Low energy background at the Gran Sasso national laboratory with respect to the VIP experiment

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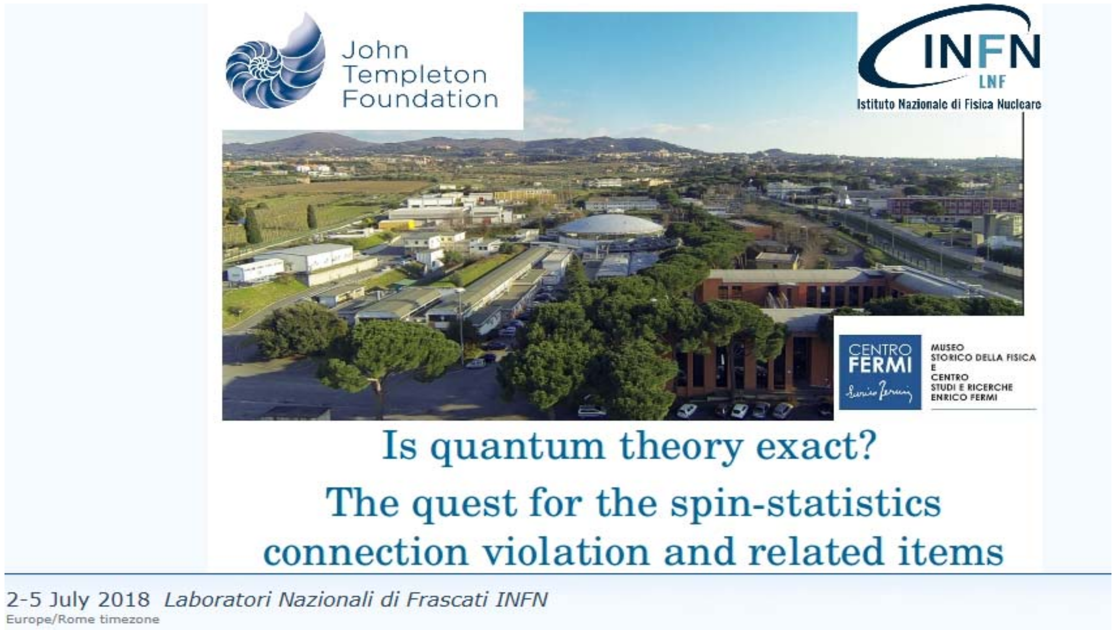
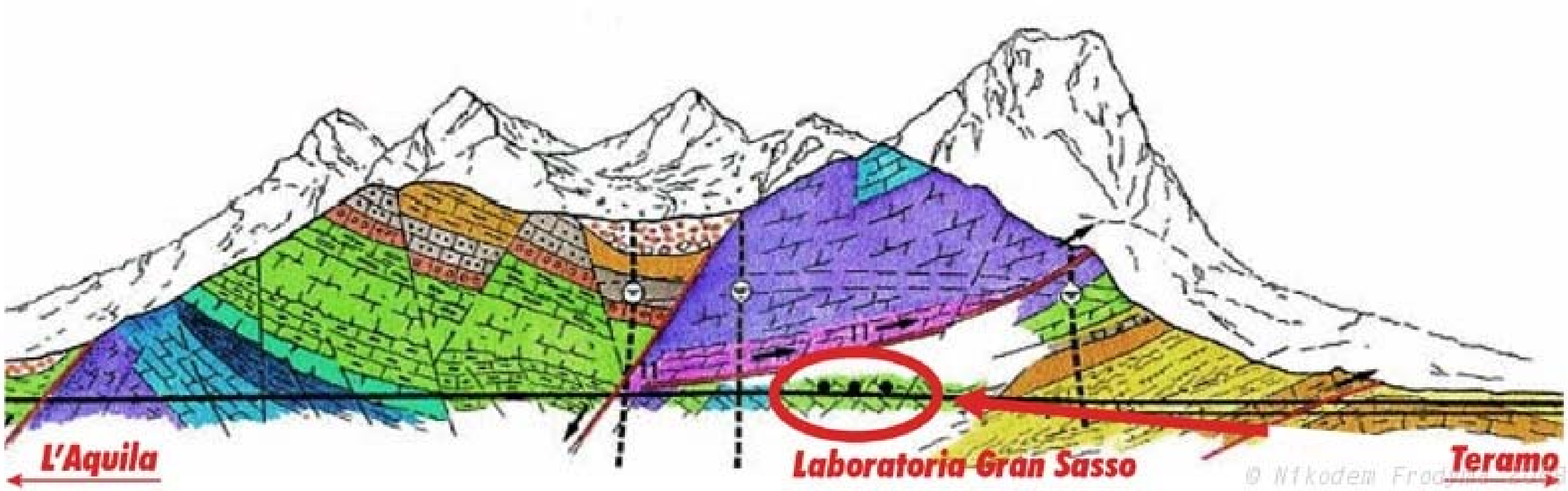


In the VIP (VIolation of the Pauli exclusion principle) experiment the 8 keV region is tested for forbidden X-rays. The sensitivity depends crucially on the background level.

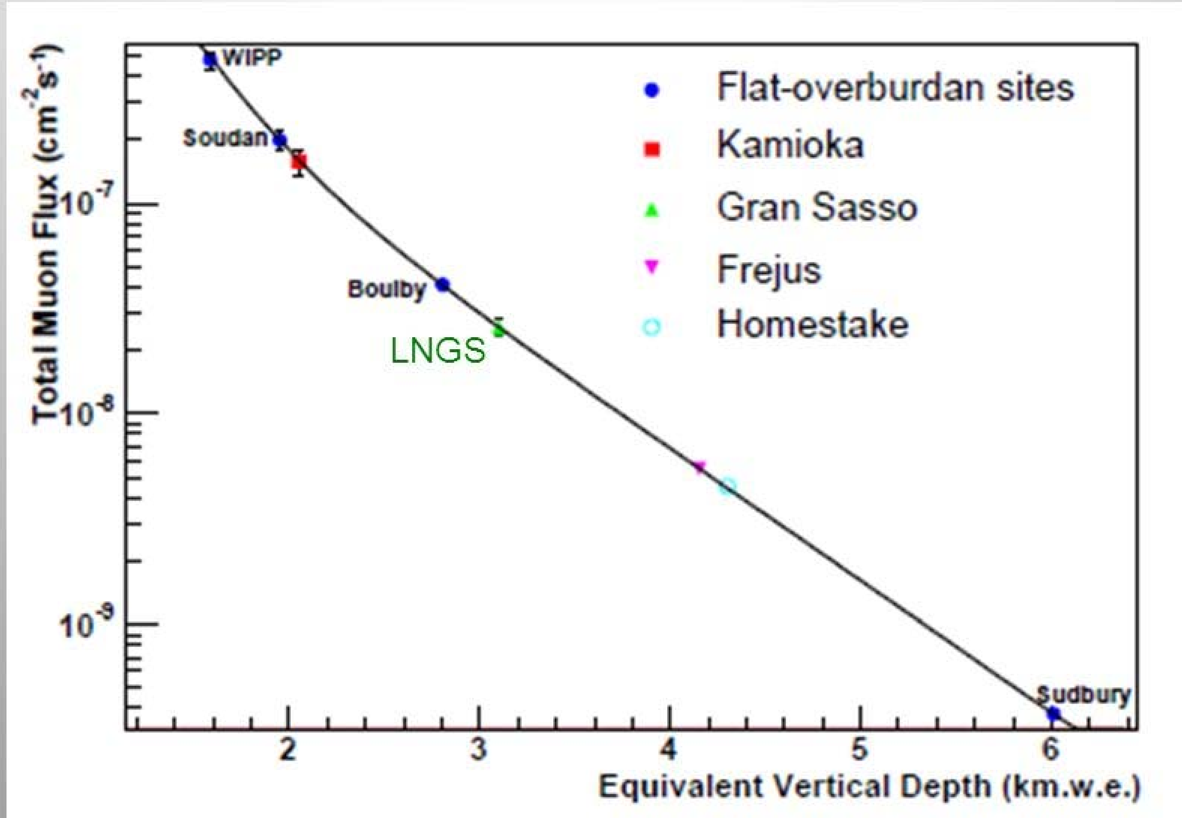


Background sources are cosmic rays and environmental radioactivity. Shielding is essential, even at this low radiation place.

cosmic rays are drastically reduced at underground sites

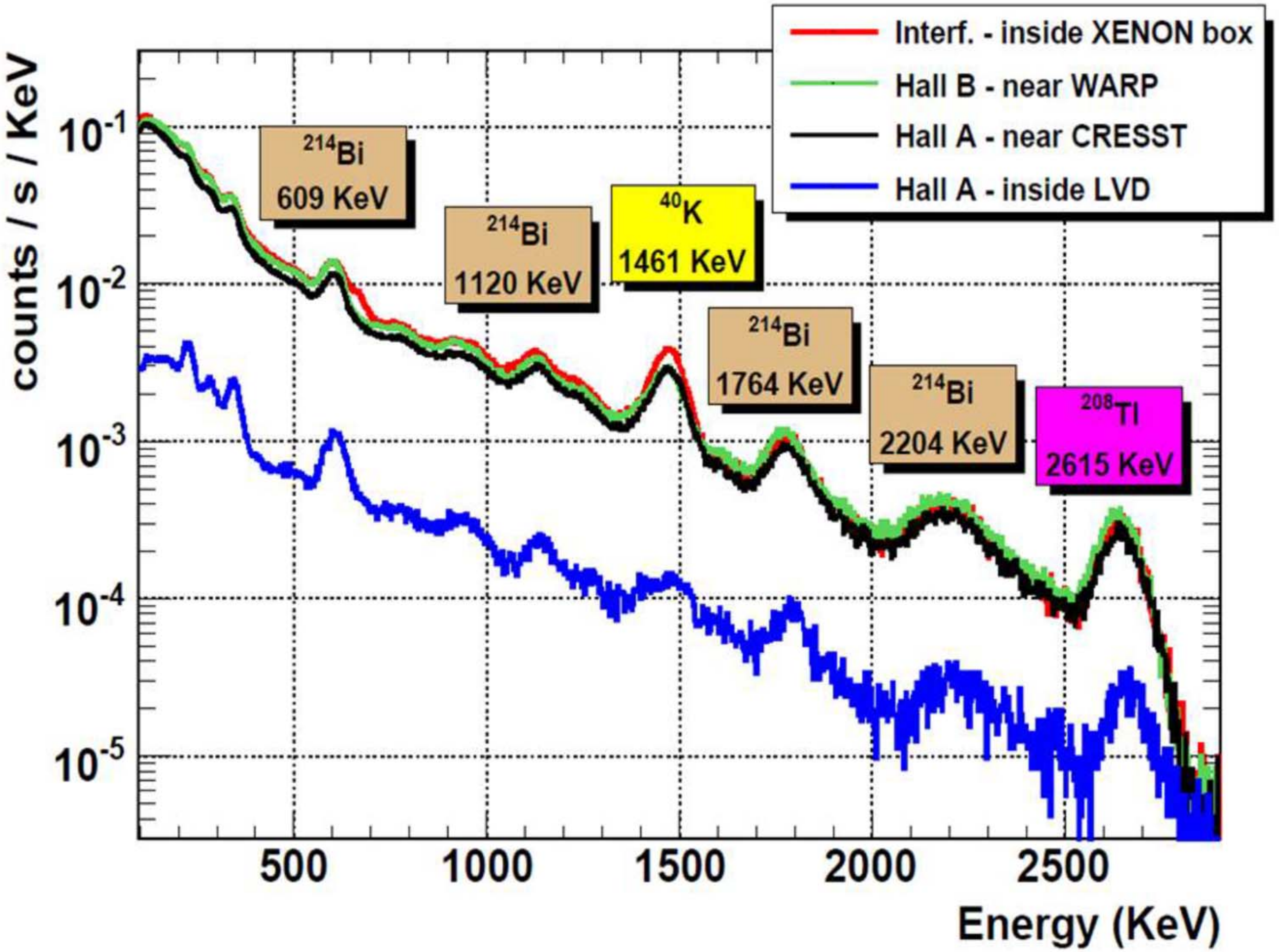
Muon Flux versus depth

LNGS: 10^{-6} wrt surface



Hime and Mei, Phys.Rev. D73 (2006) 053004

Example: background measured at LNGS, resulting from cosmics AND environmental radioactivity



A. Aleksandrov et al, arXiv:1604.04199v1 [astro-ph.IM]

Eur. Phys. J. A **41**, 155–168 (2009)
DOI 10.1140/epja/i2009-10805-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Background study and Monte Carlo simulations for large-mass bolometers

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A. Nucciotti[2,3], L. Pattavina[2,3], M. Pav

Background sources
1. *natural contaminants*, mainly 238U, 235U and 232Th with their radioactive chains and the *β*/EC decaying 40K isotope;
2. *anthropogenic contaminants*, generally residual of nuclear explosion in the atmosphere, radioactive leakages by nuclear plants and radioactive isotopes used in industrial processes, like 60Co, 90Sr, 137Cs, 134Cs and 207Bi isotopes;
3. *cosmogenic activation*, *i.e.* isotopes produced by cosmic-ray interactions (for example in copper the following isotopes are produced: 57Co, 58Co, 60Co and 54Mn);
4. *environmental background at the experiment location*: cosmic rays, environmental gammas and neutrons.

In fig. 1 we report the gamma-ray spectrum, as measured by a small Ge diode (the detector is a portable model, a HPGe 59mm in diameter and 58mm in height) in the Hall A of LNGS. The gamma-ray flux originating this spectrum was reconstructed (tables 2 and 3) using the JAZZY code,

Table 2. Intensity of the main gamma lines ($\gamma/\text{m}^2/\text{day}$) measured in the underground Hall A of LNGS. Only lines with intensity higher than $10^6\,\gamma/\text{m}^2/\text{day}$ are listed. These are due to ^{40}K, and to the ^{238}U and ^{232}Th chains.

Energy [keV]	Isotope	Intensity [$\gamma/\text{m}^2/\text{day}$]
238.6	^{212}Pb	$2.8 \cdot 10^6$
295.2	^{214}Pb	$3.8 \cdot 10^6$
352	^{214}Pb	$7.9 \cdot 10^6$
583	^{208}Tl	$3.0 \cdot 10^6$
609	^{214}Bi	$1.3 \cdot 10^7$
911	^{228}Ac	$3.1 \cdot 10^6$
934	^{214}Bi	$2.1 \cdot 10^6$
968	^{228}Ac	$2.1 \cdot 10^6$
1120	^{214}Bi	$6.3 \cdot 10^6$
1238	^{214}Bi	$2.8 \cdot 10^6$
1460	^{40}K	$2.9 \cdot 10^7$
1764	^{214}Bi	$8.2 \cdot 10^6$
2204	^{214}Bi	$3.1 \cdot 10^6$
2614	^{208}Tl	$7.8 \cdot 10^6$

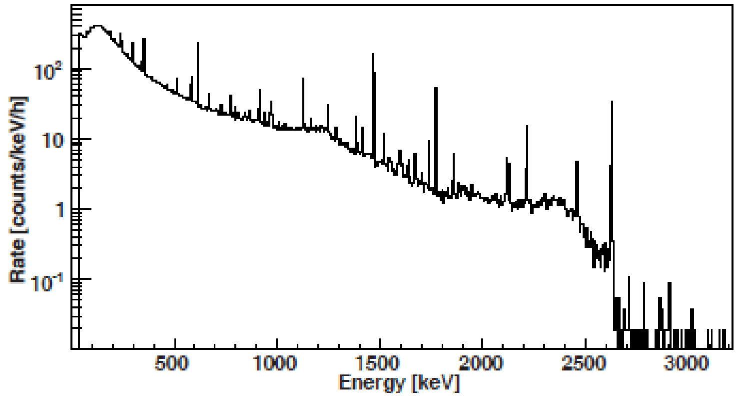


Fig. 1. Gamma-ray spectrum measured at LNGS (Hall A) with a small Ge diode.

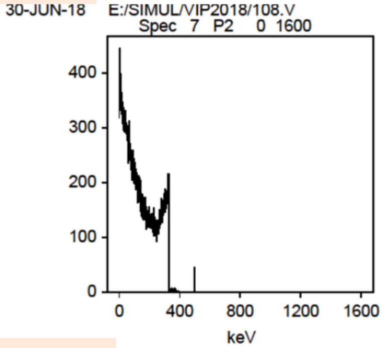
Table 3. Gamma-ray flux ($\gamma/\text{m}^2/\text{day}$) in the underground Hall A of LNGS. The integral gamma-ray flux below 3 MeV is $\sim 6.3 \cdot 10^8\,\gamma/\text{m}^2/\text{day}$.

Energy interval [keV]	gamma flux [$\gamma/\text{m}^2/\text{day}$]	
0–500	$4.4 \cdot 10^8$	0.698
500–1000	$1.1 \cdot 10^8$	0.175
1000–2000	$7.0 \cdot 10^7$	0.111
2000–3000	$1.3 \cdot 10^7$	0.021

response of 500 μm silicon to MeV gammas

36 SDD cells of 8 x 8 mm^2 (10.24 cm^2)   6.4e6 gammas hitting

source: 500 keV gamma



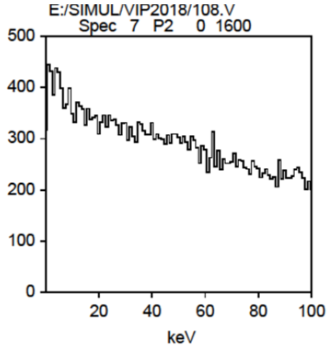
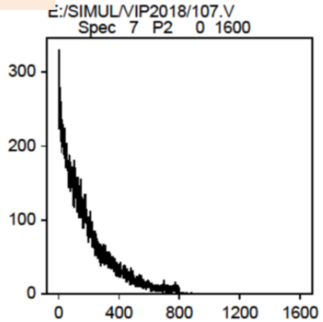


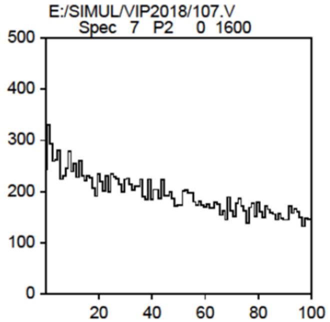
Fig.: deposited energy (keV)

Note that some compton electrons leave the SDD volume..

at 10 keV: 350 /6.4e6
=> **~ 55 e-6 /keV / gamma**

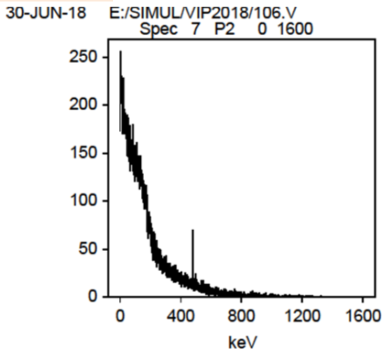
source: 1000 keV gamma

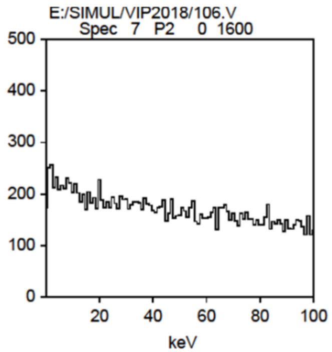




at 10 keV: 250 /6.4e6
=> **~ 39 e-6 /keV / gamma**

source: 1500 keV gamma

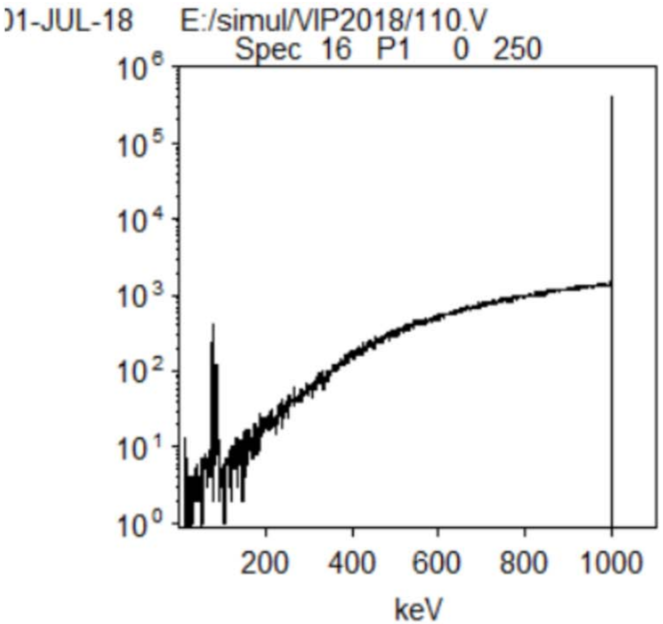




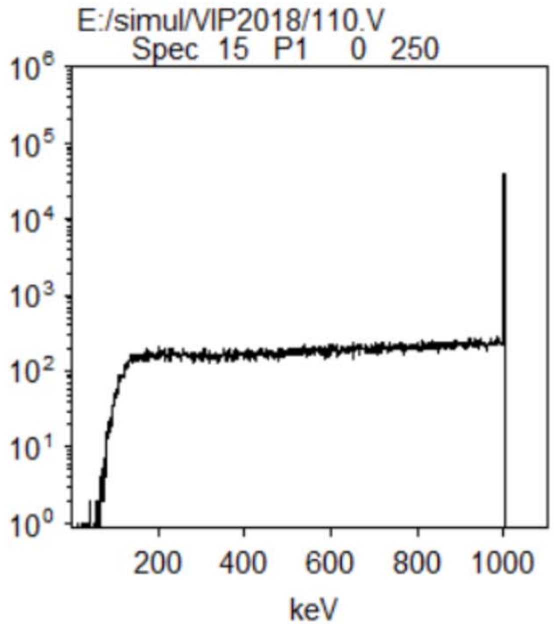
at 10 keV: 200 /6.4e6
=> **~ 31 e-6 /keV / gamma**

passive shielding of MeV gammas

Start: 2e7 1 MeV gammas



energy distribution after 5 cm Pb
0.88e6 remain



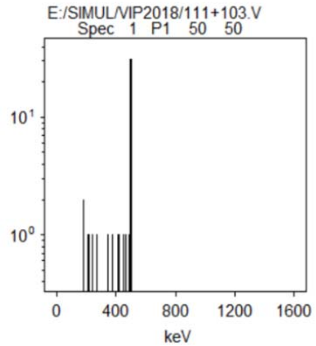
... after 5 cm Pb + 5 cm Fe
0.21e6 remain

passive shielding of MeV gammas

36 SDD cells of 8 x 8 mm^2 (10.24 cm^2) 19.2e6 gammas started, **5 cm Pb, 5 cm Fe, 1 cm Al, 4 cm plastic, 4 cm plastic**

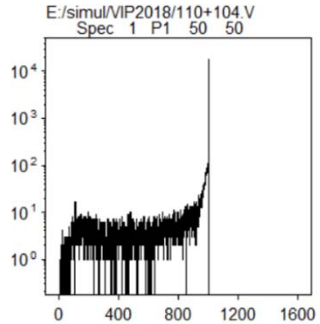
source: 500 keV gamma

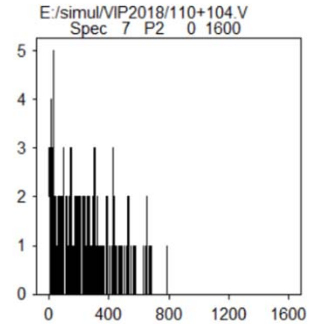
49 γ hit SDDs
=> **0.003e-3**



source: 1000 keV gamma

24.101 γ hit SDDs
=> **1.25e-3**

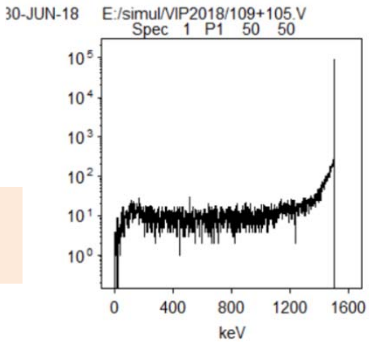


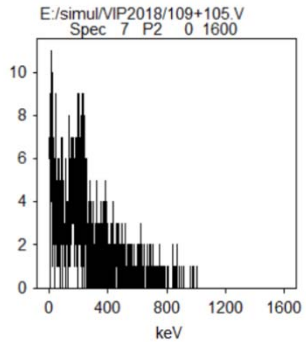


at 10 keV => ~ 0.9/19e6
=> **~ 0.05 e-6 /keV / gamma**
reduction: 1/ 780 wrt naked

source: 1500 keV gamma

116.078 γ hit SDDs
=> **6.03e-3**



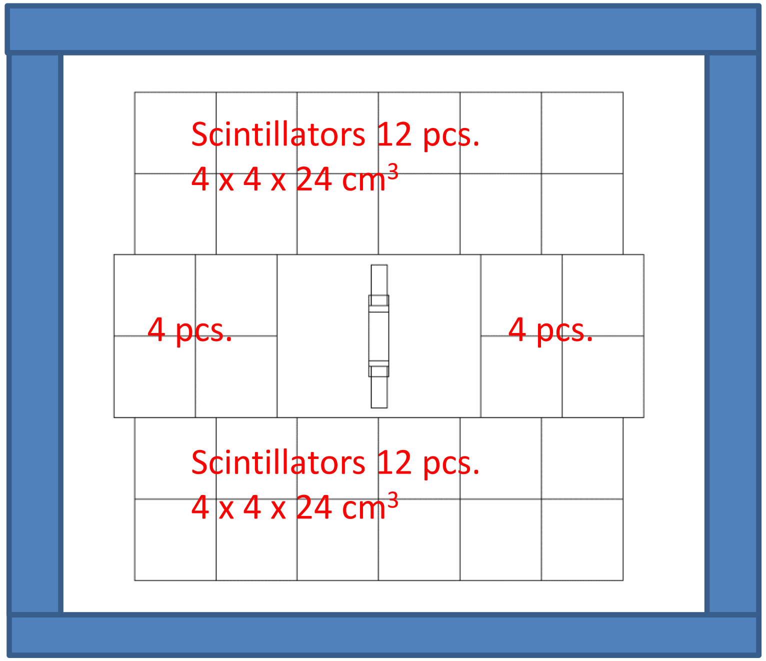


at 10 keV => ~ 5/19e6
=> **~ 0.26 e-6 /keV / gamma**
reduction: 1/ 193 wrt naked

left.: energy at hitting the SDDs

right.: deposited energy

Experimental setup and Monte Carlo model



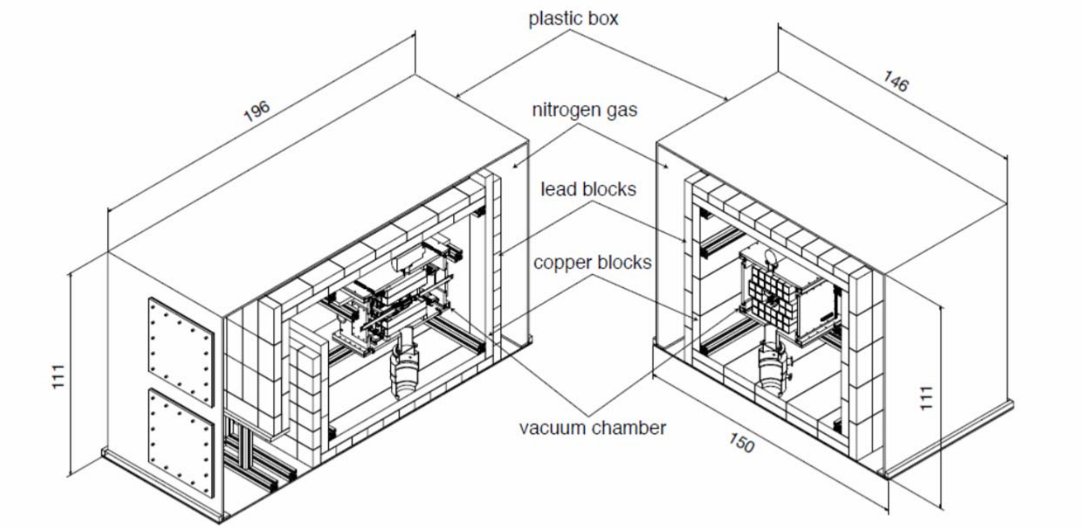


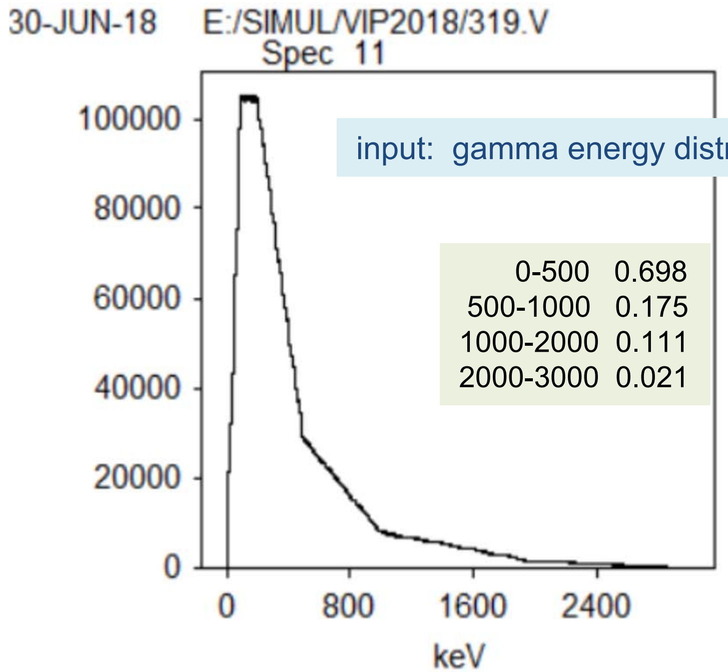
Fig. 3 Perspective views of the VIP-2 apparatus with passive shielding, with the dimensions in cm. Nitrogen gas with a slight over pressure with respect to the outside air will be circulated inside the plastic shielding.

scheme of the setup with plastic scintillators as active shielding

new setup 2018
2 modules of 3.2 x 1.6 cm^2 (4x2 cells) SDDs on each side, each 500 μm thick
Cu: 2.0 x 9.0 cm^2 25 μm thick

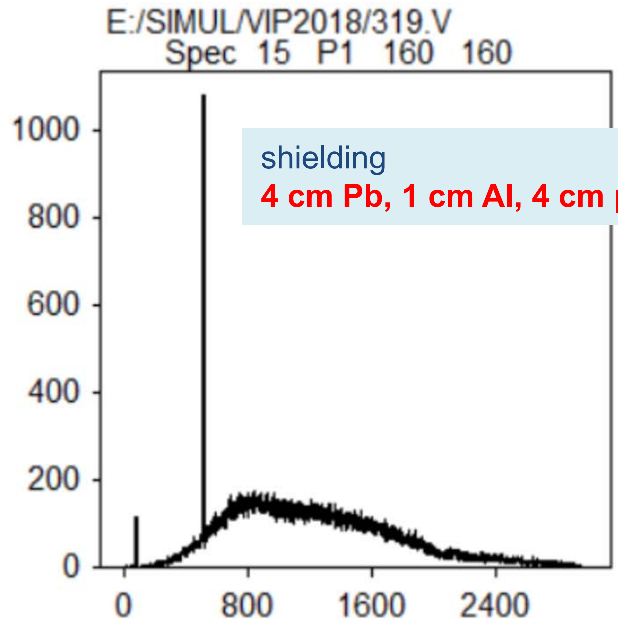
active shielding

gamma energy distribution
after the Pb, at hitting the Al box

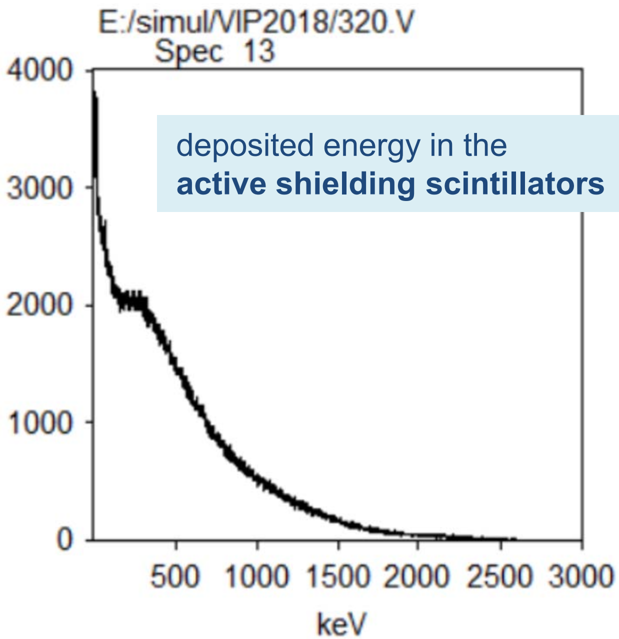


input: gamma energy distribution

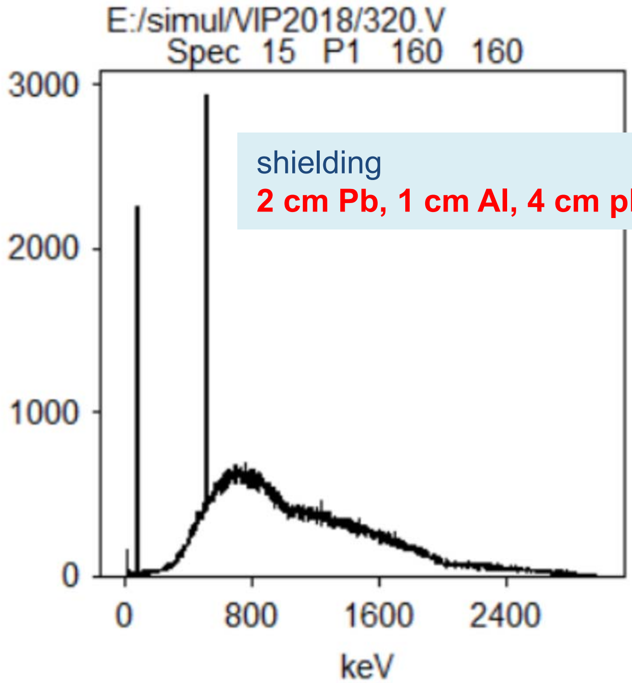
0-500	0.698
500-1000	0.175
1000-2000	0.111
2000-3000	0.021



shielding
4 cm Pb, 1 cm Al, 4 cm plastic, 4 cm plastic



deposited energy in the
active shielding scintillators

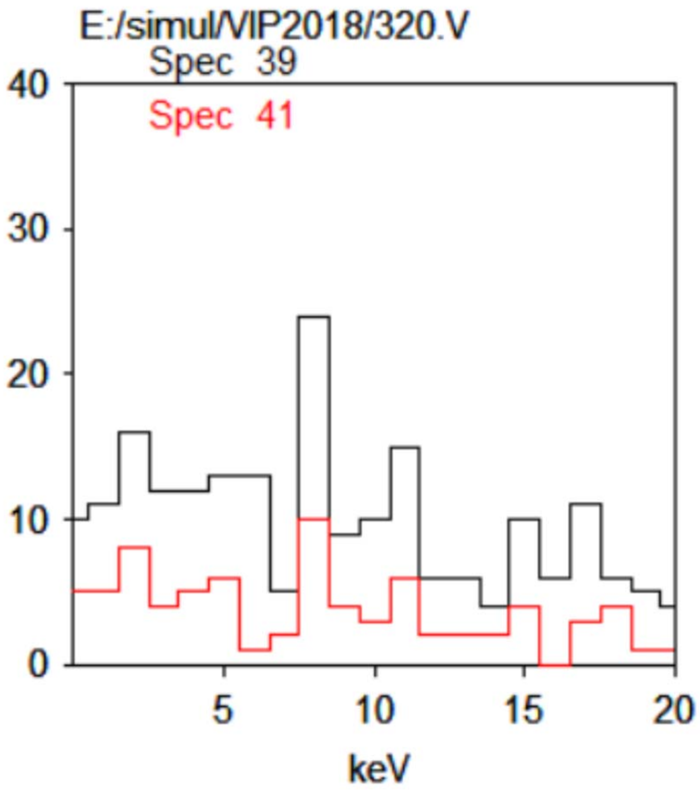


shielding
2 cm Pb, 1 cm Al, 4 cm plastic, 4 cm plastic

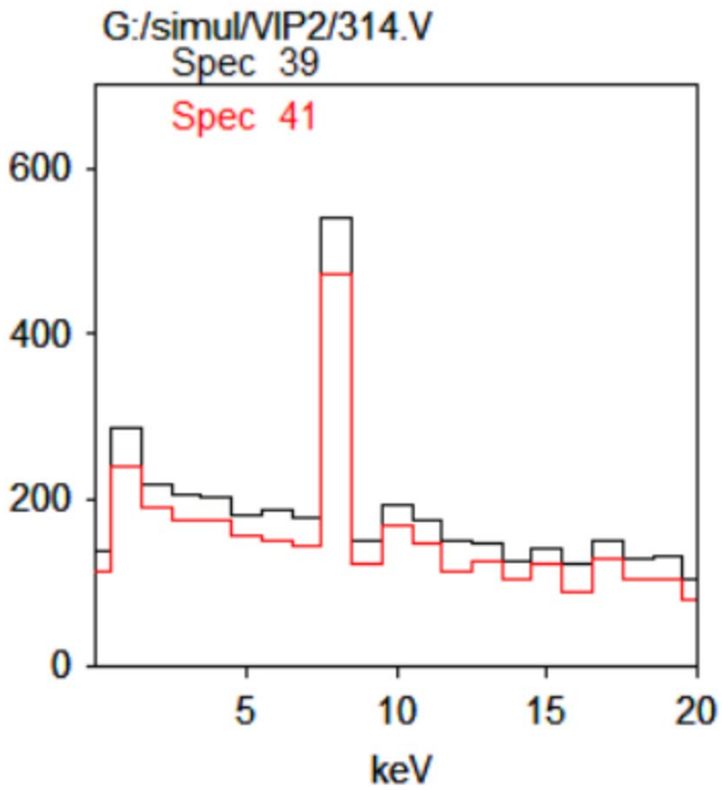
Background reduction by active shielding

shielding
2 cm Pb, 1 cm Al, 4 cm plastic, 4 cm plastic
32 plastic scintillator bars
Veto if max(dE_1,..dE_{32}) > 200 keV

shielding
1 cm Al, 4 cm plastic, 4 cm plastic
32 plastic scintillator bars
Veto if max(dE_1,..dE_{32}) > 200 keV



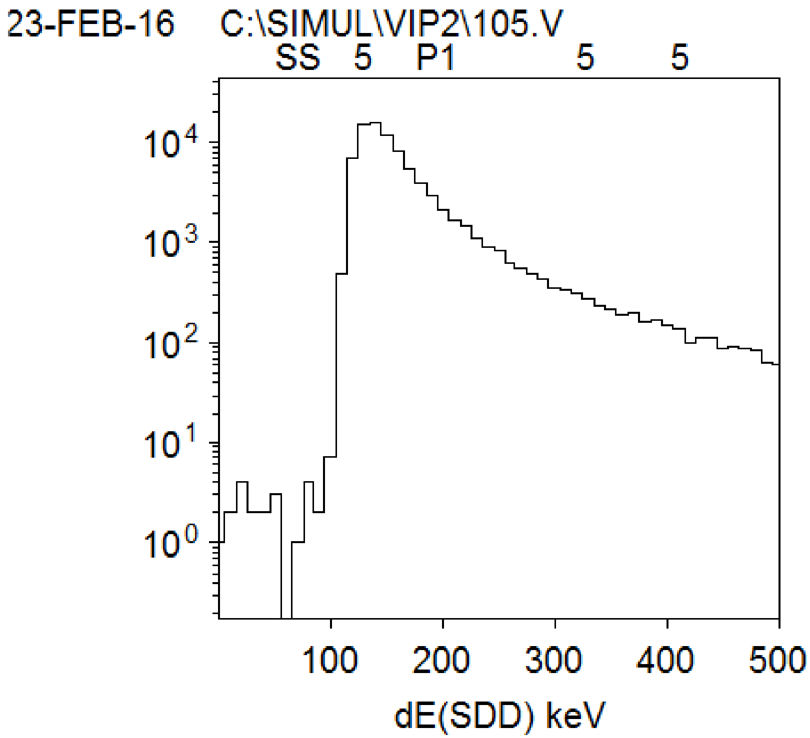
Efficient background reduction !



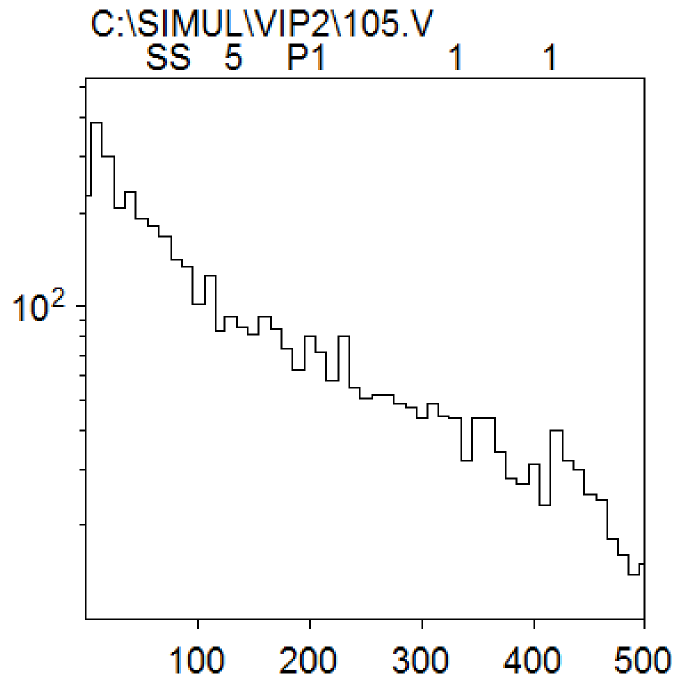
without lead-shielding, the majority of gammas is at lower energies and not detec‘d due to 200 keV threshold **=> Inefficient background reduction**

Background from cosmic muons?

from cosmic muons
(20%)



from 700 keV gamma
(80%)



not relevant for VIP

Annu. Rev. Nucl. Part. Sci. 2004. 54:361–412
doi: 10.1146/annurev.nucl.54.070103.181248

BACKGROUNDS TO SENSITIVE EXPERIMENTS UNDERGROUND

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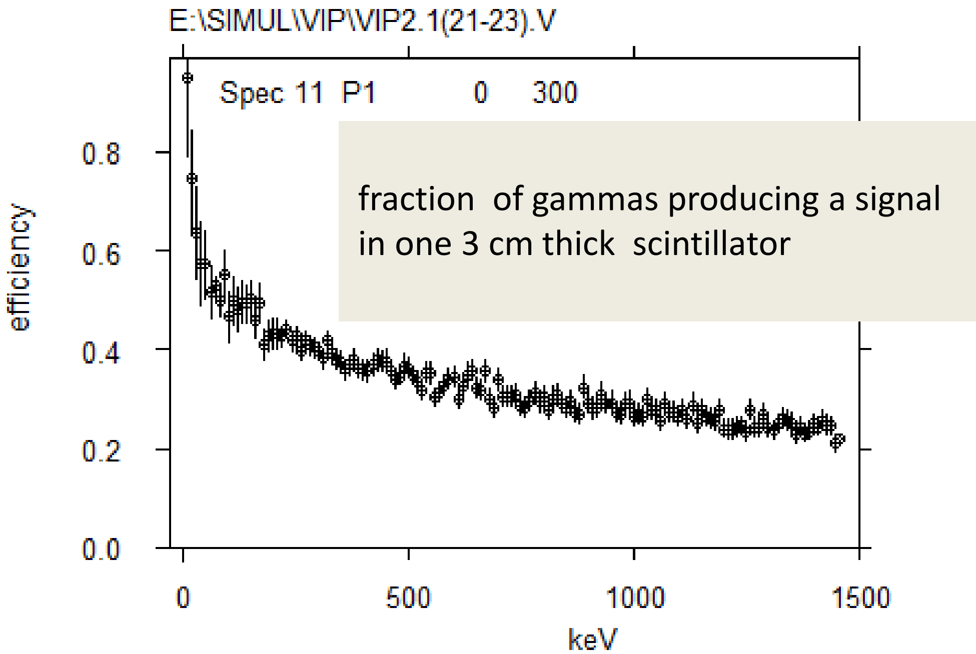
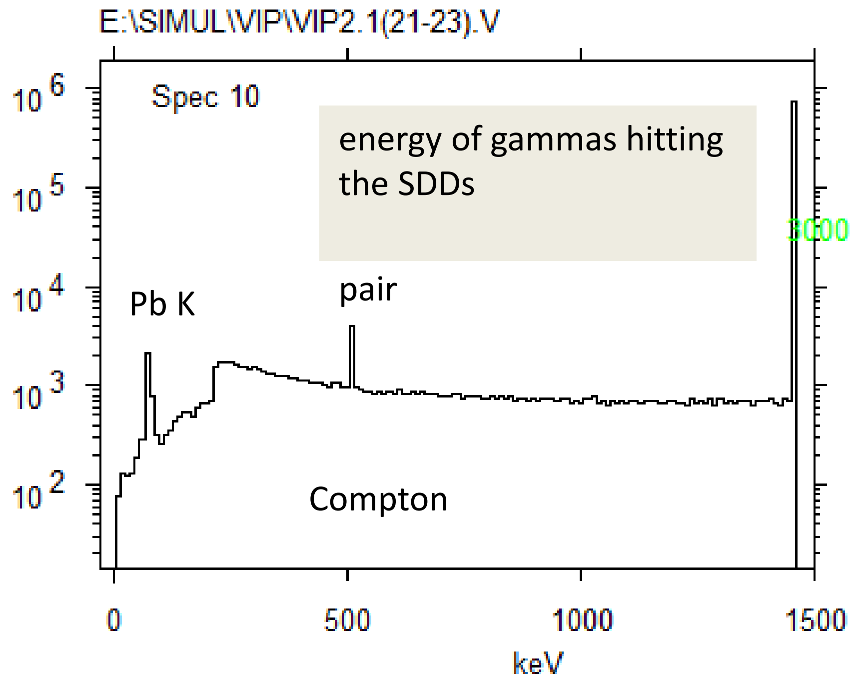
7.1.1. ^{40}K Potassium is a main source of the background gamma radiation. The lifetime of radioactive isotope ^{40}K is comparable to that of uranium and thorium at 1.*277×10⁹ y. The decay chain of* ^{40}K *is far less complex; 89.3% of the time it undergoes* a beta decay to the stable state of ^{40}Ca. However, 10.7% of the time the isotope undergoes electron-capture to form ^{40}Ar, and emits a 1460.8 keV photon from the 2^+-to-0^+ transition. The abundance of ^{40}K in natural potassium is 0.0117%, which means that for example ^{nat}KCl *has a specific gamma activity of nearly 1.5*× 10^7 Bq/kg. Potassium normally occurs in rock and concrete as K_2O and K_2CO_3, which are present at the ∼1% level. Salt mines, however, may contain veins of KCl, which must be avoided in siting laboratories.

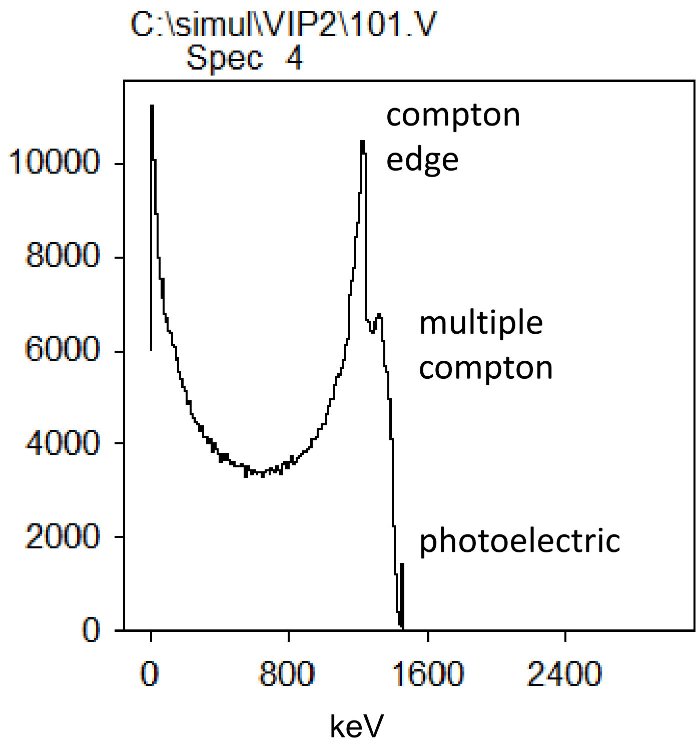
7.1.2. URANIUM AND THORIUM The presence of ^{238}U, ^{235}U, and ^{232}Th often poses a difficult challenge to experiments. These isotopes not only occur widely in the surrounding underground environment but also contribute to a wide variety of background types, mainly high-energy gamma rays, neutrons, and alpha particles. Figures 10 and 11 illustrate the decay chains for ^{238}U and ^{232}Th, respectively. After a series of alpha and beta decays, these decay chains eventually produce the stable lead isotopes ^{206}Pb and ^{208}Pb (133).
High-energy photons are produced by gamma de-excitation in the primordial alpha emitters' decay sequences. Of particular concern are the decays of ^{208}Tl (from the thorium chain) and ^{214}Bi (from the uranium chain). Thirty-six percent of the time, ^{212}Bi alpha-decays to ^{208}Tl, which then emits a 2.614 MeV gamma ray almost 100% of the time. Similarly, ^{214}Pb beta-decays to ^{214}Bi, which emits a 2.204 MeV photon 4.99% of the time and a 2.447 MeV photon 1.55% of the time. Such high-energy photons constitute serious backgrounds for almost all low-energy experiments (dark matter, neutrinoless double beta decay, and solar), unless proper shielding and purification methods are applied.

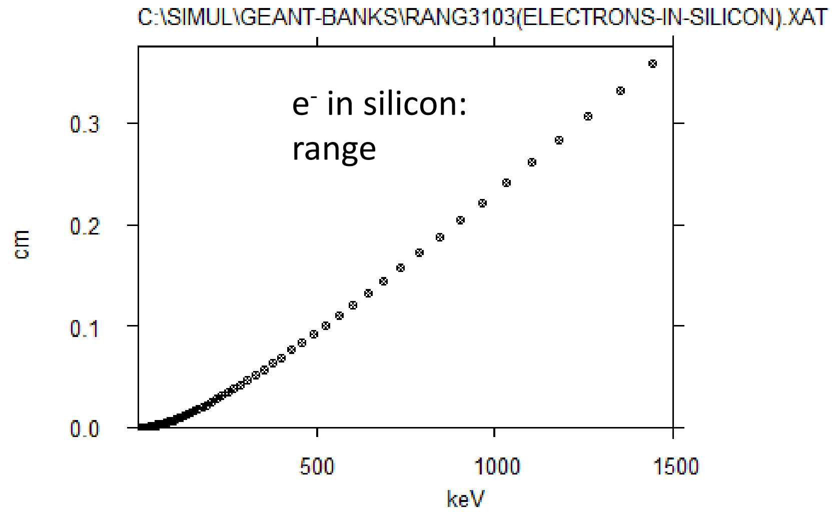
The radiation field in this simulation is from 1.46 MeV gammas (environmental radioactivity K-40 (EC) Ar-40) generated uniformly in a 30x30x30 cm^3 box and with isotropic directions. This approximates contaminations in setup materials (Pb, SDDs, ceramics, electronics, ...)

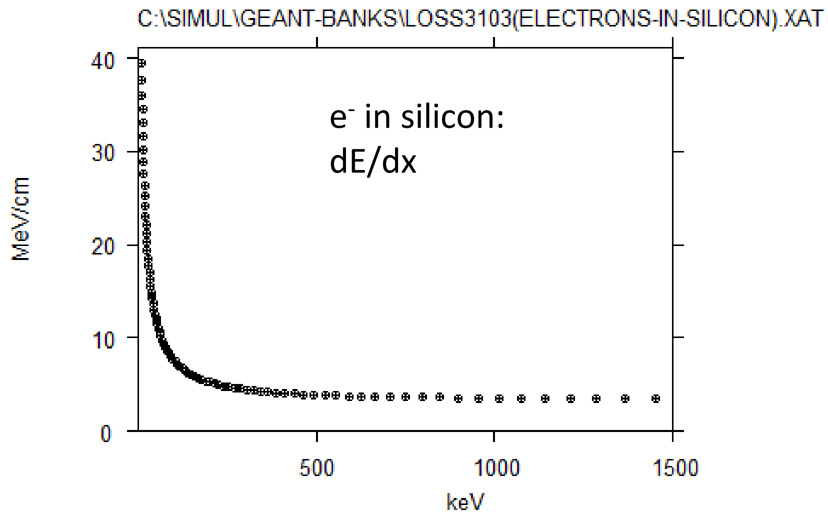




deposited energy in the scintillators
for 1.46 MeV gammas







Real data (no lead shielding) for 81 d 10 h (81.42 d) *for 6 cm^2*

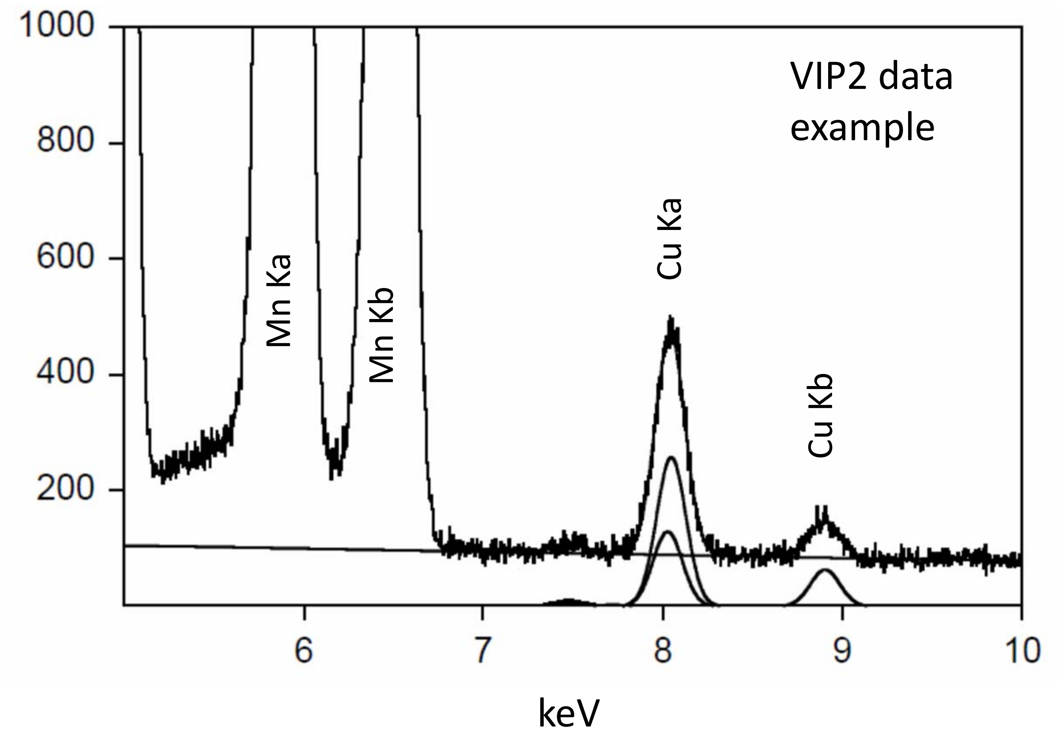
sum 7-7.5 keV = 10.425 sum 8.25-8.75 keV= 9.918

cont. bkg in 1 keV at ROI = 10.425 + 9.918 – 835(Ni Ka) = 19.569 events /keV => **240.4 /keV /d**

Cu Ka: 18.814 events **=> 231.1 /d** Ka+Kb: 22.041 **=> 270.7 /d**

Monte Carlo simulation

cont. bkg at ROI: ~ 340 / keV /d Cu fluorescence : ~ 1000 /d



passive shielding essential.
additional active shielding can reduce BG by ~ 50%