Looking for muon-induced neutrons in Ge detectors

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RISE summer students: Costanza Carissimo
Sergio Acero

Young Scientist Workshop 2013 @ Ringberg Castle

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

Outline

- Physics motivation:
  - Low Background Experiments
  - Background Sources
  - The China JinPing Laboratory
- Introduction to Germanium Detectors
- Project Description:
  - The muon-setup
  - The AmBe measurement
  - Neutrons Interactions
  - First results
- Summary & Outlook

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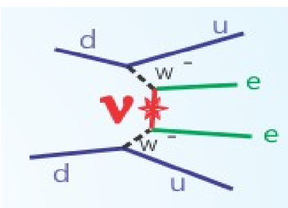
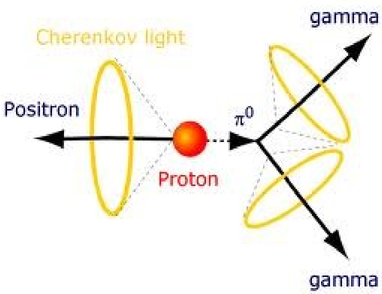
Low Background Experiments

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 a very low background!!

Expected Event Rate

What we can do to enhance the expected event rate?

- **Increase the exposure:**

  → **increase the data taking period**

Expected Event Rate

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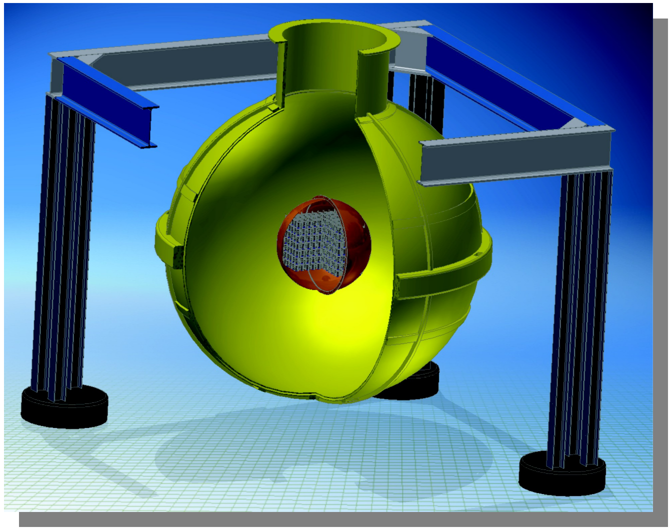


- **Increase the exposure:**

  → increase the data taking period

  → increase the mass
  → 1 Ton experiments

Expected Event Rate

What we can do to enhance the expected event rate?

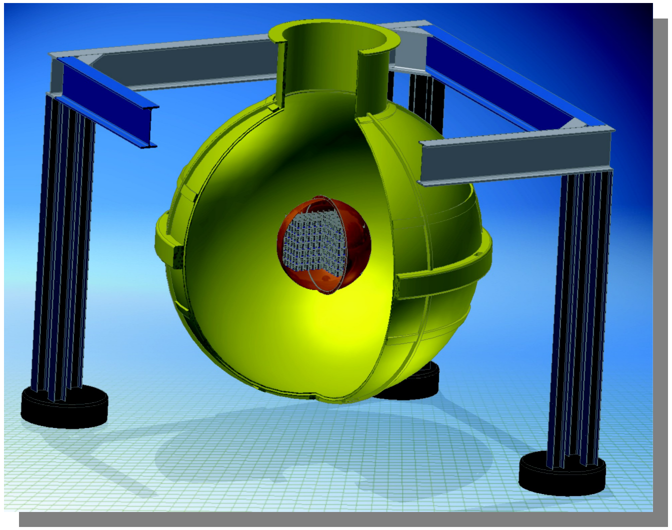
- **Increase the exposure:**

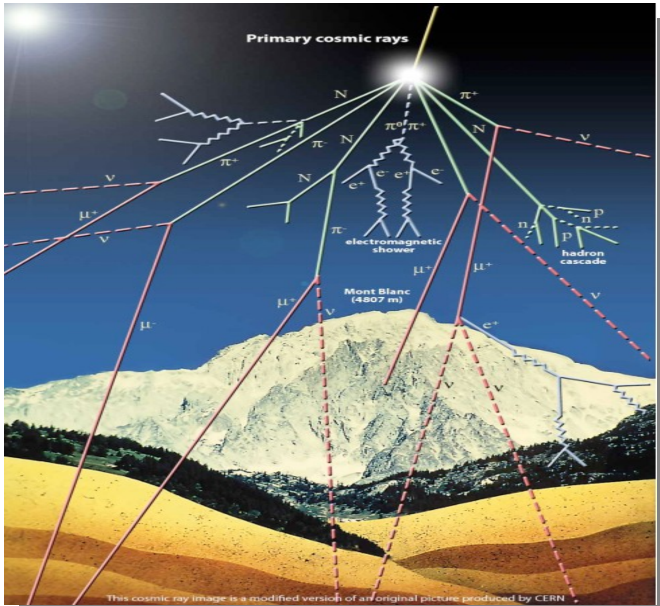
  → increase the data taking period

  → increase the mass
  → 1 Ton experiments

- **Increase the S/B ratio:**

  → reduce the background
  → Move deeper Underground
  → Effective Shielding





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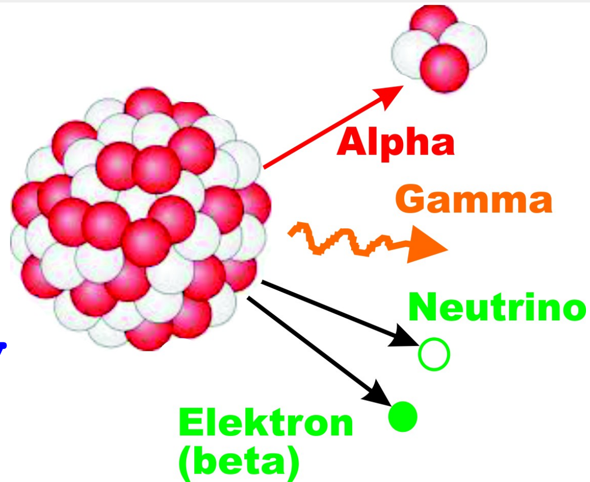
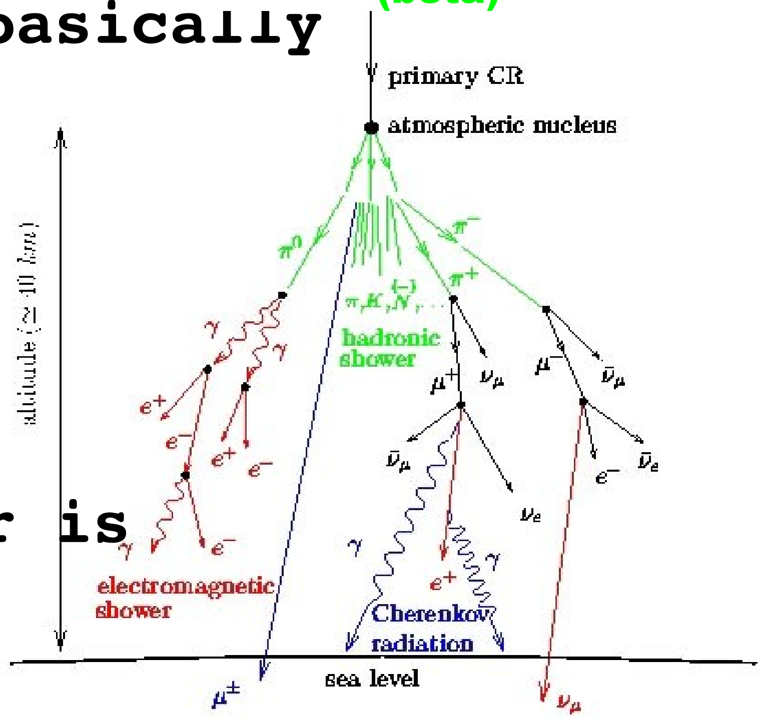
Background Sources

- **Three different sources:**
  - **Intrinsic detector radioactivity**
  - **Environmental Natural radioactivity**
  - **Cosmic Rays-induced showers** (basically muon and neutrino-induced)



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



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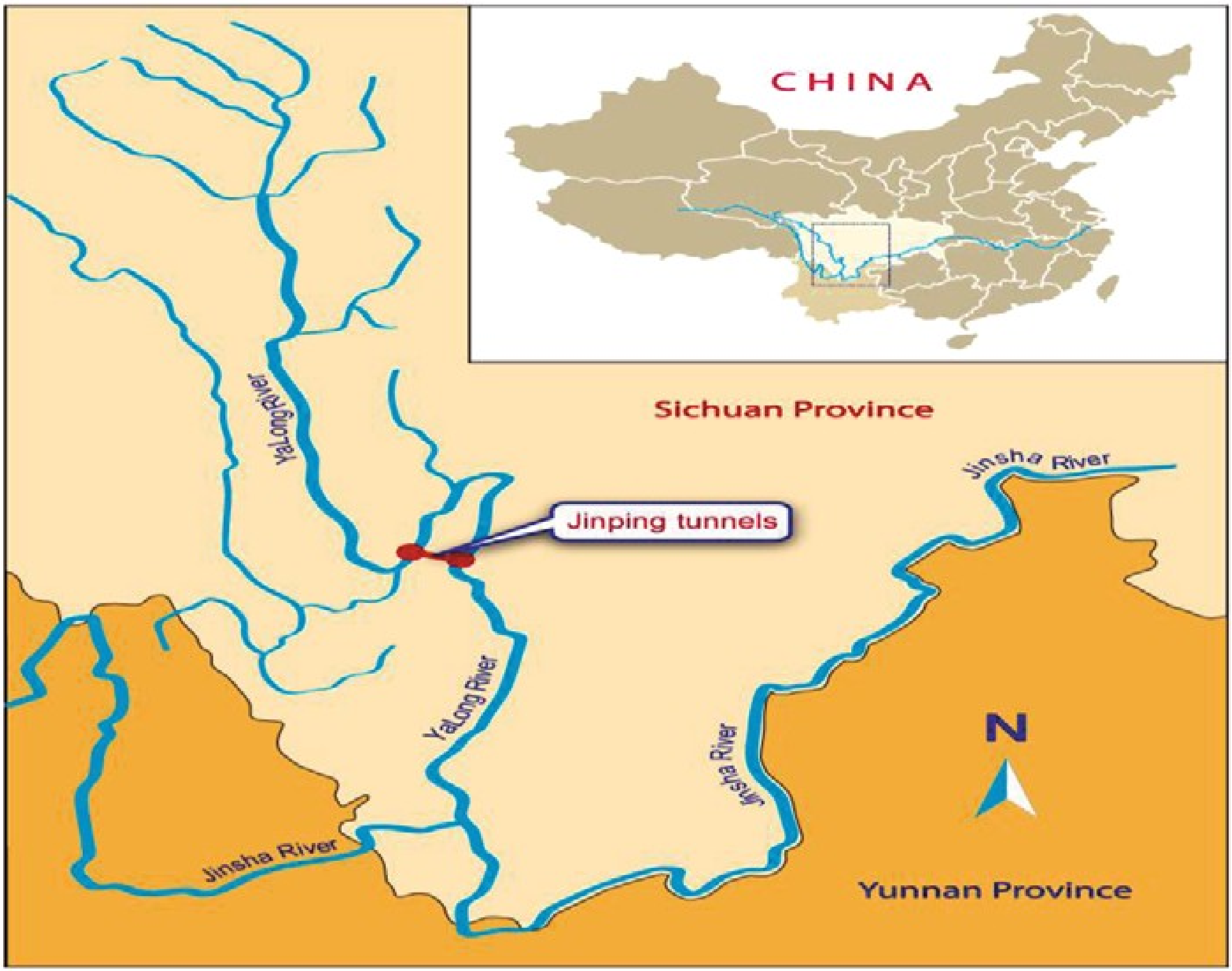
Future and Present: the China JinPing Laboratory



Sino-German GDT Cooperation

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

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

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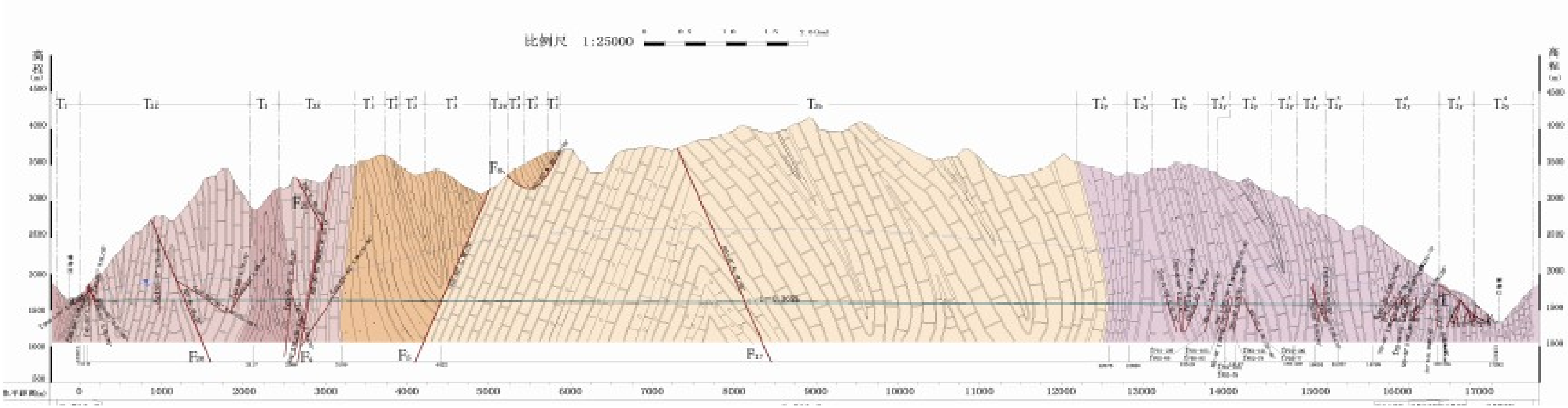

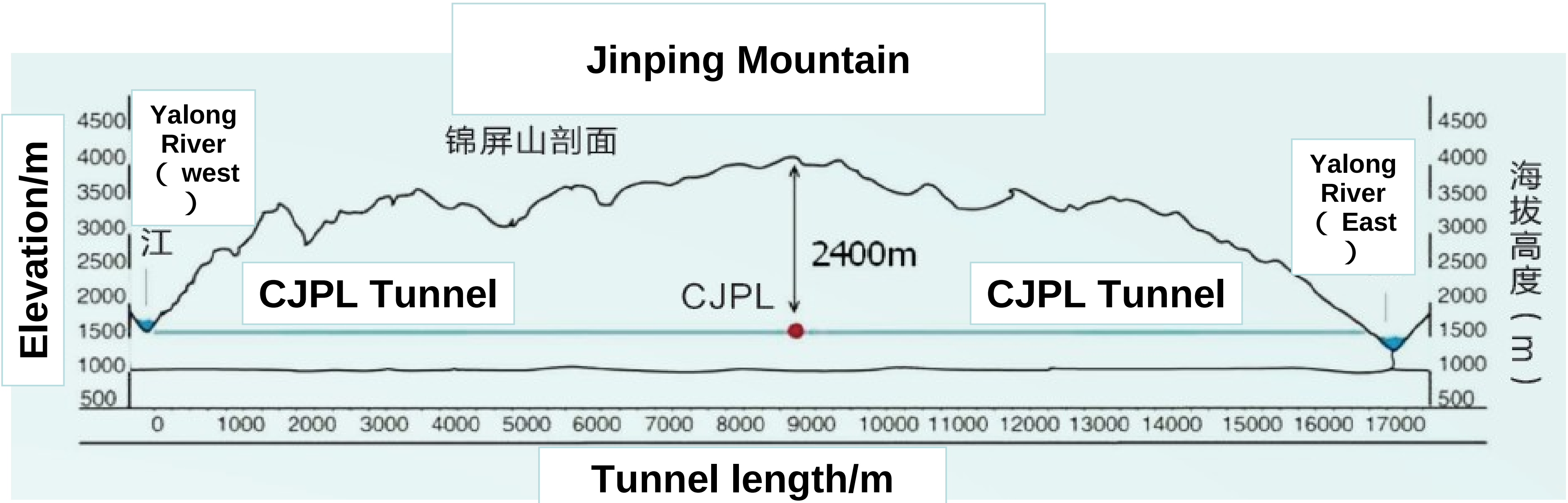

Courtesy of Prof. Zeng Zhi, Tsinghua University, Beijing

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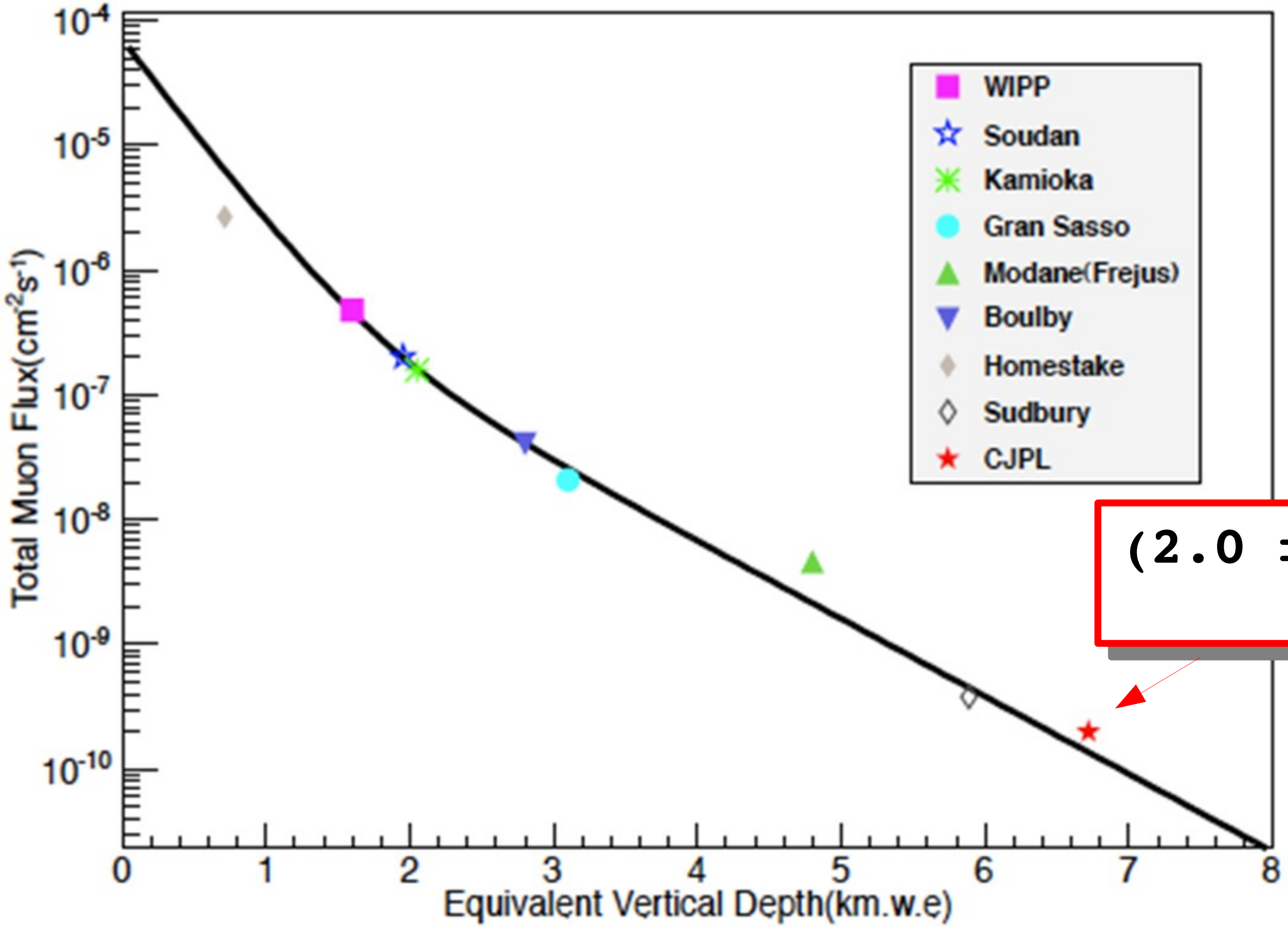

~ 60 $m^{-2}y^{-1}$

$(2.0 \pm 0.4) \times 10^{-10} cm^{-2}s^{-1}$

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Future and Present: the China JinPing Laboratory

Underground Lab	Rock Depth (m)	Muon Flux ($m^{-2}\cdot s^{-1}$)	neutron flux by muon ($m^{-2}\cdot s^{-1}$)
Boulby UK	1100	4.5×10^{-4} [3]	$8.70\times^{-6}$ [4]
Canfranc， Spain	850	$(2\sim4)\times10^{-3}$ [3]	（1.73±0.91）$\times10^{-5}$ [5]
Modane， French	1700	4.7×10^{-5} [3]	5.6×10^{-2} [3]
Gran Sasso, Italy	1400	3.0×10^{-4} [3]	3.78×10^{-2} [3]
Baksan,Russia	2100	$3.03\pm0.19\times10^{-5}$ [3]	1.4×10^{-3}（E>1.0MeV） [3]
Kamiokande, Japan	1000	3.0×10^{-3} [3]	（8.25±0.58）$\times10^{-2}$（thermol） [3] （11. 5±1.2）$\times10^{-2}$（non-thermol） [3]
SNO,CA	2000	3.0×10^{-6} [3]	4.7×10^{-2}（thermol） [3] 4.6×10^{-2}（fast） [3]
Soudan, US	700	2.0×10^{-3} [3]	-
DUSEL,US	1478	4.4×10^{-5} [6]	-
CJPL, China	2400	3.17×10^{-6}（simulation） 2.0×10^{-6}（measurement）	8.37×10^{-7}（simulation）

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Germanium Detectors

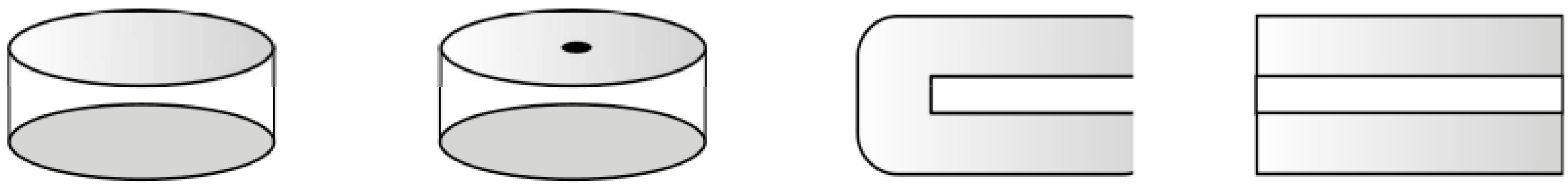
Widely used in nuclear physics experiments and DM searches

- **Concept:**
  - **Semiconductor 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

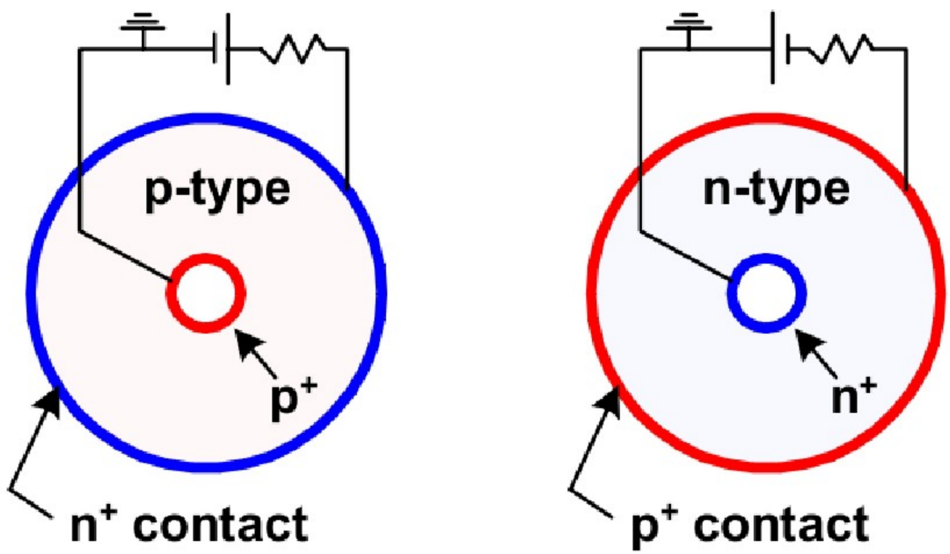
- **Detector configurations:**



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"

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Looking for neutrons

- **Project description:**
  - Muon-induced neutrons
  - Cosmogenic neutrons
  - Study of the effect of different materials
- **Challenge:**
  - Can we actually distinguish the muon-induced from the cosmogenic ones?

  $\longrightarrow$ The Background can be too high
- **Future?:**
  - Move in a shallow underground lab (CJPL??)
  - Improve the experimental setup

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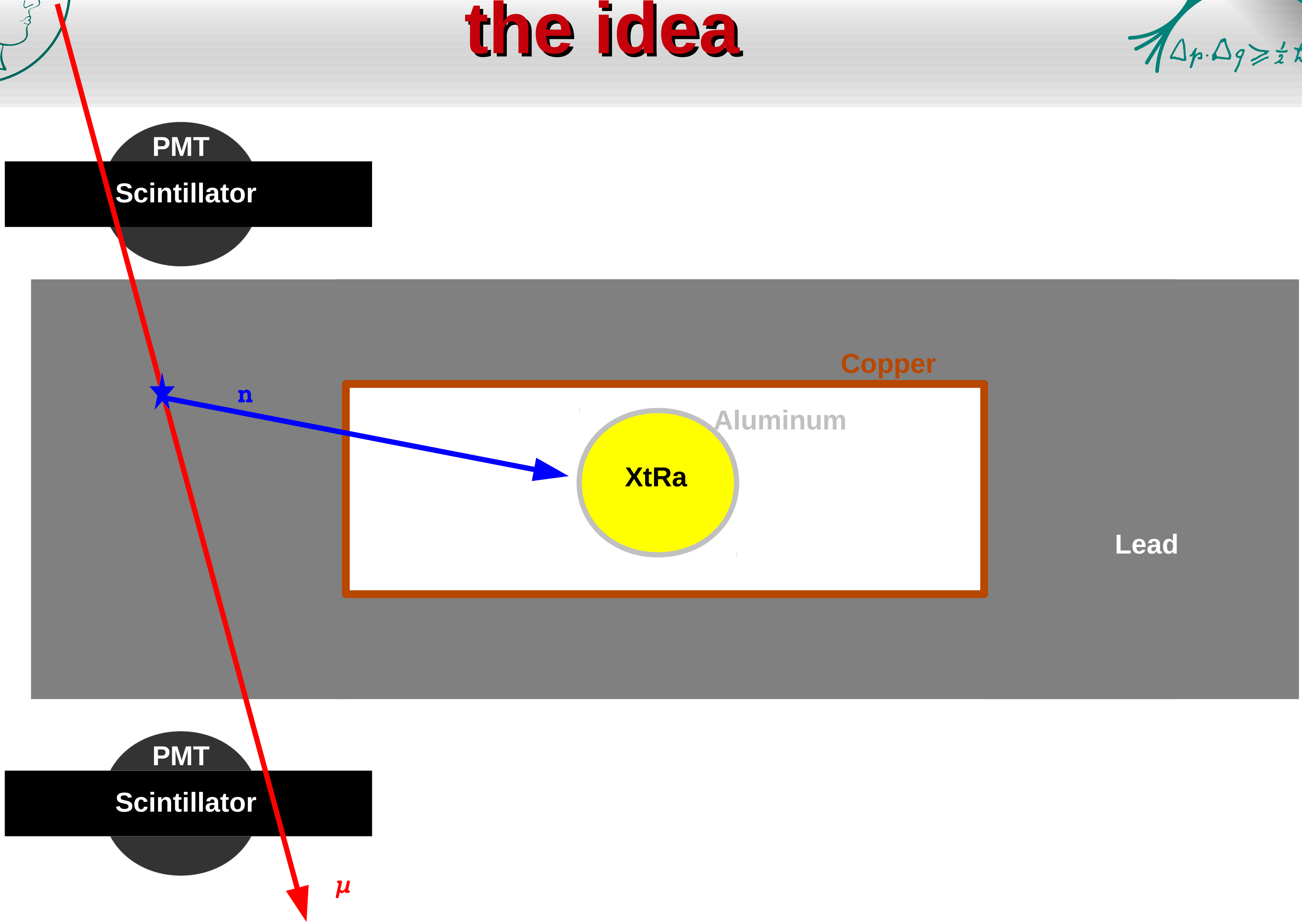
The Experimental Setup: the idea



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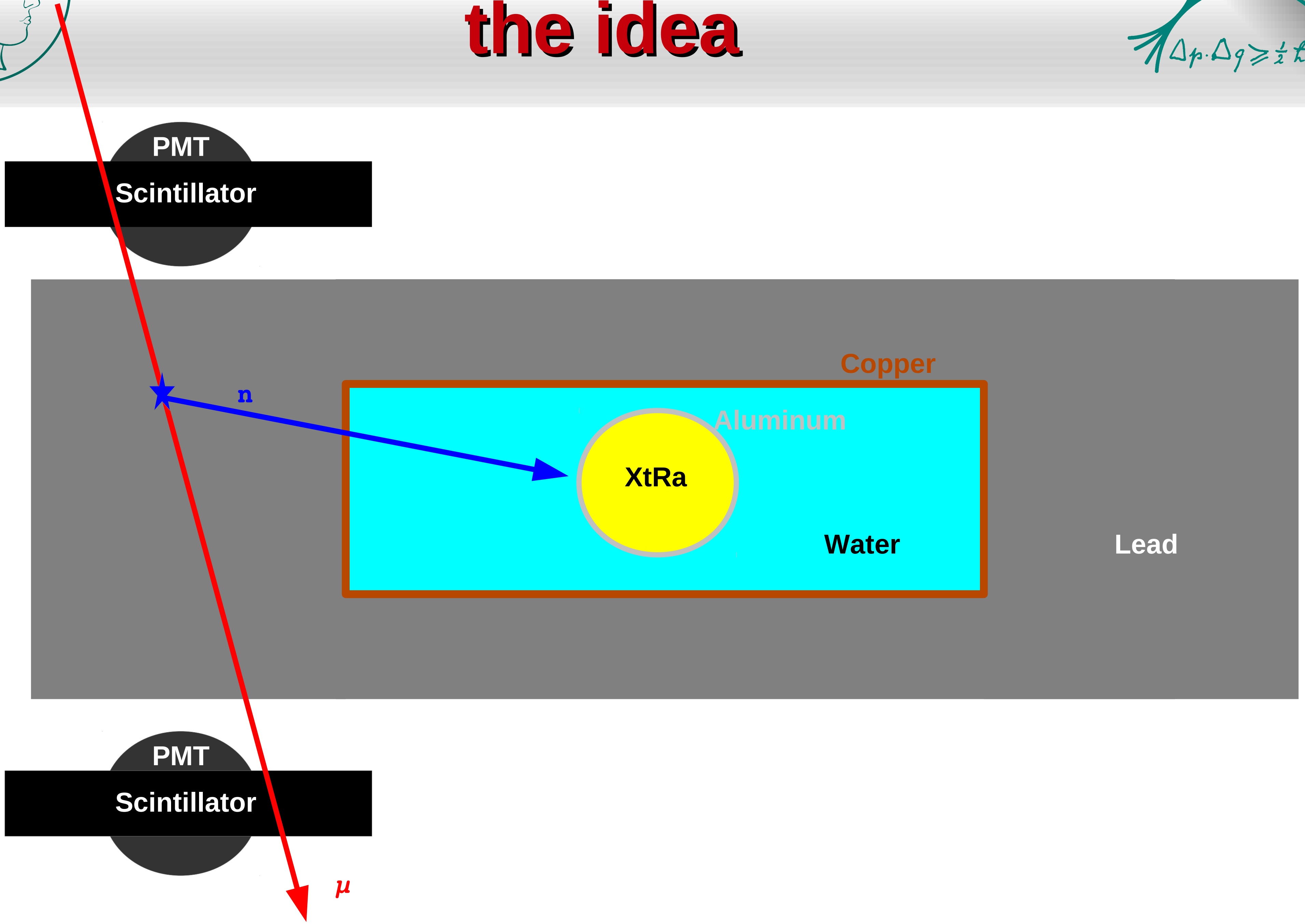

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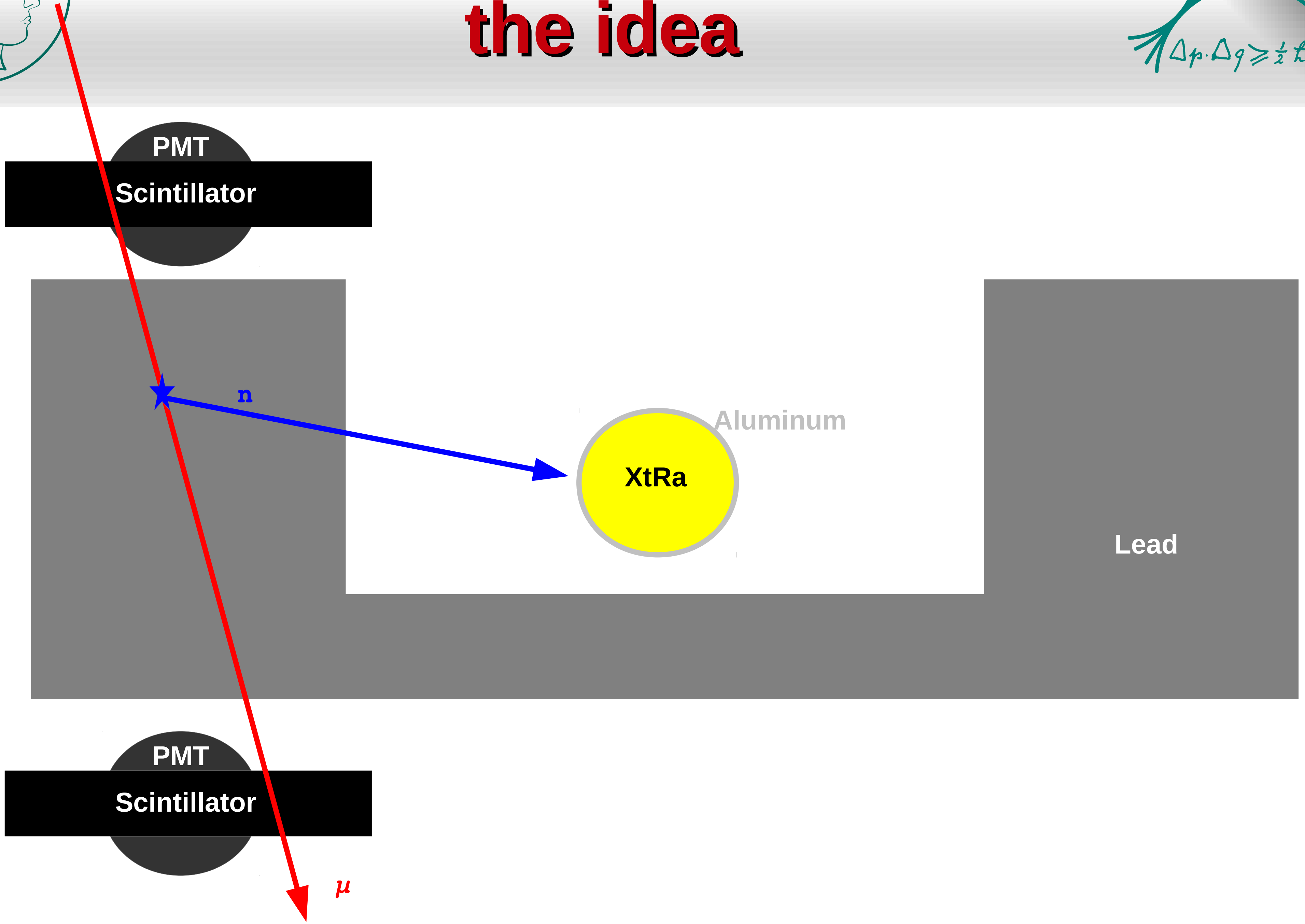

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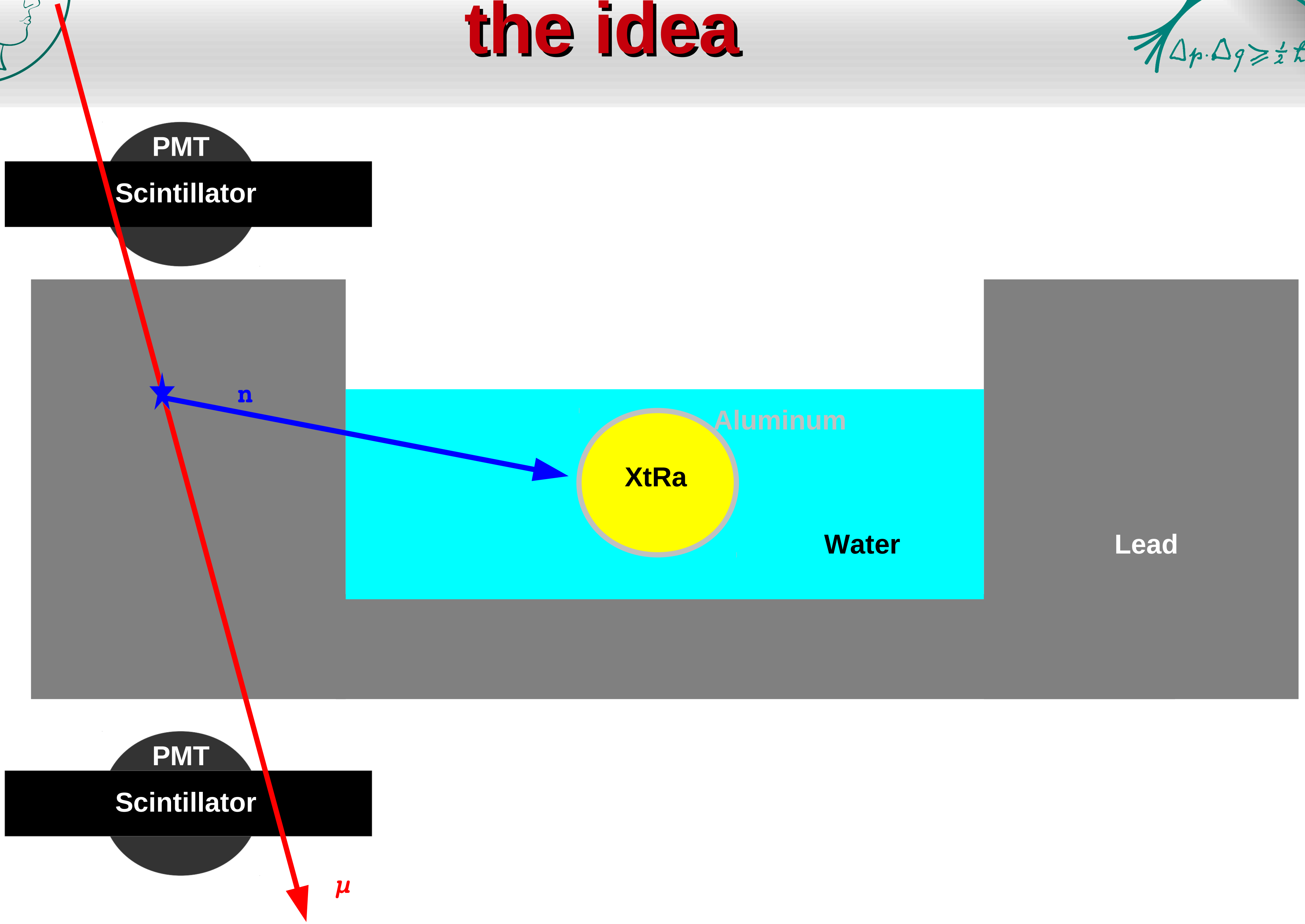
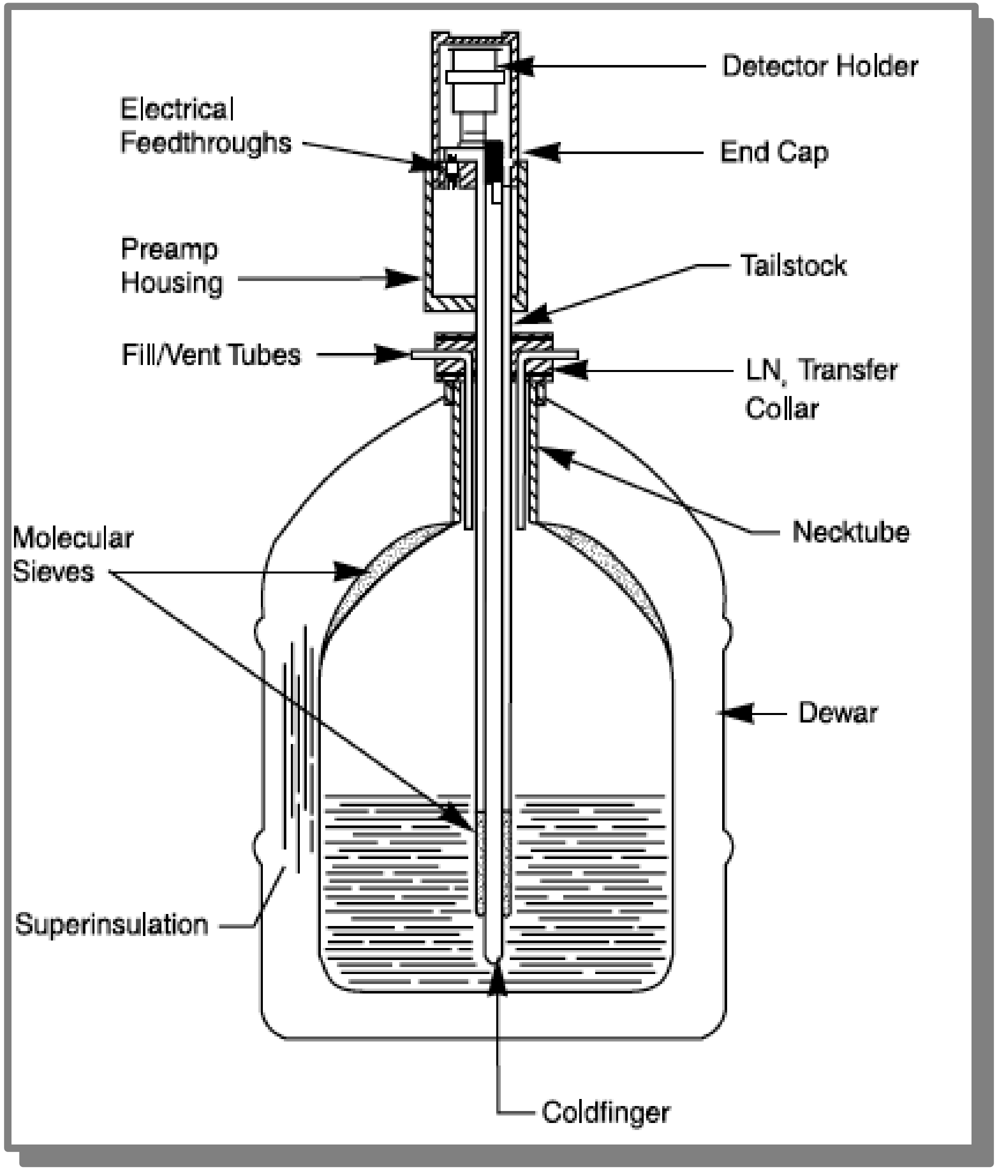
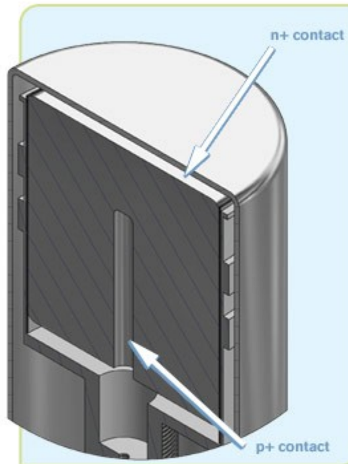
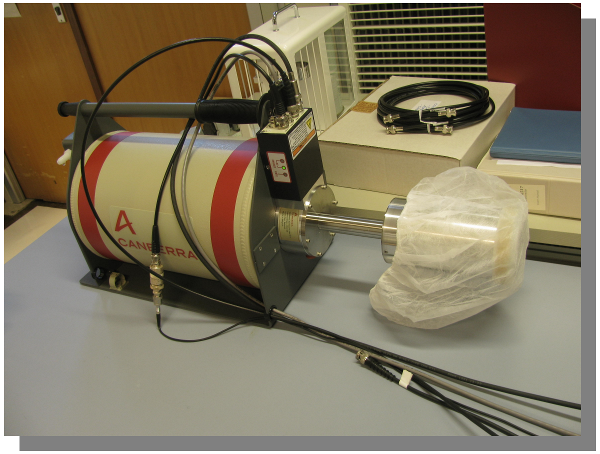


The Experimental Setup: eXtended Range GeDet



- **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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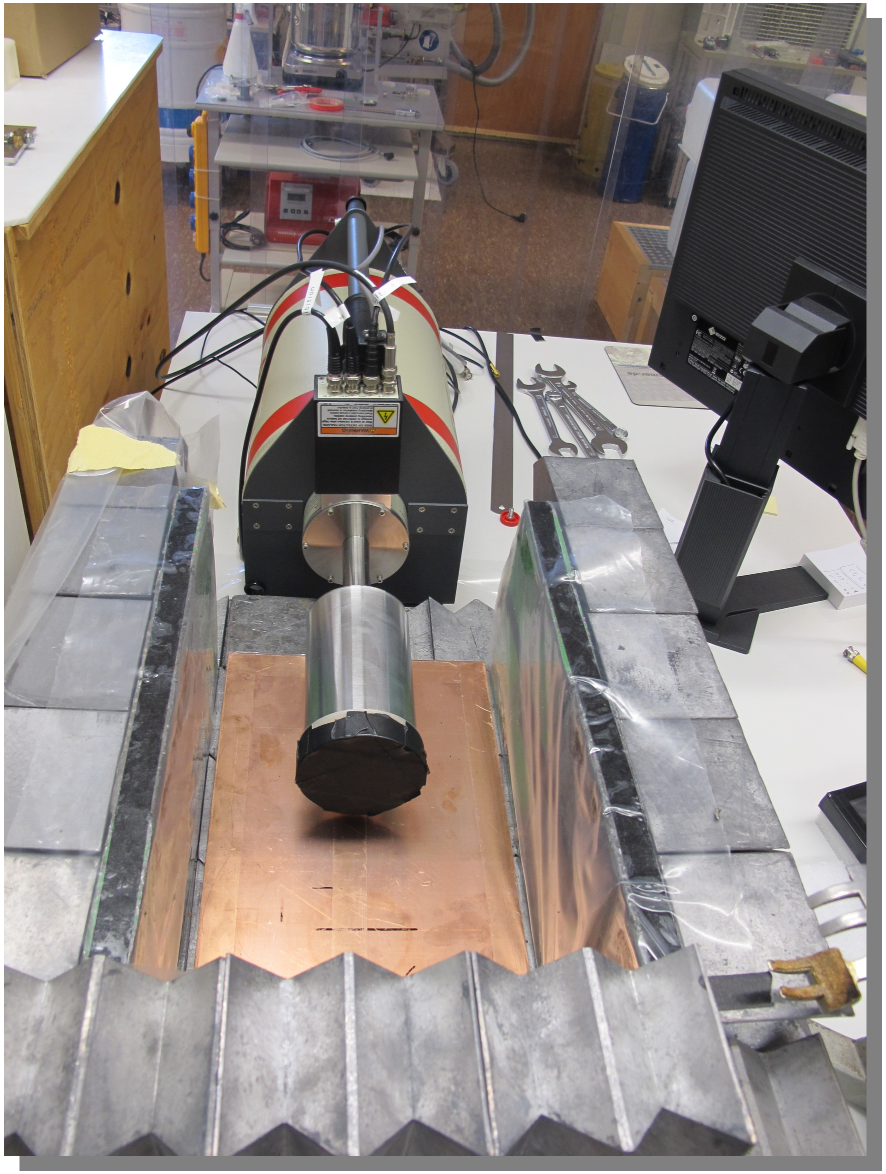
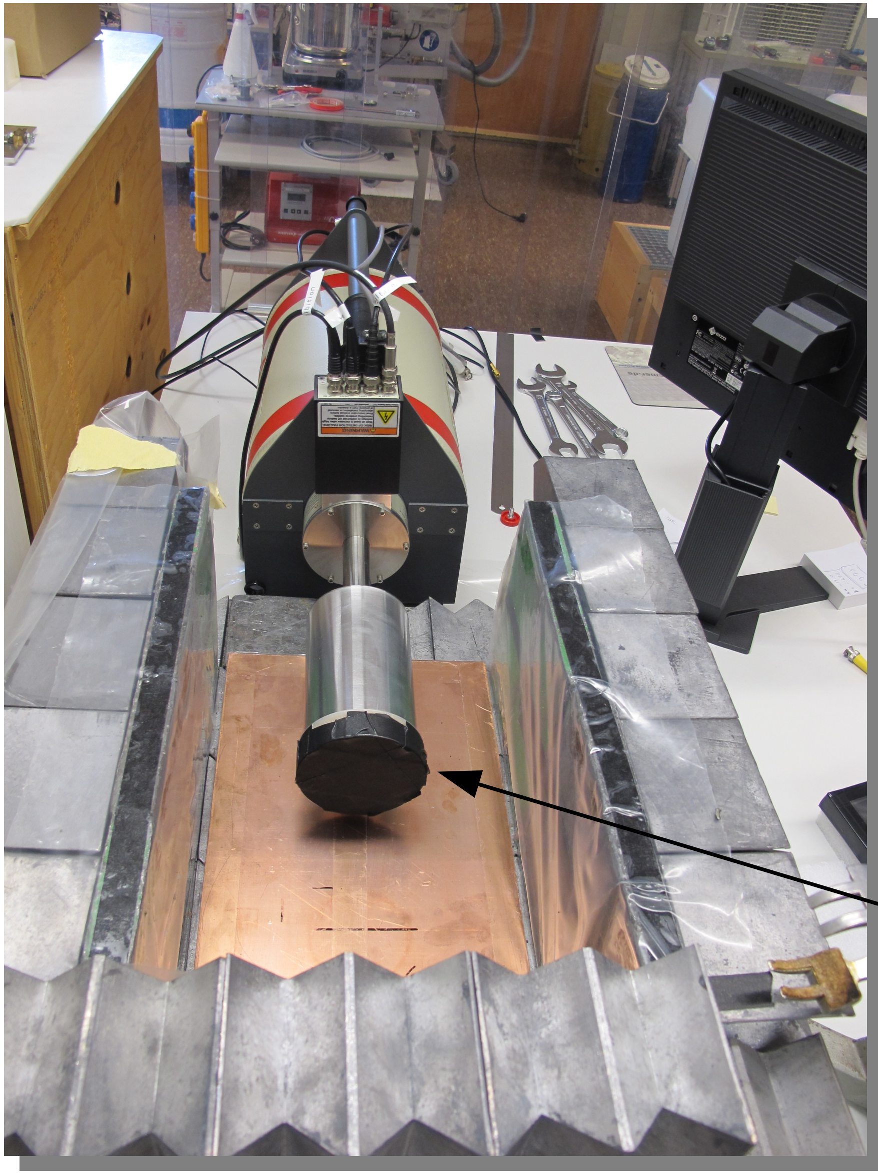


- **Lead:**
  - thickness 10.5 cm
  - height 28 cm
- **Copper shell:**
  - Thickness 0.4 cm
- **Scintillator paddles:**
  - 12 x 21 x 2 cm^3
  - distance 48.5 cm
- **DAQ:**
  - DGF Pixie-4 (high precision)
  - Sampling frequency 75 MHz
  - Spectra: 16-bit precision up to 32K channels

The Experimental Setup



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Additional plastic end-cup covered with black tape

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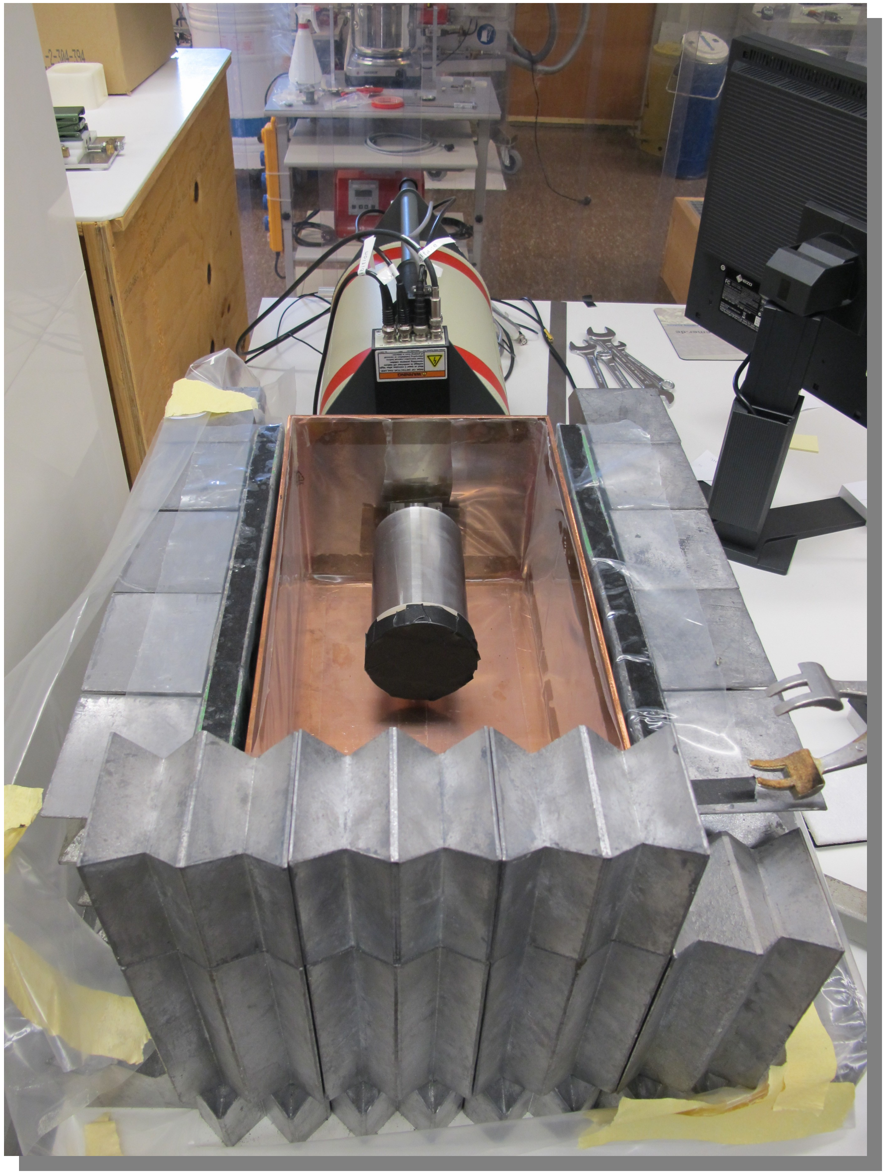

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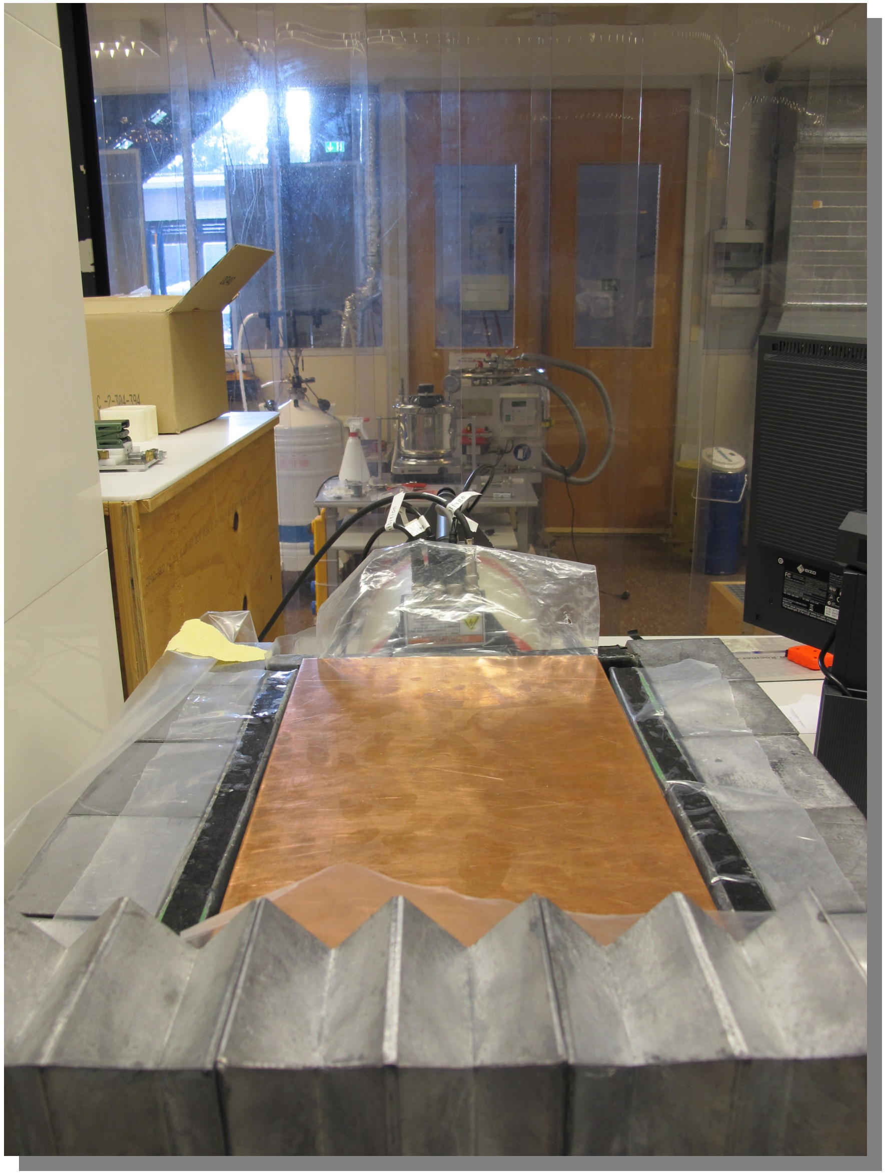

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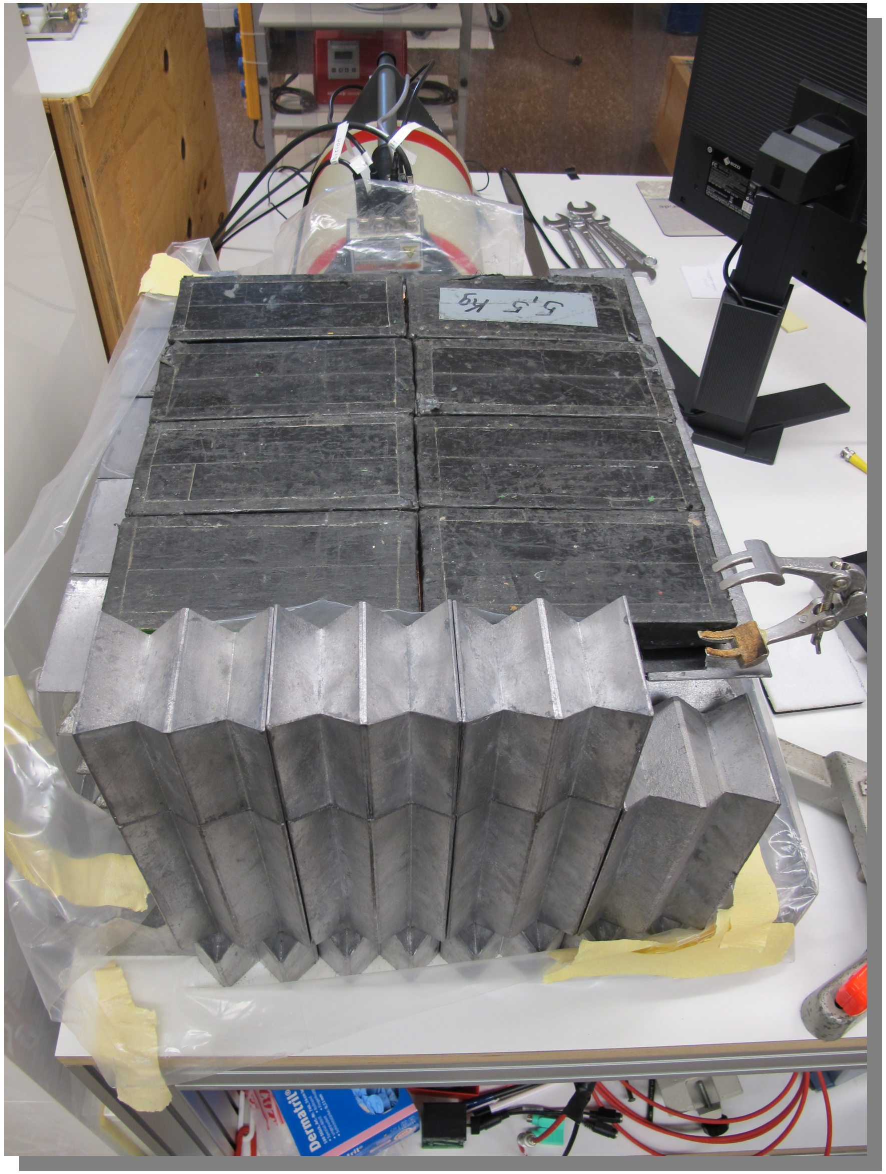

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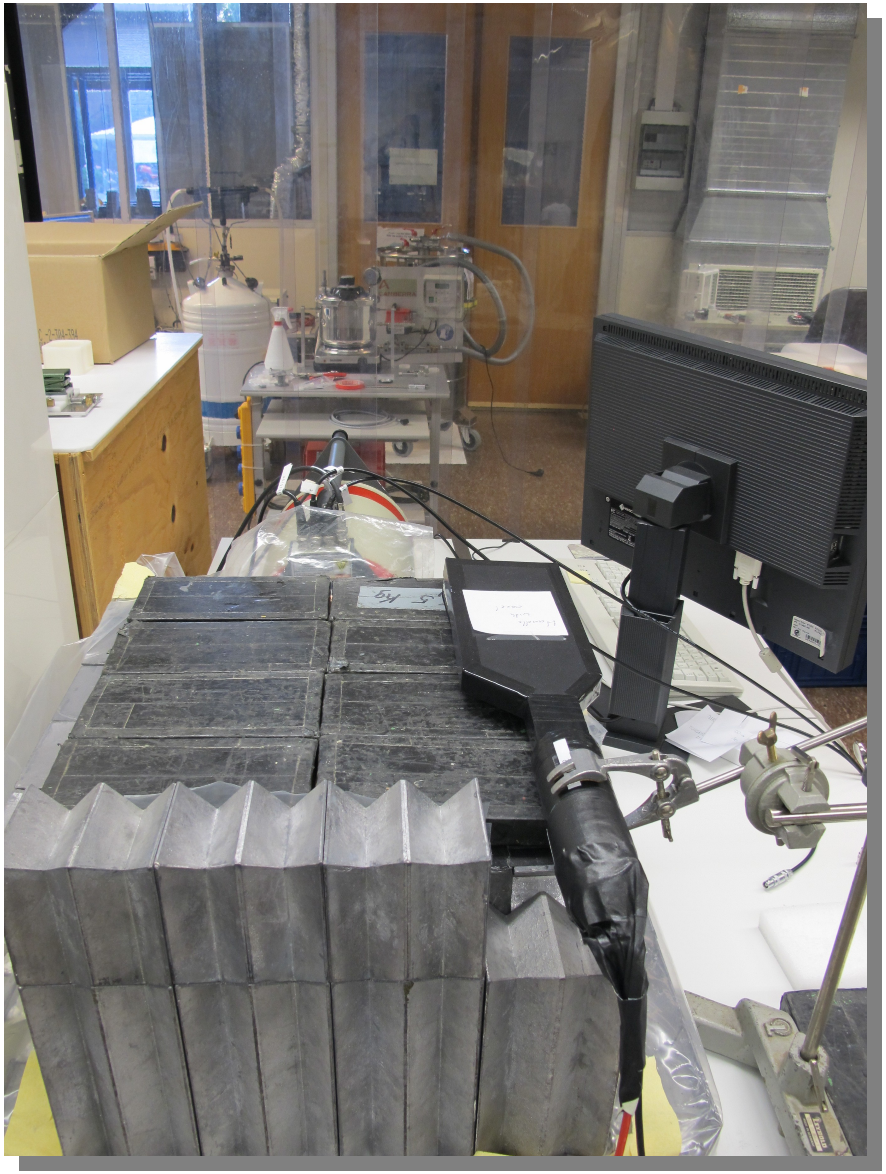

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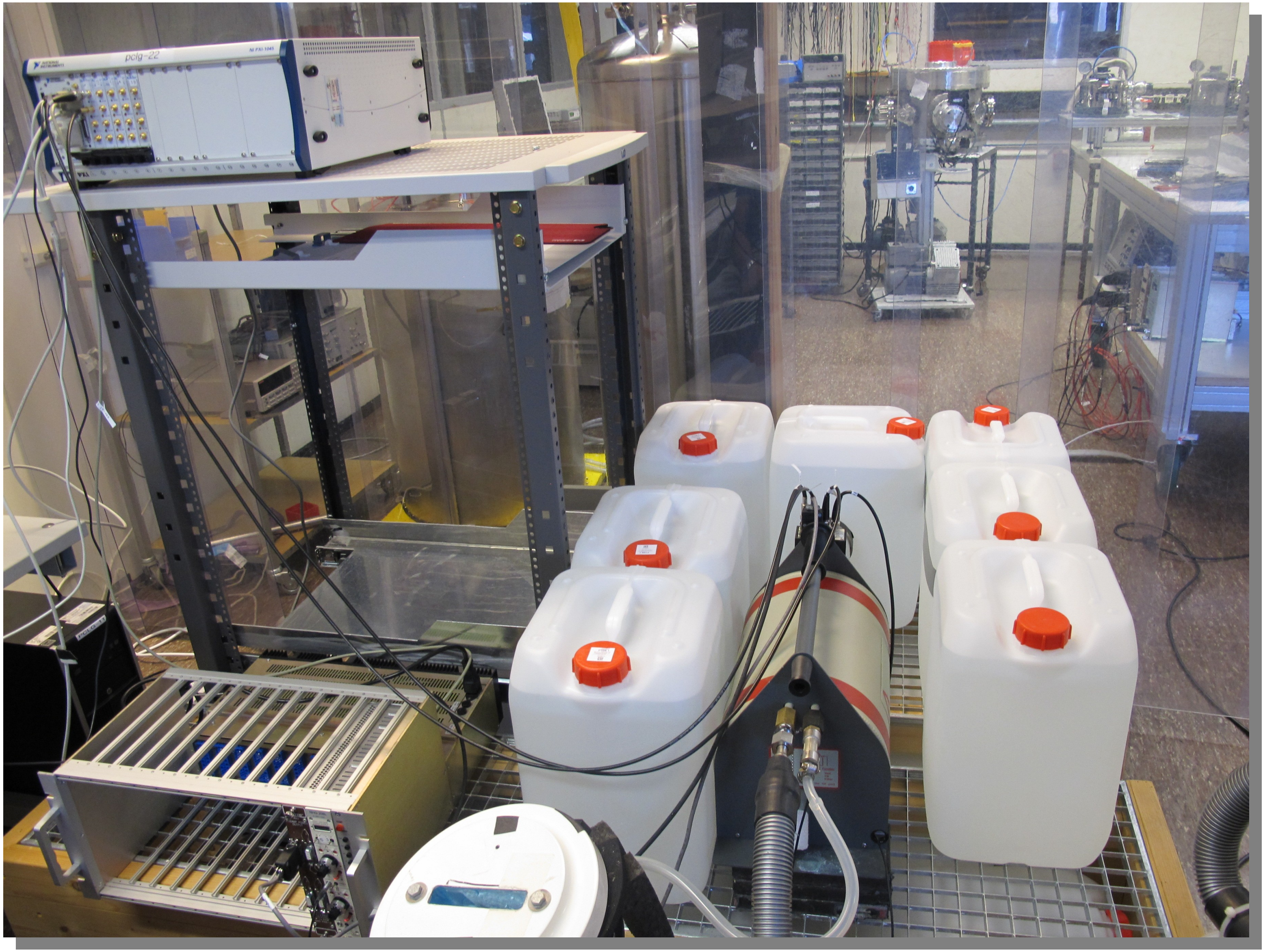

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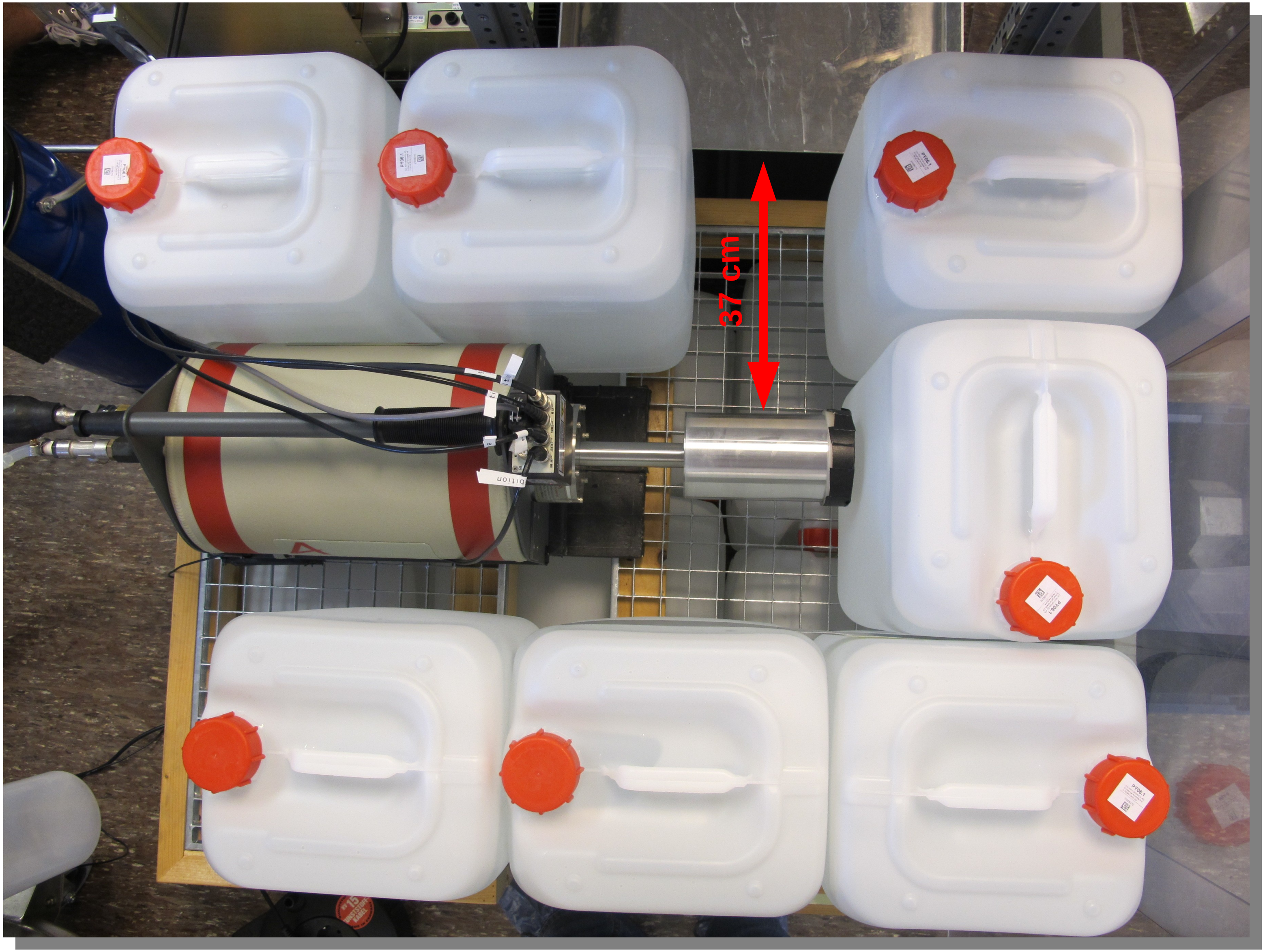

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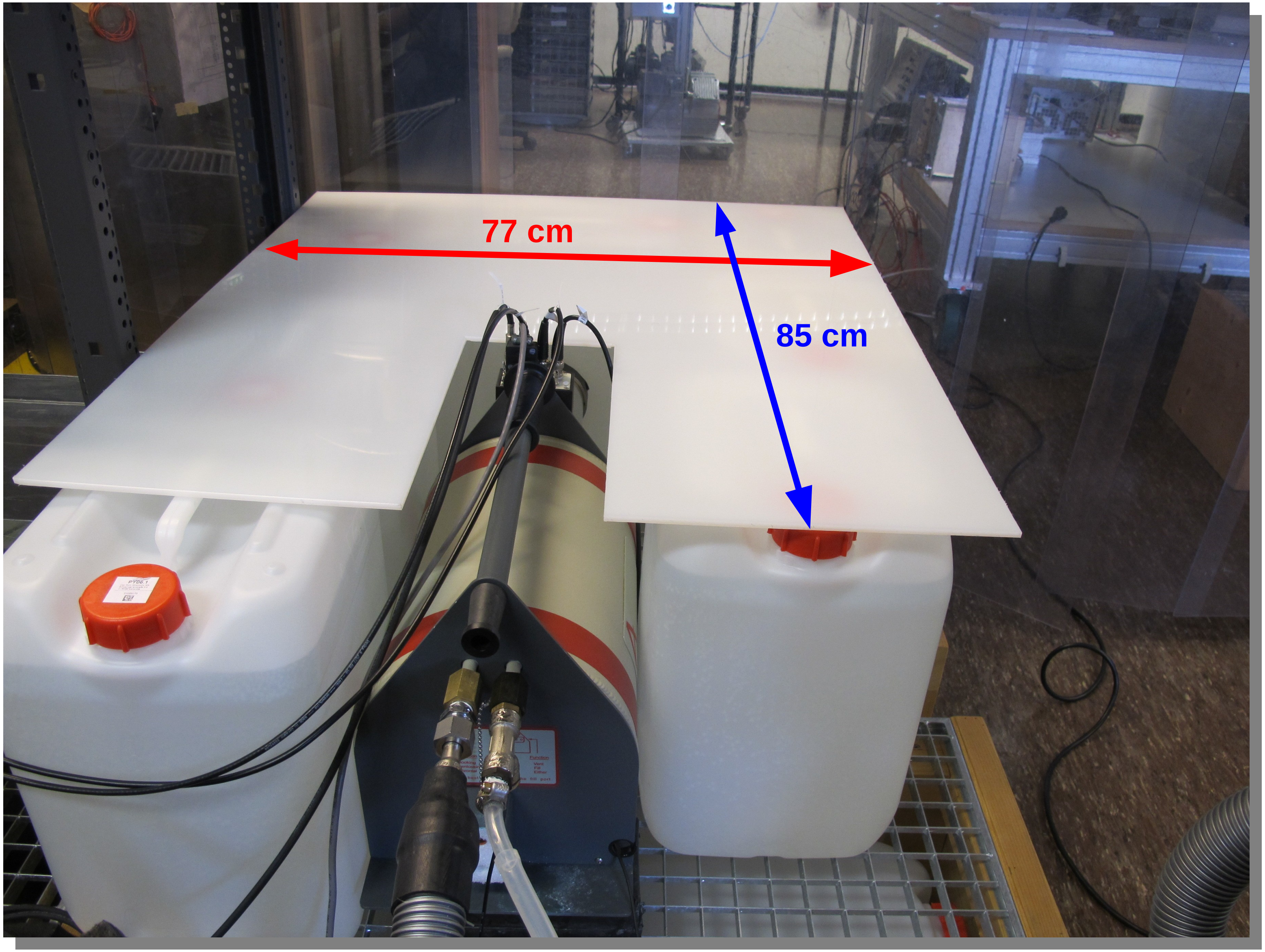

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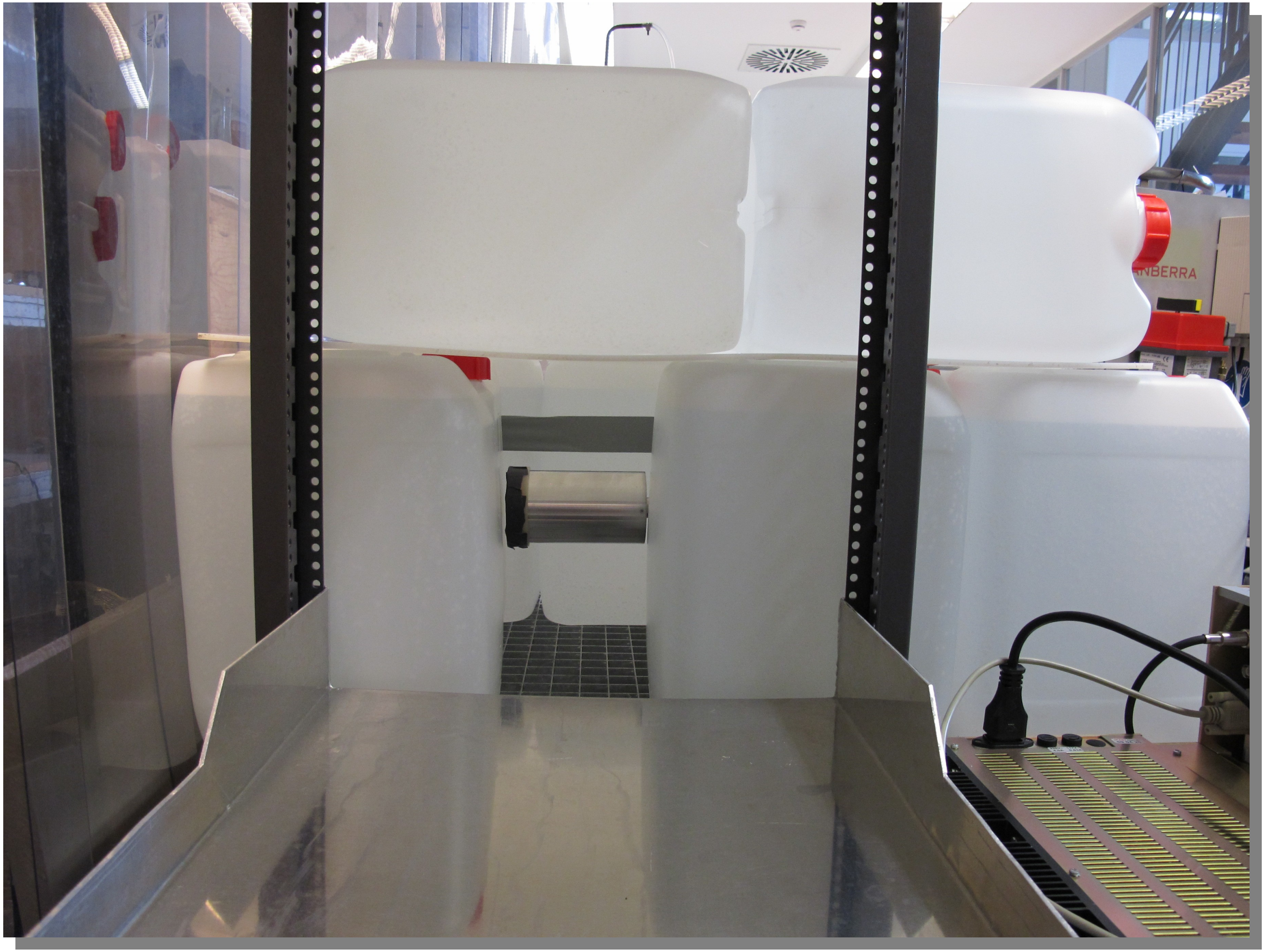

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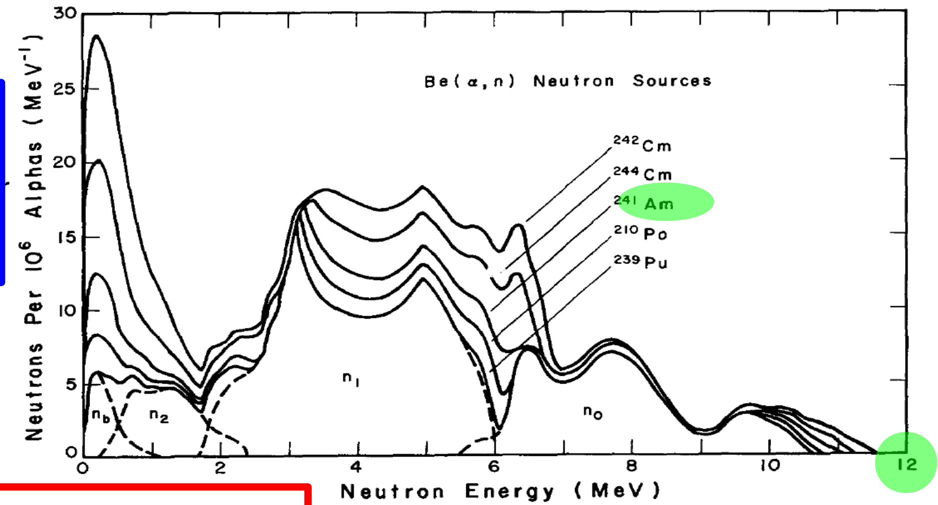
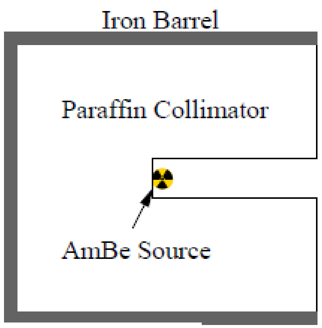
AmBe neutron source

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



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

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]

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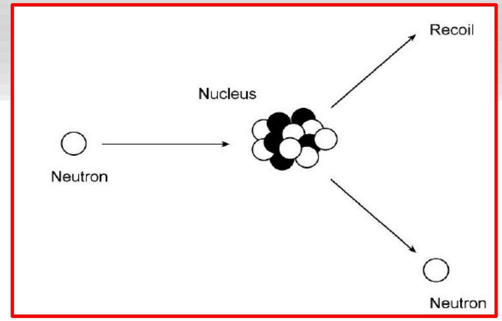
Neutrons Interactions

- **Elastic Scattering:**

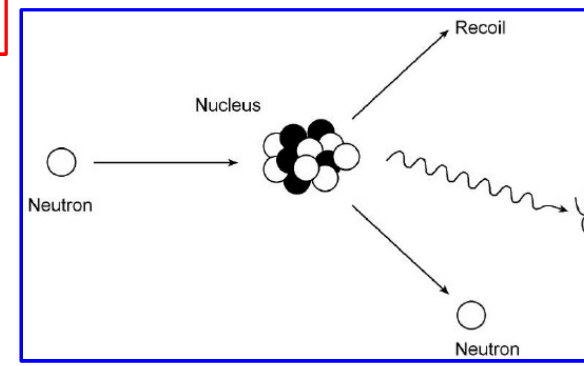
$$n + ^{A}_{Z}N \rightarrow n' + ^{A}_{Z}N$$



- **Inelastic Scattering:**

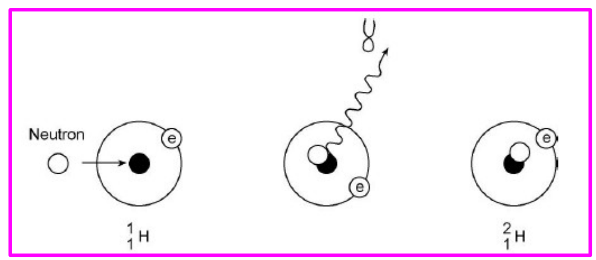
$$n + ^{A}_{Z}N \rightarrow (^{A+1}_{Z}N)^{*} \rightarrow n' + ^{A}_{Z}N + \gamma$$

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



- **Thermal Capture:**

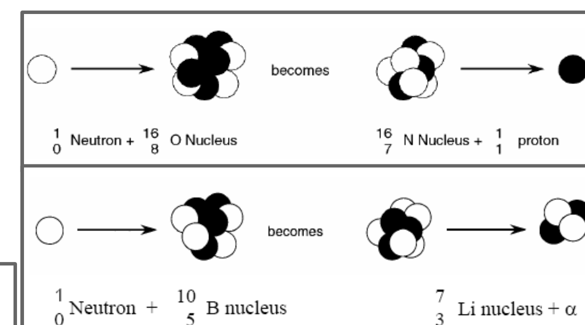
$$n + ^{A}_{Z}N \rightarrow ^{A+1}_{Z}N + \gamma$$



- **Transmutation:**

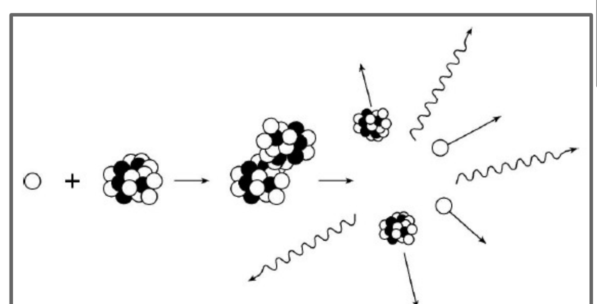
$$n + ^{A}_{Z}N \rightarrow ^{A}_{Z-1}N + p$$

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



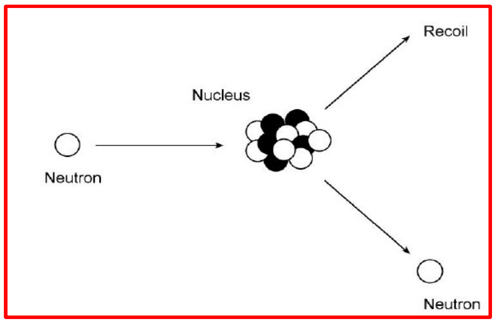
- **Fission:**

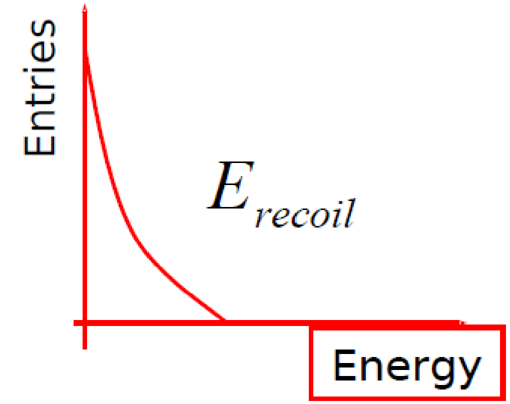
$$n + ^{A}_{Z}N \rightarrow ^{A_1}_{Z_1}X + ^{A_2}_{Z_2}Y + n$$



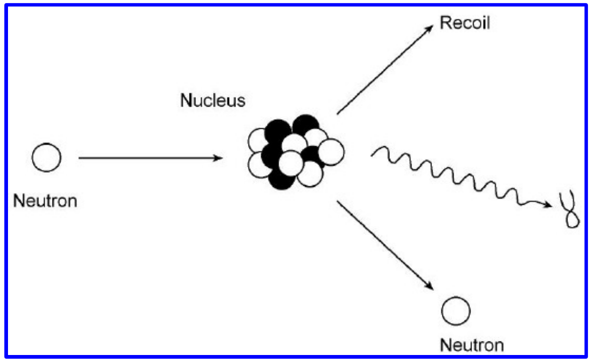
Neutrons Interactions

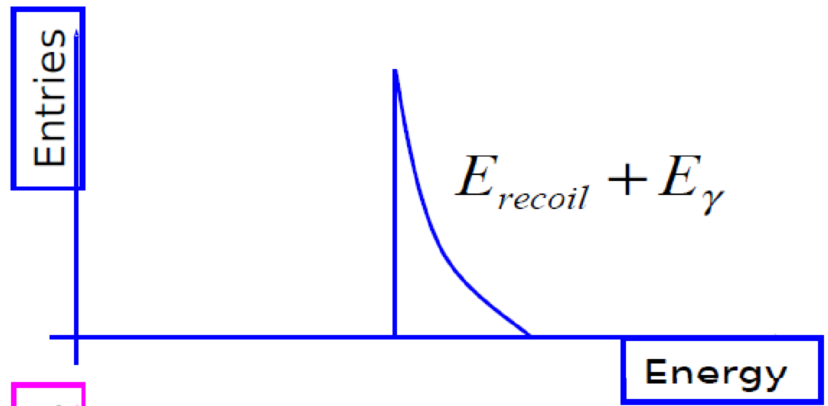
- **Elastic Scattering:**



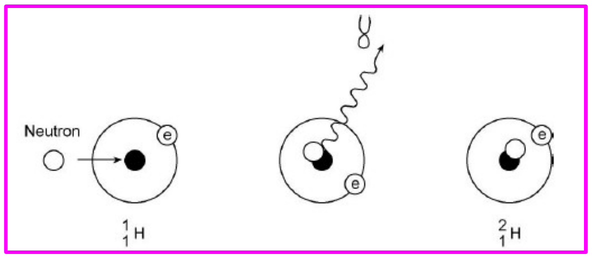


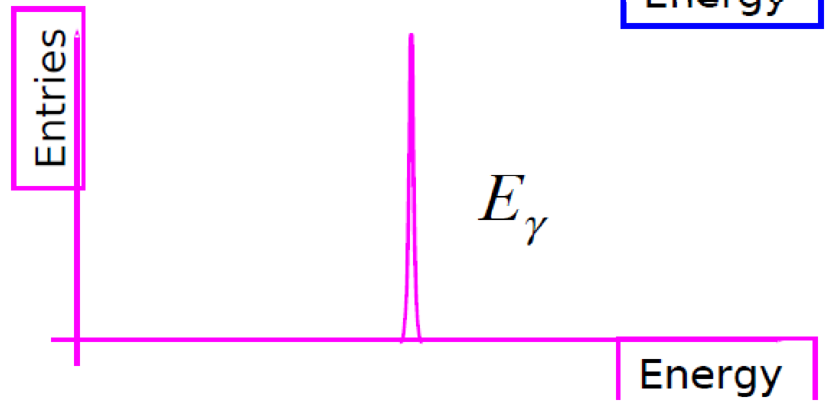
- **Inelastic Scattering:**





- **Thermal Capture:**

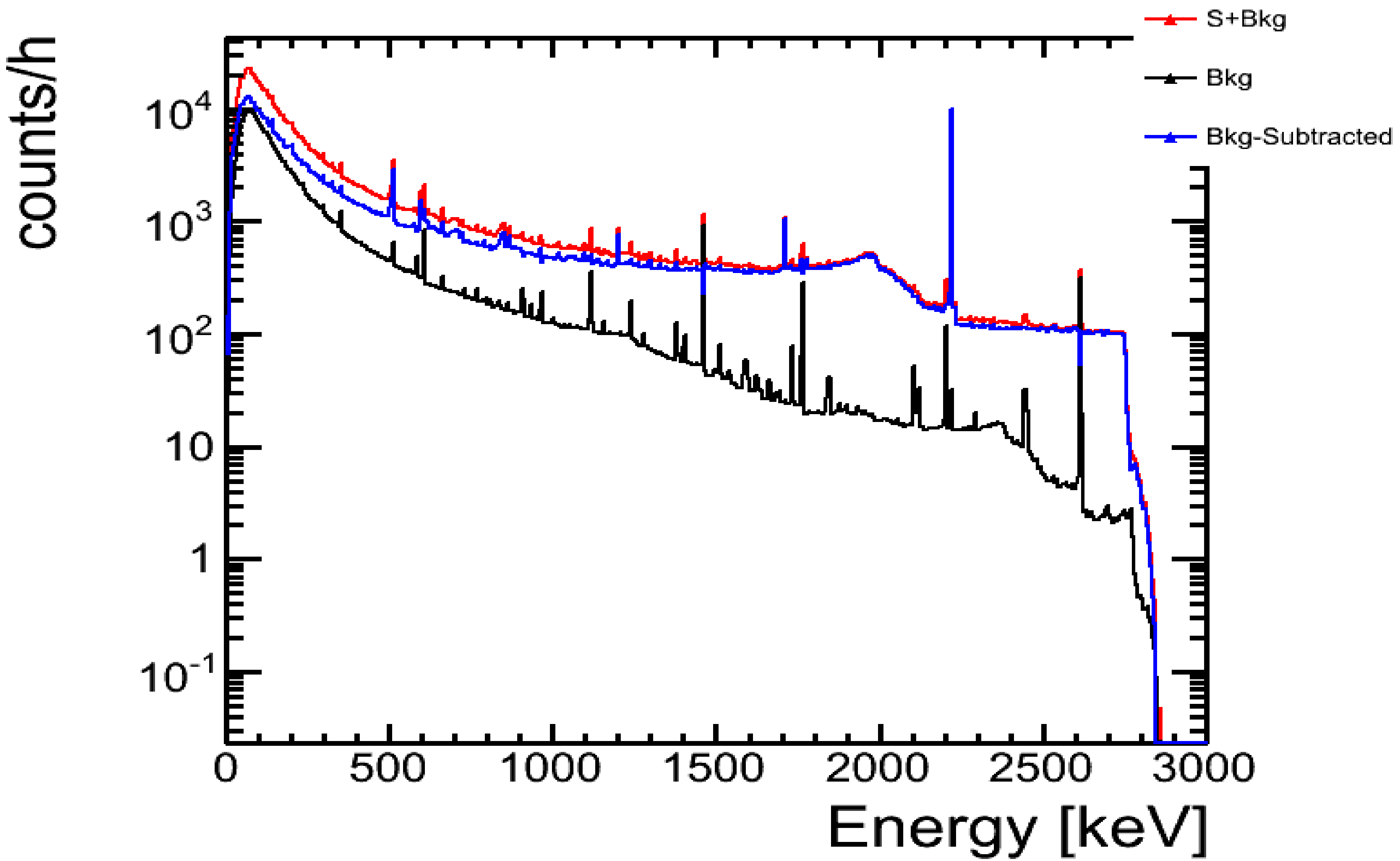




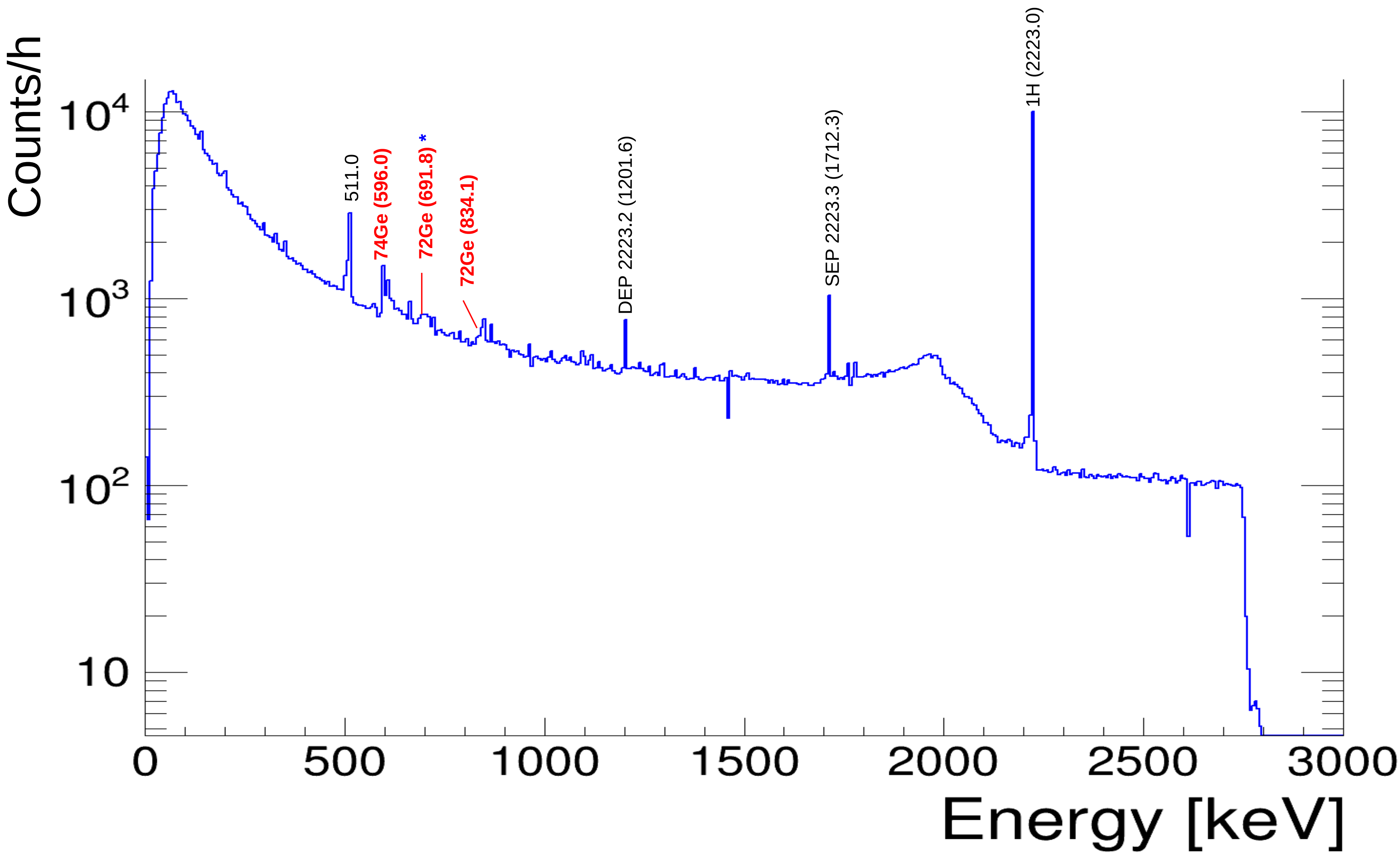
Outline

- Physics motivation:
  - Low Background Experiments
  - Background Sources
  - The China JinPing Laboratory
- Introduction to Germanium Detectors
- **Project Description:**
  - The muon-setup
  - The AmBe measurement
  - Neutrons Interactions
  - **First results**
- Summary & Outlook

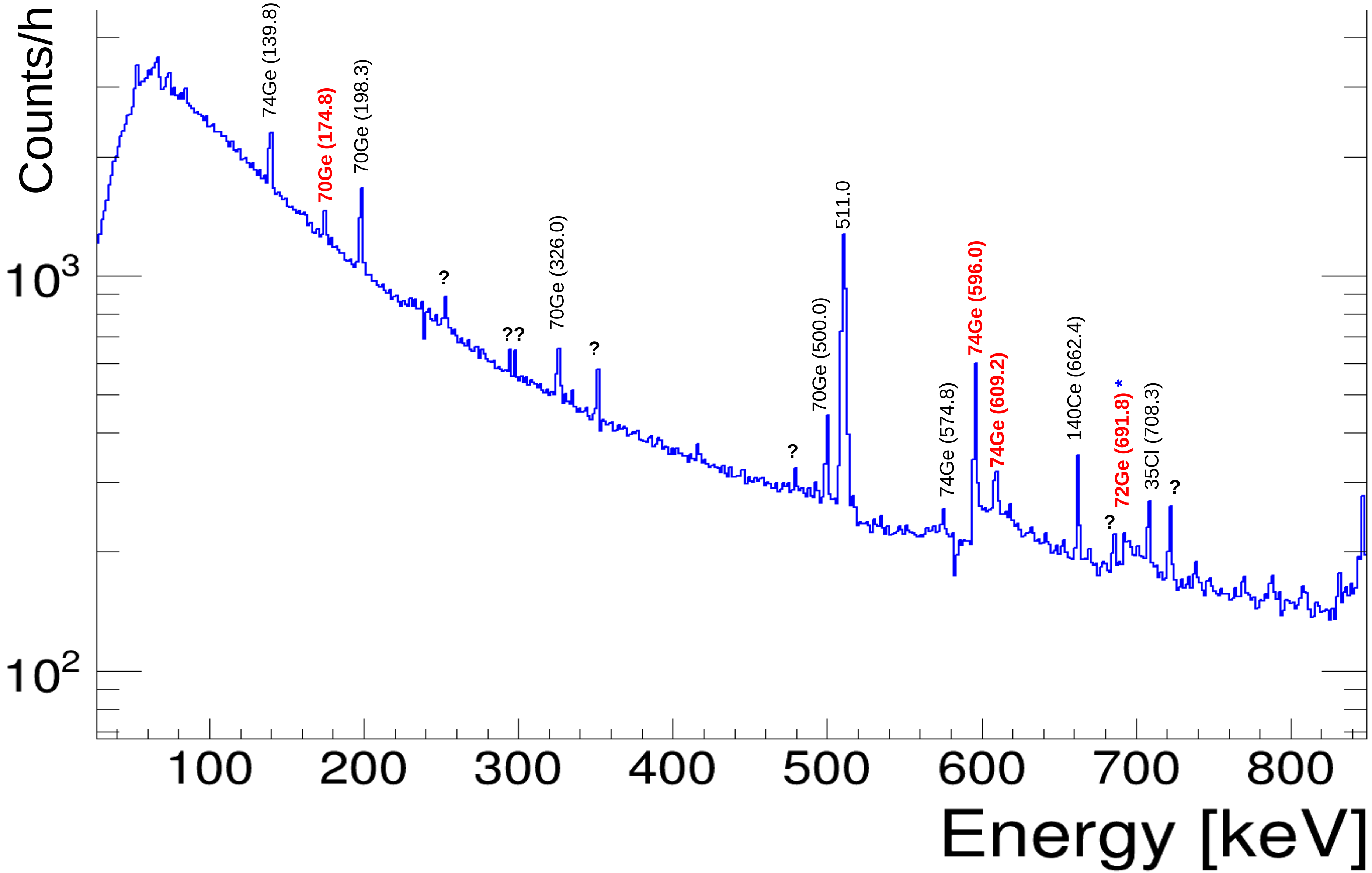
AmBe neutron source: results



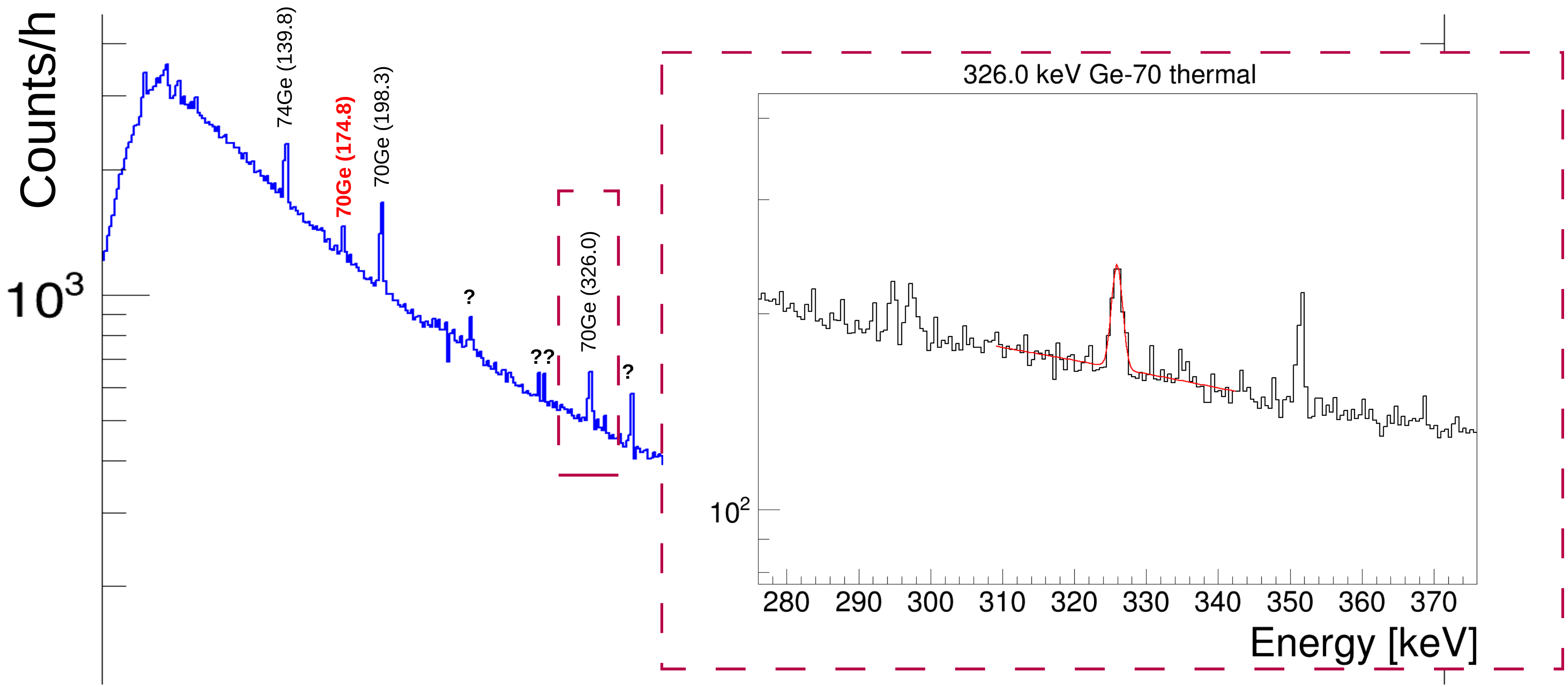
Background Subtracted



Background Subtracted: 0-0.8 MeV

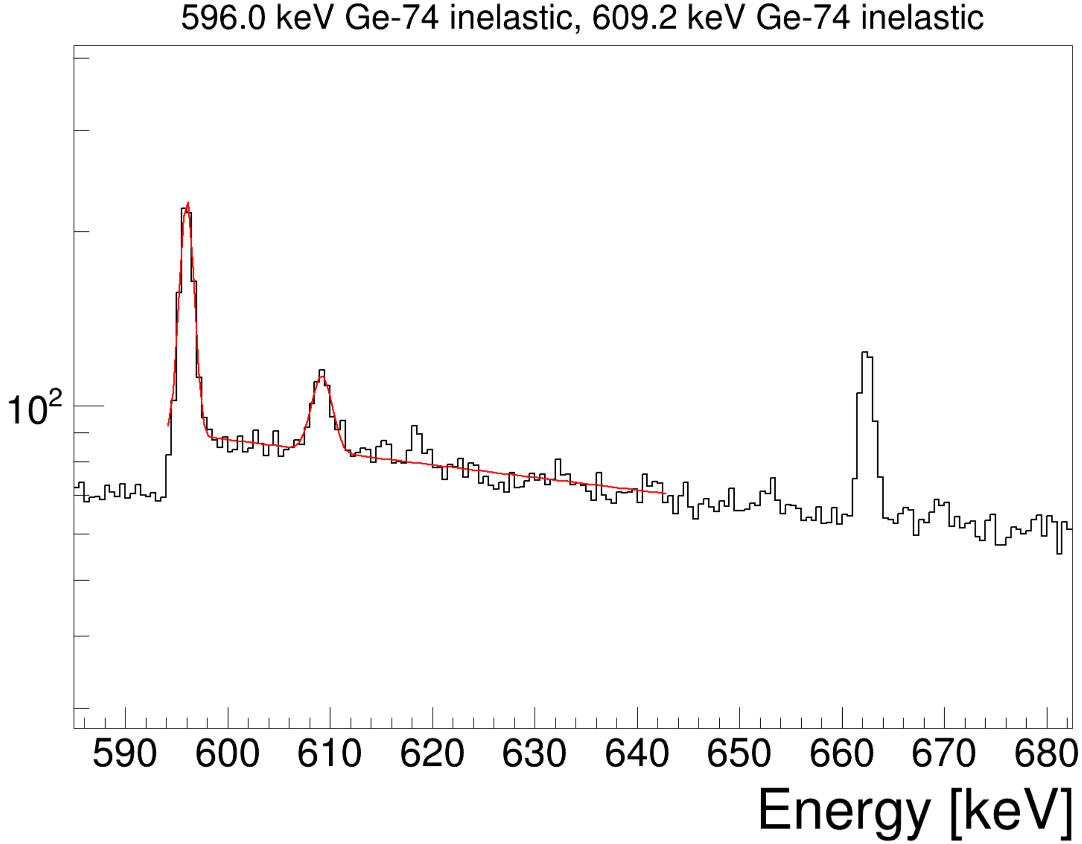


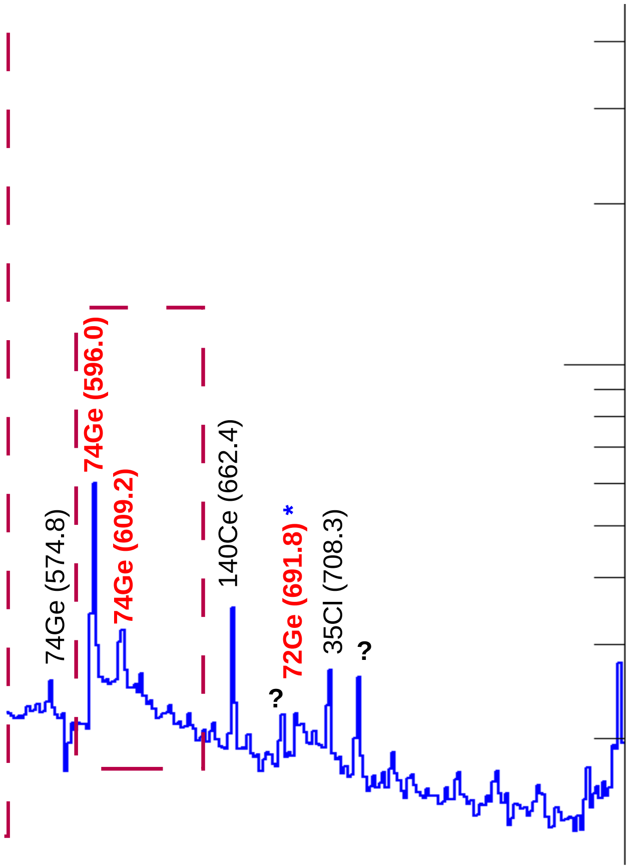
Background Subtracted: 0-0.8 MeV



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

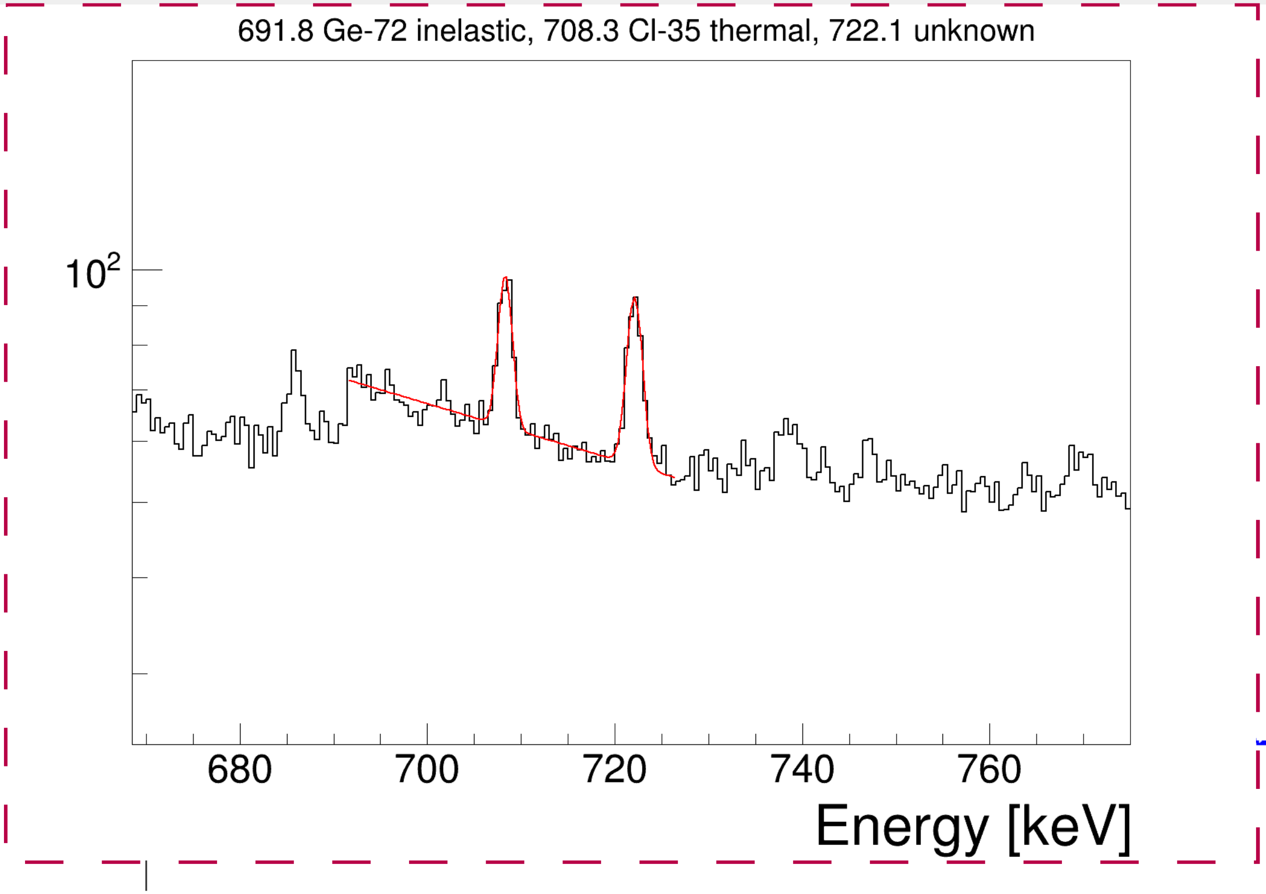
Background Subtracted: 0-0.8 MeV

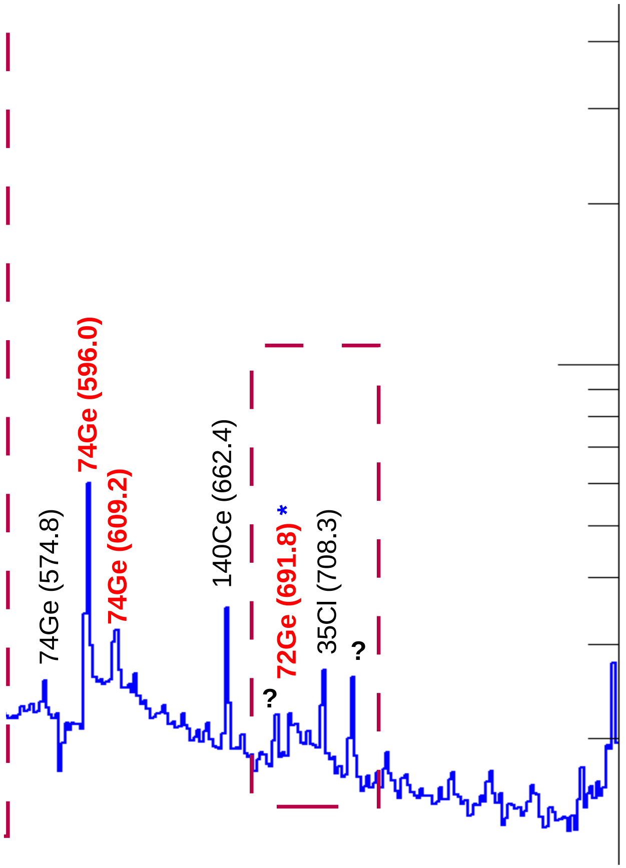




Fitted Energy [keV]	**Fitted FWHM [keV]**	**Interaction type**
596.0 ± 0.1	0.6 ± 0.1	$^{74}Ge(n,n'\gamma)$
609.2 ± 0.2	1.0 ± 0.3	$^{74}Ge(n,n'\gamma)$

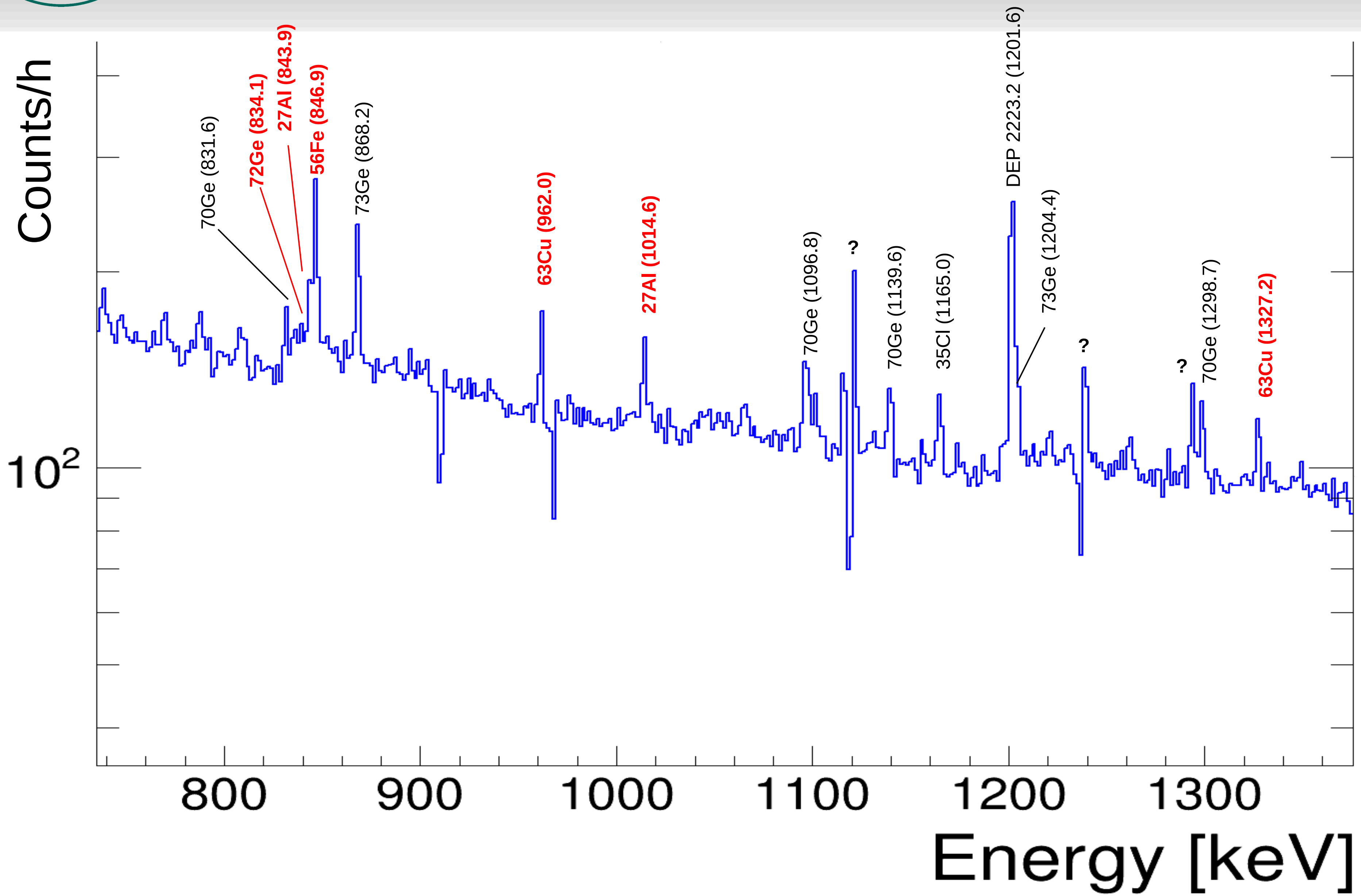
Background Subtracted: 0-0.8 MeV



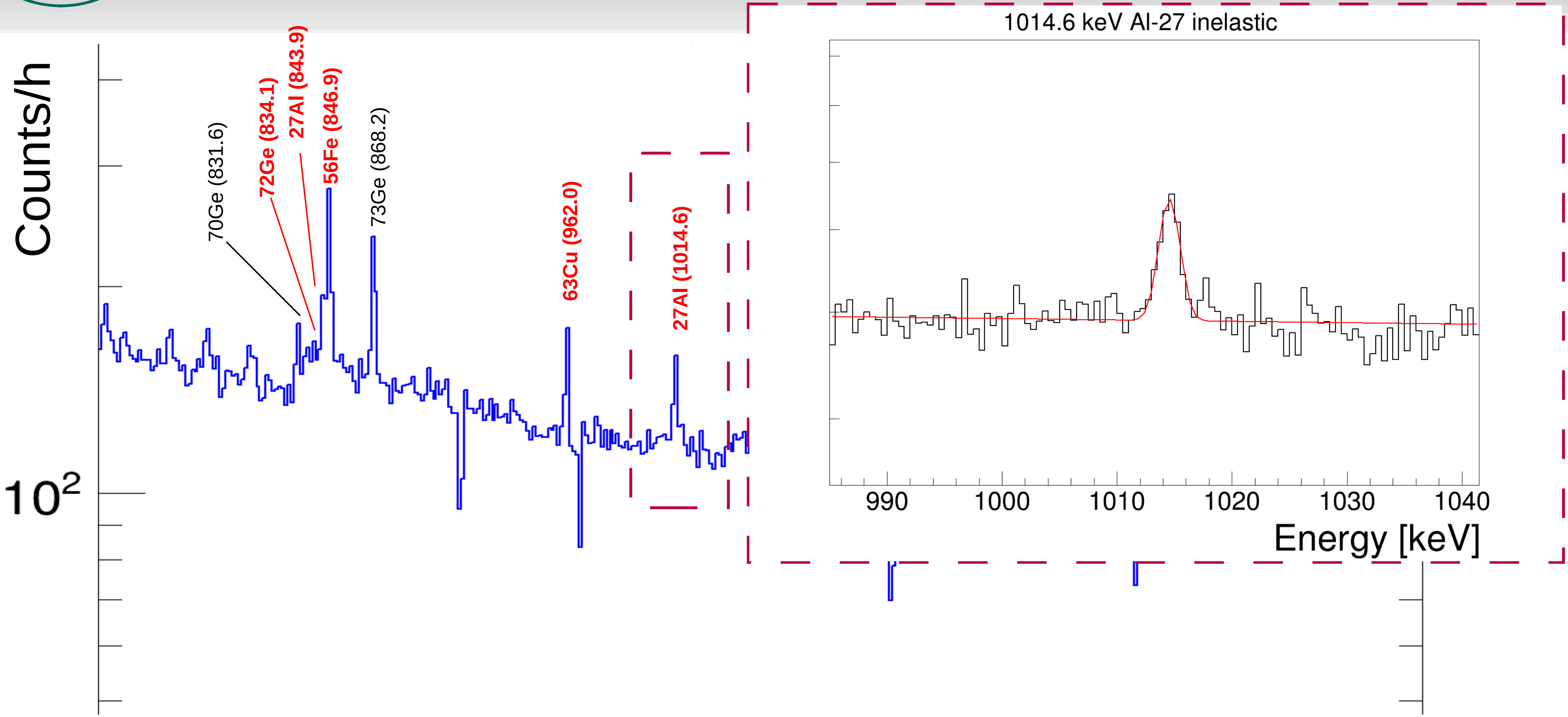


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
$691.8 \pm$ -	-	$^{72}Ge(n,n'e)$
708.3 ± 0.2	0.7 ± 0.1	$^{35}Cl(n,\gamma)$

Background Subtracted: 0.8-1.4 MeV

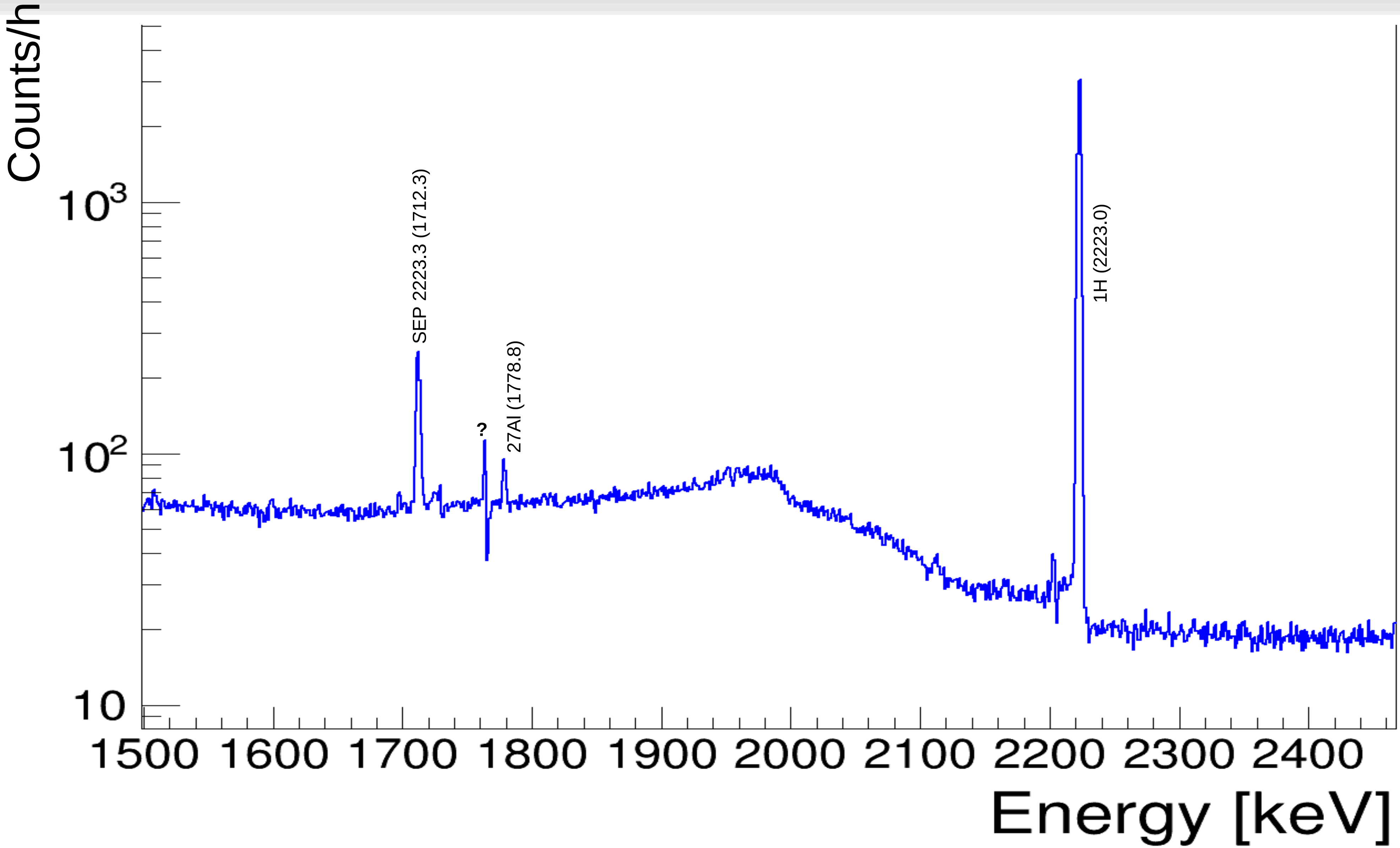


Background Subtracted: 0.8-1.4 MeV

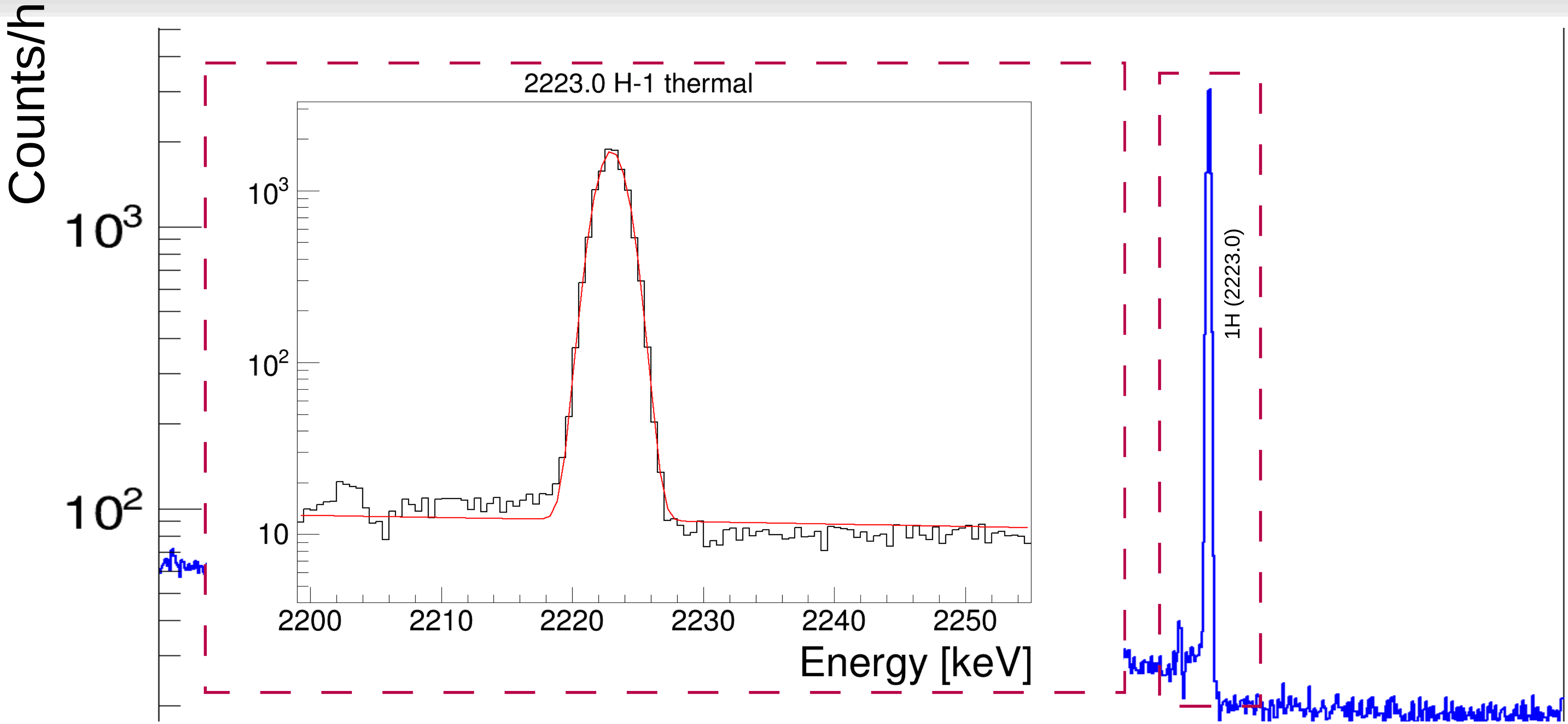


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
1014.6 ± 0.3	0.9 ± 0.3	$^{27}Al(n, n'\gamma)$

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	$^{1}H(n,\gamma)$

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Summary & Outlook

- **Summary:**
  - **Muon-induced neutrons**
  - **Cosmogenic neutrons**
  - **Study of the effect of different materials**
  - **Reference measurement with AmBe neutron source**
- **Outlook:**
  - **Perform simulations (γ-n discr., n time delay)**
  - **Move in a shallow underground lab (CJPL??)**
  - **Build a neutron spectrometer (CJPL)**

References

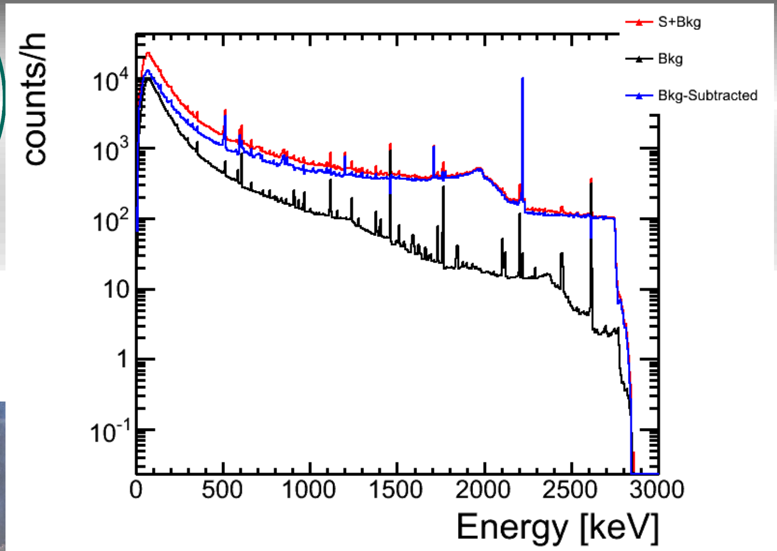
[1] I. Abt, A.Caldwell. K. Kroeninger, J. Liu, X. Liu and B. Majorovits.
"Neutron interactions as seen by a segmented germanium detector".
Eur. Phys. J. A 36, 139-149 (2008).

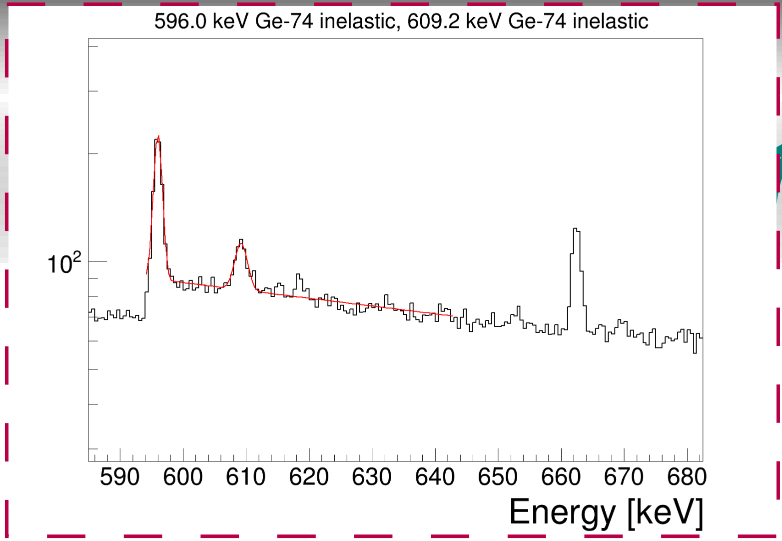
[2] T. Siiskonen, H. Toivonen.
"A model for fitting peaks induced by fast neutrons in an HPGe detector".
Nucl. Instrum. Meth. A 540 (2005) 403-411.

[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.

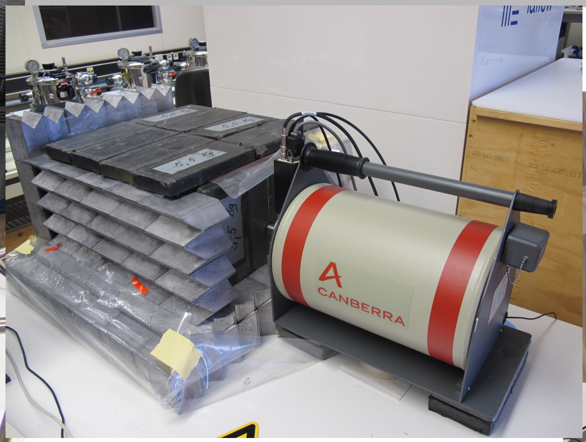
[4] K. W. Geiger, L. Van Der Zwan,
"Radioactive neutron source spectra from Be(α,n)"
Nucl. Inst. and Meth. 131 (1975) 315.

[5] J. Ljungvall, J. Nyberg,
"A study of fast neutron interactions in high-purity germanium detectors"
Nucl. Inst. and Meth. in Phy. Res. A 546 (2005) 553–573

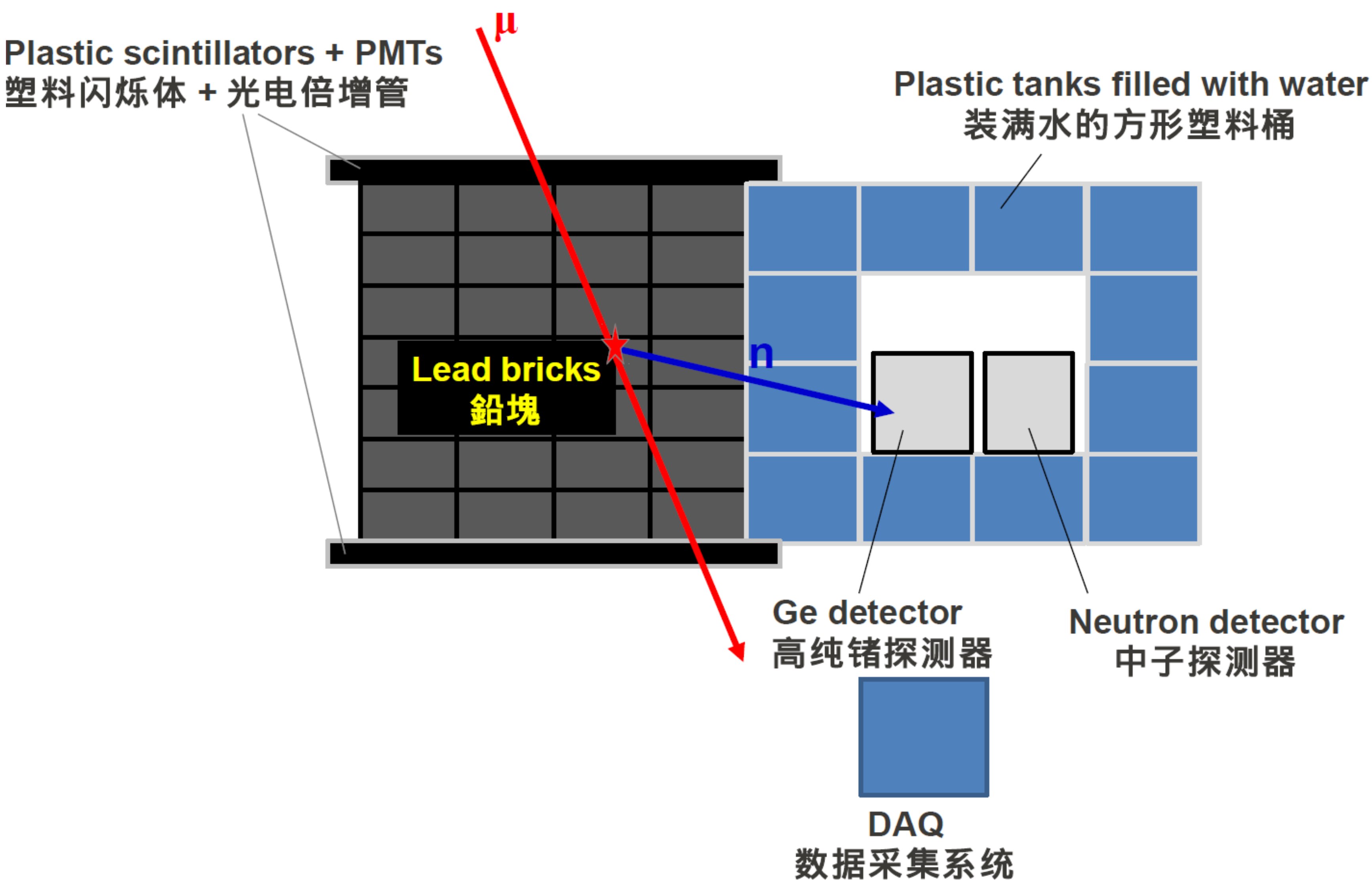




Thank You for The Attention!

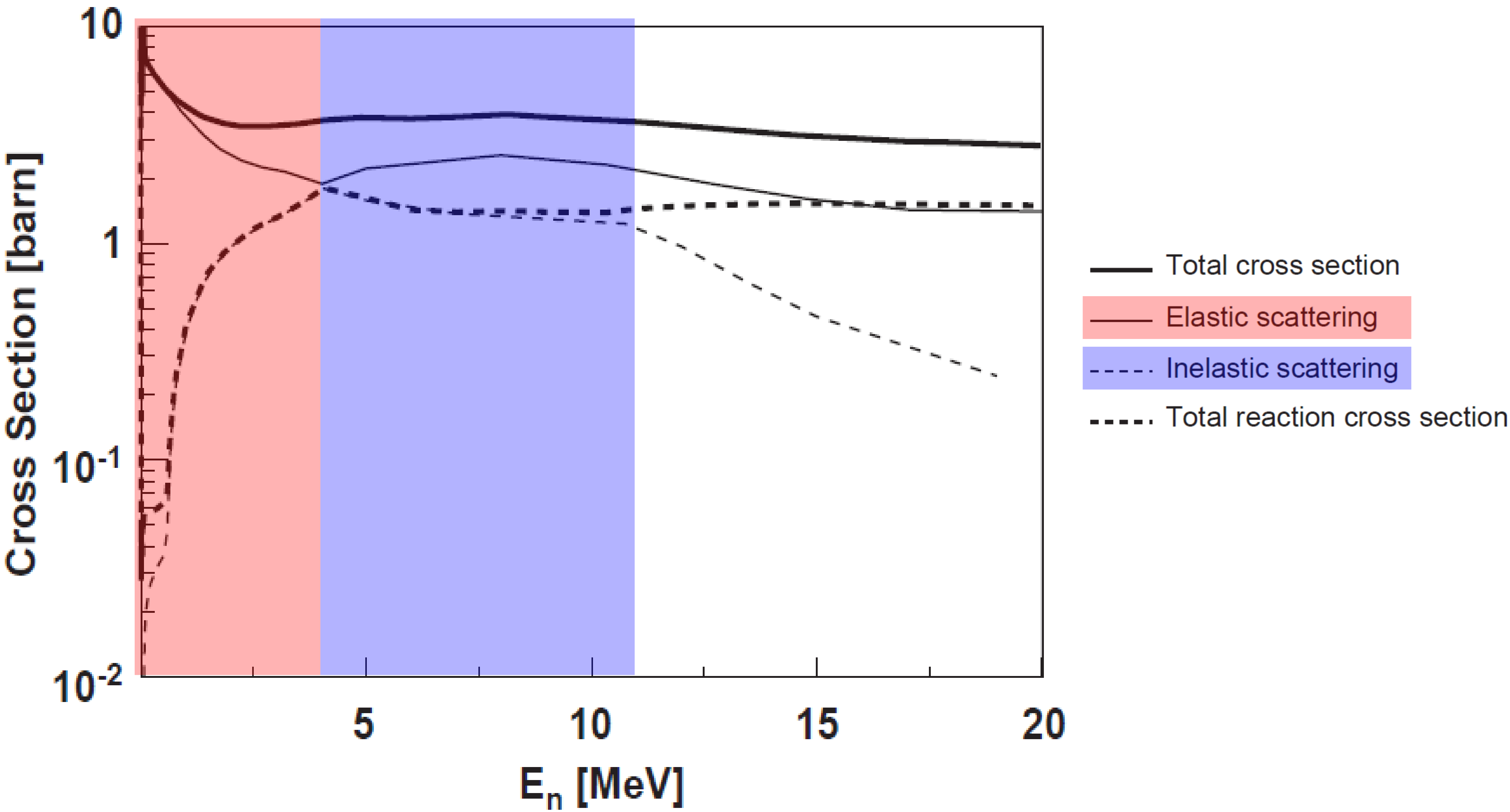


Backup

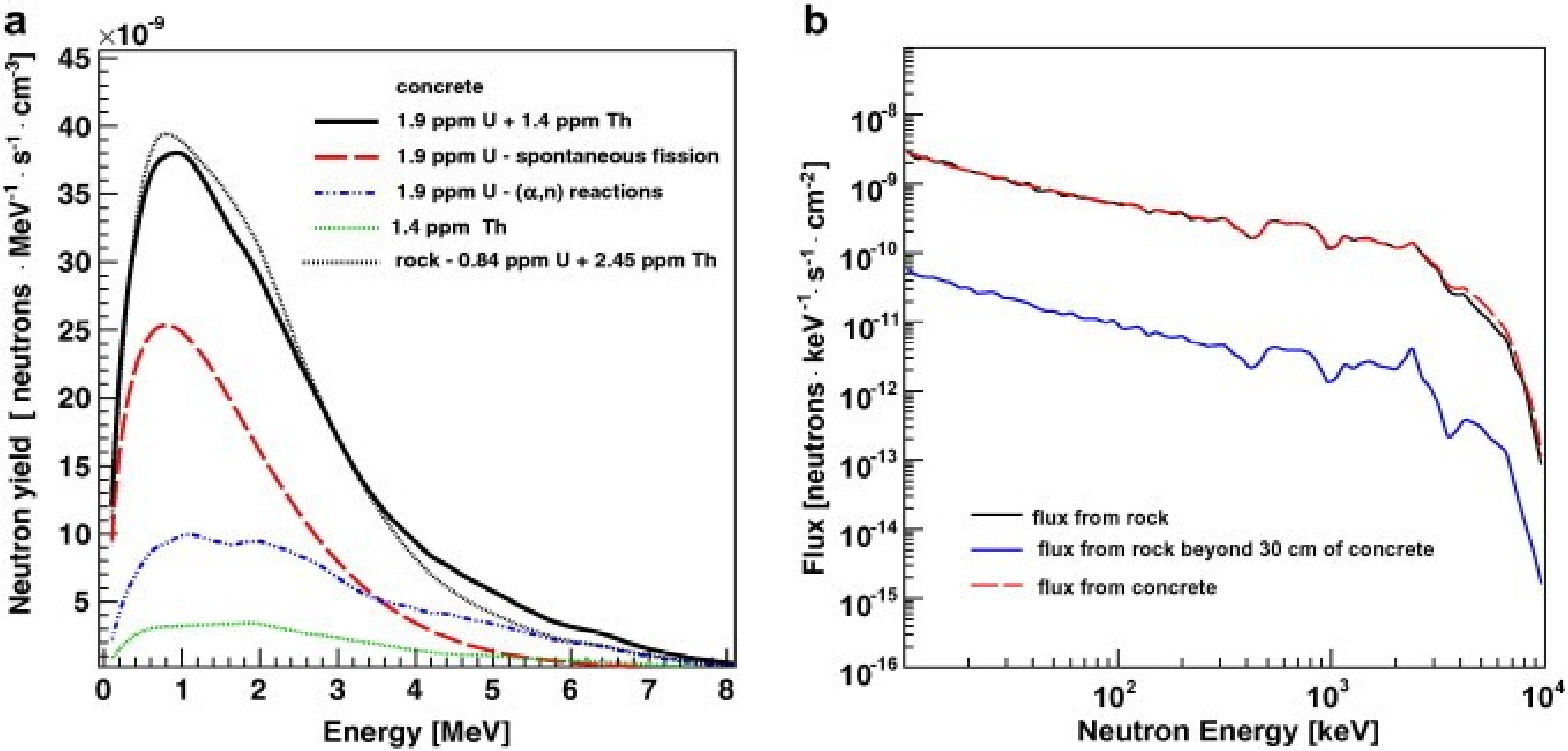


Plastic scintillators + PMTs
塑料闪烁体 + 光电倍增管
μ
Plastic tanks filled with water
装满水的方形塑料桶
n
Lead bricks
鉛塊
Ge detector
高纯锗探测器
Neutron detector
中子探测器
DAQ
数据采集系统

Neutrons Cros Section

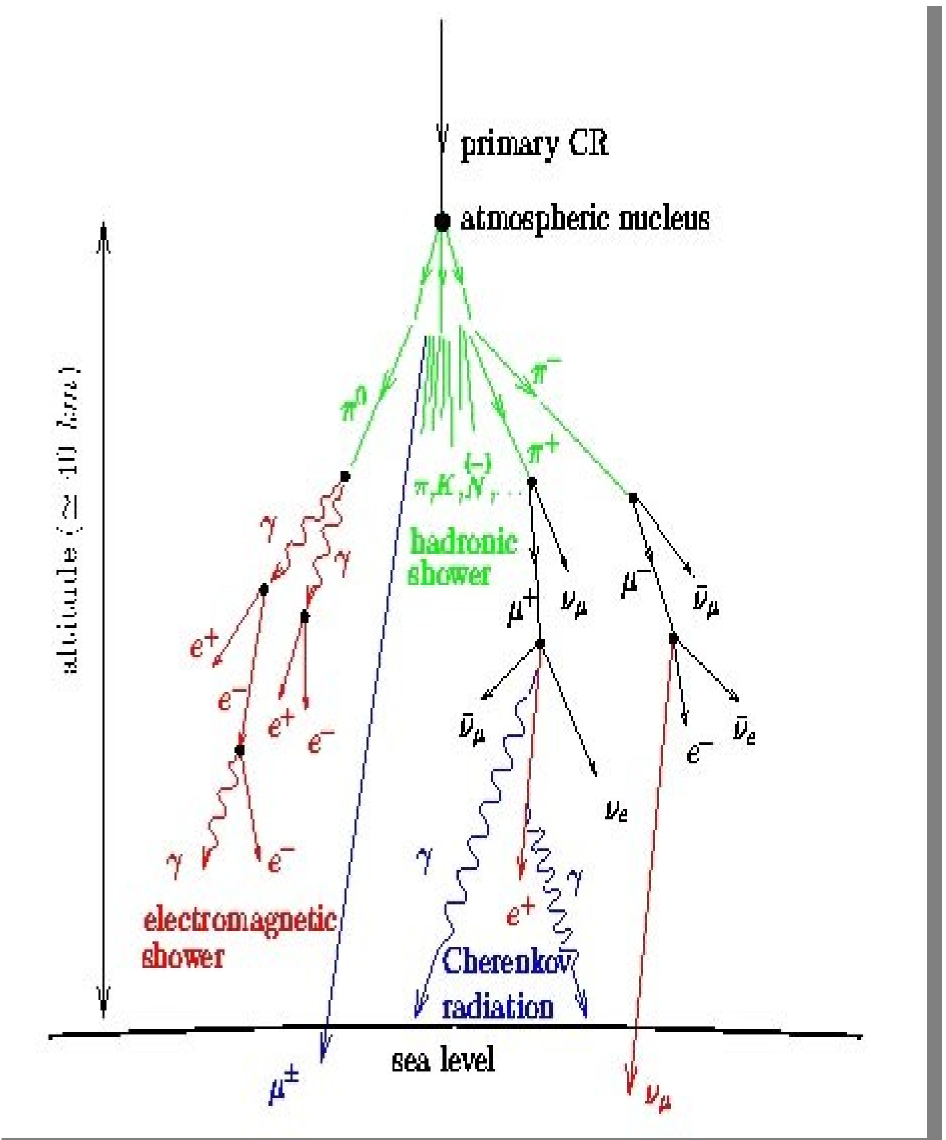


Environmental Natural Radioactivity

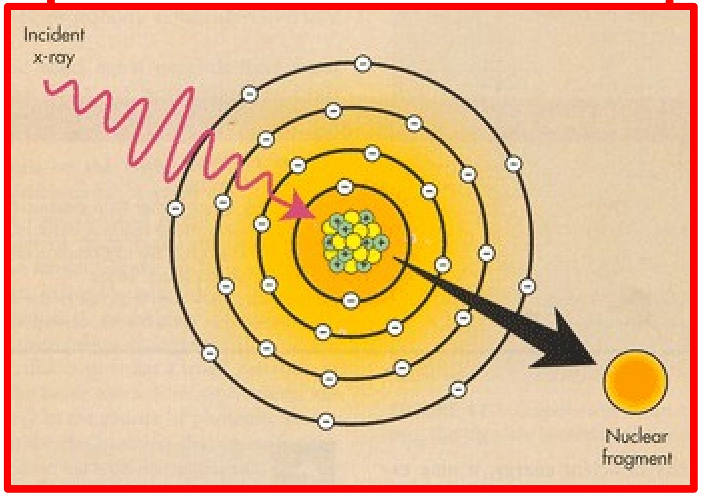


Tomasello et. al., Radioactive background in a cryogenic dark matter experiment, Astro. Phys., Vol 34, 2010

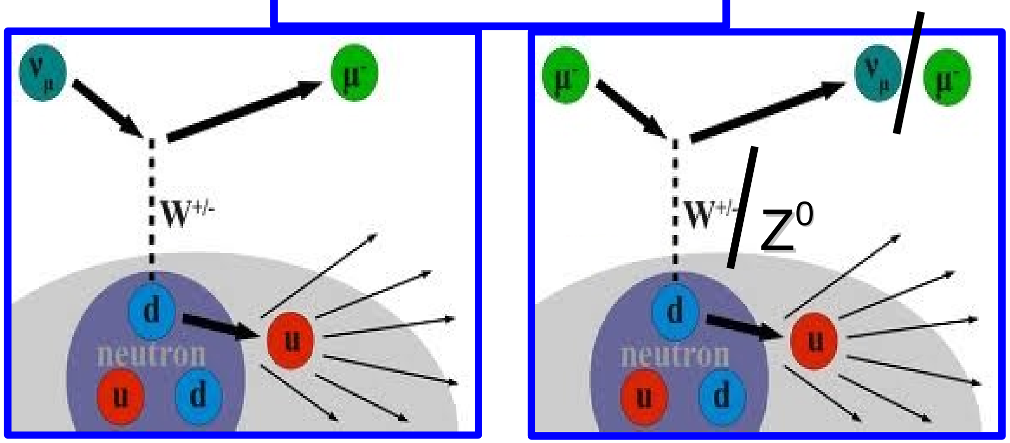
Cosmic Rays Shower

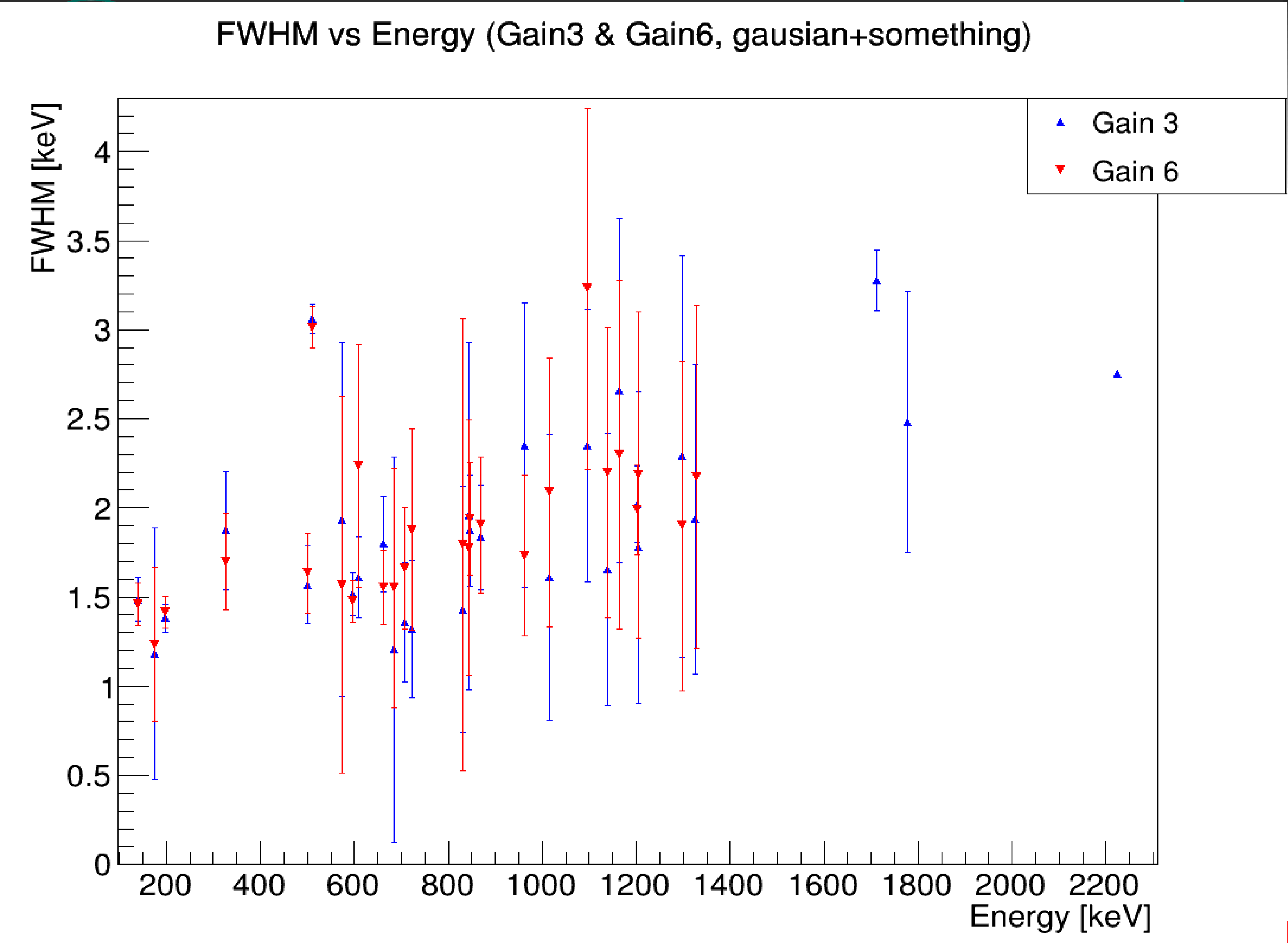


Photodisintegration



DIS



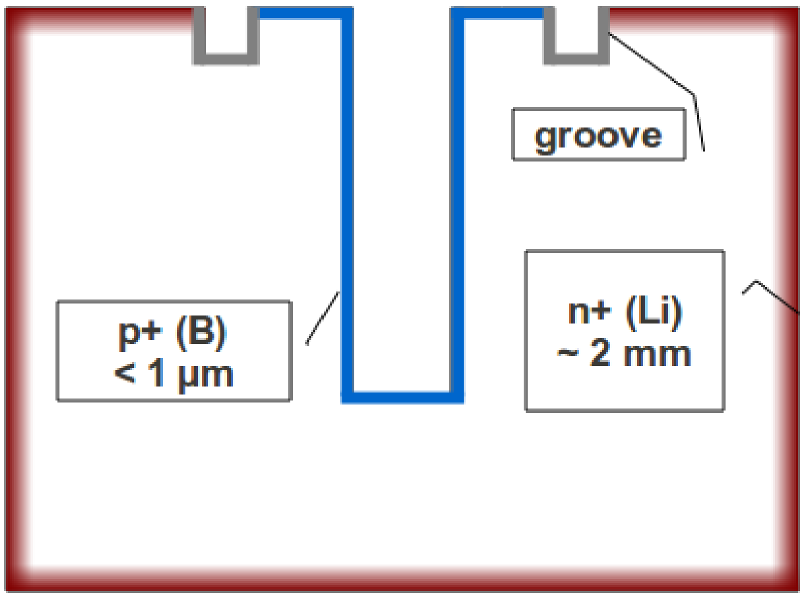

FWHM vs Energy (Gain3 & Gain6, gausian+something)
FWHM [keV]
Energy [keV]
Gain 3
Gain 6
0
0.5
1
1.5
2
2.5
3
3.5
4
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

Natural Germanium

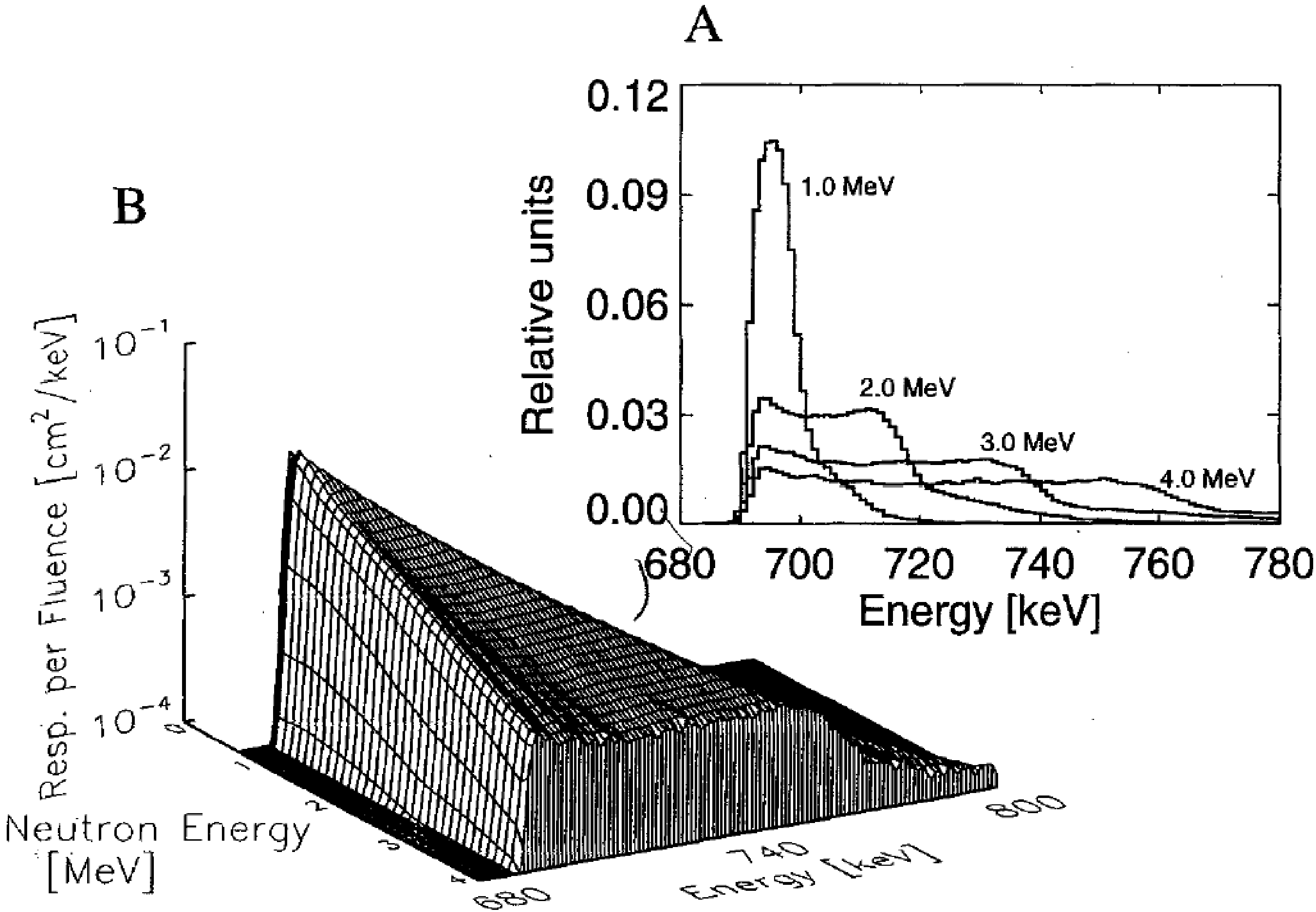
Isotope	Atomic mass (m_a/u)	Natural abundance (atom %)
^{70}Ge	69.9242497 (16)	20.84 (87)
^{72}Ge	71.9220789 (16)	27.54 (34)
^{73}Ge	72.9234626 (16)	7.73 (5)
^{74}Ge	73.9211774 (15)	36.28 (73)
^{76}Ge	75.9214016 (17)	7.61 (38)

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	$^{1}H(n,\gamma)$	-

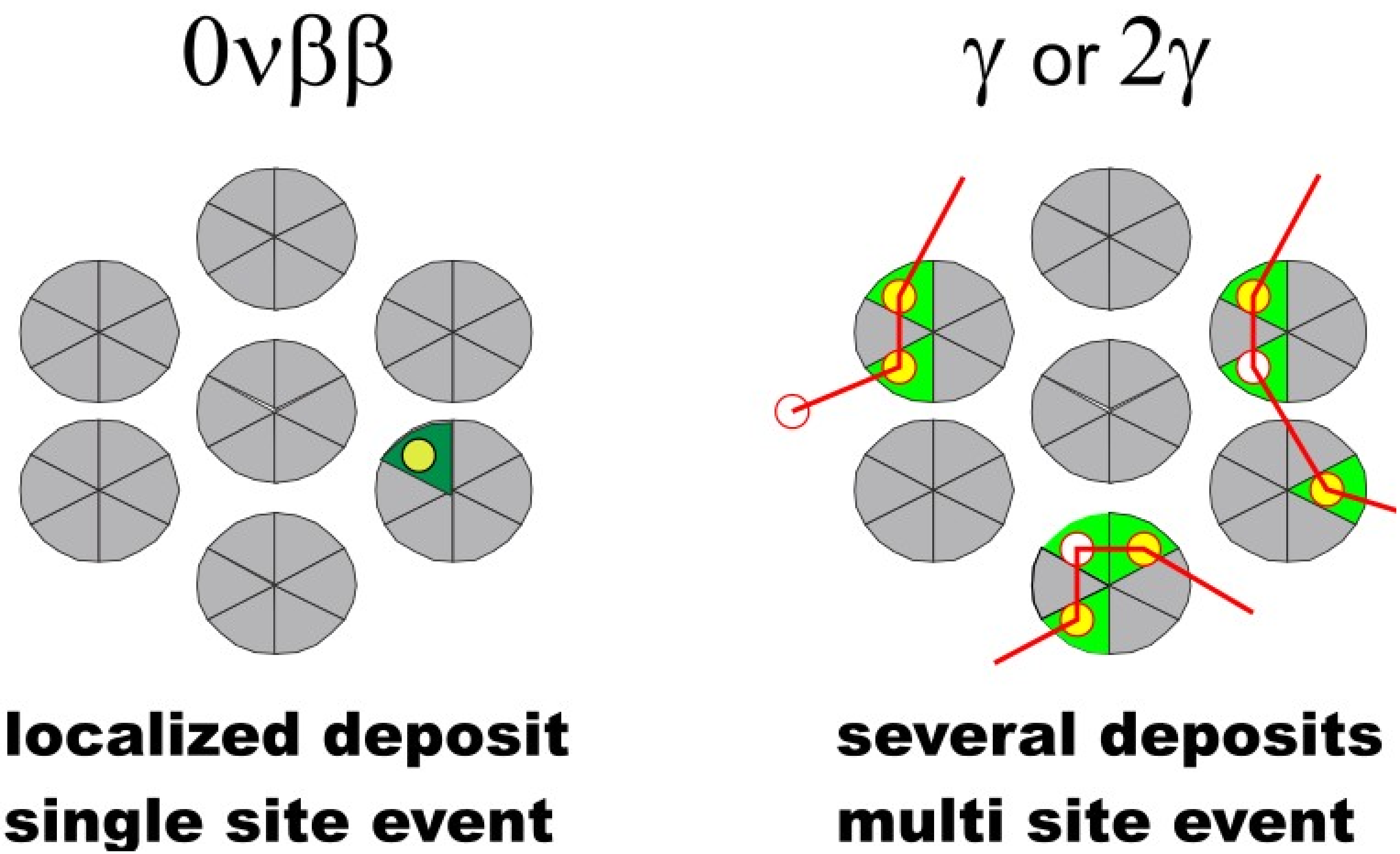
**These peaks where fitted on the gain 3 spectra.*


groove
p+ (B)
< 1 µm
n+ (Li)
~ 2 mm

Inelastic Scattering Distribution

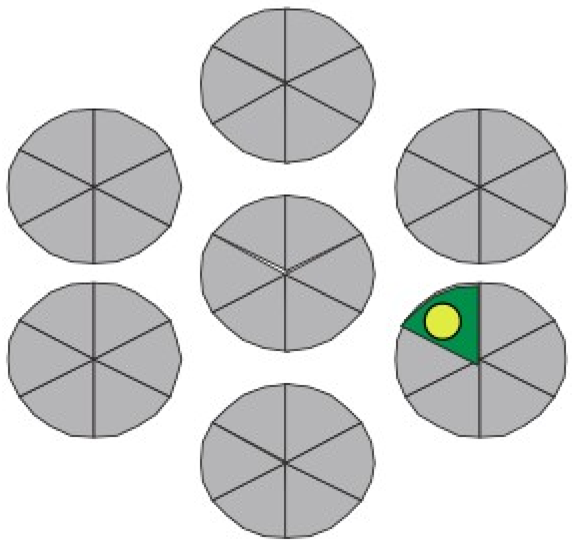


Background events



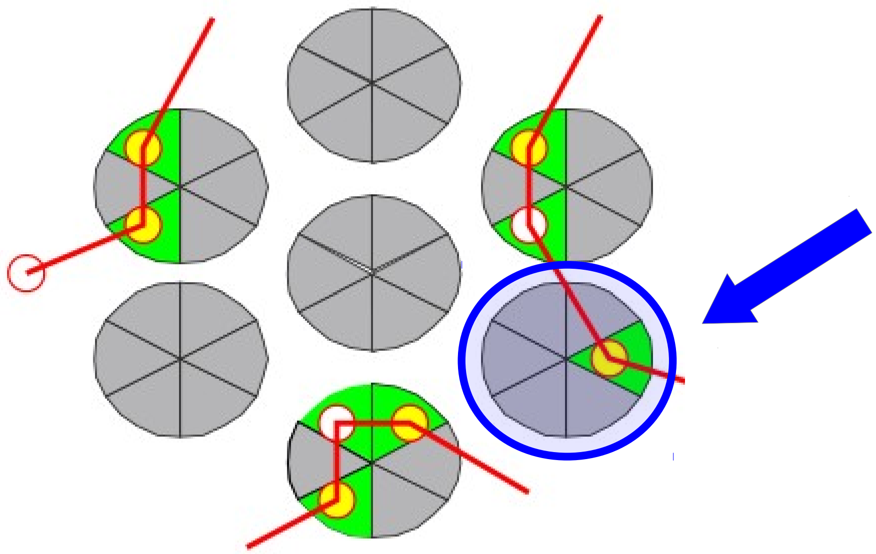
Background events

$0\nu\beta\beta$



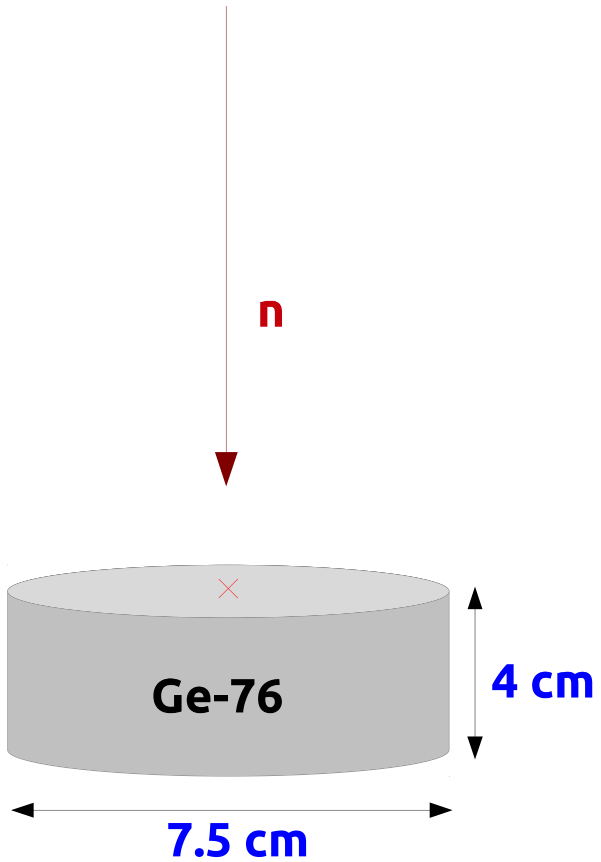
localized deposit
single site event

γ or 2γ



several deposits
multi site event

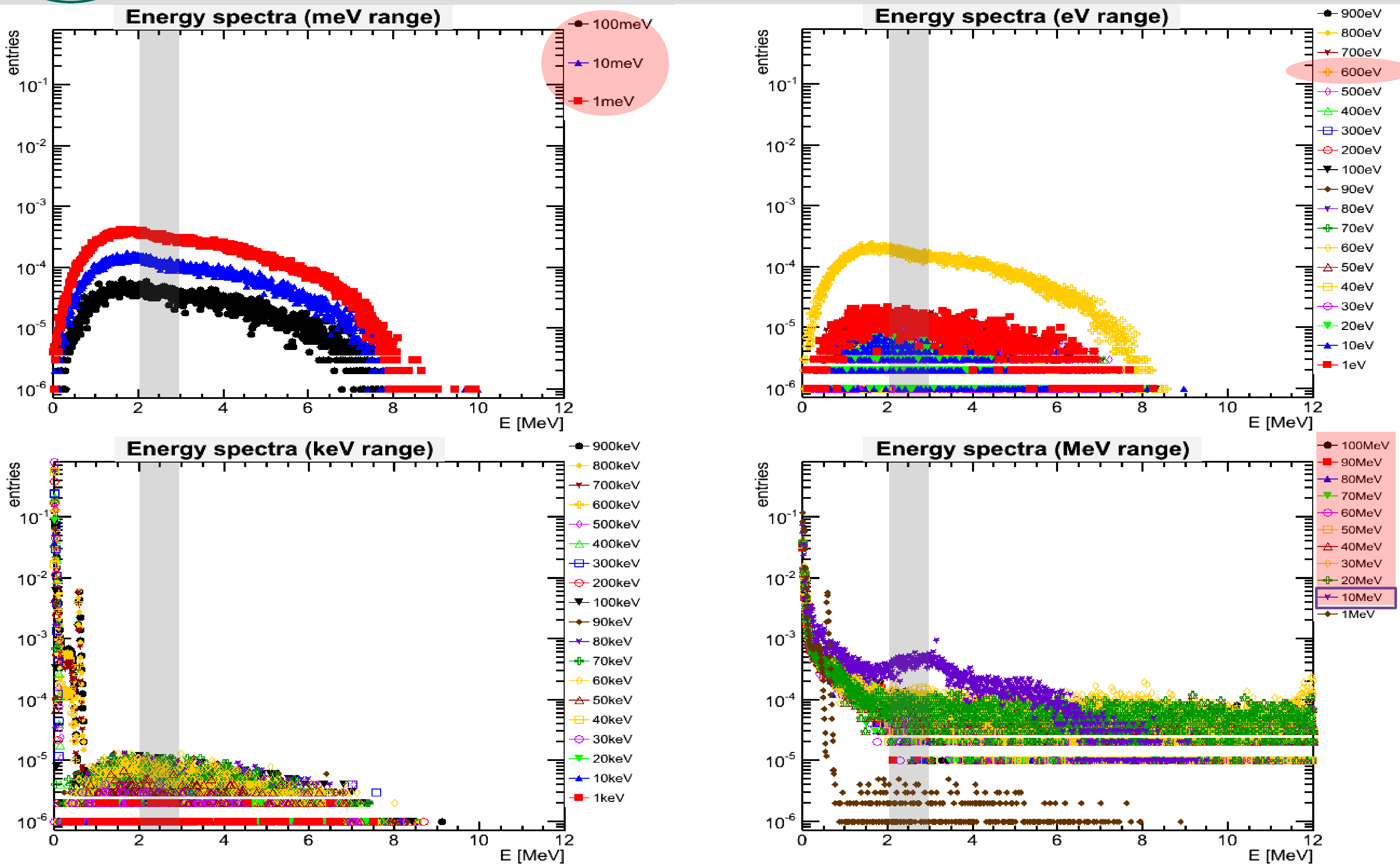
Simulation



- **Energies:**
  - meV: 1,10,100
  - eV: 1,10-100 (10 eV step)
  - eV: 100-900 (100 eV step)
  - keV: 1,10-100 (10 keV step)
  - keV: 100-900 (100 keV step)
  - MeV: 1,10-100 (10 MeV step)
- **1 million events**
- **Total energy deposition (Thr 1 keV)**

Courtesy of B. Doenmez, MPP Muenchen

Results



Energy spectra (meV range)
entries
E [MeV]
100meV
10meV
1meV
Energy spectra (eV range)
900eV
800eV
700eV
600eV
500eV
400eV
300eV
200eV
100eV
90eV
80eV
70eV
60eV
50eV
40eV
30eV
20eV
10eV
1eV
Energy spectra (keV range)
900keV
800keV
700keV
600keV
500keV
400keV
300keV
200keV
100keV
90keV
80keV
70keV
60keV
50keV
40keV
30keV
20keV
10keV
1keV
Energy spectra (MeV range)
100MeV
90MeV
80MeV
70MeV
60MeV
50MeV
40MeV
30MeV
20MeV
10MeV
1MeV

Conclusions

In terms of background contribution due to neutrons in the ROI for **$0\nu2\beta$ decay** the neutron energy ranges of **meV** and **MeV** (+600 eV) are **basically the same**

BUT

we expect less neutrons in the MeV range than in the meV range

THEREFORE

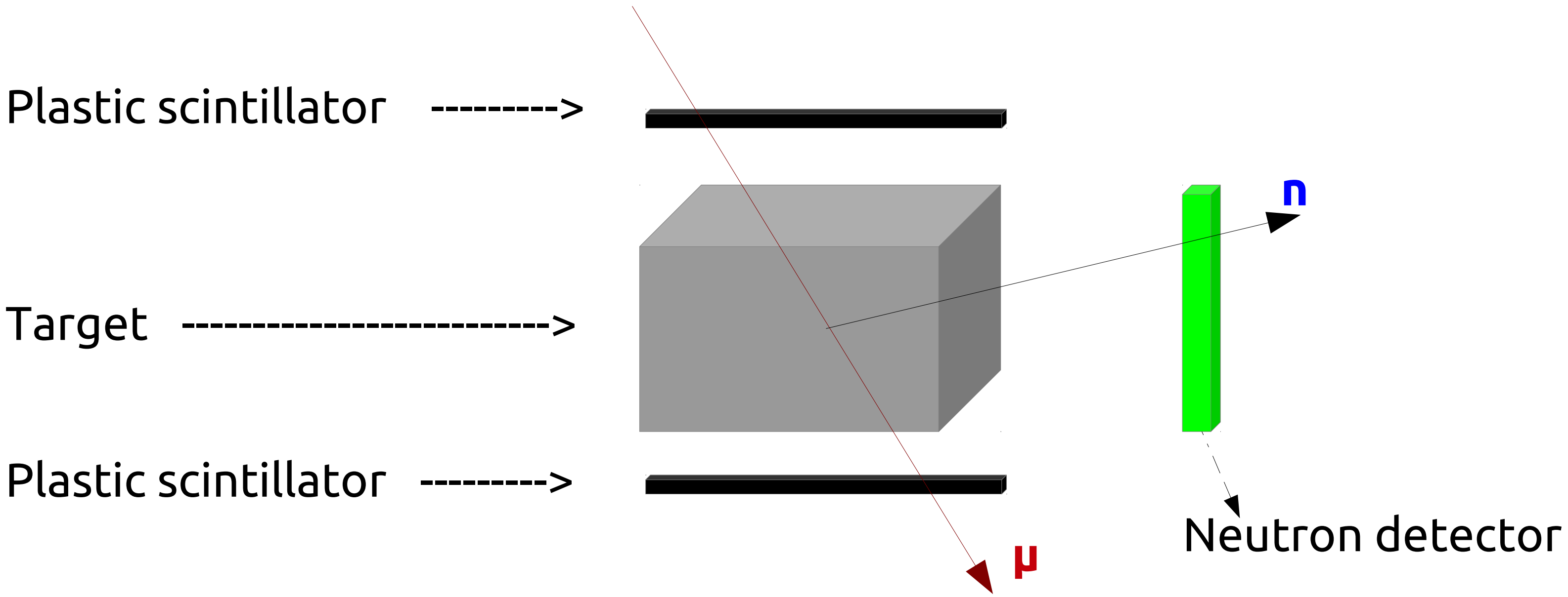
It might be better to keep few MeV neutrons rather than several meV neutrons

To be kept in mind in the choice of the shielding!

Proposal: Muon-induced Neutron Flux

A neutron detector, which is able to measure the neutrons energy, can be used to:

- **Improve the understanding of muon-induced shower via measuring the neutron flux emanating from:**
  - **Lead**
  - **Copper**
  - **Cryogenics Liquid**
  - **Rock**



Proposal:
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A neutron detector, which is able to measure the neutrons energy, can be used to:

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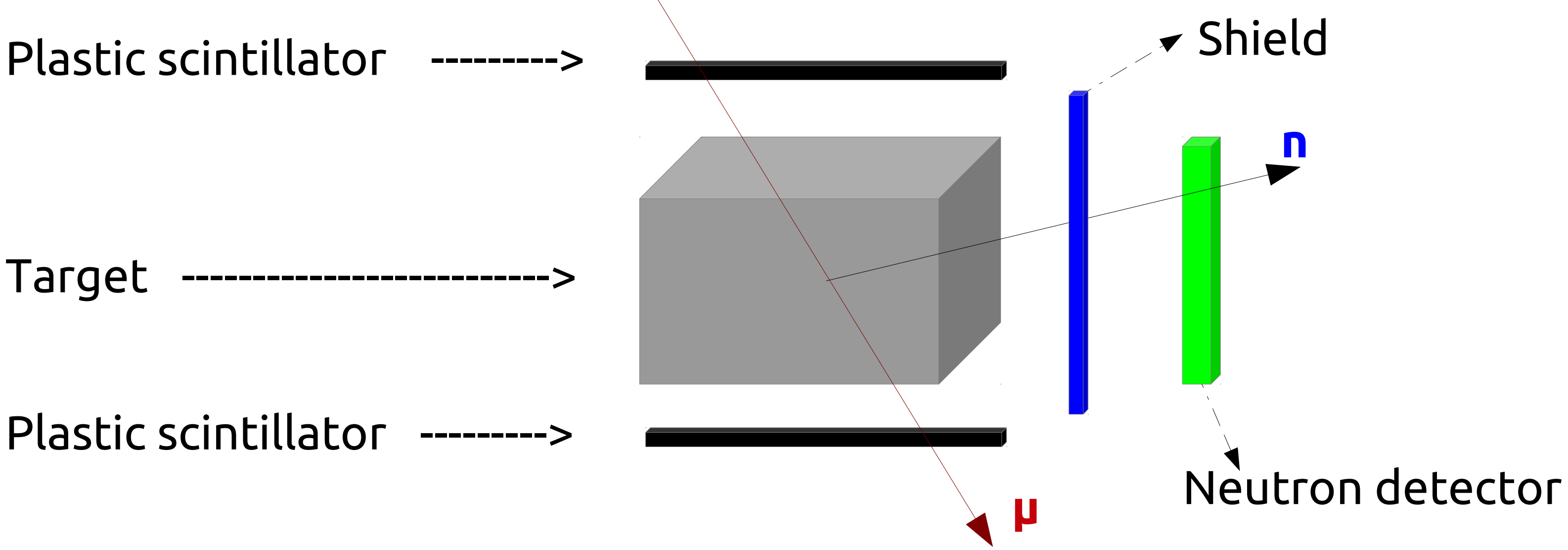
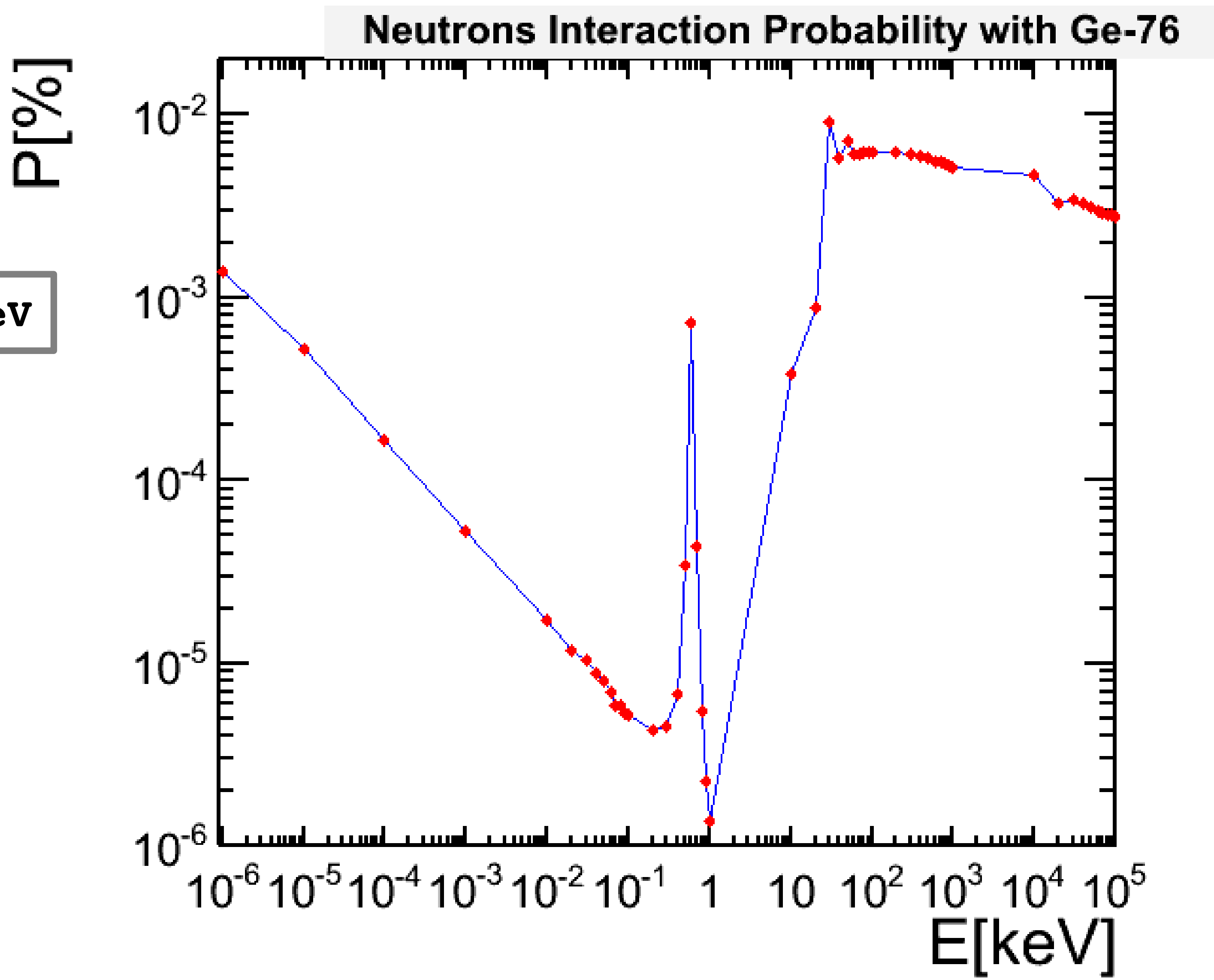
  - **Copper**
  - **Cryogenics Liquid**
  - **Rock**
- **Test shielding properties of selected materials**

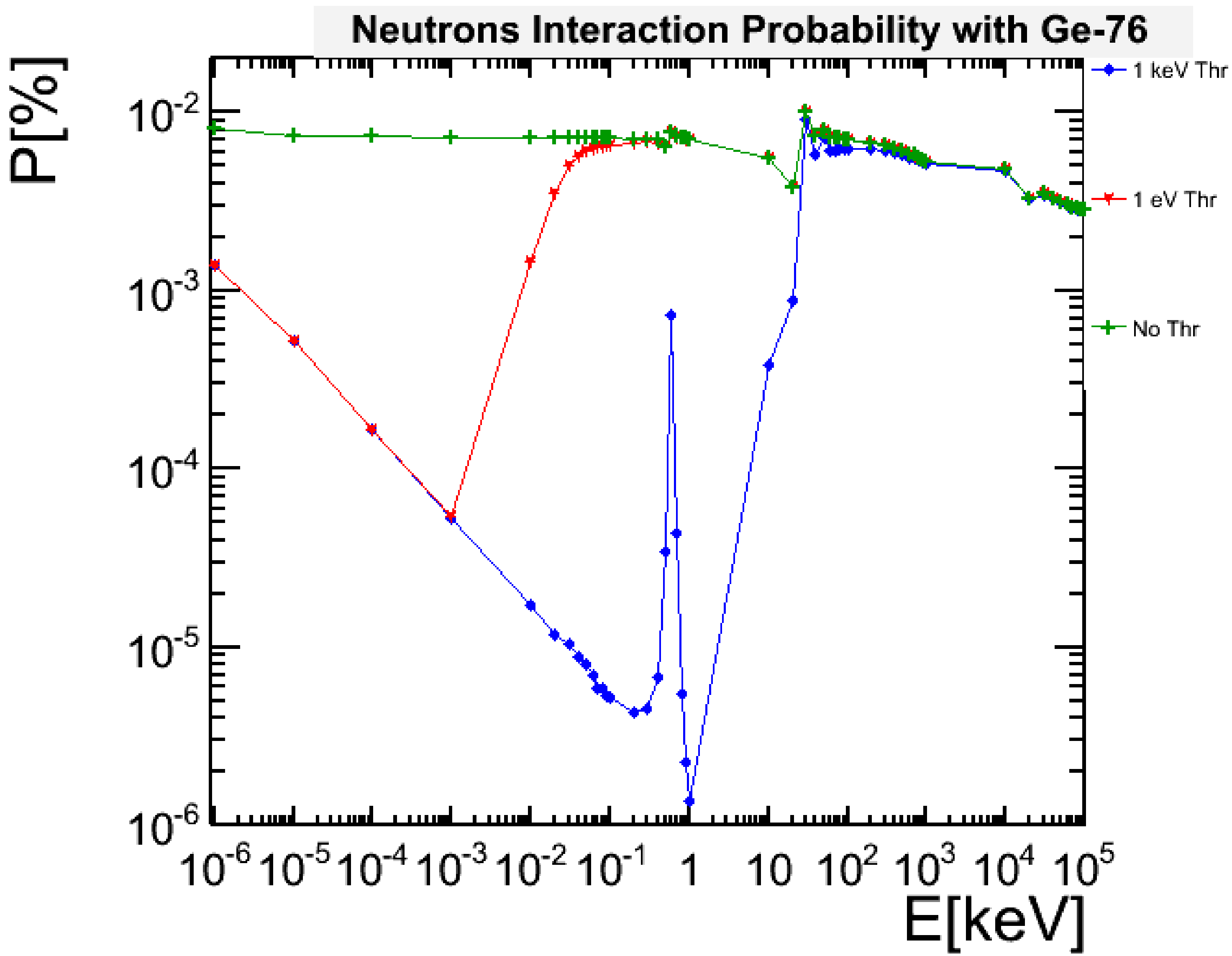


Neutrons Interaction Probability

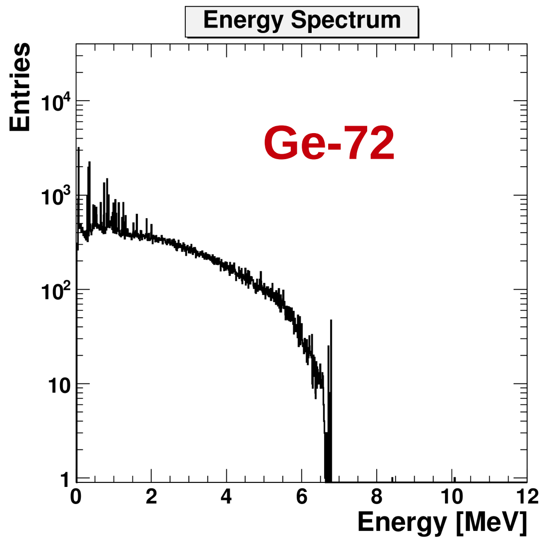
Thr @ 1 keV

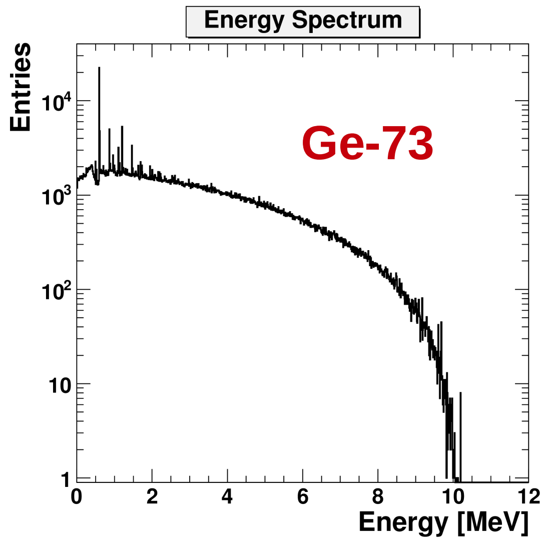


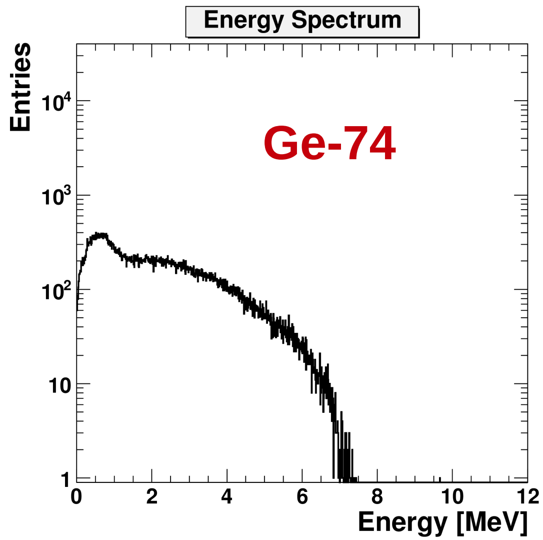
Neutrons Interaction Probability

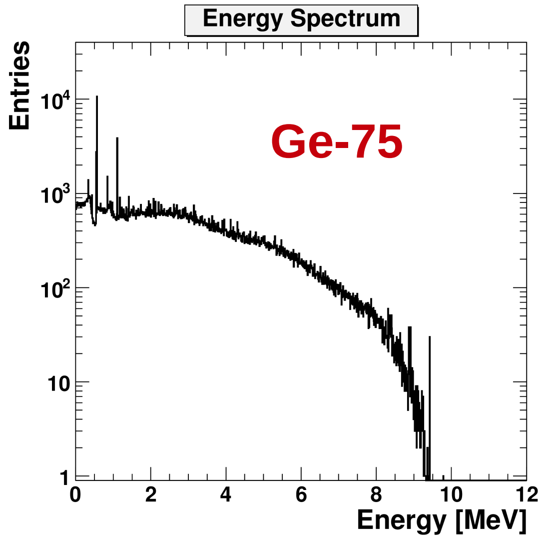


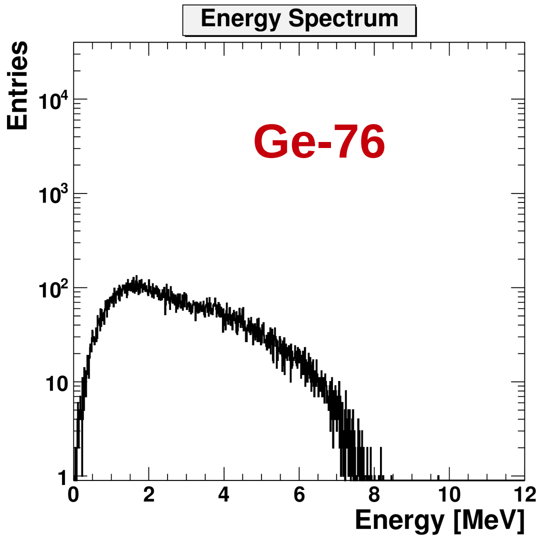
Thermal Neutrons in Ge





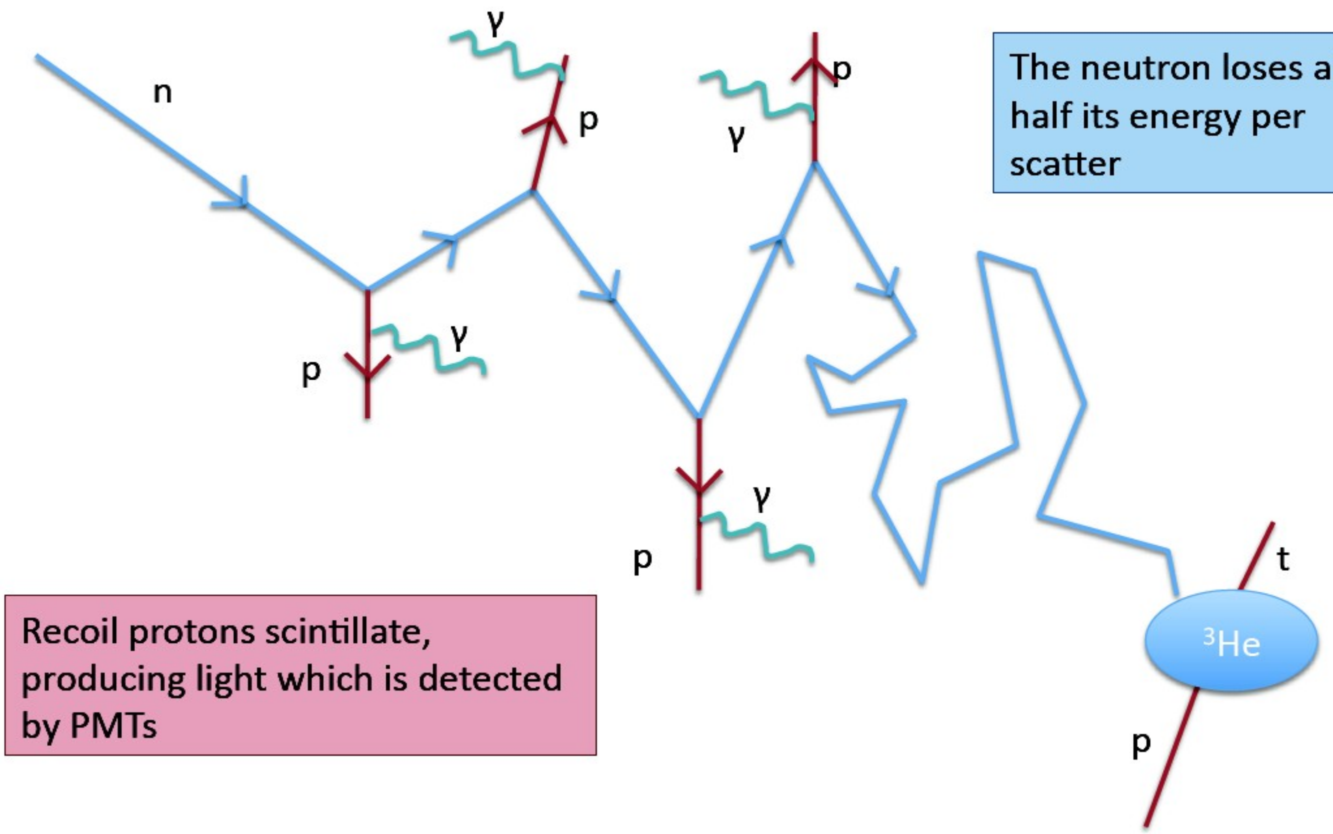






Courtesy of B. Doenmez, MPP Muenchen: 5x5x5 cm^3, E=0.024 eV, 1 million neutrons

Neutron detection principle

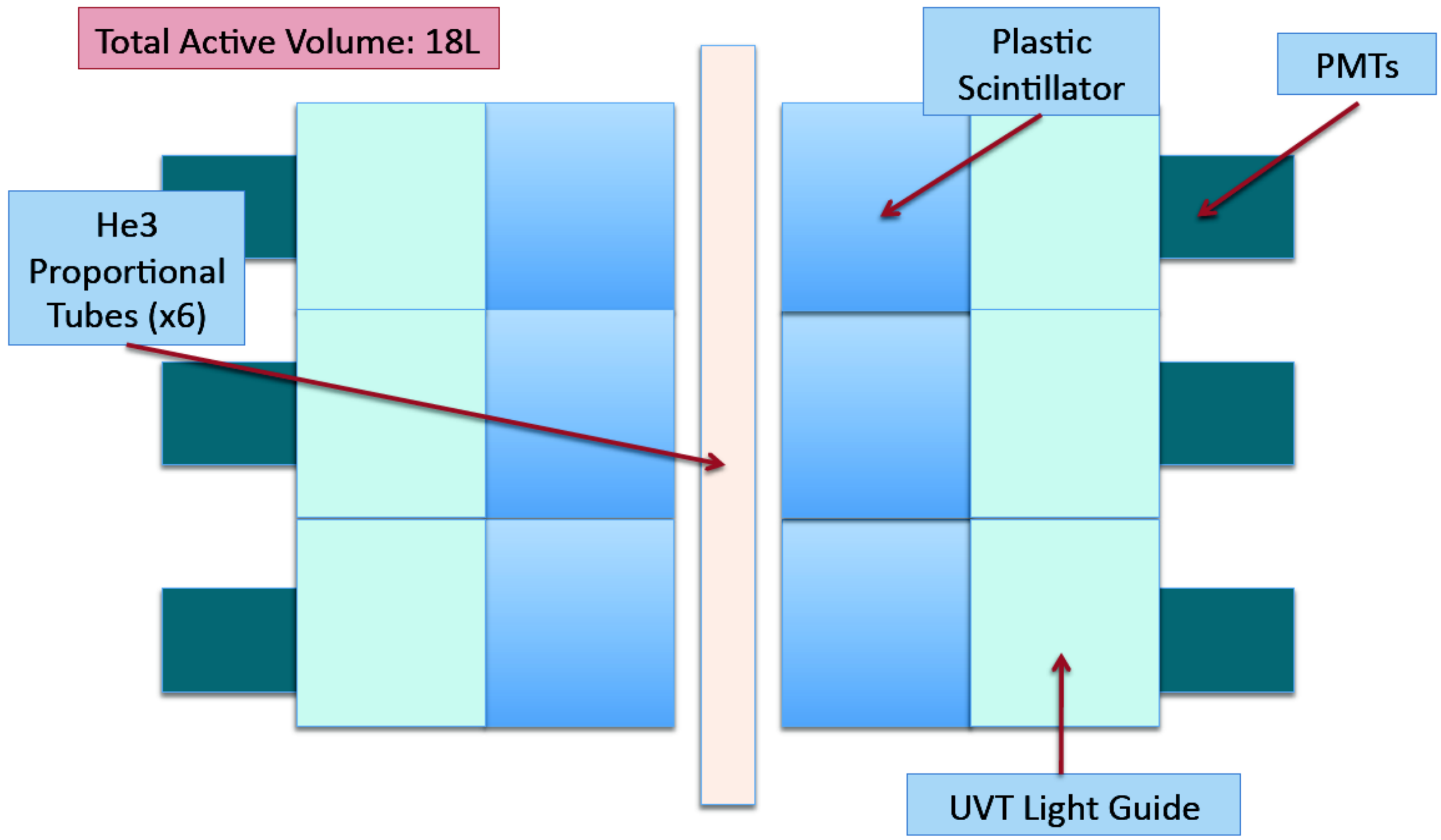


The neutron loses about half its energy per scatter

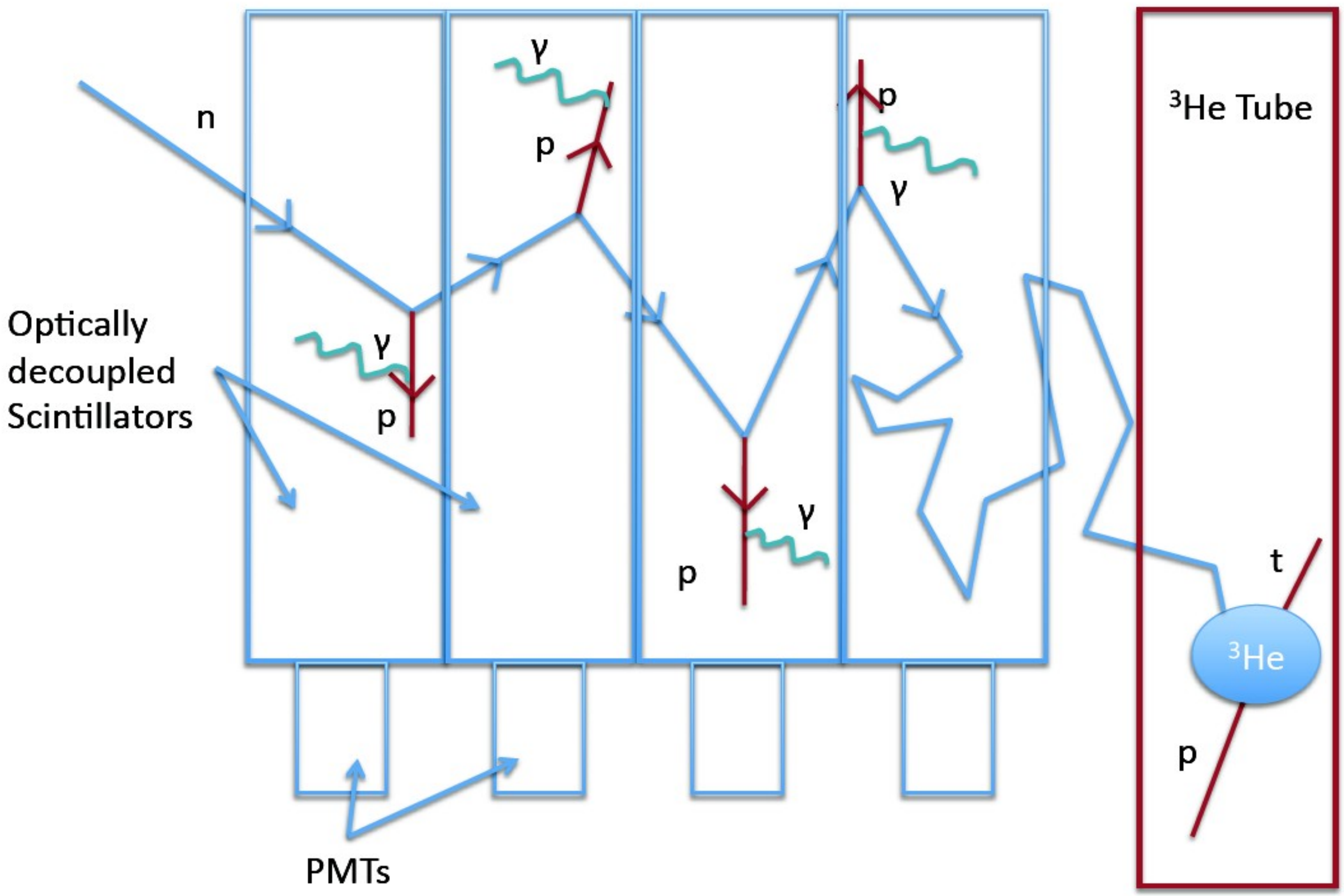
Recoil protons scintillate, producing light which is detected by PMTs

Neutron detector

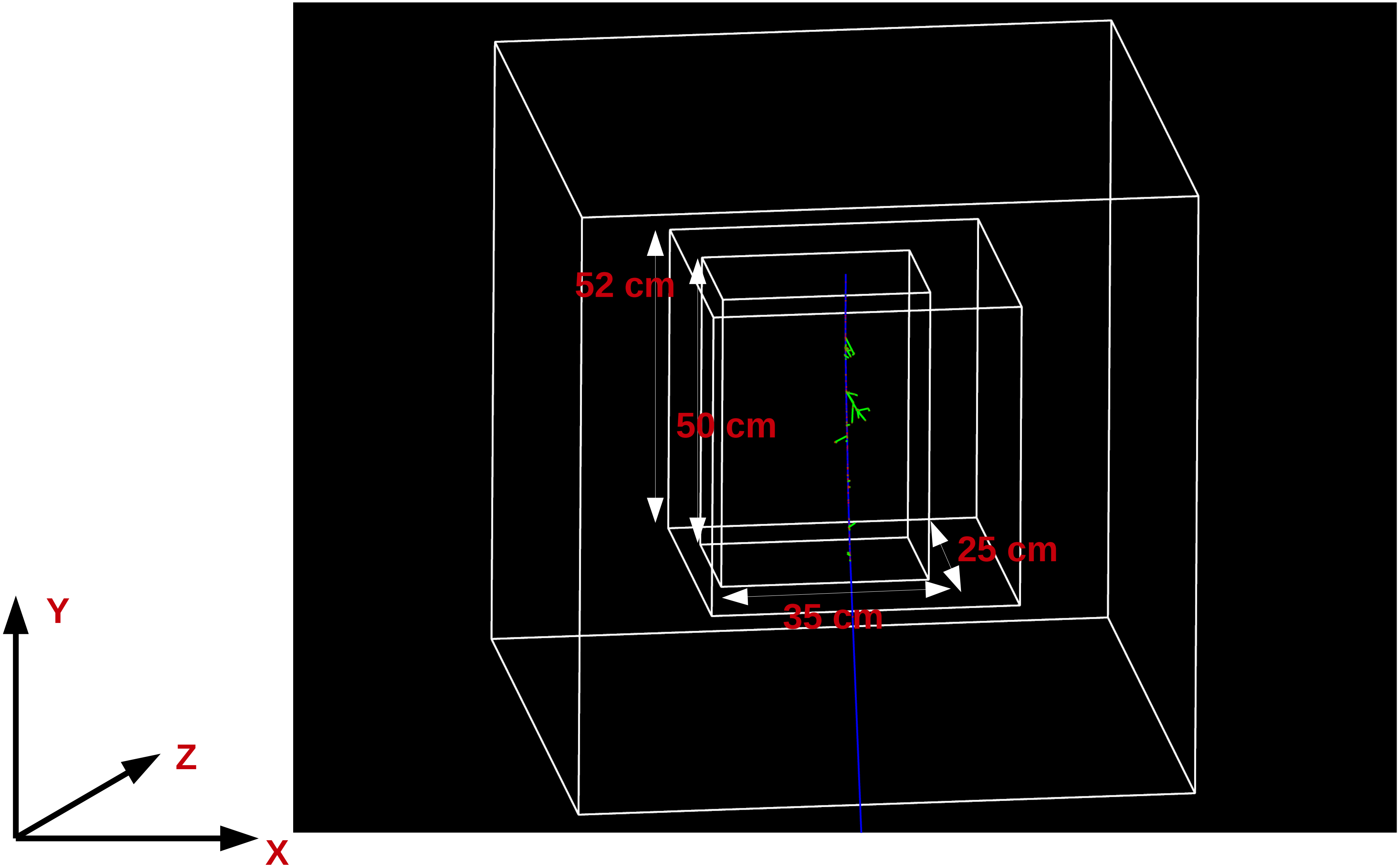
The UMD-NIST Fast Neutron Spectrometer



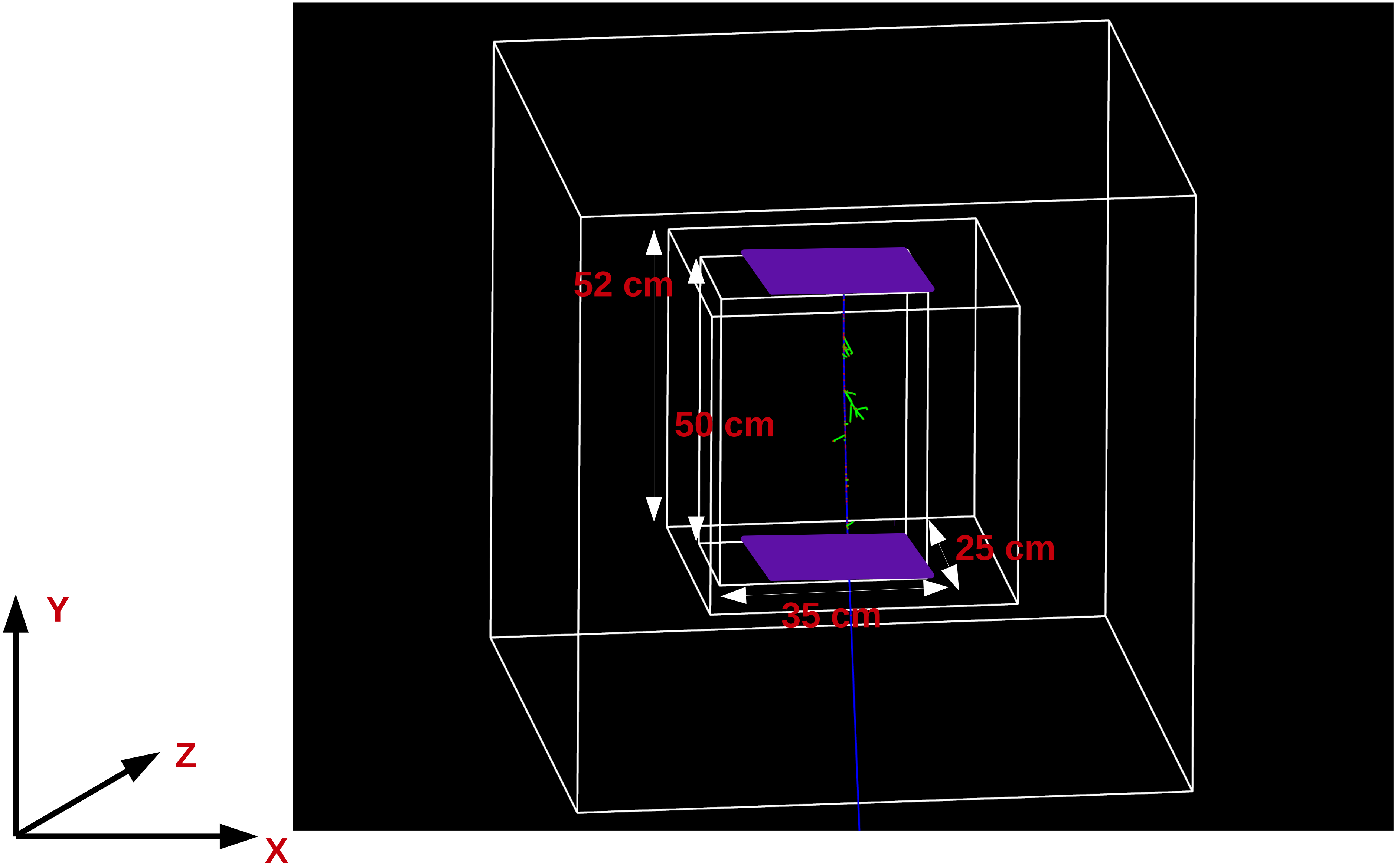
Segmentation



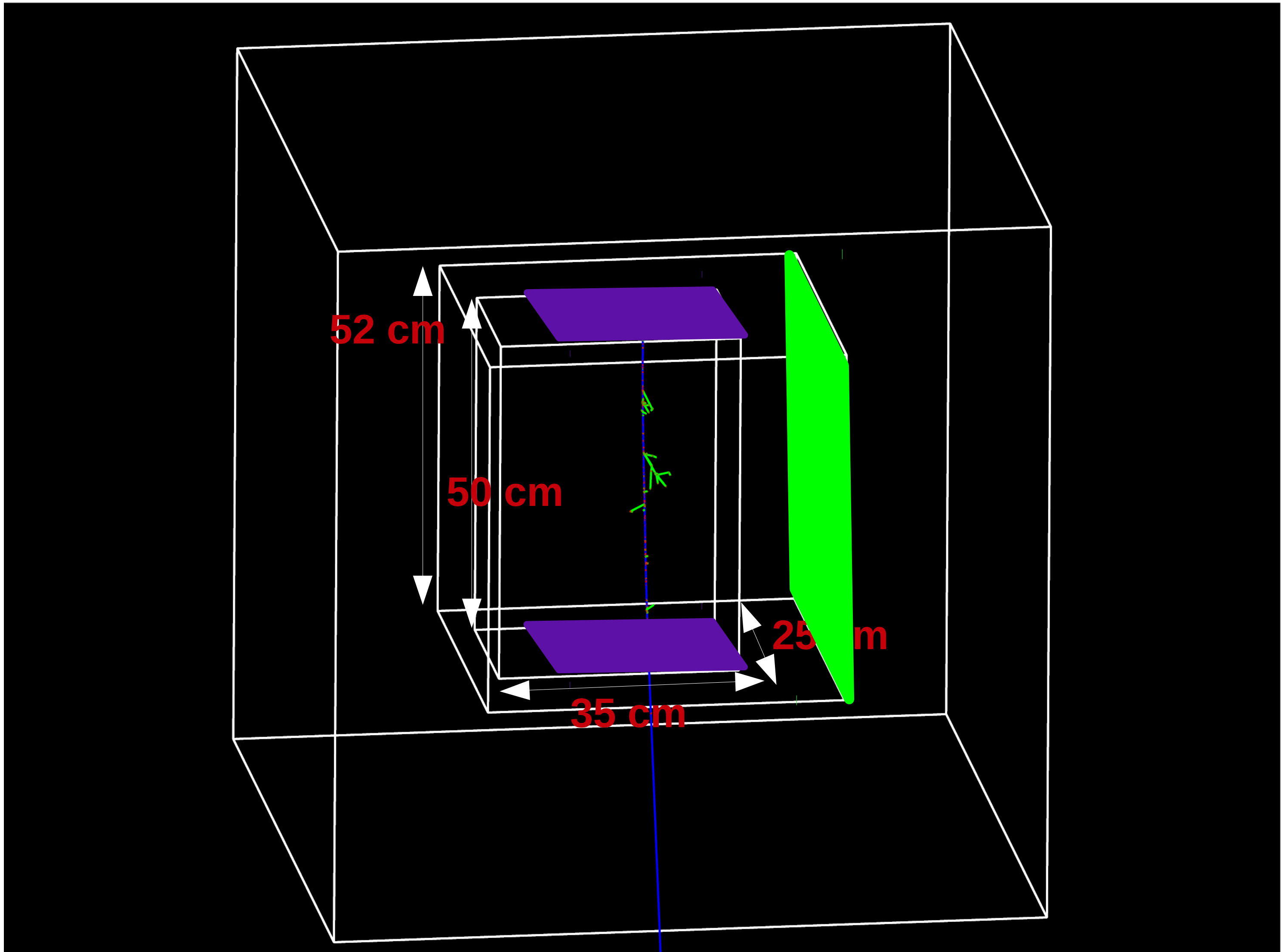
Geometry

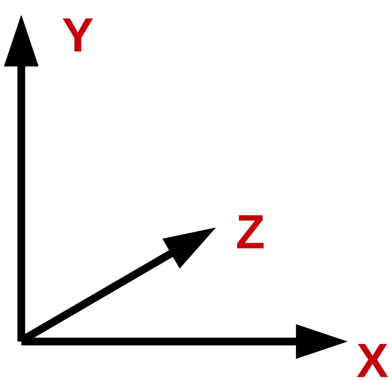


Geometry

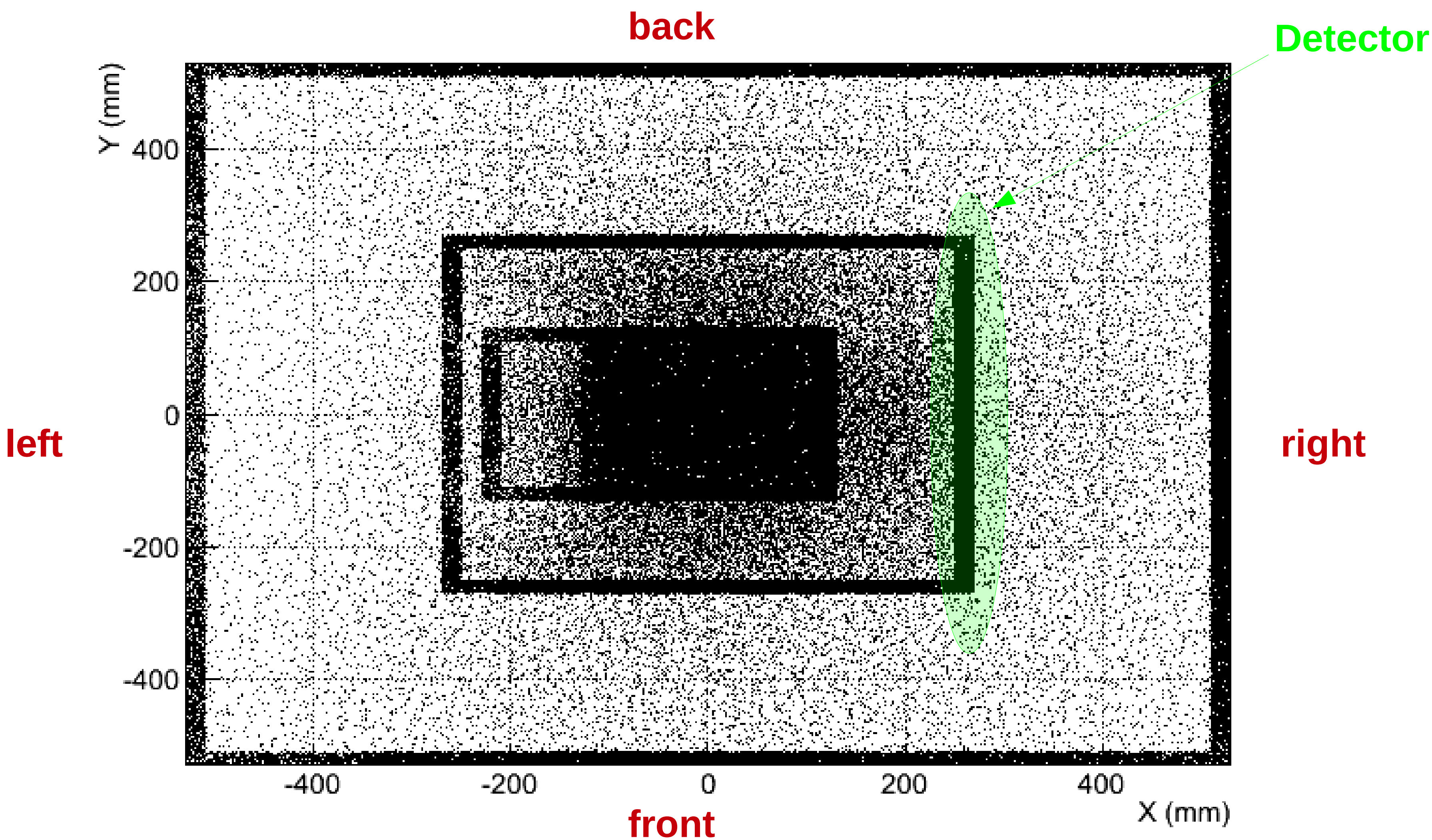


Geometry

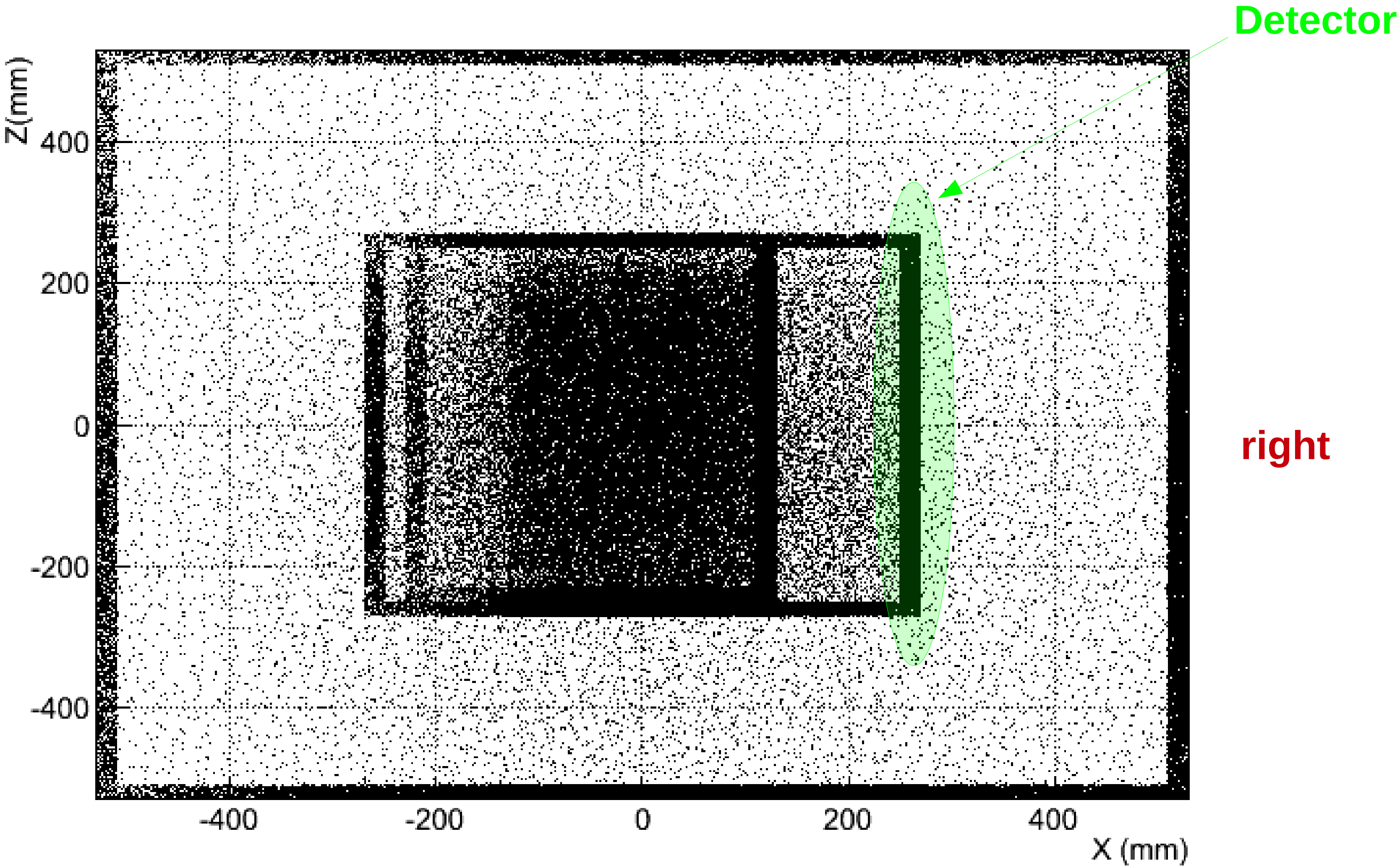




Top view


back
Detector
left
right
front
Y (mm)
400
200
0
-200
-400
-400
-200
0
200
400
X (mm)

Side view

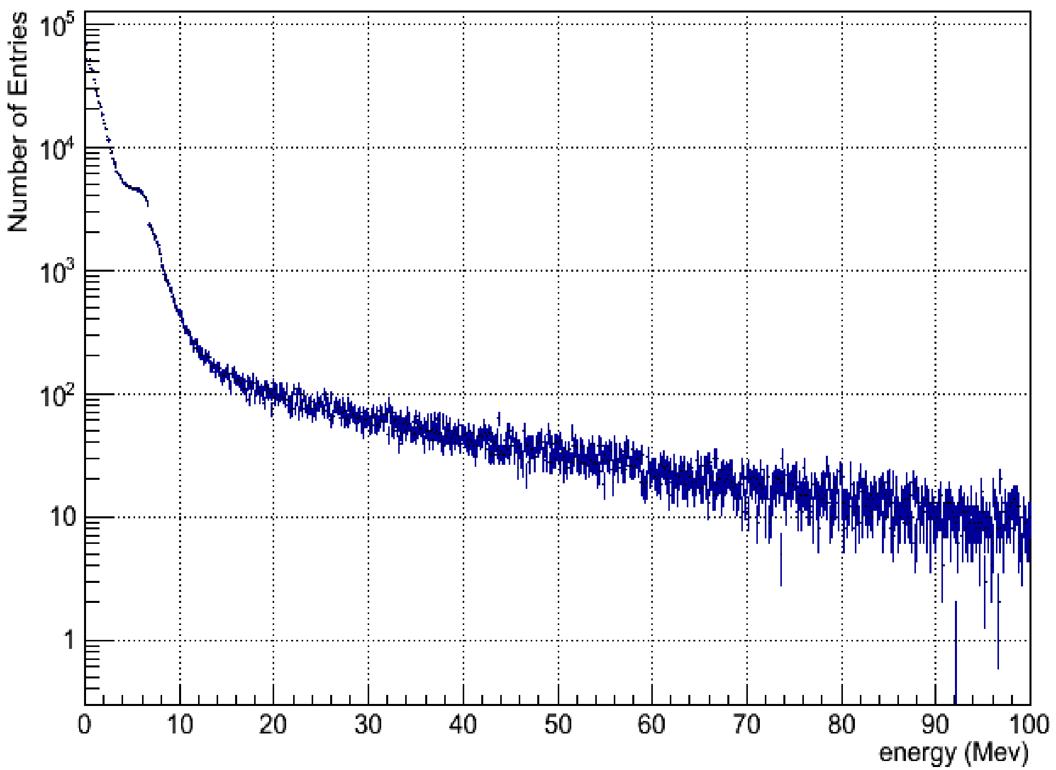


left

right

Some Results & Predictions

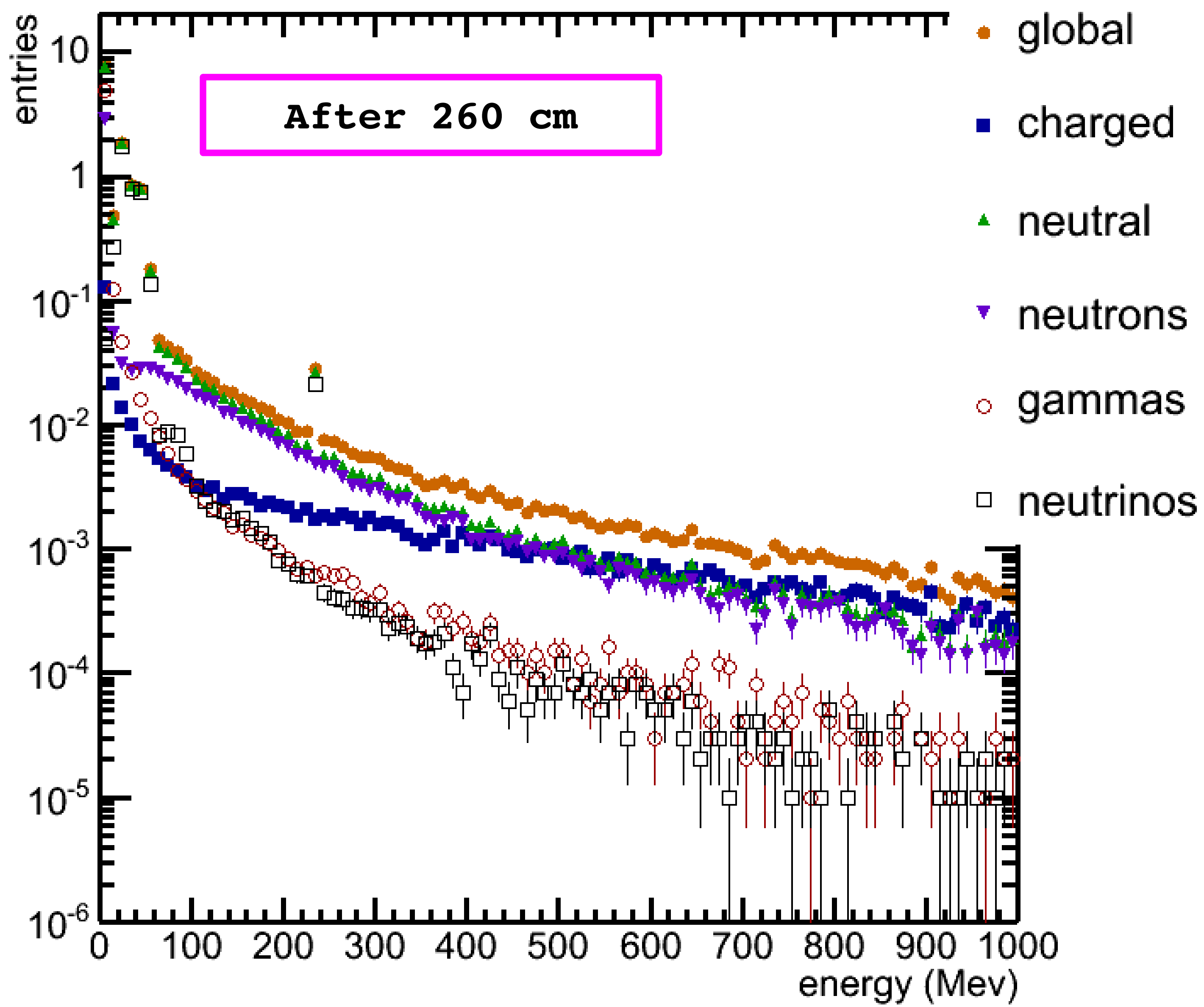
Neutron spectrum @ the detector surface



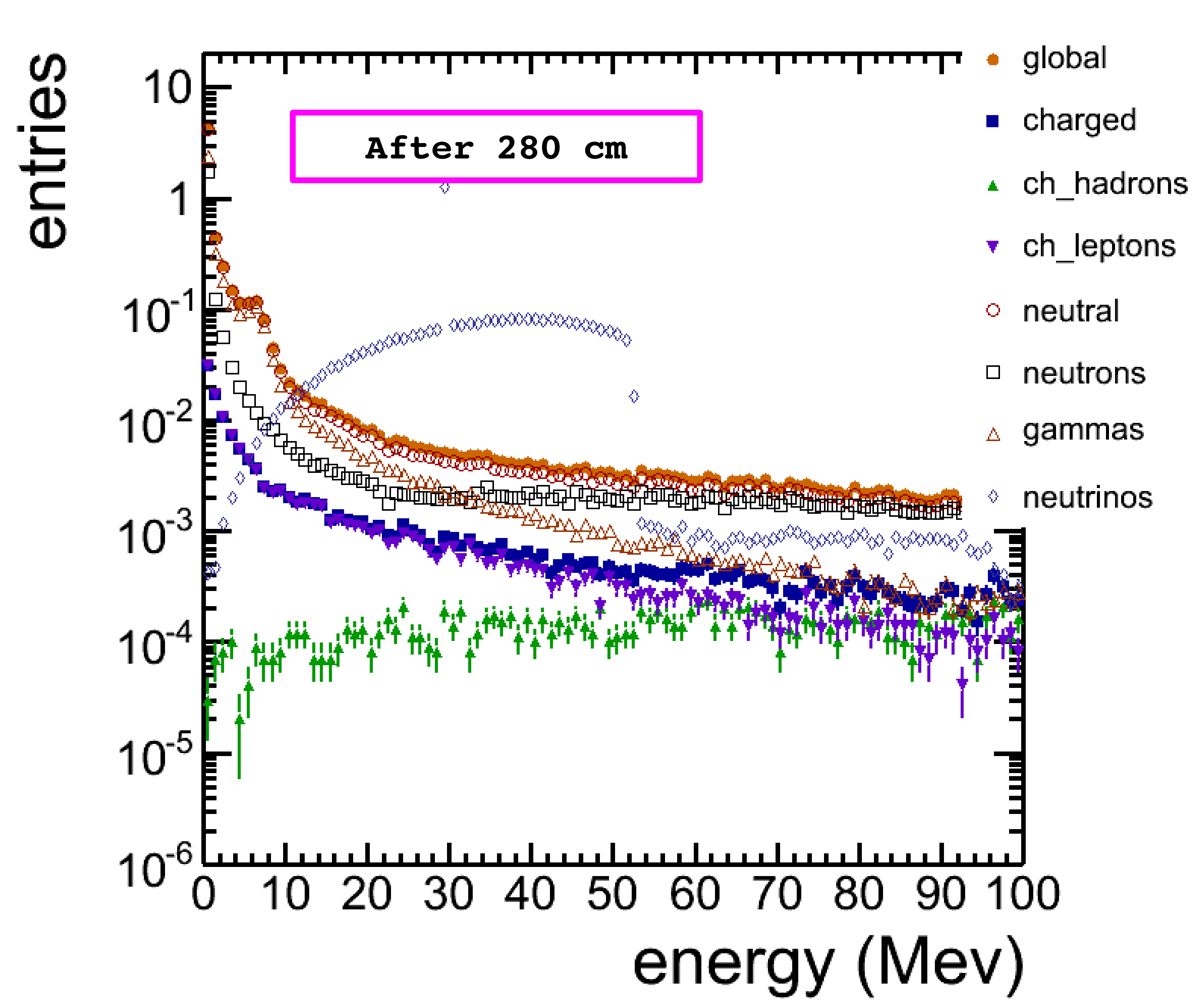
- **Generated muons ~ 10^8**
- **Neutrons at surface ~ $6x10^5$**
- **Probability to have a neutron onto the detector ~ $6.2x10^{-3}$**
- **Expected trigger rate ~ 1 Hz**
- **Detector efficiency between 0.01 – 0.1**
- **Neutrons measured after one week ~ 38 - 385**

Possible idea to enhance the rate: having a bigger trigger surface

Global Results (3)

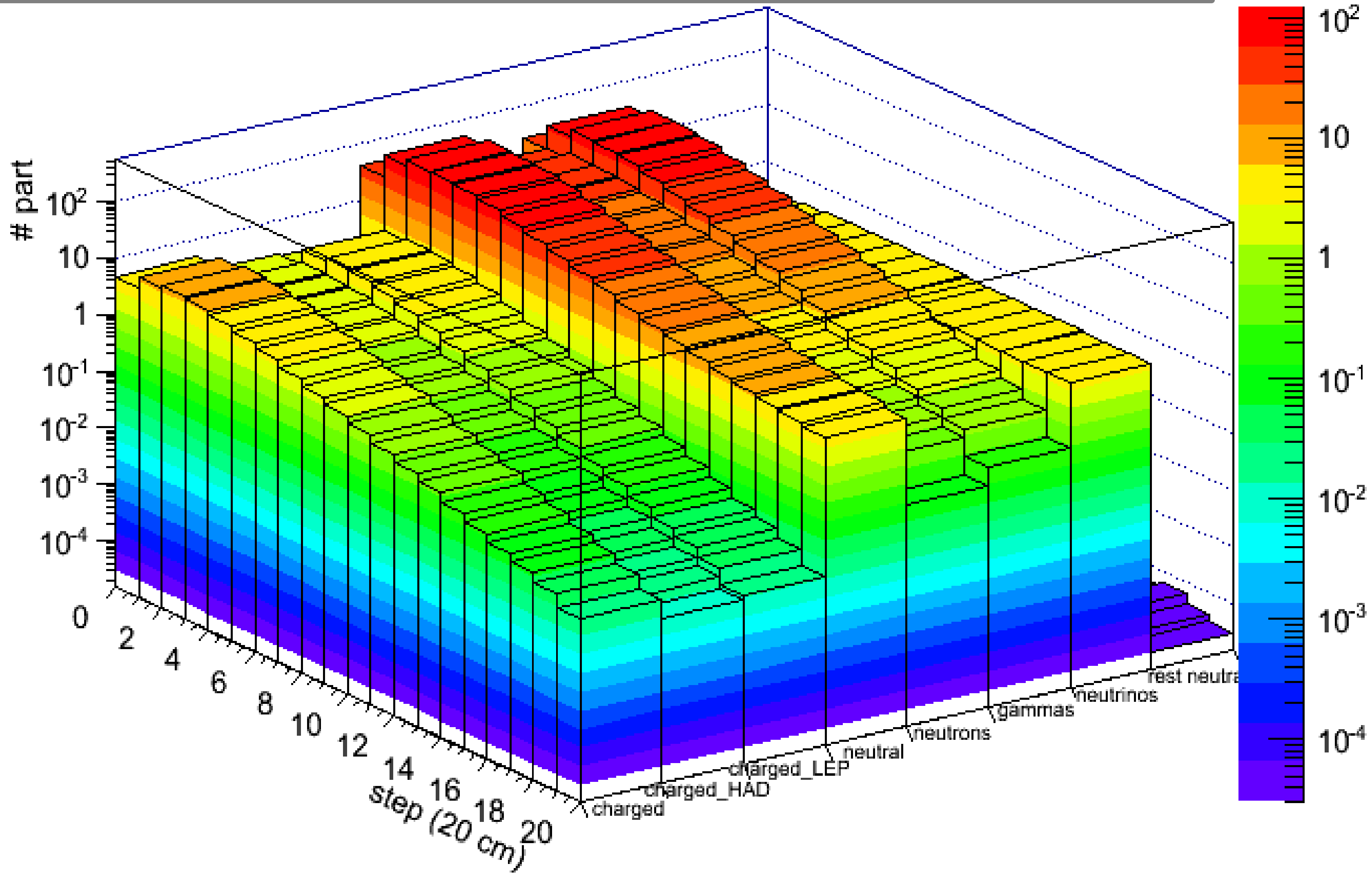


Global Results (4)



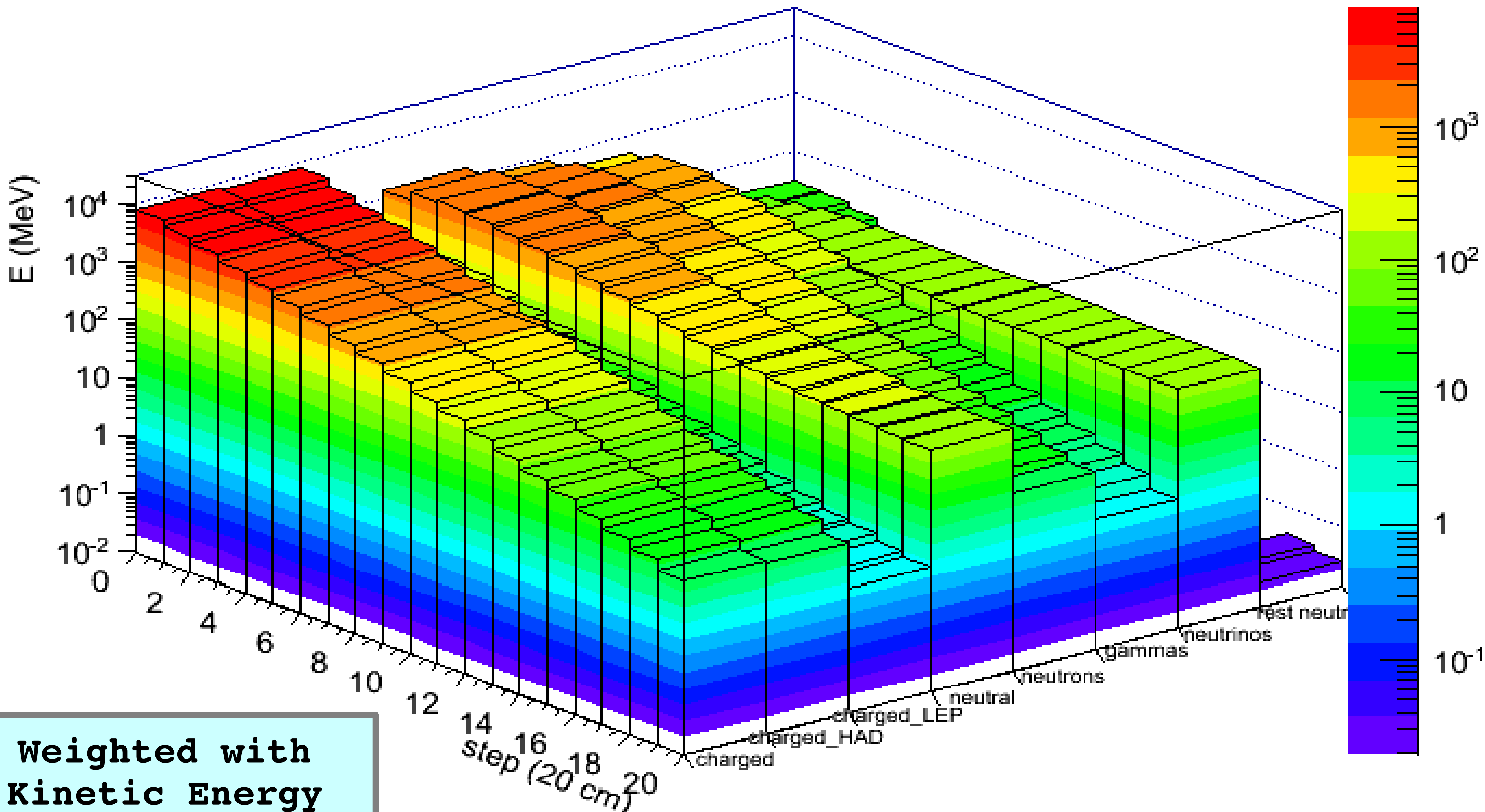
Global Results (5)

proton @ 10 GeV : particles # distribution vs step



Global Results (6)

proton @ 10 GeV : particles # distribution vs step



Weighted with Kinetic Energy