Neutron flux measurement at LNGS with CYGNO/INITIUM

35th cycle, PhD in Astroparticle Physics - 3rd year report

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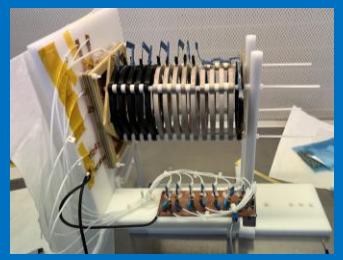
CYGNO/INITIUM

F. Amaro et al., "The Cygno Experiment", Instruments 2022, 6(1), 6

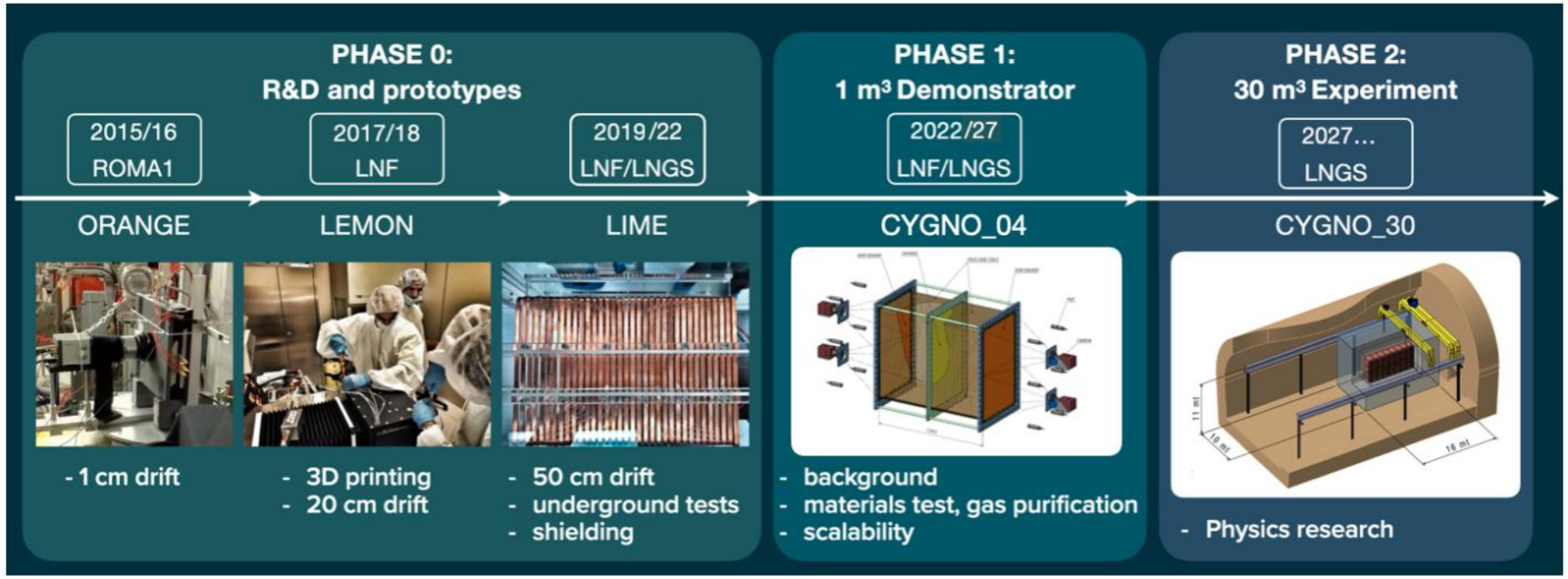
- **Directional Dark Matter** search experiment with a high resolution gaseous **TPC**
- He:CF_4 60/40 gas mixture, GEM amplification, **optical readout** with sCMOS cameras and PMTs
  - **3D** reconstruction capability (direction+head-tail)
  - Low threshold < 1 keV
- R&D phase in sinergy with **INITIUM** project on Negative Ion Drift (NID) operation
- MANGO (overground @LNGS) and LIME (underground @LNGS) prototypes currently being used

INITIUM
Currently
at LNGS

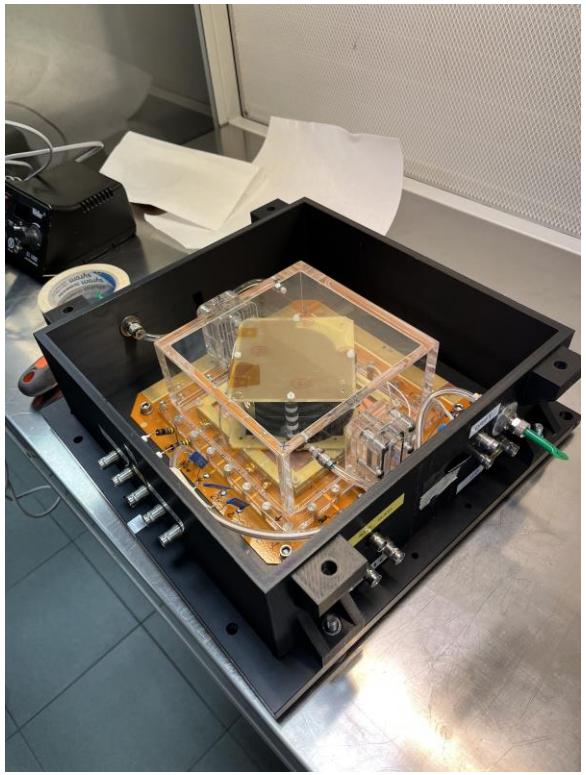
MANGO

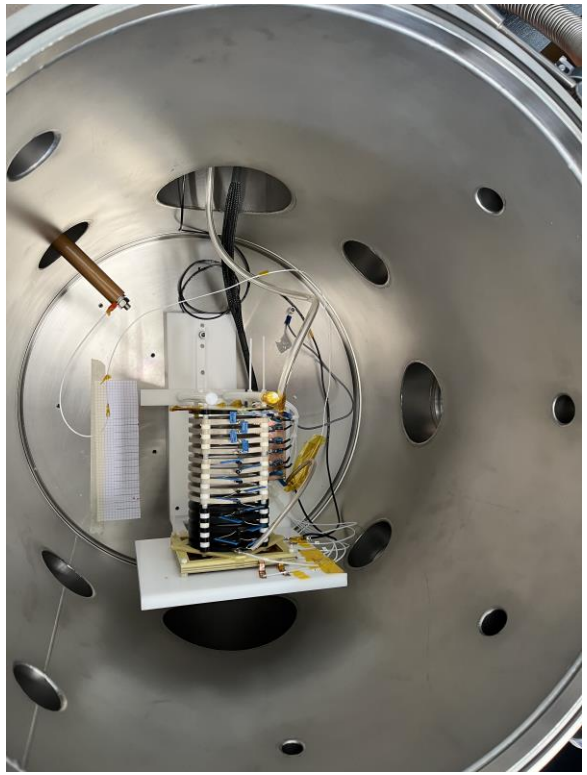


- 15 cm drift
- gas studies



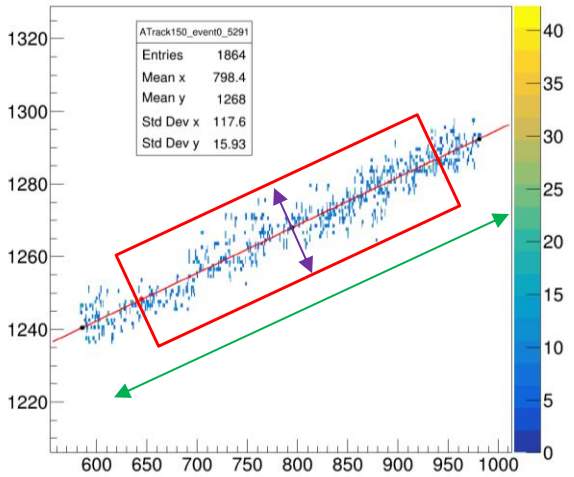
The MANGO prototype



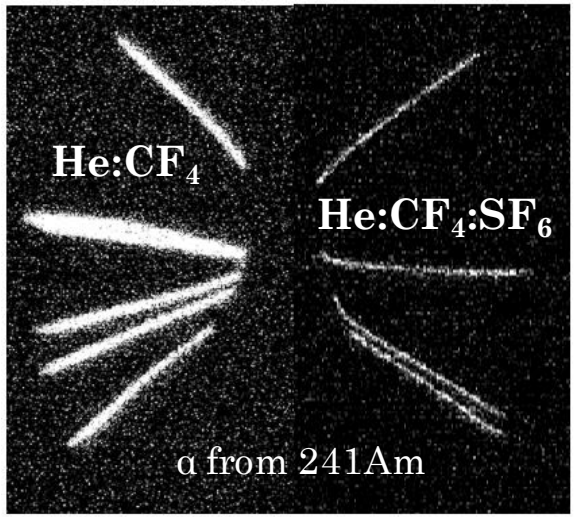


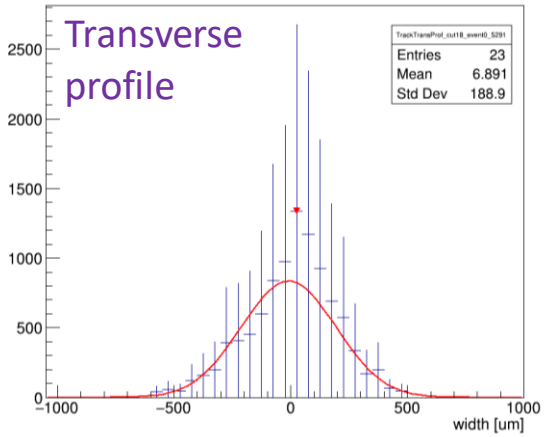
- Small prototype using $10\times10cm^2$ triple GEMs
- First operated in "flux mode" with 5 cm of maximum drift distance
- Upgraded with longer field cage (15 cm) and mounted in a vacuum vessel
  - Pressure control
  - Study diffusion as a function of the distance
- Took data with ^{241}Am alpha source in electron drift (ED) mode (**He:CF_4**, 60:40) and negative ion drift (NID) mode (**He:CF_4:SF_6**, 59:39.4:1.6)
- We want to study diffusion in NID (INITIUM project)

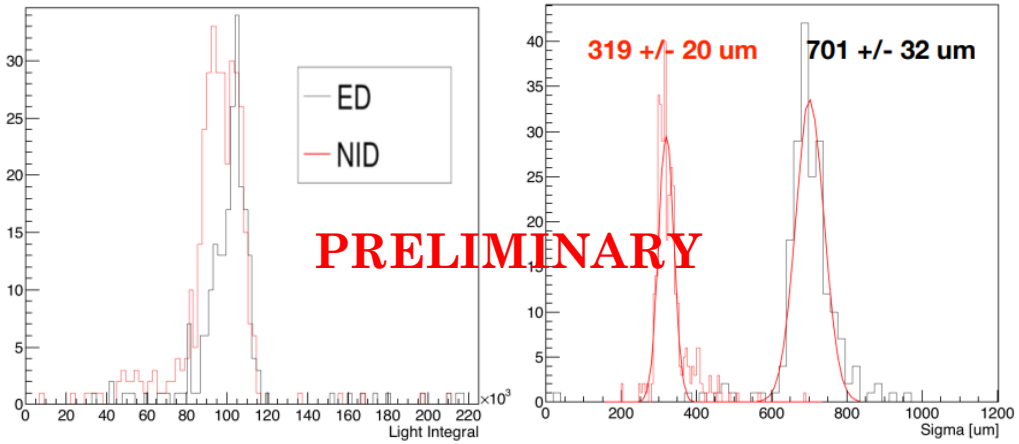
Alpha analysis in MANGO



- Principal axes found with PCA
- Central part of the track is selected
- Pixels are projected along the two directions weighted with their intensity (transverse and longitudinal profiles)
- The transverse profile is fitted with a gaussian
- Alpha tracks are selected based on length, slimness (<0.3), and on the number of peaks found in the transverse profile (only single tracks)





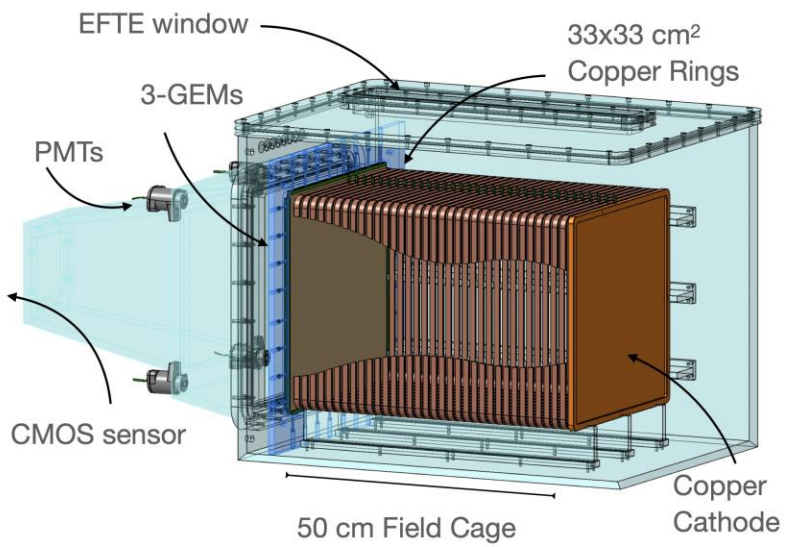


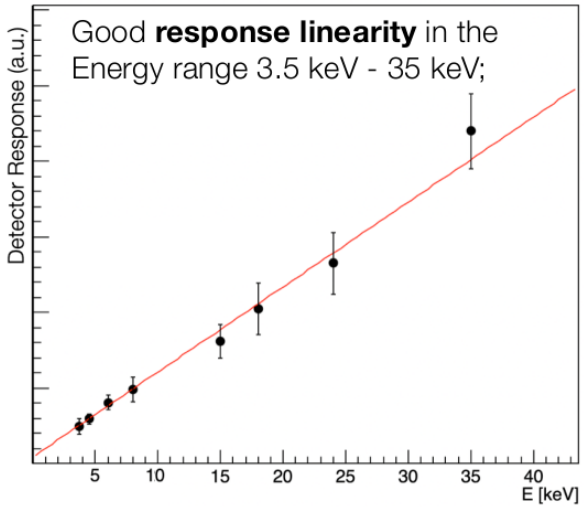
650 mbar, 12.5cm distance

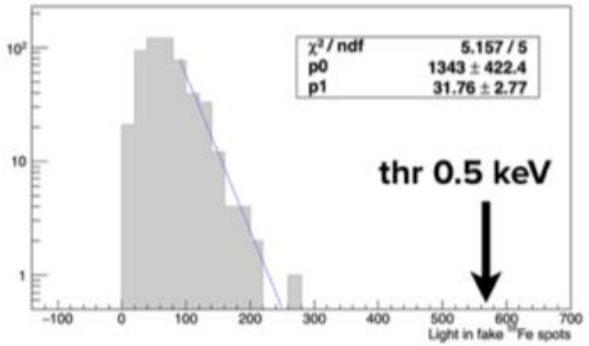
- In gain conditions with same light integral in ED and NID, we found **half the diffusion** with the addition of SF_6
- Complete set of data under analysis, paper in preparation

The LIME prototype

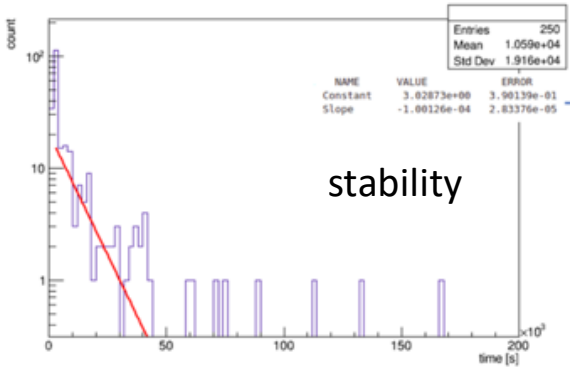
- 50 liters sensitive volume
- He:CF_4 60/40 atm.pressure
- Triple GEM amplification
- 33×33 cm^2 readout area, 50cm drift
- 1sCMOS camera + 4 PMT





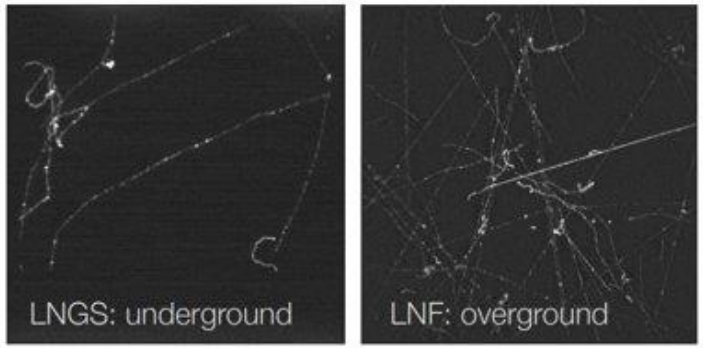


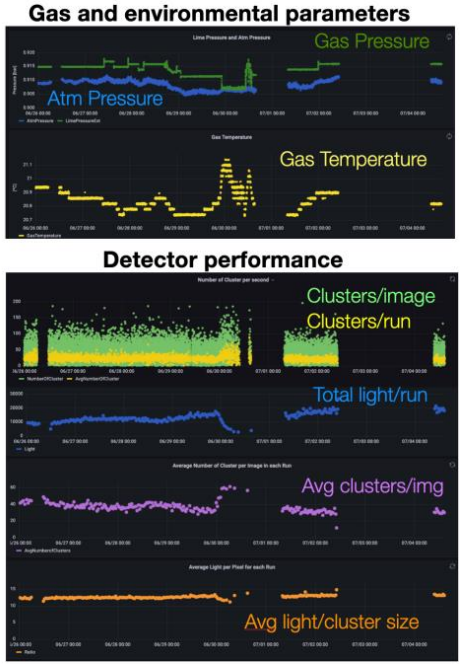
- **Stability** tested for over a month at LNF (<2.7 spikes/hr)
- **Low threshold** 0.5keV (<10 fake events/yr)
- **Linearity** of response tested with X-ray sources between 3.5keV and 35keV
- Data/MC comparison gave good consistency
- Energy resolution ~14% at 6keV (^{55}Fe)

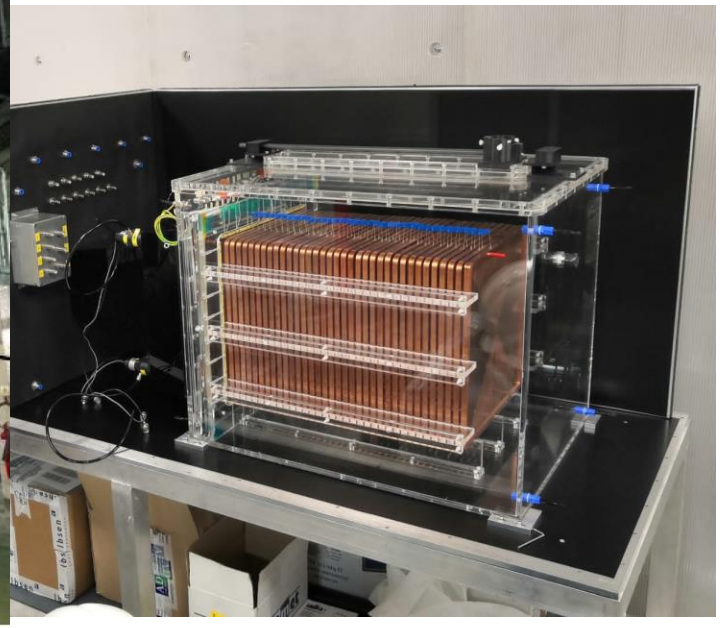


LIME underground at LNGS

- **Installed** in February 2022 in tunnel between Hall A and Hall B
- I took part in the setup of the monitoring system
- Operated continuosly during the summer with **remote shifts**
- **Remote control** of gas, DAQ, HV and environmental sensors
- Now stopped for a malfunctioning in gas system







LIME underground at LNGS

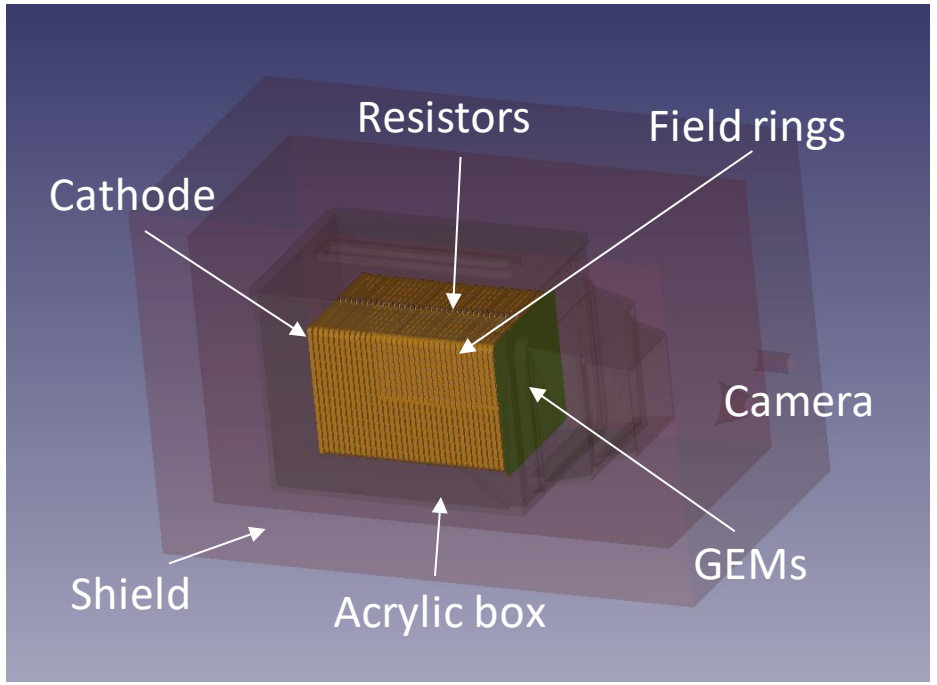
From last year's MC background simulations, the shielding design was finalised
LIME data taking underground will take place in different phases

- **No shield**:
  - Periodic calibration with ^{55}Fe X-ray source, NR test measurement with AmBe source, background measurement
- **6 cm of copper**:
  - Background measurement and periodic calibration
- **10 cm of copper**:
  - Background measurement and periodic calibration
  - Measurement of the **fast neutron flux** underground
- **10 cm of copper + 40 cm of water**:
  - Final test of LIME operation in the conditions of the future Dark Matter experiment

I performed a complete MC simulation of all expected background sources

Background sources

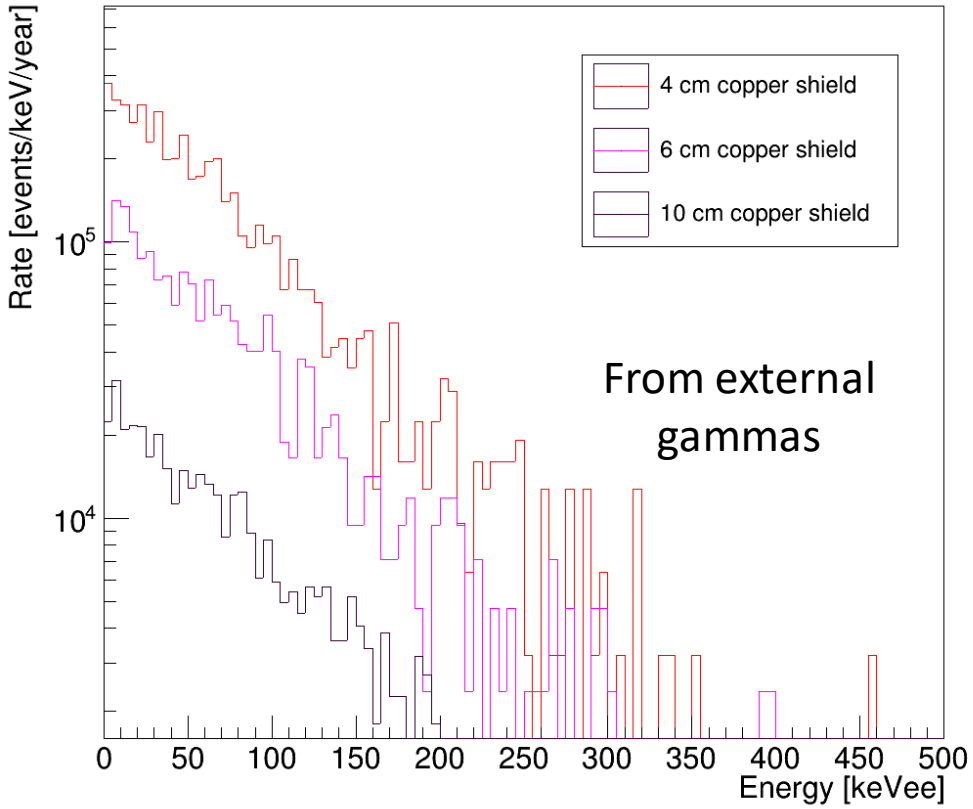
- **External**: gammas and neutrons produced in the surroundings of the lab
  - *Re-evaluated* with final shielding geometry
  - Energy spectra as measured in the underground lab (gammas measured by Sabre, neutrons from [1])
- **Internal**: radioactivity of detector's components and copper shielding
  - GEMs, copper field cage, ceramic resistors, copper cathode, acrylic box, sCMOS camera
  - OPERA copper radioactivity measurement taken as reference for the shielding
  - All main components' activity was measured underground
- **Other**: radiogenic neutrons produced in the copper shielding



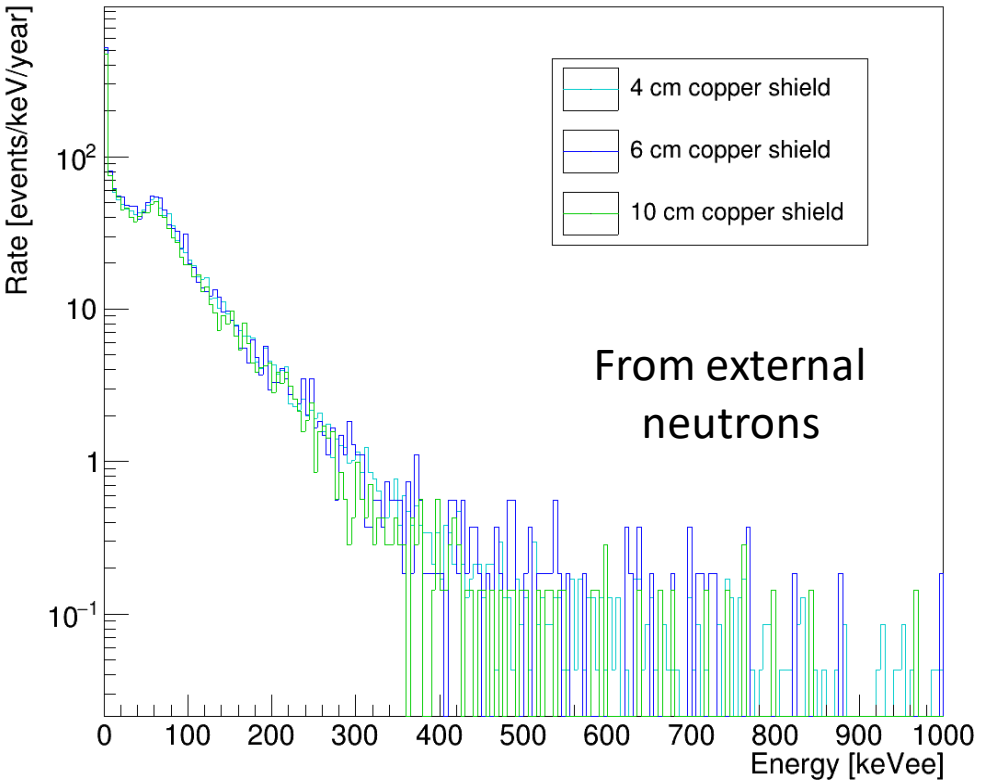
LIME CAD design, main background inducing components

[1] P. Belli et al., Il Nuovo Cimento A vol. 101, p. 959-966 (1989)

LIME background - external



4 cm of Cu: $2.68(6)\times10^7$ ER/yr
6 cm of Cu: $9.5(3)\times10^6$ ER/yr
10 cm of Cu: $1.98(5)\times10^6$ ER/yr



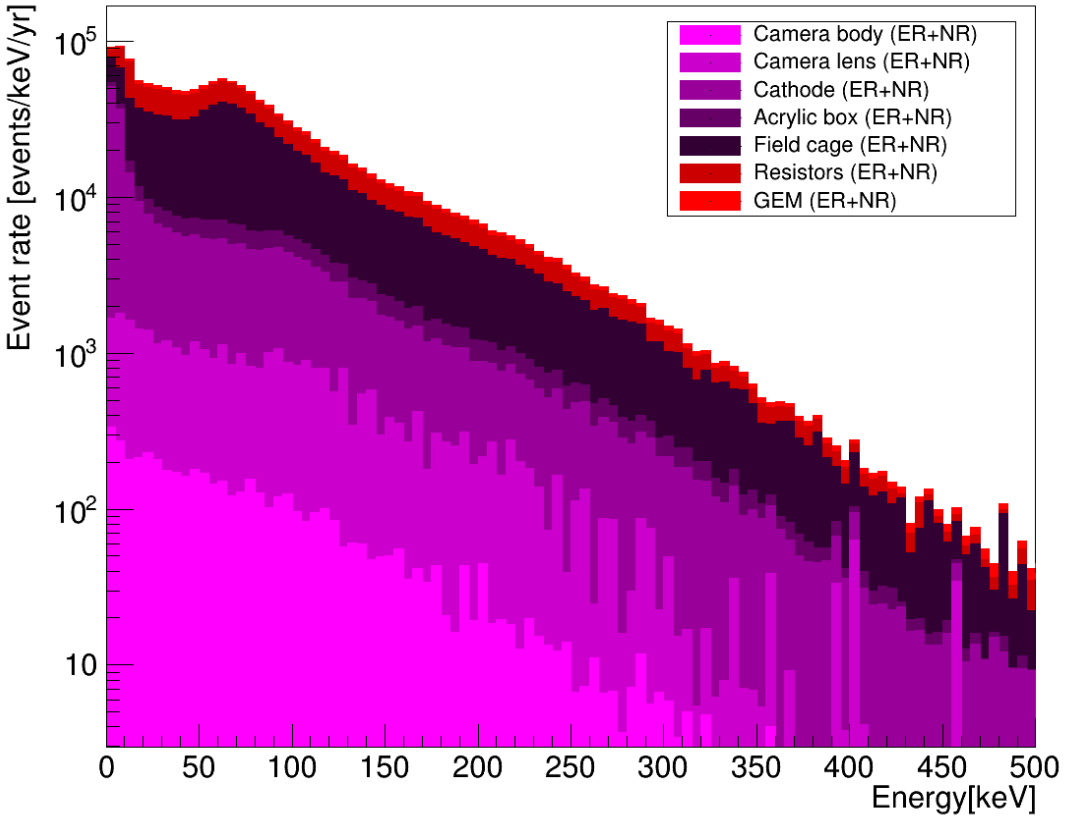
4 cm of Cu: 1020(15) NR/yr
6 cm of Cu: 1190(30) NR/yr
10 cm of Cu: 1130(30) NR/yr

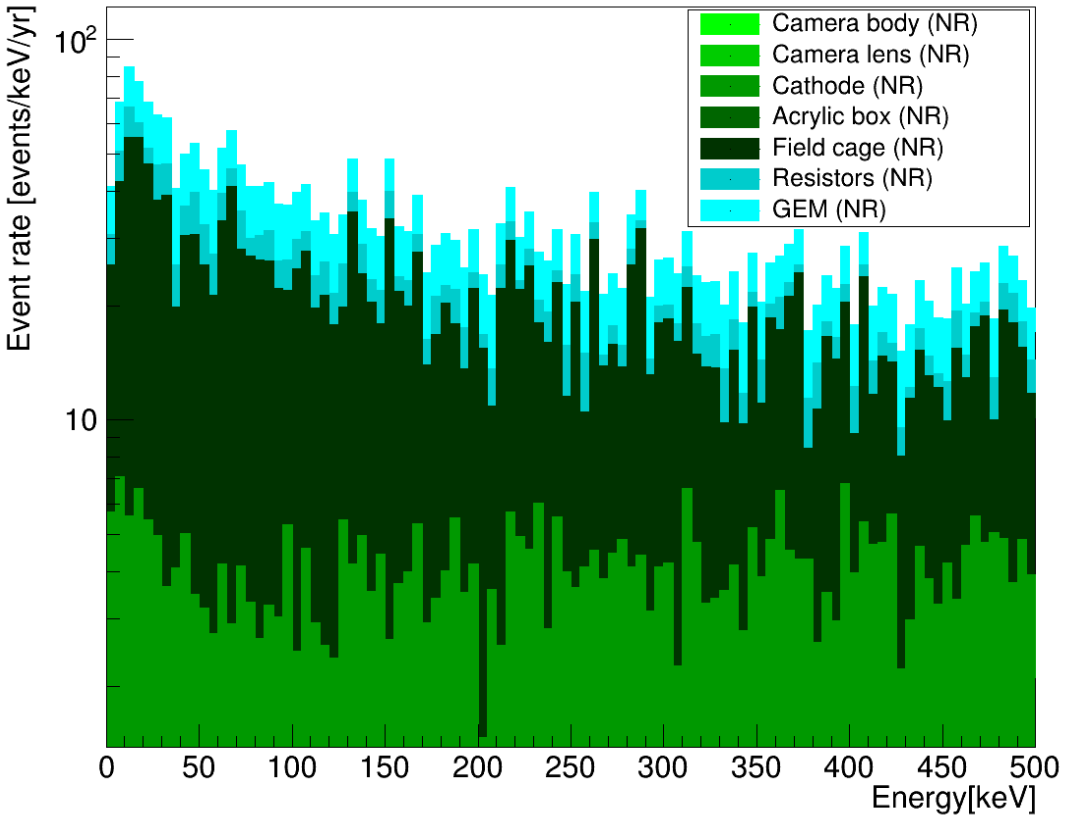
LIME background - internal

- All main components of the detector were measured underground at LNGS by M.Laubestein
- For each isotope I simulated the induced background in the detector

	Radionuclide	Field Rings	Cathode	Resistors	GEM	Acrylic	Camera body	Camera lens
^{238}U chain	234Th	<2,10E-01	<2,10E-01	1,99E+01	1,63E-01	-	3,16E+00	4,22E+00
	234mPa	<7,70E-02	<7,70E-02	2,19E+01	-	-	-	-
	226Ra	<1,30E-03	<1,30E-03	2,16E+00	3,25E-02	<3,50E-03	8,13E-01	1,92E+00
	210Pb	-	-	5,94E+02	-	-	-	-
^{232}Th chain	228Ra	<1,10E-03	<1,10E-03	3,50E+00	<3,09E-02	<5,00E-03	9,49E-01	3,61E-01
	228Th	<1,30E-03	<1,30E-03	3,36E+00	<1,56E-02	<4,50E-03	9,49E-01	3,65E-01
^{235}U chain	235U	<1,60E-03	<1,60E-03	3,37E-01	<1,58E-02	-	1,81E-01	1,45E-01
Other	40K	<6,00E-03	<6,00E-03	<1,78E+00	<3,58E-01	<3,50E-02	8,59E-01	5,15E+01
	137Cs	<4,70E-04	<4,70E-04	<7,35E-02	<8,13E-03	-	4,07E-02	<2,67E-02
	60Co	<5,70E-04	<5,70E-04	<7,73E-03	<7,48E-03	-	<5,42E-03	<4,64E-02
	58Co	9,00E-04	9,00E-04	<3,10E-03	-	-	-	-
	Mn54	<4,30E-04	<4,30E-04	<3,27E-03	-	-	-	-
	La138	-	-	-	-	-	-	2,44E+00

LIME background - internal



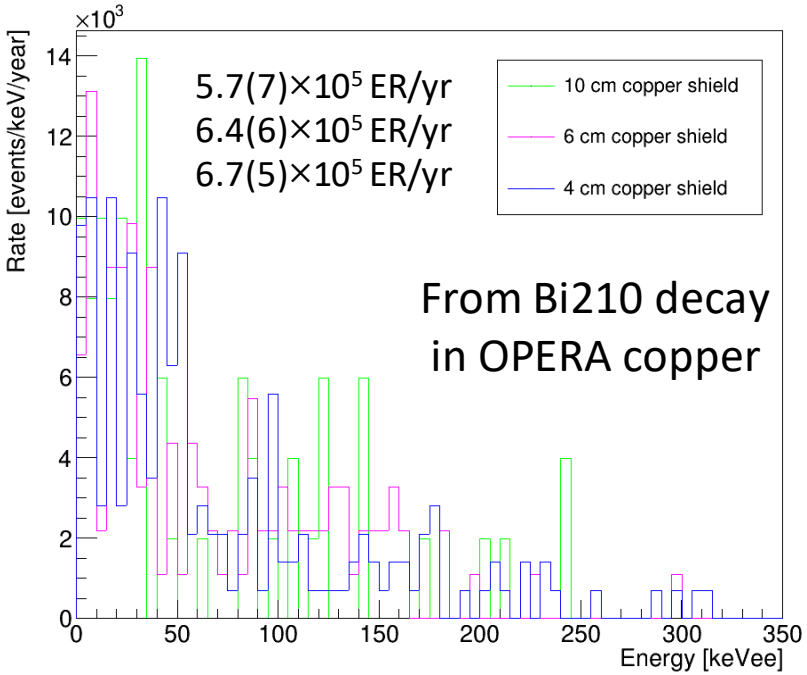


Expected background rate from radioactivity:

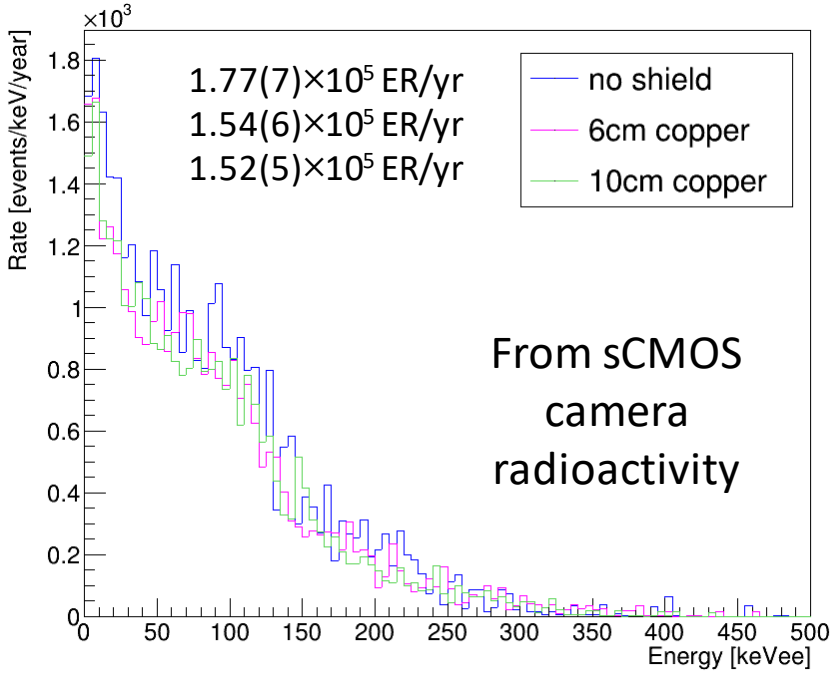
$7.34(3)\times10^{6}$ ER/yr (main contributions from copper rings and cathode and resistors)

$6.1(1)\times10^{4}$ NR/yr (main contributions from rings, cathode, resistors and GEMs)

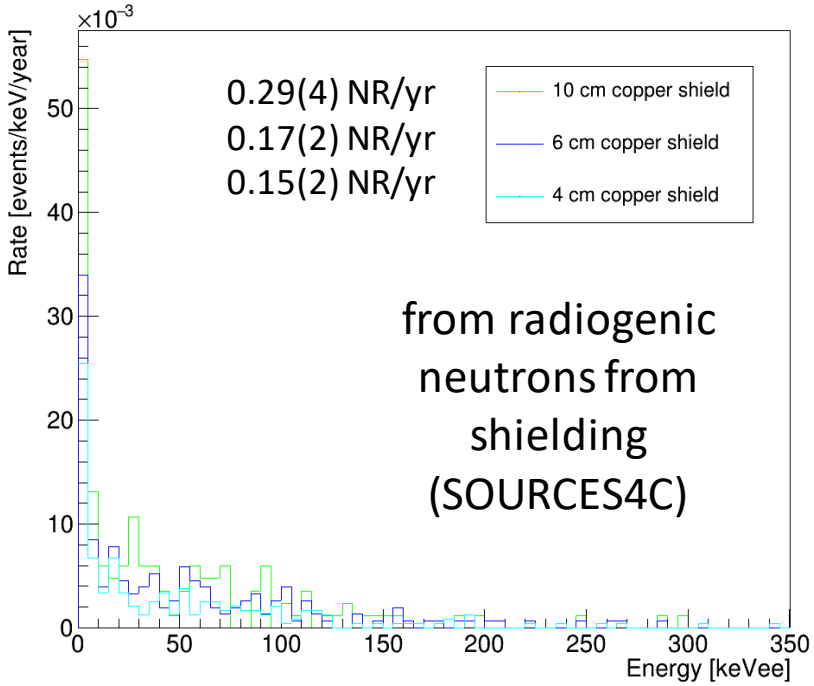
LIME background – other



No significant difference between different shield thicknesses (self-shielding effect)

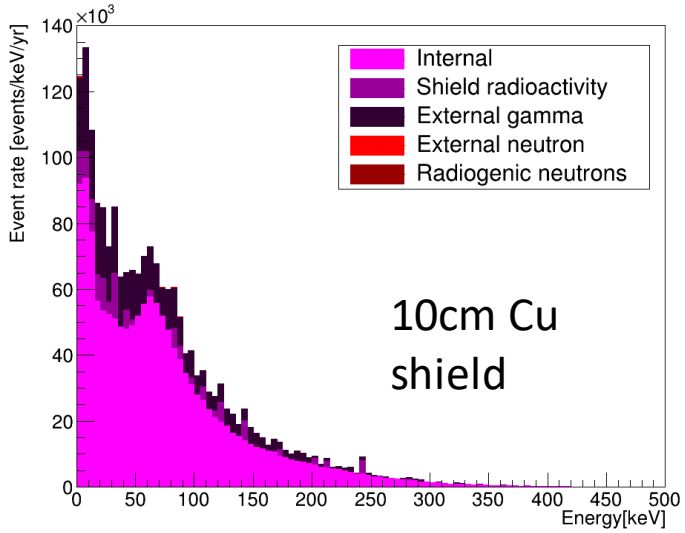


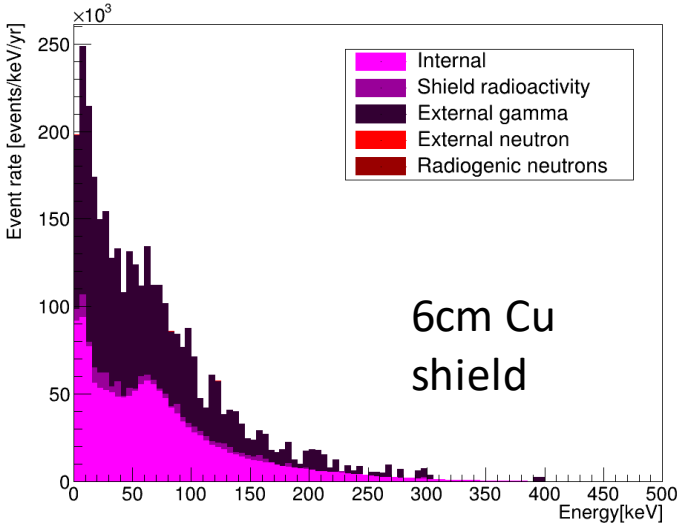
Camera shield doesn't decrease effectively the rate – need different lens

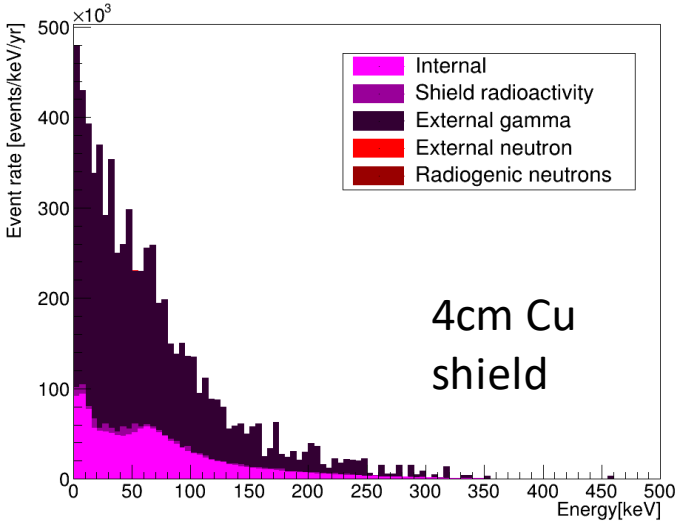


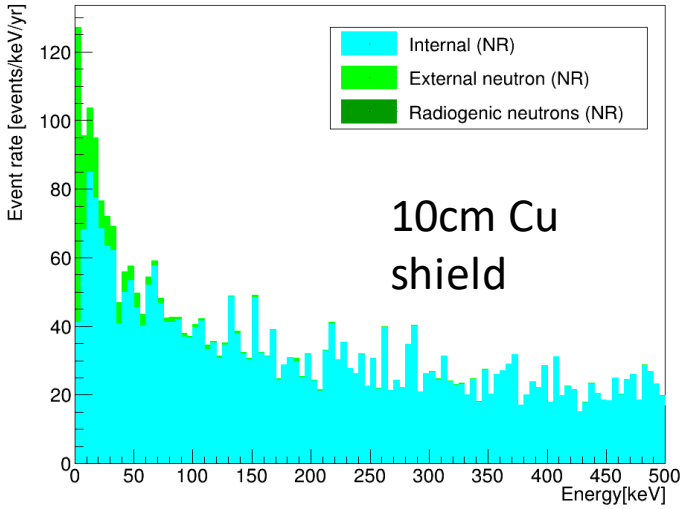
Less than one event per year is expected for all shield thicknesses

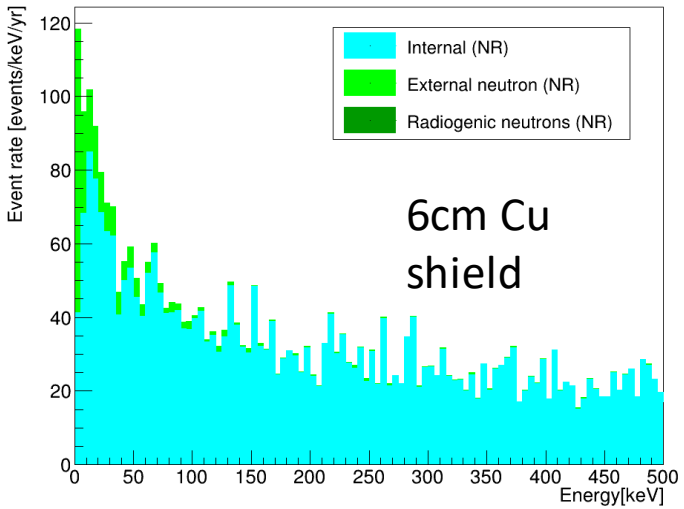
Background in LIME

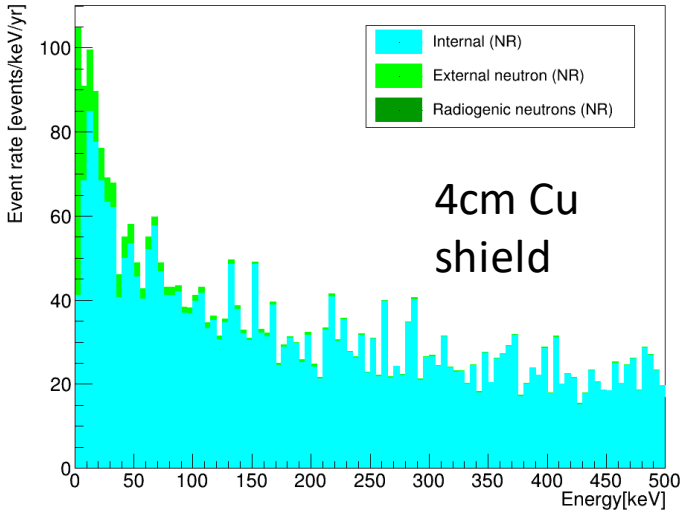




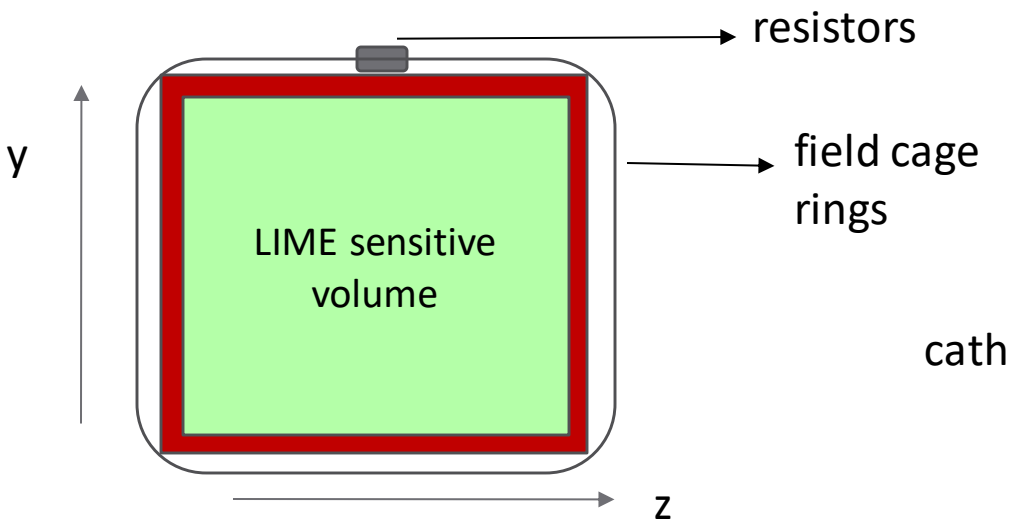


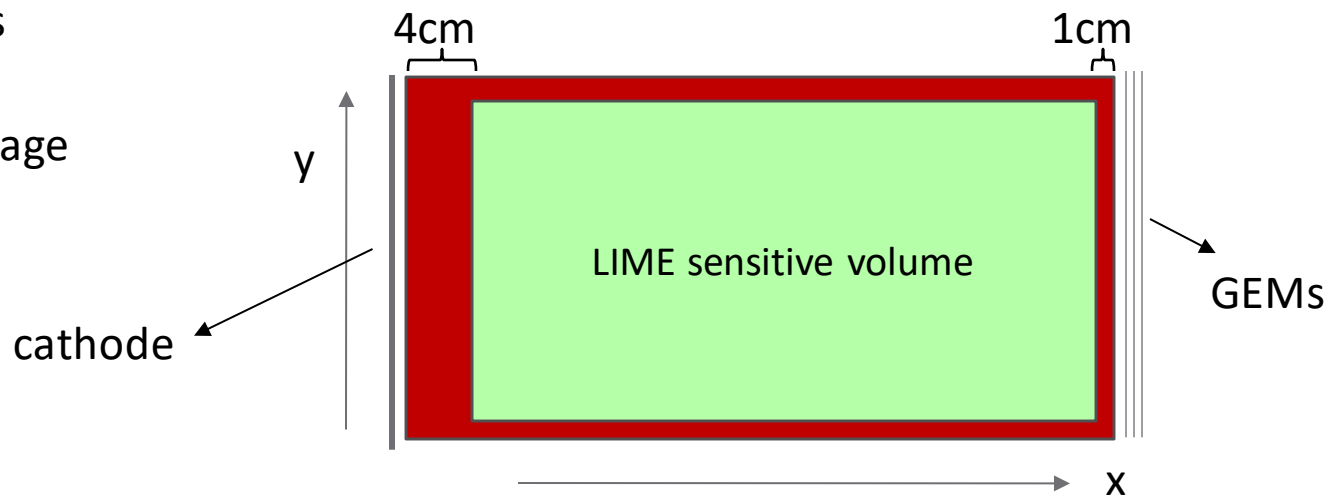




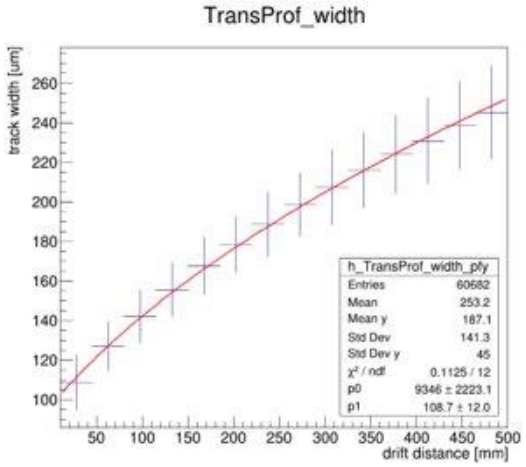


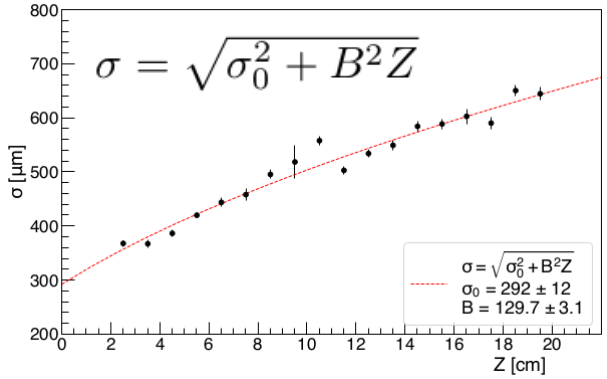
Detector fiducialization





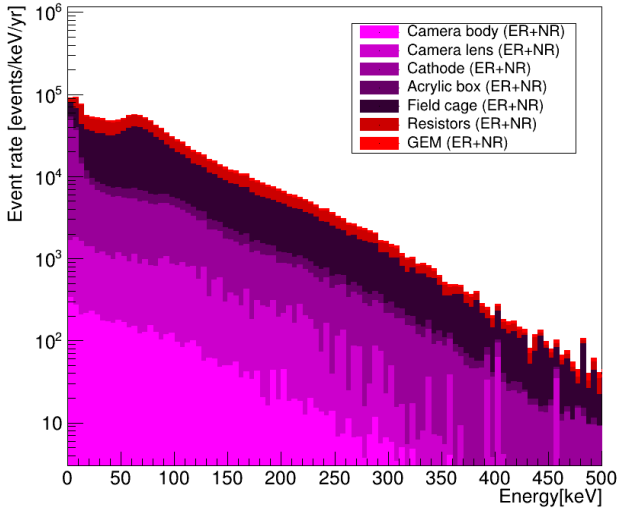
- Tracks close to the borders of the sensitive region can be excluded from analysis
- From track shape we can retrieve the distance from the GEMs (diffusion dependent on z)

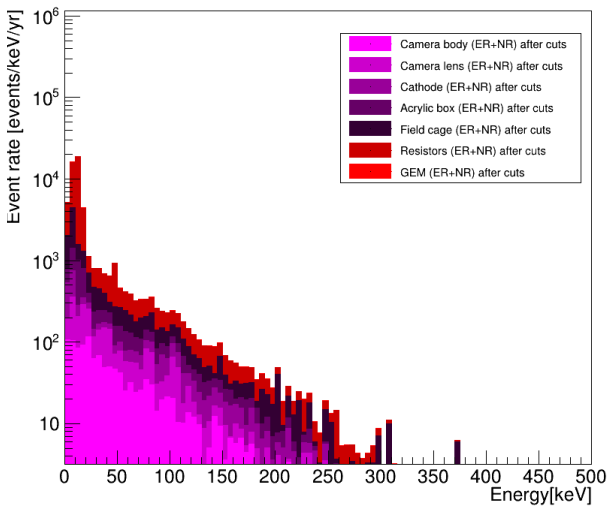




V.C. Antochi et al, NIMA 999 (2021) 165209

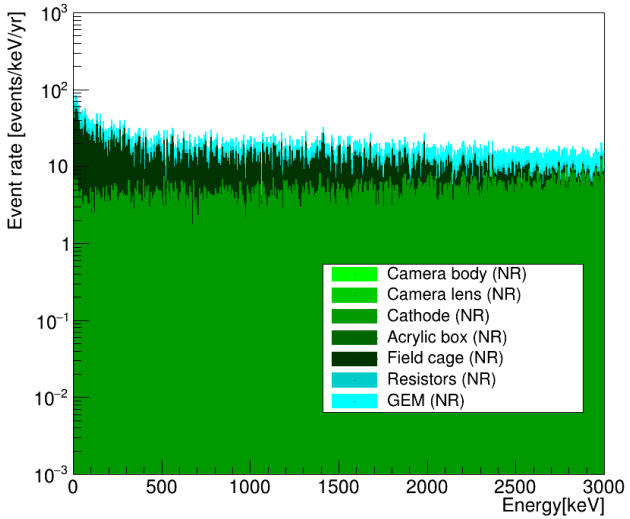
Detector fiducialization

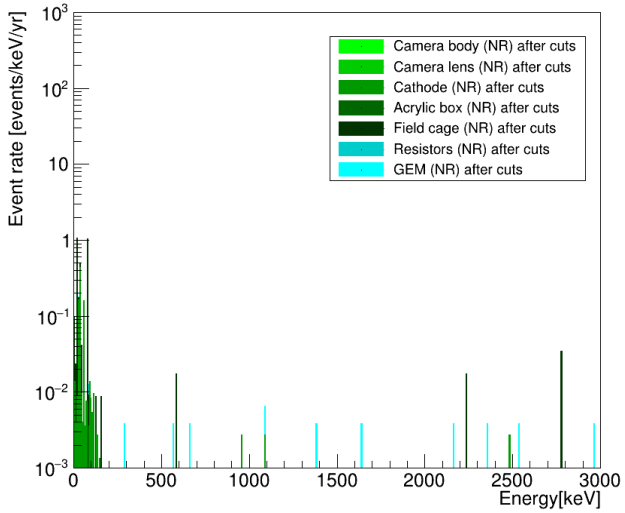




No cuts: **7.34(3)×10^6** ER/yr
After cuts: **2.8(4)×10^5** ER/yr

96% of events are excluded

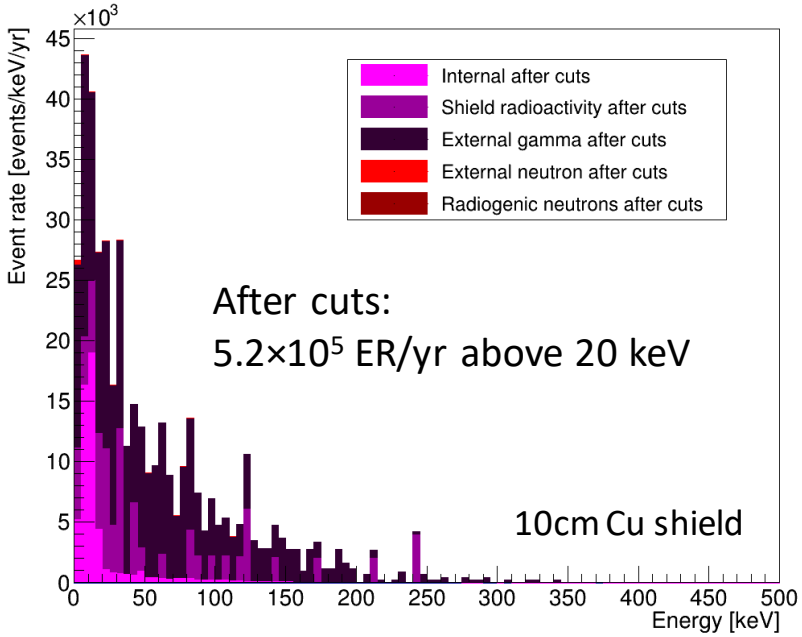


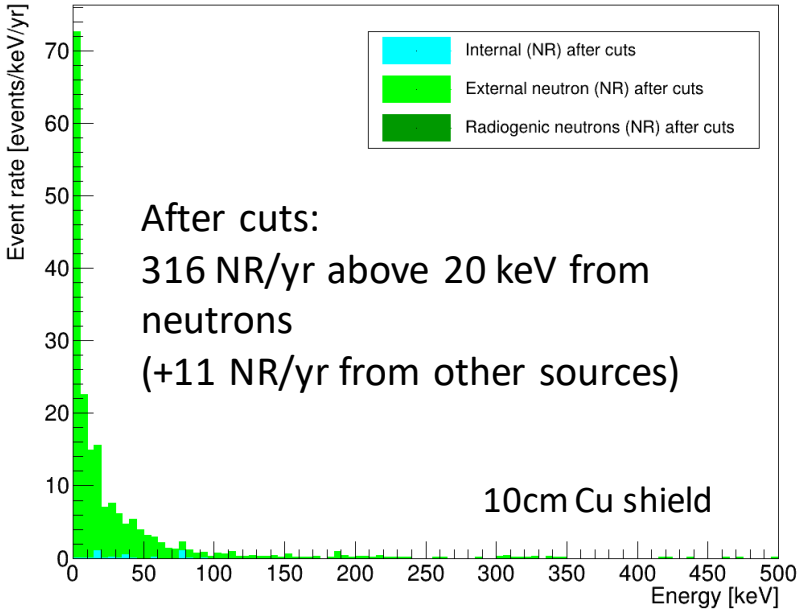


No cuts: **6.1(1)×10^4** NR/yr
After cuts: **17(1)** NR/yr left

99.97% of events are excluded

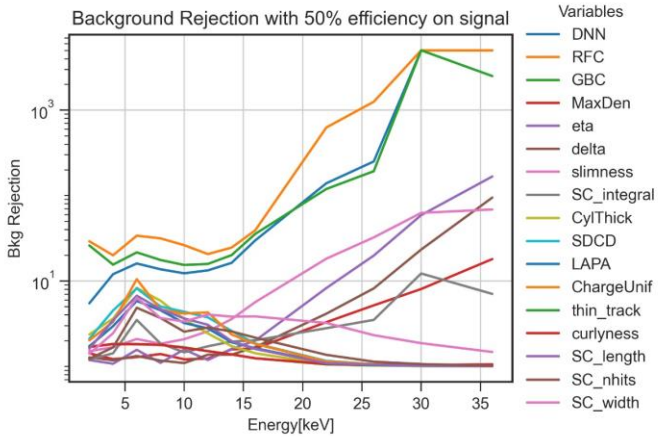
Background rates after cuts





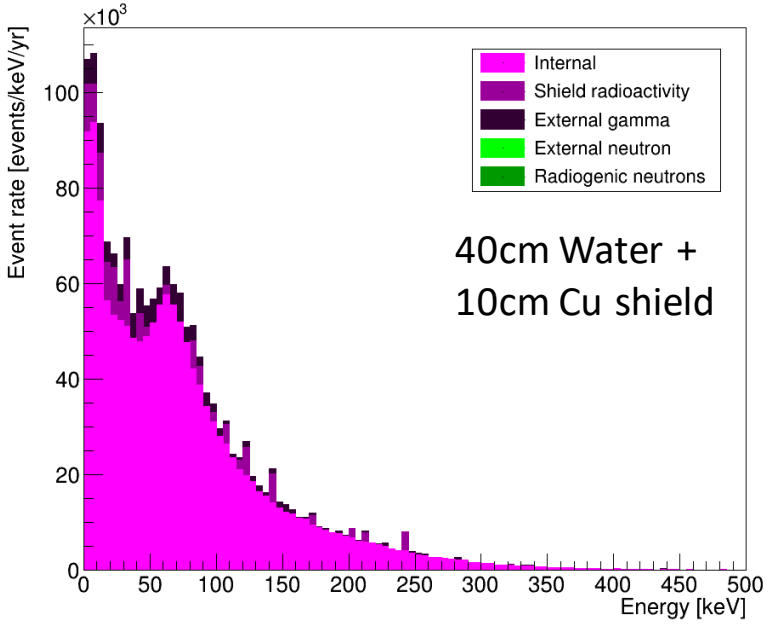
Neutron flux measurement underground:

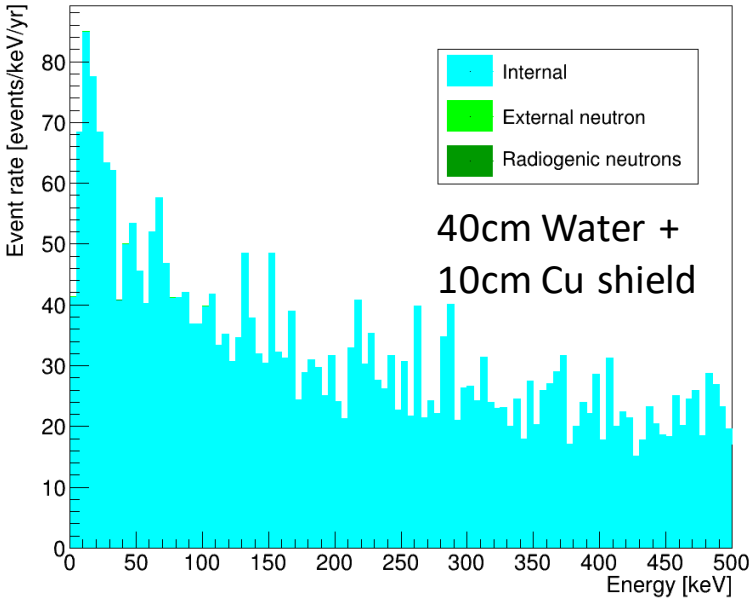
- Before cuts: **930** NR/yr above 1 keV (+**61000** background NR/yr)
- After cuts: **772** NR/yr above 1 keV (+**16** NR/yr from other sources)



- Above 20 keV we expect our capability of rejecting the ER background to rise significantly (see Atul's talk)
- After the fiducial cuts, we expect ~105 NR induced by external neutrons above 20 keV in 4 months of data taking ("background free")
- An optimization of the fiducial cuts requires a complete characterization of the detector's response

Background in LIME





External background with water shielding:

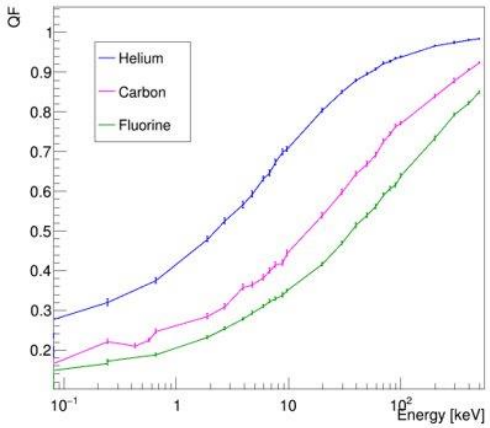
$5.13(1)\times10^5$ ER/yr (from gammas)

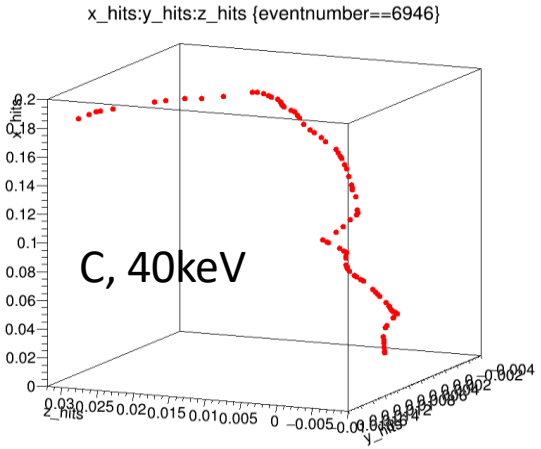
2.34(1) NR/yr (from neutrons)

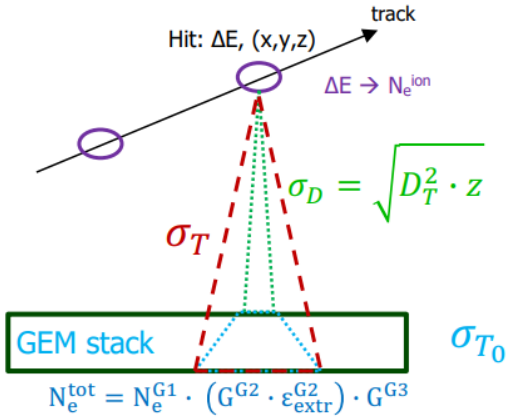
- Final phase of data taking underground: 40cm layer of water tanks to shield from neutrons
- Test of detector operation under real DM experiment conditions
- Background is dominated by events induced by radioactivity of the detector itself – internal background can be characterized and studied to reduce it in the next phase of CYGNO experiment (CYGNO_04)

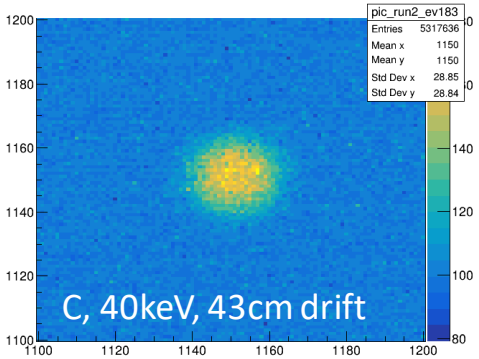
Nuclear recoils track simulation

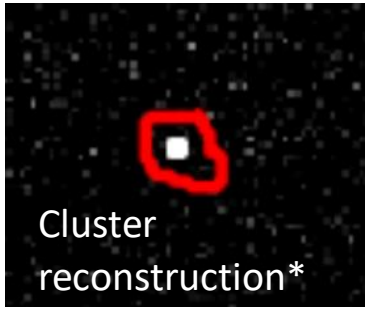
- **SRIM** (Stopping and Range of Ions in Matter) - used to simulate the passage of ions (NR) in He:CF_4 60/40
- Post processing necessary to get a 3D energy deposition profile
- Ionization quenching factor (QF) computed as $$QF(E) = \frac{E_{ionization}}{E}$$
- QF is then used to account for only the visible energy in 3D profile
- Output profiles are saved in a ROOT tree with same structure as our GEANT4 ER simulation to be used as input for production of simulated sCMOS images









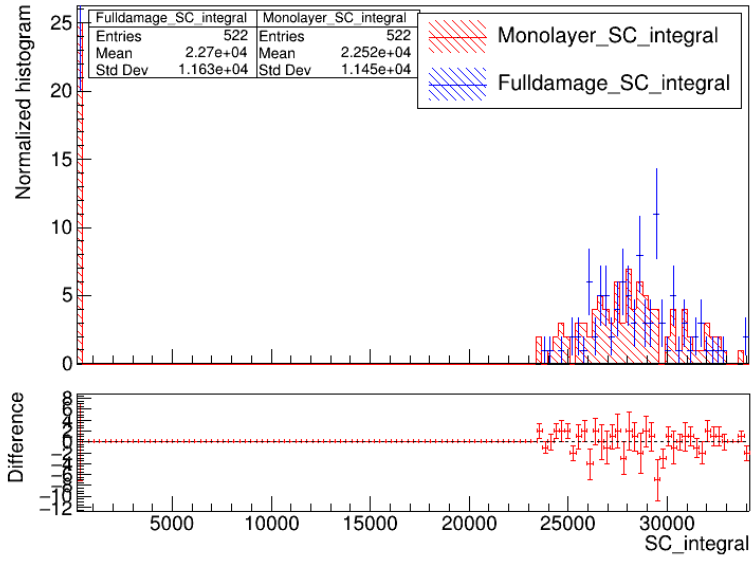


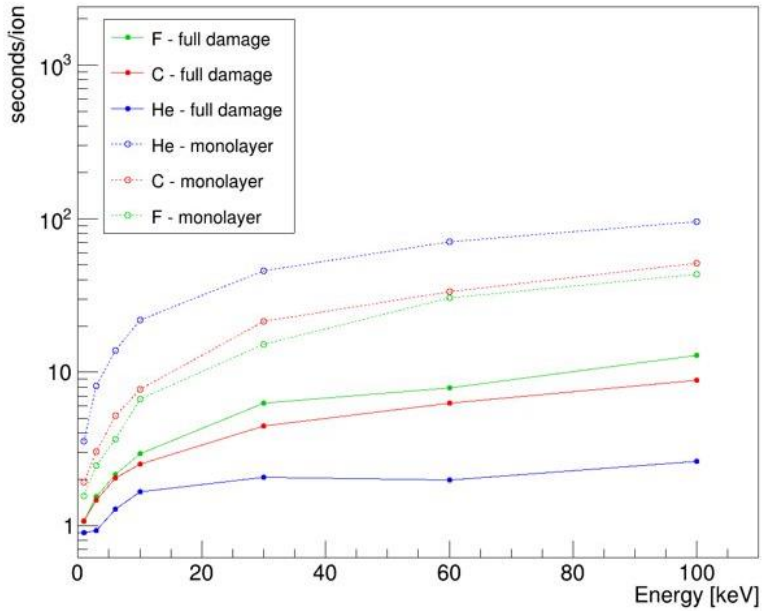
*E. Baracchini et al. JINST 15 (2020) T12003

Track simulation optimization

We need a high statistics sample – I improved the code and defined the method to run SRIM+post processing code, cutting down the time of execution by more than 90% with respect to last year

- Faster SRIM mode: less information on the ion collisions but 7 times faster
  - All variables used for discrimination resulted consistent within 1 sigma (100 ions sample)
- Pysrim (https://pypi.org/project/pysrim/) package allows execution through a Docker image – 50%-60% faster



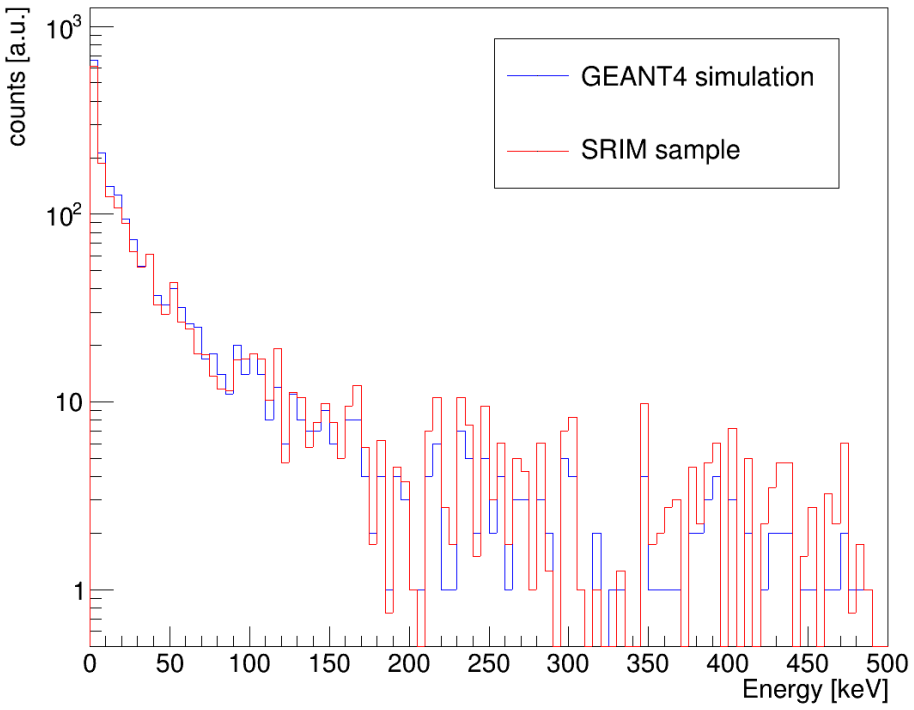


- I am also working on our new computing system based on INFN cloud (CYGNO is a beta tester)*
- It will allow parallelization of SRIM simulation

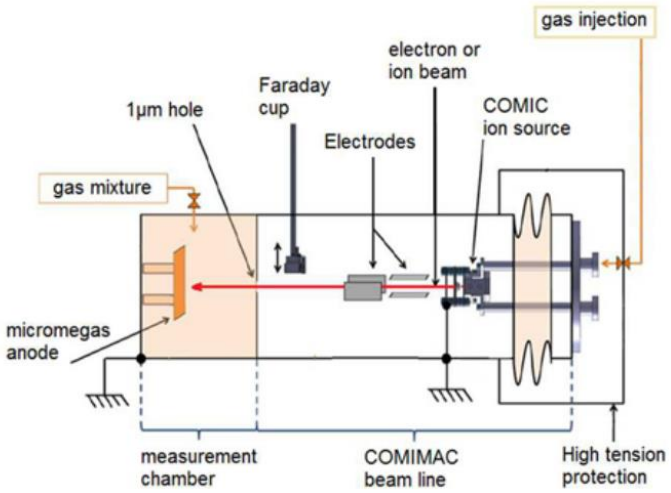
*F.Amaro et al., PoS ISGC2022 (2022), 021

Background tracks simulation

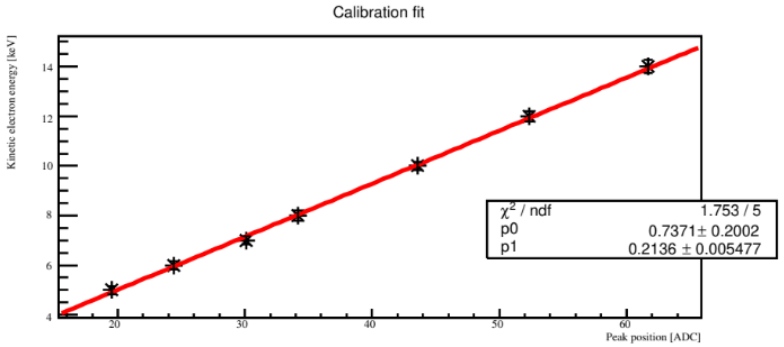
- I started working on the production of a **NR sample** following the **energy spectrum** of GEANT4 simulation of the background
- I will produce and analyse the simulated images reproducing the correct rate and **spatial and angular distribution** of NR and ER
- Optimization of **fiducial cuts**, development of **unfolding** method to retrieve the neutron spectrum, **data/MC comparison**
- I will produce a large sample of NR over broad energy range to study the **energy and angular resolution**, also necessary to test ER/NR discrimination capability and optimize the MC simulation



Quenching factor measurement



- Ionization quenching factor estimate is of primary importance: energy calibration, sensitivity reach computation, MC simulation (directionality and head-tail, ER/NR discrimination)
- Few experimental information are available for ion interactions at low energy (<100 keV) → many experiments rely on SRIM
- Measurement of QF done in different gases with COMIMAC facility [1,2,3]
- **Helium QF measurement in He:CF4 60/40 will be done at LPSC in Grenoble at the end of October**



- Calibration test runs already done at different pressures with electron beam

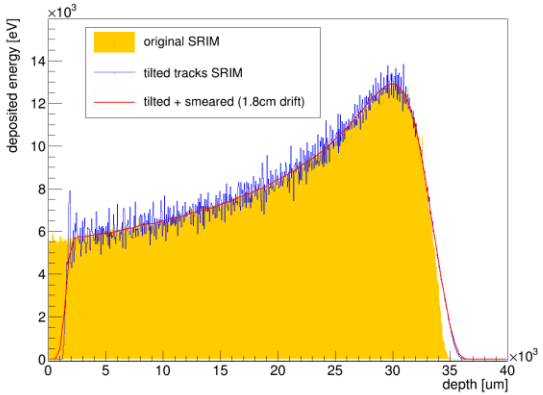
[1] B. Tampon et al., EPJ Web Conf., Vol 153, p.01014, 2017
[2] D. Santos et al., http://arxiv.org/abs/0810.1137, 2008
[3] N.-G. Collaboration et al., http://arxiv.org/abs/2201.09566, 2022

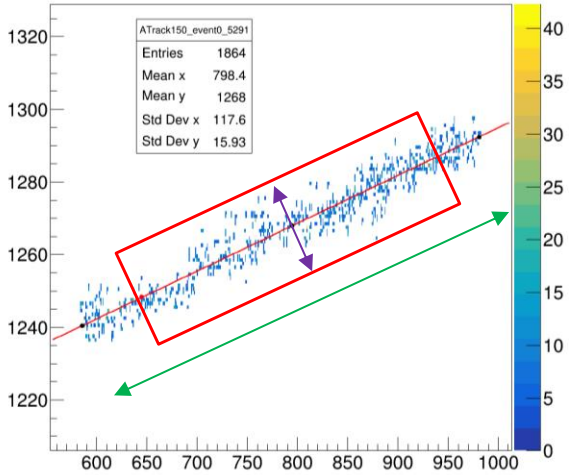
Outlook

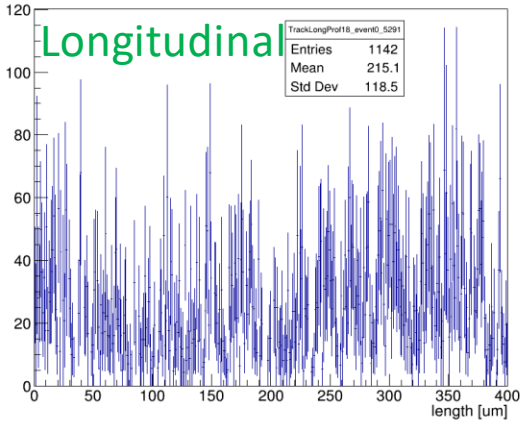
- Produce a realistic **sample of images reproducing the underground background** in LIME (optimize cuts, unfolding test for neutron measurement)
- Produce a **large sample of simulated NR** tracks to study energy and angular resolution (optimization of image simulation parameters is needed)
- Neutron detection test with **AmBe** source underground
- **Data/MC comparison** of LIME underground data (with increasing shielding thicknesses)
- **Neutron flux measurement** underground with the full 10cm copper shielding
- **Thermal neutron detection R&D** with MANGO
  - $n + {}^{3}\mathbf{He} \rightarrow p + {}^{3}H + 764keV$
  - ${}^{14}N + n \rightarrow {}^{14}C + p + 625keV$
  - ${}^{14}N + n \rightarrow {}^{11}B + \alpha - 159keV$ (1.7MeV thr.)
- **Ionization Quenching Factor measurement** at COMIMAC facility

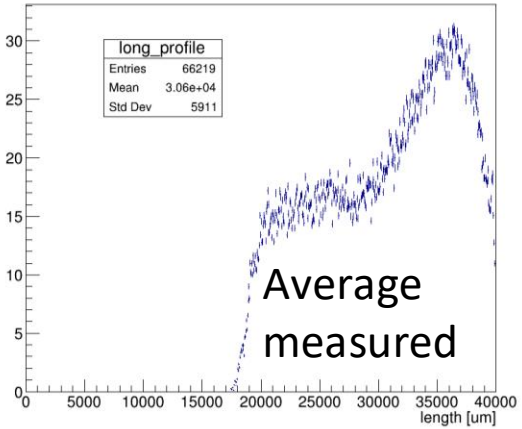
Thank you

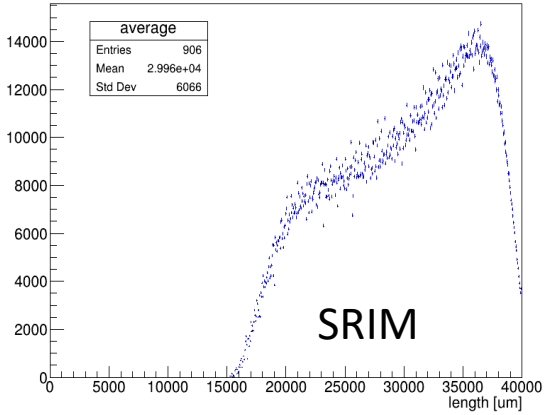
Alpha analysis











- By superimposing many tracks we can see the Bragg peak
- I tried to reproduce the shape of the profiles with MC simulation
- I simulated with SRIM the He ions at 5485 keV and 5442 keV (1000 each)
- I cut the first part of the track (as in data, depending on source distance), and I rotated the track in cones of different apertures
- Then I constructed the profile in a form comparable with data
  - Calibrated with integral over 1cm before Bragg peak
  - Need for full image simulation to account for all effects (saturation, diffusion)