Young Scientist Workshop
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Germanium Detectors and Natural Radioactivity in food

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$\Delta p \cdot \Delta q \geq \frac{1}{2} \hbar$

Outline

→ **Introduction to Germanium detectors**
- radiation detection in semiconductors
- properties of Germanium detectors

→ **Experimental setup**
- background measurement
- weak sources
- background reduction

→ **Data analysis**
- calibration with KCl salt
- measurement of food rich in Potassium

→ **Conclusions**
- summary
- outlook

Introduction to Germanium detectors

RADIATION → **DETECTOR** → **DATA**

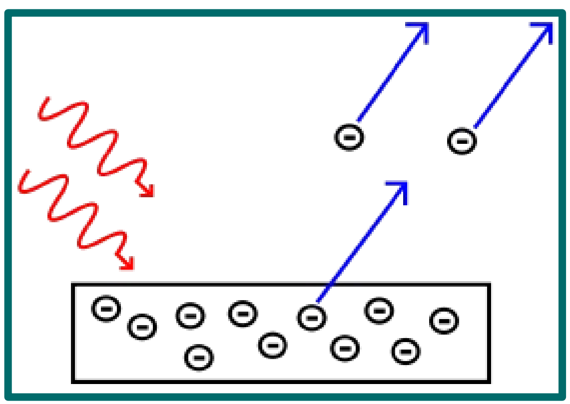
- RADIATION

a) which kind of radiation?

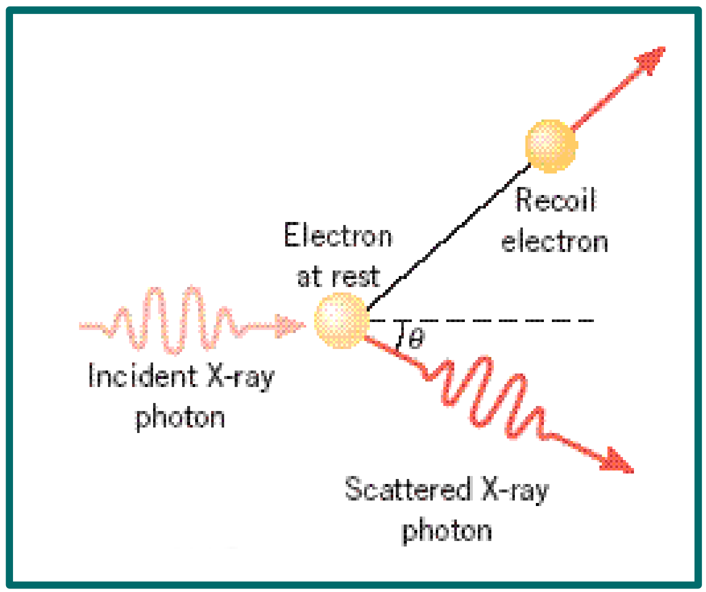
PHOTONS: produced in the decays of radioactive isotopes

b) what can they do in matter?

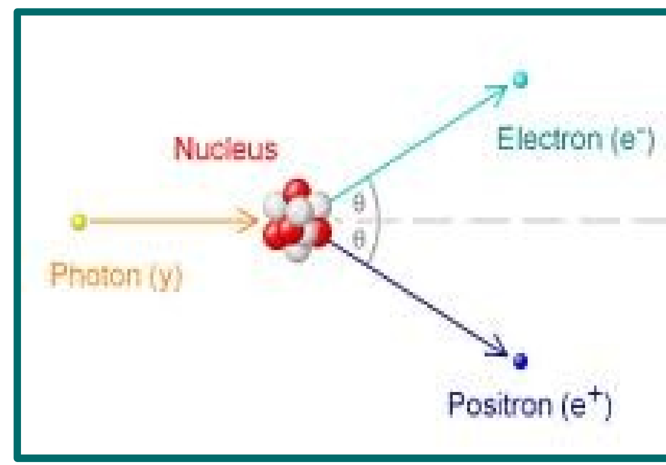
PHOTOELECTRIC EFFECT



COMPTON EFFECT



PAIR PRODUCTION



We will use TOTAL ABSORPTION EVENTS

Introduction to Germanium detectors

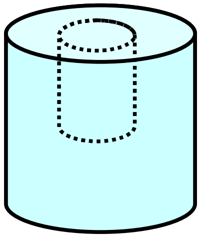
RADIATION → **DETECTOR** → **DATA**

- DETECTOR

a) which kind of detector?

Closed-ended Coaxial

eXtended Range Germanium detector

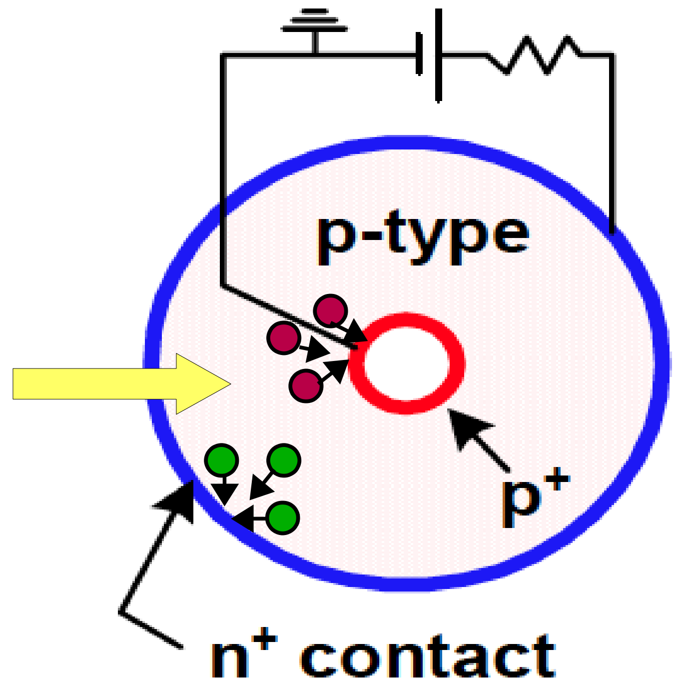


p-type crystal

b) how does it work?

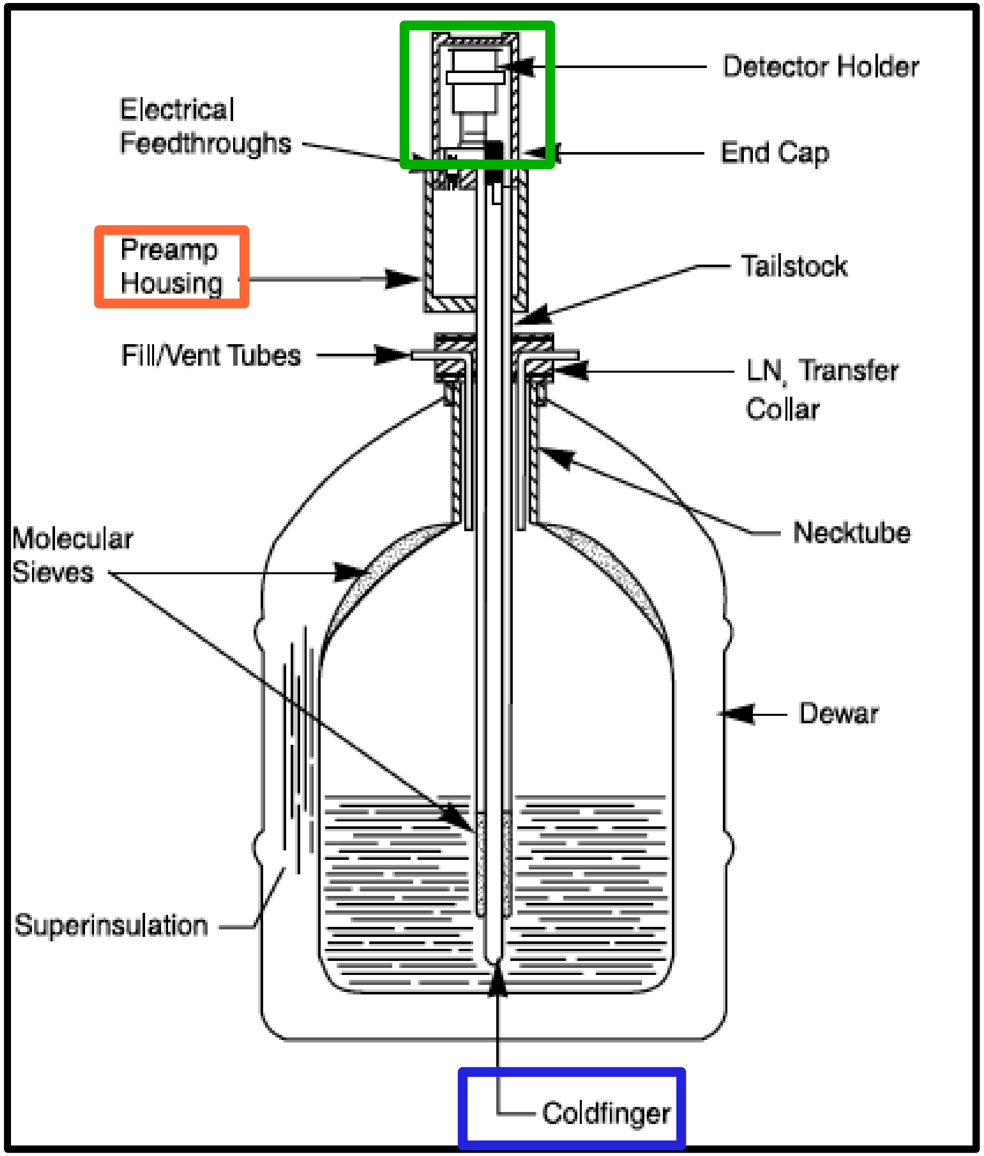
- **large diode** with a **reverse bias**
  → a POSITIVE outside potential

- **radiation** → goes into the crystal
  → electron-hole pairs
  → under Electric Field
  - ● electrons go to **n+** contact
  - ● holes go to **p+** contact



How can we use such a detector?

Introduction to Germanium detectors



A) The detector is in a **clean vacuum chamber**

B) The detector **has to be cooled**:
- reduce thermal charge carrier generation (**noise**)
- thermal contact with **LN_2**

C) charges collected on the **electrodes**

- charge sensitive **preamplifier**
- sample resulting **pulse**

Pulse amplitude proportional to energy deposited in the detector!!

What can be measured? ENERGY SPECTRA

Introduction to Germanium detectors

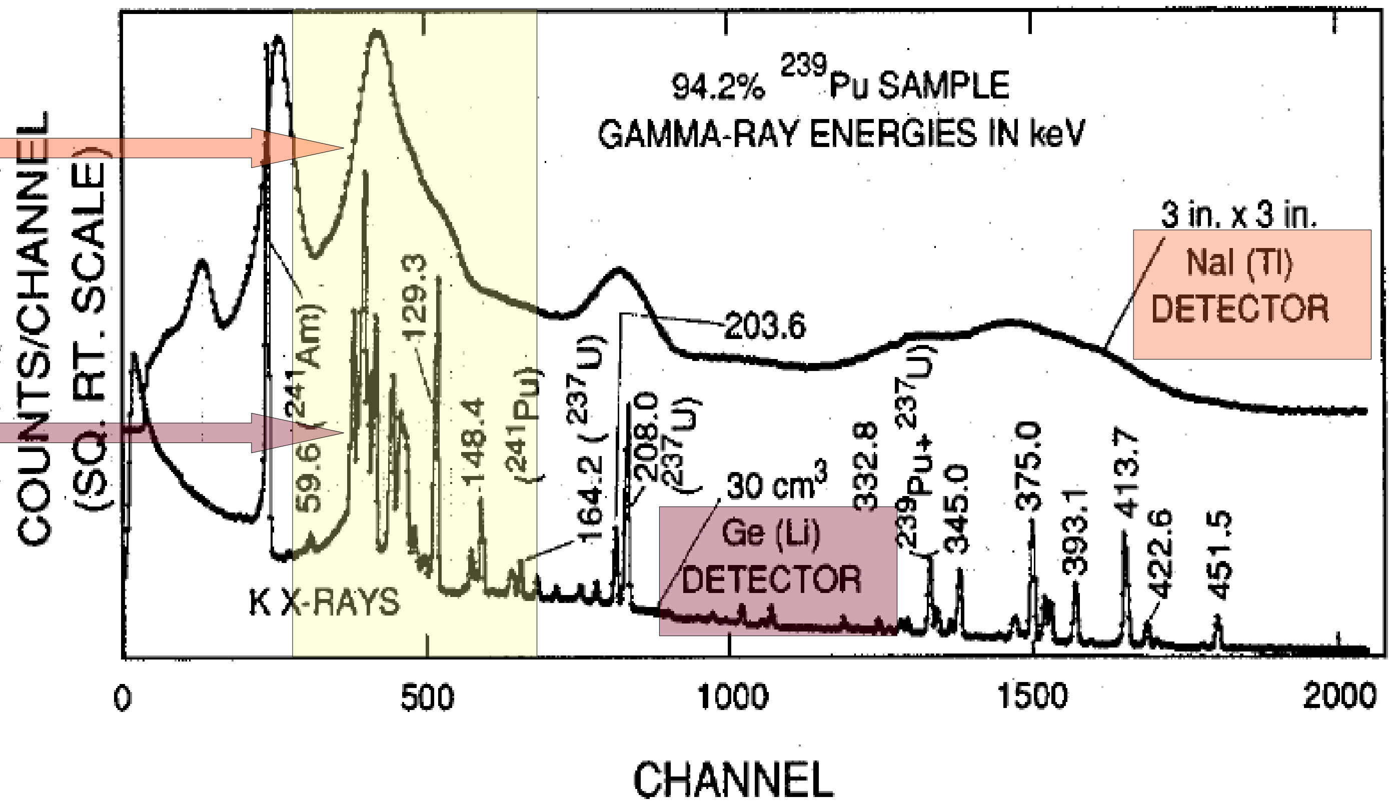
Features of Germanium detector → effect on the spectrum

- **small energy** required to **create e-h pair** → **large** output **signal**

- **ultra pure** material → **intrinsic detection efficiency** close to **100%**
→ **best possible energy resolution**

1 single line

5 different lines



- **Resolution is better than expected from statistics**
(revealed on the full energy peak)

OBSERVED VARIANCE = F*POISSON VARIANCE

→ the total number of **IONIZATION has a constraint**
THEY are **not INDEPENDENT** anymore

NO POISSONIAN STATISTICS

First evaluation of the variance **U. Fano, Phys. Rev. 72 (1947) 26**

- **energy** and **momentum conservation**
- the energy deposited is a **FIXED value E_0**
  - fluctuating **BUT** not independent variables
    - N_x lattice excitation
    - N_Q charge carriers

ε_i = 2.9 eV
$E_g = E_i$ = 0.66 eV
E_x = 21 meV

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x}N_i} = \sqrt{\frac{E_0}{\epsilon_i}}\sqrt{\frac{E_x}{E_i}\left(\frac{\epsilon_i}{E_i} - 1\right)} = \sqrt{FN_Q}$$

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Experimental setup

- what can we measure with XtRa?

Photons produced the decay chains of radioisotopes

Two kinds of measurement

Background measurements
=
everything else but a source

NATURAL RADIOACTIVITY

- cosmic radiation
- **terrestrial sources**
  - potassium
  - carbon
  - uranium and thorium (decay chain elements)
- **human produced source**
  - Cs from nuclear explosions

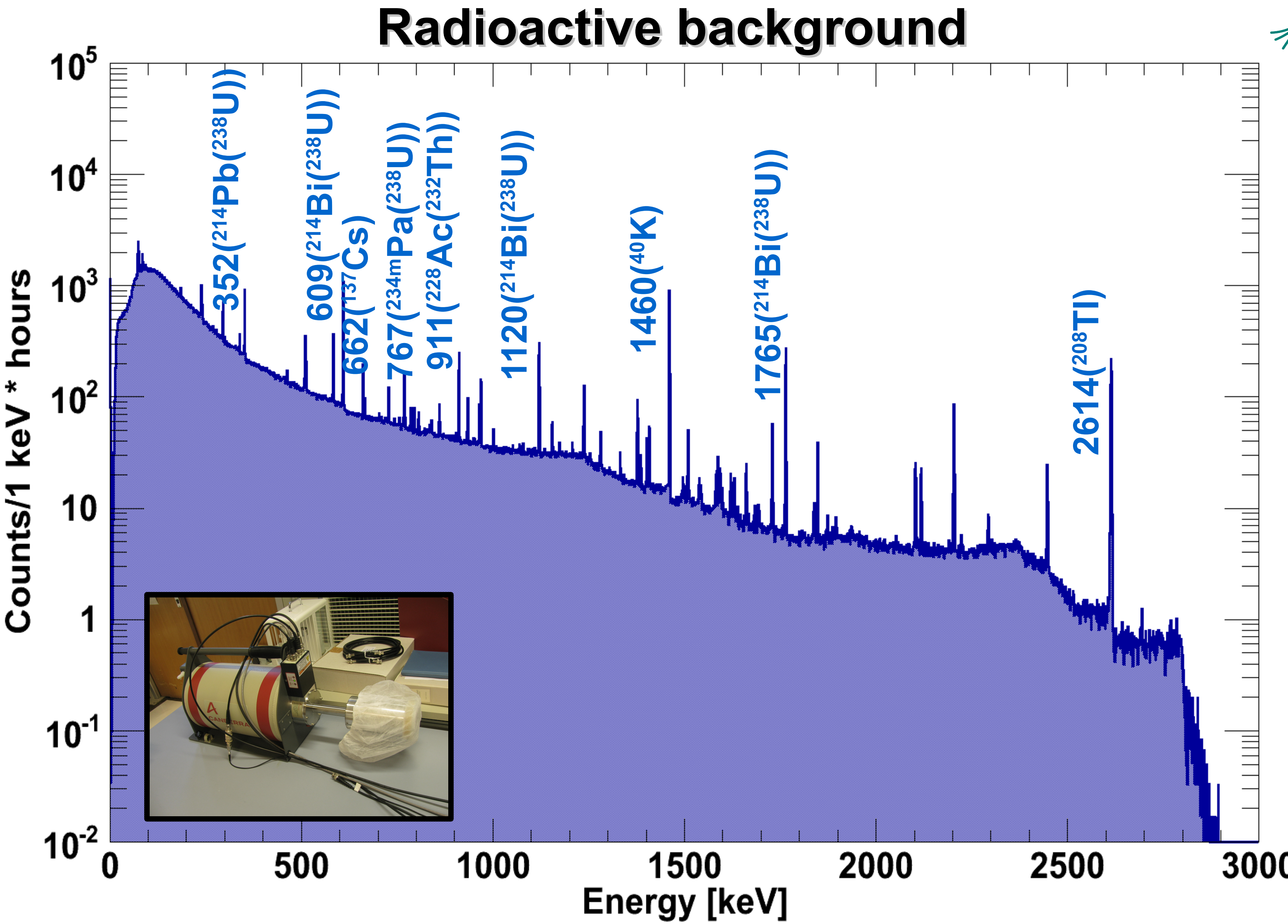
Source measurements

1) EASY
- **strong sources**
- not present in natural background

2) DIFFICULT
- **weak sources**
- present in natural background

Energy spectra → IDENTIFY RADIOISOTOPES
→ QUANTIFY THEIR ABUNDANCE

Experimental setup



- cannot measure a source without background
  - **bkg SUBTRACTION is needed**... but is it good **enough** for weak sources?

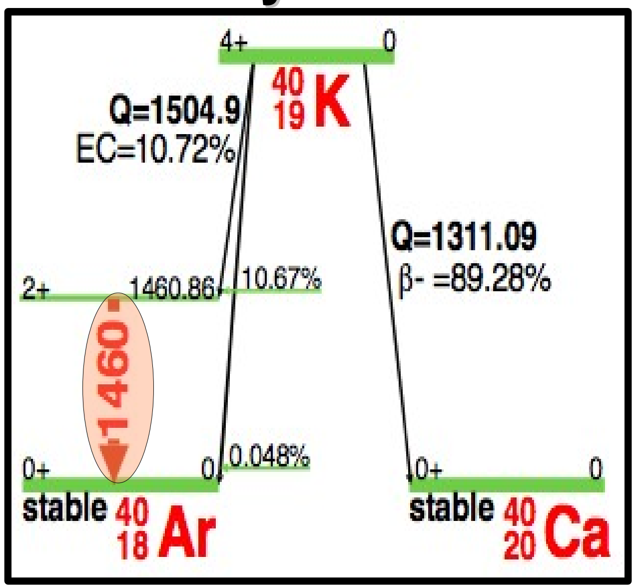
Experimental setup

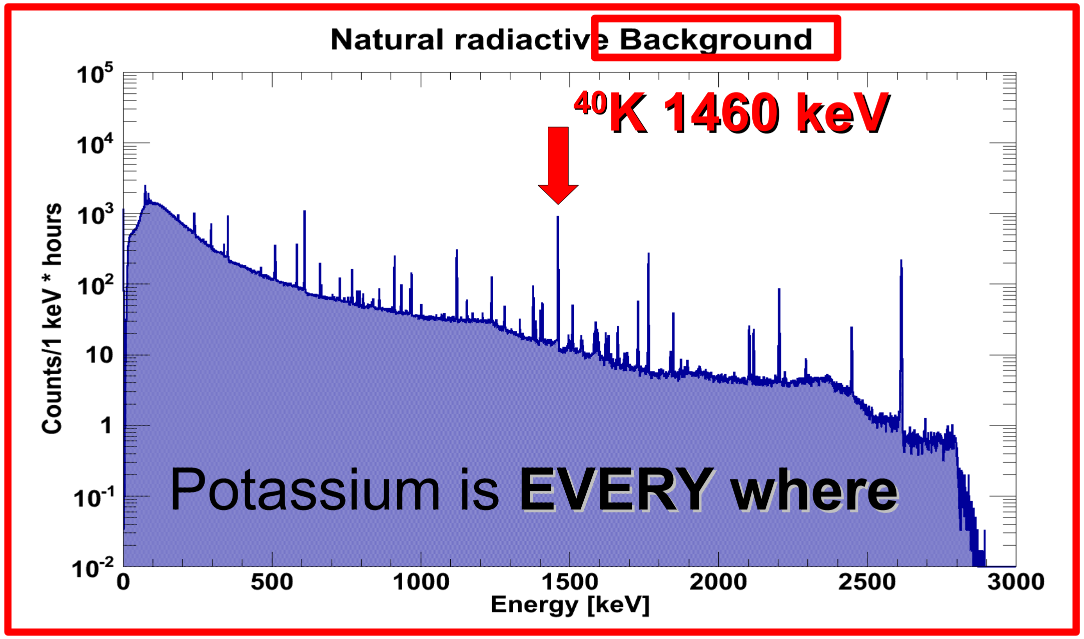
Weak Sources: Potassium in food

- each food sample contains Potassium

- **100 g of strawberry** contains **153 mg of K** and **0.018 mg** of ^{40}**K**
    - small quantity of ^{40}K → small **activity** expected!!

Decay scheme





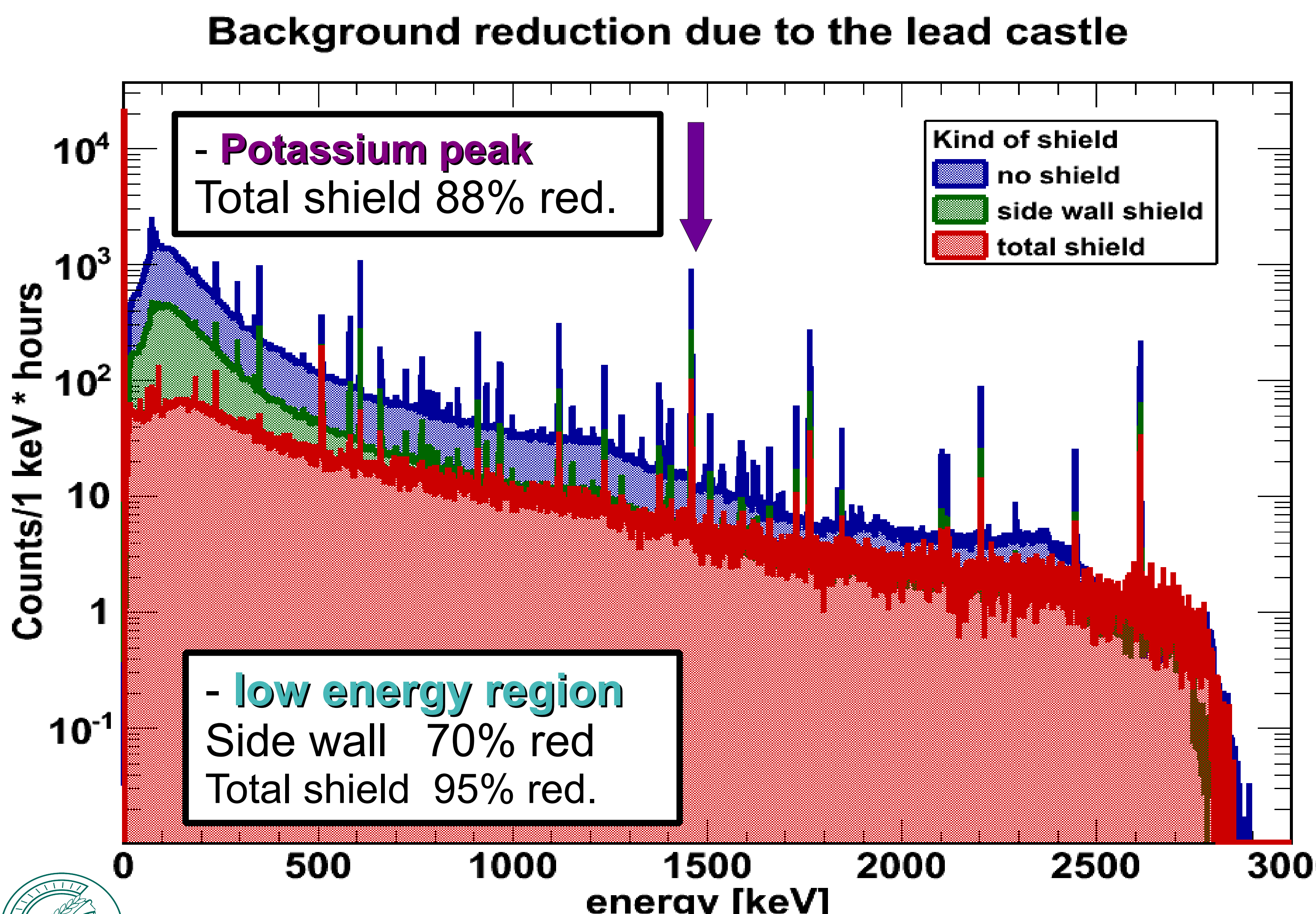
expected counts from the weak source in 1 hour → 20 counts
expected counts from the bkg radiation in 1 hour → 1000 counts

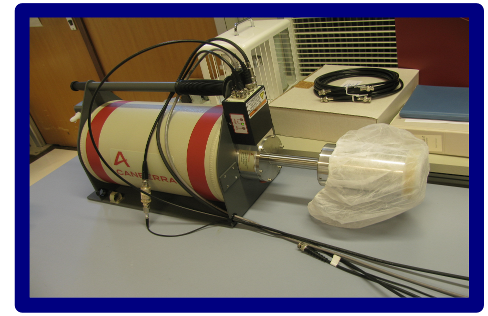
Signal is less than a fluctuation of the bkg!!! WE CANNOT SEE IT!!

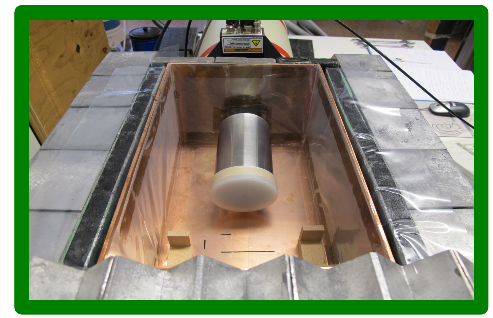
Experimental setup

How can we **reduce the counts of background**?
- shielding the detector from natural radiation

LEAD SHIELD → high density and high Z can reduce the bkg!

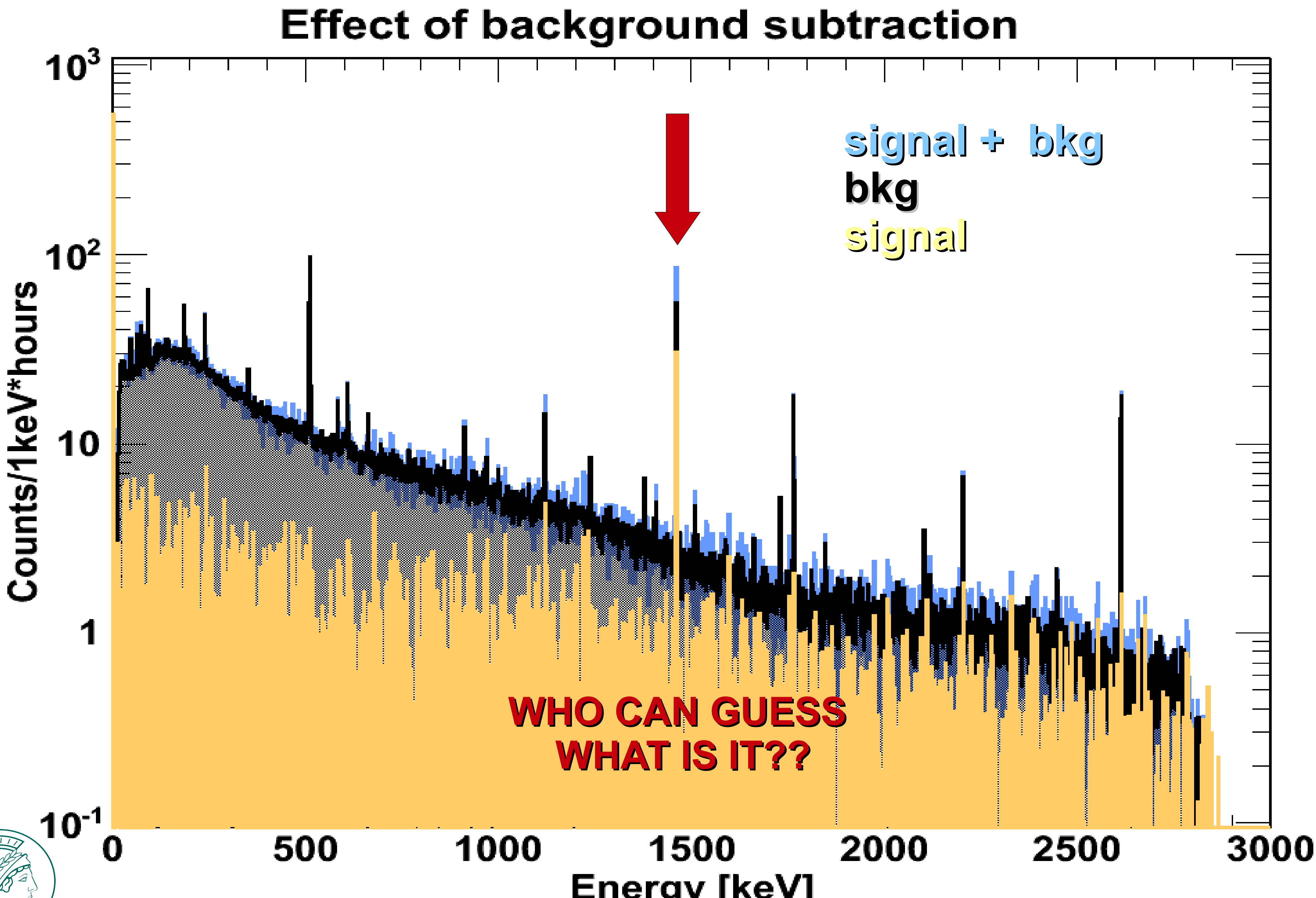






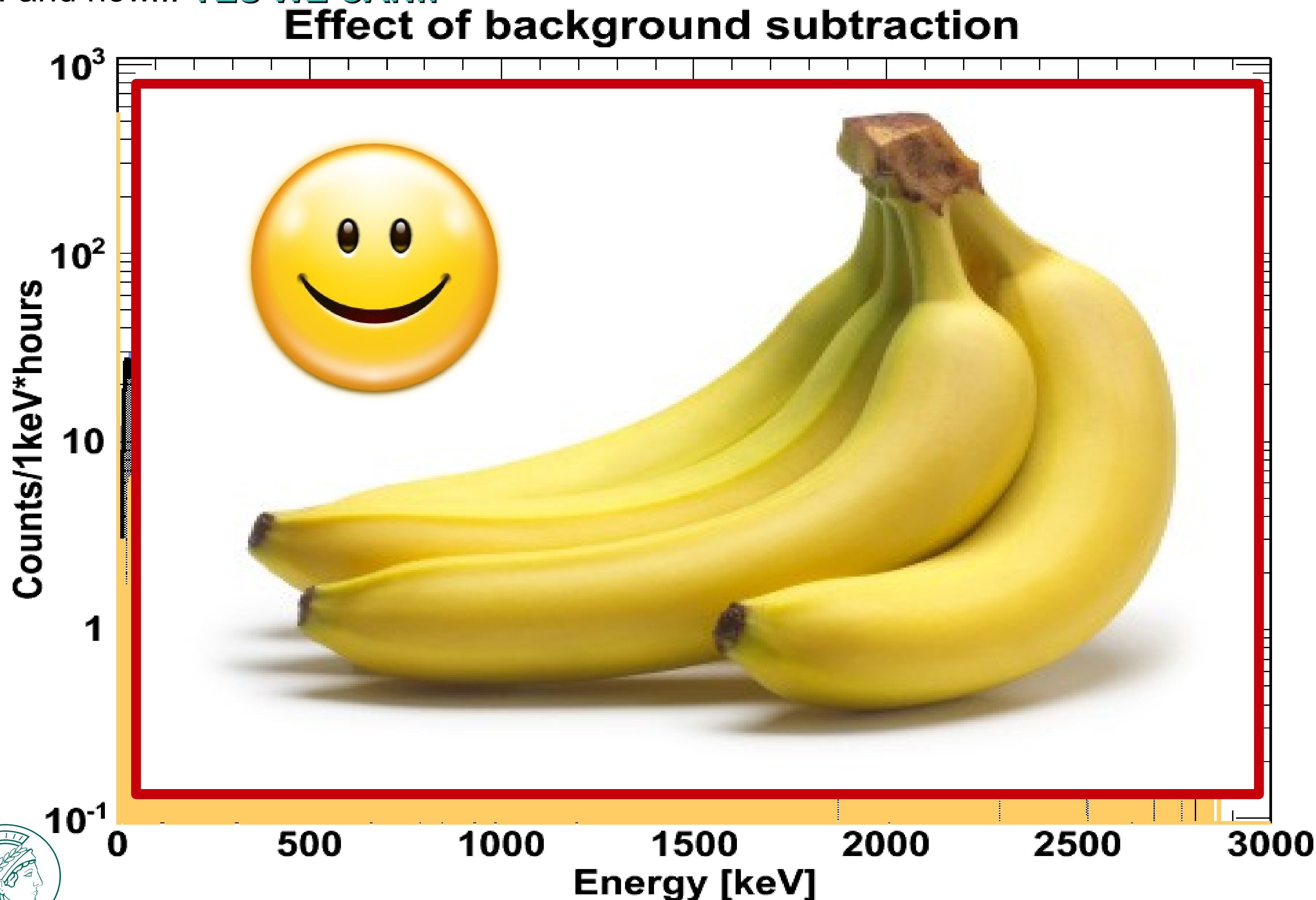
Experimental setup

… and now... **YES WE CAN!!**



Experimental setup

… and now... **YES WE CAN!!**



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- strong and weak sources
- background reduction

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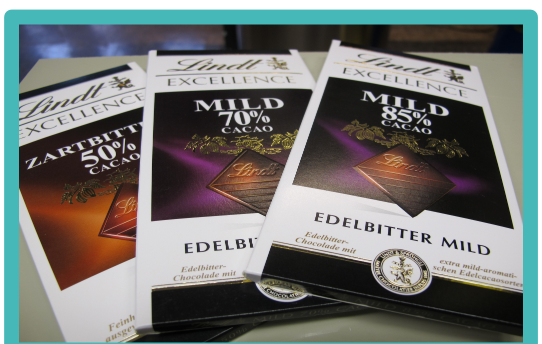
Data analysis

- with this experimental setup we can measure also **WEAK SOURCES**!
  → we can measure the **Potassium content** in different food sample

This are values that you can find in literature... but are they true??

Food	Potassium content in 1 pound [g]
Strawberry	0.76
Sugared almonds	1.27
White chocolate	1.43
kiwi	1.56
Banana	2.18
Hazelnuts	2.5
Dry Prunes	3.4
Raisins	3.74
Pistachios	5.125
Dry Apricots	9.25



Chocolate	Potassium content in 1 pound [g]
Dark Chocolate 50% cacao	3.81
Dark Chocolate 70% cacao	5.334
Dark Chocolate 85% cacao	6.477

We can do it but before...**we need to CALIBRATE the detector!**

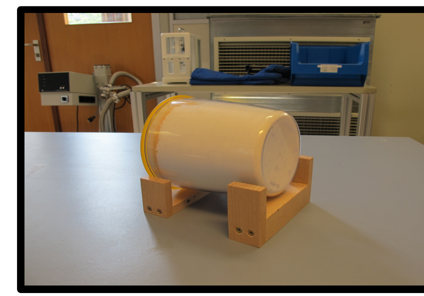
Data analysis

Check the **detector response** to a **WELL KNOWN** quantity of K

Known value of K : Spectrum$_A$ = unknown value of K : Spectrum$_B$

Define the **experimental settings**:

1) position of the plastic container:
- vertical
- horizontal



2) relative distance between source and detector

MAXIMIZING THE GEOMETRICAL ACCEPTANCE

$$a^g = \frac{N_{measured}}{N_{expected}}$$

Where: $N_{measured}$ are obtained directly f**rom the measured spectrum**
$N_{expected}$ can be **calculated from the activity** of the sample

Activity = number of decays per second

Directly from the exponential decay law for N_0 radioisotopes:

$$A = \frac{D(t)}{t} = N_0 \cdot \frac{ln2}{t_{\frac{1}{2}}}$$

if we have some amount m_I of radioisotope it will be:

$$A = \frac{D(t)}{t} = \left(\frac{m_I}{m_I^A} \cdot N_A\right) \cdot \frac{ln2}{t_{\frac{1}{2}}}$$

Potassium Chloride calibration salt

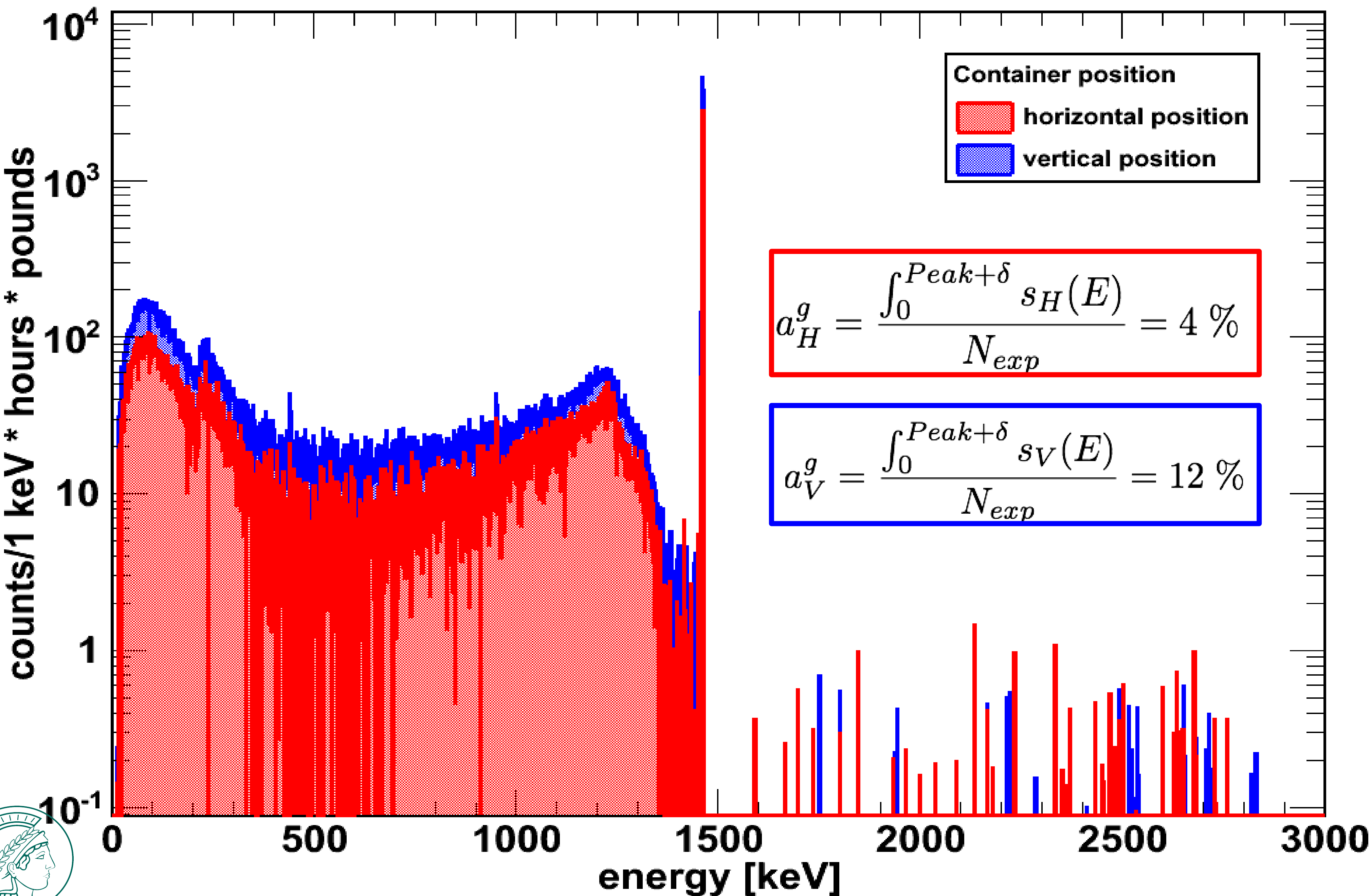
- **mass of the salt** sample
- **impurities**
- **mass of Potassium in KCl**
- **isotopic abundance** for ^{40}K
- **atomic mass of ^{40}K**

$$m_{^{40}K} = m_{KCl} \cdot (1 - i_{tot}) \cdot m_K^{KCl} \cdot a_{^{40}K}$$

$$A_{1460} = 141.9\ Bq$$

Data analysis

KCl spectra for different container positions

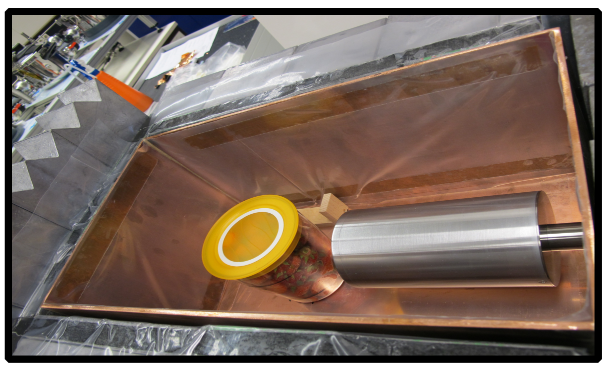


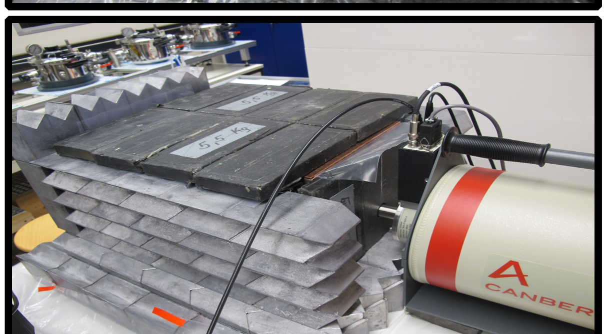
$$a^g_H = \frac{\int_0^{Peak+\delta} s_H(E)}{N_{exp}} = 4\ \%$$

$$a^g_V = \frac{\int_0^{Peak+\delta} s_V(E)}{N_{exp}} = 12\ \%$$

Data analysis

- all food samples **weighed**
- prepared in the **same plastic container**
  → try to have the **same acceptance**
- **self absorption neglected**

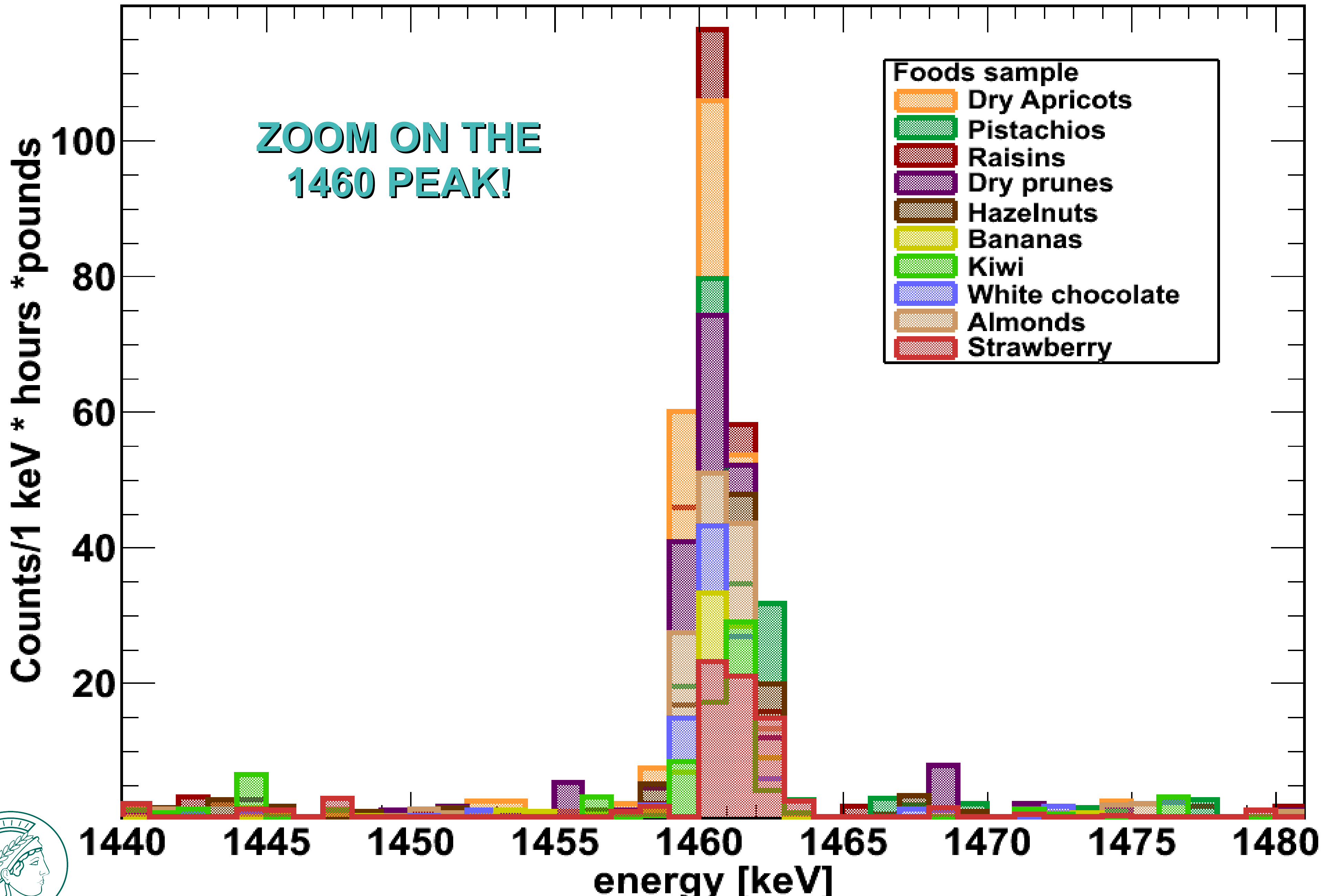




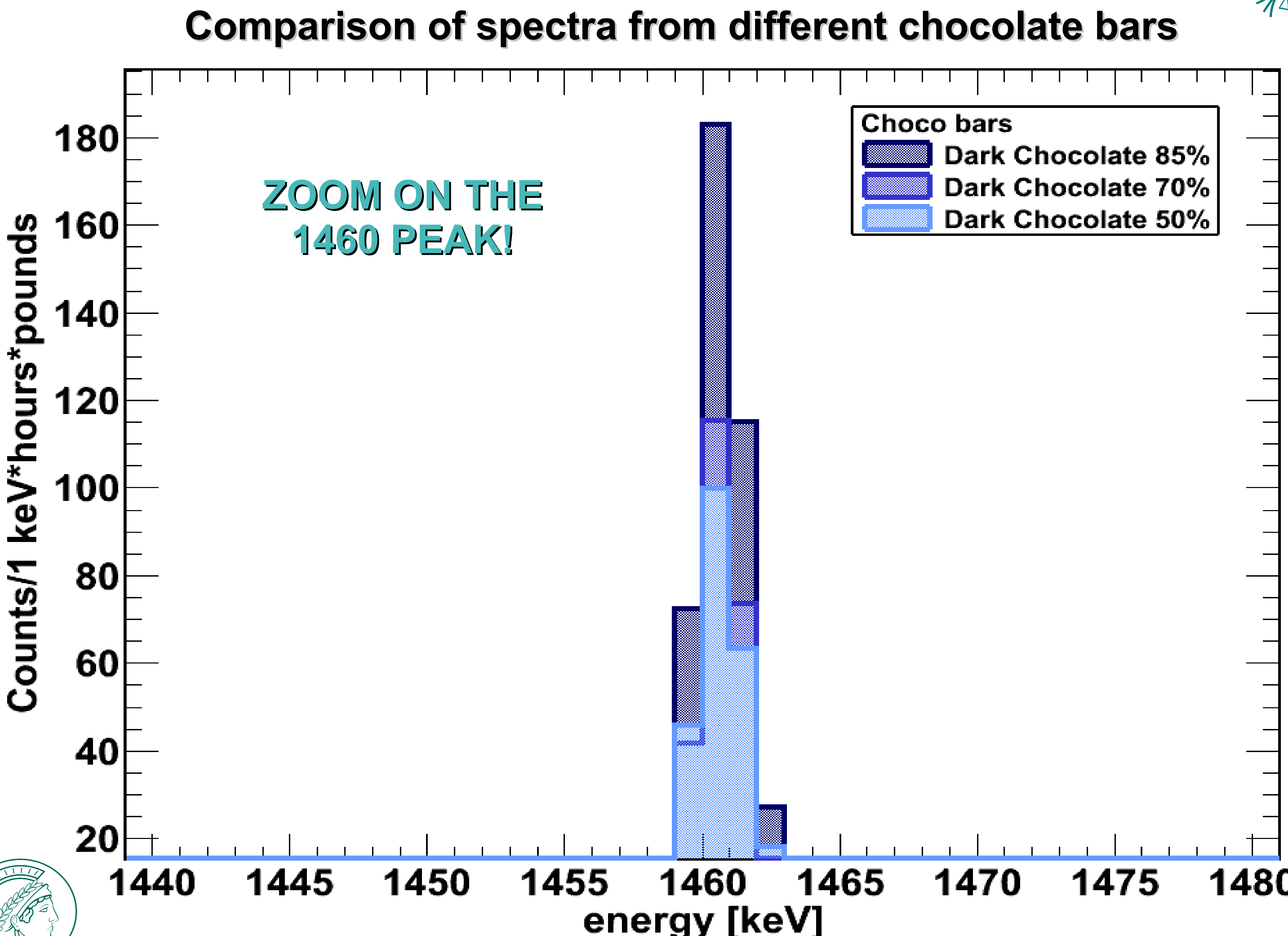
- plastic container always put **vertical**
- **same relative position of the source and the detector**

Data analysis

Comparison of spectra from different food sample rich in potassium



Data analysis

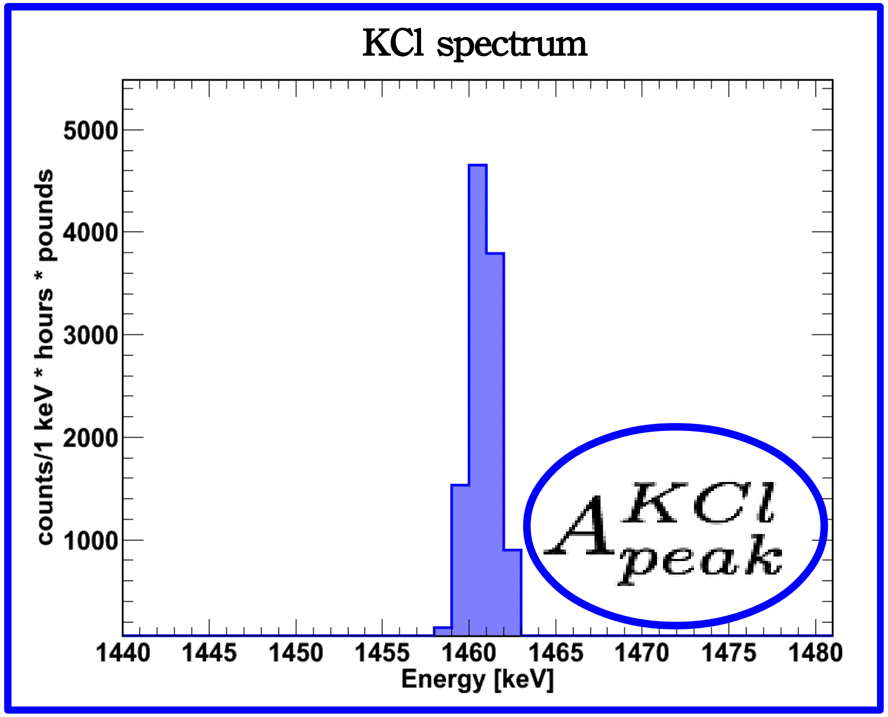


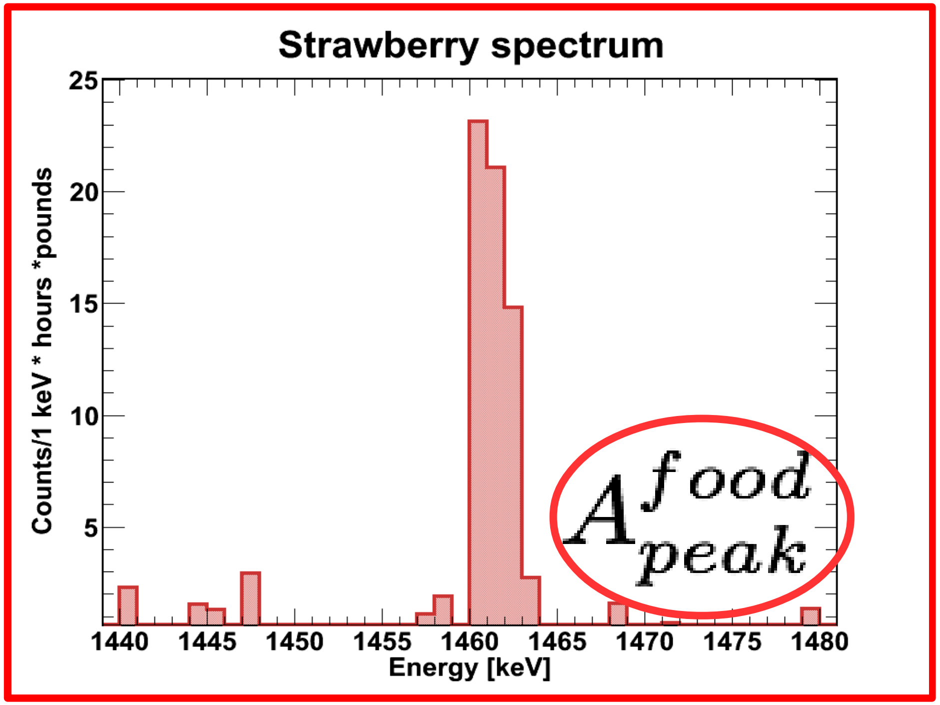
Data analysis

To be more quantitative:

- we can use the already known proportion!!

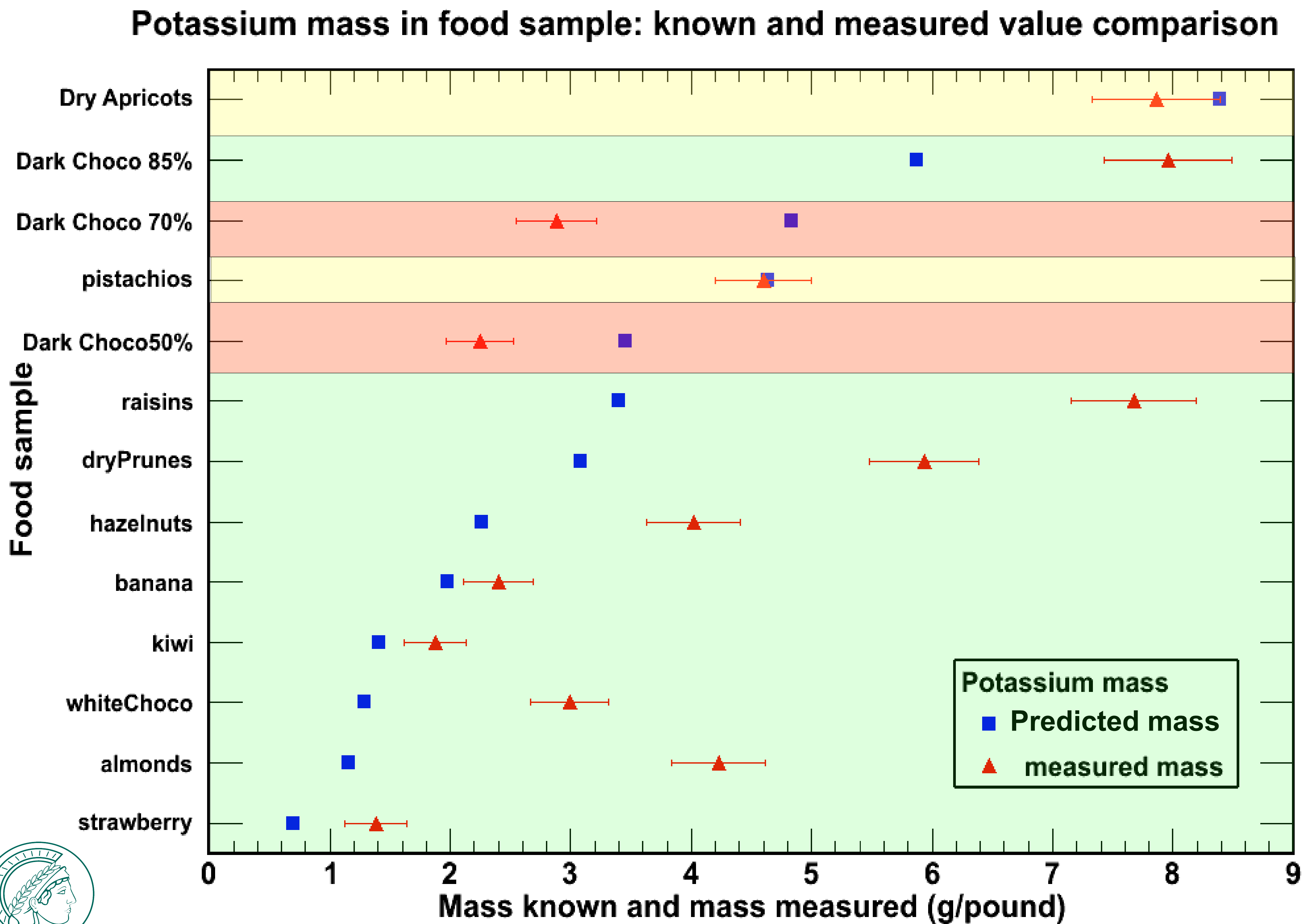
Known value of K : Spectrum$_A$ = unknown value of K : Spectrum$_B$





$$m_K^{meas} = \frac{A^{food}_{peak}}{A^{KCl}_{peak}} \cdot m_k^{KCl}$$

Data analysis



Conclusions

Just to summarize...

- built a shield with **high bkg reduction power**
- **good performances** of the detector with **weak sources** like strawberries
- measured **Potassium content** of **13** different food samples
- figured out a **non linear behaviour of the Potassium** content in different cacao percentages choco bars
    - Do they put **less cacao**?
    - Do they use **different kind of cacao**?

Outlook:

- **simulation** will be done to take into account **self absorption**

- **maybe... choco bars** measurement will be repeated with different **chocolate brands**

BACK UP SLIDES

- **Signal formation** can be described with **events**:
  - with **low probability**
  - **independent** one from each other
  - with an **avarage rate** which doesn't change in the period of interest

EXPECTED VARIANCE = POISSON VARIANCE

OBSERVED VARIANCE = F*POISSON VARIANCE with F<1

Physical reason: ENERGY and MOMENTUM CONSERVATION

ε_i = 2.9 eV

$E_g = E_i$ = 0.66 eV

- ionization => **electron-hole pairs**
- lattice exitation => **phonons**

$$E_0 = E_i N_i + E_x N_x$$

$$dE_0 = \frac{\partial E_0}{\partial N_X} dN_x + \frac{\partial E_0}{\partial N_i} dN_i = 0 \Rightarrow E_x \sigma_x = E_i \sigma_i$$

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x} N_i} = \sqrt{\frac{E_0}{\epsilon_i}}\sqrt{\frac{E_x}{E_i}\left(\frac{\epsilon_i}{E_i} - 1\right)} = \sqrt{F N_Q}$$

Data analysis

Activity = number of decays per second

- from the **exponential decay law**: if we have initially N_0 radioisotopes

$$D(t) = N_0 - N(t) = N_0\left(1 - e^{-\frac{t}{\tau}}\right)$$

is the number of decays after a time t

- if we use the half life $t_{1/2}$ and expand in **Taylor series** we can obtain

$$e^{-\frac{t}{\tau}} = 1 - \frac{t}{\tau} = 1 - \frac{t \cdot ln2}{t_{\frac{1}{2}}}$$

- if we have a **certain mass of a radioactive isotope** m_I

$$A = \frac{D(t)}{t} = \left(\frac{m_I}{m_I^A} \cdot N_A\right) \cdot \frac{ln2}{t_{\frac{1}{2}}}$$

For a Potassium Chloride (KCl) sample :

- of mass m_{KCl}
- with a cenrtain amount of impurities i_{tot} we will have:

$$m_{^{40}K} = m_{KCl} \cdot (1 - i_{tot}) \cdot m_K^{KCl} \cdot a_{^{40}K}$$

$$A_{1460} = 141.9\ Bq$$

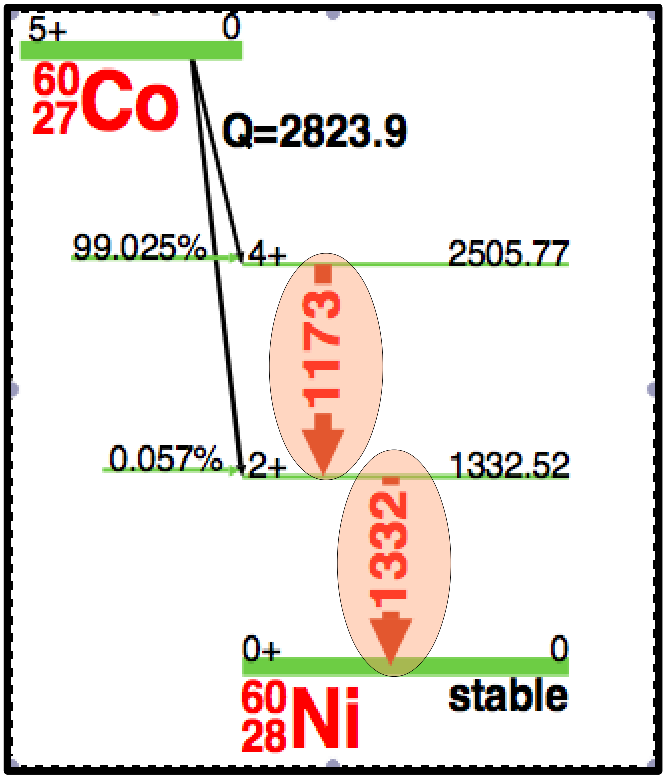
Experimental setup

Name: $^{228}_{90}$**Th**

Neutrons: **138**

Activity:

Decay chain:



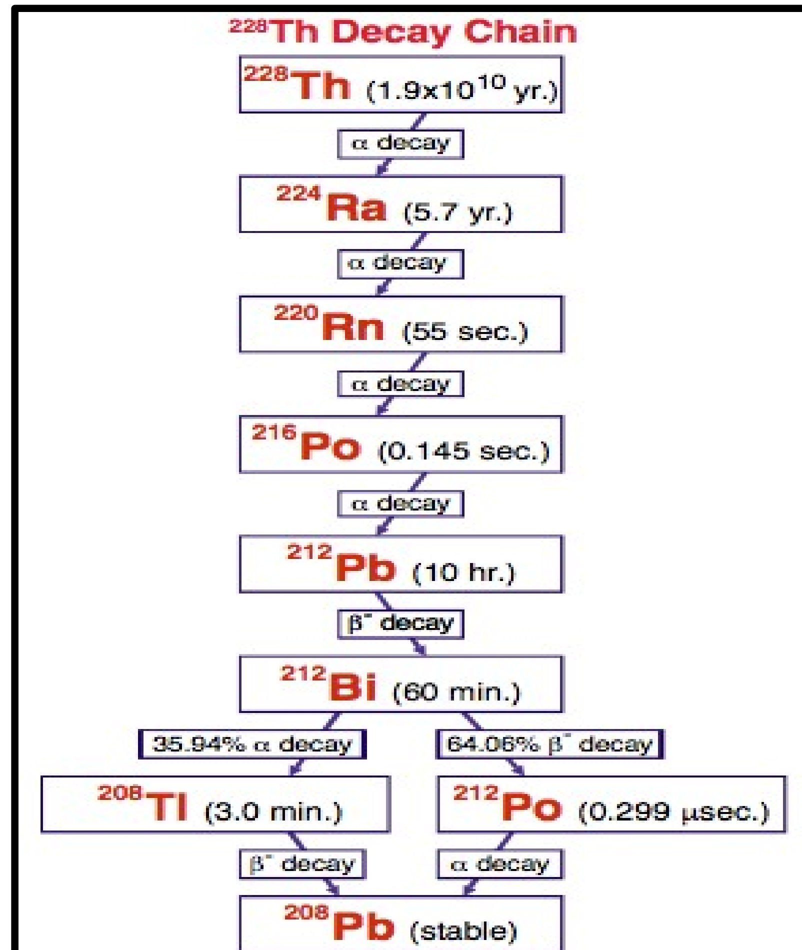
Isomeric transition
with **photon emission**

Name: $^{60}_{27}$**Th**

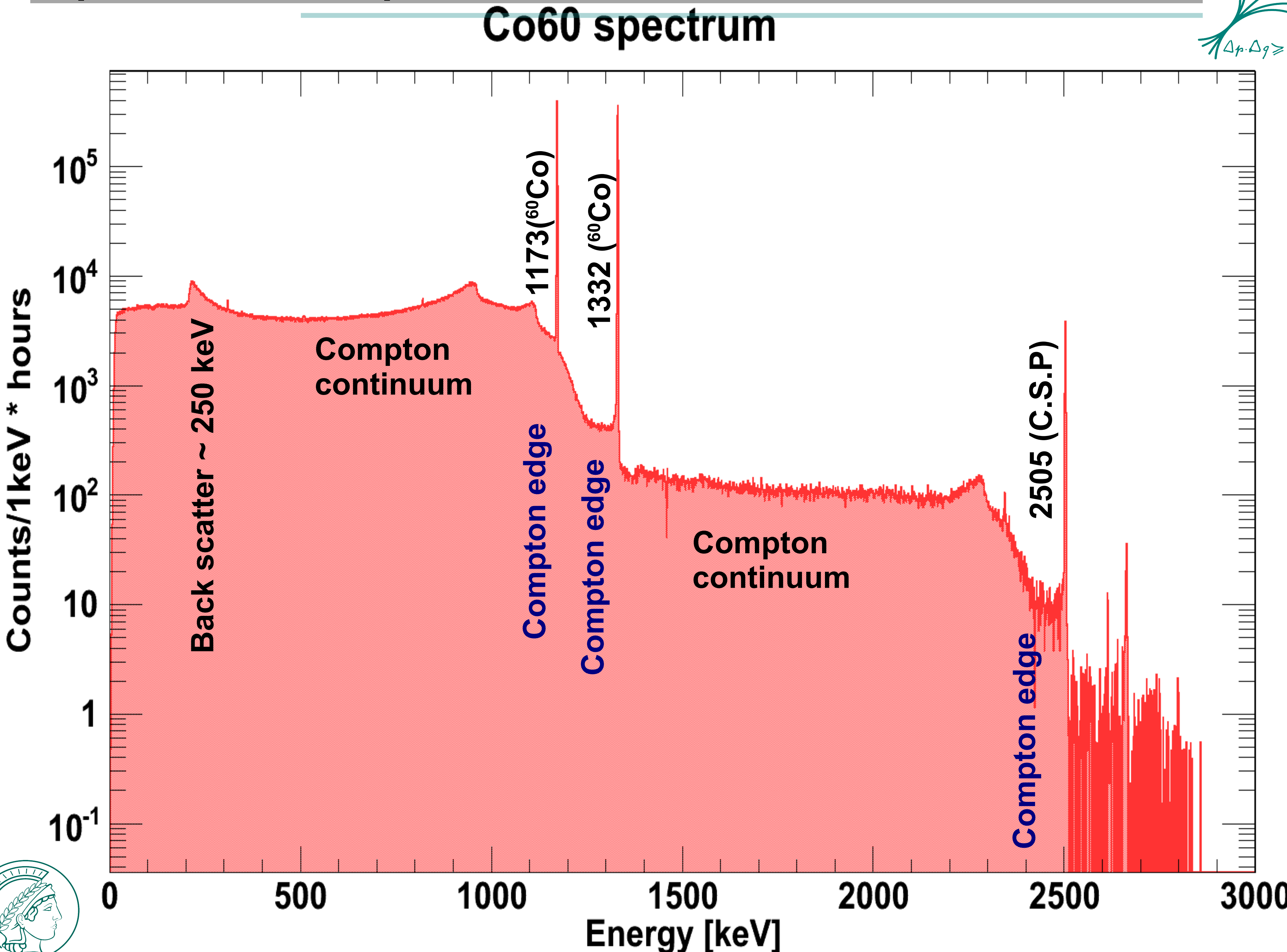
Neutrons: **33**

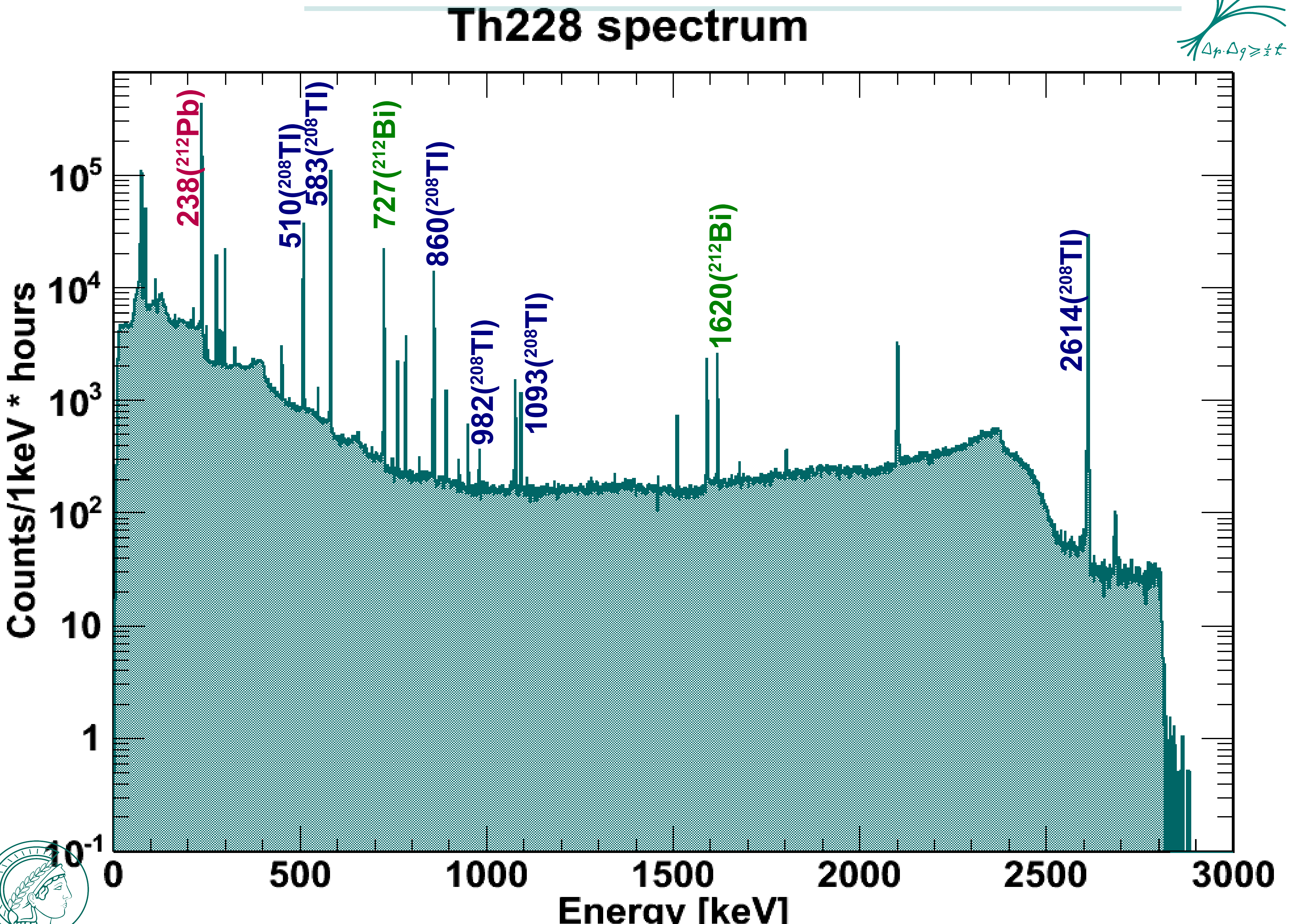
Activity:

Decay chain:



Experimental setup




Th228 spectrum
238(212Pb)
510(208Tl)
583(208Tl)
727(212Bi)
860(208Tl)
982(208Tl)
1093(208Tl)
1620(212Bi)
2614(208Tl)
Counts/1keV * hours
Energy [keV]
10^-1
1
10
10^2
10^3
10^4
10^5
0
500
1000
1500
2000
2500
3000

Data analysis

We can use strong sources to know the detector....

Fano Factor Measurement

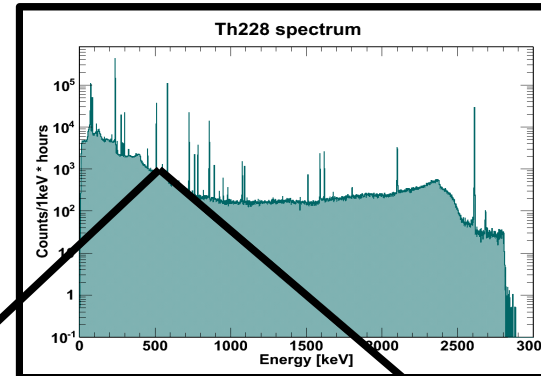
→ energy resolution depends on ENERGY

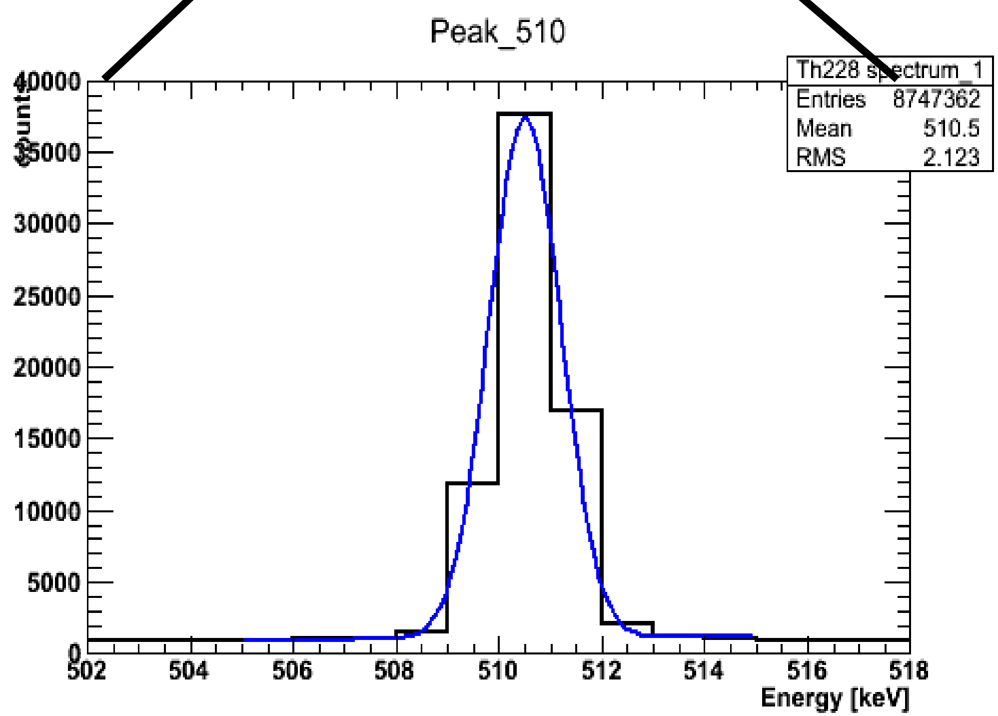
$$FWHD^2_{tot} = (2.35)^2 F\varepsilon E + b^2$$

→ scanning all the energy range in the ^{228}Th spectrum

- choosing good peaks

238	keV	^{212}Pb
510	**keV**	**^{208}Tl**
583	keV	^{208}Tl
727	keV	^{212}Bi
860	keV	^{208}Tl
982	keV	^{208}Tl
1093	keV	^{208}Tl
1620	keV	^{212}Bi
2614	keV	^{208}Tl





- fit with a Gaussian

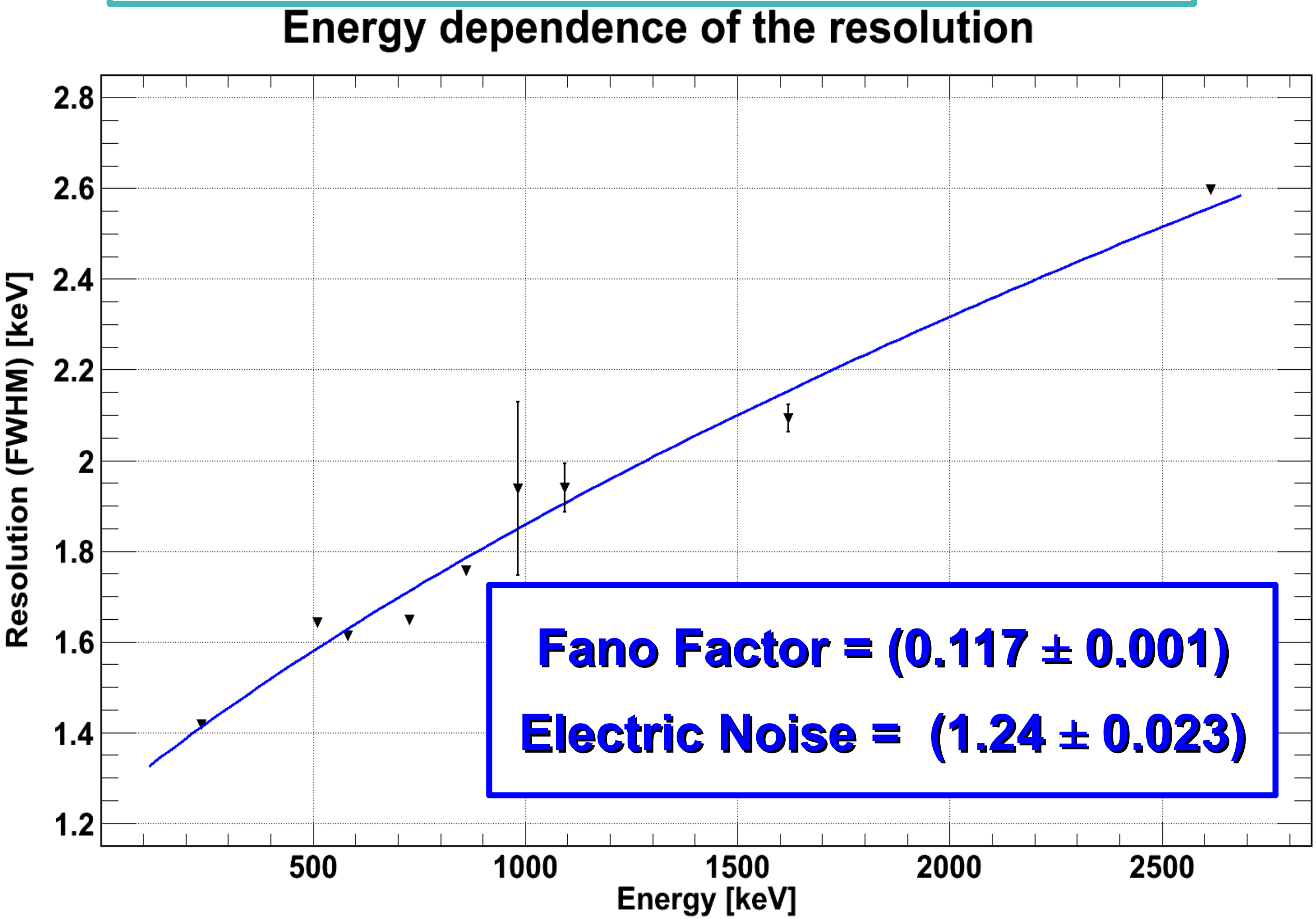
=> exract the RMS

$$RMS = (0.699 \pm 0.0026)keV$$

- check the dependence on energy

Data analysis

$$FWHM \pm \sigma_{FWHM} = 2.35 \cdot (RMS \pm \sigma_{RMS})$$



To be compared with the theoretical value: F = 0.13 in Ge

Experimental setup