Monte Carlo simulation of CYGNO, an optical readout TPC for directional Dark Matter search

CPAD Instrumentation Frontier Workshop 2021

F. Di Giambattista on behalf of the CYGNO Collaboration

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In synergy with INITIUM
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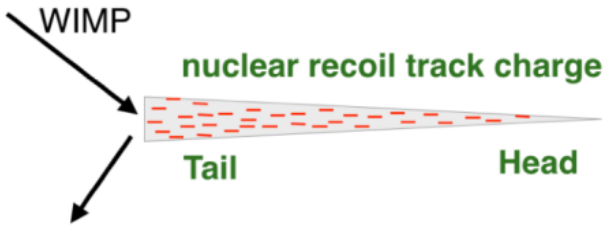
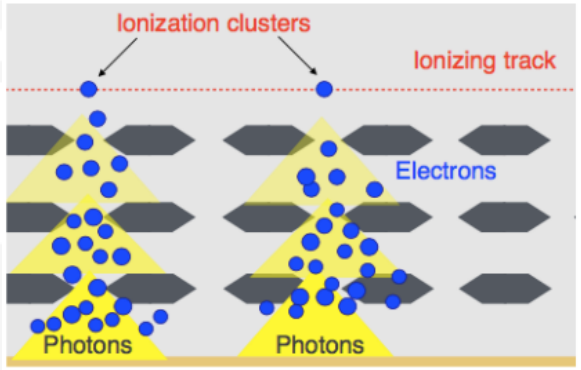
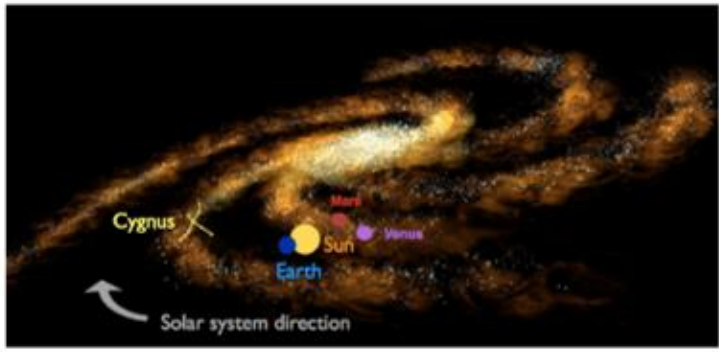
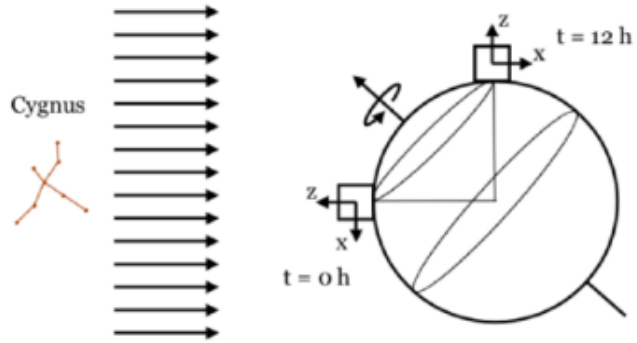
Detector concept

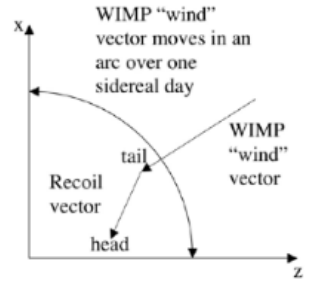




- Dark Matter directional search: unambiguous identification of WIMPs
- Gaseous TPC – He:CF_4, 60/40 @1atm, room temperature
- Triple-GEM amplification stage
- Optical readout: sCMOS + PMT
  - sCMOS: x-y tracking + energy measurements
  - PMT: z tracking + energy measurements
- Advantages: axial directionality + head/tail, background rejection, particle identification



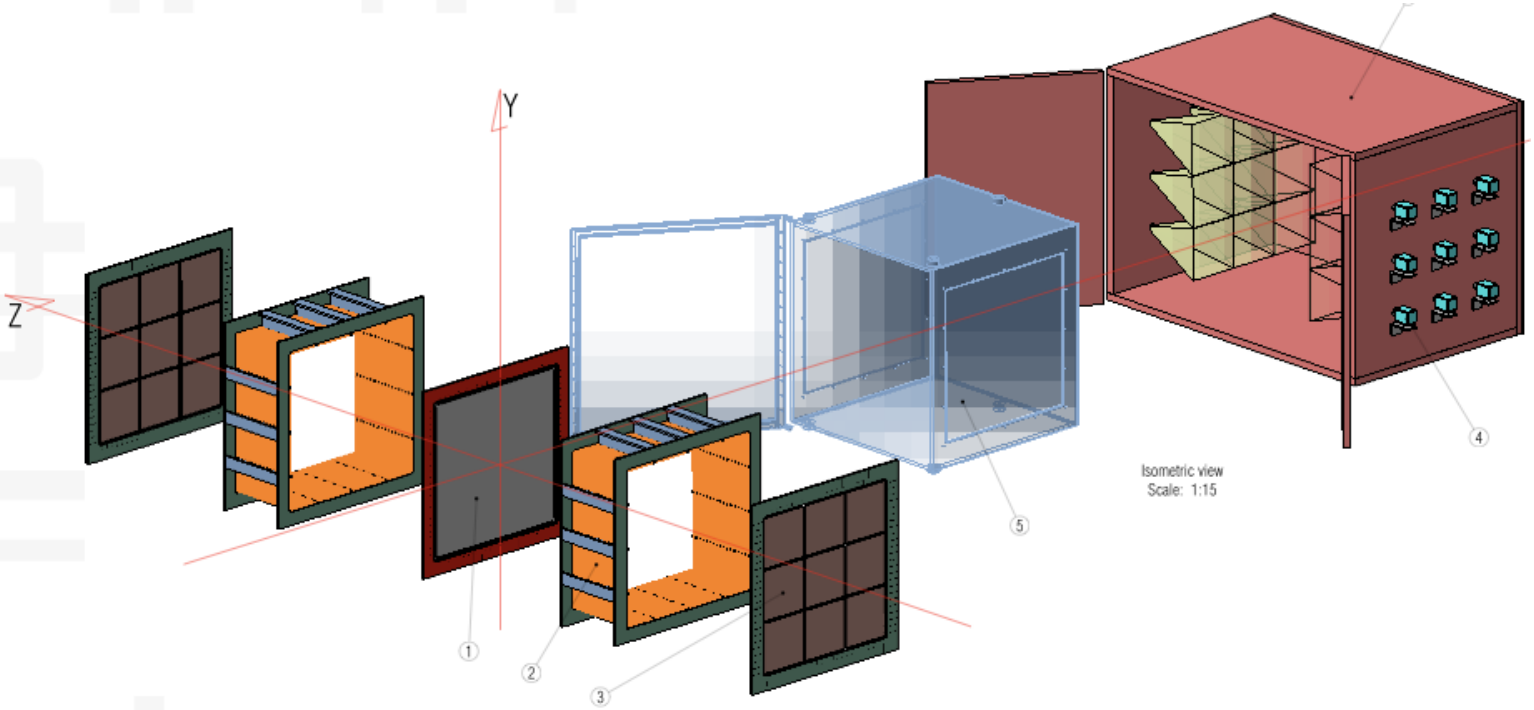


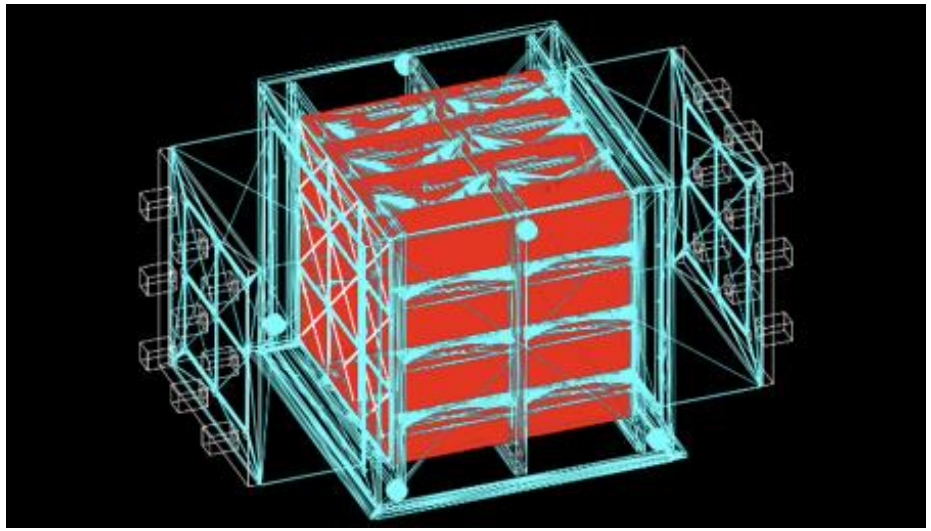


see D.Pinci's talk 18/03/21 for the details
Parallel session on Gaseous Detectors

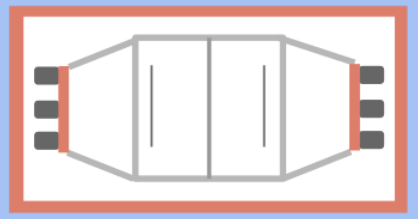
CYGNO background simulation

- Complete geometry imported in GEANT4 from CAD technical design
- We simulated external and internal background based on measurements performed at Laboratori Nazionali del Gran Sasso (LNGS) in Italy



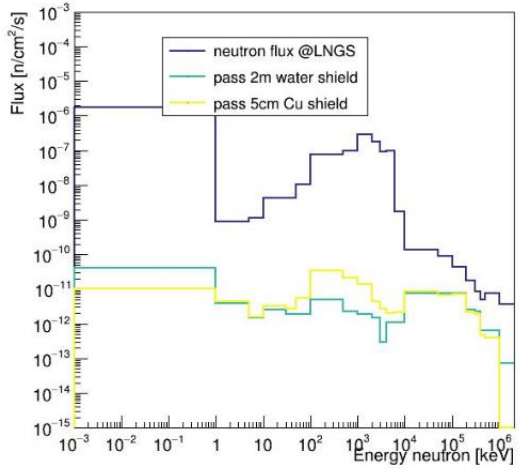


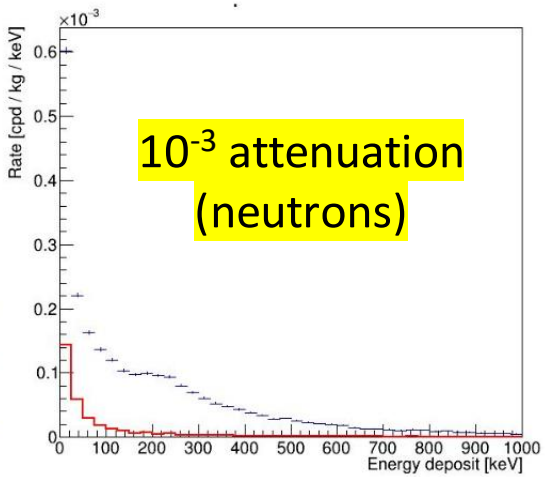
External shielding:



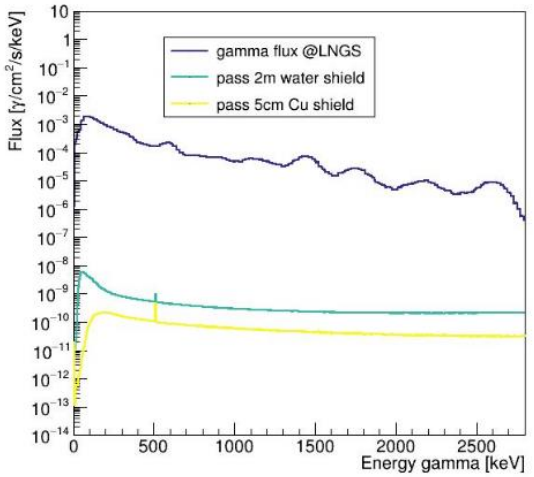
5cm of copper
200cm of water

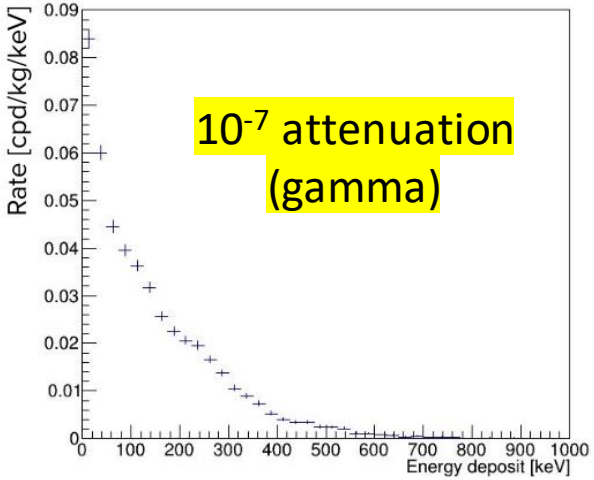
External background @LNGS



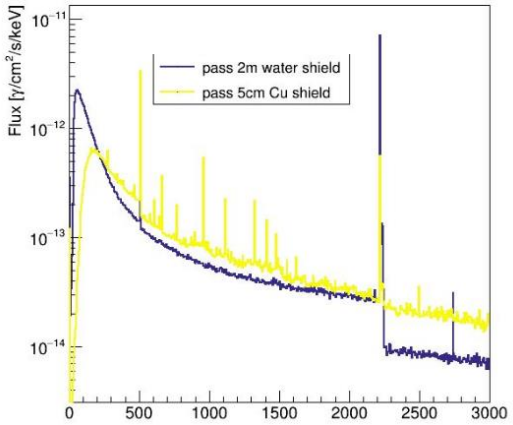


10^{-3} attenuation (neutrons)





10^{-7} attenuation (gamma)



Neutron flux @LNGS (Hall C) - measured by CUORE :
2.7×10^{-6} cm^{-2} s^{-1}
Rate of events:
7.1×10^{-4} cpd/kg/keV
= **8 NR/yr** (0-20 keV)

Gamma flux @LNGS (Hall C) - measured by SABRE :
0.56 cm^{-2} s^{-1}
Rate of events:
8.8×10^{-2} cpd/kg/keV = **10^3 ER/yr** (0-20 keV)

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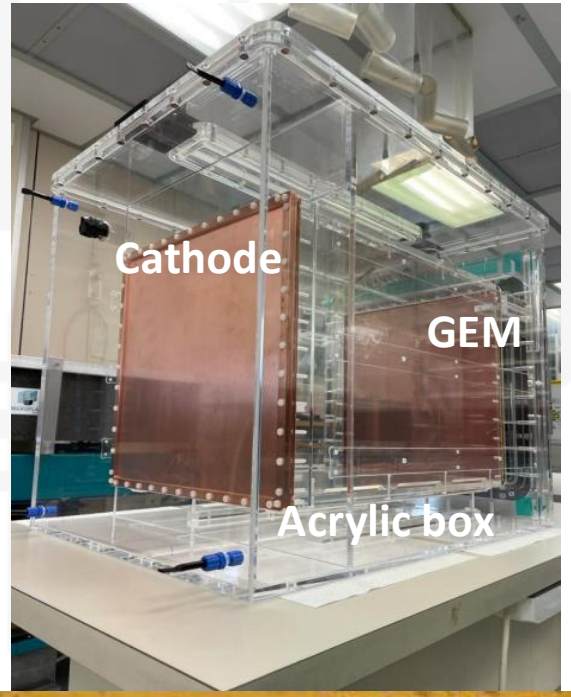
Internal background



Main radioactivity contributions come from

- sCMOS camera lens
- sCMOS camera body
- GEMs
- Acrylic box

We are working on the substitution of the most radioactive components

Different cameras were measured

Each internal component of the camera is being measured

Thanks to M.Laubenstein

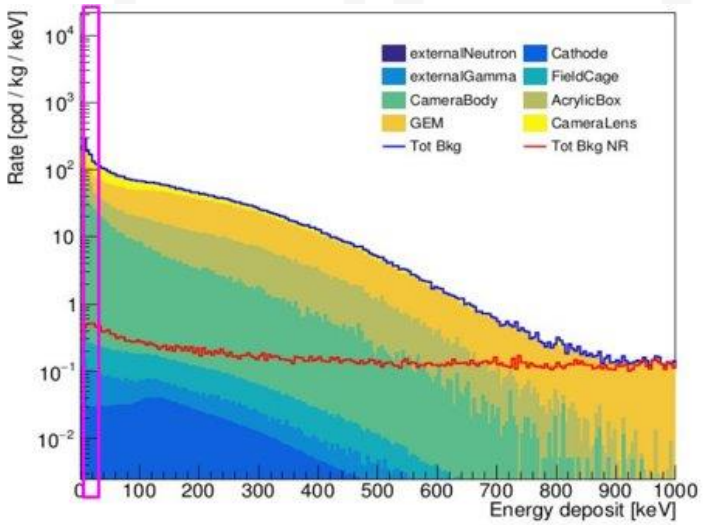
Camera Body Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	3.16E+00

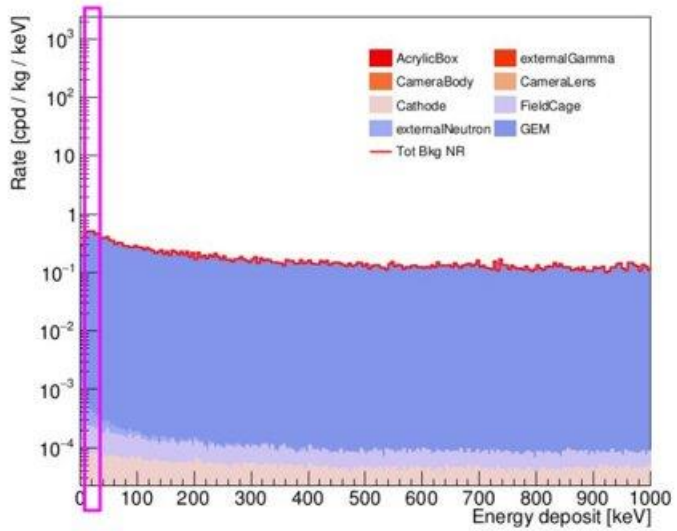
Camera Lens Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	4.22E+00
K40	M	5.15E+01

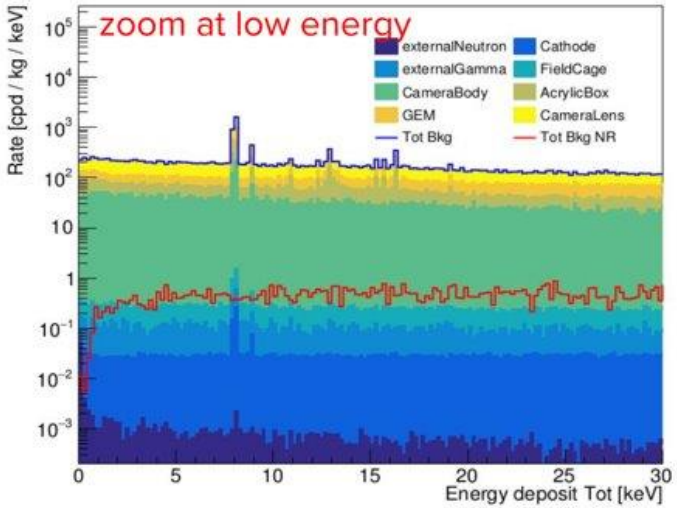
GEM	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	1.63E-01
K40	L	3.58E-01

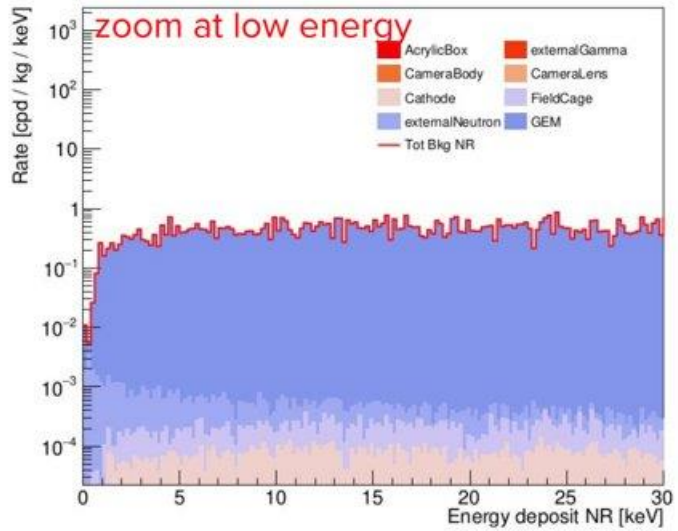
Acrylic Box	Limit/Meas	Activity (Bq/kg)
K40	L	3.50E-02

Internal background





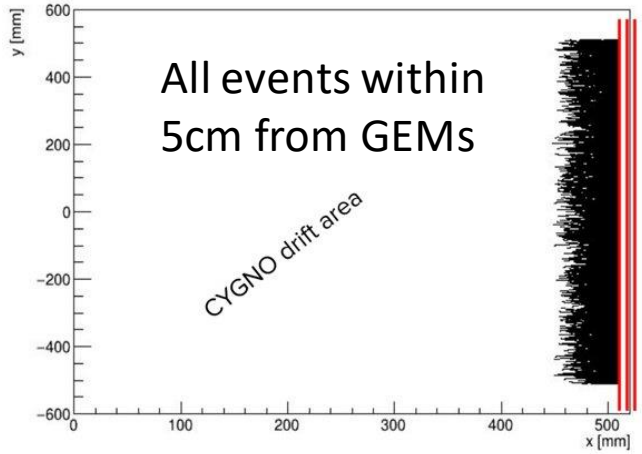




Before background rejection

	ER/yr 1-20 keV	NR/yr 1-20 keV
GEM	5.14E+05	5.07E+03
AcrylicBox	4.34E+05	-
CameraBody (shield)	4.46E+05	-
CameraLens (shield)	9.83E+05	-
External Gammas (200Water + 5Cu)	9.75E+02	-
Total	**2.38E+06**	**5.07E+03**

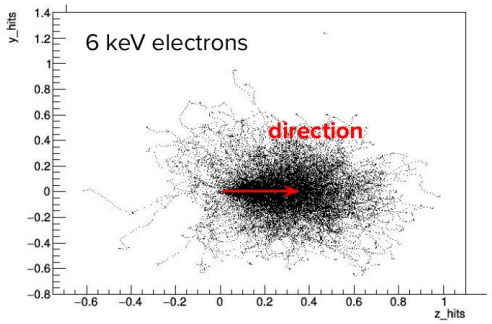
Fiducialization

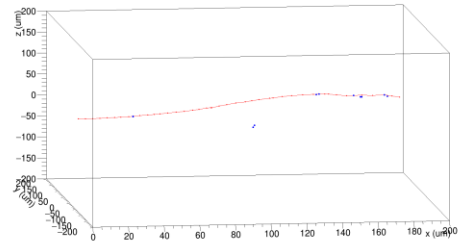


Simulation of tracks

Simulation of recoils:
- GEANT4 (for ER)
- SRIM (for NR)

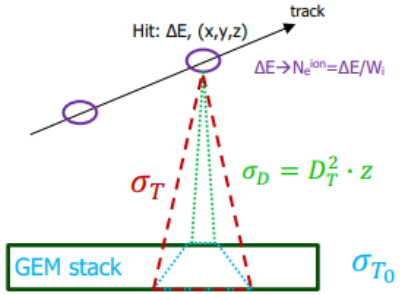
Electrons (GEANT4) and He, C, F nuclei (SRIM) at low energy

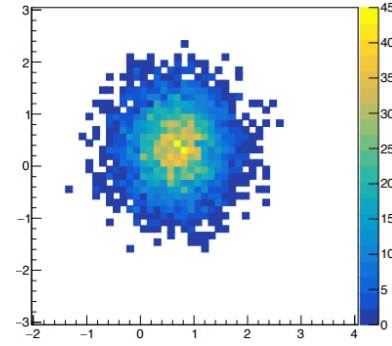




Production of **images**:
Diffusion + amplification + digitization

Images are produced taking into account diffusion and amplification of ionization electrons + the noise of the camera

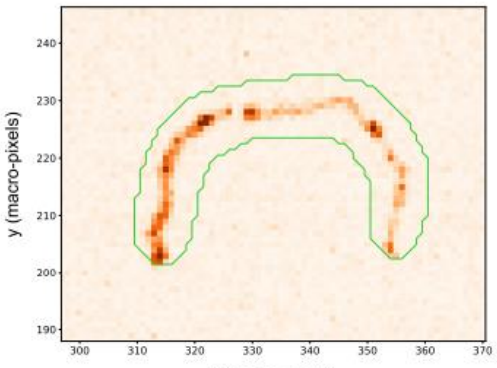




Track **reconstruction**:
Retrieve information from the image

Images are analysed using an intensity-based DBSCAN clustering algorithm

JINST 15 (2020) no.12, T12003



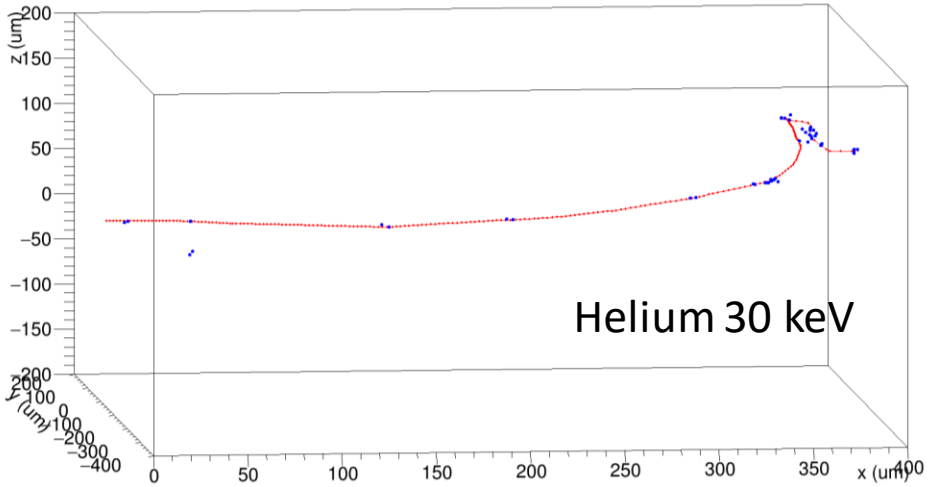
Meas. Sci. and Tech. 2020

NR simulation with SRIM

- Low energy nuclei lose only a fraction of their energy in the production of electron-ion pairs
- The ionization energy fraction is given by the quenching factor, calculated as

$$QF(E) = \frac{E^{ioniz}}{E} \qquad E^{ioniz} = \int_0^{x_{max}} \left[\left(\frac{dE}{dx} \right)_e + \left(\frac{dE}{dx} \right)_n \right] dx$$

- For each track, we multiply the deposited energy by the QF to obtain a 3D ionization profile for each ion species



We are developing an alternative approach, applying $\frac{dQF}{dE}$ to the energy deposited along the track – to reproduce the correct ionization profile (and the head-tail effect)

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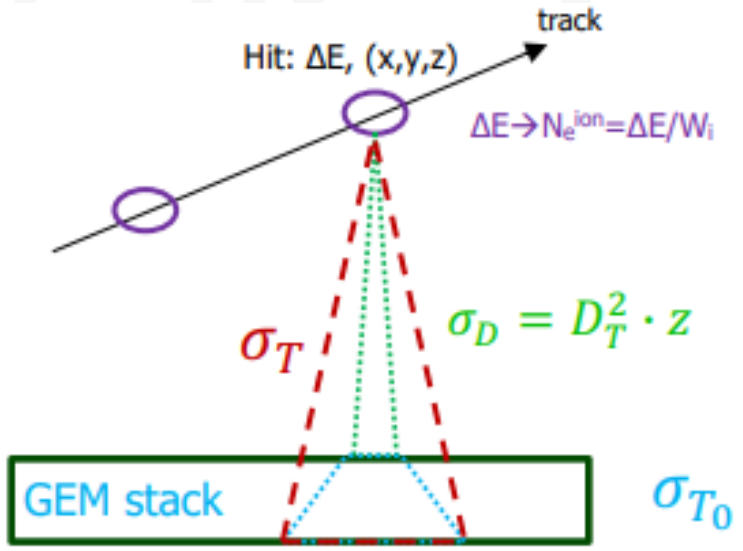
Diffusion and amplification



- The number of primary electrons is extracted from a Poisson distribution with mean ΔE/W (W=46.2 eV/pair from Garfield)
- Diffusion has two contributions

$$\sigma_T = \sqrt{\sigma_{T0}^2 \oplus D_T^2 \cdot z} \qquad D_T^{60/40} = 140\ \frac{\mu m}{\sqrt{cm}} \qquad \sigma_{T0}^{60/40} = (280 \pm 60)\ \mu m$$

- Electrons are amplified at the GEMs:
  - Multiplication factor at first GEM extracted from exponential distribution with mean $G_{GEM} = 123$; total number of electrons = $N^{G1}\ (G_{GEM})^2$

- Total number of photons extracted from Poisson distribution with mean $N_\gamma^{mean,tot} = N_e^{tot} \cdot 0.07\ ^{\gamma}/_{e}$
- Number of photons reaching the sensor depends on the solid angle $N_\gamma = N_\gamma^{tot} \cdot \Omega$ (depending on camera and detector parameters)

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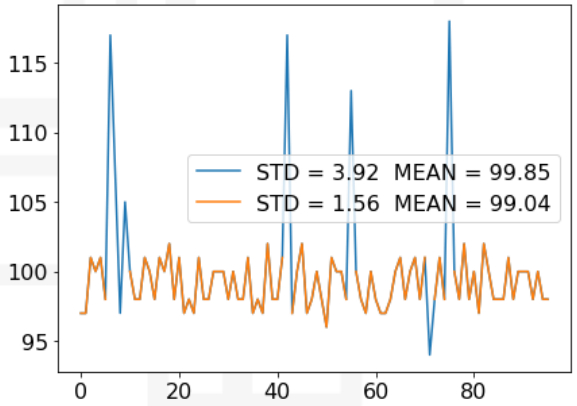
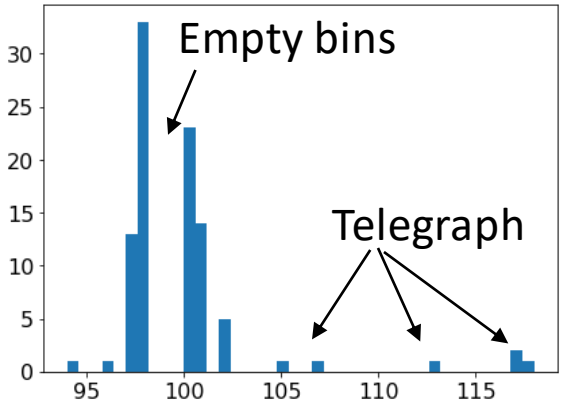
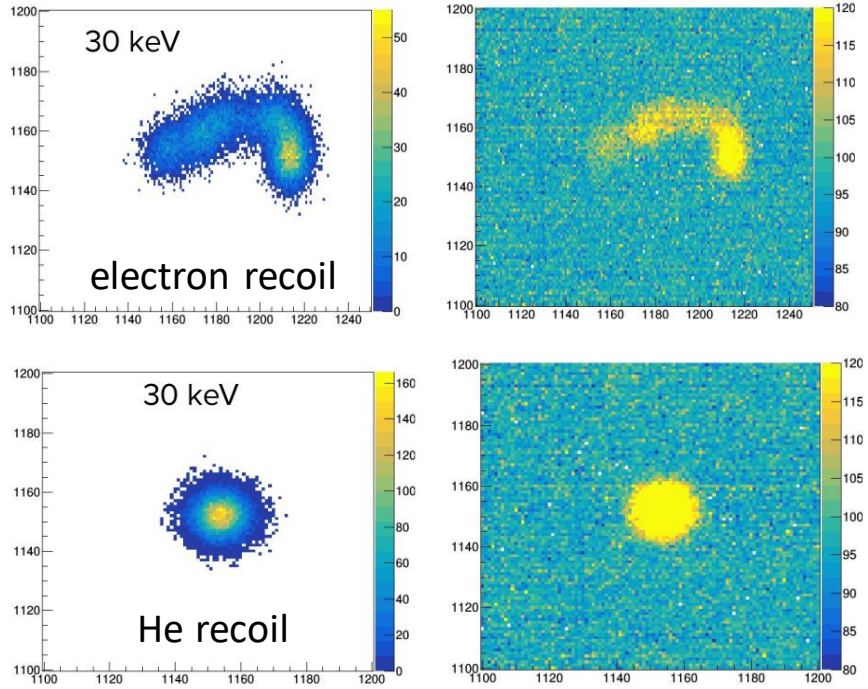
Digitized images and noise

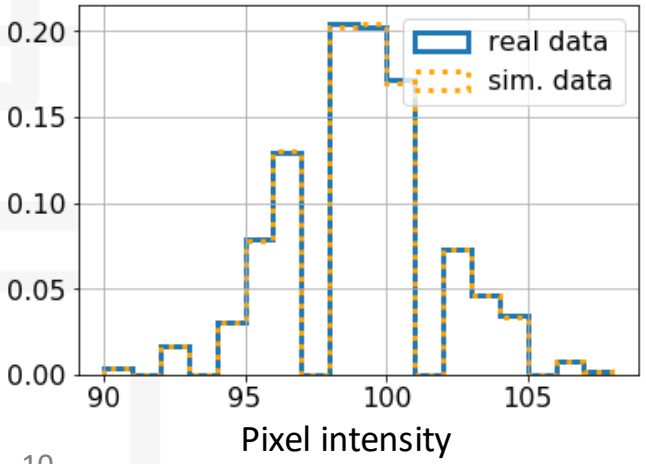
ORCA Flash sensor noise:

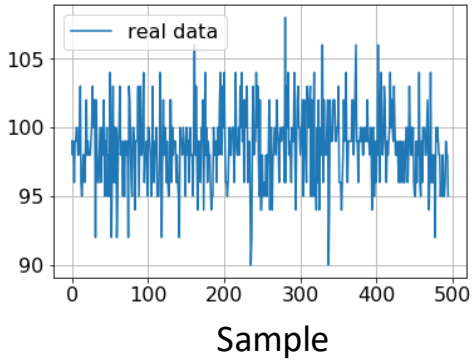


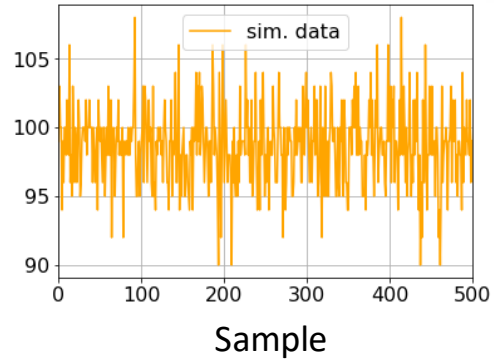




Simulation is directly based on data by reconstructing the ECDF of each pixel







Digitized images of simulated ER and NR, 30cm from GEMs, with and without noise

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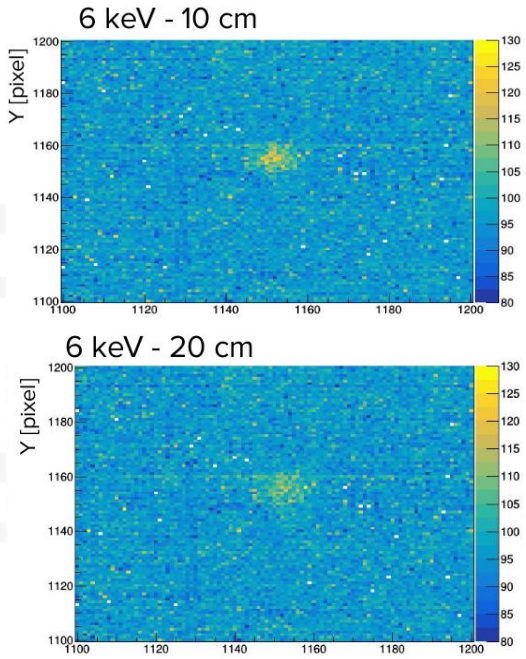
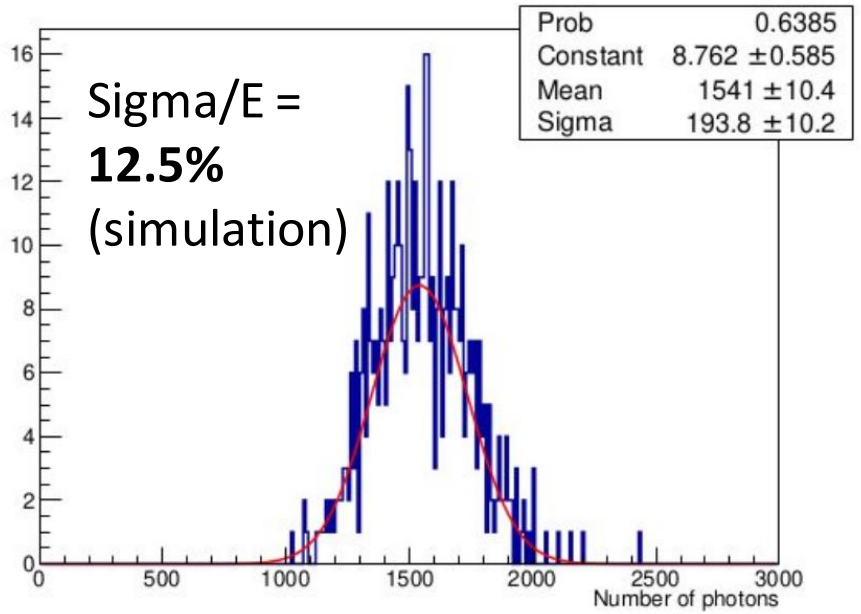
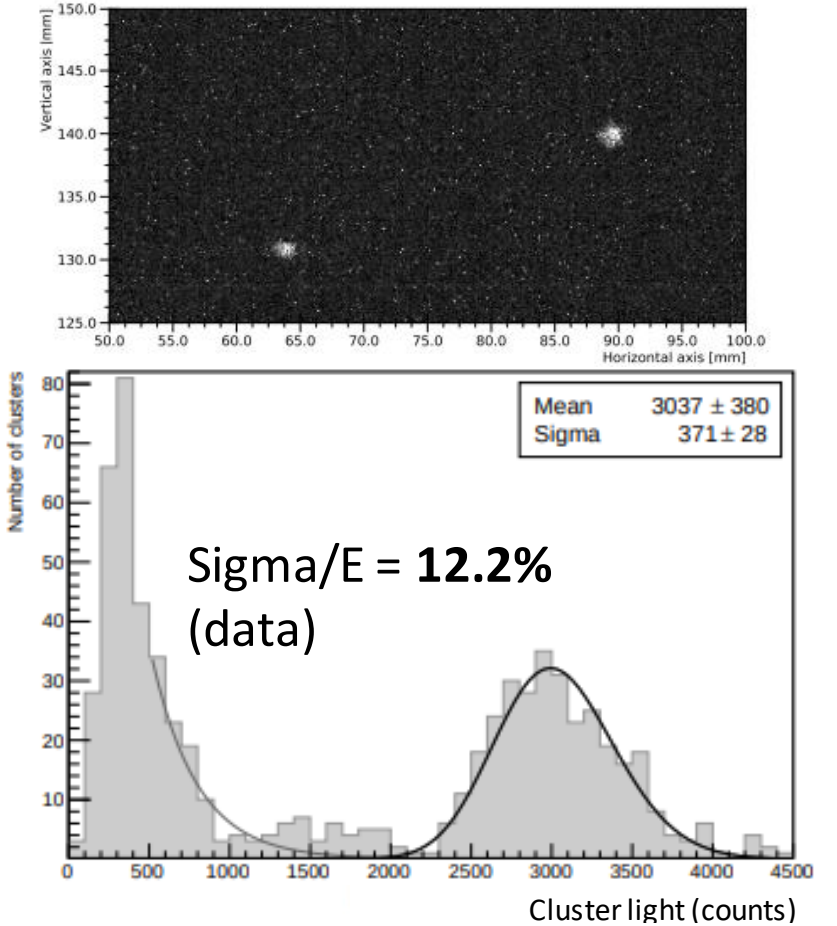
Fe-55 data comparison

- Fe-55 source – 5.9keV photons
- Data taken with LEMOn prototype: 7L active volume, 20cm drift, 500 V/cm drift field, V_{GEM}=460V
- Energy resolution: **12.2%** in data, **12.5%** in MC
- Spot size of few mm







JINST 15 (2020) no.10, P10001

Conclusions and future work

- A complete simulation of the background in the CYGNO detector was done
- Simulation of ER and NR images seems consistent with preliminary measurements
- A more detailed comparison is foreseen, also including directionality and head-tail effect
- Machine learning studies are ongoing – we are partners of the IDAO Data Analysis Olympiad

Thank you!

Backup

Internal radioactivity

Camera	^{228}Ra (Bq)	^{228}Th (Bq)	^{226}Ra (Bq)	^{234}Pa (Bq)	^{40}K (Bq)	Total activity
Hamamatsu ORCA FLASH 4.0	2.1	2.1	1.9	7.0	1.9	15.0
ORCA FLASH sensor	1.0	1.0	1.1	1.1	4.3	8.5
Photometrics Prime BSI Mode 1	-	-	-	-	-	tbm
Photometrics Prime BSI Mode 2	-	-	-	-	-	tbm
Photometrics BSI Express Mode 2	1.3	1.8	1.0	6.0	3.6	13.7
Hamamatsu Fusion Closer (LEMON)	-	-	-	-	-	tbm
Hamamatsu Fusion Farther (LIME)	-	-	-	-	-	tbm
Thorlab Quantalux	0.3	0.6	0.2	3.0	1.2	5.3

Camera Lens Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	4.22E+00
U238 (Ra226)	M	1.92E+00
U235	M	1.45E-01
Th232 (Ra228)	M	3.61E-01
Th232 (Th228)	M	3.65E-01
K40	M	5.15E+01
Cs137	L	2.67E-02
Co60	L	4.64E-02
La138	M	2.44E+00

Camera Body Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	3.16E+00
U238 (Ra226)	M	8.13E-01
U235	M	1.81E-01
Th232 (Ra228)	M	9.49E-01
Th232 (Th228)	M	9.49E-01
K40	M	8.59E-01
Cs137	M	4.07E-02
Co60	L	5.42E-03

Radioactivity of the different components of the camera, and of samples from the GEMs and the acrylic box were measured underground at @LNGS with HPGe detectors

Thanks to M. Laubenstein

GEM	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	1.63E-01
U238 (Ra226)	M	3.25E-02
U235	L	1.58E-02
Th232 (Ra228)	L	3.09E-02
Th232 (Th228)	L	1.56E-02
K40	L	3.58E-01
Cs137	L	8.13E-03
Co60	L	7.48E-03

Acrylic Box	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	L	3.50E-03
U238 (Ra226)	L	3.50E-03
Th232 (Ra228)	L	5.00E-03
Th232 (Th228)	L	4.50E-03
K40	L	3.50E-02

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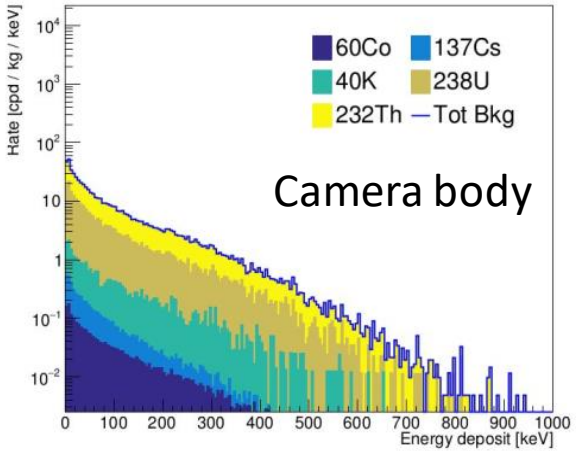
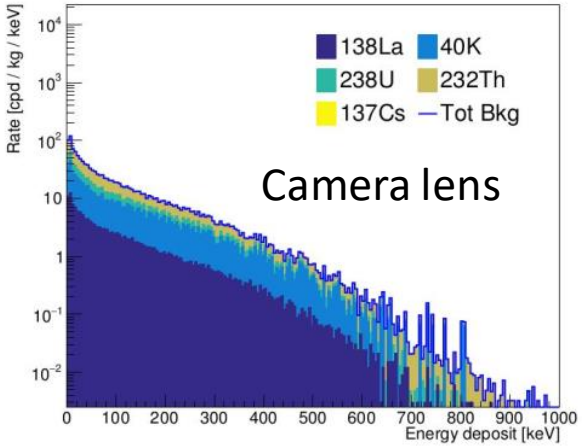
GSSI

Internal background



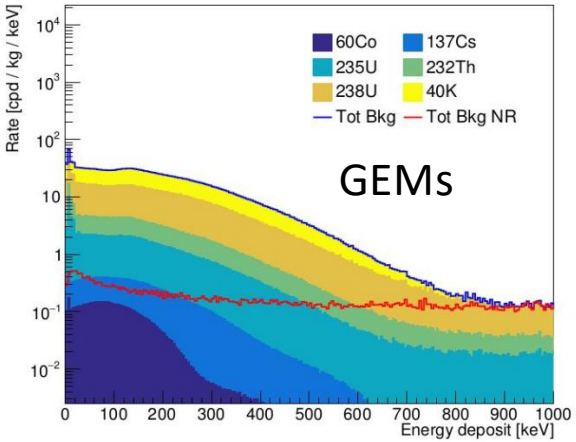
4.46x10^5 ER/yr (1-20 keV)

- Substitute PCB with lower radioactivity material
- Copper shielding (4.5cm layer)



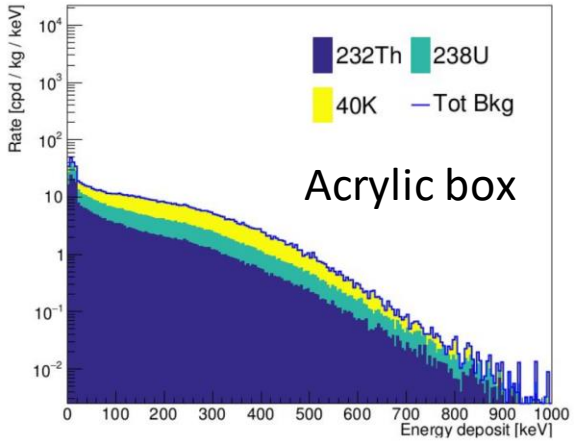
9.83x10^5 ER/yr (1-20 keV)

- Substitute with Suprasil
- Synthetic quartz 5cm layer



5.14x10^5 ER/yr (1-20 keV)
5.07x10^3 NR/yr (1-20 keV)

- Substitute kapton – under study



4.34x10^5 ER/yr (1-20 keV)

- Substitute with lower radioactive plastic

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