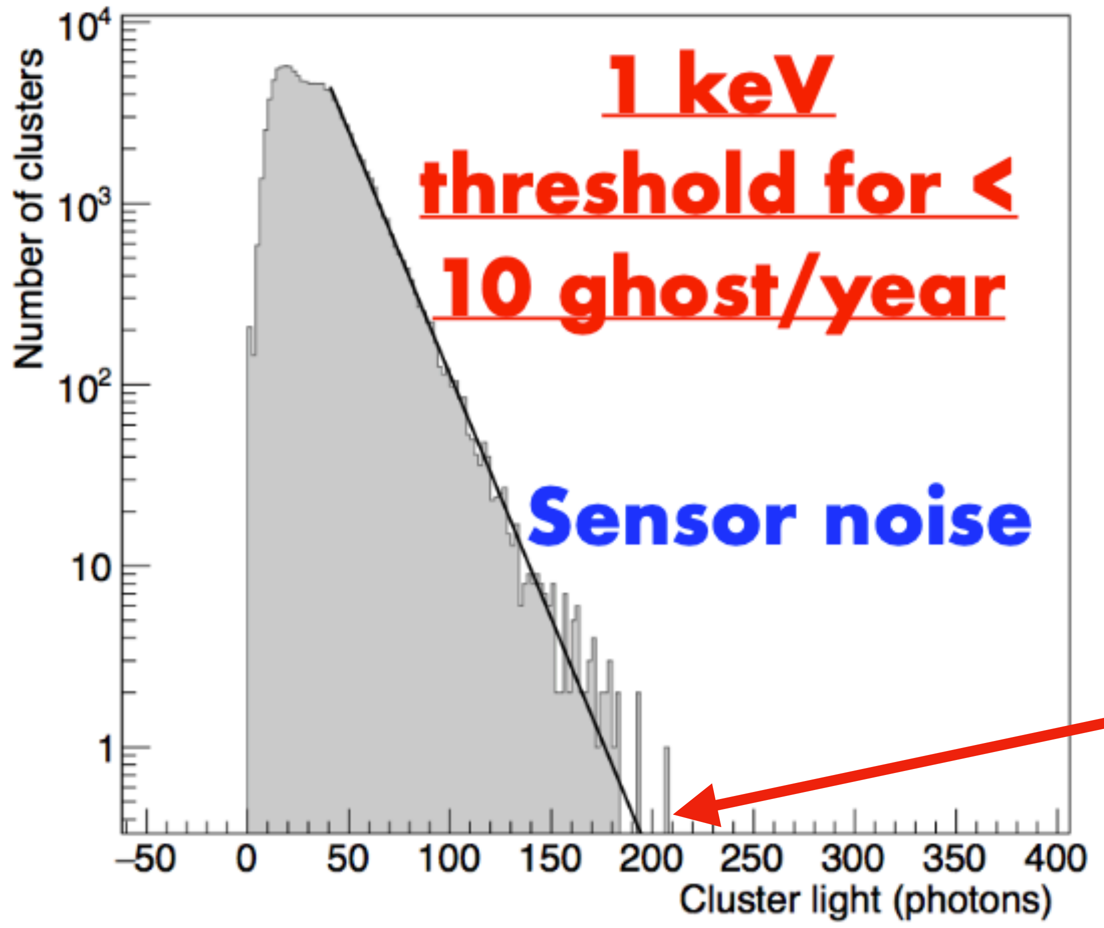






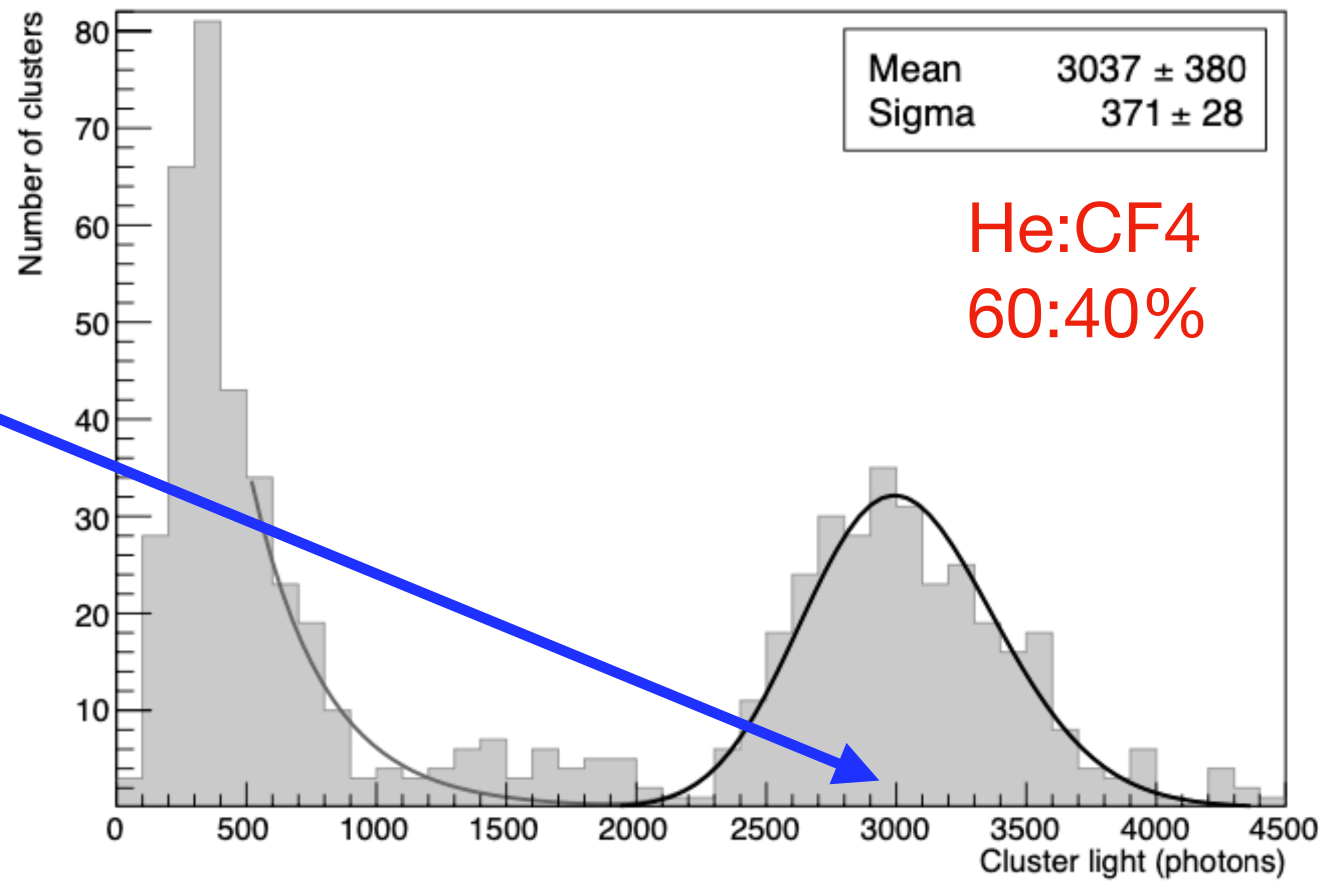
sCMOS

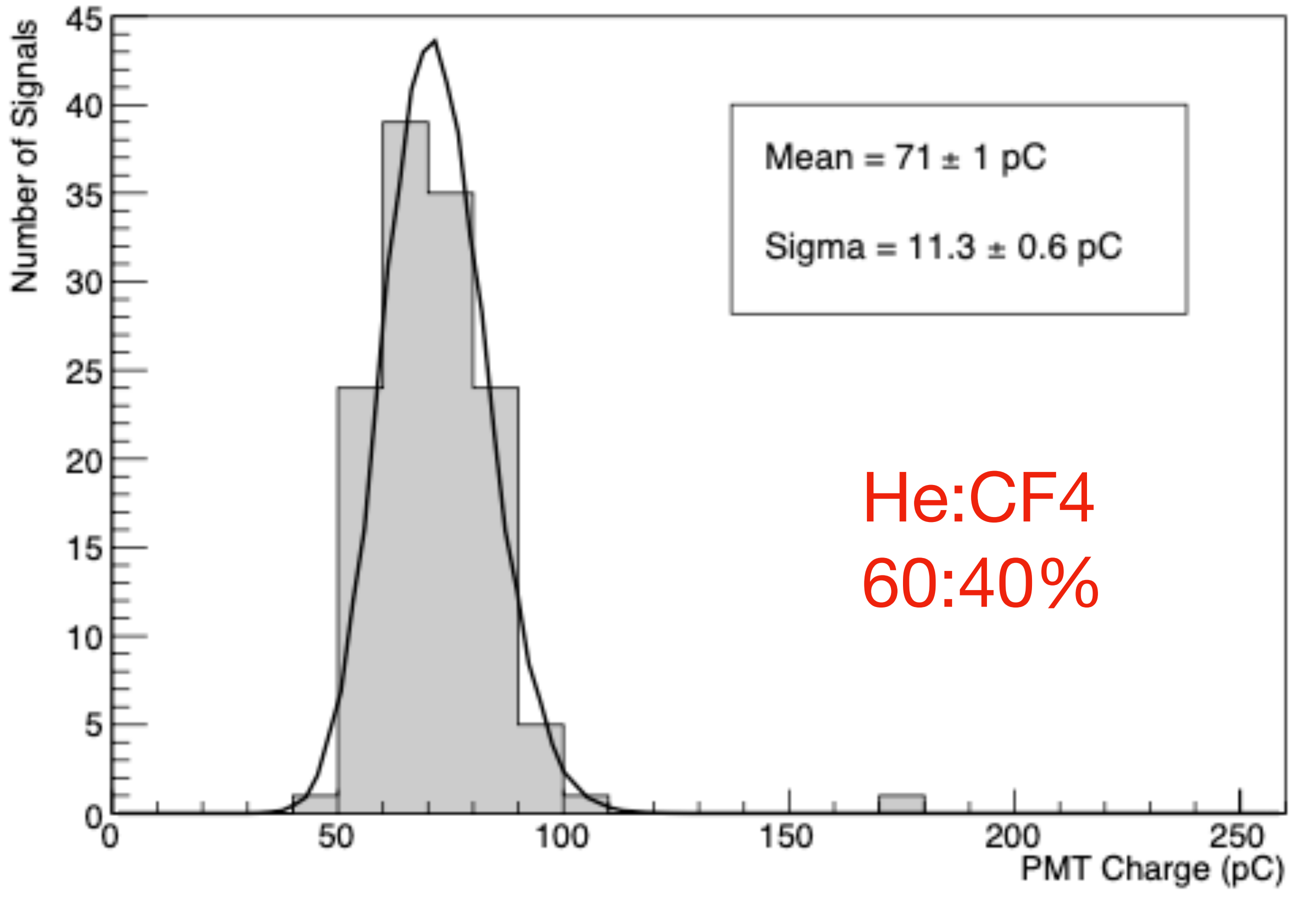
PMT



500 collected photon per keV

sensor noise below 200 ph (400 eV)





Energy resolution of 15% at 5.9 keV$_{ee}$ with sCMOS and PMT

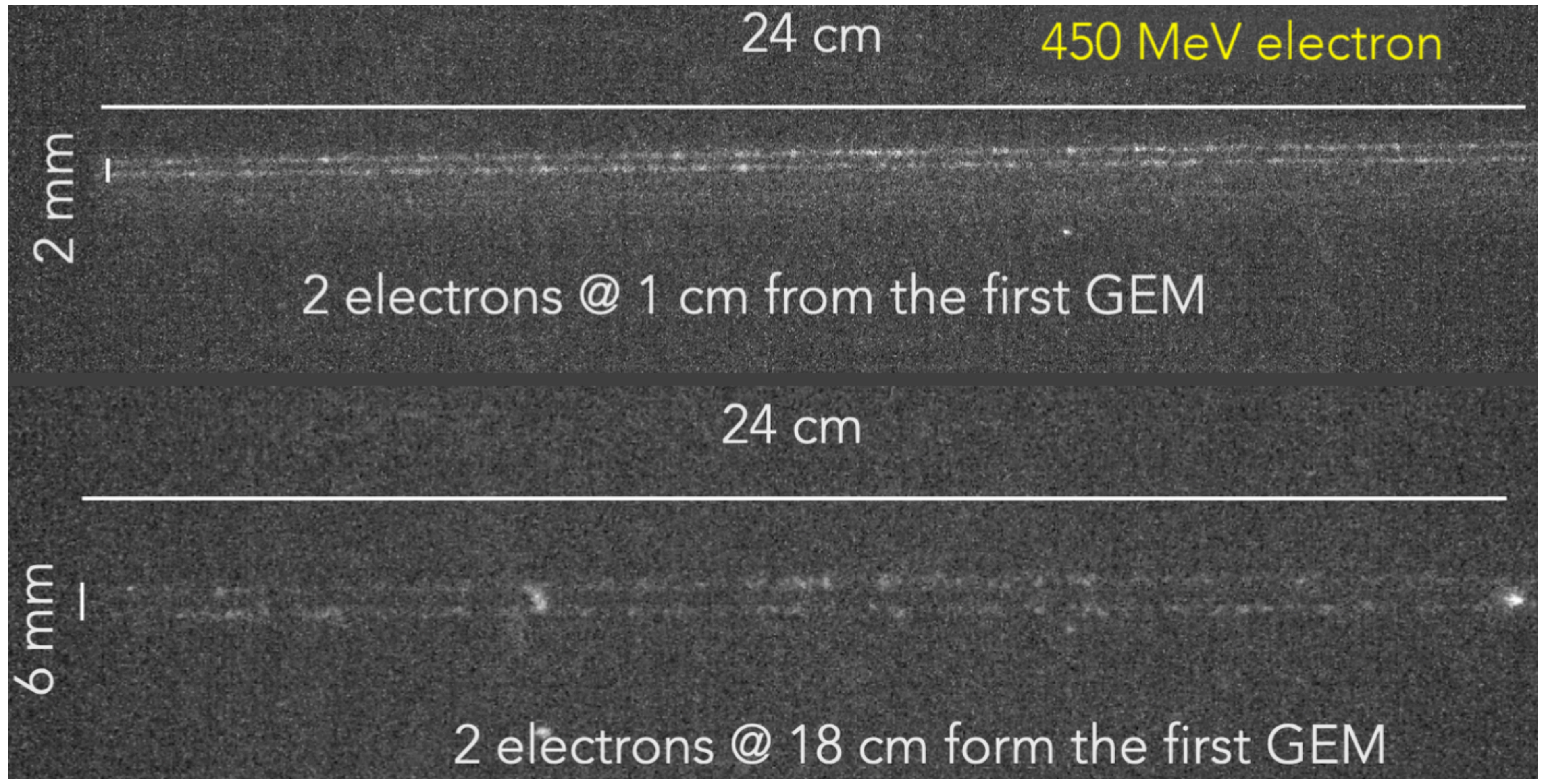
Response high energy electrons: tracking and fiducalization

NIM A 999 (2021) 165209

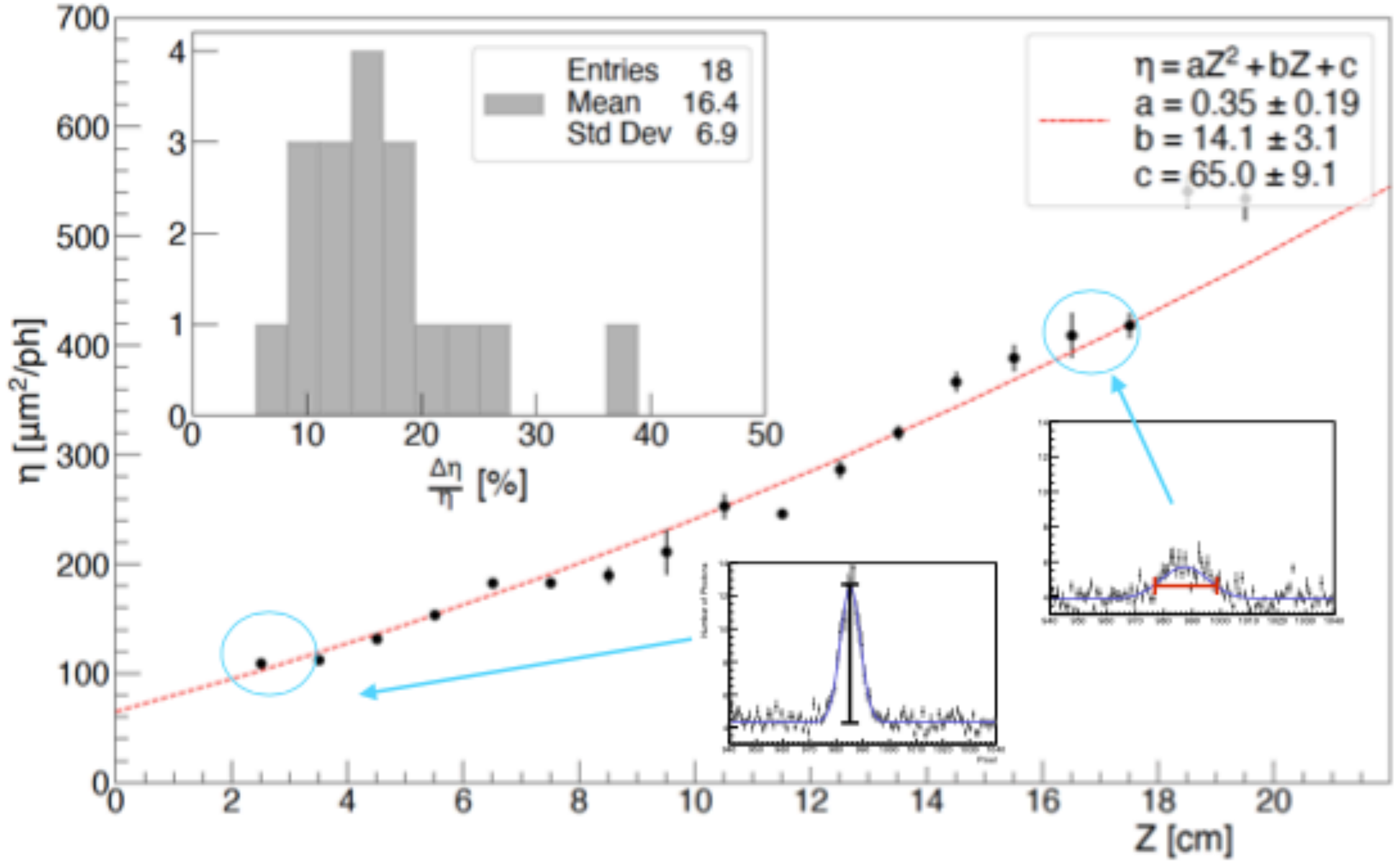
The diffusion can be exploited to estimate the z position of the event.

The width (S) and amplitude (A) of the transverse light profile and PMT waveform become larger and smaller respectively with increasing distance from the GEM (z position).

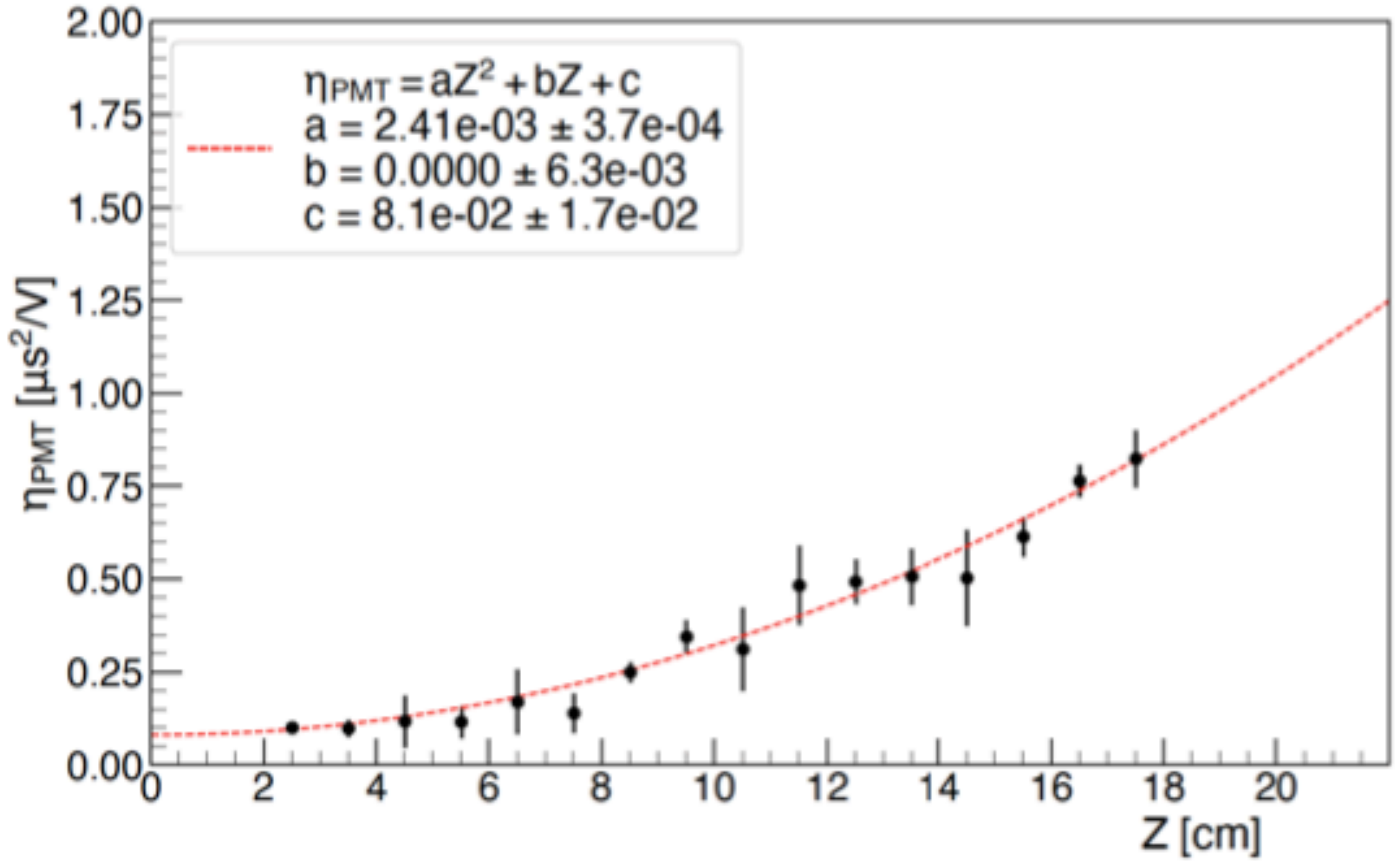
Thus $\eta = \dfrac{S}{A}$ increases



sCMOS



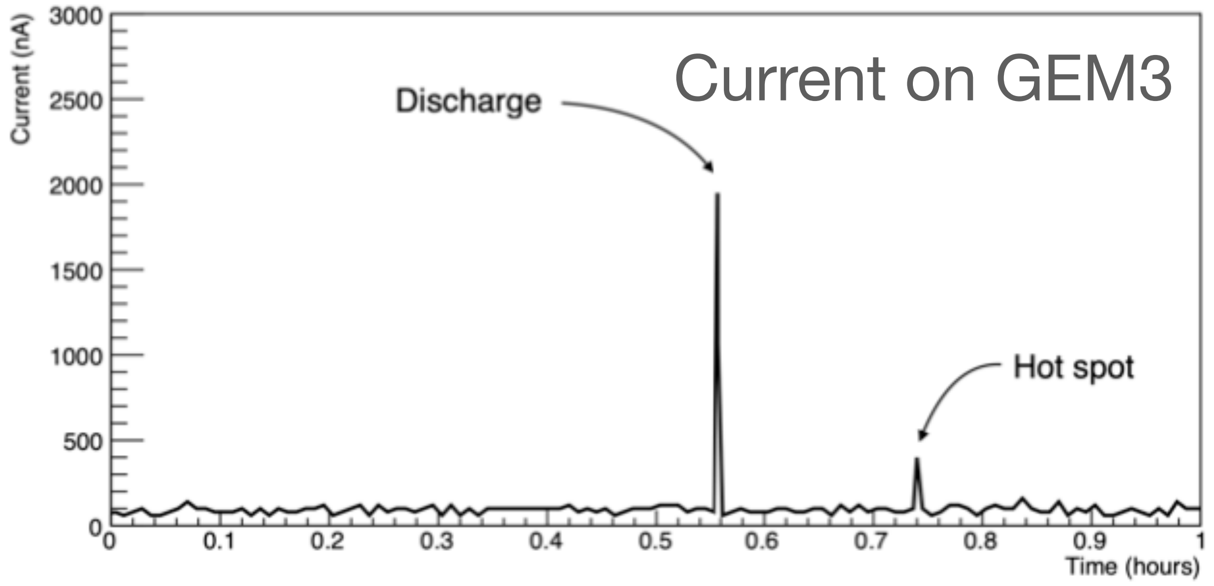
PMT

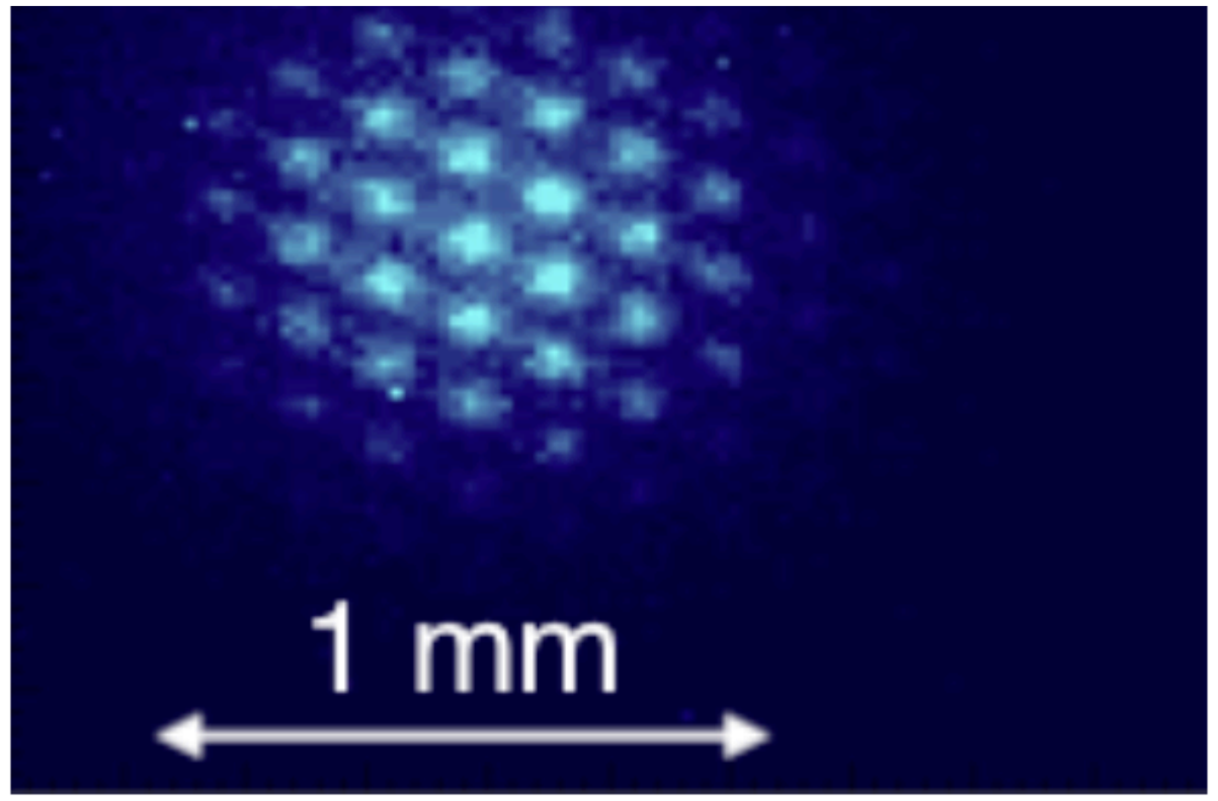


Both with light and charge 15% z position resolution (y evaluated with 100-300 μm resolution)

Large prototypes stability tests

JINST 15 (2020) P10001



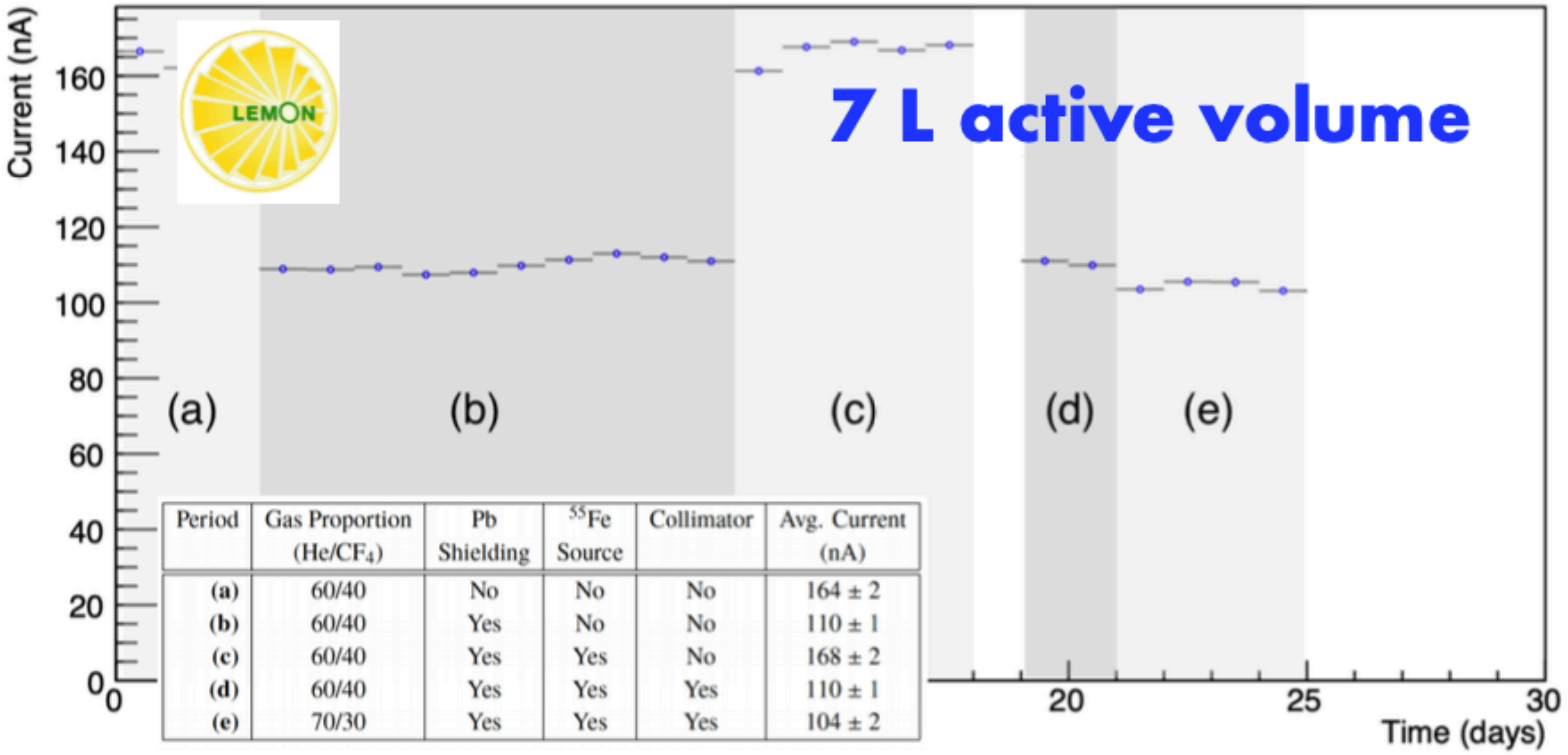


Hot spots and **Discharges:** dumped by lowering GEMs voltage to 100 V and raising it again (3 min deadtime)

He:CF4 60:40% 1 atm

LEMOn successfully operated for 25 consecutive days with automatic GEM hot spots recovery procedure

Similar stability with LIME: (less than 1 evt/hour) in agreement with a factor of 2 larger GEMs



Period	Gas Proportion (He/CF_4)	Pb Shielding	^{55}Fe Source	Collimator	Avg. Current (nA)
(a)	60/40	No	No	No	164 ± 2
(b)	60/40	Yes	No	No	110 ± 1
(c)	60/40	Yes	Yes	No	168 ± 2
(d)	60/40	Yes	Yes	Yes	110 ± 1
(e)	70/30	Yes	Yes	Yes	104 ± 2