

Material screening for rare event search

Stefano Nisi
Lorenzo Pagnanini

Material screening: why?

Rare event experiments aim to discover new phenomena, producing **O(10) events** in **O(10 yr)** of data taking.

Since very low cross sections are involved (neutrino / dark matter), or a very long half-life (neutrinoless double beta decay), we need **tonne-scale detectors**.

Moreover, such detectors demand for **massive shieldings** against external background:

γ -radiation => Lead + Copper

neutrons => Polyethylene (Borated) / Water Tank

muons => Active Veto (e.g. Plastic Scintillators)

Detector + Shieldings = huge amount of different materials (active or passive)

What's happen if do not select those materias?

Material screening: why?

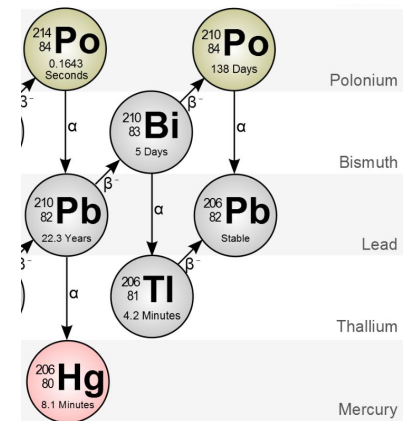
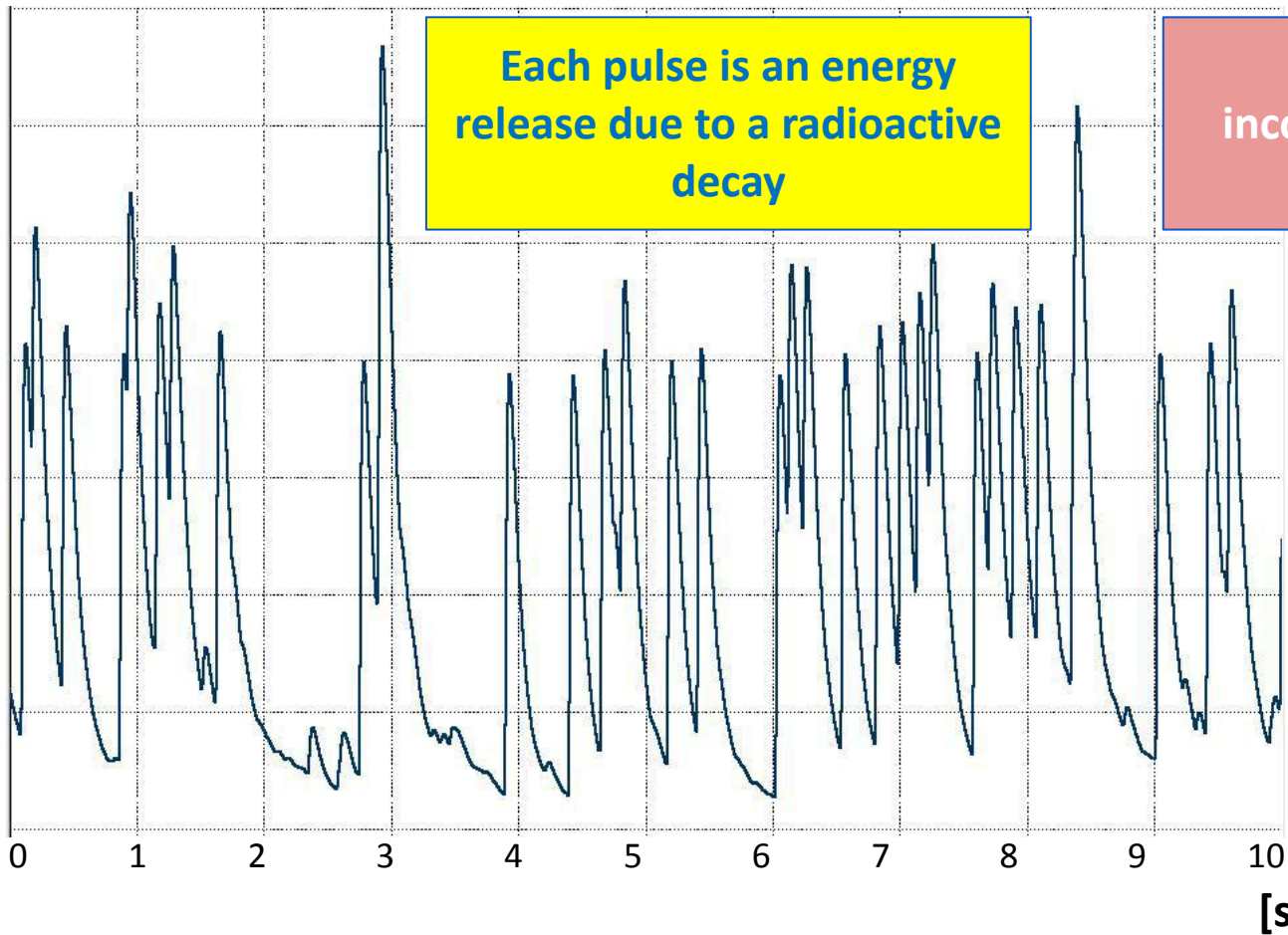
Commercial crystal

Data stream of a 1 cm^3 lead tungstate (PbWO_4) cryogenic calorimeter!!

1 V/div

Each pulse is an energy release due to a radioactive decay

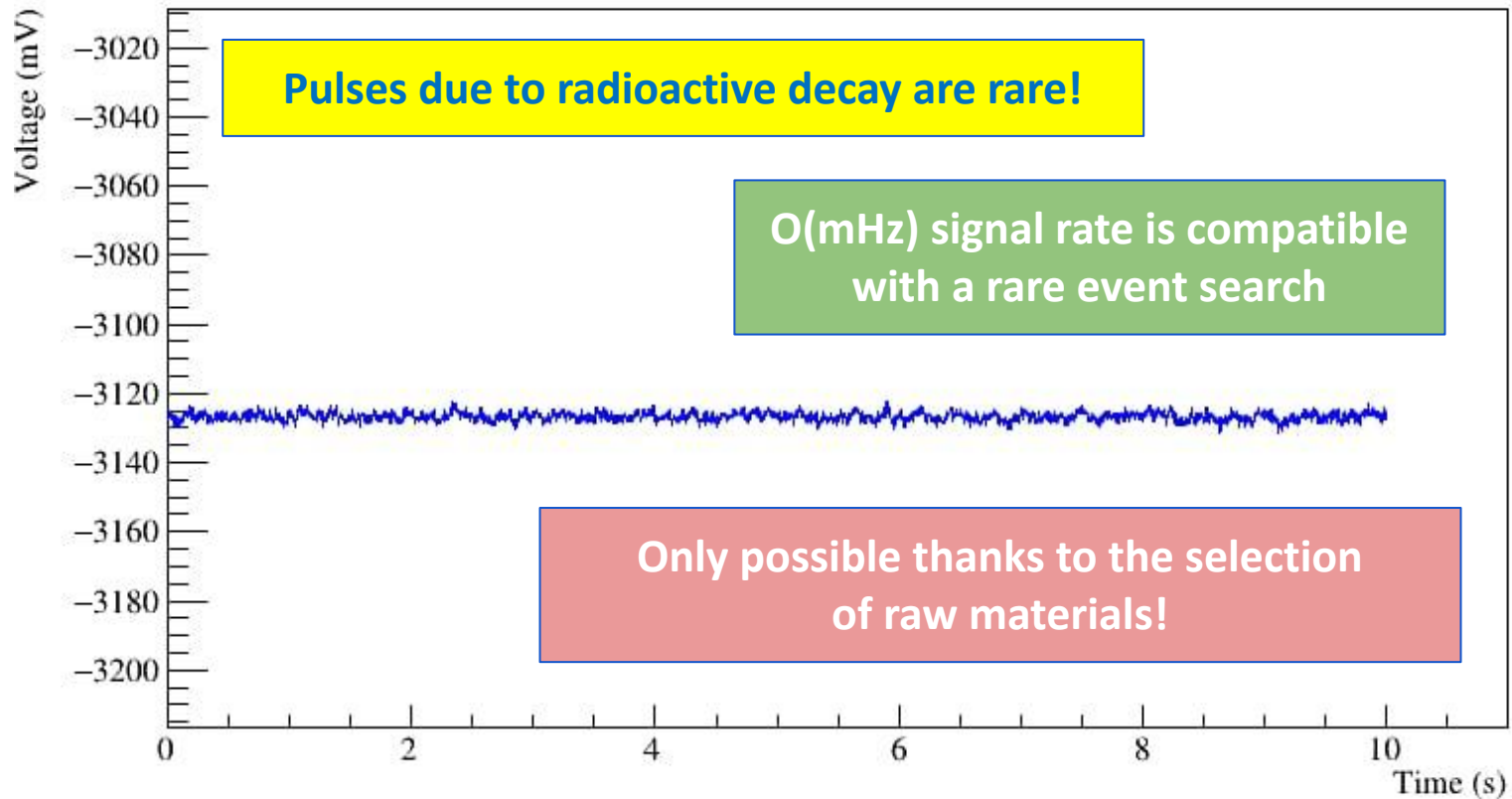
3 Hz trigger rate is incompatible with a rare event search



Material screening: why?

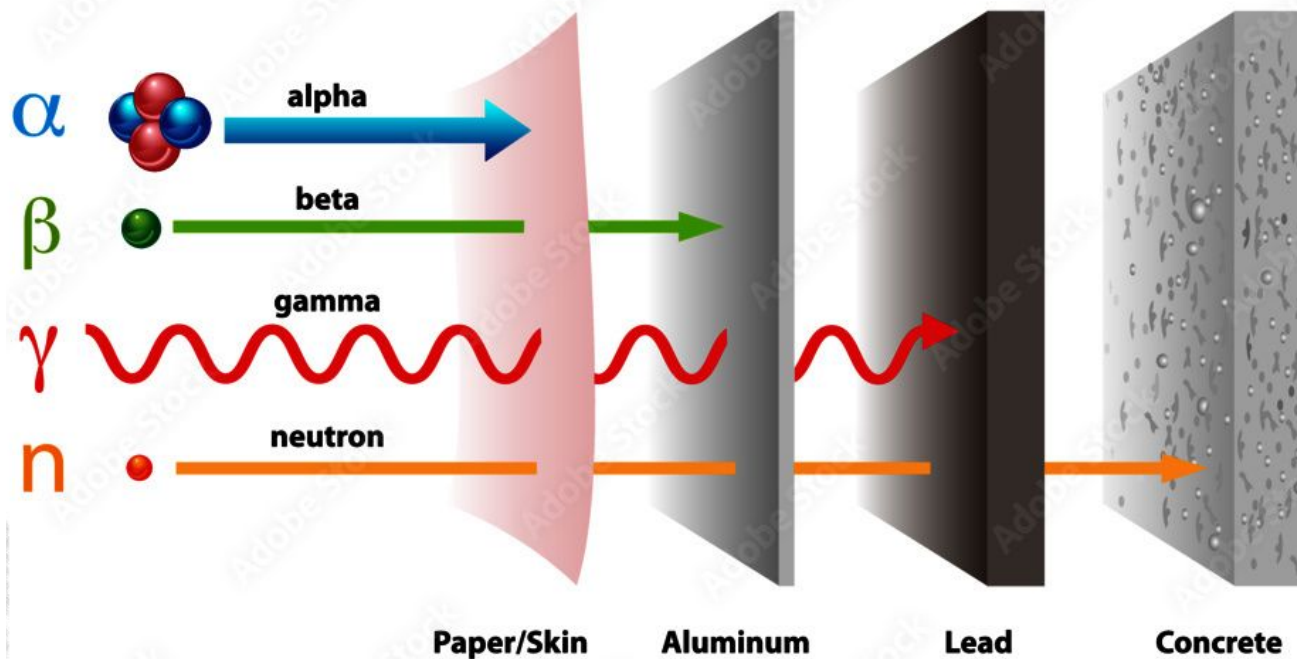
Crystal from selected materials

Data stream of a **100 cm³ selected** lead tungstate (PbWO_4) cryogenic calorimeter!!



Material screening: why?

The closer the material is, the cleaner it must be...not only due to the solid angle!



Materials **near** the detector produce α , β , and γ background.
Materials **far** from the detector produce “only” γ background.

Material screening: how?

To characterize the contamination in a sample there are, at least, two ways

Concentration measurement

$$N(t) = N_0 e^{-t/\tau}$$



Atom counting

Activity measurement

$$A(t) = A_0 e^{-t/\tau} = N_0/\tau e^{-t/\tau}$$



Decay counting

The choice between the two are directly connected with:

1. the decay constant (mean life) of the isotope
2. the sensitivity of the instrumentation
3. the measurement time

The characterization of materials is connected with the **specific activity** measurement

$$A_s = A/\text{Mass}$$

$$[A_s] \equiv [\text{Bq/kg}]$$

Concentration vs Activity

Relation between **Bq/kg** and **g/g** for a selected isotope

Mean life τ [sec] Molar mass m_m [g]

$$1 \frac{\text{Bq}}{\text{kg}} = \frac{\tau [\text{sec}]}{N_A} \frac{m_m [\text{g}]}{1000} \frac{\text{g}}{\text{g}}$$

Natural isotopes

^{232}Th 1 Bq/kg $\equiv 2.4 \cdot 10^{-7}$ g/g = 240 ppb

^{238}U 1 Bq/kg $\equiv 8.3 \cdot 10^{-8}$ g/g = 83 ppb

^{40}K 1 Bq/kg $\equiv 3.9 \cdot 10^{-9}$ g/g

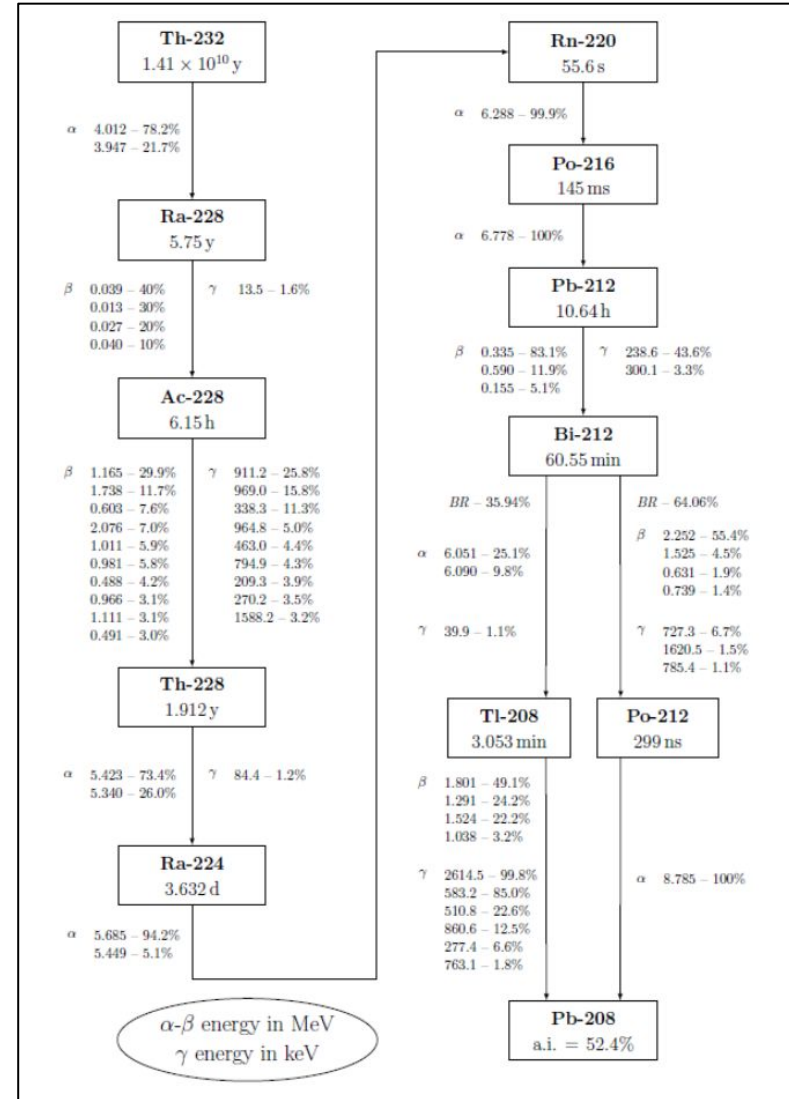
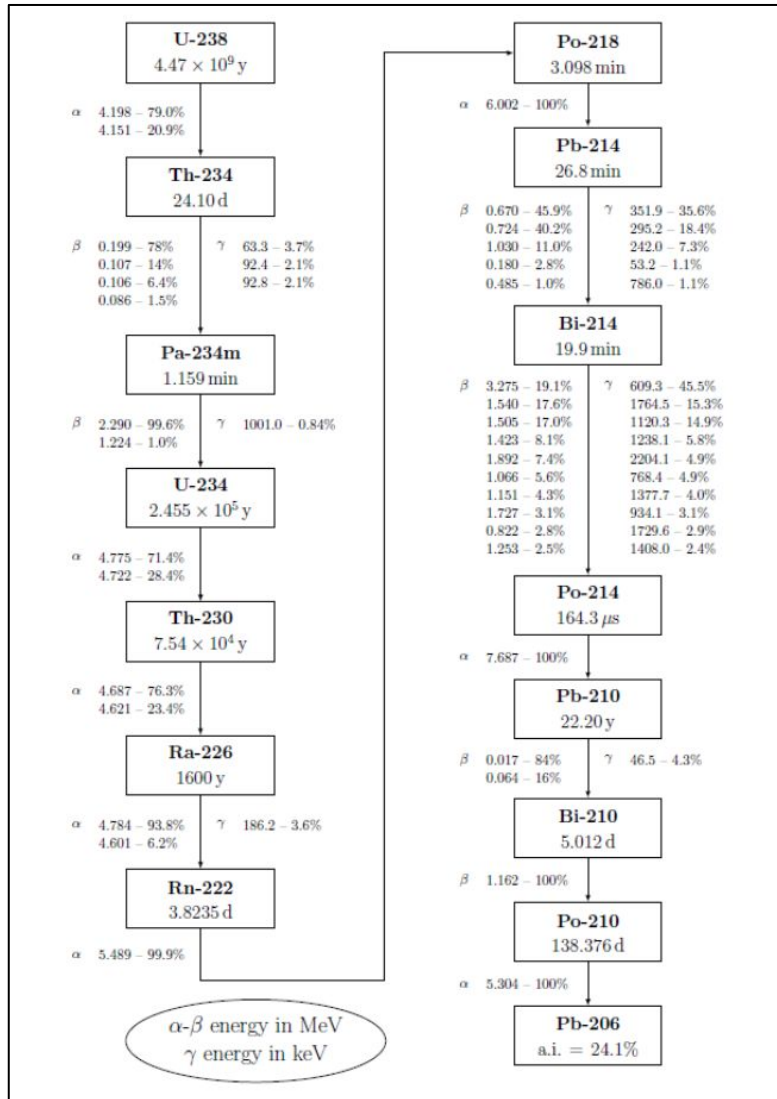
Anthropogenic isotopes

^{60}Co 1 Bq/kg $\equiv 2.4 \cdot 10^{-17}$ g/g

^{137}Cs 1 Bq/kg $\equiv 3.1 \cdot 10^{-16}$ g/g

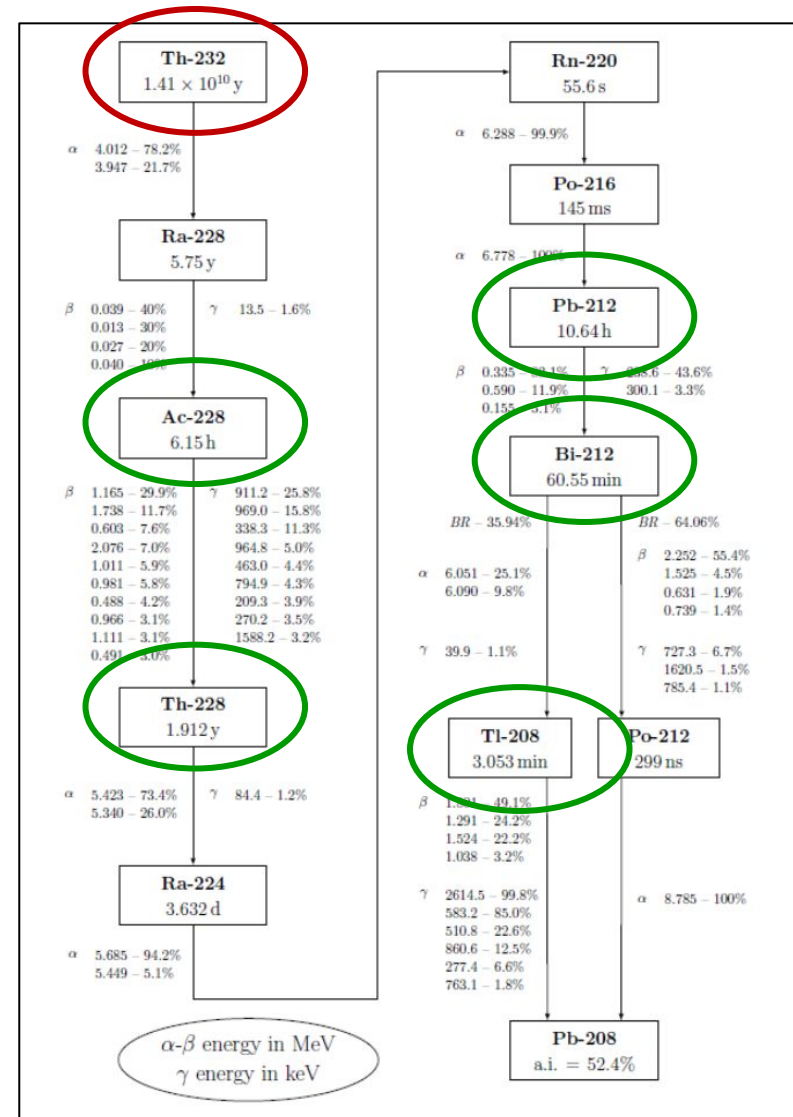
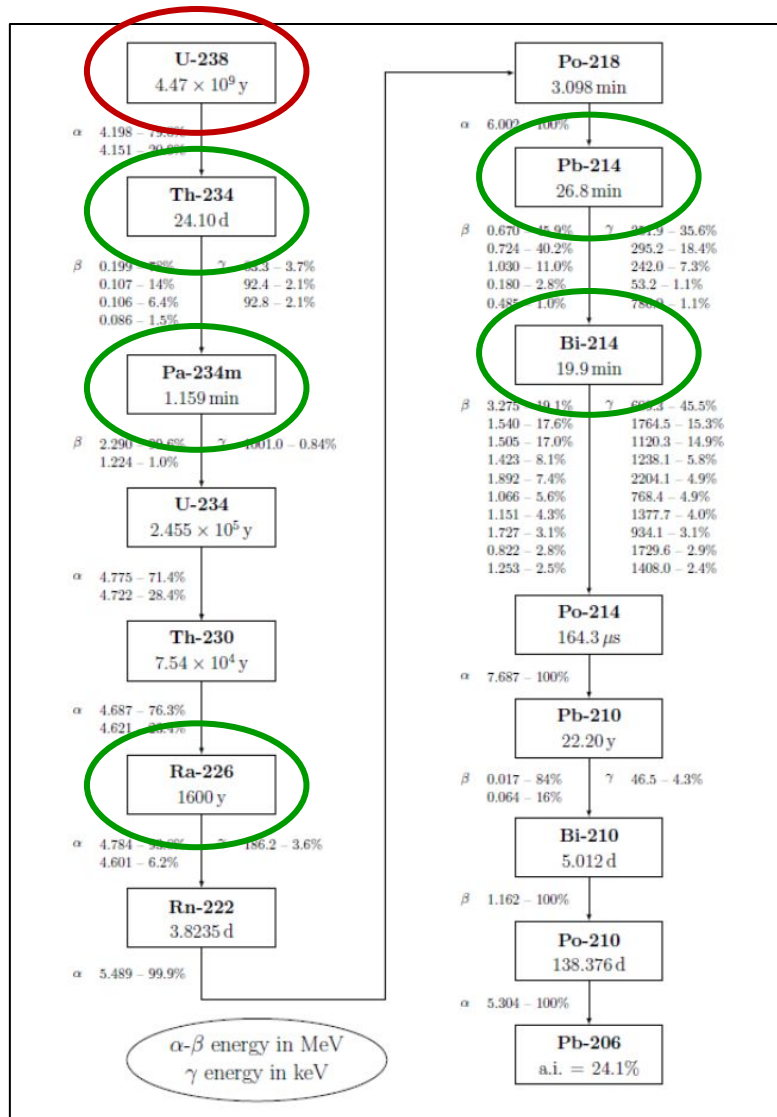
^{239}Pu 1 Bq/kg $\equiv 4.4 \cdot 10^{-13}$ g/g

Uranium and thorium decay chains



Uranium and thorium decay chains

Activity



Current sensitivity of different techniques

method	suited for	sensitivity for U/Th
Ge-spectroscopy*	γ emitting nuclides	10-100 $\mu\text{Bq/kg}$
Rn emanation assay	^{226}Ra , ^{228}Th	0.1-10 $\mu\text{Bq/kg}$
Neutron activation	primordial parents	0.01 $\mu\text{Bq/kg}$
Liquid scintillation counting	α, β emitting nuclides	1 mBq/kg
Mass spectrometry (ICP-MS; A-MS)	primordial parents	0.01 $\mu\text{Bq/kg}$
Alpha spectroscopy	^{210}Po , α emitting nuclides	0.1 $\mu\text{Bq/cm}^2$

* needs counting time of several weeks to month

only Ge-spectroscopy with its high energy resolution is able to control equilibrium breaking

see e.g.: Borexino Collaboration, Arpesella, C. et al., Measurements of extremely low radioactivity levels in Borexino, *Astrop. Phys.* 18 (2002) 1-25

Some specific considerations

We will focalize our attention on two very powerful analytical methods

Concentration

Activity

HR ICP-MS

- Liquids/dissolved Solids
- Sensitivity to primordial isotopes
- Small amount of material (< 1 g)
- Short running time (days)
- Techniques under fast evolution

Neutron Activation

- Solids and Liquids
- Sensitivity to primordial isotopes
- Moderate amount of material (tens of g)
- Medium running time, few weeks
- Technique under development for low level contaminations

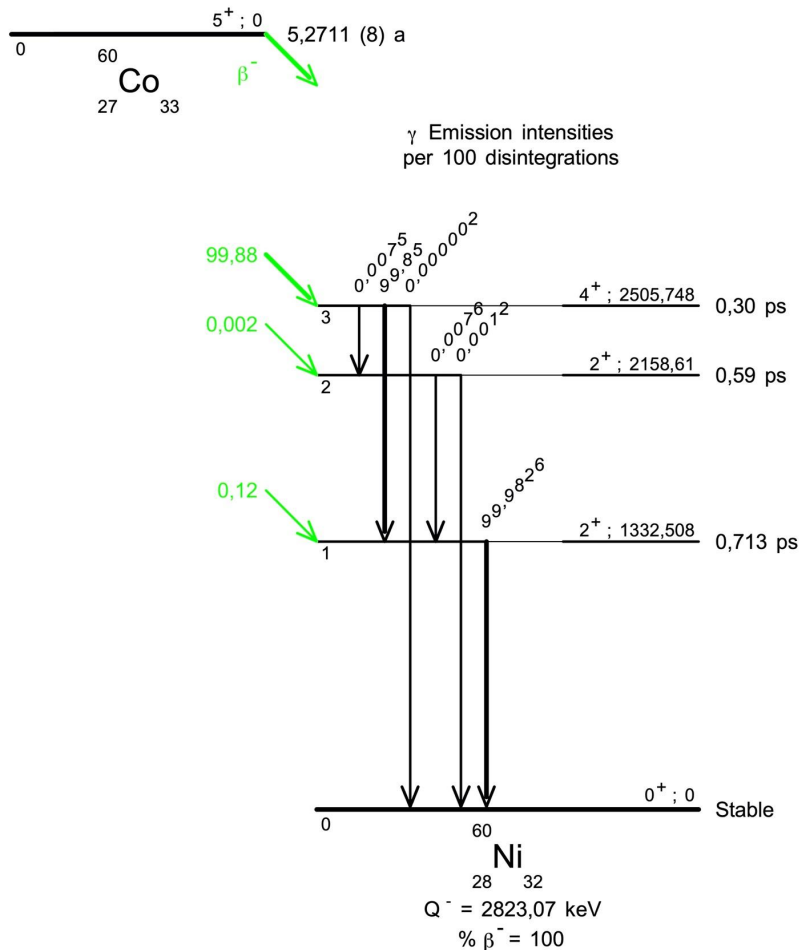
Gamma Spectroscopy

- Solids and Liquids
- Sensible to gamma emitters
- **Few kilograms of material**
- Long running time measurement many weeks/months
- Well established technique

Alpha Spectroscopy

- Suitable only surface analysis
- **Sensitivity to whole radioactive chains**
- **Small amount of material, < 1 g**
- Long running time, months
- Techniques with some specific applications

Gamma Ray Spectroscopy



The emission of gamma rays from nuclei is normally associated with an α or β decays and it is due to the nuclear level structure.

Since the emission is normally immediate (on the scale of psec), detection of gamma rays can be directly connected with the previous decay.

Gamma rays features:

- Well defined energy
- Characteristic of the decay
- Sometime cascades are present
- Ratio respect to decay (BR) is well established

Specific activity determination

To determine the specific activity for an unknown source with gamma ray spectroscopy

$$A_{Sp} \left[\frac{Bq}{kg} \right] = \frac{Counts_{source} - Counts_{Background}}{M_S t_{meas} BR \epsilon}$$

- **Counts_{Source}** are the total counts collected during the measurement with the source
- **Counts_{Background}** are the total counts collected during the background measurement
- **M_S** is the mass of the sample
- **t_{meas}** is the total live time of the measurement (i.e. real_time - dead_time)
- **BR** is the branching ratio of the decay
- **ε** is the efficiency of the measurement apparatus (Monte Carlo)

To strongly increase the sensitivity it is necessary

- Reduce **Counts_{Background}**
- Increase **M_S t_{meas} ε**



But...

Specific activity determination

There are some correlation between parameters:

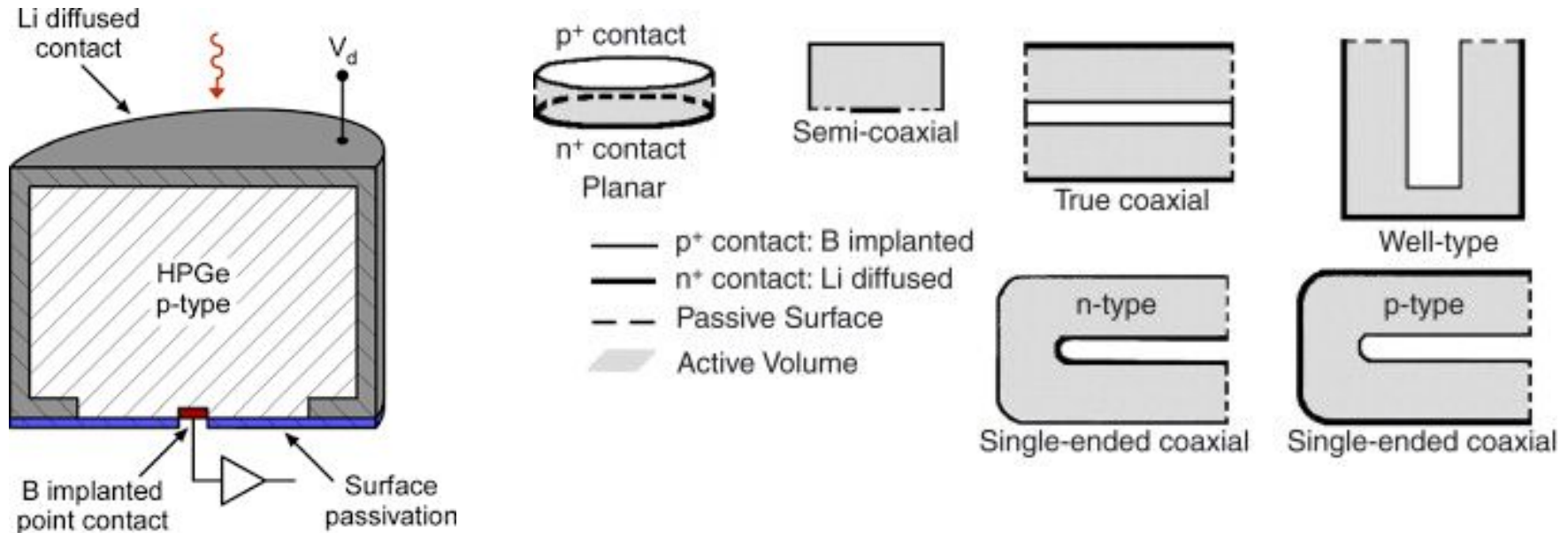
- $M_s \uparrow \Rightarrow \epsilon \downarrow$
- $t_{\text{meas}} \uparrow \Rightarrow \text{Counts}_{\text{Background}} \uparrow$

We can conclude that it is mandatory:

- **reduce the radioactive background**
 - selecting radio-pure detector compounds
 - shielding the detector (the mountains are also worth it)
 - vetoing muons if aboveground
- **maximize of the product $M_s \epsilon$**
 - optimizing also sample shape and position
 - exploiting Monte Carlo simulations and experience

The first important issue to be addressed is the background reduction

High purity Germanium Detectors

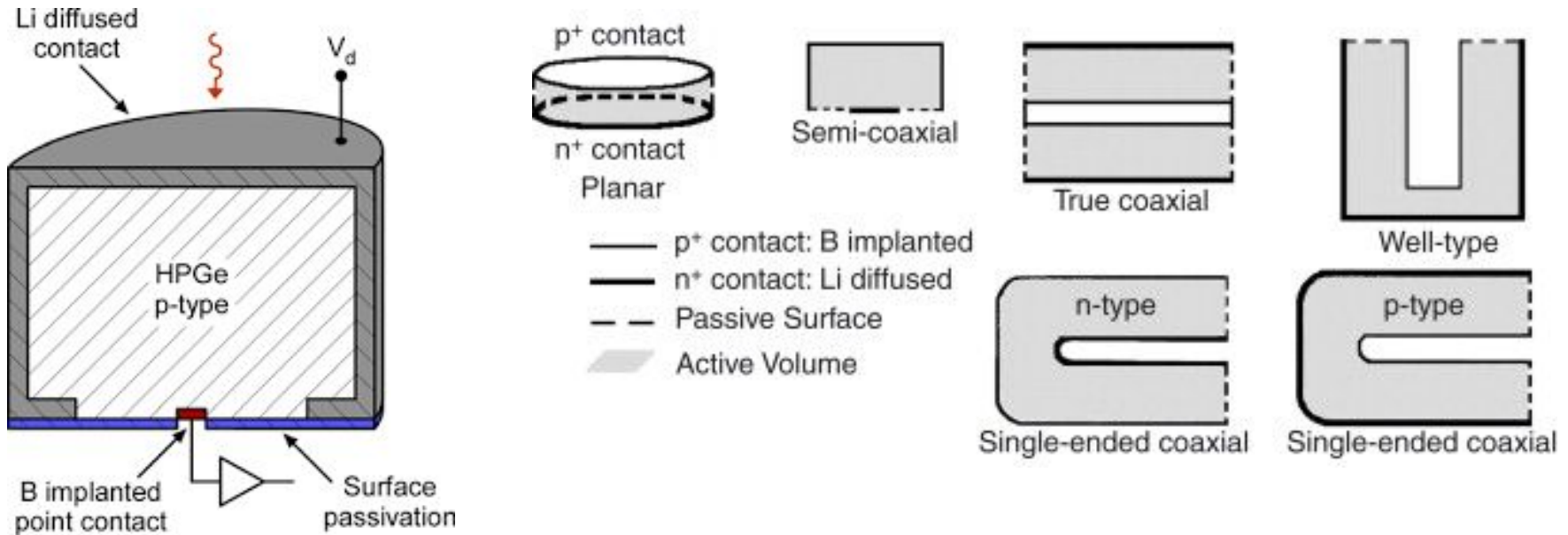


The long story short:

- **p-n junction operated as diode** (reverse bias) with a uniform electric field (High Voltage)
- a photon interacting in the depletion zone produces **a current proportional to the energy**
- due to the small $E_{\text{gap}} = 0.7 \text{ eV}$ the **thermal excitations** produce a leakage current (I_d)
- we have to operate the detector **nitrogen temperature (77 K)**

$$I_d(T) \propto T^2 \exp\left[-\frac{E_{\text{gap}}}{2k_B T}\right] \Rightarrow \frac{I_d(T_2)}{I_d(T_1)} = \left(\frac{T_2}{T_1}\right)^2 \exp\left[-\frac{E_{\text{gap}}}{2k_B} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]$$

High purity Germanium Detectors



Pros:

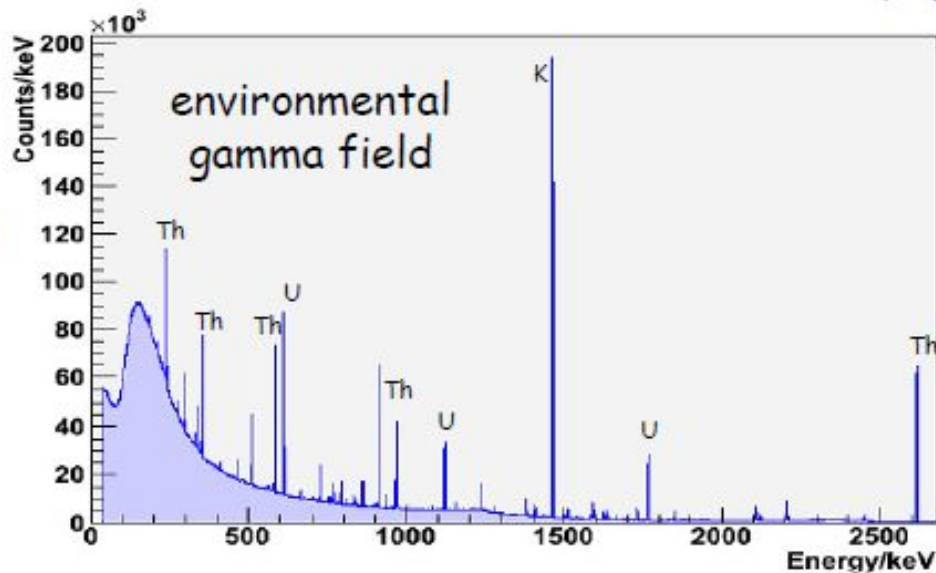
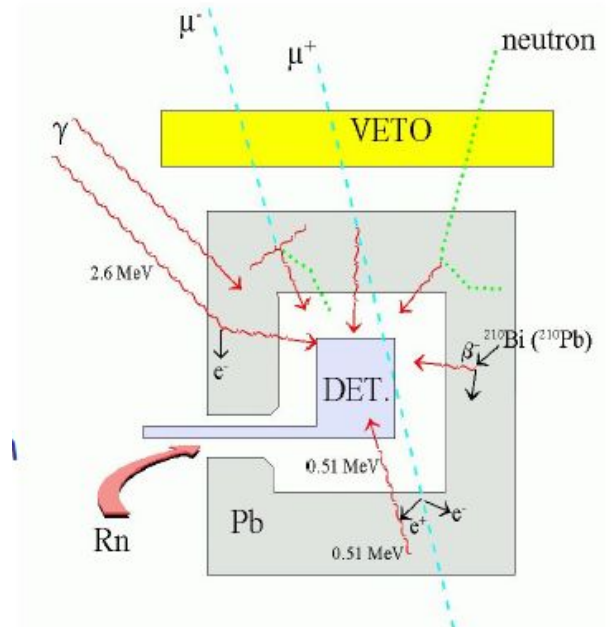
- large active volume (hundreds cm³)
- very high energy resolution (2 keV at 1332 keV)
- fast signals
- intrinsic radiopurity
- pulse shape discrimination

Cons:

- low detection efficiency
- quite expensive

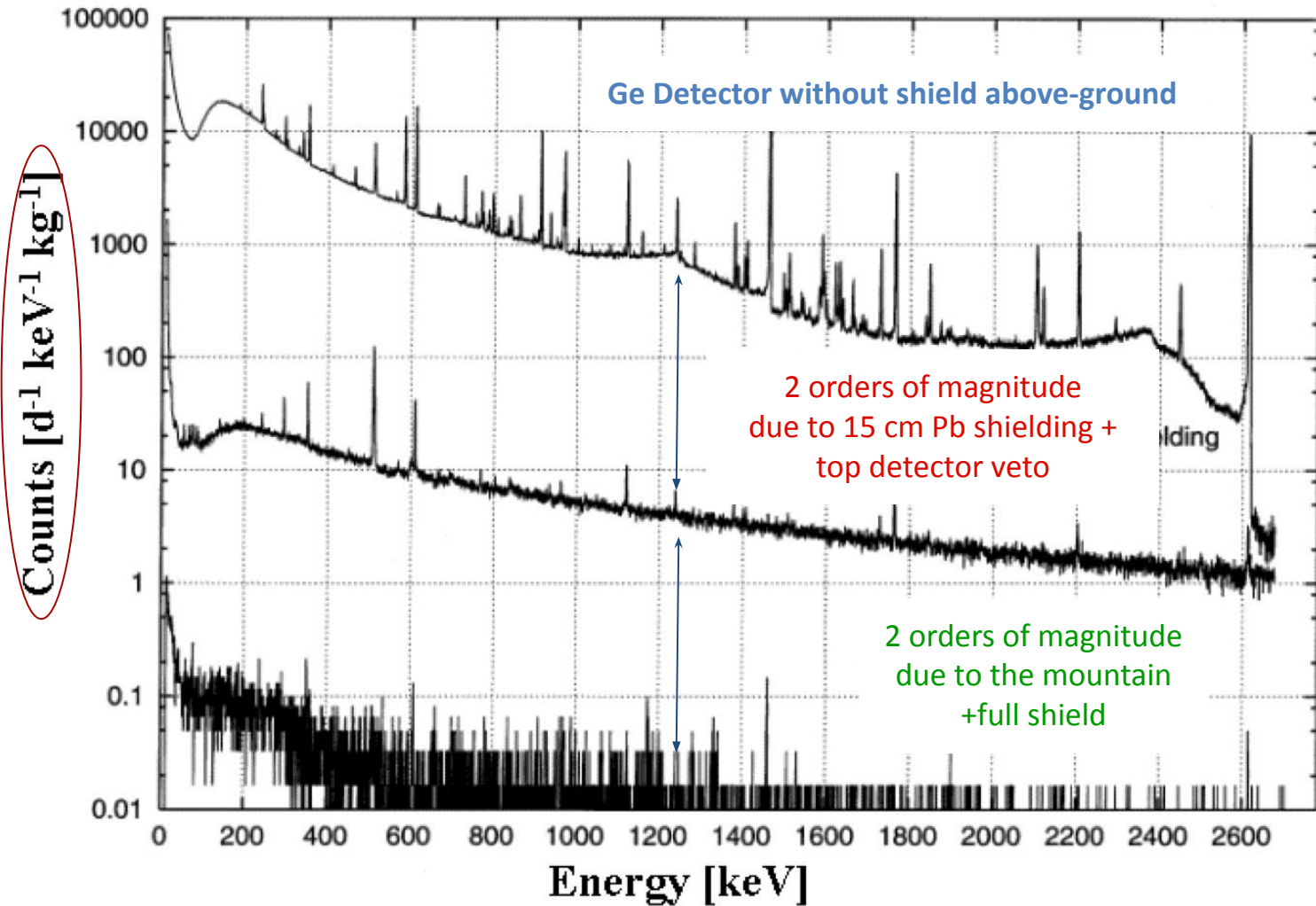
Background sources in HPGe measurements

1. **Environmental radioactivity**
2. **Contaminants in detector** and shield material:
 - a. primordial, anthropogenic, cosmogenic
3. **Radon and its progenies**
4. Cosmic rays secondaries:
 - a. muons
 - b. neutrons
5. Neutrons from natural fission and (α, n) reactions

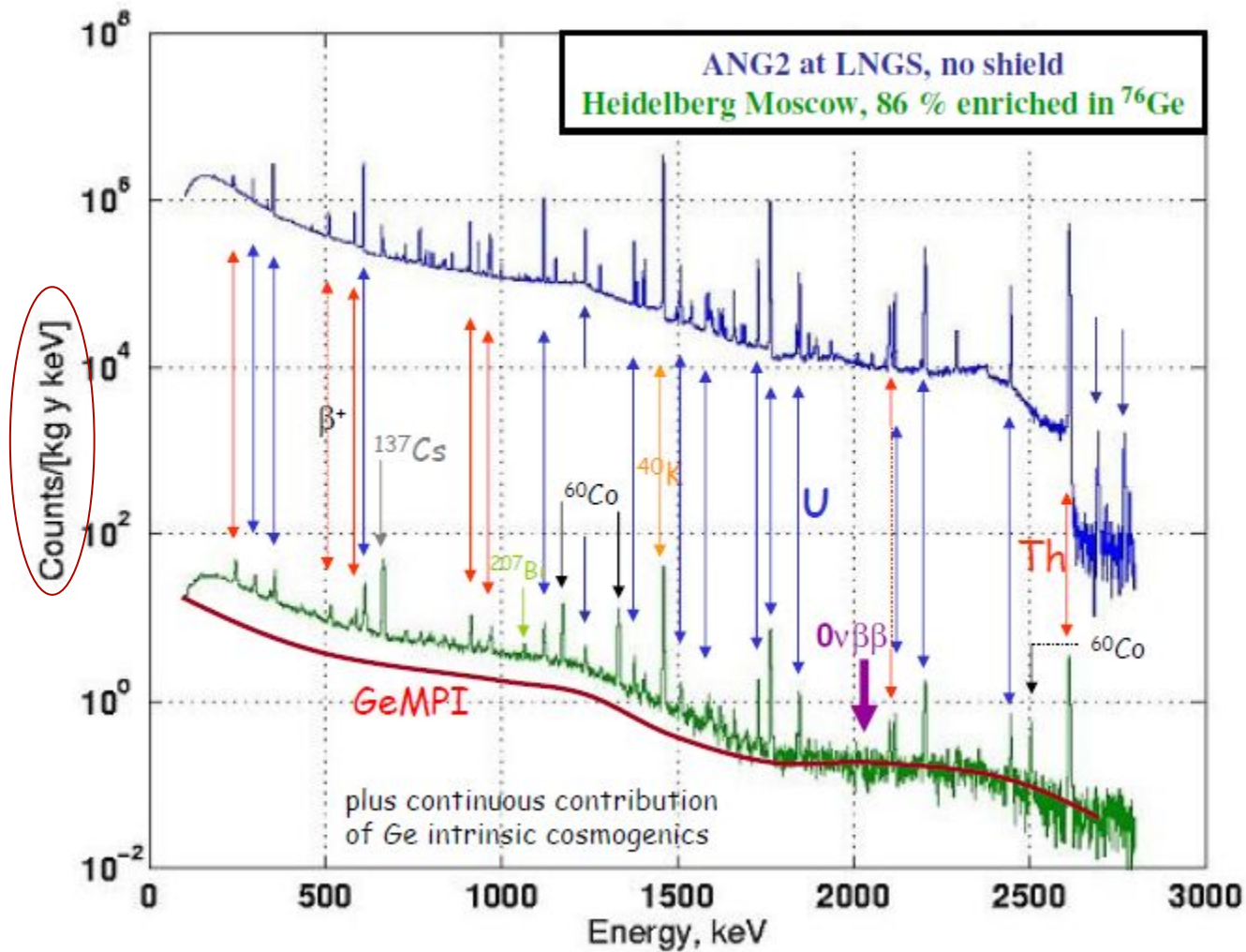


	concentration [Bq/kg]		
rock	^{238}U	^{232}Th	^{40}K
granite	60	80	1000
limestone	30	7	90

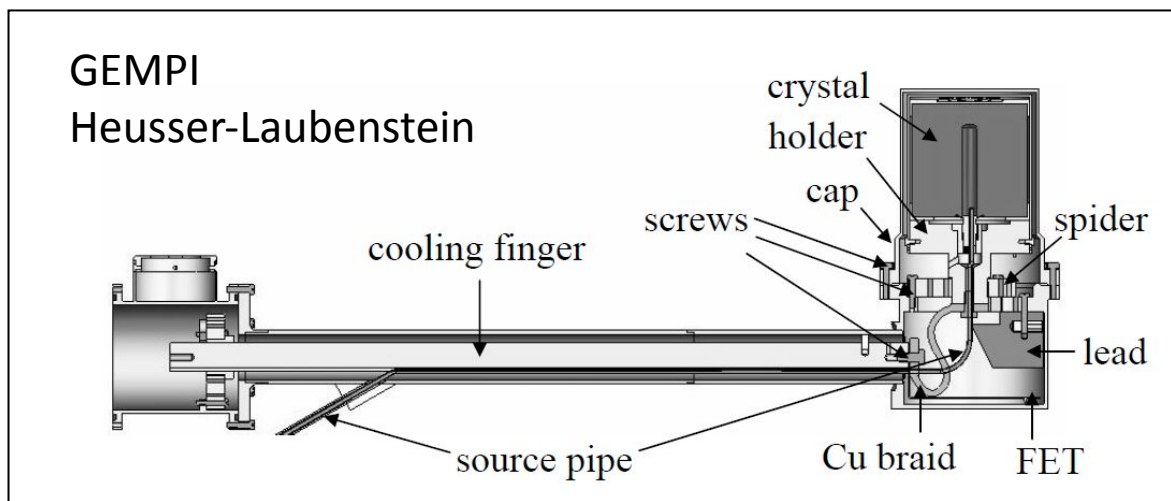
1. Environmental background



1. Environmental background



2. Contaminants in detector and shield materials



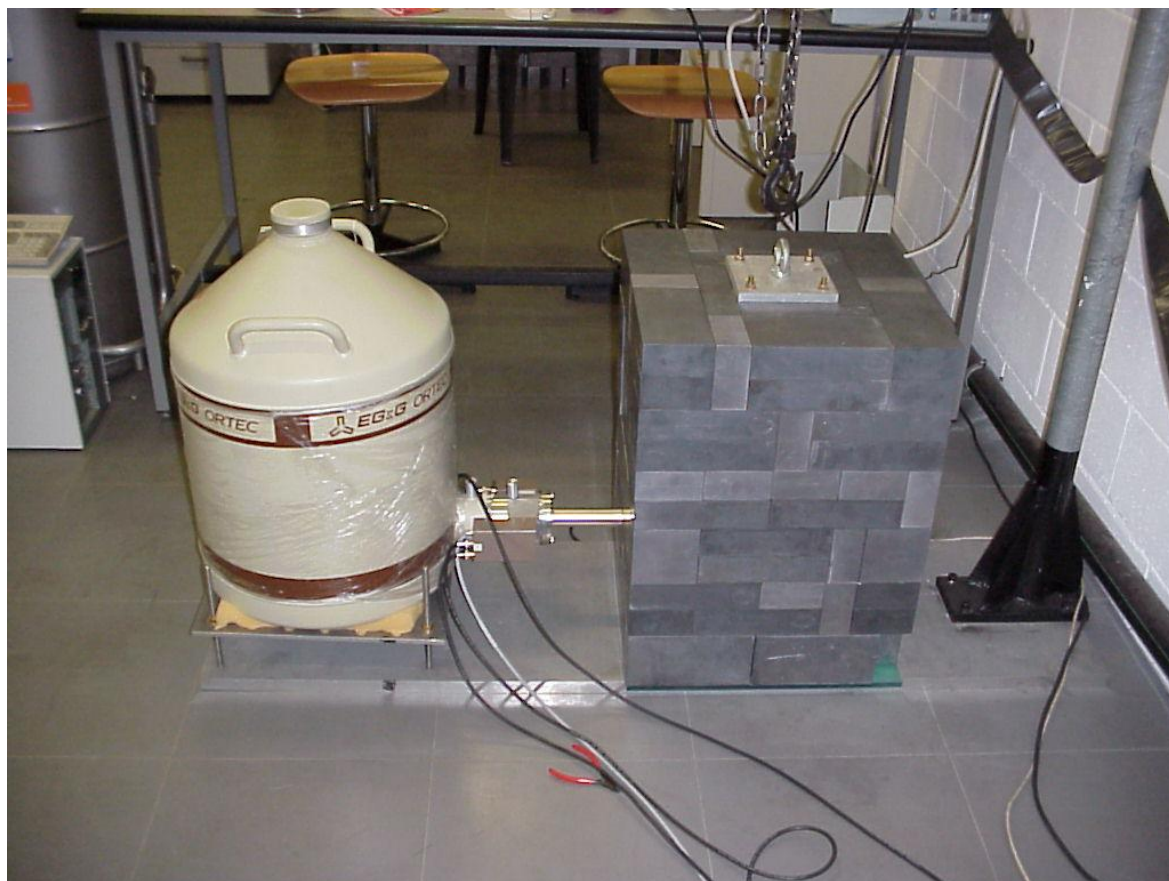
All possible radioactive materials must be avoided or shielded
Front end electronics must be put “far away” to Ge crystal

Very pure copper is normally used to built many cryostat and shielding parts (e.g. end cap)

Location	Purity Issue	Exposure	Activation Rate	Equiv. Achieved Assay	Reference
Germanium	^{68}Ge , ^{60}Co	100 d	1 atom/kg/day		[Avi92]
		Component Mass	Target Purity		
Inner Mount	^{208}Tl in Cu ^{214}Bi in Cu	2 kg	0.3 $\mu\text{Bq/kg}$ 1.0 $\mu\text{Bq/kg}$	0.7-1.3 $\mu\text{Bq/kg}$	Current work also [Arp02]
Cryostat	^{210}Tl in Cu ^{214}Bi in Cu	38 kg	0.1 $\mu\text{Bq/kg}$ 0.3 $\mu\text{Bq/kg}$	0.7-1.3 $\mu\text{Bq/kg}$	Current work also [Arp02]
Cu Shield	^{208}Tl in Cu ^{214}Bi in Cu	310 kg	0.1 $\mu\text{Bq/kg}$ 0.3 $\mu\text{Bq/kg}$	0.7-1.3 $\mu\text{Bq/kg}$	Current work also [Arp02]
Small Parts	^{208}Tl in Cu ^{214}Bi in Cu	1 g/crystal	30 $\mu\text{Bq/kg}$ 100 $\mu\text{Bq/kg}$	1000 $\mu\text{Bq/kg}$	

ICP MS

2. Contaminants in detector and shield materials



We have to “protect” our detector from the radioactivity component present in the environment of the laboratory

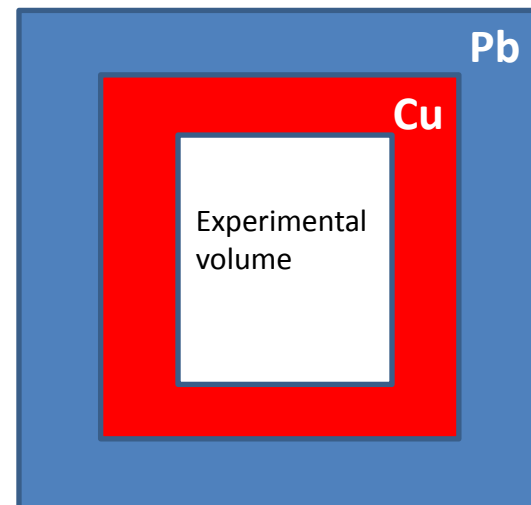
To reduce the gamma ray flux on the detector that comes from the environment a lead shield is installed

Why we use lead?

2. Contaminants in detector and shield materials

material	activity [$\mu\text{Bq/kg}$]				E-6 attenuation of 2.61 MeV γ
	^{226}Ra (U)	^{228}Th (Th)	^{40}K	various	
lead	$\leq 29^{\text{a)}$	$\leq 22^{\text{a)}$	$270^{\text{a)}$	$\leq 4 \text{ E}3 \text{ }^{210}\text{Pb}^{\text{b)}$	28.5 cm
copper	$\leq 16^{\text{a)}$	$9^{\text{c)}$ $\leq 19^{\text{a)}$	$\leq 88^{\text{a)}$	$\leq 10 \text{ }^{60}\text{Co}^{\text{a)}$	40.9 cm
steel	$130^{\text{a)}$	$\leq 40^{\text{a)}$	$50^{\text{a)}$	$140 \text{ }^{60}\text{Co}^{\text{a)}$	46.2 cm
water	$\leq 1^*$	$0.04^{\text{d)}$ $0.008^{\text{e)}$	$\leq 2^{\text{d)}$		324 cm
liq. sc. (PC)	10^{-6 f)	$\leq 10^{-6 \text{ f)}$	$\leq 0.001^{\text{f)}$		373 cm
liq. nitrogen	$\leq 0.3^*$		$10^{-3 \text{ }^{39}\text{Ar}^{\text{g)}$ $0.04 \text{ }^{85}\text{Kr}^{\text{g)}$		443 cm
liq. argon	600^*		$10^6 \text{ }^{39}\text{Ar}^{\text{h)}$		276 cm
liq. xenon			$1 \text{ }^{85}\text{Kr}^{\text{i)}$		120 cm

Typical material for HPGe Detectors shielding

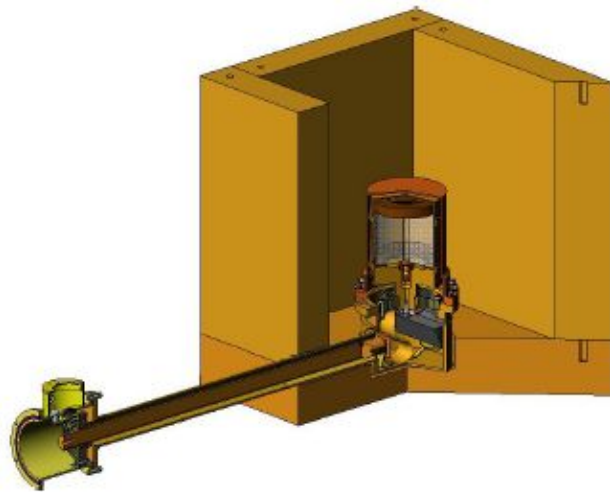


^{a)} GeMPI; ^{b)} bolometric Milano; ^{c)} Ge PNNL; ^{d)} ^{232}Th by ICP-MS Ispra;
^{e)} ^{232}Th by NAA TU München; ^{f)} $^{226}\text{Ra} + ^{228}\text{Th}$ by Bi-Po Borexino;
^{*} ^{222}Rn MPI-K; ^{g)} Rare Gas MS MPI-K ^{h)} PC Bern, WARP; ⁱ⁾ XMASS

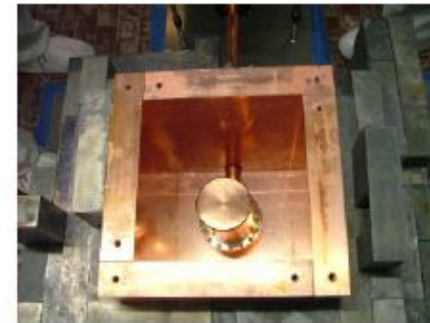
2. Contaminants in detector and shield materials

GeMPI

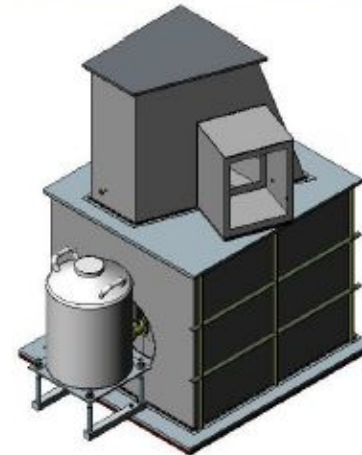
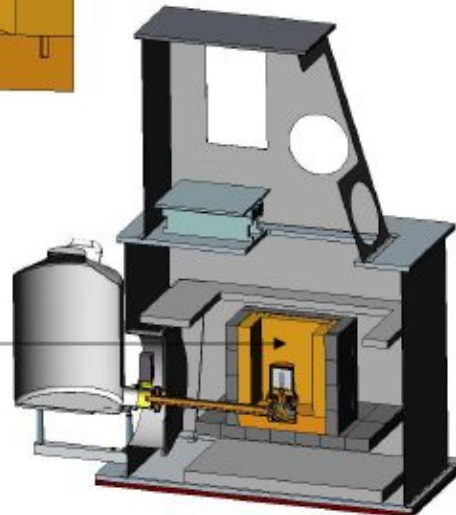
Ge spectrometer of MPI-K
at LNGS since 1997
(still state of the art)



High purity copper
directly placed
underground after
electrolysis



15 l sample chamber
holds e.g. 125 kg Cu
or 157 kg Pb



2. Contaminants in detector and shield materials

The ultimate background in HPGe is due to bremsstrahlung produced from the electrons emitted in the ^{210}Bi decay.

Archaeological Lead is a possible solution.

lead sample	weight [kg]	time [d]	specific activity [$\mu\text{Bq/kg}$]				
			^{226}Ra	^{228}Th	^{40}K	^{207}Bi	^{210}Pb
DowRun	144.6	101.7	< 29	< 22	440 ± 140	98 ± 24	$(2.7 \pm 0.4) \times 10^7$
Boliden	144.3	75.0	< 46	< 31	460 ± 170	< 13	$(2.3 \pm 0.4) \times 10^7$
roman	22.1	37.2	< 45	< 72	< 270	< 19	$< 1.3 \times 10^6$
	bolometric measurement: Allesandrello et al. NIM B142 (1998) 163						$< 4 \times 10^3$

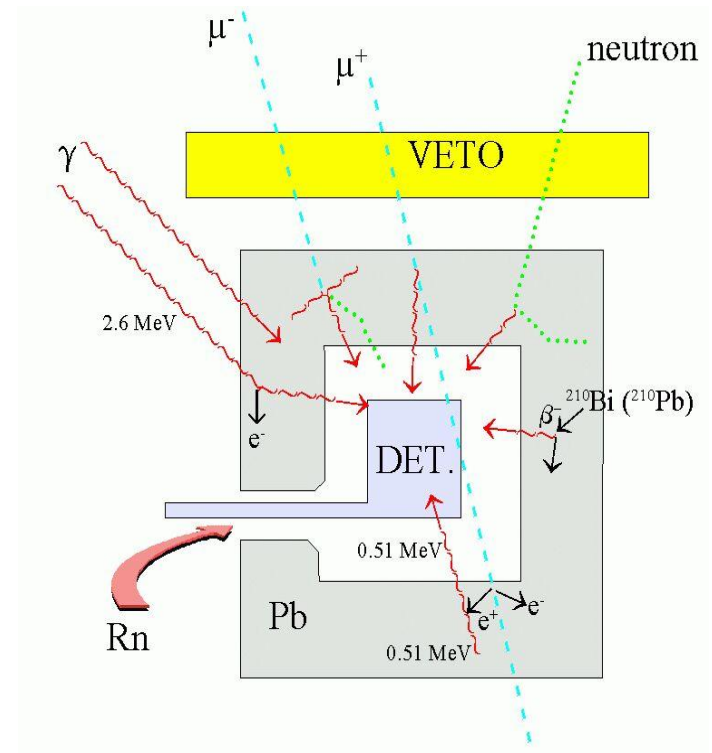
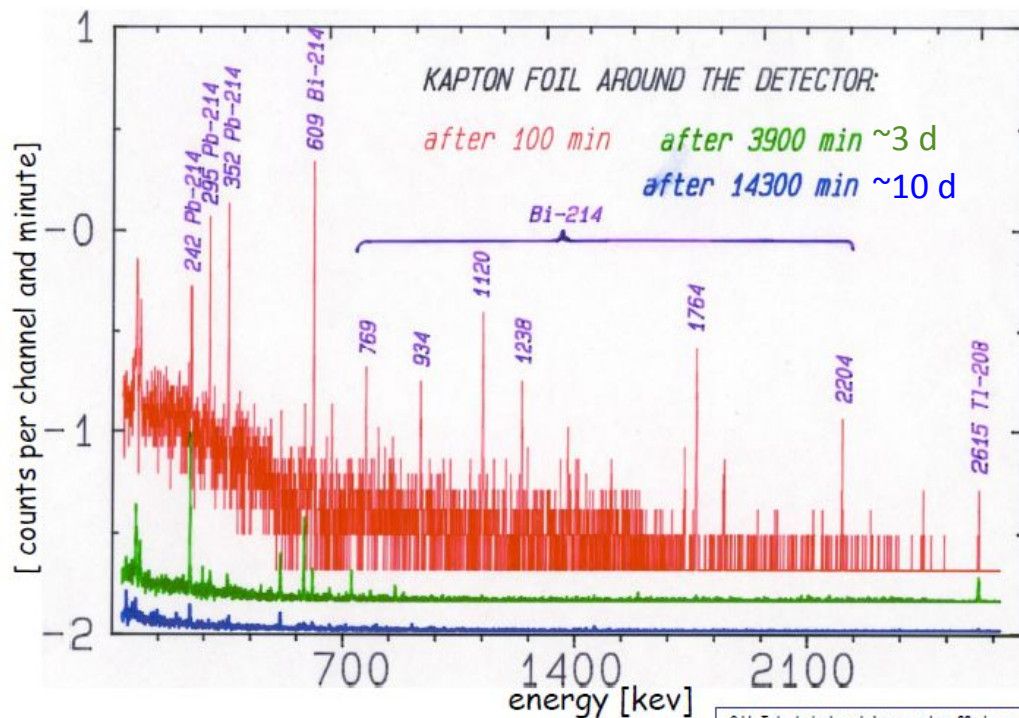


3. Radon and its progenies

Radon, as noble gas, emanates from materials containing U and Th. In particular ^{222}Rn with an half-time of 3.8 days can diffuse far away. It can flow close to HPGe detector entering inside the shield.

To avoid radon close to detector it is possible:

- flux the internal part of the shield with N
- pump the internal part of the shield
- hermetically close the shield (and wait)



G Heusser MPI Munich

4. Cosmic rays secondaries

Copper shield of HPGe crystal can produce some background due to cosmic rays activation

Cosmogenic activation produce larger activity in copper respect to primordials

cosmogenic production rates in Cu at sea level

radionuclide	halflife	production rate (saturation activity) [$\mu\text{Bq/kg}$]		
		exposed	unexposed	estimated*
cosmogenic				
^{56}Co	77.31 d	230 ± 30		557
^{57}Co	271.83 d	1800 ± 400		2147
^{58}Co	70.86 d	1650 ± 90		3878
^{60}Co	5.27 y	2100 ± 190	< 10	2367
^{54}Mn	312.15 d	828 ± 82		791
^{59}Fe	44.5 d	118 ± 32		157
^{46}Sc	83.79 d	53 ± 18		93
^{48}V	15.97 d	110 ± 40		
primordial				
^{226}Ra (U)	1600 y	< 35	< 16	
^{228}Th (Th)	1.91 y	< 20	< 19	
^{40}K	1.277×10^9 y	< 120	< 110	

M. Laubenstein, G. Heusser, Appl. Radiat. Isot. 67 (2009) 750-754

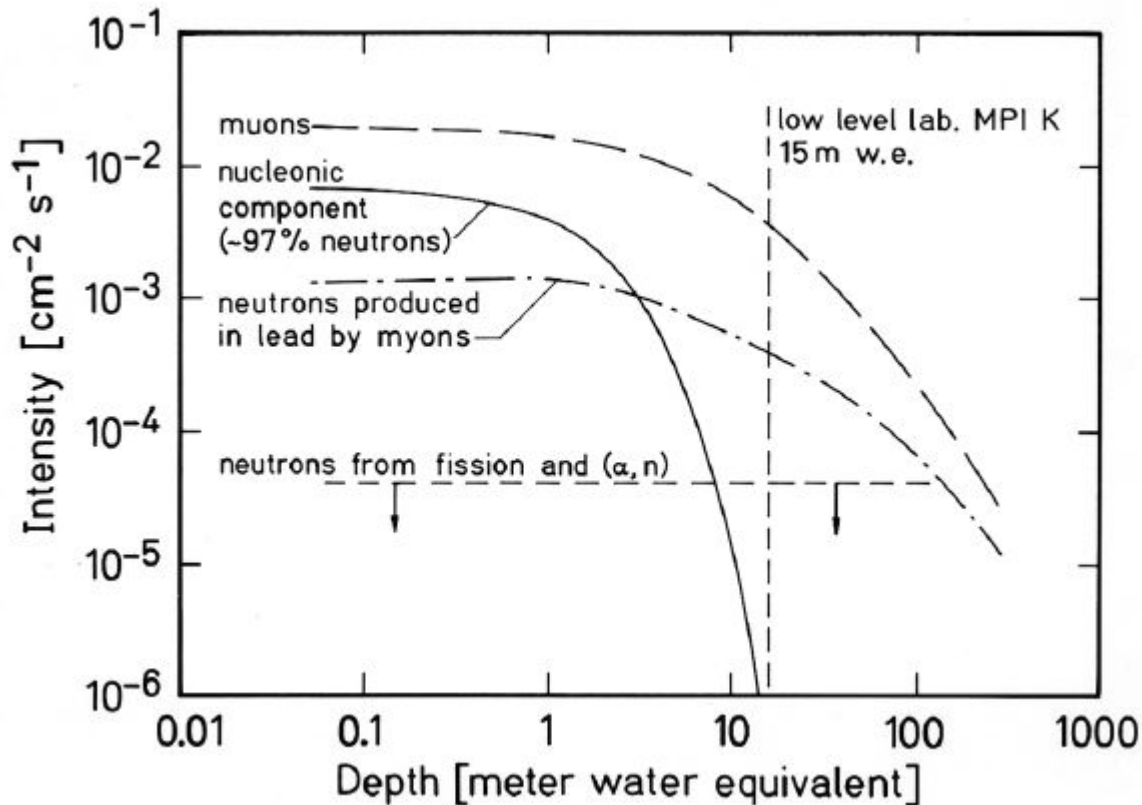
Cebrian et al., Astrop. Phys.33 (2010) 316-329

4. Cosmic rays secondaries

At sea level, the **charged component of cosmic rays** give a strong contribution to background

This also produces **neutrons** in interaction with the lead shield

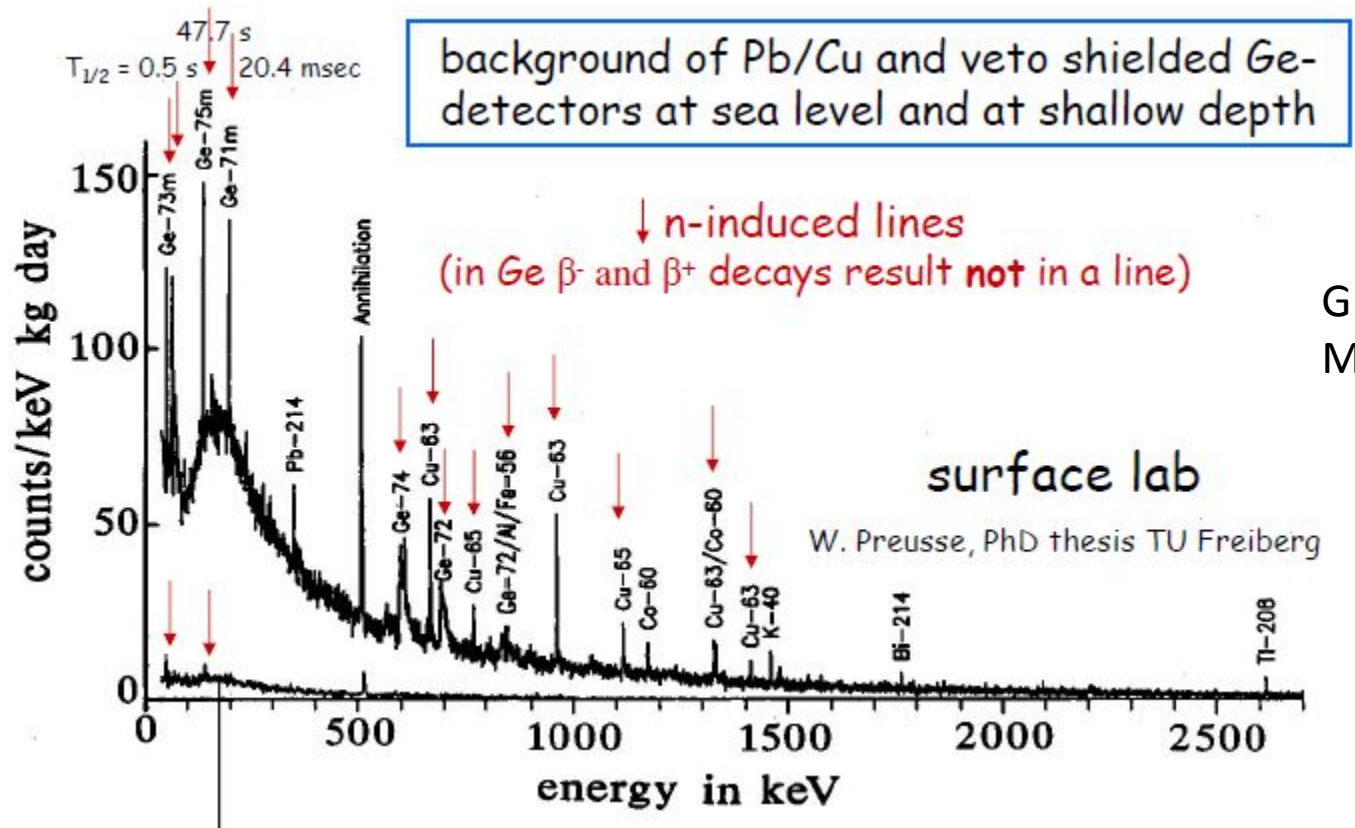
Neutron interaction will produce **activation** of the spectrometer



At LNGS, muons are reduced by 6 orders of magnitude thanks to 3600 mwe of rock.

4. Cosmic rays secondaries

Observation of HPGe spectrum give us also the indication of neutron activated isotopes



G. Heusser
MPI Munich

5. Neutron production by (α, n) reaction

Neutron flux on detector can be produced also by natural radioactivity

TABLE 9 Uranium and thorium concentrations for various types of rocks, along with estimates on neutron production from such sources. Granite types A, B, and C are from rock samples taken in Karkonosze, Poland. Salt types I and II are from Wieliczka Salt Mine, Poland. Tabulation from Reference (144) with permission

Type of rock	U (ppm)	Th (ppm)	U(α, n)	Th(α, n)	Fission	Total yield
	Concentration (ppm)		(neutrons/g/y)			
Granite	5	11	7.85	7.755	2.33	17.9
Limestone	1	1	0.64	0.285	0.467	1.4
Sandstone	1	1	0.837	0.38	0.467	1.7
Granite A	1.32	7.79	2.24	5.92	0.62	8.8
Granite B	6.25	4.59	10.62	3.49	2.92	17.0
Granite C	1.83	4.38	3.11	3.33	0.85	7.3
Salt I	0.30	2.06	1.60	4.77	0.14	6.5
Salt II	0.13	1.80	4.17	0.69	0.06	4.9

J. A. Formaggio, C. J. Martoff, *Annu. Rev. Nucl. Part. Sci.* 2004. 54:361-412

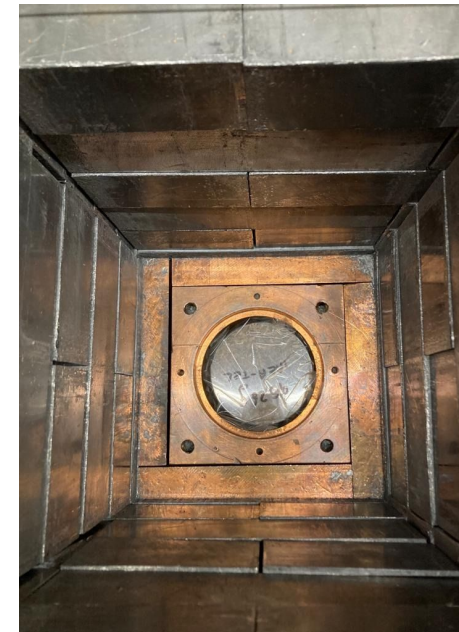
Material screening: where?

SubTErranean Low Level Assay @ LNGS

One of the best applications of the recipe:

- 14 HPGe installed underground
- Shielded with selected copper and lead
- Continuous anti-radon flux system

type	volume [cm ³]	rel. efficiency	FWHM [keV]
GeBer n-type	235	56%	2.0
GeMi p-type	403	86%	1.9
GePV p-type	363	91%	1.8
GsOr p-type	414	96%	1.9
GeMPI p-type	413	102%	1.9
GePaolo p-type	518	113%	2.0
GeCris p-type	465	120%	2.0
GeMulti p-type	4×225	4×96%	2.0



Thanks to M. Laubenstein

Best installation of HPGe measurements

At LNGS a lot of work was done to optimize HPGe detector background
In collaboration with the producers new and innovative approaches are tested
In particular very low background instruments were realized and used

background improvement ↓

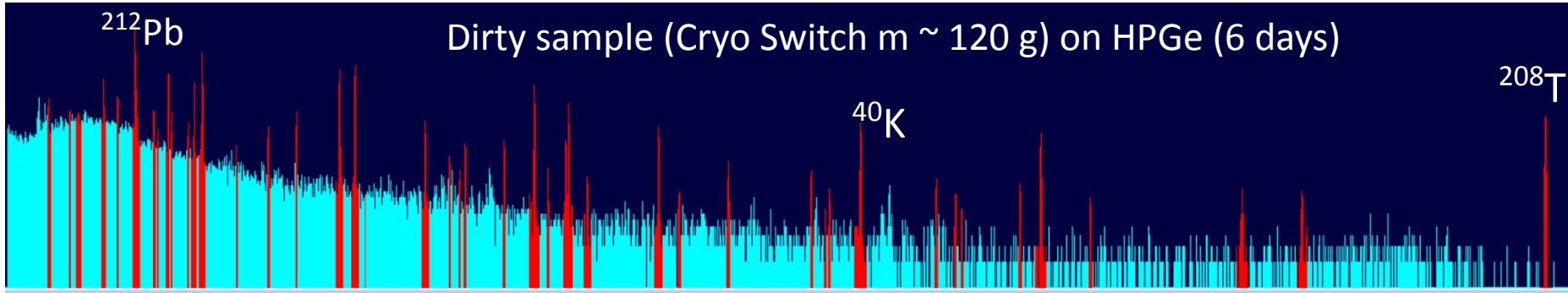
detector	total and peak background count rate [$d^{-1} kg^{-1}_{Ge}$]			
	40-2700 keV	352 keV	583 keV	1461 keV
<i>GeMi</i>	555 ± 7	4.1 ± 1.0	1.4 ± 0.5	6.1 ± 0.8
<i>GePV</i>	498 ± 5	2.6 ± 0.7	1.8 ± 0.4	3.2 ± 0.4
<i>GsOr</i>	442 ± 5	2.0 ± 0.5	0.76 ± 0.35	4.2 ± 0.5
<i>GePaolo</i>	222 ± 2	1.1 ± 0.3	0.31 ± 0.16	1.8 ± 0.2
<i>GeCris</i>	77 ± 2	0.29 ± 0.22	< 0.13	0.88 ± 0.22
<i>GeMPI</i>	30 ± 2	< 0.07	< 0.06	0.24 ± 0.03

Examples from everyday life

Clean sample (CuPEN m = 100 g) on ultra clean HPGe (15 days)



Dirty sample (Cryo Switch m \sim 120 g) on HPGe (6 days)



Search for gamma lines:

<http://www.lnhb.fr/nuclear-data/module-lara/>

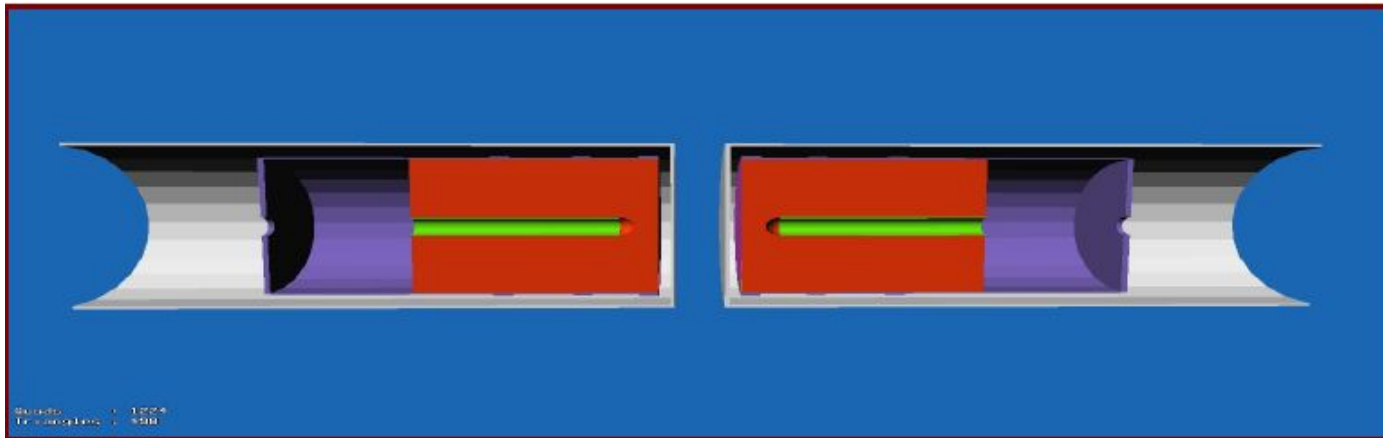
Backup slides

Other approach to the background reduction

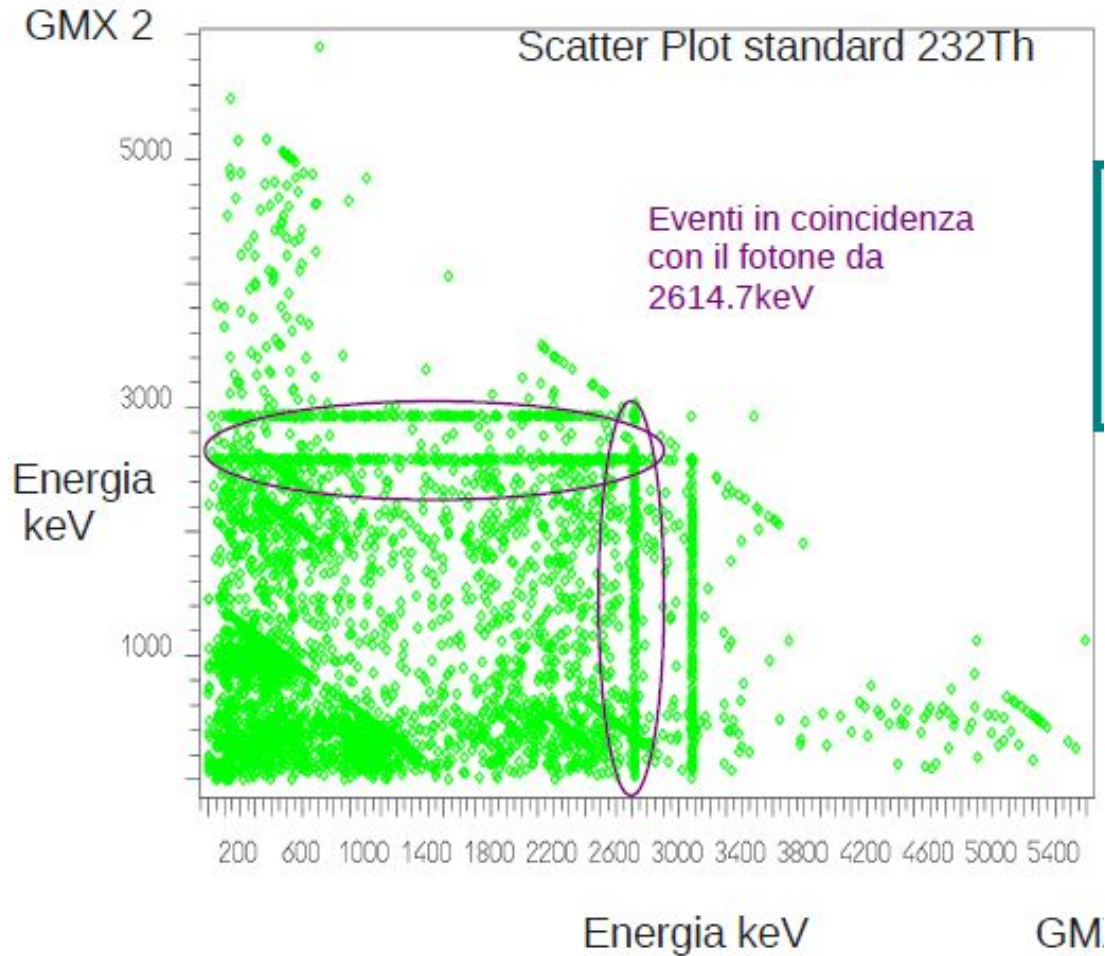
An **active rejection method** can be applied to background reduction

Two low background HPGe detectors operated in parallel to look for

- coincidence events
- anticoincidence events



Gamma-gamma coincidence



- Analysis can study
- Full energy peak
 - Compton scattering

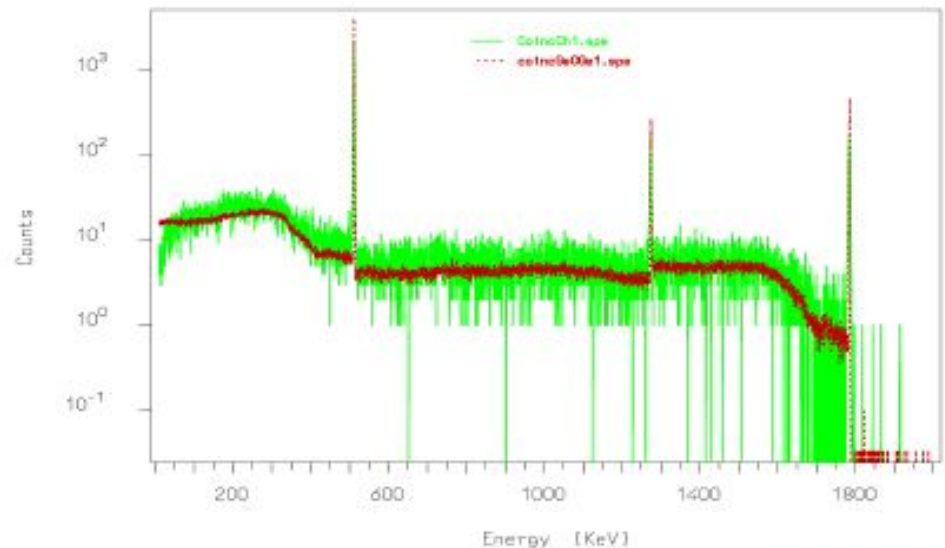
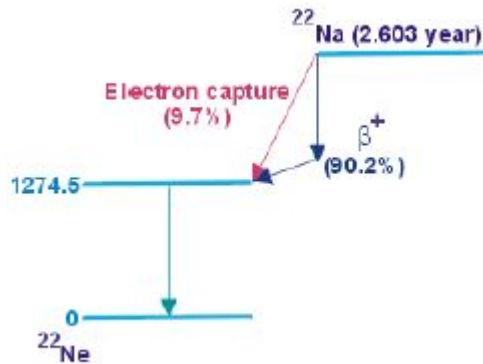


This will improve detection efficiency

Coincidence spectra

Coincidence spectrum of ^{22}Na

Measured and theoretical spectrum are the same



Tue Sep 20 15:37:53 2011

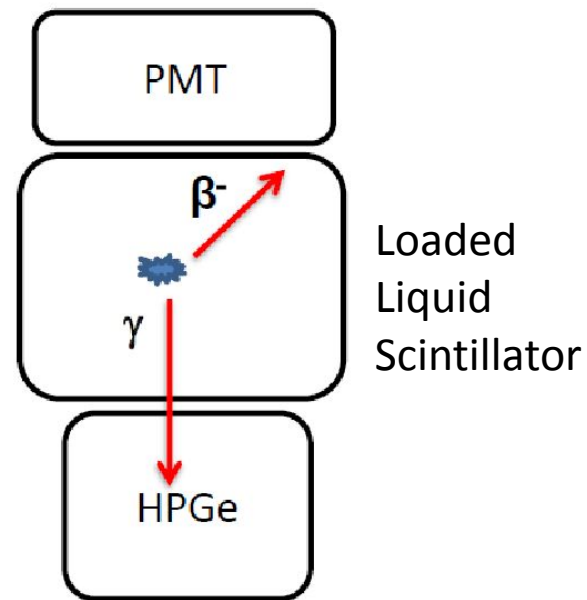
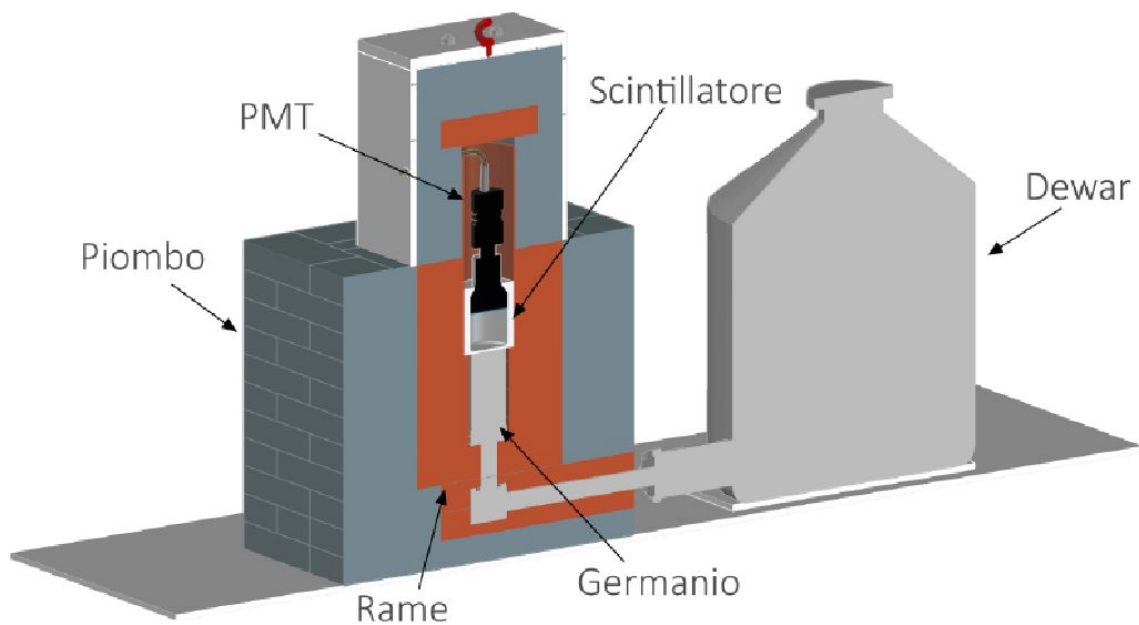
Considering

- the background of the detectors
- the global coincidence efficiency

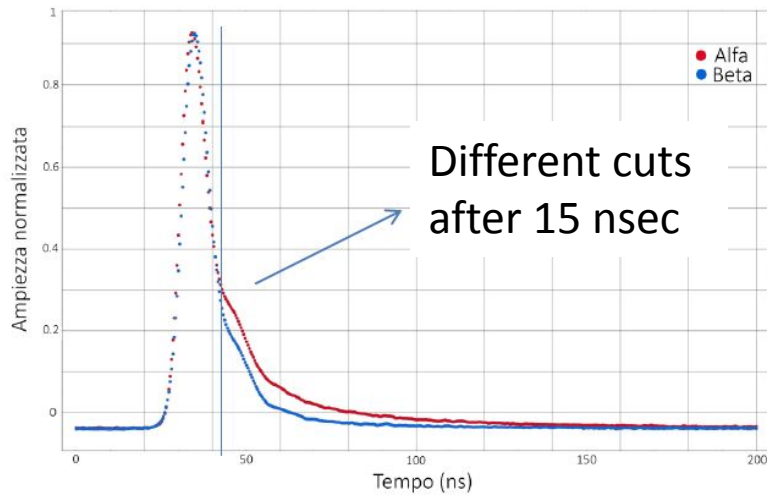
It is possible to evaluate a sensitivity of **100 $\mu\text{Bq/kg}$** for ^{232}Th measurements without placing the detector underground..

Beta-gamma coincidence

If you can dissolve your sample in a liquid scintillator...

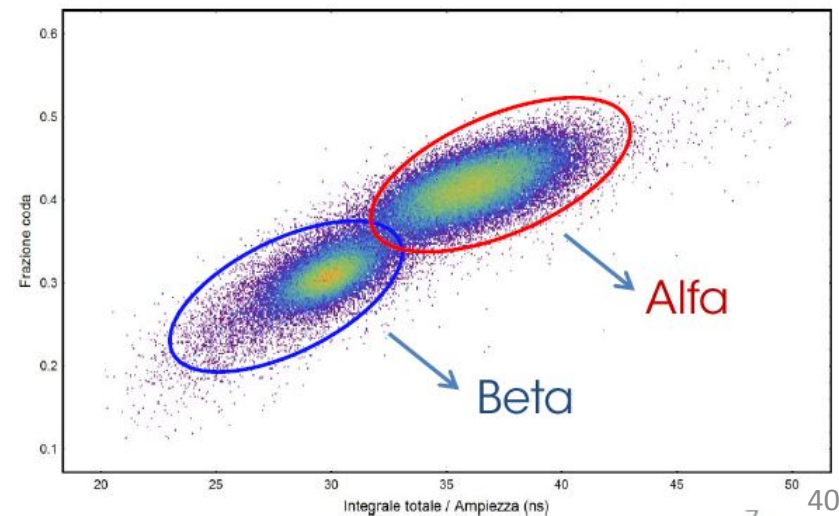
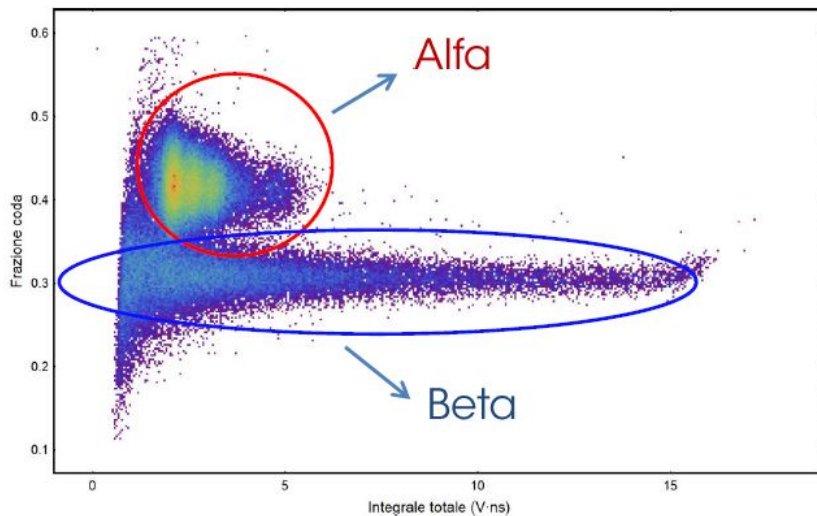


Alpha/beta discrimination

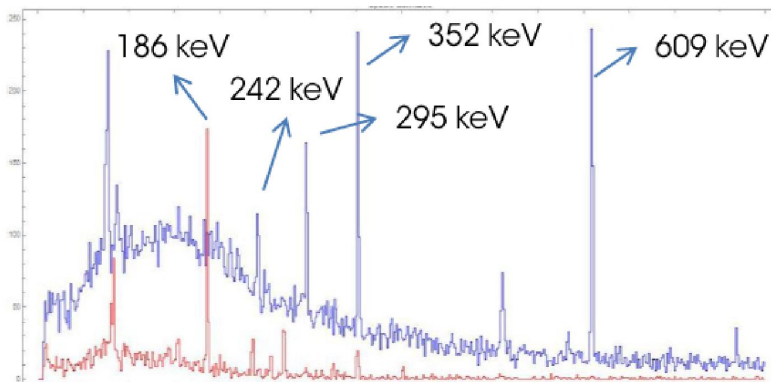
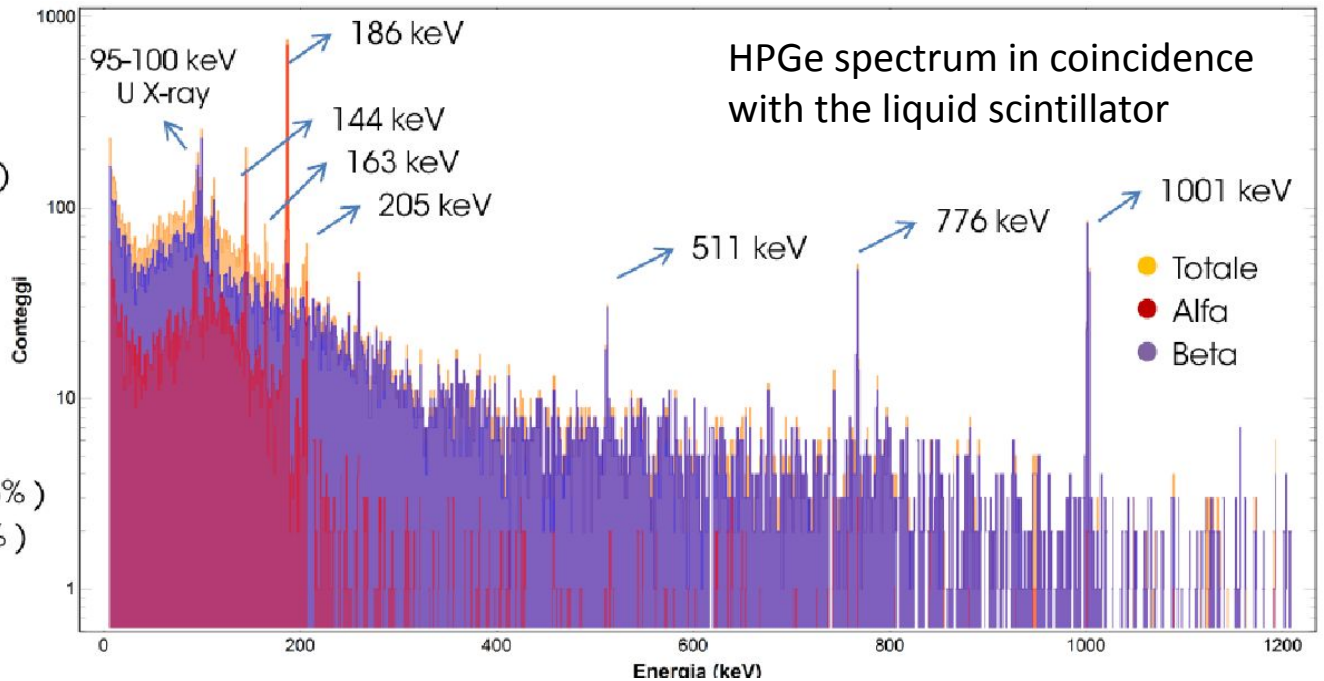
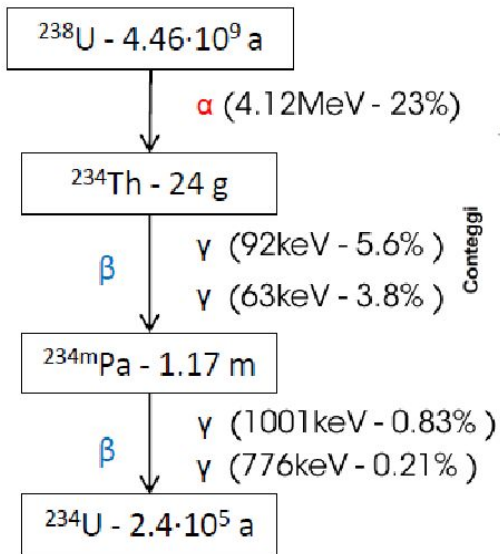


It is possible to discriminate alphas from beta particles

$$PSD = \frac{\text{Tail Area}}{\text{Total Area}}$$



Alpha/beta discrimination



Mass x Efficiency optimization

Efficiency is an important parameter for the optimization of the HPGe measurements

- ϵ must be calibrated with dedicated measurement
- ϵ must be maximized
- ϵ is connected with each detector but also with each sample

In a standard approaches ϵ is determined using calibrated sources but

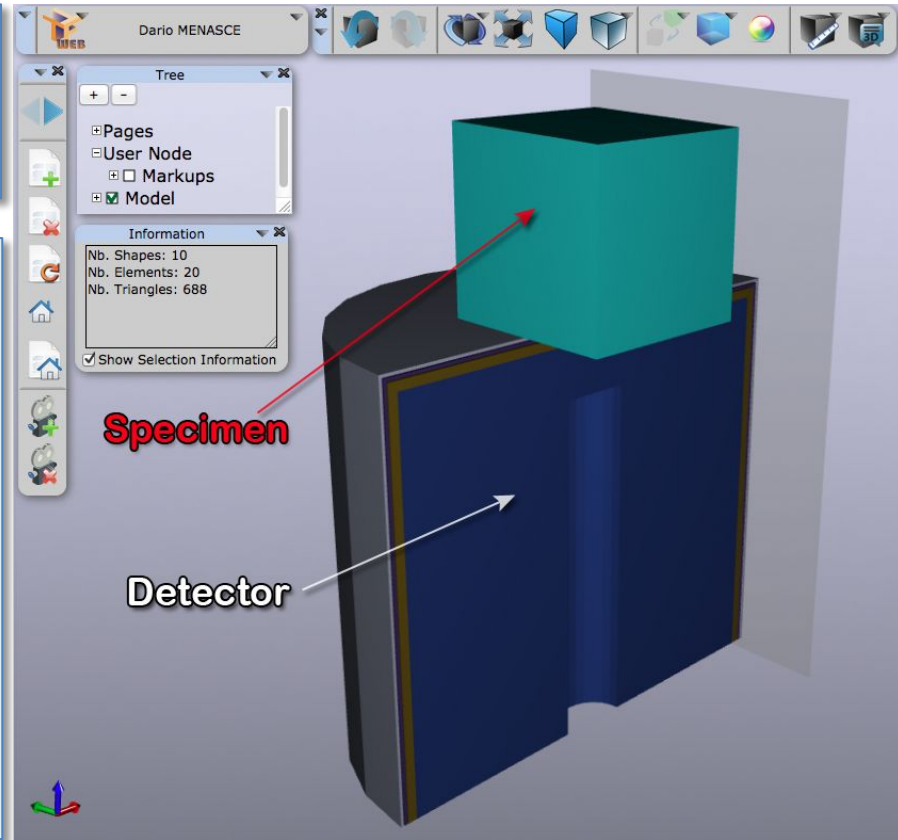
- only specific geometrical configuration will be calibrated
- only specific energy will be determined
- only specific radio nuclide can be tested

A possible solution can be found using Monte Carlo simulations

Monte Carlo simulations

As a guideline we'll consider the following use case:

- A user would like to compute the correction curve for a detector coupled to the surface of a simple cubic specimen.
- What is needed is just the following
 - ✓ A detailed geometric description of the specimen and the detector plus their mutual position in space
 - ✓ A description of the materials involved
 - ✓ The strategy to compute the efficiency curve for this specific setup



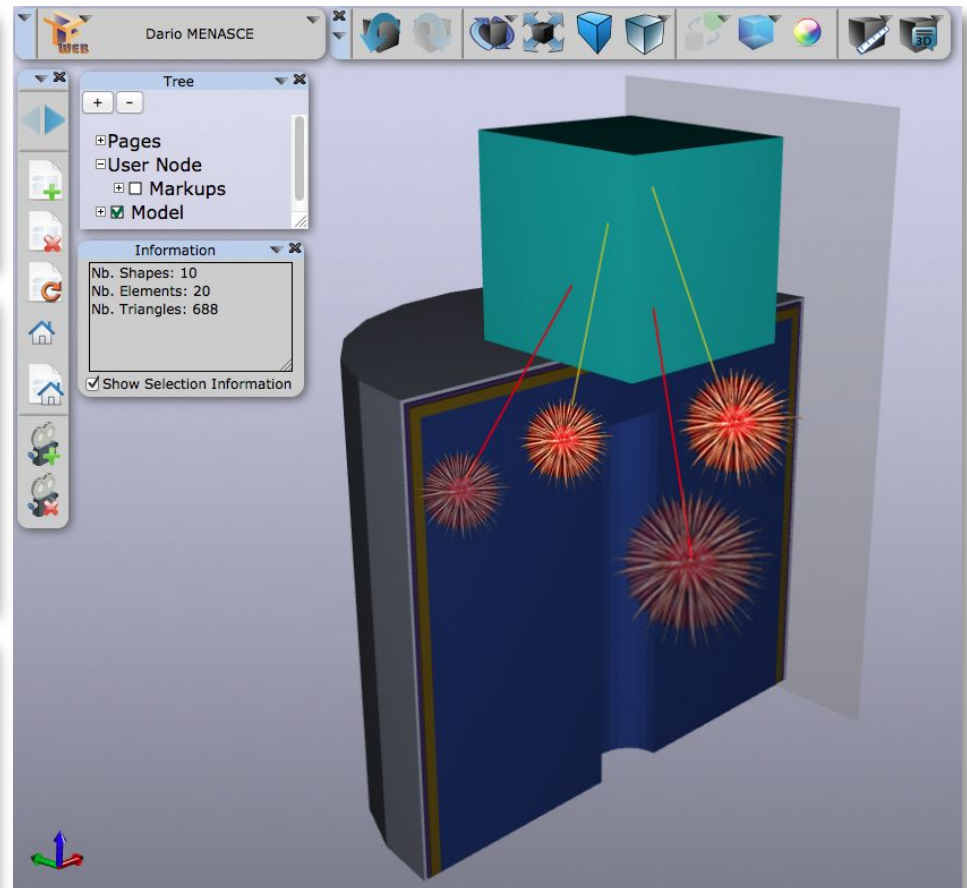
Monte Carlo simulations

There are notoriously several possible strategies to adopt for computing the efficiency response curve of a given setup. The one adopted in our demo is the simplest one:

a sampling of **monochromatic gamma rays** emitted at different energies from the specimen and collected by the detector

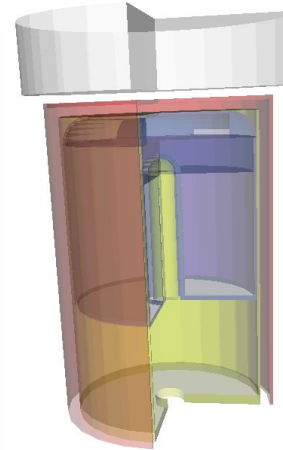
The choice of the energy sampling points, their number and their value is fully under the user's control. This of course affects the granularity of the response curve obtained.

We'll discuss other possibilities which are implemented in the simulation tool but not yet in the web interface version

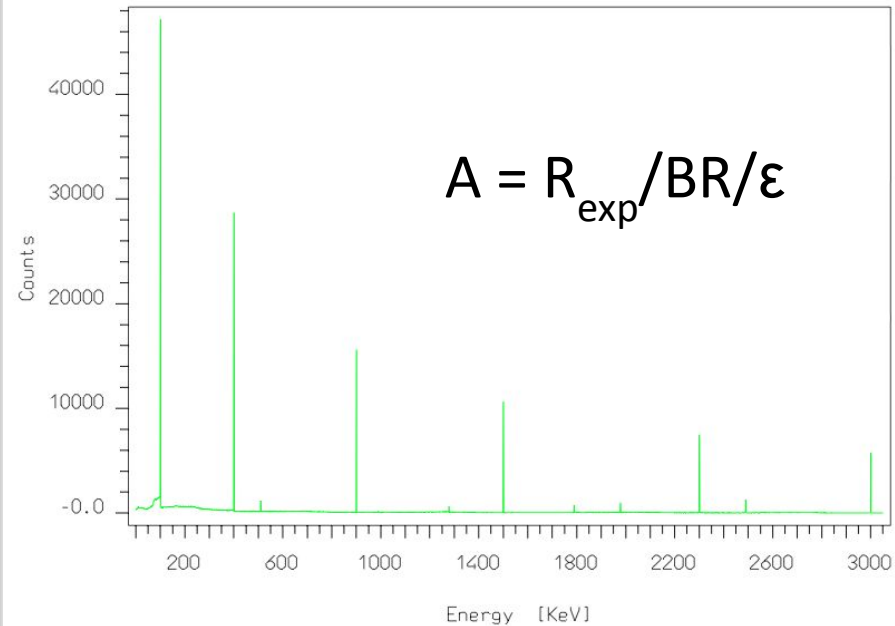


Monte Carlo simulation strategy

- Define/Choose Geometry:
 - Detector (Ge Coax)
 - Source (Disc)
- Define source features:
 - Material (e.g. iron)
 - Radioisotopes distribution (e.g uniform)
- Define the list of γ energy lines, E_k , on which to build the efficiency curve
- Generate (independently) N gamma's for each line energy E_k
- Build spectra of detected energy depositions in the detector
- Build the efficiency curve as a set of points (E_k , $\epsilon=N_k/N$) where N_k are the numbers of fully detected photons



Energy	Efficiency (%)
100	4.76 ± 0.02
400	2.86 ± 0.02
900	1.55 ± 0.01
1500	1.06 ± 0.01
2300	0.75 ± 0.01
3000	0.57 ± 0.01

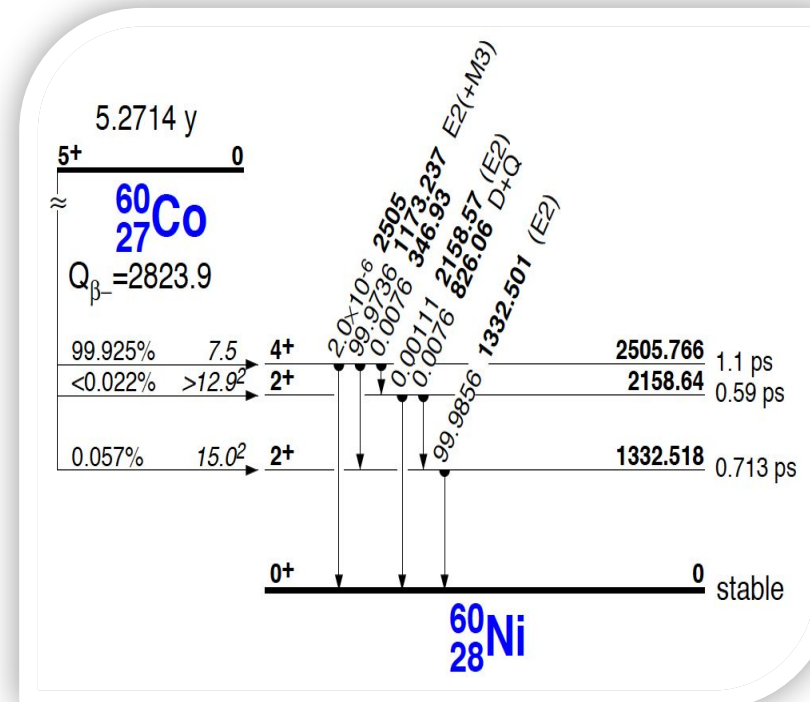


Monte Carlo simulation strategy

Nuclear cascades correlate different gamma lines which can interact simultaneously. Coincident events **subtract counts from photo-peaks** and efficiency are lowered.

Nuclear cascades are correctly described starting from the nuclear level schemes
Corresponding spectra (source dependent) are then produced

Efficiency curve (source dependent) is generated as pairs $(E_k, N_k/N)$ where N is the total number of generated nuclear decays, E_k are the gamma energies of the radioactive isotope and N_k are the corresponding numbers of detected counts



Monte Carlo simulation strategy

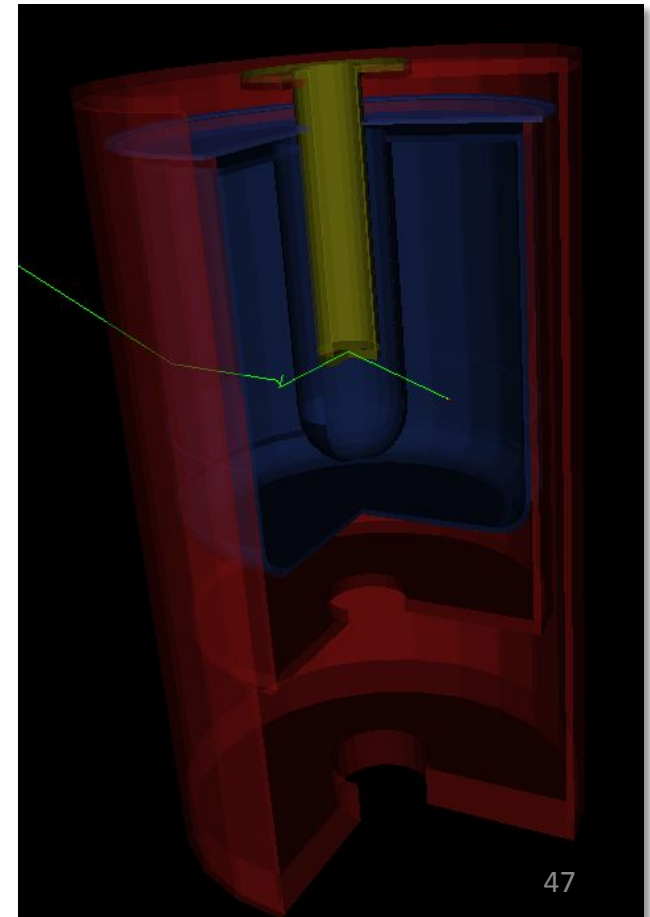
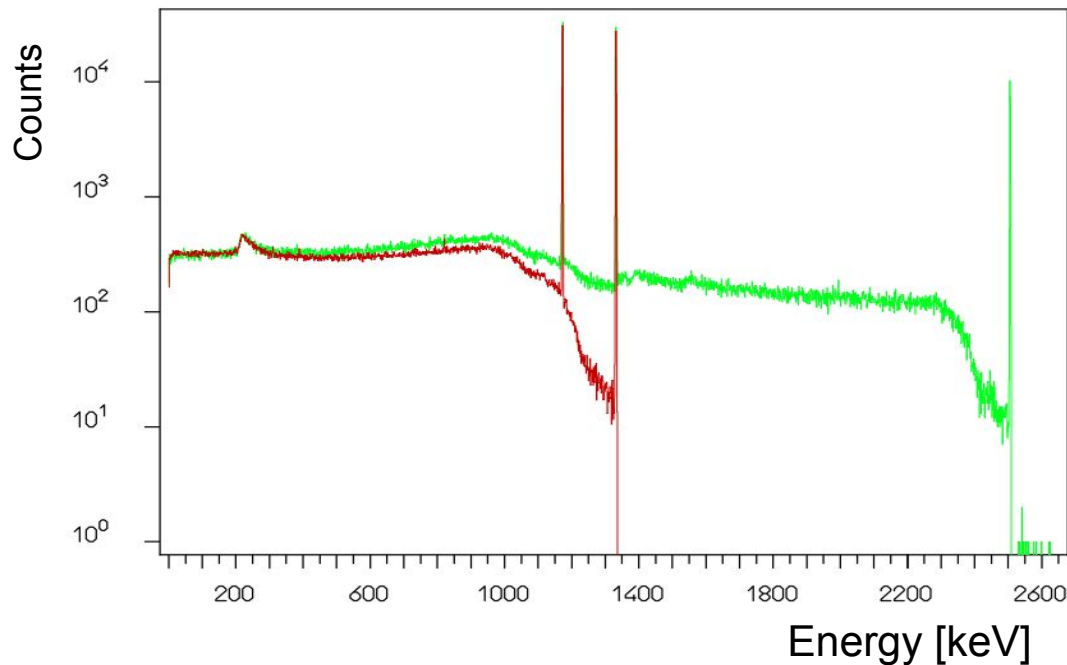
Cascade effect increase with the solid angle under which the source illuminates the detector.

An interesting example is a point-like source inside a well detector.

This approximates a 4π coverage and we expect significant corrections.

^{60}Co

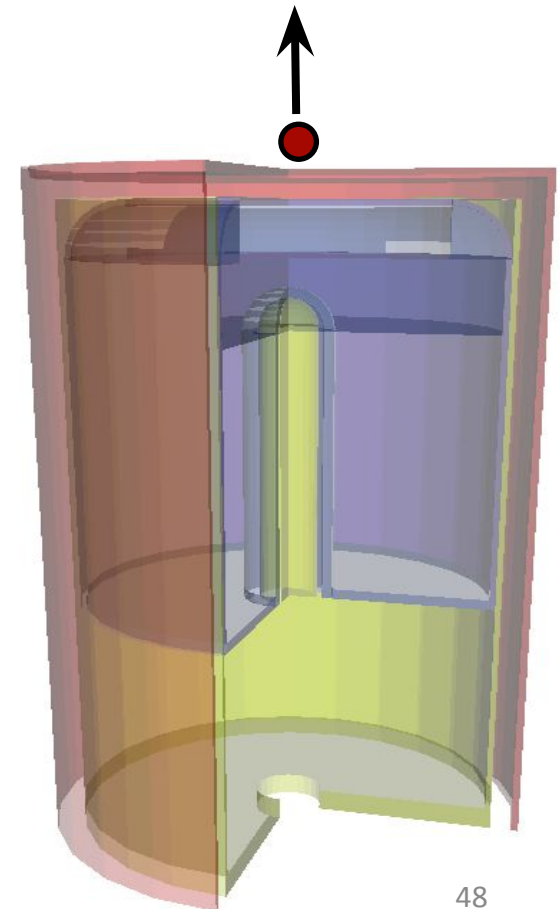
Energy	No Cascade	Cascade
1173	16.2 ± 0.06	7.81 ± 0.04
1332	14.6 ± 0.06	6.8 ± 0.04



Monte Carlo simulation strategy

- A source point placed in contact to the detector generates coincidences (due to cascade effects) which distort the efficiency measurement.
- The farther away the source, the less severe this problem becomes due to solid angle effects.
- The simulation program correctly considers the convolution of these effects for a spatially distributed source

Distance	Energy	Efficiency with no cascade	Efficiency with cascade
0	1173	3.21 ± 0.03	2.71 ± 0.03
	1332	2.92 ± 0.03	2.42 ± 0.02
5	1173	0.50 ± 0.01	0.49 ± 0.01
	1332	0.45 ± 0.01	0.45 ± 0.01
30	1173	$2.95E^{-02} \pm 2.70E^{-03}$	$2.84E^{-02} \pm 2.70E^{-03}$
	1332	$2.62E^{-02} \pm 2.60E^{-03}$	$2.23E^{-02} \pm 2.40E^{-03}$

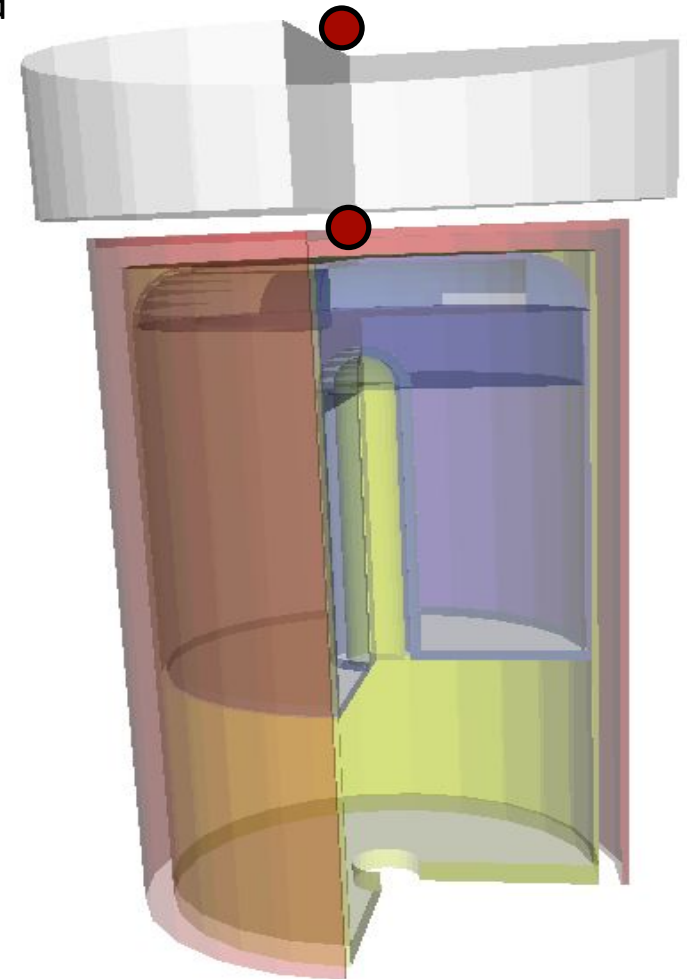


Monte Carlo simulation strategy

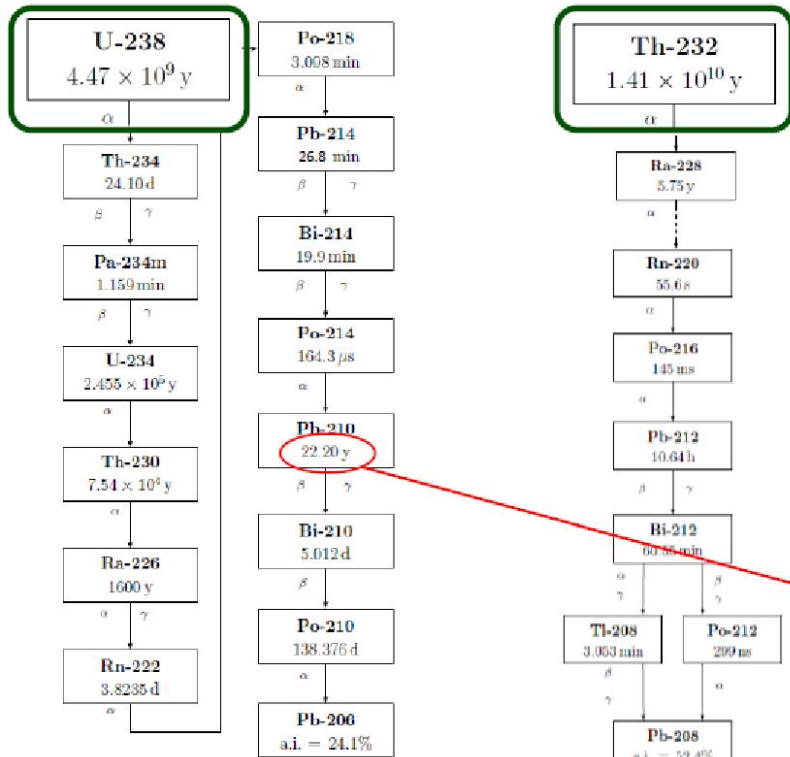
A STD way to approximate efficiency curves for distributed sources is by averaging experimental efficiency curves for point-like sources at extreme positions.

The reliability of this approximation depends usually on the source extension and can imply significant errors

Energy (keV)	Efficiency (%) Average	Efficiency (%) Distributed
100	13.11 ± 0.11	4.9 ± 0.04
400	6.95 ± 0.08	3.05 ± 0.03
900	3.44 ± 0.06	1.67 ± 0.02
1500	2.29 ± 0.04	1.14 ± 0.02
2300	1.54 ± 0.04	0.82 ± 0.02
3000	1.18 ± 0.03	0.61 ± 0.01



Alpha Spectroscopy



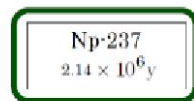
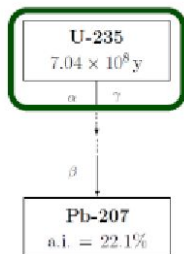
U and Th chains show a sequence of alpha decay

It will be possible to test all the chains from primordial to the last nucleus

Due to the high dE/dx of alpha particles:

- Measurements are **sensitive on surfaces**
- We can study the **contamination profiles**
- We can measure **specific chain parts**

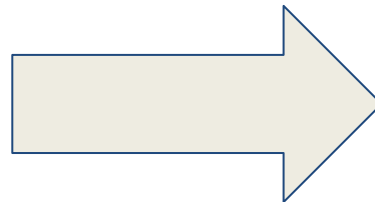
Large detector **surfaces** are useful



Alpha Spectroscopy - System

A Complete Alpha Spectroscopy System Consists of:

- **Alpha Particle Detector** with high resolution, low background, and detection efficiency appropriate for the application.
- **Vacuum Chamber** to ensure α -particles can reach the detector as they are easily attenuated by air.
- **Recoil Contamination Avoidance Package (RCAP)** to keep the detectors from becoming contaminated by daughter products that may leave the sample material (negatively biasing the sample holders, to repel the ions from the detector).
- **Electronics** for detector signal processing and storing the energy data
- **Analysis Software** to control the electronics, analyze spectra, establish quality control processes, and integrate data with laboratory data management systems.

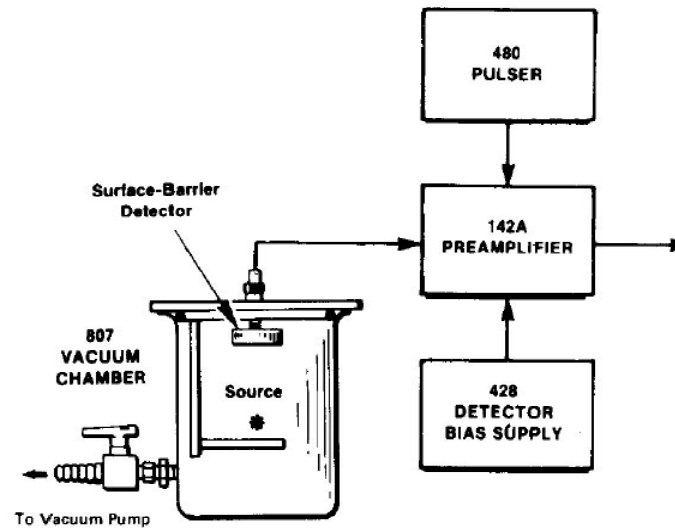
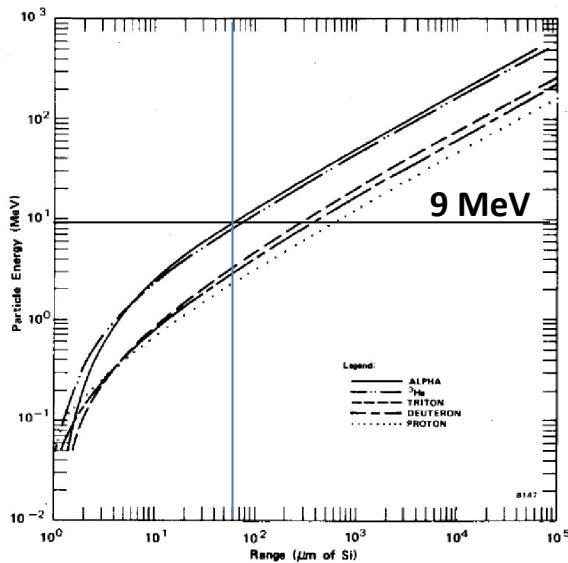


Alpha Spectroscopy - Detector



Silicon Surface barrier detectors:

- High energy resolution (~ 35 keV)
- Thin entrance window (40 nm)
- Intrinsic low background
- Small thickness to minimize cosmic ray effects
- Small/medium surface area (10 cm²)
- Unclear environmental background



Alpha Spectroscopy

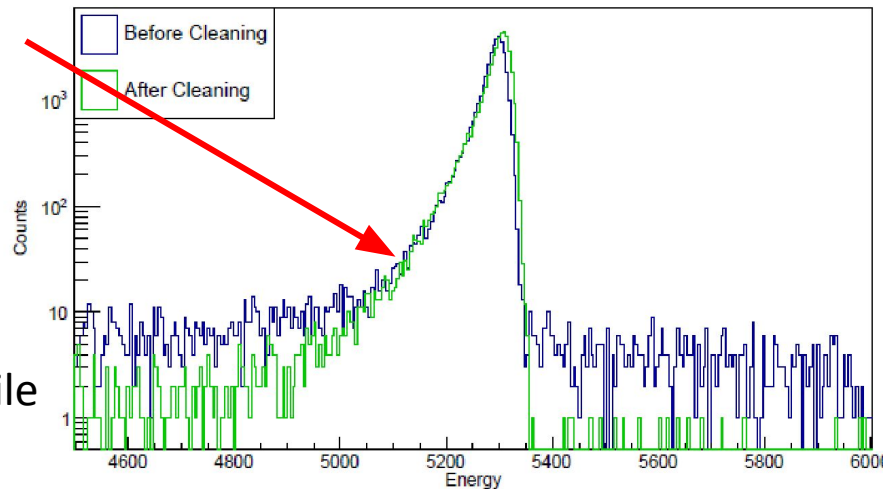
Surface contamination became an important aspect for future low background experiments

Strategies to identify surface treatments are crucial in order to minimize the effects

Spectral shapes



Identification of contamination profile



Minimization of counts

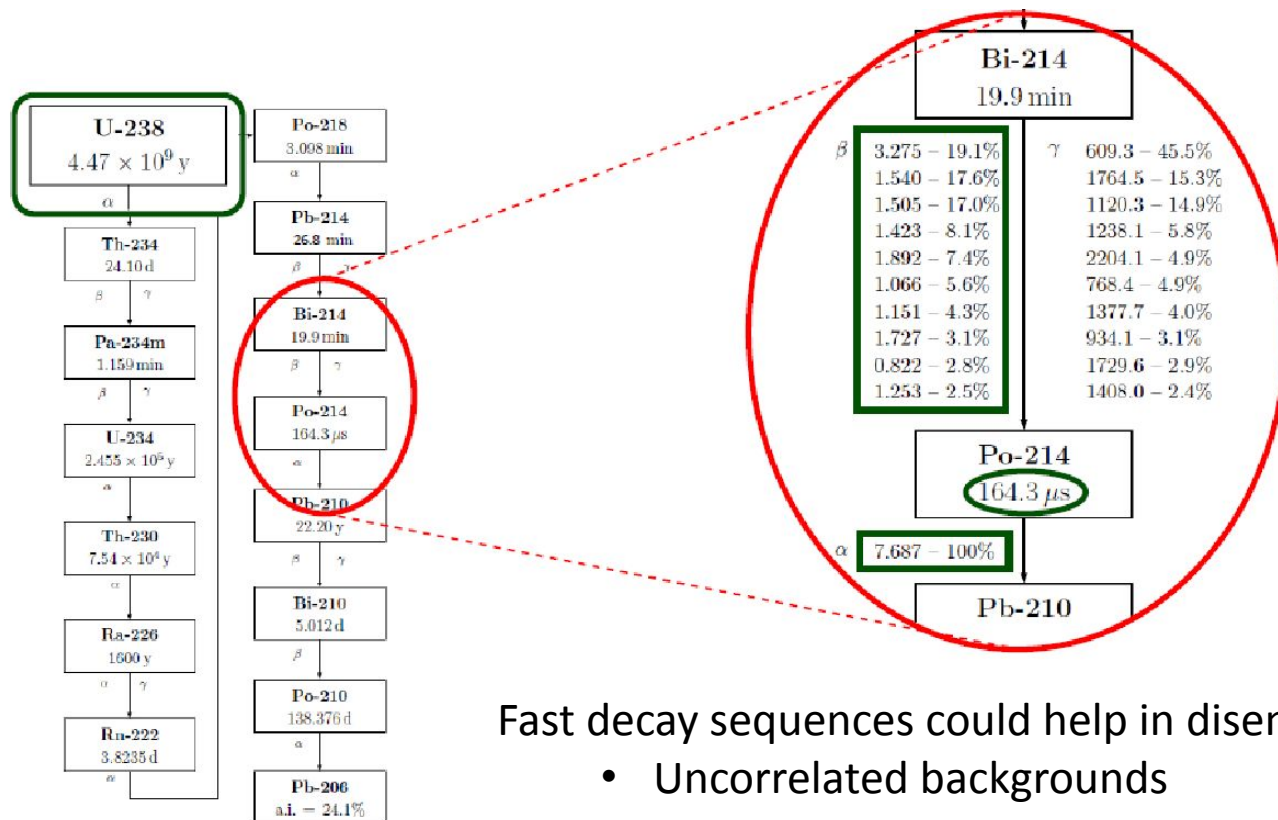


Impact of surface treatments

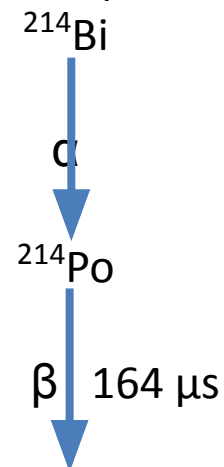
Detailed analysis could be possible if detector background is under control

Typical sensitivities $10^{-7}/10^{-8}$ Bq/kg

(not only) Alpha Spectroscopy



Typical sequence



Fast decay sequences could help in disentangle:

- Uncorrelated backgrounds
- Cosmic rays
- Timing correlations

Alpha Spectroscopy

Sample: ^{222}Rn contaminated copper plate

$^{214}\text{Bi} - ^{214}\text{Po}$
coincidence

$$R_{\text{Bi-Po}}(t) = \frac{A_{\text{Pb}}(0)\lambda_{\text{Bi}}}{\lambda_{\text{Bi}} - \lambda_{\text{Pb}}} \left(e^{-\lambda_{\text{Pb}}t} - e^{-\lambda_{\text{Bi}}t} \right) + A_{\text{Bi}}(0)e^{-\lambda_{\text{Bi}}t}$$

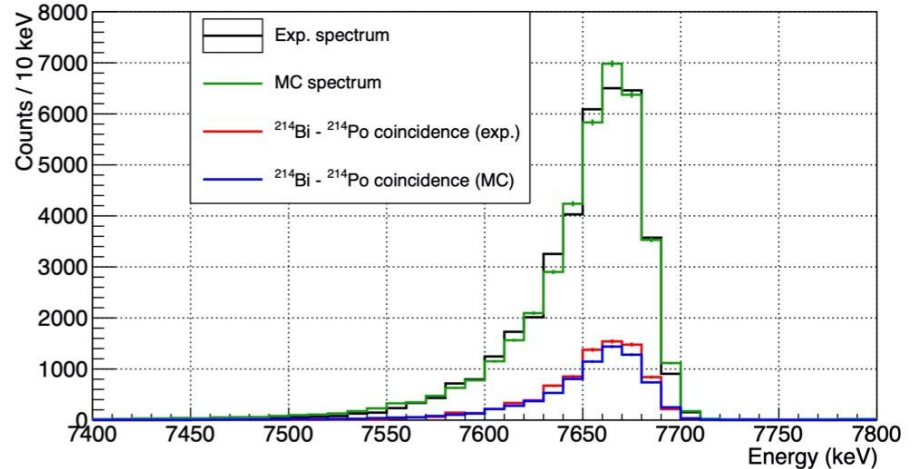
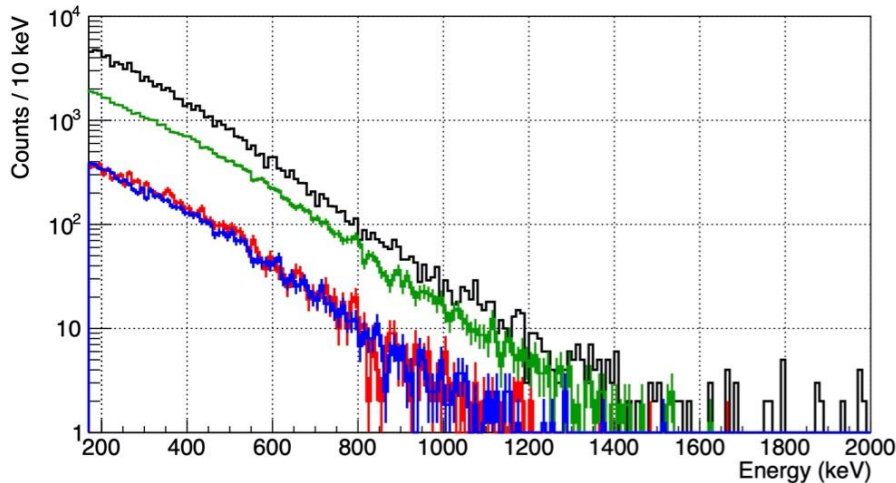
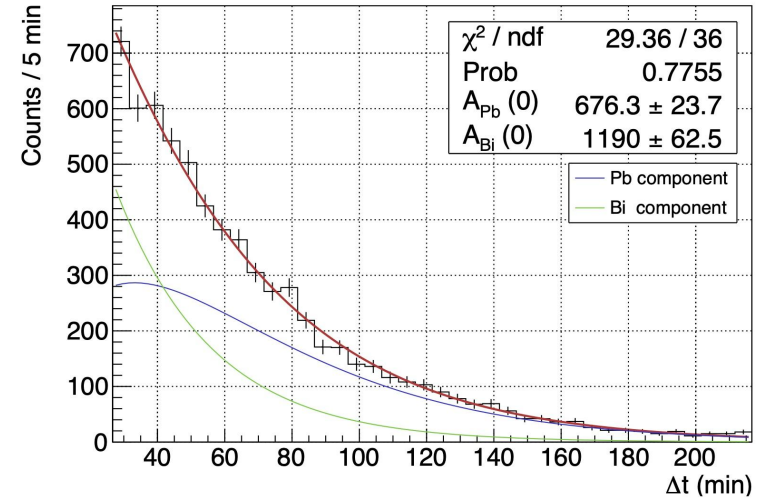


Fig. 1 Experimental data (black) and MC simulations (green) referring to the measurement of the copper plate contaminated with the ^{222}Rn daughters belonging to the ^{238}U chain. In the left pad we show the lower energy range where we searched for ^{214}Bi β -events in time coincidence with ^{214}Po α -events (right pad). The MC spectrum, comprised of ^{214}Bi and ^{214}Po events only, is normalized at the ^{214}Po α peak and, as expected, does not match the experimental data at low energies because of contributions from other β -emitters and environmental background. By selecting $^{214}\text{Bi} - ^{214}\text{Po}$ delayed coincidences in both experimental (red) and MC (blue) data, we get a good reconstruction of both ^{214}Po α -peak and ^{214}Bi β -spectrum.

Alpha Spectroscopy

Sample: ^{232}Th contaminated copper plate

$^{220}\text{Rn} - ^{216}\text{Po}$ coincidence (Th232)

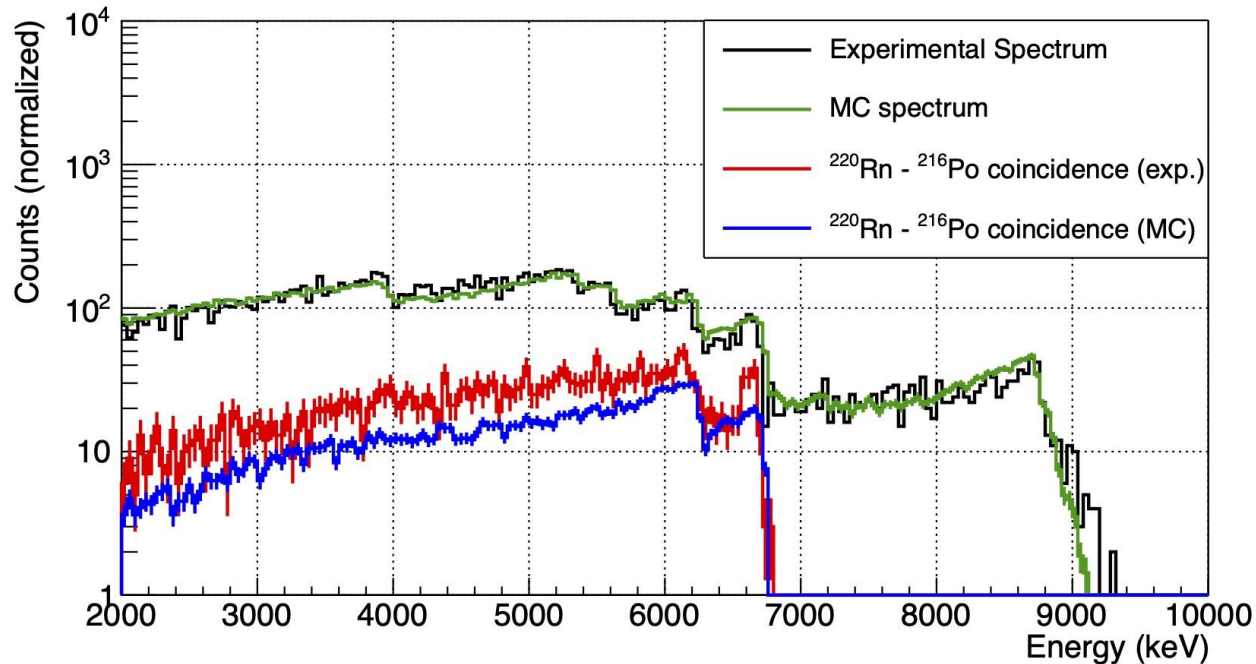
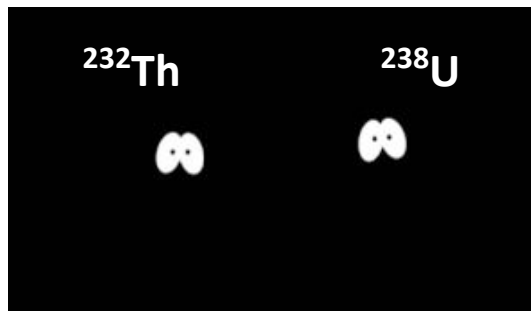


Fig. 5 Measured spectrum (black) and selection of $^{220}\text{Rn}-^{216}\text{Po}$ delayed coincident events (red). We show the MC simulated spectrum of the full ^{232}Th chain (green) normalized to the same integral of the measured spectrum in the $E > 2$ MeV range, and the corresponding selection of $^{220}\text{Rn}-^{216}\text{Po}$ coincidences (blue). The difference between the selected coincidences in the experimental data with respect to the MC simulations is compatible with the number of random coincidences estimated from the plateau in the fit of Fig. 6.

Alpha Spectroscopy

Sample: pure copper plate



Identifying the source in a flat continuum

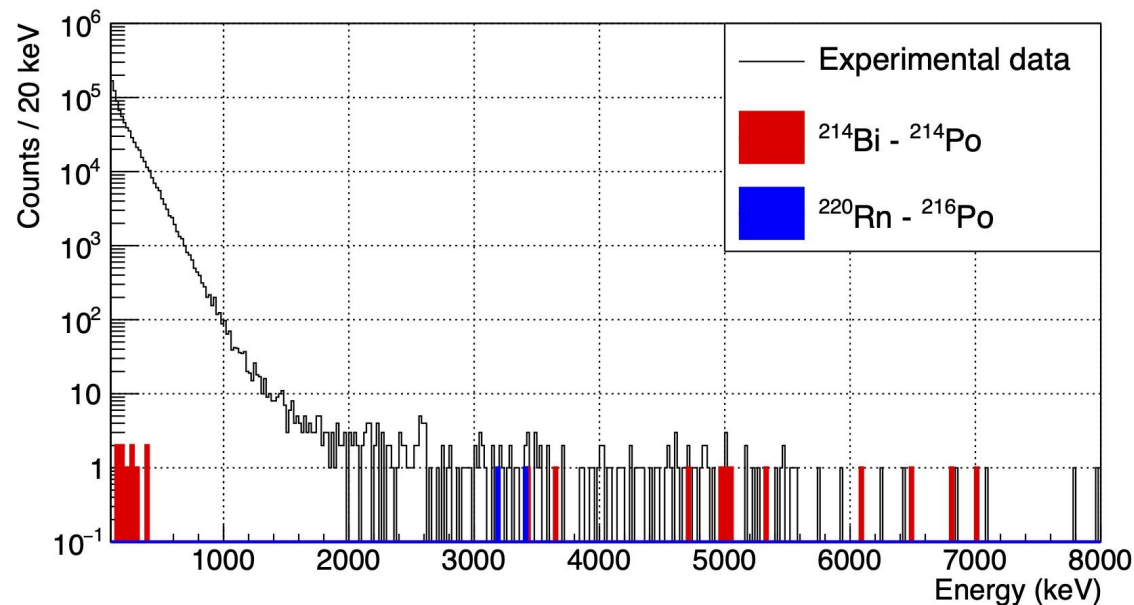


Fig. 7 Measured spectrum (black) and selection of $^{214}\text{Bi} - ^{214}\text{Po}$ (red) and $^{220}\text{Rn} - ^{216}\text{Po}$ (blue), belonging to the ^{238}U and ^{232}Th decay chains, respectively. The analysis of time correlations allows to disentangle the ^{238}U and ^{232}Th contamination in the continuum produced by energy-degraded α s.

Alpha Spectroscopy - Calorimetric approach

Also operating a certain material as cryogenic calorimeter, we can perform interesting **α -spectroscopy analysis**

CUPID -0 DATA

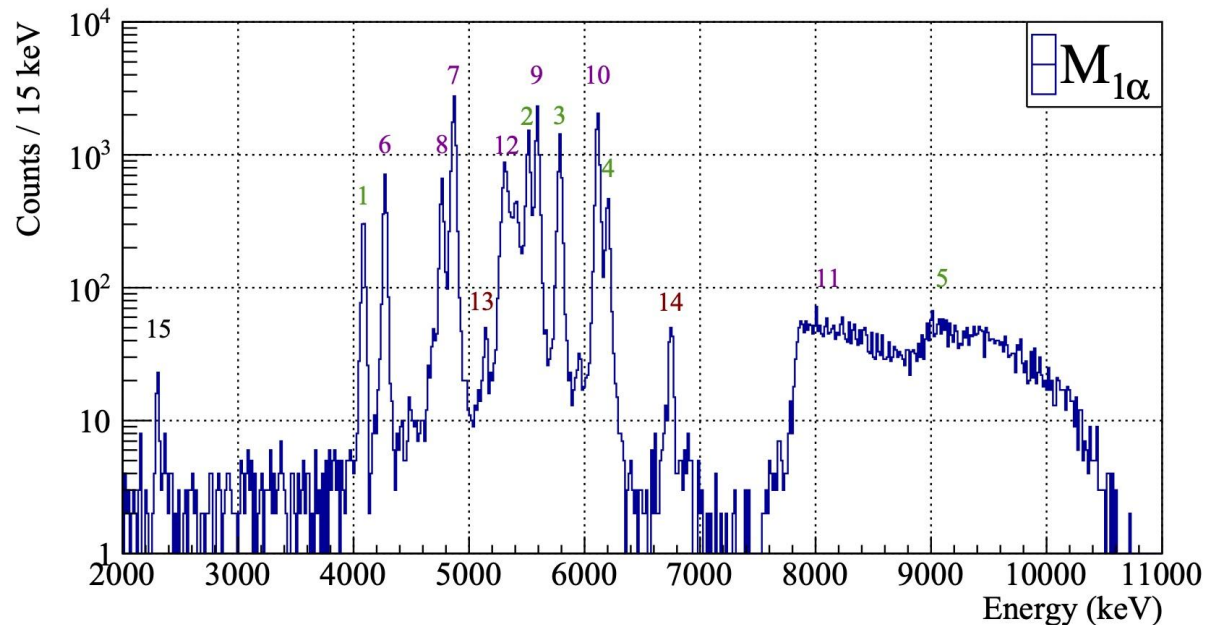
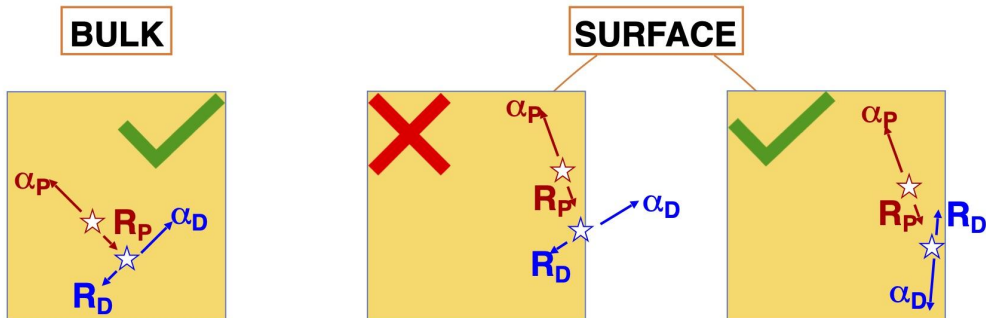


Fig. 2 Top left: CUPID-0 $\mathcal{M}_{1\beta/\gamma}$ spectrum with the following peak labeling: (1) ^{65}Zn , (2) ^{40}K , (3) ^{208}Tl . Top right: $\mathcal{M}_{1\alpha}$ spectrum with the following peak labeling: (1) ^{232}Th , (2) ^{228}Th , (3) ^{224}Ra , (4) ^{212}Bi , (5) $^{212}\text{Bi} + ^{212}\text{Po}$, (6) ^{238}U , (7) $^{234}\text{U} + ^{226}\text{Ra}$, (8) ^{230}Th , (9) ^{222}Rn ,

(10) ^{218}Po , (11) $^{214}\text{Bi} + ^{214}\text{Po}$, (12) ^{210}Po , (13) ^{231}Pa , (14) ^{211}Bi , (15) ^{147}Sm . Bottom left: \mathcal{M}_2 spectrum. Bottom right: Σ_2 spectrum with the same labels used for $\mathcal{M}_{1\beta/\gamma}$ peaks

Alpha Delayed Coincidences - Calorimetric approach

We can exploit delayed coincidences to investigate the **bulk vs. surface** contaminant location



$$P(D_Q | P_Q) \approx 1$$

$$P(D_Q | P_Q) < 1$$

Containment efficiency and detection probability of delayed coincidence depend on the contaminant location

