Universität
Münster

Low backgrounds for low energy rare event searches

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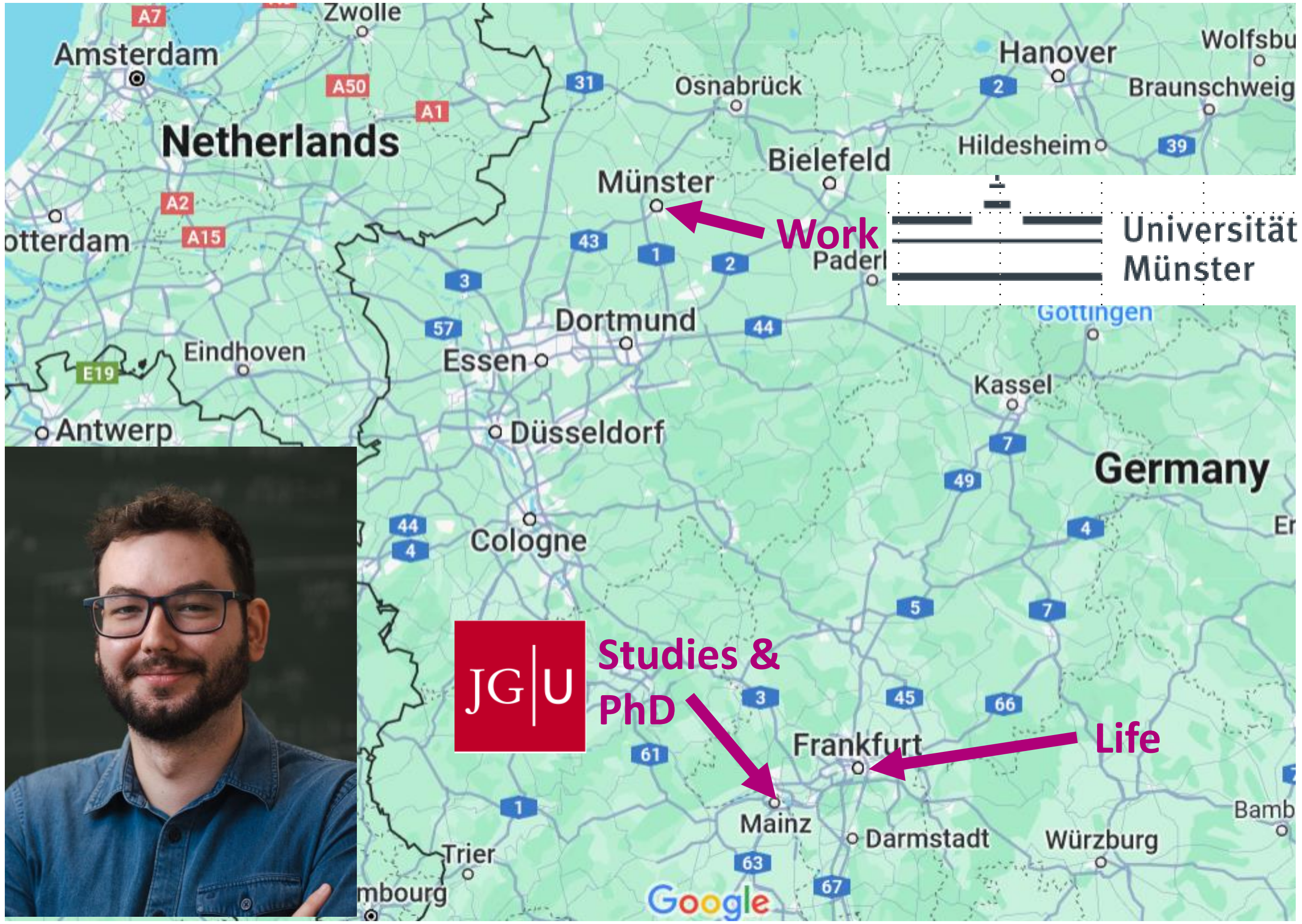
TRISEP Summer School 2024

About me:

- Studies and PhD in Mainz in group of Prof. Oberlack
  - **Working on LXe applications**
  - **XENONnT**
  - **Finished PhD October 2023**
- Currently working in Münster in group of Prof. Weinheimer
  - **LowRad project**
  - **XENONnT analysis coordinator since November 2023**



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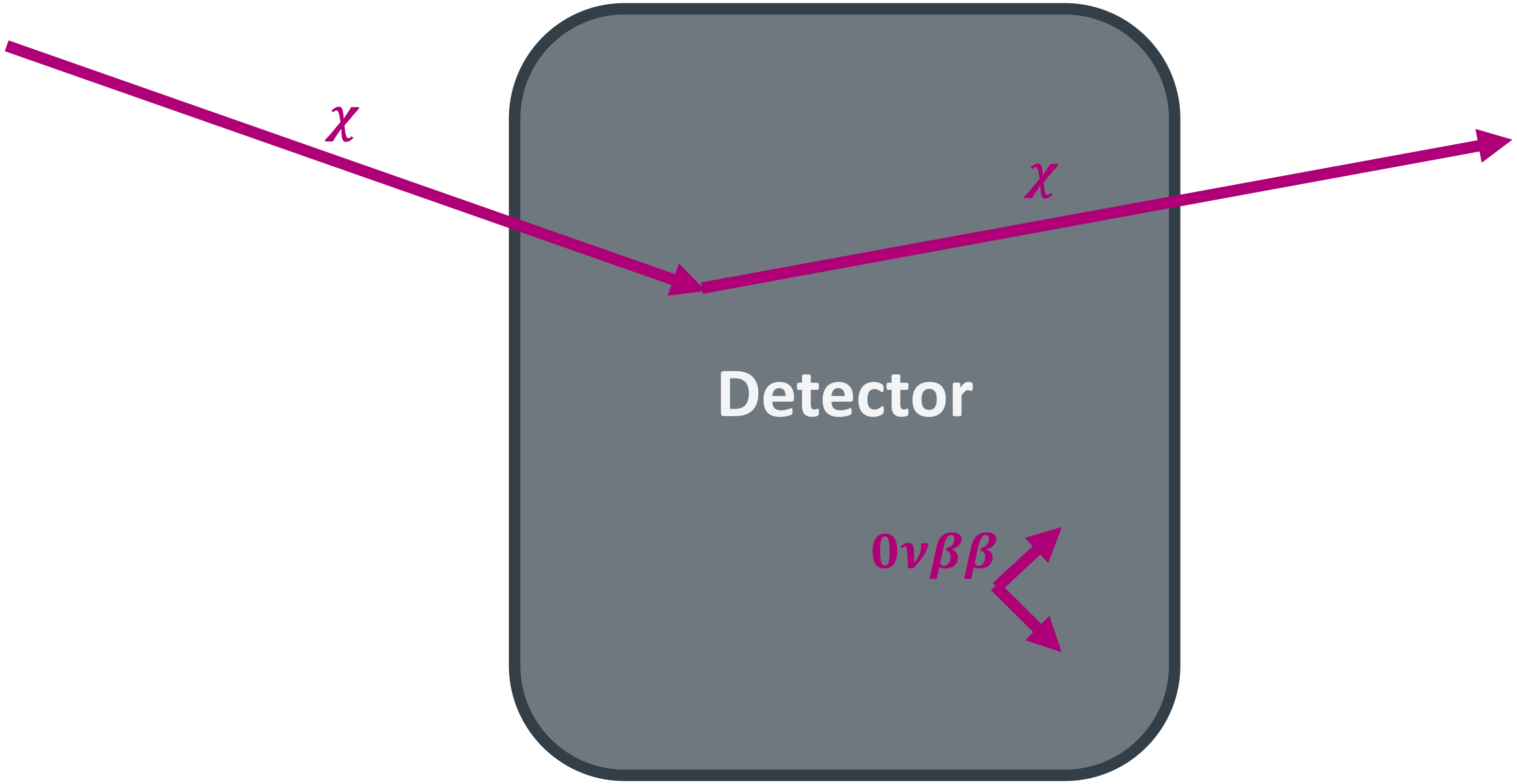
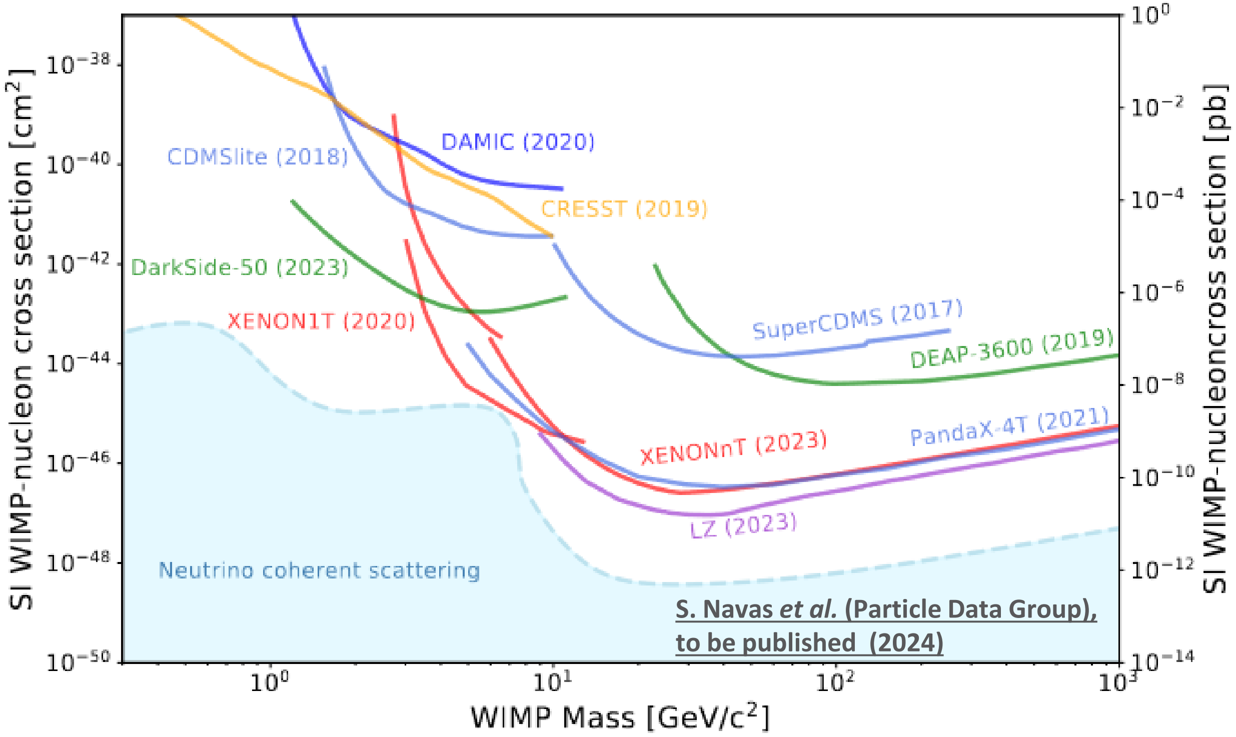


Rare event searches:

- WIMP dark matter cross section on the order of the weak scale.
  - $\boldsymbol{R_{\chi,N} \propto N_N \cdot \Phi_\chi \cdot \sigma_{\chi,N} \propto M_T}$
  - **High detector mass increases number of targets**



S. Navas *et al.* (Particle Data Group), to be published (2024)

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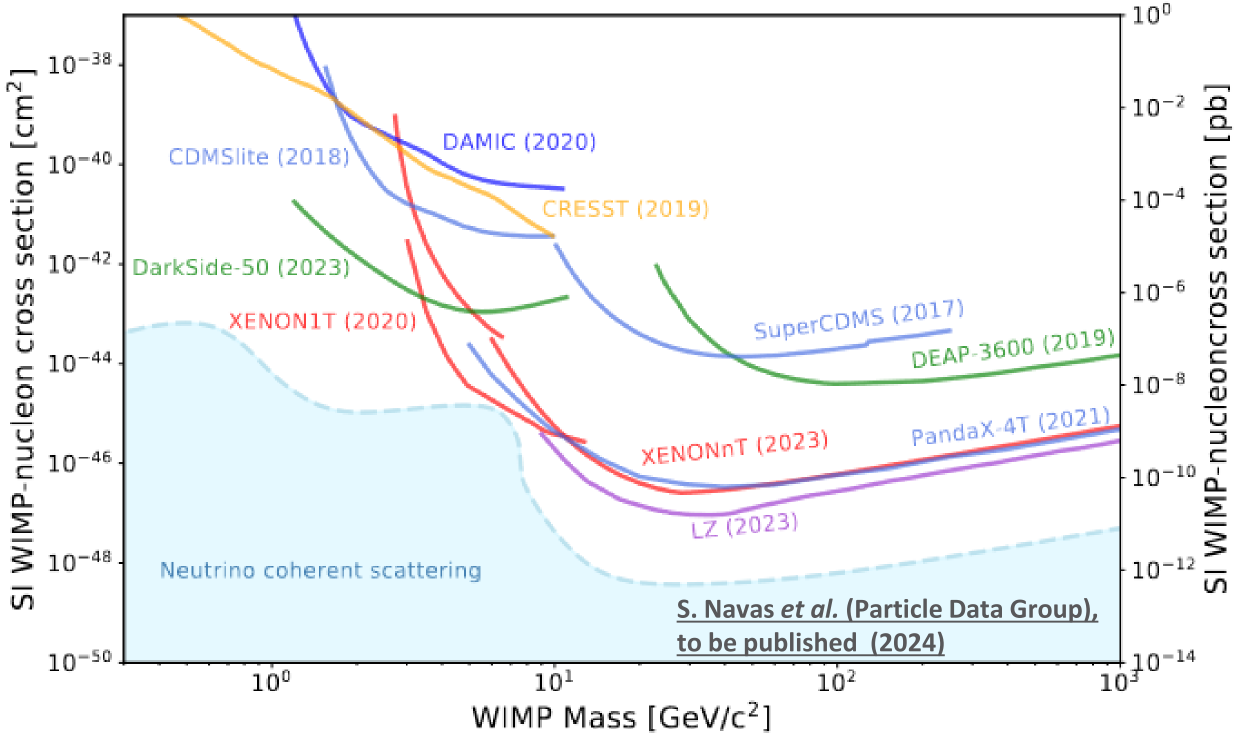
  - **High detector mass increases number of targets**
- Recoils spectrum approximately exponential
  - **Energy range from sub-keV to a few 10 keV**
  - **Assume elastic scattering of WIMP on target**
  - $E_R = \left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2 \frac{v^2}{m_N}(1-\cos(\theta))$



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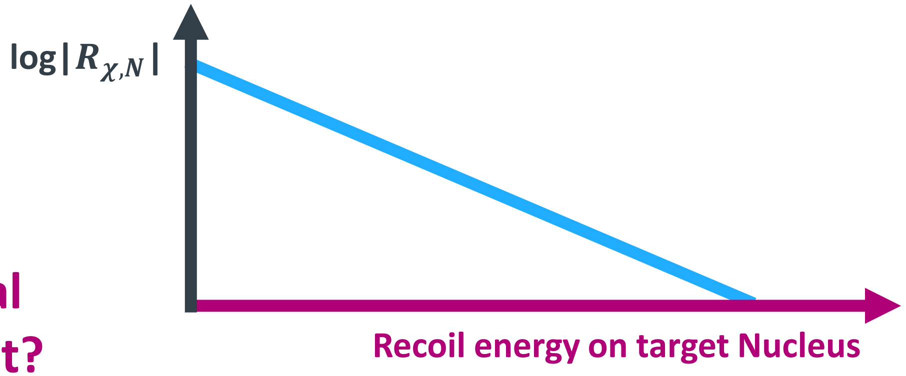
$E_{R,max} \approx 30$ keV ($m_\chi = m_N = 100$ GeV, V=220 km/s)

How many events do I expect per tonne material and year of measurement?



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- Expected number of events: $\sim 20 \frac{1}{\text{tonne x year}}$

($\sigma \sim 10^{-46}$ cm^2, $m_\chi = 100$ GeV, in LXe, using the wimprates package, no efficiencies)

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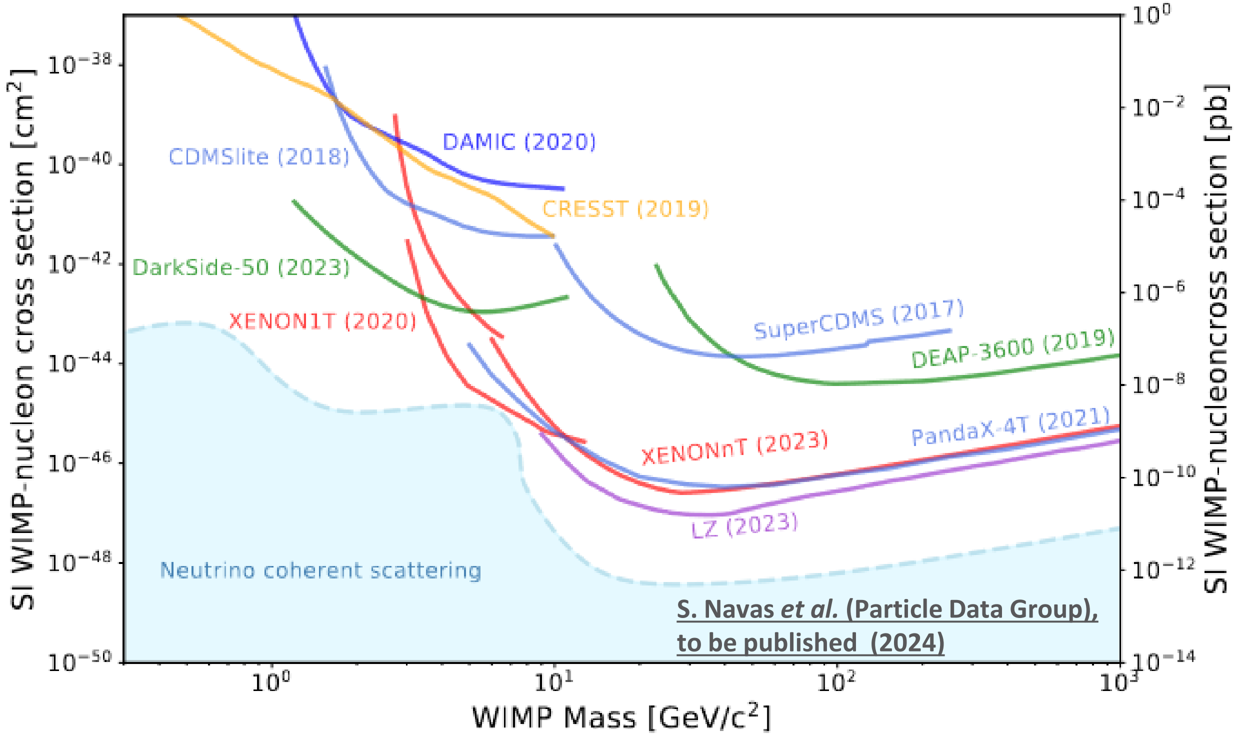

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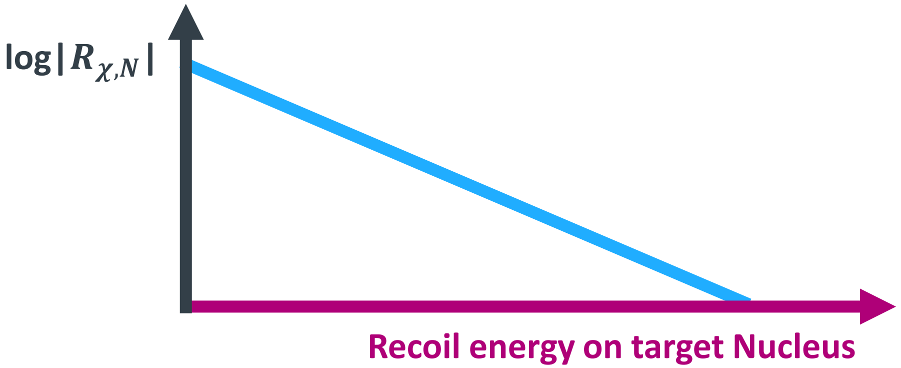
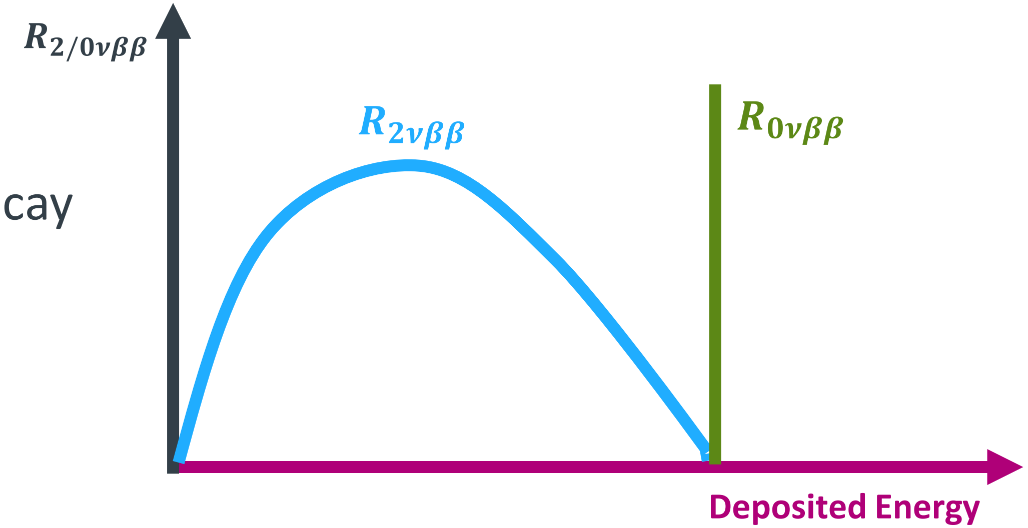


Rare event searches:

- Neutrinoless double beta decay leads to a mono-energetic line at the end of a continues spectrum
- Depending on the used isotope the energy of the $0\nu\beta\beta$ decay is expected to be on the order of 2000 keV
  - **Energy threshold can be higher, but resolution is important!**



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- Upper limits exists for different isotopes measured by different experiments.
  - **Let us assume $T_{1/2}^{0\nu\beta\beta} \geq 10^{26}$ years**
  - **Given 1 tonne of e.g. ^{136}Xe:**

$$R^{0\nu\beta\beta} \propto \frac{m_{Xe136}}{M_{Xe136} \cdot T_{1/2}^{0\nu\beta\beta}} \approx$$

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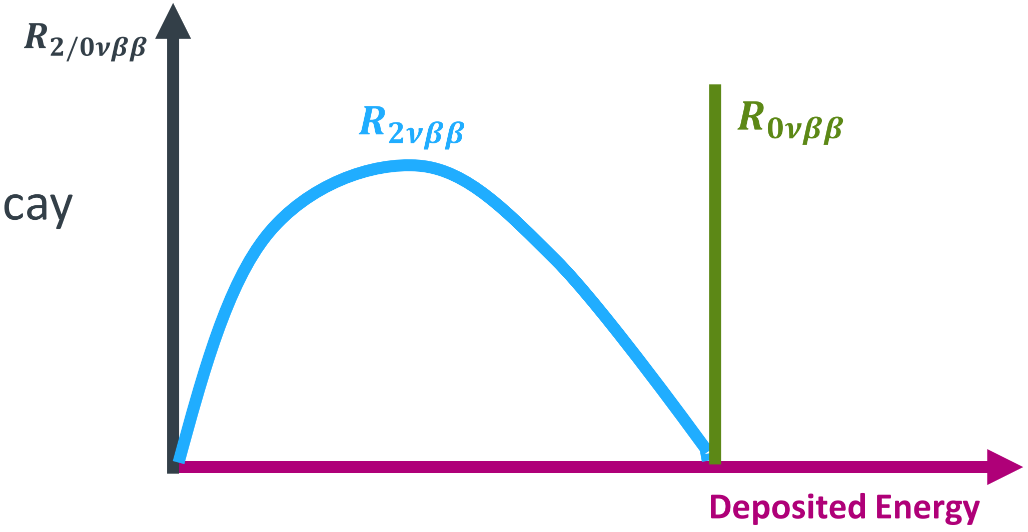

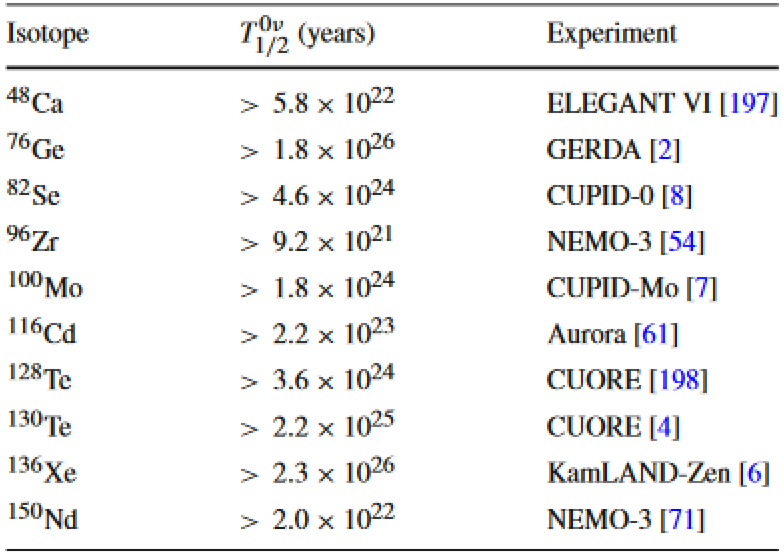

Isotope	$T^{0\nu}_{1/2}$ (years)	Experiment
^{48}Ca	$> 5.8 \times 10^{22}$	ELEGANT VI [197]
^{76}Ge	$> 1.8 \times 10^{26}$	GERDA [2]
^{82}Se	$> 4.6 \times 10^{24}$	CUPID-0 [8]
^{96}Zr	$> 9.2 \times 10^{21}$	NEMO-3 [54]
^{100}Mo	$> 1.8 \times 10^{24}$	CUPID-Mo [7]
^{116}Cd	$> 2.2 \times 10^{23}$	Aurora [61]
^{128}Te	$> 3.6 \times 10^{24}$	CUORE [198]
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Juan José Gómez-Cadenas et al,
10.1007/s40766-023-00049-2

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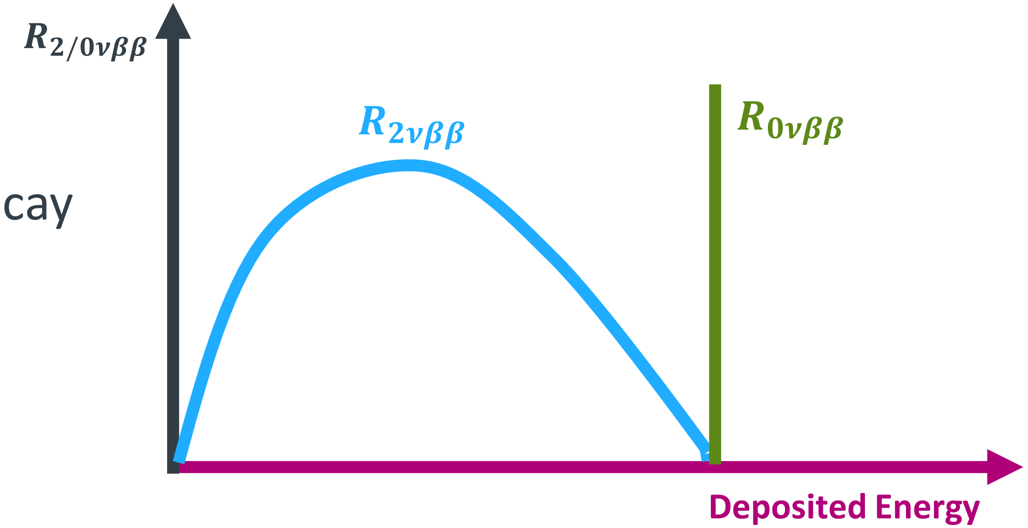
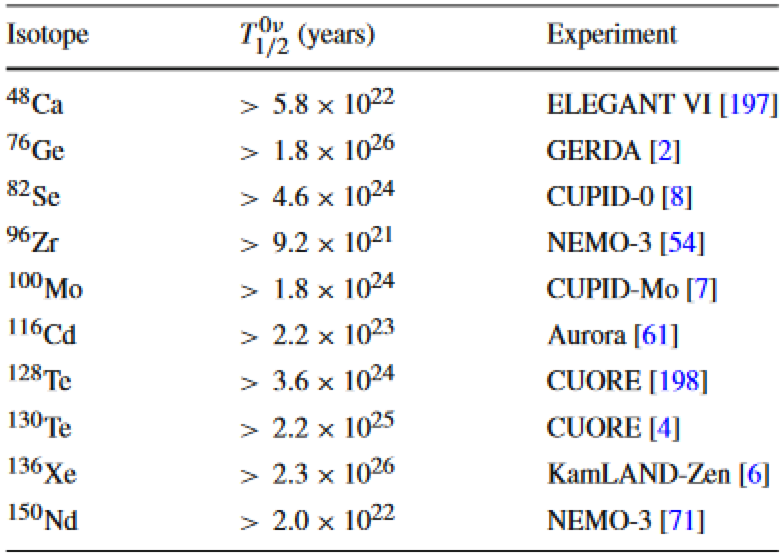
$$R^{0\nu\beta\beta} \propto \frac{m_{Xe136}}{M_{Xe136}\cdot T_{1/2}^{0\nu\beta\beta}} \approx 20\,\frac{1}{\text{tonne x year}}$$

($^{nat.}$Xe only contains 8.9 % of ^{136}Xe)





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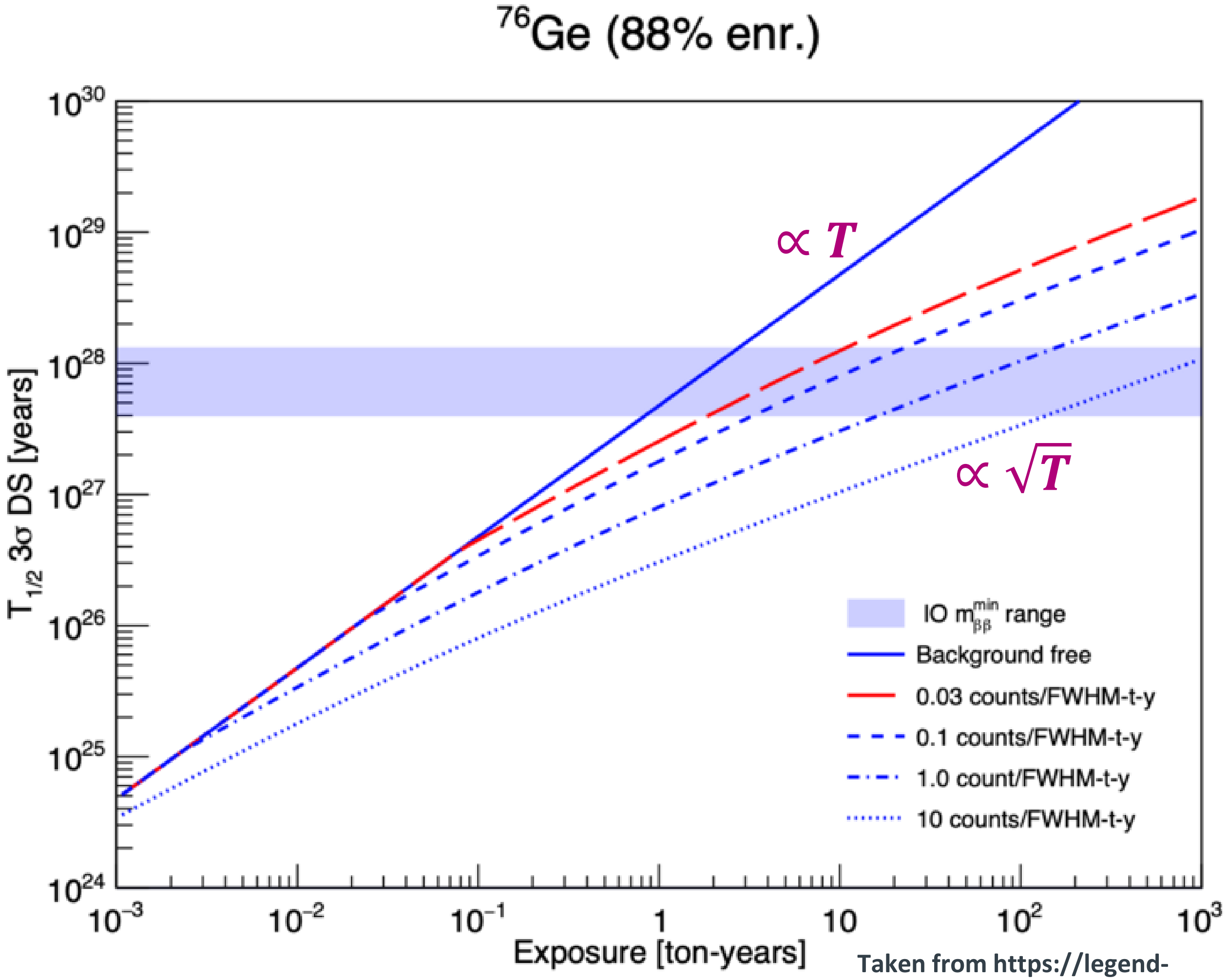
Rare event searches:

- "Extreme counting experiments"
    - **Independent of DM search or $0\nu\beta\beta$ search, looking for signal over background**
    - **Excluded signal rate R ∝ $\sigma_{WIMP}, \text{or} \frac{1}{T_{\frac{1}{2}}}$**

Rare event searches:

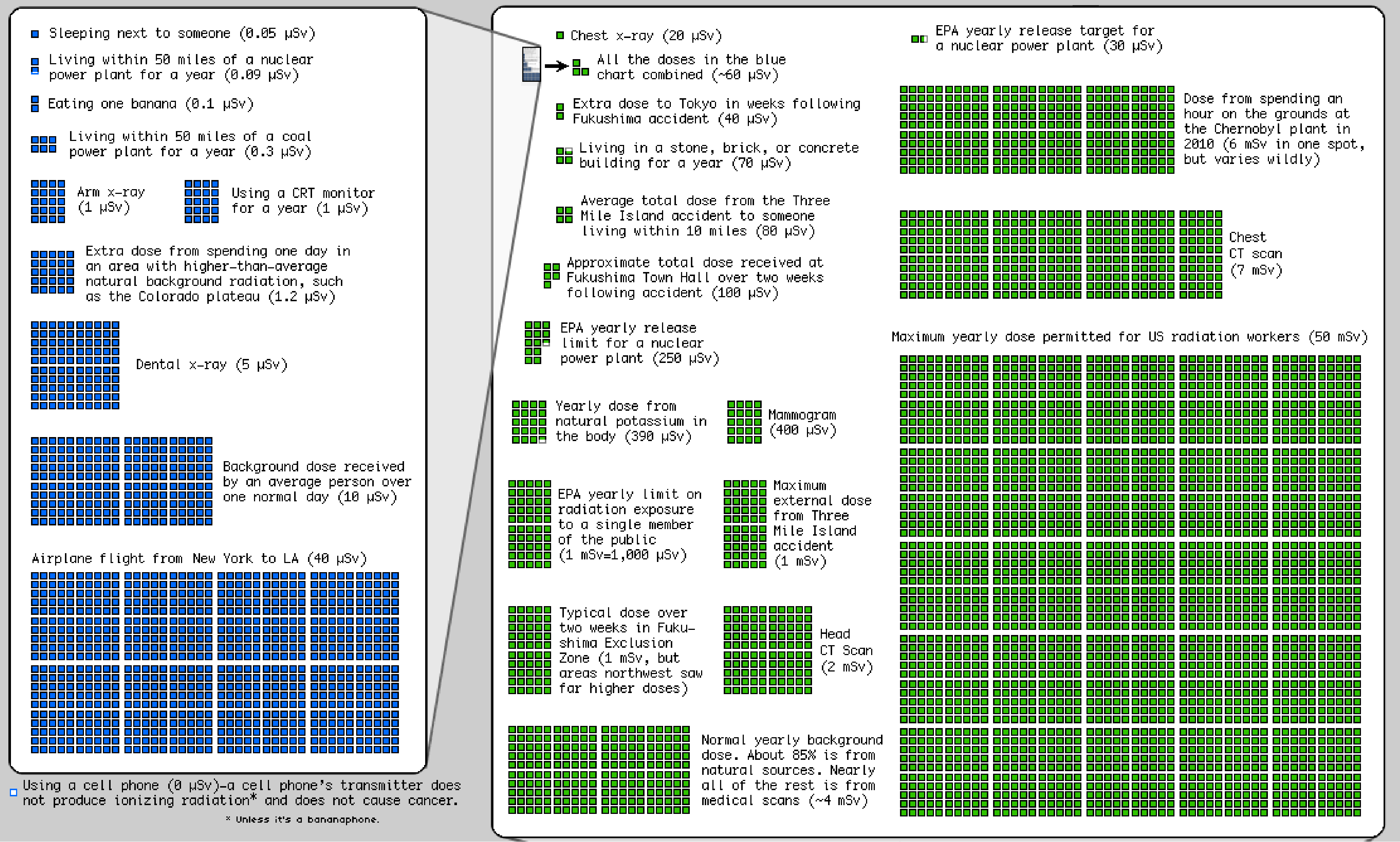
- “Extreme counting experiments”
  - **Independent of DM search or $0\nu\beta\beta$ search, looking for signal over background**
  - **Excluded signal rate R $\propto \sigma_{WIMP}$, or $\frac{1}{T_{\frac{1}{2}}}$**
  - **Background free experiment scales with exposure *T (mass x time)***
  - **Background dominated scales with $\sqrt{T}$**
  - **Scaling can be understood intuitively from Poisson statistics:**

$$\Rightarrow \propto \frac{\sqrt{N_{Bkg.}}}{N_{Bkg.}} \propto \frac{\sqrt{R_{Bkg.}\cdot T}}{R_{Bkg.}\cdot T} \propto \frac{1}{\sqrt{T}}$$



Taken from https://legend-exp.org/science/neutrinoless-bb-decay/discovery-potential

The problem: We live in a radioactive world:



https://en.m.wikipedia.org/wiki/File:Radiation_Dose_Chart_by_Xkcd.png

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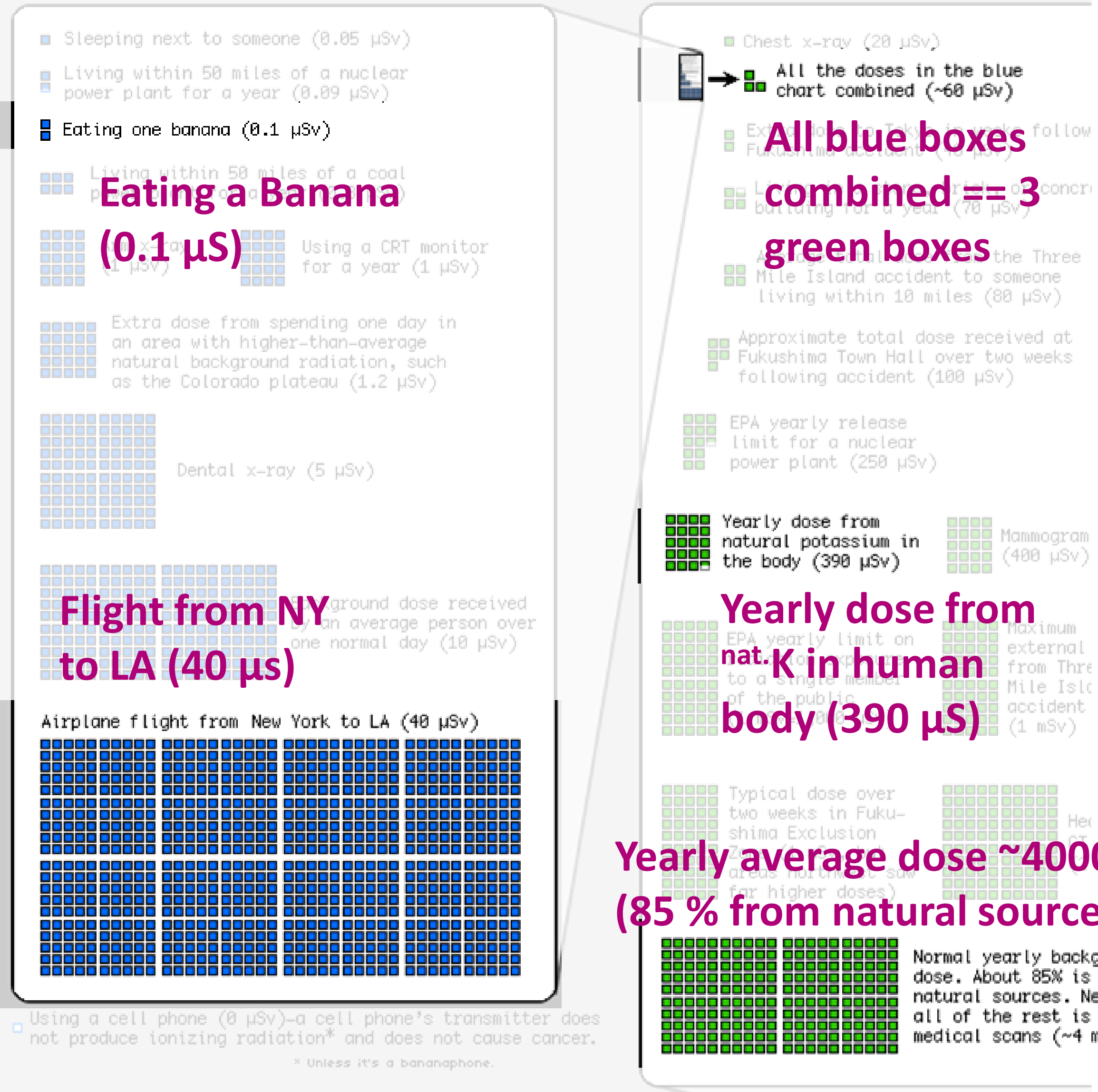

Eating a Banana (0.1 µS)

Flight from NY to LA (40 µs)

All blue boxes combined == 3 green boxes

Yearly dose from $^{nat.}$K in human body (390 µS)

Yearly average dose ~4000 µS (85 % from natural sources)

- Two main problems:
  - Cosmic radiation
  - Natural abundant isotopes

How many ^{40}K decays per tonne humans per year do you expect?

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Eating a Banana (0.1 µS)

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Yearly average dose ~4000 µS (85 % from natural sources)

- Two main problems:
  - Cosmic radiation
  - Natural abundant isotopes
  - ^{40}K decay in a human body:

$$\sim 4000\ \mathrm{Bq}\ \sim 10^{12}\ \frac{1}{\text{human tonne x year}}$$

(1 tonne humans ~ 15 people)

  - Reminder expected signal rates

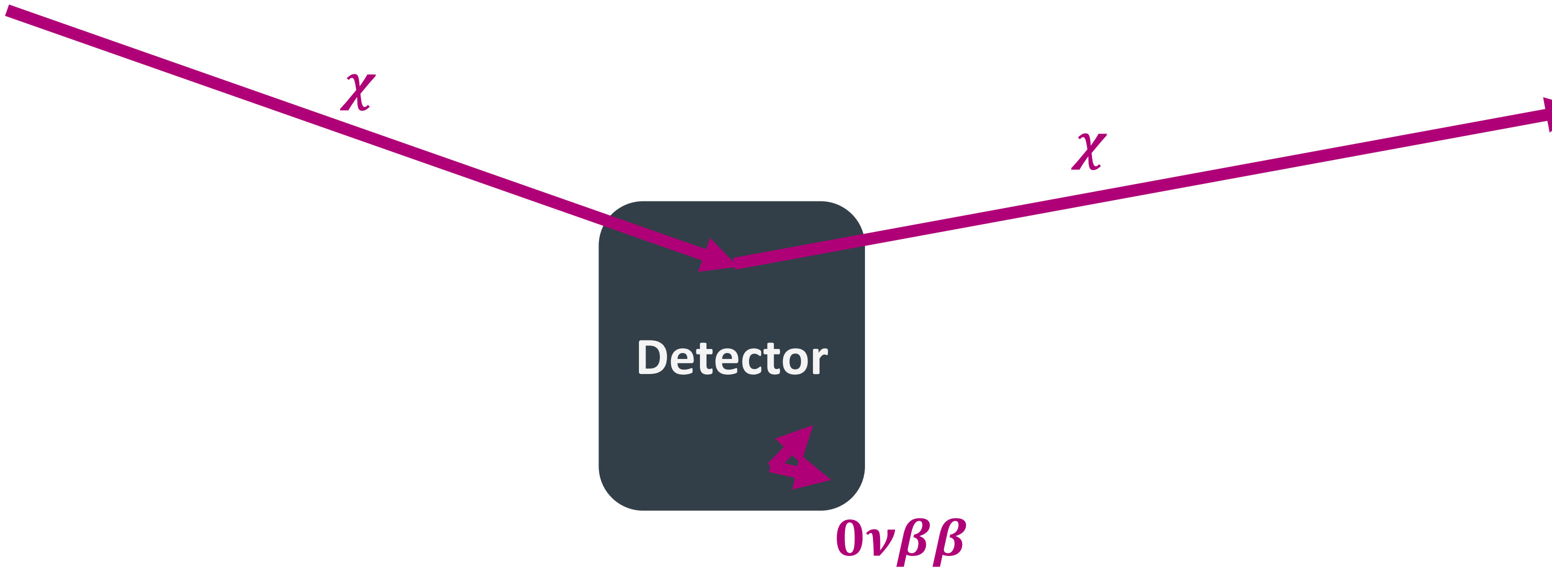
$$\sim 20\ \frac{1}{\text{tonne x year}}$$

We must reduce and characterize our backgrounds!

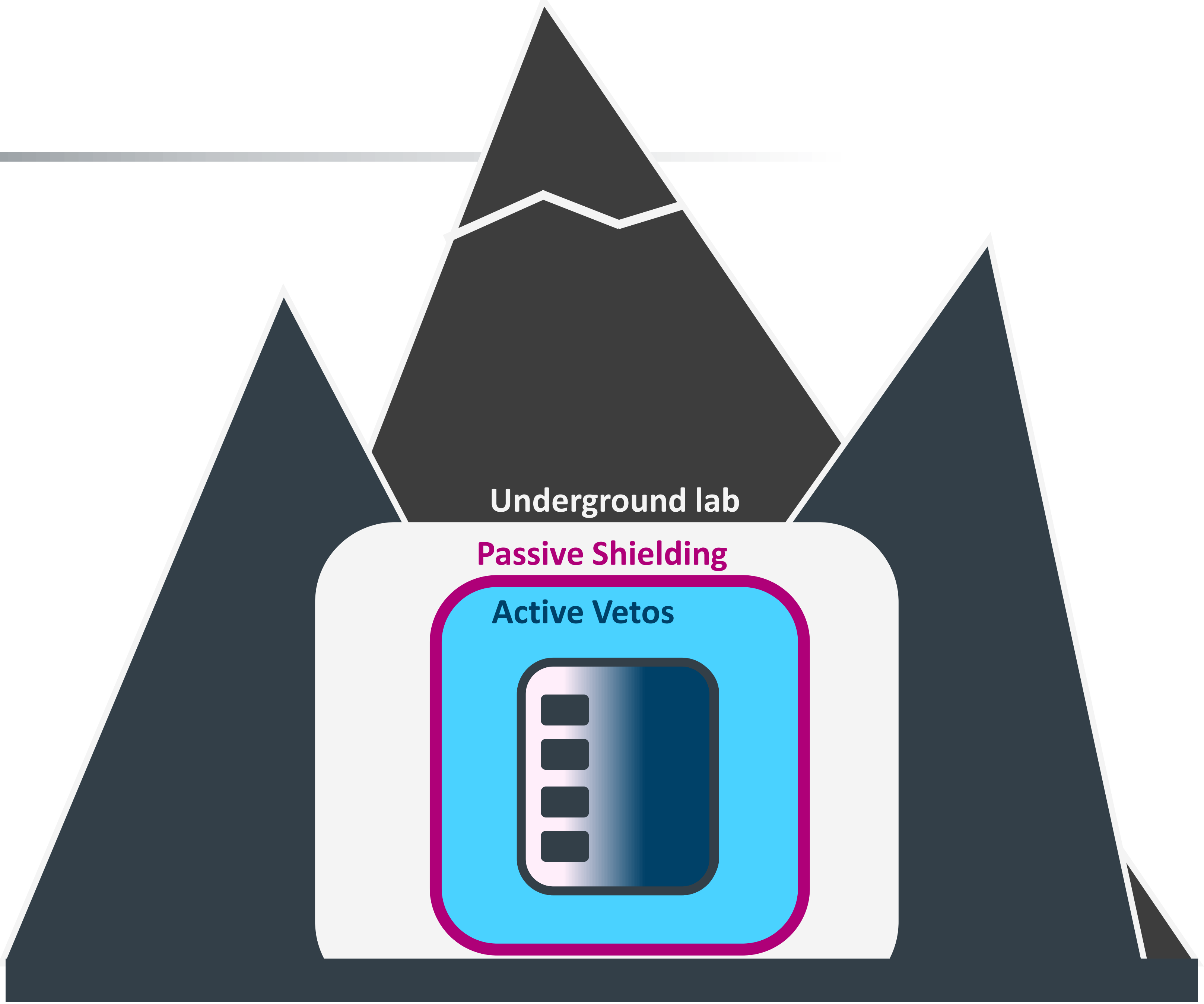
Recap: Low energy rare event searches

- Sensitivity of background free experiments scale with exposure T
- Background dominated experiments with $\sqrt{T}$
- Search for the needle in the haystack
  - **Current experiment expect rates of $\sim 20 \frac{1}{\text{tonne x year}}$**
  - **Problem, we live in a radioactive world:**

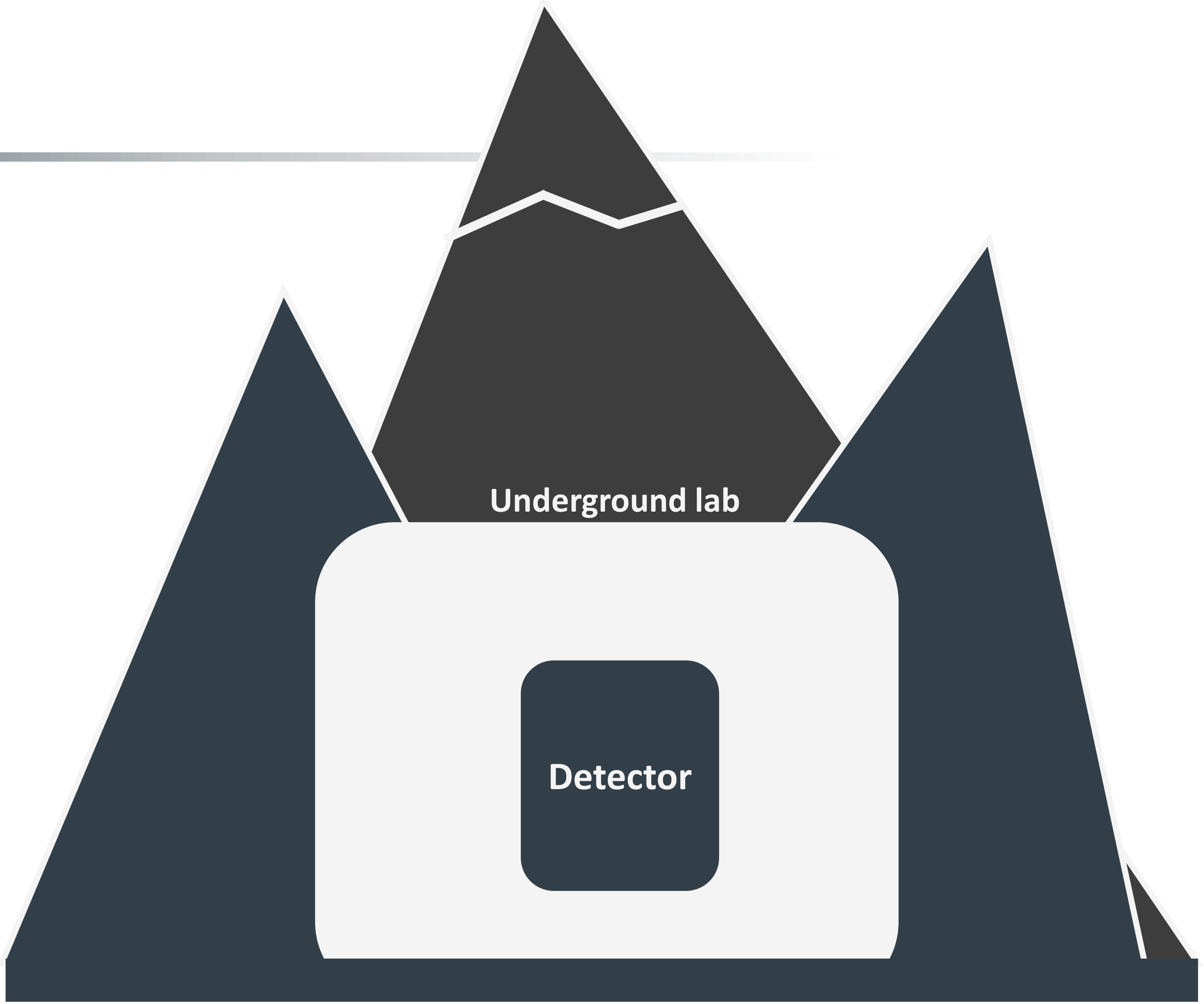
$$\sim 10^{12} \frac{1}{\text{human tonne x year}}$$



Overview



Underground laboratories



Underground laboratories

- High energy protons hit $^{nat.}$N and $^{nat.}$O in upper atmosphere
  - **Spallation leads to production of neutron, proton, pions Kaons**
  - **K's and $\pi's$ decay further into muons via weak force e.g.**

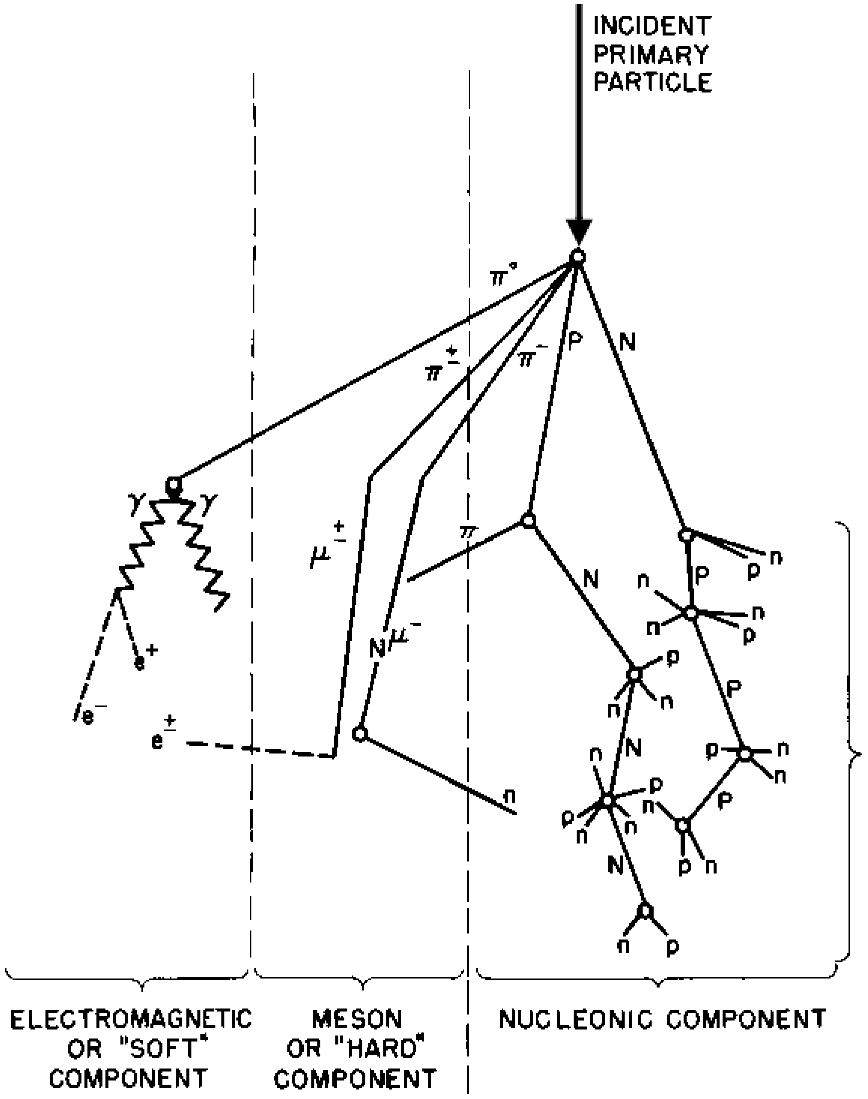
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \, , \; \pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

- Rate at sea level is about $\mathrm{R}_\mu \approx 0.01\ \mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$

  *([sr] = steradian, unit of solid angle, full sphere is 4 pi)

About 1 μ/min/cm^2 → **1 m^2 detector about 170 μ/s**

- Typical energy scale of Muon's GeV

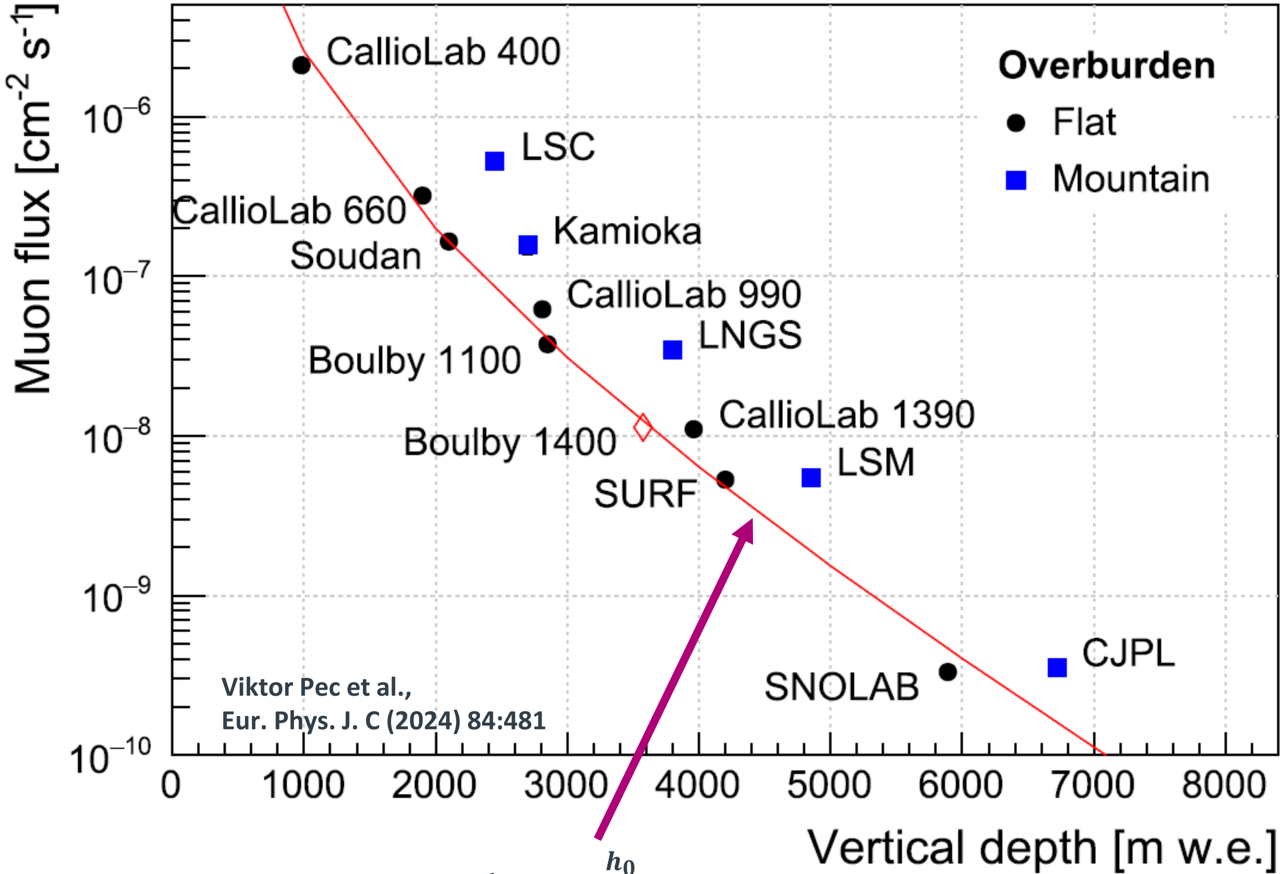


https://www.ngdc.noaa.gov/stp/image/shower.gif

Underground laboratories

- Solution go into underground laboratories to shield $\mu' s$
  - **Reduced muon flux by about 5-7 orders of magnitudes!**
  - **Use “standard rock” (A = 22, Z = 11, ρ = 2.65 g cm^{-3}) to convert to physical depth: 1000 m.w.e = 380 m of standard rock**

Why do laboratories in mountains not follow the same model as laboratories with flat overburden?



Viktor Pec et al.,
Eur. Phys. J. C (2024) 84:481

$$I_\mu(h_0) = \left(67.97 \cdot 10^{-6}\, e^{-\frac{h_0}{2850\ m.w.e}} + 2.071 \cdot 10^{-6} e^{-\frac{h_0}{6980\ m.w.e}}\right) \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

D.-M. Mei and A. Hime,
arXiv:astro-ph/0512125v2

m.w.e == Meter water equivalent

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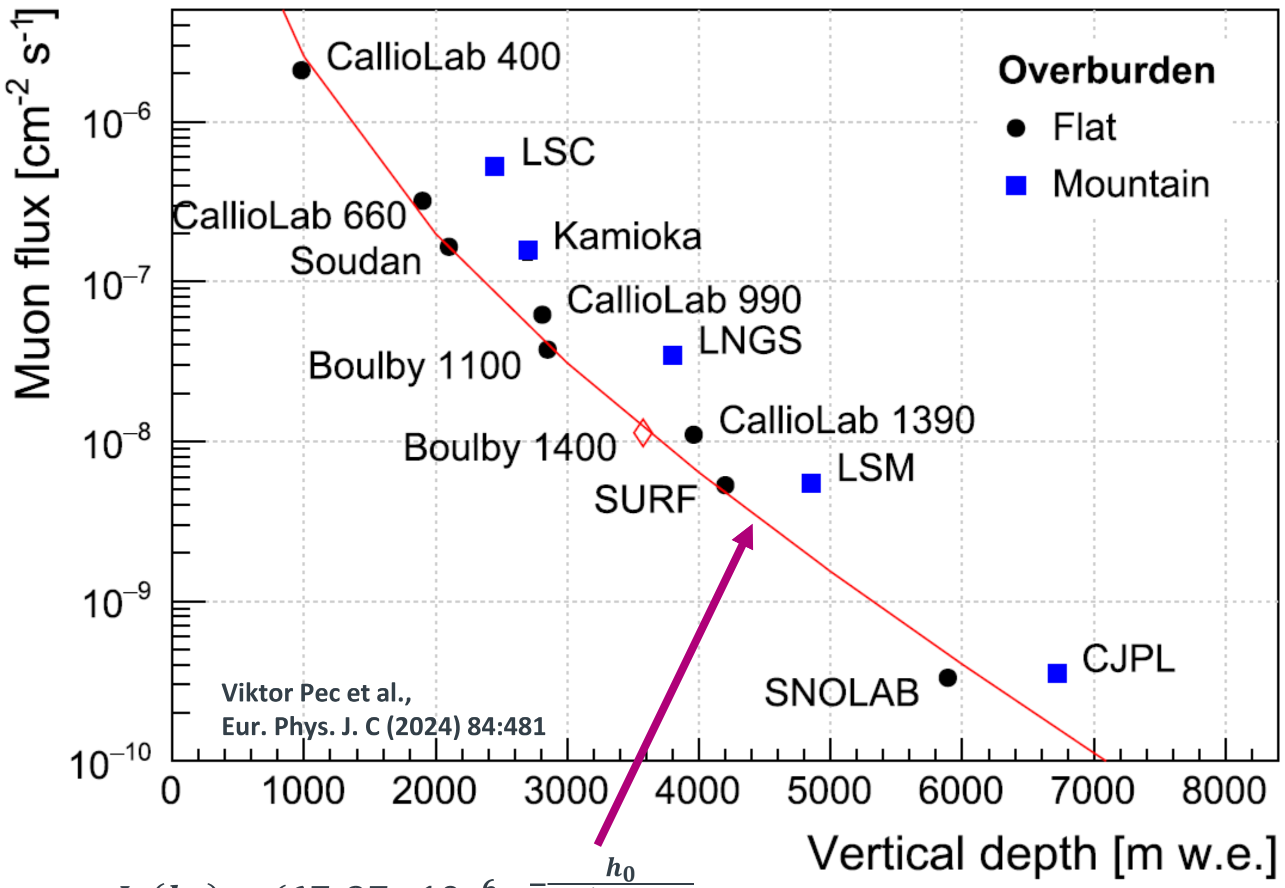
Why do we need to go deep underground? Muons should produce large signals?



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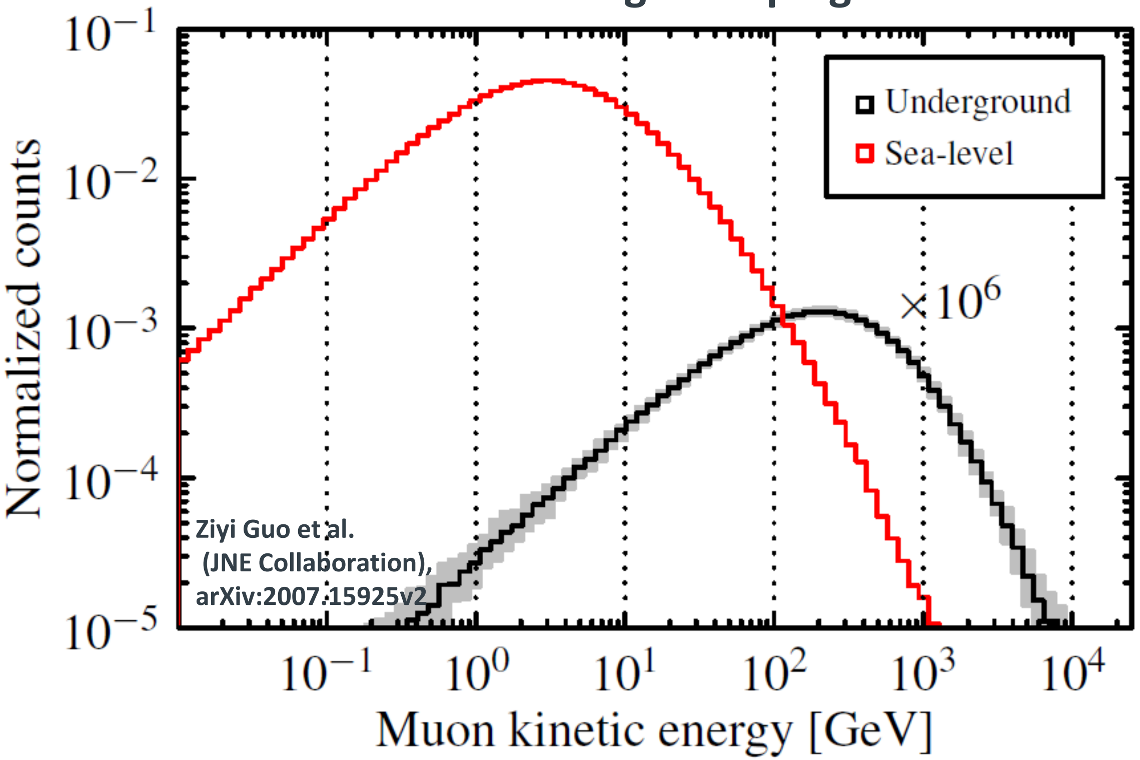
Underground laboratories

- Why are muons so important to shield?
  - **The average μ energy of about 4 GeV at sea level shifts to higher energies for the remaining μs when going underground**
  - **Binding energy nucleons ~8 MeV per nucleon**

μ induced spallation and hadronic shower lead to neutrons and material activation!

Simulated muon energies Jinping UL



Ziyi Guo et al. (JNE Collaboration), arXiv:2007.15925v2

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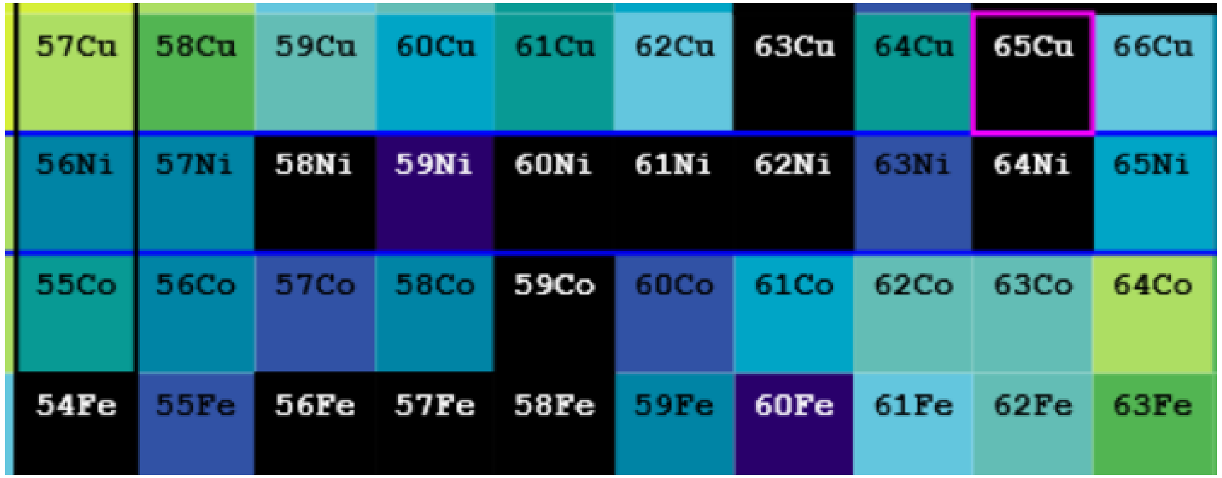

57Cu	58Cu	59Cu	60Cu	61Cu	62Cu	63Cu	64Cu	65Cu	66Cu
56Ni	57Ni	58Ni	59Ni	60Ni	61Ni	62Ni	63Ni	64Ni	65Ni
55Co	56Co	57Co	58Co	59Co	60Co	61Co	62Co	63Co	64Co
54Fe	55Fe	56Fe	57Fe	58Fe	59Fe	60Fe	61Fe	62Fe	63Fe

Image of nudat database nuclide chart https://www.nndc.bnl.gov/nudat3/

Which isotopes due to you expect to be harmful in case of copper? Do you know any of these isotopes from your lab courses?

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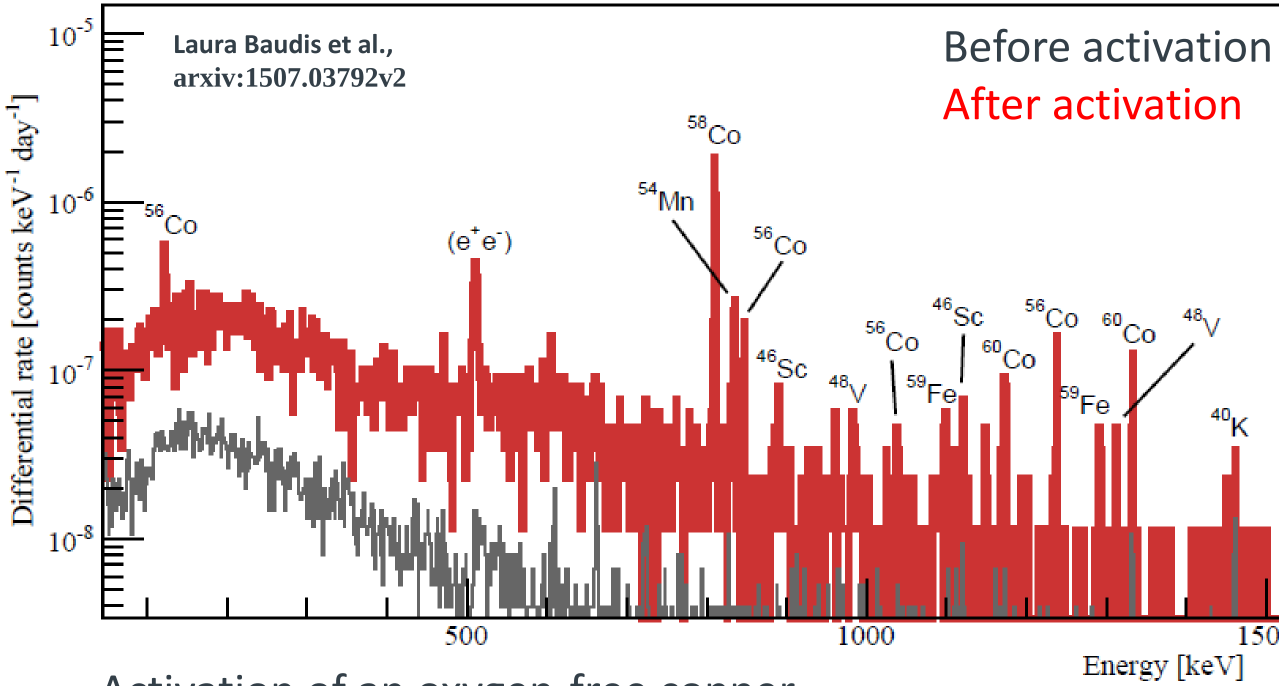
μ induced spallation and hadronic shower lead to neutrons and material activation!

- **Activation of detector materials lead to a whole range of different isotopes:**
  - **^{3}H, ^{39}Ar, ^{42}Ar, ^{60}Co, ^{68}Ge, ^{127}Xe, PTFE (C_2F_4) (^{19}F -> ^{17}N -> ^{17}O + β -> ^{16}O + n)**

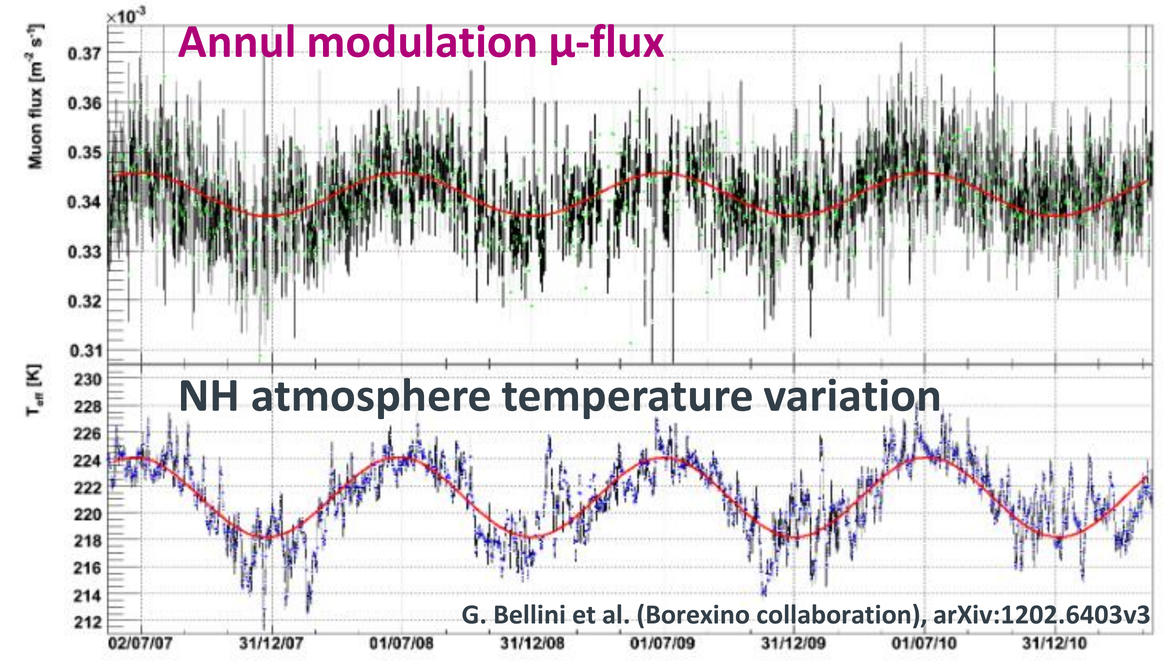


Laura Baudis et al., arxiv:1507.03792v2

Activation of an oxygen-free copper sample after 345 days in 3470 m height.

Underground laboratories

Seasonal temperature variations in the upper atmosphere lead to variations in the μ-flux!



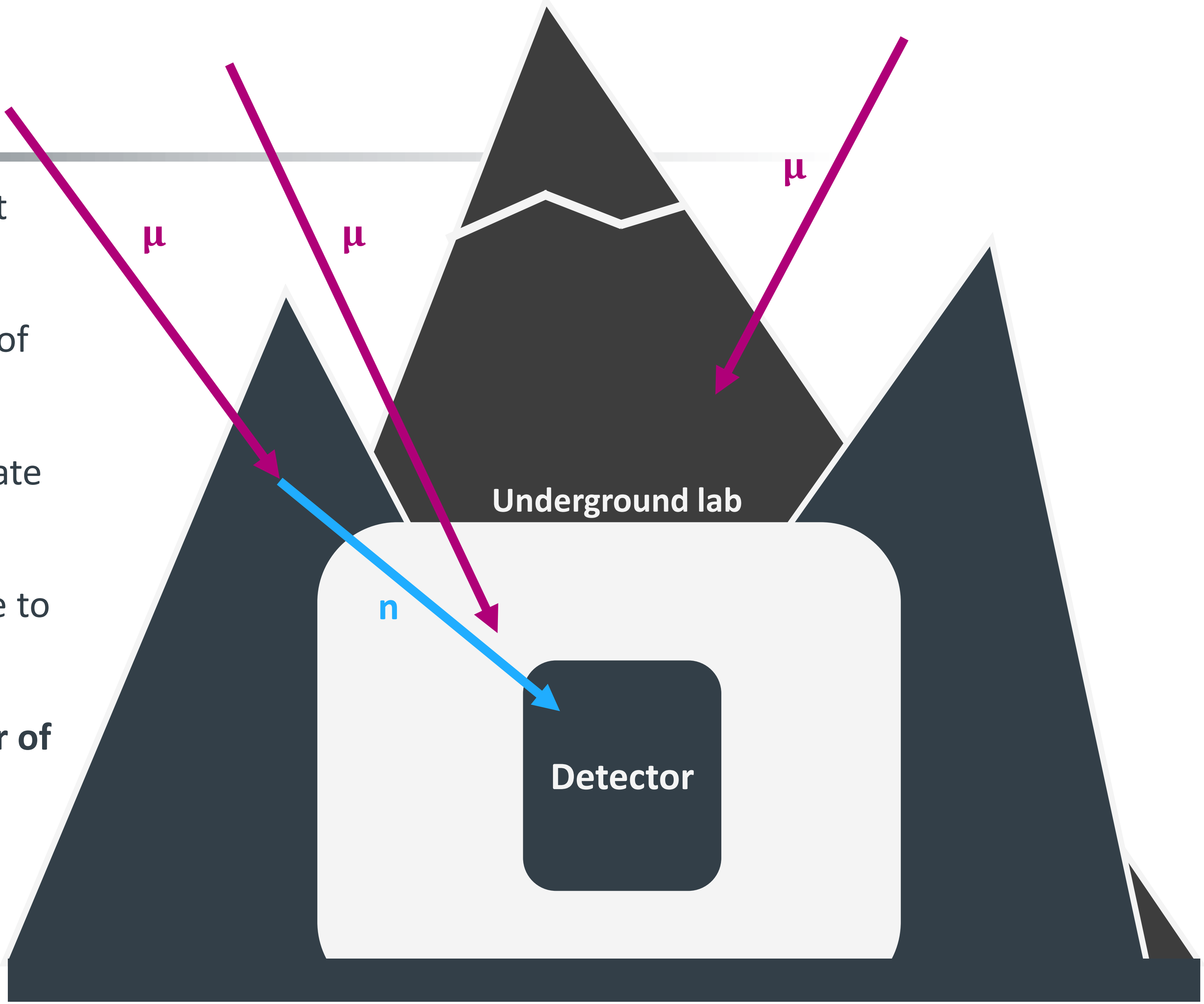
G. Bellini et al. (Borexino collaboration), arXiv:1202.6403v3

Keep in mind when looking for annul modulation signal in DM searches

Taken from: Yeongduk Kim, TAUP 2023

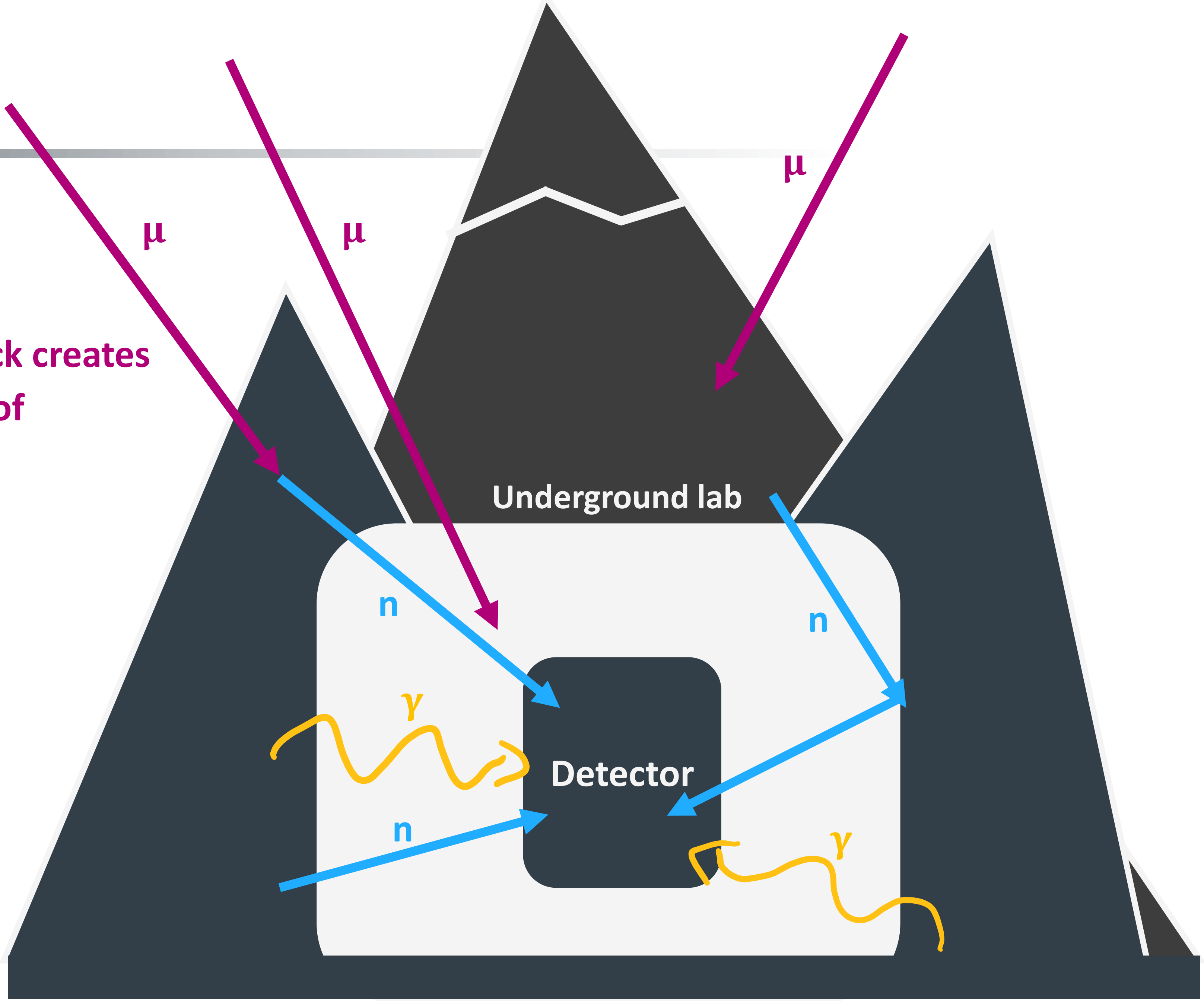
Underground laboratories

- Typical muon rate at sea level about 1 μ/min/cm^2
- Typical muon energies in the order of 1 GeV
- Muons produce neutrons and activate detector materials!
- Underground environment effective to reduce Muon induced backgrounds
  - **Typical suppression by 5-7 order of magnitudes**



Overview

However, surrounding rock creates new background in form of gammas and neutrons.



Underground laboratories

- Underground environment introduces new backgrounds in from of gammas and neutrons
- Main contribution from primordial isotopes with a long half-life:

**Which isotopes do you think play a role, and
how much Bq per kg soil do we typically have?**

Underground laboratories

- Underground environment introduces new backgrounds in from of gammas and neutrons
- Main contribution from primordial isotopes with a long half-life:
  - **^{238}U,^{235}U (16-110 Bq/kg)***
  - **^{232}Th (17-60 Bq/kg)***
  - **^{40}K (100-1000 Bq/kg)***

*Matthias Laubenstein and Ian Lawson, 10.3389/fphy.2020.577734

Side note: You can "feel" the abundance of these elements when going deep into mines. They contribute to the geothermal energy budget with about 50 %*.

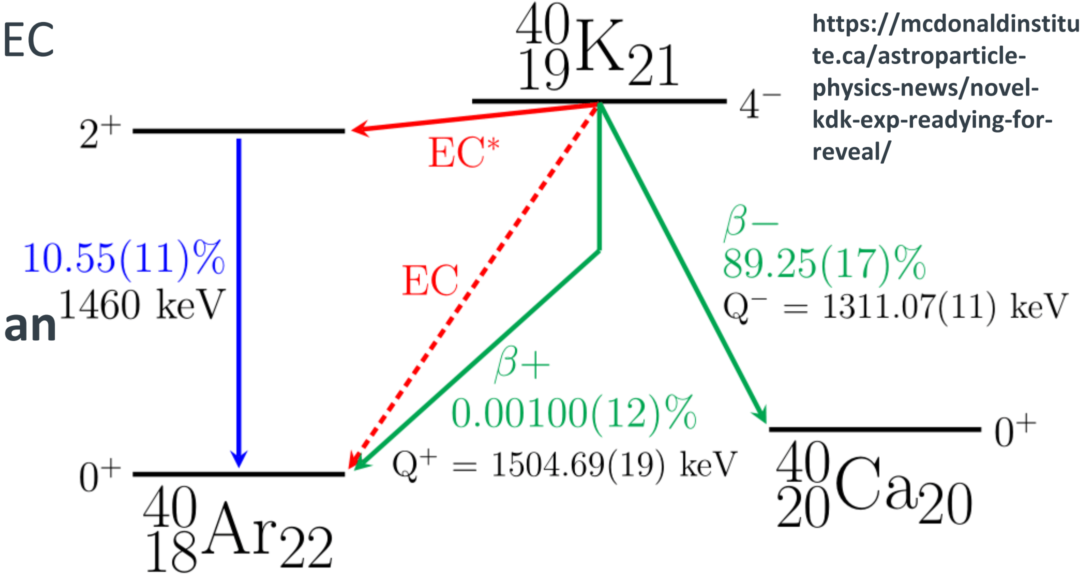
***(number is still under debate and should be taken with a grain of salt).**

- Other isotopes also play a role, but depend more on the detector type and application (see later)

Underground laboratories

- ^{40}K decays mostly either via beta emission or EC followed by the emission of a gamma ray.
  - **It has a half life of 1.251×10^{9} y**
  - **Since it can be found everywhere it plays an important role for all low background experiments**

Which other element has similar chemical properties and is used in many DM experiments?



Taken from: https://mcdonaldinstitute.ca/astroparticle-physics-news/novel-kdk-exp-readying-for-reveal/

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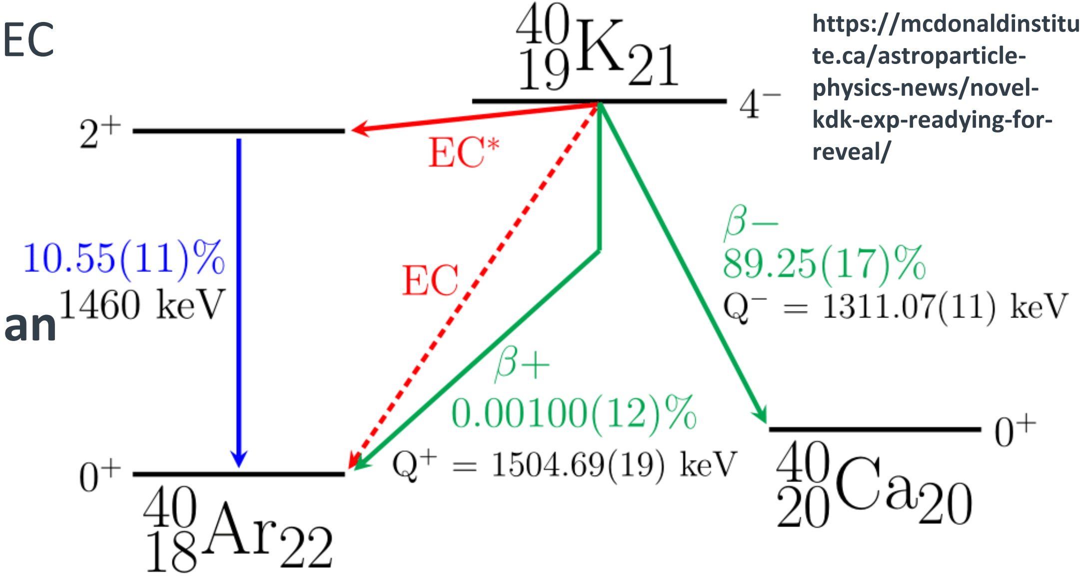

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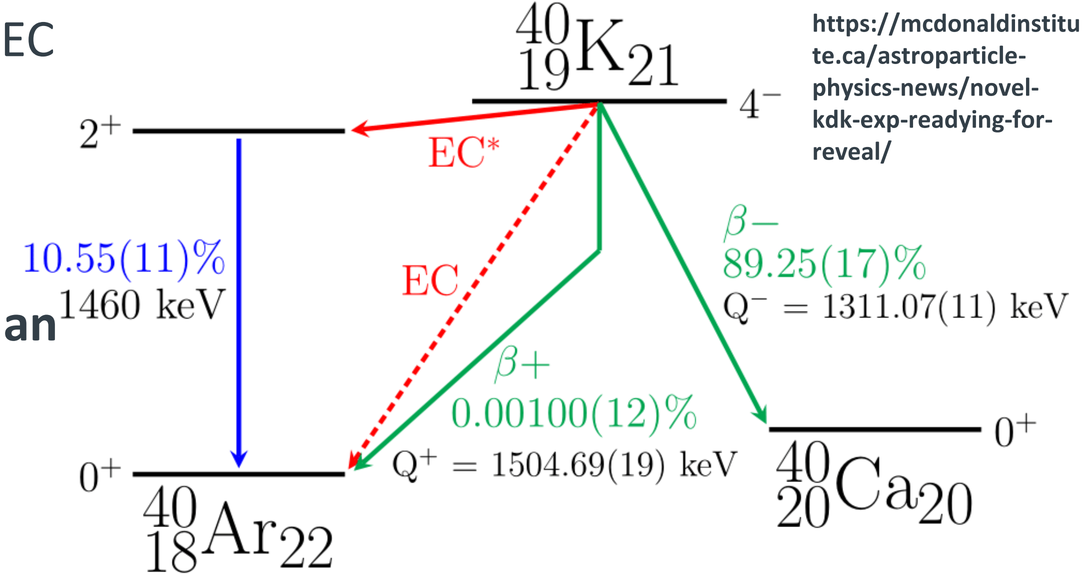

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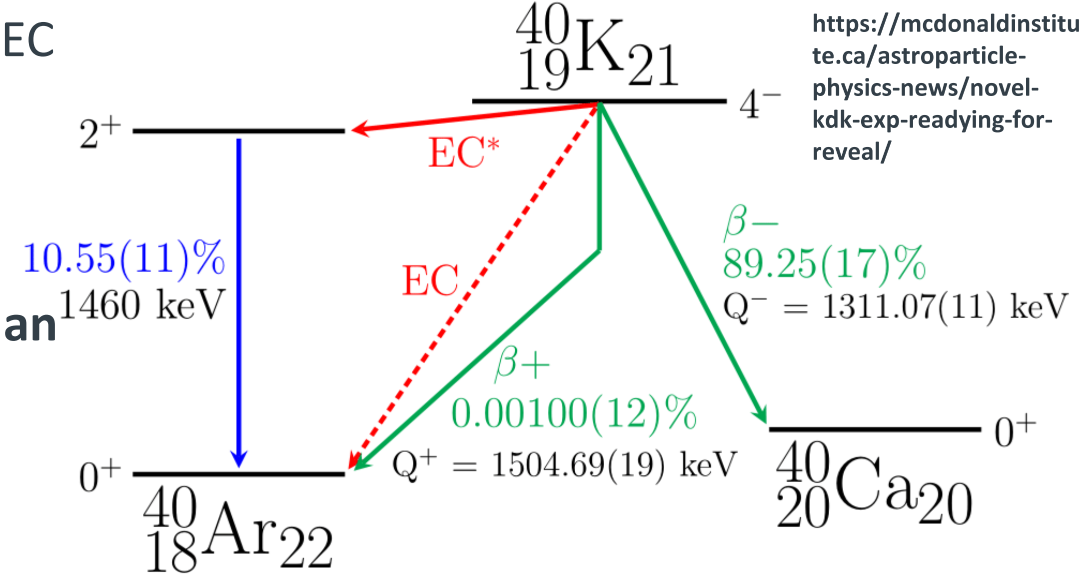
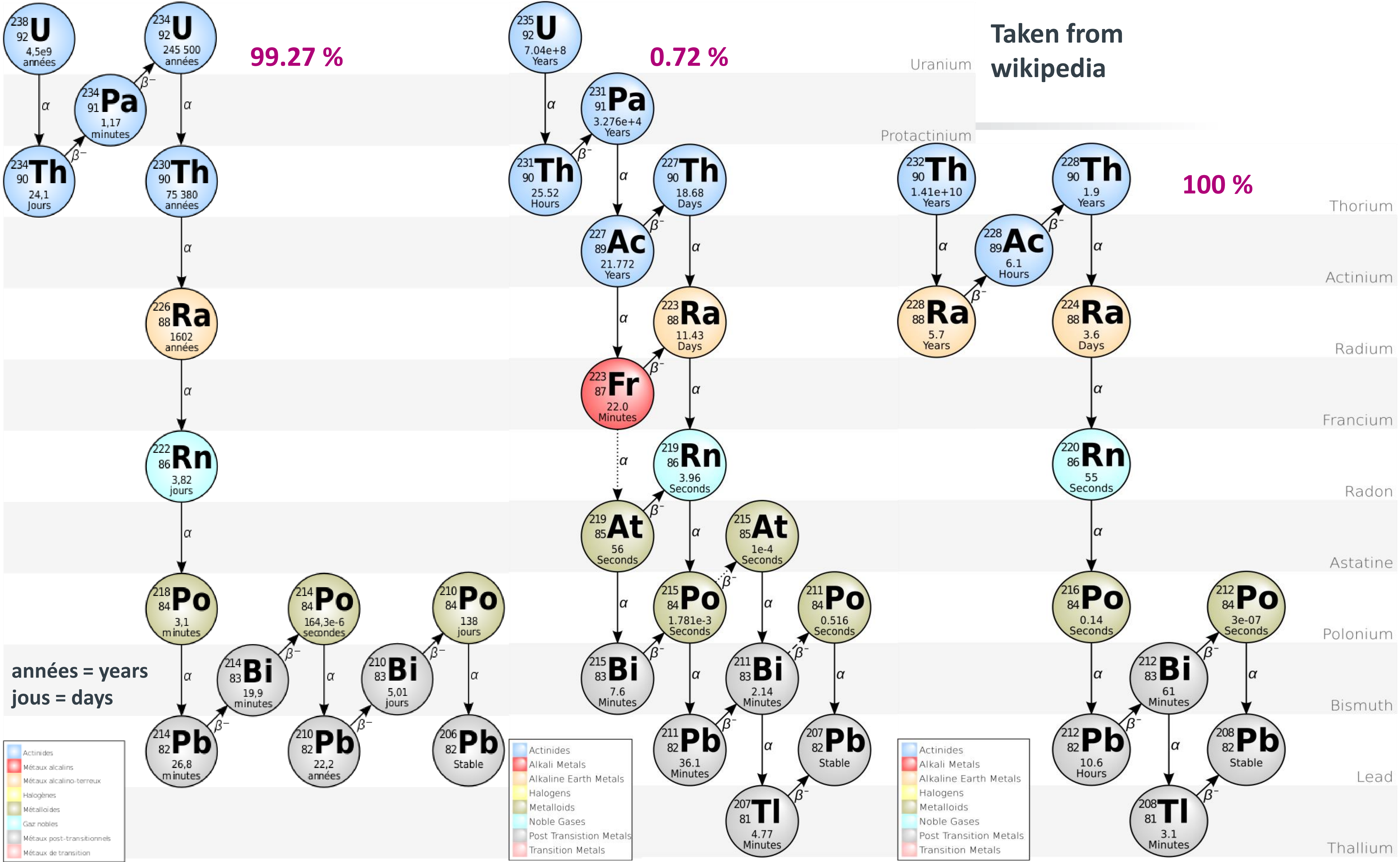
Which other element has similar chemical properties and is used in many DM experiments?

Why is ^{40}K important for liquid argon experiments?

Nearly all argon on earth comes from ^{40}K decays!



Taken from: https://mcdonaldinstitute.ca/astroparticle-physics-news/novel-kdk-exp-readying-for-reveal/



Taken from wikipedia

99.27 %

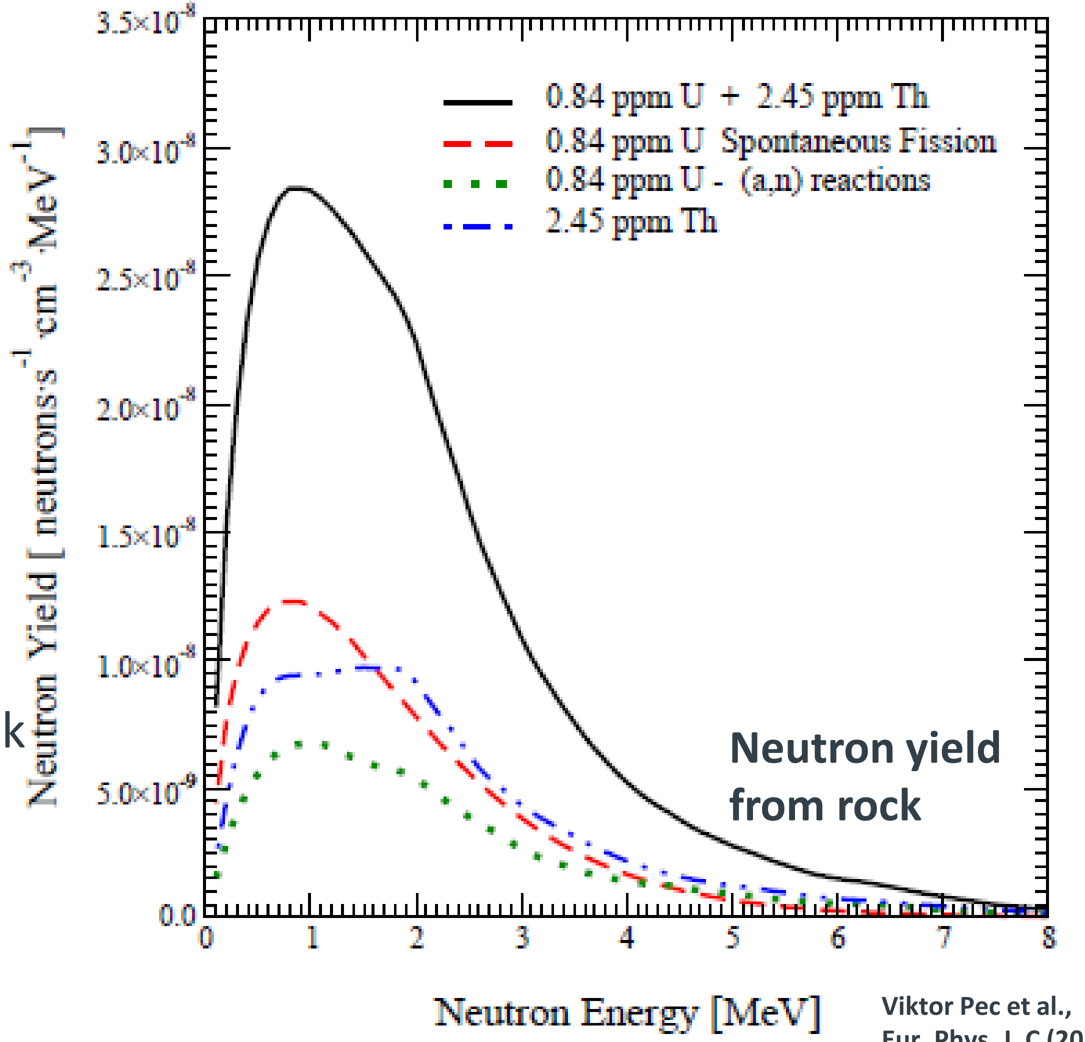
0.72 %

100 %

années = years
jous = days

Underground laboratories

- Neutrons are emitted from
  - **Spontaneous fission (mostly ^{238}U)**
  - **(alpha, n) reactions on light nuclei ($\alpha + A \rightarrow B^{*} + n$)**
    - **(heavy nuclei are suppressed due to Coulomb barrier)**
    - **(higher alpha energy -> higher probability to produce neutrons)**
- Neutrons can activate or scatter in detector and target material
- Need to know chemical composition of the surrounding rock for detailed simulations
- Different detector materials have different neutron yields from (alpha, n) reactions



Neutron yield from rock

Viktor Pec et al., Eur. Phys. J. C (2024) 84:481

Underground laboratories

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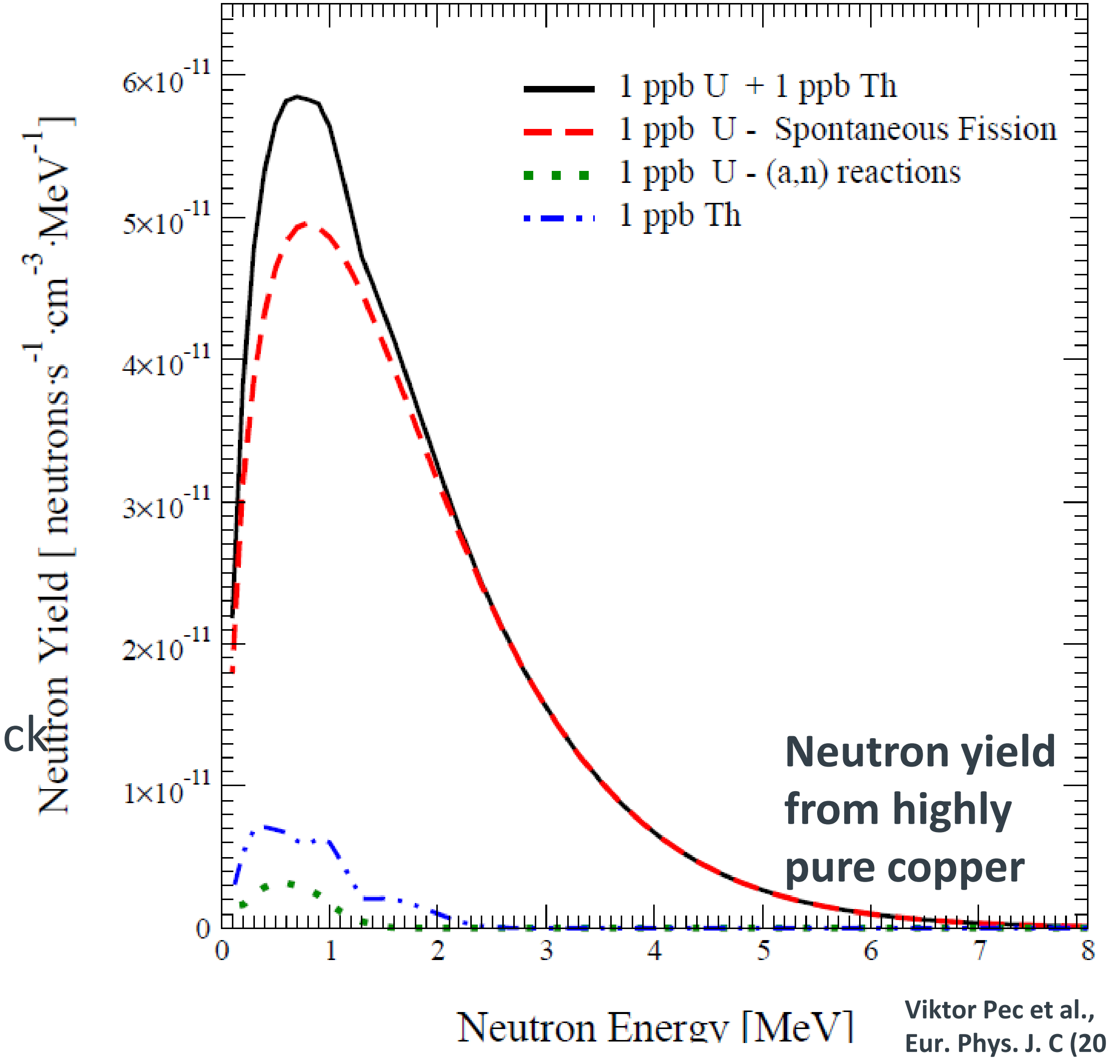
- Neutrons can activate or scatter in detector and target material
- Need to know chemical composition of the surrounding rock for detailed simulations
- Different detector materials have different neutron yields from (alpha, n) reactions.
  - **Cu better than stainless steel (less low A material)**

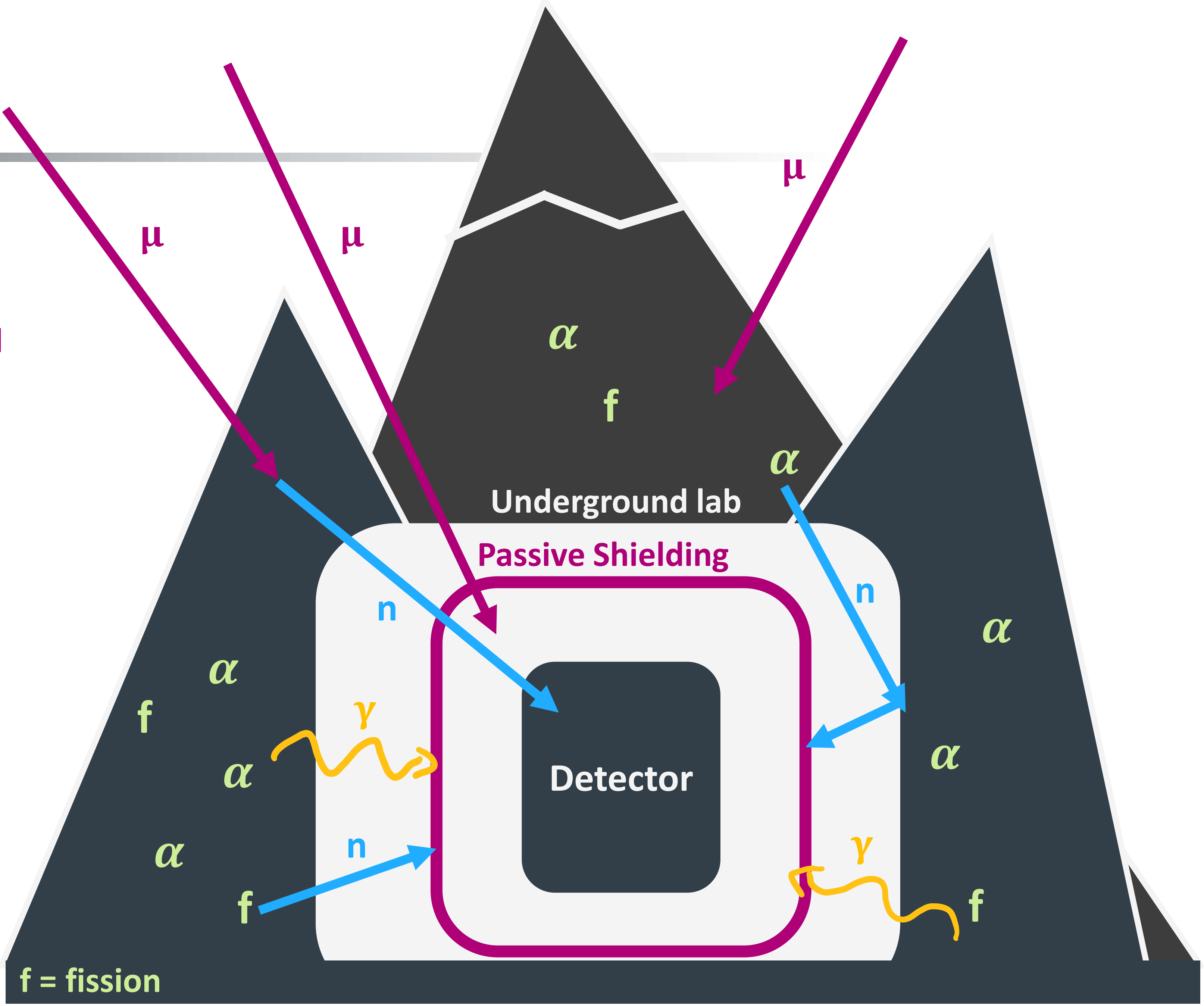


Neutron yield from highly pure copper

Viktor Pec et al., Eur. Phys. J. C (2024) 84:481

Overview

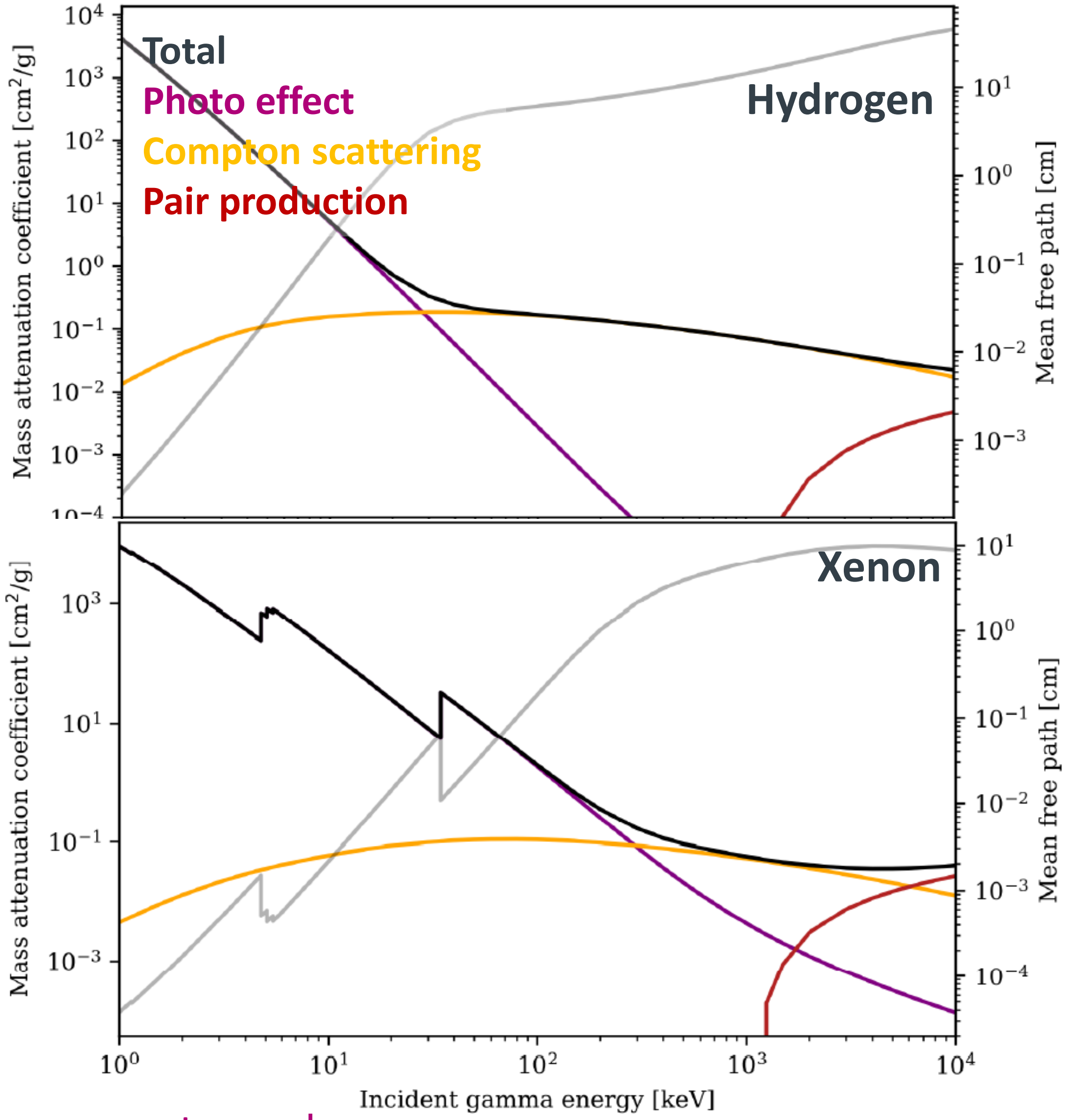
➡ **Build passive shielding layers to reduce environmental influence, from α-decays and fission**



Passive and active shields

- Photons interact with matter through
  - **Photo effect, Compton scattering and pair production**
  - **High Z material is favorable as photo effect scales with $\approx Z^5$**
- Use as passive shield for example lead
  - **Use ancient or low background lead to reduce intrinsic background of ^{210}Pb.**

Why does ancient lead not contain much ^{210}Pb?



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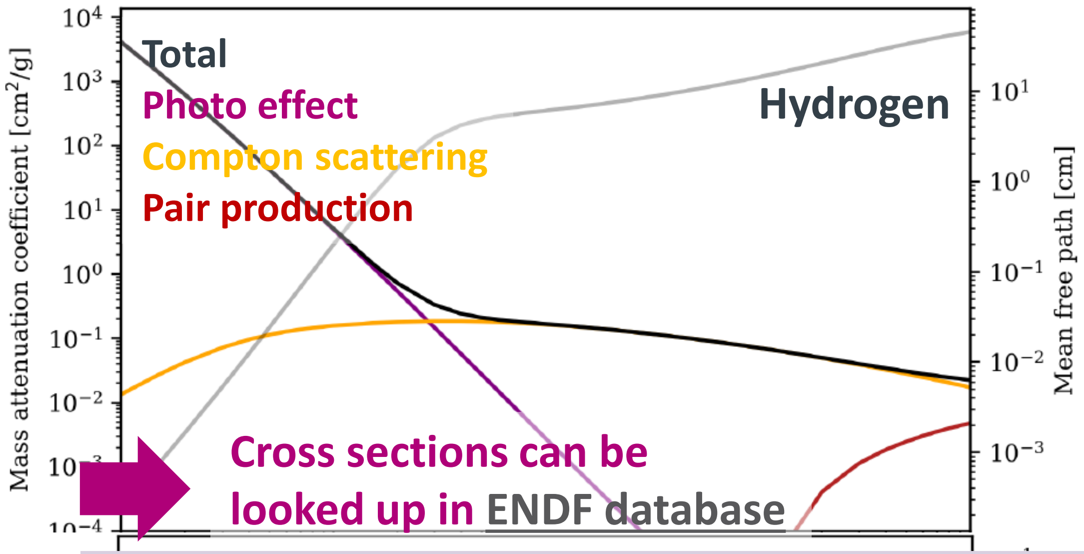
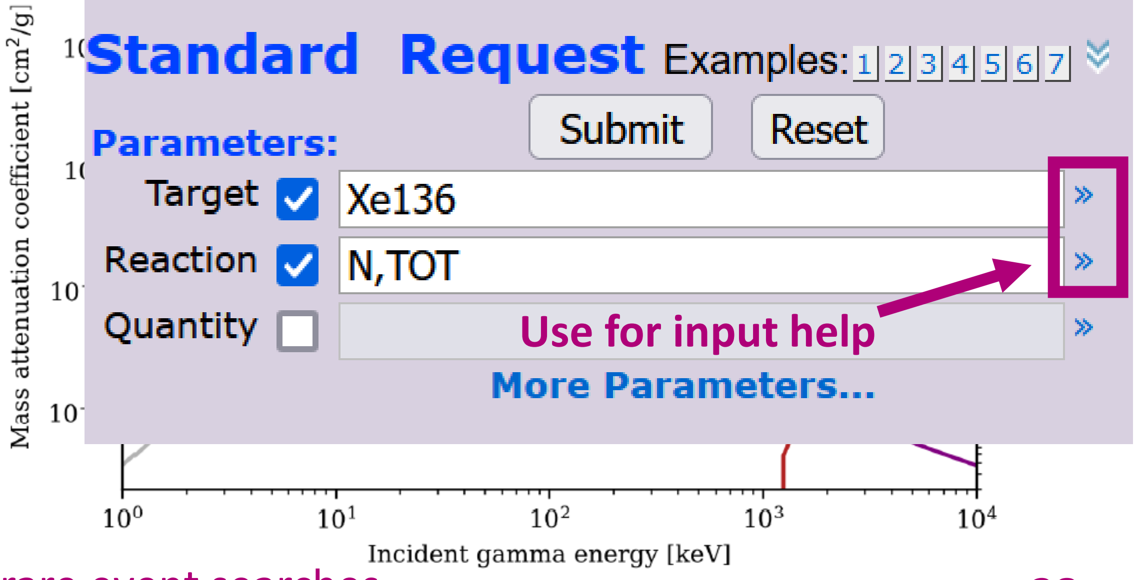


Cross sections can be looked up in ENDF database



Target ☑ Xe136

Reaction ☑ N,TOT

Quantity ☐

Use for input help

Passive and active shields

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  - **High Z material is favorable as photo effect scales with $\approx Z^5$**
- Use as passive shield for example lead
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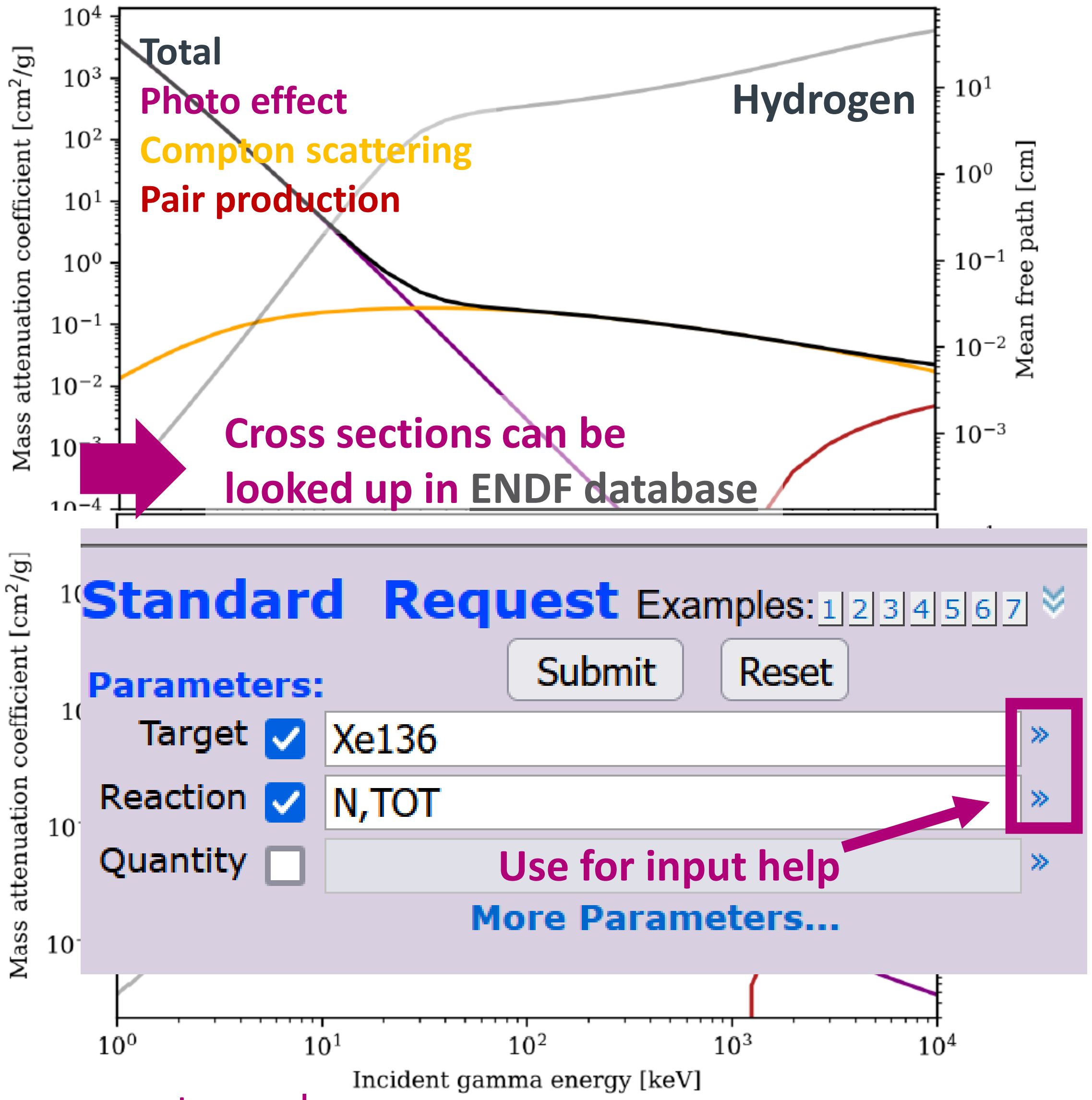
Lead often contains also Uranium, ancient lead was purified many years ago most of ^{210}Pb decayed.

Lead works for gammas, but how do we shield best neutrons?



Cross sections can be looked up in ENDF database

Target ☑ Xe136

Reaction ☑ N,TOT

Quantity ☐

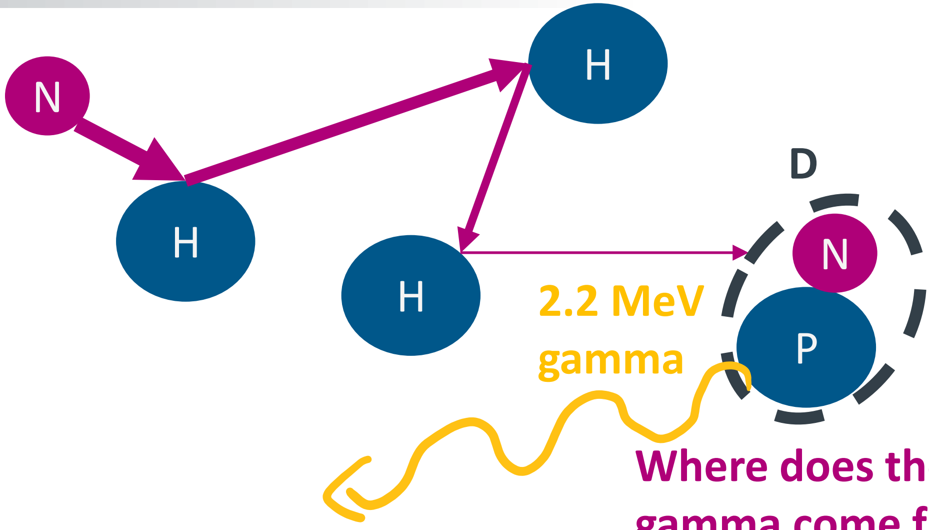
Use for input help

Passive and active shields

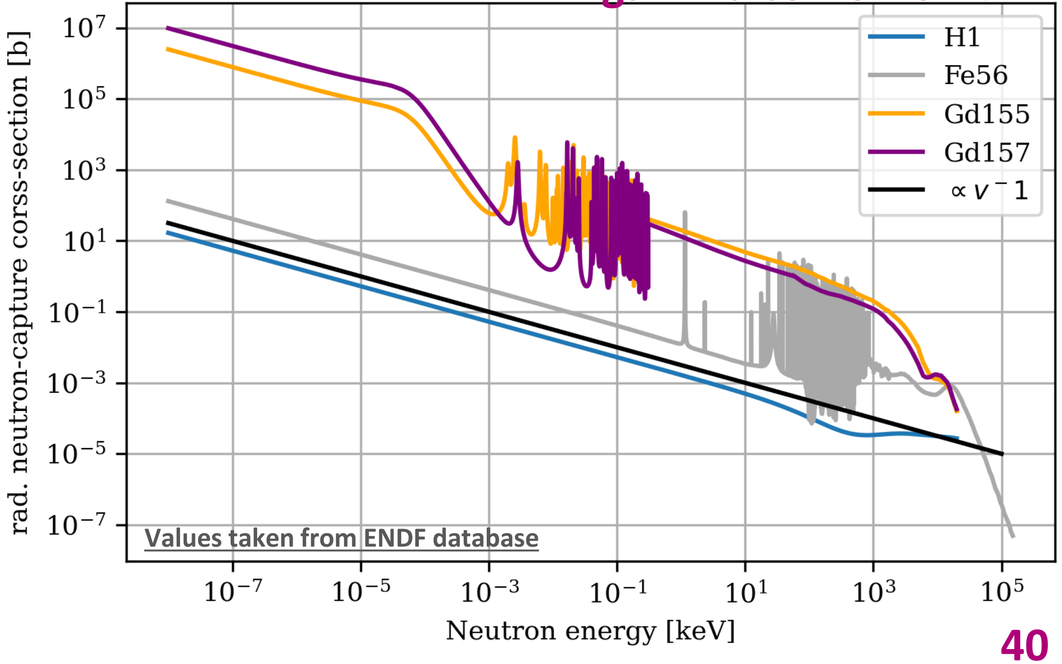
- Neutrons are only shielded through collisions on nuclei
  - **Reminder recoil energy:**

$$E_R = \left(\frac{m_\chi m_N}{m_\chi+m_N}\right)^2 \frac{v^2}{m_N}\left(1-\cos(\theta)\right)$$

  - **Use materials which contains a lot of hydrogen like water (H_2O) or plastics (C_NH_M)**
  - **Neutrons elastically scatter until being captured.**
  - **Enhance neutron absorption through isotopes with high neutron capture cross section, e.g. Boron (^{10}B), or Gadolinium (^{155}Gd, ^{157}Gd)**



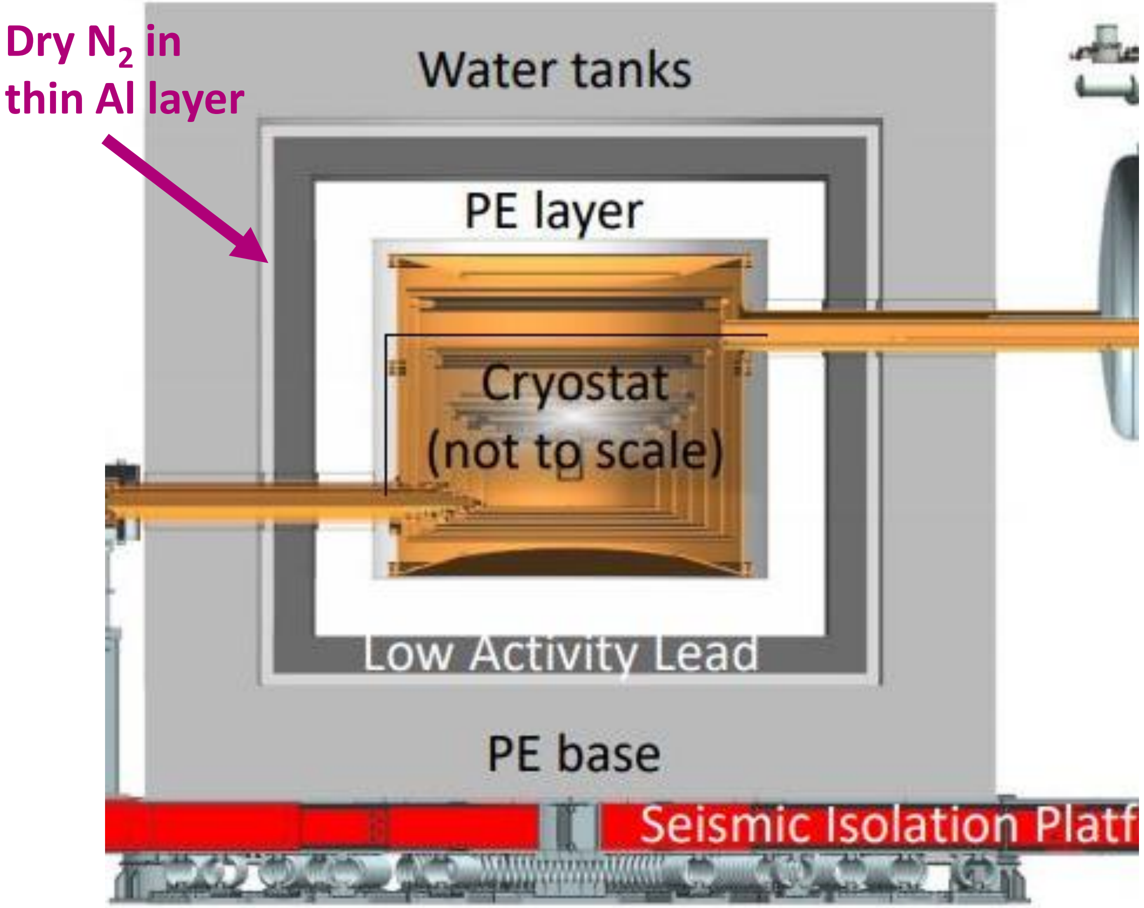
Where does the 2.2 MeV gamma come from?



Values taken from ENDF database

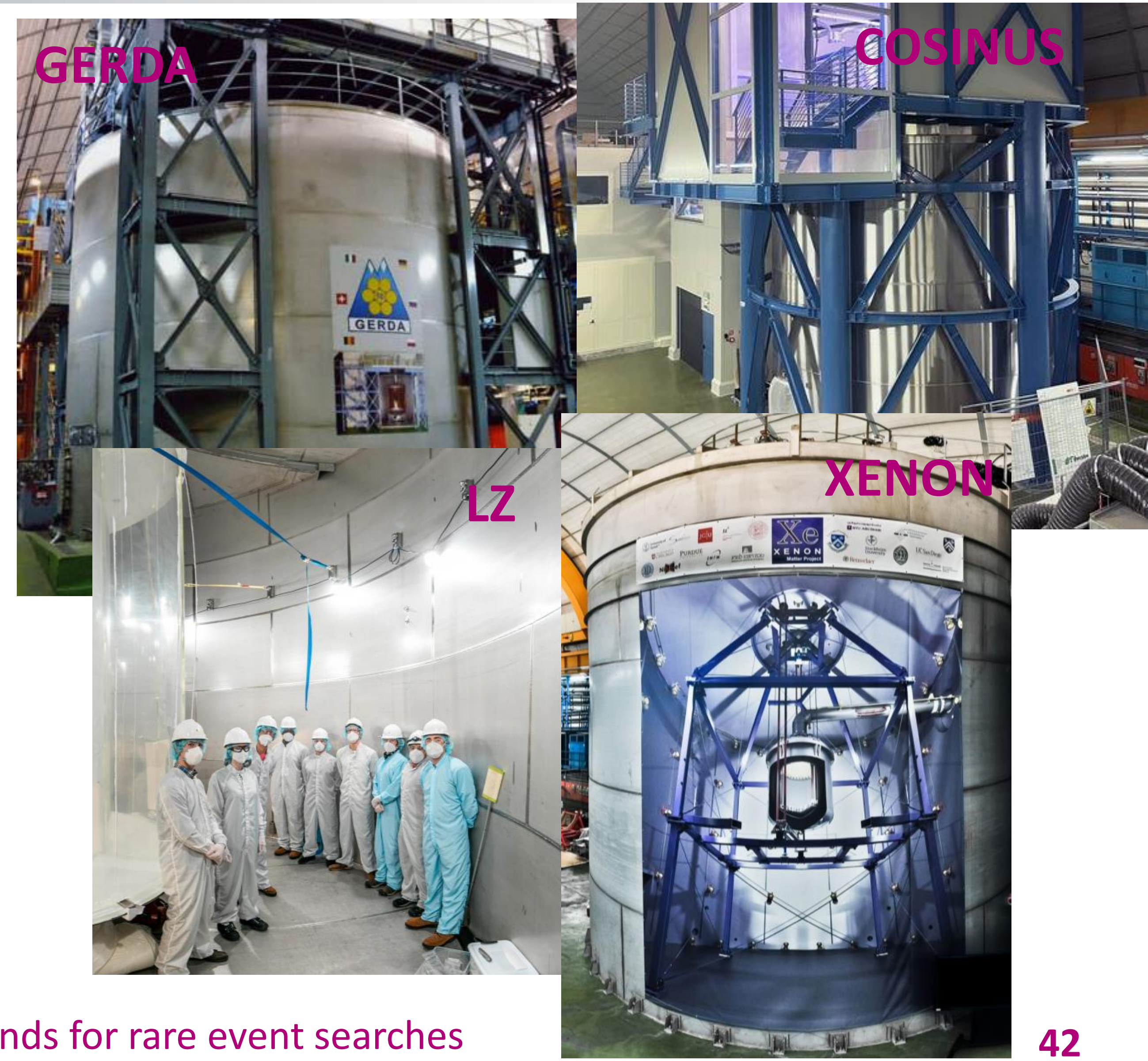
Passive and active shields

- Use multilayer shielding to absorb both neutrons and gammas
- Example superCDMS at SNOLAB
  - **Water and PE layer to moderate and absorb neutrons (low Z)**
  - **Low activity Pb to shield gammas (high Z)**
  - **Thin dry-nitrogen layer to reduce ^{222}Rn contamination from surrounding rock**
  - **Polyethylene to moderate and absorb again neutrons (low Z)**
  - **Cupper housing reduces further gamma background and bremsstrahlung**


Dry N_2 in thin Al layer

Passive and active shields

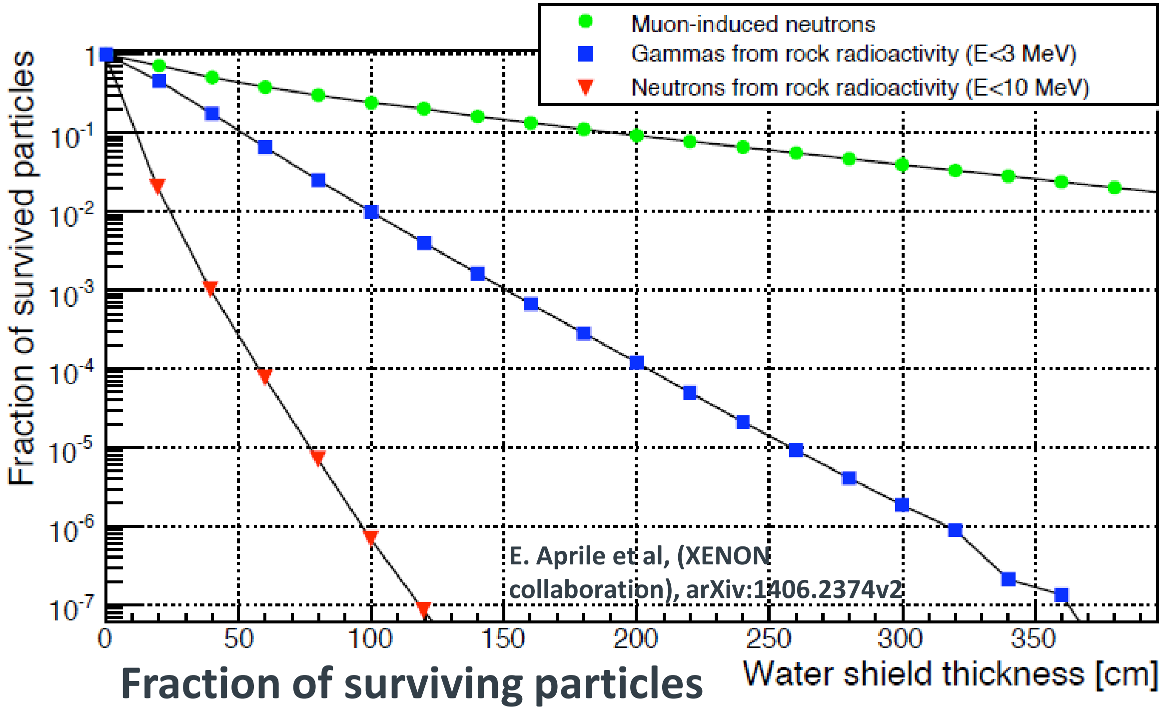
- Deionized water is used as a passive shield by many experiments which are not as deep as SNOLAB
  - **XENON, LZ, COSINUS, GERDA,…**



Passive and active shields

- Deionized water is used as a passive shield by many experiments which are not as deep as SNOLAB
  - **XENON, LZ, COSINUS, GERDA,…**
- Already 3-4 meter are enough to shield environmental neutrons and gammas
- Only high energy neutrons from μ's can penetrate most shields!
  - **Reminder this is an issue for neutron activation!**

What is the advantage of using water as a shielding material?

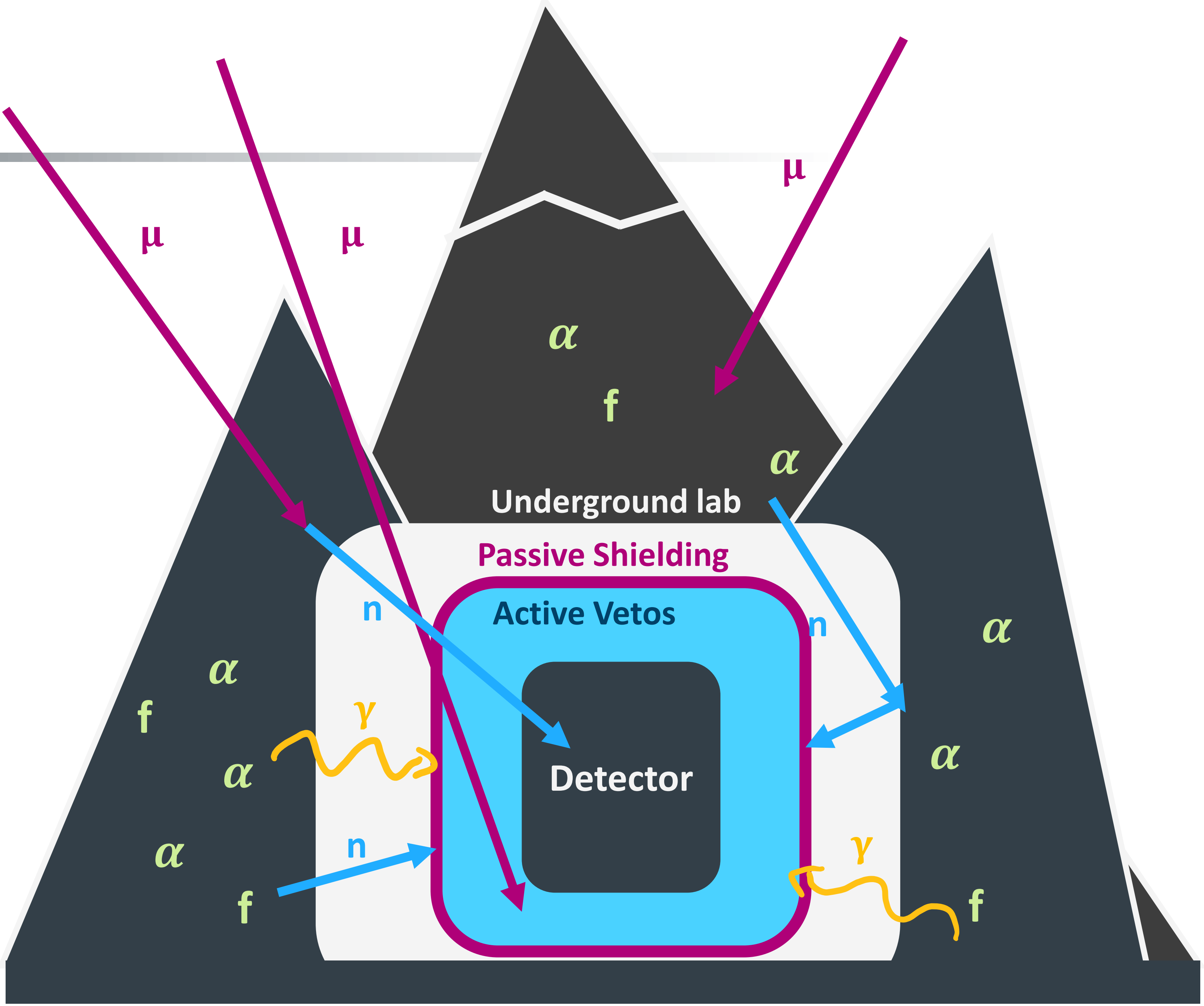


E. Aprile et al, (XENON collaboration), arXiv:1406.2374v2

Fraction of surviving particles using GEANT4 simulations.

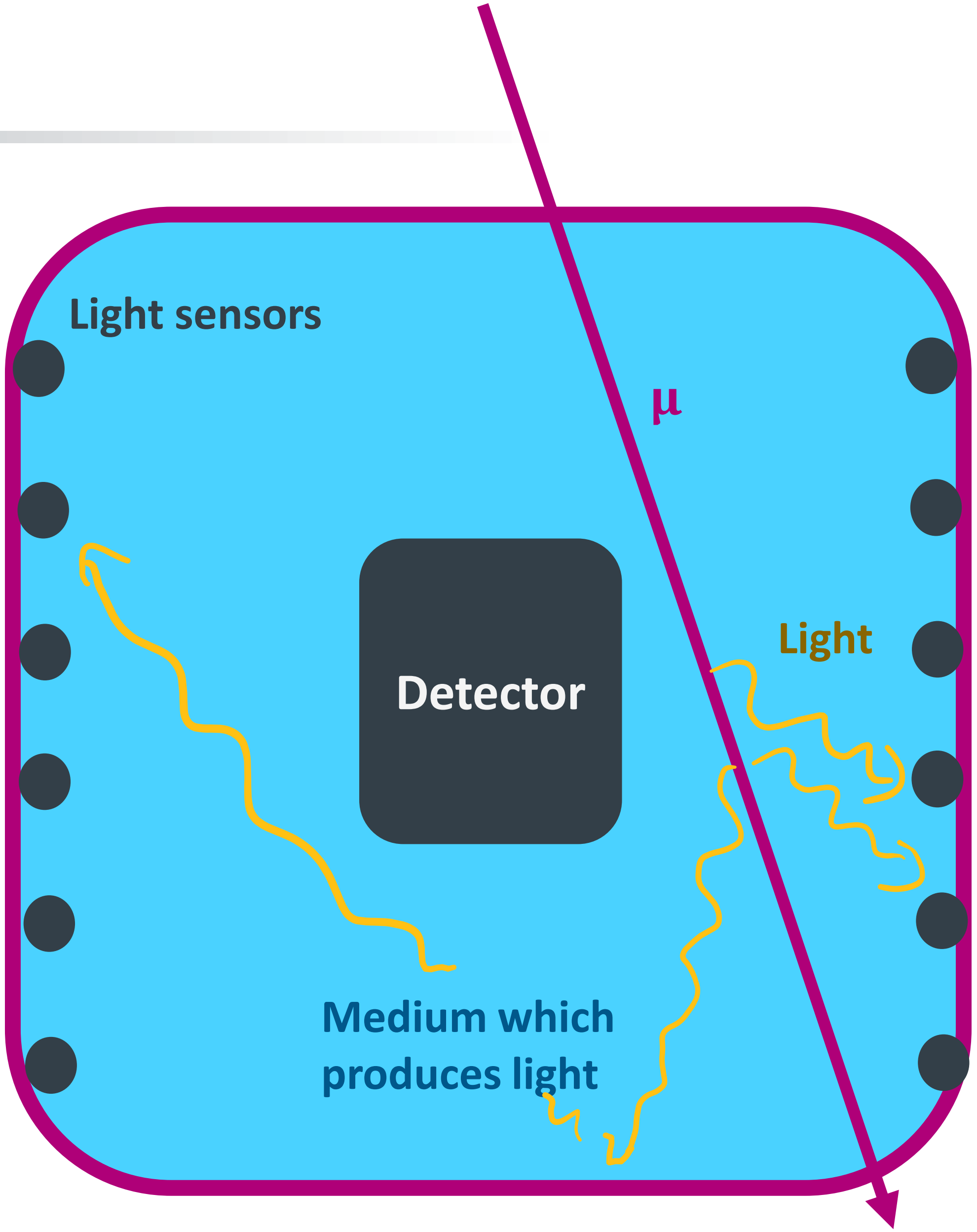
Overview

➡ **Use passive shielding also as an active veto!**



Passive and active shields

- Active veto idea is always the same:
  - **Build detector around experiment**
  - **Fill outer detector with a medium which produces light when a background particle interacts**
  - **Add light sensors to measure the emitted light**
  - **Veto all signals in the main detector which are in coincidence with the outer detector**



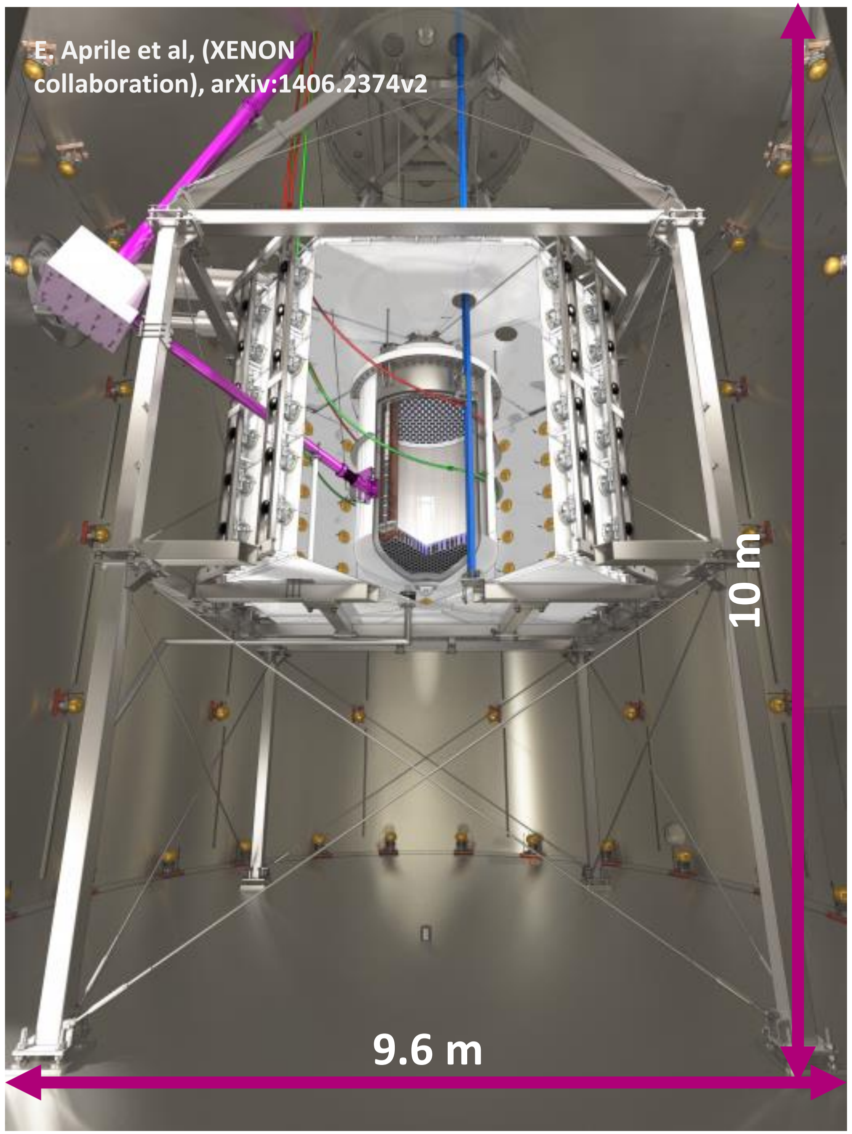
Passive and active shields

- Water Cherenkov detector to suppress remaining muon background.
  - **Cherenkov spectrum is continuous peaking in the ultra-violet**
  - **Emitted number of photons given by**

***(for 300 nm < λ < 500 nm)**

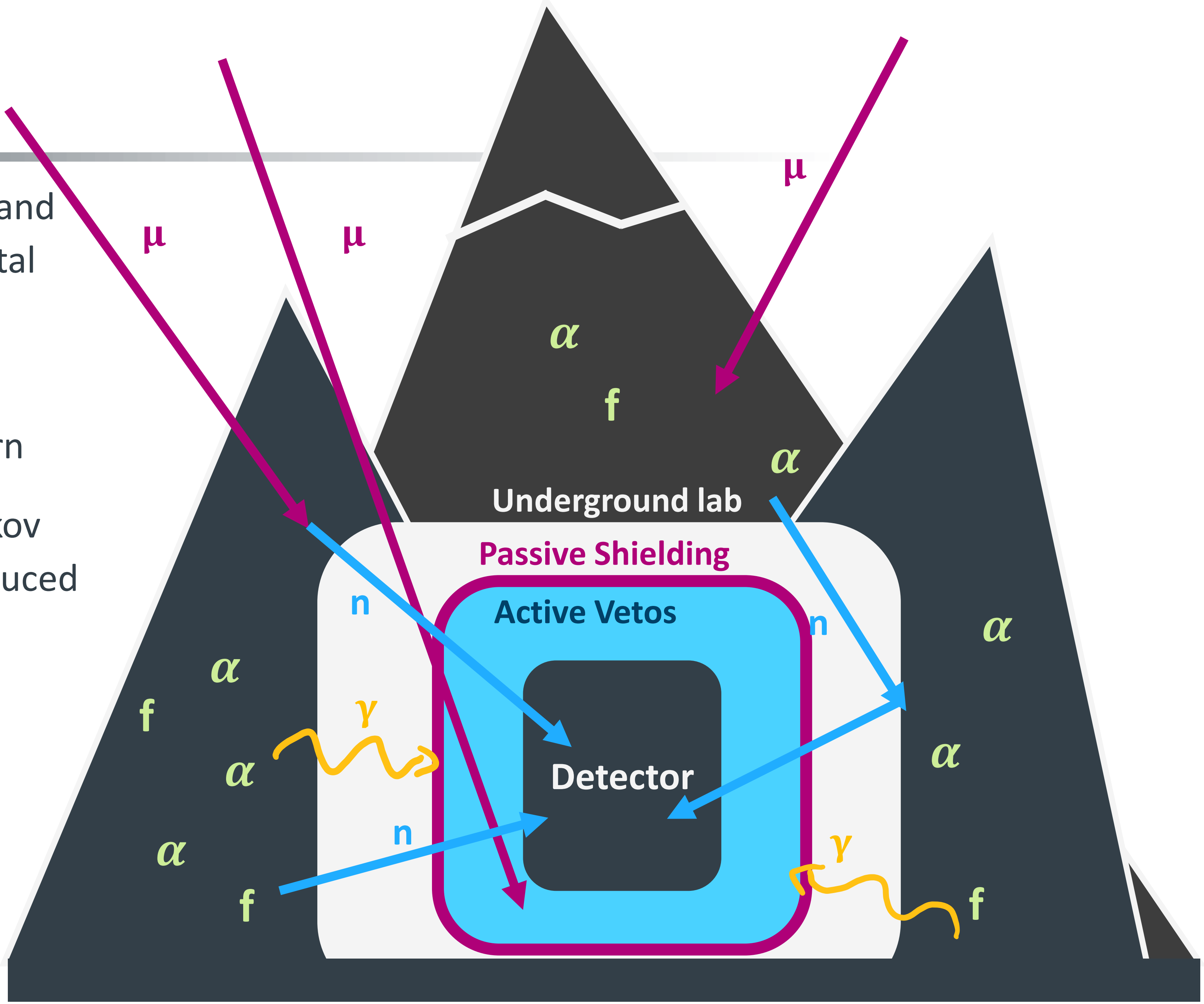
$$\frac{\mathrm{d}N}{\mathrm{d}\lambda\mathrm{d}x} = \frac{2\,\pi z^2\alpha}{\lambda^2}\cdot\left(1\ -\frac{1}{\beta^2 n(\lambda)^2}\right) \approx \frac{\mathrm{d}N}{\mathrm{d}x}\Big|_{*} \approx 250\,\frac{\mathrm{ph}}{\mathrm{cm}}$$

- XENON1T/nT µ-veto detection efficiency from GEANT4 simulations
  - **Direct µ-crossing: ~100 %**
  - **Indirect µ shower: ~70 %**
  - **Lifetime loss ~1% (try to also veto decays with short $T_{1/2}$)**


E. Aprile et al, (XENON collaboration), arXiv:1406.2374v2

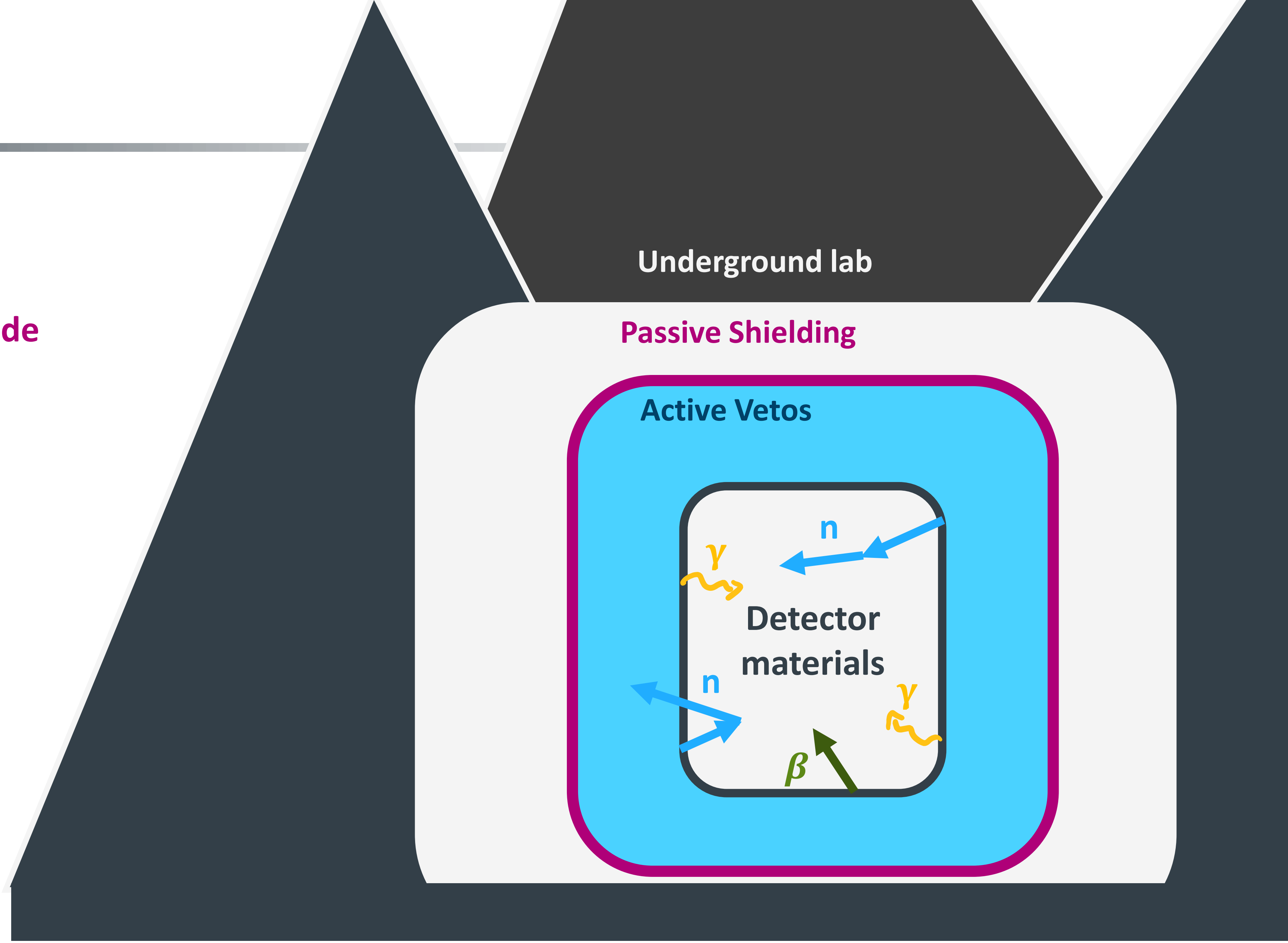
Overview

- Passive shielding layers such as Pb and Cu help to shield from environmental gammas
- Plastics and water help to shield neutrons from the laboratory cavern
- Active vetos such as water Cherenkov detectors help to also reduce μ-induced backgrounds further.



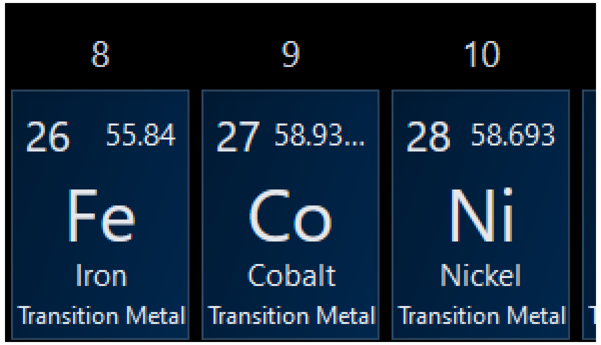
Overview

New problem: Our detector is also made from something



Detector materials

- Reminder Uranium, Thorium and Potassium are everywhere:
  - **^{238}U,^{235}U (16-110 Bq/kg), ^{232}Th (17-60 Bq/kg), ^{40}K (100-1000 Bq/kg)**



- Some materials are purer than others:
  - **Oxygen-free, high conductivity copper has a purity of 99.99%**
  - **Stainless steel is an alloy containing besides Fe and others also Ni which can contain ^{60}Co**
    - **Other issue recycling of activated stainless steel containing ^{60}Co (German law: 100 Bq/kg)**
    - **^{60}Co is also used as a tracer in blast furnaces** Matthias Laubenstein and Ian Lawson, 10.3389/fphy.2020.577734
  - **Must screen every piece of metal, plastic, cable, bolt and nut which enters the detector!**
  - **If possible, screen raw materials and work together with vendors** **Tao Zhang et al., https://arxiv.org/pdf/1609.07515**

Detector materials

- Inductively coupled mass spectroscopy (ICP-MS)
  - **Dissolve small samples in a liquid**
  - **Convert spray of liquid into ionized plasma**
  - **Measure atoms or polyatomic ions based on their charge-to-mass ratio**
  - **No direct measurement of the radioactive decay**
  - **Calibration with reference samples for absolute concentration**
  - **Highly sensitive ~nBq/kg**
  - **Only small samples are required, and measurement times are short**
  - **Sample will be destroyed in the process**
  - **Measures only ^{238}U and ^{232}Th concentration**

Matthias Laubenstein and Ian Lawson, 10.3389/fphy.2020.577734

Careful, decay chain might not be in secular equilibrium!

Detector materials

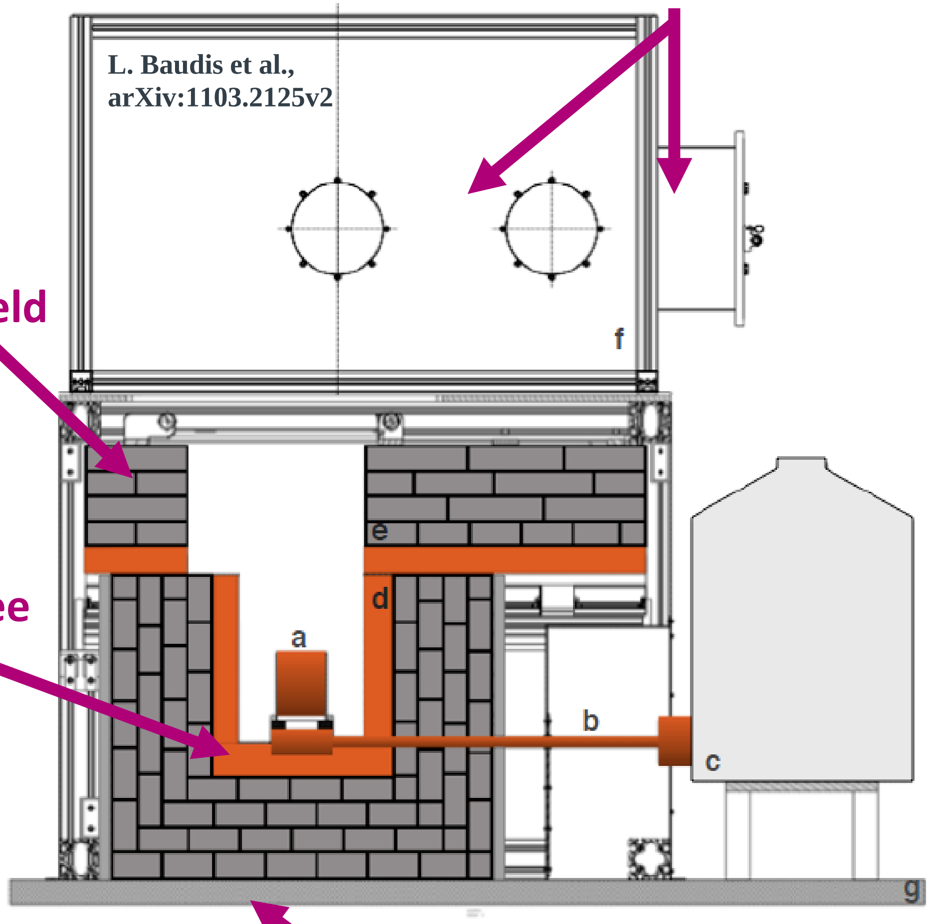
- Gamma-ray spectroscopy using high purity Germanium detectors
  - **Low background experiment in itself!**
  - **Direct measurement of radioactive isotopes**
  - **Requires large amount of material and long counting periods.**
  - **Sensitivity 10-100 µBg/kg**

Matthias Laubenstein and Ian Lawson, 10.3389/fphy.2020.577734

  - **Requires large amounts of materials and long measurement times.**

How long does it take to get to a 10 % uncertainty for a 100 µBq rate?

  - **Samples are not destroyed in the process**
  - **Measures gamma spectrum of the full U- and Th-chain directly.**



Airlock and glove box with dry N_2 overpressure

Lead shield

Oxygen free copper

Polyethylene shield against neutrons

Detector materials

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  - **Low background experiment in itself!**
  - **Direct measurement of radioactive isotopes**
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  - **Sensitivity 10-100 µBg/kg**
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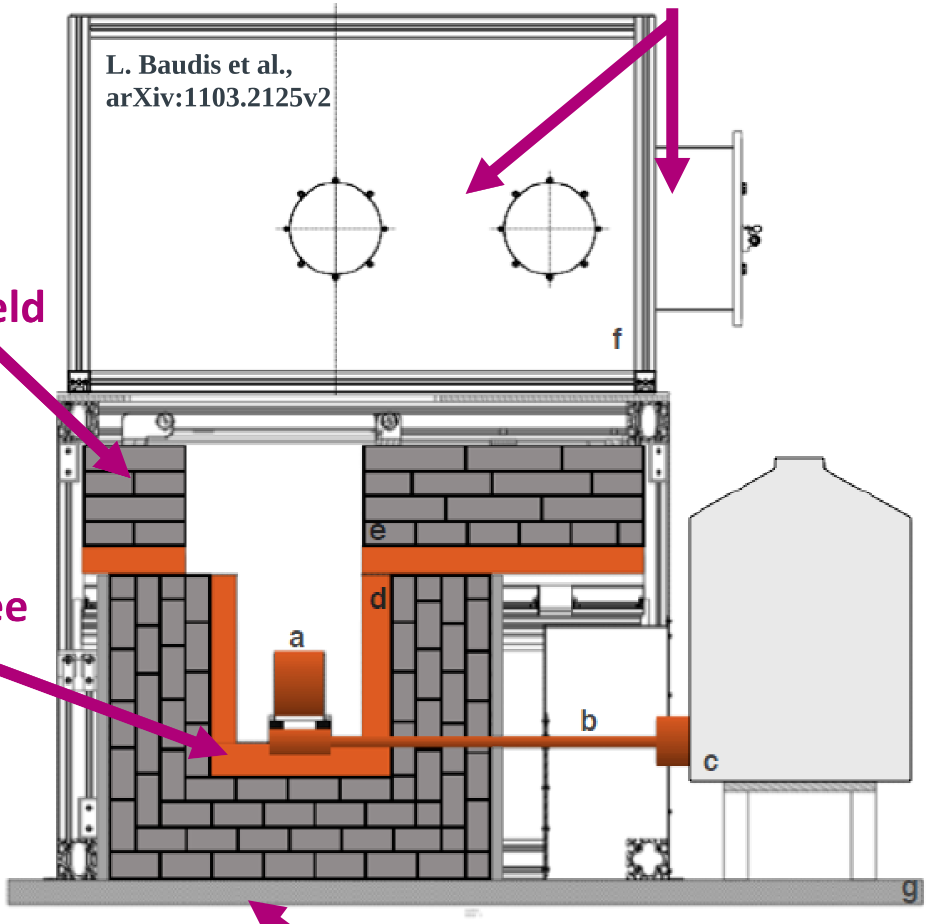
  - **Samples are not destroyed in the process**
  - **Measures full decay U- and Th-chain directly.**

Matthias Laubenstein and Ian Lawson, 10.3389/fphy.2020.577734

(For 100 µBg and a 1 kg sample ~11 days are needed to get a 10 % uncertainty)



Airlock and glove box with dry N_2 overpressure

Lead shield

Oxygen free copper

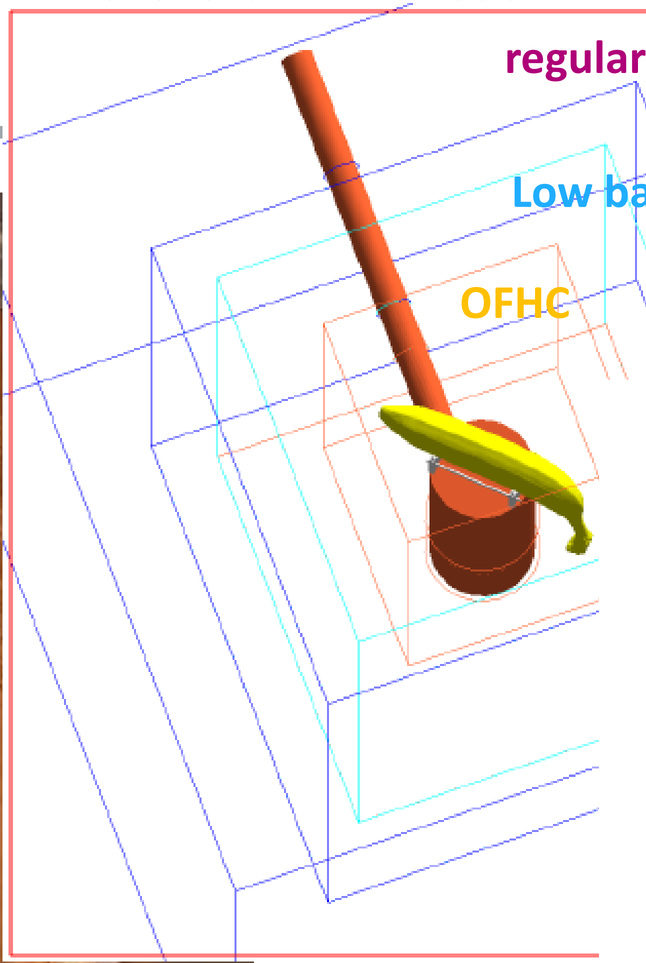
Polyethylene shield against neutrons

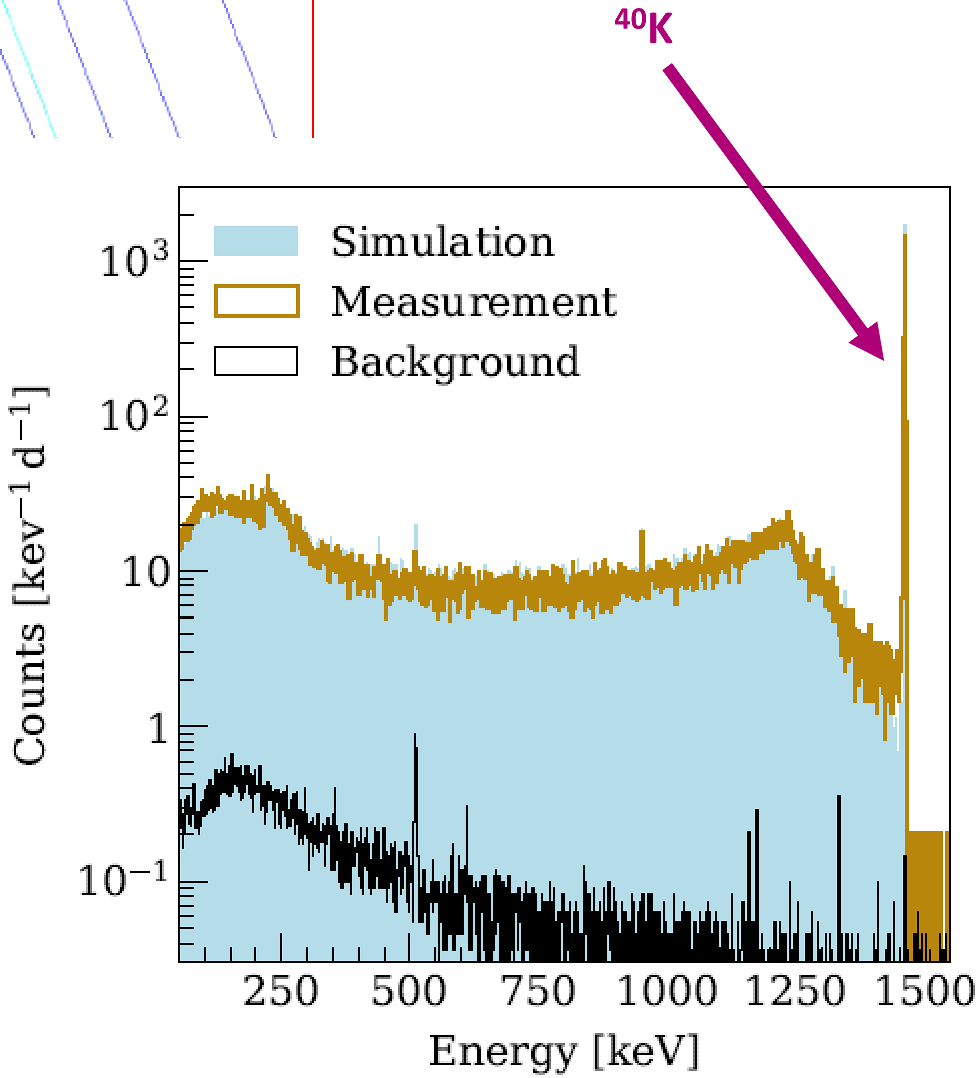
Detector materials

Banana in aluminum foil in GeMSE

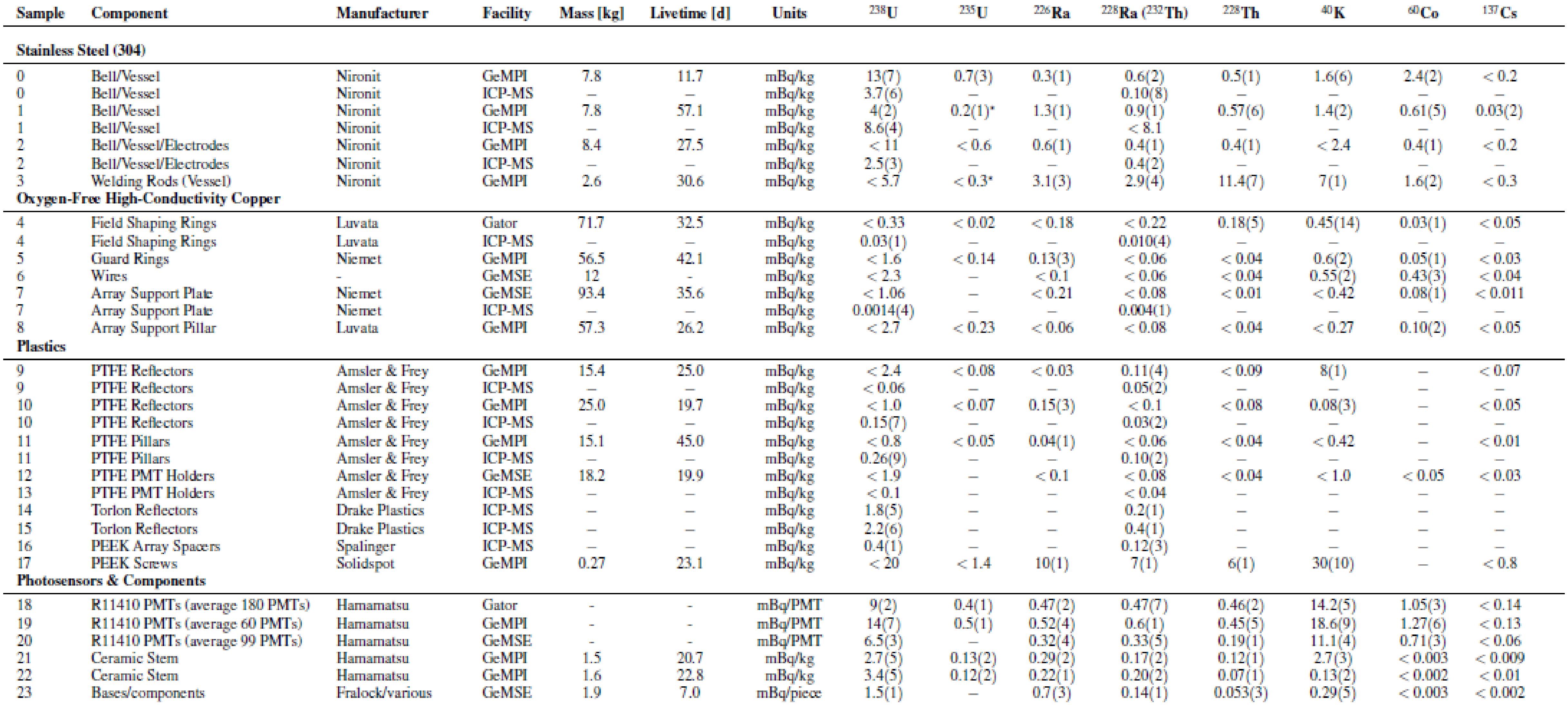
D. Ramierze, 10.6094/UNIFR/228338

Banana GEANT4 model





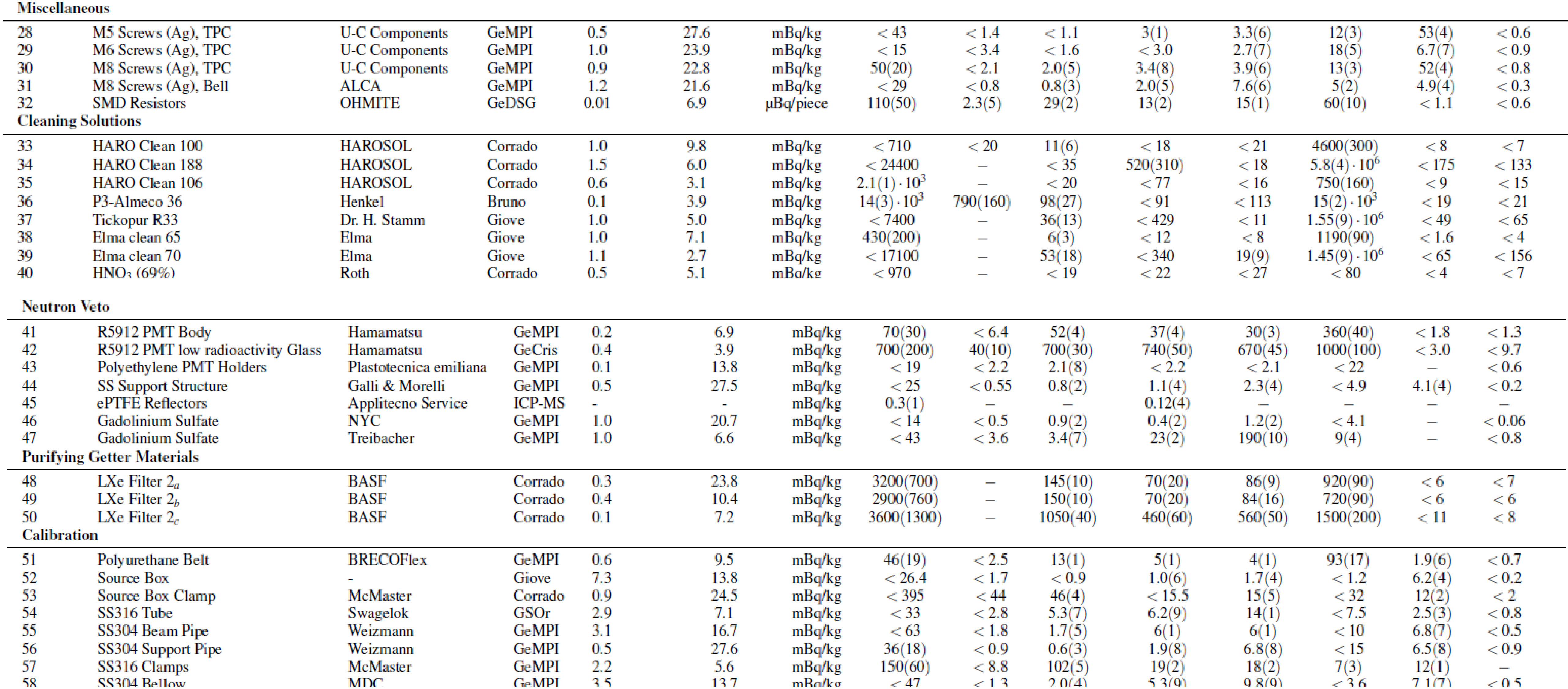
Detector materials



Sample	Component	Manufacturer	Facility	Mass [kg]	Livetime [d]	Units	^{238}U	^{235}U	^{226}Ra	^{228}Ra (^{232}Th)	^{228}Th	^{40}K	^{60}Co	^{137}Cs
Stainless Steel (304)														
0	Bell/Vessel	Nironit	GeMPI	7.8	11.7	mBq/kg	13(7)	0.7(3)	0.3(1)	0.6(2)	0.5(1)	1.6(6)	2.4(2)	< 0.2
0	Bell/Vessel	Nironit	ICP-MS	–	–	mBq/kg	3.7(6)	–	–	0.10(8)	–	–	–	–
1	Bell/Vessel	Nironit	GeMPI	7.8	57.1	mBq/kg	4(2)	0.2(1)*	1.3(1)	0.9(1)	0.57(6)	1.4(2)	0.61(5)	0.03(2)
1	Bell/Vessel	Nironit	ICP-MS	–	–	mBq/kg	8.6(4)	–	–	< 8.1	–	–	–	–
2	Bell/Vessel/Electrodes	Nironit	GeMPI	8.4	27.5	mBq/kg	< 11	< 0.6	0.6(1)	0.4(1)	0.4(1)	< 2.4	0.4(1)	< 0.2
2	Bell/Vessel/Electrodes	Nironit	ICP-MS	–	–	mBq/kg	2.5(3)	–	–	0.4(2)	–	–	–	–
3	Welding Rods (Vessel)	Nironit	GeMPI	2.6	30.6	mBq/kg	< 5.7	< 0.3*	3.1(3)	2.9(4)	11.4(7)	7(1)	1.6(2)	< 0.3
Oxygen-Free High-Conductivity Copper														
4	Field Shaping Rings	Luvata	Gator	71.7	32.5	mBq/kg	< 0.33	< 0.02	< 0.18	< 0.22	0.18(5)	0.45(14)	0.03(1)	< 0.05
4	Field Shaping Rings	Luvata	ICP-MS	–	–	mBq/kg	0.03(1)	–	–	0.010(4)	–	–	–	–
5	Guard Rings	Niemet	GeMPI	56.5	42.1	mBq/kg	< 1.6	< 0.14	0.13(3)	< 0.06	< 0.04	0.6(2)	0.05(1)	< 0.03
6	Wires	-	GeMSE	12	-	mBq/kg	< 2.3	–	< 0.1	< 0.06	< 0.04	0.55(2)	0.43(3)	< 0.04
7	Array Support Plate	Niemet	GeMSE	93.4	35.6	mBq/kg	< 1.06	–	< 0.21	< 0.08	< 0.01	< 0.42	0.08(1)	< 0.011
7	Array Support Plate	Niemet	ICP-MS	–	–	mBq/kg	0.0014(4)	–	–	0.004(1)	–	–	–	–
8	Array Support Pillar	Luvata	GeMPI	57.3	26.2	mBq/kg	< 2.7	< 0.23	< 0.06	< 0.08	< 0.04	< 0.27	0.10(2)	< 0.05
Plastics														
9	PTFE Reflectors	Amsler & Frey	GeMPI	15.4	25.0	mBq/kg	< 2.4	< 0.08	< 0.03	0.11(4)	< 0.09	8(1)	–	< 0.07
9	PTFE Reflectors	Amsler & Frey	ICP-MS	–	–	mBq/kg	< 0.06	–	–	0.05(2)	–	–	–	–
10	PTFE Reflectors	Amsler & Frey	GeMPI	25.0	19.7	mBq/kg	< 1.0	< 0.07	0.15(3)	< 0.1	< 0.08	0.08(3)	–	< 0.05
10	PTFE Reflectors	Amsler & Frey	ICP-MS	–	–	mBq/kg	0.15(7)	–	–	0.03(2)	–	–	–	–
11	PTFE Pillars	Amsler & Frey	GeMPI	15.1	45.0	mBq/kg	< 0.8	< 0.05	0.04(1)	< 0.06	< 0.04	< 0.42	–	< 0.01
11	PTFE Pillars	Amsler & Frey	ICP-MS	–	–	mBq/kg	0.26(9)	–	–	0.10(2)	–	–	–	–
12	PTFE PMT Holders	Amsler & Frey	GeMSE	18.2	19.9	mBq/kg	< 1.9	–	< 0.1	< 0.08	< 0.04	< 1.0	< 0.05	< 0.03
13	PTFE PMT Holders	Amsler & Frey	ICP-MS	–	–	mBq/kg	< 0.1	–	–	< 0.04	–	–	–	–
14	Torlon Reflectors	Drake Plastics	ICP-MS	–	–	mBq/kg	1.8(5)	–	–	0.2(1)	–	–	–	–
15	Torlon Reflectors	Drake Plastics	ICP-MS	–	–	mBq/kg	2.2(6)	–	–	0.4(1)	–	–	–	–
16	PEEK Array Spacers	Spalinger	ICP-MS	–	–	mBq/kg	0.4(1)	–	–	0.12(3)	–	–	–	–
17	PEEK Screws	Solidspot	GeMPI	0.27	23.1	mBq/kg	< 20	< 1.4	10(1)	7(1)	6(1)	30(10)	–	< 0.8
Photosensors & Components														
18	R11410 PMTs (average 180 PMTs)	Hamamatsu	Gator	-	-	mBq/PMT	9(2)	0.4(1)	0.47(2)	0.47(7)	0.46(2)	14.2(5)	1.05(3)	< 0.14
19	R11410 PMTs (average 60 PMTs)	Hamamatsu	GeMPI	-	-	mBq/PMT	14(7)	0.5(1)	0.52(4)	0.6(1)	0.45(5)	18.6(9)	1.27(6)	< 0.13
20	R11410 PMTs (average 99 PMTs)	Hamamatsu	GeMSE	-	-	mBq/PMT	6.5(3)	–	0.32(4)	0.33(5)	0.19(1)	11.1(4)	0.71(3)	< 0.06
21	Ceramic Stem	Hamamatsu	GeMPI	1.5	20.7	mBq/kg	2.7(5)	0.13(2)	0.29(2)	0.17(2)	0.12(1)	2.7(3)	< 0.003	< 0.009
22	Ceramic Stem	Hamamatsu	GeMPI	1.6	22.8	mBq/kg	3.4(5)	0.12(2)	0.22(1)	0.20(2)	0.07(1)	0.13(2)	< 0.002	< 0.01
23	Bases/components	Fralock/various	GeMSE	1.9	7.0	mBq/piece	1.5(1)	–	0.7(3)	0.14(1)	0.053(3)	0.29(5)	< 0.003	< 0.002

E. Aprile et al.,
arXiv:2112.05629v2

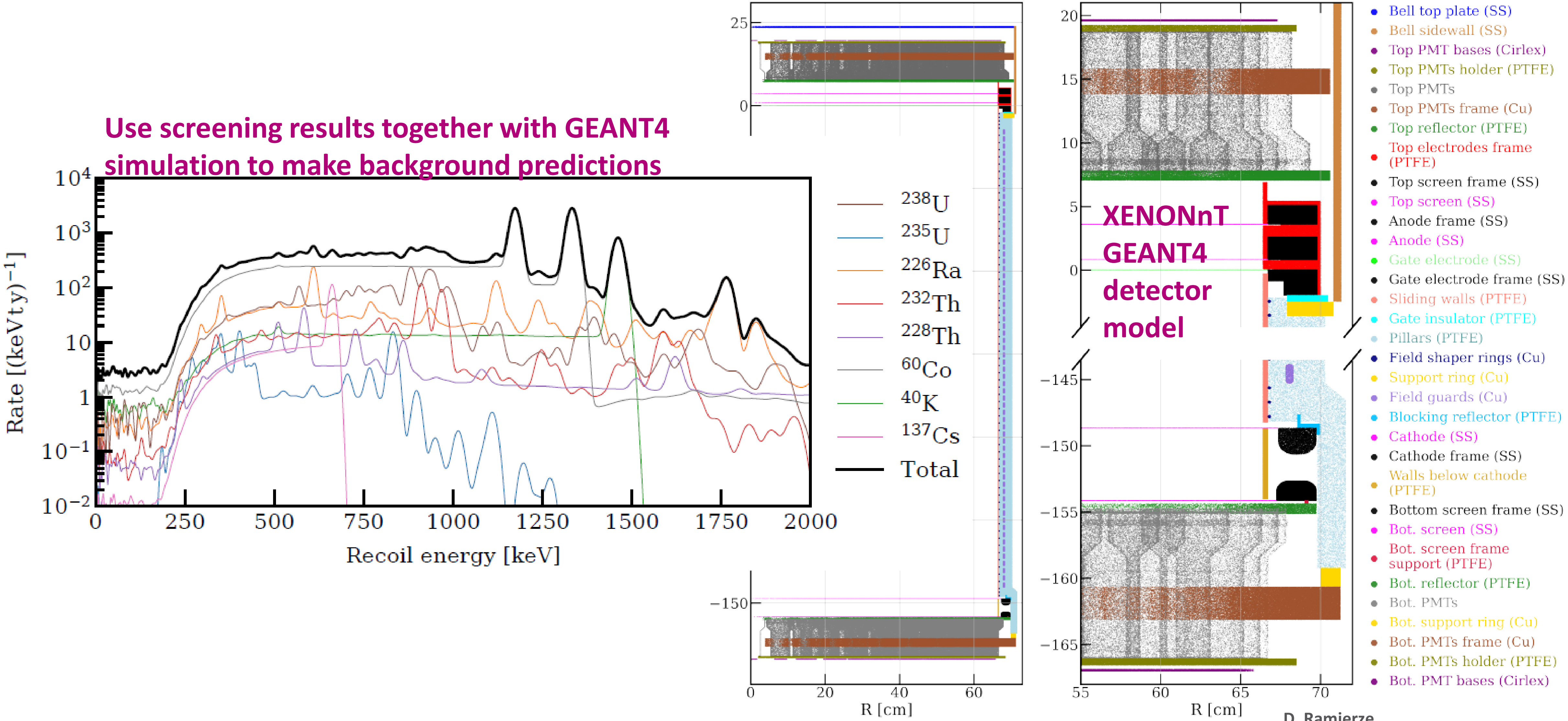
Detector materials



Miscellaneous														
28	M5 Screws (Ag), TPC	U-C Components	GeMPI	0.5	27.6	mBq/kg	< 43	< 1.4	< 1.1	3(1)	3.3(6)	12(3)	53(4)	< 0.6
29	M6 Screws (Ag), TPC	U-C Components	GeMPI	1.0	23.9	mBq/kg	< 15	< 3.4	< 1.6	< 3.0	2.7(7)	18(5)	6.7(7)	< 0.9
30	M8 Screws (Ag), TPC	U-C Components	GeMPI	0.9	22.8	mBq/kg	50(20)	< 2.1	2.0(5)	3.4(8)	3.9(6)	13(3)	52(4)	< 0.8
31	M8 Screws (Ag), Bell	ALCA	GeMPI	1.2	21.6	mBq/kg	< 29	< 0.8	0.8(3)	2.0(5)	7.6(6)	5(2)	4.9(4)	< 0.3
32	SMD Resistors	OHMITE	GeDSG	0.01	6.9	µBq/piece	110(50)	2.3(5)	29(2)	13(2)	15(1)	60(10)	< 1.1	< 0.6
Cleaning Solutions														
33	HARO Clean 100	HAROSOL	Corrado	1.0	9.8	mBq/kg	< 710	< 20	11(6)	< 18	< 21	4600(300)	< 8	< 7
34	HARO Clean 188	HAROSOL	Corrado	1.5	6.0	mBq/kg	< 24400	–	< 35	520(310)	< 18	$5.8(4)\cdot10^6$	< 175	< 133
35	HARO Clean 106	HAROSOL	Corrado	0.6	3.1	mBq/kg	$2.1(1)\cdot10^3$	–	< 20	< 77	< 16	750(160)	< 9	< 15
36	P3-Almeco 36	Henkel	Bruno	0.1	3.9	mBq/kg	$14(3)\cdot10^3$	790(160)	98(27)	< 91	< 113	$15(2)\cdot10^3$	< 19	< 21
37	Tickopur R33	Dr. H. Stamm	Giove	1.0	5.0	mBq/kg	< 7400	–	36(13)	< 429	< 11	$1.55(9)\cdot10^6$	< 49	< 65
38	Elma clean 65	Elma	Giove	1.0	7.1	mBq/kg	430(200)	–	6(3)	< 12	< 8	1190(90)	< 1.6	< 4
39	Elma clean 70	Elma	Giove	1.1	2.7	mBq/kg	< 17100	–	53(18)	< 340	19(9)	$1.45(9)\cdot10^6$	< 65	< 156
40	HNO$_3$ (69%)	Roth	Corrado	0.5	5.1	mBq/kg	< 970	–	< 19	< 22	< 27	< 80	< 4	< 7
Neutron Veto														
41	R5912 PMT Body	Hamamatsu	GeMPI	0.2	6.9	mBq/kg	70(30)	< 6.4	52(4)	37(4)	30(3)	360(40)	< 1.8	< 1.3
42	R5912 PMT low radioactivity Glass	Hamamatsu	GeCris	0.4	3.9	mBq/kg	700(200)	40(10)	700(30)	740(50)	670(45)	1000(100)	< 3.0	< 9.7
43	Polyethylene PMT Holders	Plastotecnica emiliana	GeMPI	0.1	13.8	mBq/kg	< 19	< 2.2	2.1(8)	< 2.2	< 2.1	< 22	–	< 0.6
44	SS Support Structure	Galli & Morelli	GeMPI	0.5	27.5	mBq/kg	< 25	< 0.55	0.8(2)	1.1(4)	2.3(4)	< 4.9	4.1(4)	< 0.2
45	ePTFE Reflectors	Applitecno Service	ICP-MS	-	-	mBq/kg	0.3(1)	–	–	0.12(4)	–	–	–	–
46	Gadolinium Sulfate	NYC	GeMPI	1.0	20.7	mBq/kg	< 14	< 0.5	0.9(2)	0.4(2)	1.2(2)	< 4.1	–	< 0.06
47	Gadolinium Sulfate	Treibacher	GeMPI	1.0	6.6	mBq/kg	< 43	< 3.6	3.4(7)	23(2)	190(10)	9(4)	–	< 0.8
Purifying Getter Materials														
48	LXe Filter 2_a	BASF	Corrado	0.3	23.8	mBq/kg	3200(700)	–	145(10)	70(20)	86(9)	920(90)	< 6	< 7
49	LXe Filter 2_b	BASF	Corrado	0.4	10.4	mBq/kg	2900(760)	–	150(10)	70(20)	84(16)	720(90)	< 6	< 6
50	LXe Filter 2_c	BASF	Corrado	0.1	7.2	mBq/kg	3600(1300)	–	1050(40)	460(60)	560(50)	1500(200)	< 11	< 8
Calibration														
51	Polyurethane Belt	BRECOFlex	GeMPI	0.6	9.5	mBq/kg	46(19)	< 2.5	13(1)	5(1)	4(1)	93(17)	1.9(6)	< 0.7
52	Source Box	-	Giove	7.3	13.8	mBq/kg	< 26.4	< 1.7	< 0.9	1.0(6)	1.7(4)	< 1.2	6.2(4)	< 0.2
53	Source Box Clamp	McMaster	Corrado	0.9	24.5	mBq/kg	< 395	< 44	46(4)	< 15.5	15(5)	< 32	12(2)	< 2
54	SS316 Tube	Swagelok	GSOr	2.9	7.1	mBq/kg	< 33	< 2.8	5.3(7)	6.2(9)	14(1)	< 7.5	2.5(3)	< 0.8
55	SS304 Beam Pipe	Weizmann	GeMPI	3.1	16.7	mBq/kg	< 63	< 1.8	1.7(5)	6(1)	6(1)	< 10	6.8(7)	< 0.5
56	SS304 Support Pipe	Weizmann	GeMPI	0.5	27.6	mBq/kg	36(18)	< 0.9	0.6(3)	1.9(8)	6.8(8)	< 15	6.5(8)	< 0.9
57	SS316 Clamps	McMaster	GeMPI	2.2	5.6	mBq/kg	150(60)	< 8.8	102(5)	19(2)	18(2)	7(3)	12(1)	–
58	SS304 Bellow	MDC	GeMPI	3.5	13.7	mBq/kg	< 47	< 1.3	2.0(4)	5.3(9)	9.8(9)	< 3.6	7.1(7)	< 0.5

Detector materials

Use screening results together with GEANT4 simulation to make background predictions



XENONnT GEANT4 detector model

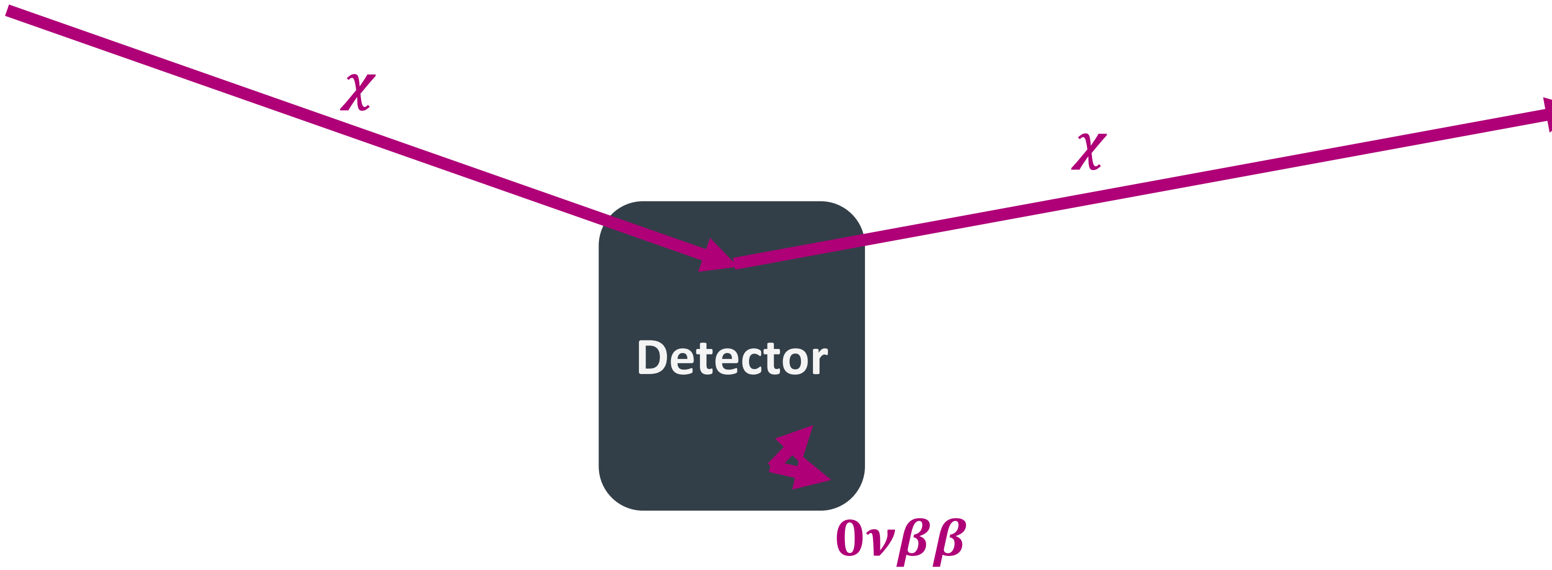
D. Ramierze, 10.6094/UNIFR/228338


XENON

Recap: Low energy rare event searches

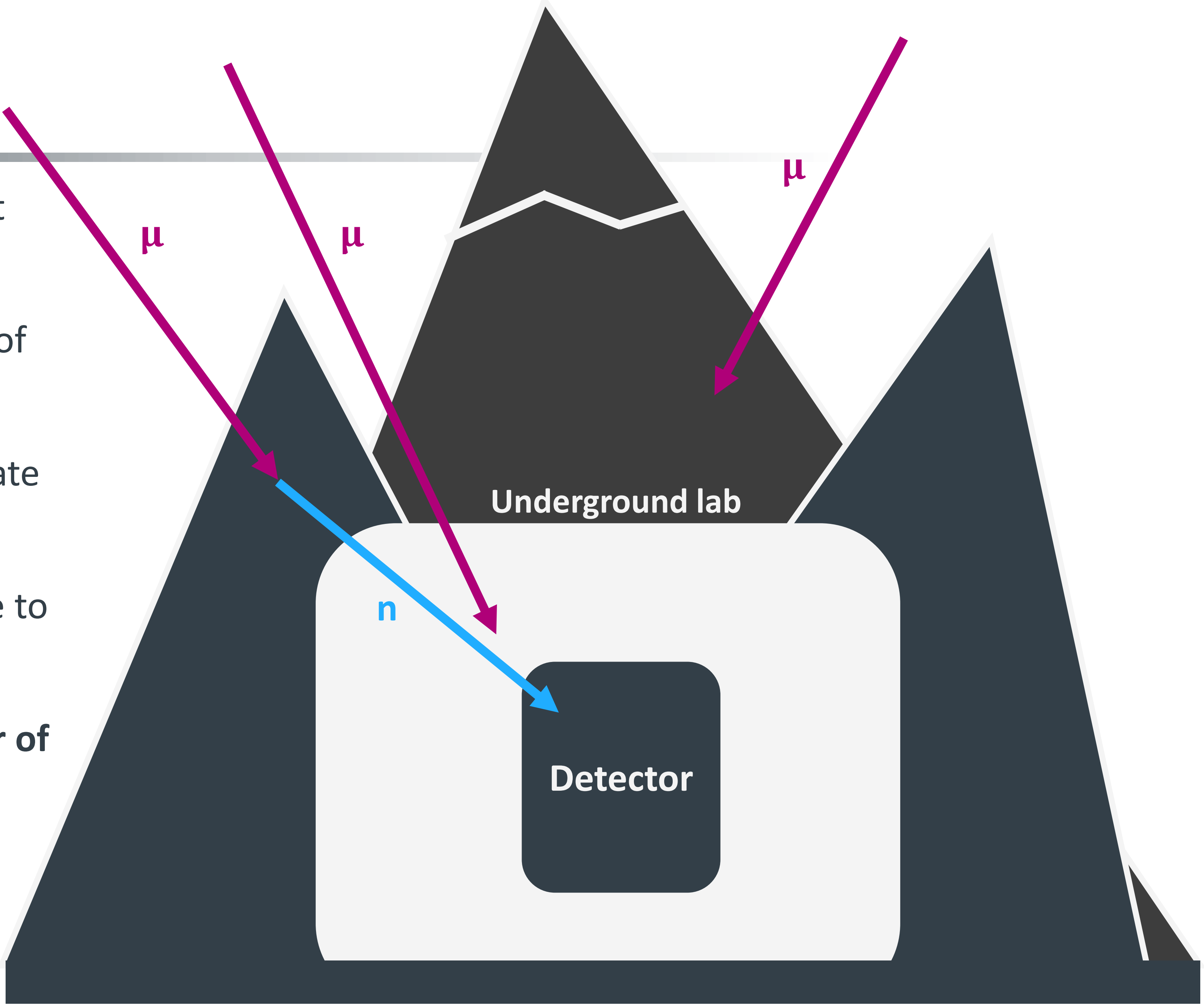
- Sensitivity of background free experiments scale with exposure T
- Background dominated experiments with $\sqrt{T}$
- Search for the needle in the haystack
  - **Current experiment expect rates of $\sim 20 \frac{1}{\text{tonne x year}}$**
  - **Problem, we live in a radioactive world:**

$$\sim 10^{12} \frac{1}{\text{human tonne x year}}$$



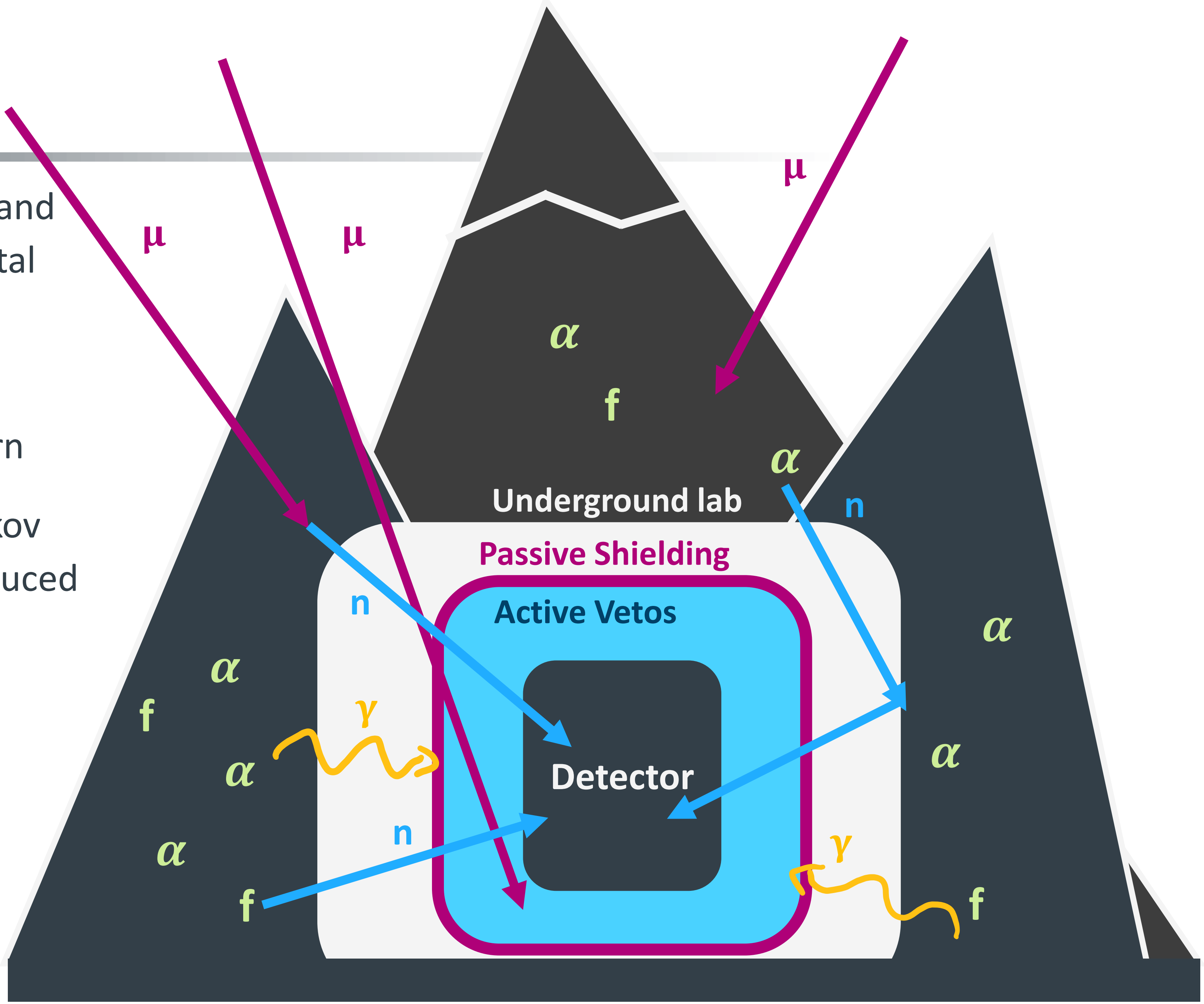
Underground laboratories

- Typical muon rate at sea level about 1 μ/min/cm^2
- Typical muon energies in the order of ~10 GeV
- Muons produce neutrons and activate detector materials!
- Underground environment effective to reduce Muon induced backgrounds
  - **Typical suppression by 5-7 order of magnitudes**



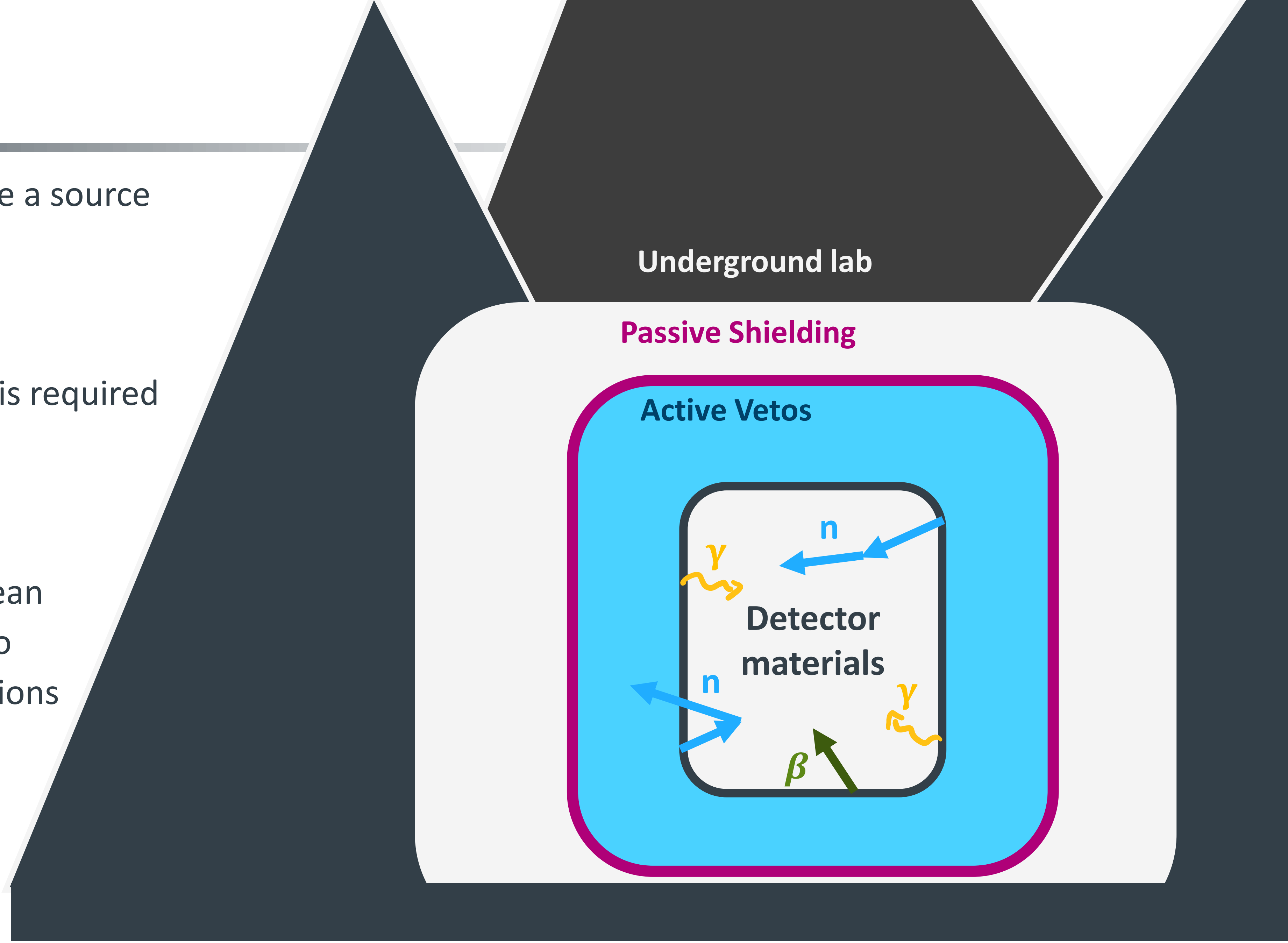
Overview

- Passive shielding layers such as Pb and Cu help to shield from environmental gammas
- Plastics and water help to shield neutrons from the laboratory cavern
- Active vetos such as water Cherenkov detectors help to also reduce μ-induced backgrounds further.



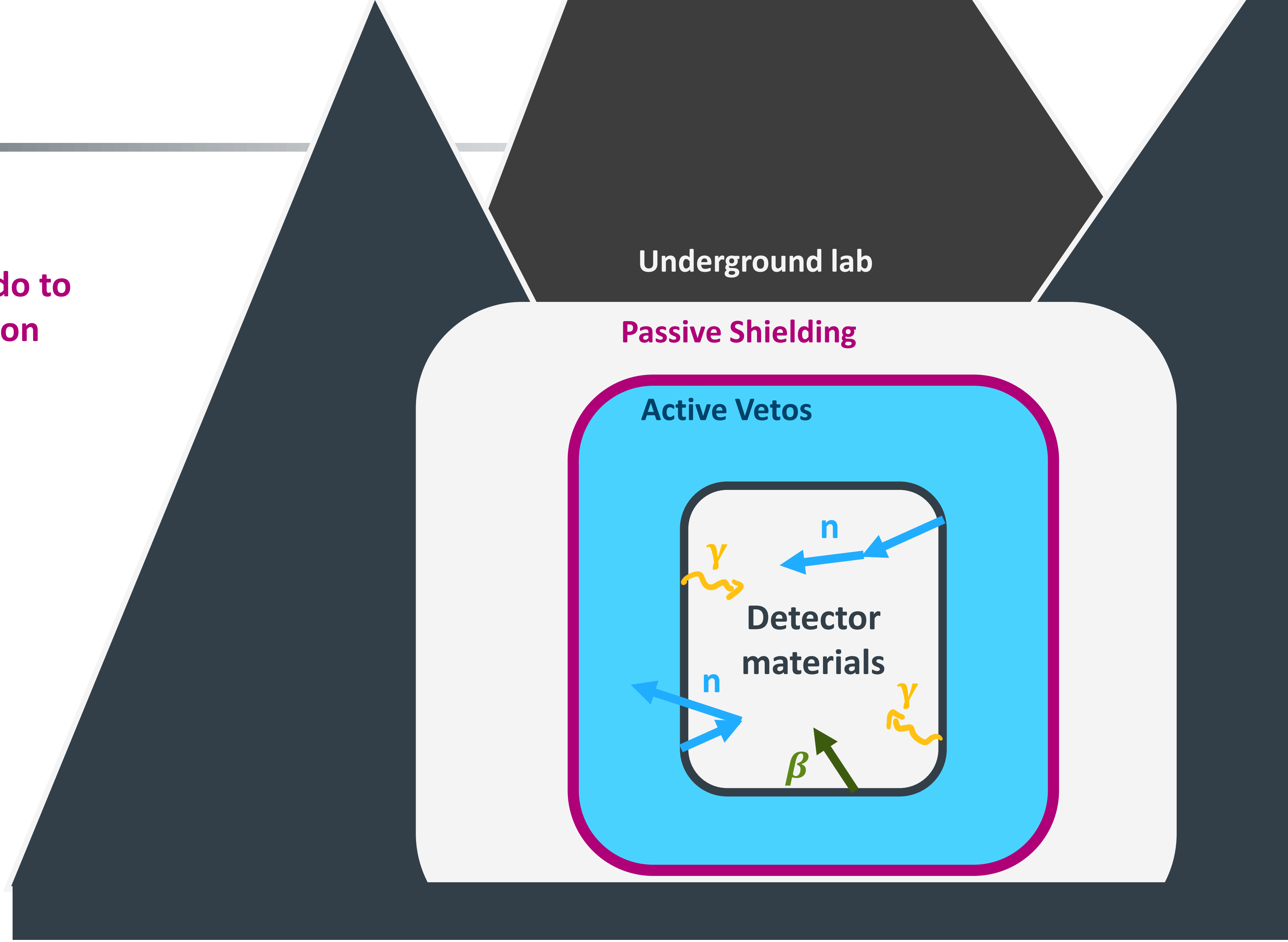
Overview

- Detector materials itself are a source of backgrounds:
  - **U, Th, K, Co,…**
- Careful material screening is required to reduce backgrounds:
  - **HPGe, ICP-MS, NAA,…**
- Cleaning and working in clean environments is required to reduce surface contaminations



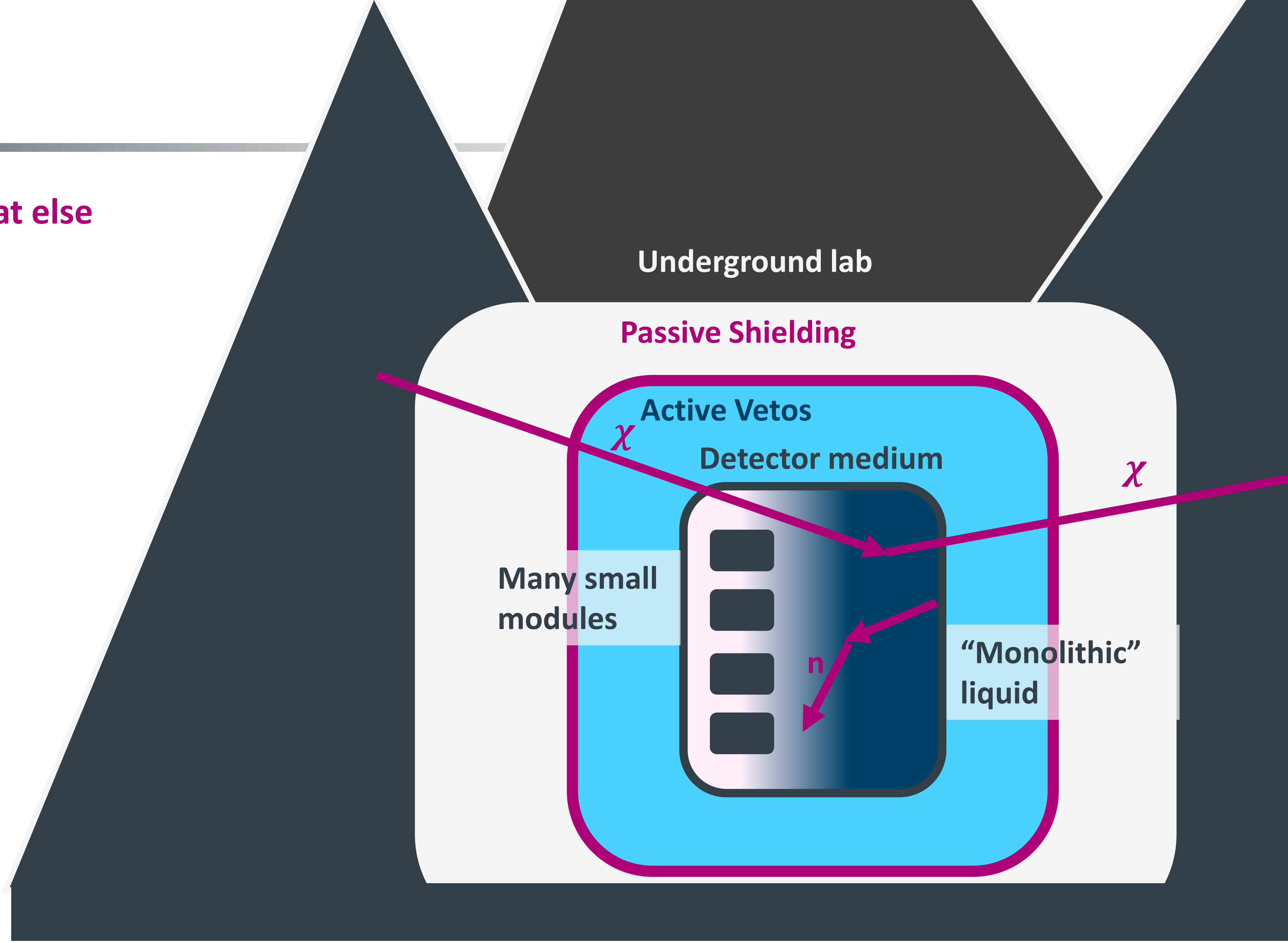
Overview

➡ **What else can we do to reduce the impact on detector material background?**



Overview

The detector is built, but what else can we do?
Be smart about your signal!
Exploit signal topologies.



Overview

➡ What else can we do to reduce the impact on detector material background?