Università degli studi di Ferrara

Master's degree in Physics

Performance validation of a lightweight collimated gamma – ray spectrometer for *in situ* survey

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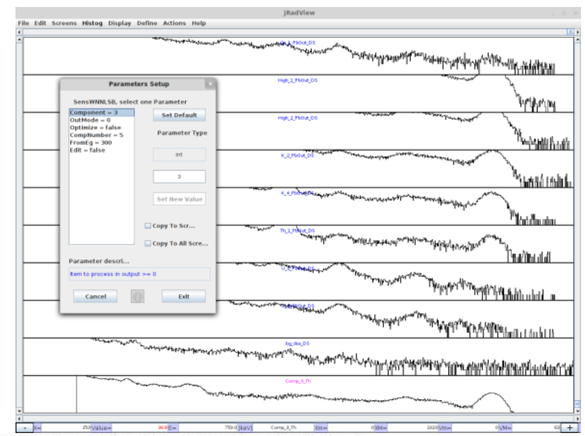
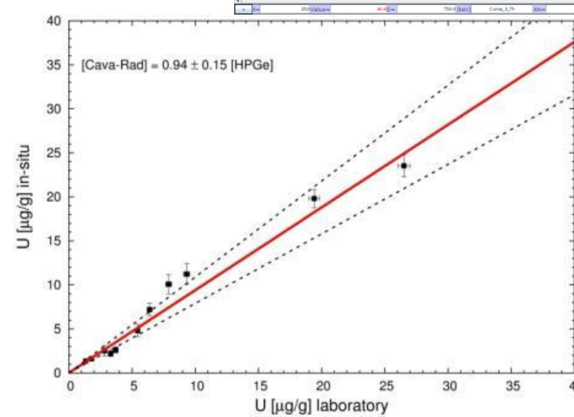
Summary

Cava_Rad: lightweight collimated gamma–ray spectrometer for in situ survey

- ✓ **Why** has Cava_Rad been developed?
- ✓ What does Cava_Rad **consist of**?



- ✓ How does Cava_Rad perform **measurements**?
- ✓ How **calibration** was accomplished?

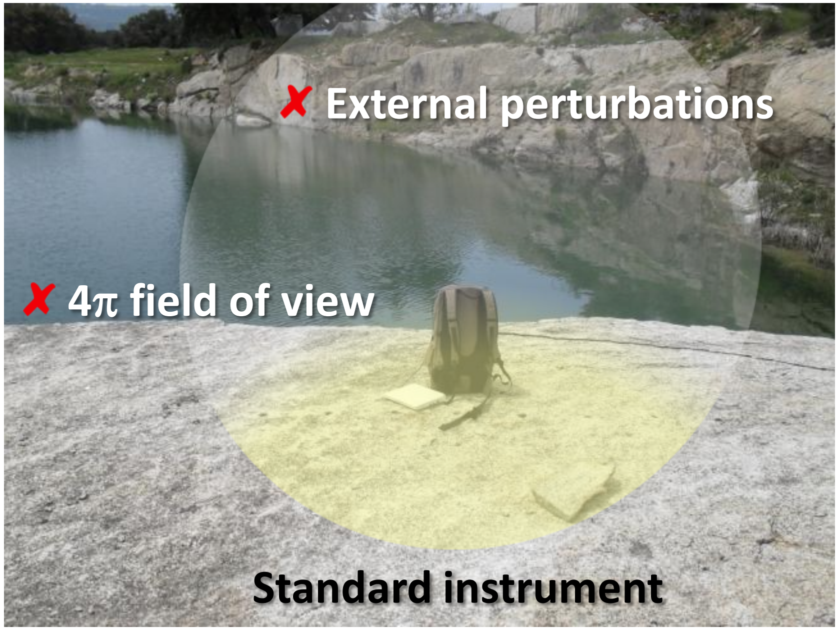


- ✓ What are the Cava_Rad **performances**?

Scientific and technological motivations

Desiderata

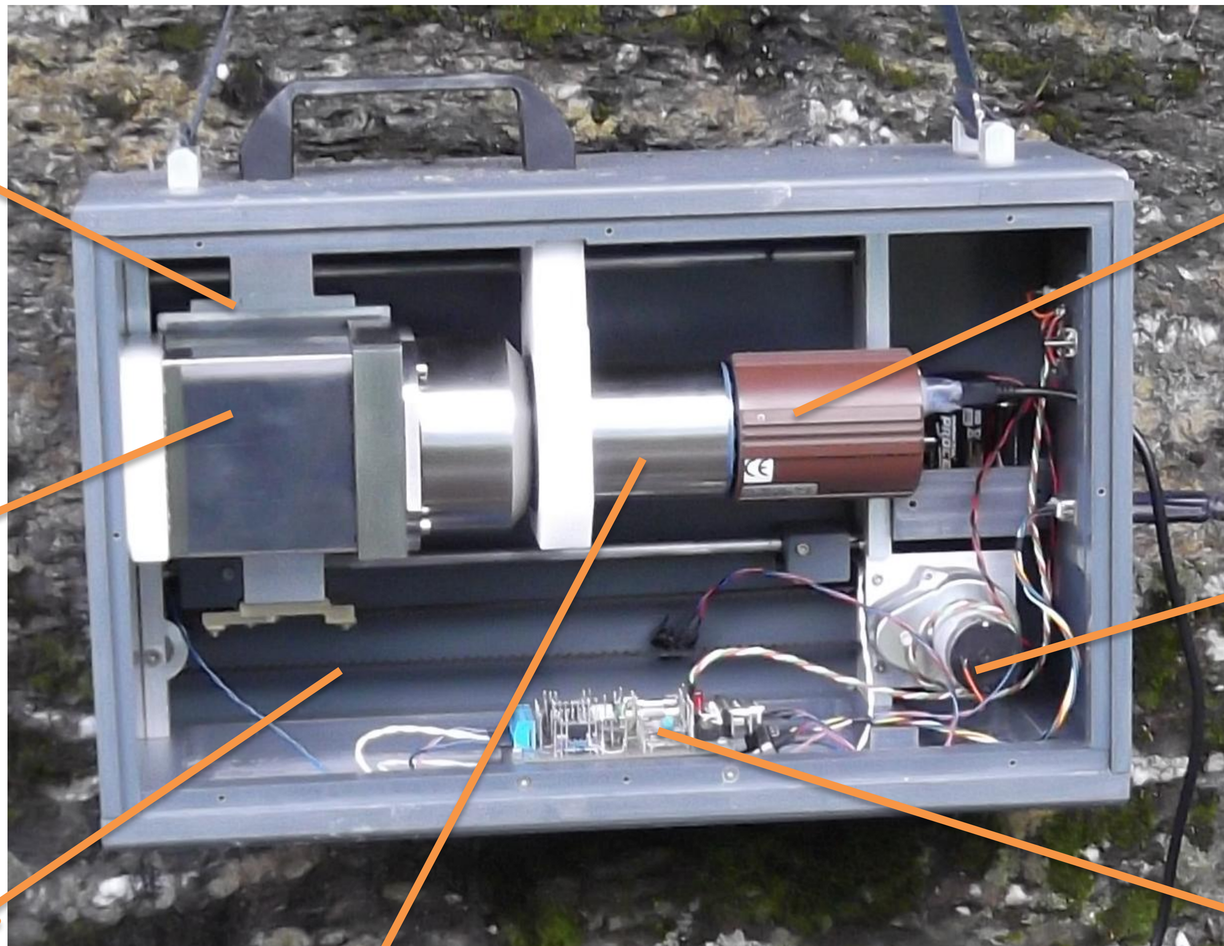
- In situ identification of radionuclides
- Portable instrument
- Fast measurement
- Restricted field of view



APPLICATIONS
Envrionment radioactivity survey (e.g. decorative stones)
Geophysical survey (e.g identification of uranium and thorium ore veins)
Homeland security (e.g. orphan source identification)

Cava_Rad: a hand-held gamma spectrometer

Weight: 8 kg   Dimensions: h.27 x w. 43 x t. 13 cm



Lead slab
9x9x3 cm

NaI(Tl)
7.3% at 662 keV
Cubic 3’’

Conveyor belt

Photomultiplier tube

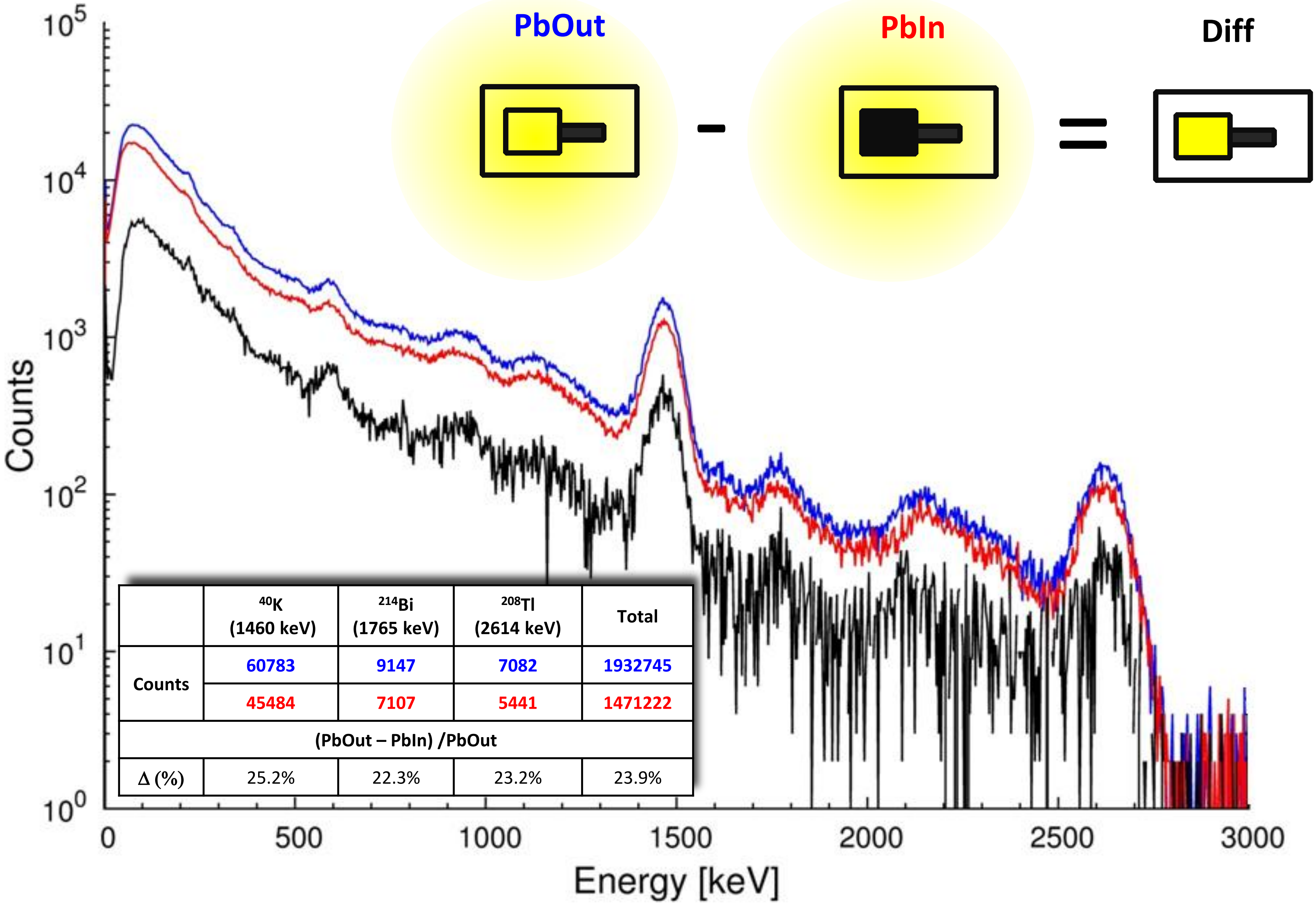
digiBASE
(MCA)

Electric
motor

Electronic
set up
for
moving
shield

Performing measurements

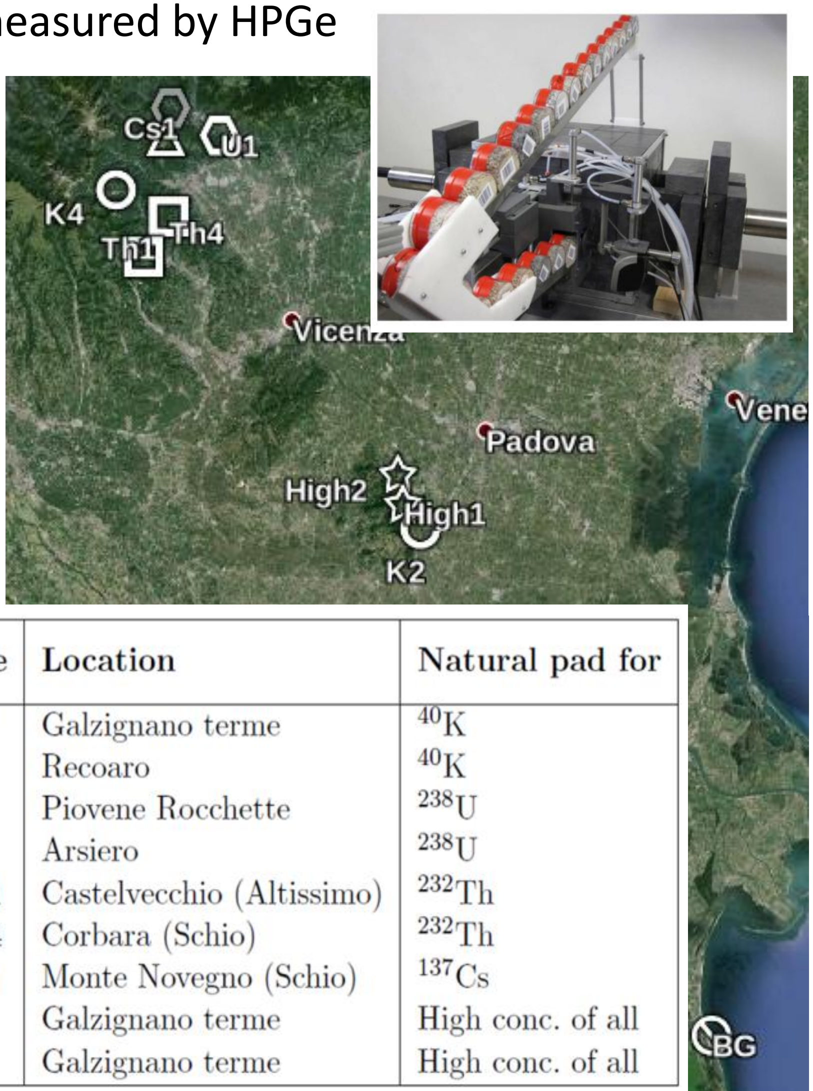
Cava_Rad measured spectra



	^{40}K (1460 keV)	^{214}Bi (1765 keV)	^{208}Tl (2614 keV)	Total
Counts	60783	9147	7082	1932745
	45484	7107	5441	1471222
(PbOut – PbIn) /PbOut				
Δ (%)	25.2%	22.3%	23.2%	23.9%

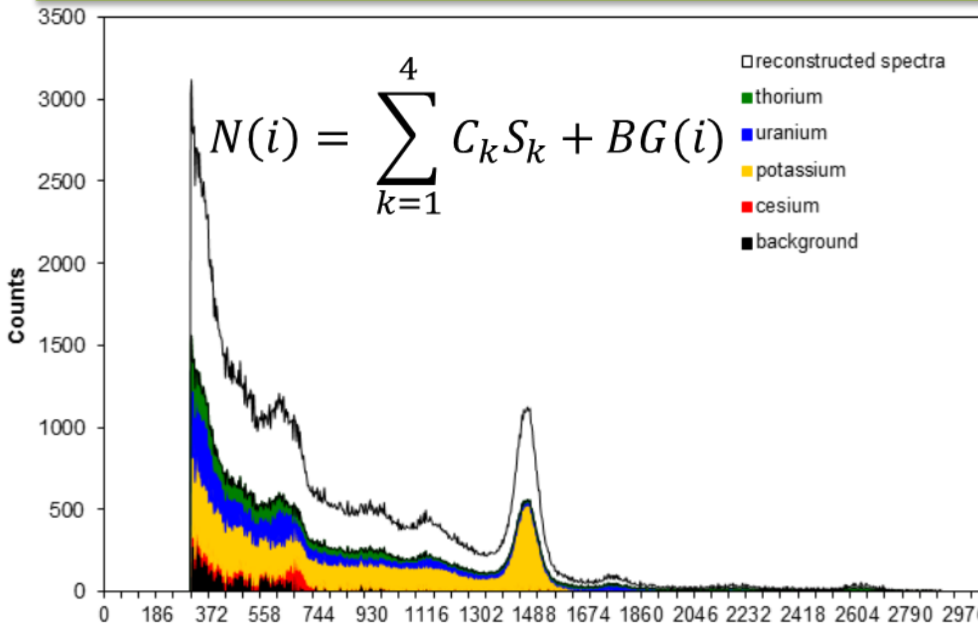
Method of analysis

The radioactivity content of reference sites used for calibration of Cava_Rad is measured by HPGe



Site	Location	Natural pad for
K2	Galzignano terme	^{40}K
K4	Recoaro	^{40}K
U1	Piovene Rocchette	^{238}U
U3	Arsiero	^{238}U
Th1	Castelvecchio (Altissimo)	^{232}Th
Th4	Corbara (Schio)	^{232}Th
Cs1	Monte Novegno (Schio)	^{137}Cs
H1	Galzignano terme	High conc. of all
H2	Galzignano terme	High conc. of all

Full Spectrum Analysis with Non Negative Least Squares constraints



$$N(i) = \sum_{k=1}^{4} C_k S_k + BG(i)$$

$$\chi^2 = \frac{1}{n-5} \sum_{i=1}^{n} \left[N(i) - \sum_{k=1}^{4} C_k S_k(i) - BG(i) \right]^2 \frac{1}{N(i)}$$

- $N(i)$ counts in the channel i,
- C_k concentration of the element k,
- $S_k(i)$ associated counts to fundamental spectrum of the element k in the channel i,
- $BG(i)$ counts in the channel i due to the background.

Input abundances

For each calibration site:

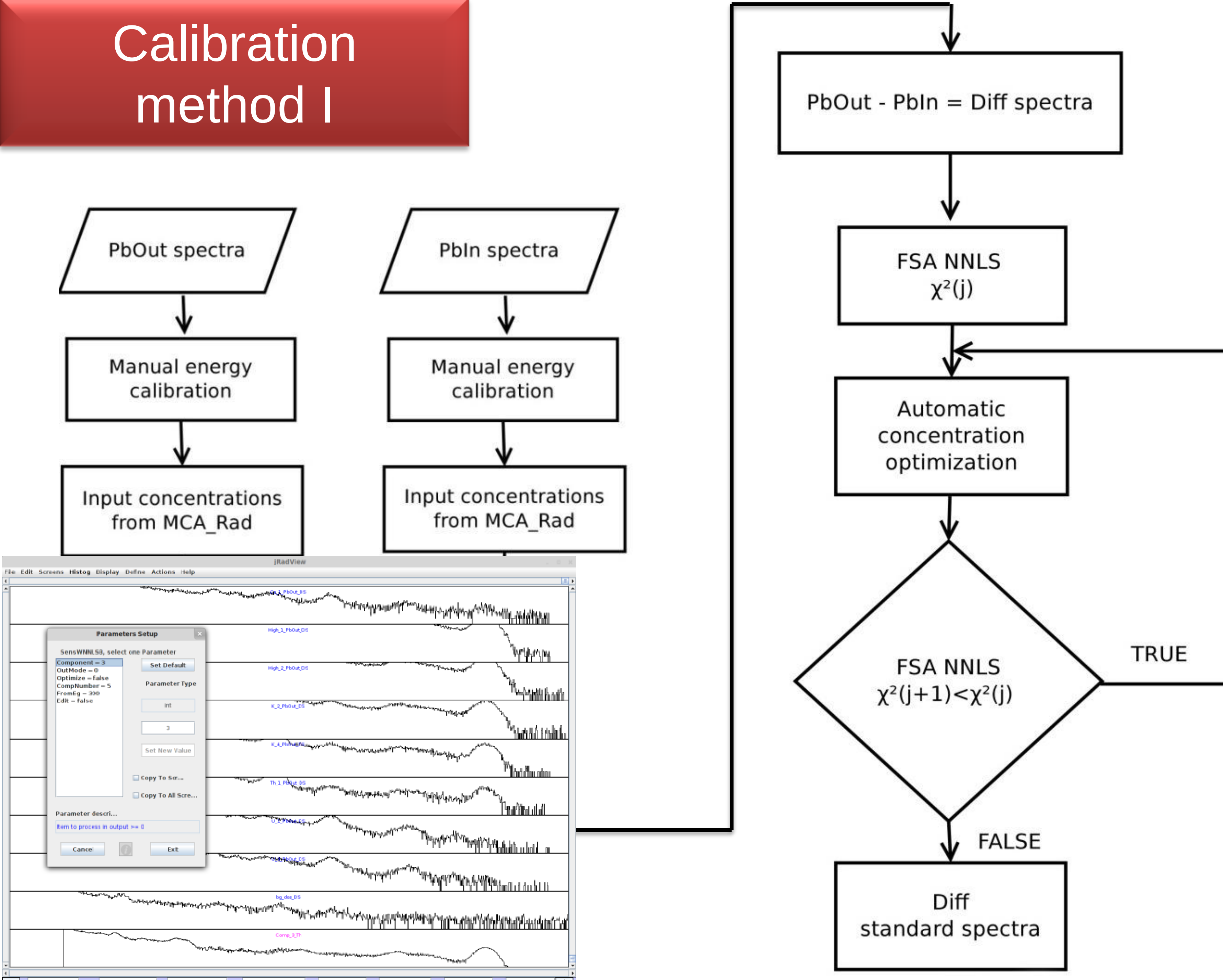
1 rock sample
AROUND the detector
(< 60 cm radius)

1 rock sample
UNDER the detector

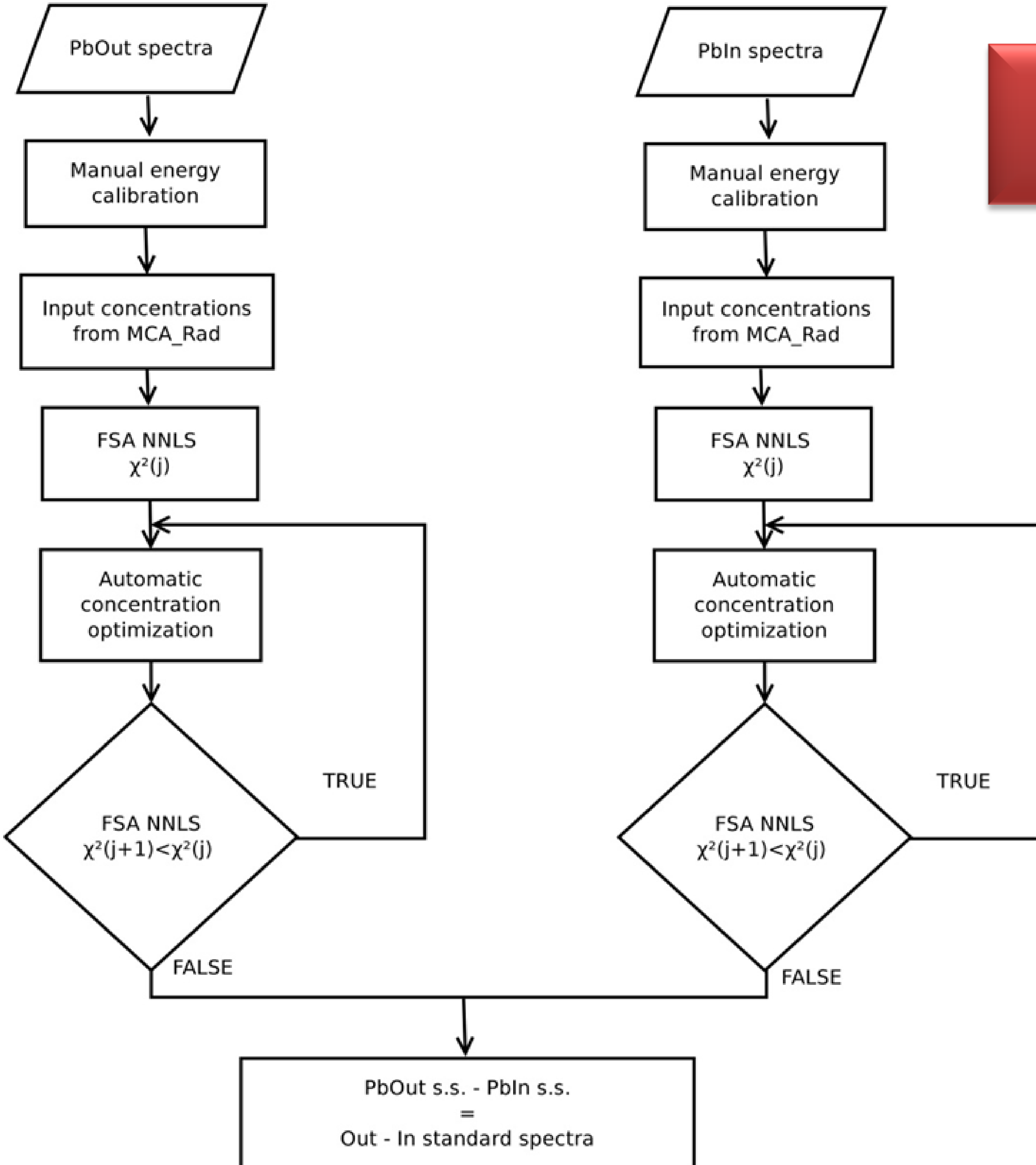
Analysis in laboratory

Spectra	Field of view	Input abundances
PbIn	~ 1 m^2	Around
PbOut		Average
Diff	~ 100 cm^2	Under

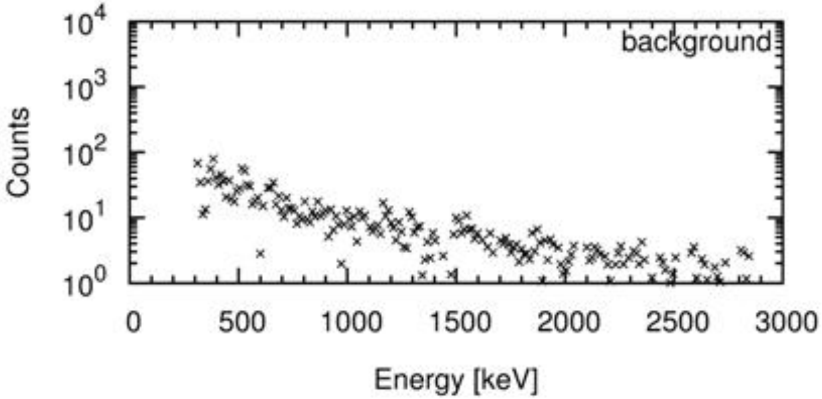
Calibration method I



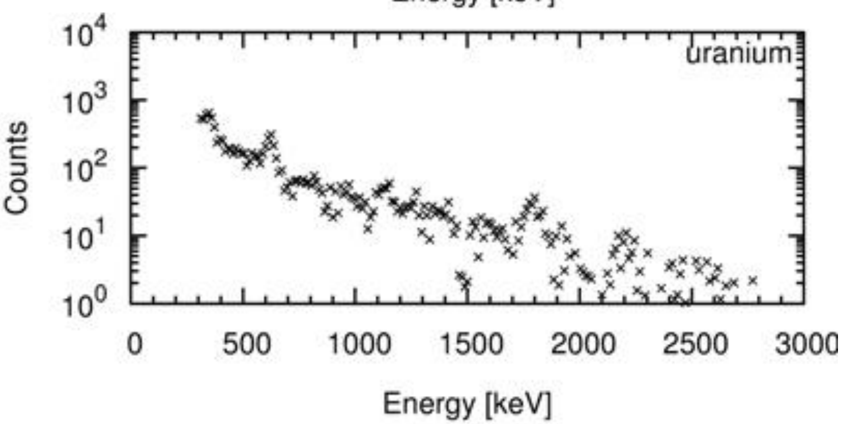
Calibration method II

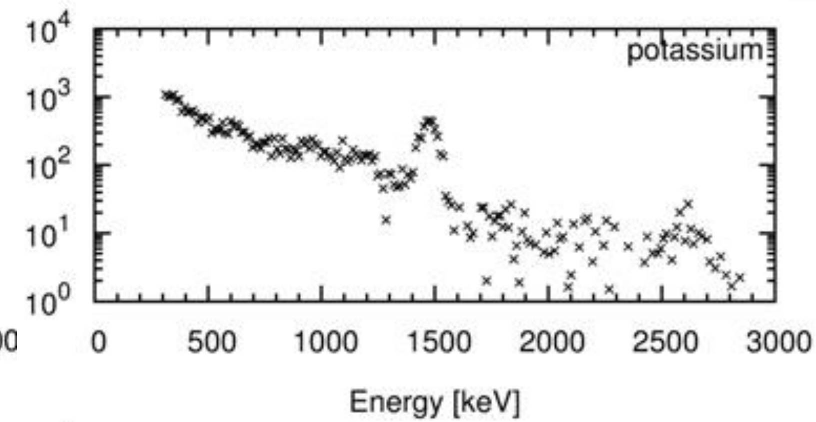


Standard spectra

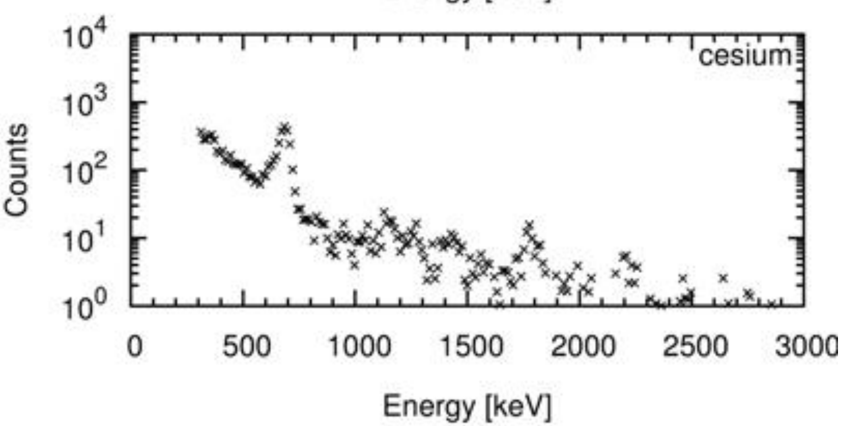


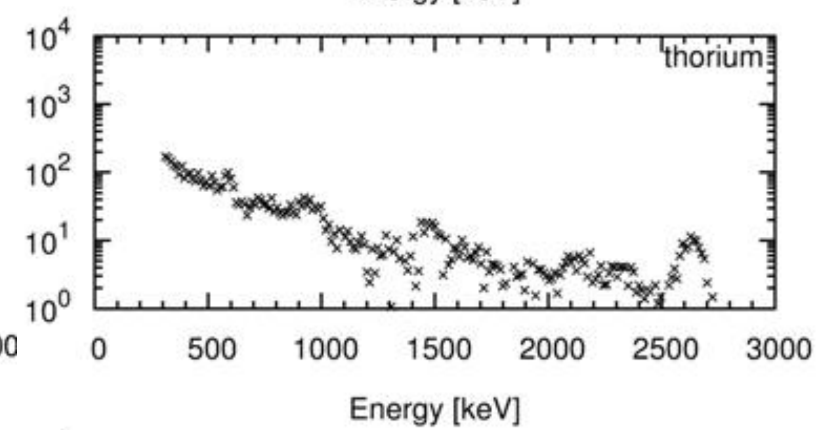
Background: internal BG, cosmic rays and atmospheric radon





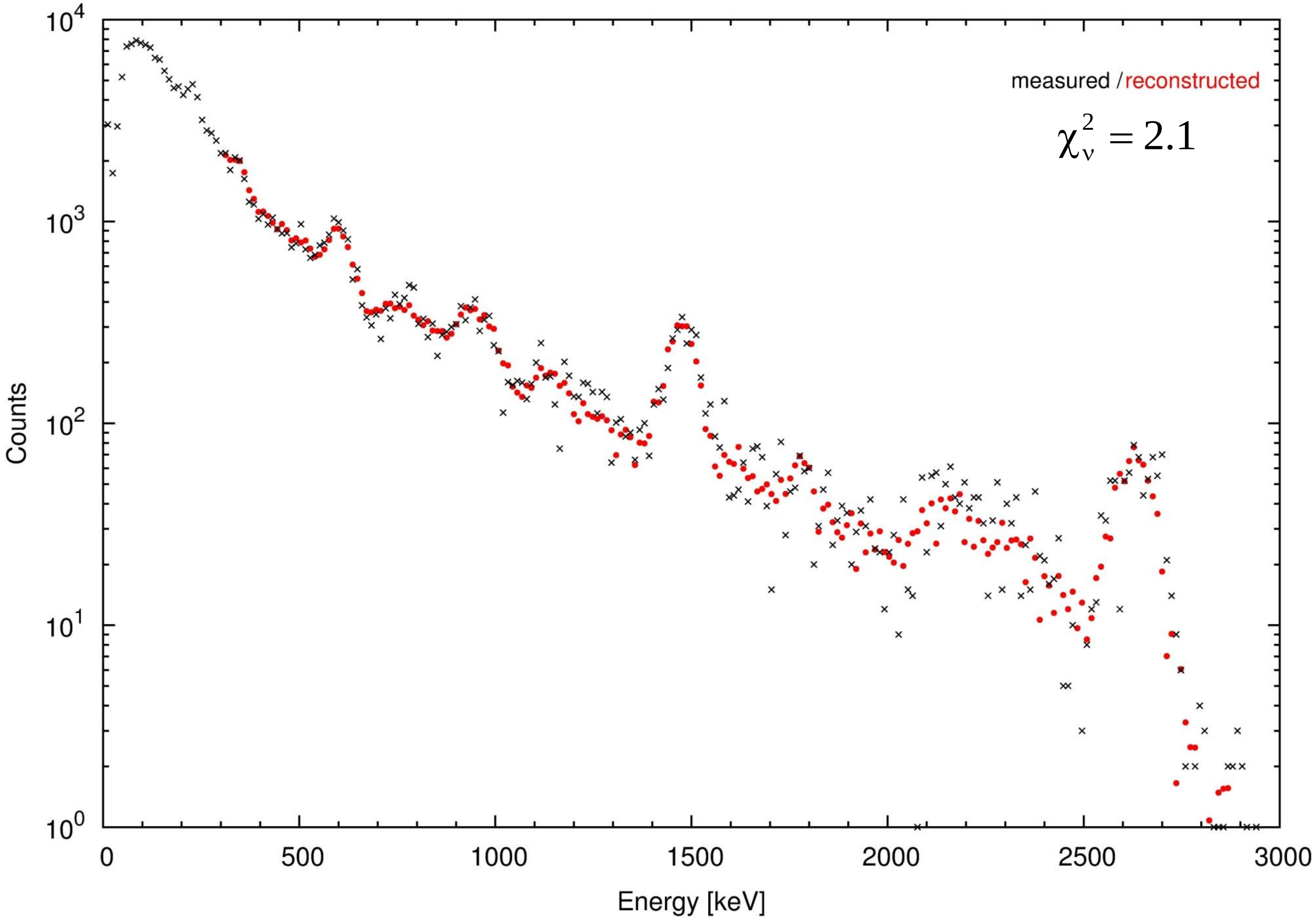
✓ **The obtained spectra show the expected shape**





✗ **The standard spectra are affected by low statistics**

Measured and reconstructed spectrum



Internal cross-validation

By means of **standard spectra**, I calculate the **radioactivity content** of the **calibration sites**, using FSA with NNLS constraints.

I compare the results with the **input abundances** obtained by HPGe values.

	Regression line slope $m \pm \sigma$			
	Optimized		Non-optimized	
	Method 1	Method 2	Method 1	Method 2
K	0.95±0.06	0.72±0.09	1.07±0.03	0.89±0.07
U	0.94±0.07	0.75±0.07	0.87±0.08	0.86±0.06
Th	1.07±0.03	0.78±0.02	0.89±0.02	0.90±0.02
Cs	0.84±0.02	0.49±0.06	0.74±0.03	1.10±0.03

- Method 1 better than method 2 in reproducing input data
- Optimization process improves the fit (χ^2_ν)
- The algorithm functions for both methods are validated

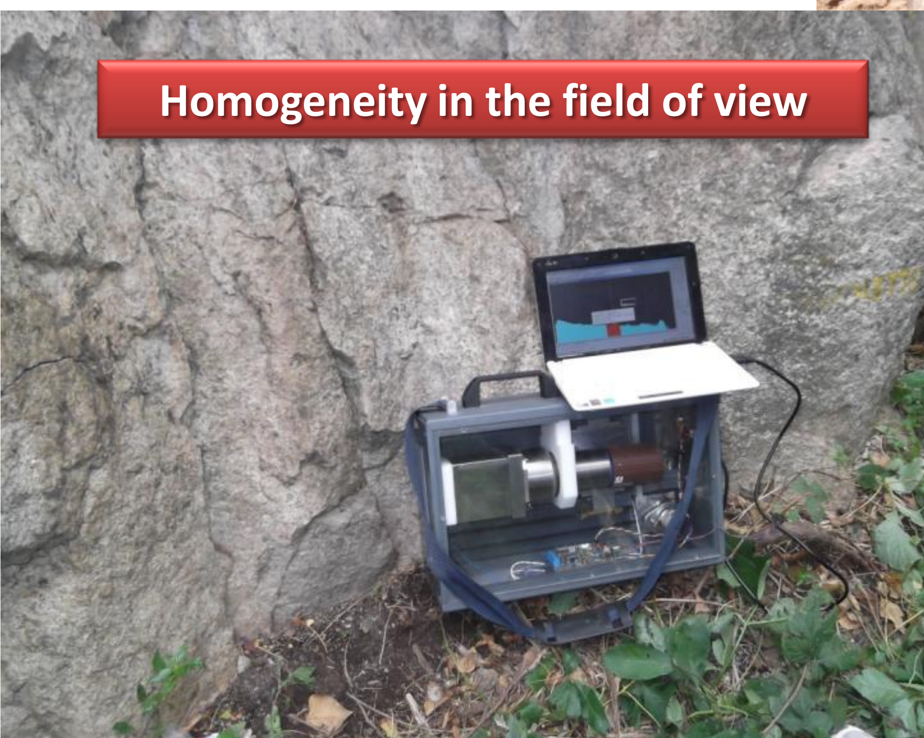
Measurements for performance validation

Monti Vulsini (south Tuscany)

Deposits of different piroclastic rocks due to volcanic activity (~300.000 years ago). High spatial variability of radionuclides abundances.

Euganean Hills (Veneto)

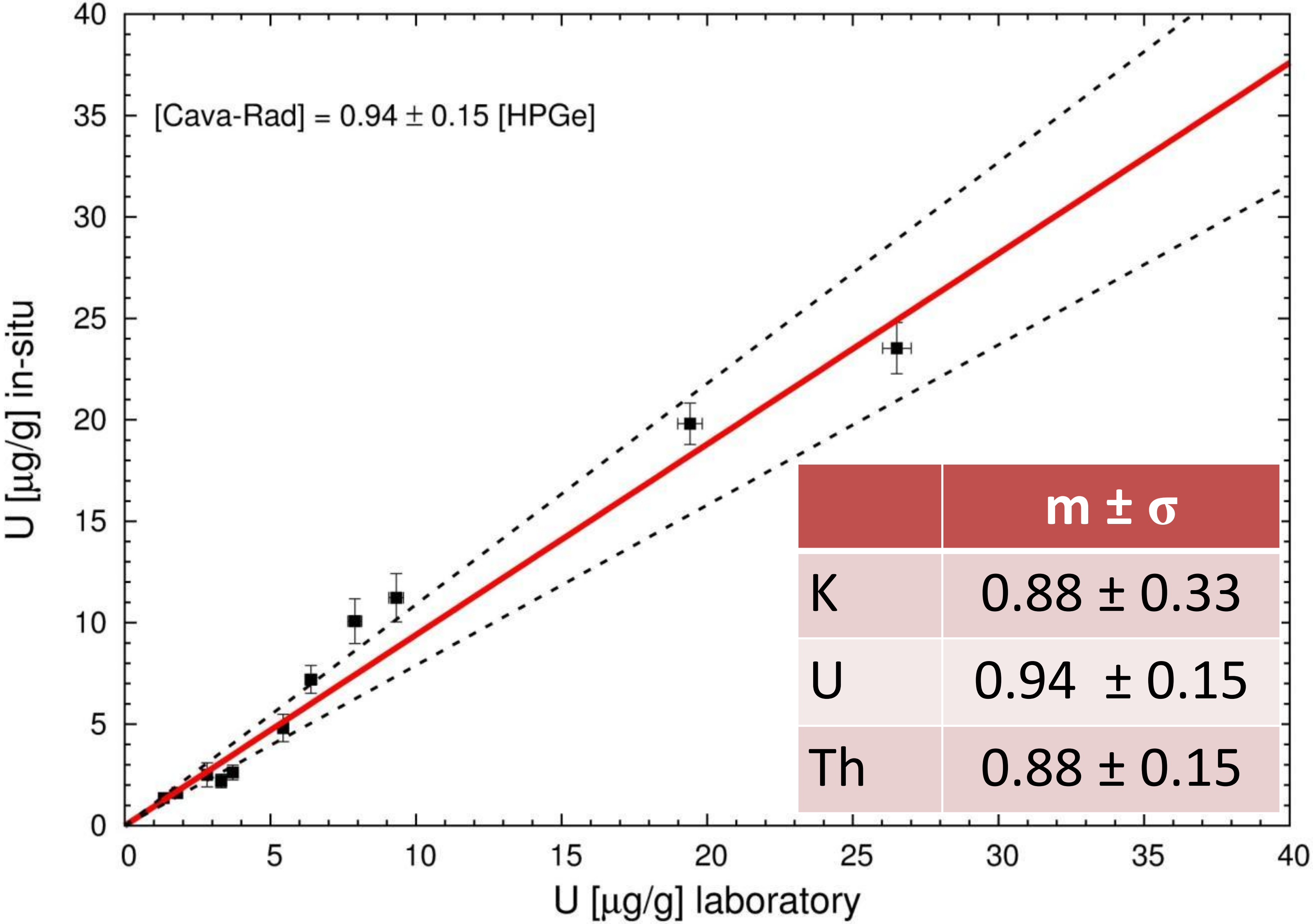
Homogeneous outcrops of acid effusive rocks.



In-situ:
- PbOut and PbIn measurements
- Acquisition time: 5 or 10 minutes

In-laboratory:
- Sample collection, under the detector
- Analysis in laboratory (MCA_Rad)

In situ measurements analysis: Euganean Hills

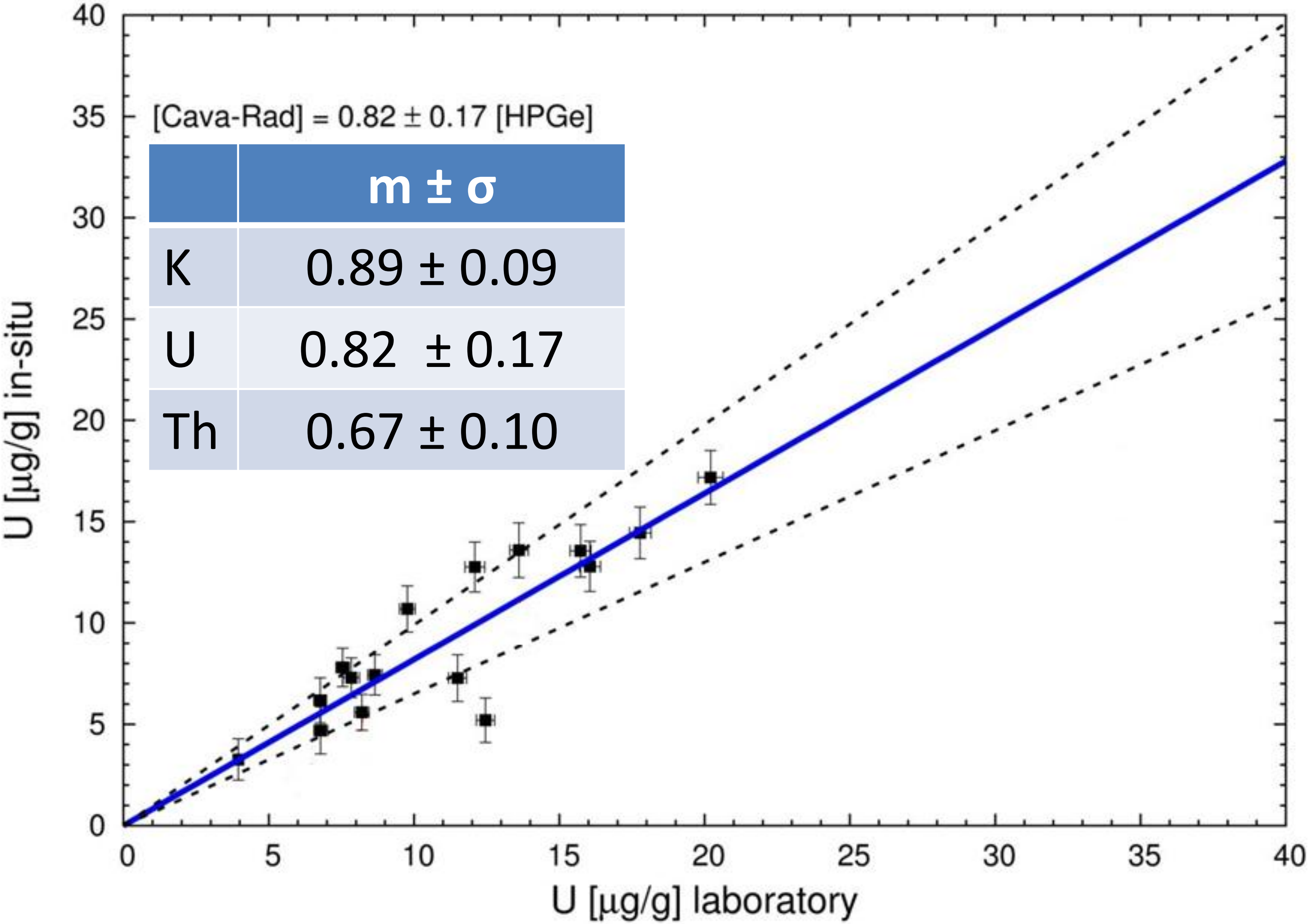


	m ± σ
K	0.88 ± 0.33
U	0.94 ± 0.15
Th	0.88 ± 0.15

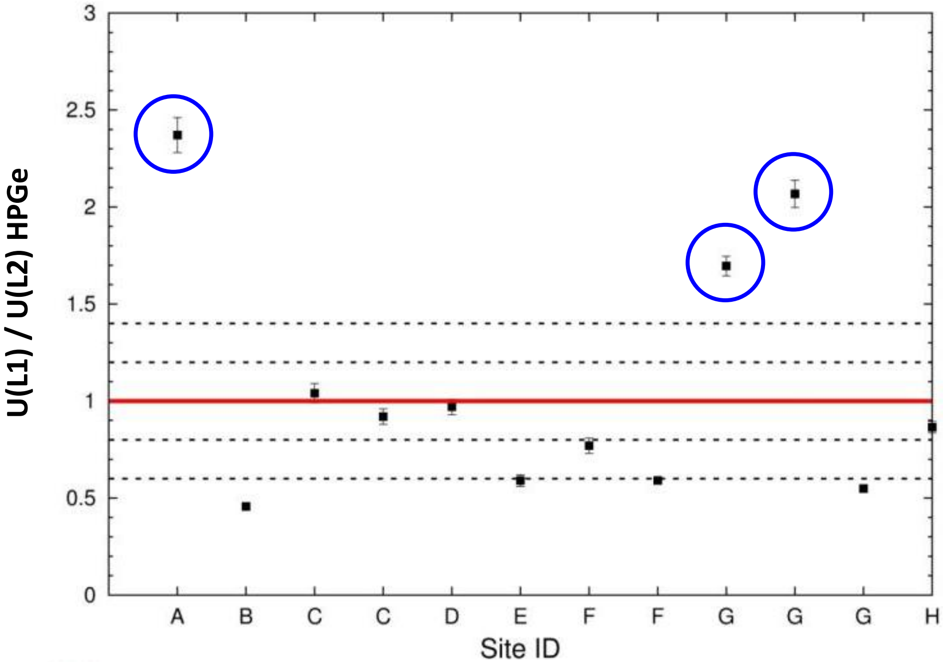
^{137}Cs is not included because it is not present in the fresh outcrops.

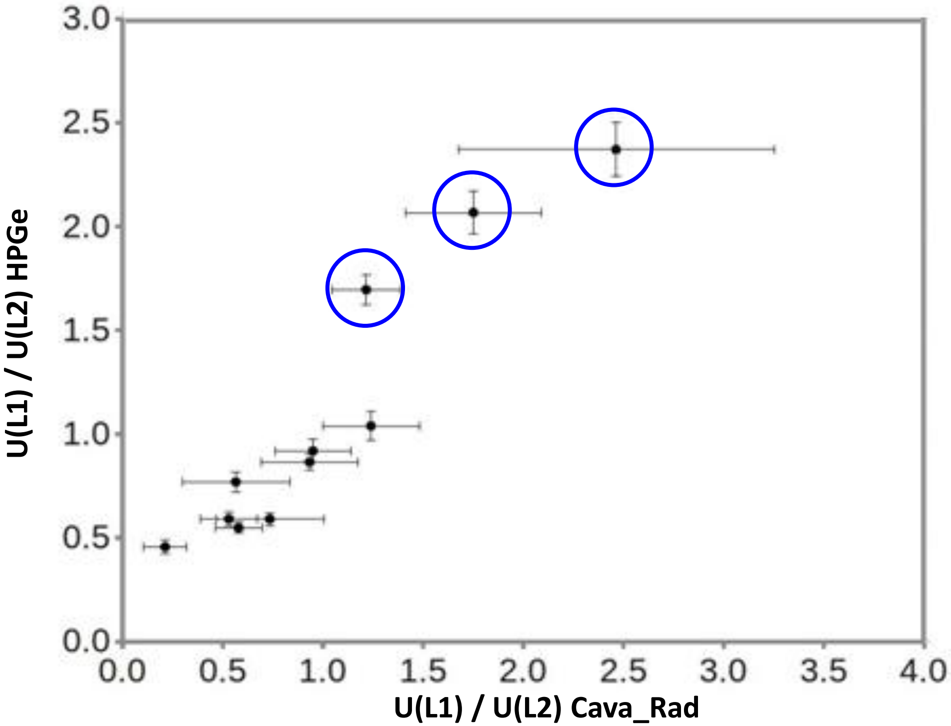
In situ measurements analysis: Monti Vulsini

	m ± σ
K	0.89 ± 0.09
U	0.82 ± 0.17
Th	0.67 ± 0.10



Testing spatial sensitivity in Monti Vulsini sites

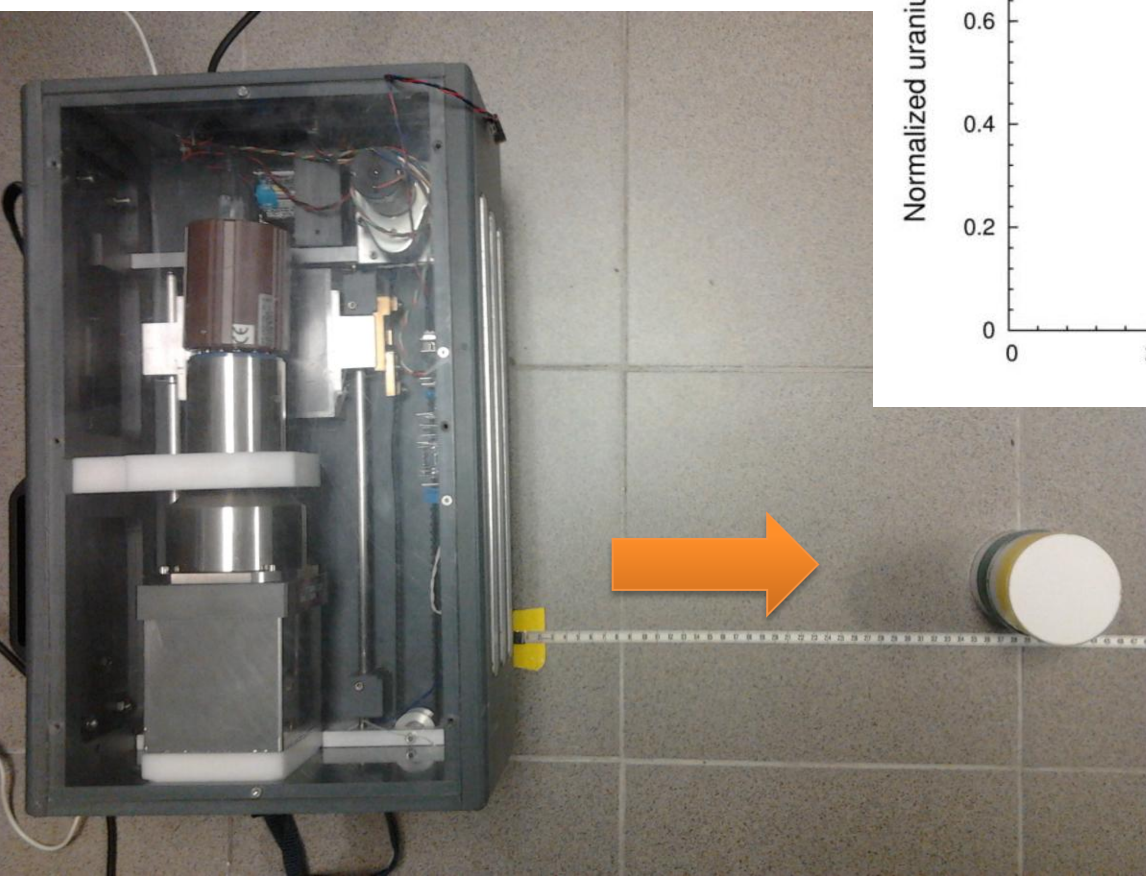


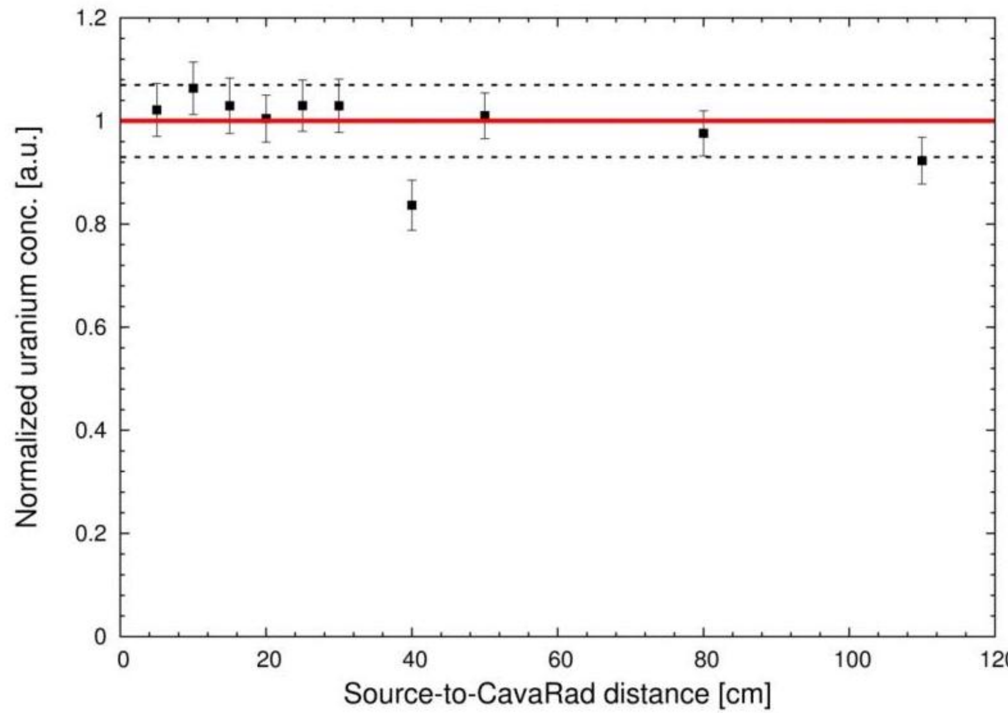


- Two consecutive layers (L1 and L2) correspond to different eruptions.
- The variability of radioactivity content is measured by HPGe in 12 couple of layers.
- The sensitivity of Cava_Rad to the spatial variability is confirmed in the case of remarkable inhomogeneity.
- Visible relative contrast [*a*(L1) / *a*(L2)] > 1.2

Side noise study in laboratory

- **Source**: Uranium ore (~1200 µg/g) under the detector.
- **Noise**: 2 boxes containing uranium ores (400 µg/g) diluted in silica powder.





Uranium abundances are normalized on their mean value

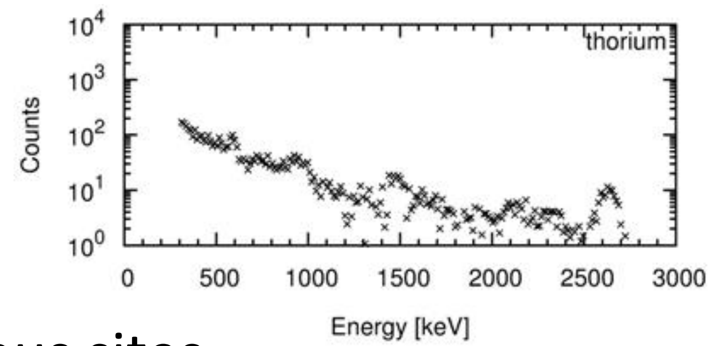
Varying the strength of the noise, the Uranium content is measured with 7% precision

(PbOut – PbIn) filters lateral noise

Conclusions

- **Cava_Rad is calibrated** with the best approach: method 1 with optimization of input abundances.
- A **set of standard spectra** is included in the software ready to use in-situ measurements.
- The **counting uncertainty** is on the order of 15%.
- The **side** and **background noise** are successfully filtered.
- In **homogeneous sites** the in-situ and laboratory measurements are comparable at 1σ level.
- The sensitivity of Cava_Rad to the **spatial variability** of radioactivity content in thin layers is checked.

Future perspectives



Further studies:

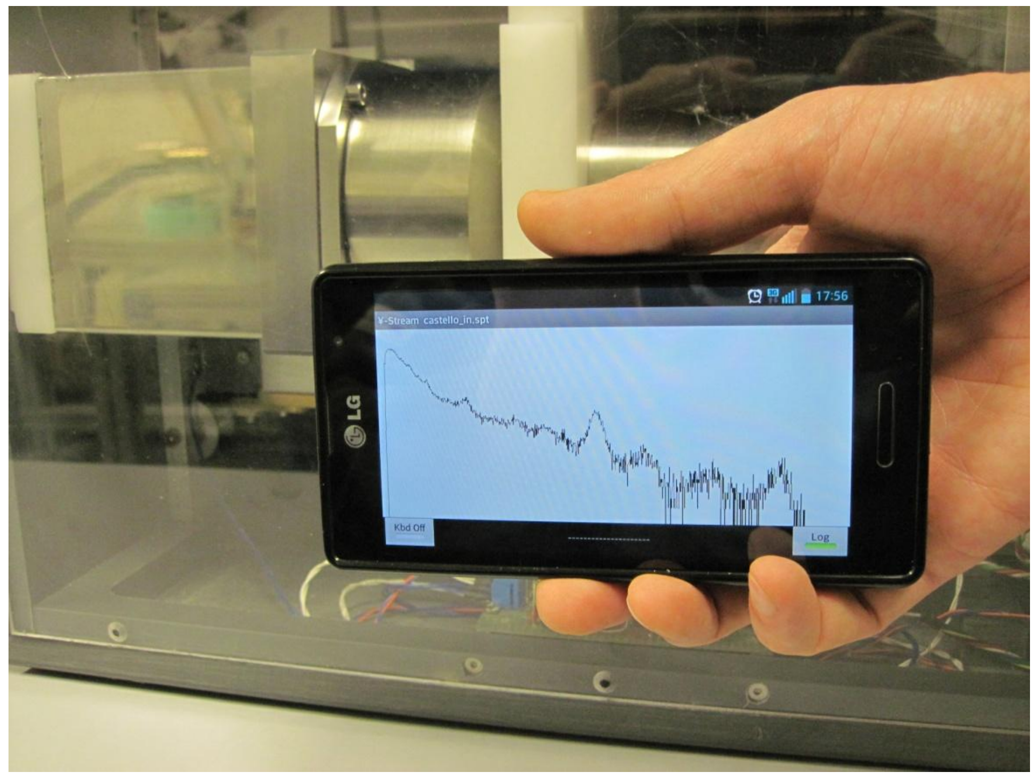
- longer acquisition time in calibration measurements
- thorium underestimation in inhomogeneous sites

Software implementation:

- a dedicated software with automatic spectrum analysis

Hardware implementations:

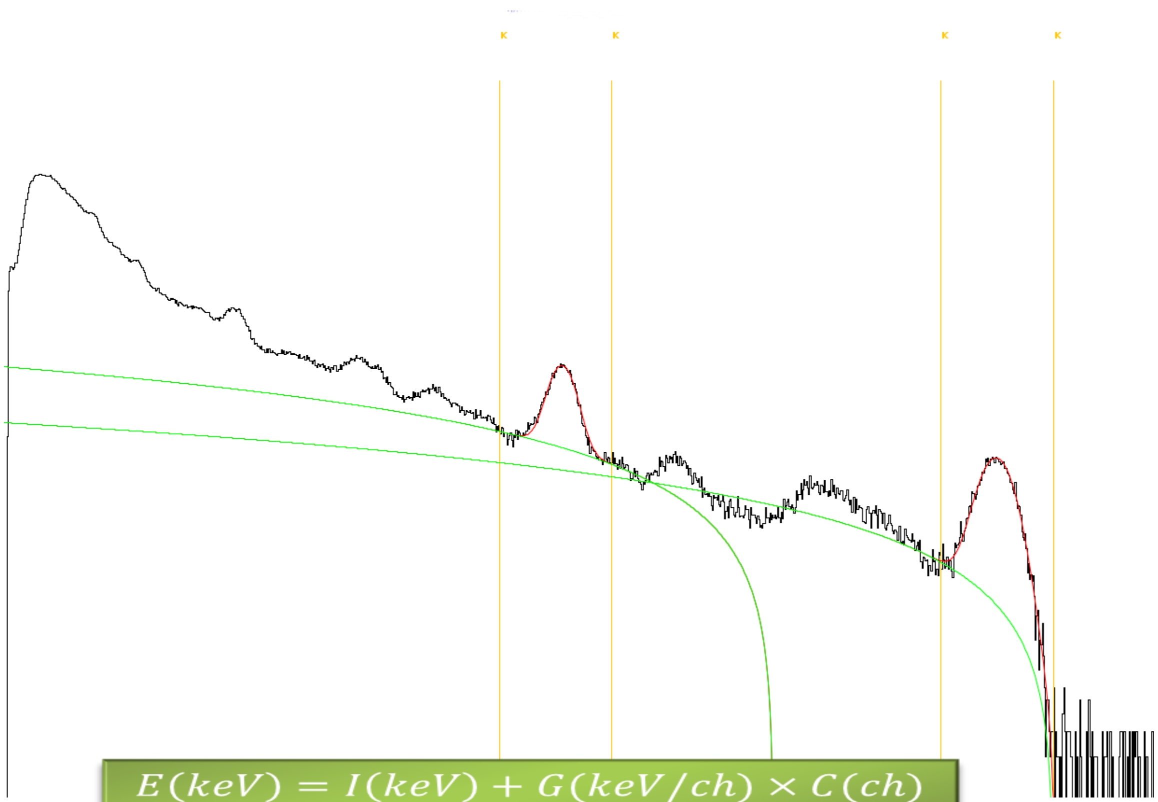
- wireless connection to tablet
- miniaturization of the box and optimization of the electronics



Thank you for your kind attention

Energy calibration

Gamma-ray spectrum interpreted in terms of gamma- ray energy rather than channel number.



$$E(keV) = I(keV) + G(keV/ch) \times C(ch)$$

- To each selected peak is associated a radionuclide decay energy.

$^{40}K \rightarrow$ 1460 keV

$^{208}Tl \rightarrow$ 2614 keV

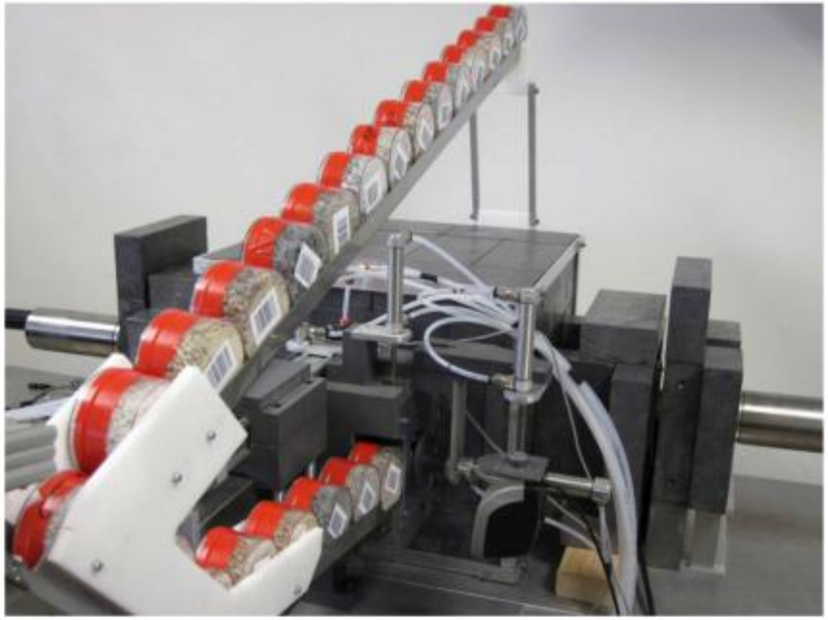
- Centroid fit with gaussian function

- Rebining 12 keV/ch

Collected samples analysis with MCA_Rad

Samples are:

1. crushed,
2. constant weight dried in a special thermostatic oven at 105°C,
3. sealed in polycarbonate boxes
4. left sealed for a period of about 1 month (^{226}Ra - ^{222}Rn equilibrium)
5. measured by MCA_Rad



Spectrum Analysis Methods

WAM

Windows Analysis Method

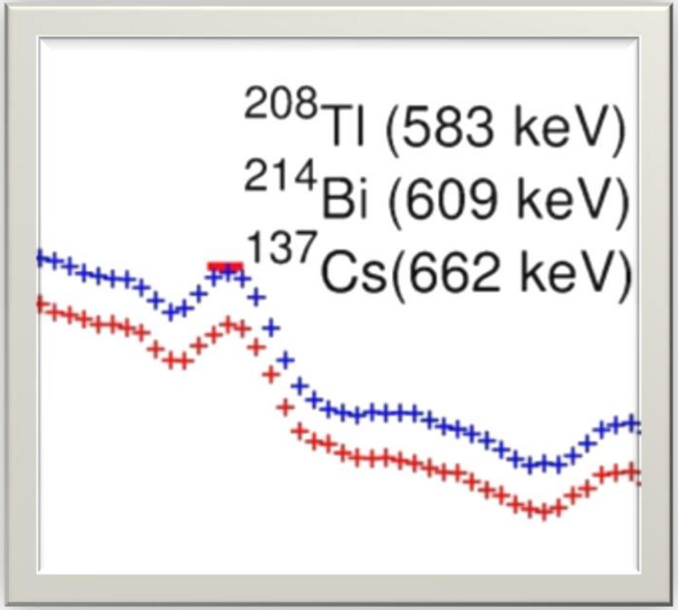
The activity concentration is determined by the net counts in the energetic windows chosen around the photopeaks

FSA

Full Spetrum Analysis

All the spectrum is analyzed, and the activity concentration is determined by a linear combination of the standard spectra, by means of $\chi 2$ minimization

WAM



The Cava_Rad NaI(Tl) does not resolve the triplet in energetic range of ^{137}Cs

Window	Radionuclide	Peak energy keV	Energy band keV
Total counts		40 - 2810	
Potassium	^{40}K	1460	1370 – 1570
Uranium	^{214}Bi	1765	1660 – 1860
Thorium	^{208}Tl	2614	2410 – 2810

FSA

$$\boldsymbol{N} = \boldsymbol{C}\boldsymbol{S}$$

- n_{ij} is the counts rate in the j -th channel for the i-th site,
- c_{ik} is is k-th element concentration corrected for the background, in the i-th site,
- s_{kj} is the detector sensitivity for the k-th element in the j -th channel.

Solve this overdetermined system

The number of chosen calibration sites (9) is larger than the radioelement number, i.e. K, U, Th, Cs.

A standard approach to approximate the solution of an overdetermined system are the least squares

FSA for Calibration

$$\boldsymbol{S} = \boldsymbol{C}^{+}\boldsymbol{N}$$

Iterative process: small quantities variation of the site abundances C_k around the previous values, until the x^2 reaches a minimum.

x^2 minimization can generate unphysical result for instance standard spectra with region of negative energy.

Full Spectrum Analysis with Non Negative Least Squares (NNLS)

Calibration sites

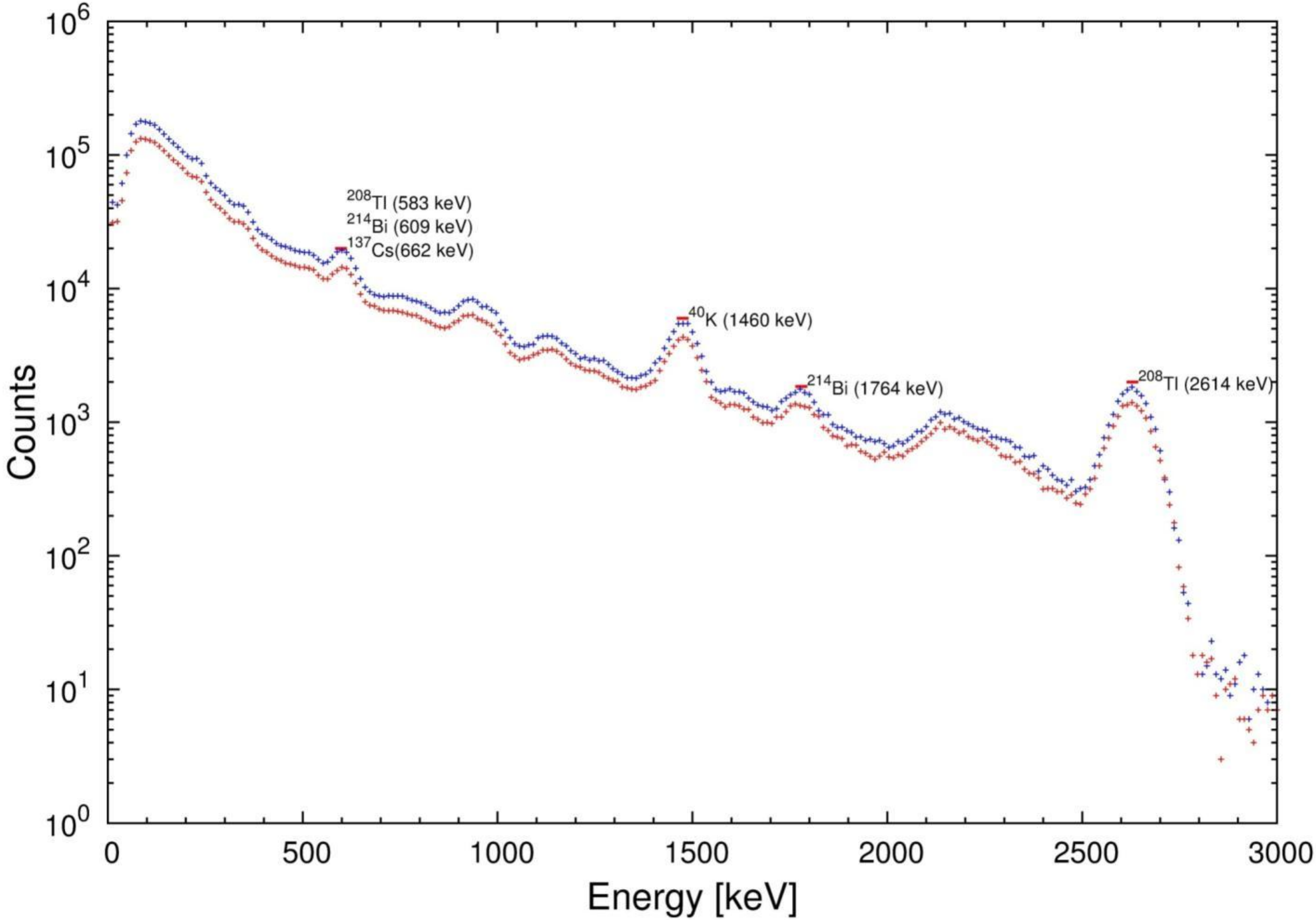
Site	Location	Natural pad for
K2	Galzignano terme	^{40}K
K4	Recoaro	^{40}K
U1	Piovene Rocchette	^{238}U
U3	Arsiero	^{238}U
Th1	Castelvecchio (Altissimo)	^{232}Th
Th4	Corbara (Schio)	^{232}Th
Cs1	Monte Novegno (Schio)	^{137}Cs
H1	Galzignano terme	High conc. of all
H2	Galzignano terme	High conc. of all

- Natural calibration sites
- PbOut and PbIn measurements
- Acquisition time: 30 minutes
- Two rock/soil samples collected in each site: **under** the dector and **around** (1 m)

Background site

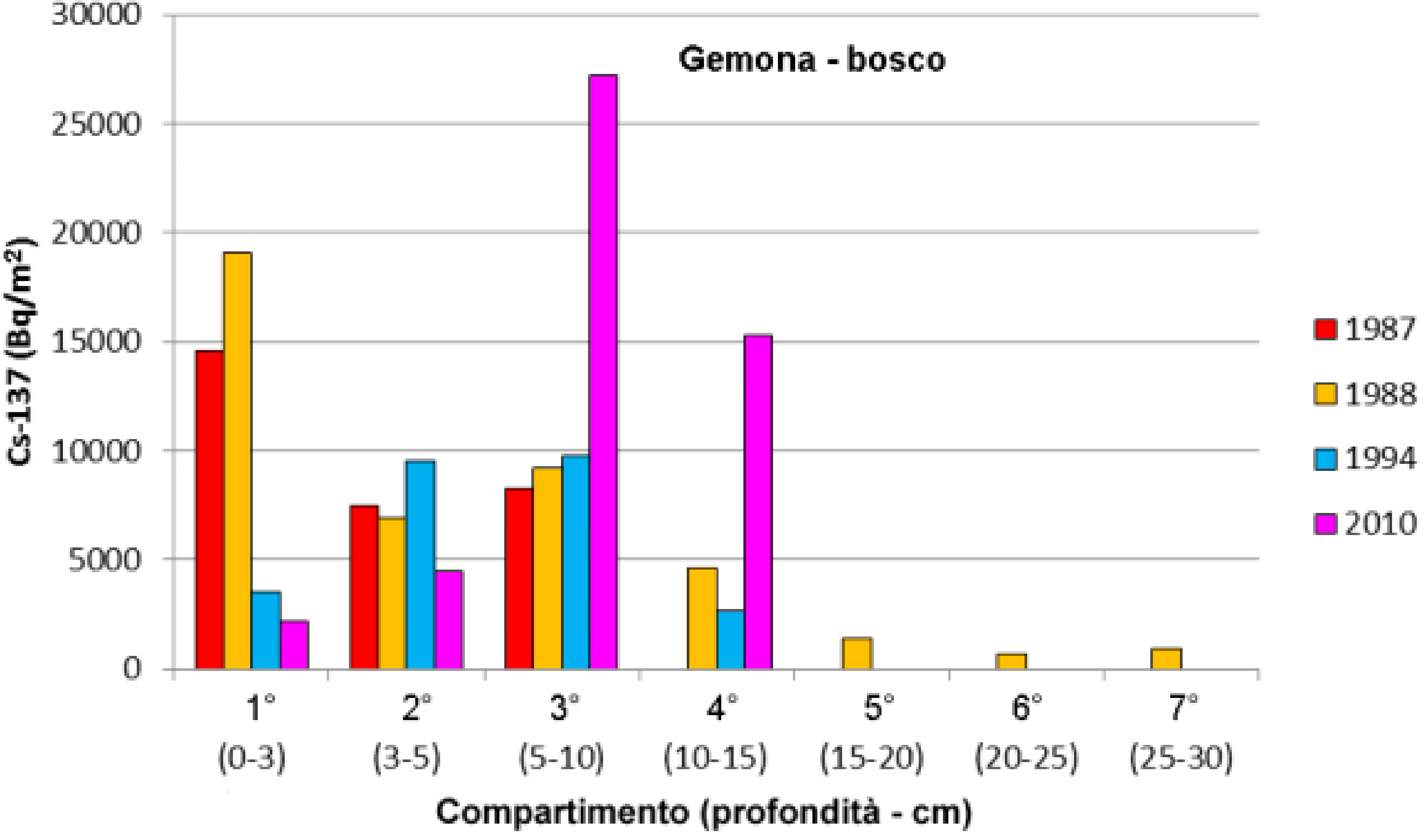
- Location: Lido di Spina (FE)
- Acquisition time: 1h
- Water depth: 3 m

Background main contributions:
- Cosmic rays
- Atmospheric radon
- Radiation interaction with shield



Counts
Energy [keV]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
0
500
1000
1500
2000
2500
3000
^{208}Tl (583 keV)
^{214}Bi (609 keV)
^{137}Cs(662 keV)
^{40}K (1460 keV)
^{214}Bi (1764 keV)
^{208}Tl (2614 keV)

Cs-137 vertical distribution



Units of measurement

- 1%K = 313Bq/kg
- 1µg/g eU = 12.35Bq/kg
- 1µg/g eTh = 4.06Bq/kg
- 1ng/g Cs = 3200Bq/kg