Feasibility study for muon-induced neutrons in Shallow Underground Labs

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Mainz

On behalf of the GeDet group
Max-Planck-Institut für Physik, München

Outline

- **Low Background Physics Issues**
- Feasibility Simulation Study:
  - Reference measurement
  - Setup description and results
- Summary & Outlook

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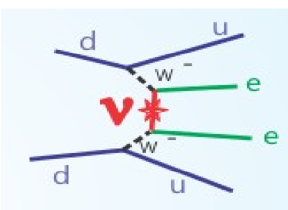
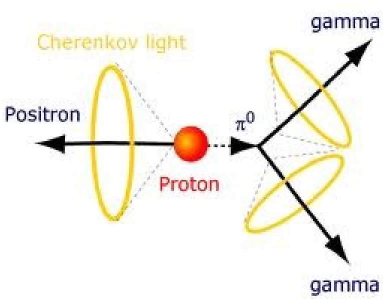
Low Background Experiments

Particularly rare physics processes like:





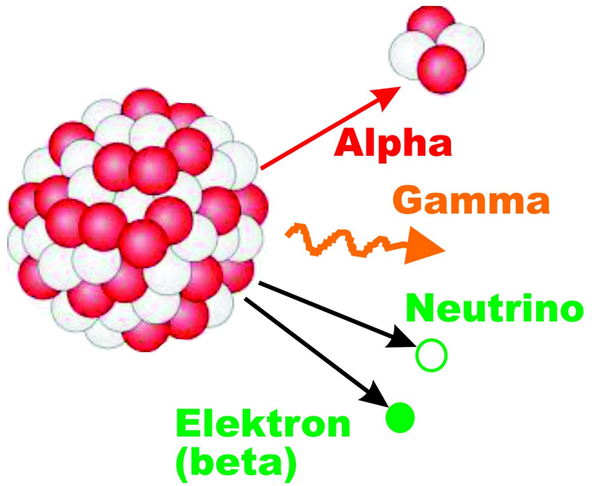
- **Direct Dark Matter interaction**
- **Neutrinoless Double Beta Decay**
- **Low Energy Neutrinos' interaction (solar, sterile neutrinos etc)**
- **Proton decay**

Experiments have very small expected event rates!!
(e.g. $0\nu2\beta$ decay < 0.1 events/(kg y))

They ALL need:
- **very low background**
- **very good detectors**

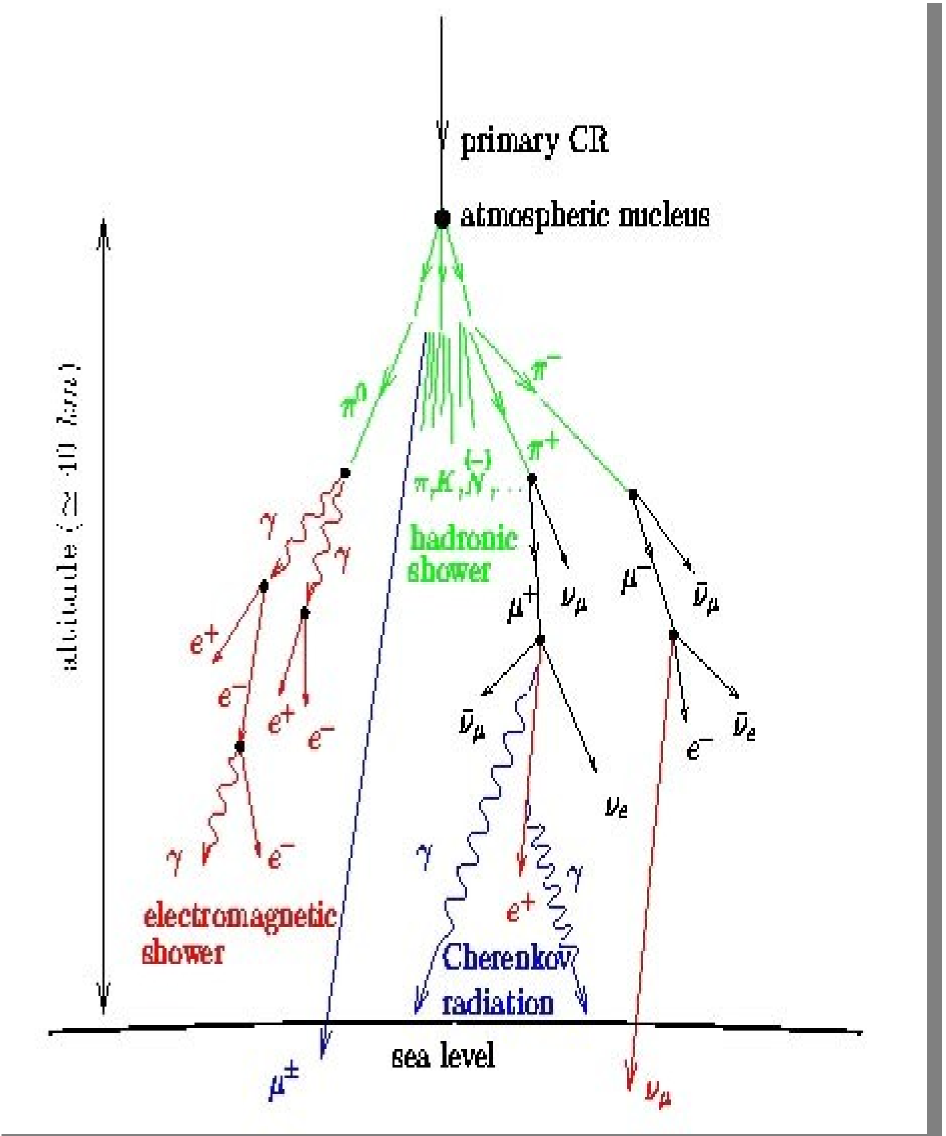
Background Sources

- **Three different sources:**
  - **Intrinsic detector radioactivity**
  - **Environmental Natural radioactivity**
  - **Cosmic Rays-induced showers**
    (μ and ν-induced)



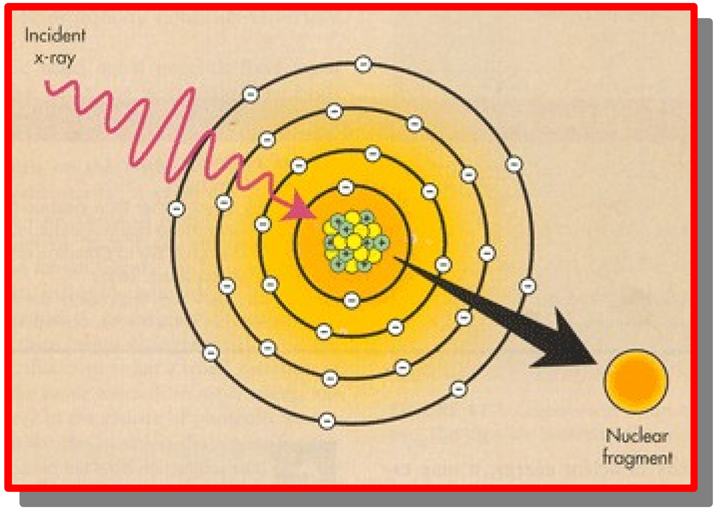
- **Two different components:**
  - **Charged** → easy to veto
  - **Neutral** → high shielding power is required (neutron, gammas)

Cosmic Rays Shower



Production mechanism:

- **Photodisintegration**



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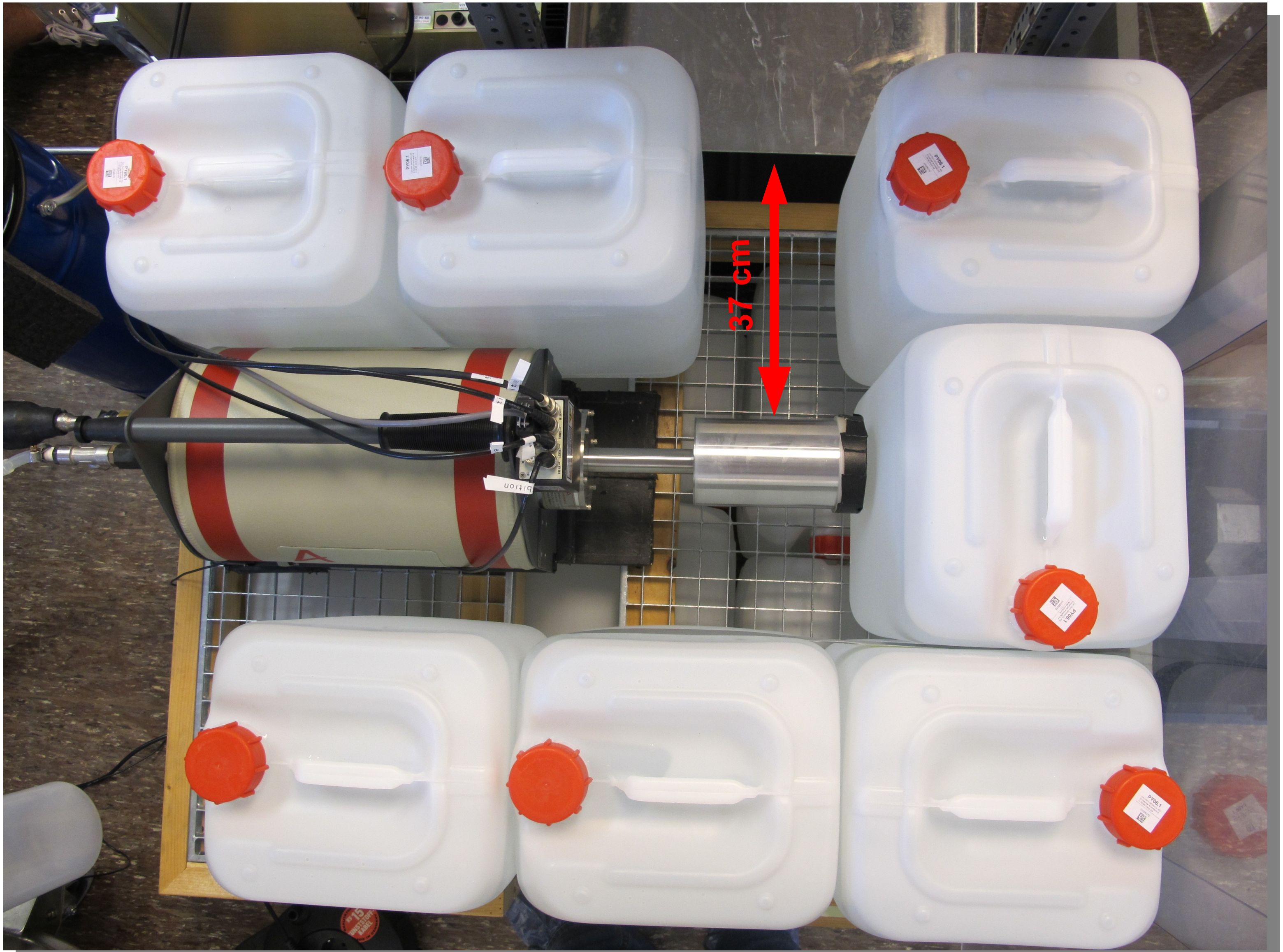
Reference measurement: AmBe



Reference measurement: AmBe

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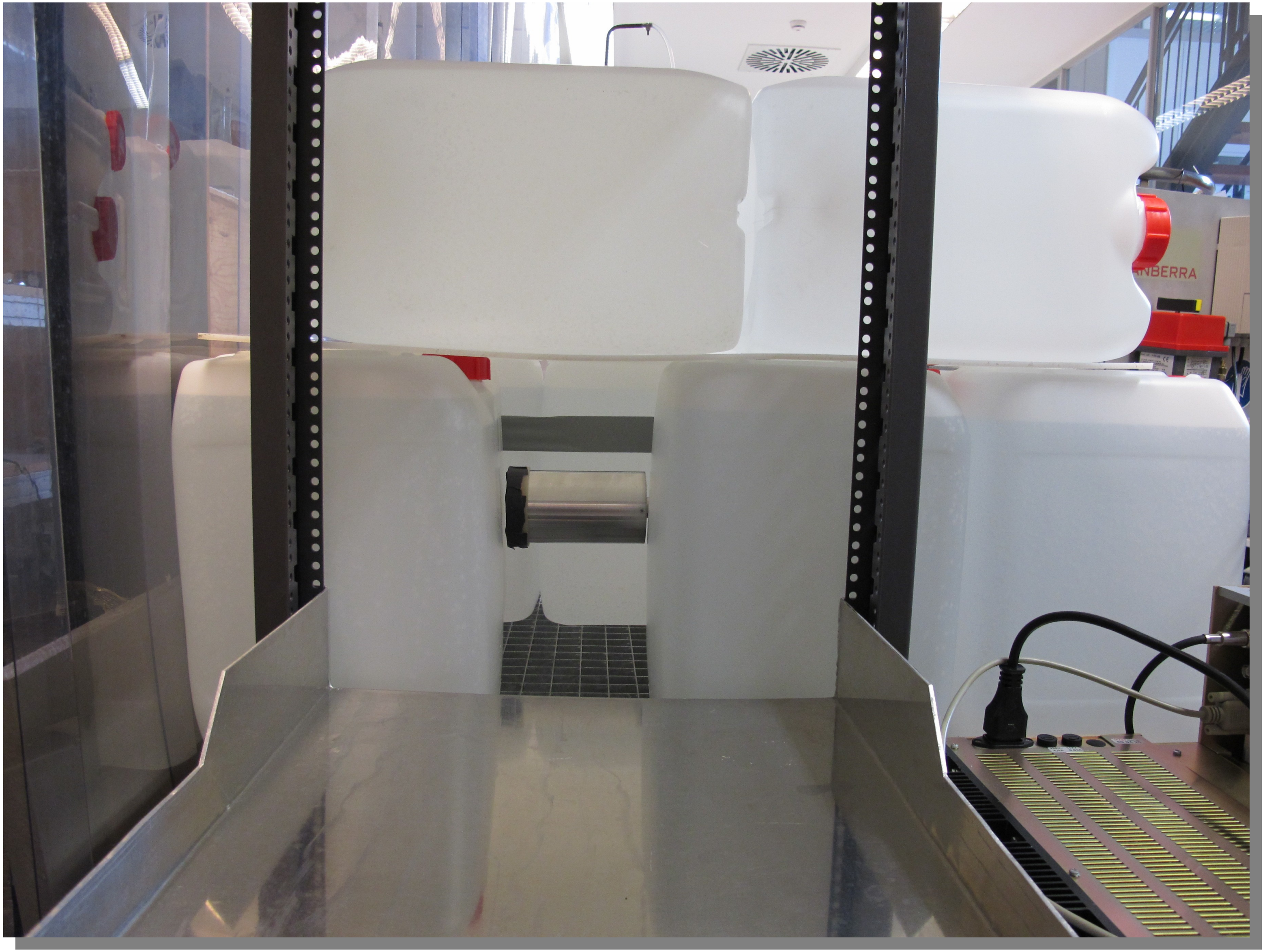

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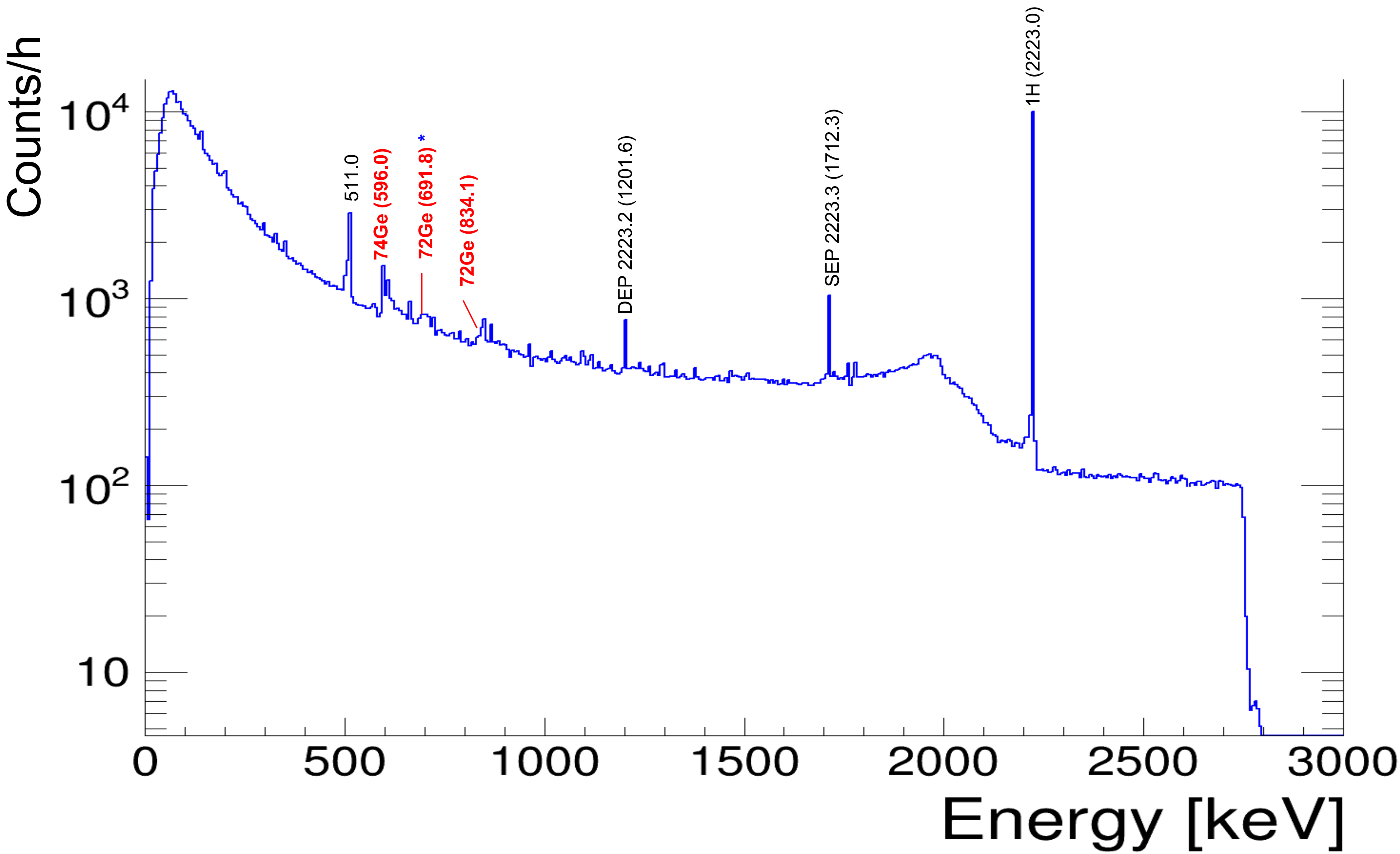

Counts/h
10^4
10^3
10^2
10
511.0
74Ge (596.0)
72Ge (691.8)
*
72Ge (834.1)
DEP 2223.2 (1201.6)
SEP 2223.3 (1712.3)
1H (2223.0)
0
500
1000
1500
2000
2500
3000
Energy [keV]

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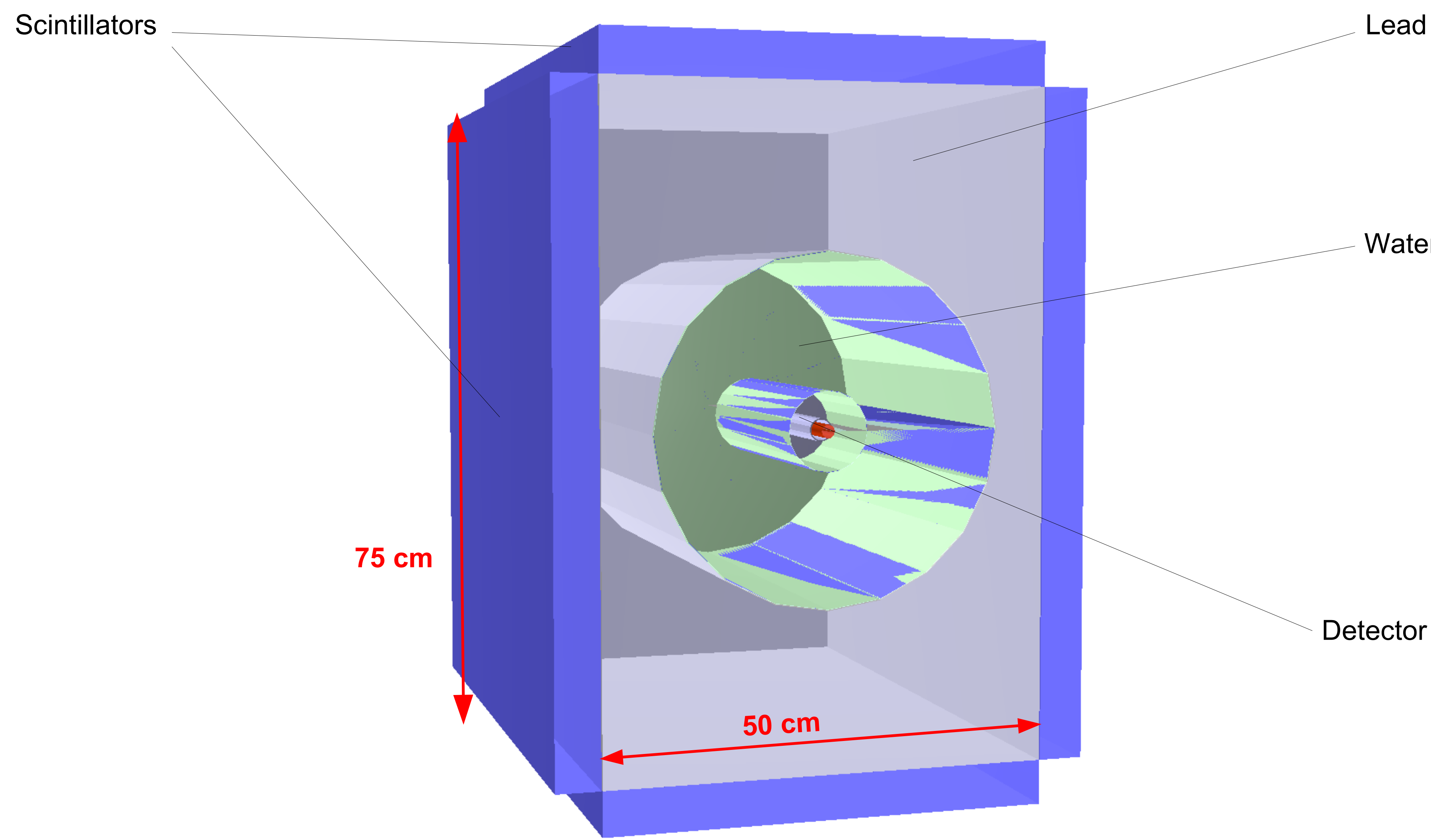
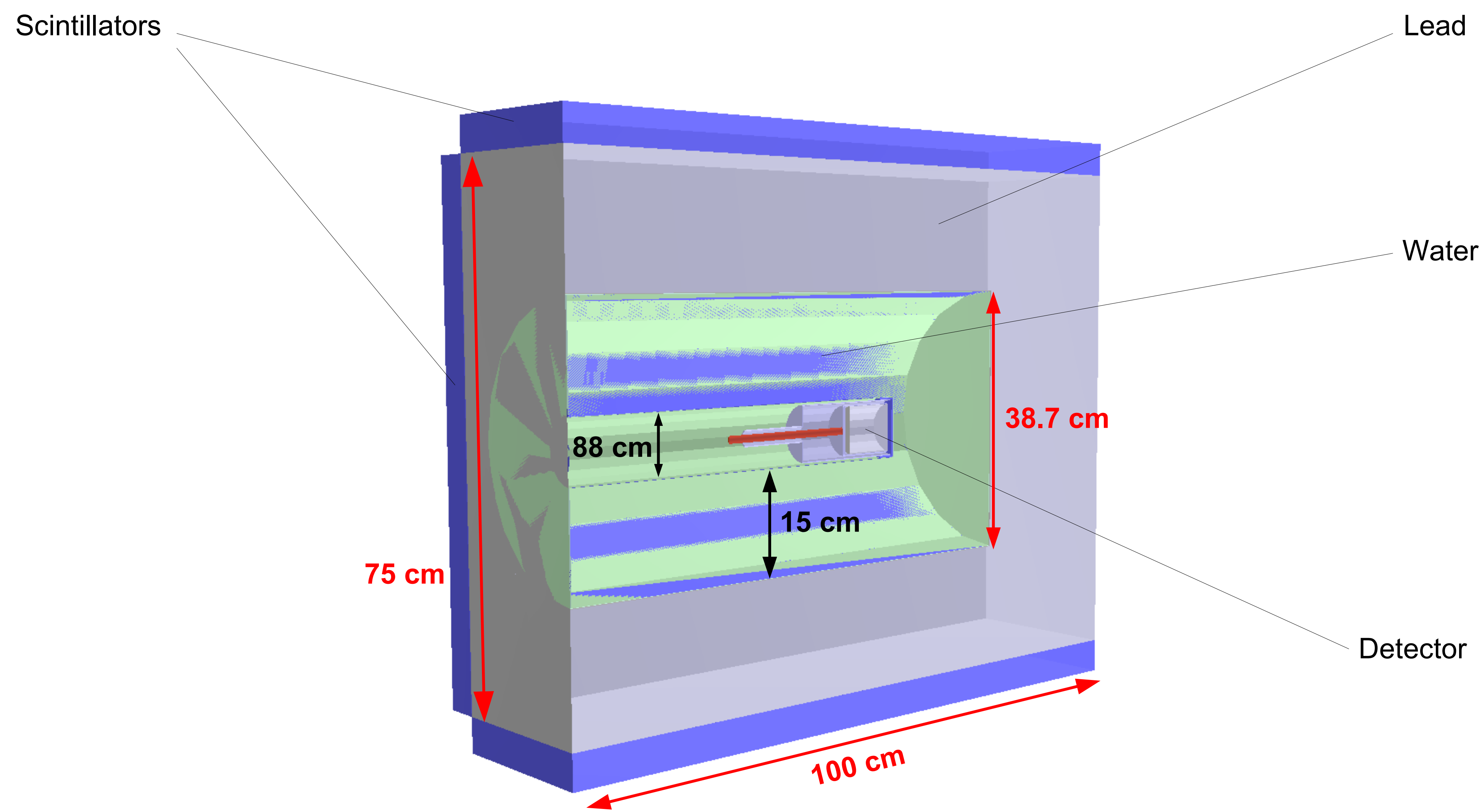
The Setup

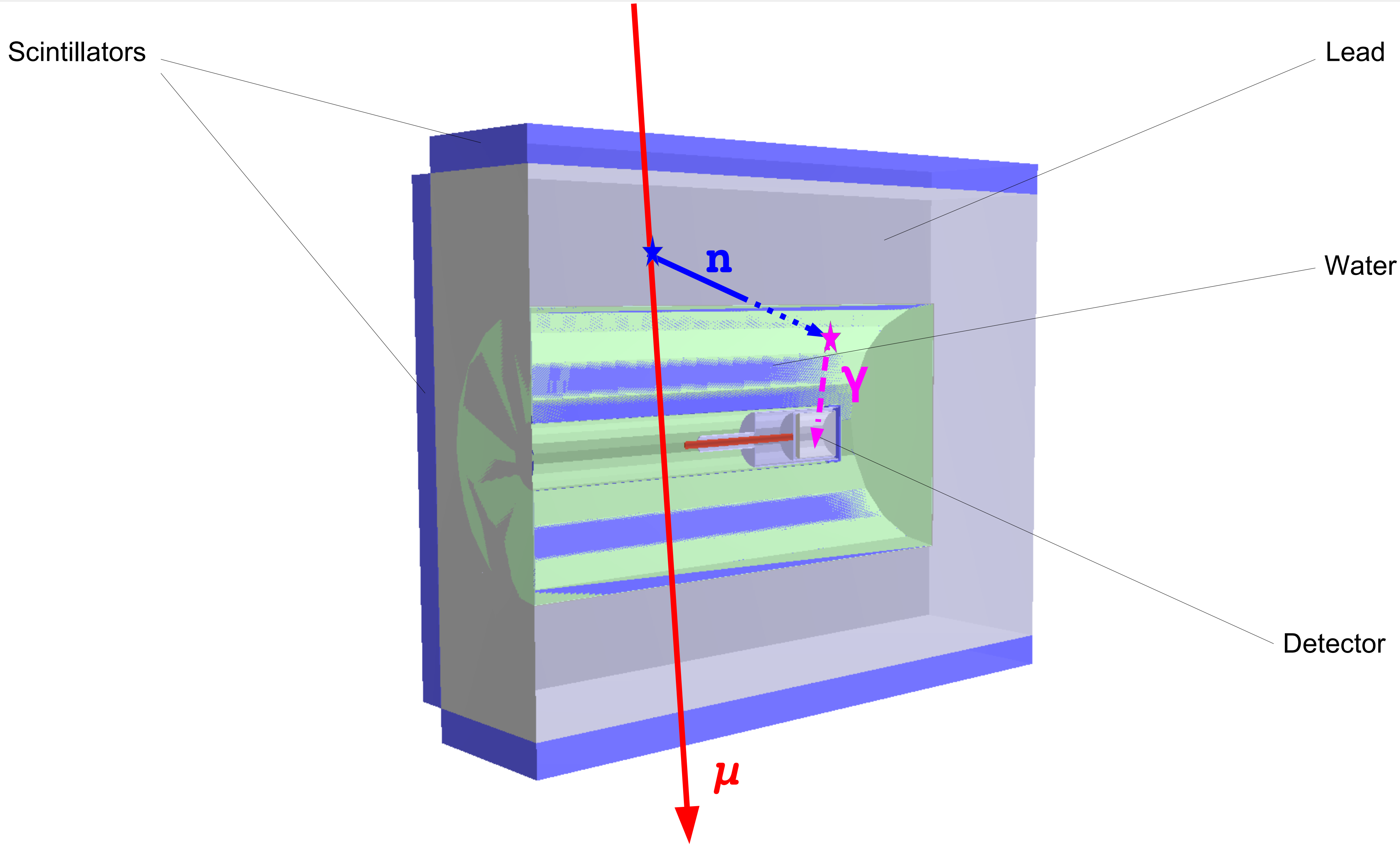


The Setup

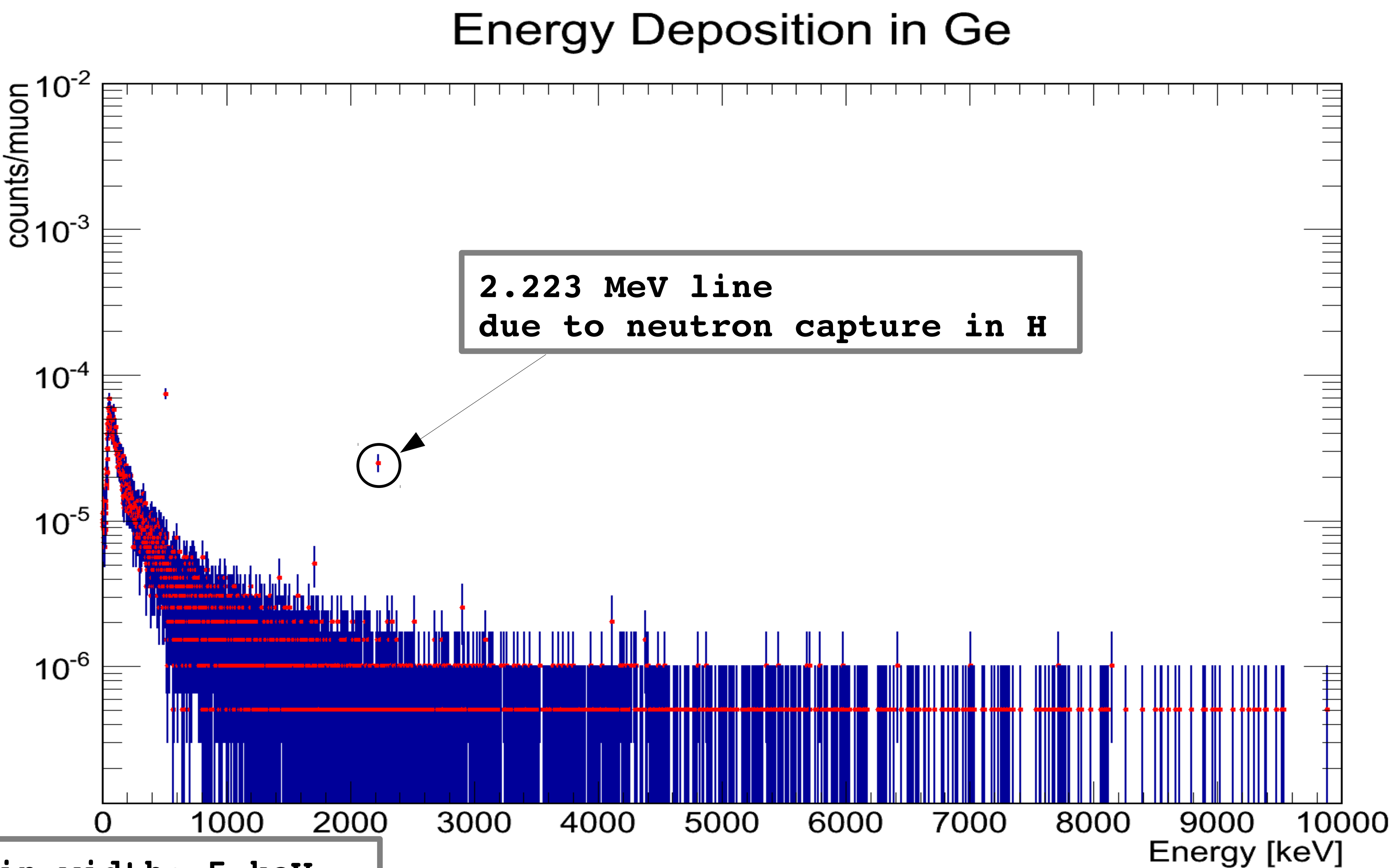


Scintillators
Lead
Water
38.7 cm
88 cm
15 cm
75 cm
Detector
100 cm

The Setup



Particle Energy Deposition in Ge



bin width: 5 keV

Efficiencies Results

	Efficiency (tot ev.: 1.92952e07 μ)
n OUT from Lead	5.1×10^{-2}
n OUT from Water	6.8×10^{-4}
n IN @GeDet	4.0×10^{-4}
2.2 γ OUT from Water	2.1×10^{-4}
2.2 γ IN @GeDet	1.1×10^{-4}
2.2 γ IN @GeDet after 1 ms	1.6×10^{-6}
2.2 γ Detected by GeDet	2.5×10^{-5}

~ 1%

Water OK:

– γ energy

- thickness

Efficiencies Results

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2.2 γ OUT from Water	2.1×10^{-4}
2.2 γ IN @GeDet	1.1×10^{-4}
2.2 γ IN @GeDet after 1 ms	1.6×10^{-6}
2.2 γ Detected by GeDet	2.5×10^{-5}

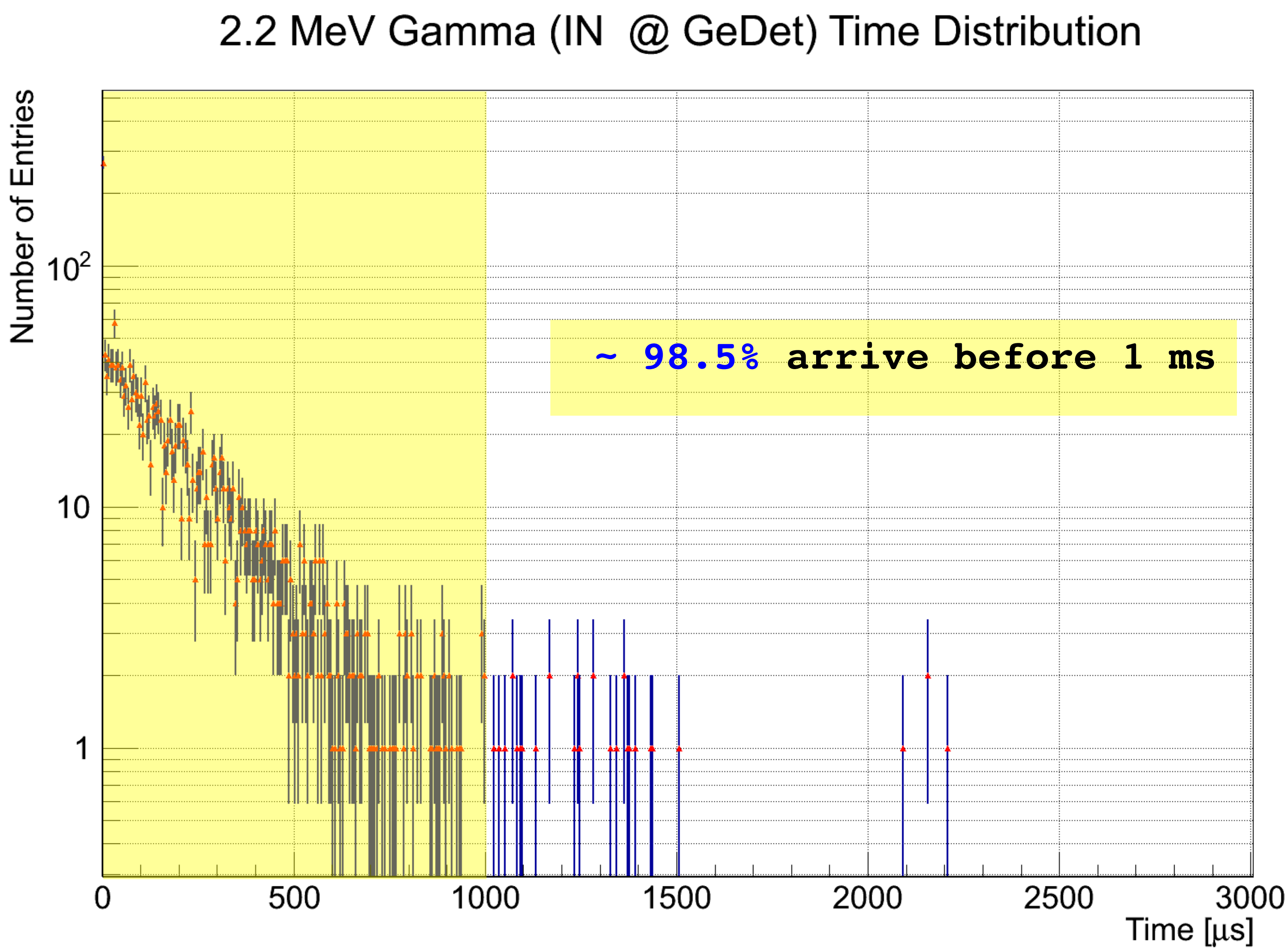
~ 60%
hitting the
detector

Efficiencies Results

	Efficiency (tot ev.: 1.92952e07 μ)
n OUT from Lead	**5.1×10^{-2}**
n OUT from Water	**6.8×10^{-4}**
n IN @GeDet	**4.0×10^{-4}**
2.2 γ OUT from Water	**2.1×10^{-4}**
2.2 γ IN @GeDet	**1.1×10^{-4}**
2.2 γ IN @GeDet after 1 ms	**1.6×10^{-6}**
2.2 γ Detected by GeDet	**2.5×10^{-5}**

~ 1.5%
=> most γs arrive before 1 ms

2.2MeV γ Time Distribution INCOMING @ GeDet



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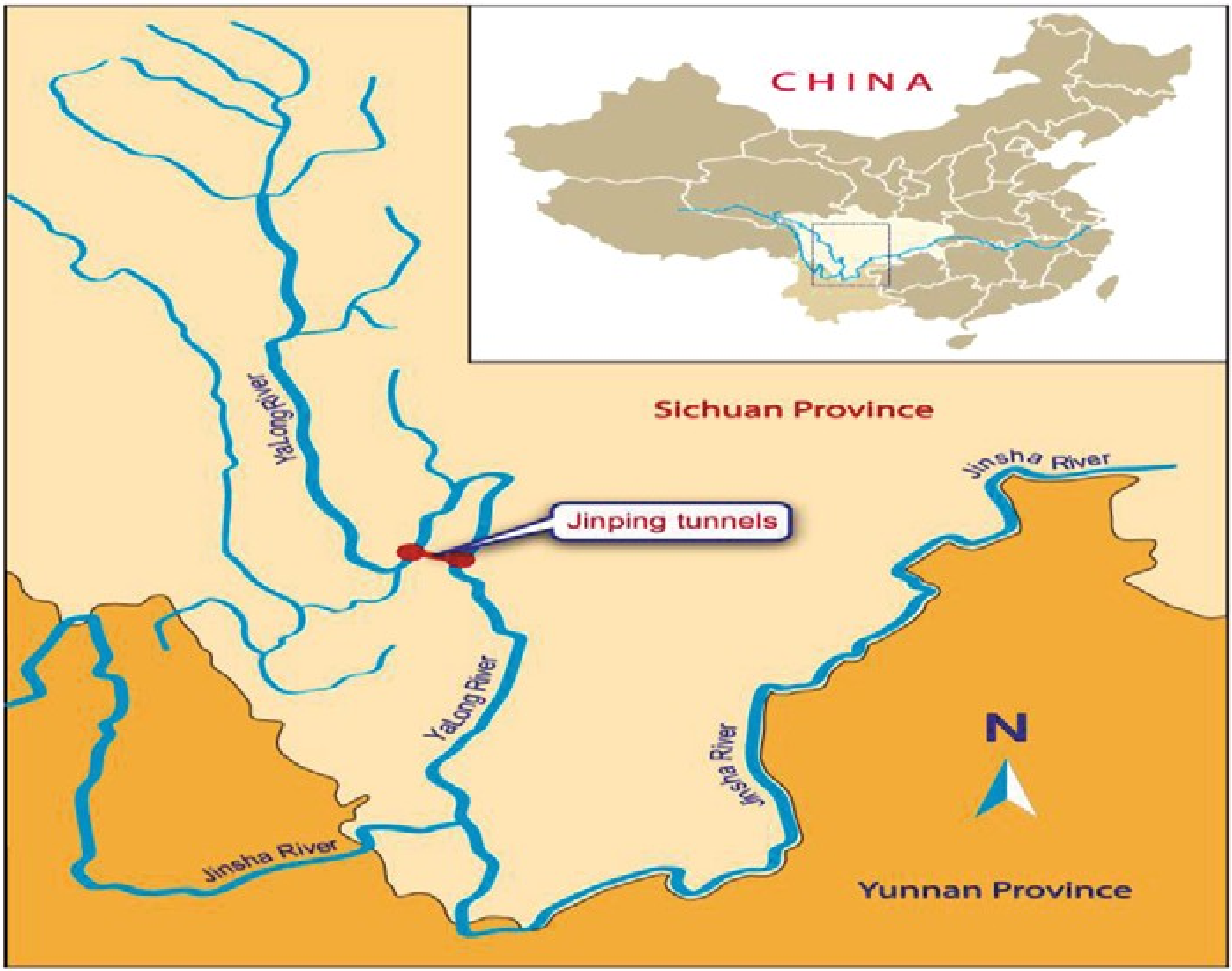
Summary & Outlook

- **Summary:**
  - Simple and relatively cheap setup
  - Integrated 2.2 MeV gamma yield per muon DEPOSITING FULL energy into Ge-det ~ 2.5×10^{-5}
  - Desired muon flux ~ 6×10^{-3} cm^{-2} s^{-1} with a bkg level of ~ 5×10^{3} events/day ==> S/B ~ 10
- **Outlook:**
  - Prototype measurement above ground (1 ms time window)
  - Find a proper shallow underground site
  - Neutron flux bkg measurement
  - Bkg in ROI in Ge measurement

The China JinPing Laboratory



Sino-German GDT Cooperation

Deutsch-Chinesische-Kooperationsgruppe

Development of High Purity Germanium Detector Techniques for Applications in Fundamental Research

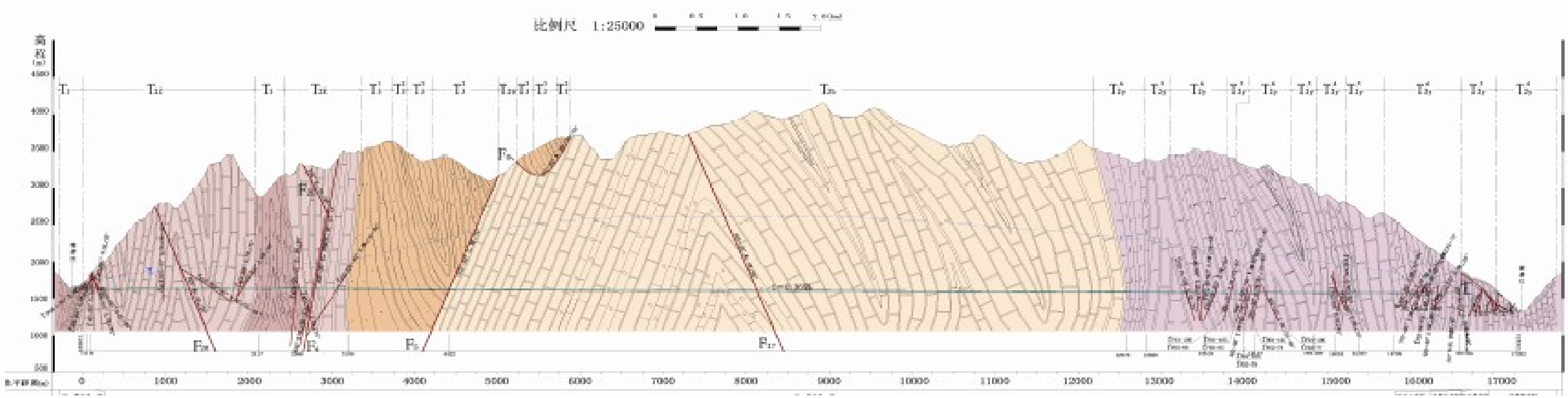
Finanziell unterstützt durch: Chinesisch-Deutsches Zentrum für Wissenschaftsförderung Peking, China

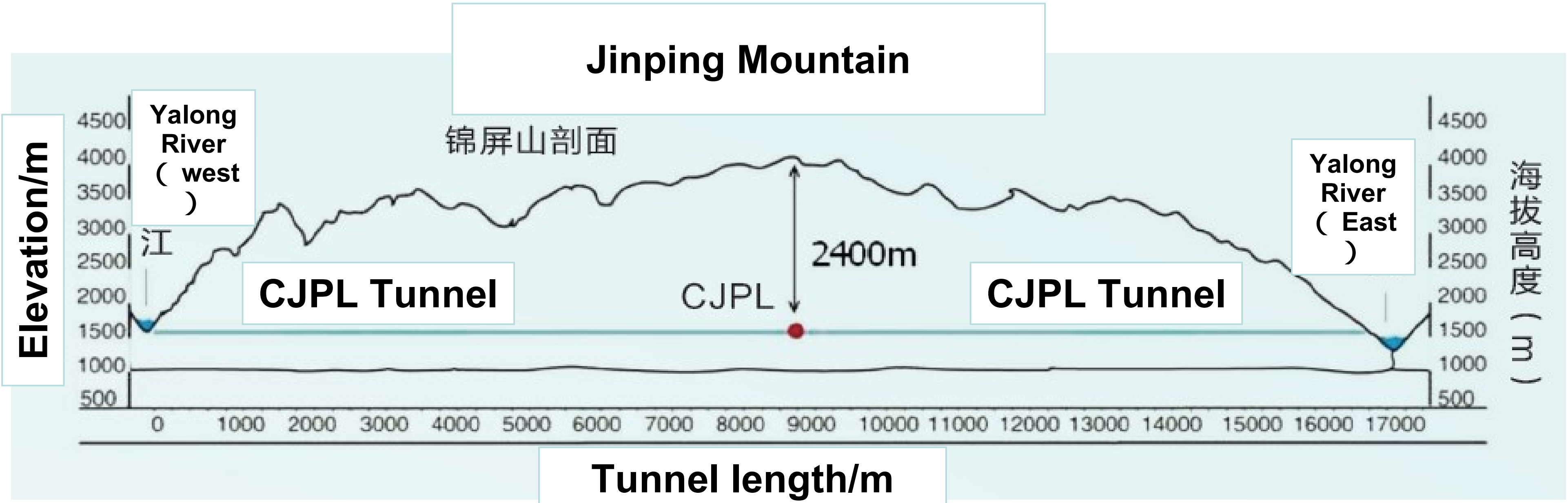
中德合作研究小组

应用于基础研究的高纯锗探测器技术研发

资助者:中德科学中心 / 中国 北京

The China JinPing Laboratory





Courtesy of Prof. Zeng Zhi, Tsinghua University, Beijing

Efficiency Results

- integrated 2.2MeV gamma yield per muon **DEPOSITING FULL energy** into Ge-det ~ 2.5×10^{-5}

- Estimated muon flux @ SUL(CJPL) ~ 7×10^{-5} cm^{-2} s^{-1}
  - For 100x50 cm^2 scintillator area ==> 0.35 Hz
  - Assuming that are all energetic enough
    ==> 1 mu every ~3 s
    ==> 2 events every 3 days

  ==> **Not doable!!!**

  ==> Need ~ two order of magnitude higher flux

References

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"Neutron interactions as seen by a segmented germanium detector".
Eur. Phys. J. A 36, 139-149 (2008).

[2] T. Siiskonen, H. Toivonen.
"A model for fitting peaks induced by fast neutrons in an HPGe detector".
Nucl. Instrum. Meth. A 540 (2005) 403-411.

[3] N. Jovancevic, M. Krmar, D. Mrda, J. Slivka and I. Bikit.
"Neutron induced background gamma activity in low level GE-spectroscopy systems". Nucl. Instrum. Meth. A 612 (2010) 303-308.

[4] K. W. Geiger, L. Van Der Zwan,
"Radioactive neutron source spectra from Be(α,n)"
Nucl. Inst. and Meth. 131 (1975) 315.

[5] J. Ljungvall, J. Nyberg,
"A study of fast neutron interactions in high-purity germanium detectors"
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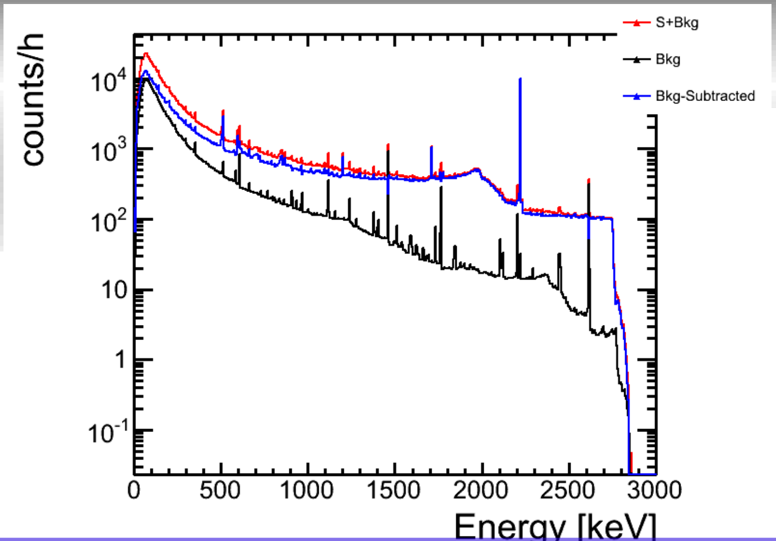
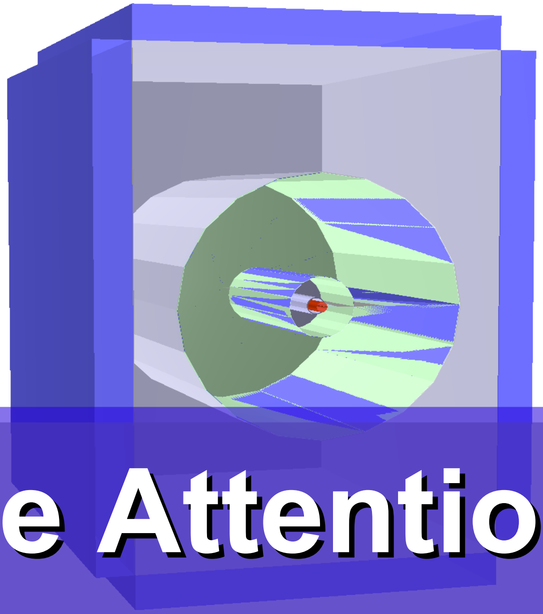
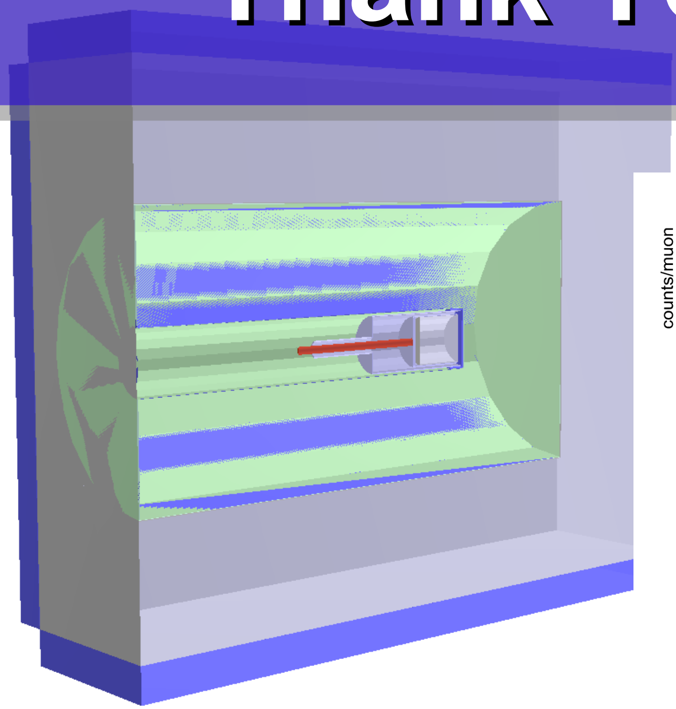
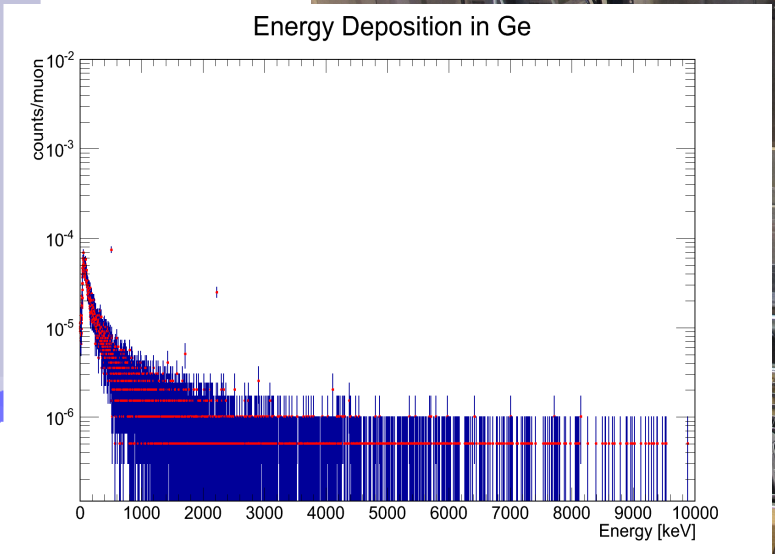




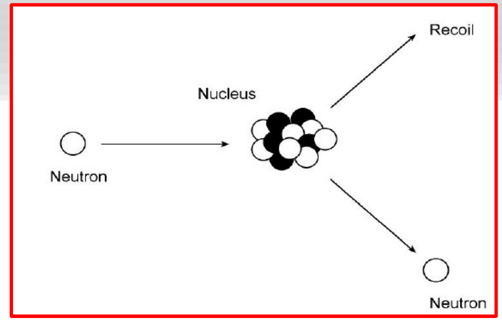
Thank You for The Attention!





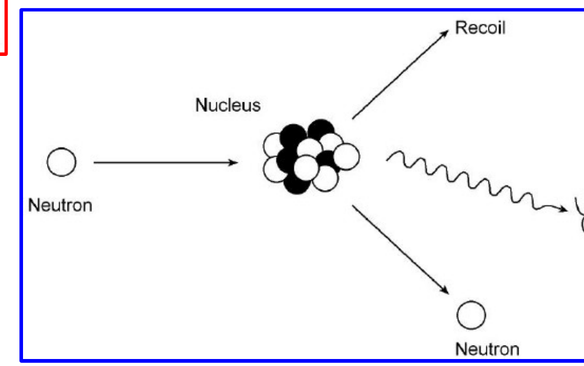
Backup

Neutrons Interactions



- **Elastic Scattering:**

$$n + ^A_Z N \rightarrow n' + ^A_Z N$$



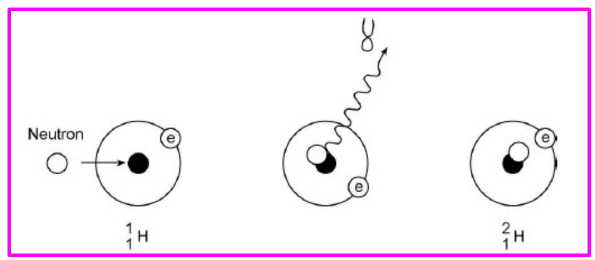
- **Inelastic Scattering:**

$$n + ^A_Z N \rightarrow (^{A+1}_{Z} N)^* \rightarrow n' + ^A_Z N + \gamma$$

$$n + ^A_Z N \rightarrow (^{A+1}_{Z} N)^* \rightarrow n' + ^A_{Z+1} N^+ + e^-$$

- **Thermal Capture:**

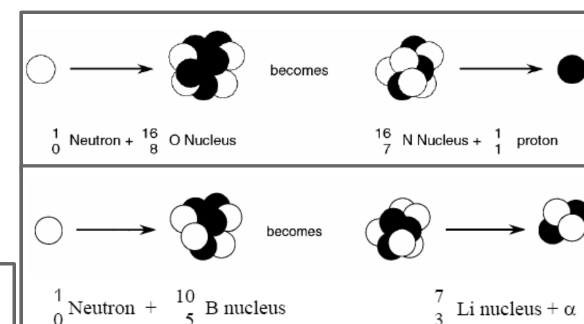
$$n + ^A_Z N \rightarrow ^{A+1}_{Z} N + \gamma$$



- **Transmutation:**

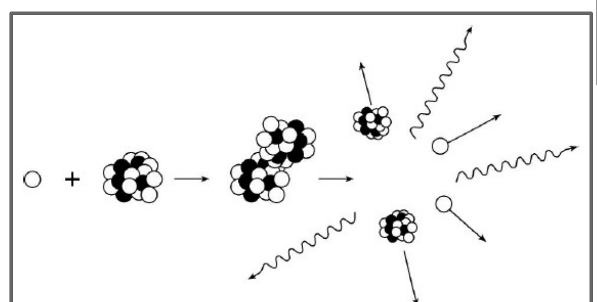
$$n + ^A_Z N \rightarrow ^A_{Z-1} N + p$$

$$n + ^A_Z N \rightarrow ^{A-3}_{Z-2} N + ^4_2 \alpha$$



- **Fission:**

$$n + ^A_Z N \rightarrow ^{A_1}_{Z_1} X + ^{A_2}_{Z_2} Y + n$$



Neutrons Interactions

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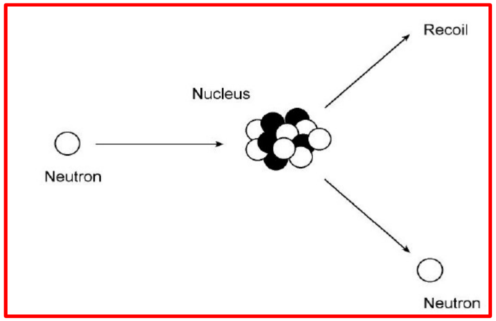

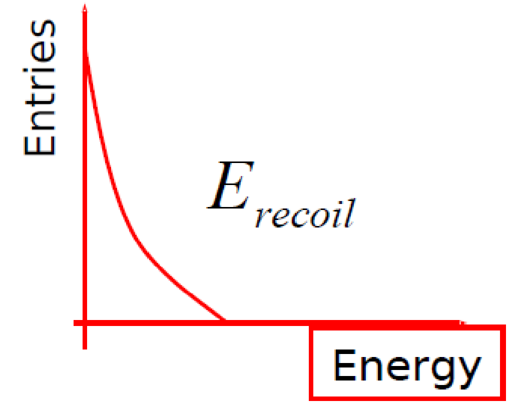

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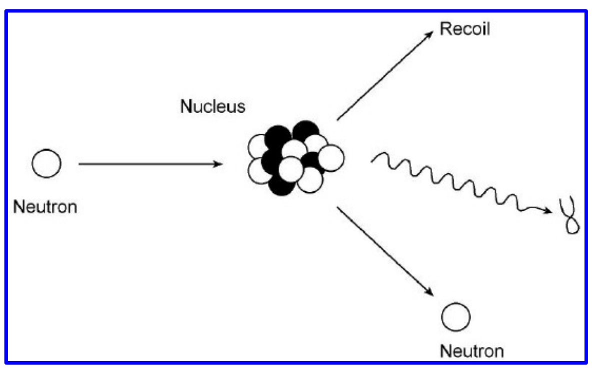
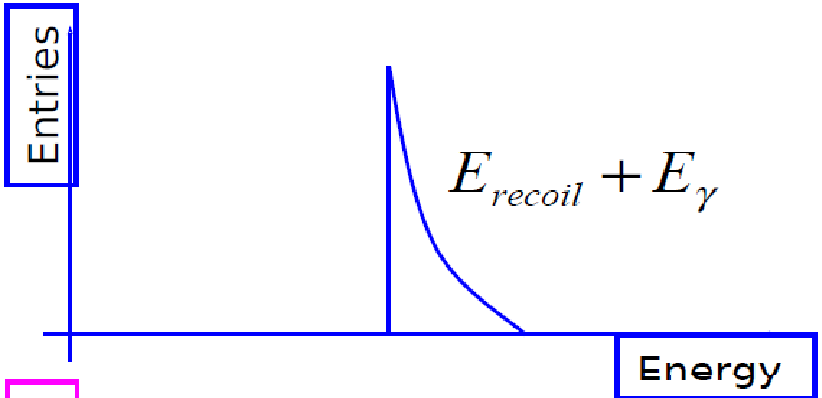
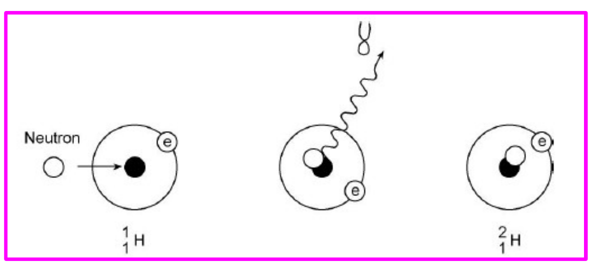
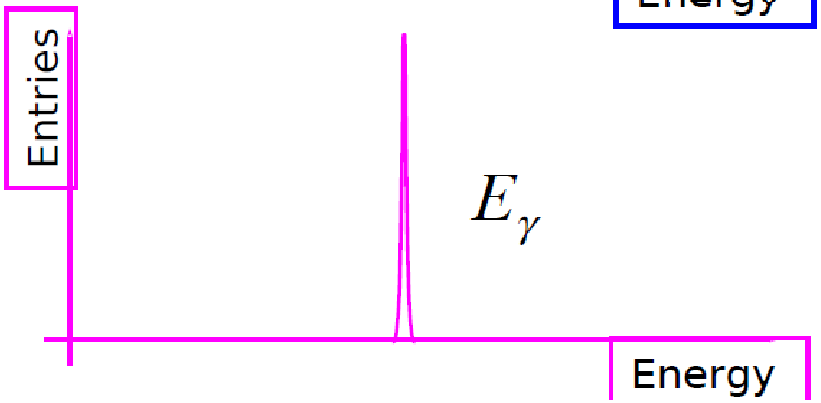




- **Thermal Capture:**





Efficiency Results

- **Integrated neutron yield per muon ~ 0.7×10^{-1}**
  - **but on average ~ 3.4 neutrons/interaction ==> not every 10th muon produces neutrons**

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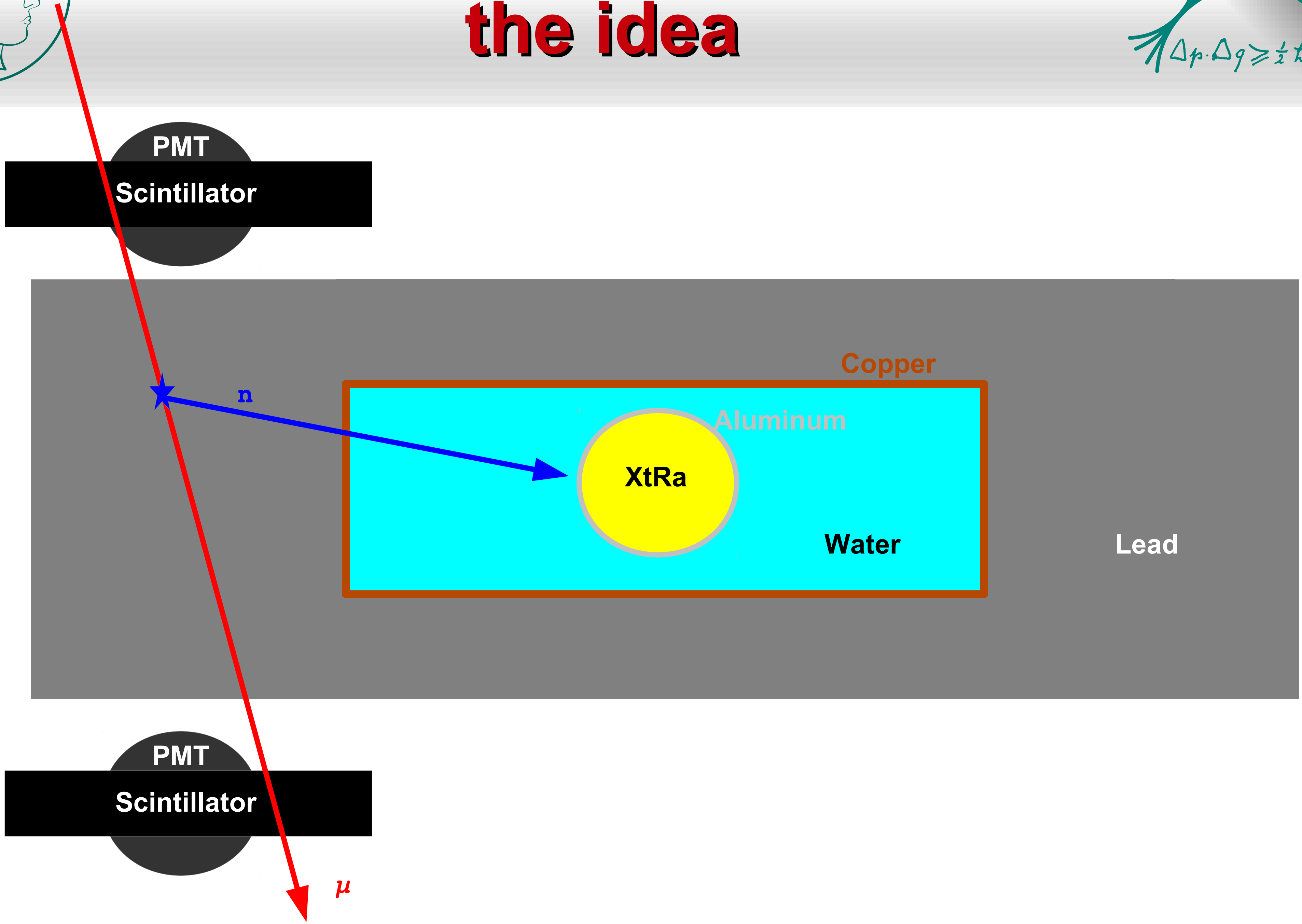
Efficiencies Comparison

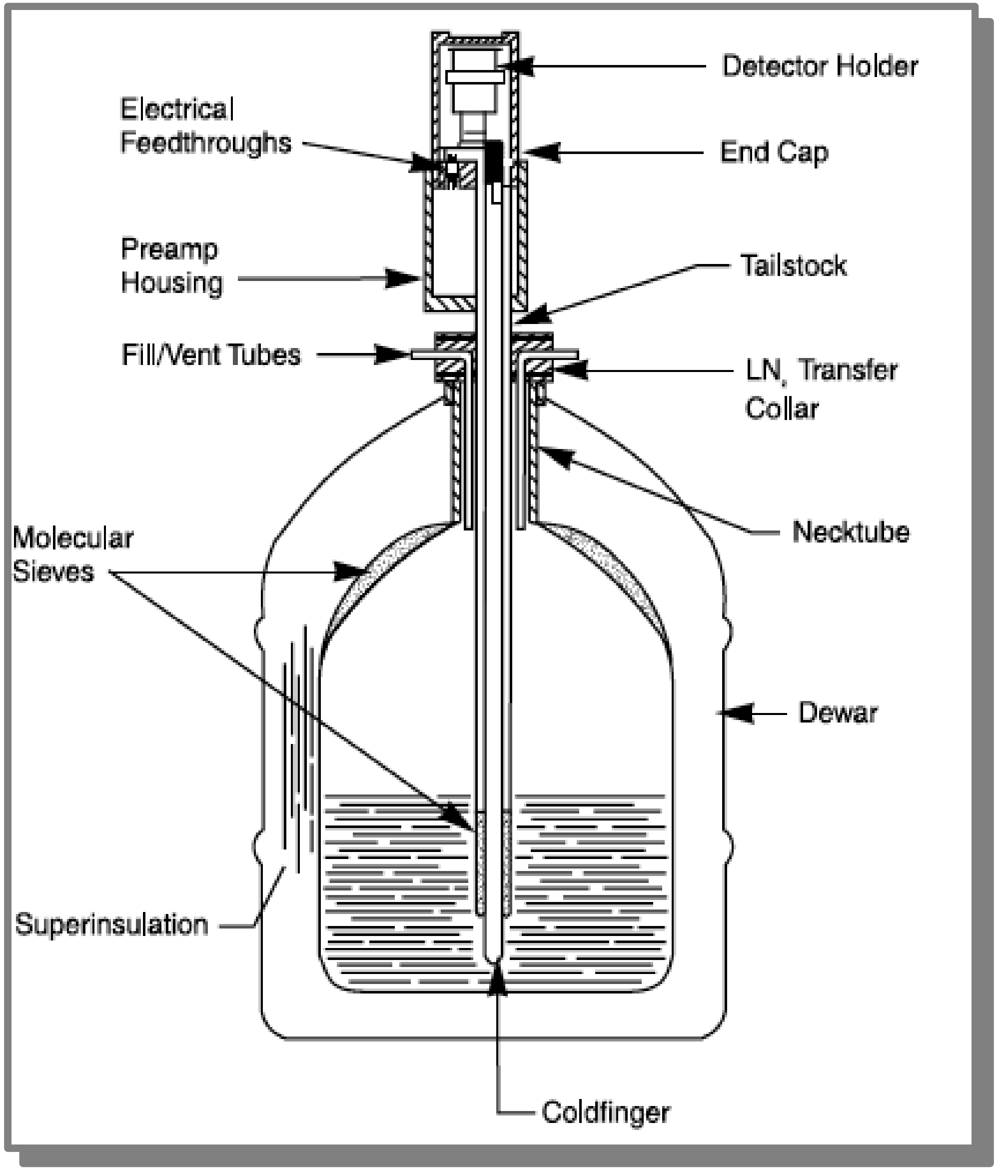
	Water Wall (tot ev.: 6.225e07 μ)	**Cylindrical** (tot ev.: 1.92952e07 μ)
n OUT from Lead	7.0×10^{-2}	5.1×10^{-2}
n OUT from Water	8.7×10^{-4}	6.8×10^{-4}
n IN @GeDet	1.2×10^{-5}	4.0×10^{-4}
2.2 γ OUT from Water	1.9×10^{-3}	2.1×10^{-4}
2.2 γ IN @GeDet	2.2×10^{-5}	1.1×10^{-4}
2.2 γ IN @GeDet after 1 ms	3.2×10^{-7}	1.6×10^{-6}
2.2 γ Detected by GeDet	5.6×10^{-6}	2.5×10^{-5}

=> ~ 60%
=> ~ 2%

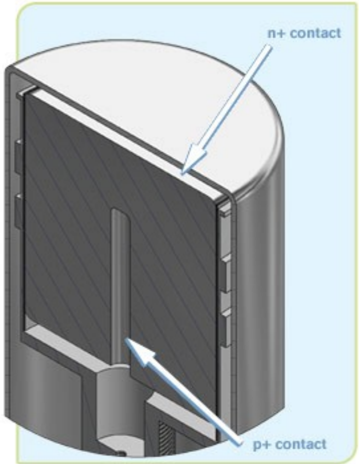
The Experimental Setup: the idea

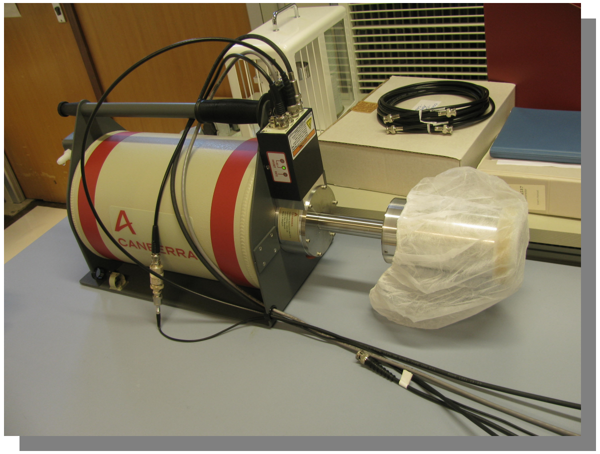


The Experimental Setup: eXtended Range GeDet



- Resolution: 2 keV @ 1.33 MeV
- p-type
- Peak/Compton 67:1
- Aluminum End Cup
- Copper Holder
- HV = +3000 V
- Charge sensitive pre-amp
- Diameter 6.9 cm
- Lenght 7.2 cm
- Outer electrode (n+) 0.6 mm
- Inner electrode (p+) 0.3 μm





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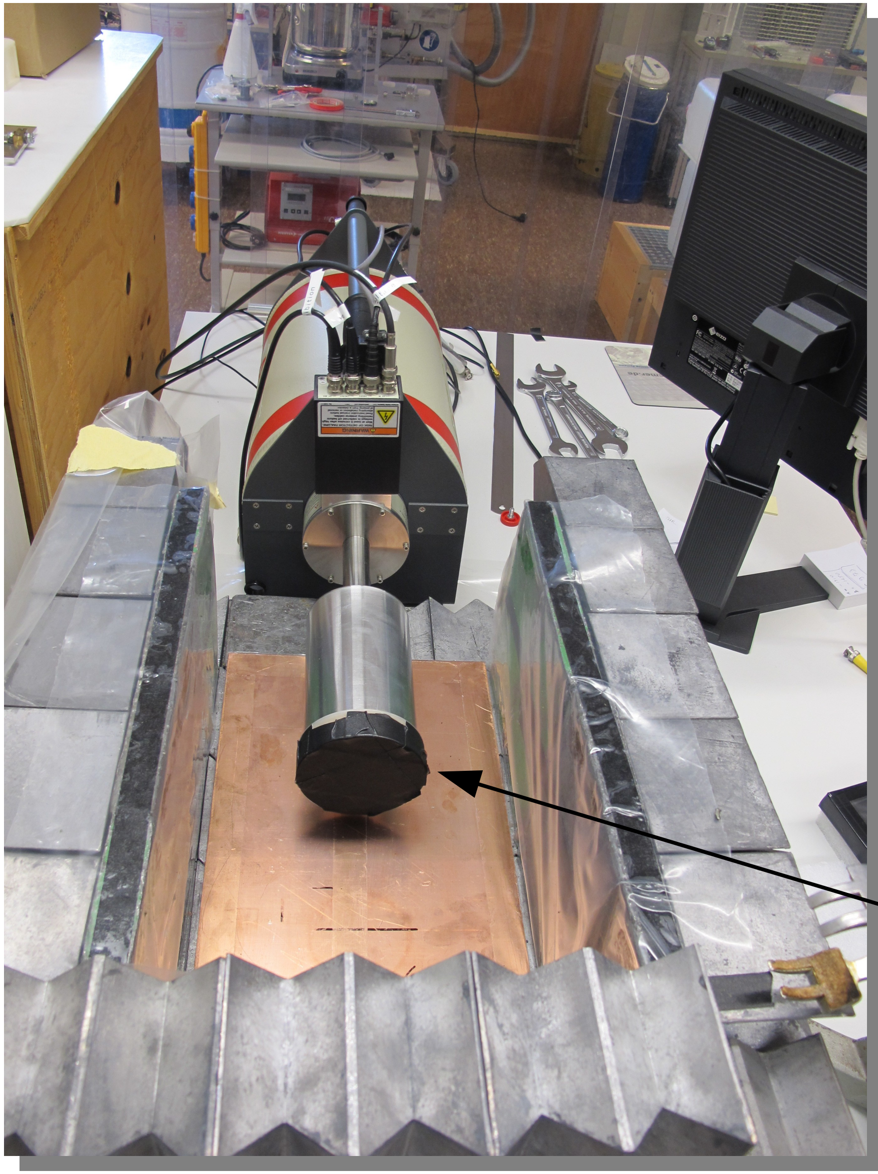
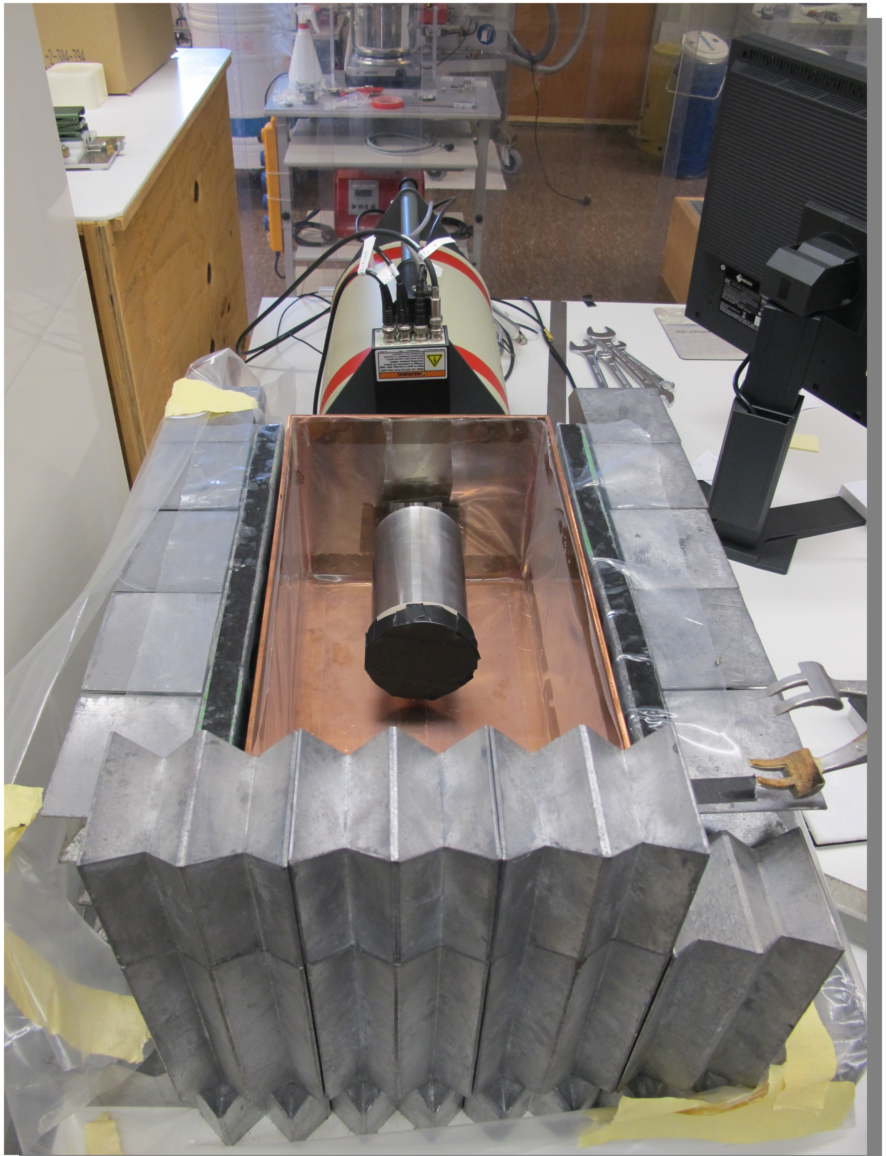


- **Lead:**
  - thickness 10.5 cm
  - height 28 cm
- **Copper shell:**
  - Thickness 0.4 cm
- **Scintillator paddles:**
  - 12 x 21 x 2 cm^3
  - distance 48.5 cm
- **DAQ:**
  - DGF Pixie-4 (high precision)
  - Sampling frequency 75 MHz
  - Spectra: 16-bit precision up to 32K channels

Additional plastic end-cup covered with black tape

The Experimental Setup



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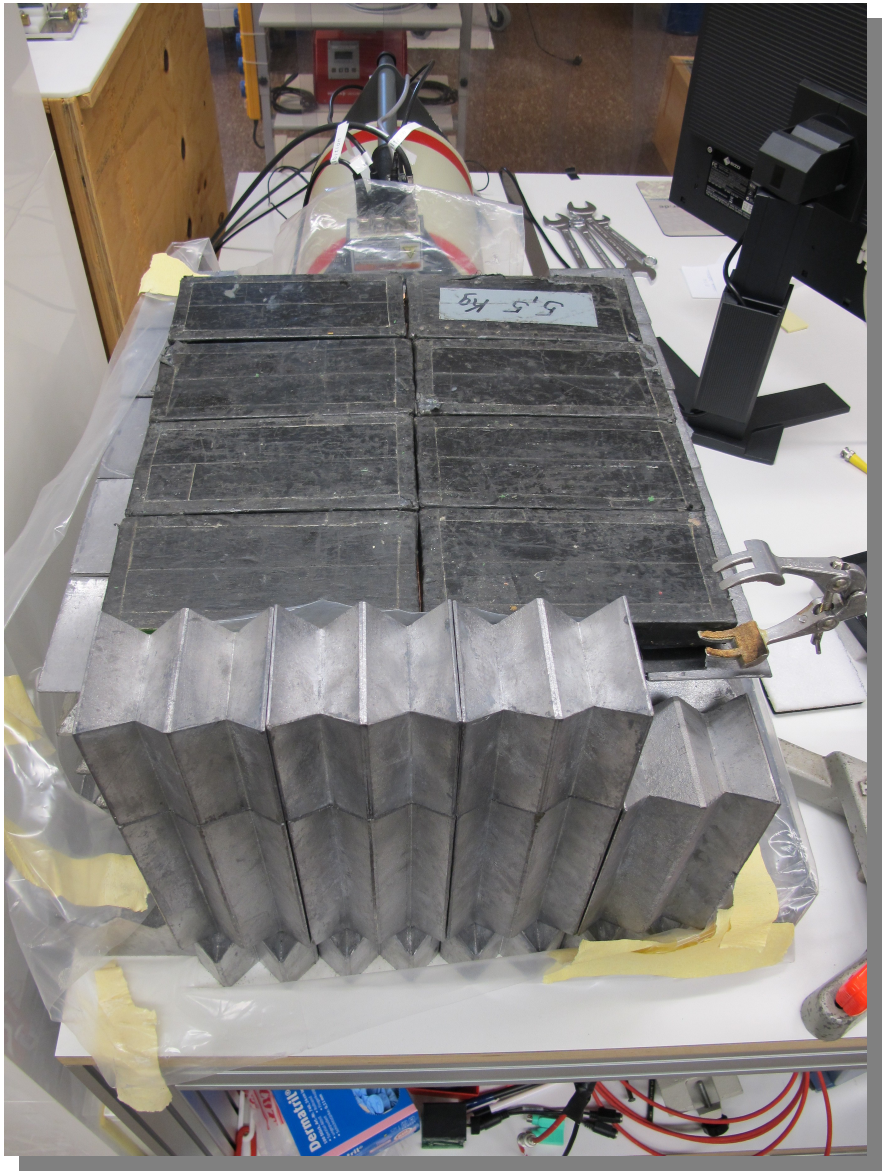

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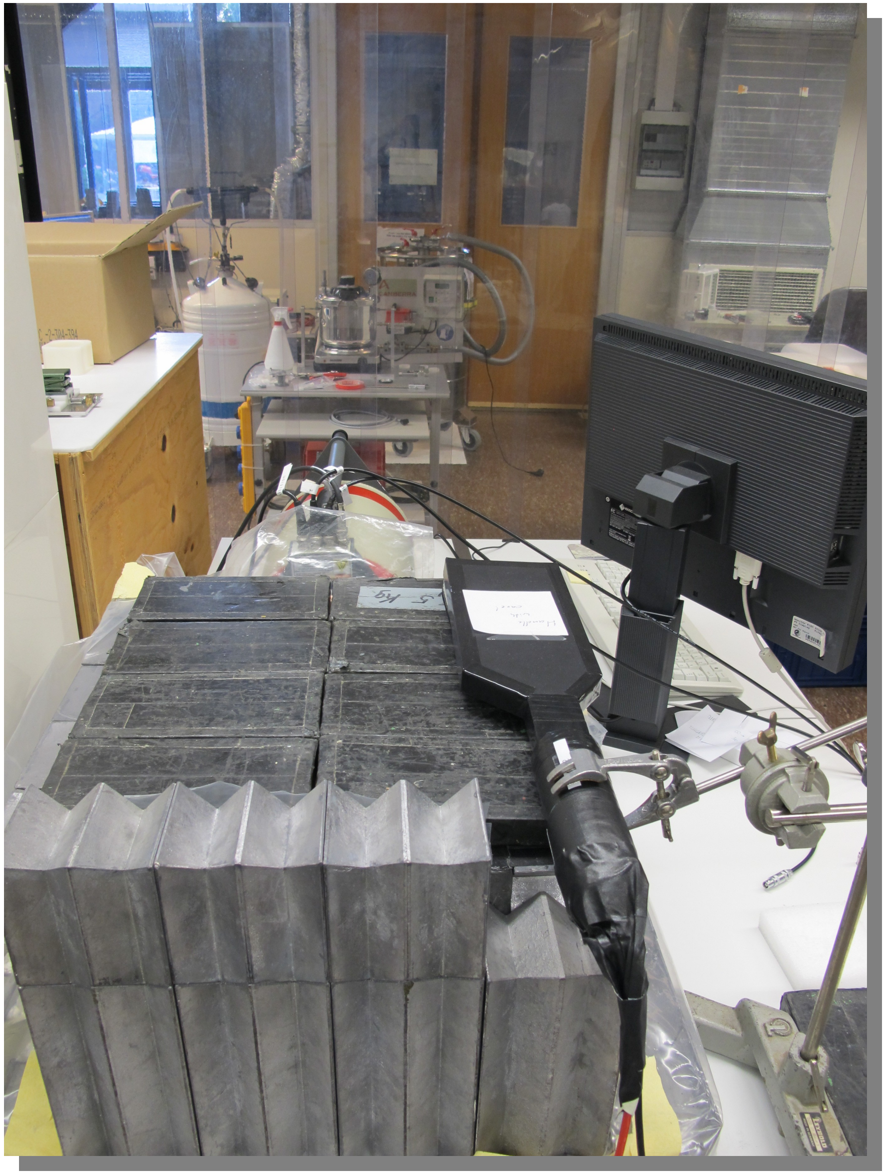

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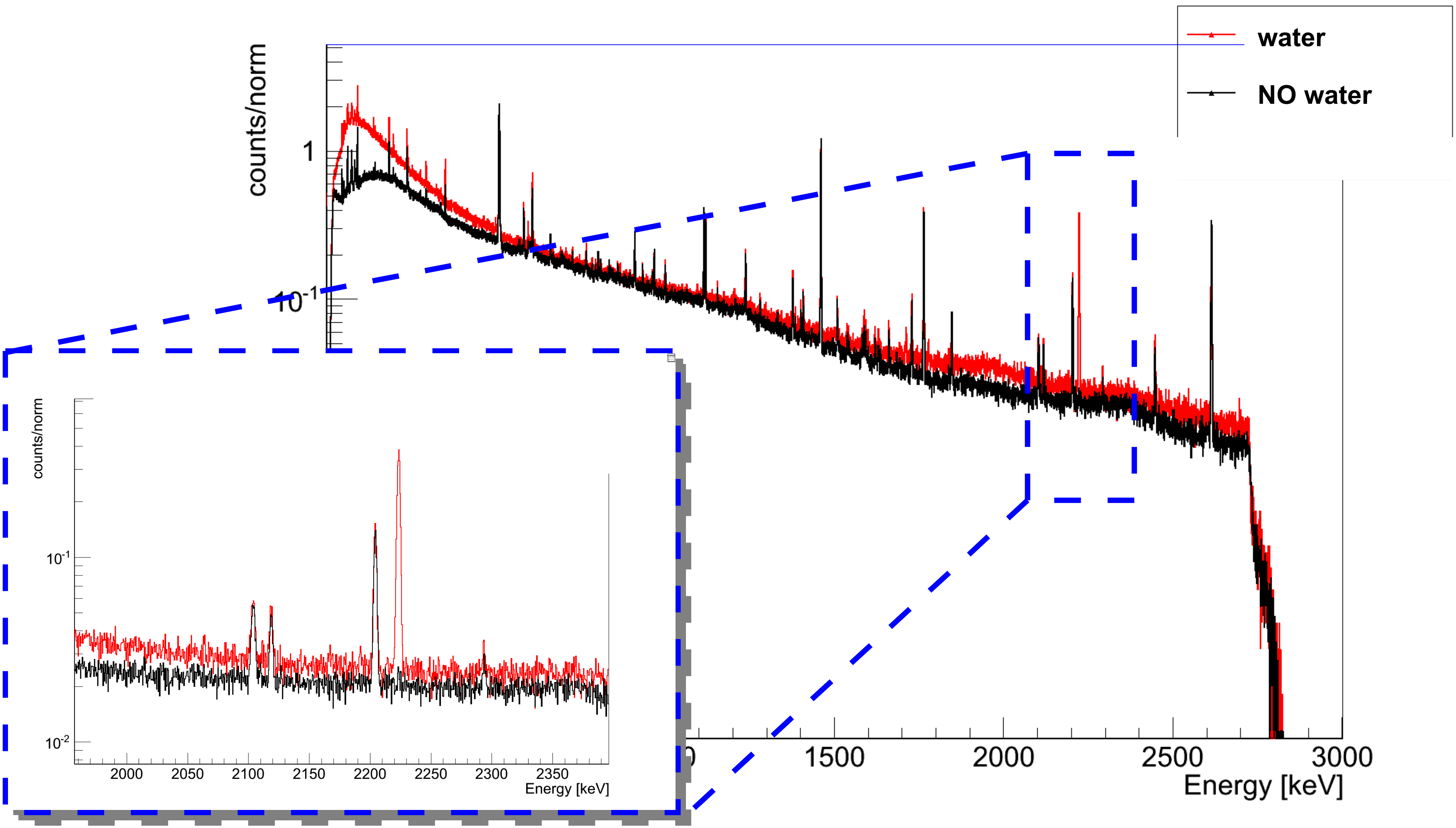
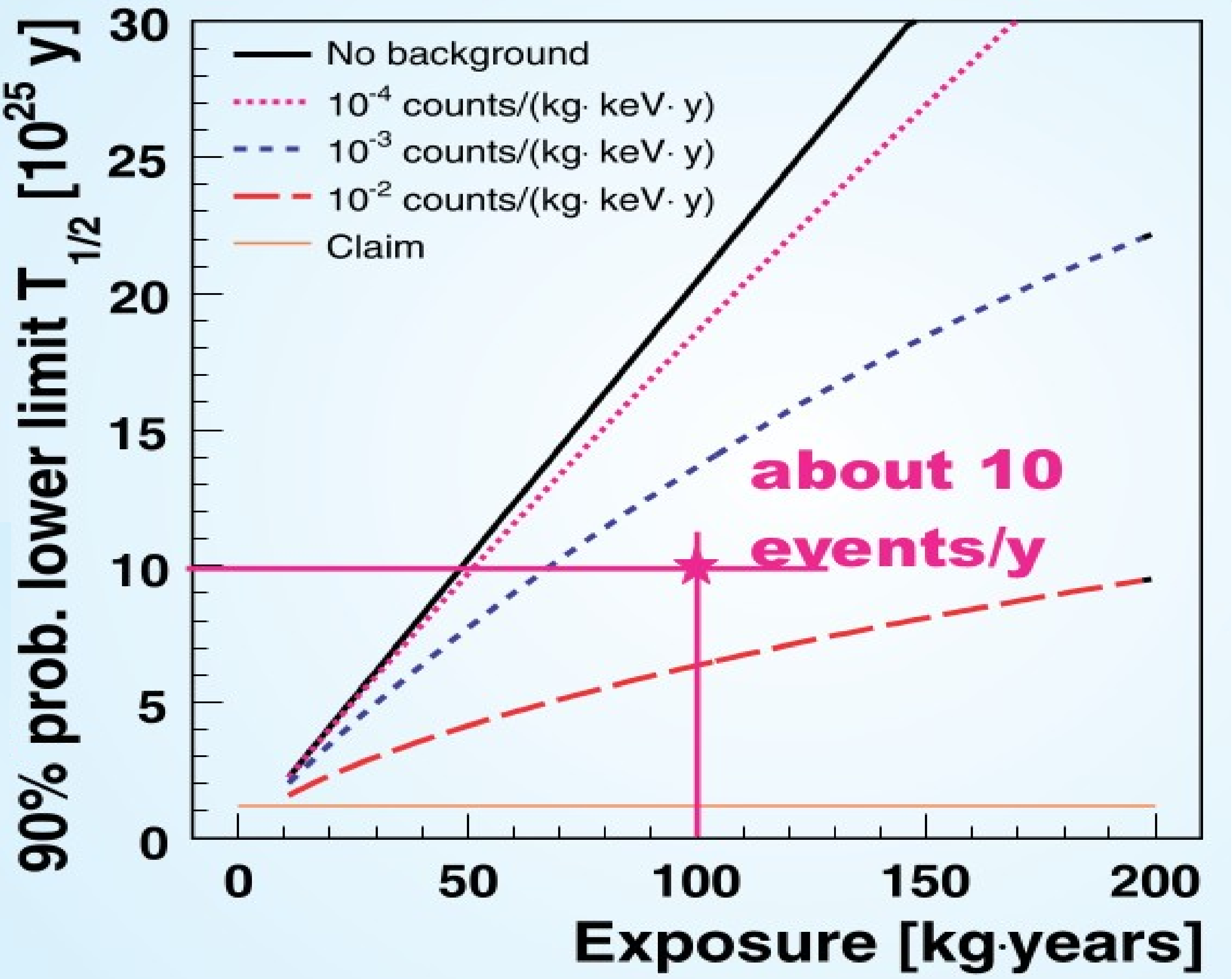
Pre-test Above Ground

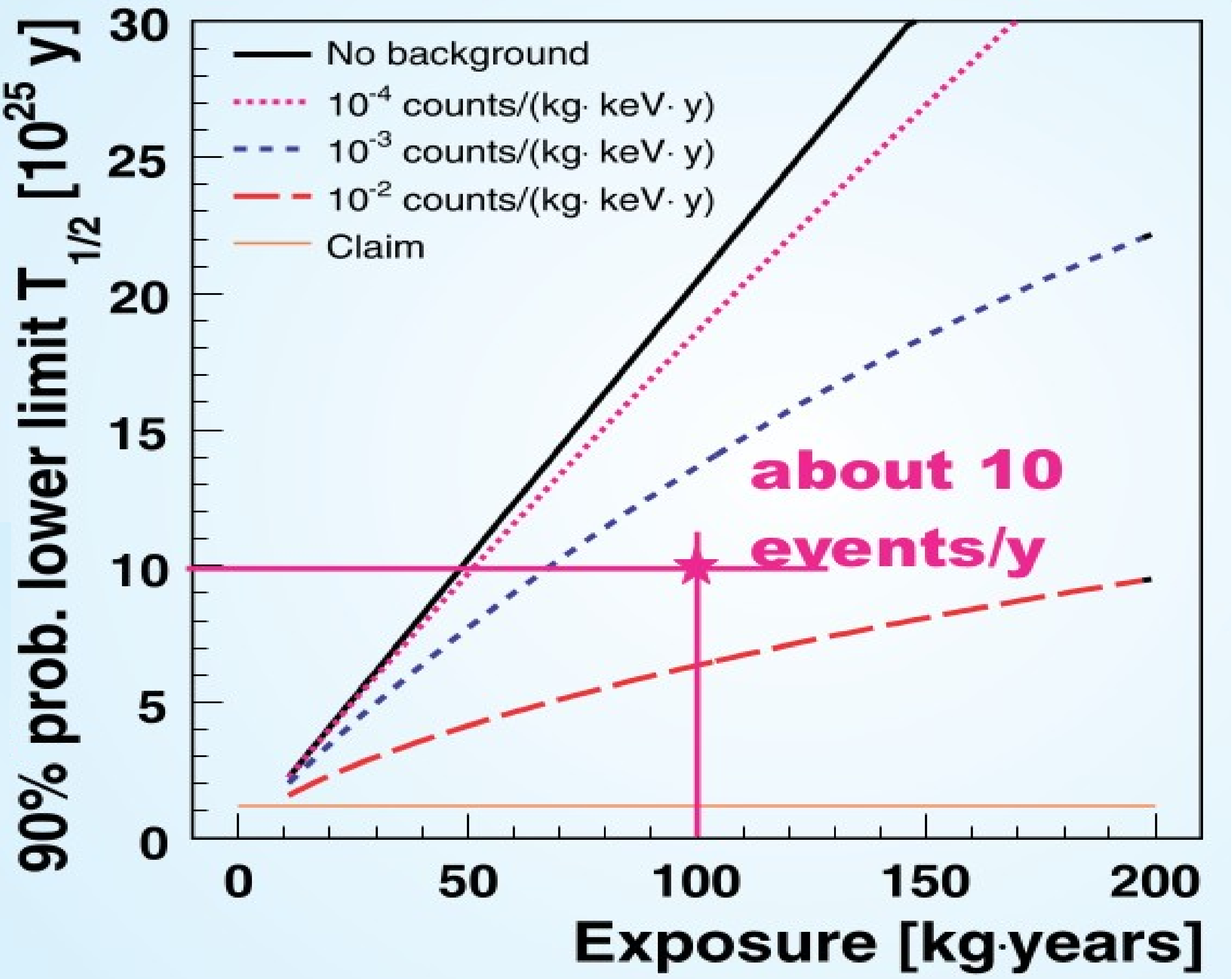


Importance of Background



Allen Caldwell, Kevin Kröninger, Phys.Rev.D 74 (2006) 092003

Importance of Background



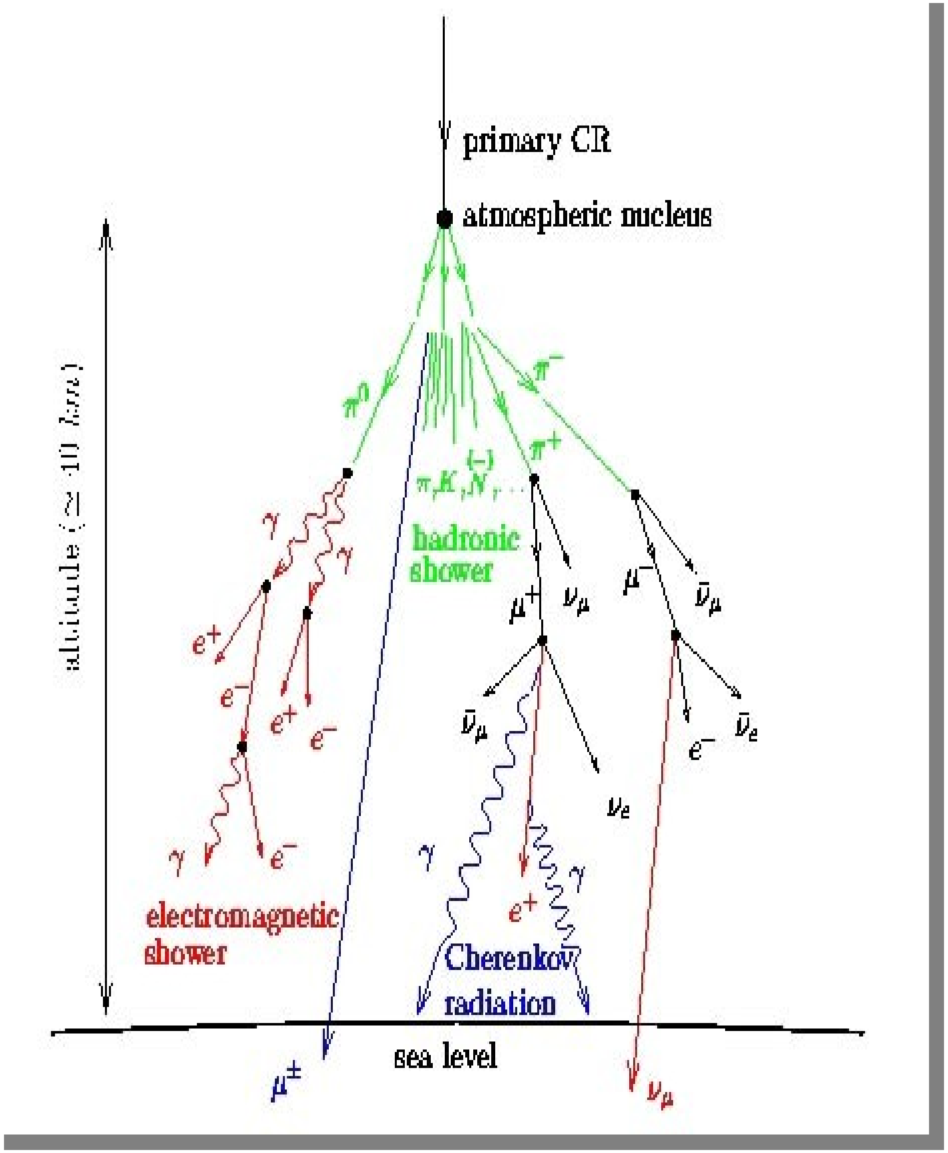
To build an experiment is crucial to know which level of background you can allow and which you can not!

Allen Caldwell, Kevin Kröninger, Phys.Rev.D 74 (2006) 092003

Simulation Info

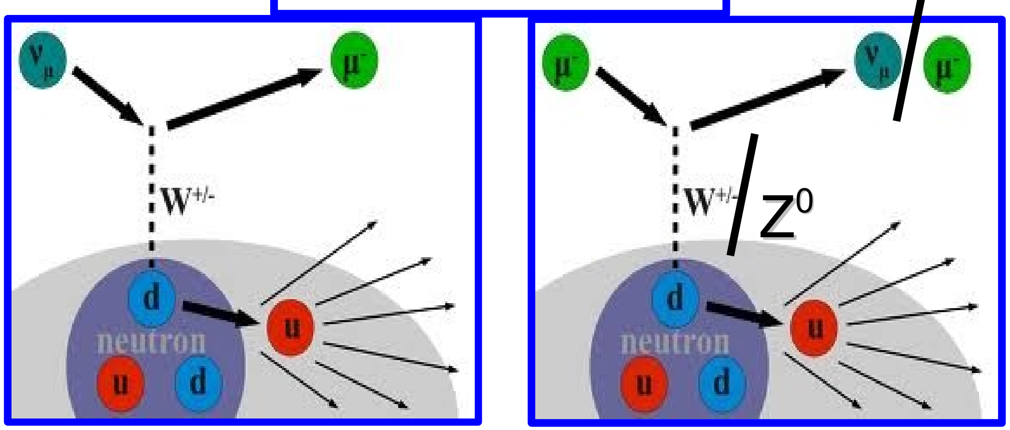
- **Particle injected: mu+ and mu-**
- **Muon spectrum: ground level starting from 1.897 GeV**
- **Physics list used: qgsp_hadron_list**
- **Muons generation plane == uppuermost scintilator surface**
- **Shooting direction: vertical**

Cosmic Rays Shower

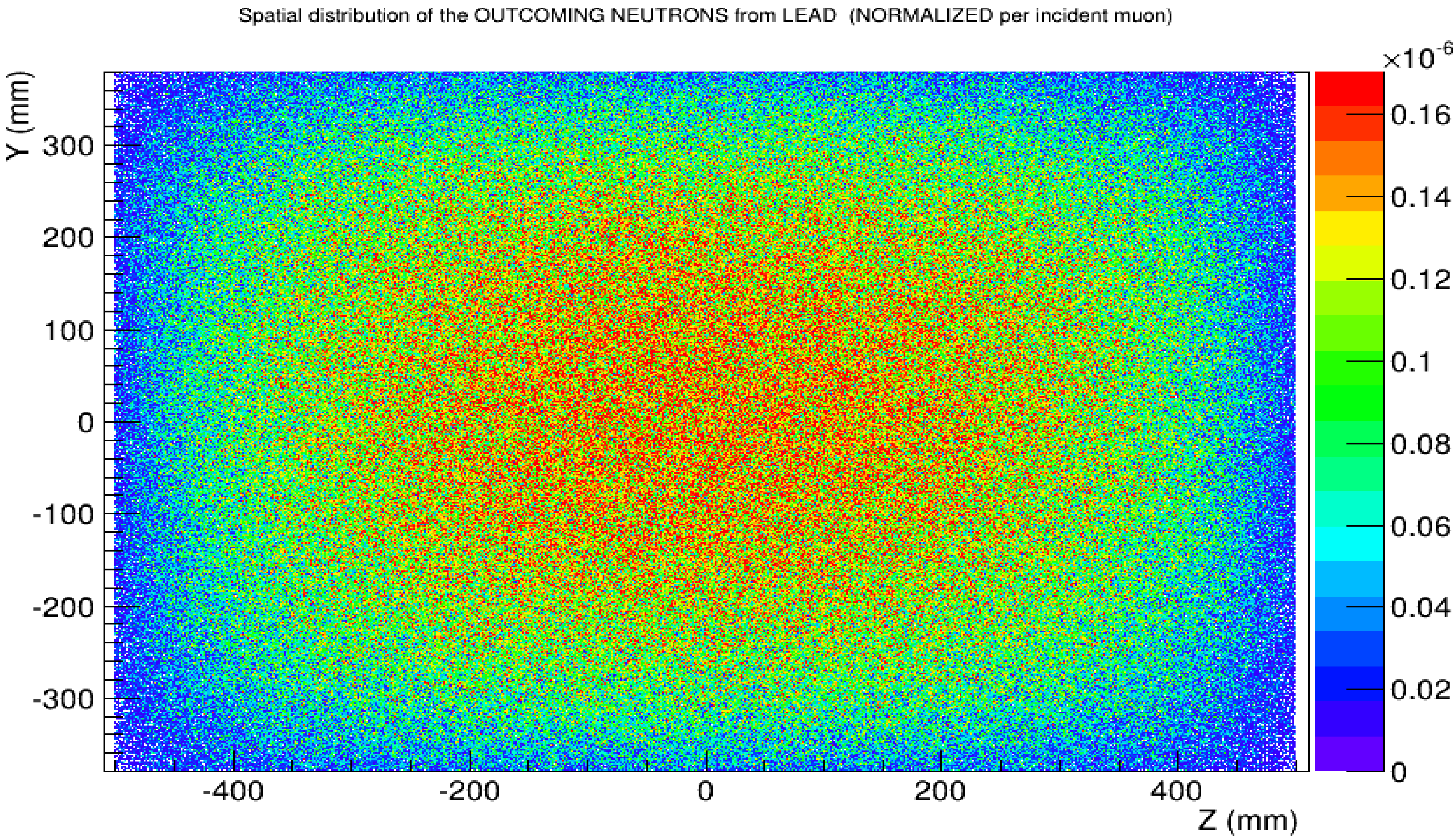


Photodisintegration

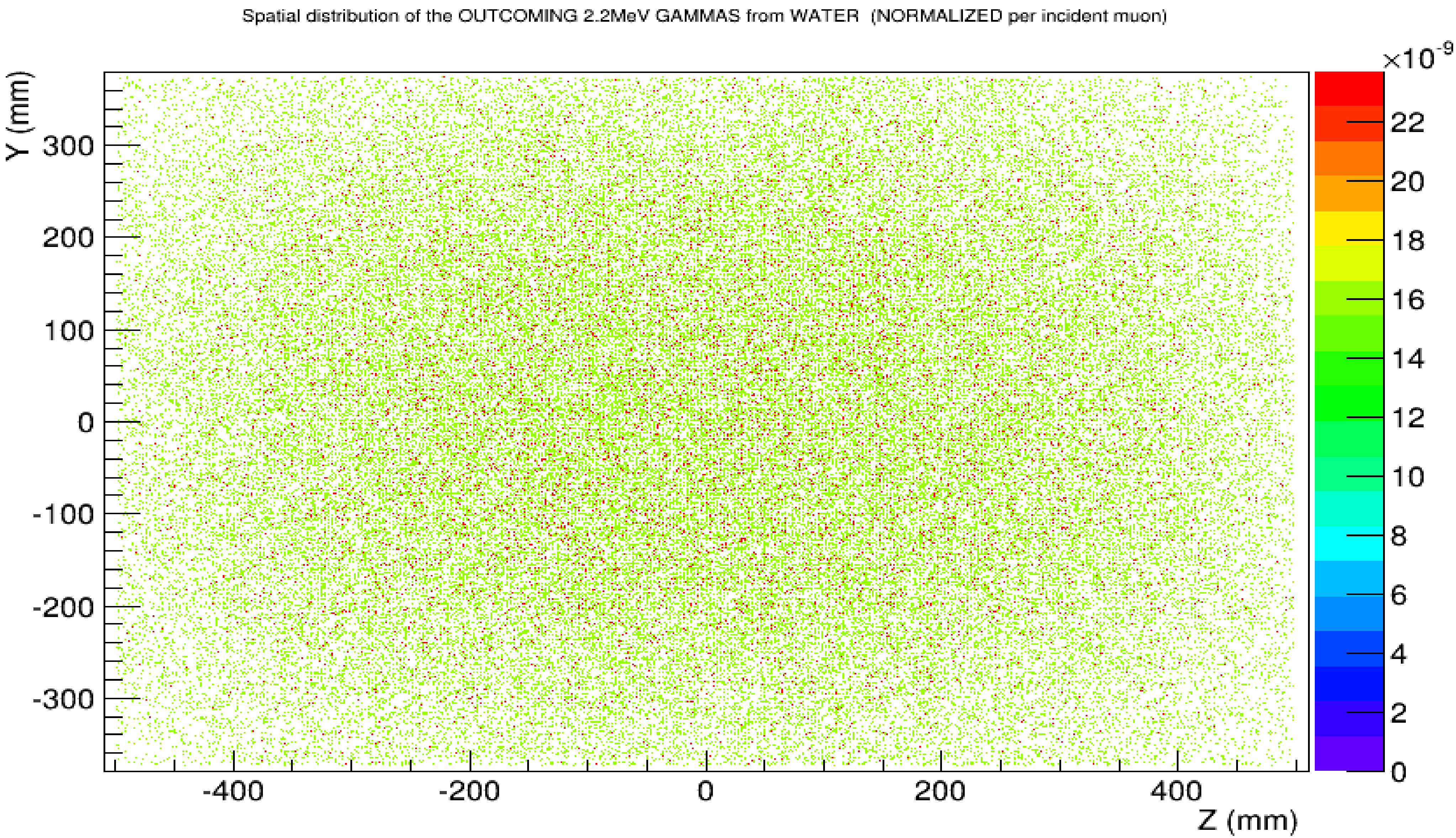
DIS



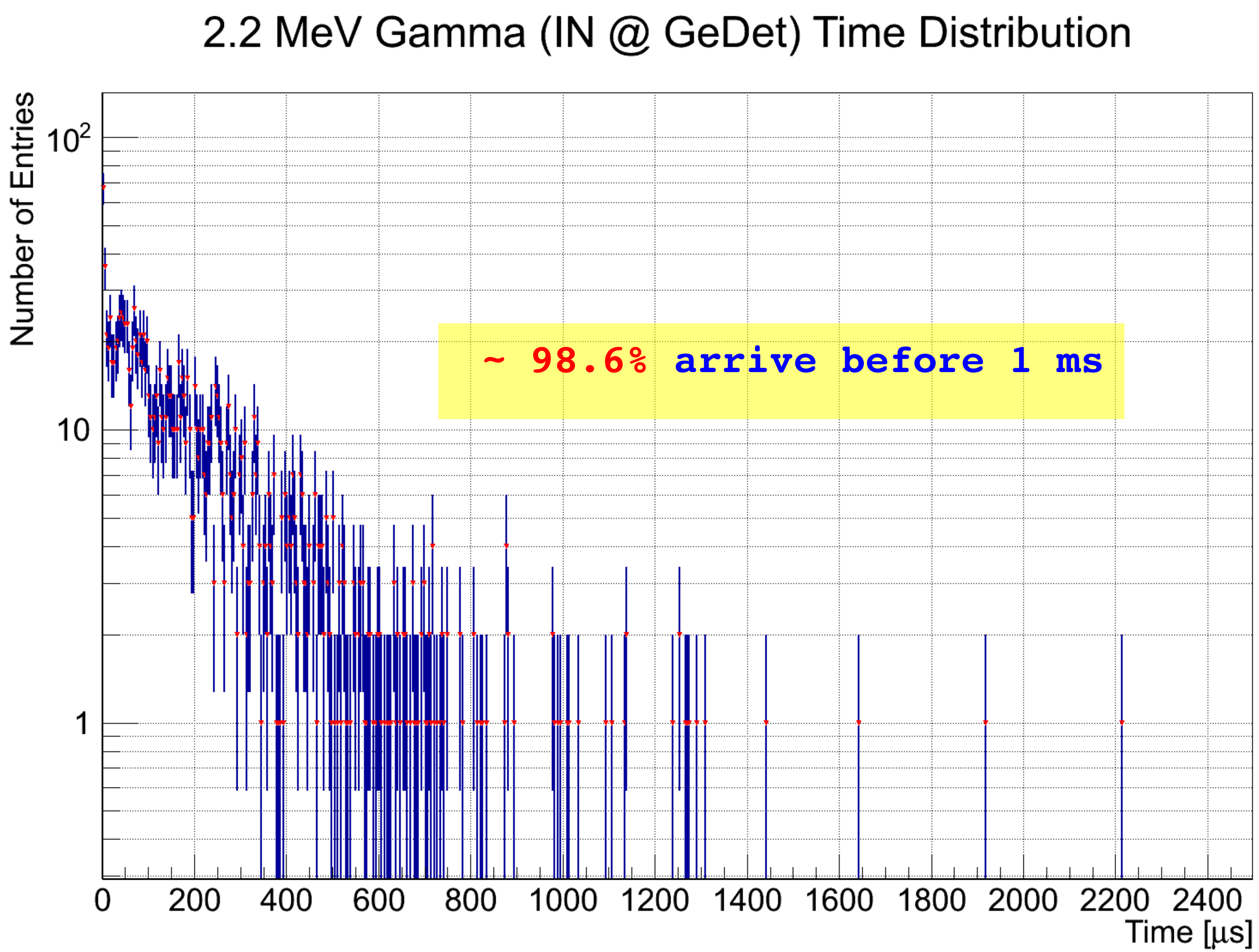
OUTGOING Neutrons @ LEAD wall



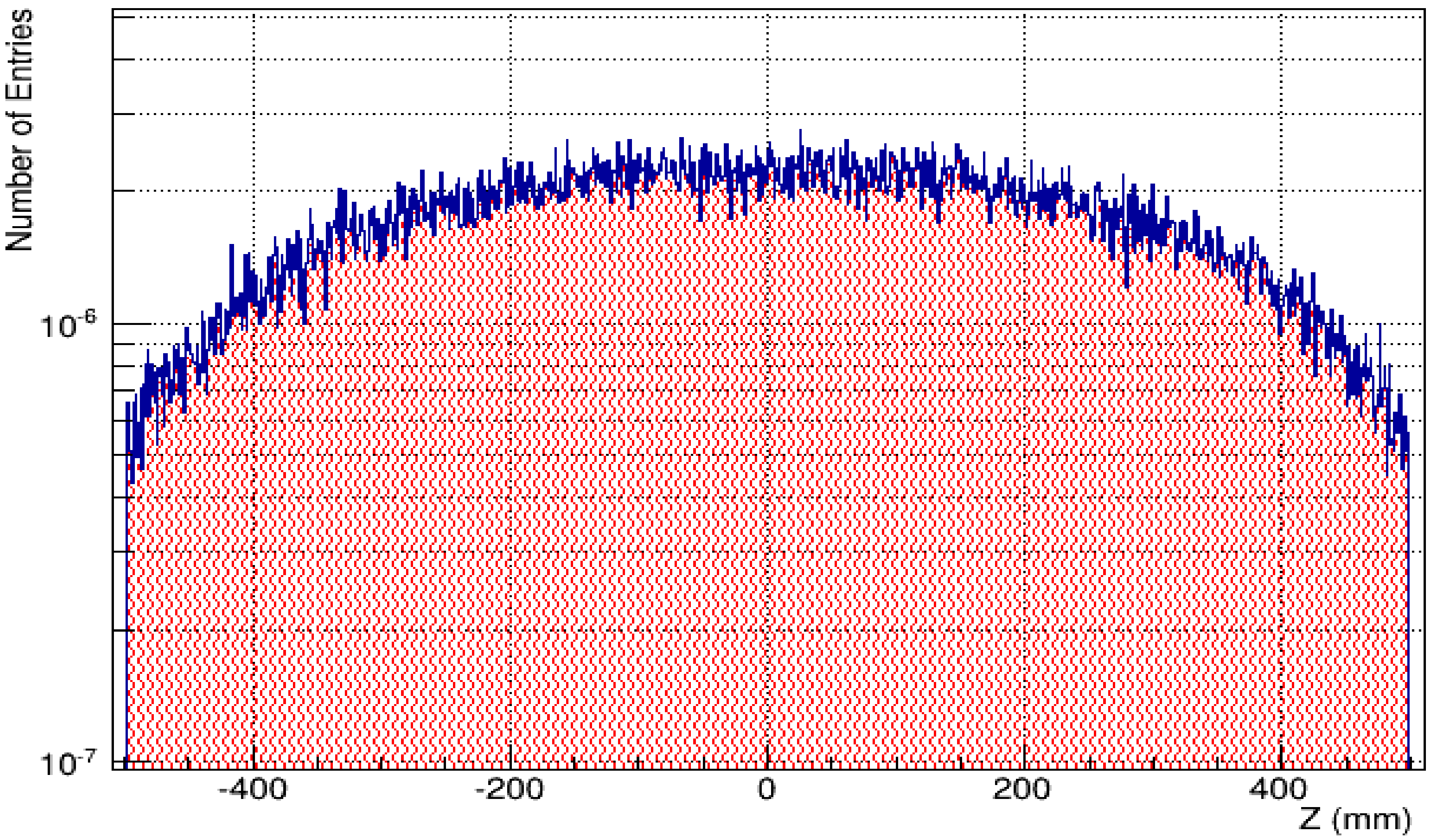
OUTGOING 2.2 MeV Gammas @ Water wall



2.2MeV γ Time Distribution INCOMING @ GeDet

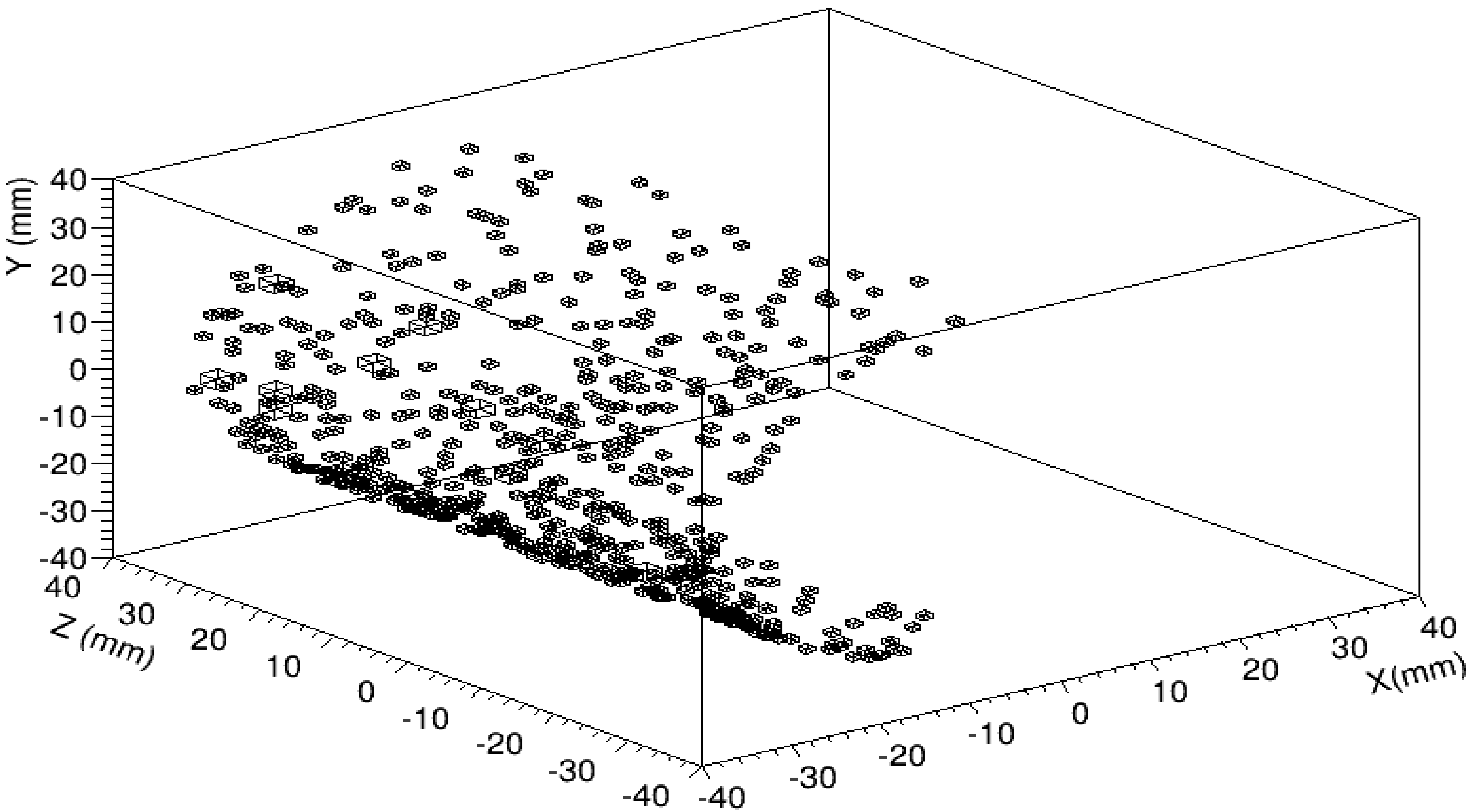


OUTGOING 2.2 MeV Gammas @ Water wall

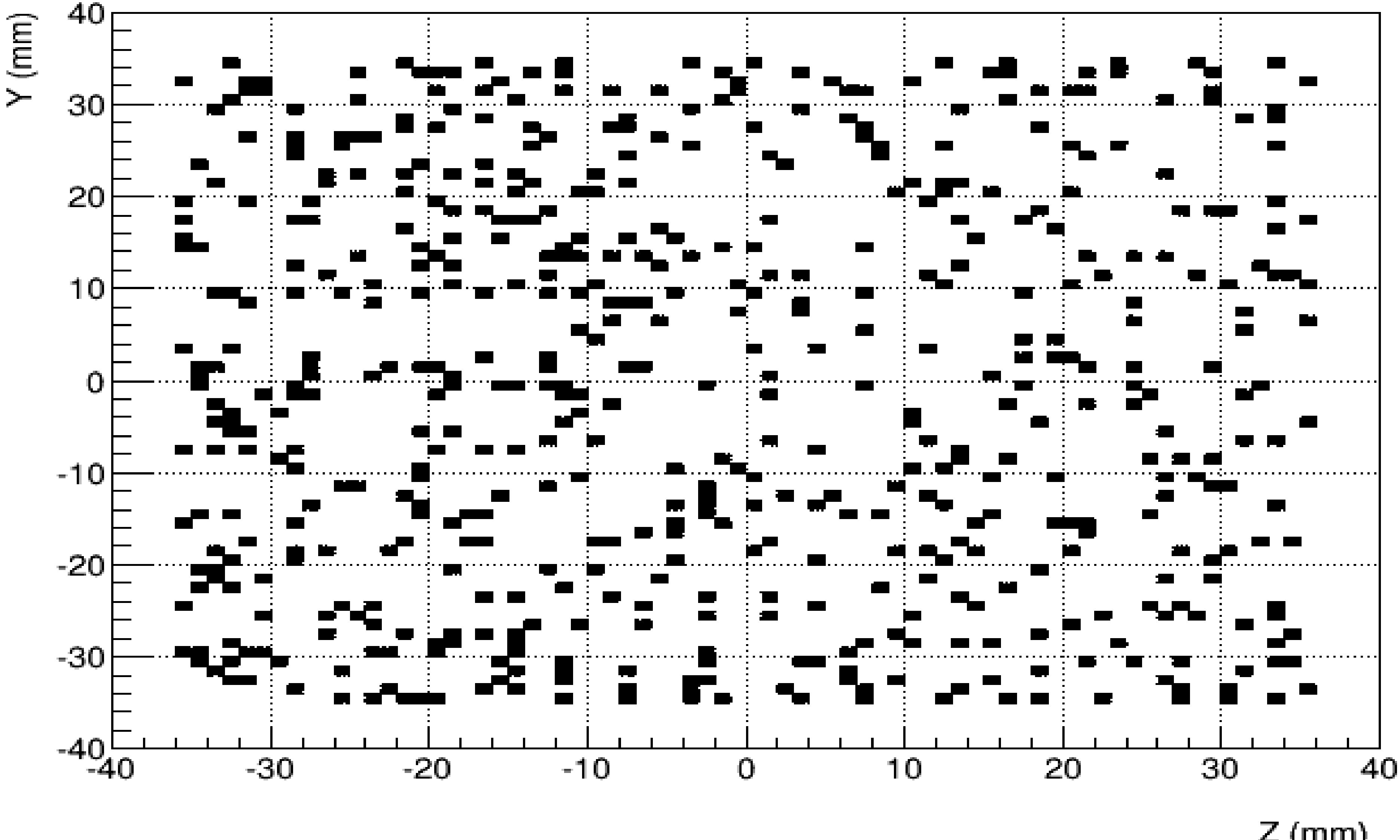


INCOMING 2.2 MeV Gammas into GeDet

Spatial distribution of the INCOMING 2.2MeV gammas in GeDet (NORMALIZED per incident muon)

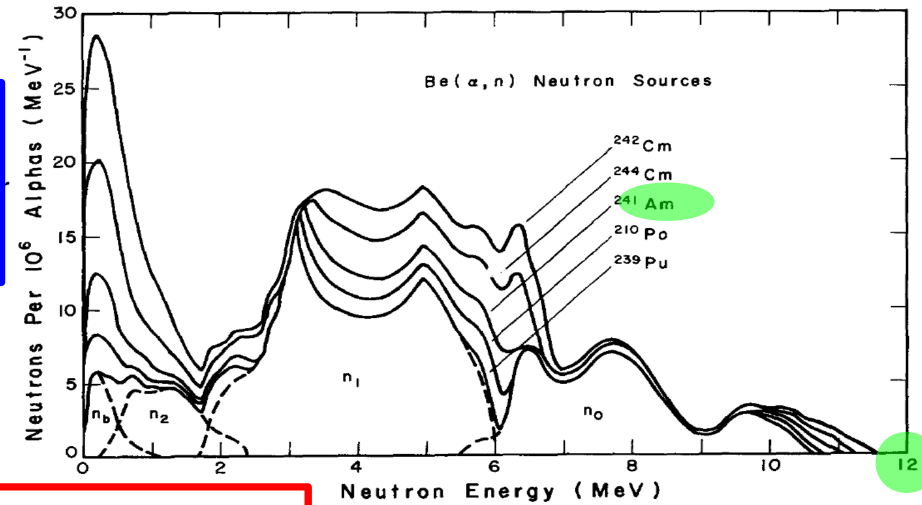


INCOMING 2.2 MeV Gammas into GeDet



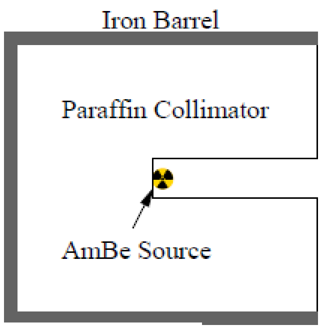
AmBe neutron source

$$^{241}_{95}Am \rightarrow ^{4}_{2}\alpha + ^{237}_{93}Np$$



$$^{4}_{2}\alpha + ^{9}_{4}Be \rightarrow (^{12}_{6}C)^{*} + n$$

de-excitation gammas



- **1.1 GBq**
- **Am-241 → 432.2 y half life**

Characteristics of Be(α,n) sources.

Source	E_α (MeV)	Yield per 10^6 alphas: This work	Yield per 10^6 alphas: Maximum experimental	Yield per 10^6 alphas: Y from eq. (7)	Fraction with $E_n < 1.5$ MeV: This work (%)	Fraction with $E_n < 1.5$ MeV: Literature (%)	E_n: This work (MeV)	E_n: Literature (MeV)
1	2	3	4	5	6	7	8	9
^{241}Am–Be	5.48	82 ± 8	70 ± 3[18]	72	14 ± 2	15[25] 23[21]	4.46	3.9[27] 4.3[26]

Germanium Detectors

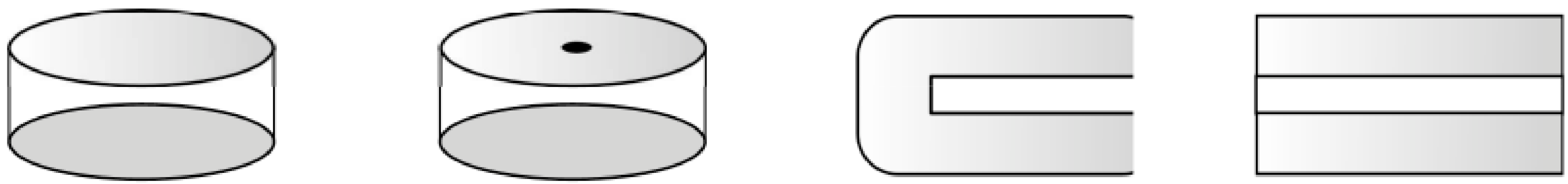
Widely used in nuclear physics experiments and DM searches

- **Concept:**
  - **Secmiconductor diodes with p- or n- structure**
  - **Reverse biasing**
  - **Sensitive to ionizing radiation**
  - **Depleted,sensitive thickness of several cm (for Si only mm)**
  - **Cryogenic Temperatures**

- **Advantages:**
  - **Measurement of low levels of radioactivity**
  - **High gamma-ray detection efficiency**
  - **Excellent energy resolution (~keV)**

Germanium Detectors

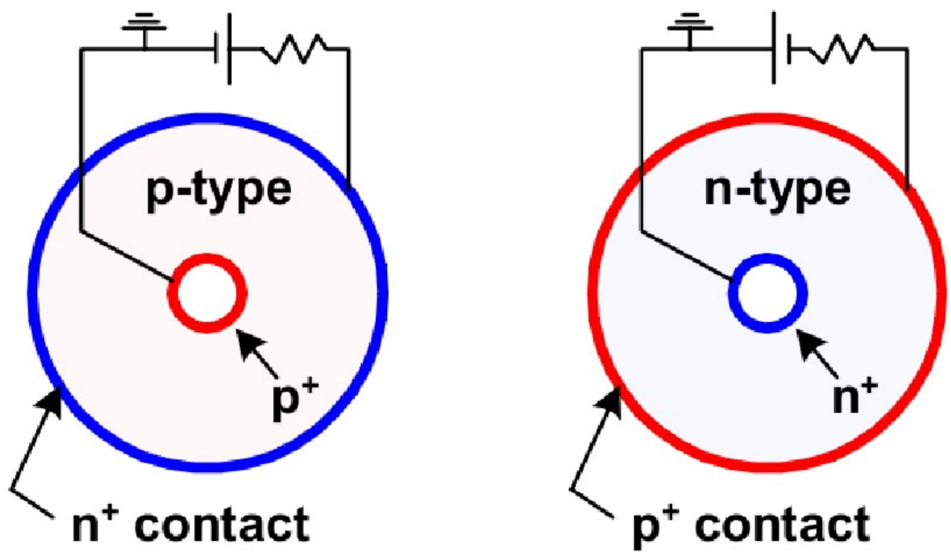
- **Detector configurations:**



Planar | Point-contact | Closed-ended coaxial | True-coaxial

- **Electrode configurations for coaxial detectors:**

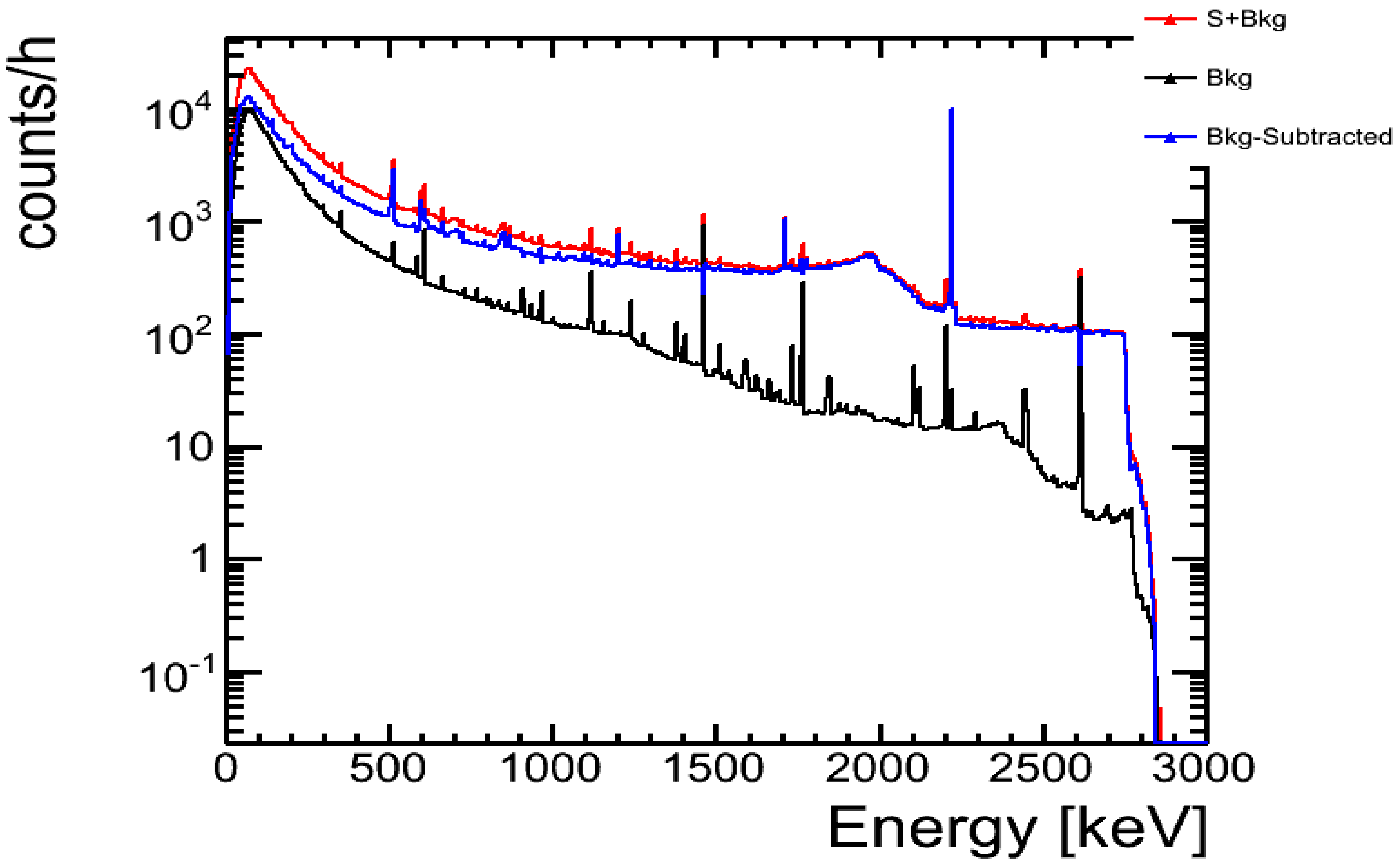
Lithium Diffusion Layer (~mm)



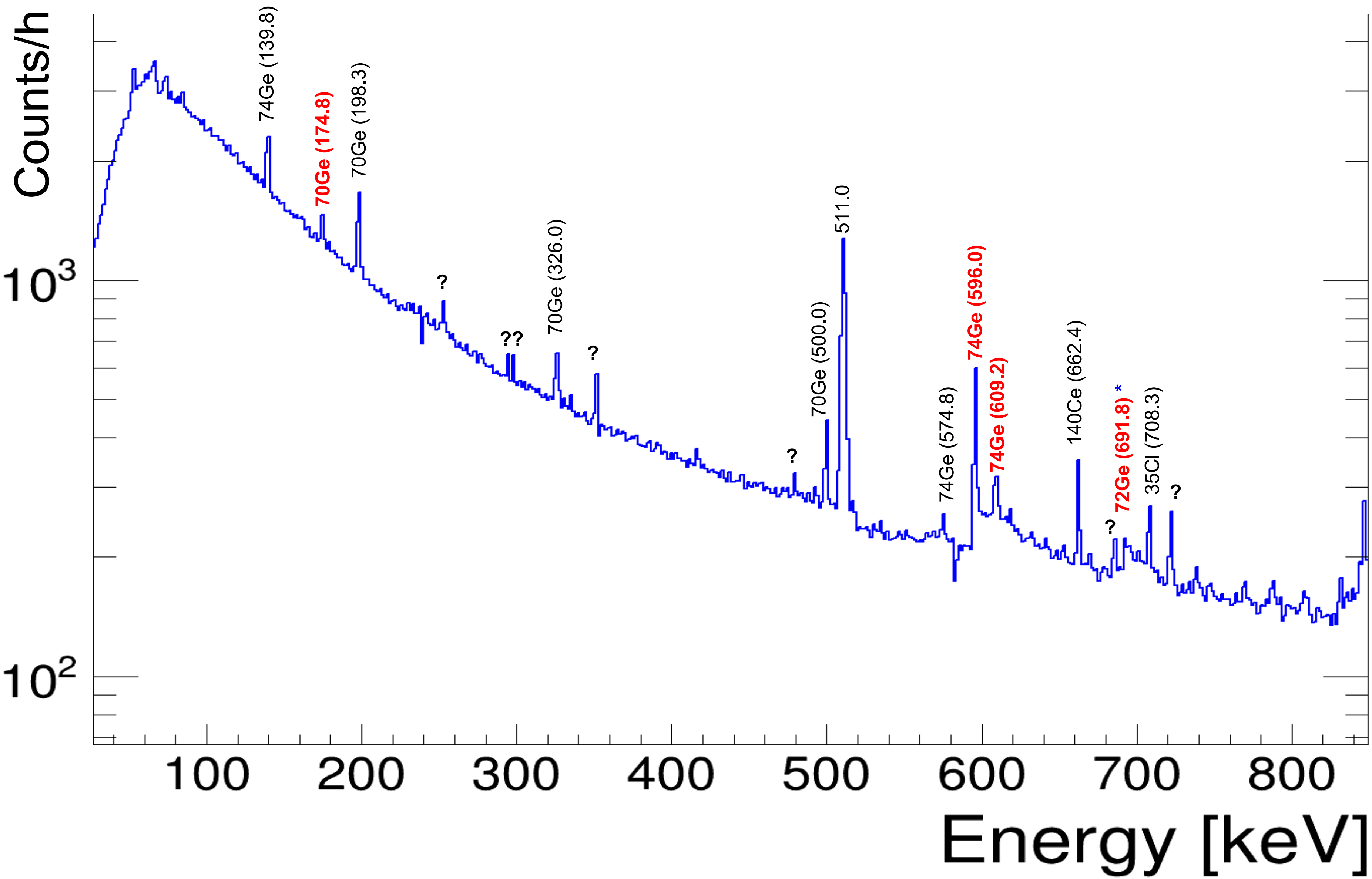
Boron Implantation (~μm)

Source: Med Phys 4R06/6R03 Radioisotopes and Radiation Methodology
Chapter 8: "Hyper-Pure Germanium Detector"

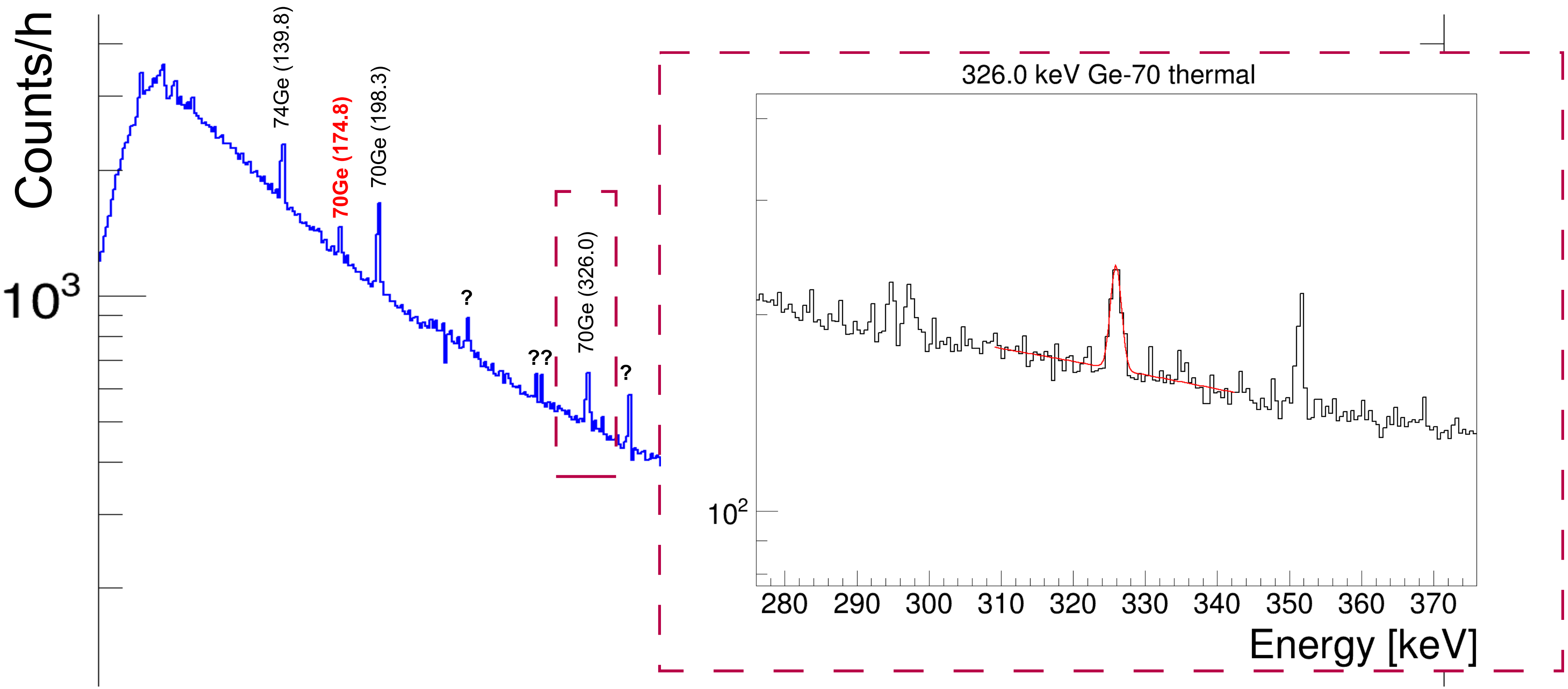
AmBe neutron source: results



Background Subtracted: 0-0.8 MeV

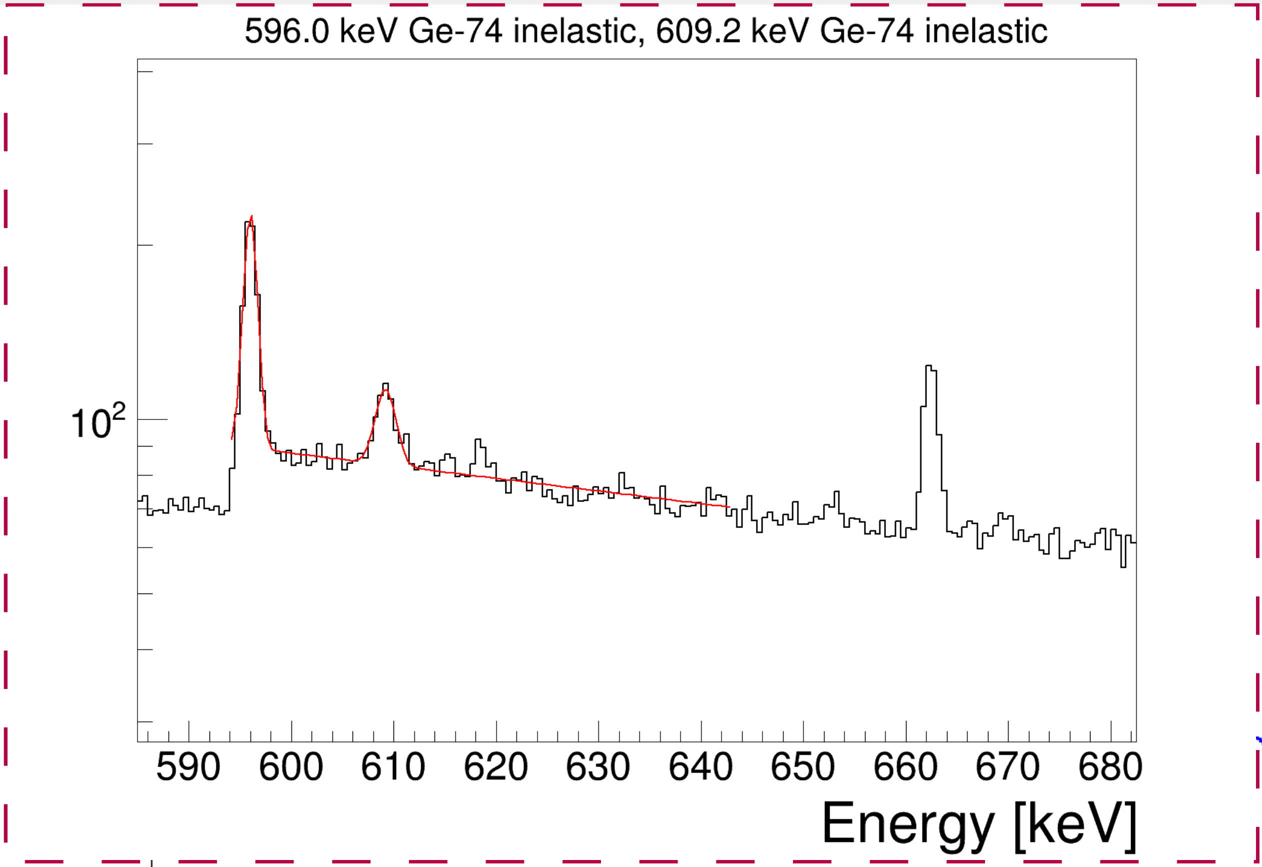


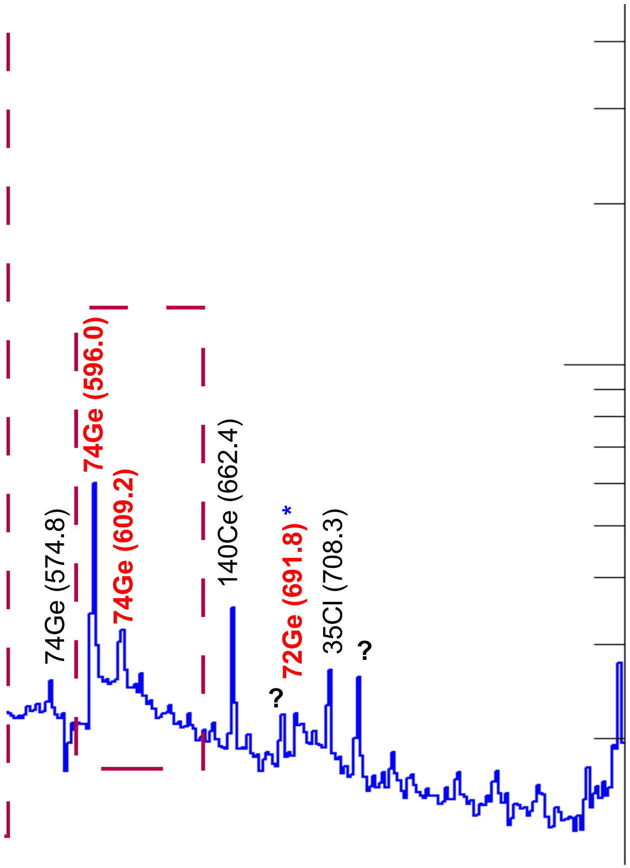
Background Subtracted: 0-0.8 MeV



Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
326.0 ± 0.1	0.7 ± 0.1	$^{70}Ge(n,\gamma)$

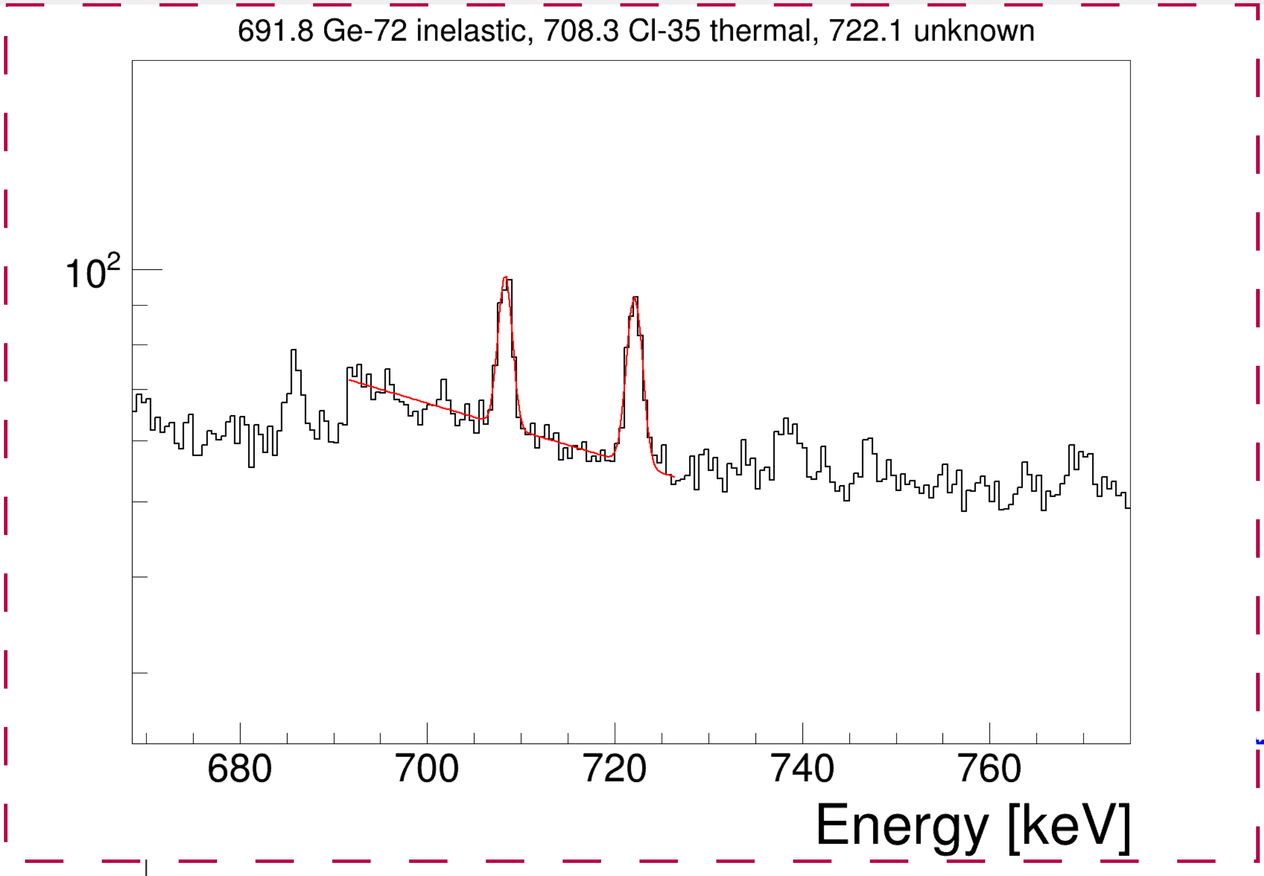
Background Subtracted: 0-0.8 MeV

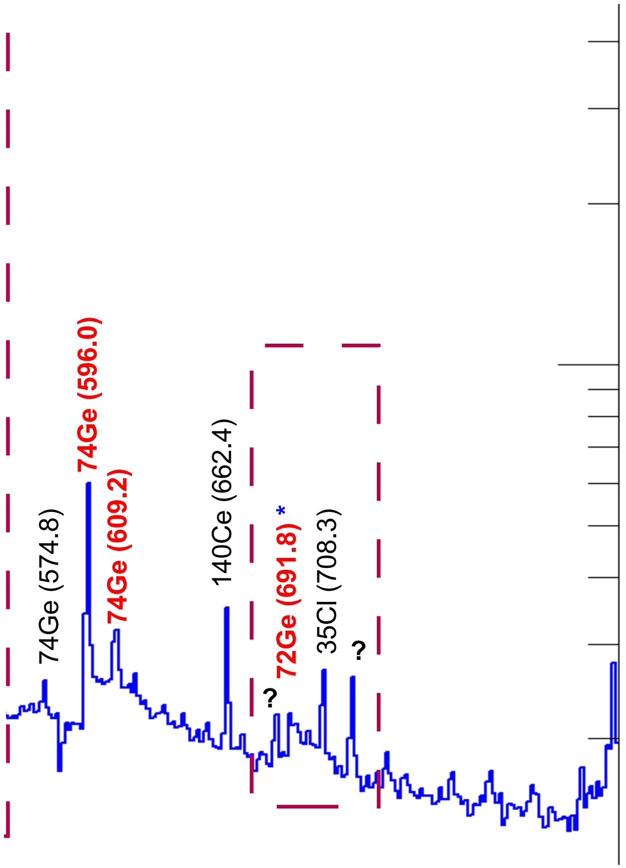




Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
596.0 ± 0.1	0.6 ± 0.1	$^{74}Ge(n, n'\gamma)$
609.2 ± 0.2	1.0 ± 0.3	$^{74}Ge(n, n'\gamma)$

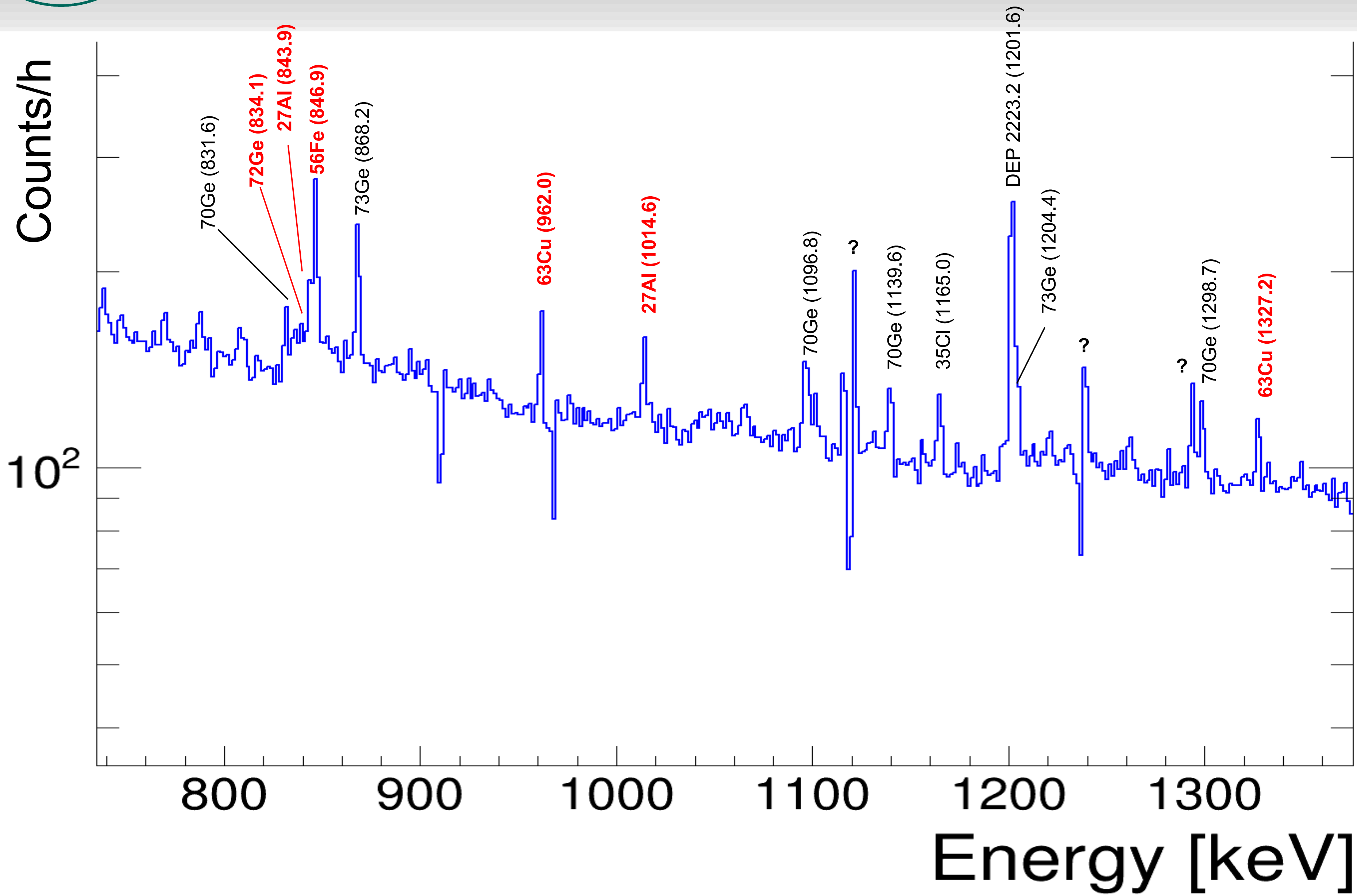
Background Subtracted: 0-0.8 MeV



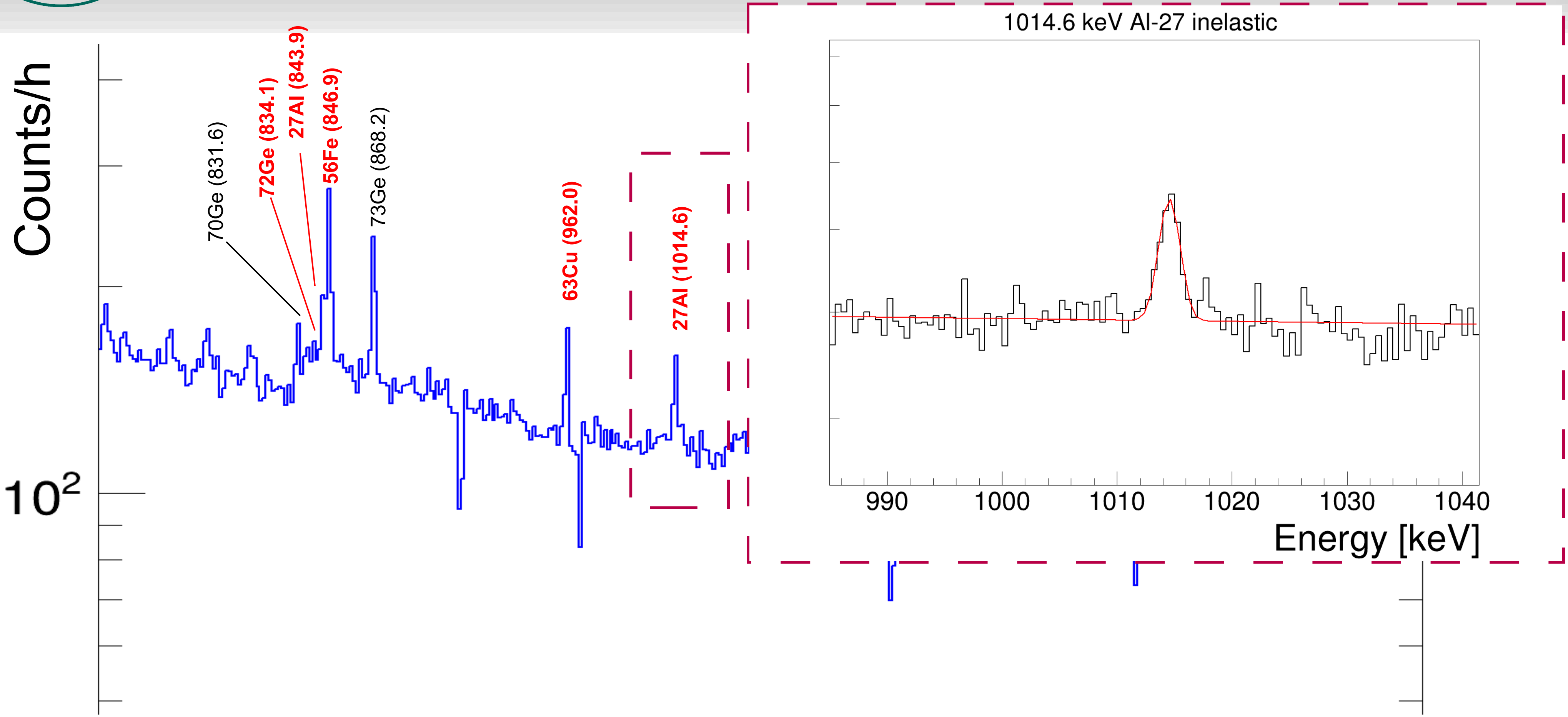


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
691.8 ± -	-	$^{72}Ge(n, n'e)$
708.3 ± 0.2	0.7 ± 0.1	$^{35}Cl(n, \gamma)$

Background Subtracted: 0.8-1.4 MeV

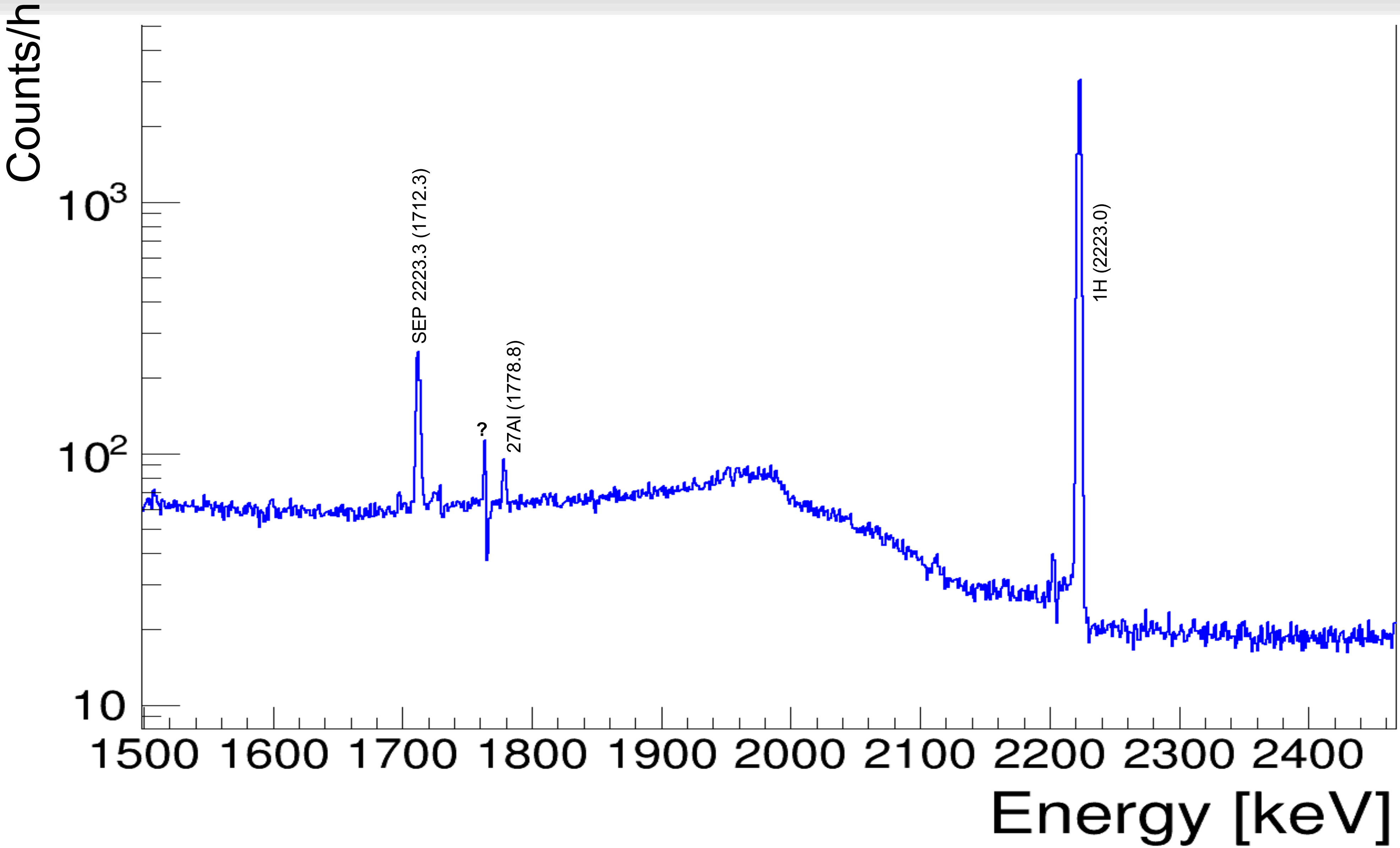


Background Subtracted: 0.8-1.4 MeV

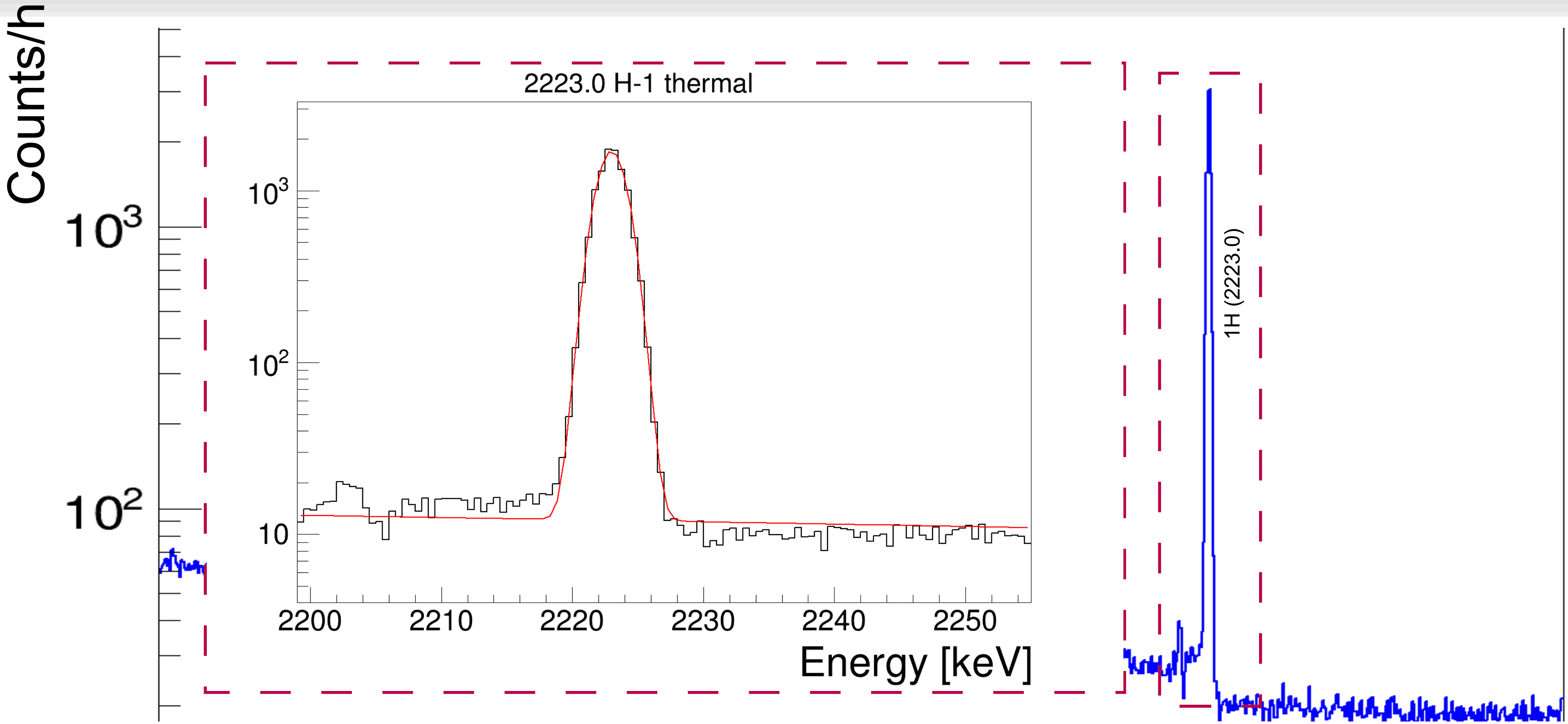


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
1014.6 ± 0.3	0.9 ± 0.3	$^{27}Al(n, n'\gamma)$

Background Subtracted: 1.5-2.5 MeV

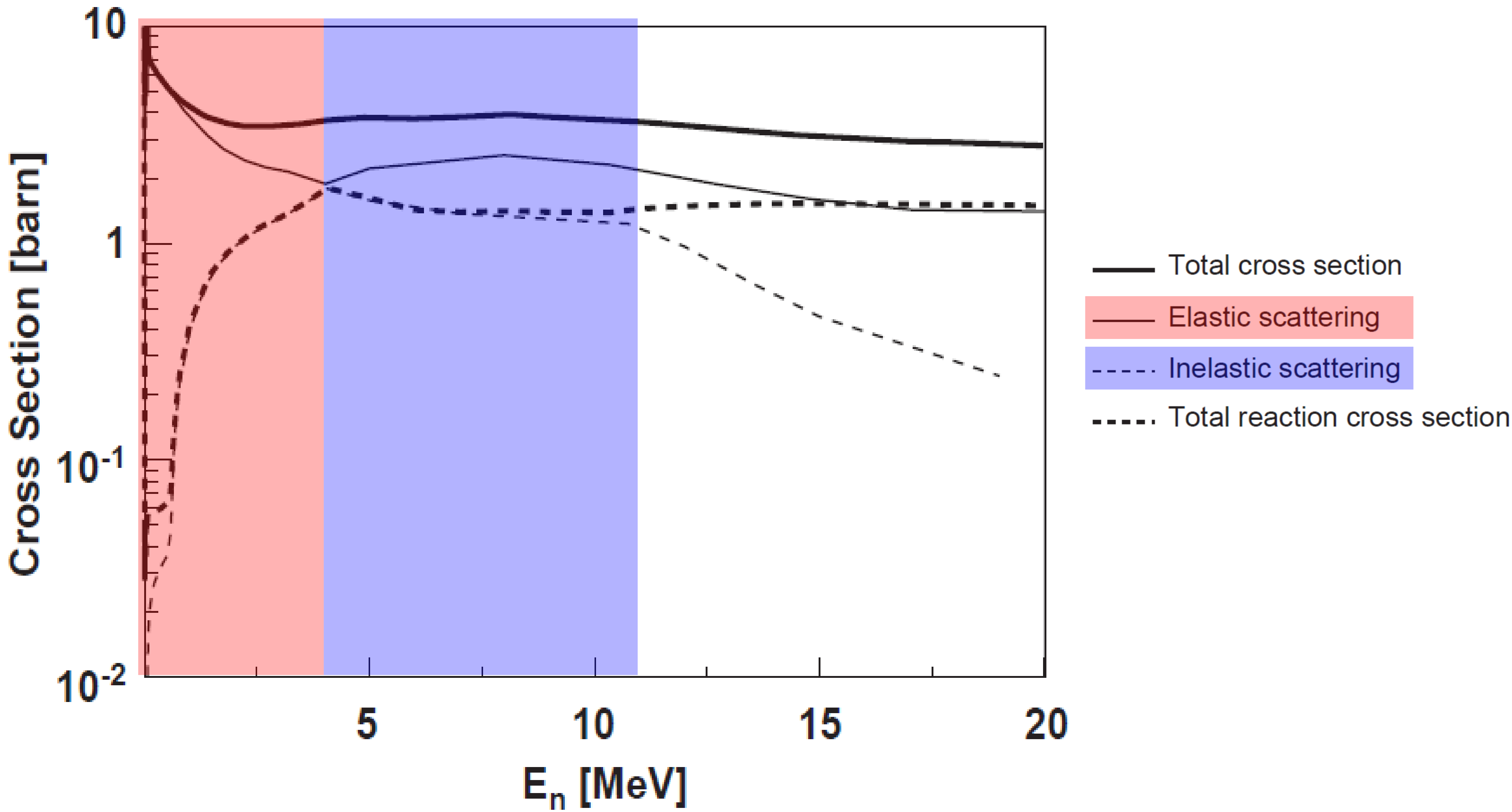


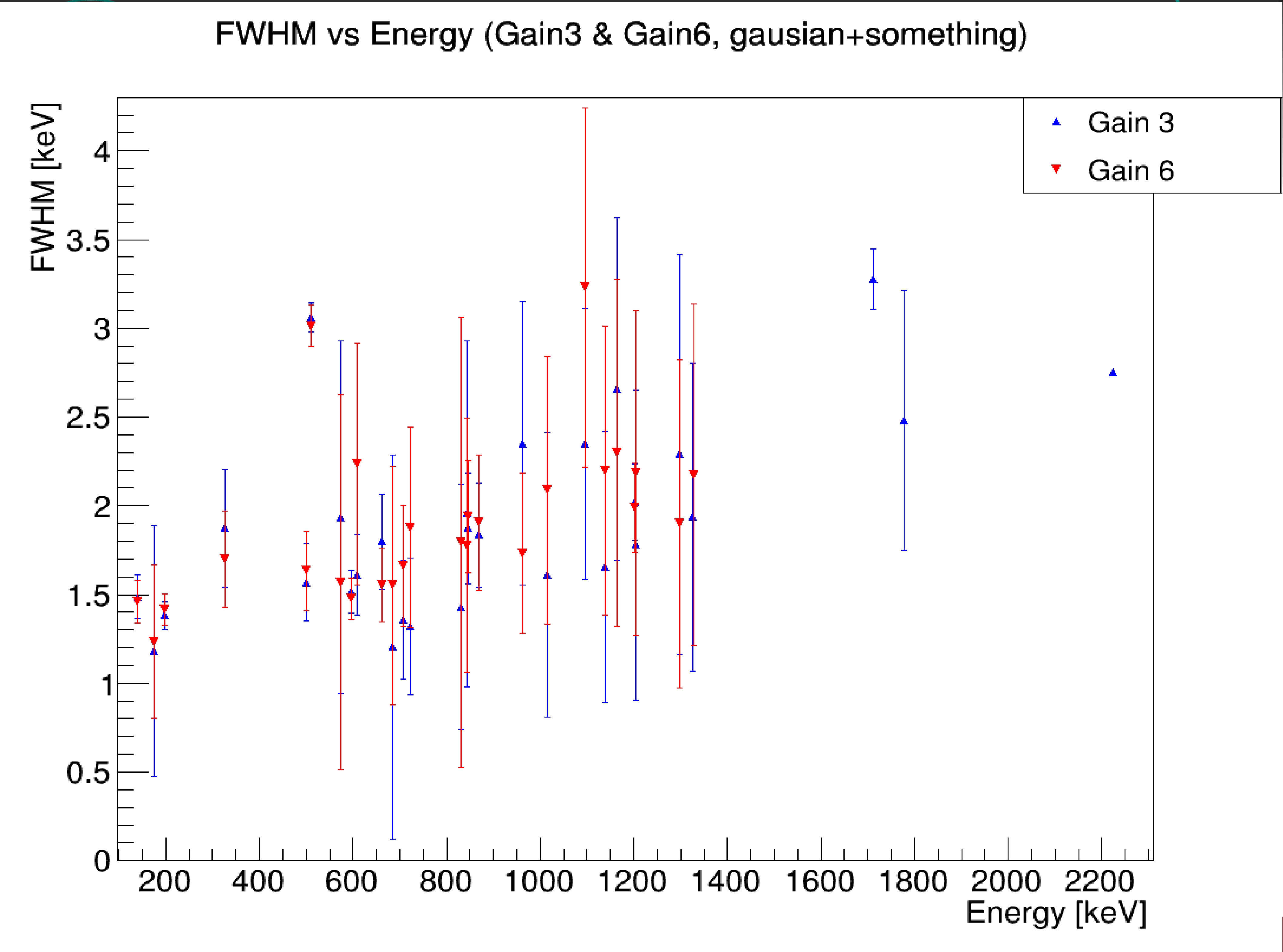
Background Subtracted: 1.5-2.5 MeV



Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
2223.0* $\pm$ 0.0	1.2 $\pm$ 0.0	$^{1}H(n,\gamma)$

Neutrons Cros Section



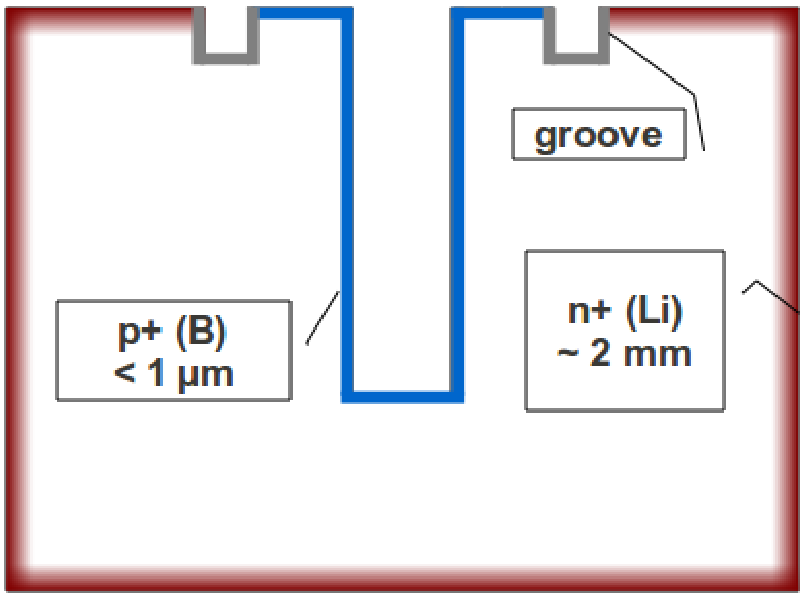

FWHM vs Energy (Gain3 & Gain6, gausian+something)
FWHM [keV]
0
0.5
1
1.5
2
2.5
3
3.5
4
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Energy [keV]
Gain 3
Gain 6

Natural Germanium

Isotope	Atomic mass (m_a/u)	Natural abundance (atom %)
^{70}Ge	69.9242497 (16)	20.84 (87)
^{72}Ge	71.9220789 (16)	27.54 (34)
^{73}Ge	72.9234626 (16)	7.73 (5)
^{74}Ge	73.9211774 (15)	36.28 (73)
^{76}Ge	75.9214016 (17)	7.61 (38)

Peaks due to neutron interactions			
Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type	Threshold [keV]
139.6 ± 0.0	0.6 ± 0.1	$^{74}Ge(n,\gamma^m)$	-
174.8 ± 0.1	0.5 ± 0.2	$^{70}Ge(n,n'\gamma)$	?
198.3 ± 0.0	0.6 ± 0.0	$^{70}Ge(n,\gamma^m)$	-
326.0 ± 0.1	0.7 ± 0.1	$^{70}Ge(n,\gamma)$	-
500.0 ± 0.1	0.7 ± 0.1	$^{70}Ge(n,\gamma)$	-
574.8 ± 0.4	0.7 ± 0.4	$^{74}Ge(n,\gamma)$	-
596.0 ± 0.1	0.6 ± 0.1	$^{74}Ge(n,n'\gamma)$	?
609.2 ± 0.2	1.0 ± 0.3	$^{74}Ge(n,n'\gamma)$	?
662.4 ± 0.1	0.7 ± 0.1	$^{140}Ce(n,\gamma)$	-
691.8 ± -	-	$^{72}Ge(n,n'e)$	?
708.3 ± 0.2	0.7 ± 0.1	$^{35}Cl(n,\gamma)$	-
831.6 ± 0.4	0.9 ± 0.4	$^{70}Ge(n,\gamma)$	-
834.1 ± -	-	$^{72}Ge(n,n'\gamma)$	?
843.9 ± 0.4	0.7 ± 0.3	$^{27}Al(n,n'\gamma)$	?
846.9 ± 0.1	0.8 ± 0.1	$^{56}Fe(n,n'\gamma)$	?
868.2 ± 0.1	0.8 ± 0.2	$^{73}Ge(n,\gamma)$	-
962.0 ± 0.2	0.7 ± 0.2	$^{63}Cu(n,n'\gamma)$	?
1014.6 ± 0.3	0.9 ± 0.3	$^{27}Al(n,n'\gamma)$	?
1096.8 ± 1.1	1.4 ± 0.4	$^{70}Ge(n,\gamma)$	-
1139.7 ± 0.4	0.9 ± 0.3	$^{70}Ge(n,\gamma)$	-
1165.0 ± 0.4	1.0 ± 0.4	$^{35}Cl(n,\gamma)$	-
1201.6 ± 0.1	0.8 ± 0.1	DEP of 2223.2	-
1204.4 ± 0.4	0.9 ± 0.4	$^{73}Ge(n,\gamma)$	-
1298.7 ± 0.3	0.8 ± 0.4	$^{70}Ge(n,\gamma)$	-
1327.2 ± 0.4	0.9 ± 0.4	$^{63}Cu(n,n'\gamma)$	?
1712.3*± 0.1	1.4 ± 0.1	SEP of 2223.2	-
1778.8*± 0.3	1.0 ± 0.3	$^{27}Al(n,\gamma)$	-
2223.0*± 0.0	1.2 ± 0.0	$^{1}H(n,\gamma)$	-

**These peaks where fitted on the gain 3 spectra.*


groove
p+ (B)
< 1 μm
n+ (Li)
~ 2 mm

Inelastic Scattering Distribution