Background simulations for CYGNO detector

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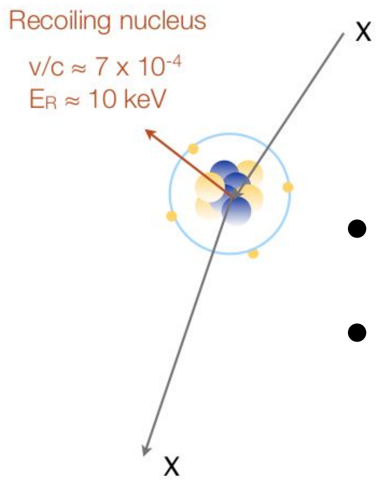
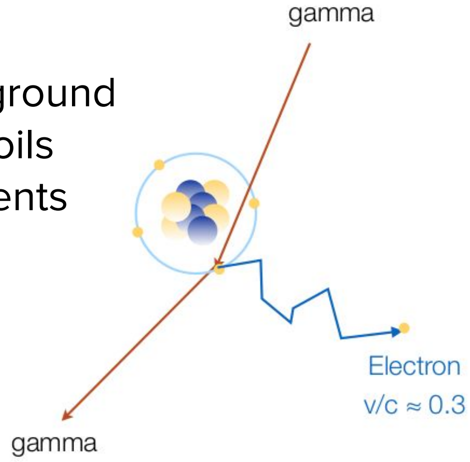
20-21/12/21
CYGNO Collaboration Meeting

Signal and backgrounds for dark matter search



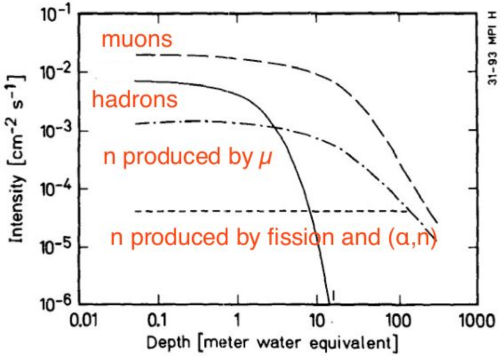
- Signal events produce nuclear recoil
- Neutrons produce nuclear recoils similar to a WIMP

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



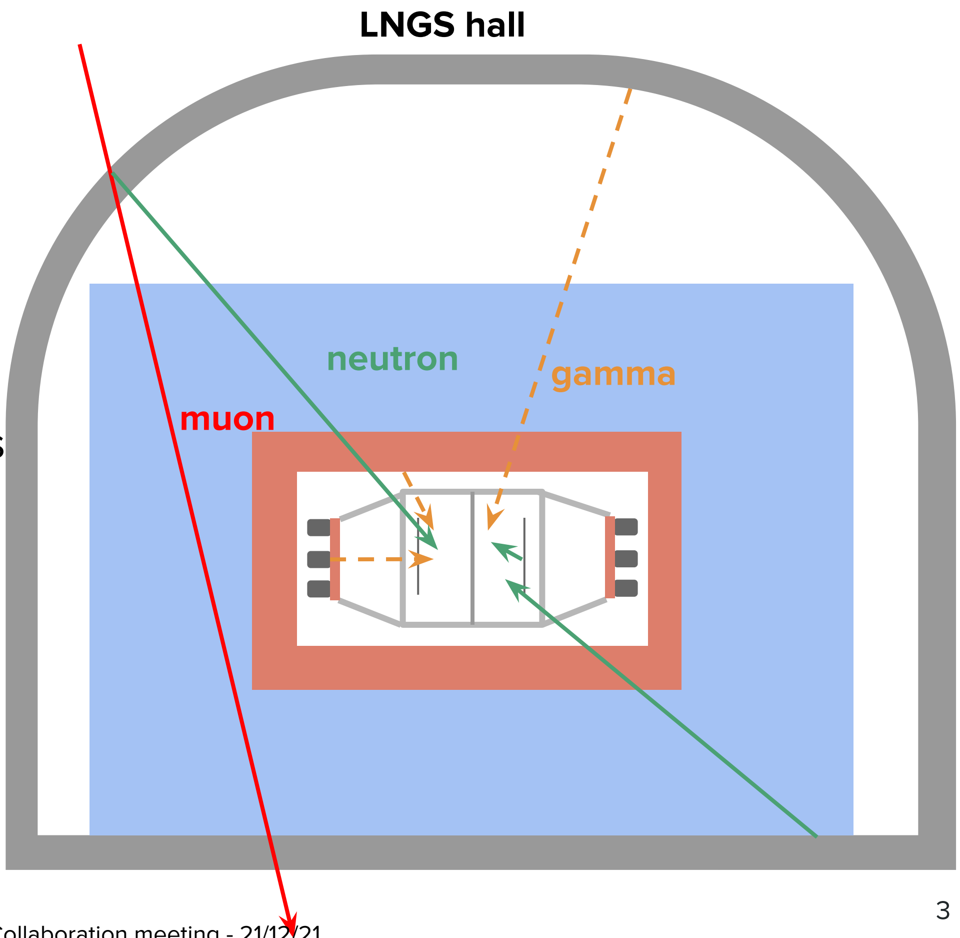
Background sources:

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



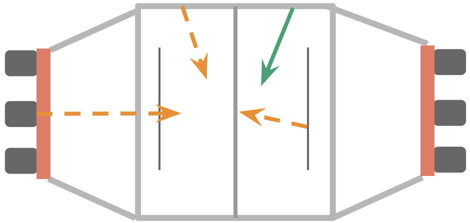
Background components

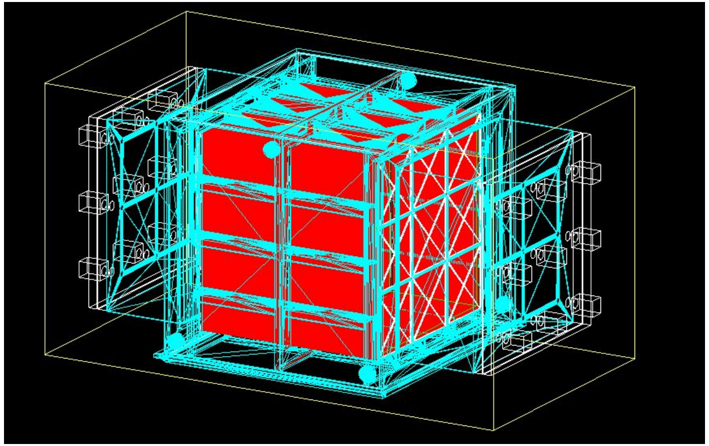
- Internal radiogenic neutrons/gammas (origin: radioactivity of the materials in setup)
- External radiogenic neutrons/gammas (origin: radioactivity of rocks and concrete of the lab)
- External cosmogenic neutrons (origin: muon interactions)



Internal backgrounds

Radioactivity of materials





GEANT4 implementation of the detector

- 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

Radioactivity of cameras

- Body and lens of ORCA Flash from M. Laubenstein measurements @LNGS

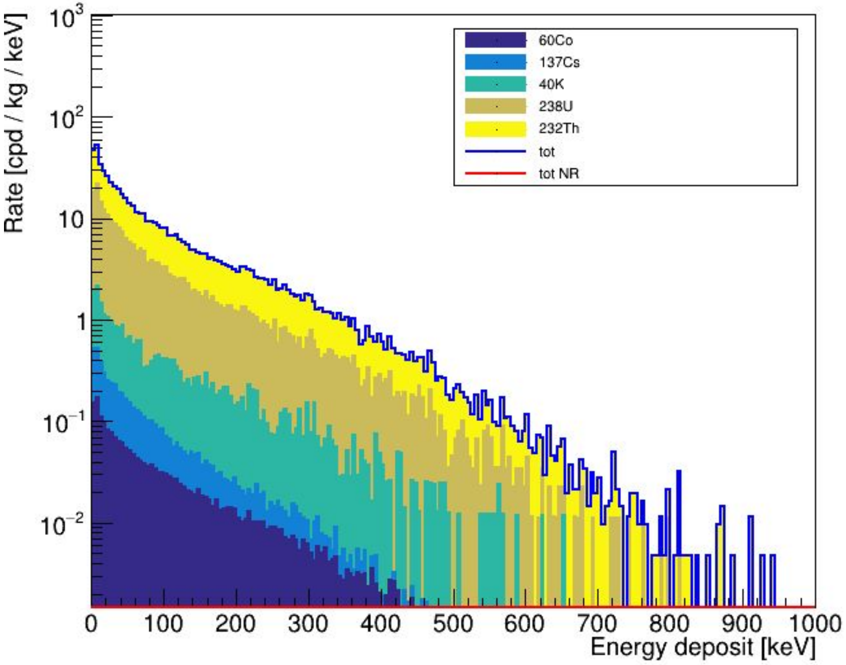
Camera Lens (glass)	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U238 (Th234)	Laubenstein @LNGS	M	4.22E+00	3.843
U238 (Ra226)	Laubenstein @LNGS	M	1.92E+00	3.843
U235	Laubenstein @LNGS	M	1.45E-01	3.843
Th232 (Ra228)	Laubenstein @LNGS	M	3.61E-01	3.843
Th232 (Th228)	Laubenstein @LNGS	M	3.65E-01	3.843
K40	Laubenstein @LNGS	M	5.15E+01	3.843
Cs137	Laubenstein @LNGS	L	2.67E-02	3.843
Co60	Laubenstein @LNGS	L	4.64E-02	3.843
La138	Laubenstein @LNGS	M	2.44E+00	3.843

Camera Body	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U238 (Th234)	Laubenstein @LNGS	M	3.16E+00	3.98E+01
U238 (Ra226)	Laubenstein @LNGS	M	8.13E-01	3.98E+01
U235	Laubenstein @LNGS	M	1.81E-01	3.98E+01
Th232 (Ra228)	Laubenstein @LNGS	M	9.49E-01	3.98E+01
Th232 (Th228)	Laubenstein @LNGS	M	9.49E-01	3.98E+01
K40	Laubenstein @LNGS	M	8.59E-01	3.98E+01
Cs137	Laubenstein @LNGS	M	4.07E-02	3.98E+01
Co60	Laubenstein @LNGS	L	5.42E-03	3.98E+01

- Alternative material for lens: fused silica

Camera Lens (fused	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U	Haereus Suprasil: http	M	1.23E-04	3.843
Th	Haereus Suprasil: http	M	4.07E-05	3.843
K	Haereus Suprasil: http	M	3.10E-04	3.843

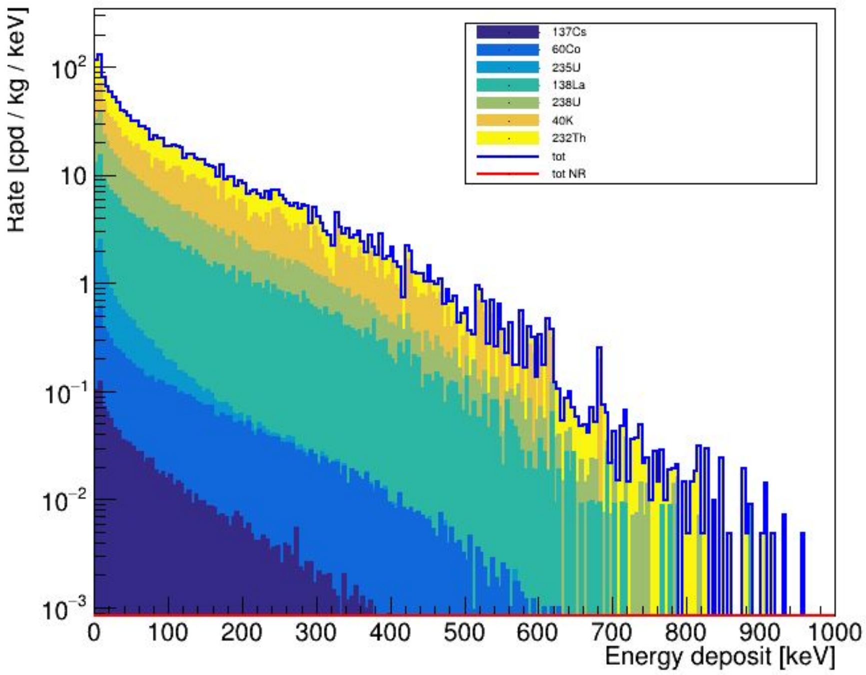
Background from camera body



Using activities from M.Laubenstein measurements @LNGS

- **ER rate [1-20] keV = 4.5x10^5 cts/yr**
- **NR rate [1-20] keV = 0 cts/yr**

Background from camera lens



Using activities from M.Laubenstein measurements @LNGS

- **ER rate [1-20] keV = 1.7x10^{6} cts/yr**
- **NR rate [1-20] keV = 0 cts/yr**

Radiopure lens made of fused silica**:**

- **ER rate [1-20] keV = 68 cts/yr**
- **NR rate [1-20] keV = 0 cts/yr**

Radioactivity of acrylic box

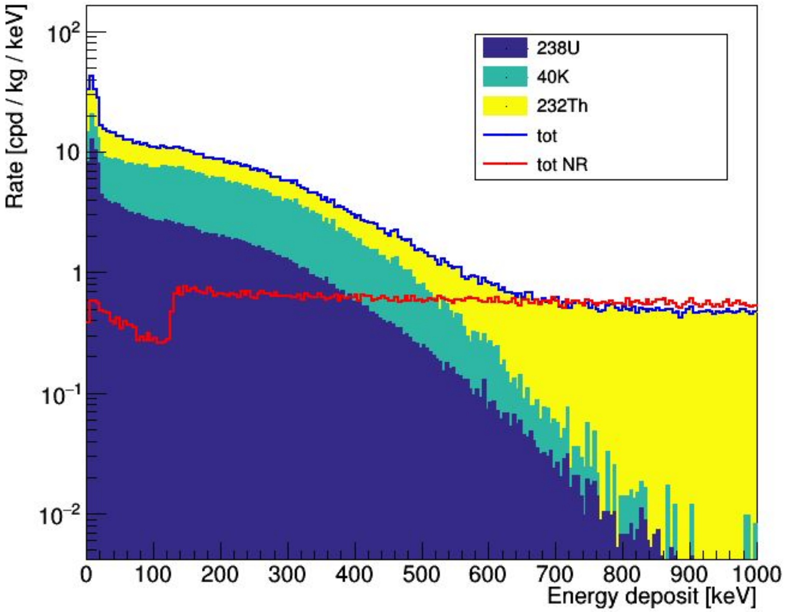
- U, Th, K activities from M.Laubenstein measurements @LNGS (upper limits)

Acrylic	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U238 (Ra226)	Laubenstein @LNGS	L	3.50E-03	2.01E+02
Th232 (Ra228)	Laubenstein @LNGS	L	5.00E-03	2.01E+02
Th232 (Th228)	Laubenstein @LNGS	L	4.50E-03	2.01E+02
K40	Laubenstein @LNGS	L	3.50E-02	2.01E+02

- SNO acrylic much lower radioactivity (from radiopurity.org database)

Acrylic	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U	SNO: https://www.radi	L	2.96E-04	2.01E+02
Th	SNO: https://www.radi	L	5.69E-05	2.01E+02
K	SNO: https://www.radi	L	7.12E-05	2.01E+02

Radioactivity background from Acrylic Box



Using activities from M.Laubenstein measurements @LNGS (upper limits)

- **ER rate [1-20] keV < 3.6x10^5 cts/yr**
- **NR rate [1-20] keV < 6.1x10^3 cts/yr**

With radiopure acrylic (SNO)**:**

- **ER rate [1-20] keV < 1.2x10^4 cts/yr**
- **NR rate [1-20] keV < 76 cts/yr**

Radioactivity of GEMs

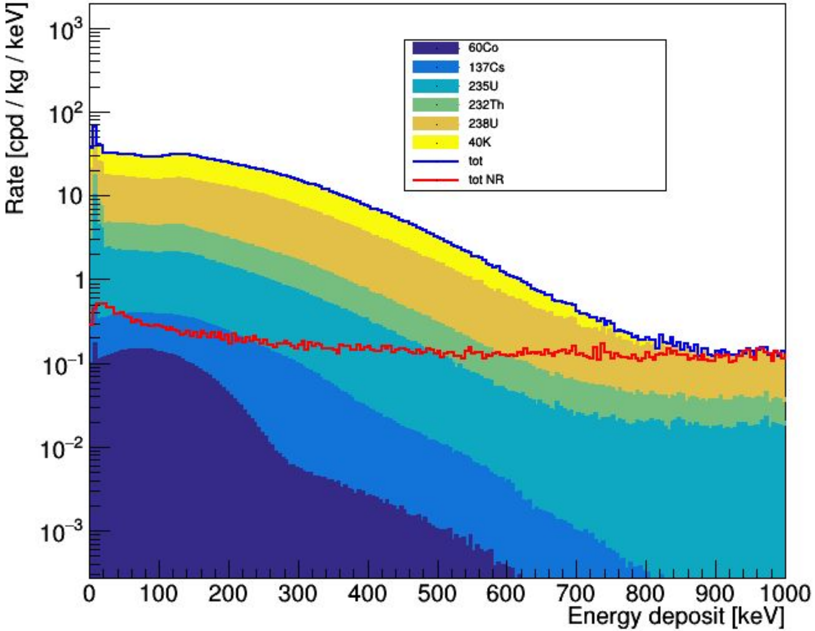
- Activities from M.Laubenstein measurements @LNGS

GEM	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
U238 (Th234)	Laubenstein @LNGS	M	1.63E-01	0.7
U238 (Ra226)	Laubenstein @LNGS	M	3.25E-02	0.7
U235	Laubenstein @LNGS	L	1.58E-02	0.7
Th232 (Ra228)	Laubenstein @LNGS	L	3.09E-02	0.7
Th232 (Th228)	Laubenstein @LNGS	L	1.56E-02	0.7
K40	Laubenstein @LNGS	L	3.58E-01	0.7
Cs137	Laubenstein @LNGS	L	8.13E-03	0.7
Co60	Laubenstein @LNGS	L	7.48E-03	0.7

- Activities from TREX paper

GEM	Reference	Limit/Me	Activity (Bq/kg)
U238	TREX https://link.sp	L	1.32E-02
Th232	TREX https://link.sp	M	5.45E-03
U235	TREX https://link.sp	M	2.80E-02
K40	TREX https://link.sp	M	6.31E-02
Co60	TREX https://link.sp	L	2.34E-03
Cs137	TREX https://link.sp	L	1.56E-03

Radioactivity background from GEMs



Using activities from M.Laubenstein measurements @LNGS

- **ER rate [1-20] keV = 5.1×10^5 cts/yr**
- **NR rate [1-20] keV = 5.0×10^3 cts/yr**

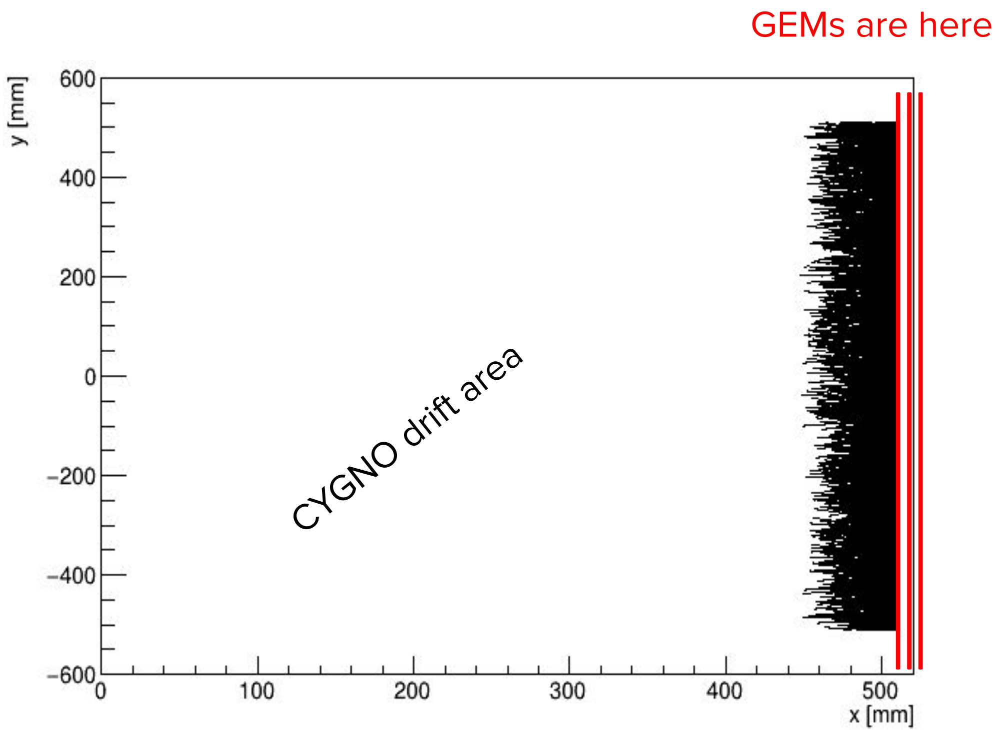
With TREX GEM**:**

- **ER rate [1-20] keV = 3.6×10^5 cts/yr**
- **NR rate [1-20] keV = 4.3×10^3 cts/yr**

NOTE: GEM frames are not included in this simulation

Fiducialization

- GEM energy deposits from nuclei in one of the CYGNO drift regions (checked ➔ they are all alphas)
- GEANT4 saves the info if the alpha is primary (from alpha radioactivity) or secondary (ex. He nuclei in the gas)
- Secondary alpha are ~16% of the total and with same distribution of primary
- All contained in the first ~5 cm of gas ➔ **expect to reject almost all NR with fiducialization**



Quick qualitative study, more detailed study needed, but looks promising...

Radioactivity of cathode

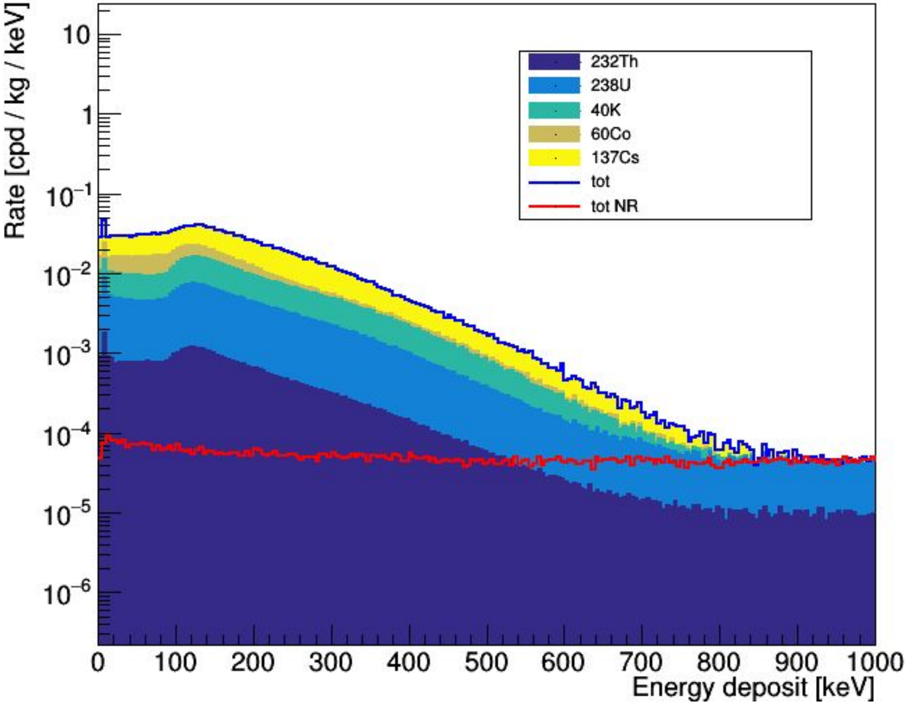
- Activities from TREX copper

Copper Cathode	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
238U	Cu from TREX: https:/	L	1.20E-05	0.98408
232Th	Cu from TREX: https:/	L	4.10E-06	0.98408
40K	Cu from TREX: https:/	M	6.10E-05	0.98408
60Co	Cu from TREX: https:/	L	2.40E-04	0.98408
137Cs	Cu from TREX: https:/	L	2.90E-04	0.98408

NOTE:

- Standard copper activities can be 10x higher
- Cosmogenic activity NOT taken into account: ^{57}Co, ^{58}Co, ^{54}Mn

Radioactivity background of cathode



Using activities from TREX copper

- **ER rate [1-20] keV = 3.6x10^3 cts/yr**
- **NR rate [1-20] keV = 0.8 cts/yr**

NOTE:

- Standard copper activities can be 10x higher
- Cosmogenic activity NOT taken into account: ^{57}Co, ^{58}Co, ^{54}Mn

Radioactivity of field cage

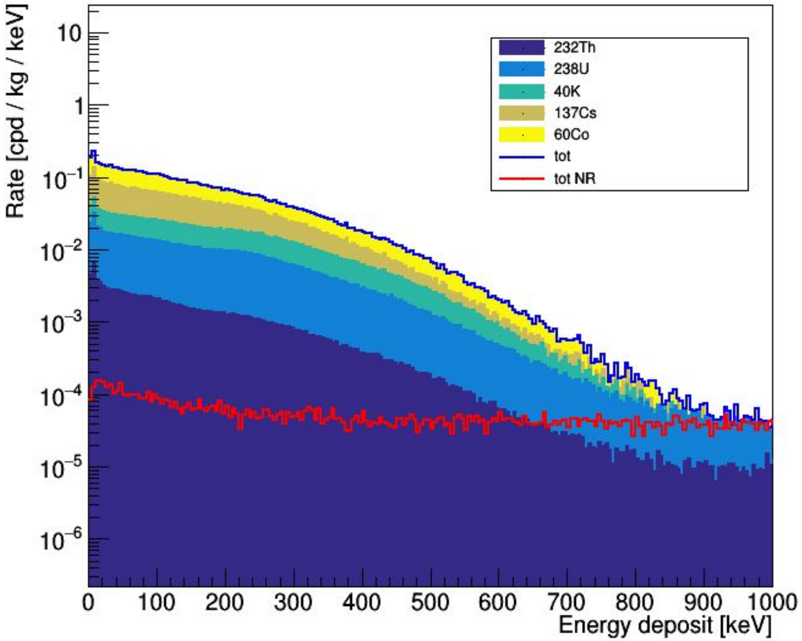
- Activities from TREX copper

Copper Field Cage	Reference	Limit/Me	Activity (Bq/kg)	mass (kg)
238U	Cu from TREX: https:/	L	1.20E-05	42.4915
232Th	Cu from TREX: https:/	L	4.10E-06	42.4915
40K	Cu from TREX: https:/	M	6.10E-05	42.4915
60Co	Cu from TREX: https:/	L	2.40E-04	42.4915
137Cs	Cu from TREX: https:/	L	2.90E-04	42.4915

NOTE:

- Standard copper activities can be 10x higher
- Cosmogenic activity NOT taken into account: ^{57}Co, ^{58}Co, ^{54}Mn

Radioactivity background from FC



Using activities from TREX copper

- **ER rate [1-20] keV = 2.0x10^3 cts/yr**
- **NR rate [1-20] keV = 1.5 cts/yr**

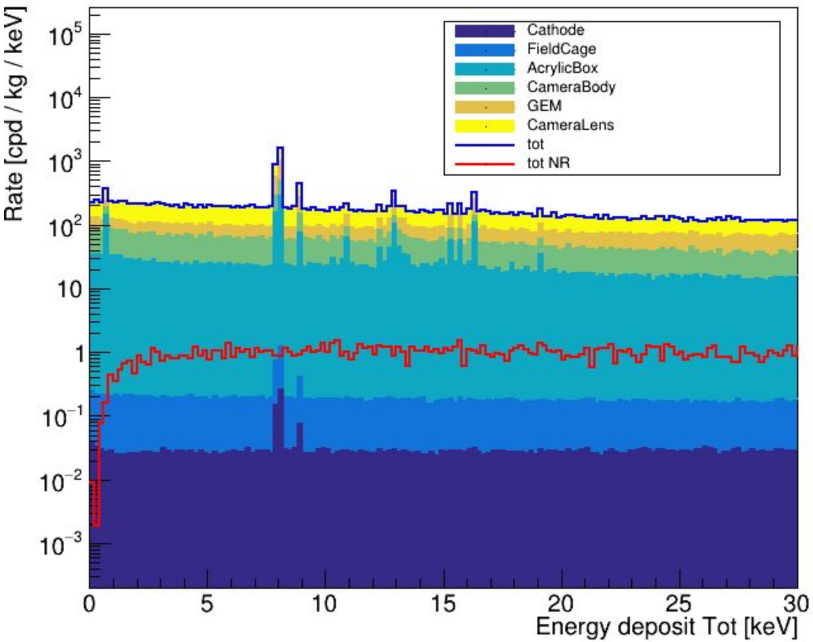
NOTE:

- Standard copper activities can be 10x higher
- Cosmogenic activity NOT taken into account: ^{57}Co, ^{58}Co, ^{54}Mn

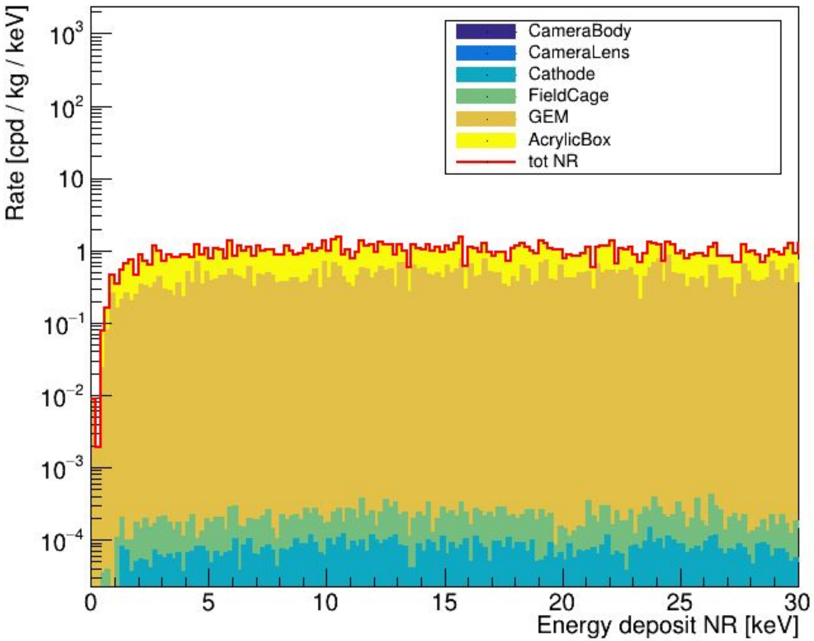
NOTE: Resistors are not included in the simulation

Summary of internal backgrounds

- **ER rate [1-20] keV = 2.3x10^6 cts/yr**



- **NR rate [1-20] keV = 1.1x10^4 cts/yr**



Summary of internal backgrounds

	CYGNO		CHINOTTO *		
Summary Table	**NR/yr 1-20 keV**	**ER/yr 1-20 keV**	**NR/yr 1-20 keV**	**ER/yr 1-20 keV**	**Reference**
GEM (LNGS)	5.07E+03	5.09E+05	1.00E+03	1.01E+05	Laubenstein@LNGS
GEM (TREX)	4.27E+03	3.61E+05	8.44E+02	7.14E+04	T-REX GEM
AcrylicBox (LNGS)	6.07E+03	3.61E+05	1.56E+03	9.32E+04	Laubenstein@LNGS
AcrylicBox (SNO)	7.67E+01	1.17E+04	1.98E+01	3.02E+03	SNO acrylic
CameraBody	0.00E+00	4.46E+05	0.00E+00	8.81E+04	Laubenstein@LNGS
CameraLens (LNGS)	0.00E+00	1.07E+06	0.00E+00	2.12E+05	Laubenstein@LNGS
CameraLens (fused silica)	0.00E+00	6.68E+01	0.00E+00	1.32E+01	Haereus "Suprasil"
Cathode (Cu)	8.58E-01	3.63E+02	1.69E-01	7.18E+01	T-REX copper
Field Cage (Cu)	1.51E+00	2.00E+03	2.99E-01	3.96E+02	T-REX copper
Total (LNGS)	**1.11E+04**	**2.39E+06**	**2.57E+03**	**4.94E+05**	
Total (low rad)	**4.35E+03**	**8.21E+05**	**8.64E+02**	**1.63E+05**	

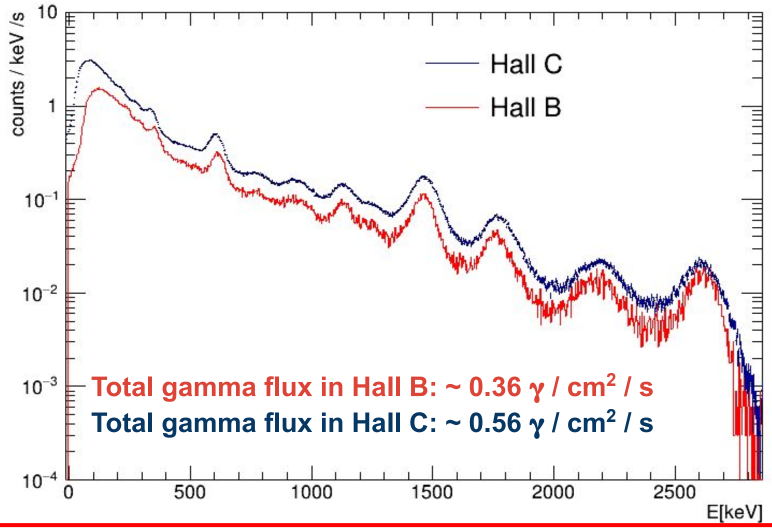
- NR for the low-rad option mostly come from GEM ➔ could be reduced with fiducialization
- ER for the low-rad option mostly come from GEM and Camera body

* Rates for CHINOTTO are obtained scaling from CYGNO numbers

External background and shielding studies

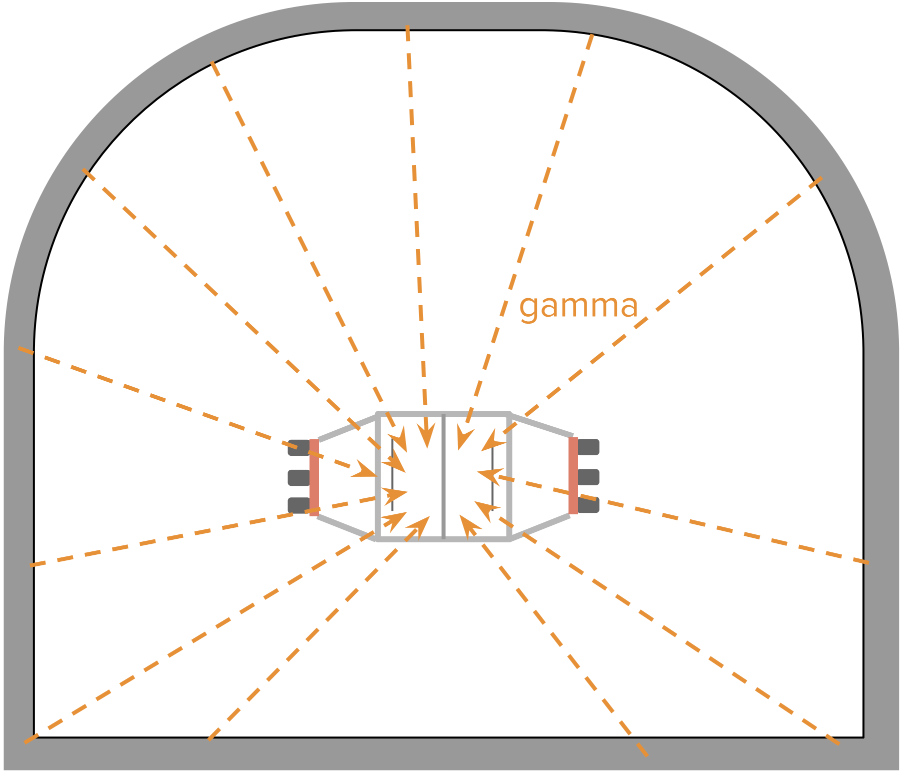
Ambient gammas

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



Without shield **10^{10} evts/yr** in the CYGNO detector
➔ need shielding with **attenuation power 10^{-6}-10^{-7}**

LNGS hall



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

Materials

Materials considered for the shielding:

- **copper** → high density, compact shield, can be produced very radiopure, ...but expensive (~25 euro/kg)
- **water** → radiopure, cheap, ...low density, need large volume
- **lead** → high density, compact shield, ...but very radioactive and secondary neutrons

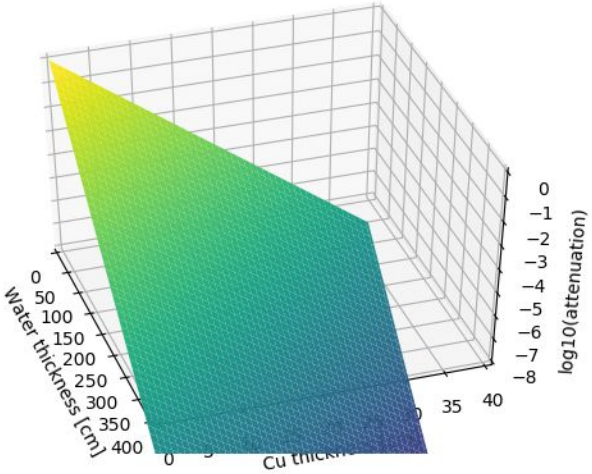
Other materials used in low background experiment

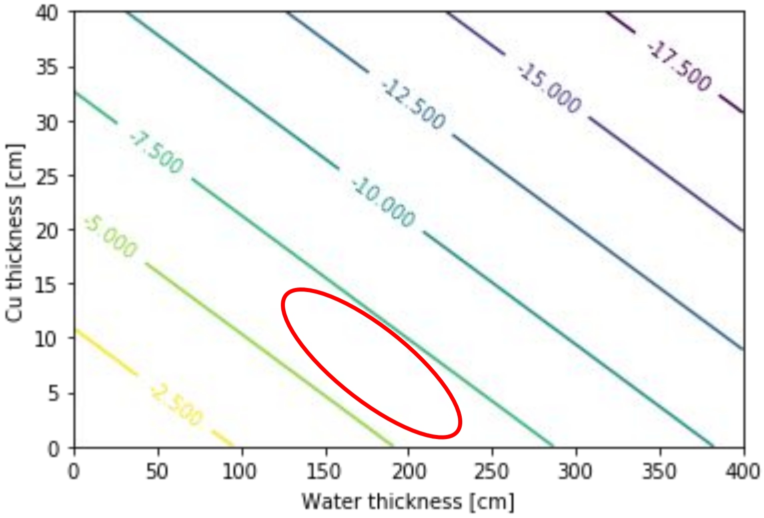
- **polyethylene** → similar shielding properties to water but more expensive

Focused our study on copper+ water shield.

Attenuation of Cu + water

Approximate calculation (not full MC simulation, use tables for gamma attenuation at E~MeV)



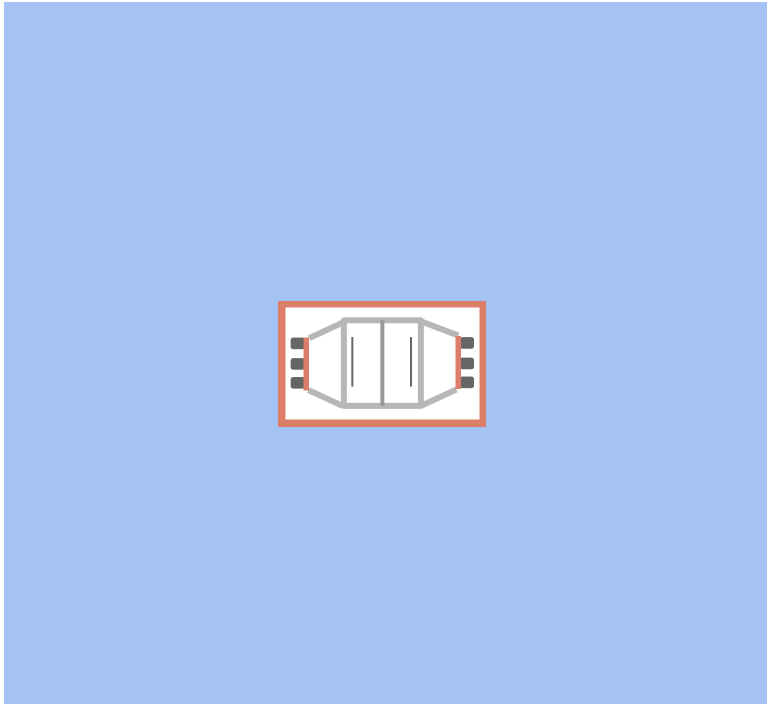


We need ~10^{-6} -10^{7} gamma attenuation:

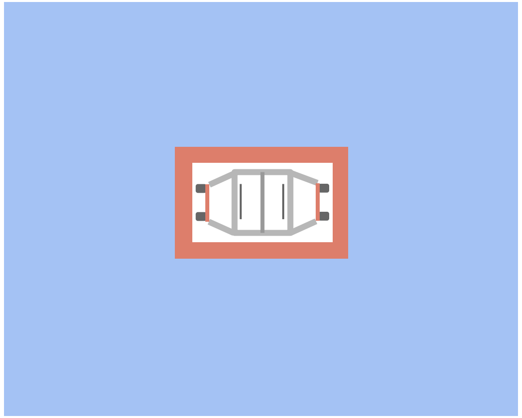
- Cu thickness limited by cost
- water thickness limited by space

Shielding options studied

1) 200 cm water shield
+ 5 cm copper shield

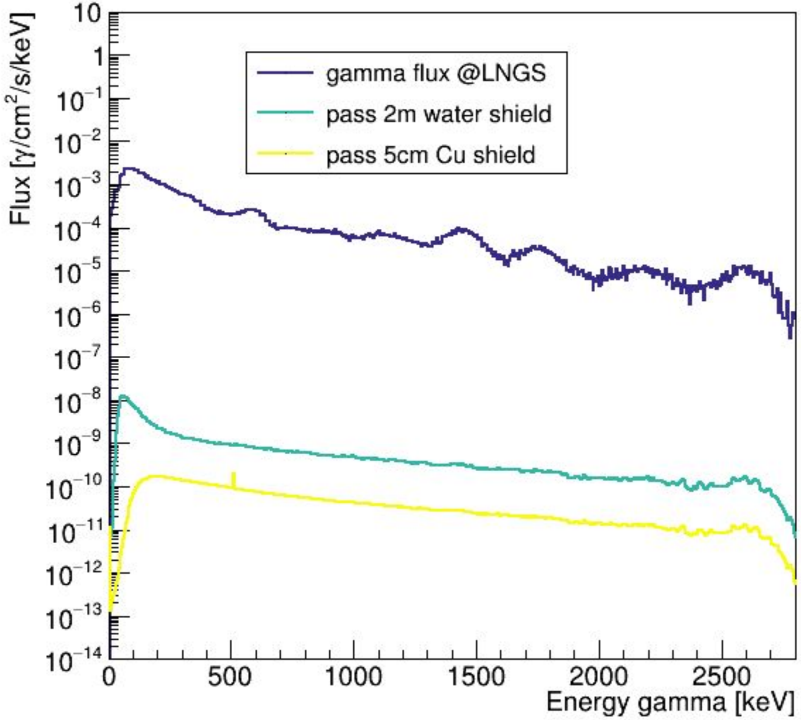


2) 110 cm water shield
+ 10 cm copper shield
2x2 LIME modules (CHINOTTO)

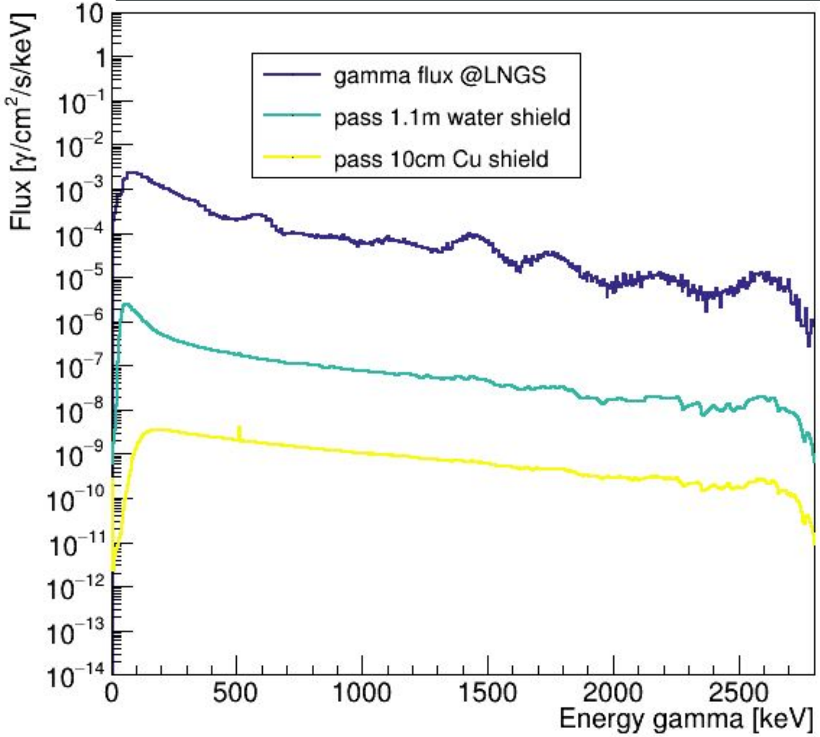


Gamma flux

gamma flux entering shield: 1.8×10^{-7} cm^{-2}s^{-1}

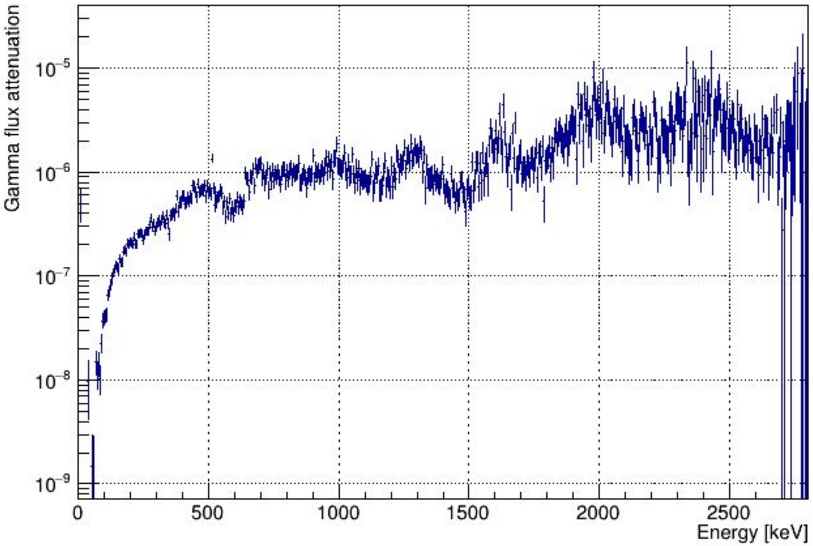


gamma flux entering shield: 2.4×10^{-6} cm^{-2}s^{-1}

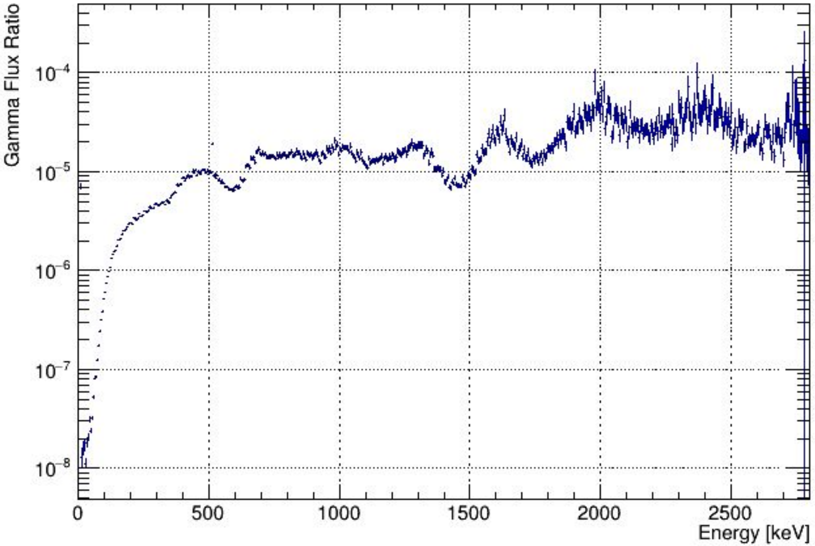


Gamma flux attenuation

1) 200 cm water shield
+ 5 cm copper shield

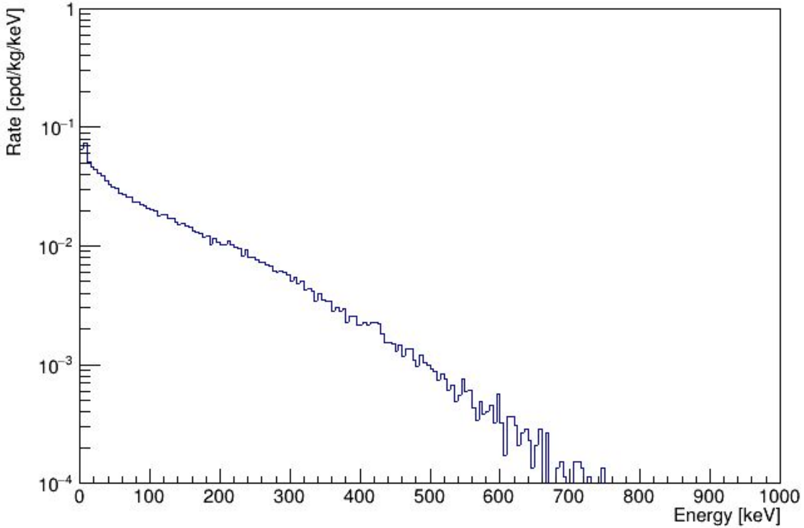


2) 110 cm water shield
+ 10 cm copper shield
2x2 LIME modules (CHINOTTO)

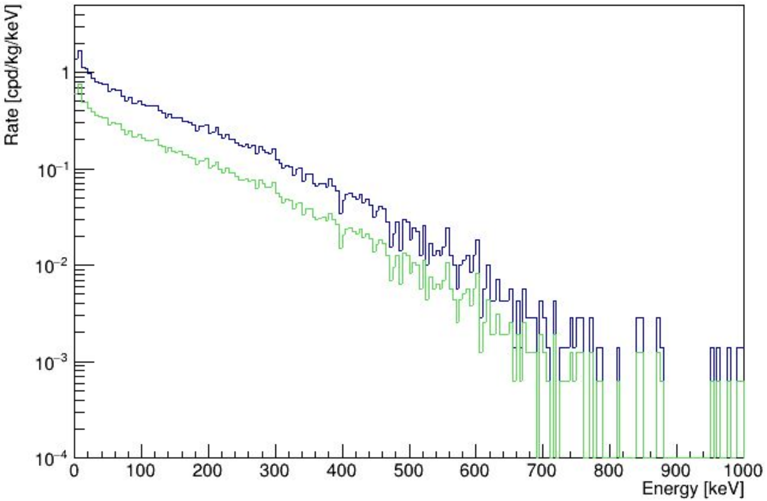


External gamma background

- **Rate [1-20] keV = 650 cts/yr**

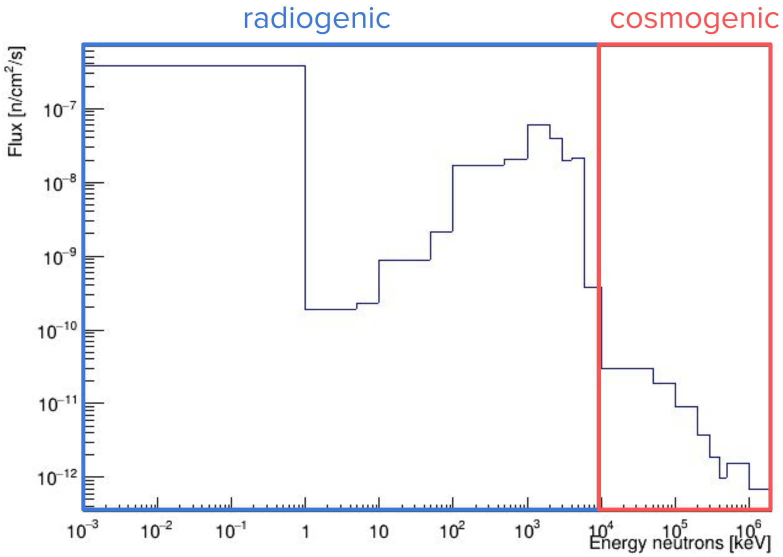


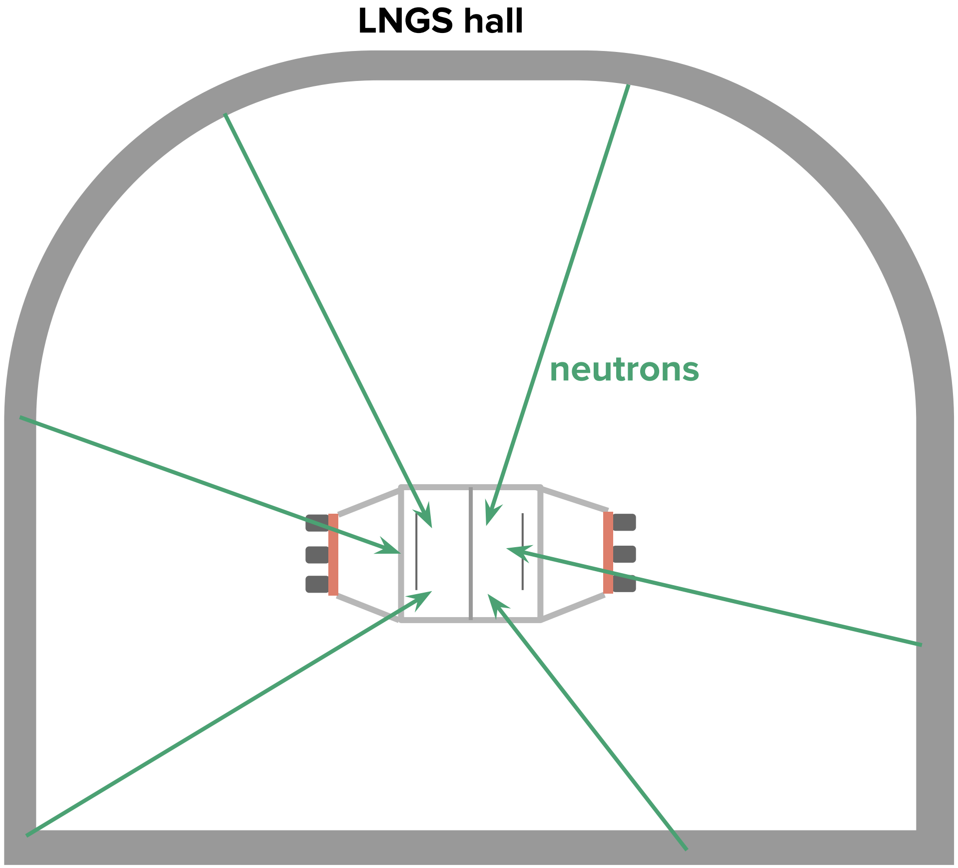
- **Rate [1-20] keV = 1.4x10^4 cts/yr (CYGNO)**
- **Rate [1-20] keV = 6.4x10^3 cts/yr (CHINOTTO)**



Ambient neutrons

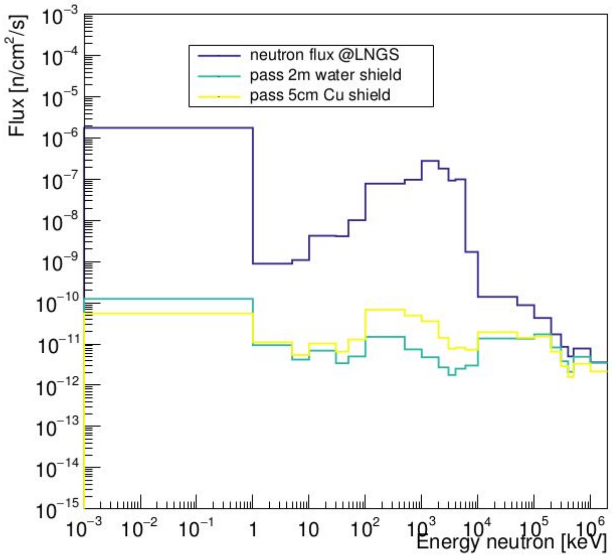
- Ambient neutrons from radioactivity in the rock
- Spectrum from CUORE MC
  ➡ measurements Belli/Arneodo (radiogenic, E<10 MeV) and Hime (cosmogenic E>10 MeV)





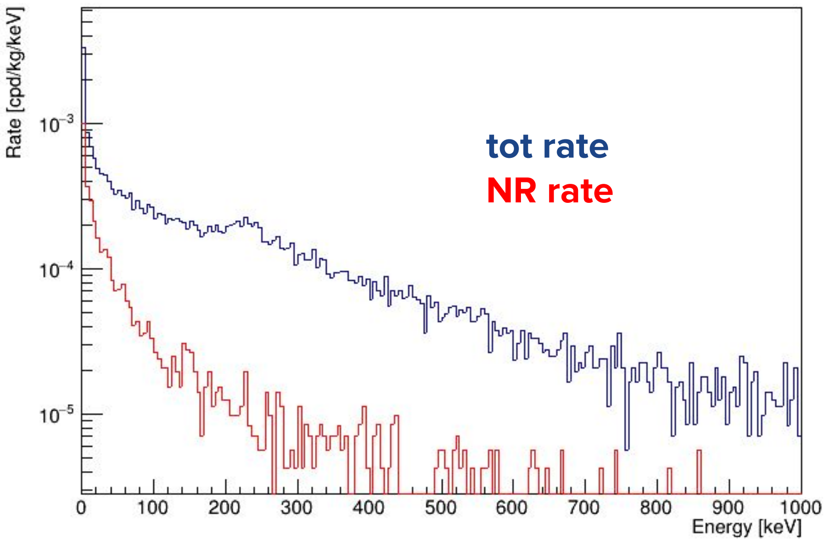
Neutron background shield (option 1)

- Neutron flux entering shield $2.3x10^{-9}$ cm^{-2} s^{-1}
- Secondary gamma flux from neutron interactions $2x10^{-9}$ cm^{-2} s^{-1}
  ➜ for comparison external gamma flux is 10^{-7}



Rates at low energy 1-20 keV:

- **NR rate [1-20] keV = 4.3 cts/yr**
- **ER rate [1-20] keV = 4.7 cts/yr**



Summary

- Total **internal background** in CYGNO using low radioactivity materials is of the order of **10^5 ER/yr** and **10^3 NR/yr**
- Internal background is dominated by GEMs and cameras
  - need to optimize materials for low background experiments
  - fiducialization could reduce the NR rate
- **External gamma background** with a shielding of **2m water+5 cm Cu** is reduced to **$<10^3$ ER/yr**
- **External neutron background** is of **<10 NR/yr**
  - background due to secondary gammas is negligible
- Time to write a paper summarizing these results

Backup

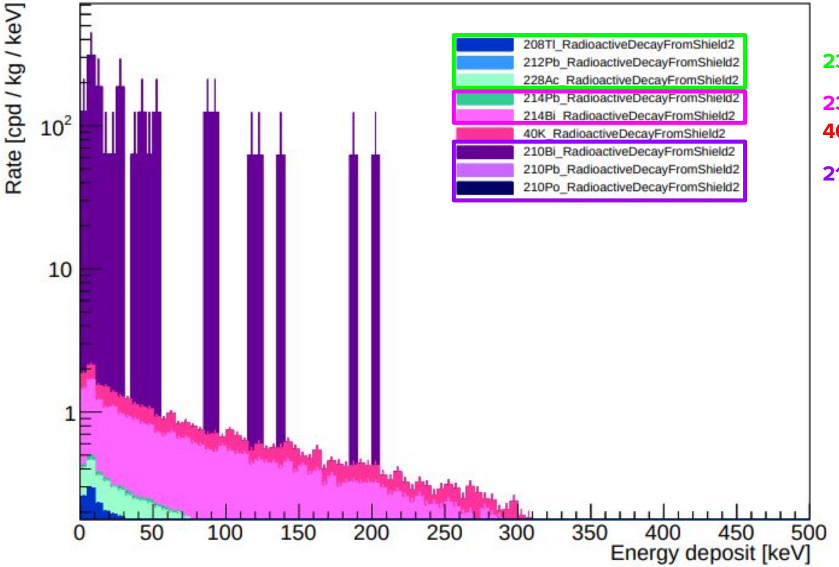
Lead shield radioactivity

- 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 background of lead shield

- Energy deposit in CYGNO detector from lead shield radioactivity
- assume ^{210}Pb of OPERA lead (**2-3 times better than common lead**)
- U, Th, K activities from T-REX paper (arxiv 1812.04519)
- shielding made of 50 cm water + 5 cm Pb + 5 cm Cu



^{232}Th chain
^{238}U chain
^{40}K
^{210}Pb

	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
A 5 cm-thick shield of lead for 1 m^3 detector gives a large background, unless using archaeological lead.