Comprehensive estimate of *(particle)* backgrounds at sub-keV energies

for the NUCLEUS experiment

The Magnificent CEvNS 2024

València

12-14 June 2024

Chloé Goupy, on behalf of the NUCLEUS collaboration

IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

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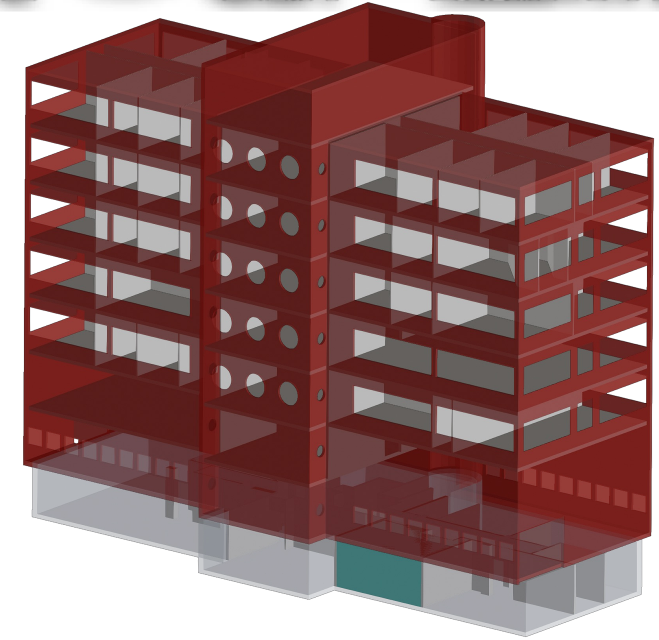
NUCLEUS contributions
E. Bossio – *Status of the NUCLEUS experiment* (Talk, Wed. 12/04)
L. Peters – *A new data analysis tool for NUCLEUS and first results from the commissioning phase* (Poster, Wed. 12/04)

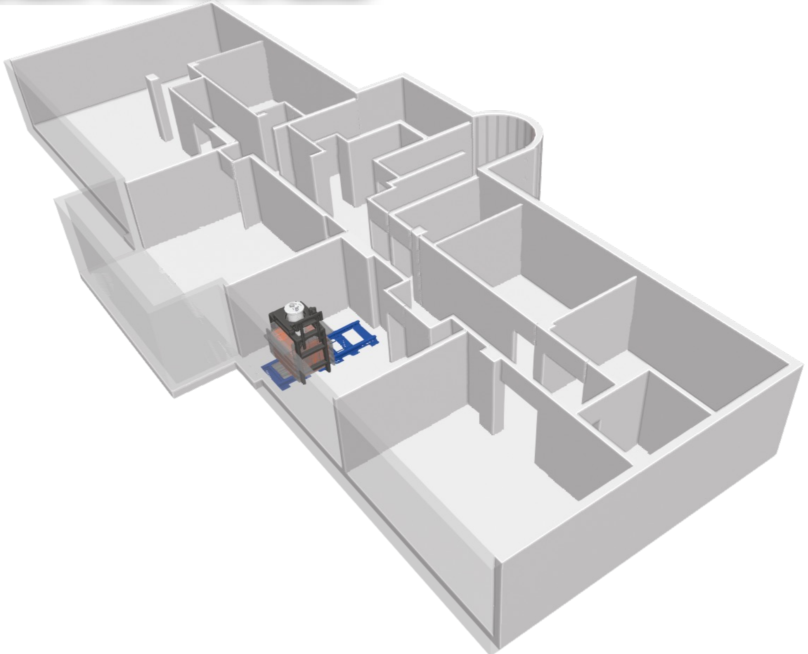
The NUCLEUS experimental site

Chooz B nuclear power plant:
Thermal power of 2 x 4.25 GW_{th}

Experimental site: the "Very Near Site" (VNS)
102 m and 72 m from the two reactor cores
Expected neutrino flux : $1.7\times10^{12}\ \overline{\upsilon}\ /(s\ cm^2)$

24 m^2 room in the basement of a 6-storey tertiary building
overburden of 3 meters water equivalent
(Ricochet: 15 m.w.e., CONUS: ~24 m.w.e.)





Goals and CEνNS signal

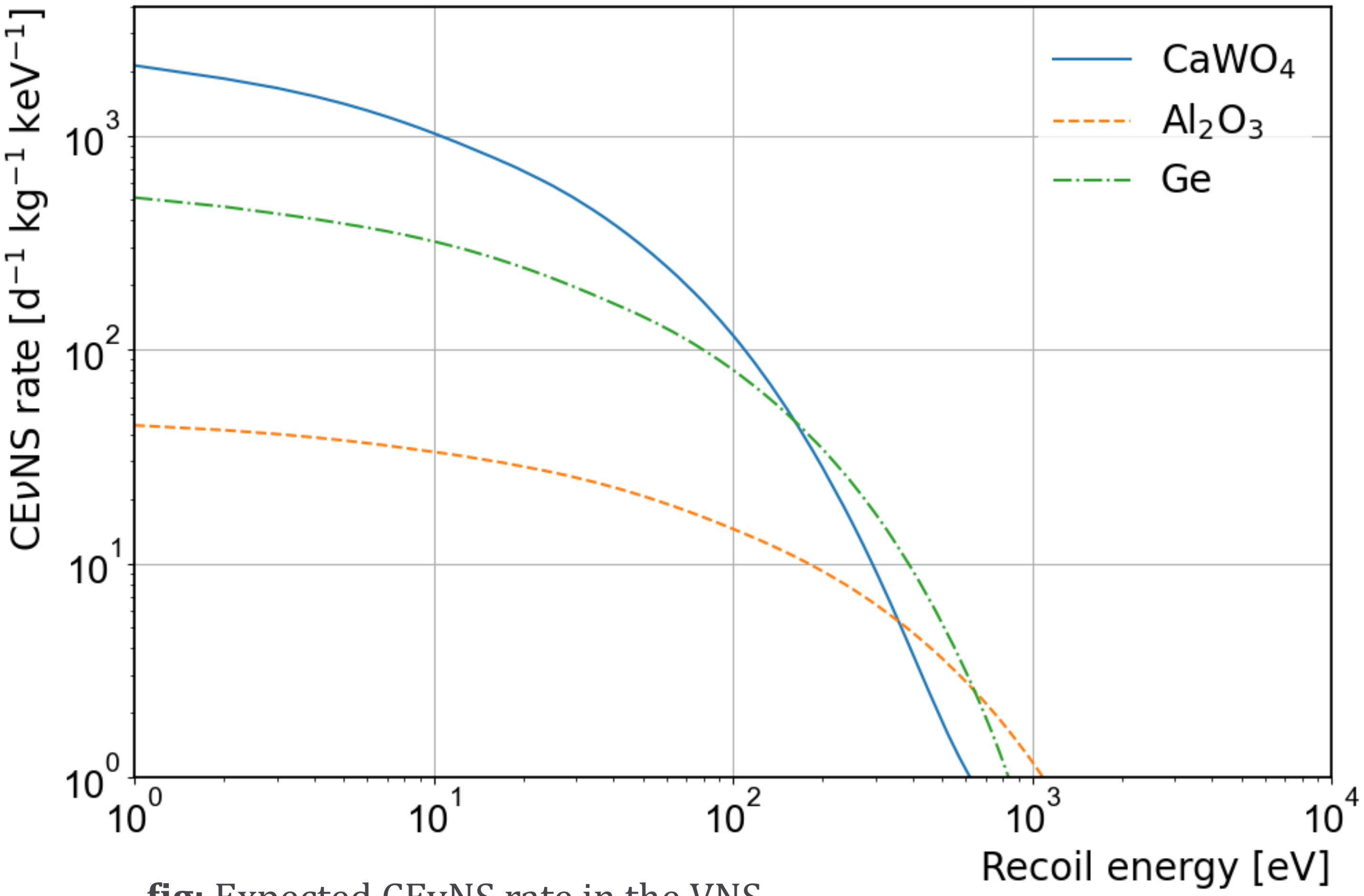


fig: Expected CEνNS rate in the VNS

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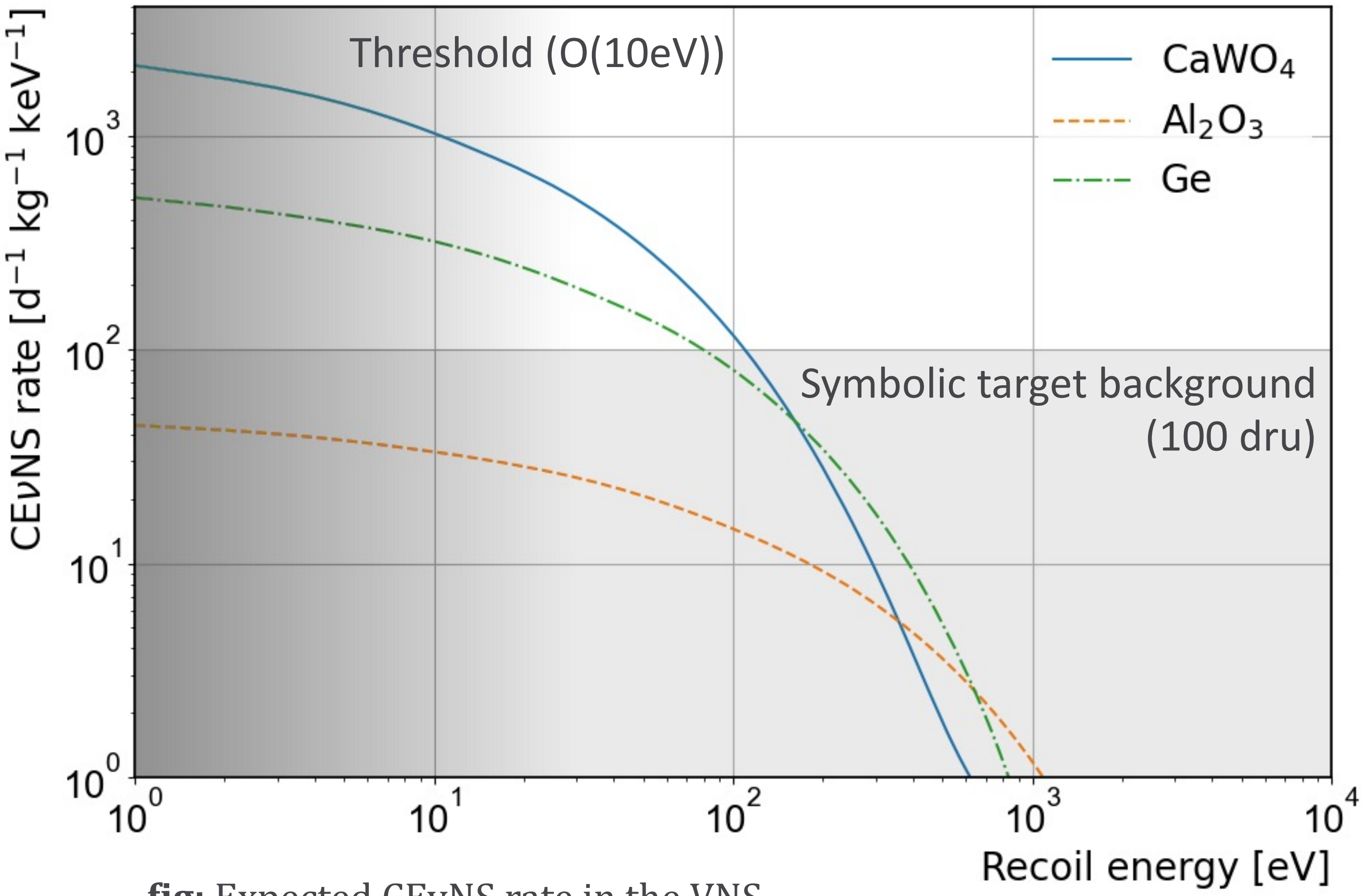

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NUCLEUS ROI: O(10eV)-100eV

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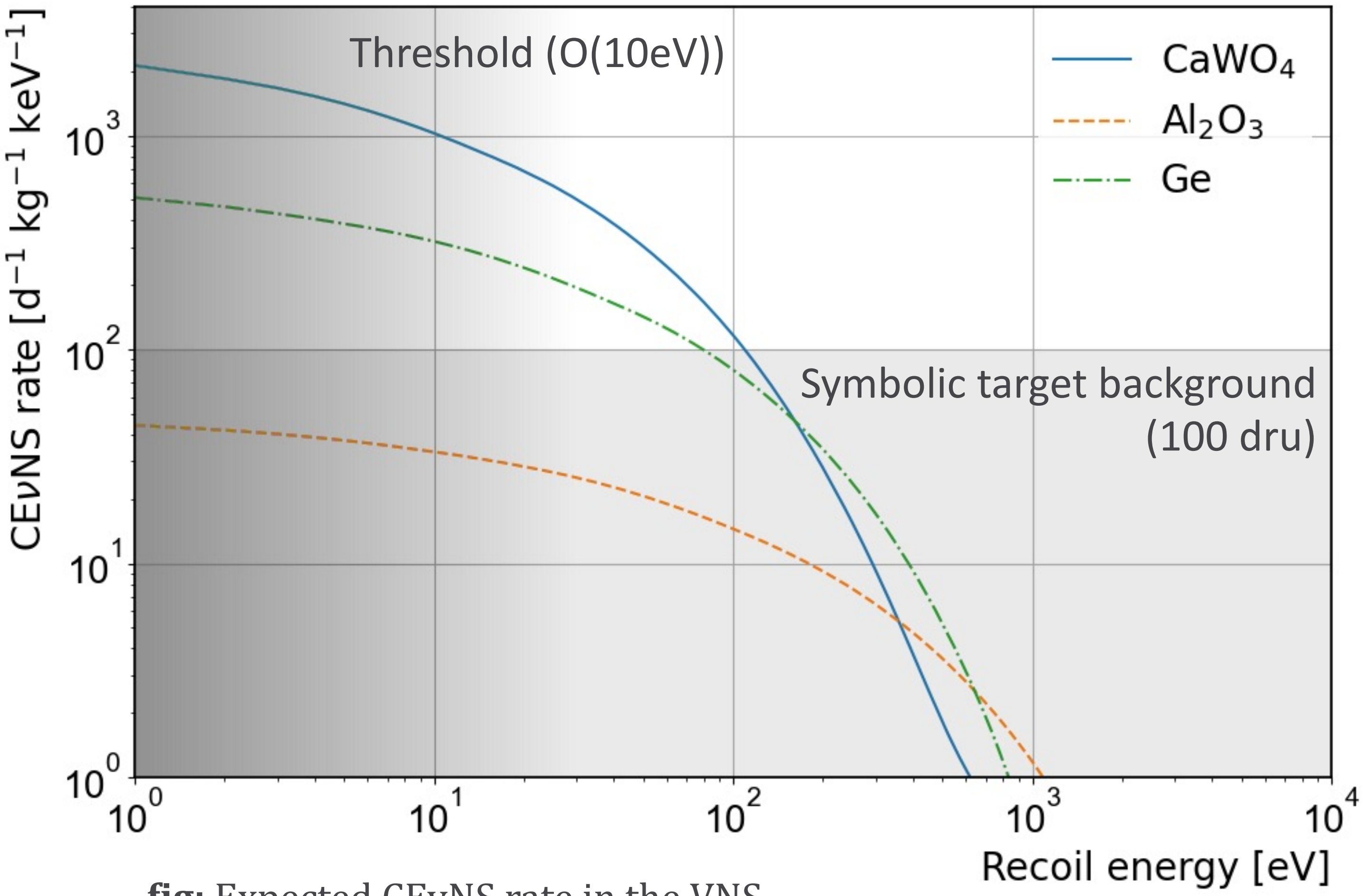

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NUCLEUS ROI: O(10eV)-100eV

NUCLEUS target detectors

In $CaWO_4 \Rightarrow$ 32 events/day/kg in [10-100] eV

Chooz reactor duty cycle ~ 80% over a year:

$\Rightarrow$ 25.6 events/day/kg in [10-100] eV

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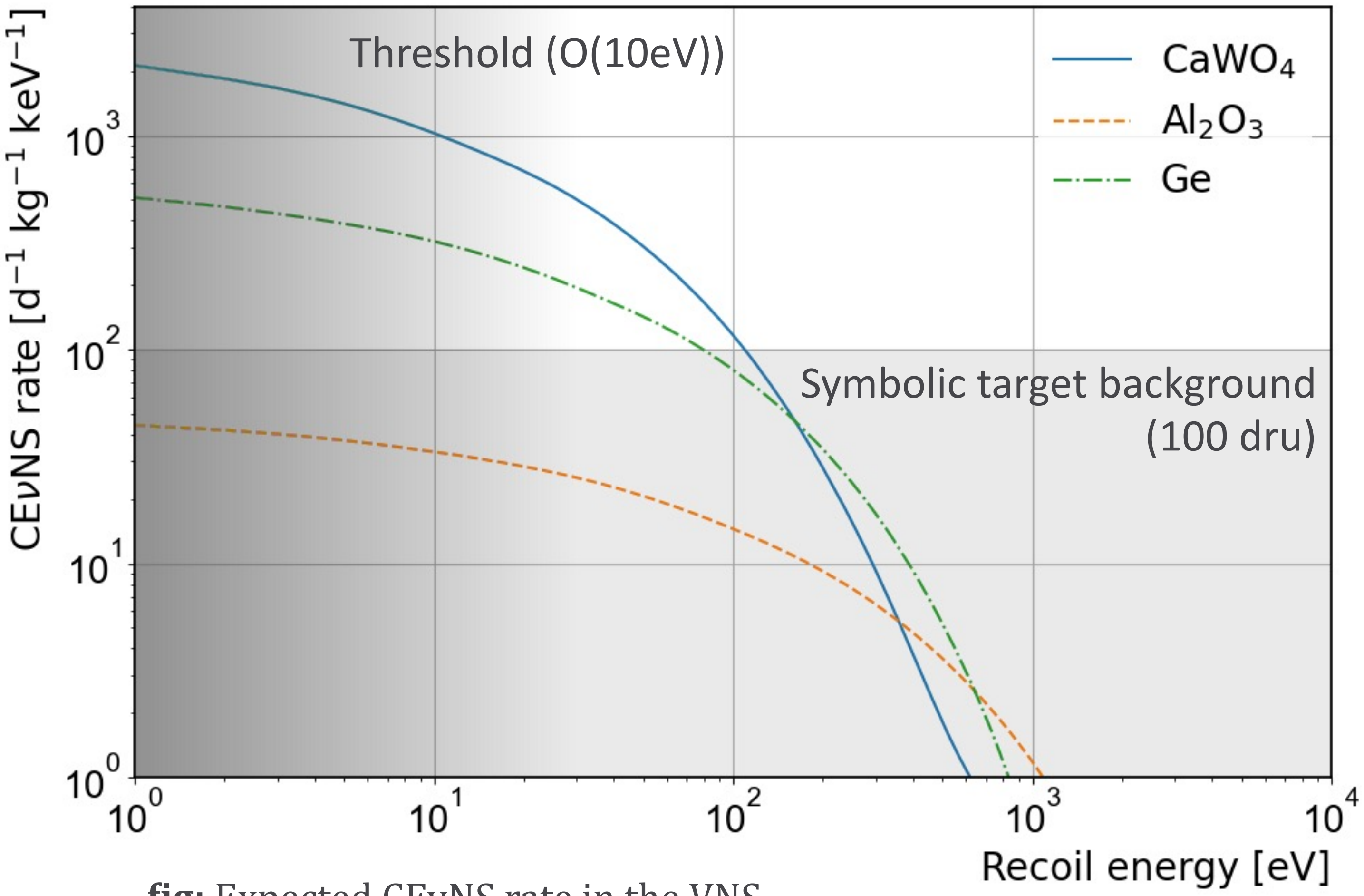

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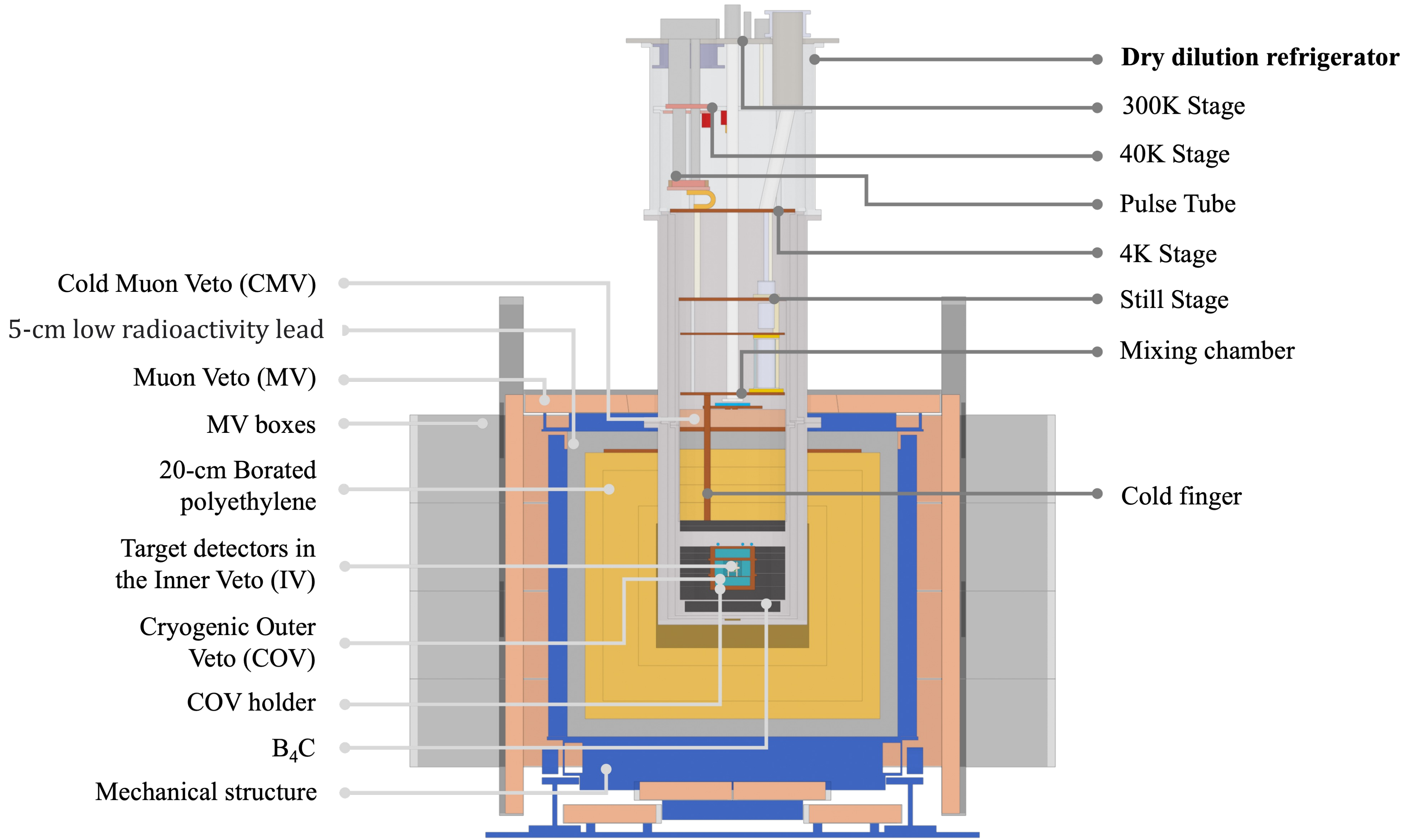
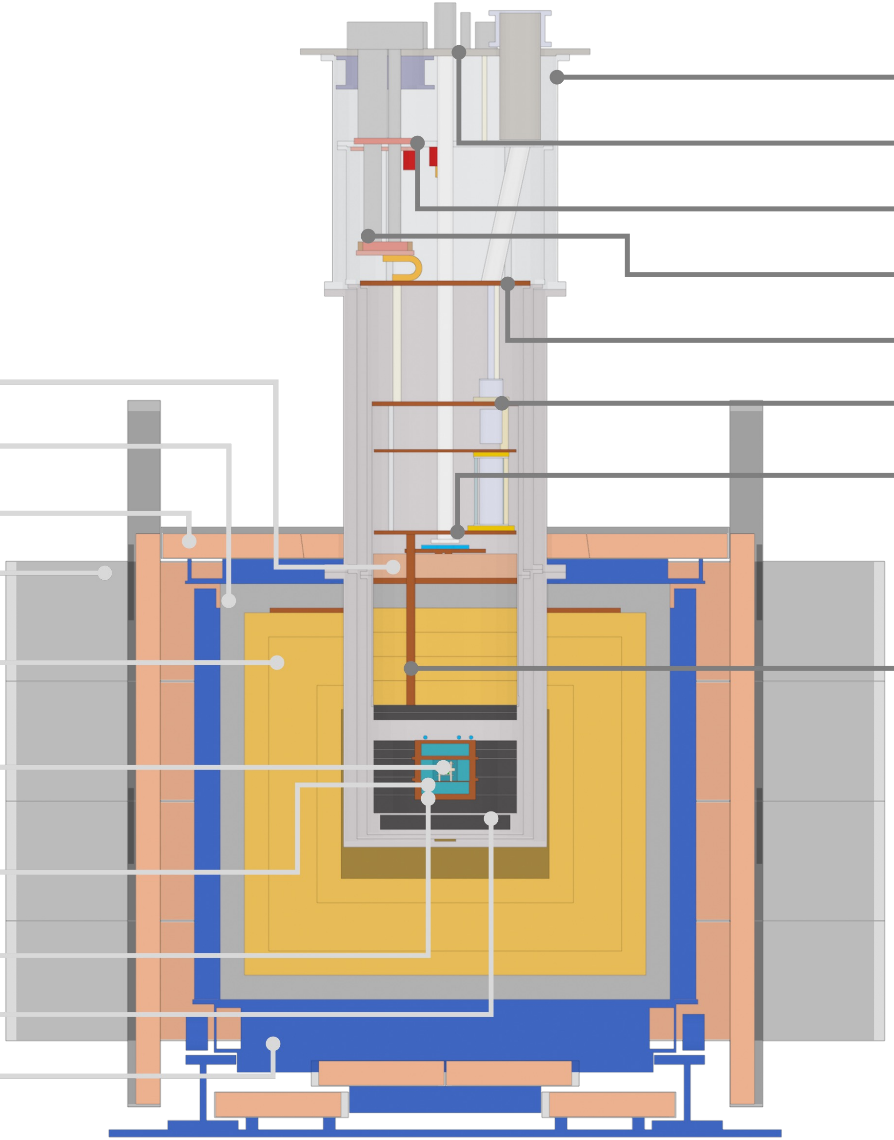
Background level goal: S/B $\geq$ 1

The NUCLEUS experiment's design



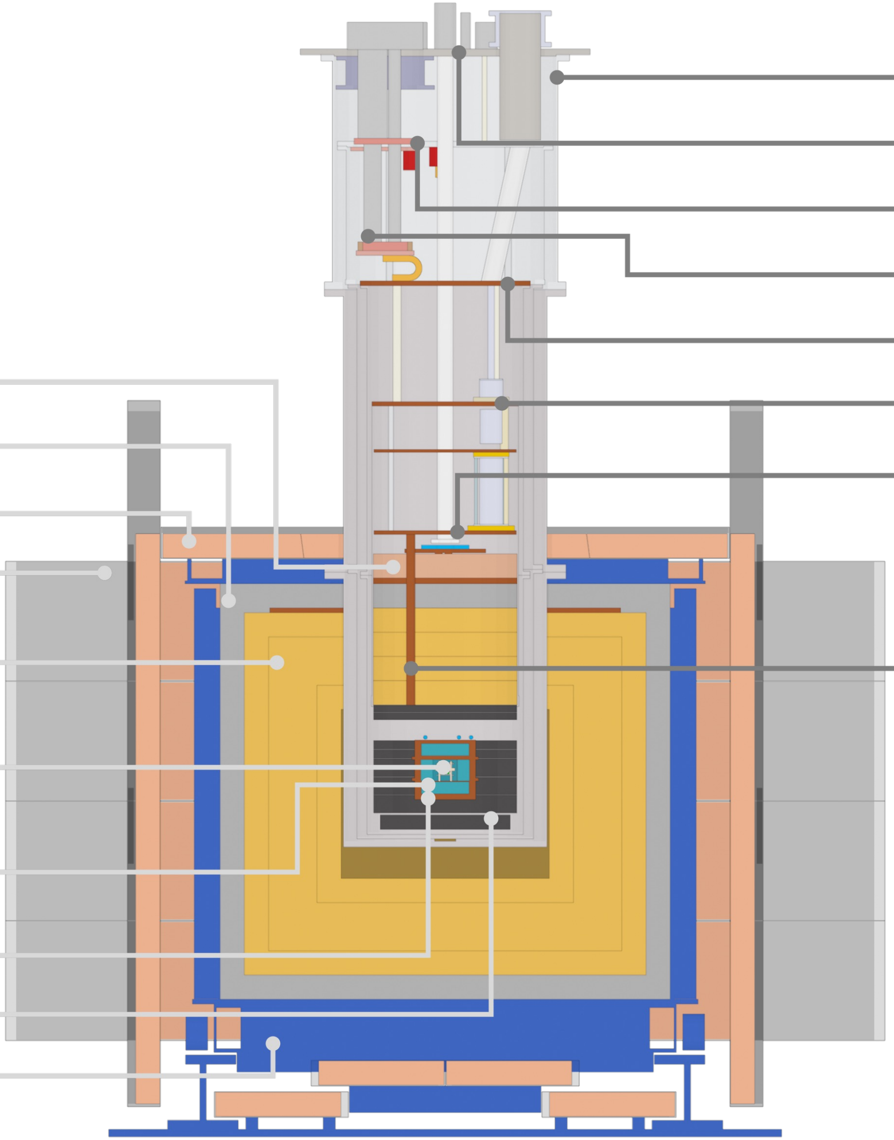
The NUCLEUS experiment's design

Muon shielding



The NUCLEUS experiment's design

Muon shielding
Neutron shielding



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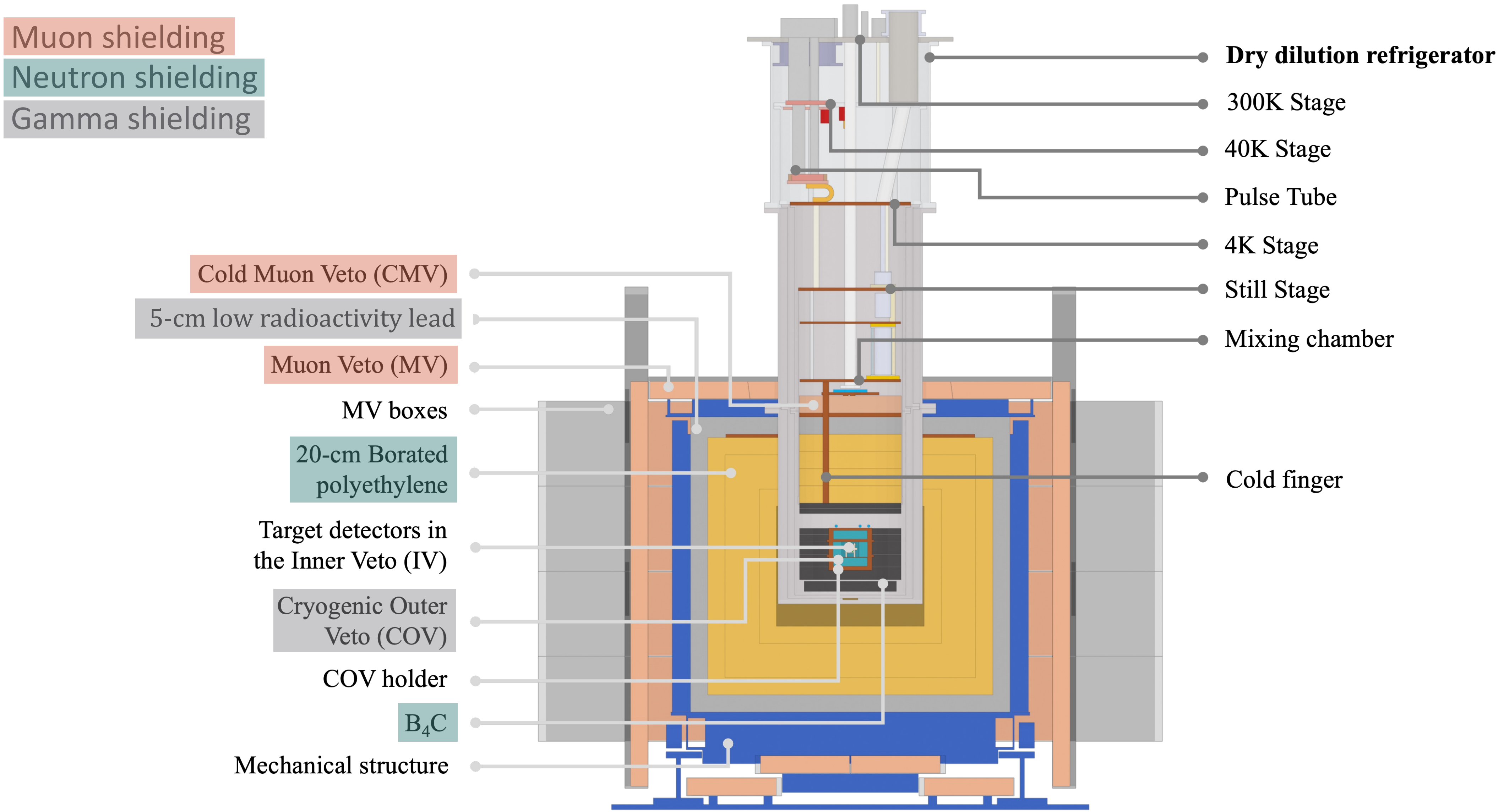

Main background sources at shallow depth

Sources of background at sea level:

- Cosmogenic:
  - Atmospheric muons
  - Atmospheric neutrons

- Radiogenic:
  - Primordial radioactivity (concrete, building materials, rocks and soils) ⇒ ^{40}K, ^{238}U, ^{232}Th decays
  - Material contamination and airborne radon

External source		Flux or concentration	References
Atmospheric muons		0.0190 ± 0.0012 /cm^2/s	DOI: 10.1103/PhysRevD.74.053007
Atmospheric neutrons		0.0134 ± 0.003 /cm^2/s	DOI: 10.1109/TNS.2004.839134 DOI: 10.1557/mrs2003.41
Ambient gammas (in concrete in France)	^{40}K series	[58; 118] Bq/kg	DOI: 10.1016/j.jenvrad.2011.10.001
	^{238}U series	[8; 126] Bq/kg	
	^{232}Th series	[4; 106] Bq/kg	

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nucleus EXPERIMENT

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Background sources characterization

Measurement of atmospheric muon attenuation

Angloher et al., the NUCLEUS collaboration (2019) 10.1140/epjc/s10052-019-7454-4

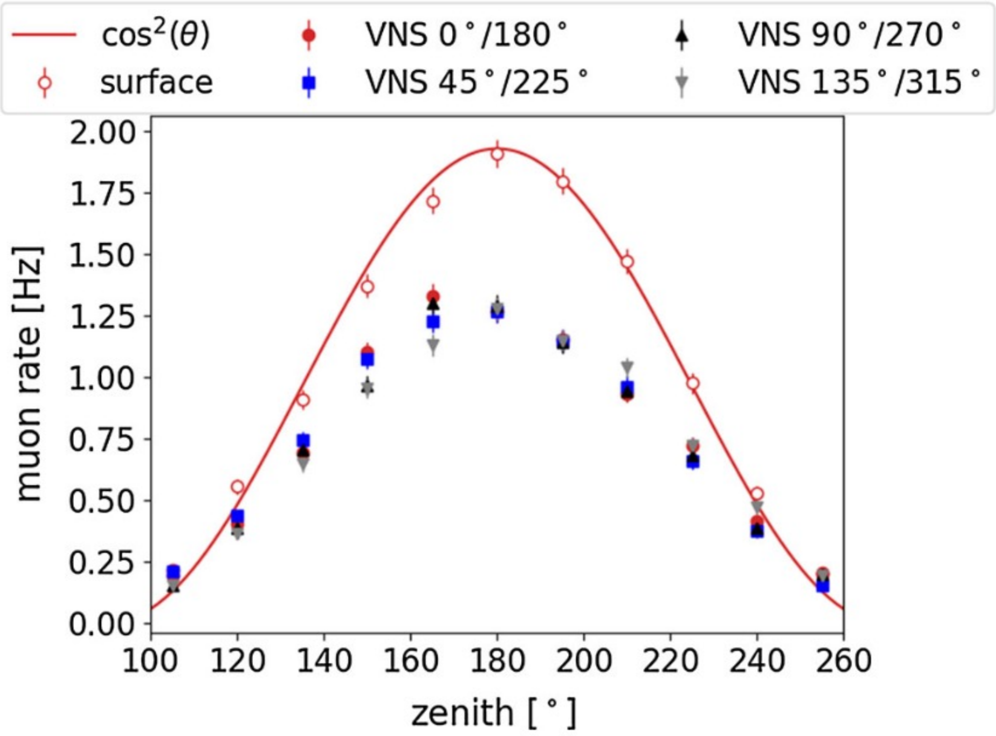
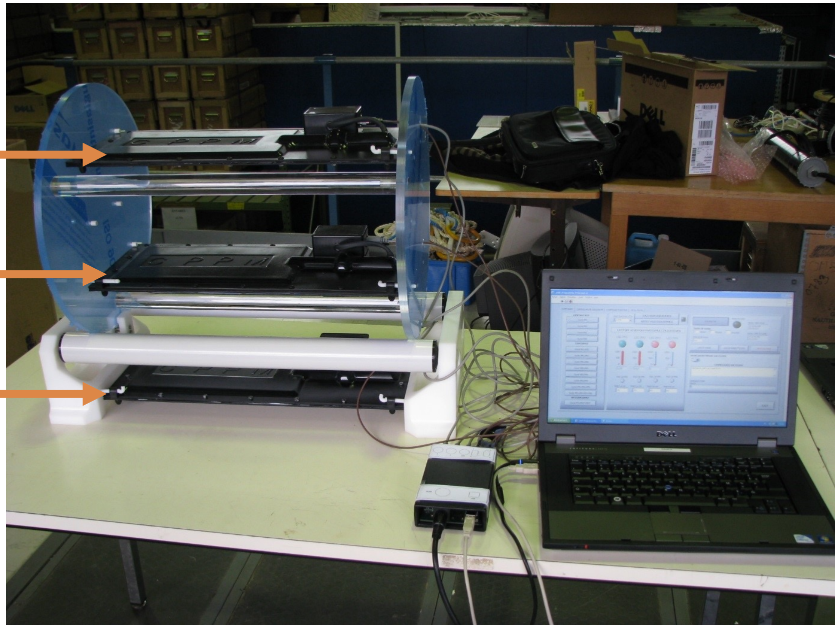


Fig. 3 Measurement of the muon rate at the surface (open data points) and at the VNS (filled data points) as a function of zenith angle for different azimuthal orientations. The muon flux at the surface follows the expected $\cos^2\theta$-law. Uncertainties are statistical only

Muon wheel ("science à l'école" program CPPM)

https://www.sciencesalecole.org/plan-cosmos-a-lecole-materiel/

3 scintillators in coincidence to tag cosmic muons and zenith angle up to 70°



(29 ± 0.01) % attenuation

⇒ Overburden of (2.9 ± 0.1) m.w.e.

Characterization of the atmospheric neutron reduction

Energy of atmospheric neutrons producing background in NUCLEUS

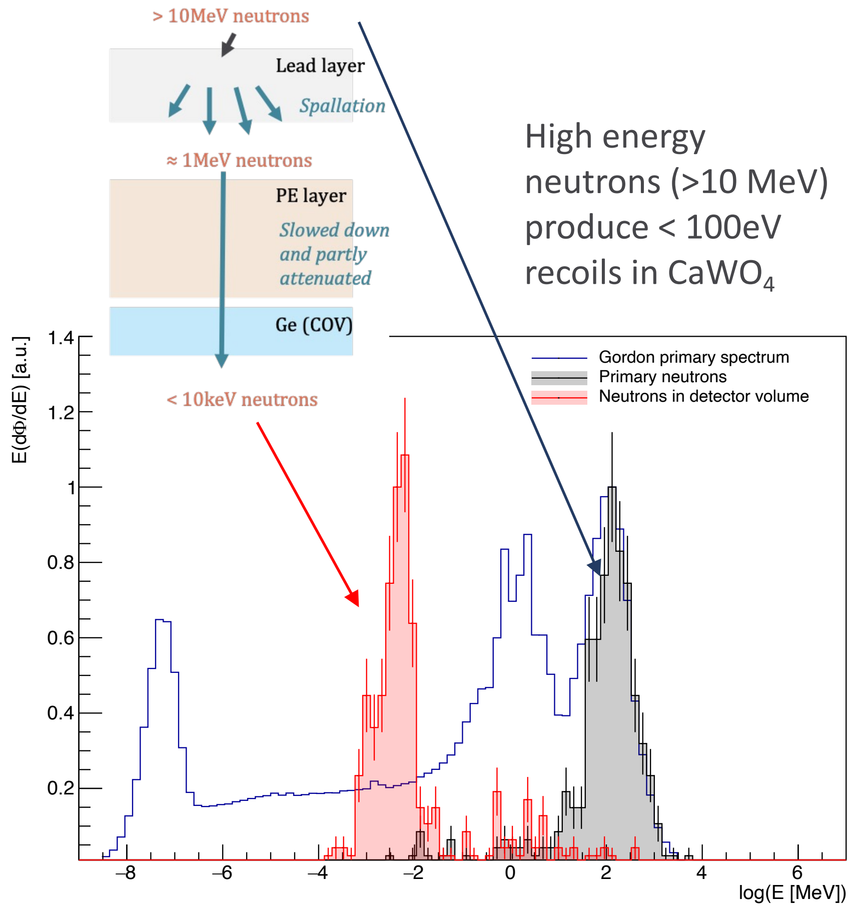


***fig:** Energy of neutrons responsible for background in the ROI*

High energy neutrons (>10 MeV) produce < 100eV recoils in $CaWO_4$

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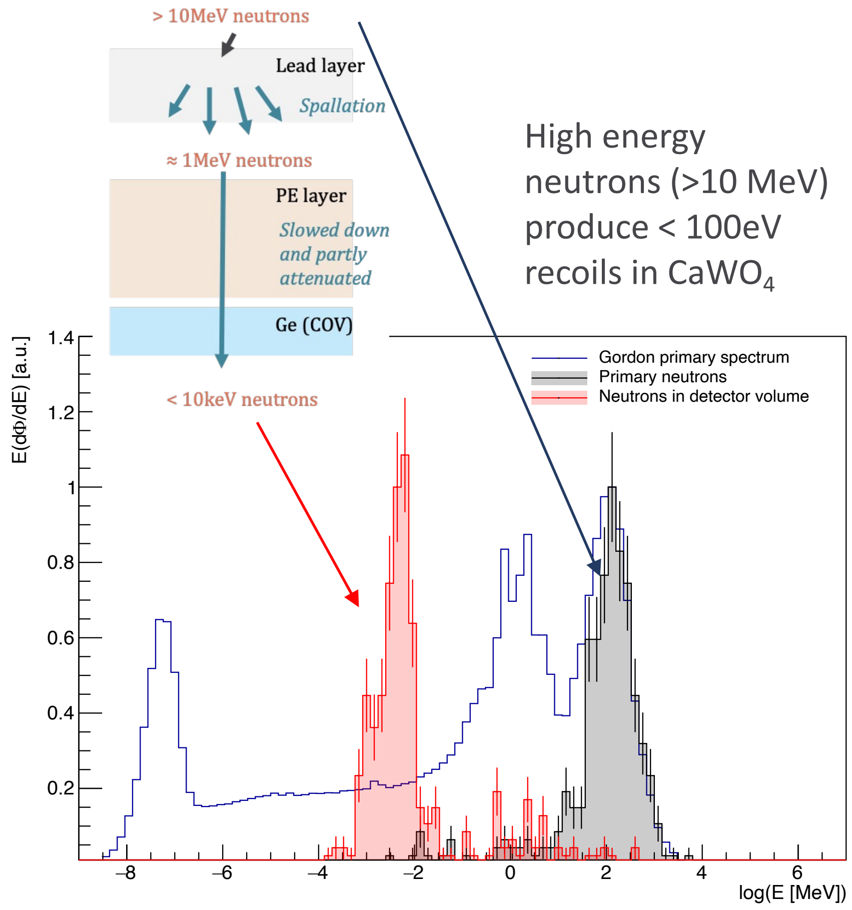

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fig: Energy of neutrons responsible for background in the ROI

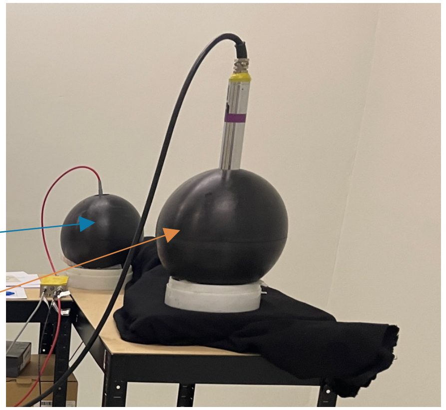
Experimental setup (Bonner sphere spectrometer)

LiI[Eu] probe

+

8’’ PE

9’’ Pb+PE spheres



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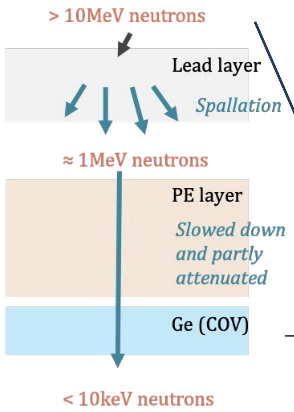

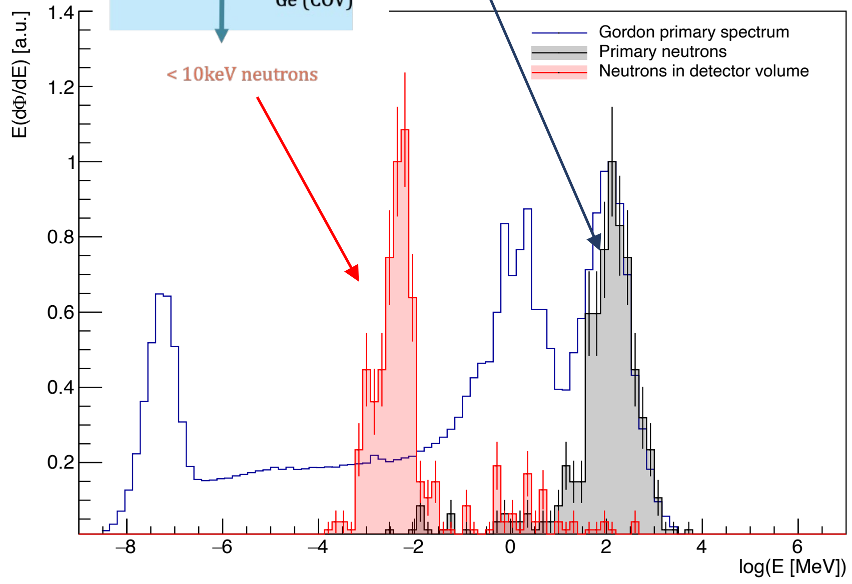

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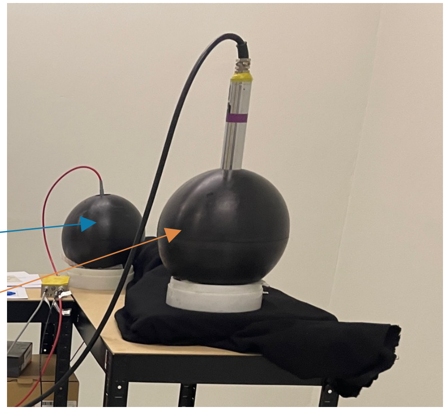


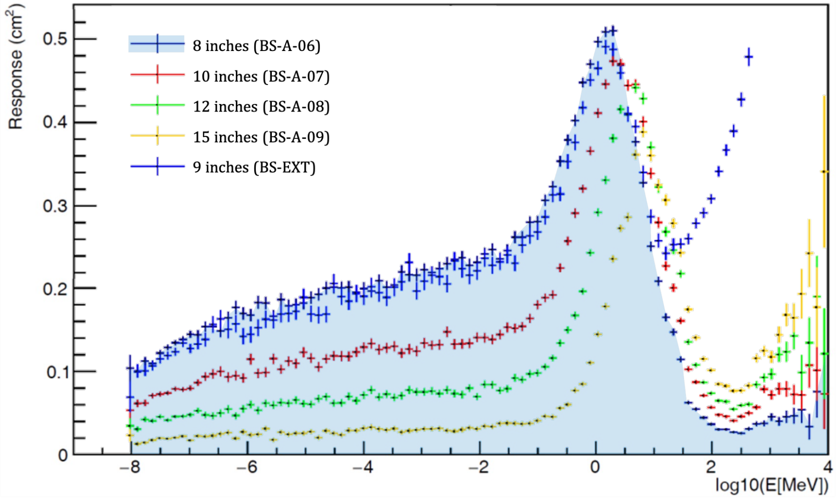


fig: *Response of the Li[Eu] in different spheres to the atmospheric neutron spectrum*

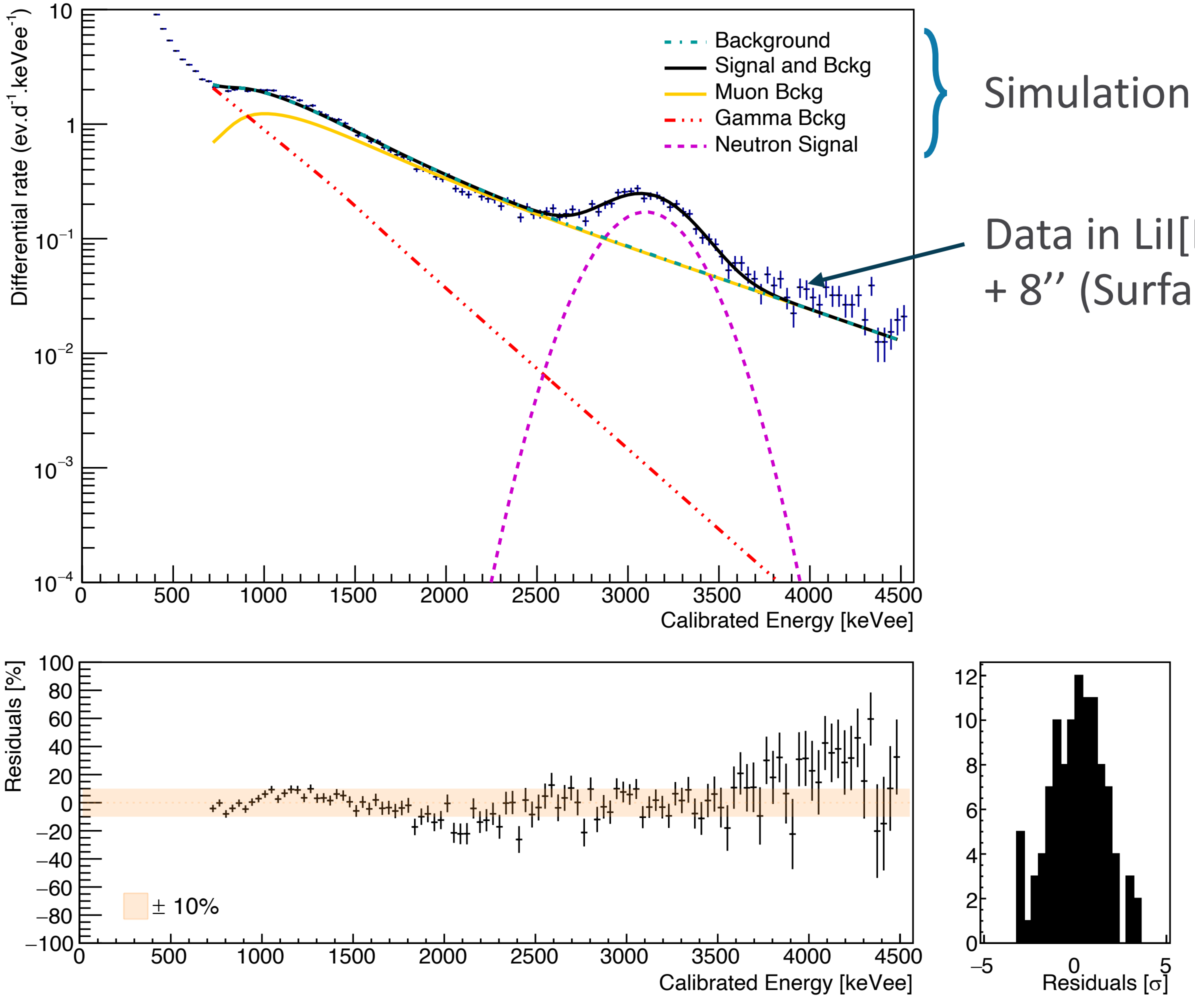
Identical response to neutron spectrum < 10MeV

And above 10MeV:
9’’ response >> 8’’ response

>10 MeV *n* ≈ 9’’-8’’

Characterization of the atmospheric neutron reduction

Result of the measurement (~ 100 days/sphere)



Simulation

Data in LiI[Eu] + 8'' (Surface)

Fit done on data taken at surface and in the VNS for both spheres:

Difference of rate R:

$$\mathcal{R}^{>10\,\mathrm{MeV}}_{\mathrm{Surface}} = \Delta\mathcal{R}^{\mathrm{np,fit}}_{\mathrm{DCHut}} = 47.8 \pm 5.0\ (\mathrm{stat.}) \pm 3.2\ (\mathrm{syst.})\ \mathrm{d}^{-1}$$

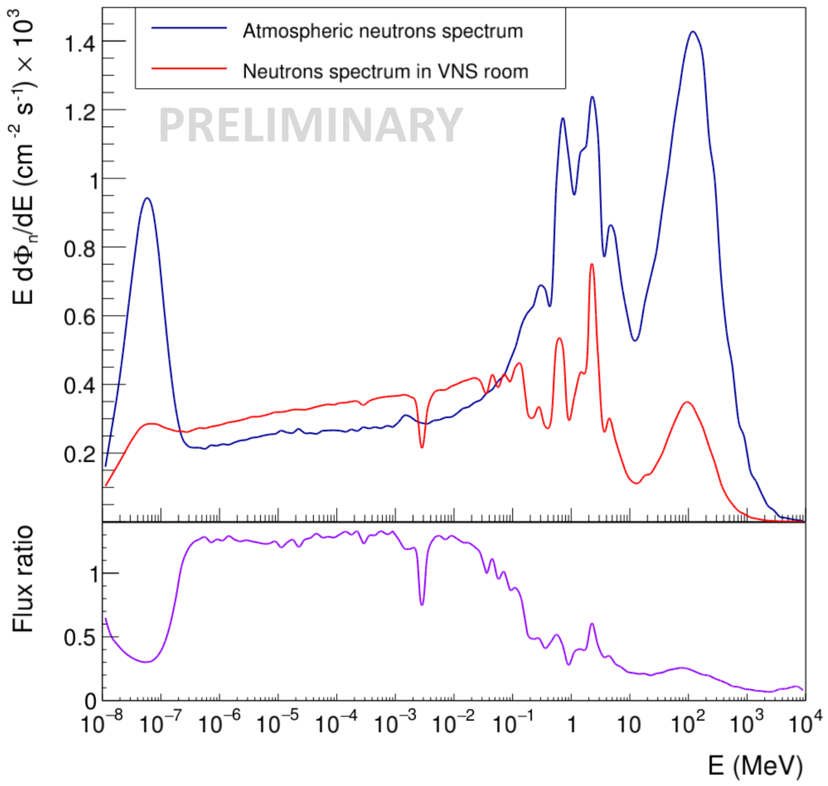
$$\mathcal{R}^{>10\,\mathrm{MeV}}_{\mathrm{VNS}} = \Delta\mathcal{R}^{\mathrm{np,fit}}_{\mathrm{VNS}} = 6.6 \pm 1.4\ (\mathrm{stat.}) \pm 1.3\ (\mathrm{syst.})\ \mathrm{d}^{-1}$$

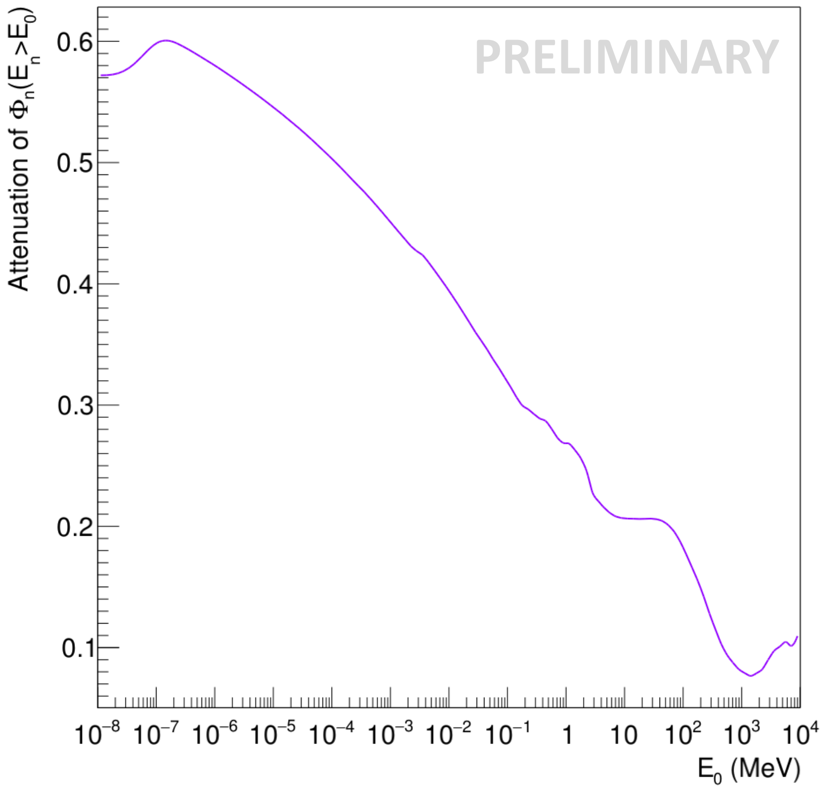
Most probable attenuation obtained from Monte Carlo simulations

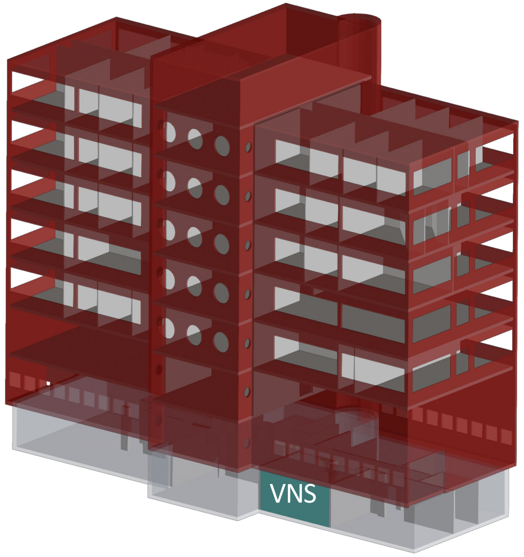
Factor of $6.38^{+2.65}_{-1.45}$ attenuation on >10 MeV neutrons

Characterization of the atmospheric neutron reduction

Simulation of the VNS building attenuation to atmospheric neutrons

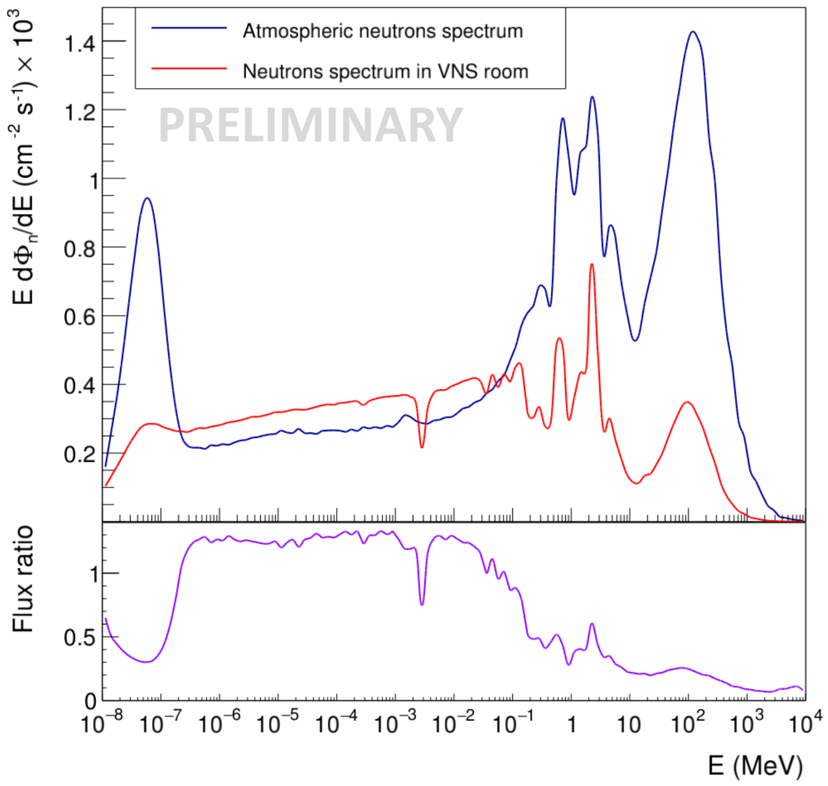


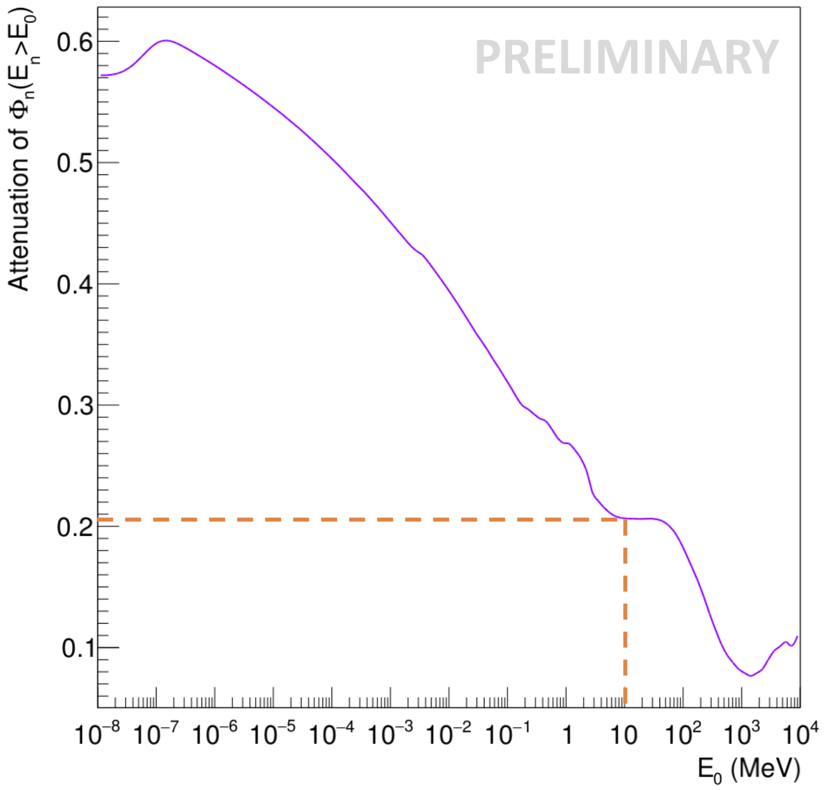


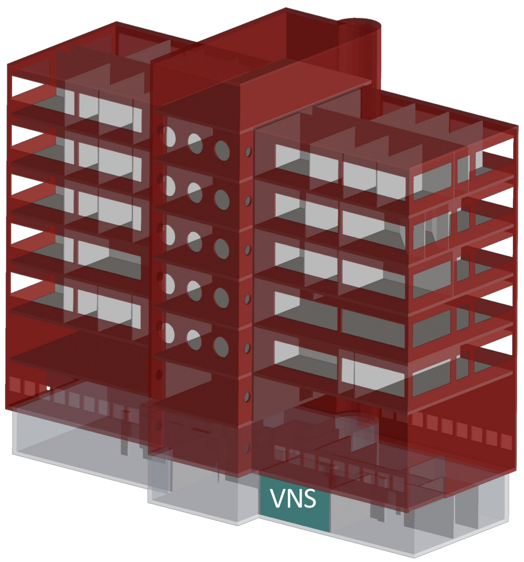


Atmospheric neutrons

Simulation of the VNS building attenuation to atmospheric neutrons







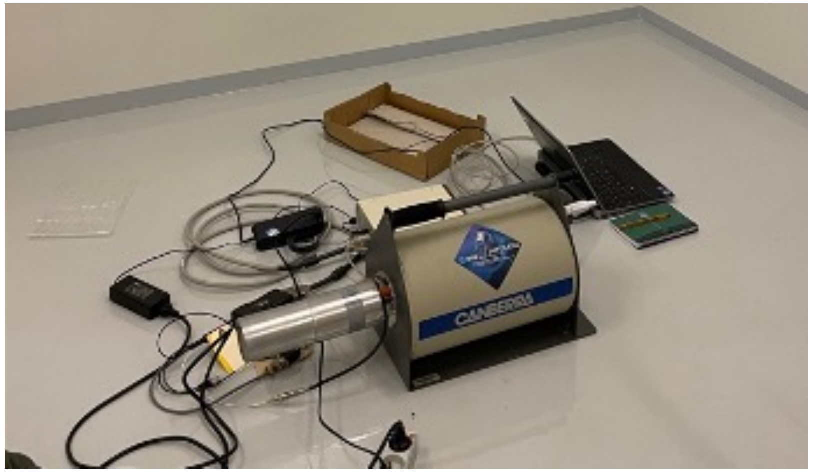
Factor of ~ 4.85 attenuation on >10 MeV neutrons

(measurement: $6.38^{+2.65}_{-1.45}$)

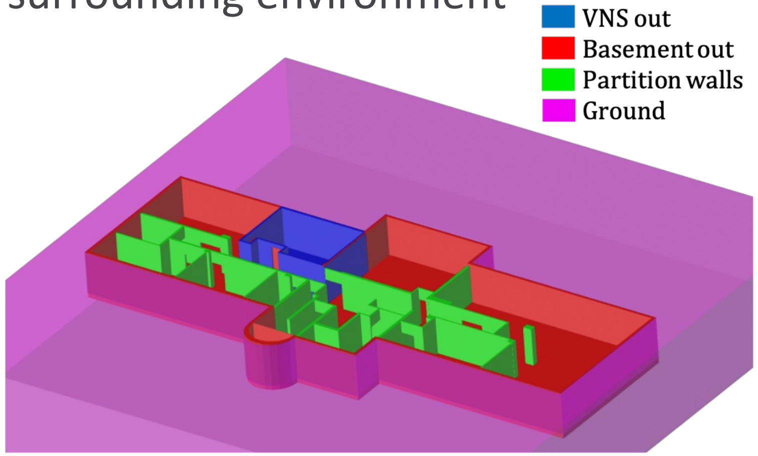
Conservative factor 5 attenuation

Measurement of the gamma-ray ambiance

Camberra – Portable LN n-type HPGe



G4 simulations of ^{40}K, ^{238}U, ^{232}Th decays in surrounding environment



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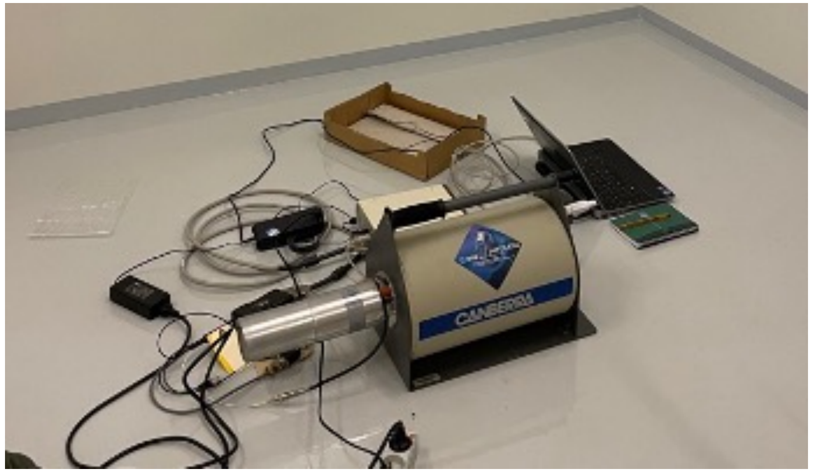

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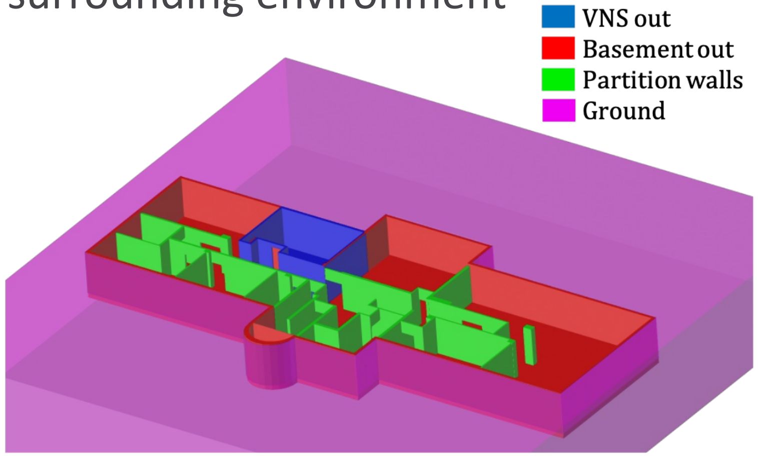
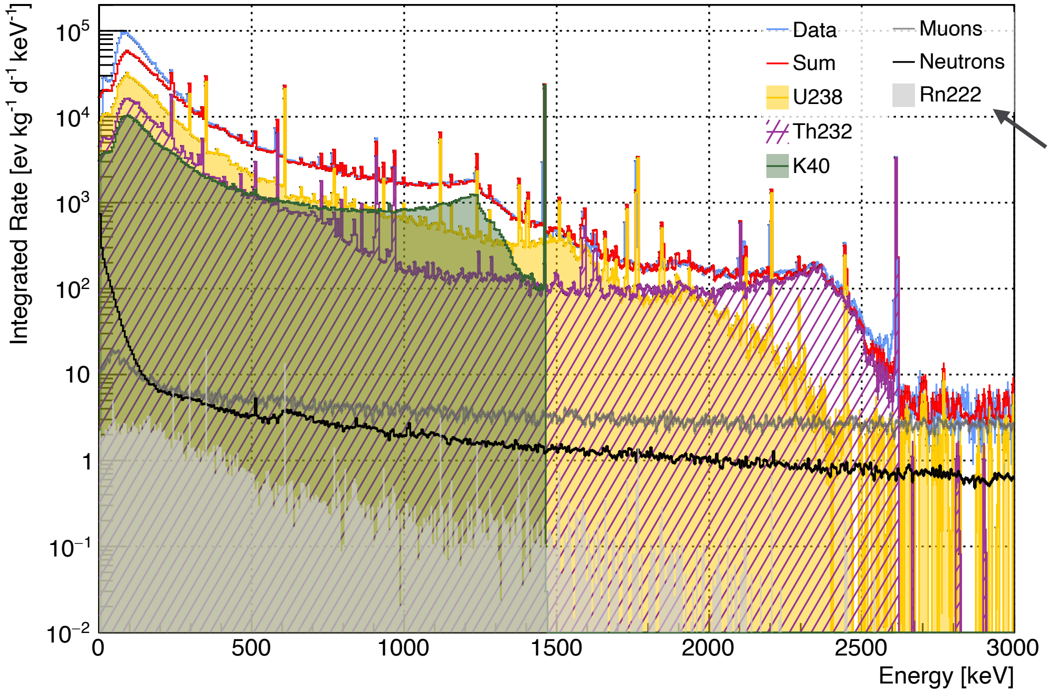
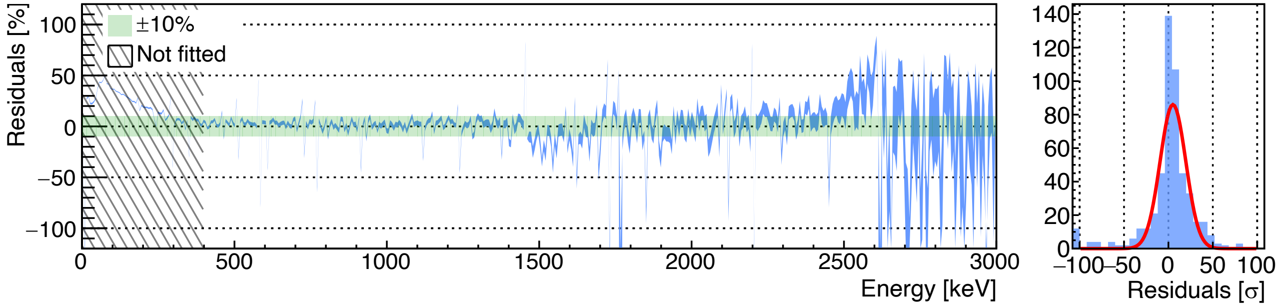


Simulation fitted on data



Airborne Rn concentration in the room measured separately with a ALPHARAD detector



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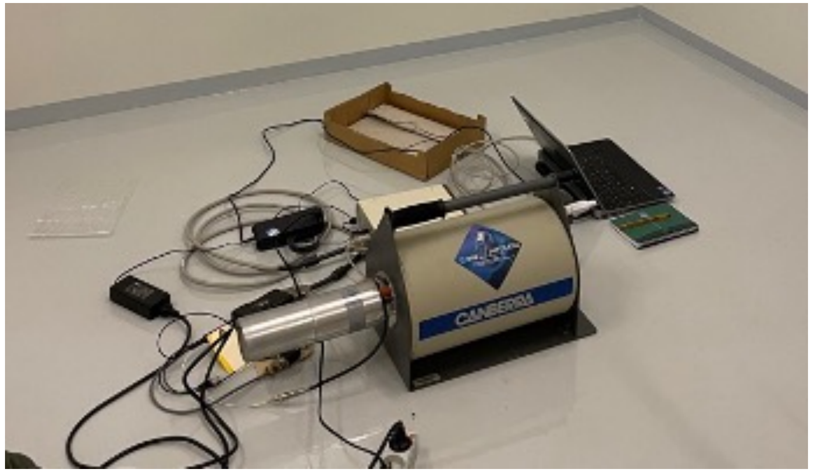

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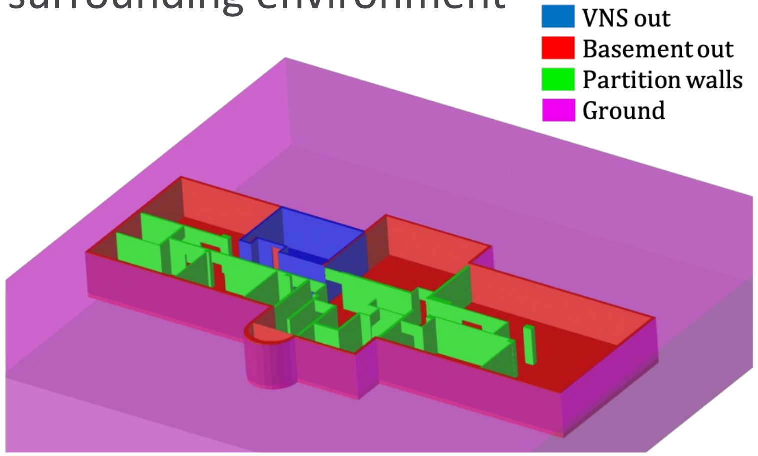

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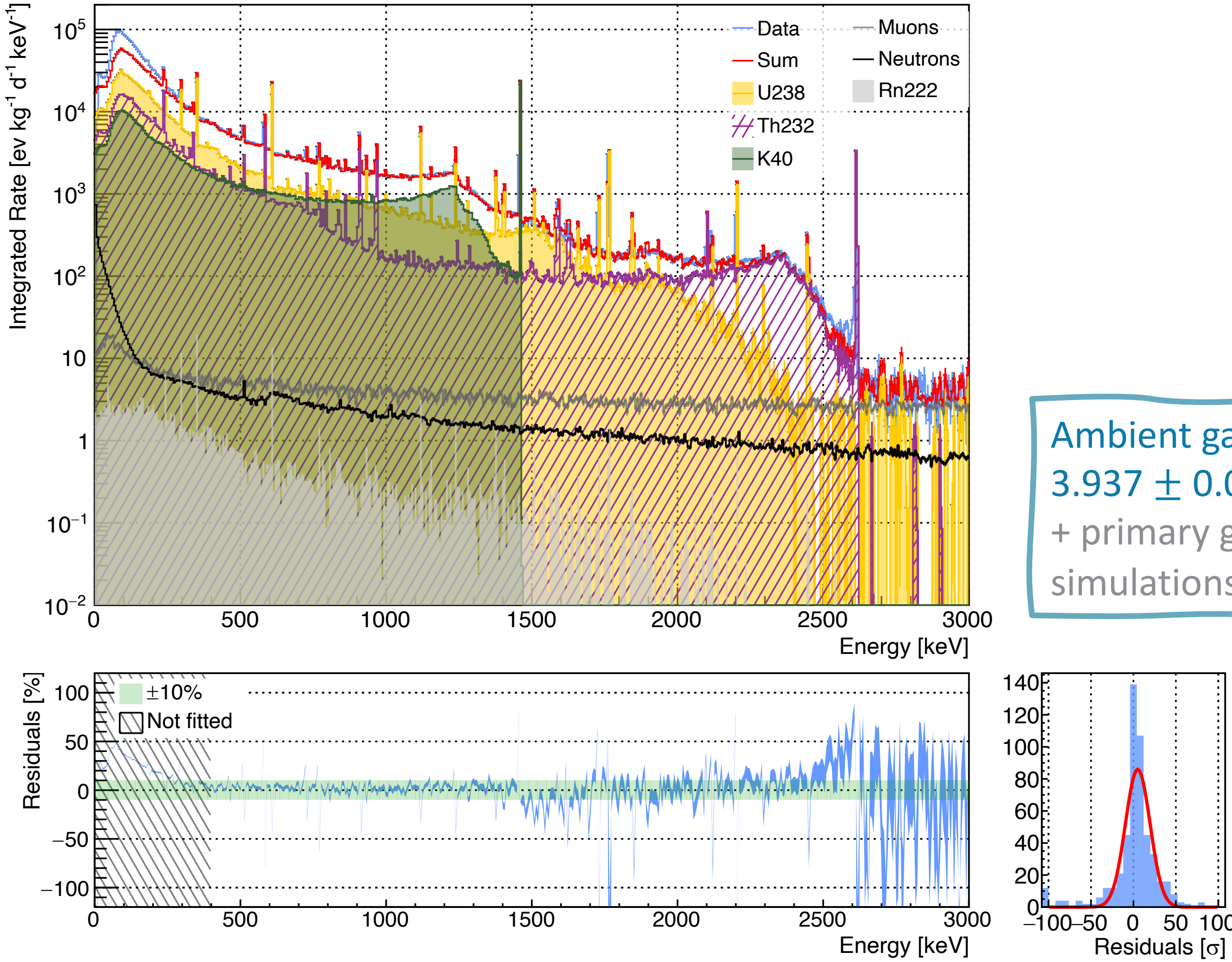

Ambient gamma flux:
3.937 ± 0.018 (stat.) /cm^2/s
+ primary generator for simulations

Material screening

STELLA (SubTErranean Low Level Assay)
Low background facility at LNGS
HPGe detectors

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PRELIMINARY

	^{232}Th series				^{238}U series		
Component	^{228}**Ra**	^{228}**Th**	^{40}**K**	^{235}**U**	^{238}**U**	^{226}**Ra**	^{210}**Pb**
Mechanical Structure (Steel)	< 16	6 ± 3	< 98	< 3.4	< 170	12 ± 3	
Pb external	< 16	< 13	< 95	< 32	< 270	< 2.8	$(89 \pm 7) \times 10^3$
Pb inner	< 15	< 14	< 71	< 29	< 310	< 10.6	$(40 \pm 4) \times 10^3$
Polyethylene	1.0 ± 0.5	1.5 ± 0.3	13 ± 4	< 0.73	< 21	2.7 ± 0.4	
B_4C shielding	240 ± 30	460 ± 40	< 360	30 ± 10	800 ± 300	260 ± 20	
Vacuum/50K vessels (Al)	40 ± 14	370 ± 30	< 160	130 ± 40	3500 ± 800	< 8.3	
4K vessel	120 ± 60	320 ± 50	< 520	500 ± 100	$(10 \pm 2) \times 10^3$	< 42	
Still vessel	< 14	< 14	< 130	< 6.2	< 76	< 14	
Detector Cu	< 3.3	< 4.1	< 23	< 3.8	< 92	< 3.5	

tab: activities in mBq/kg of the main contributing materials in the intrinsic radioactivity of the shielding, upper limits at 90% C.L.

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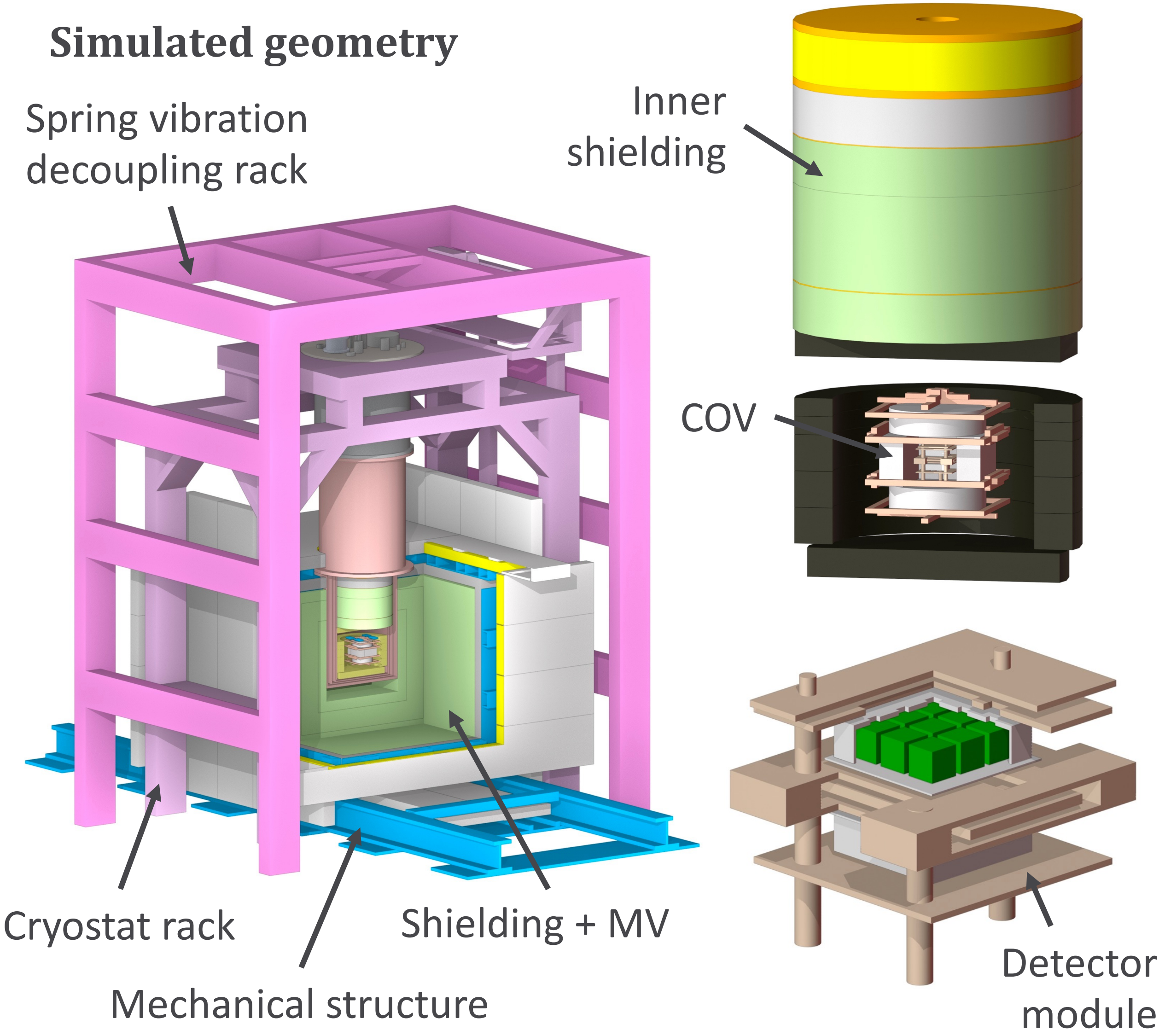
Geant 4 background predictions with NUCLEUS shielding

Simulation features and analysis method

Simulated geometry



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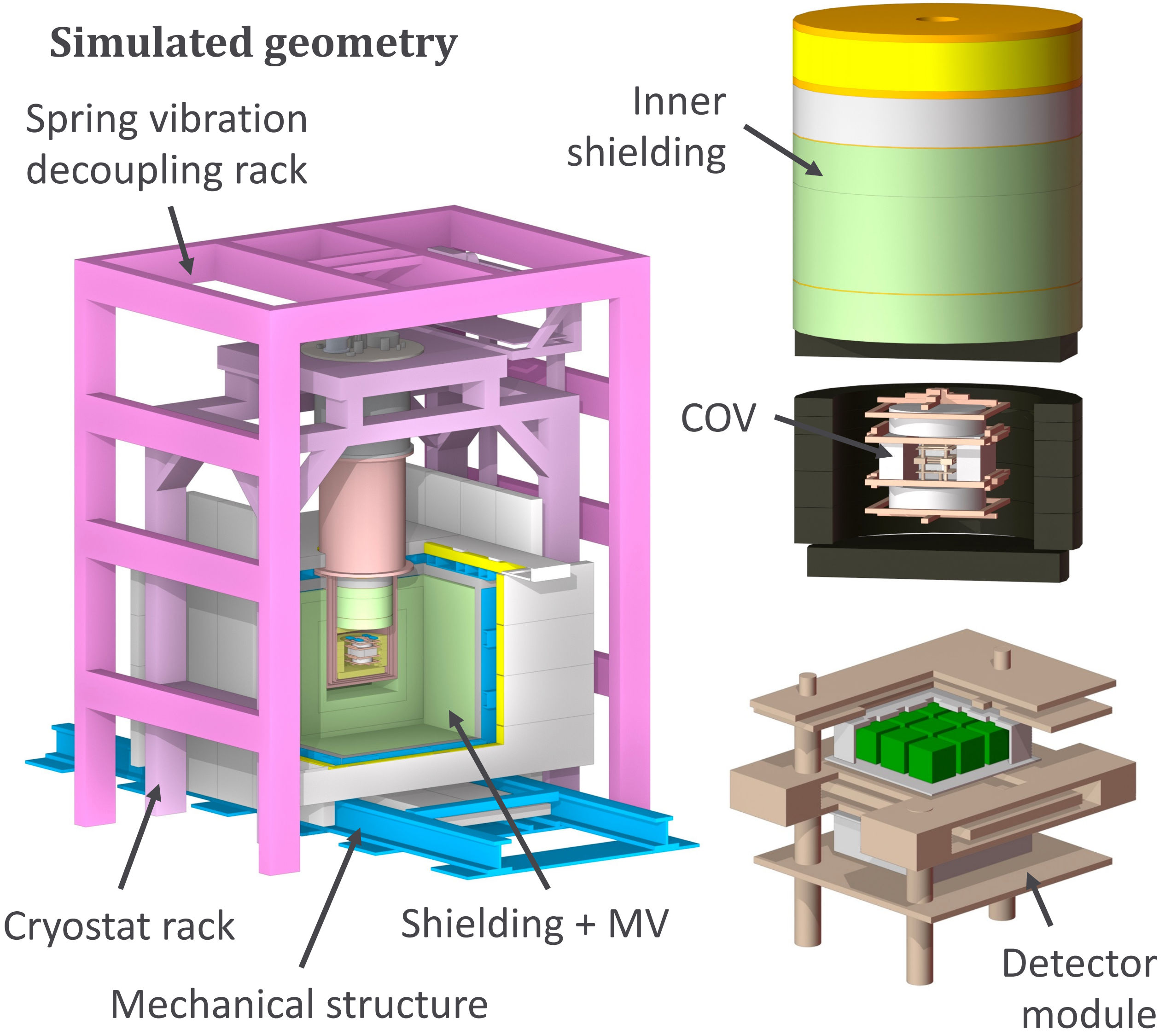

I- Primary event generators

- Tangent plane method
- **Muons:**
  - ❖ Modified Gaisser parametrization (2π)
- **Neutrons:**
  - ❖ Energy: measured *(Gordon et al.)*
  - ❖ Position: uniform (2π)
- **Environmental gammas:**
  - ❖ Energy: simulation waited from measurements
  - ❖ Position: uniform (4π)
- **Material contamination:**
  - ❖ Full decay of ^{238}U, ^{40}K, ^{235}U, ^{232}Th
  - ❖ Scaled by measured activities
  - ❖ Different activities of sub-chains considered

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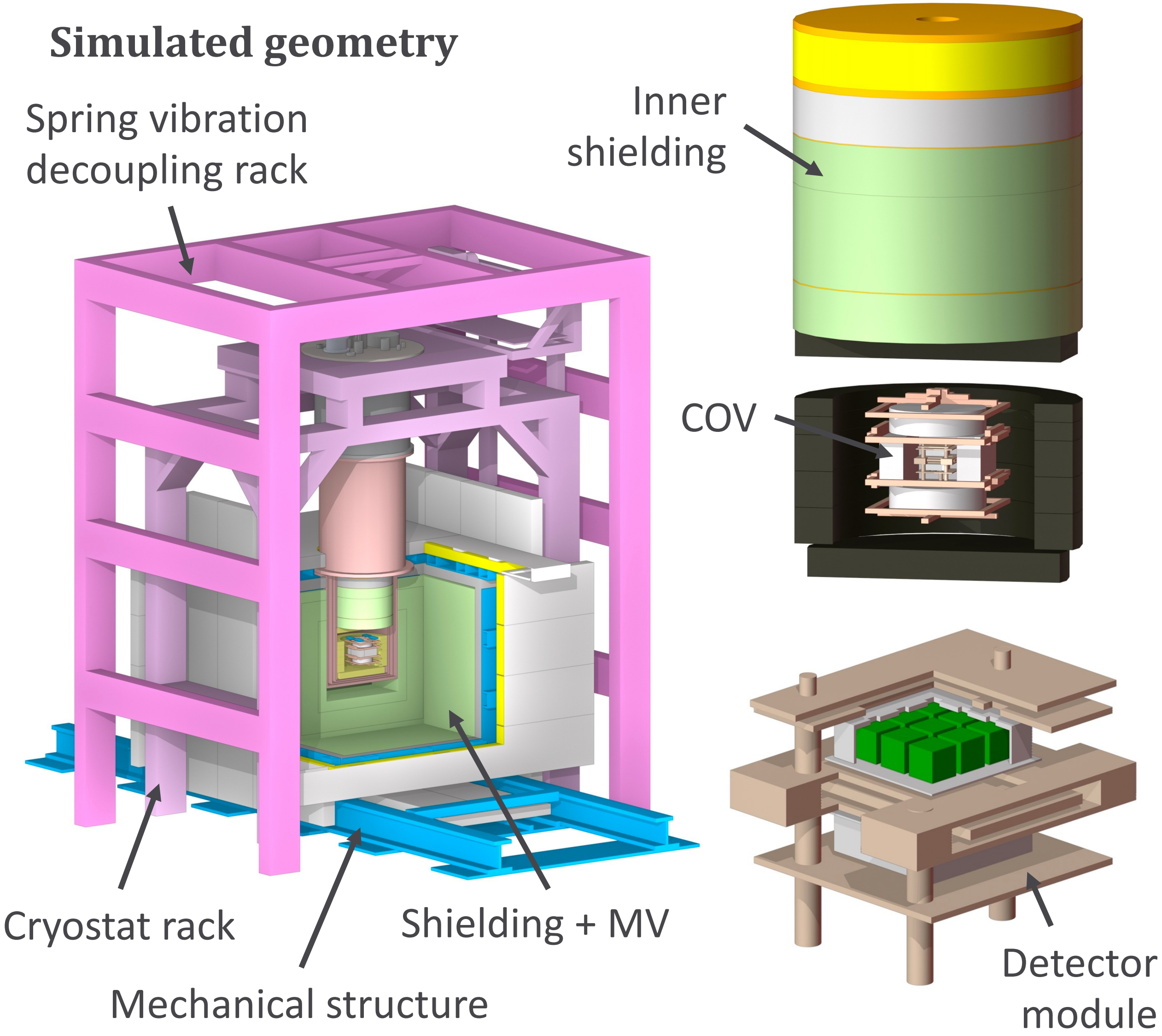

II - Analysis criteria

- Anticoincidence with veto

Veto system	Energy threshold
Muon Veto (MV)	5 $\mathrm{MeV_{ee}}$
Cryogenic Outer Veto (COV)	1 $\mathrm{keV_{ee}}$
Inner Veto (IV)	30 $\mathrm{eV_{ee}}$

- Unicity (only one detector triggers) ⇒ Anti coincidence between target detectors (AC)
- Threshold in $\mathrm{keV_{ee}}$ ⇒ factor 5 quenching factor applied to neutron-induced energy deposition in COV independently of the energy deposition process

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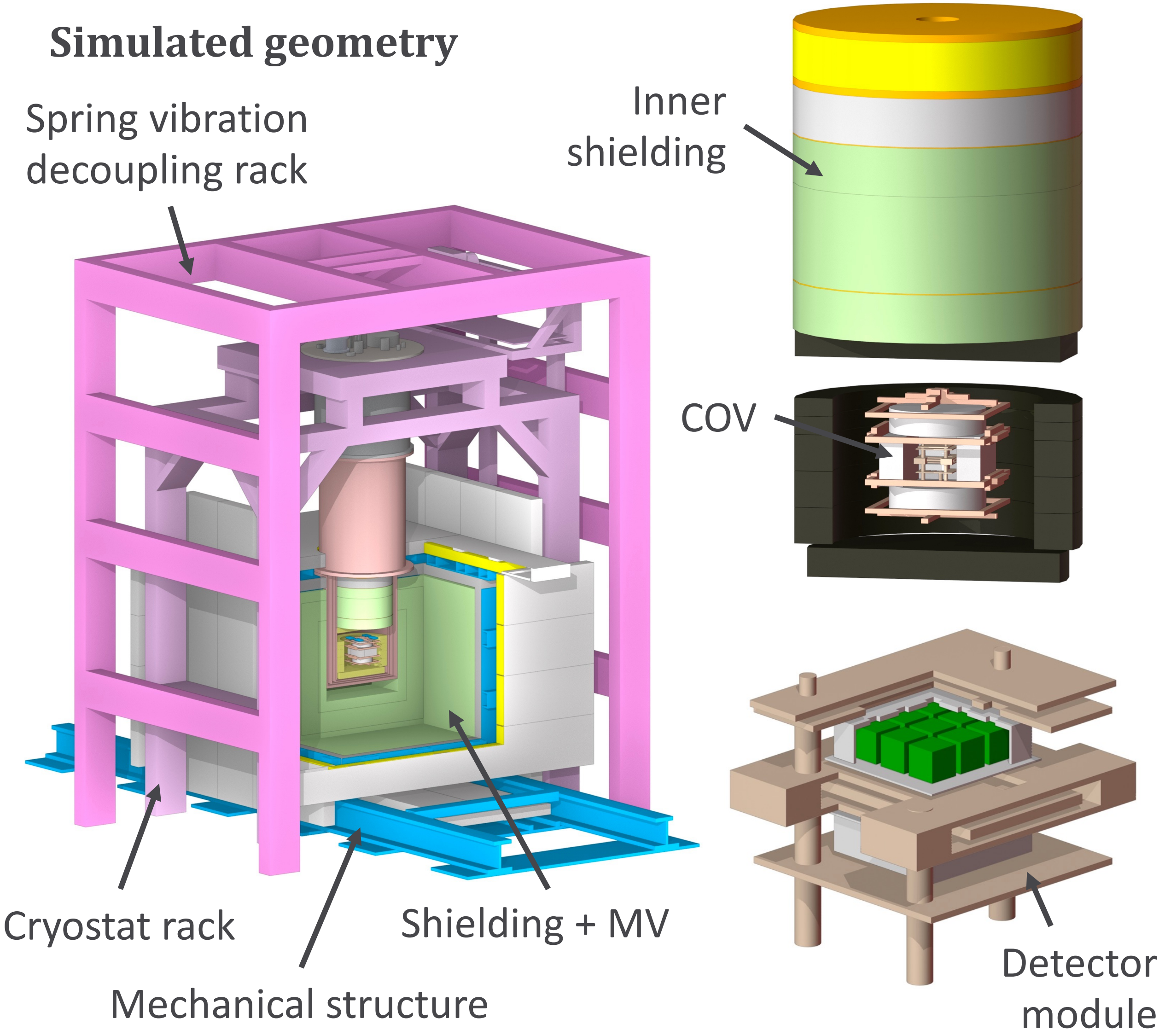

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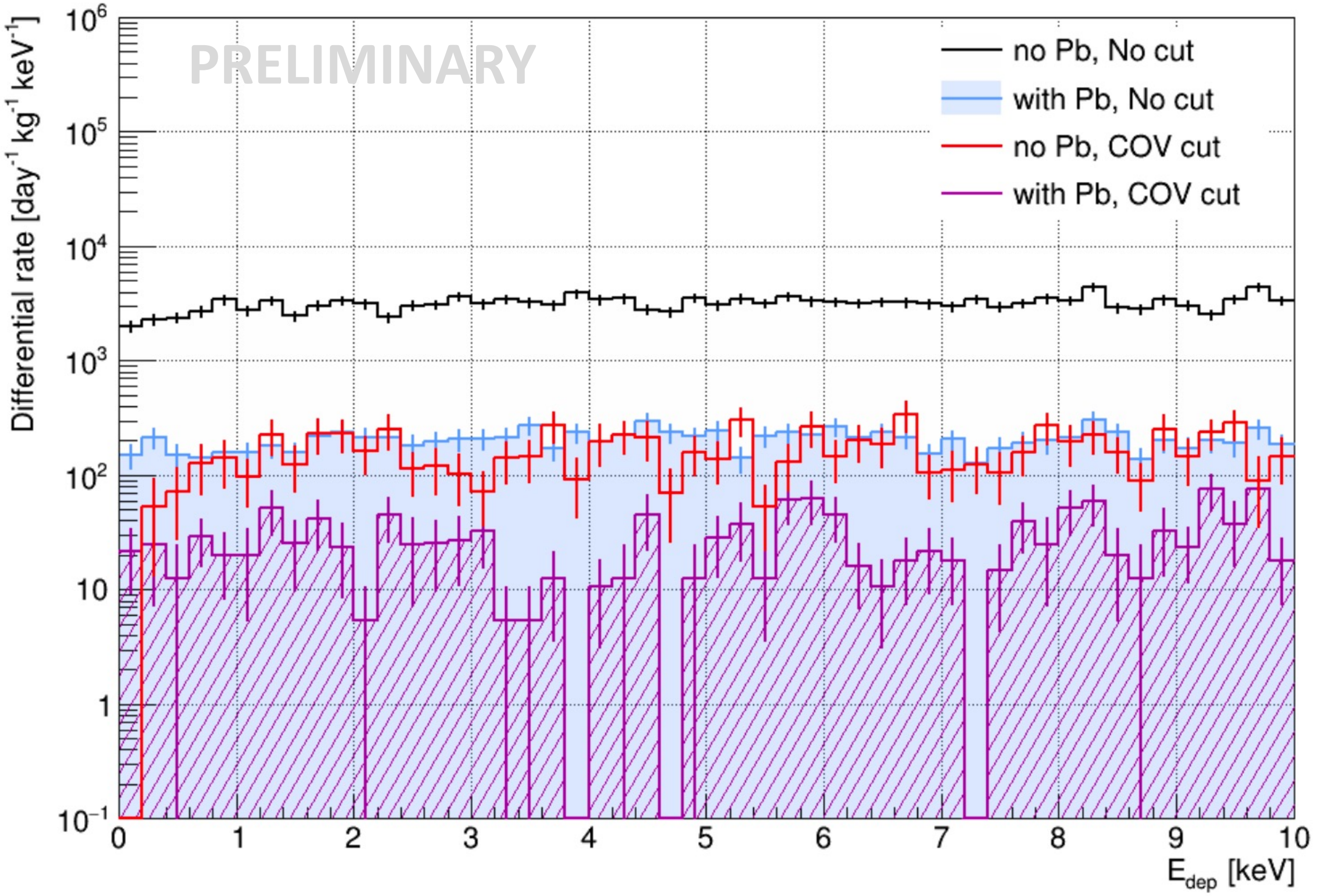
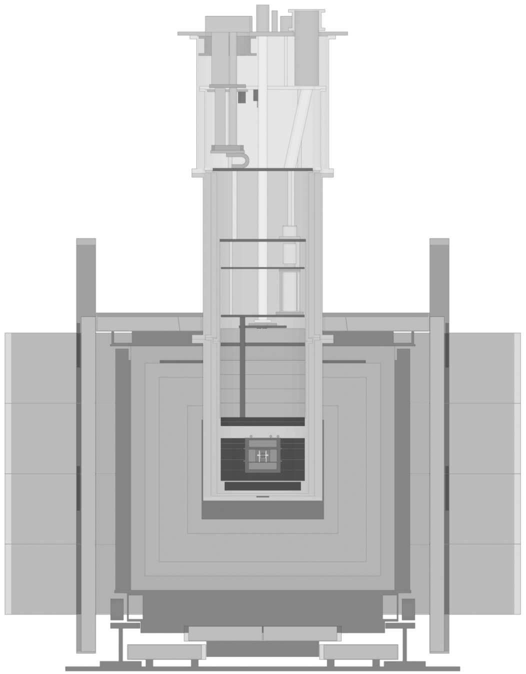
II- Timing information

- Particle track “lifetime” > ~100 μs (target detectors rise time) ⇒ “time-delayed” events: taken into account in veto treatment

Main results: impact of NUCLEUS shielding elements

Ambient gammas in $CaWO_4$





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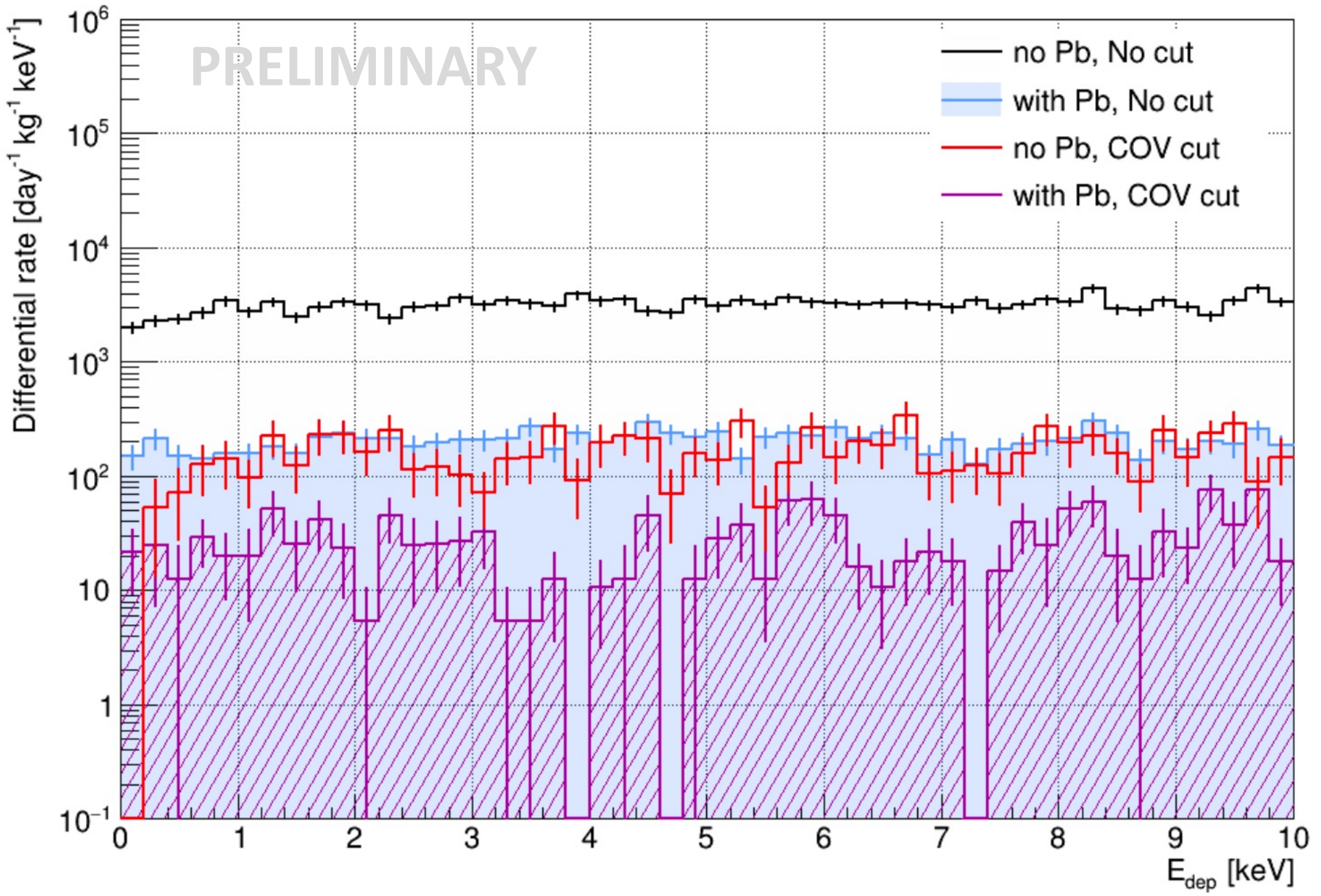
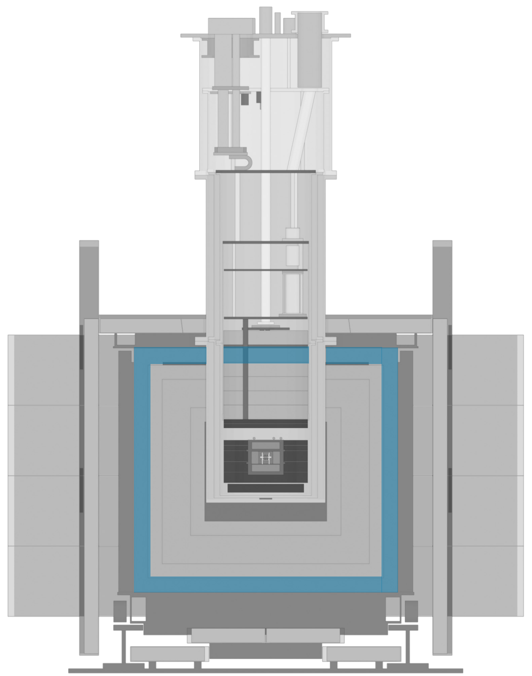


Effect of the Pb



Pb: factor 10 reduction in [0-1keV]

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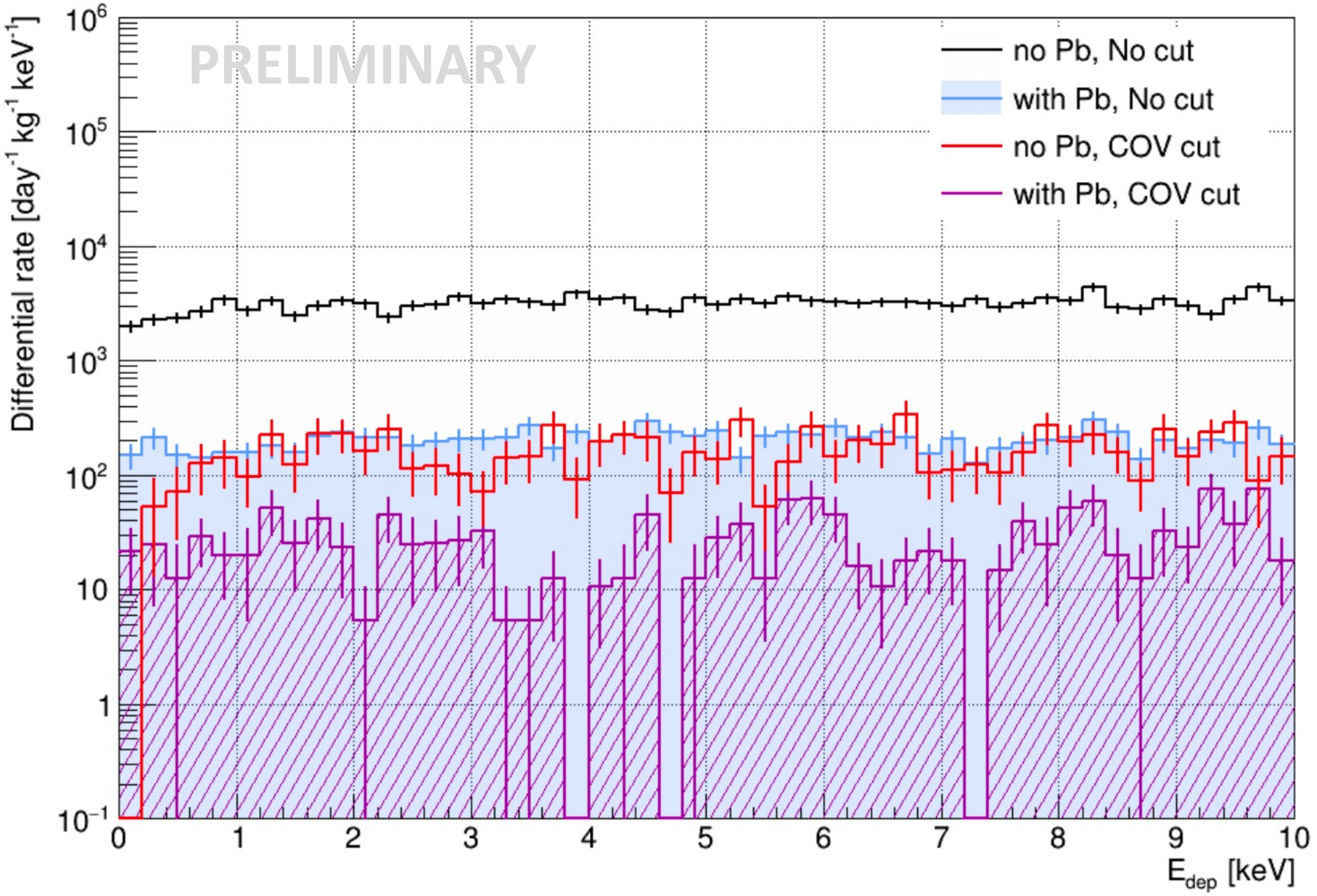
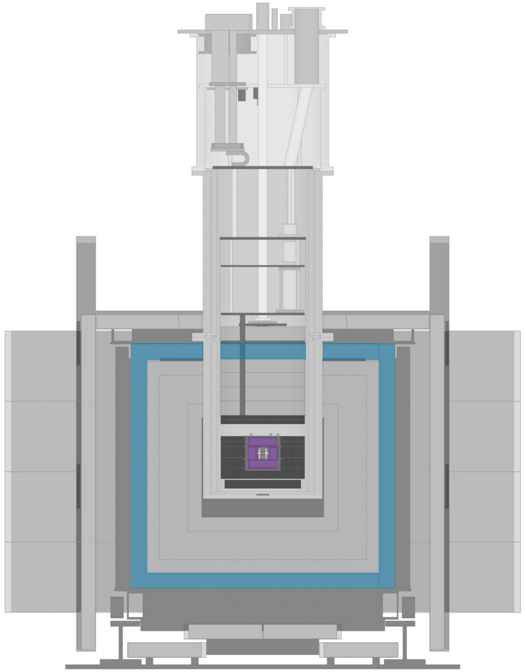


Effect of the Pb

Effect of the COV



Pb: factor 10 reduction in [0-1keV]

COV:

- **Thr 1 keV_{ee}:** factor 8.5 reduction in [0-1keV]
- **Thr 10 keV_{ee}:** factor 6.8 reduction in [0-1keV]

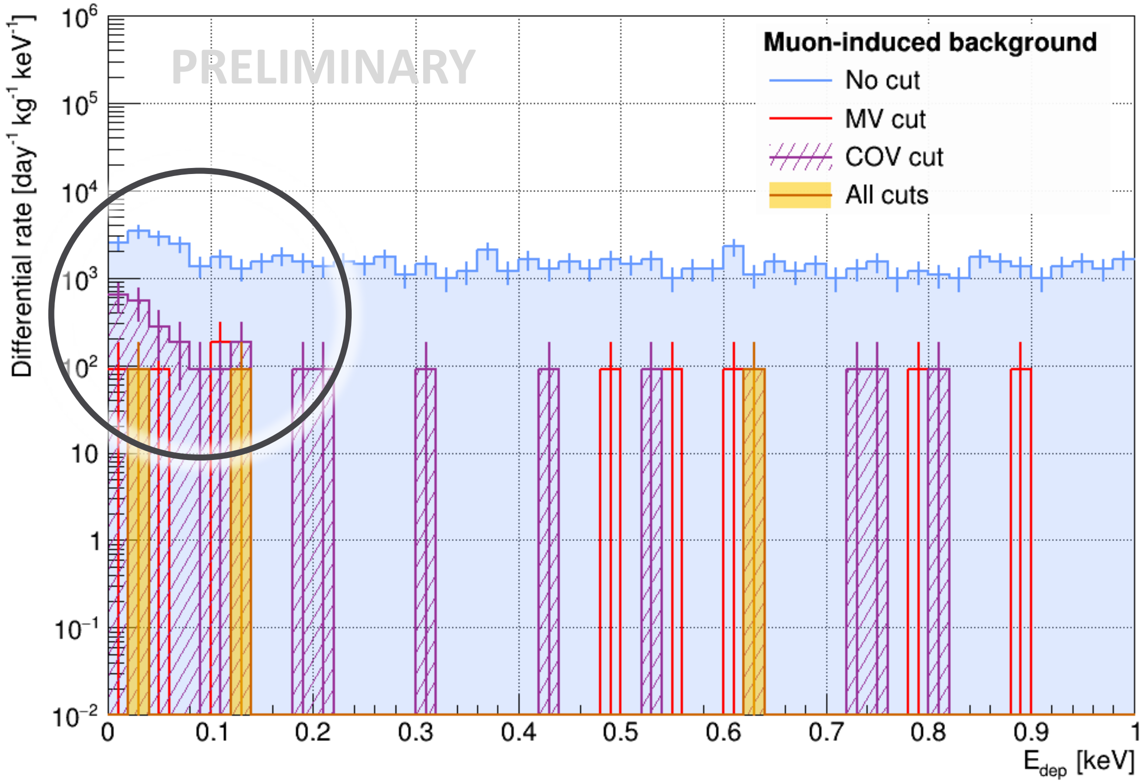
Main results: impact of NUCLEUS shielding elements

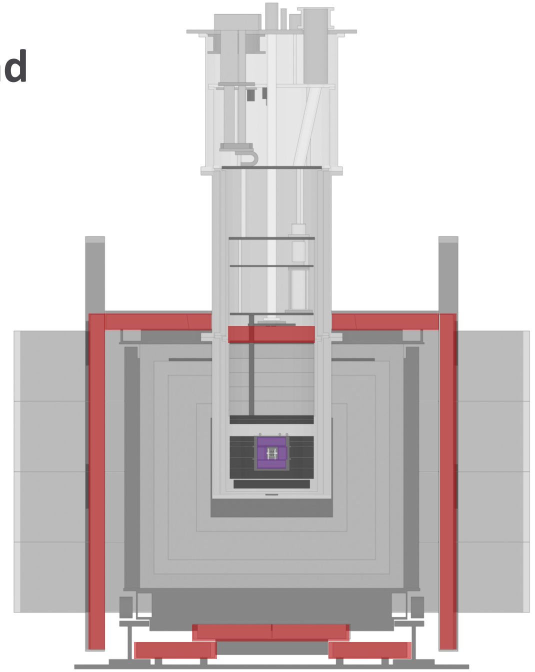
Atmospheric muons in $CaWO_4$

Background induced by muons in the ROI is mainly neutrons produced **via spallation in the lead**

- COV alone not efficient to tag those neutrons
- MV allows to tag the muons before entering the shielding

⇒ the combination of the two is a highly efficient veto against muons





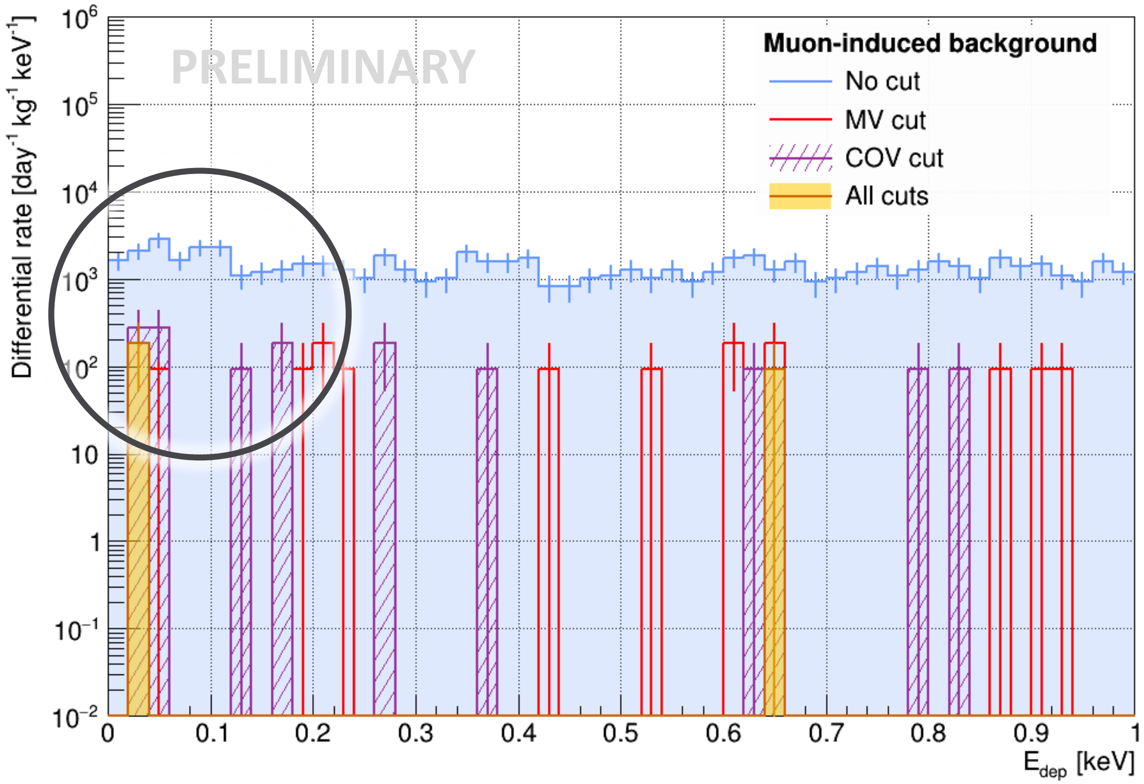
MV: factor 42 reduction in [0-1keV]

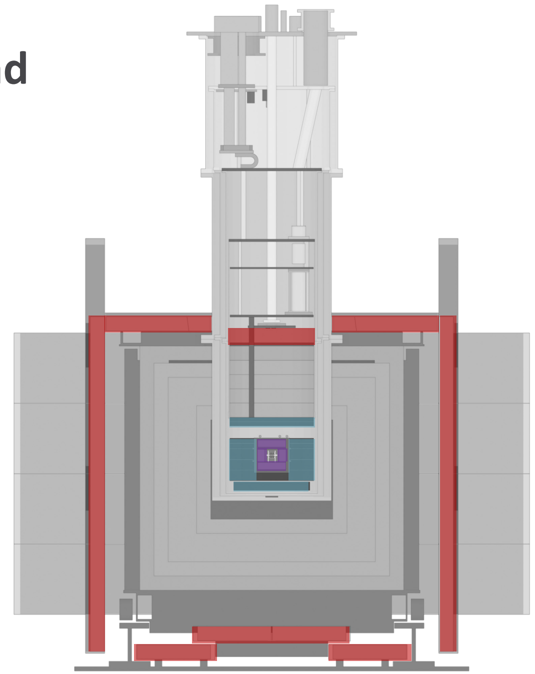
Main results: impact of NUCLEUS shielding elements

Atmospheric muons in $CaWO_4$

Background induced by muons in the ROI is mainly neutrons produced **via spallation in the lead**

- Adding the **B_4C layer** ⇒ excellent muon-induced rejection
  >> ^{10}B captures low energy neutrons

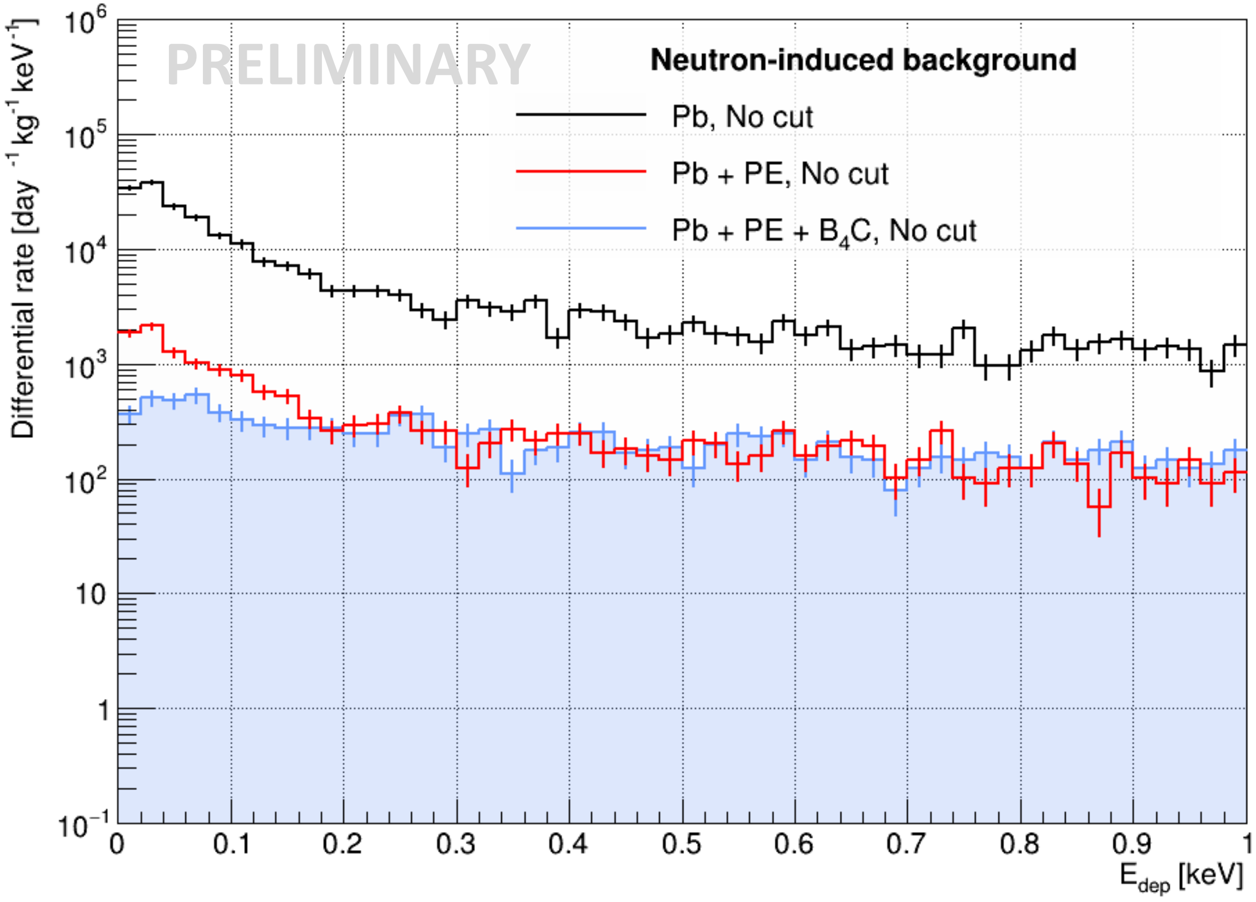




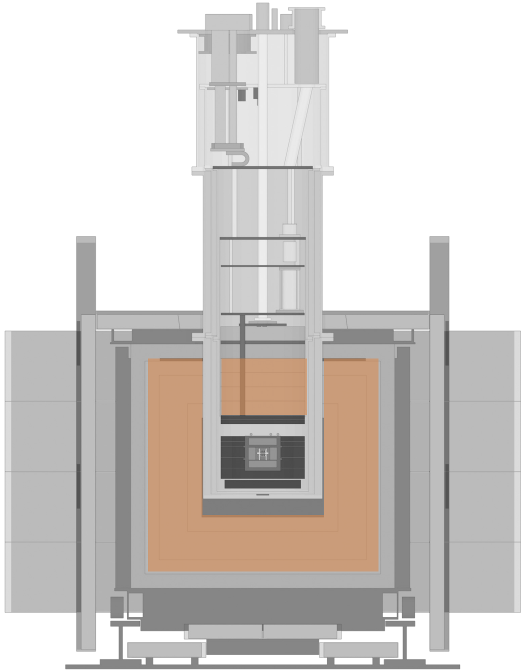
MV: factor 42 reduction in [0-1keV]

Main results: impact of NUCLEUS shielding elements

Atmospheric neutrons in $CaWO_4$



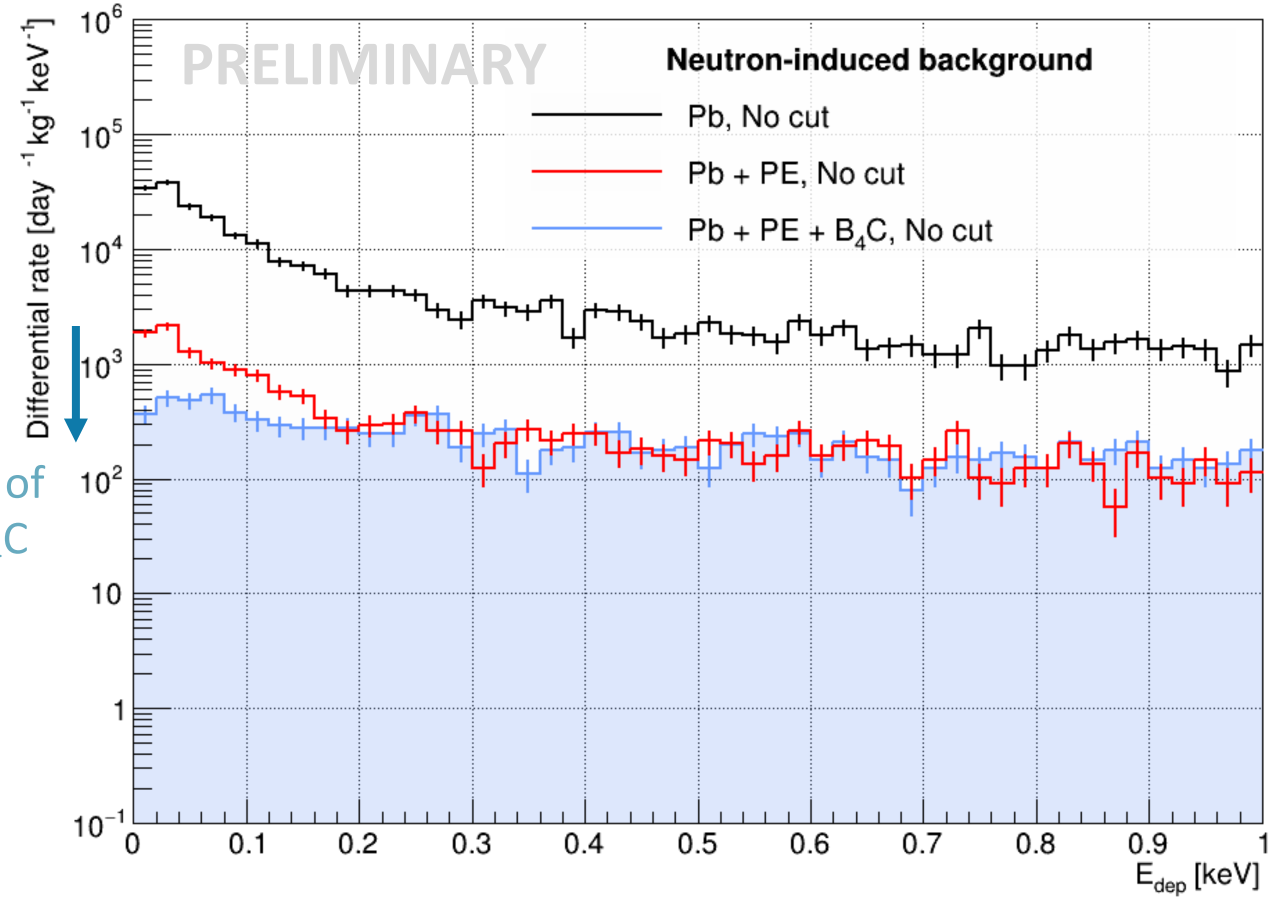
Effect of the PE



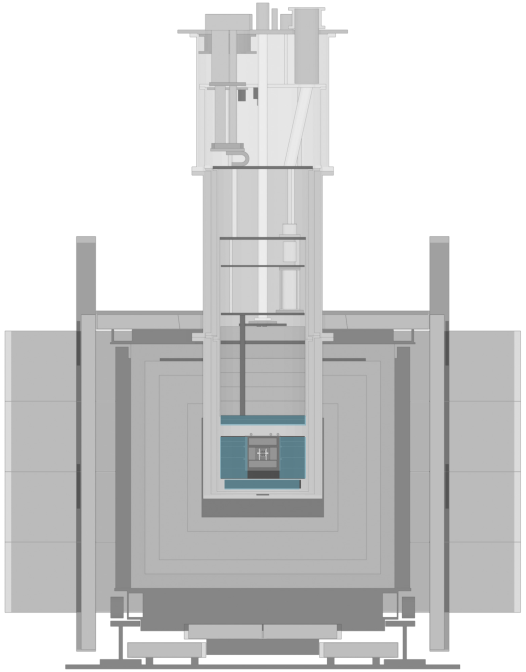
PE: factor 10 reduction in [0-1keV]

Main results: impact of NUCLEUS shielding elements

Atmospheric neutrons in $CaWO_4$



Effect of the B_4C

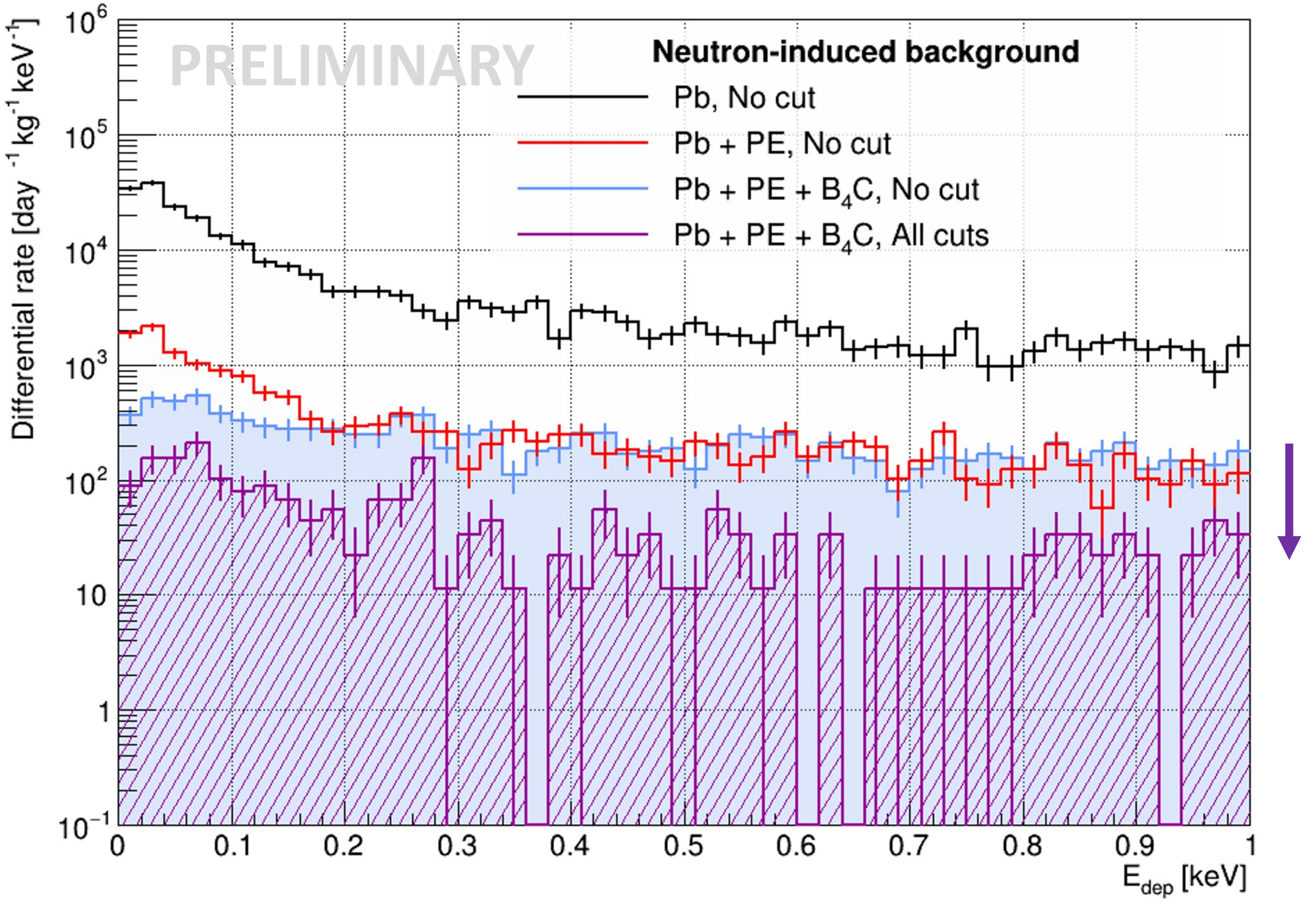


PE: factor 10 reduction in [0-1keV]

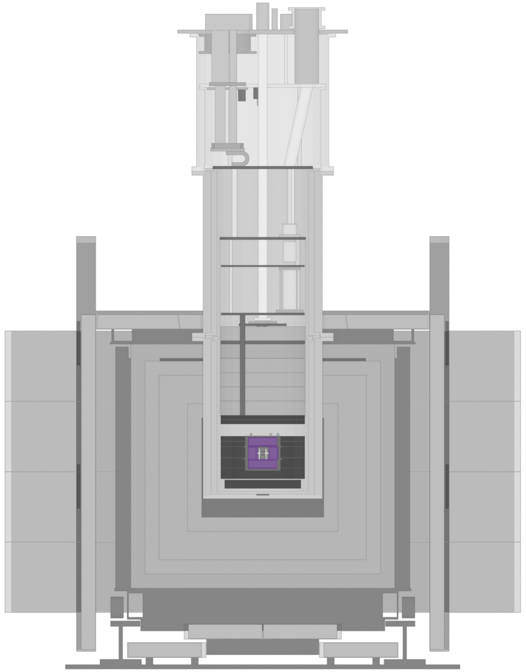
B_4C: factor ~3 reduction <200 eV

Main results: impact of NUCLEUS shielding elements

Atmospheric neutrons in $CaWO_4$



Effect of the vetos (~COV)



PE: factor 10 reduction in [0-1keV]

B_4C: factor ~3 reduction <200 eV

COV:

- **Thr 1 keV_{ee}:** add. factor 3.3 reduction in [0-1keV]
- **Thr 10 keV_{ee}:** add. factor 2.5 reduction in [0-1keV]

NUCLEUS background budget

nucleus EXPERIMENT

Rate in CaWO4 target detectors after applying all rejection criteria [counts/day/kg] PRELIMINARY

Source (simulated equiv. time)	**Flux** $[s^{-1}cm^{-2}]$	**10-100 eV**	**0.1-1 keV**	**1-10 keV**
Ambient gammas (642 days)	3.937	< 1.2	3.2 ± 1.3	51.4 ± 8.4
Atmospheric muons (328 days)	0.019/1.4	< 3.0	< 1.4	4.0 ± 1.3
Atmospheric neutrons (7809 days)	0.0134/5.0	20.9 ± 0.6	39.4 ± 0.9	116.1 ± 1.5
Material contamination	*(sum)*	0.91 ± 0.18	11.47 ± 0.65	133.8 ± 2.21
Sum		$\mathbf{23.6 \pm 1.1}$	$\mathbf{54.7 \pm 1.8}$	$\mathbf{305.4 \pm 8.9}$
No shielding		$\mathbf{(5.6 \pm 0.4) \times 10^3}$	$\mathbf{(3.8 \pm 0.1) \times 10^4}$	$\mathbf{(5.05 \pm 0.04) \times 10^5}$
CEvNS signal				
full (100 %)		32.0	8.9	
avg (80%)		25.6	7.1	

Reminder

Veto system	**Energy threshold**
Muon Veto (MV)	$5\,MeV_{ee}$
Cryogenic Outer Veto (COV)	$1\,keV_{ee}$
Inner Veto (IV)	$30\,eV_{ee}$

NUCLEUS background budget

Rate in $CaWO_4$ target detectors after applying all rejection criteria [counts/day/kg] PRELIMINARY

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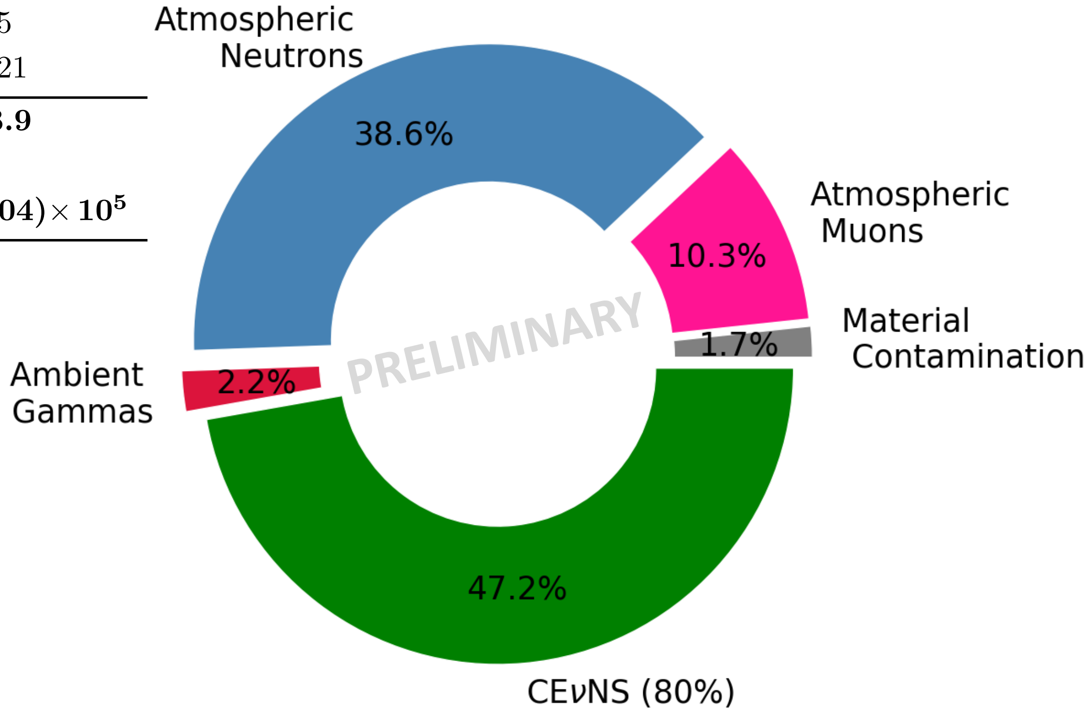
Simulated contributions to signal in $CaWO_4$ in [10-100 eV] (bckg upper limits)



$S/B \approx 1$

Take home message

Take home message

Background measurements

- Measurement of the muon and neutron attenuations
  - \- 30% for muons
  - Factor 5 for >10 MeV neutrons
- Absolute neutron flux measurement remains to be done (assumed 0.0134 $/cm^2/s$ at 0 m.w.e.)
- Gamma flux measurement in VNS

Take home message

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Background budget

- The NUCLEUS experiment designed to reduce muons/neutrons/gammas
  - Efficient Muon Veto
  - 20 cm Borated PE + ~ 4 cm B_4C (against neutrons)
  - 5 cm Pb and Ge veto (COV) (against gammas)
- NUCLEUS shielding strategy with known background
  - \> 2 orders of magnitude background reduction
  - Signal/(known) background ≈ 1

Take home message

Background measurements

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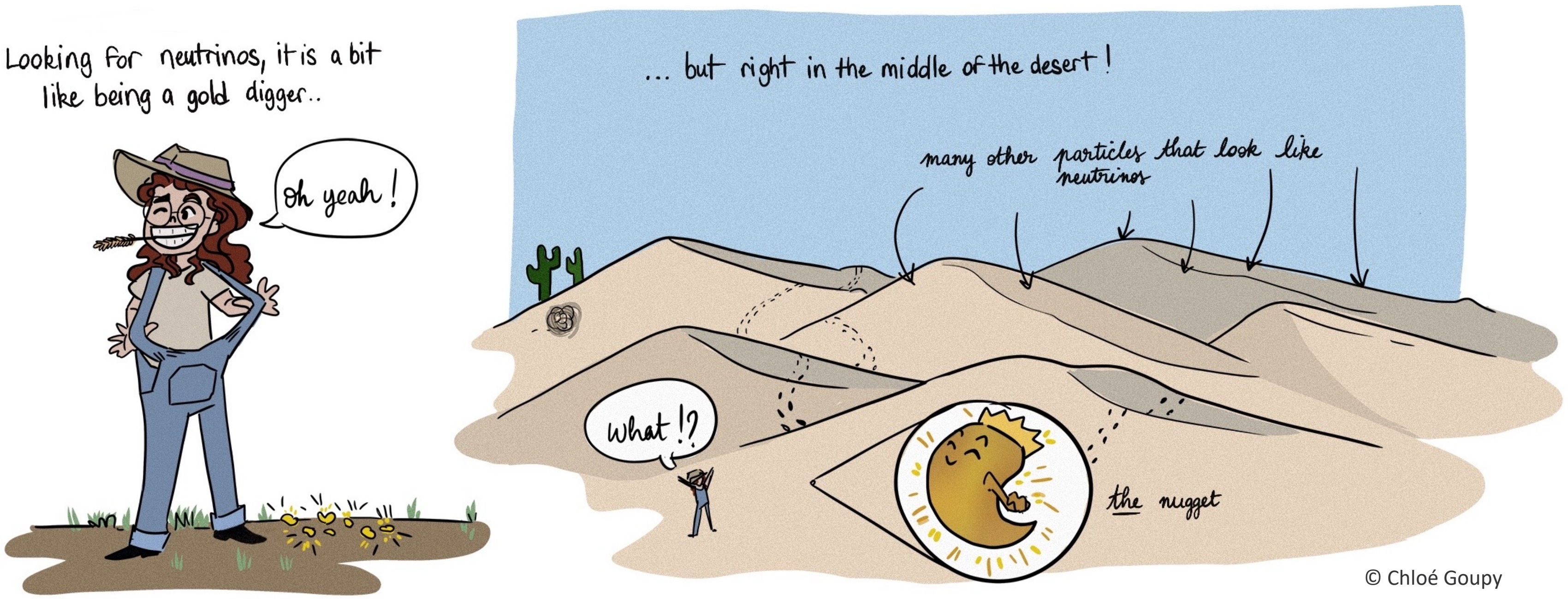
- NUCLEUS shielding strategy with known background
  - > 2 orders of magnitude background reduction
  - Signal/(known) background ≈ 1

Perspectives

- Available background budget for long background measurement in the UGL
  → comparison data/simulation coming soon
- Article in preparation

Thanks for your attention



nucleus EXPERIMENT

https://nucleus-experiment.org

The magnificent CEvNS 2024
València
12-14 June 2024

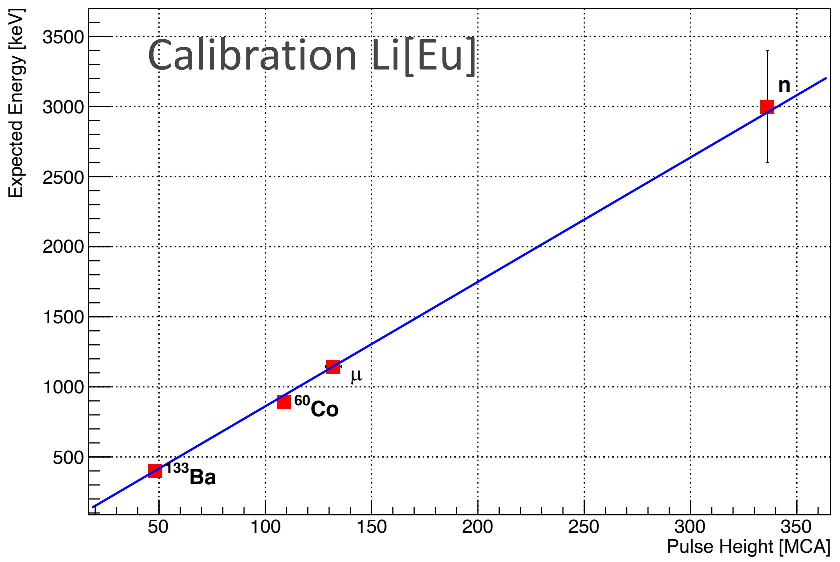
THE MAGNIFICENT CEvNS

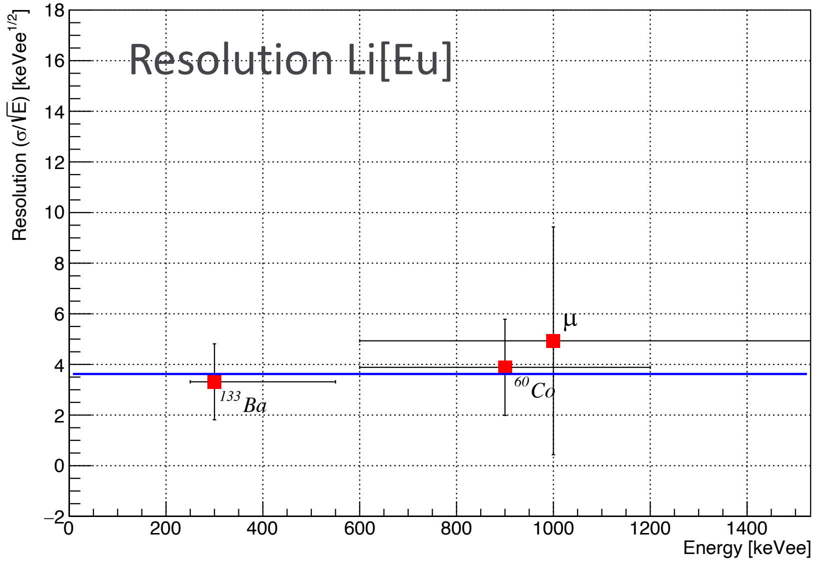
Estimation of *(particle)* backgrounds at sub-keV energies

for the NUCLEUS experiment

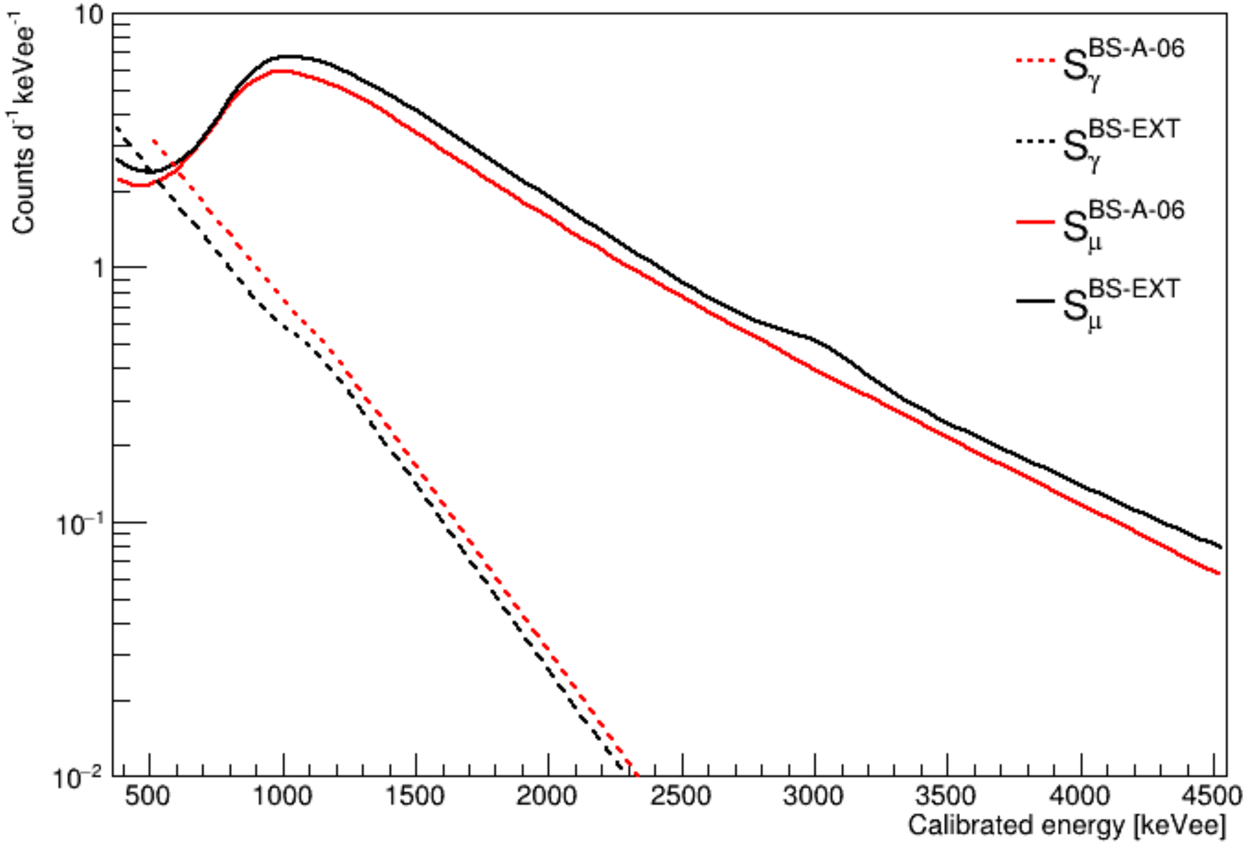
Back-up slides

Bonner sphere measurements



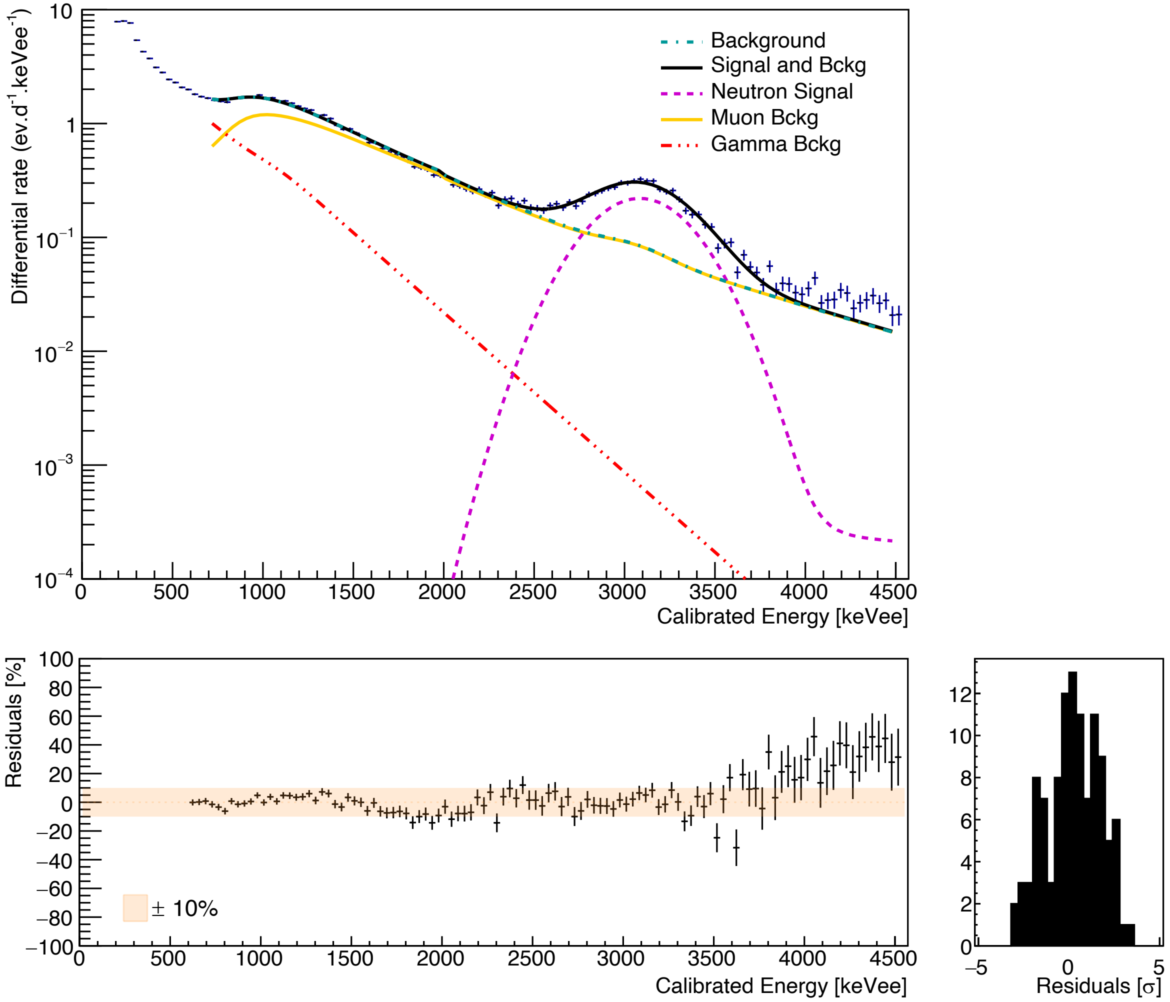


Simulation models for backgrounds

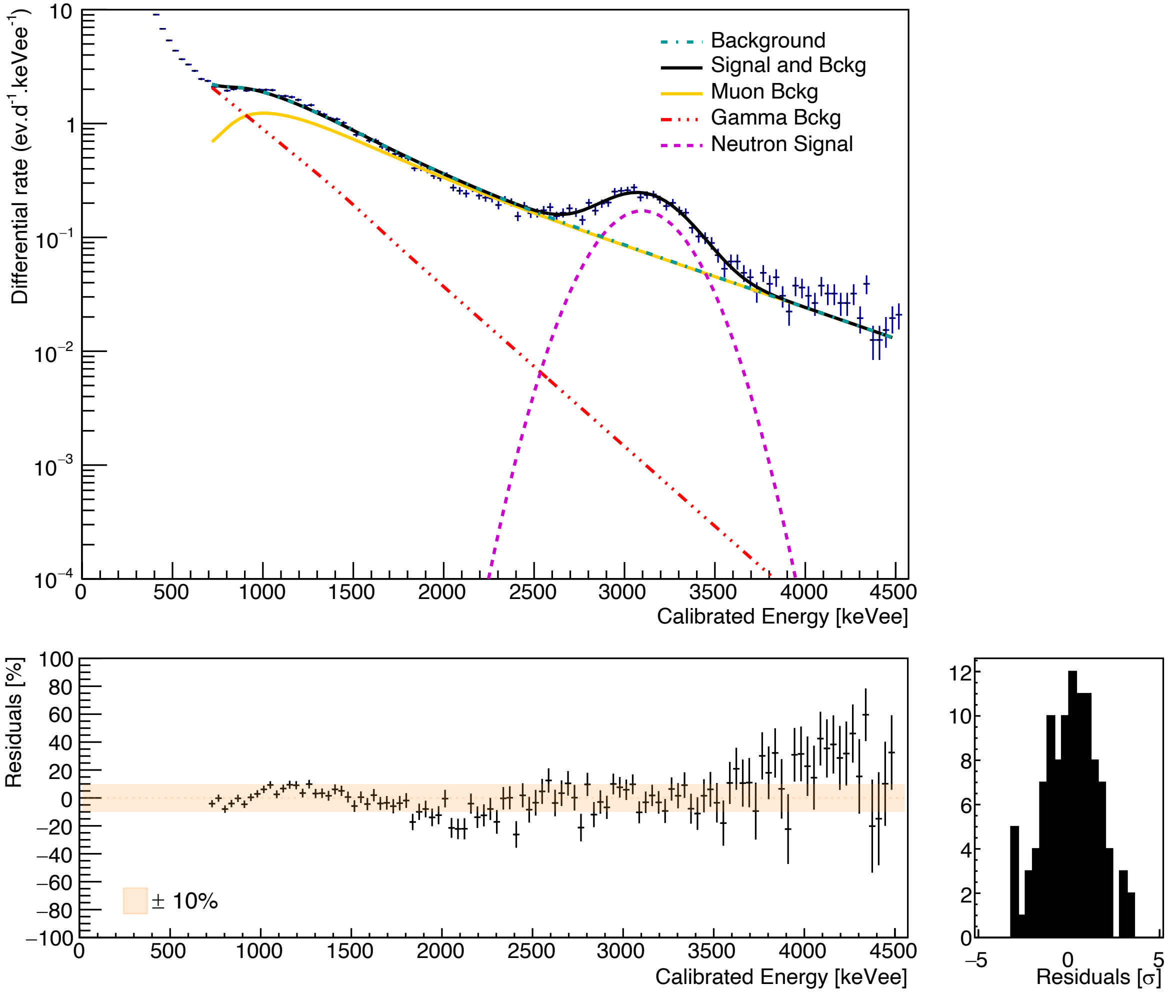


Bonner sphere measurements

9'' Surface

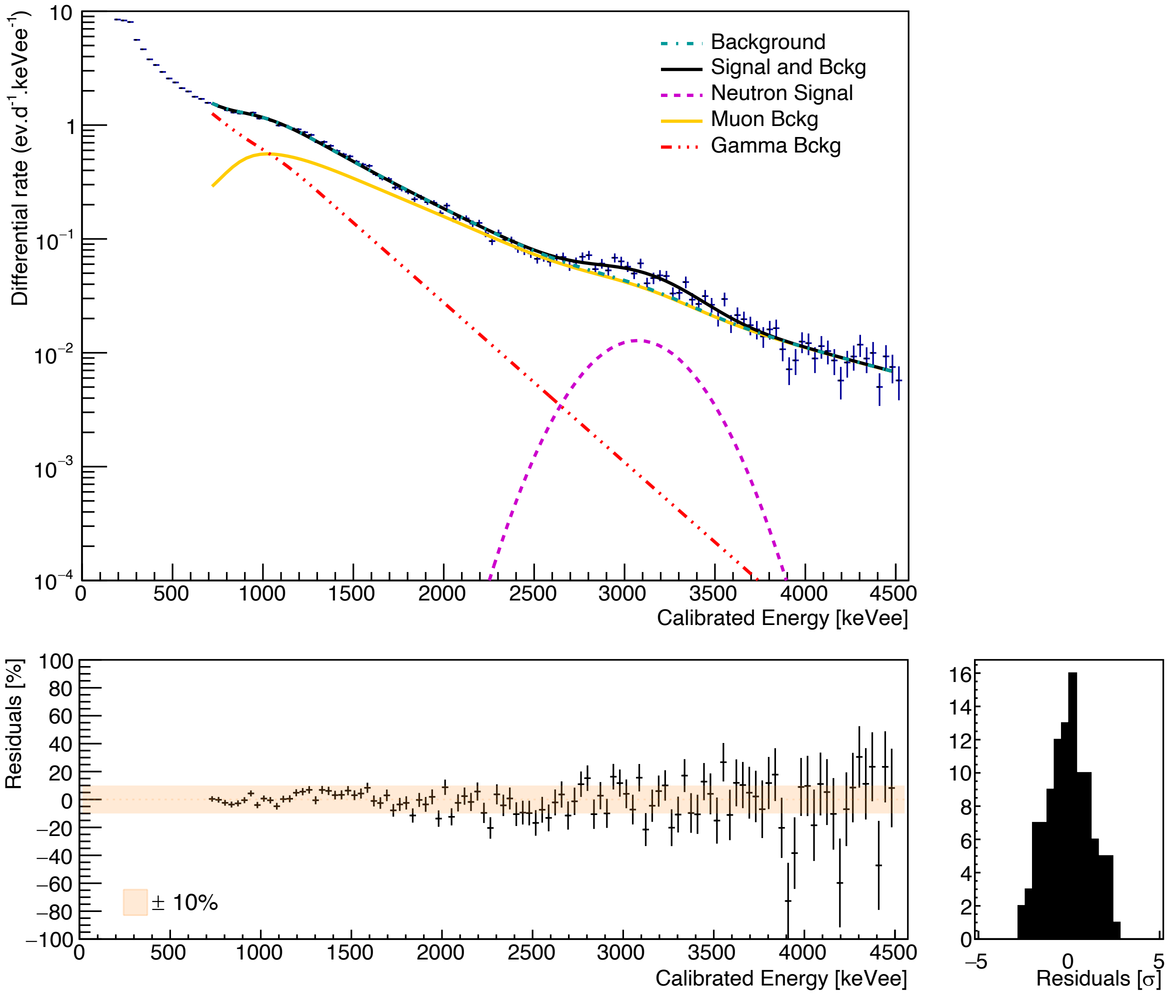


8'' Surface

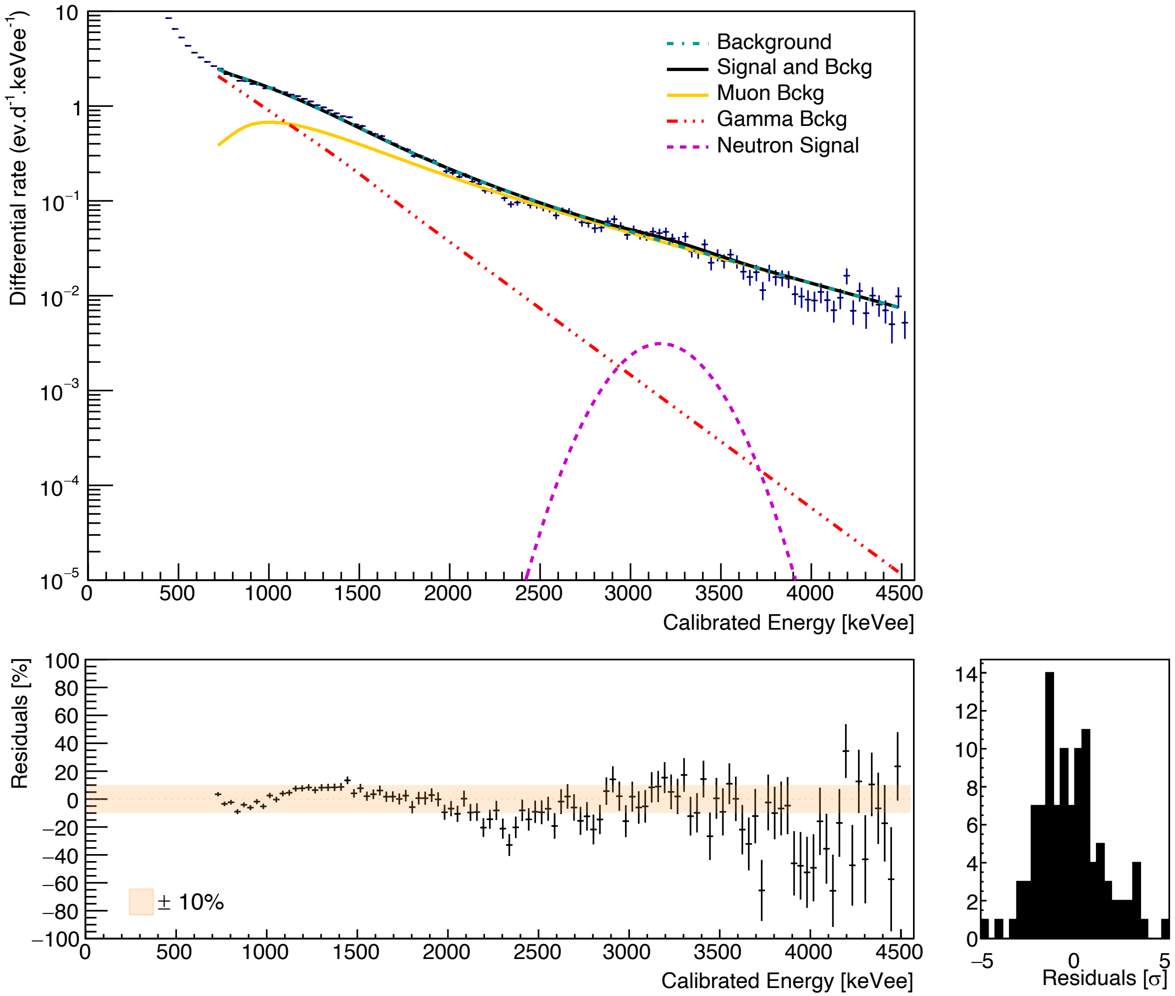


Bonner sphere measurements

9'' VNS



8'' VNS



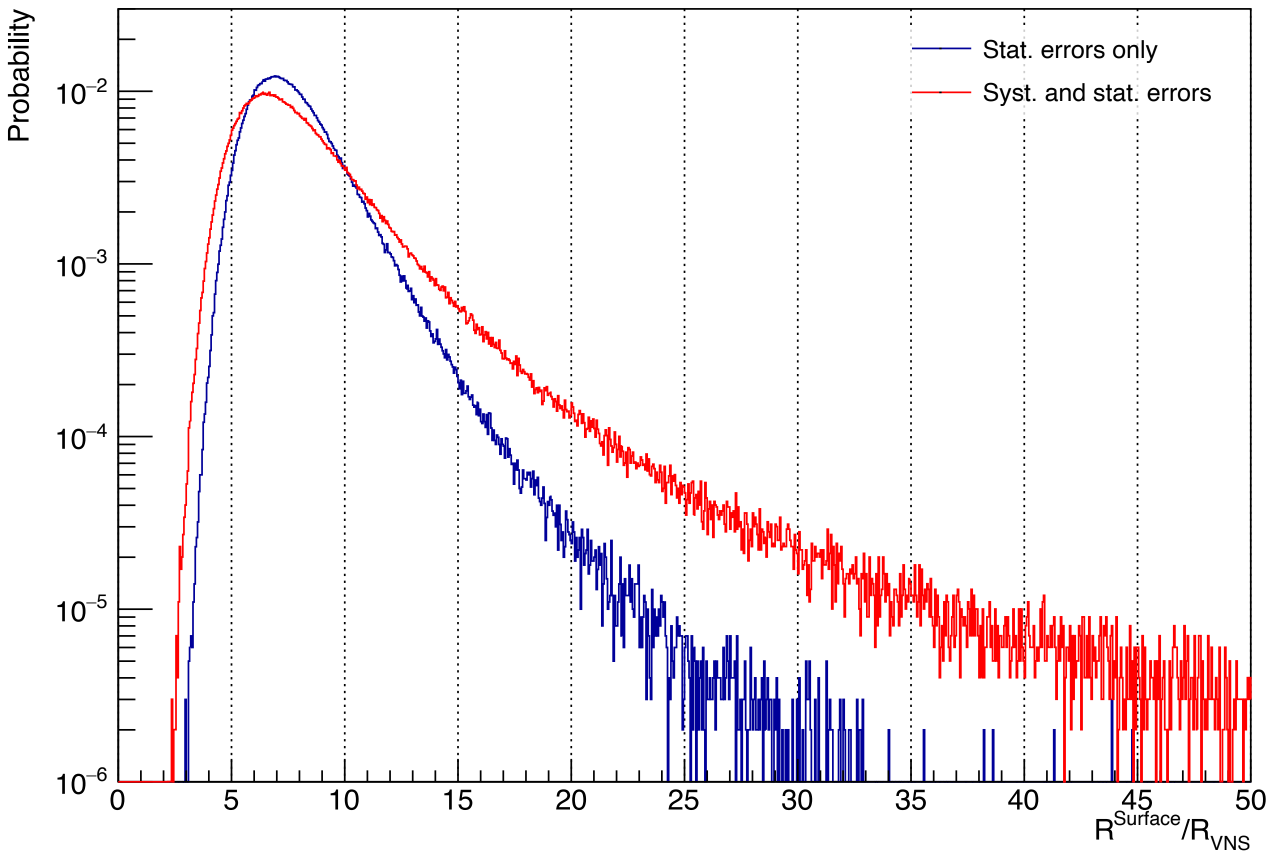
Bonner sphere measurements

Sphere	Site	χ^2/Ndf	$\mathcal{R}^{tot}$ [d^{-1}]	$\mathcal{R}^{bckg}$ [d^{-1}]	$\mathcal{R}^{np}$ [d^{-1}]	S/N
BS-EXT	DC Hut	2.3	253.5 ± 2.7	106.8 ± 1.2	143.4 ± 3.3	1.4
	VNS	1.7	59.5 ± 1.1	51.6 ± 0.4	7.9 ± 1.0	0.15
BS-A-06	DC Hut	2.4	205.5 ± 3.2	105.4 ± 1.1	95.7 ± 3.6	0.9
	VNS	3.2	59.1 ± 1.1	58.8 ± 0.4	2.1 ± 0.9	0.04

$$\mathcal{R}_{\mathrm{Surface}}^{>10\,\mathrm{MeV}} = \Delta\mathcal{R}_{\mathrm{DCHut}}^{\mathrm{np,fit}} = 47.8 \pm 5.0\ (\mathrm{stat.}) \pm 3.2\ (\mathrm{syst.})$$

$$\mathcal{R}_{\mathrm{VNS}}^{>10\,\mathrm{MeV}} = \Delta\mathcal{R}_{\mathrm{VNS}}^{\mathrm{np,fit}} = 6.6 \pm 1.4\ (\mathrm{stat.}) \pm 1.3\ (\mathrm{syst.})$$

MPV = $6.38^{+2.65}_{-1.45}$
95% probability to be > 4.7

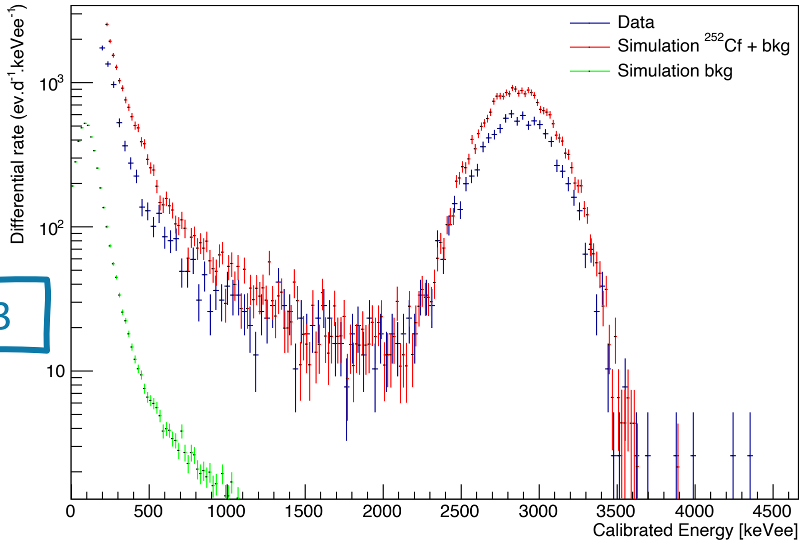


Bonner sphere measurements: absolute fluxes

^{252}Cf calibration

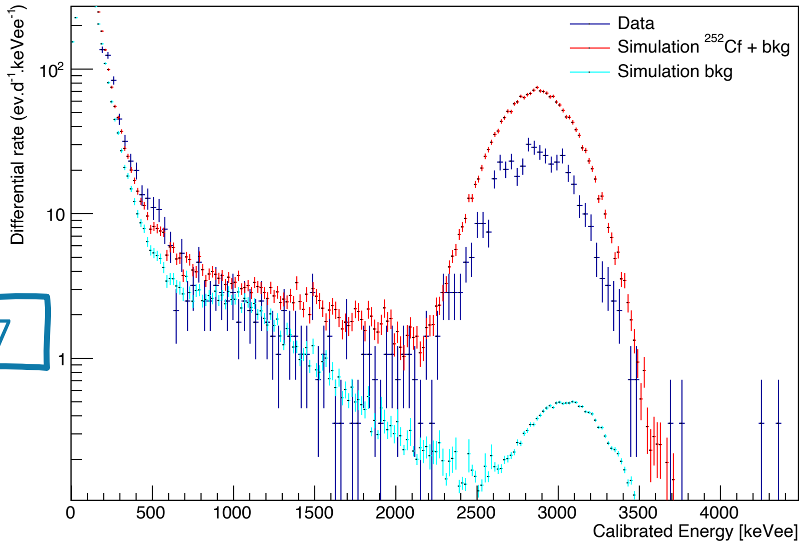
500 kBq

Factor 1.49 ± 0.03



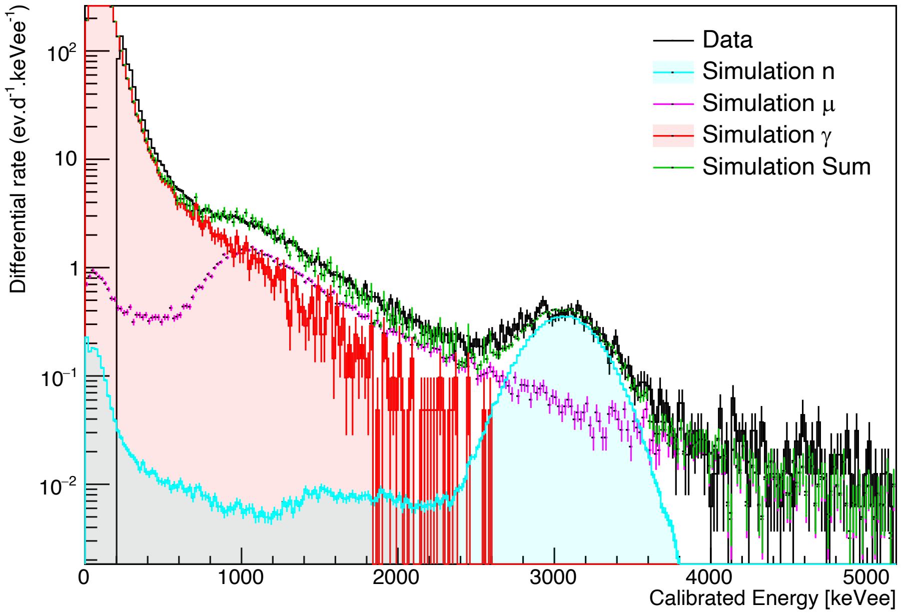
12 kBq

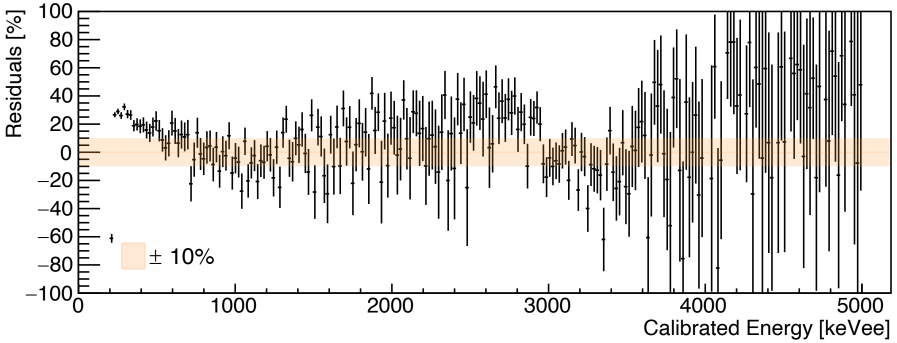
Factor 2.48 ± 0.07

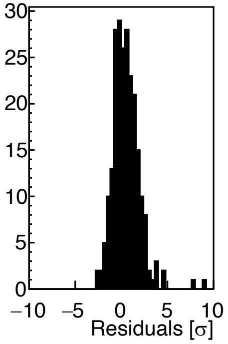


Atm neutrons manually scaled at 0.0107 $/cm^2/s$

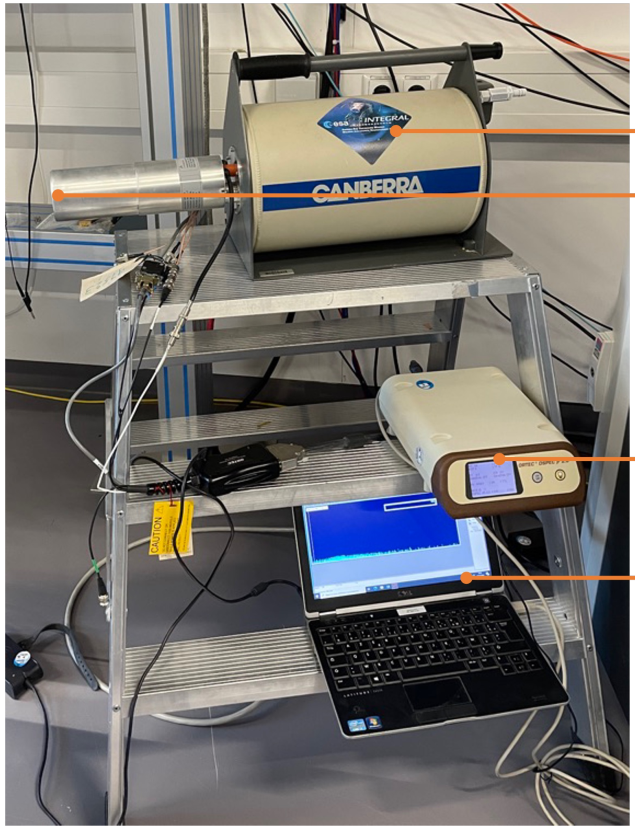
⇒ agreement

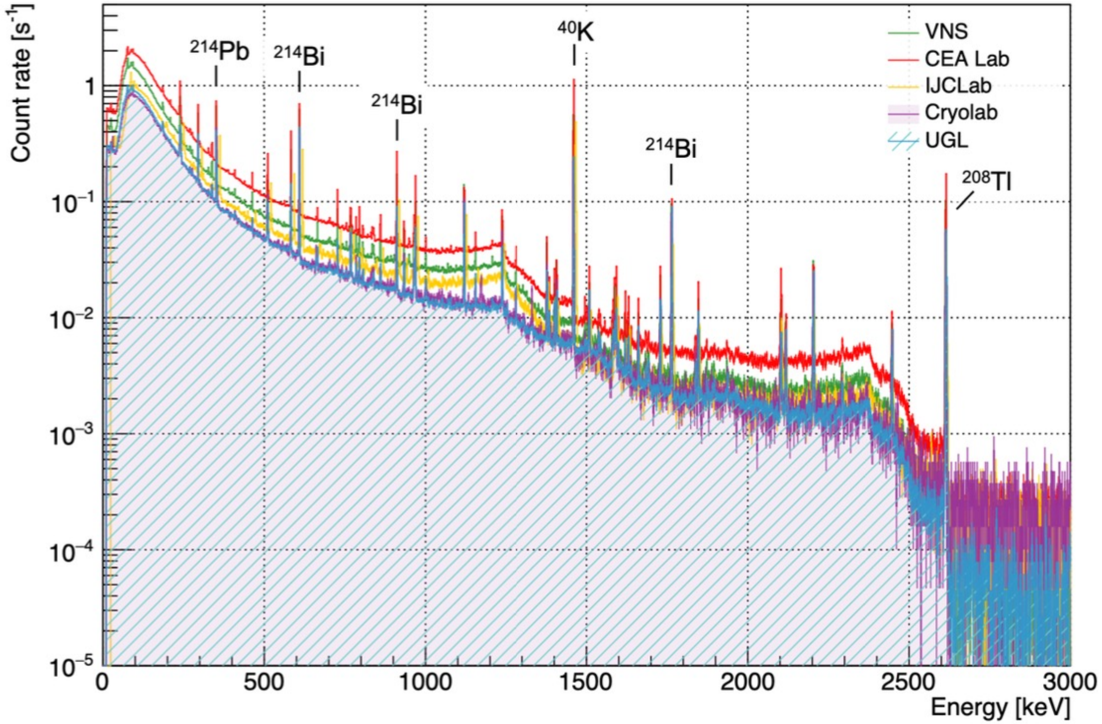






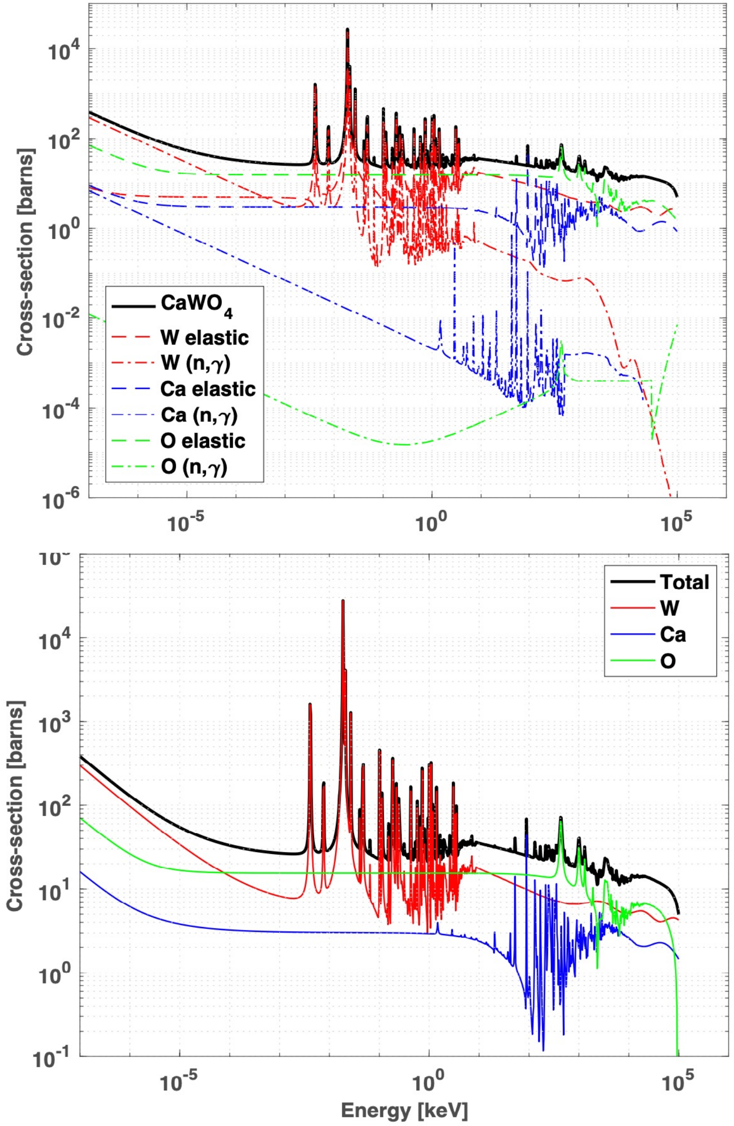
Gamma measurements

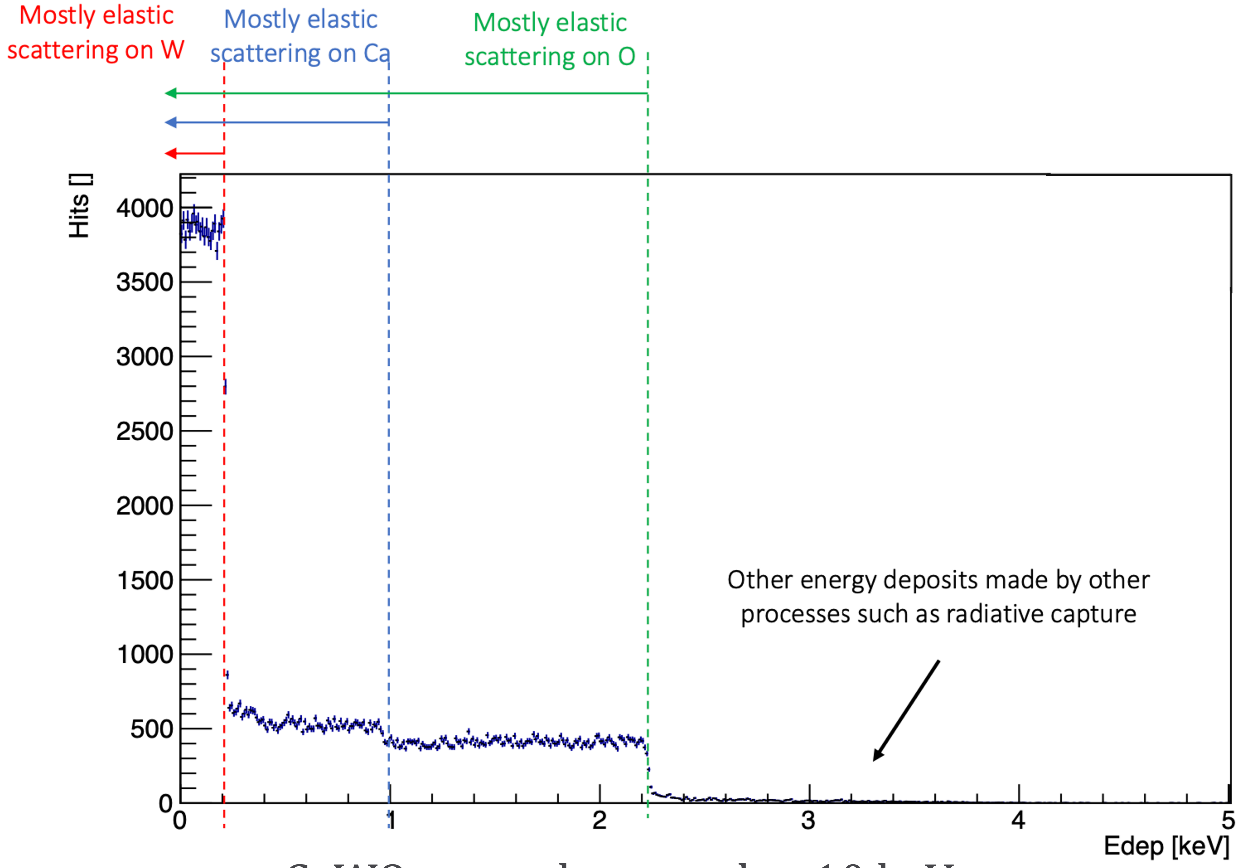




Site	^{40}K	^{238}U	^{232}Th	Total
VNS	0.912 ± 0.004	1.987 ± 0.012	1.038 ± 0.007	3.937 ± 0.018
UGL	0.271 ± 0.002	1.523 ± 0.007	0.618 ± 0.004	2.411 ± 0.009
CryoLab	0.333 ± 0.004	1.362 ± 0.012	0.583 ± 0.007	2.278 ± 0.013
CEA's Lab	1.388 ± 0.006	2.319 ± 0.017	2.013 ± 0.012	5.721 ± 0.026
IJCLab	1.054 ± 0.005	0.986 ± 0.014	0.962 ± 0.010	3.003 ± 0.007

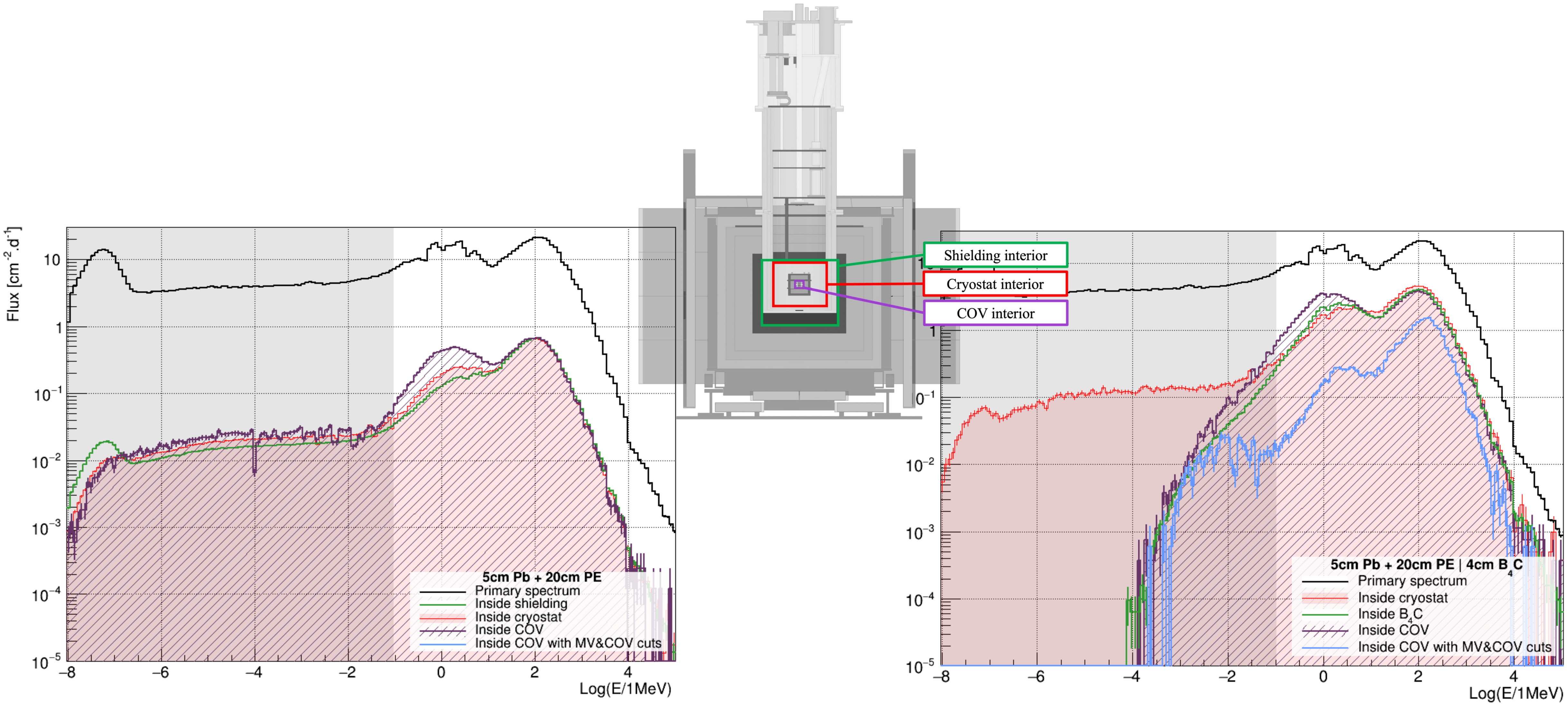
Neutrons recoils in the NUCLEUS ROI





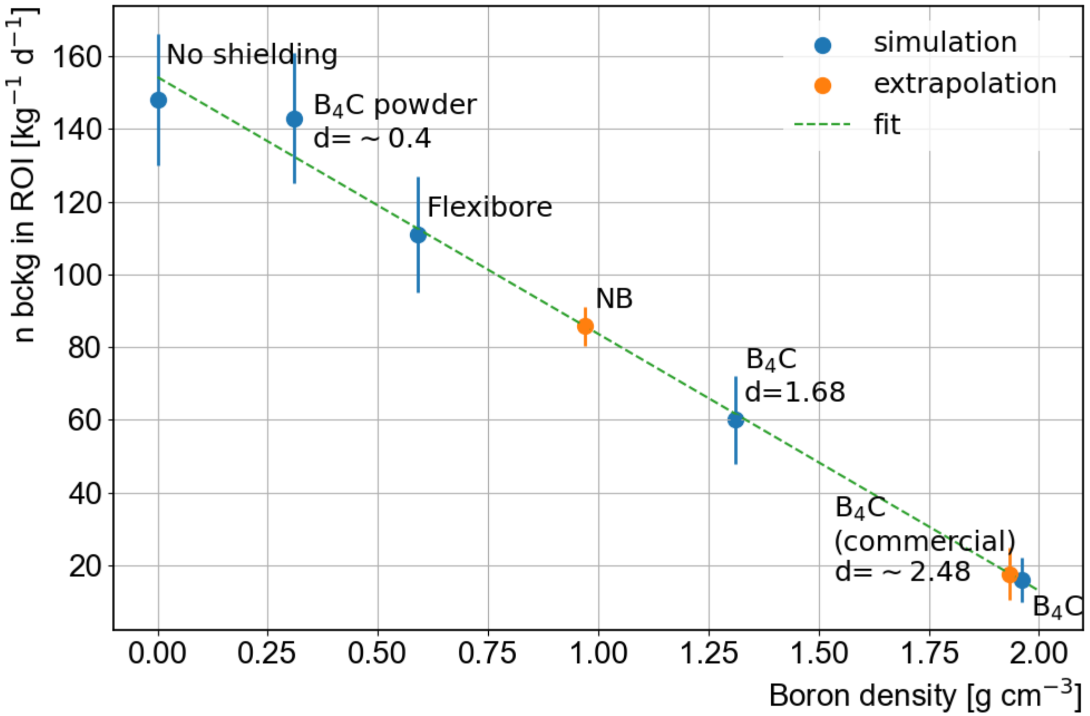
$CaWO_4$ crystal exposed to 10 keV neutrons

Neutron shielding: B_4C impact

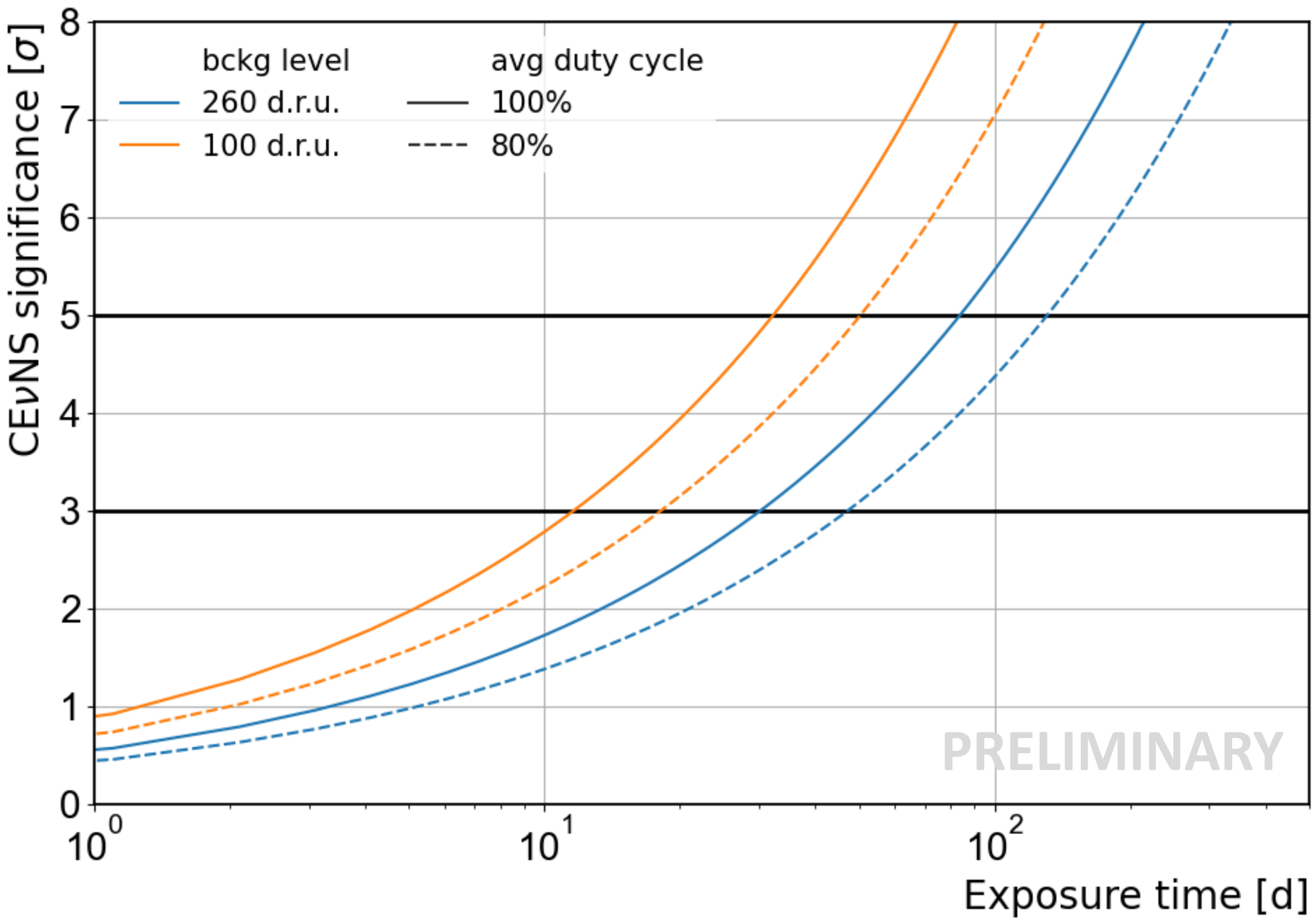


Neutron shielding: B_4C impact

Shielding	10-100 eV	0.1-1 keV	1-10 keV
5 cm Pb - 20 cm PE	249 ± 22 1.7 ± 0.2	209 ± 21 1.4 ± 0.1	330 ± 26 2.3 ± 0.2
5 cm Pb - 19 cm PE - 1 cm B_4C	171 ± 29 1.2 ± 0.2	201 ± 31 1.4 ± 0.2	352 ± 42 2.4 ± 0.3
5 cm Pb - 15 cm PE - 5 cm B_4C	83 ± 14 0.57 ± 0.10	157 ± 19 1.1 ± 0.1	406 ± 32 2.8 ± 0.2
5 cm Pb - 20 cm PE | 4 cm B_4C	28 ± 6 0.19 ± 0.04	100 ± 12 0.68 ± 0.07	313 ± 20 2.2 ± 0.2
5 cm Pb - 20 cm PE | 4 cm Flexibore®	164 ± 20 1.1 ± 0.1	170 ± 20 1.1 ± 0.1	300 ± 27 2.0 ± 0.2



Towards sensitivity studies



S/B ≈ 1

3σ after ~ 50 days

5σ after ~ 140 days

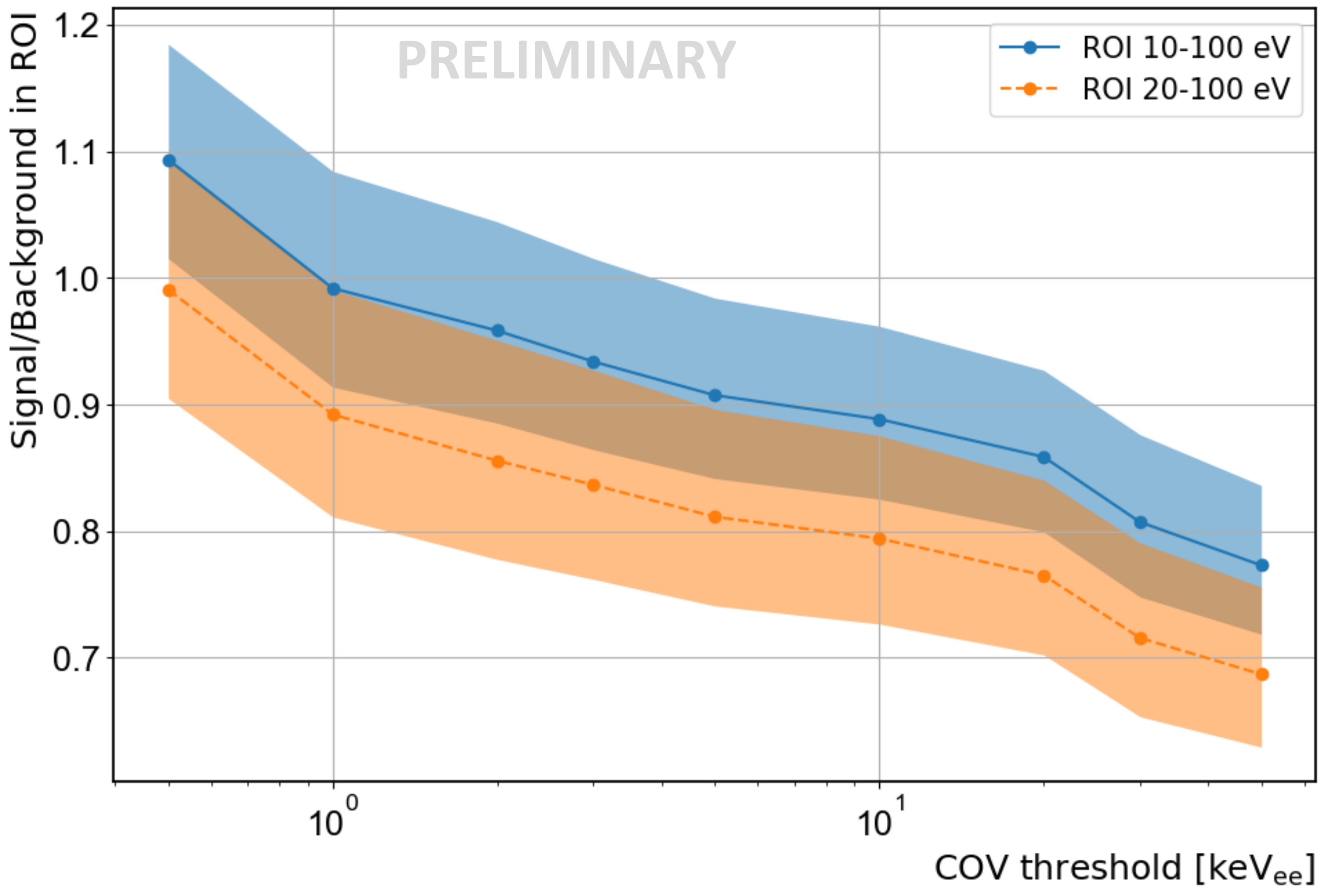
Very strong hypotheses!

- Flat background
- Target detectors threshold @10 eV
- No EXCESS
- No detector efficiency
- No dead time

⇒ Detailed sensitivity studies are on-going

COV threshold impact

S/B ratio as a function of the COV threshold and the NUCLEUS ROI



- Lower values of the contaminations considered
- 80% CEνNS (avg duty cycle)
- Neutron energy deposition in COV quenched by a factor 5 (independently of the process)

Signal/[(known) Background] ∈ [0.7-1.2]

Full background budget

nu cleus EXPERIMENT

PRELIMINARY

Source (simulated equiv. time)	**Flux [$s^{-1}cm^{-2}$]**	**Anti-coincidence criteria**	**10-100 eV**	**0.1-1 keV**	**1-10 keV**
Ambient gammas	3.937	None	6.0 ± 2.4	89.1 ± 10.5	1068.1 ± 37.4
(642 days)	*(sum)*	MV	6.0 ± 2.4	89.1 ± 10.5	1068.1 ± 37.4
		COV (1 keV_{ee})	1.3 ± 0.8	10.7 ± 3.7	145.2 ± 14.3
		COV (10 keV_{ee})	1.3 ± 0.8	11.3 ± 3.8	156.7 ± 14.9
		MV & COV (1 keV_{ee})	1.3 ± 0.8	10.7 ± 3.7	145.2 ± 14.3
		All (COV@1 keV_{ee})	< 1.2	3.2 ± 1.3	51.4 ± 8.4
Atmospheric muons	0.019/1.4	None	212.3 ± 13.3	1262.1 ± 32.3	9696.8 ± 89.7
(176 days)		MV	6.6 ± 2.3	29.9 ± 5.0	136.0 ± 10.6
		COV (1 keV_{ee})	7.5 ± 2.5	17.4 ± 3.8	137.6 ± 10.7
		COV (10 keV_{ee})	8.3 ± 2.6	21.6 ± 4.2	155.9 ± 11.4
		MV & COV (1 keV_{ee})	< 5.6	¡5.6	14.9 ± 3.5
		All (COV@1 keV_{ee})	< 5.6	¡5.6	12.4 ± 3.2
Atmospheric neutrons	0.0134/5.0	None	70.7 ± 1.2	242.8 ± 2.1	917.4 ± 4.2
(7809 days)		MV	50.2 ± 1.0	172.9 ± 1.8	656.6 ± 3.5
		COV (1 keV_{ee})	33.5 ± 0.8	62.9 ± 1.1	173.4 ± 1.8
		COV (10 keV_{ee})	38.6 ± 0.9	96.9 ± 1.3	283.9 ± 2.3
		MV & COV (1 keV_{ee})	23.7 ± 0.7	44.7 ± 0.9	132.5 ± 1.6
		All (COV@1 keV_{ee})	20.9 ± 0.6	39.4 ± 0.9	116.1 ± 1.5
Material contamination	*(sum)*	All (COV@1 keV_{ee})	0.91 ± 0.18	11.47 ± 0.65	133.8 ± 2.21
Sum		**None**	**308.1 ± 14.1**	**1593.9 ± 34.1**	**11682.3 ± 97.2**
		MV	**64.5 ± 3.7**	**291.8 ± 11.8**	**1860.8 ± 39.0**
		COV (1 keV_{ee})	**42.3 ± 2.7**	**91.0 ± 5.4**	**456.2 ± 17.9**
		COV (10 keV_{ee})	**48.2 ± 2.9**	**129.8 ± 5.8**	**596.5 ± 18.8**
		MV&COV (1 keV_{ee})	**27.5 ± 1.8**	**57.9 ± 4.1**	**292.6 ± 14.8**
		All (1 keV_{ee})	**24.8 ± 1.6**	**56.7 ± 2.2**	**313.8 ± 9.3**