Universität Münster

Low backgrounds for low energy rare event searches

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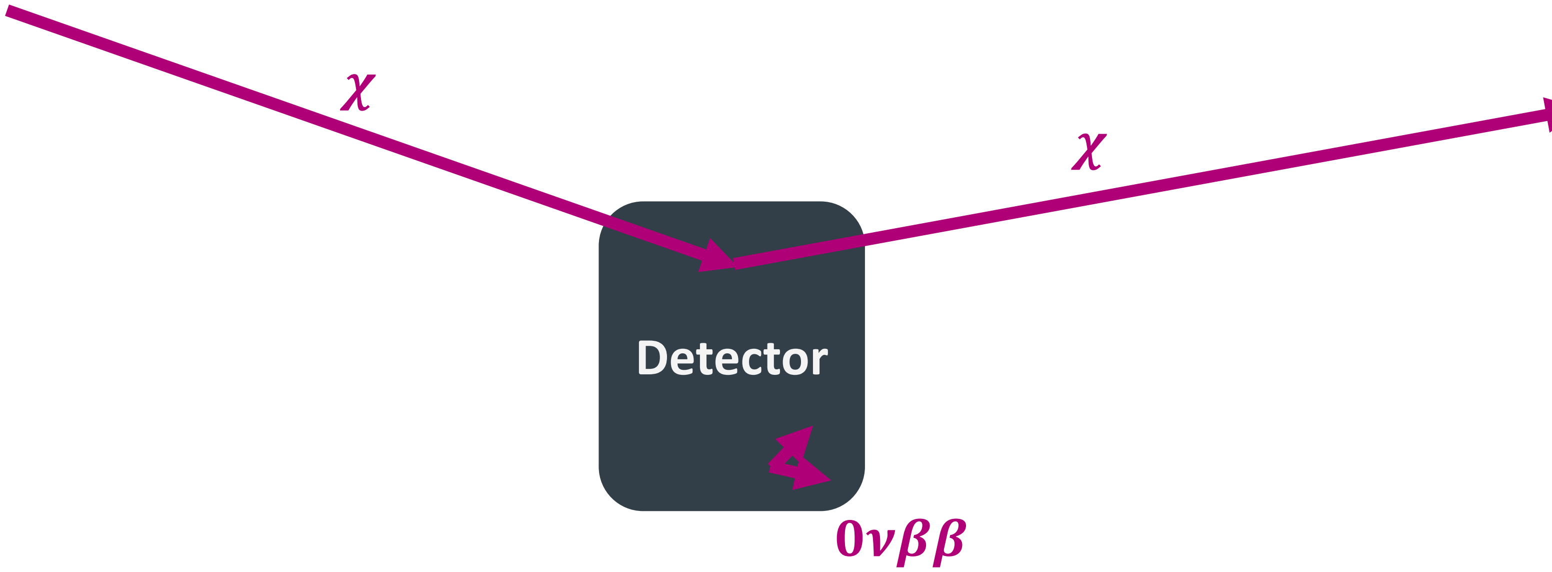
TRISEP Summer School 2024

Recap: Low energy rare event searches

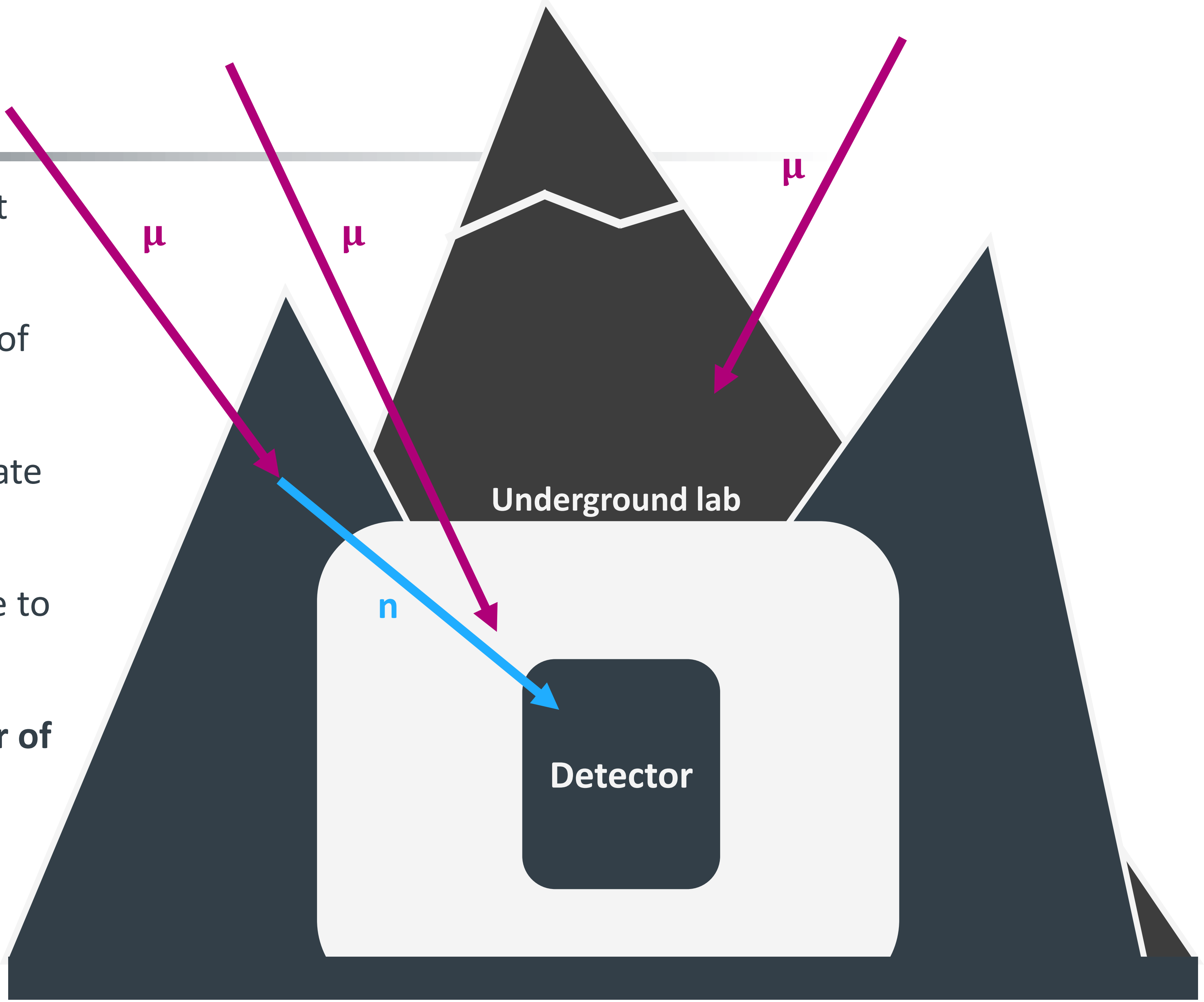
- Sensitivity of background free experiments scale with exposure T
- Background dominated experiments with $\sqrt{T}$
- Search for the needle in the haystack
    - **Current experiment expect rates of** $\sim 20 \frac{1}{\text{tonne x year}}$
    - **Problem, we live in a radioactive world:**

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



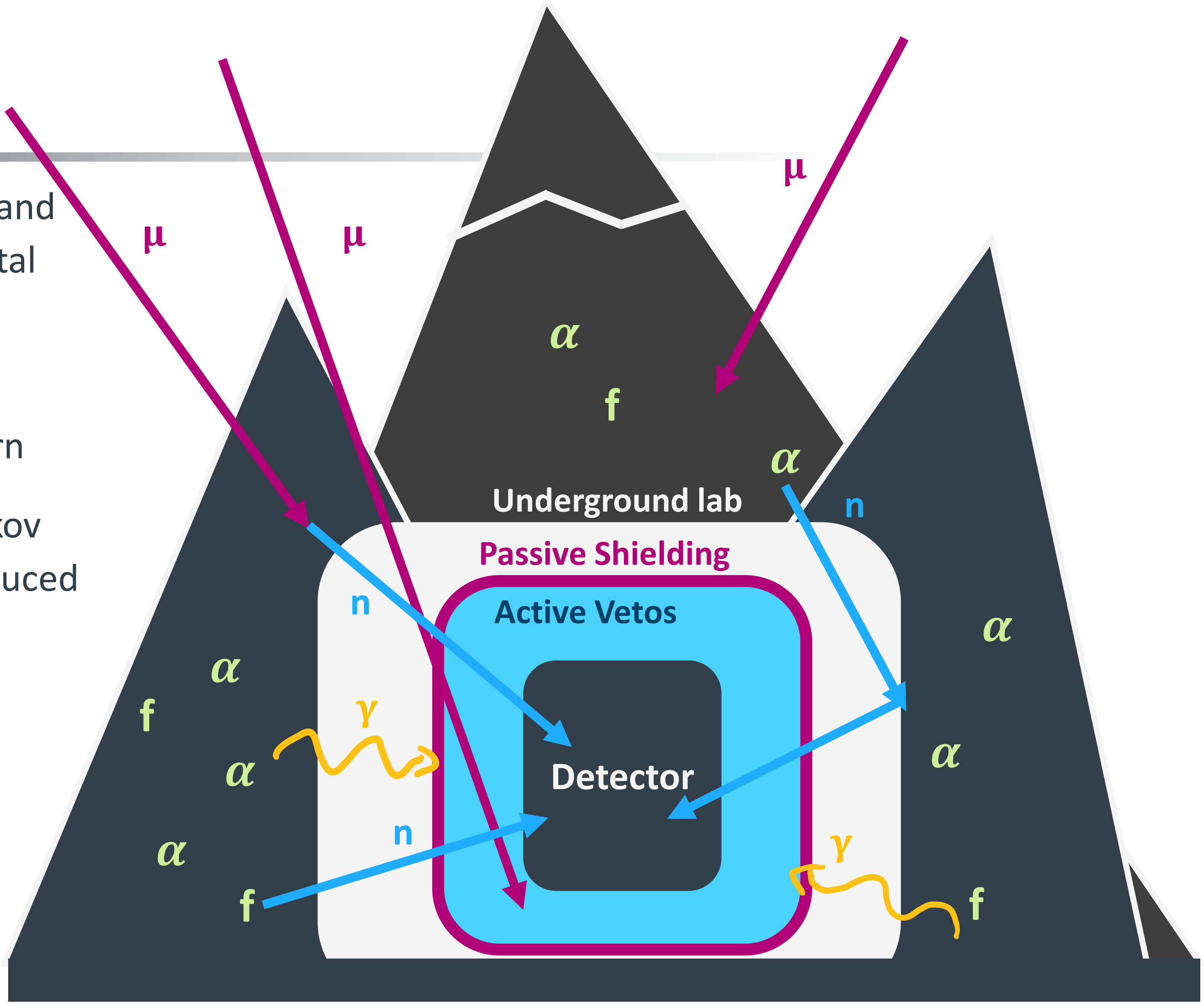
Underground laboratories

- 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**



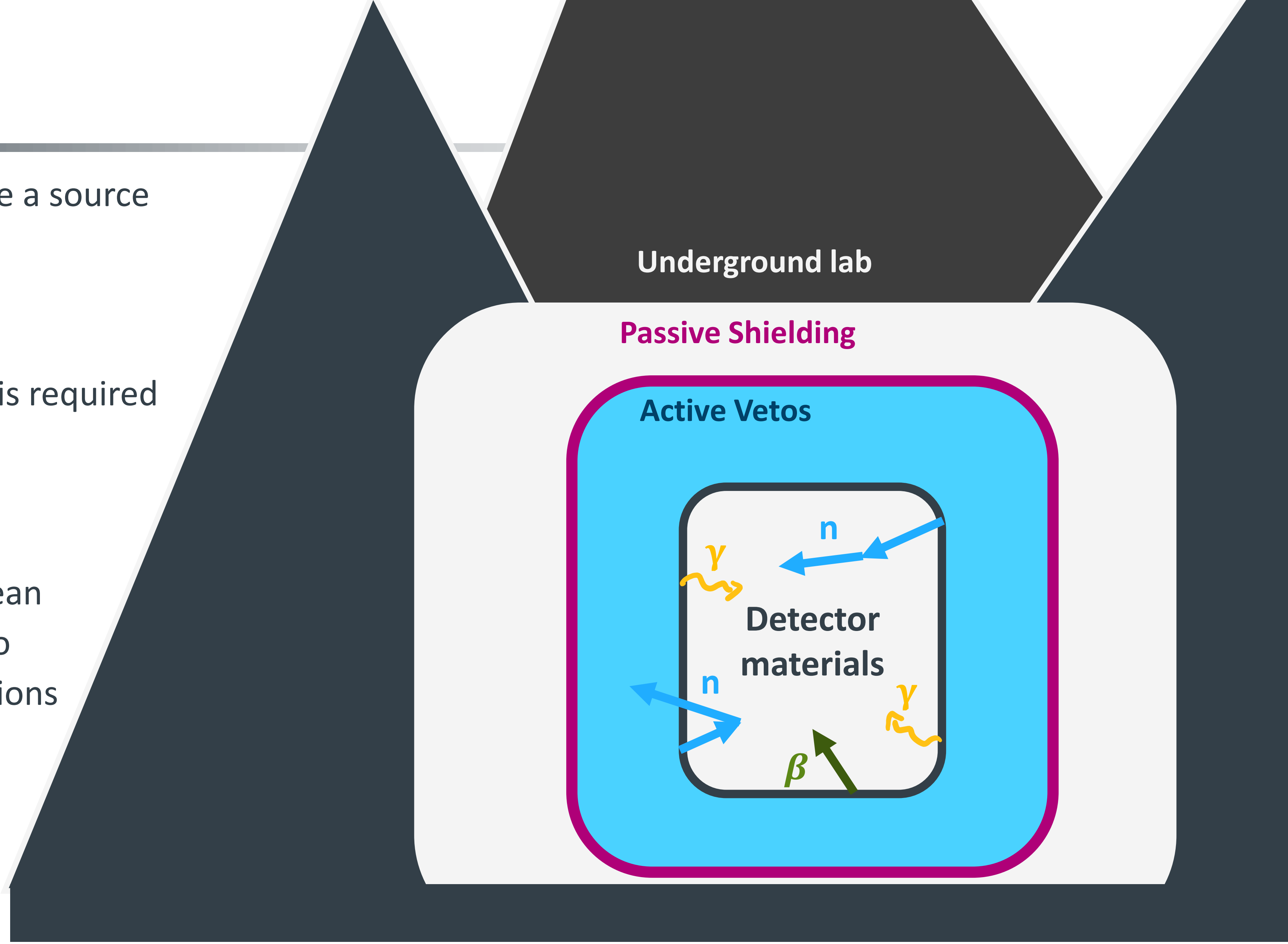
Overview

- 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.



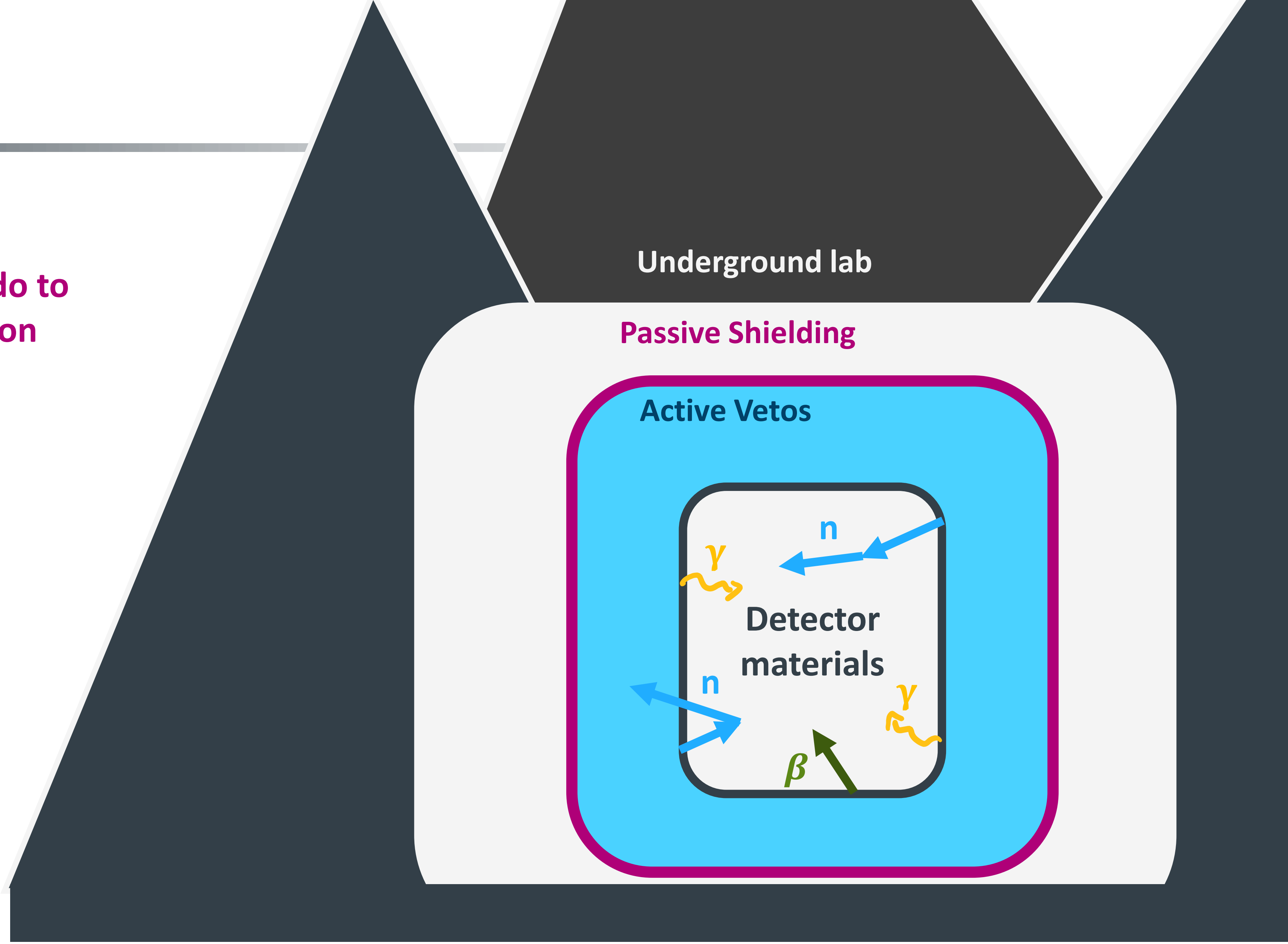
Overview

- 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



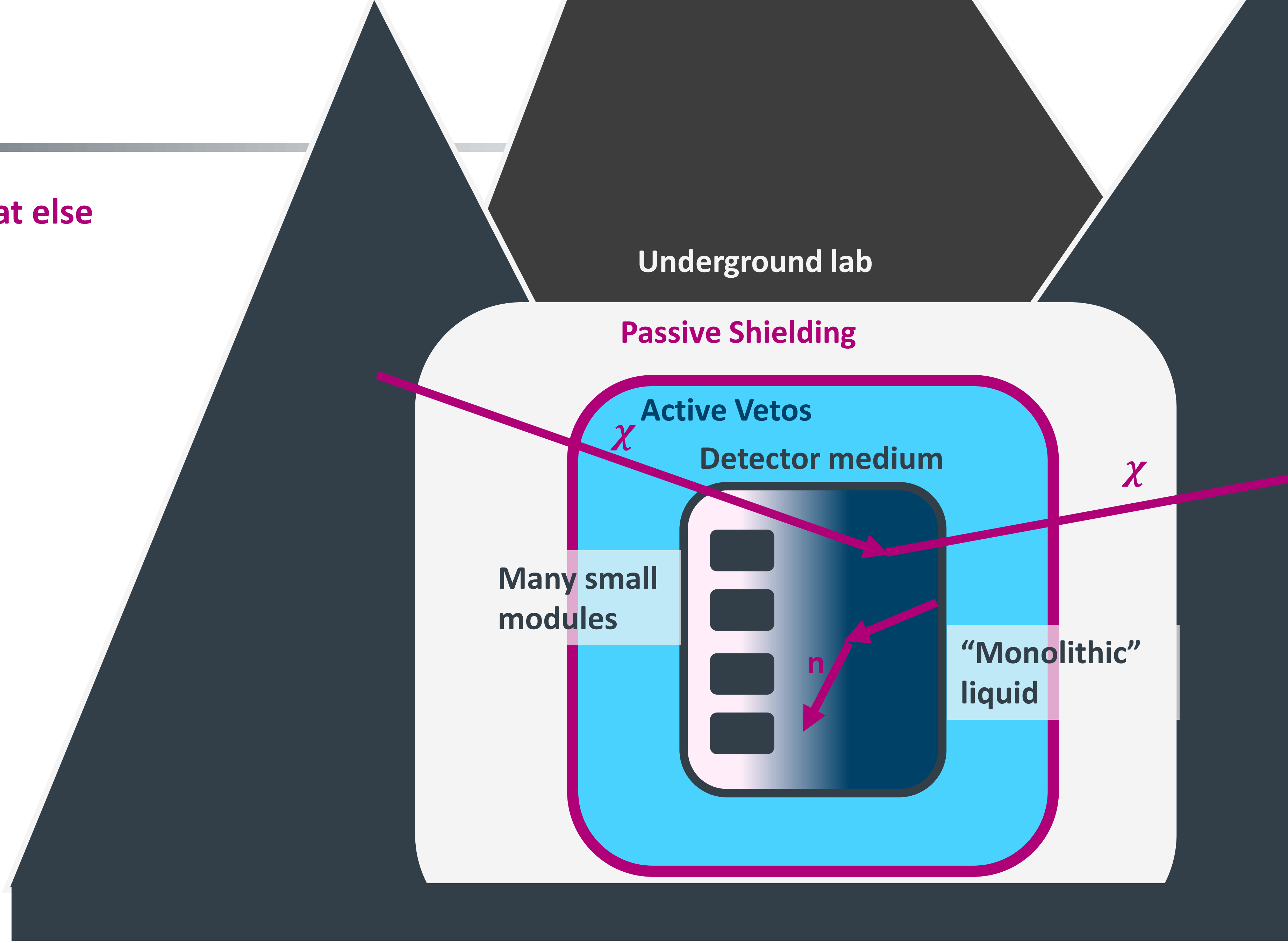
Overview

➡ **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

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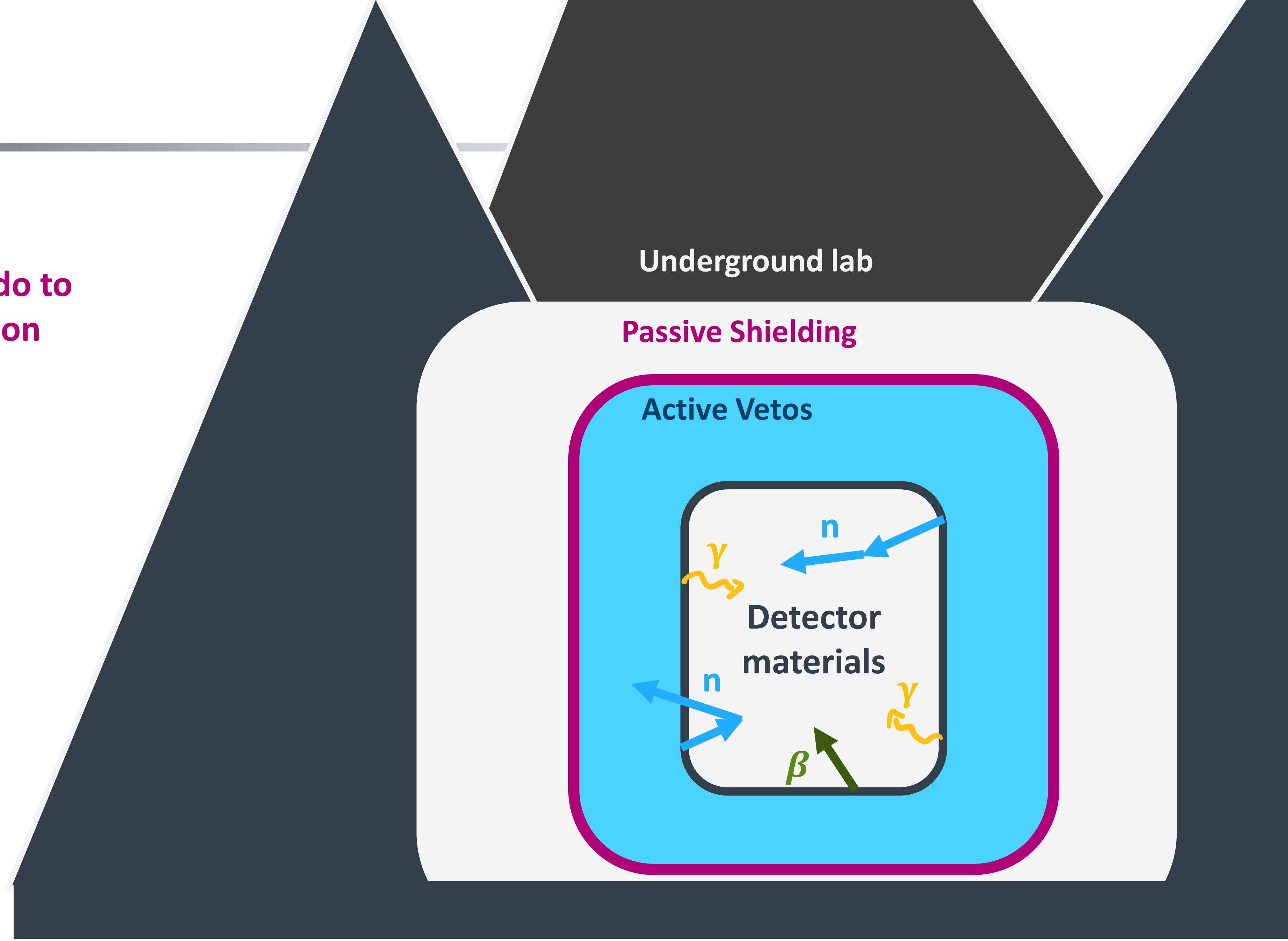
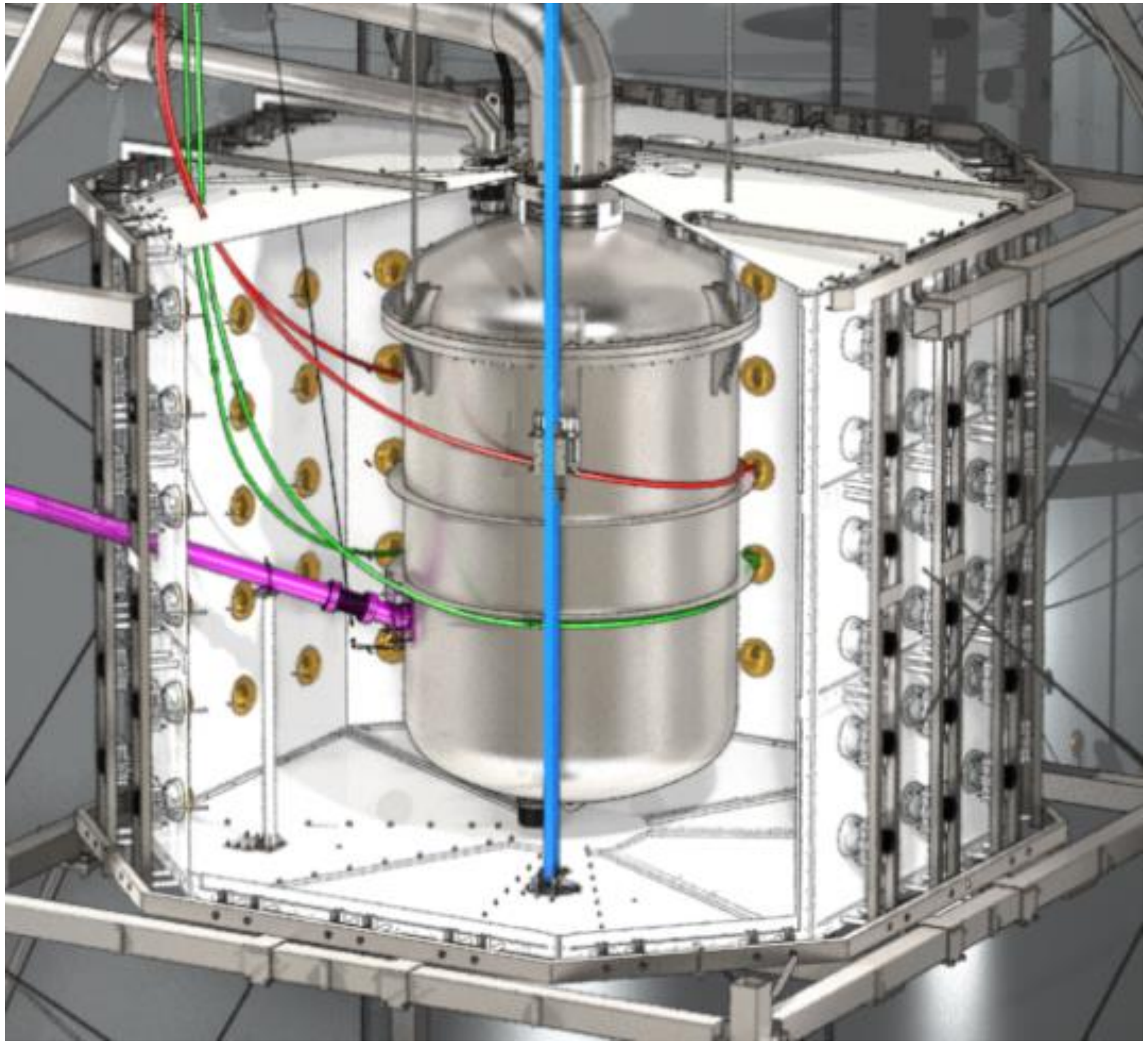


Detector materials

- Material backgrounds can be further mitigated by adding additional active anti-coincidence vetos.
- Example XENONnT uses an additional water Cherenkov detector to veto neutron background



Detector materials

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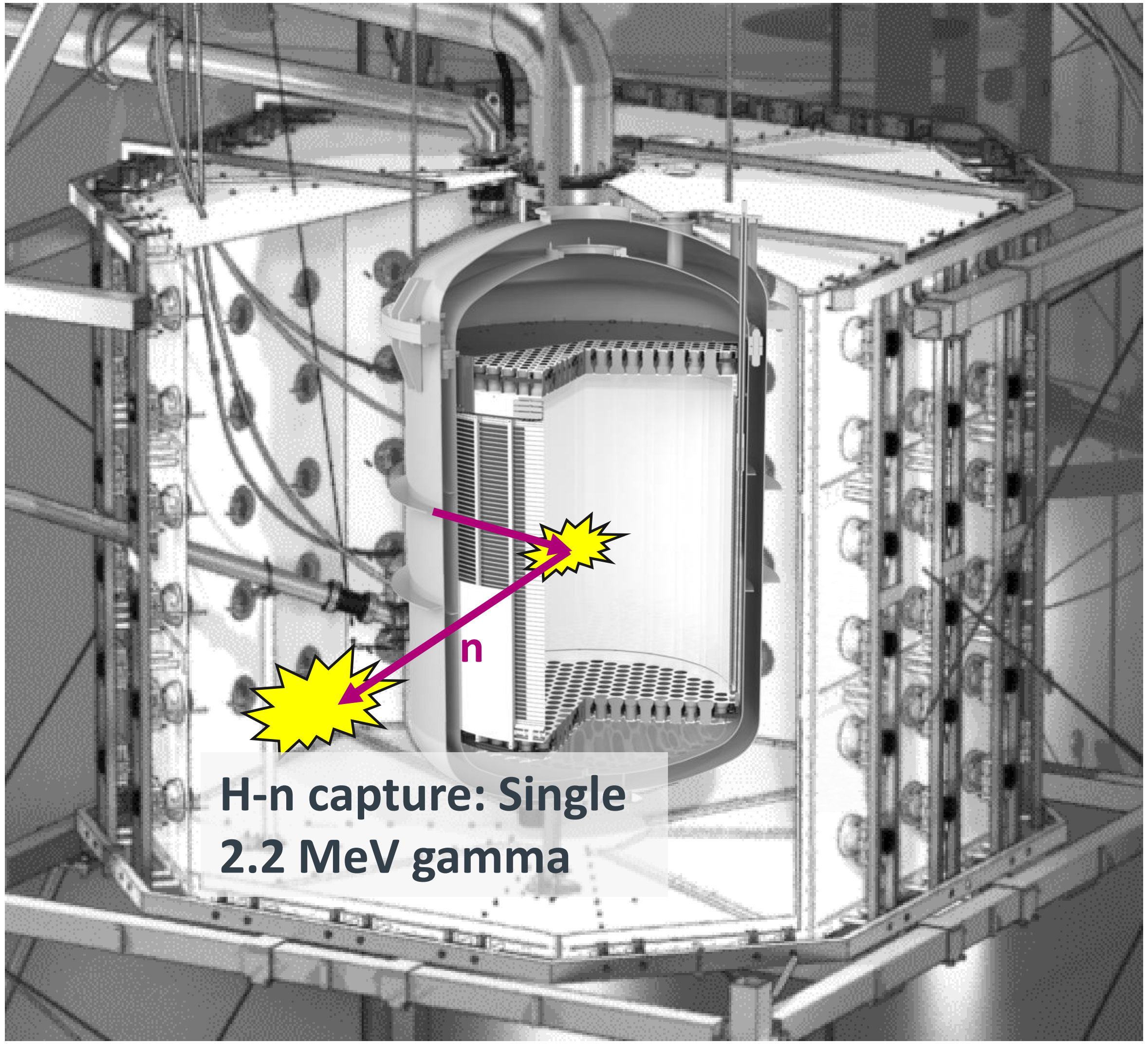
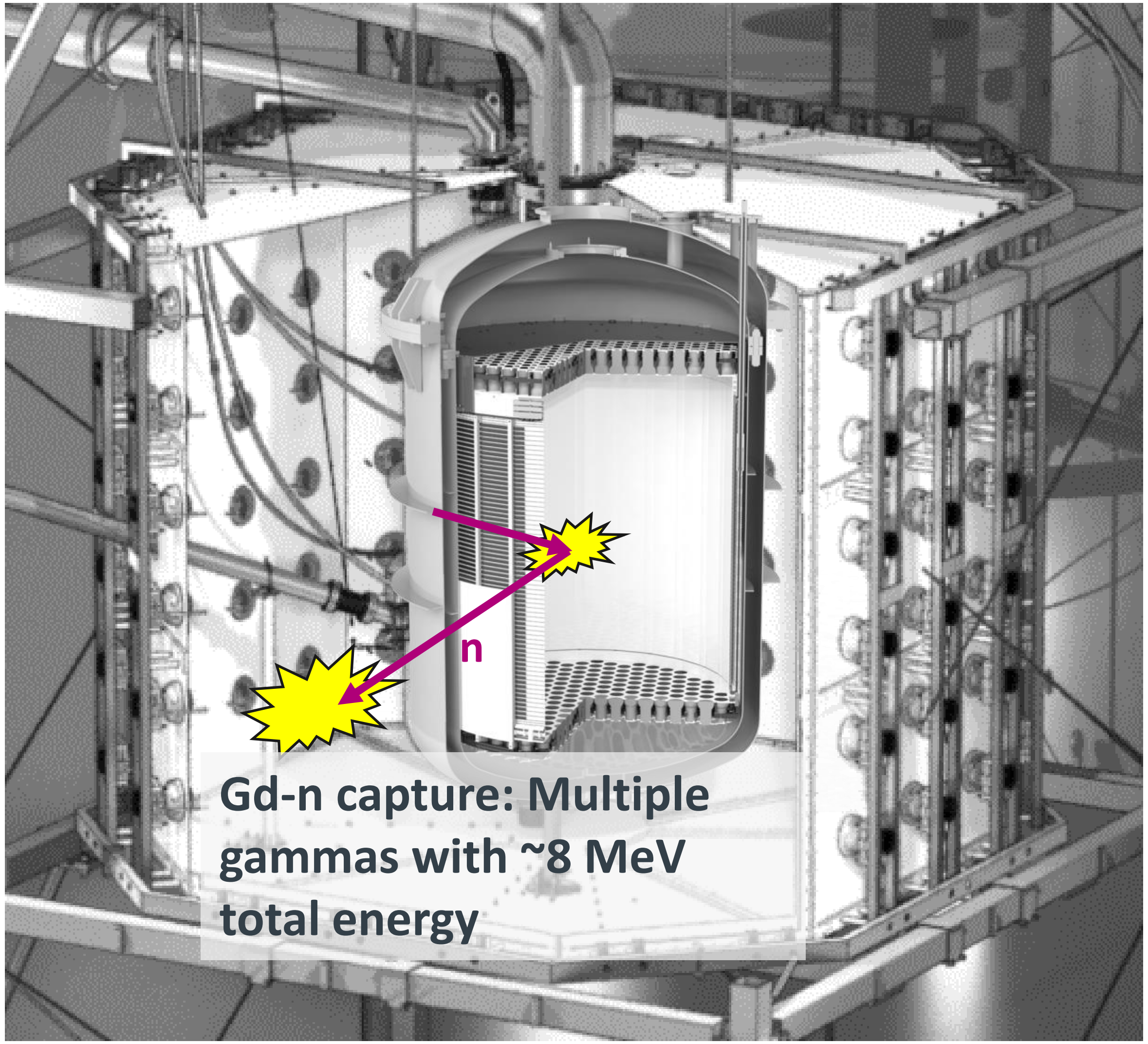
- Example XENONnT uses an additional water Cherenkov detector to veto neutron background
- Neutron tagging via Cherenkov light of neutron capture on hydrogen



Detector materials

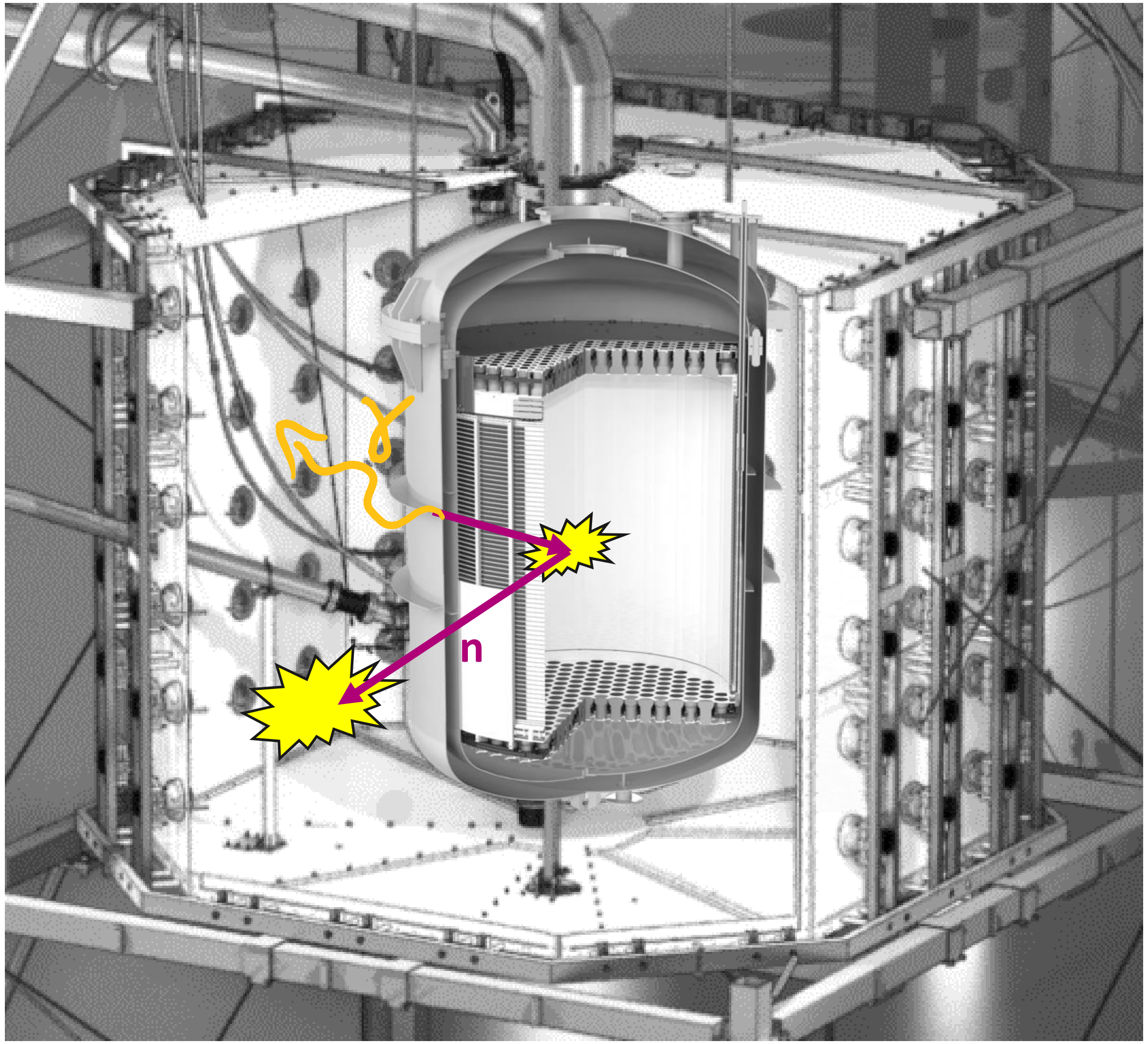
- Material backgrounds can be further mitigated by adding additional active anti-coincidence vetos.
- Example XENONnT uses an additional water Cherenkov detector to veto neutron background
- Neutron tagging via Cherenkov light of neutron capture on hydrogen
- Loading water with Gd_2S0_4
  - **Will increase deposited energy to 8 MeV**
  - **Reduce capture time due to large cross section**
  - **Will increase resulting tagging efficiency from about 50 % to about 90 %**

Elena Aprile et al., (XENON Collaboration), JCAP 11 (2020) 031



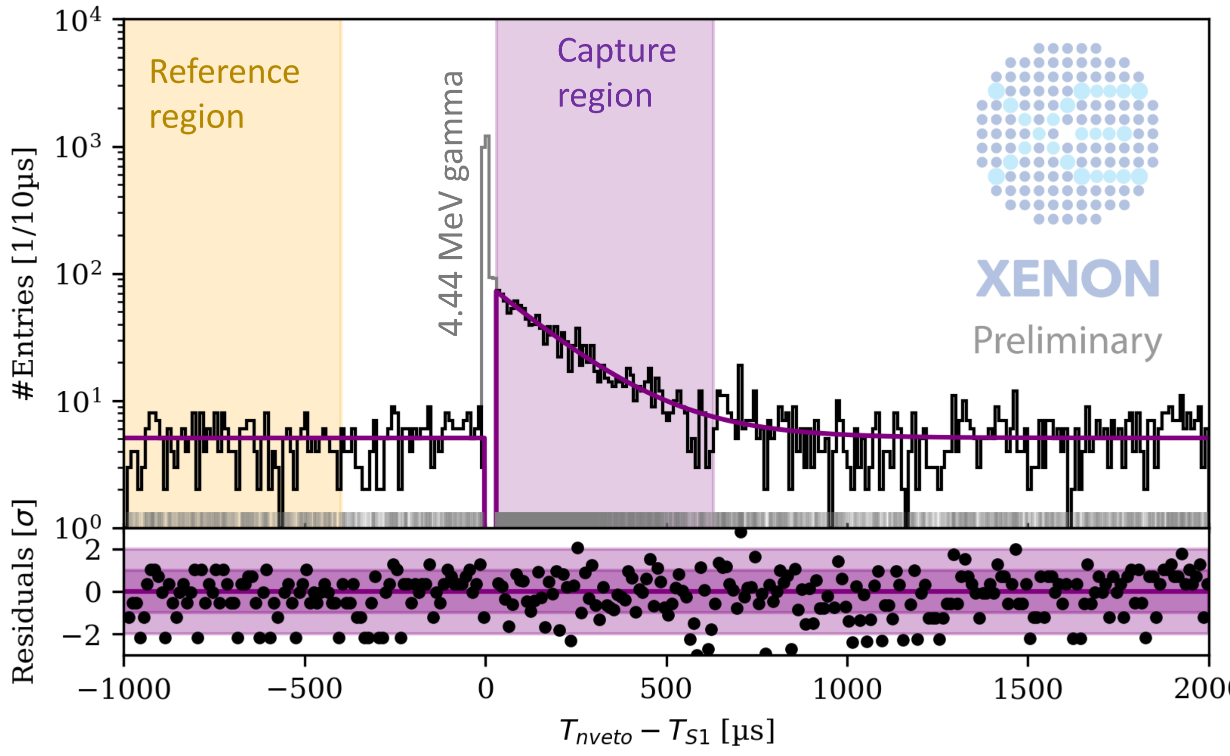
Detector materials

- Calibration of active veto efficiency via an AmBe alpha-neutron source
  - **Advantage emits in about 50 % of all cases an addition 4.4 MeV gamma-ray**



Detector materials

- Calibration of active veto efficiency via an AmBe alpha-neutron source
  - **Advantage emits in about 50 % of all cases an addition 4.4 MeV gamma-ray**
- Neutron tagging via Cherenkov light of n-H capture
  - **Tagging efficiency:** $(53 \pm 3)\%$ **(250 µs window)**
  - Detection efficiency: $(82 \pm 1)\%$ (600 µs window)



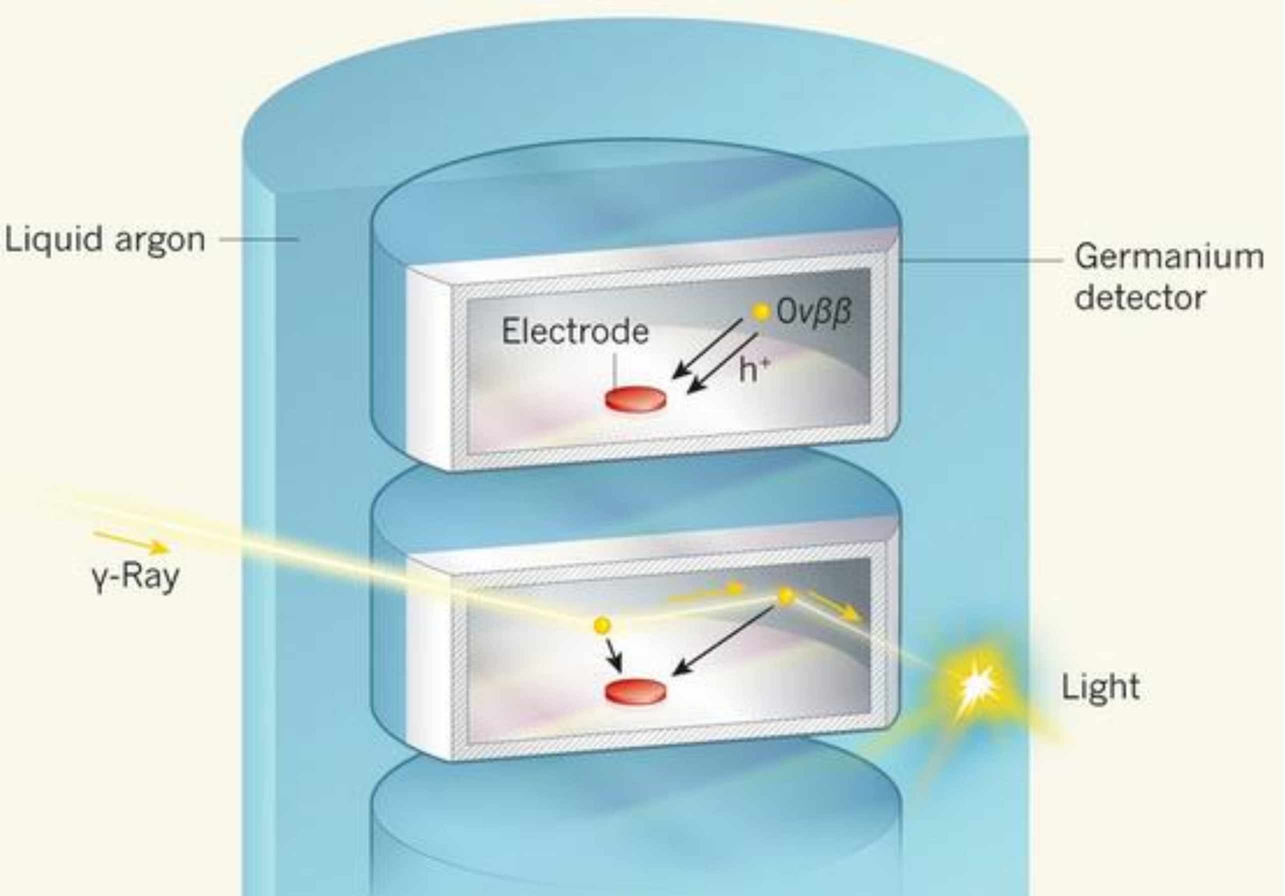
Highest neutron detection efficiency ever measured in a water Cherenkov detector!

Neutron veto calibration using tagged neutrons from an AmBe neutron source

XENON

Detector materials

- Other experiments use other active anti-coincidence vetos
  - **E.g. liquid scintillator by LZ, or LAr in Legend or DarkSide**
  - **Idea is the same: If seen by both detector, it is a background signal**



Barbeau, P. Nature 544, 38–39 (2017)

Detector materials

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  - **E.g. liquid scintillator by LZ, or LAr in Legend or DarkSide**
    - **In LEGEND light is collected by wavelength shifting fibers onto silicon photomultipliers (light sensors)**
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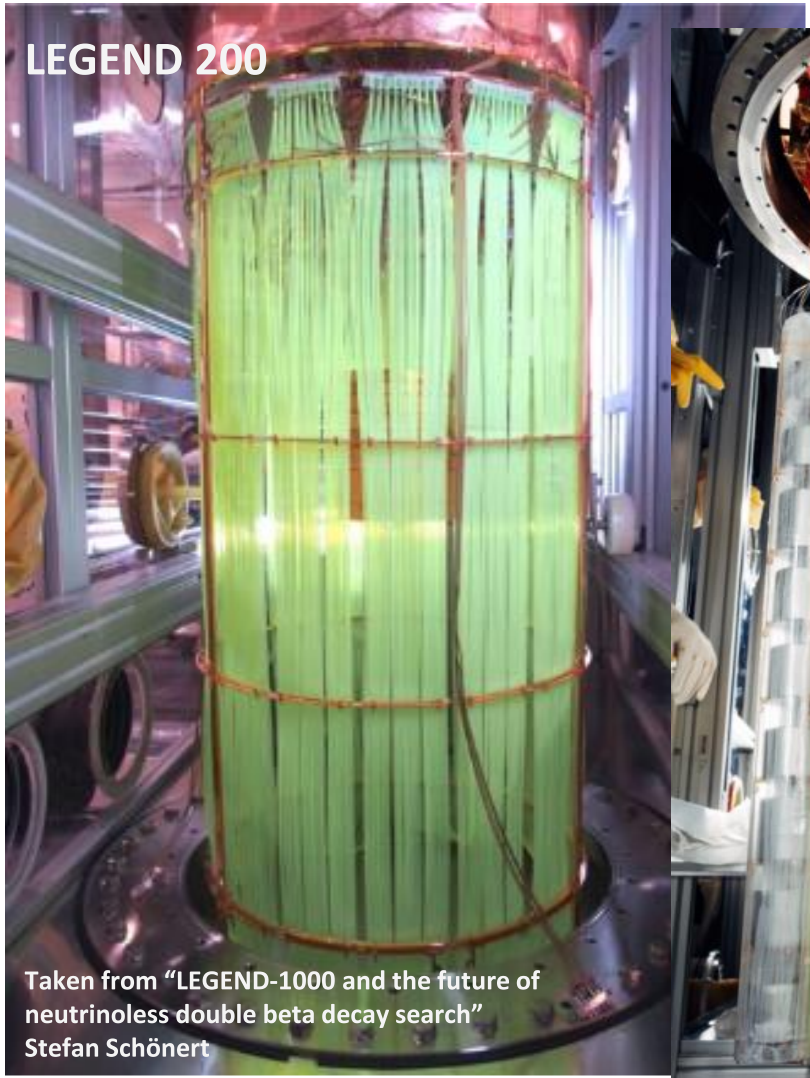

Taken from "LEGEND-1000 and the future of neutrinoless double beta decay search" Stefan Schönert


Taken from Susanne Mertens

Detector materials

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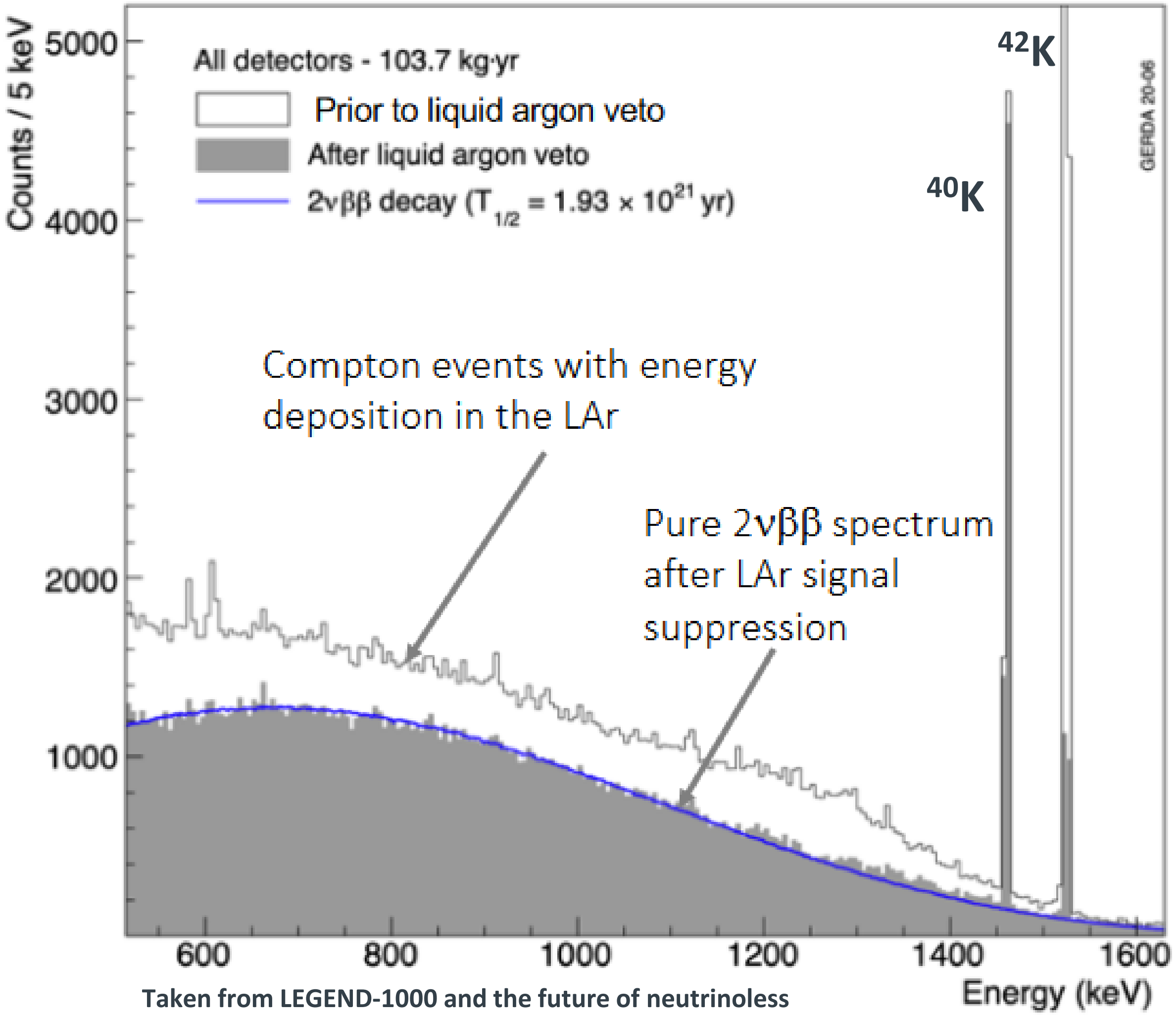
  - **E.g. liquid scintillator by LZ, or LAr in Legend or DarkSide**
    - **In LEGEND light is collected by wavelength shifting fibers onto silicon photomultipliers (light sensors)**
  - **Idea is the same: If seen by both detector, it is a background signal**
  - **However, LAr itself has intrinsic radioactive isotopes (^{39}Ar, ^{42}Ar) which contribute to the detector background!**

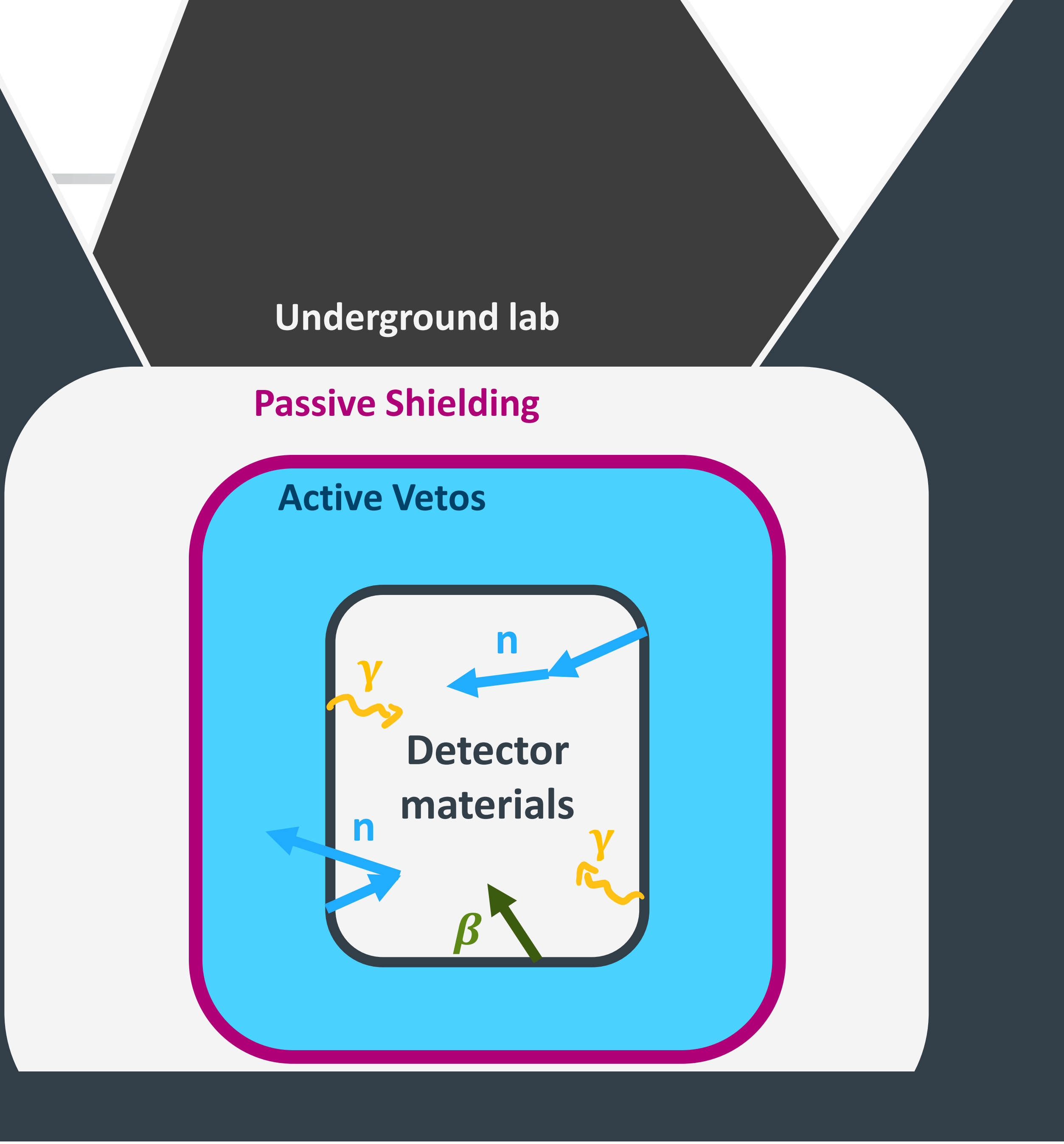
Both ^{39}Ar and ^{42}Ar are produced from cosmogenic activation



Taken from LEGEND-1000 and the future of neutrinoless double beta decay search
Stefan Schönert

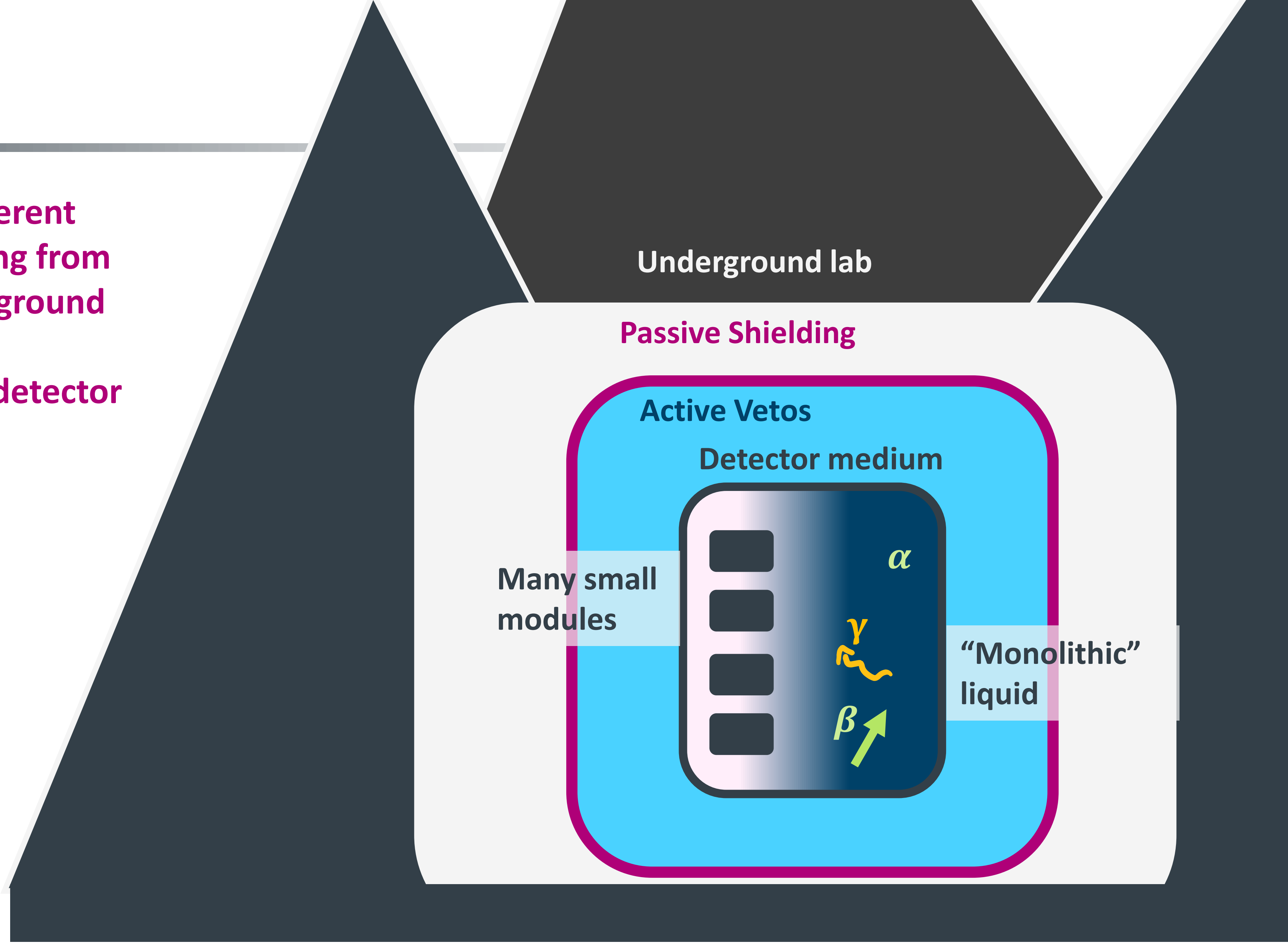
Overview

- Active veto systems can help to further mitigate background signals via an **anti-coincidence** with the main detector
- The design of the veto detector varies depending on the application.



Overview

Now we mitigated many different source of backgrounds ranging from cosmogenic introduced background to materials.
However, what is about our detector medium itself?

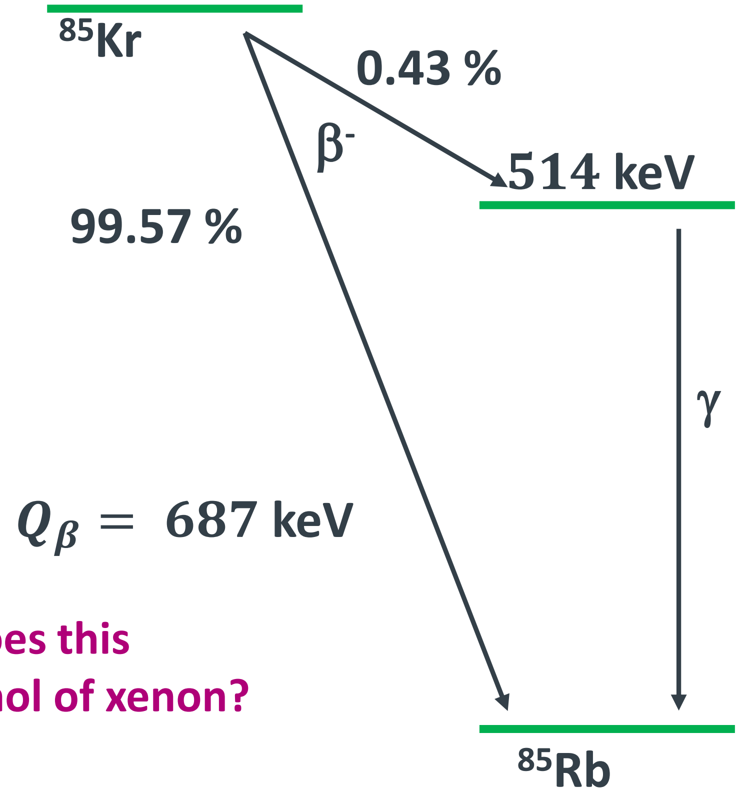


Detector medium

- Our detector media can also contain different isotopes producing background signals
  - **In Argon: ^{37}Ar $t_{1/2}$~35 d, ^{39}Ar $t_{1/2}$~ 268 y, ^{42}Ar $t_{1/2}$~33 y**
  - **In Xenon: ^{137}Xe (cosmogenic $t_{1/2}$~36 d), only ^{85}Kr and ^{222}Rn, as well as long-lived xenon isotopes**
  - **In Germanium: ^{68}Ge (cosmogenic $t_{1/2}$~270 d)**
  - …

Detector medium

- ^{85}Kr, anthropogenically produced in nuclear fission
  - **Decays via β^- emission**
  - **Has a long half-life of about 10.8 years**
  - 2×10^{-11} **^{85}Kr in ^{nat}Kr**
  - **Commercial Xe: ^{nat}Kr/Xe > 10^{-9} (ppb)**
  - **Defined requirements in**
    - **XENONnT: ^{nat}Kr/Xe of 0.2 ppt (ppt=$10^{-12}\,\frac{\text{mol}}{\text{mol}}$)** **How many atoms does this correspond to in 1 mol of xenon?**
    - **DARWIN/XLZD: : ^{nat}Kr/Xe of 0.05 ppt**



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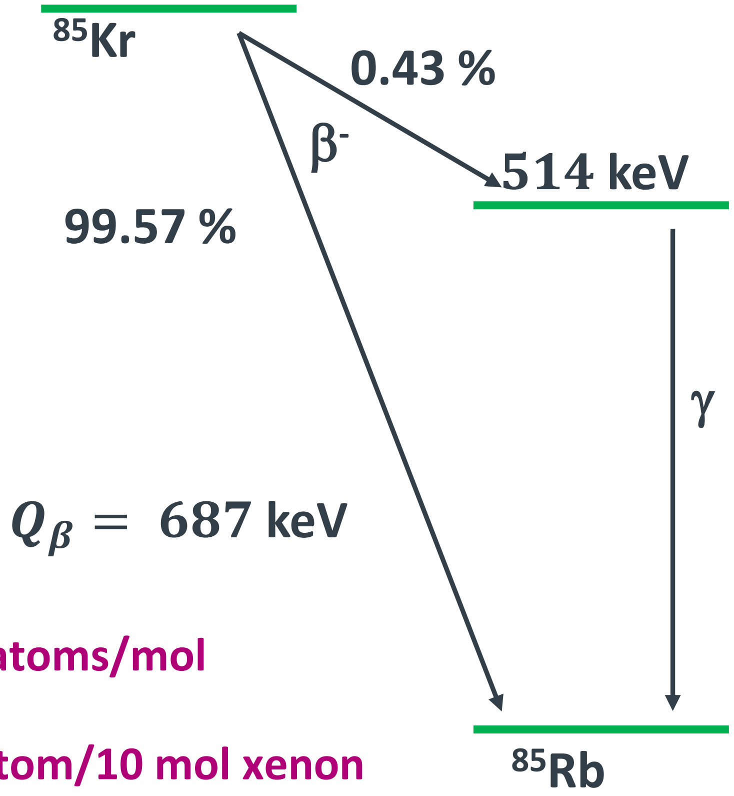
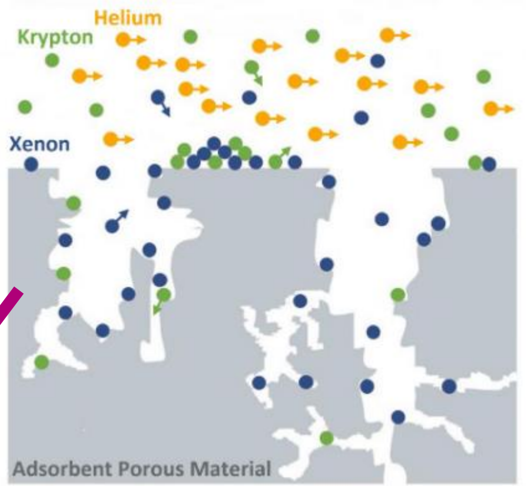
    - **XENONnT: ^{nat}Kr/Xe of 0.2 ppt (ppt=$10^{-12}\,\frac{\text{mol}}{\text{mol}}$)** **$0.2$ ppt ≈ 2.4 ^{85}Kr atoms/mol**
    - **DARWIN/XLZD: : ^{nat}Kr/Xe of 0.05 ppt** **0.05 ppt ≈ 1 ^{85}Kr atom/10 mol xenon**
  - **Good thing: Can only enter through air leaks and thus only need to be removed ones.**
  - **Challenge: needs to be constantly monitored.**

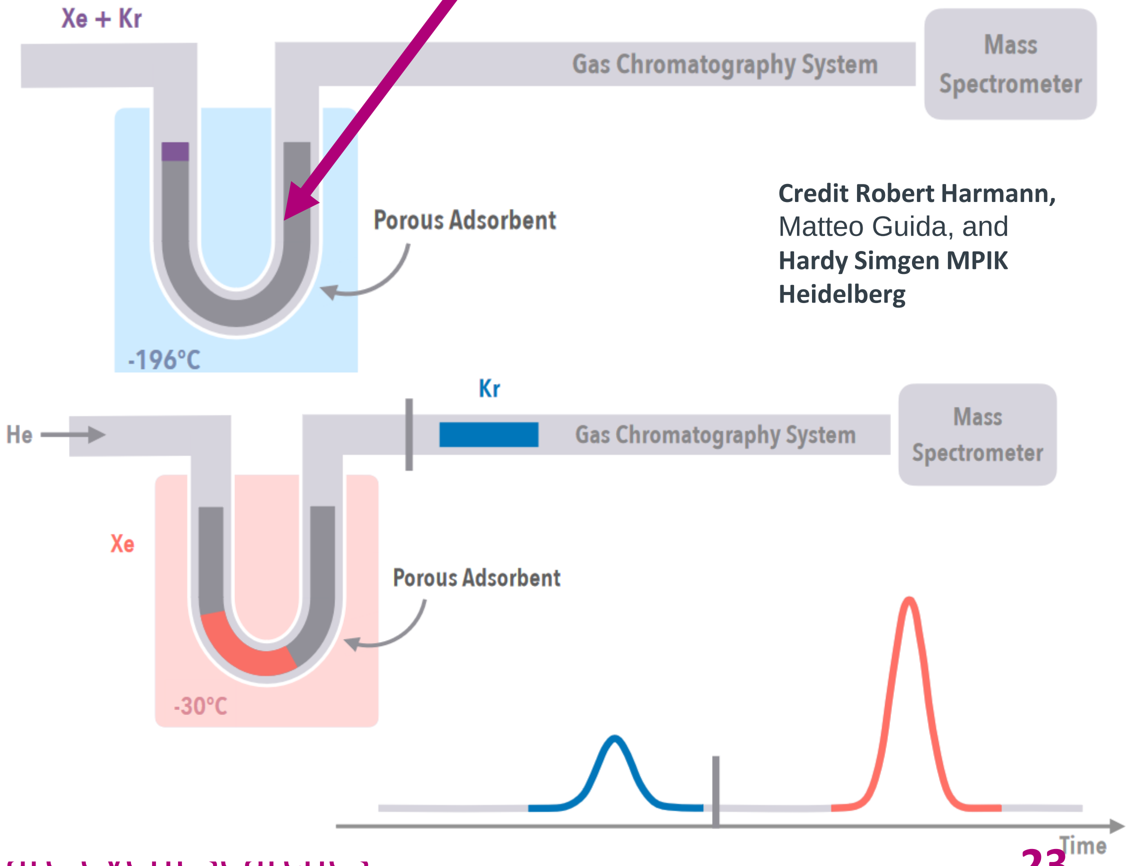


Detector medium

- Steps to measure krypton concentration in xenon gas:
  - **Krypton + xenon mixture is taken from the detector using a clean pipe with multiple volumes separated by valves**
  - **The mixture is flushed with helium as carrier gas into an absorption trap to separate krypton and xenon using Van der Waals force.**
  - **$^{nat.}$Kr concertation is measured by mass spectroscopy using a residual gas analyzer (RGA)**

Pores material with large surface to volume ratio, e.g. charcoal.





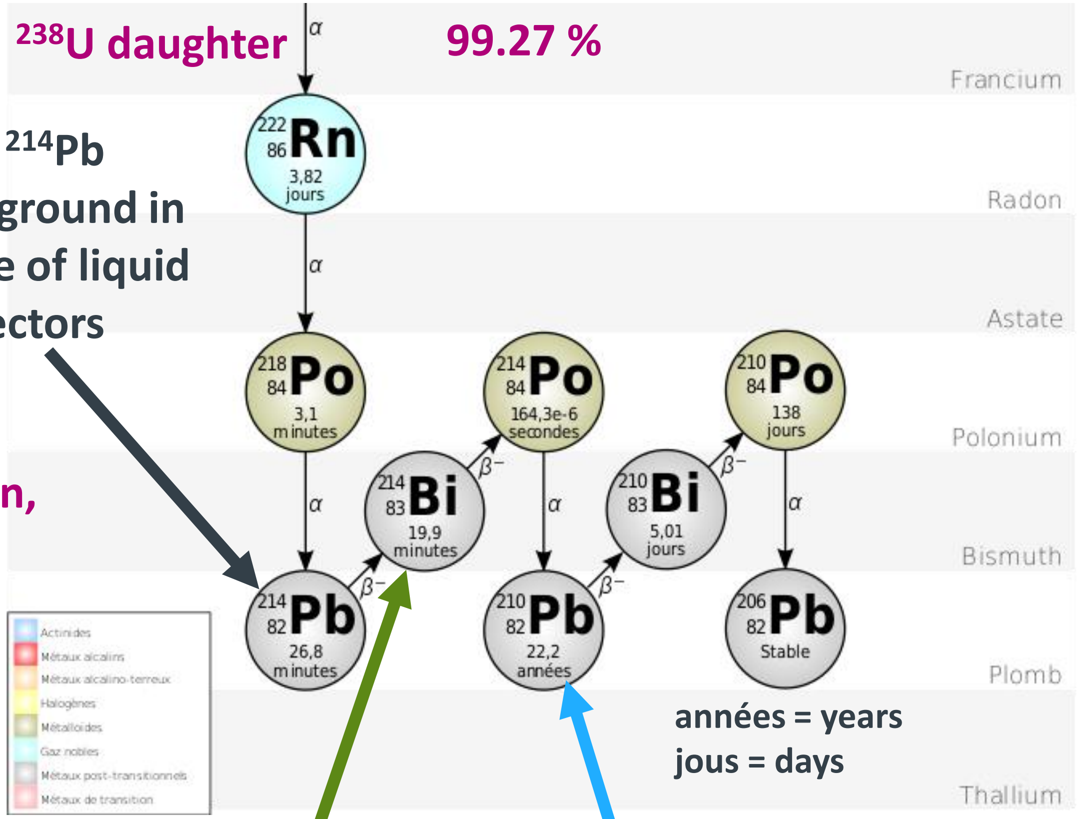
Credit Robert Harmann, Matteo Guida, and **Hardy Simgen MPIK Heidelberg**

Detector medium

- Rare event particle physicists hate this isotope.

Detector medium

- Rare event particle physicists hate this isotope.
- Daughters of ^{222}Rn lead to multiple issues.



Beta decays of ^{214}Pb produces background in fiducial volume of liquid noble DM detectors

Why are beta decays of ^{214}Pb for DM experiments a concern, but not ^{214}Bi and ^{210}Bi?

Why does only ^{210}Pb and its daughters play a role for plate out?

Gamma emission following the decay leads to background for $0\nu\beta\beta$ experiments using ^{136}Xe

Plate out of ^{218}Po on surfaces leads to background signals from ^{210}Pb and daughters in nearly every experiment

Detector medium

- Rare event particle physicists hate this isotope.
- Daughters of ^{222}Rn lead to multiple issues.
- Defined requirements in
  - **XENONnT: ~1 µBq/kg**
  - **DARWIN/XLZD: ~0.1 µBq/kg**

How many atoms does this correspond to in 1 mol xenon?

- ^{222}Rn emanates constantly from material surfaces.
- Reduce contamination through material **selection, mitigation** and **removal**.

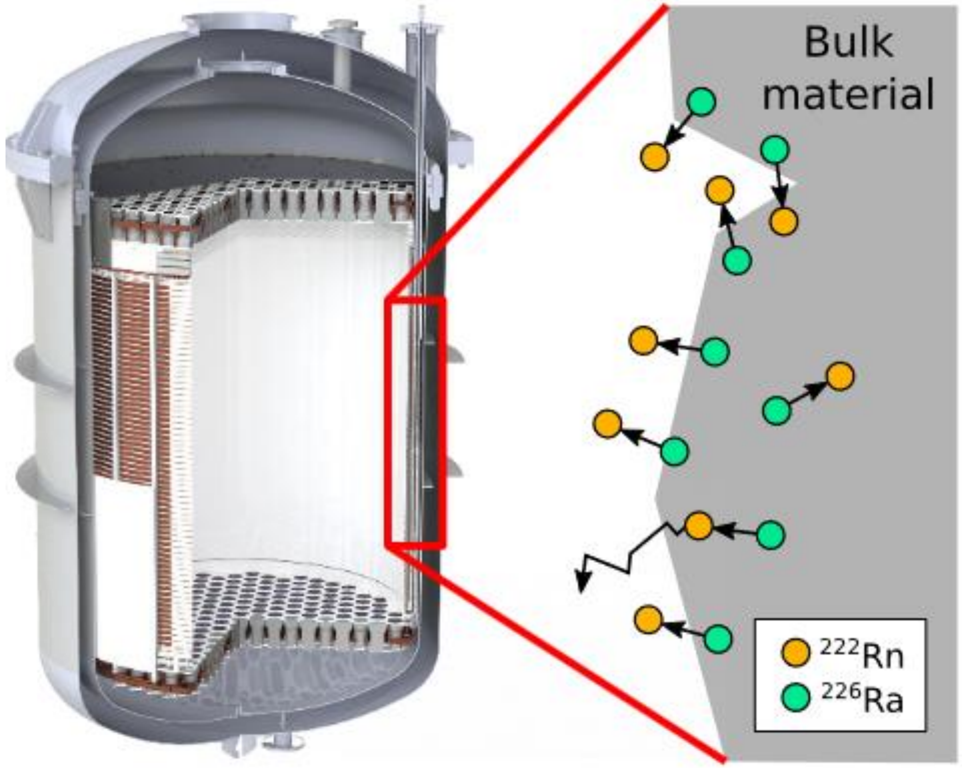


Figure kindly provided by Florian Jörg, Giovanni Volta and Hardy Simgen

Detector medium

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- Defined requirements in
  - **XENONnT: ~1 µBq/kg**
  - **DARWIN/XLZD: ~0.1 µBq/kg**

➔ 1 atom in 16 mol xenon (This corresponds to one drop of water in the Atlantic)

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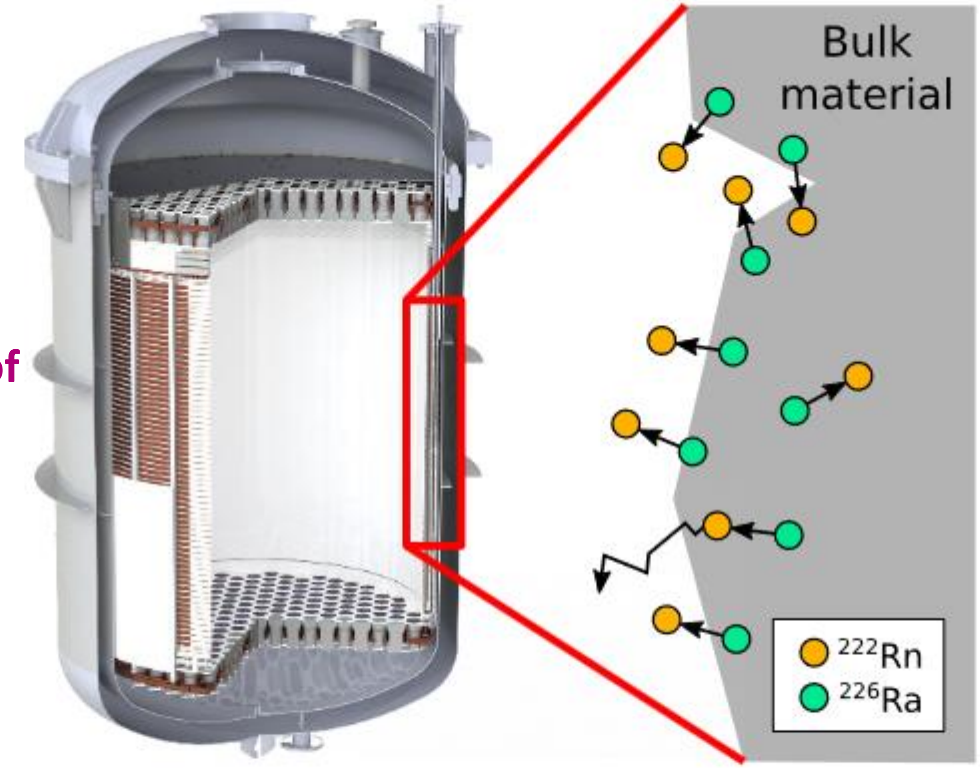
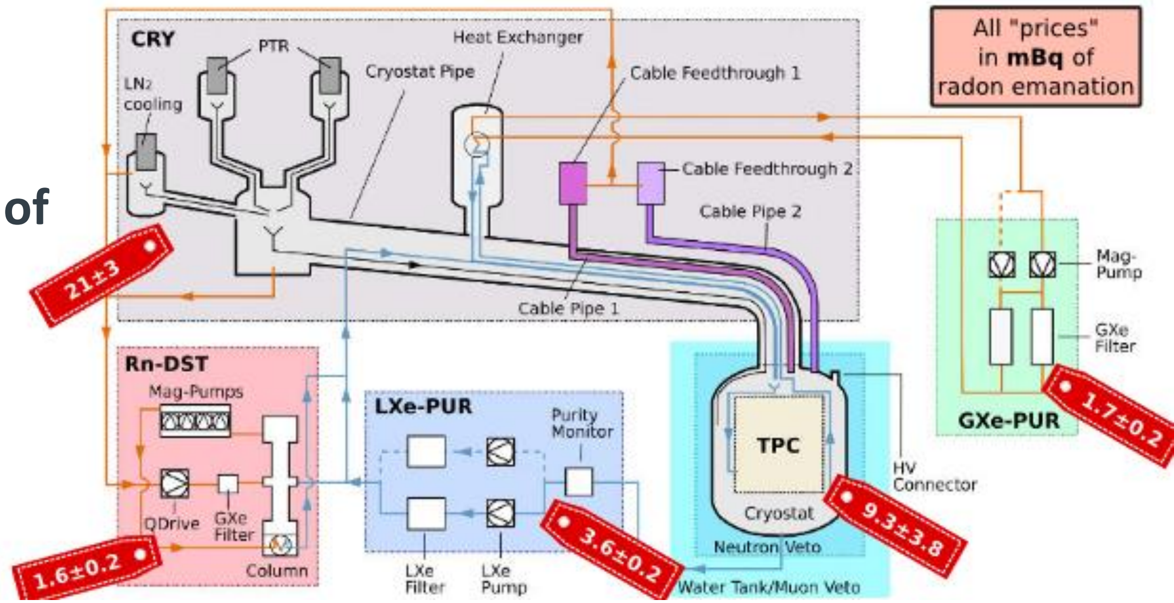
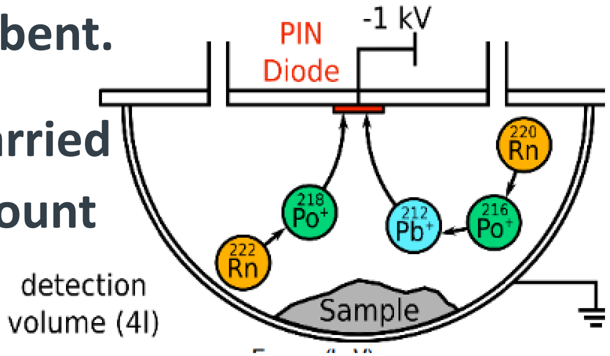


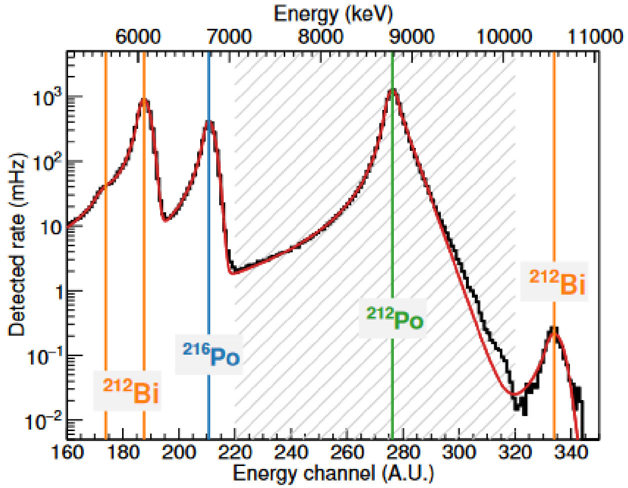
Figure kindly provided by Florian Jörg, Giovanni Volta and Hardy Simgen

Detector medium

- Steps required to measure the radon emanation in a mounted experiment:
  - **In XENONnT radon was sampled from different parts of the experiment after mounting.**
  - **To sample radon a certain section is first pumped before it is flushed with nitrogen as carrier gas**
  - **Afterwards the nitrogen + radon mixture is extracted through a cold trap to trap the radon in an adsorbent.**
  - **In the last step the radon daughter ion ^{218}Po is carried using a different carrier gas into a PIN-diode to count the daughters of the ^{218}Po decay.**



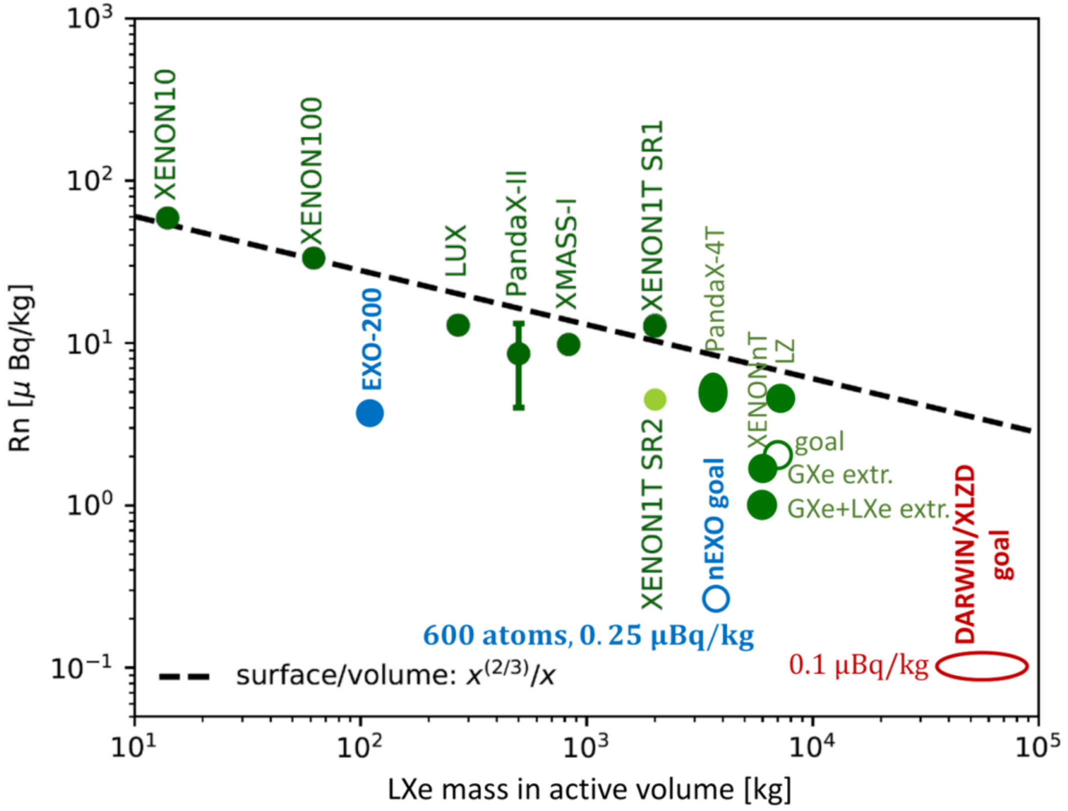




Credit Florian Jörg and Hardy Simgen MPIK Heidelberg

Detector medium

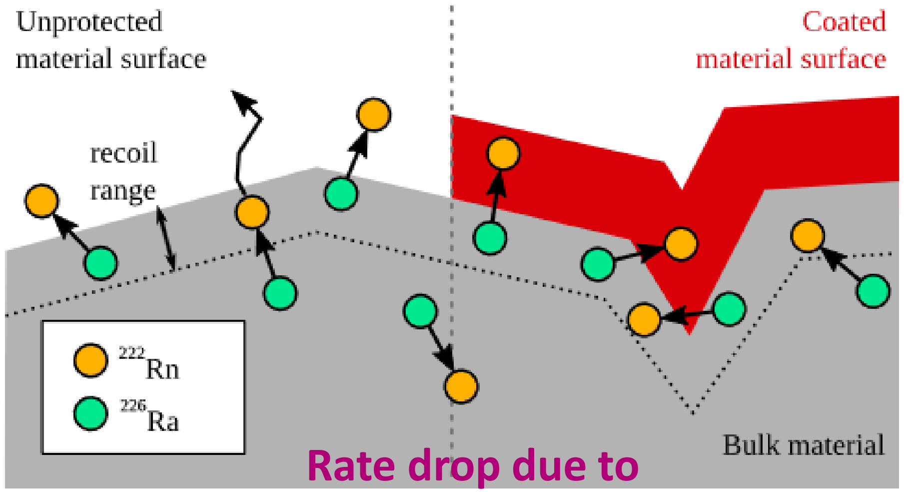
- How to reduce ^{222}Rn in liquid noble gas detectors?
  - **Increase mass (volume-to-surface ratio)**



Detector medium

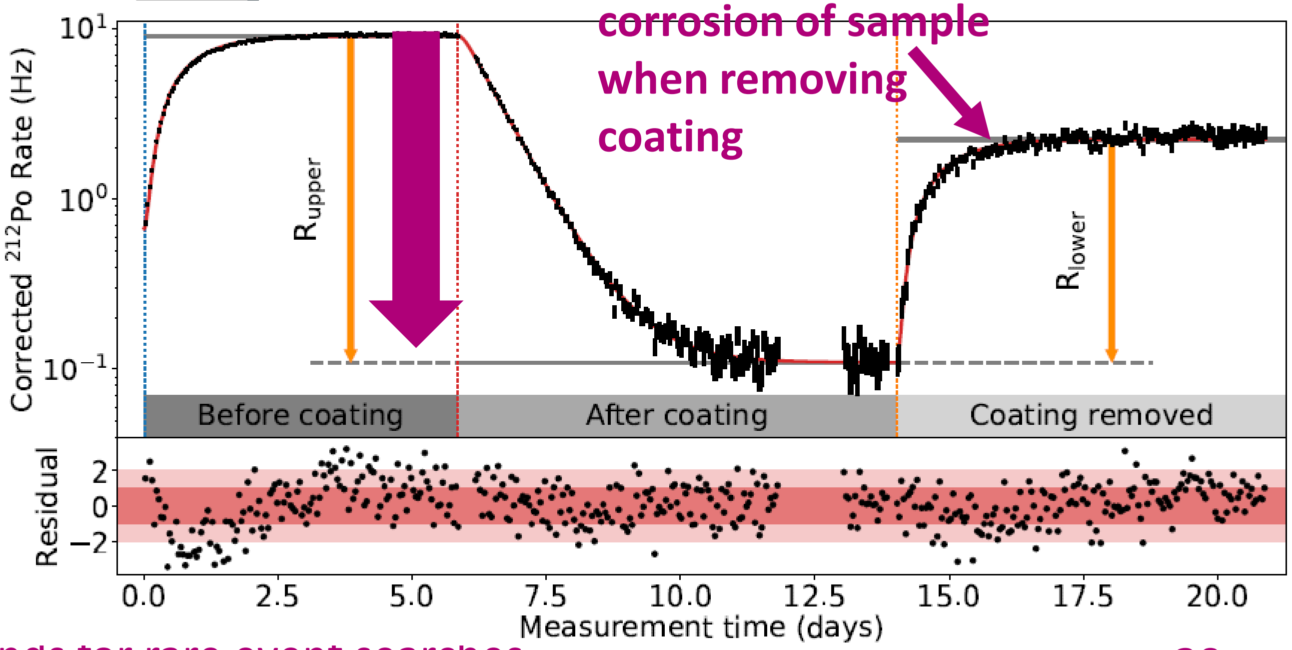
What is the typical recoil energy of the 222Ra atom?

- How to reduce ^{222}Rn in liquid noble gas detectors?
  - **Increase mass (volume-to-surface ratio)**
  - **Coat surfaces or build hermetically sealed TPC.**
    - **Coat surface for example with a copper layer**
    - **Prevents emanation of Radon from recoil of ^{226}Ra decay**
    - **Downside: Not all surfaces in a detector can be easily coated**



Florian Jörg, PhD thesis

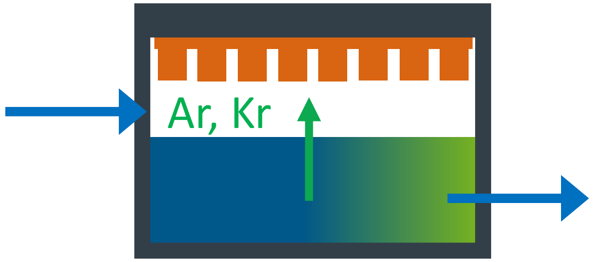
Rate drop due to corrosion of sample when removing coating



Detector medium

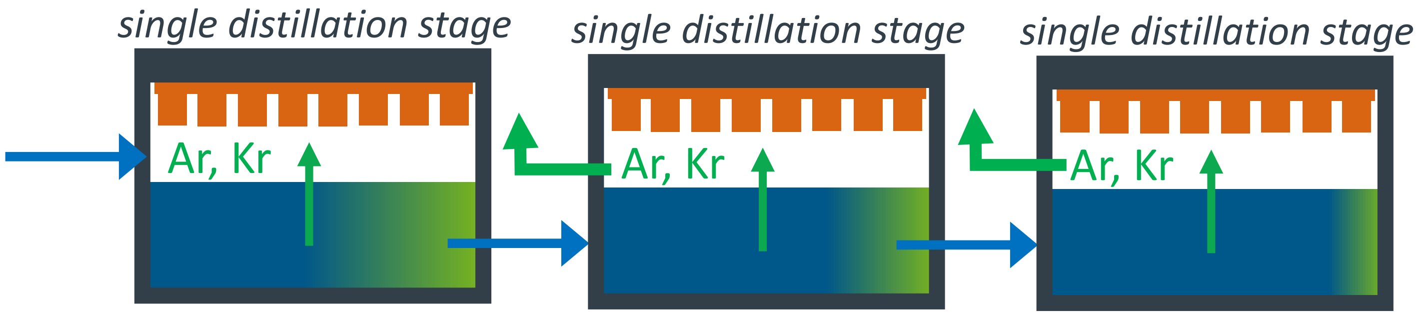
- Cryogenic distillation exploits vapor pressure difference of gases for a given temperature
  - **Krypton has a higher volatility ($\alpha = 10.5$ (@ -100 °C) and thus accumulates more in the gas phase**

single distillation stage

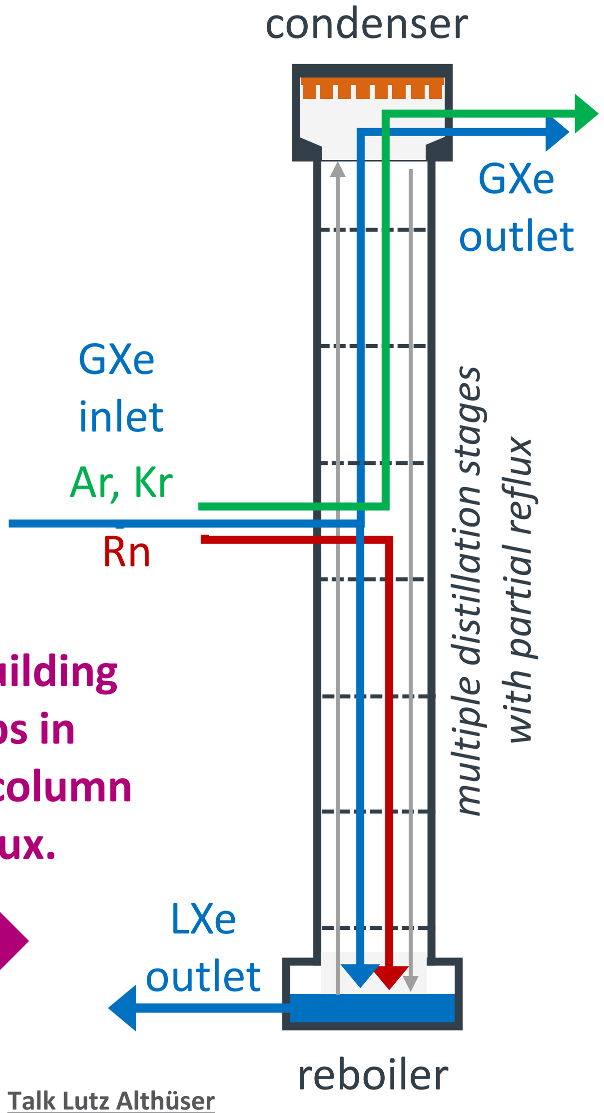


Detector medium

- Cryogenic distillation exploits vapor pressure difference of gases for a given temperature
  - **Krypton has a higher volatility ($\alpha = 10.5$ (@ -100 °C) and thus accumulates more in the gas phase**
  - **By repeating we can gradually deplete krypton in the liquid and accumulate it in the gas phase.**
  - **The liquid goes back to the detector the gas needs to be extracted as an off-gas**



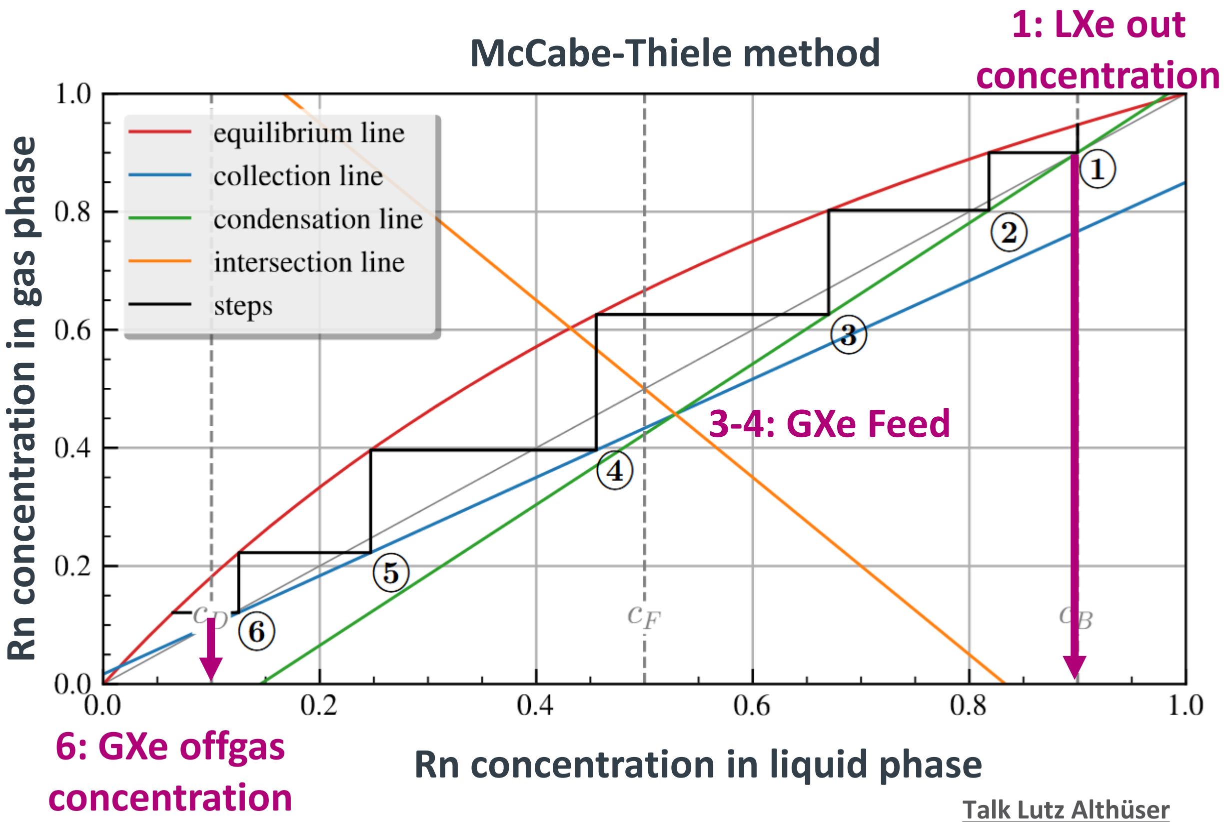
Instead of building multiple steps in series build column with LXe reflux.



Talk Lutz Althüser

Detector medium

- Virtual number of stages can be computed using the McCabe-Thiele method
  - **Method based on a set of coupled equations which are described by the difference in vapor pressure of the used gaseous and mass flux conservation**
  - **The number of virtual stages can be read from the graph directly**

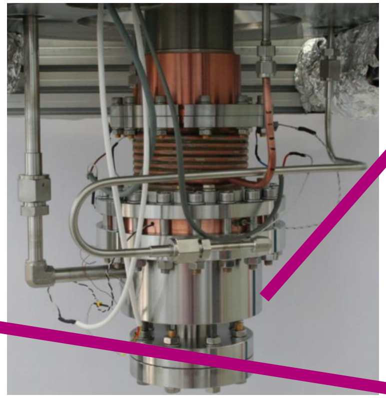


Talk Lutz Althüser

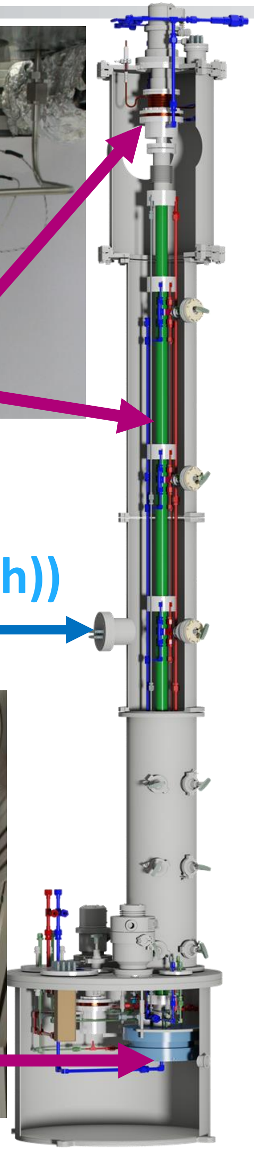
Detector medium

Detector medium

Top condenser



Package material with large surface for condensation

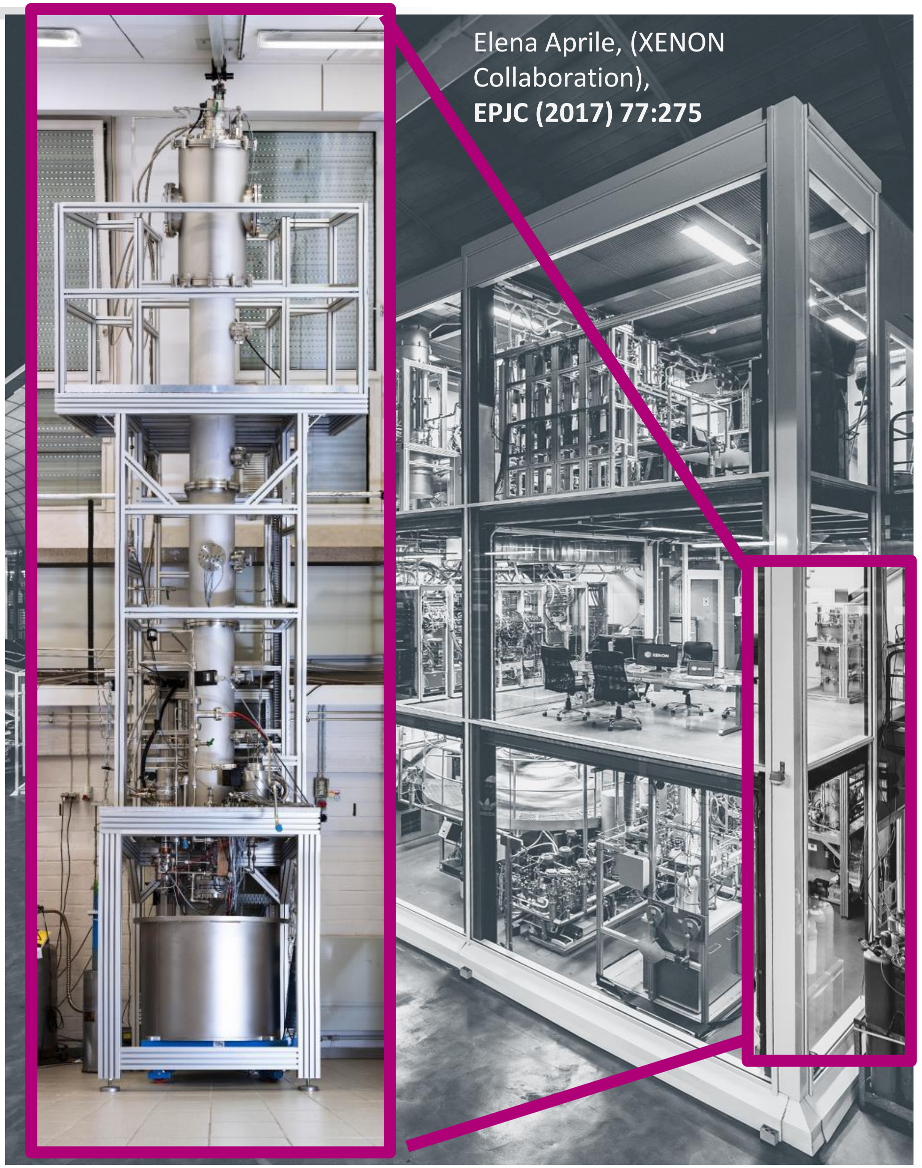


GXe inlet (8.3 slpm (3 kg/h))

- Separation of about 10^5 achieved
  Residual ^{nat}Kr/Xe $< 0.05 \times 10^{-12}$ (50 ppq) achieved.
- 99 % of xenon recovered, 1 % loss as offgas

➡ Reduction already sufficient for next generation experiments

Reboiler



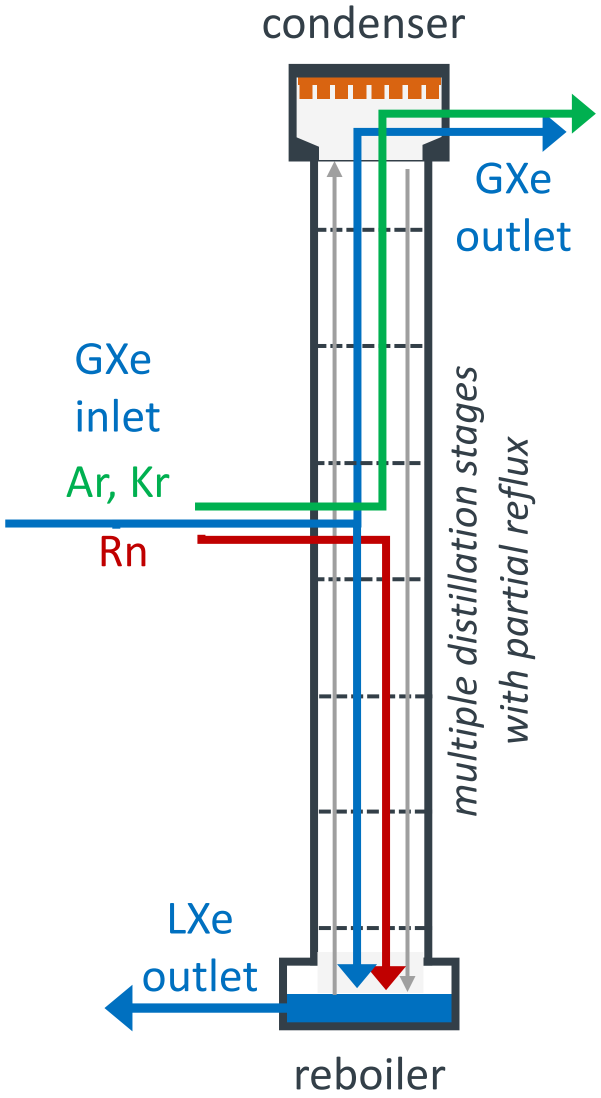
Elena Aprile, (XENON Collaboration), **EPJC (2017) 77:275**

Detector medium

- Cryogenic distillation exploits vapor pressure difference of gases for a given temperature
  - **Radon has a lower volatility ($\alpha = 0.1$ (@ -100 °C)) as xenon and thus accumulates in the liquid phase.**
  - **Drop ^{222}Rn in the reboiler of the column and let it decay ($T_{1/2} = 3.8$ d).**
  - **Extract radon deplete gas from the top of the column and reliquefy it.**

What is the big difference between krypton and radon distillation?

What does this mean for the xenon circulation speed?



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  - **Extract radon deplete gas from the top of the column and reliquefy it.**
  - **Need to extract the radon before it can decay inside our detector!**
  - **Requires high fluxes!**

What is the big difference between krypton and radon distillation?

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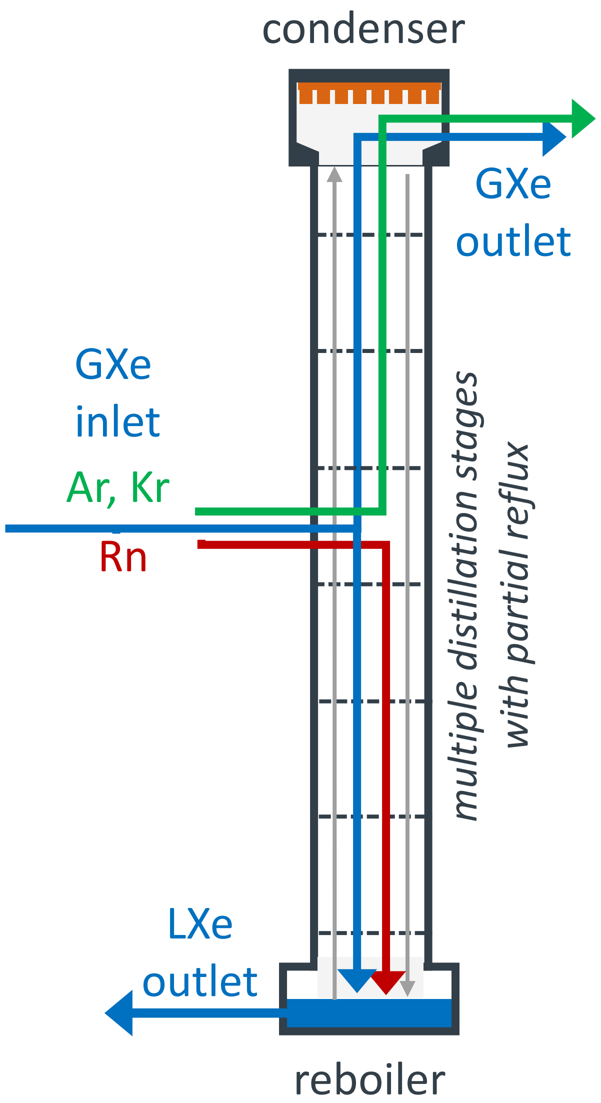
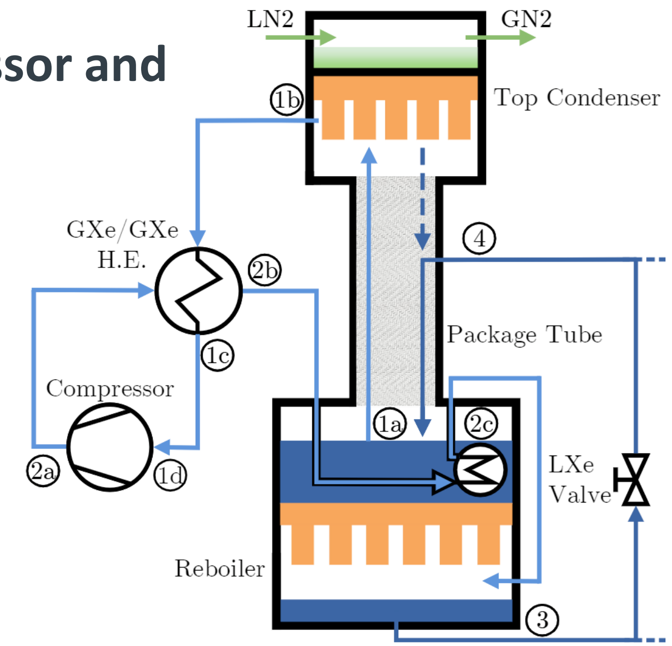
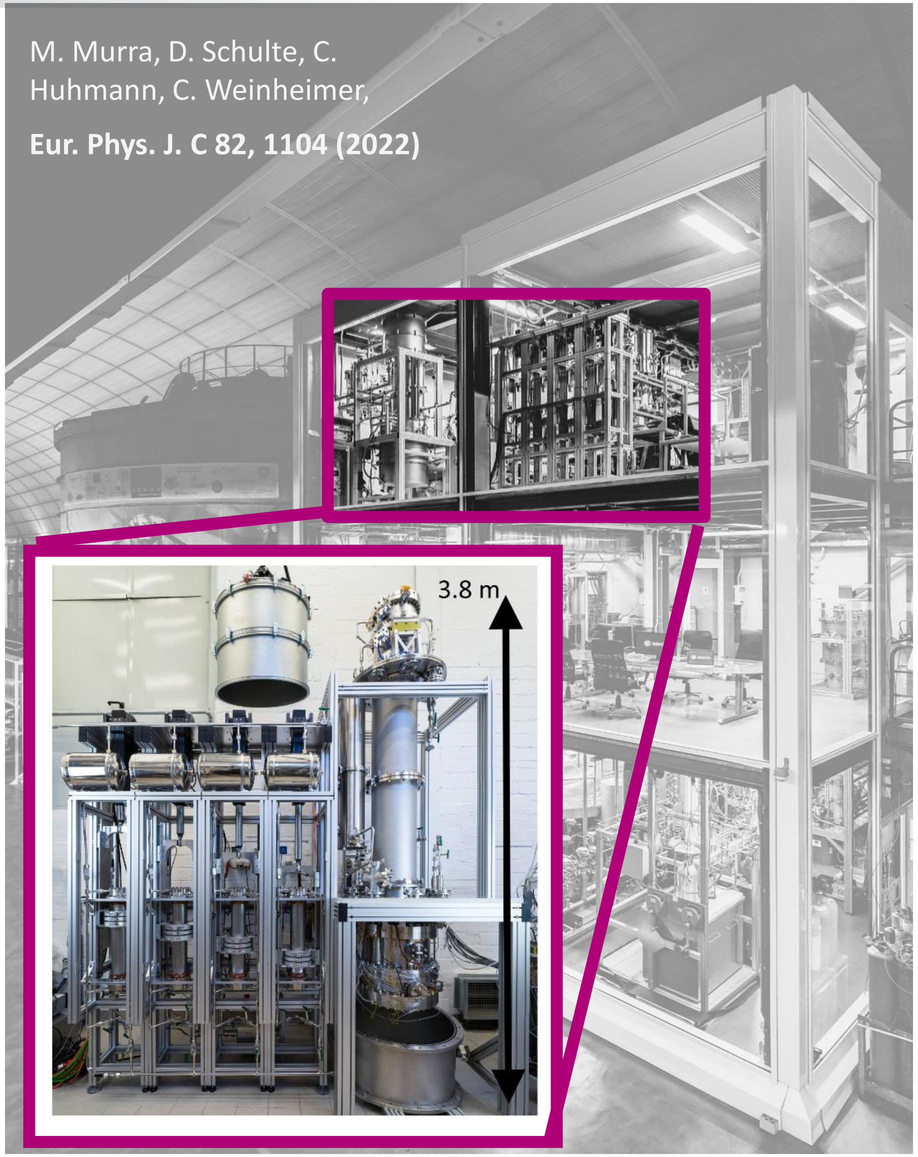


Detector medium

- “Online” Rn distillation due to constant outgassing
  - **No offgas, but requires high LXe circulation (~3 kW cooling and heating power required)**
  - **XENONnT uses Clausius-Rankine cycle to reduce power requirement**
  - **Requires radon free compressor and heat exchanger**

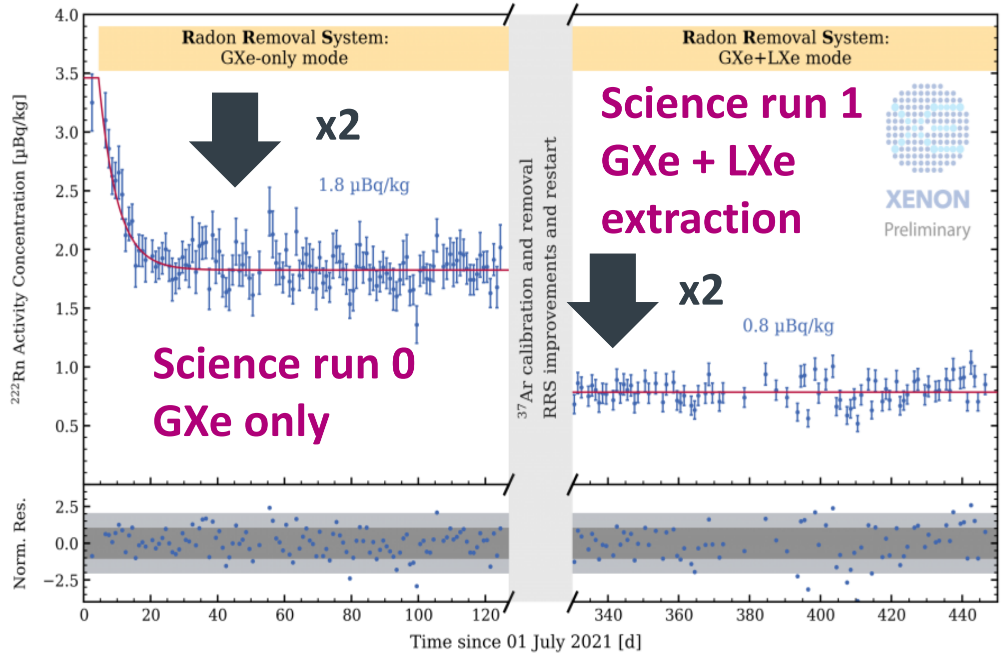




Detector medium

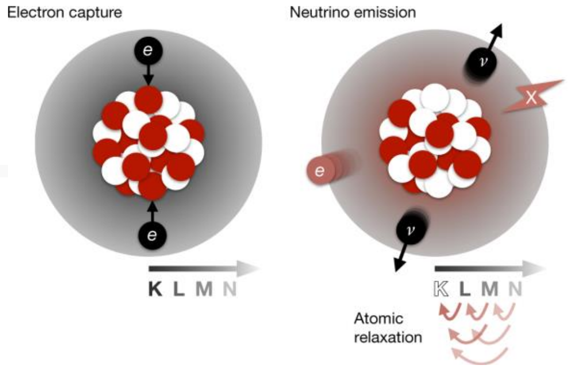
- "Online" Rn distillation due to constant outgassing
  - **^{222}Rn decay within column ($T_{1/2} = 3.8$ d)**
  - **No offgas, but requires high LXe circulation (~3 kW cooling and heating power required)**
  - **GXe (gaseous xenon) only extraction: 25 slpm (9 kg/h)**
  - **GXe + LXe (liquid xenon) extraction: 25 slpm + 200 slpm**

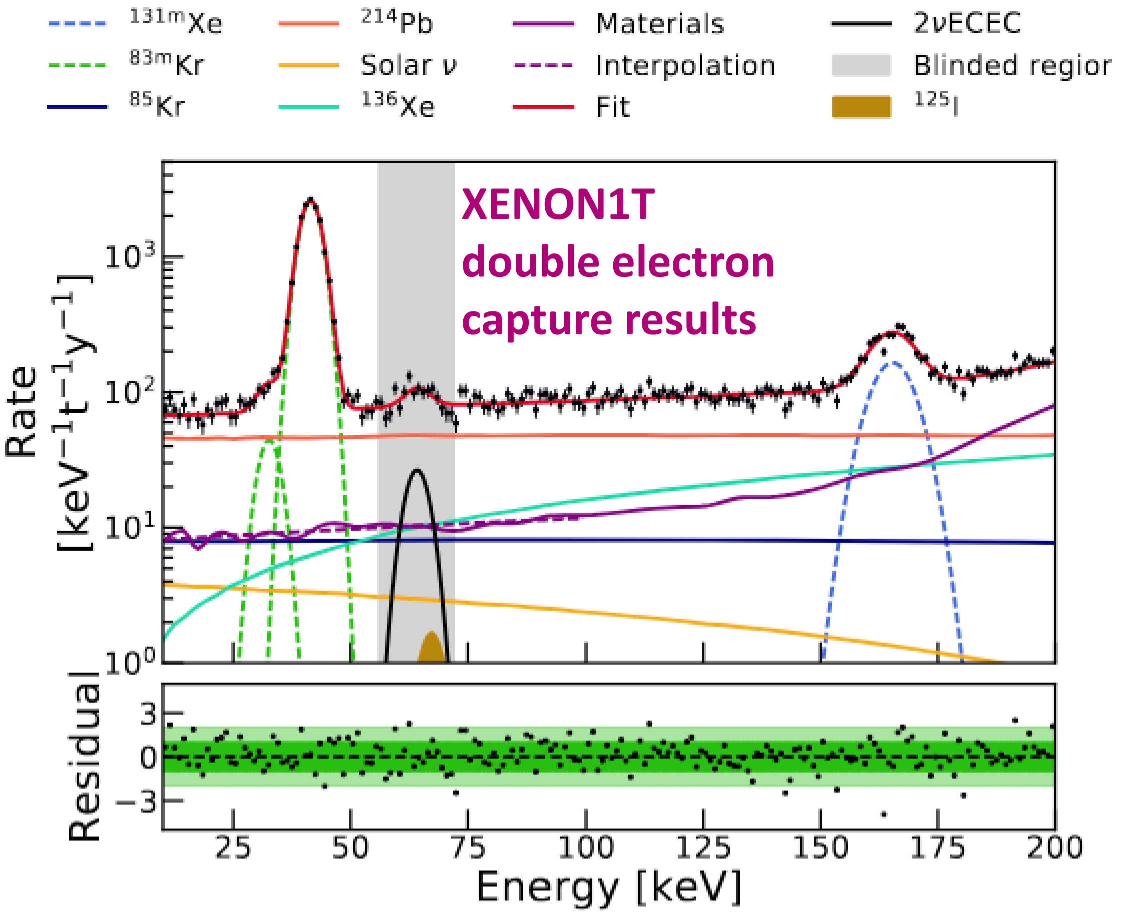
    (81 kg/h -> entire 8.5 t xenon volume in about 4 days)
  - **LXe ^{222}Rn reduction factor given by** $r_{LXe} \cong \frac{\lambda_{Rn222} + F_{LXe}/m_{LXe}}{\lambda_{Rn222}}$



Detector medium

- Due to a strict material selection, cleaning procedure and cryogenic radon distillation XENONnT improved its background significantly compared to XENON1T





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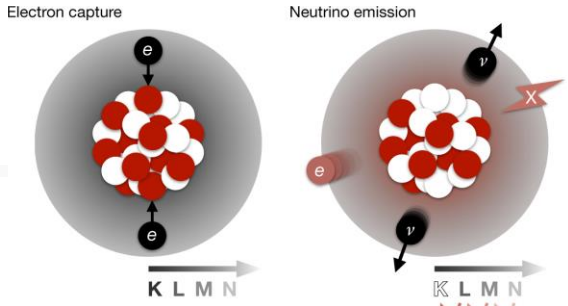
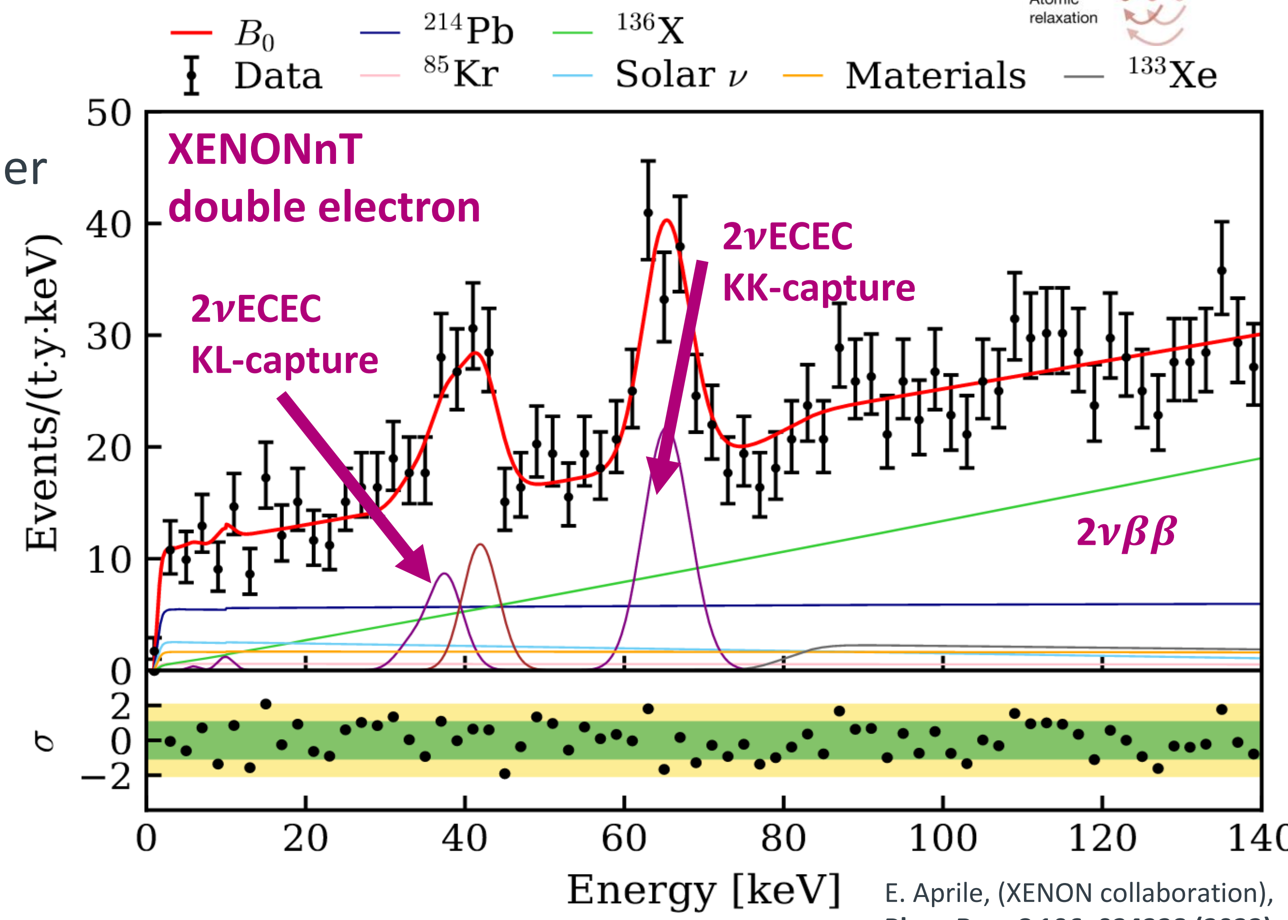


- Due to a strict material selection, cleaning procedure and cryogenic radon distillation XENONnT improved its background significantly compared to XENON1T
- Electronic recoil spectrum dominated by second order weak processes!
  - **Double electron capture (EC) on ^{124}Xe**

    $$T_{1/2}^{2\nu ECEC} = (1.15 \pm 0.13_{stat} \pm 0.14_{sys}) \cdot 10^{22}\ yr$$

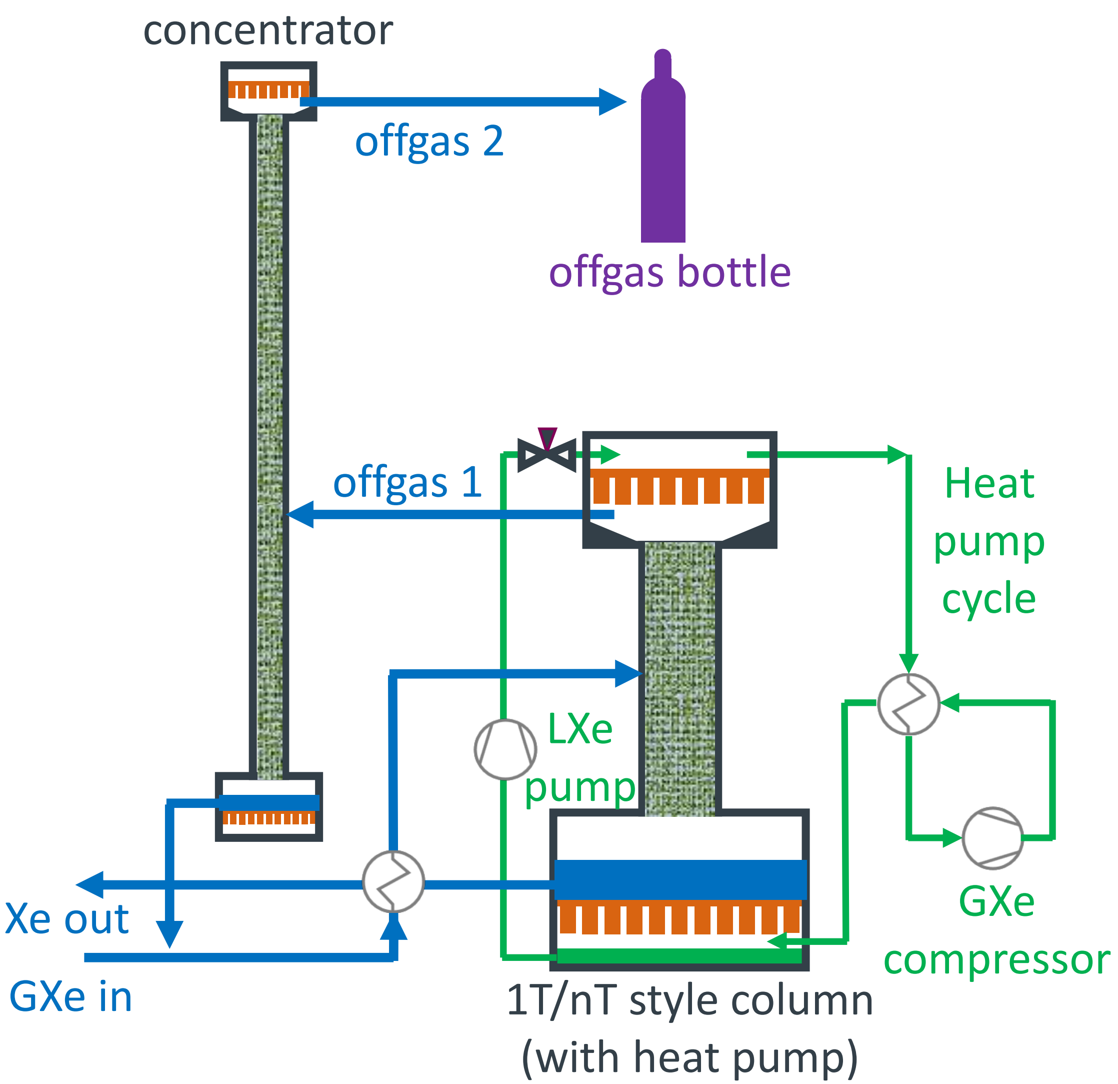
    (longest half-life ever measured)
  - **2 neutrinos double beta decay ($2\nu\beta\beta$) of ^{136}Xe**
  - **Goal of next generation experiments:**
    - **Factor 10 lower ^{222}Rn rate than solar neutrino background**



E. Aprile, (XENON collaboration), **Phys. Rev. C 106, 024328 (2022)**

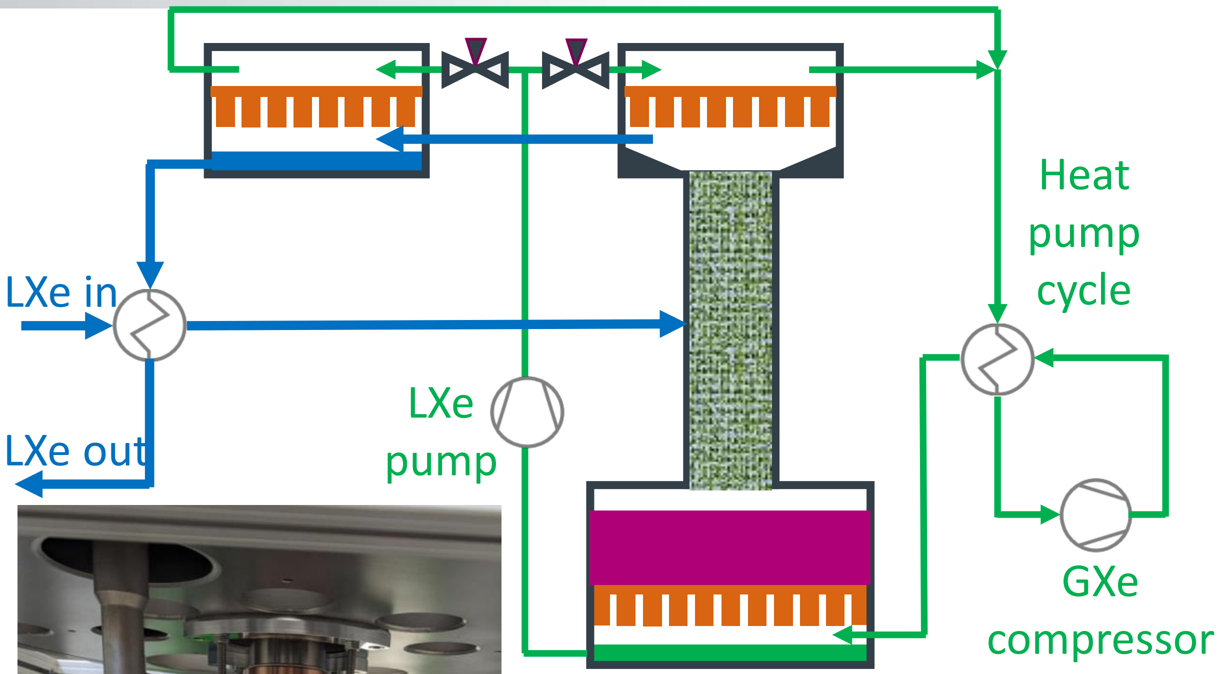
Detector medium

- ERC LowRad project at Münster aims to develop the distillation systems for the next generation liquid xenon dark matter experiment
- Current ^{85}Kr distillation column already sufficient for next generation
- Add ^{85}Kr concentrator to reduce off gas to allow for online distillation
  - **Current offgas** $1\,\% \sim 4\,\frac{\mathrm{kg}}{\mathrm{d}} \approx 8\,\frac{\mathrm{tonne}}{5\,\mathrm{year}}$
  - **Goal:** $4\,\frac{\mathrm{g}}{\mathrm{d}} \approx 8\,\frac{\mathrm{kg}}{5\,\mathrm{year}}$
- Krypton concentrator is currently being build in Münster



Detector medium

- Next generation dark matter experiment requires a x10 reduction in ^{222}Rn
- This requires a x10 increase in LXe flux to 750 kg/h
- This will require about 30 kW of cooling and heating power!
- Build full and hermetically decoupled cryogenic heat-pump concept using LXe as working medium.
- First small few kg prototype is currently being build in Münster



Recap

- Detector media intrinsic radioactive isotopes lead to additional background signals
- Especially ^{222}Rn and its daughters are harmful for most of the rare event experiments.
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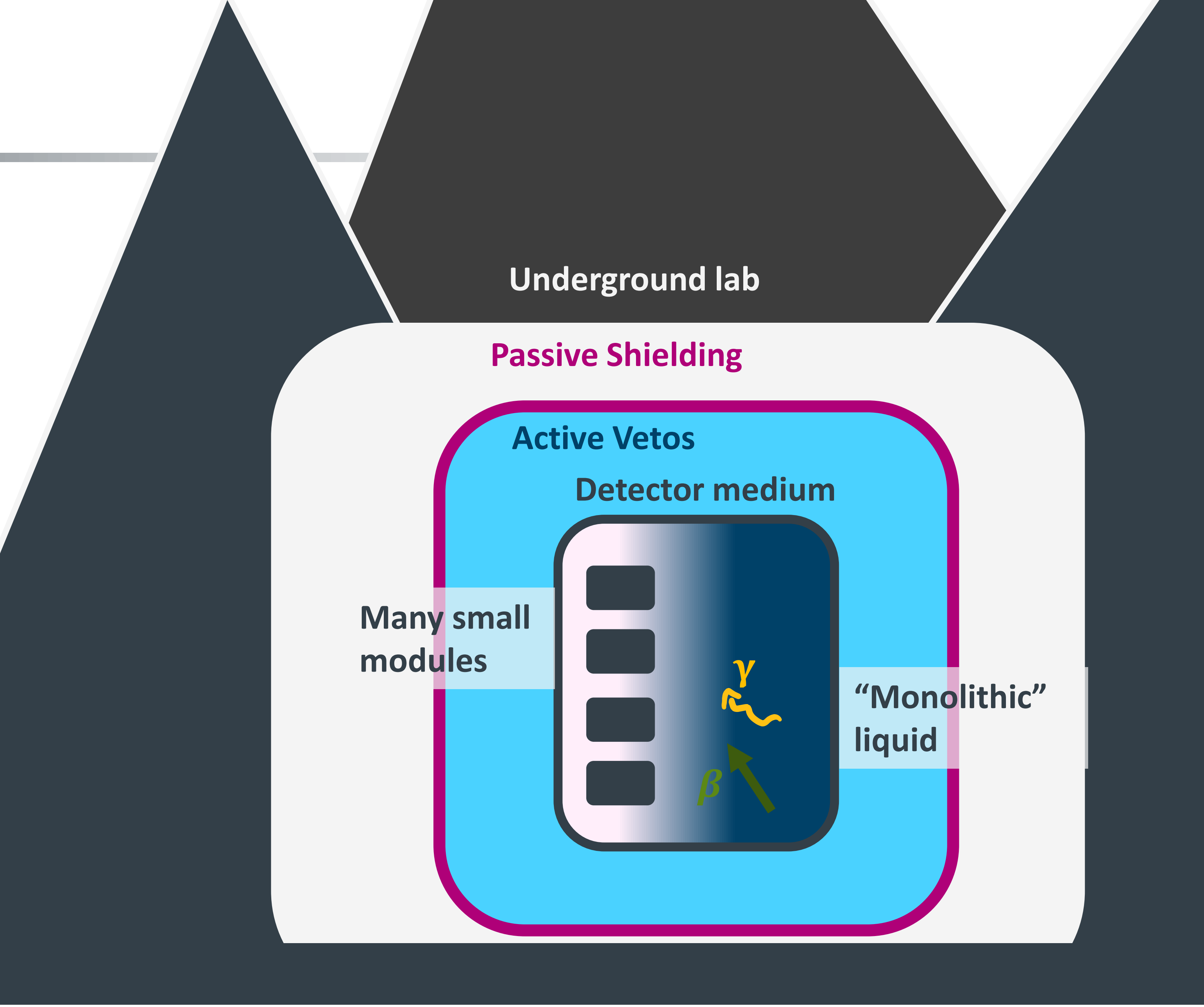
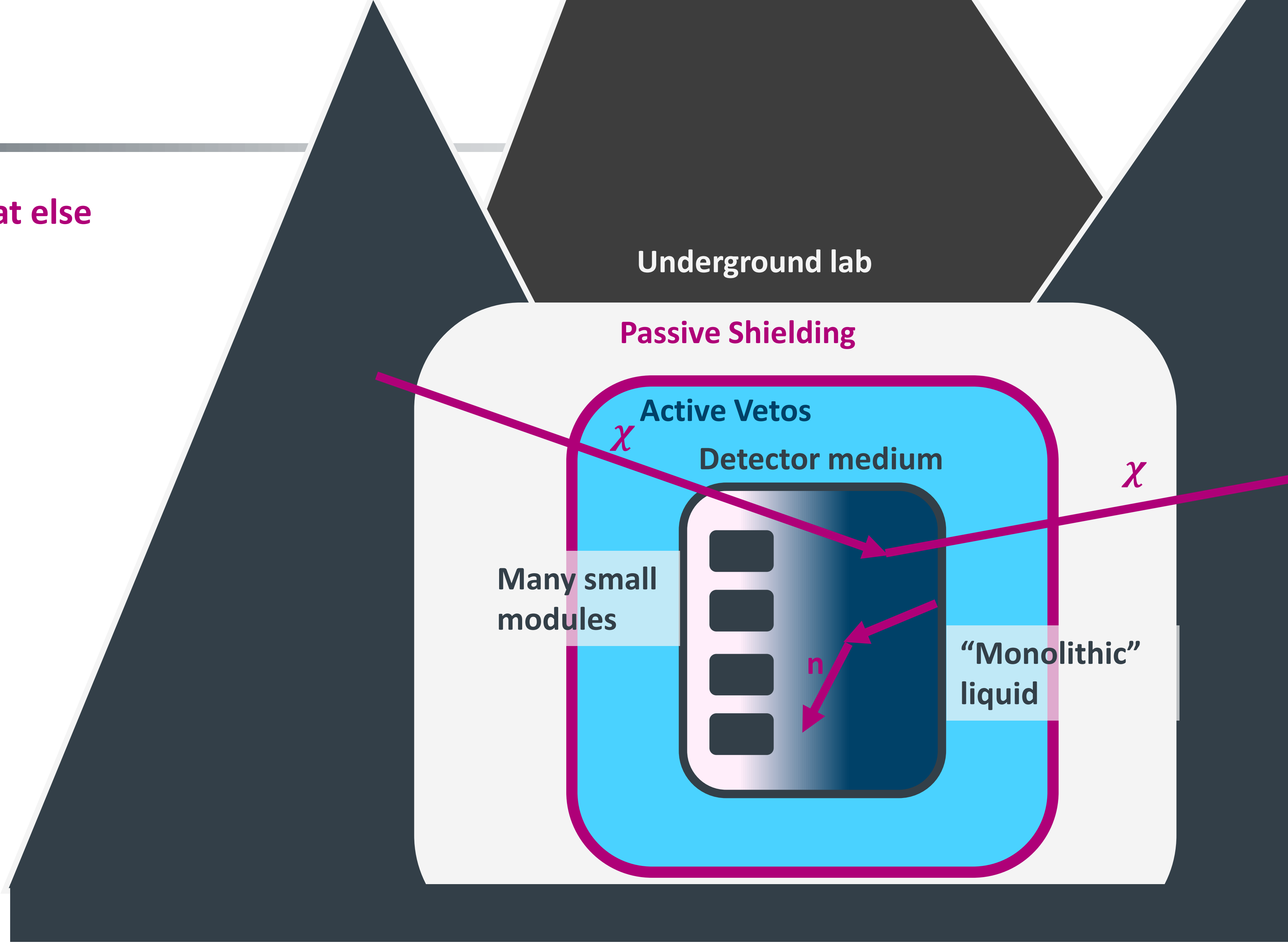
- Current radon background is on level of 1 Rn Atom in 10 mol of xenon

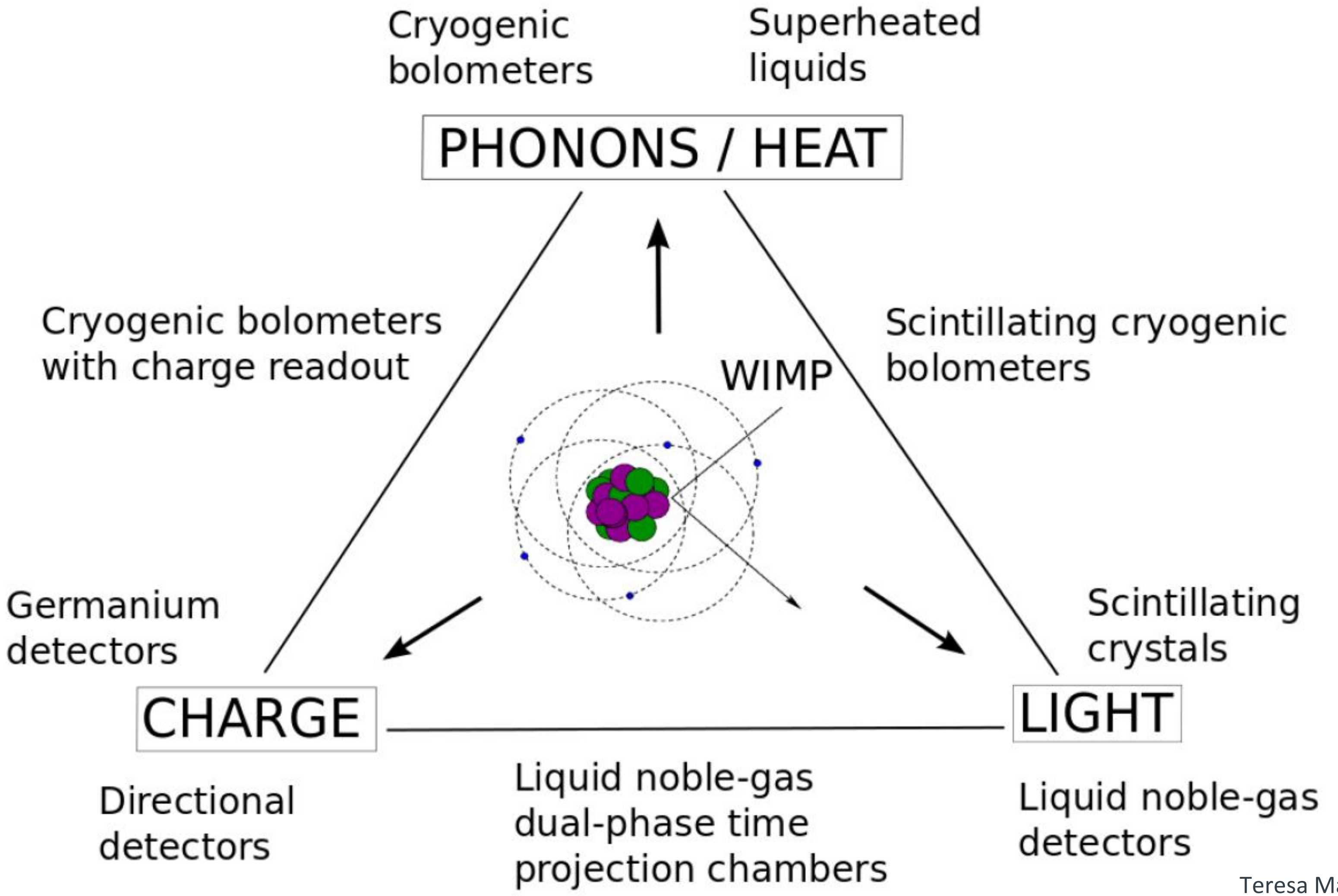


Overview

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



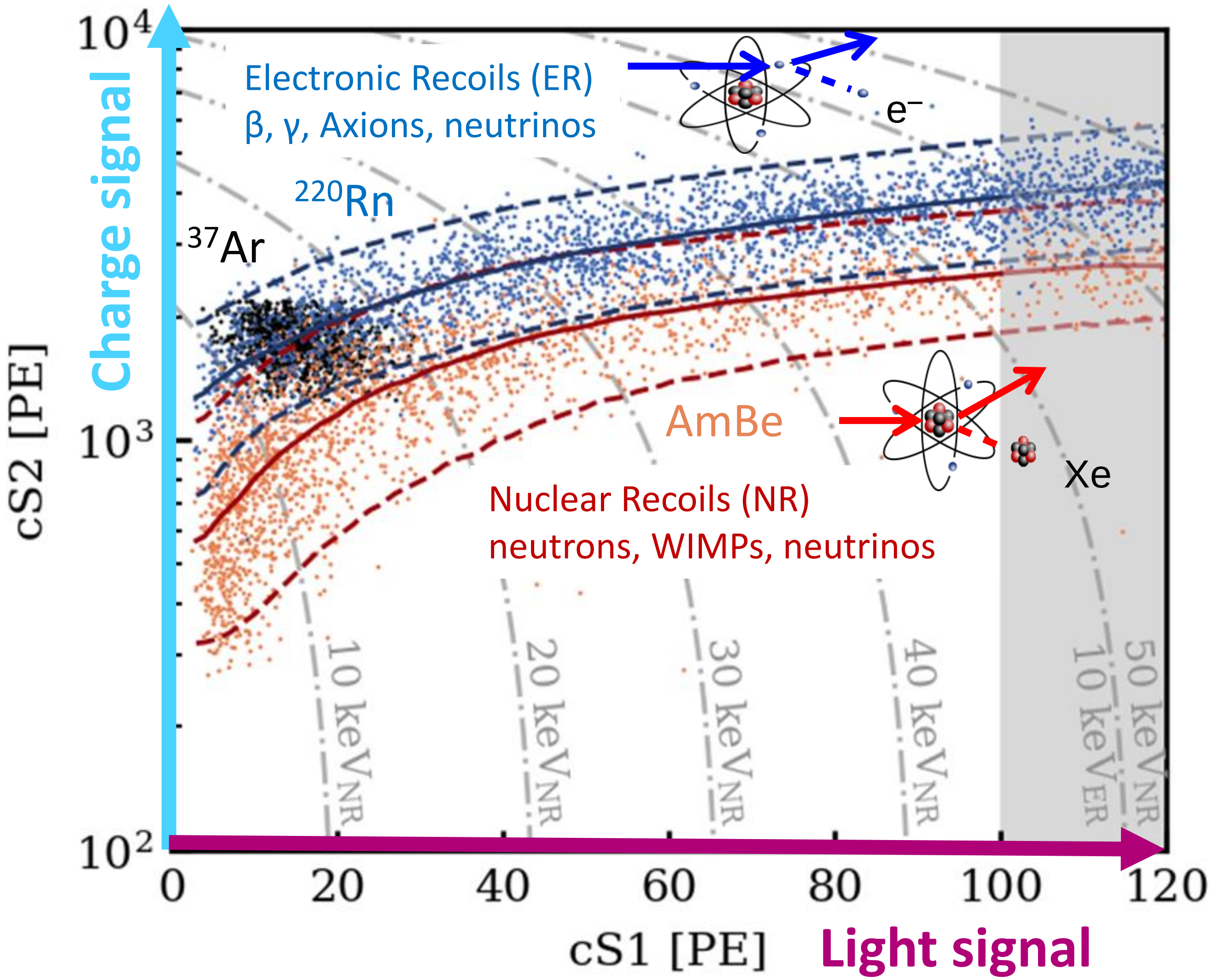
Signal topology



Teresa Marrodán Undagoitia et al.,
J. Phys. G43 (2016) no.1, 013001

Signal topology

- Depending on the detector type, ratios of different signal carriers can be used to identify signal from background.
  - **LXe detector can use charge-to-light ratio**
    - **Only search for WIMPs below NR median**
    - **Typical ER reduction 99.X %**



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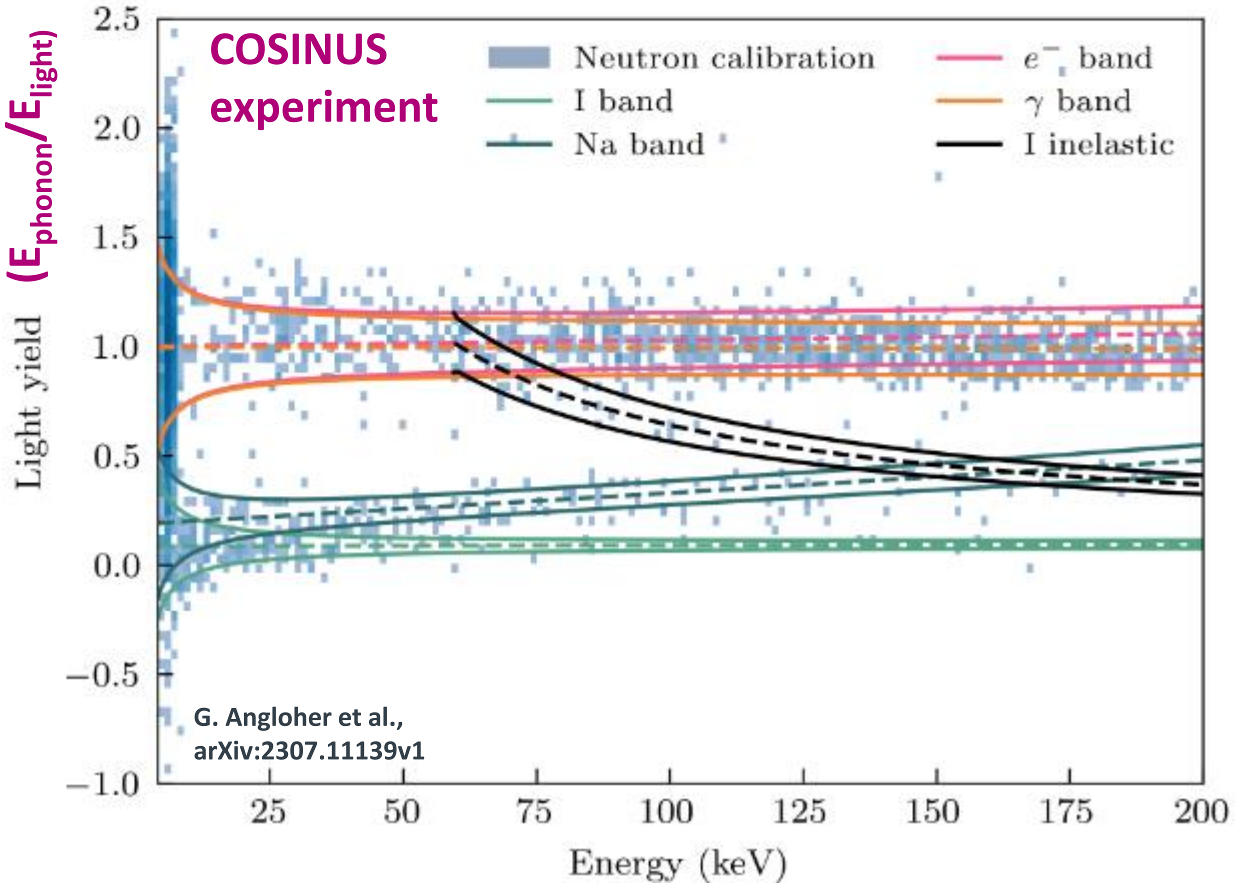

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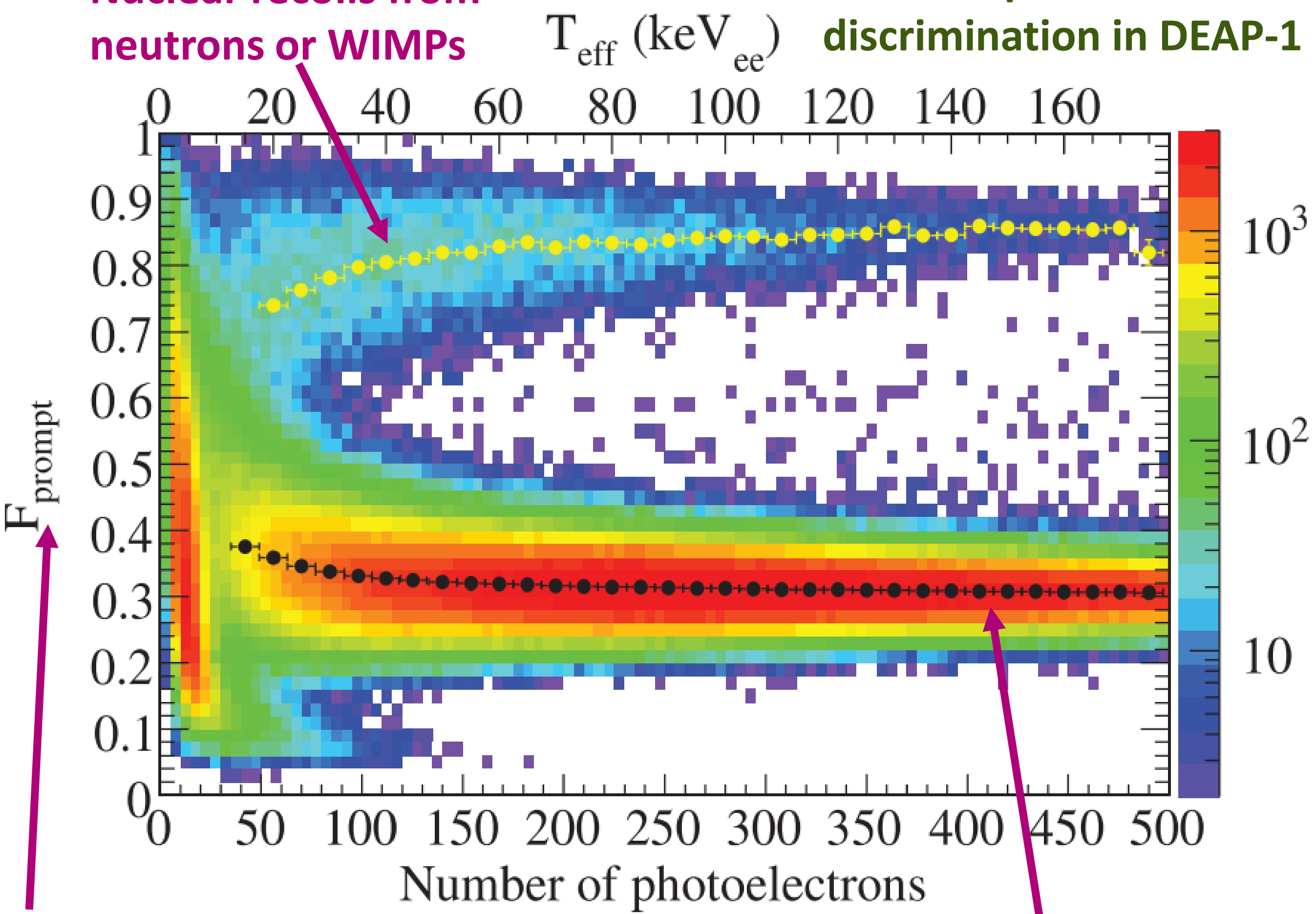
  - **Liquid scintillator and liquid Argon use pulse shape discrimination**

Nuclear recoils from neutrons or WIMPs

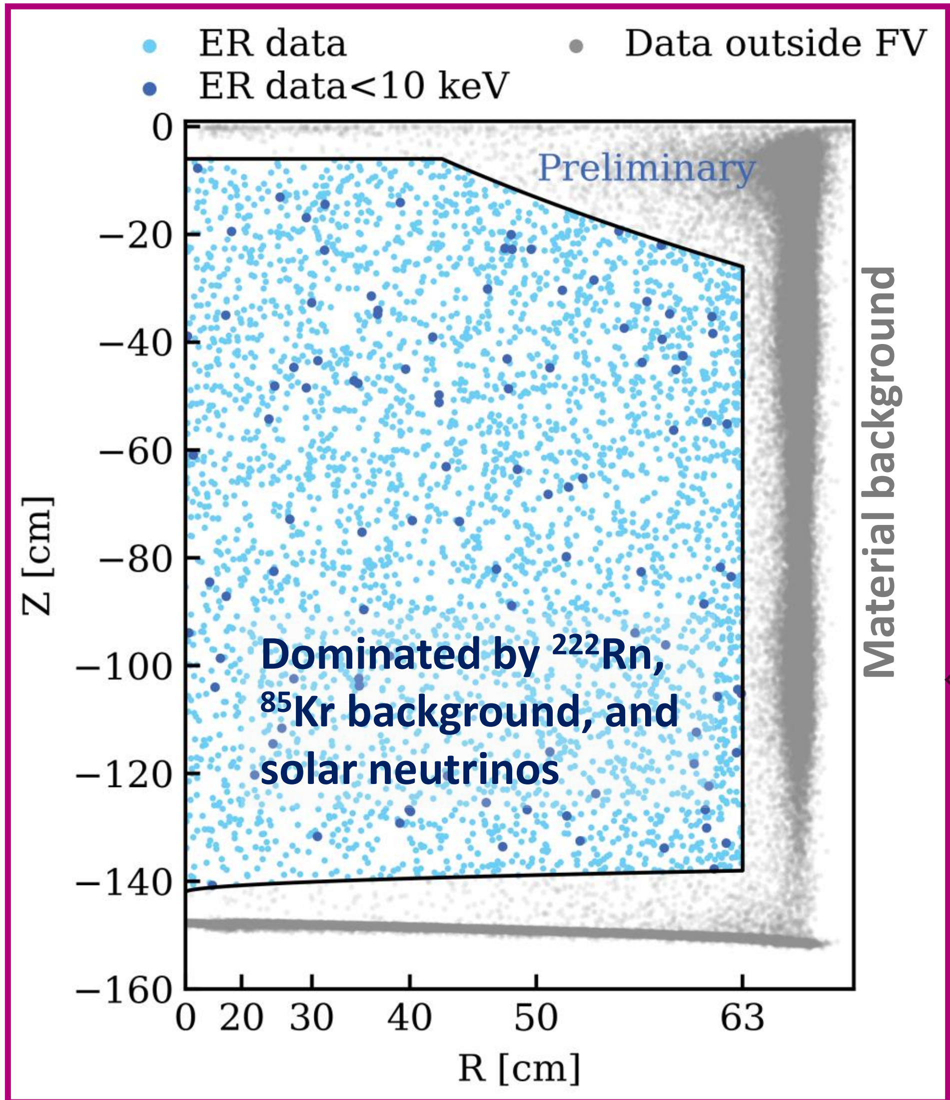
Pulse shape discrimination in DEAP-1



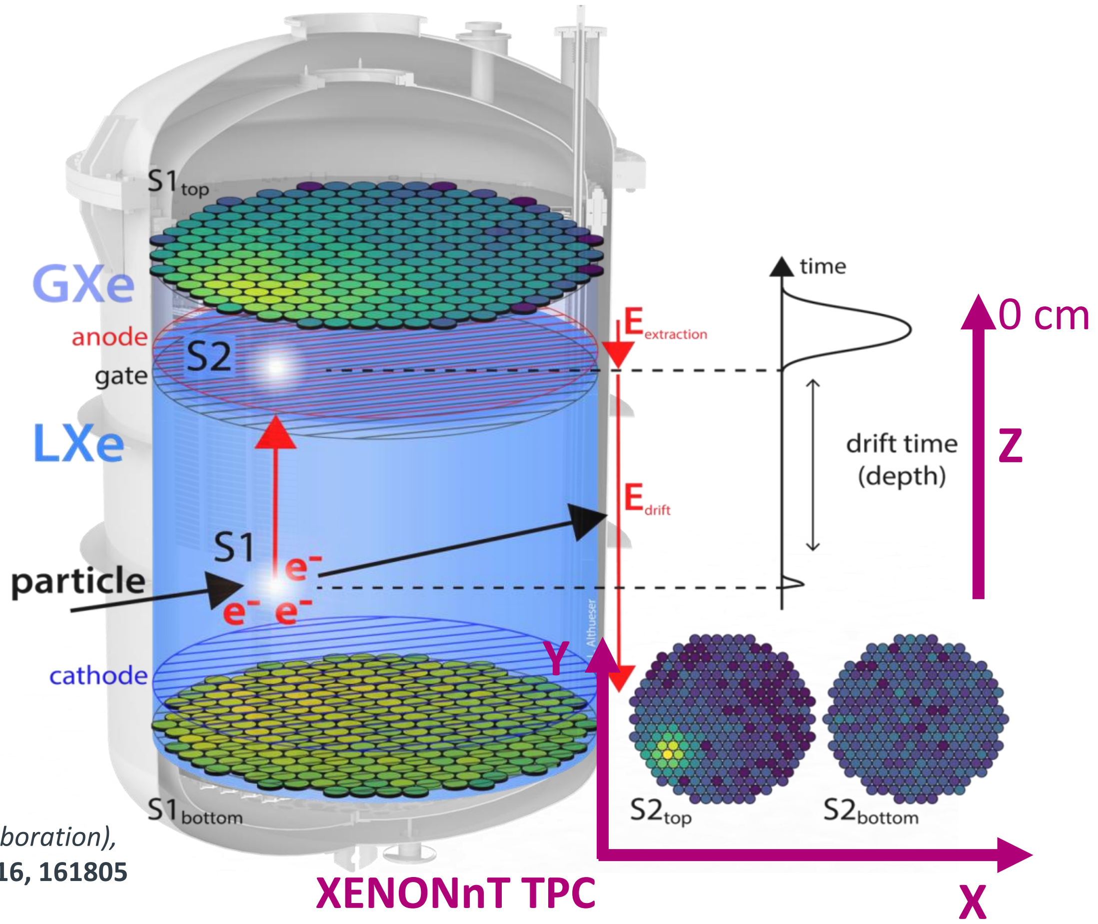
Fraction of prompt light emission (within 150 ns) over delayed emission (150 ns to 9 µs)

Electronic recoils from beta/gammas

Signal topology



- Use 3d interaction vertex reconstruction to reject background

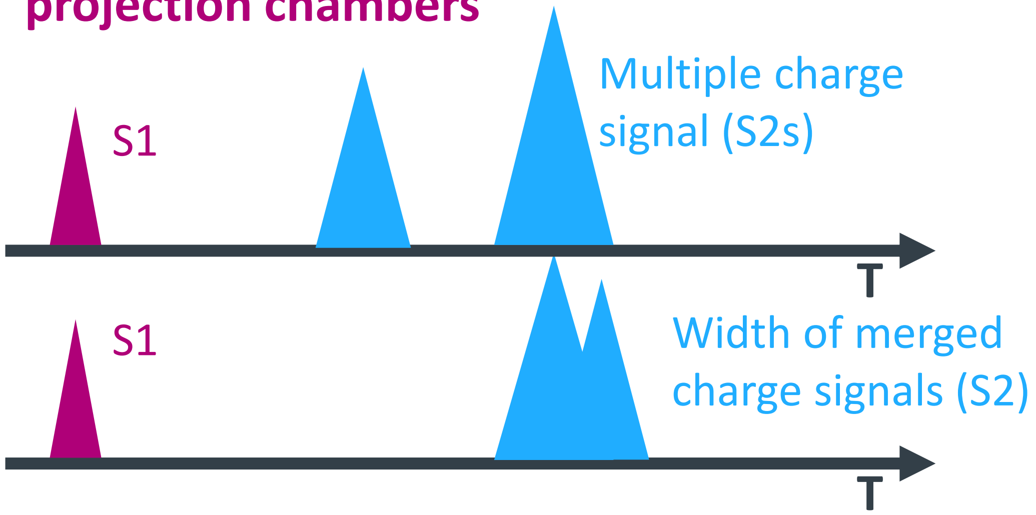


E. Aprile *et al (XENON collaboration)*,
Phys.Rev.Lett. 129 (2022) 16, 161805

Signal topology

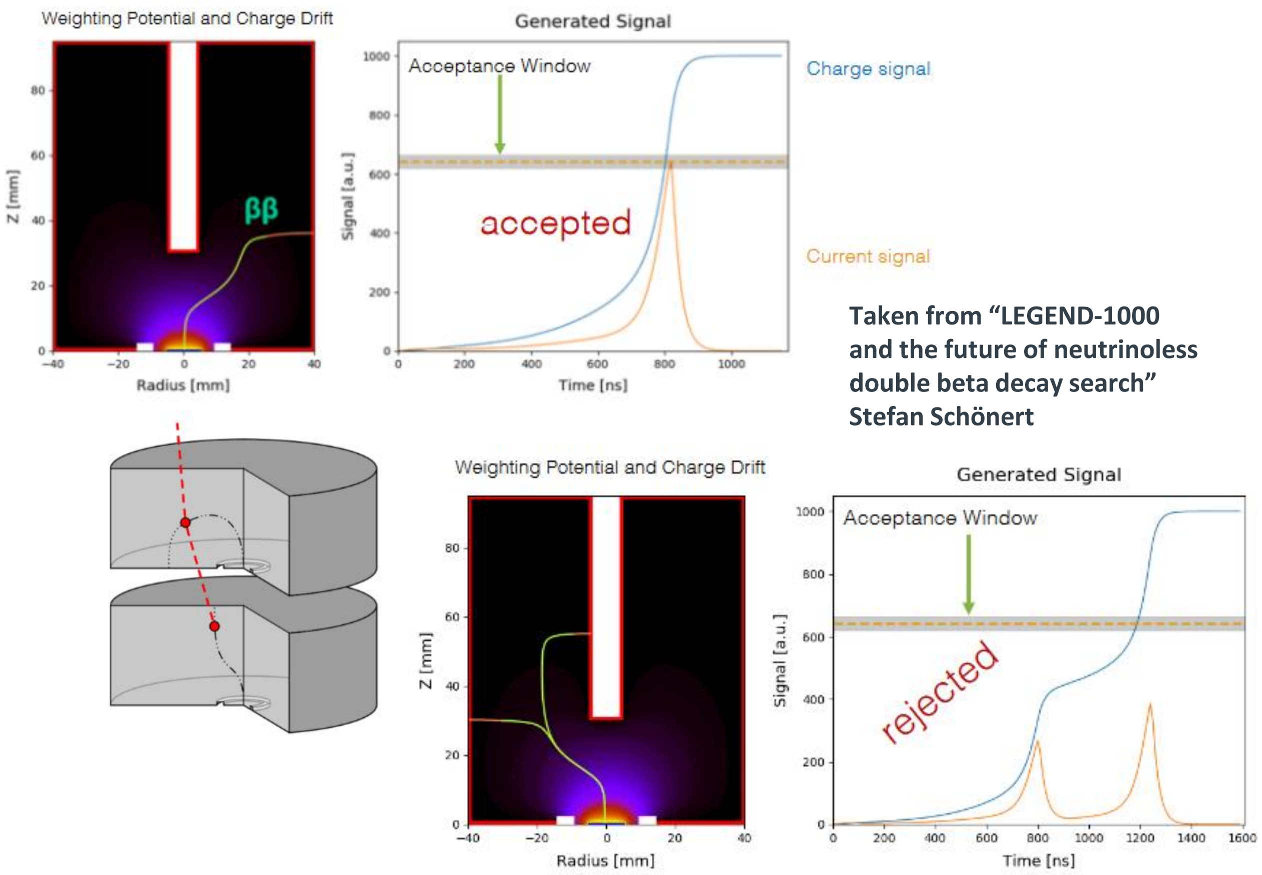
- Multi-scatter rejection of either Compton scatters or neutrons

Liquid nobel time projection chambers



Do you have another idea how one can identify merged S2 signals?

LEGEND multi-scatter rejection



Taken from "LEGEND-1000 and the future of neutrinoless double beta decay search" Stefan Schönert

Signal topology

- Fake signals from detector sensors are one of the most challenging backgrounds.
  - **Experiments using time projection chambers(TPCs, like XENONnT, LZ, DarkSide,…) suffer from accidental coincidences**

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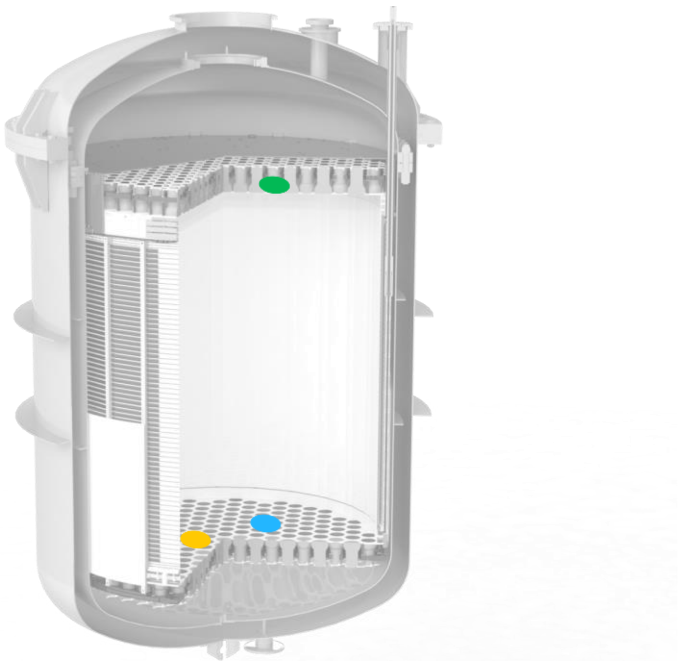

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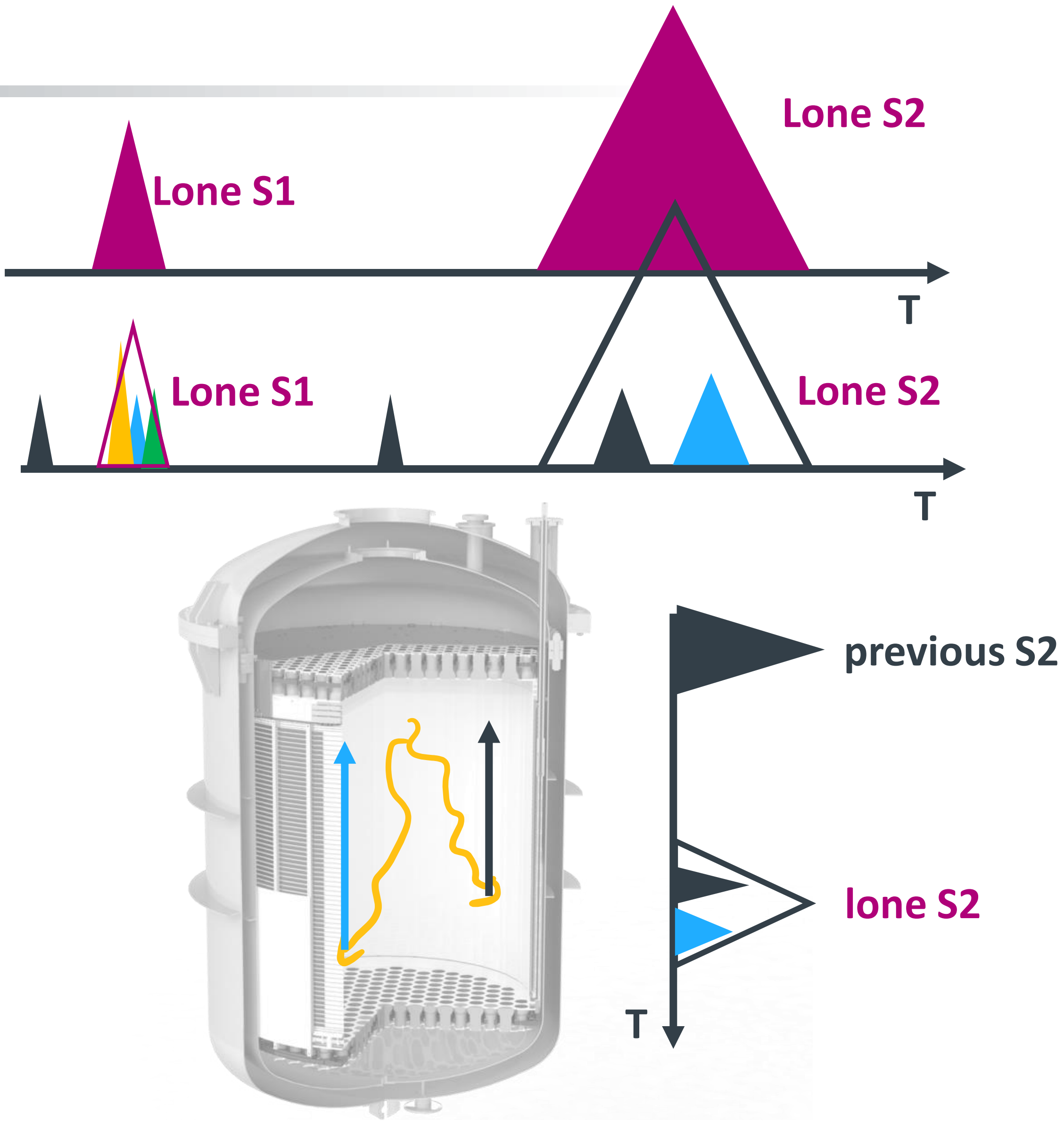
  - **Experiments using time projection chambers(TPCs, like XENONnT, LZ, DarkSide,…) suffer from accidental coincidences**
  - **Lone S1 signal made from false sensor signals from thermal emission**
  - **Lone S2 from ionization due to scintillation light, delayed extraction of electrons…**
  - **Discriminate signals via shape and pattern properties use machine learning techniques**

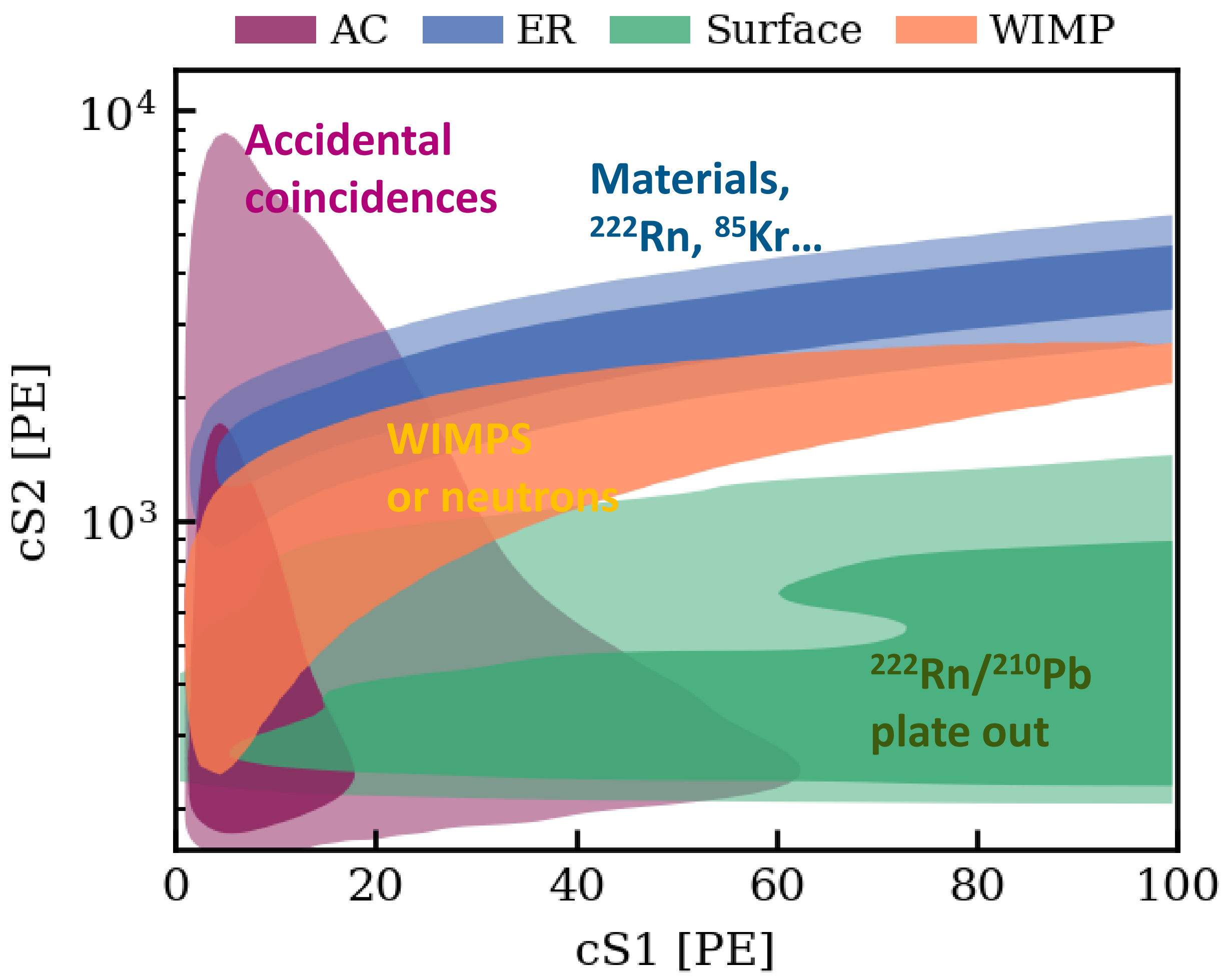


What other sensor or experiment specific artificial backgrounds do you know?

Signal topology

- After reducing all backgrounds all artificial signals as much as possible, build detector and background model.

There is one last source of bias which needs to be mitigated. What could it be?



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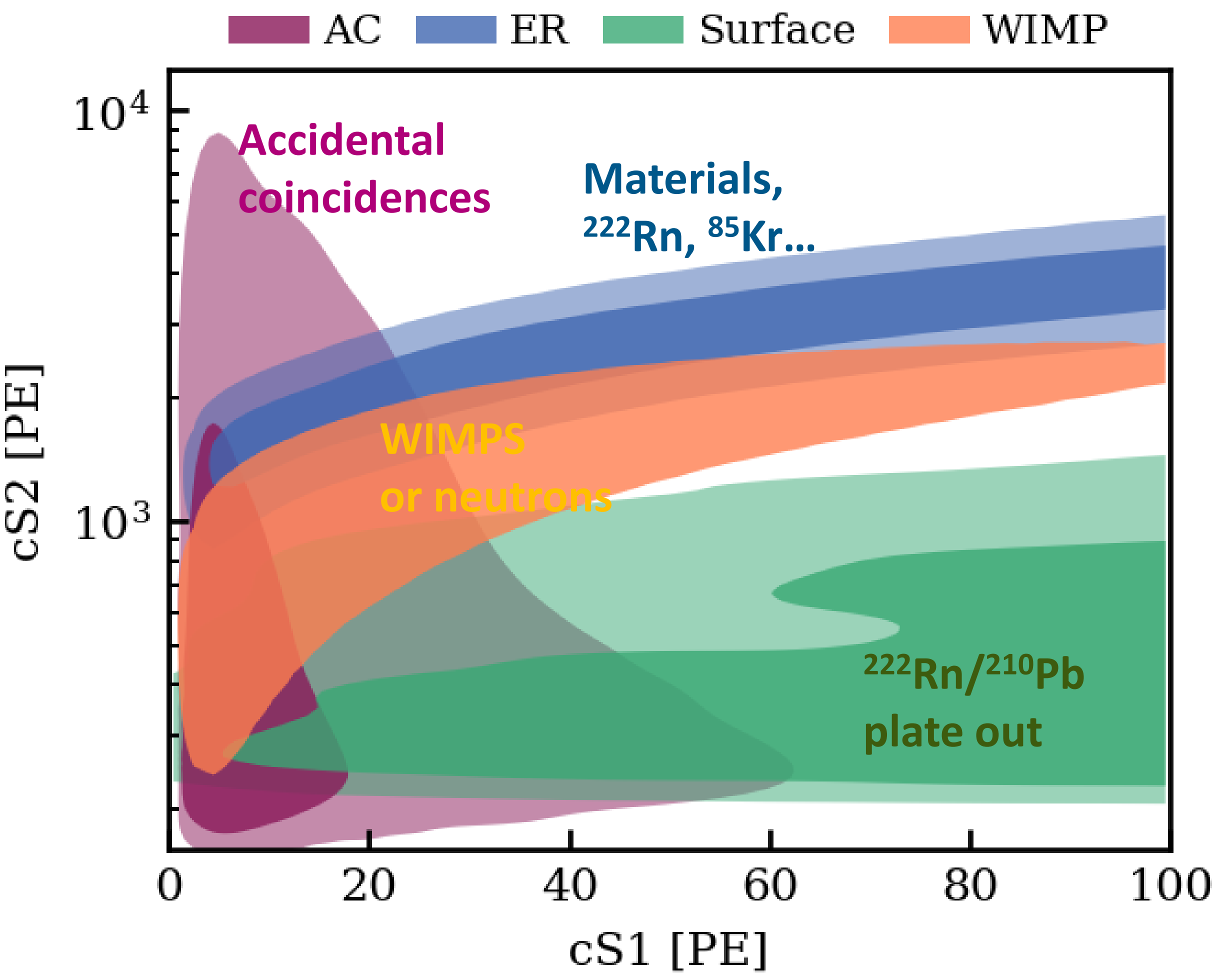
- Use calibration and side band data to confirm your models



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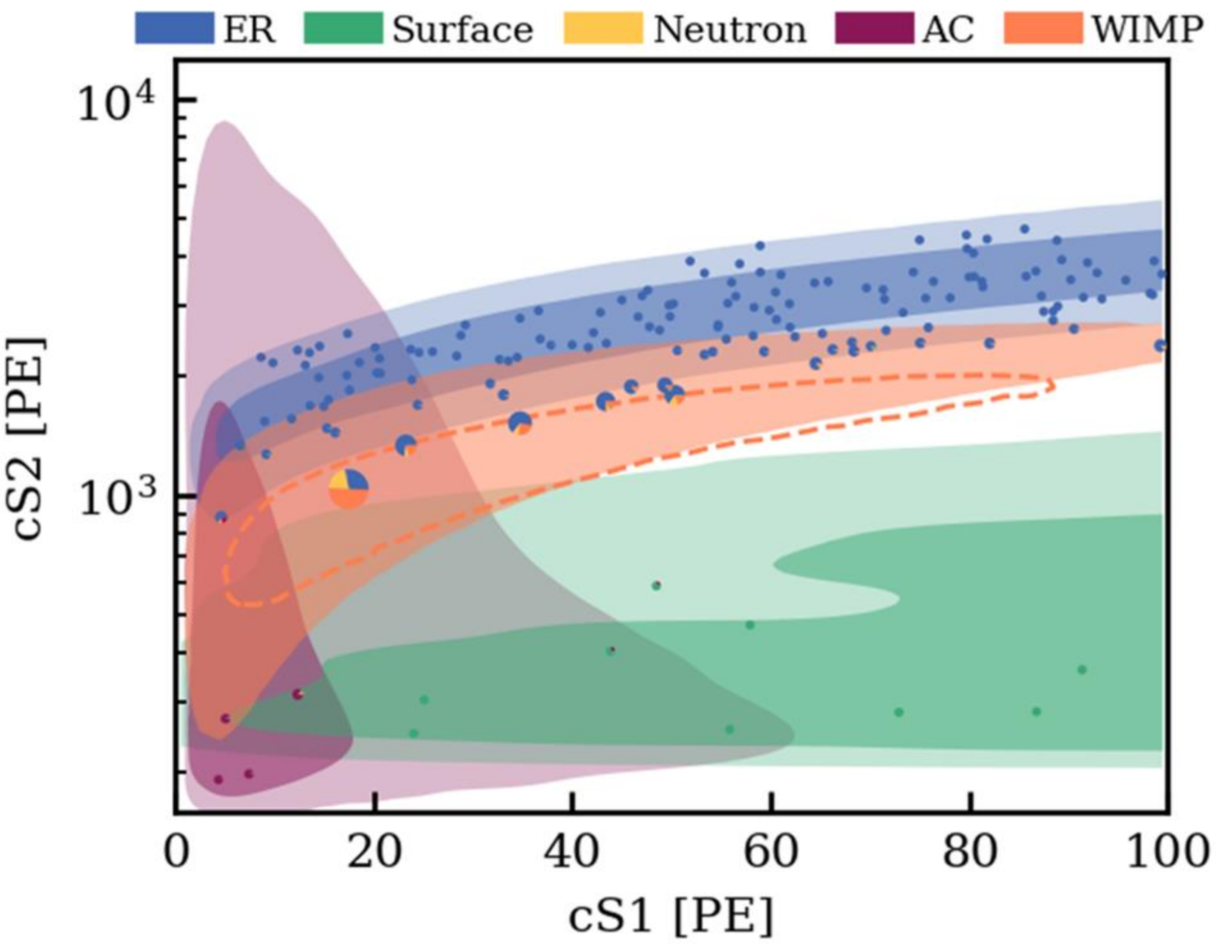
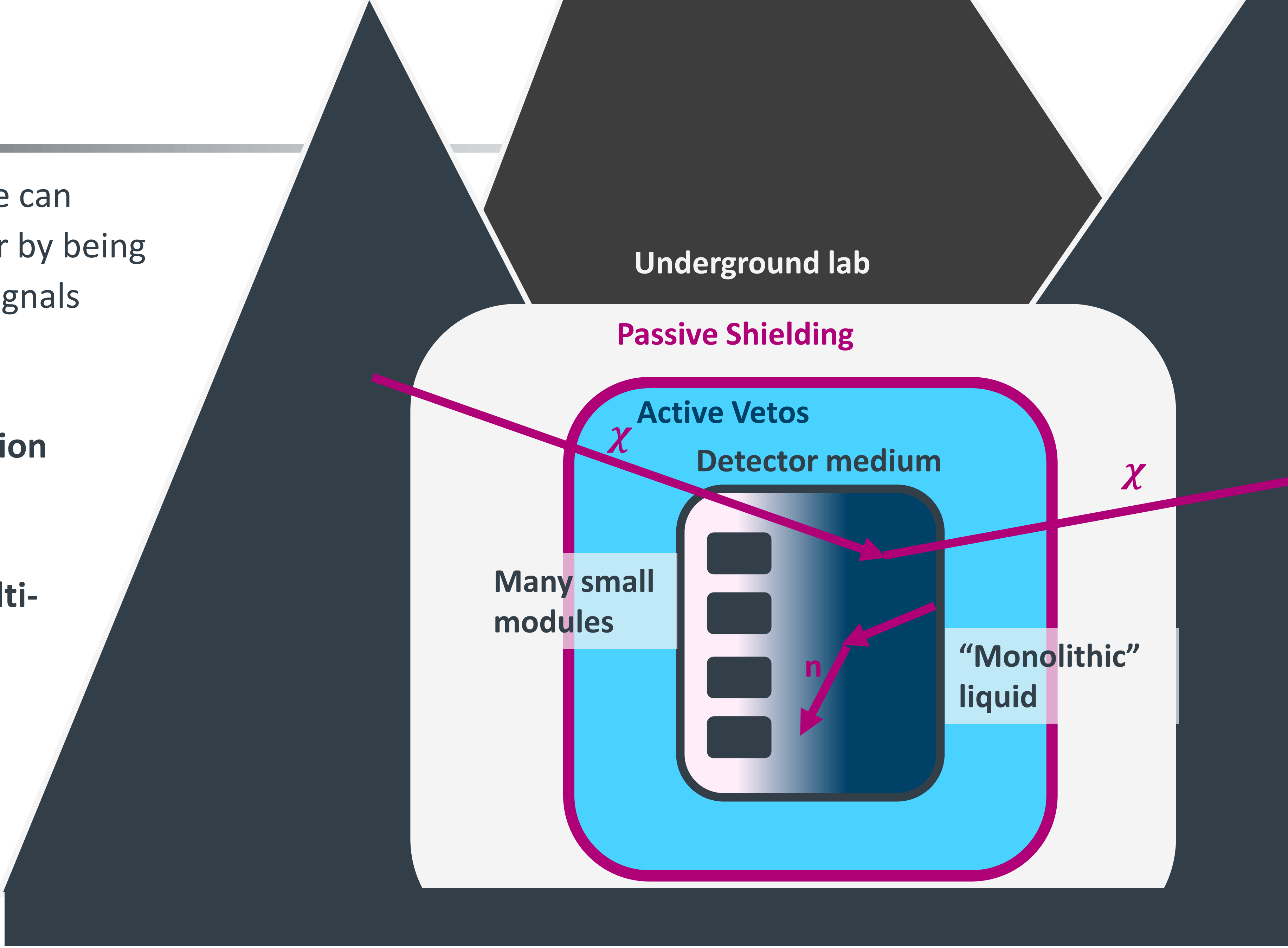
- Use calibration and side band data to confirm your models
- Only unblind your data once your model and selections are fixed.



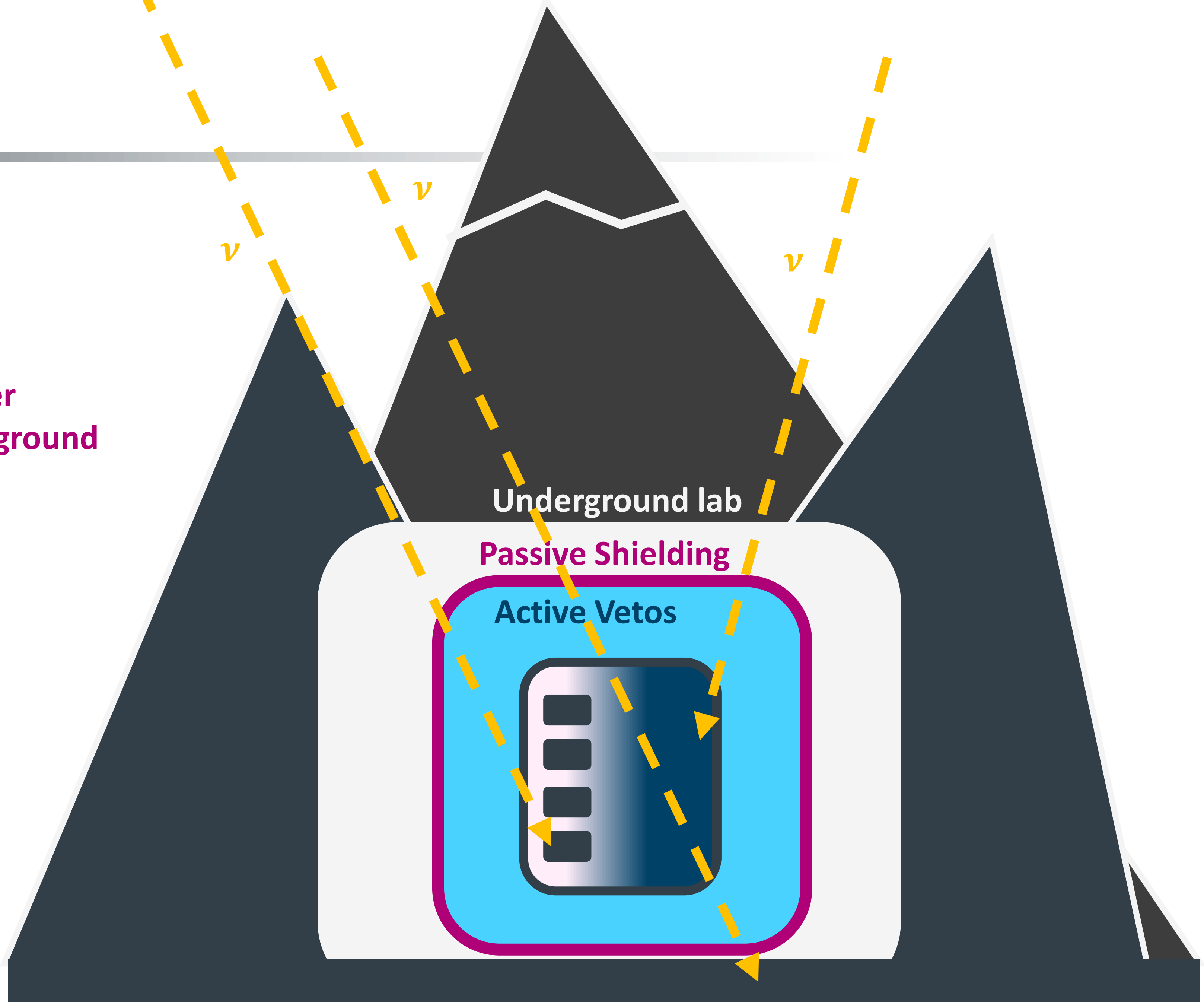
Recap

- After building a detector we can reduce backgrounds further by being smart about our detector signals
  - **Signal ratio**
  - **Pulse shape discrimination**
  - **Fiducilization**
  - **Signal topology e.g. multi-scatter rejection**
  - **Machine learning**
  - …
- Avoid human bias! Blind, salt or scramble your data!



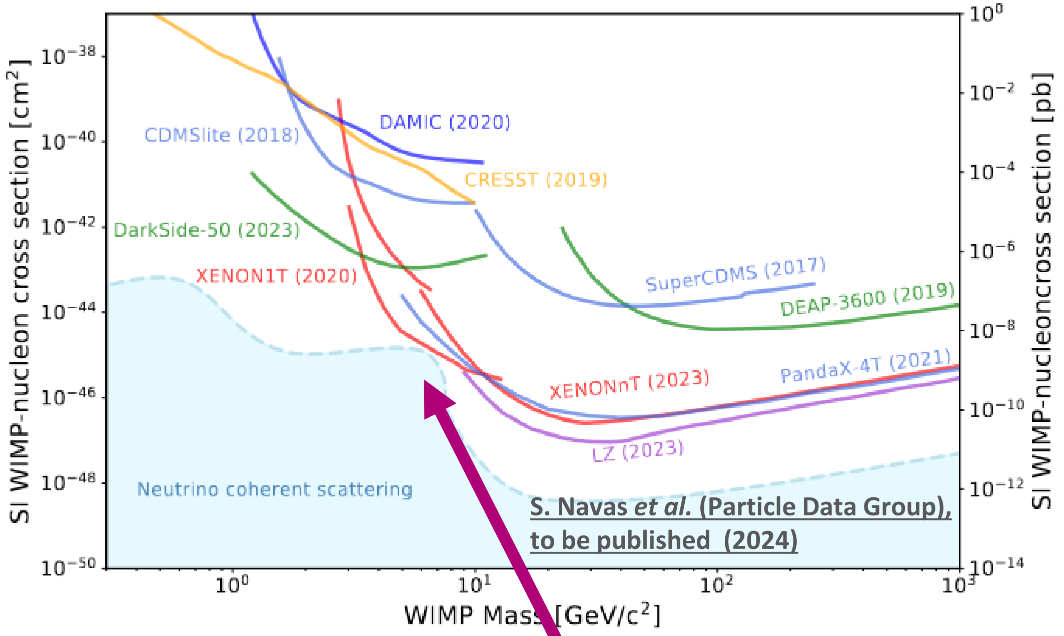
The ultimate background

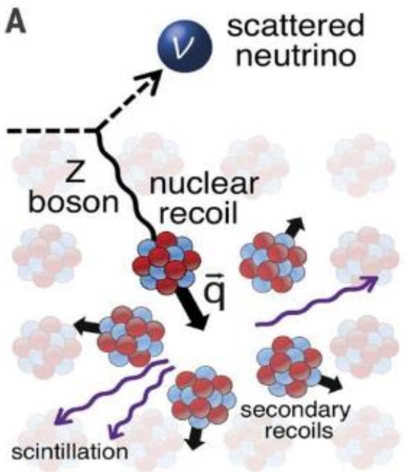
After mitigating every other background, the only background (signal) which remains are neutrinos!



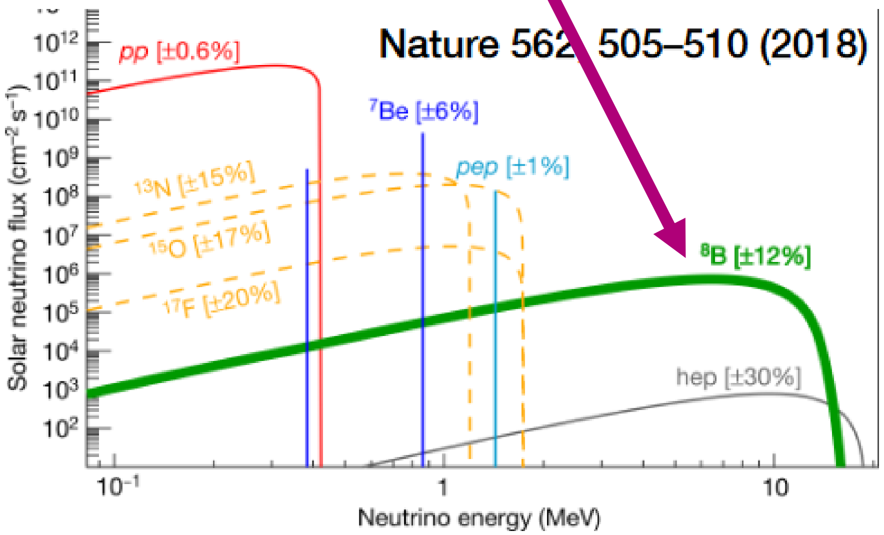
The ultimate background for DM searches

- Neutrino fog represents ultimate challenge for today’s direct detection DM experiment
  - **Interaction through coherent elastic neutrino nucleus scattering (CEvNS)**
  - **Lower spectrum dominated by solar neutrinos, upper spectrum by atmospheric neutrinos**





D. Akimov et al, Science 357 (2017)



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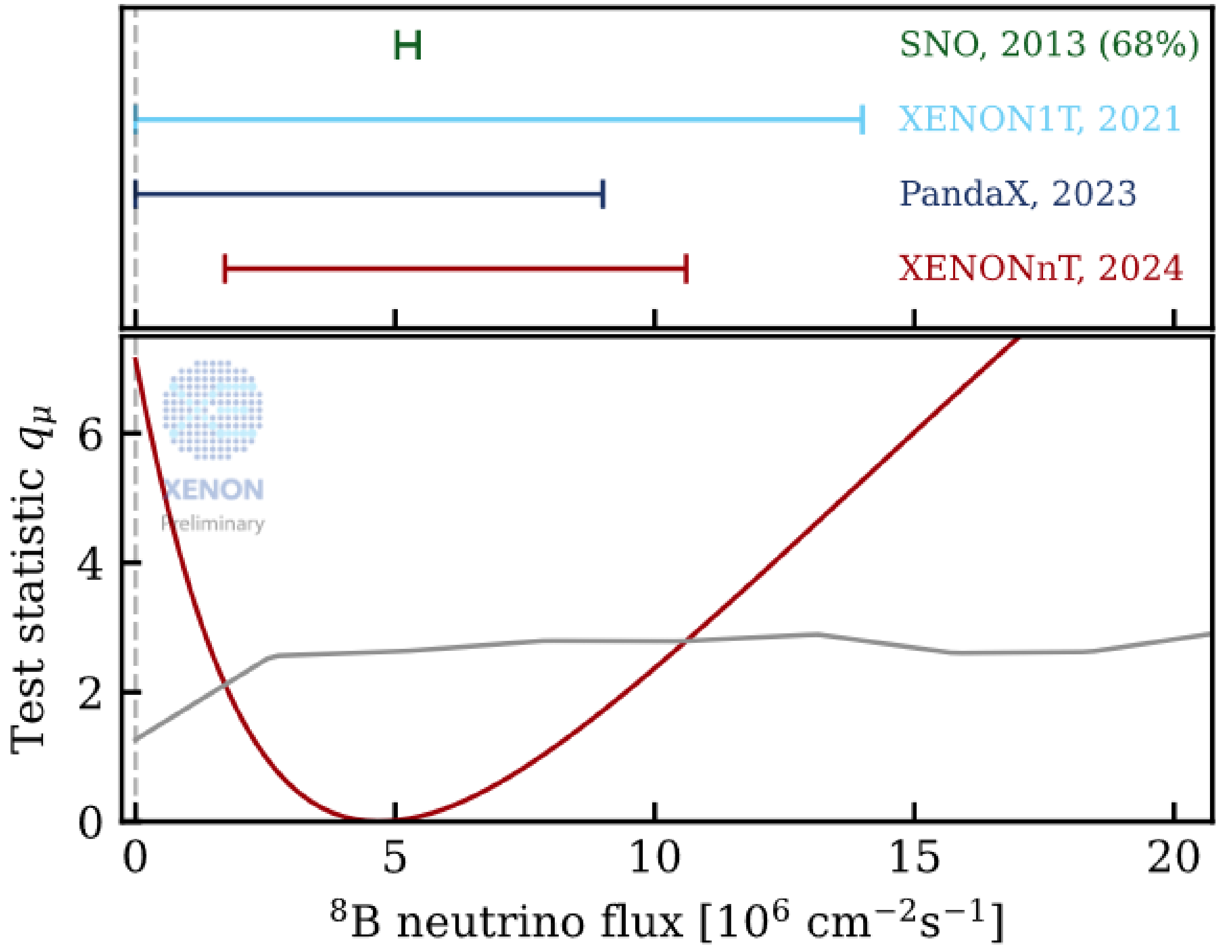
  - **Interaction through coherent elastic neutrino nucleus scattering (CEvNS)**
  - **Lower spectrum dominated by solar neutrinos, upper spectrum by atmospheric neutrinos**

First measurement of solar neutrinos through CEvNS in XENONnT @2.73 σ (see also talk by Fei Gao at IDM, paper under preparation)

First observation of nuclear recoils through weak force.



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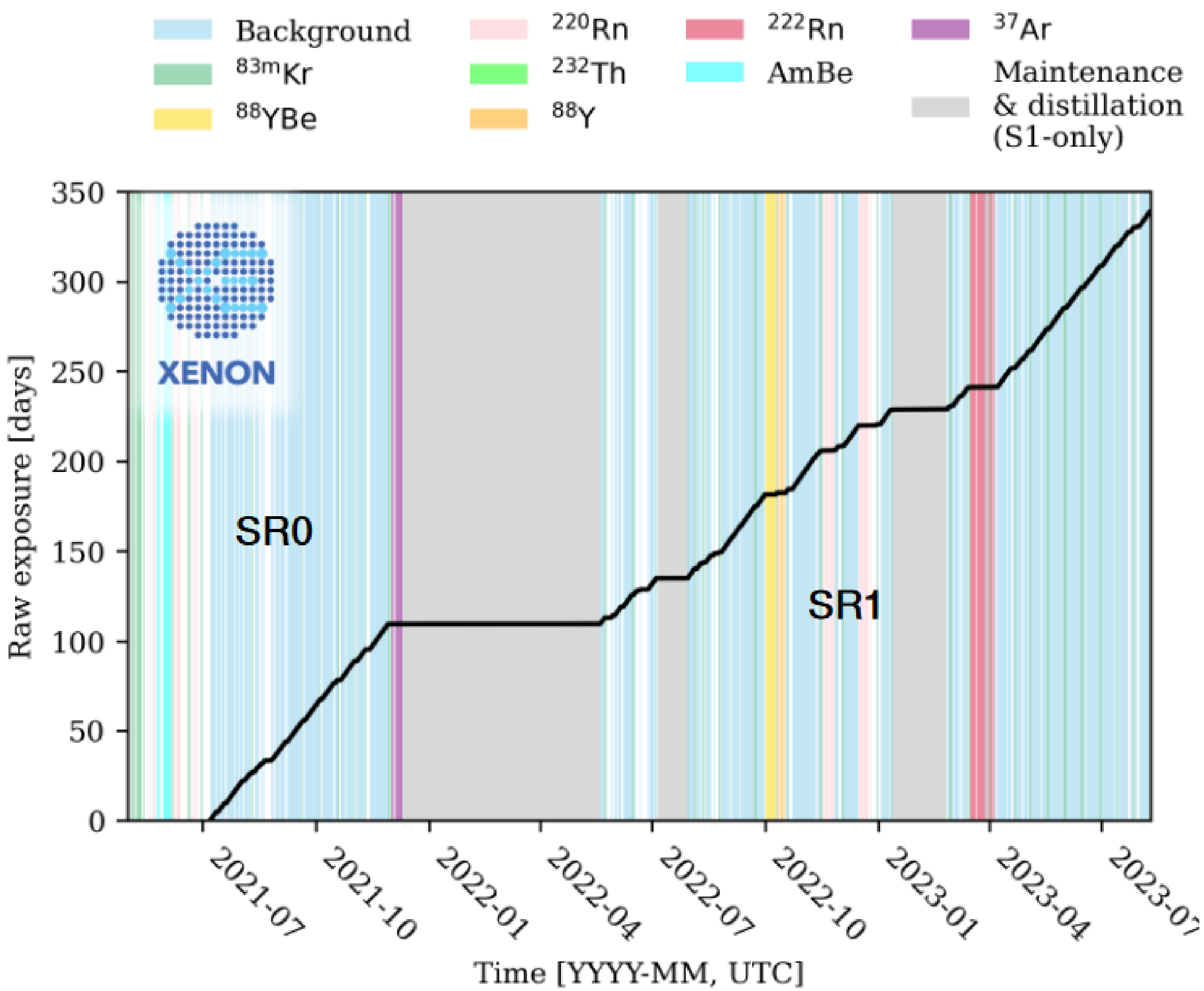
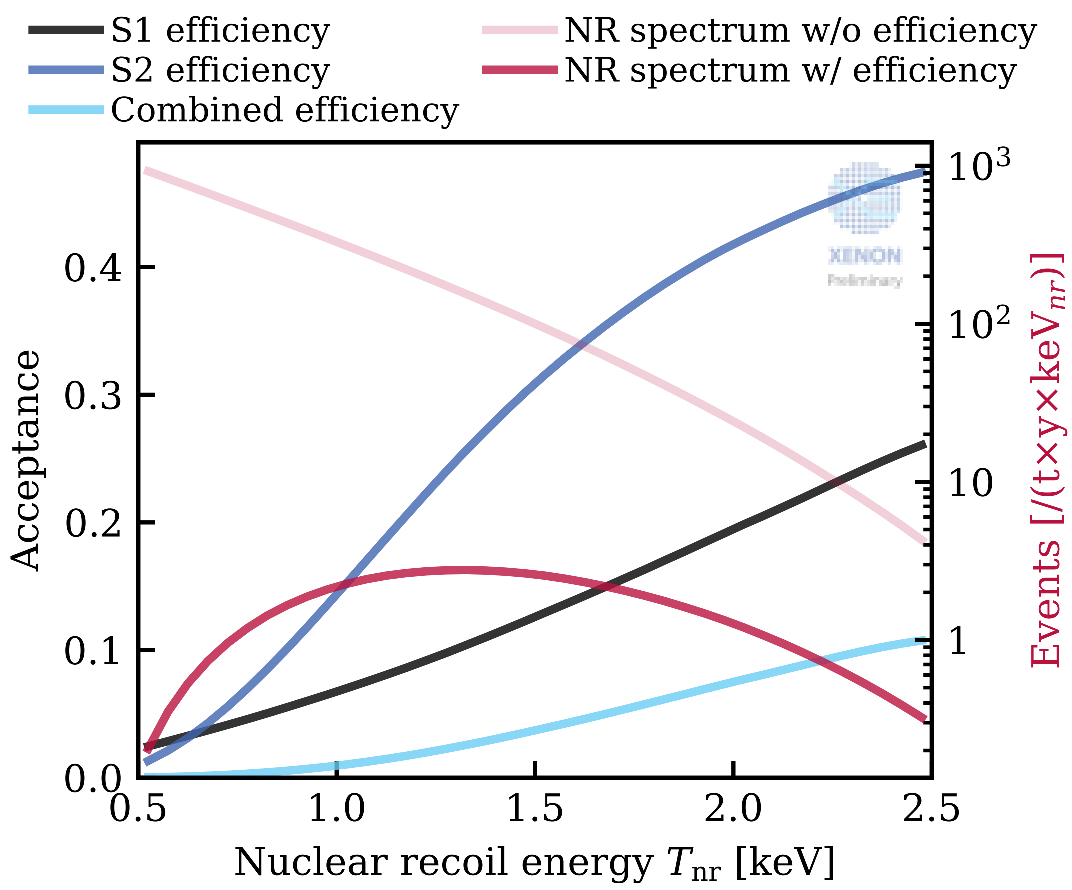
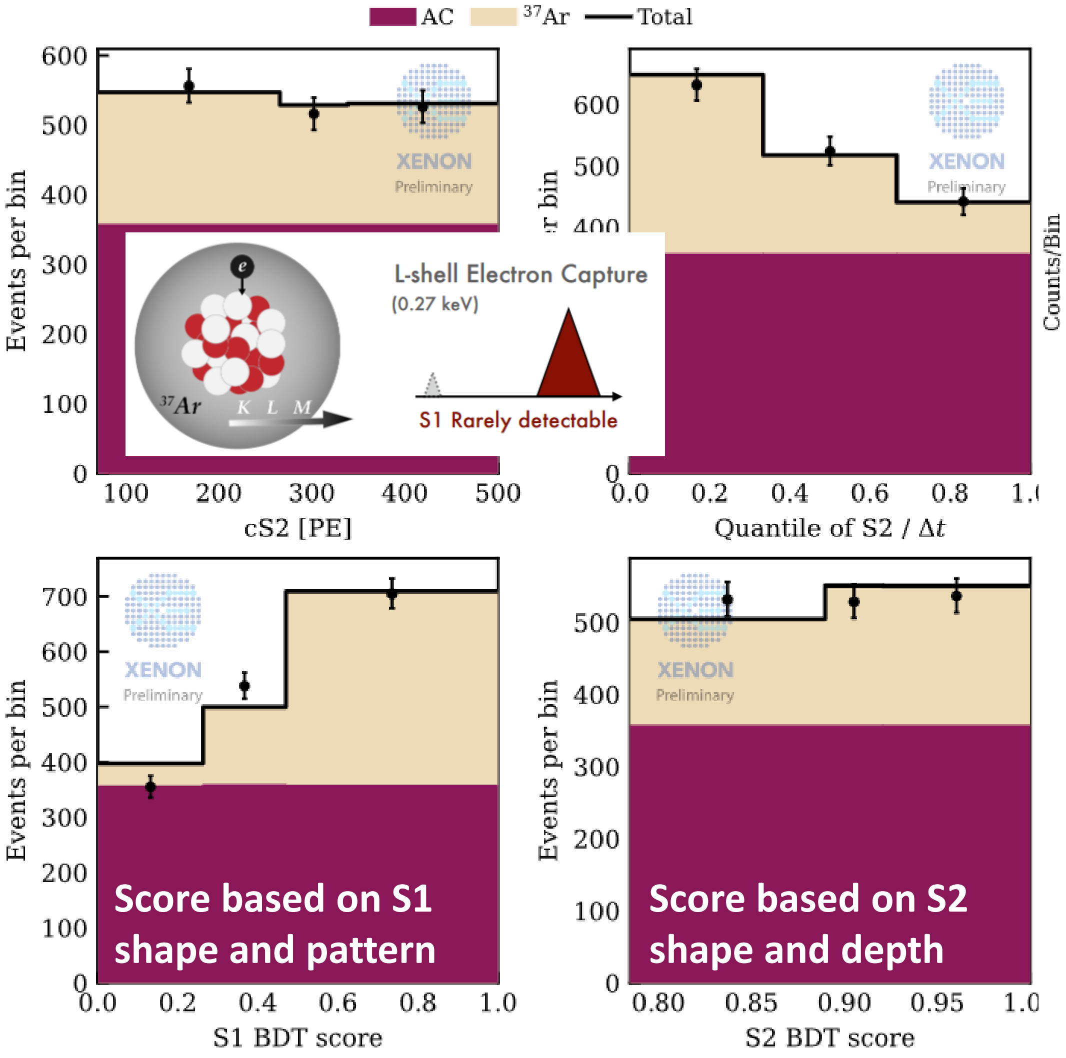


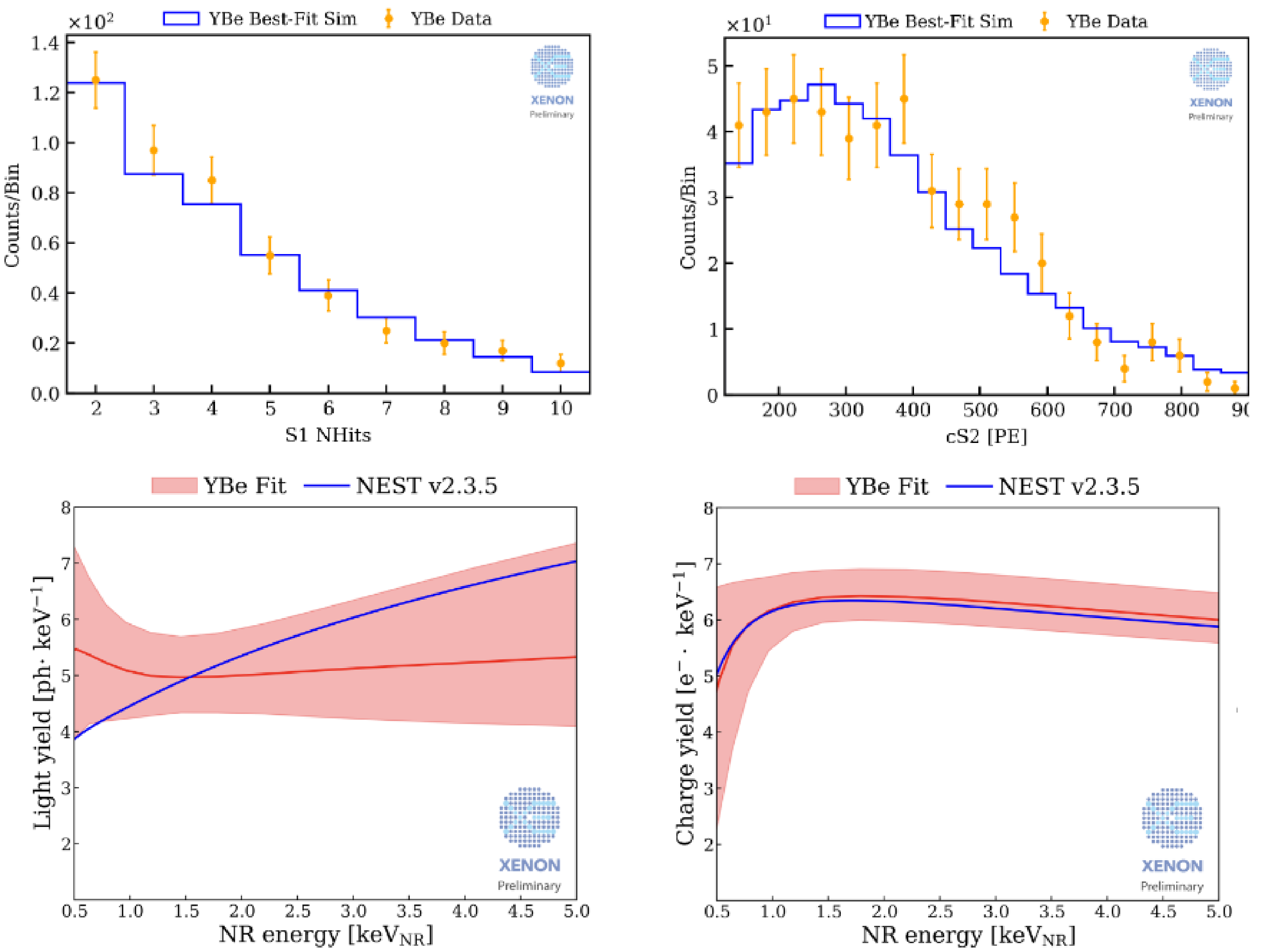


The ultimate background for DM searches

Validation of analysis dimensions using ^{37}Ar



NR model calibrated using low energy photo-neutrons from YBe



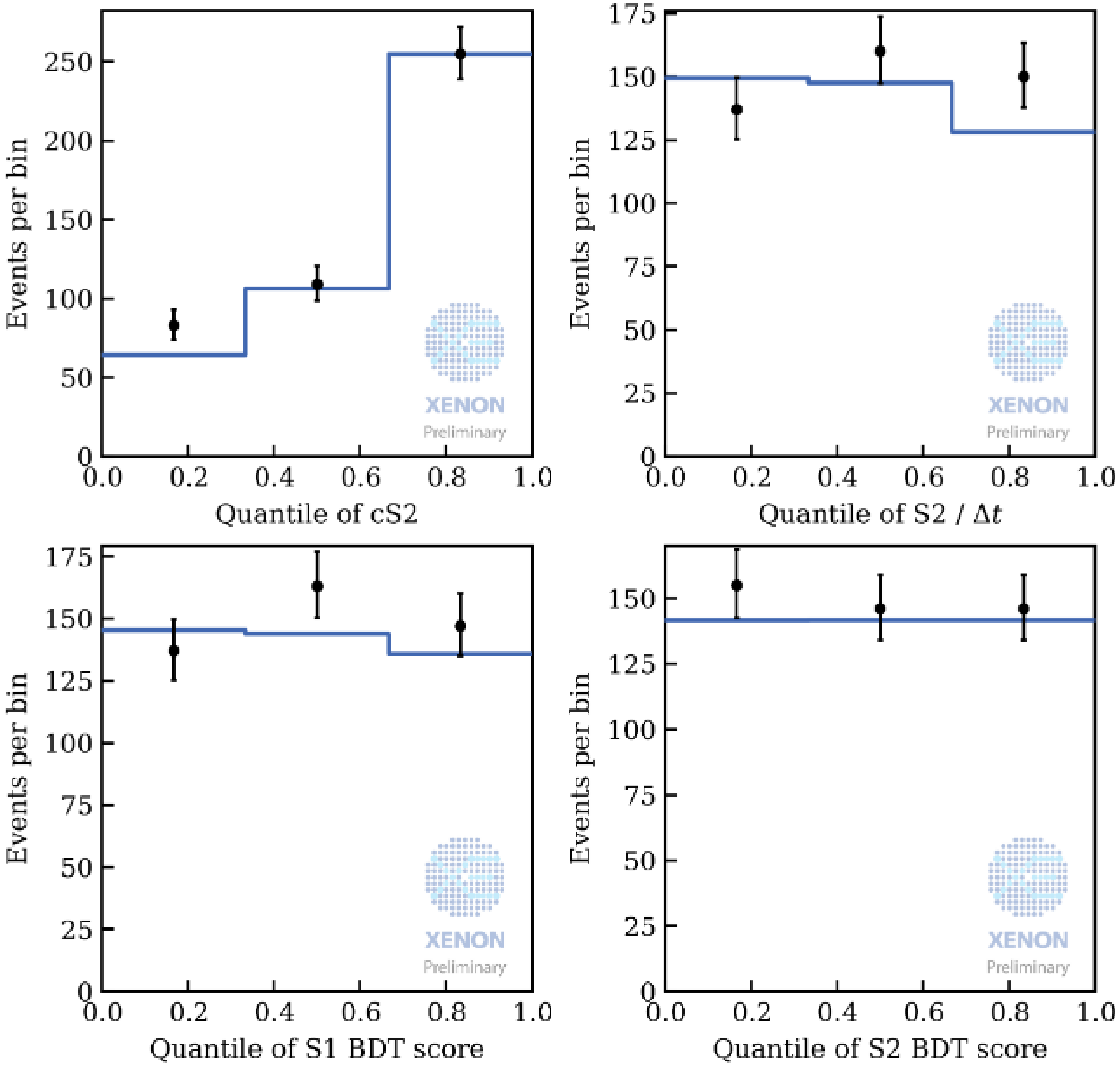
Daniel Wenz

Low ba

The ultimate background for DM searches

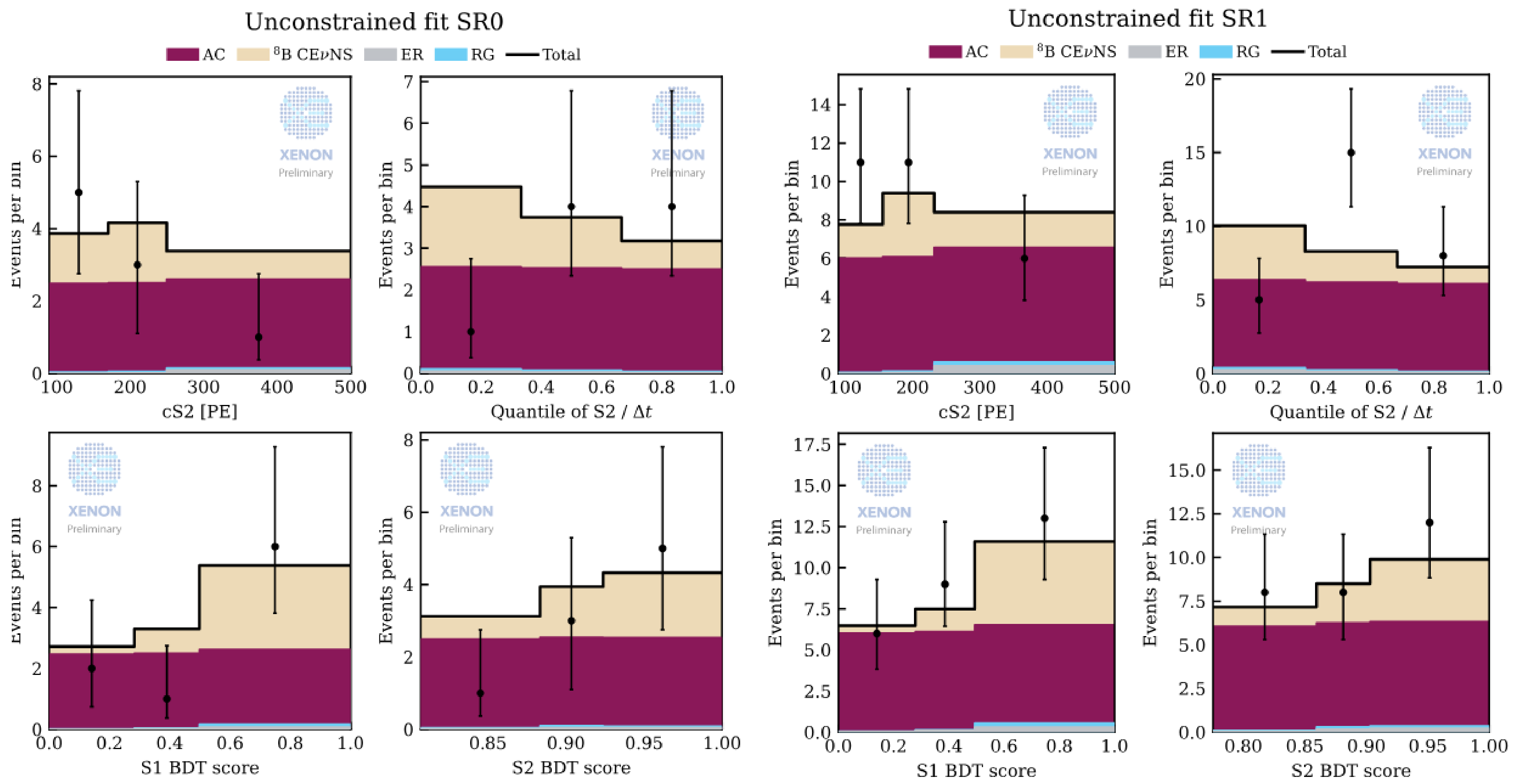
- AC background dominant background
  - **Used sideband unblinding to confirm background model.**
  - **Import define tests and procedure before unblinding!**
  - **Raised threshold at cost of signal acceptance since model could not handle too small S2s**
  - **Remaining discrepancy added as a systematic uncertainty**

Science Run	Expectation	Observation	P-value (4D)	Deviation from expectation
SR0	122.7	121	0.33	-0.15 sigma
SR1	290.0	310	0.252	1.17 sigma



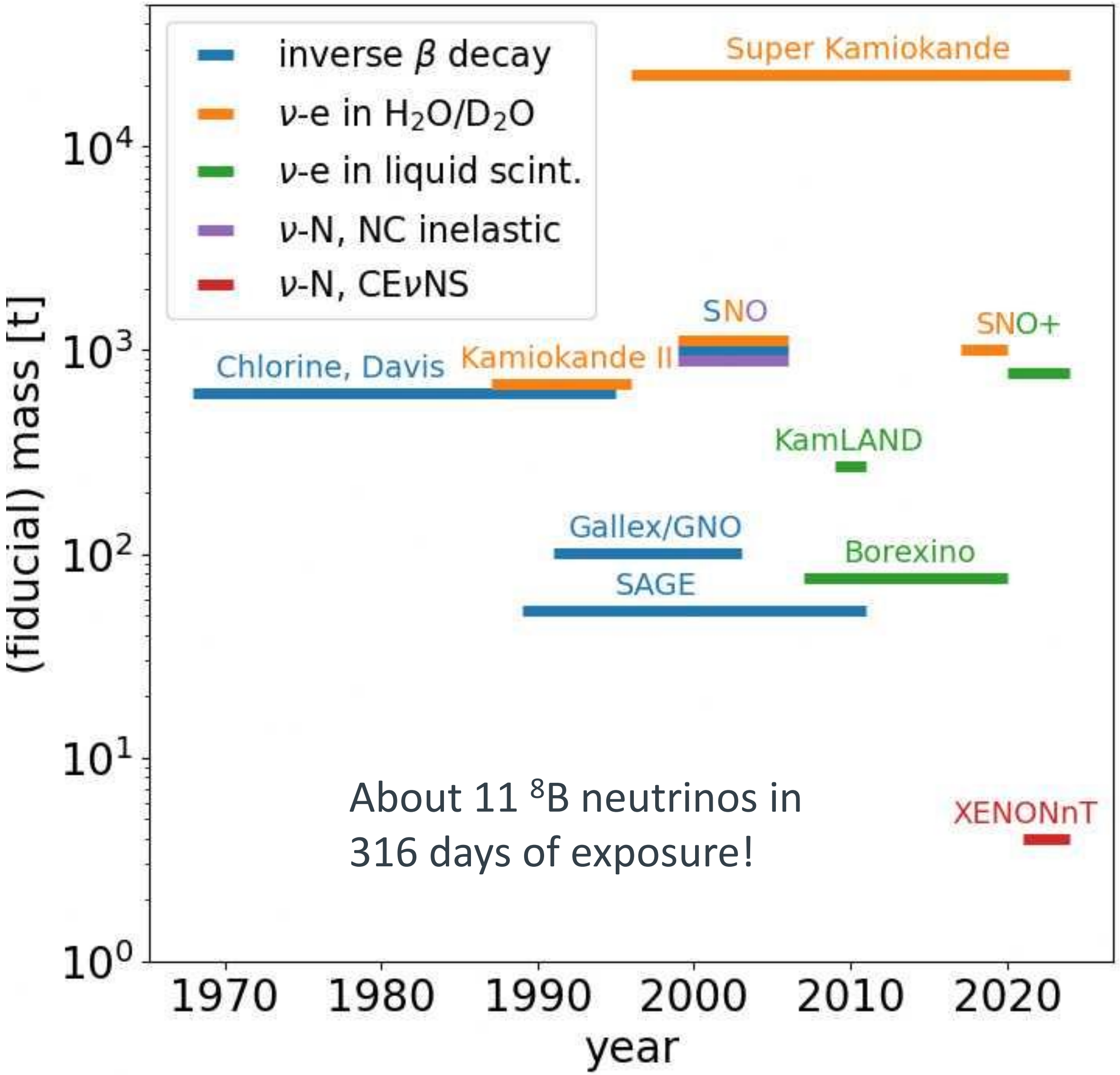
The ultimate background for DM searches

After verifying background and signal models, unblind data and perform fit in 4 analysis dimensions



The ultimate background for DM searches

Component	Background only fit	Background + ^{8}B fit	Nominal Expectation
AC - SR0	7.55	7.36	7.48 ± 0.52
AC - SR1	18.26	17.90	17.77 ± 1.23
ER	0.74	0.54	0.68 ± 0.68
NR	0.50	0.45	0.47 ± 0.32
Total Background	27.05	26.24	26.4 ± 1.5
^{8}B	-	10.71	11.9 ± 3.1
Observed		37	

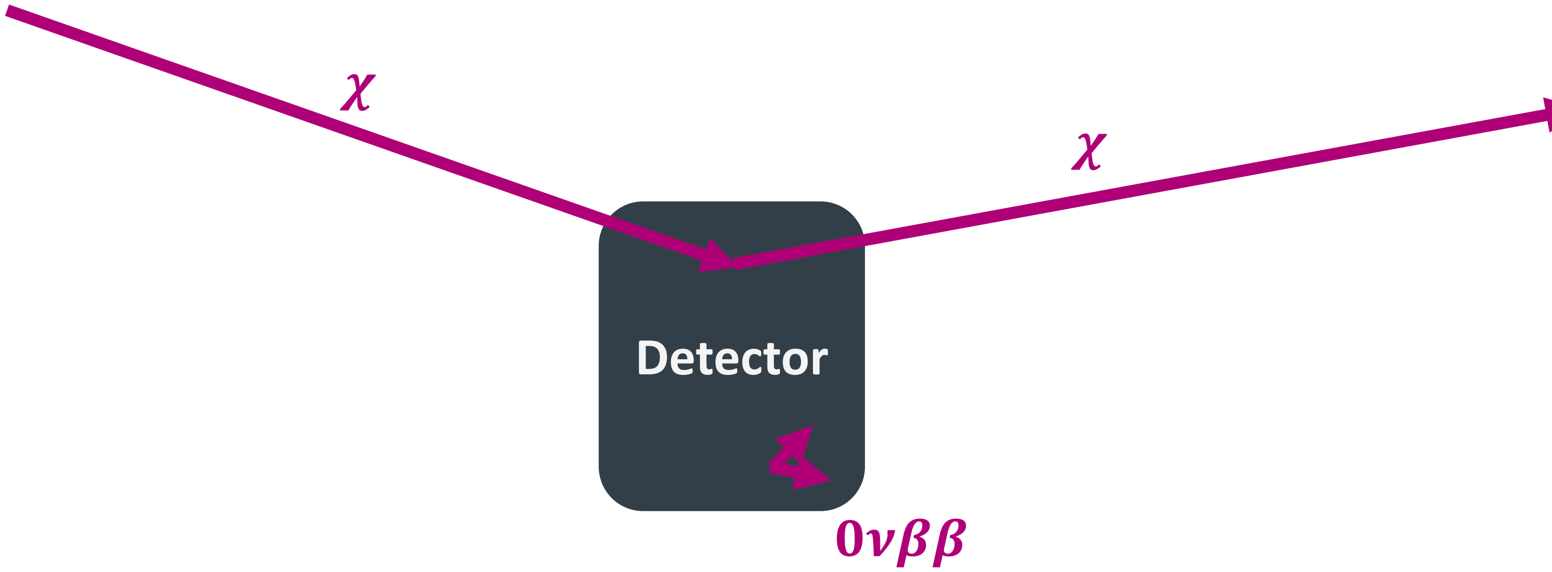


About 11 ^{8}B neutrinos in 316 days of exposure!

Recap: Low energy rare event searches

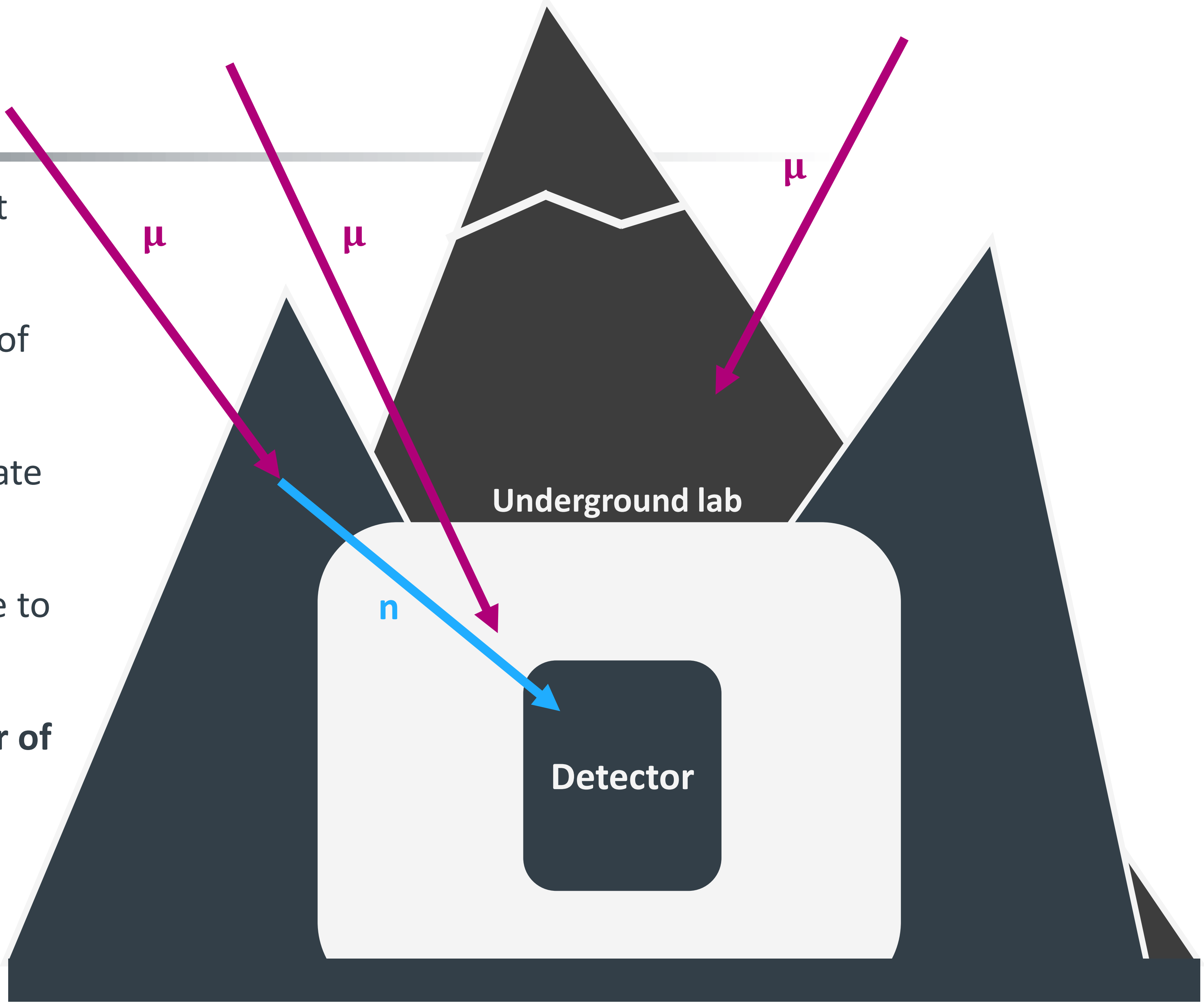
- Sensitivity of background free experiments scale with exposure T
- Background dominated experiments with $\sqrt{T}$
- Search for the needle in the haystack
  - **Current experiment expect rates of $\sim 20 \frac{1}{\text{tonne x year}}$**
  - **Problem, we live in a radioactive world:**

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



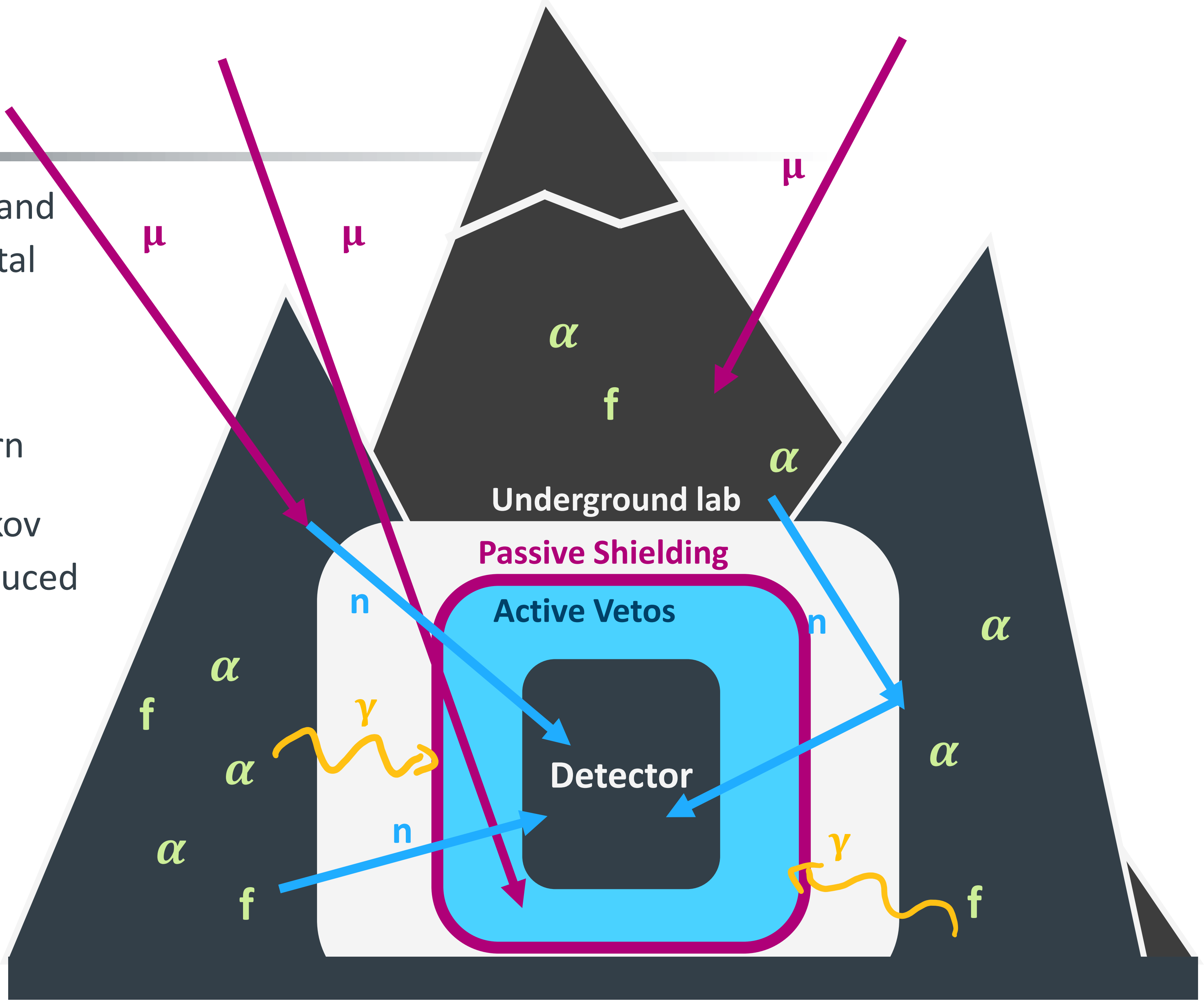
Underground laboratories

- Typical muon rate at sea level about 1 μ/min/cm^2
- Typical muon energies in the order of 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**



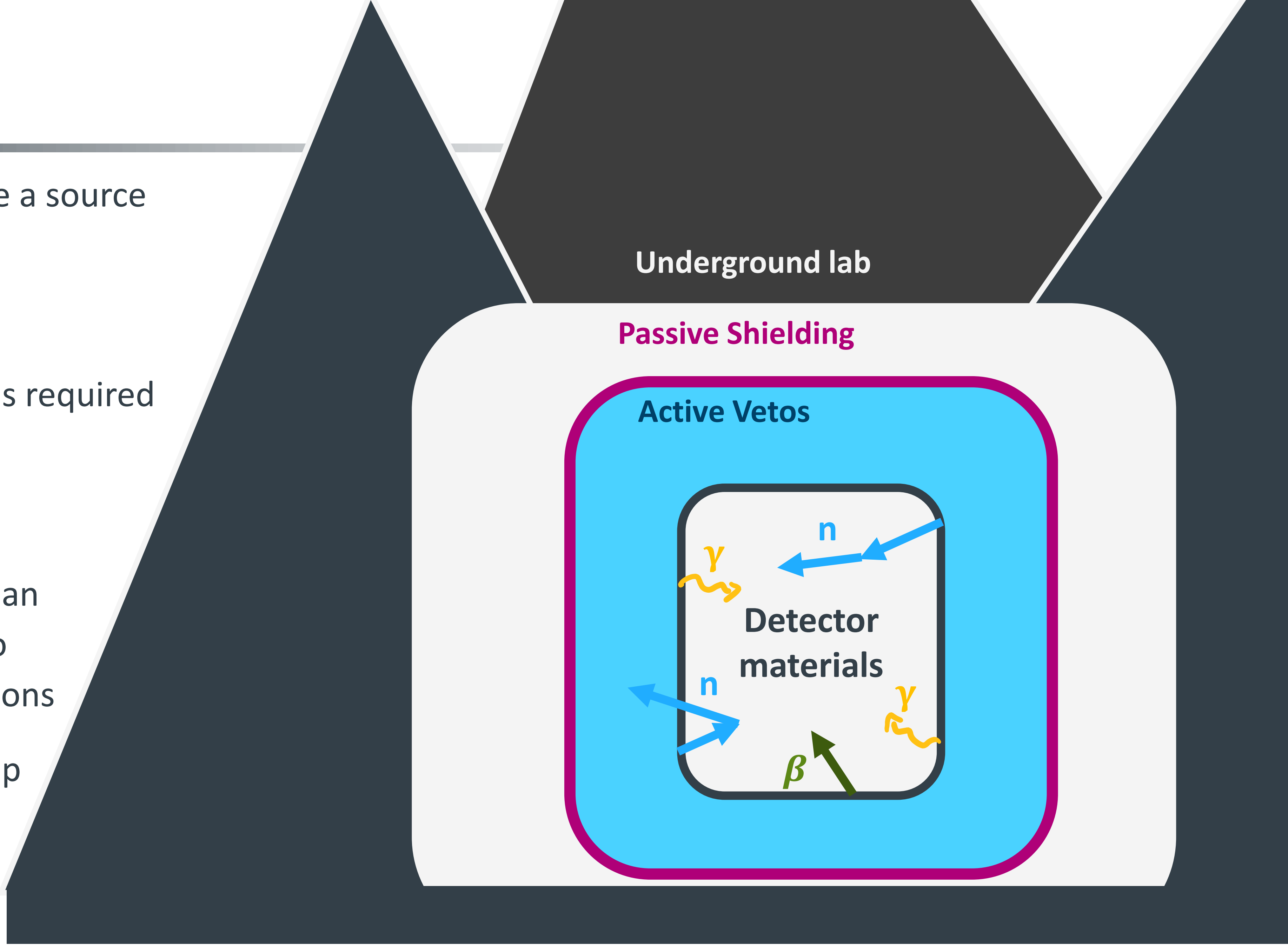
Overview

- 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**
- Cleaning and working in clean environments is required to reduce surface contaminations
- Active veto systems can help to further mitigate backgrounds via **anti-coincidences**



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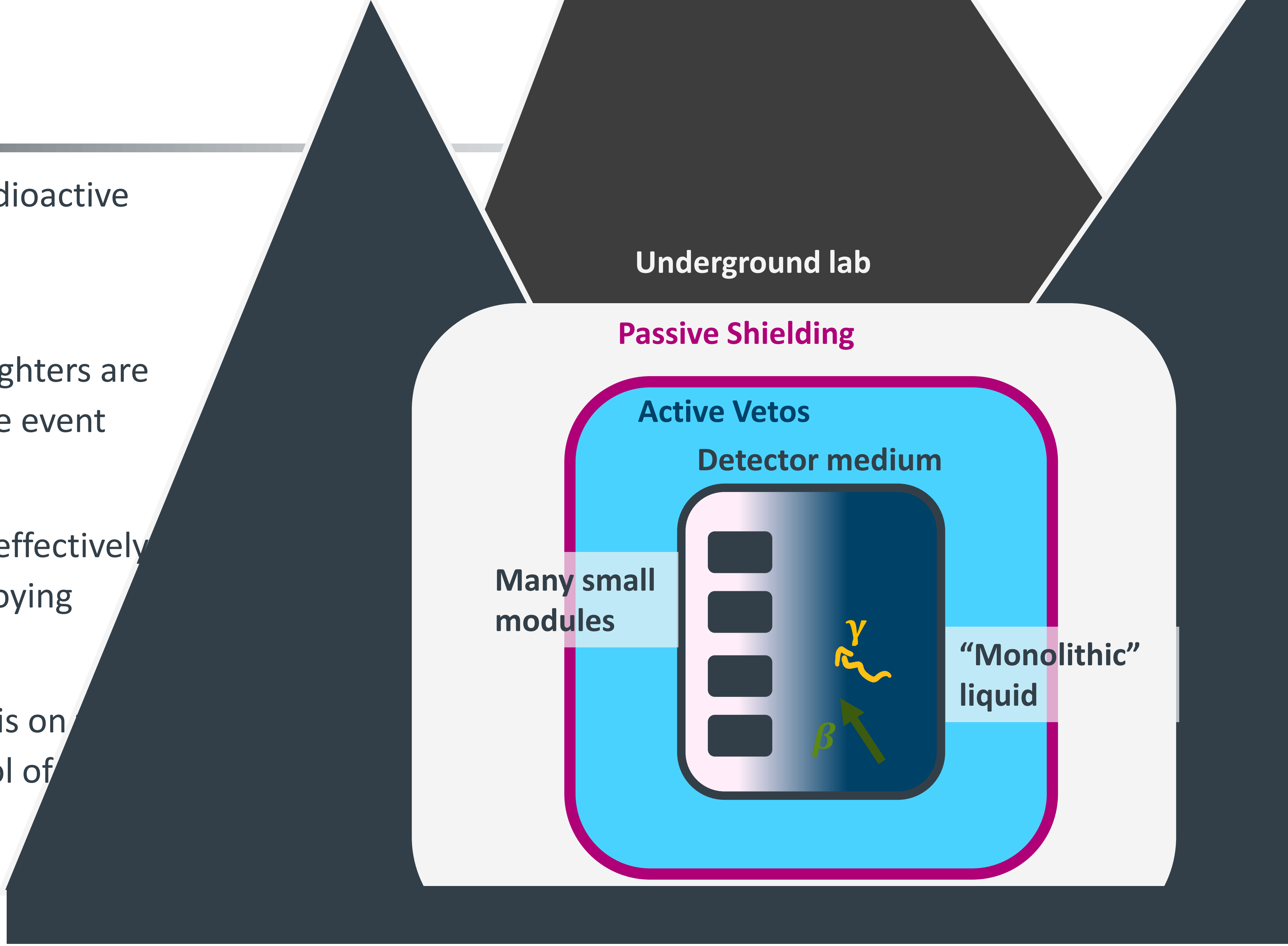

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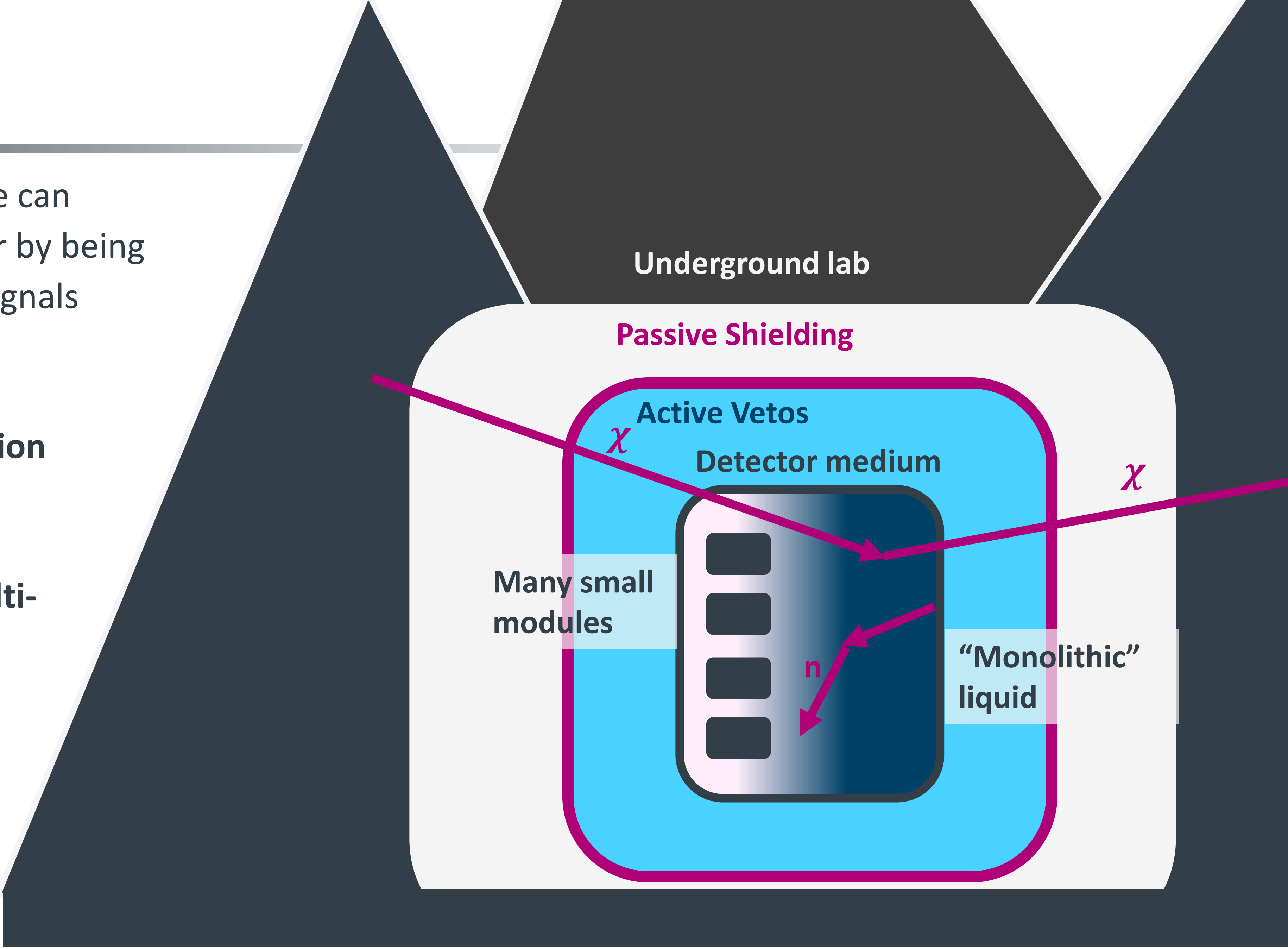

Searching for rare events is awesome and it is all about knowing your backgrounds!