Summary of background simulations

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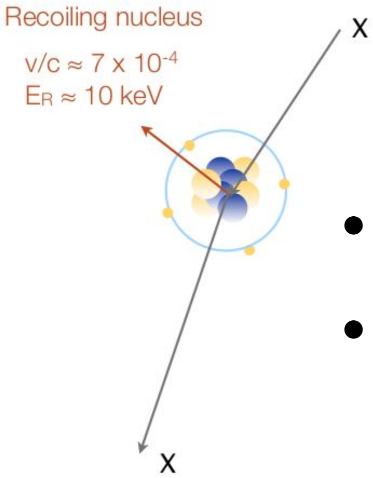
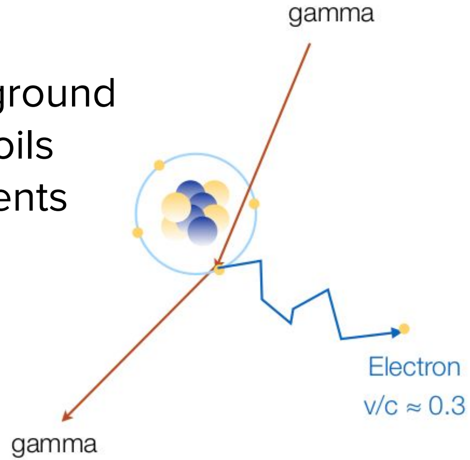
19/12/19
CYGNO General Meeting, Frascati

Signal and backgrounds



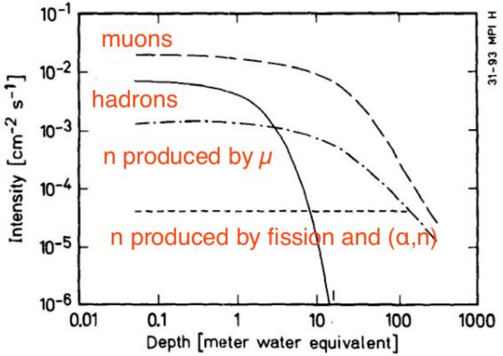
- Signal events produce nuclear recoil
- Neutrons produce nuclear recoils similar to a WIMP

- Most of the background from electron recoils caused by β/γ events



Background sources:

➔ **Radioactivity** of **surroundings** (laboratory environment)
➔ **Radioactivity** of **detector** and shield materials
➔ **Cosmic rays** and **secondary** reactions (need to go **underground**, LNGS 3700 mwe)

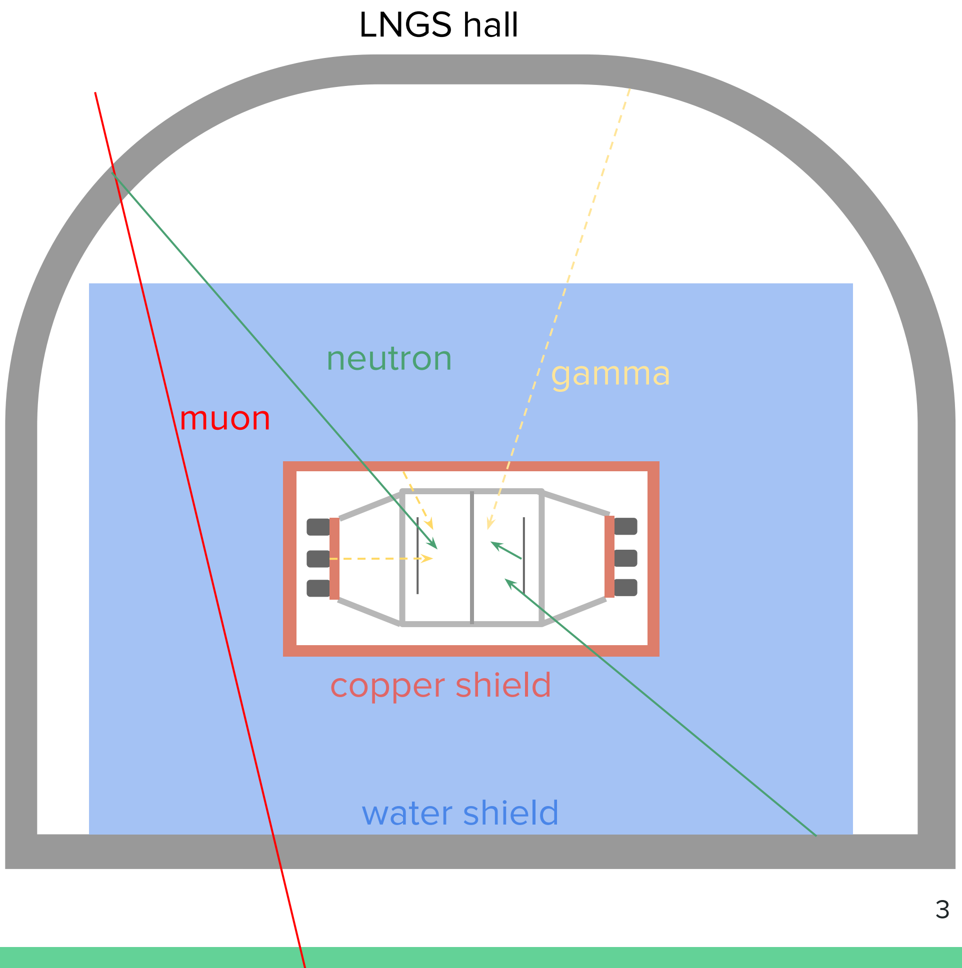


Background components

- Ambient neutrons/gammas
  (origin: outside setup, mostly rock)

- "Radiogenic" neutrons/gammas
  (origin: materials in setup)

- Cosmogenic neutrons
  (origin: muon interactions)



Geant4 simulation

The simulation code is available in a repository in the CYGNUS-RD organization on github
https://github.com/CYGNUS-RD/CYGNO-MC

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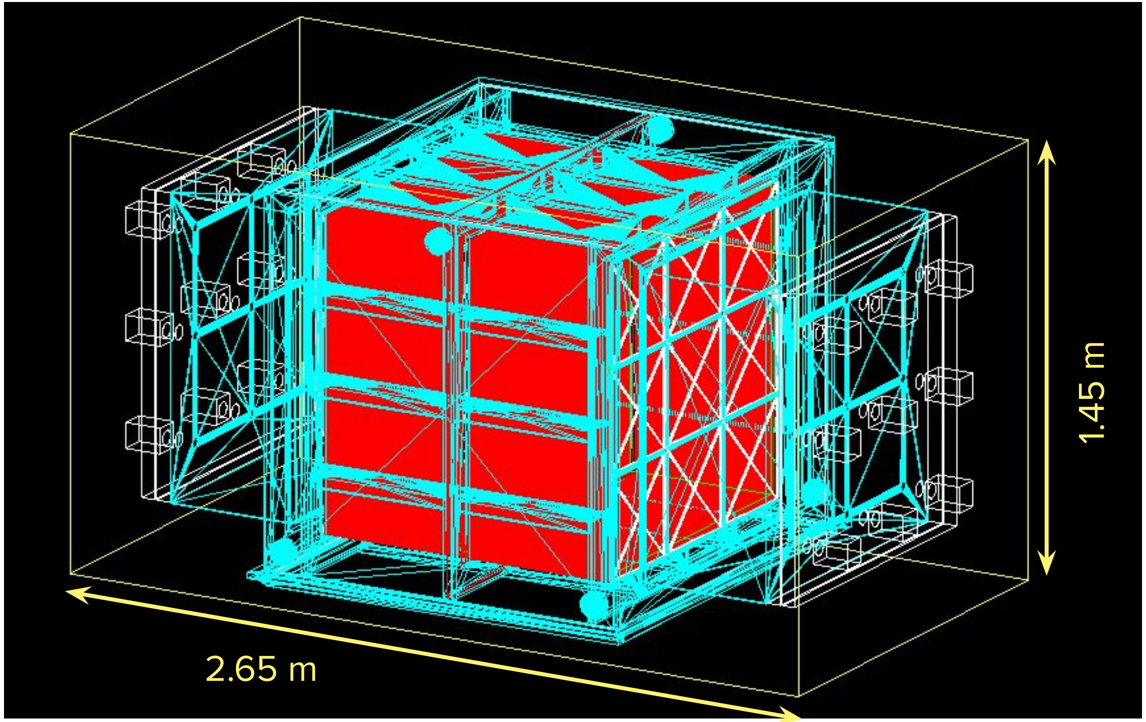
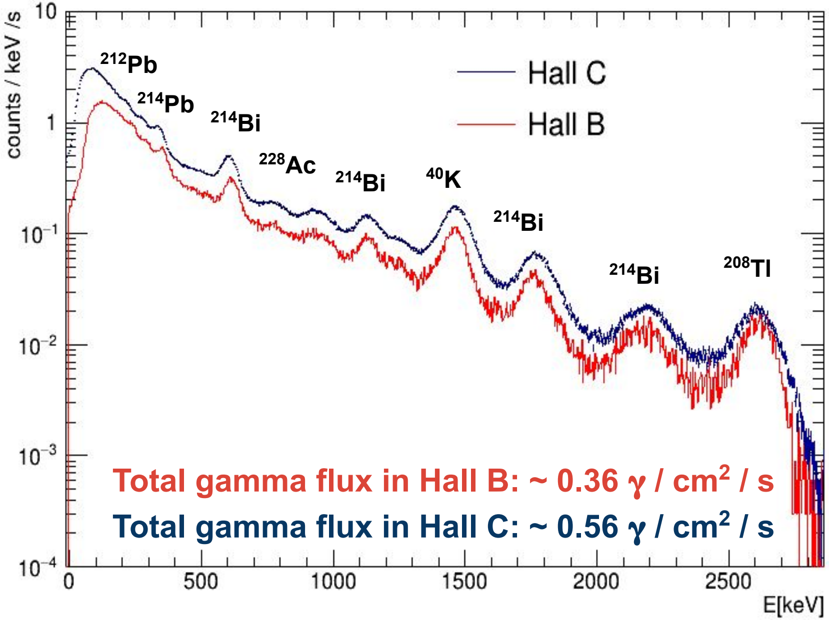
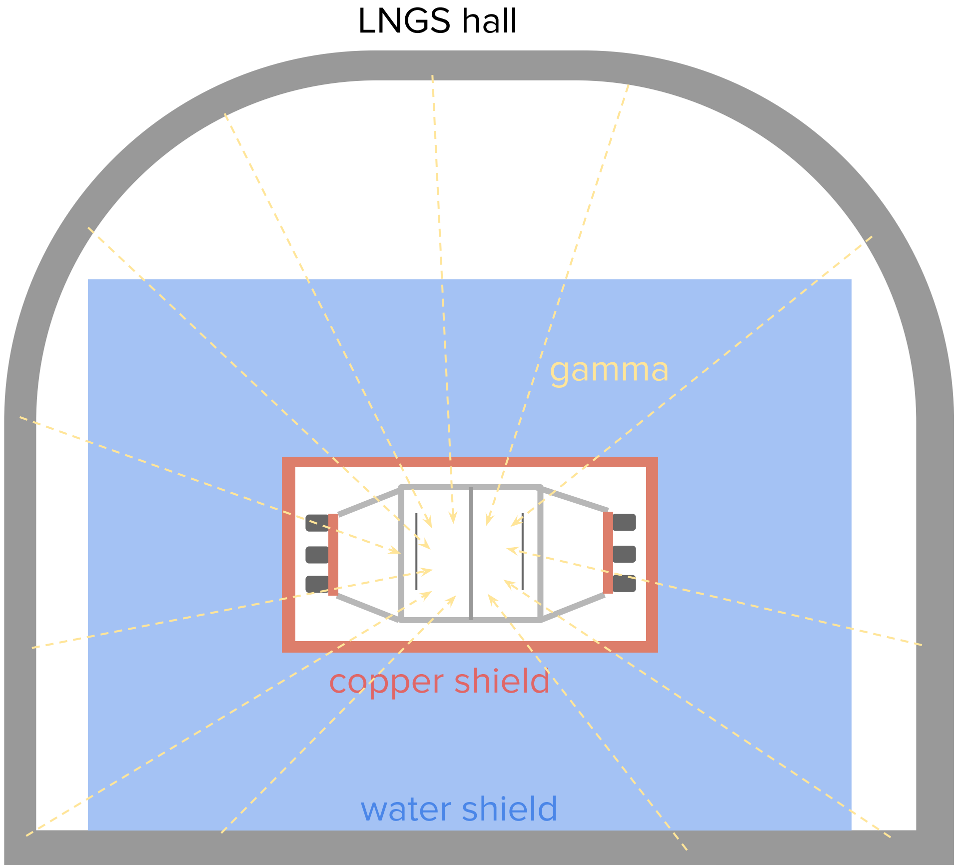


External background and shielding studies

Ambient gammas

- Gammas mostly from **K, U** chain and **Th** chain
- Spectrum measured by SABRE collaboration(*)
- used as input for CYGNO simulations





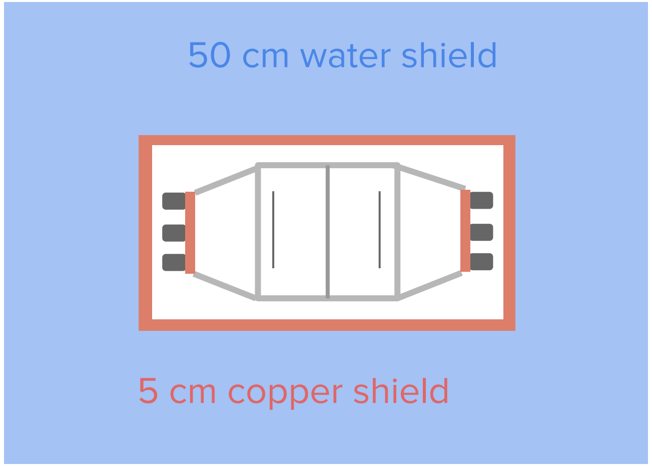
(*) in agreement with H. Wulandari et al. Astroparticle Physics 22 (2004) 313–322

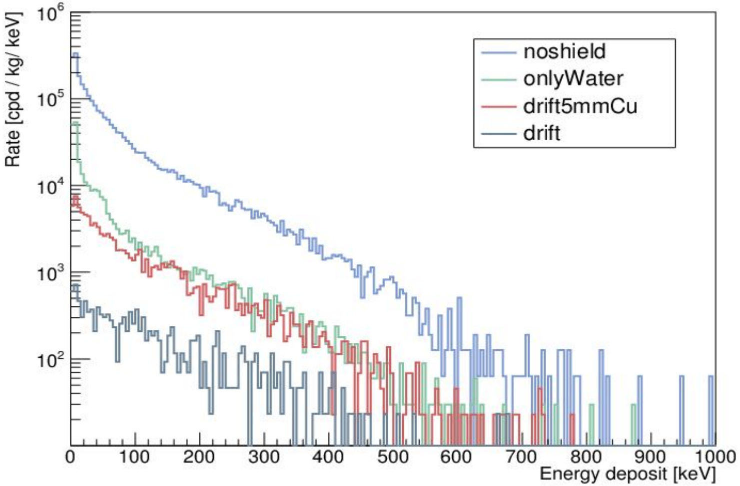
Shielding option 1

Cost of materials:
- Cu : ~25 euro/kg
- Lead : ~5 euro/kg
- PE : ~5 euro/kg

Material	Thickness [cm]	Mass [kg]	Cost [keuro]
Water	50	16e3	-
Cu	5	8.7e3	217.5

1) 50 cm water + 5 cm Cu





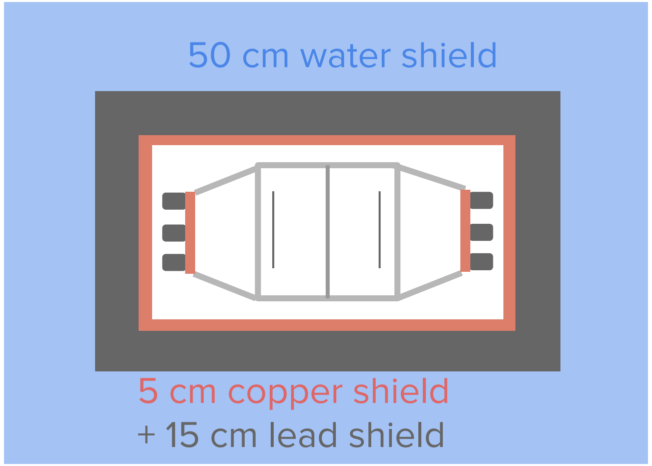
Rate [0-20] keV = 7 10^2 cpd/kg/keV → **8 10^6 cts/yr** in CYGNO detector

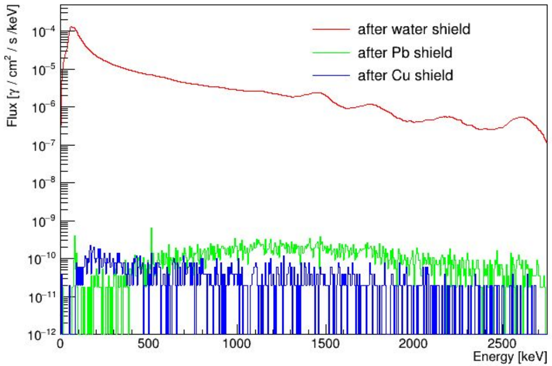
Shielding option 2

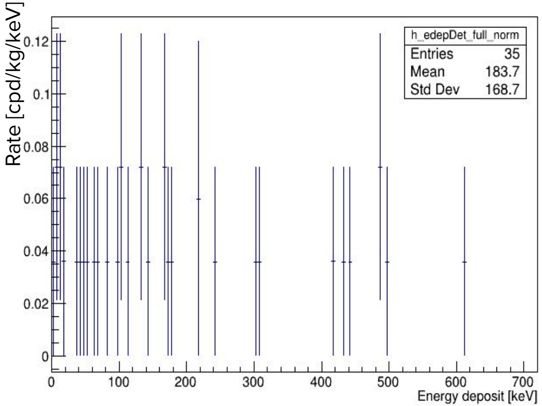
Cost of materials:
- Cu : ~25 euro/kg
- Lead : ~5 euro/kg
- PE : ~5 euro/kg

Material	Thickness [cm]	Mass [kg]	*Cost [keuro]
Water	50	16e3	-
Pb	15	42e3	210
Cu	5	9e3	225

2) 50 cm water + 15 cm Pb + 5 cm Cu





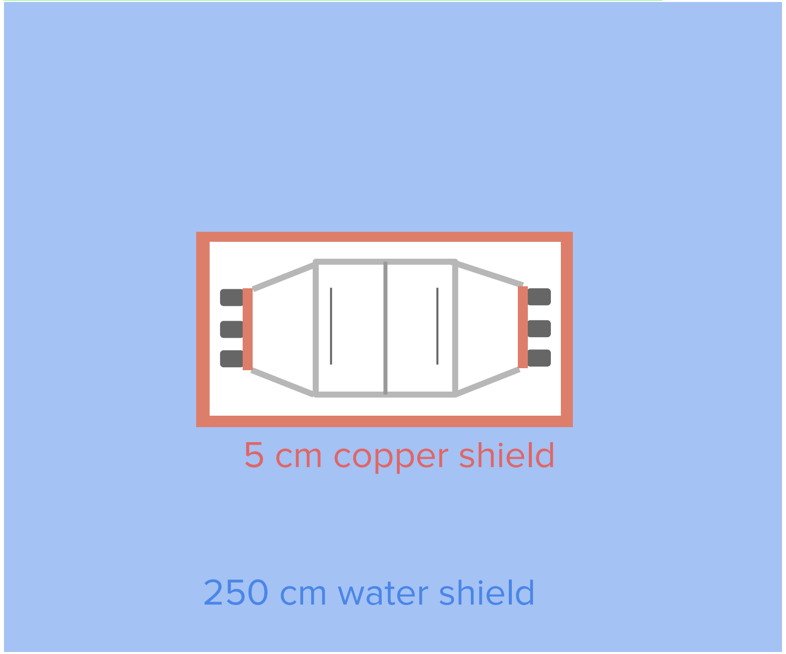


Rate [0-20] keV = 0.054 cpd/kg/keV ➔ **630 cts/yr** in CYGNO detector

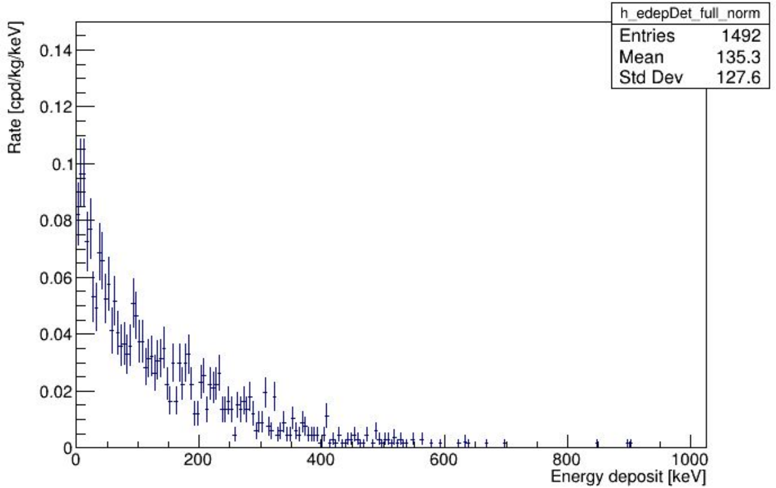
Shielding option 3

Cost of materials:
- Cu : ~25 euro/kg
- Lead : ~5 euro/kg
- PE : ~5 euro/kg

3) 250 cm water + 5 cm Cu



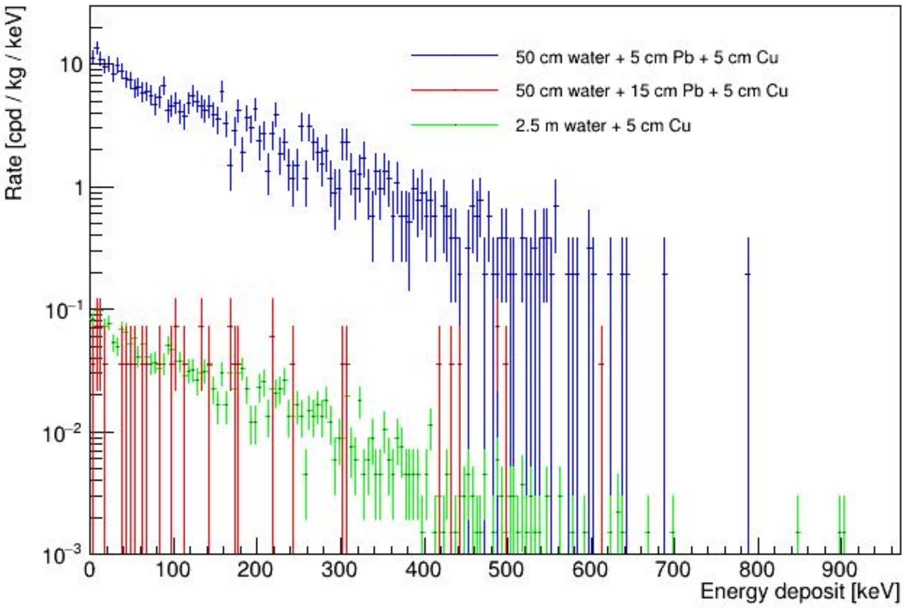
Volume	Material	Thickness [cm]	Mass [kg]	Cost [keuro]
Shield2	Water	250	312e3	-
Shield3	Cu	5	8.7e3	217.5



Rate [0-20] keV = 7 10^2 cpd/kg/keV → **8 10^6 cts/yr** in CYGNO detector

Background from ambient gammas

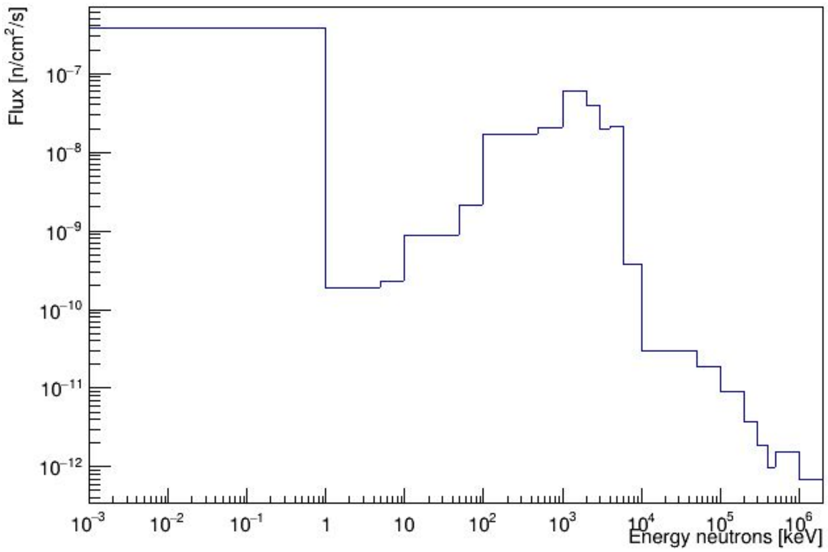
Goal total background < **10^4 evt/yr**
➜ option 1 unacceptable **8 10^6 cts/yr**
➜ both options (2 and 3) **~10^3 evt/yr**

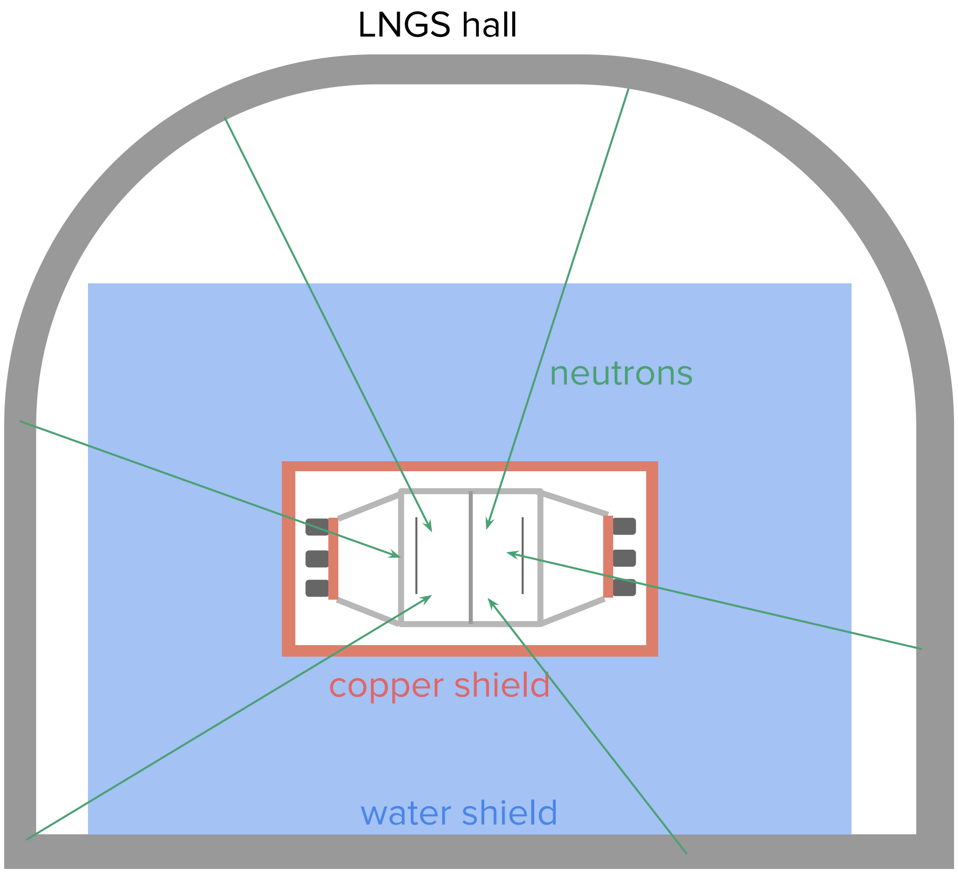


Ambient neutrons

- Ambient neutrons from radioactivity in the rock
- Spectrum from CUORE MC

  ➜ measurements Belli/Arneodo (<10 MeV) and Hime (>10 MeV)

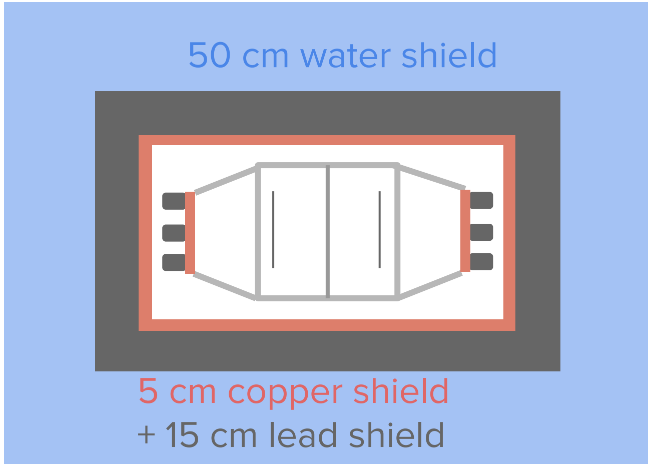


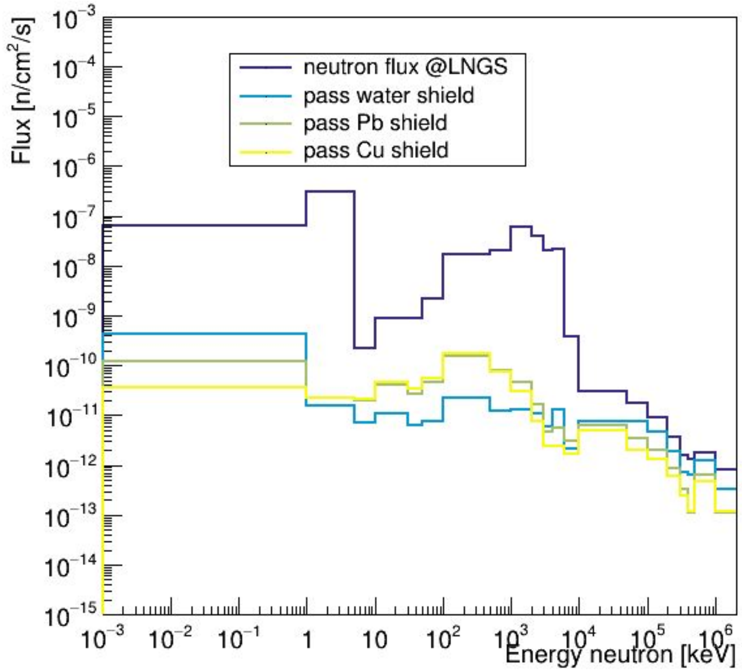


Neutron flux with shield option 2

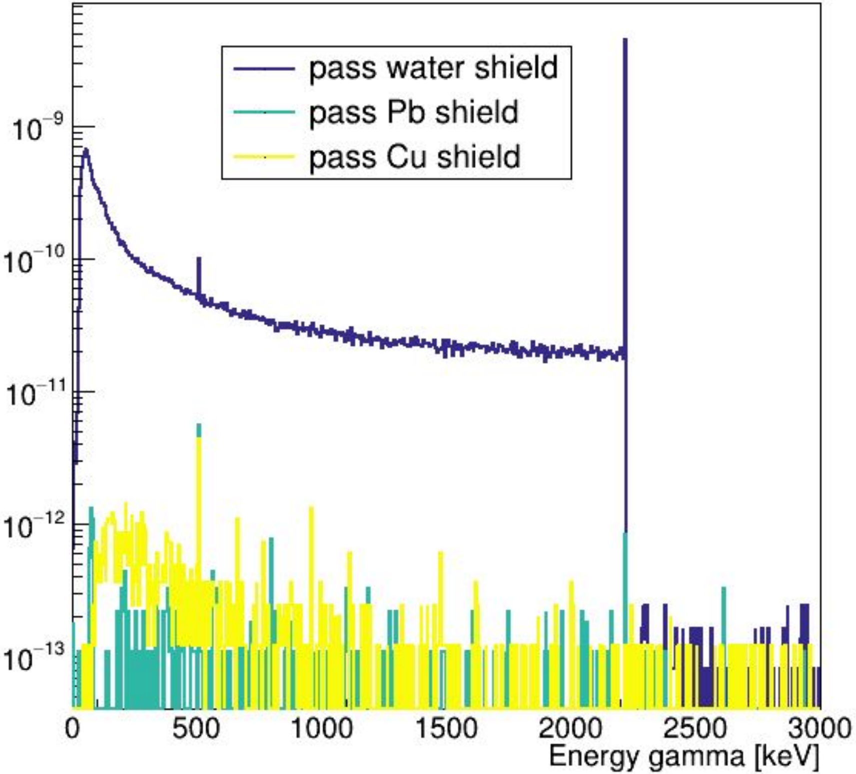
Neutron Flux @LNGS 2.55e-06 cm^-2 s^-1
Neutron Flux after water shield 2.16e-09 cm^-2 s^-1
Neutron Flux after Pb shield 2.31e-09 cm^-2 s^-1
Neutron Flux after Cu shield 1.76e-09 cm^-2 s^-1

2) 50 cm water + 15 cm Pb + 5 cm Cu



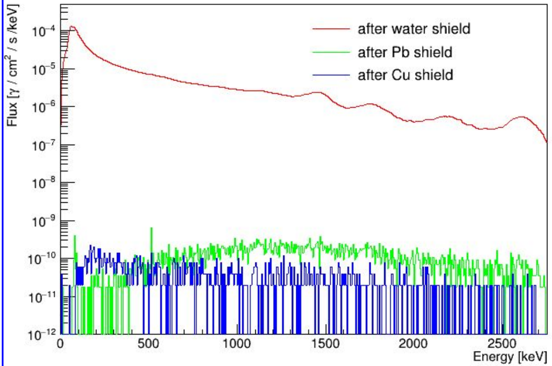


Secondary gamma flux with shield option 2



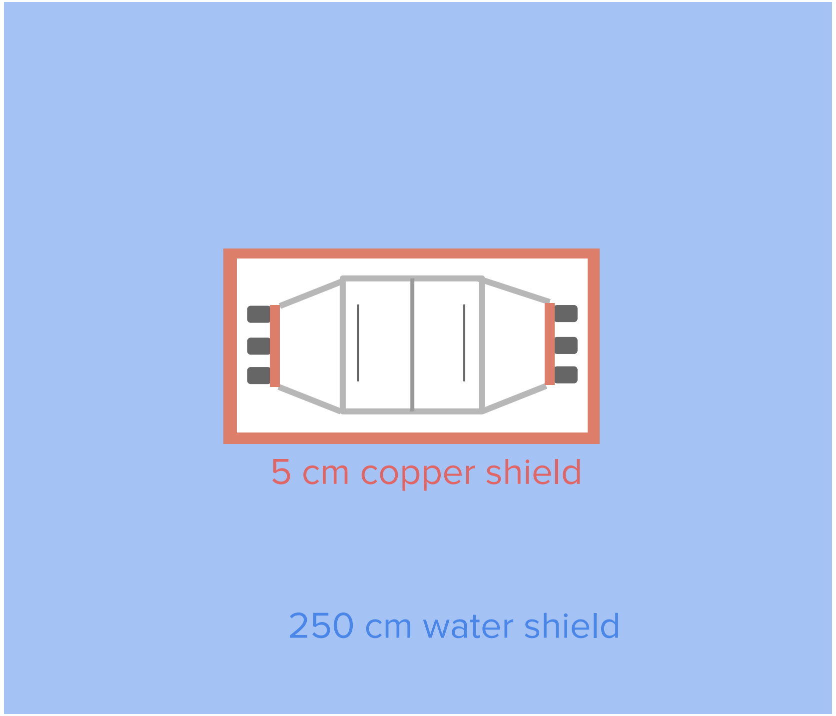
Gamma Flux after water shield 1.45e-07 cm^-2 s^-1
Gamma Flux after Pb shield 1.84e-10 cm^-2 s^-1
Gamma Flux after Cu shield 4.21e-10 cm^-2 s^-1

For reference:
Ambient gamma flux entering the full shield option 2 is 4 10^{-7} cm^{-1} s^{-1}

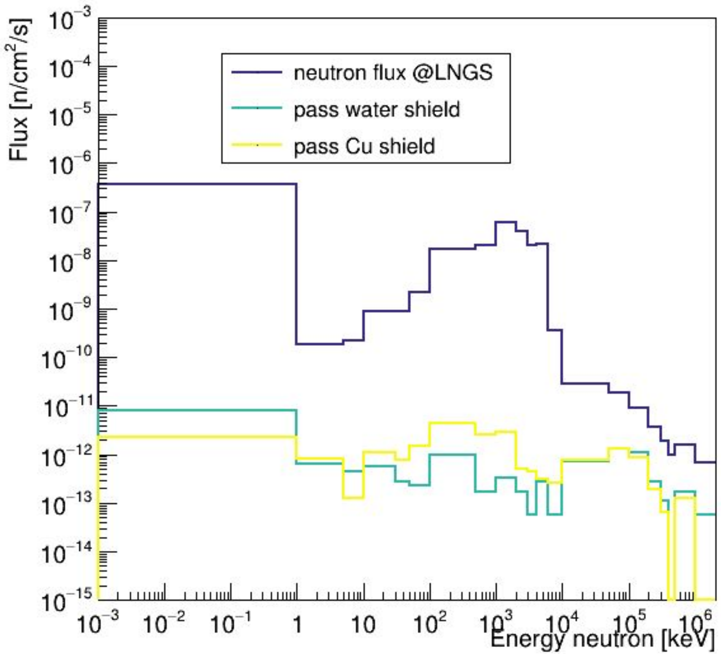


Neutron flux with shield option 3

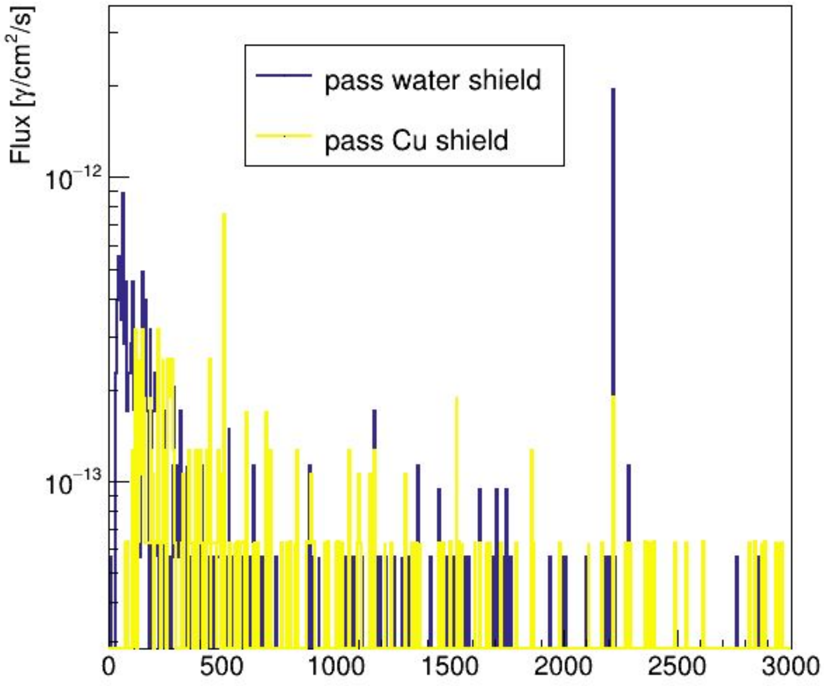
2) 250 cm water + 5 cm Cu



Neutron Flux @LNGS 2.55e-06 cm^-2 s^-1
Neutron Flux after water shield 1.41e-10 cm^-2 s^-1
Neutron Flux after Cu shield 6.31e-11 cm^-2 s^-1
~30 times better than option 2



Secondary gamma flux with shield option 3



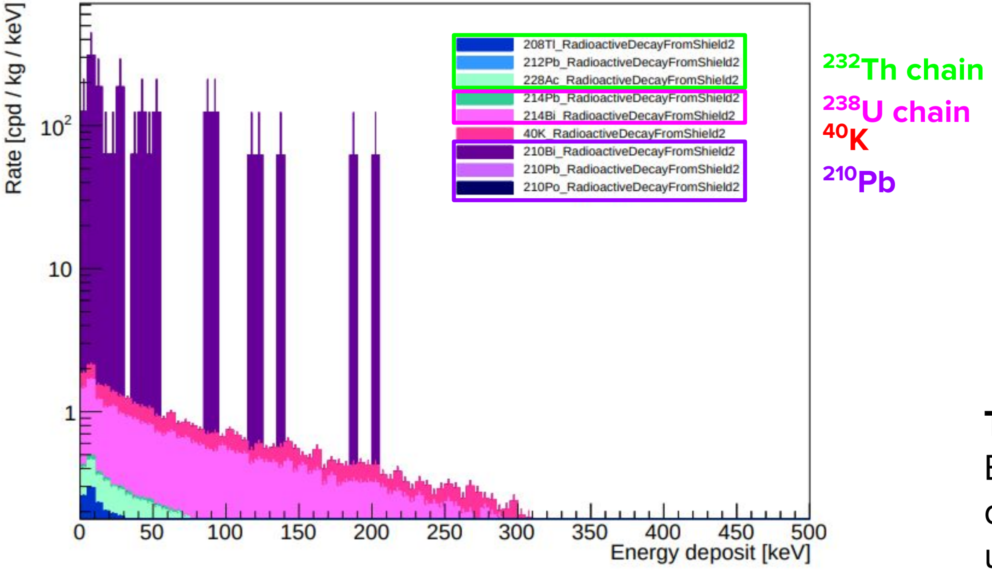
Gamma Flux after water shield 9.89e-11 cm^-2 s^-1
Gamma Flux after Cu shield 6.97e-11 cm^-2 s^-1
~6 time better than option 2

For reference:
Ambient gamma flux entering the full shield option 2 is 4 10^{-7} cm^{-1} s^{-1}

Not enough statistics to produce a background spectrum, but expected to be small.

Radioactivity background of lead shield (OPERA)

- Energy deposit in CYGNO detector from lead shield radioactivity
- assume ^{210}Pb of OPERA lead
- U, Th, K activities from T-REX paper (arxiv 1812.04519)
- shielding made of 50 cm water + **5 cm Pb** + 5 cm Cu



	Activity [mBq/kg]	**Rate** [cts/yr]
^{238}U	0.33	11.2 10^3
^{210}Pb	**10^5**	**1.97 10^6**
^{232}Th	0.10	4.51 10^3
^{40}K	1.2	4.6 10^3

Total rate 2 10^6 cts/yr
Even a 5 cm-thick shield of lead for 1 m^3 detector gives a large background, unless using archaeological lead.

Summary shielding options

- 50 cm water + 15 cm Pb + 5 cm Cu is good in terms of
  - **ambient gammas**
  - **neutrons and secondary gammas**
  - **compact size**

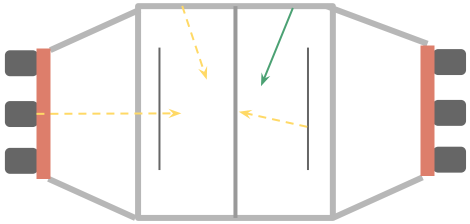
  ➔ **But**
  - **expensive**
  - **need to use archaeological lead (even more expensive), otherwise too radioactive**

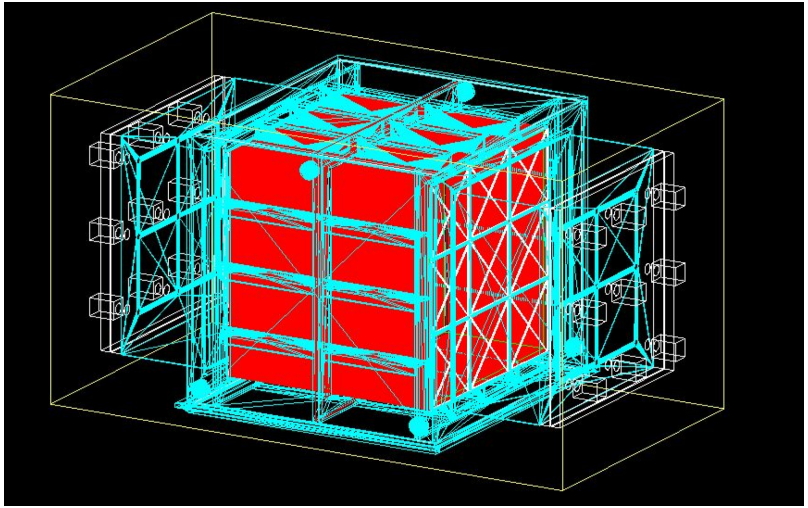
- 2.5 m water + copper (no lead) shielding is good in terms of
  - **ambient gammas**
  - **neutrons and secondary gammas**
  - **low radioactivity**
  - **low cost**

  ➔ **But**
  - **large size**

Internal backgrounds

Radioactivity of materials





- natural radioactivity: U, Th and K
- radon
- cosmogenically activated isotopes
    -
- alpha, beta, gamma , neutrons can come from radioactivity

➔ usually the most worrisome backgrounds are internal (externals can be shielded)

➔ Careful evaluation of the material activities is important to predict the background

Camera radioactivity

Measured with HPGE at LNGS
High content of U, Th and K in the camera body, mostly K in the camera lens

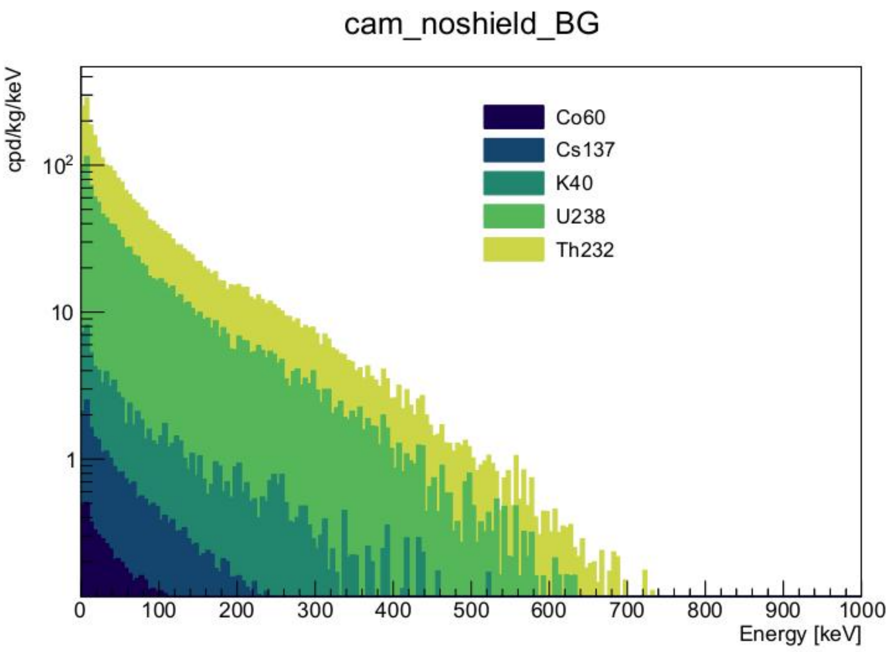
Camera body

```
=========================================================================
sample:          camera, Hamamatsu, orca-flash4.0, 2.1275 kg, CYGNO
number:          1
live time:       83383 s
detector:        GeMPI

radionuclide concentrations:

Th-232:
Ra-228:          (2.1 +- 0.2) Bq/pc
Th-228:          (2.1 +- 0.1) Bq/pc

U-238:
Ra-226           (1.8 +- 0.1) Bq/pc
Pa-234m          (7 +- 2) Bq/pc

U-235:           (0.4 +- 0.1) Bq/pc

K-40:            (1.9 +- 0.3) Bq/pc

Cs-137:          (0.09 +- 0.03) Bq/pc

Co-60:           < 0.012 Bq/pc   @ start of measurement: 12-JUL-2018
```

Camera lens

```
=========================================================================
sample:          objective of Hamamatsu orcaflash4.0, 213.5 g (with plastic cap), CYGNO
number:          1
live time:       504104 s
detector:        GePaolo

radionuclide concentrations:

Th-232:
Ra-228:          (0.077 +- 0.009) Bq/pc
Th-228:          (0.078 +- 0.006) Bq/pc

U-238:
Ra-226           (0.41 +- 0.02) Bq/pc
Pa-234m          (0.9 +- 0.3) Bq/pc

U-235:           (0.031 +- 0.008) Bq/pc

K-40:            (11 +- 1) Bq/pc

Cs-137:          < 0.0057 Bq/pc

Co-60:           < 0.0099 Bq/pc  @ start of measurement: 10-JUL-2018

La-138:          (0.52 +- 0.04) Bq/pc
```

Background from cameras (body + lens)

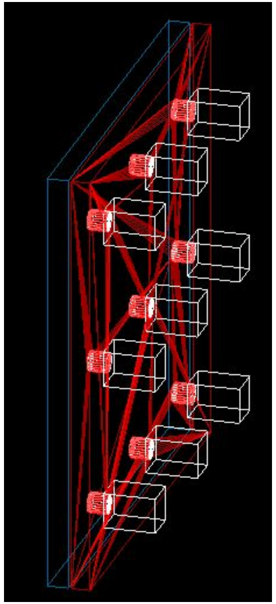


Energy deposit in CYGNO detector:

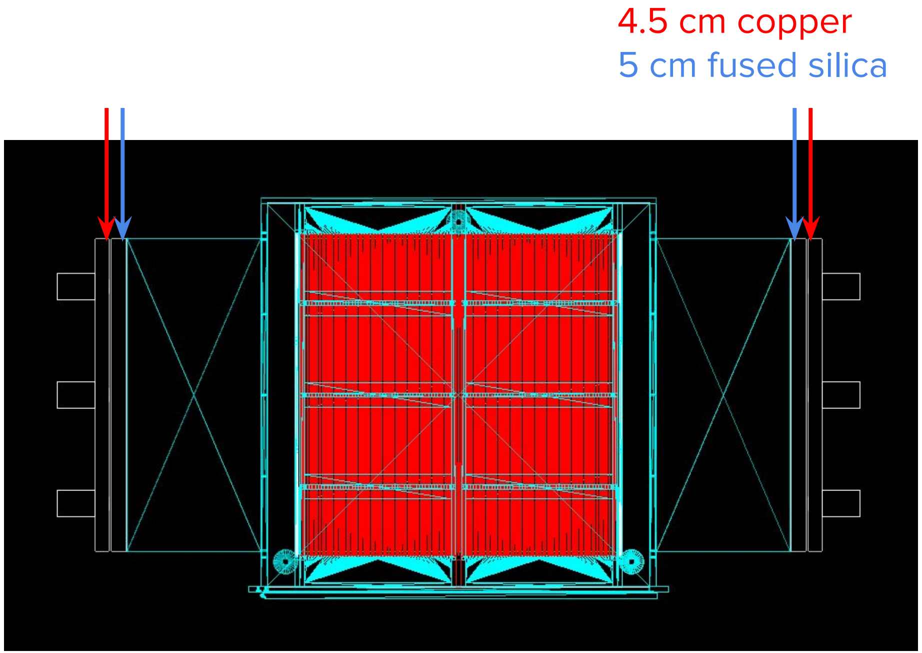
- Events in [0-20] keV: **2.05 x 10^7 cpy**

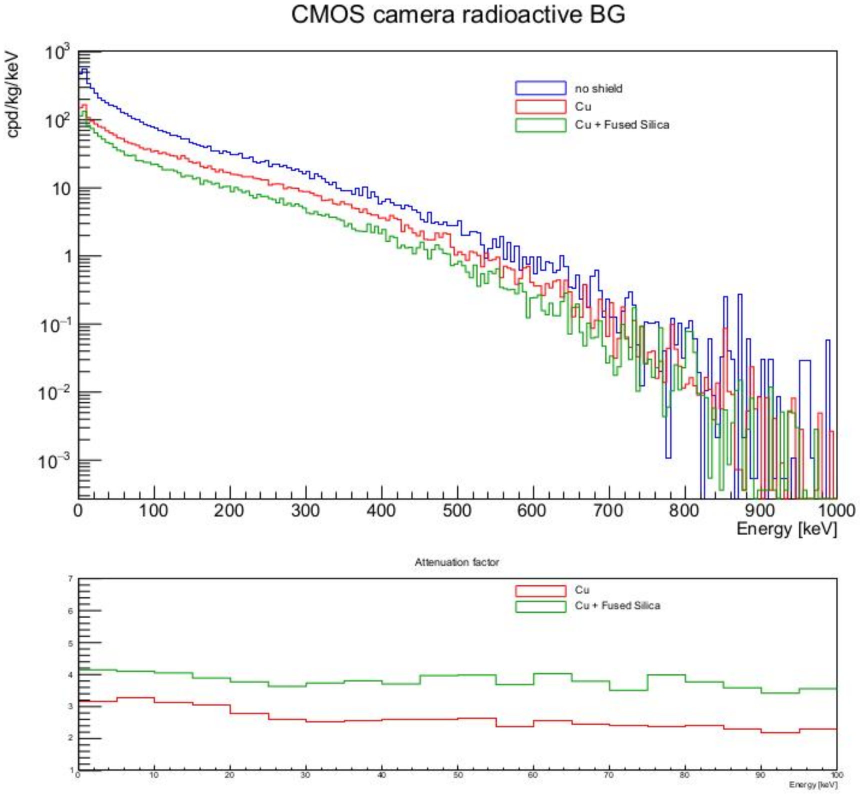
We investigated the effect of a copper shielding to the camera body and a fused silica layer between lens and acrylic box

4.5 cm copper
5 cm fused silica



Study for camera shielding





Energy deposit in CYGNO detector:

- Events in [0-20] keV: **6.60 x 10^6 cpy**
- **shielding is not sufficient**

Radioactivity of acrylic box

- U, Th, K activities from M.Laubenstein measurements @LNGS (upper limits)
- Radiopurity.org measurements for acrylic/plexiglass depend form the sample (ex. SNO acrylic much lower radioactivity)

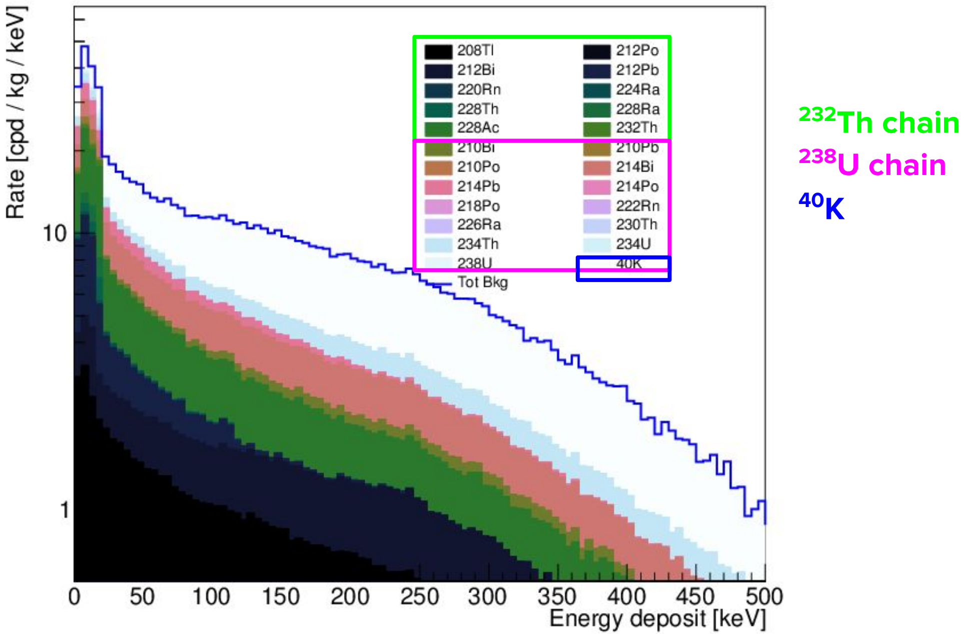
	Activity [mBq/kg]	**Concentration** [ppb]
^{238}U	< 3.5 (^{226}Ra)	< 0.28
^{232}Th	< 5 (^{228}Ra) < 4.5 (^{212}Pb)	< 1.2 < 1.1
^{40}K	< 35	<1.1 10³

From radiopurity.org

Grouping	Name	Isotope	Amount	Isotope	Amount	
ILIAS UKDM	Acrylic, Plexiglass	Th-232	4 ppb	U-238	10 ppb	...
ILIAS UKDM	Acrylic, Polycast, UVT 450	Th-232	1.2 ppb	U-238	1.2 ppb	...
EXO (2008)	SNO acrylic	Th	14 ppt	U	24 ppt	...
ILIAS UKDM	Acrylic, Lucite, RAL stores	Th-232	0.64 ppb	U-238	3 ppb	...
TEST	Acrylic, Perspex, Harris Spur Ltd	Th-232	0.01 ppb	U-238	0.01 ppb	...
EXO (2008)	SNO acrylic	Th	1.1 ppt	U	1.1 ppt	...

Radioactivity background from Acrylic Box

- Use U, Th, K activities from M.Laubenstein measurements @LNGS (upper limits)
- Energy deposit in CYGNO detector from la **2 cm thick** acrylic box (~200 kg)



Total rate < 4.5 10^5 cts/yr in [0-20] keV
➔ need more precise measurement of radioactivity

With radiopure acrylic (for ex. SNO acrylic or similar) **this background could be much reduced**

Status background study & to do

- Cameras (body+lens) are the most radioactive element of the setup
- Understand what part of the camera body is most radioactive
  ➜ dismounted camera now under measurement at LNGS (results expected in january 2020)

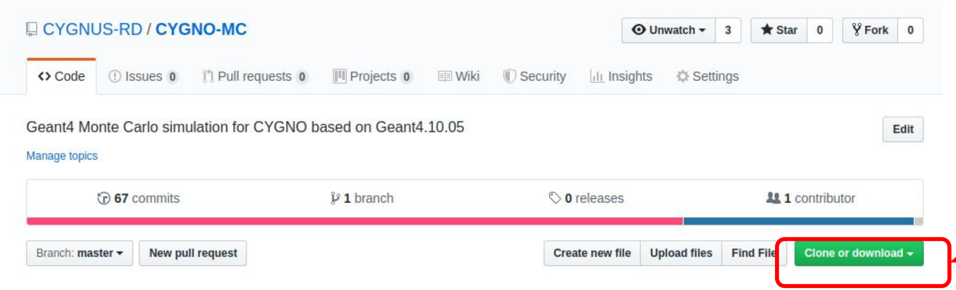
- To do:
  systematic background budget, starting from the parts close to the sensitive region (GEM, field cage, etc..)

Backup

GEANT4 simulation repository

The simulation code is available in a repository in the CYGNUS-RD organization on github
https://github.com/CYGNUS-RD/CYGNO-MC

- need github account (free) and membership of CYGNUS-RD (contact Emanuele Di Marco)
- then we can add collaborators to CYGNO-MC repository with read and/or write permissions
- instructions to setup and run the code are available in the README file in the repository



to clone the repository on your working area

Working area:

- for simple tests, can be run in local
- pre-requisites ROOT, GEANT4, CadMesh (all open source and free software)
- for MC production Roma group is working on Roma3 cluster `ui7-01.roma3.infn.it`
- working area @LNGS farm?

Table of shielding materials and costs

Cost of materials:

- Cu : ~25 euro/kg
- Lead : ~5 euro/kg
- PE : ~5 euro/kg

50 cm water + 5 cm Cu

Volume	Material	Thickness [cm]	Mass [kg]	Cost [keuro]
Shield2	Water	50	16e3	-
Shield3	Cu	5	8.7e3	217.5

50 cm water + 10 cm Pb + 2 cm Cu

Volume	Material	Thickness [cm]	Mass [kg]	Cost [keuro]
Shield1	Water	50	19e3	-
Shield2	Pb	10	24e3	120
Shield3	Cu	2	3.3e3	82.5

50 cm water + 15 cm Pb + 5 cm Cu

Volume	Material	Thickness [cm]	Mass [kg]	*Cost [keuro]
Shield1	Water	50	16e3	-
Shield2	Pb	15	42e3	210
Shield3	Cu	5	9e3	225

only PE

Volume	Material	Thickness [cm]	Mass [kg]	Cost [keuro]
Shield3	PE	50	15e3	75

Lead shield radioactivity

- The highest background contribution from lead is ^{210}Pb
- ^{210}Pb is not in equilibrium with ^{238}U decay chain
- half life of ^{210}Pb is quite long (22 years)
- ^{210}Pb daughters have shorter half life, therefore they are in equilibrium with ^{210}Pb
- commercial lead has typically several 100 Bq/kg of ^{210}Pb. OPERA lead available at LNGS has 80 Bq/kg, CUORE roman Pb has <4 mBq/Kg activity
- ^{210}Pb ➔ 100% BR beta decay with q-value 63.5 keV
- **^{210}Bi** ➔ 100% BR beta decay with q-value 1162.1 keV
  ➔ **bremsstrahlung gives significant contribution to bkg**
- ^{210}Po ➔ 100% BR alpha q-value 5407.4 keV

$T_{1/2}$	Isotope	E_α(MeV)	I (%)	Activity
$4.468 \cdot 10^9\, y$	^{238}U			
	$\downarrow \alpha$	4.18	99.9	A0
$24.1\, d$	^{234}Th			
	$\downarrow \beta$			
$1.17\, m$	^{234m}Pa			
	$\downarrow \beta$			
$2.455 \cdot 10^5\, y$	^{234}U			
	$\downarrow \alpha$	4.75	99.8	A1
$7.538 \cdot 10^4\, y$	^{230}Th			
	$\downarrow \alpha$	4.66	99.7	A2
$1600\, y$	^{226}Ra			
	$\downarrow \alpha$	4.78	94.4	A3
$3.8\, d$	^{222}Rn			
	$\downarrow \alpha$	5.49	99.9	A3
$3.10\, m$	^{218}Po			
	$\downarrow \alpha$	6.00	99.9	A3
$26.8\, m$	^{214}Pb			
	$\downarrow \beta$			
$19.9\, m$	^{214}Bi			
	$\downarrow \beta$			
$164.3 \mu\, s(*)$	^{214}Po			
	$\downarrow \alpha$	7.69	99.9	A3
$22.3\, y$	^{210}Pb			
	$\downarrow \beta$			
$5.01\, d$	^{210}Bi			
	$\downarrow \beta$			
$138.4\, d$	^{210}Po			
	$\downarrow \alpha$	5.30	100	A4
Stable	^{206}Pb			

Radioactivity of materials

#	Material,Supplier	Method	Unit	^{238}U	^{226}Ra	^{232}Th	^{228}Th	^{235}U	^{40}K	^{60}Co	^{137}Cs
1	Pb, Mifer	GDMS	mBq/kg	0.33		0.10			1.2		
2	OFE Cu, Luvata	GDMS	mBq/kg	<0.012		<0.0041			0.061		
3	ETP Cu, Sanmetal	GDMS	mBq/kg	<0.062		<0.020					
4	ETP Cu, Sanmetal	Ge Oroel	mBq/kg	<27	<1.0	<1.1	<0.76	<0.56	<3.1	0.24±0.05	<0.29
5	PFA tube, Emtecnik	Ge Paquito	mBq/m	<31	<0.58	<0.53	<0.34	<0.29	<2.6	<0.16	<0.18
6	PTFE tube, Tecnyfluor	Ge Paquito	mBq/m	<19	<0.48	<0.54	<0.41	<0.26	<2.5	<0.14	<0.17
7	Kapton-Cu PCB, LabCircuits	Ge Paquito	μBq/cm^2	<42	<1.3	<1.1	<0.66	<0.41	<4.0	<0.24	<0.28
8	Epoxy Hysol, Henkel	Ge Paquito	mBq/kg	<273	<16	<20	<16		<83	<4.2	<4.5
9	SM5D resistor, Finechem	Ge Paquito	mBq/pc	0.4±0.2	0.022±0.007	<0.023	<0.016	0.012±0.005	0.17±0.07	<0.005	<0.005
10	Mylar, Goodfellow	Ge Paquito	μBq/cm^2	<29	<0.59	<0.80	<0.36	<0.29	<3.3	<0.18	<0.21
11	Nylon (3D printer), CNM	Ge Latuca	mBq/kg	<436	<9.2	<11	<3.4	<2.6	<29	<1.0	<1.2
12	Nylon (3D printer), CNM	ICPMS	mBq/kg	36		2.9					
13	Teflon, Sanmetal	ICPMS	mBq/kg	<0.062		<0.041					
14	Extruded PTFE, Gore	ICPMS	mBq/kg	<0.124		<0.041					
15	Gold connectors, Fujipoly	Ge Paquito	mBq/pc	<25	4.45±0.65	1.15±0.35	0.80±0.19		7.3±2.6	<0.1	<0.4
16	Silver connectors, Fujipoly	Ge Paquito	mBq/pc	<55	5.68±0.81	6.1±1.1	6.17±0.72		12.2±3.8	<0.3	<0.3
17	Carbon connectors, Fujipoly	Ge Paquito	mBq/pc	14.5±6.0	2.77±0.38	1.17±0.23	1.14±0.14		7.5±2.3	<0.1	<0.1
18	Final Gold connectors, Fujipoly	Ge Paquito	mBq/pc	<12	2.80±0.38	0.49±0.10	0.58±0.09		5.3±1.6	<0.08	<0.07
19	Kapton connectors, Samtec	Ge Paquito	mBq/pc	<3.6	<0.065	<0.072	<0.040	0.043±0.015	<0.32	<0.020	<0.021
20	Flat cable, Somacis	Ge Paquito	mBq/pc	<14	0.44±0.12	<0.33	<0.19	<0.19	1.8±0.7	<0.09	<0.10
21	Teflon cable, Druflon	Ge Paquito	mBq/kg	<104	<2.2	<3.7	< 1.7	<1.4	21.6±7.4	<0.7	<0.8
22	Coaxial cable, Axon	Ge Paquito	mBq/kg	<650	<24	<15	<9.9	<7.9	163±55	<4.3	<5.1
23	Electronic board, CEA	Ge Paquito	Bq/kg	94±38	41.4±5.6	59±10	53.6±7.4		19.5±6.1	<0.67	<1.1
24	AGET chips, CEA	Ge Paquito	mBq/pc	<8.7	0.48±0.07	0.16±0.06	0.47±0.09		0.83±0.29	<0.04	<0.04
25	Ceramic AGET chips, CEA	Ge Paquito	mBq/unit	(0.64±0.24)10^3	539±94	116±20	113±21		43±14	<2.2	
26	Classical micromegas, CAST	Ge Paquito	μBq/cm^2	<40		4.6±1.6		<6.2	<46	<3.1	
27	Microbulk MM, CAST	Ge Paquito	μBq/cm^2	26±14		<9.3		<14	57±25	<3.1	
28	Kapton-Cu foil, CERN	Ge Paquito	μBq/cm^2	<11		<4.6		<3.1	<7.7	<1.6	
29	Cu-kapton-Cu foil, CERN	Ge Paquito	μBq/cm^2	<11		<4.6		<3.1	<7.7	<1.6	
30	Microbulk MM, CERN	Ge Latuca	μBq/cm^2	<49	<0.70	<1.2	<0.35	<0.22	<2.3	<0.14	<0.13
31	Micromegas GEM, CERN	Ge Oroel	μBq/cm^2	<5.2	<0.10	<0.22	<0.08	<0.03	3.45±0.40	<0.02	<0.02
32	Micromegas GEM 1st cleaning	Ge Oroel	μBq/cm^2	7.41±0.81	<0.21	0.19±0.05	<0.11	0.36±0.04	0.84±0.16	<0.02	<0.03
33	Micromegas GEM 2nd cleaning	Ge Oroel	μBq/cm^2	7.87±0.89	<0.17	0.14±0.04	0.07±0.02	0.36±0.04	0.81±0.15	<0.03	<0.02
34	Pyralux, Saclay	Ge Paquito	μBq/cm^2	<19	<0.61	<0.63	<0.72	<0.19	4.6±1.9	<0.10	<0.14
35	Isotac adhesive, 3M	Ge Paquito	μBq/cm^2	<18	<0.45	<0.43	<0.22	<0.18	<2.3	<0.10	<0.14
36	Stainless steel mesh	Ge Paquito	μBq/cm^2	<53	<1.5	<1.7	<0.9	<0.6	<8.7	<0.3	<0.5
37	Micromegas, CNM	Ge Paquito	μBq/cm^2	<462	<10	<11	<6.3	<4.5	<61	<3.8	<3.7

#	Material,Supplier	Method	Unit	^{214}Bi	^{208}Tl
38	Microbulk MM, CAST	BiPo-3	μBq/cm^2	<0.134	<0.035
39	Cu-kapton-Cu foil, CERN	BiPo-3	μBq/cm^2	<0.141	<0.012
40	Microbulk MM, CERN	BiPo-3	μBq/cm^2	<0.045	<0.014
41	Kapton-epoxy foil, CERN	BiPo-3	μBq/cm^2	<0.033	<0.008
42	Pyralux foil, Saclay	BiPo-3	μBq/cm^2	<0.032	<0.013

From T-REX screening campaign http://arxiv.org/abs/1812.04519v1

Radioactivity GEM

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========================================================================
sample:             GEM, copper clad Kapton foil, 12.3 g, CYGNO
number: 2



Th-232:
Ra-228:             < 0.19 mBq/pc
Th-228:             < 0.096 mBq/pc

U-238:
Ra-226        (0.2 +- 0.1) mBq/pc
Th-234        (1.0 +- 0.4) mBq/pc
Pa-234m             < 5.0 mBq/pc

U-235:        < 0.097 mBq/pc

K-40:         < 2.2 mBq/pc

Cs-137:             < 0.050 mBq/pc

Co-60:        < 0.046 mBq/pc
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Radioactivity GEM frame

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sample:           GEM, frame with copper clad kapton foil, 150 g, CYGNO

number: 2

Th-232:
Ra-228:           (3.4 +- 0.2) Bq/pc
Th-228:           (3.4 +- 0.2) Bq/pc

U-238:
Ra-226      (2.6 +- 0.1) Bq/pc
Pa-234m           (3.1 +- 0.4) Bq/pc

U-235:      (0.14 +- 0.02) Bq/pc

K-40:       (5.0 +- 0.5) Bq/pc

Cs-137:           < 0.0033 Bq/pc

Co-60:      < 0.0083 Bq/pc
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