Low radioactivity techniques for Large TPCs in rare event searches

- Background components
- Mitigation techniques and tools:
  - Undeground facilities and shieldings
  - Material radiopurity
  - Discrimination techniques
  - Simulation and codes

11th Symposium on Large TPCs for low-energy rare event detection

Paris, 13th December 2023

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- ✓ **Cosmic rays** Muons ➡ γ, neutrons

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  • **Radioactivity** in materials (primordial, cosmogenic, anthropogenic): ^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{210}Pb, ... ➡ α, β γ

internal
external

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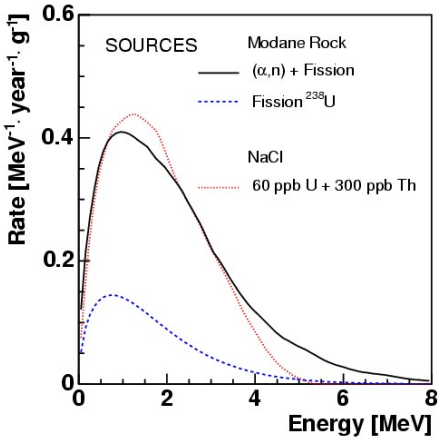
  - **Neutrons**: radiogenic: fission, (α,n) reactions in rock, cosmogenic: induced by μ

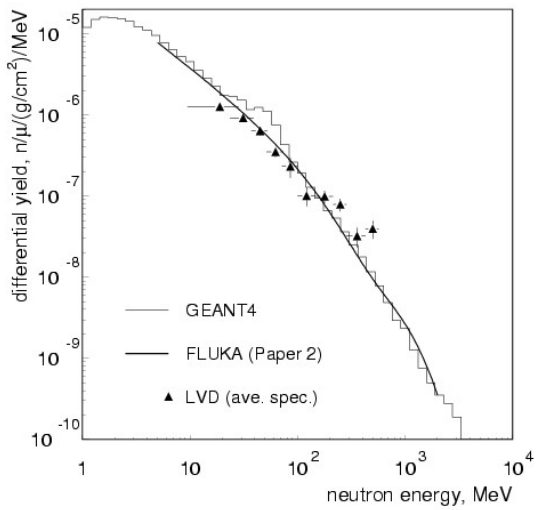


spectrum: up to GeV

flux: ~10^{-9} n/cm^2/s (~3 km w.e.)

spectrum: up to few MeV

flux: ~10^{-6} n/cm^2/s



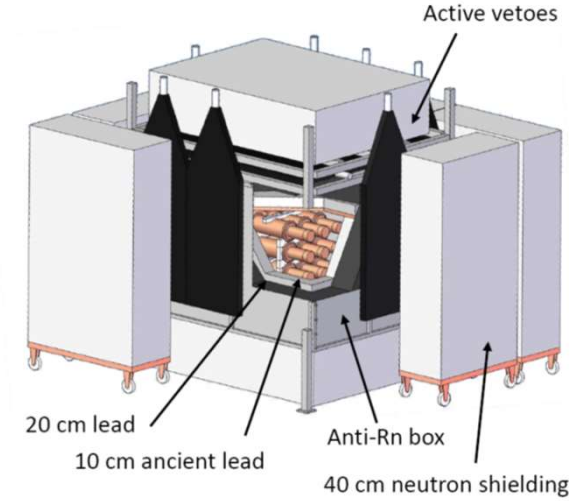
➡ (n,γ) capture; inelastic scattering → γ, …

elastic scattering → WIMP-like recoils!

Mitigation techniques and tools

Reducing the flux of background-creating radiation

- Underground facilities
- Passive shielding
  - γ: Pb, Cu
  - *Neutrons*: water, polyethylene, Cd
- Control of radiopurity of materials
  - Measurements
  - Material treatment: bulk, surface
  - Minimizing cosmogenic activation



ANAIS (*Annual modulation with NaI Scintillators*) at Canfranc

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Active event tagging

- Active shielding
  - Anticoincidence
  - Fiducial volumen
  - Vetos
- Techniques for background rejection
  - Pulse Shape Discrimination
  - Topology of events
  - Simultaneous measurements of heat and light/ionization signals
  - …

CUORE (*Cryogenic Underground Observatory for Rare Events*) at Gran Sasso

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Monte Carlo simulations of background

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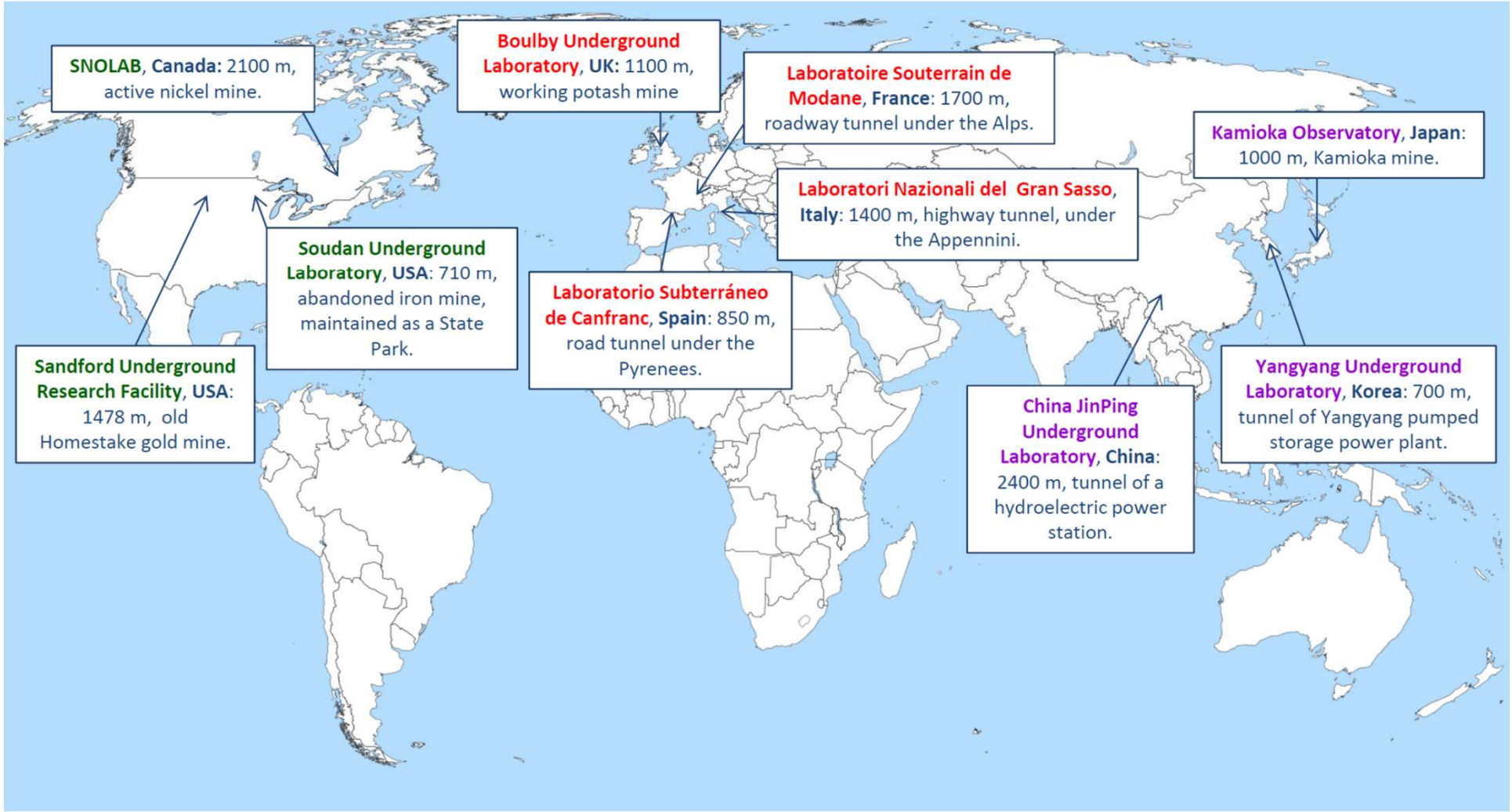
Underground facilities



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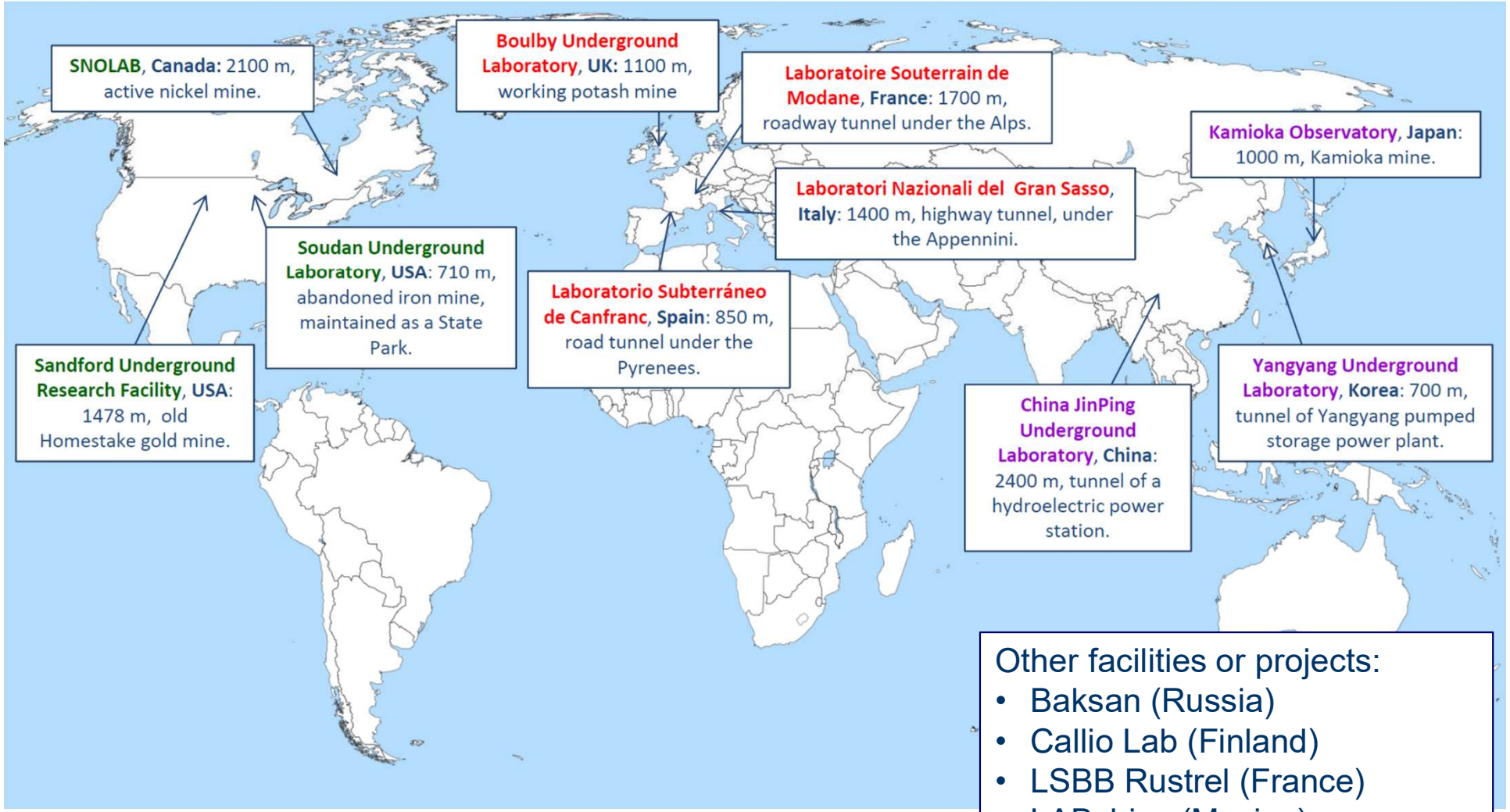


Other facilities or projects:

- Baksan (Russia)
- Callio Lab (Finland)
- LSBB Rustrel (France)
- LABchico (Mexico)
- ANDES (Chile-Argentina)
- Stawell Laboratory (Australia)
- India, South Africa

Underground facilities

SNOLAB, Canada: 2100 m, active nickel mine.

Boulby Underground Laboratory, UK: 1100 m, working potash mine

Laboratoire Souterrain de Modane, France: 1700 m, roadway tunnel under the Alps.

Kamioka Observatory, Japan: 1000 m, Kamioka mine.

Laboratori Nazionali del Gran Sasso, Italy: 1400 m, highway tunnel, under the Appennini.

Soudan Underground Laboratory, USA: 710 m, abandoned iron mine, maintained as a State Park.

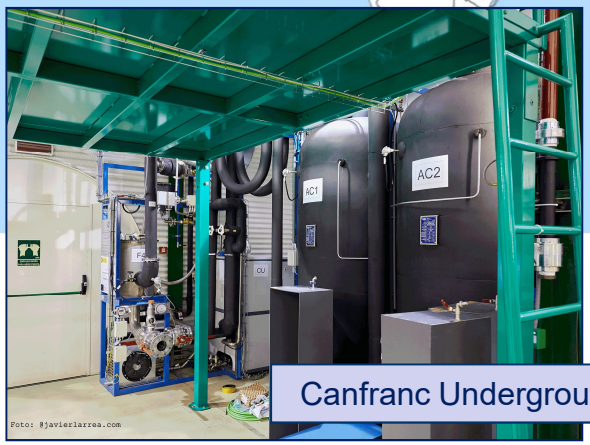
Laboratorio Subterráneo de Canfranc, Spain: 850 m, road tunnel under the Pyrenees.

Sandford Underground Research Facility, USA: 1478 m, old Homestake gold mine.

China JinPing Underground Laboratory, China: 2400 m, tunnel of a hydroelectric power station.

Yangyang Underground Laboratory, Korea: 700 m, tunnel of Yangyang pumped storage power plant.

+ Radioassay facilities, Radon abatement systems, clean rooms, specialized services, …



Canfranc Underground Laboratory

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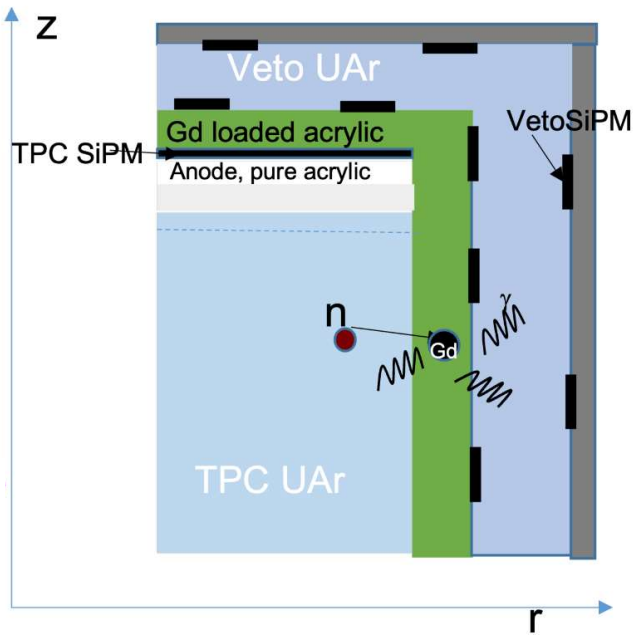
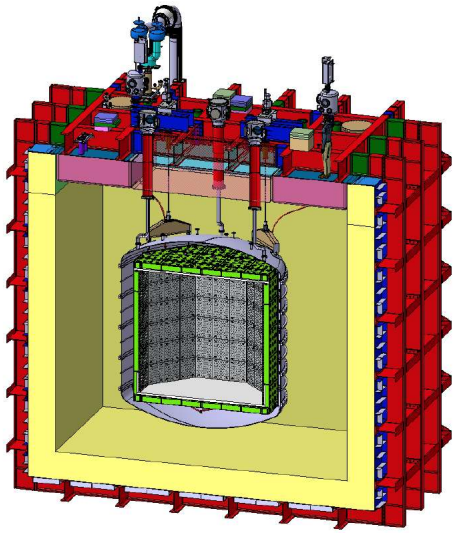
Shielding

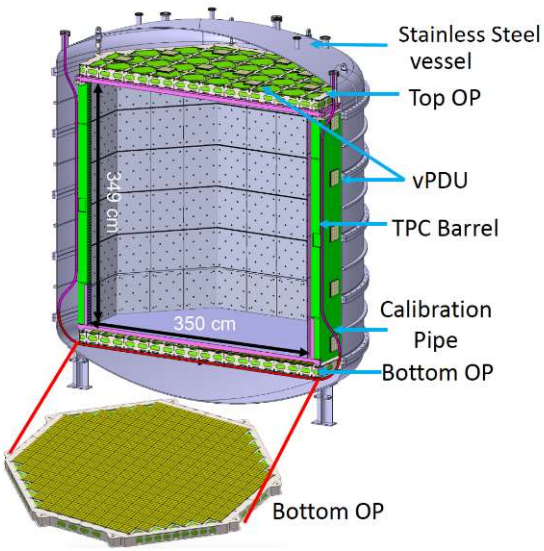
Active shielding: veto for neutrons

- In DarkSide-20k: TPC walls made of Gd-loaded acrylic between two liquid Ar buffers read by SiPMs

→ neutrons thermalized and captured are tagged by gamma rays







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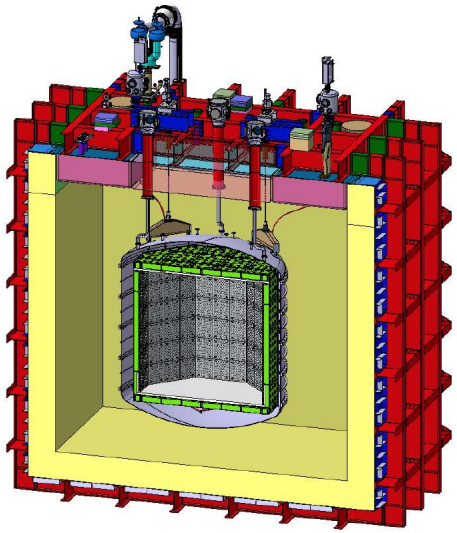

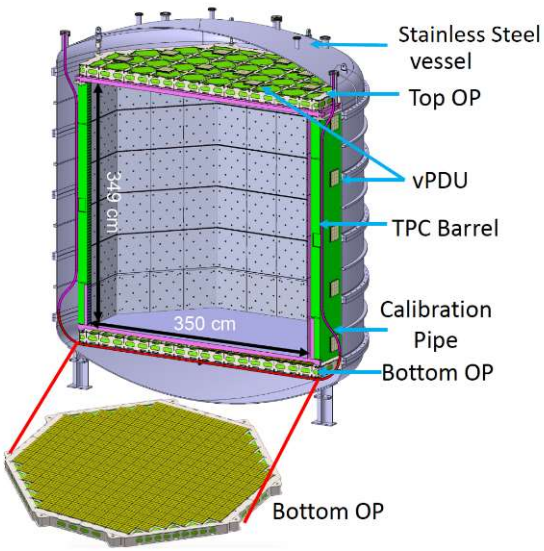

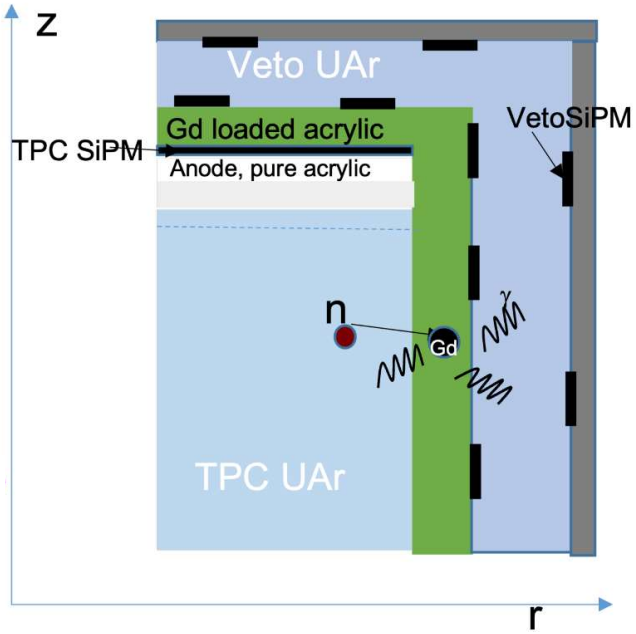

- In XENONnT / LUX-ZEPLIN: tank of Gd-loaded water / liquid scintillator surrounding the Xe TPC

Control of radiopurity: radioassays

Screening of materials: radioactivity below mBq/kg (ppb in Th, U; ppm in K)

1. Select materials and components in the design of all the parts of the set-up.
2. Provide inputs for the development of background models based on Monte Carlo simulations.

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→ the testing and certification of materials (different providers, batches) involve precision measurements that consume significant amounts of time, cost and an enormous effort

"Selecting candidate low-radioactivity materials is as much an art as it is a science"

J. C. Loach et al, Nucl.Instrum.Meth.A 839 (2016) 6

NEXT (*Neutrino Experiment with a Xe TPC*) at Canfranc

Control of radiopurity: radioassays

- Glow Discharge Mass Spectrometry (GDMS)
- Inductively Coupled Plasma Mass Spectrometry (ICPMS)
  - Providing concentrations of U, Th and K

☺ Fast: results provided within a few days
☺ Very small samples required
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☺ Sensitive to particular radioactive isotopes
☹ Large samples, long measurements required


Canfranc Underground Laboratory


SURF

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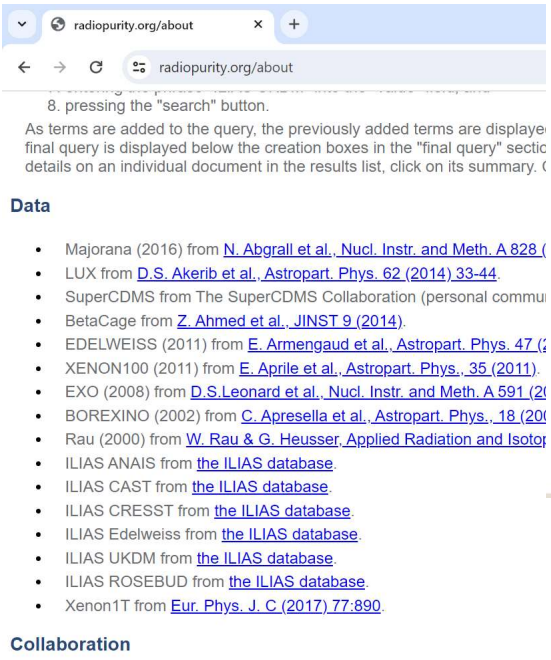
- Alpha spectroscopy
- Radon emanations

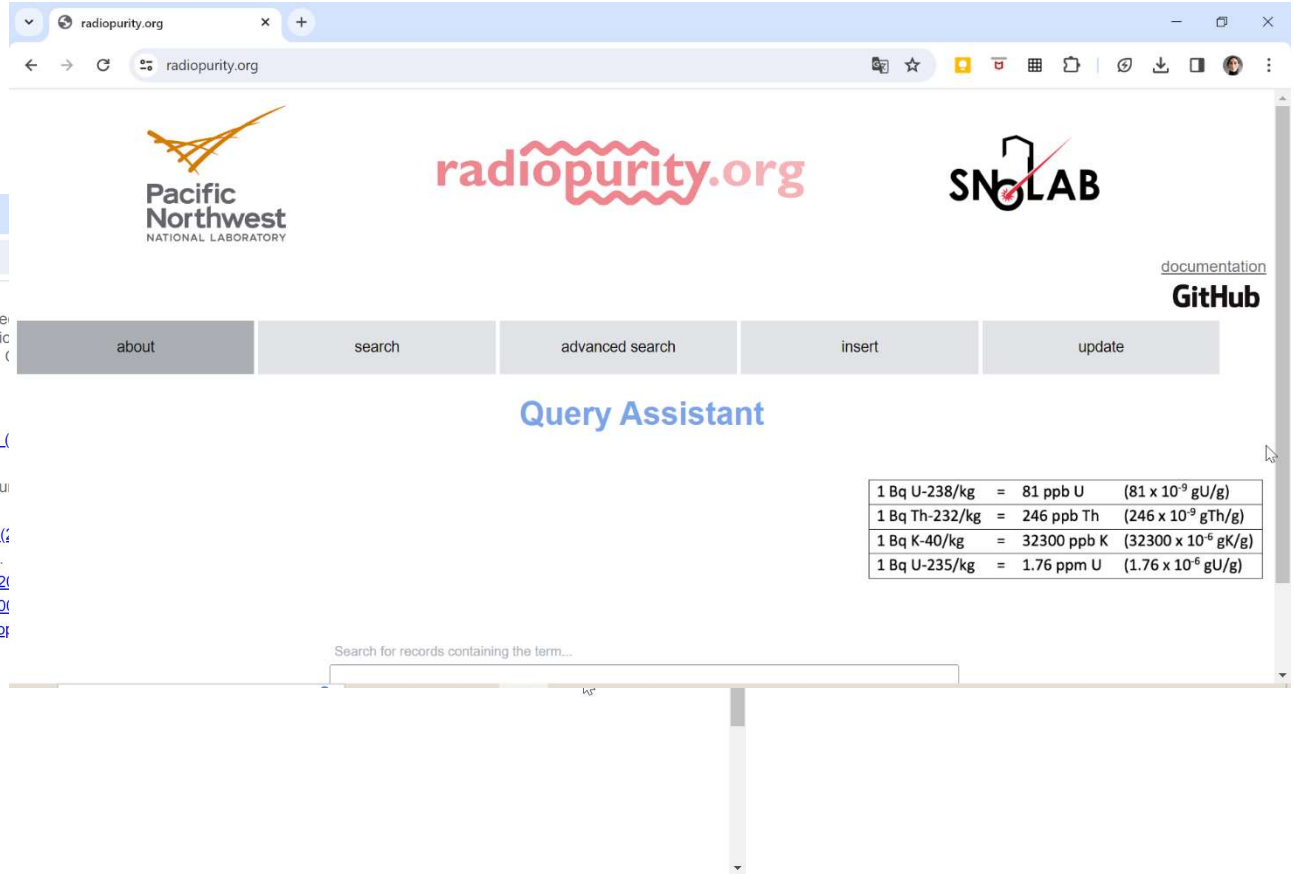
Control of radiopurity: radioassays

Attempts of creating single public repositories of radiopurity measurements

Radiopurity.org: https://www.radiopurity.org

J.C. Loach et al., Nucl. Instrum. Meth. A 839 (2016)





Control of radiopurity: material treatments

- **Purification methods for bulk activity:**

– **Distillation:** liquid Ar

^{39}Ar activity in Ar reduced by distillation at the Aria facility

P. Agnes et al, Eur. Phys. J. C 81 (2021) 359

E. Aaron et al, Eur. Phys. J. C 83 (2023) 453

– **Zone melting:** Ge, NaI

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Electroformation facility in Canfranc

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  - **Clean machining**
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TREX-DM experiment in Canfranc

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- Applied to Cu, stainless steel, PTFE, … reduction factors of up to 50-100
- Attention to radiopurity of chemicals, gloves, wipes, …
- Control of particulate fallout and assembly in clean rooms required to avoid recontamination

TREX-DM experiment in Canfranc

Control of radiopurity: cosmogenic activation

Production of long-lived radioactive isotopes in materials due to exposure to cosmic rays (mainly by spallation) can be an hazard for ultra-low background experiments

- Store materials underground and limit surface residency time
- Avoid flights
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Recipe for estimates:

1. To know the **production rates** ***R*** of relevant isotopes in the targets, from

– Scarce experimental data from irradiation/controlled exposure experiments

– Calculations from production cross sections and cosmic ray spectrum:

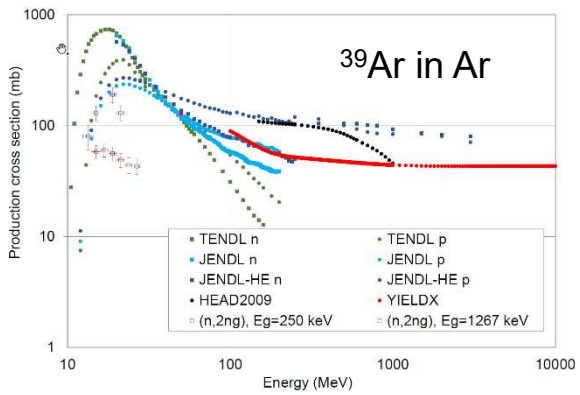
$$R = N_t \int \sigma(E)\phi(E)dE$$

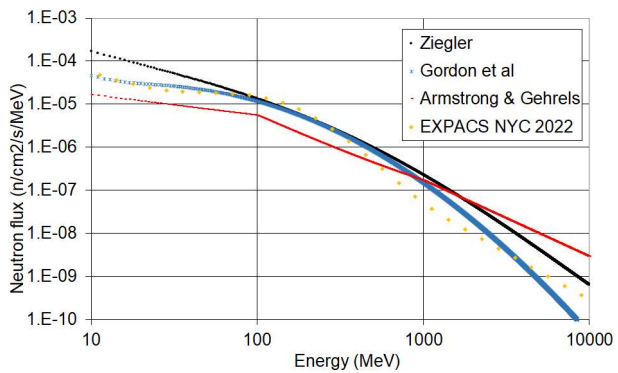
N_t = number of target nuclei

ϕ = flux of cosmic rays

σ = production cross section

E = particle energy





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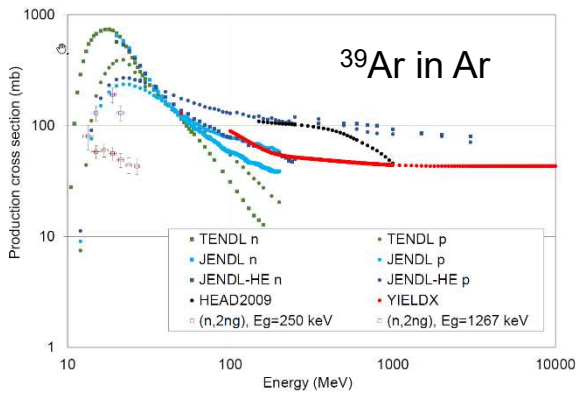
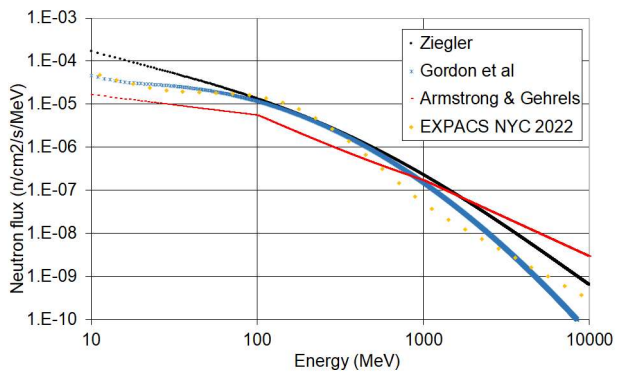




2. To estimate the **induced activity** ***A*** knowing the exposure history to cosmic rays

$$A = R[1 - \exp(-\lambda t_{exp})]\exp(-\lambda t_{cool})$$

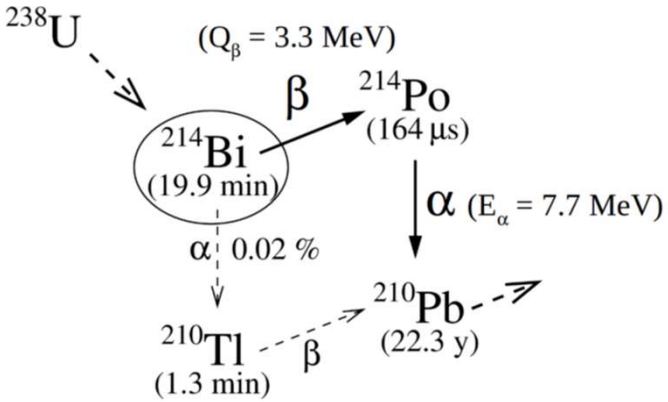
t_{exp} = exposure time

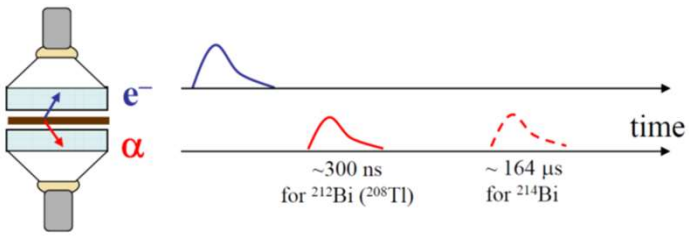
t_{cool} = cooling time underground

Control of radiopurity: special detectors

BiPo detector built by the SuperNEMO collaboration and operated in Canfranc, sensitive to levels of **μBq/kg** of the lower parts of ^{238}U, ^{232}Th through **BiPo** α–β **coincidences** in **very thin samples**

A.S. Barabash et al, 2017 JINST 12 P06002





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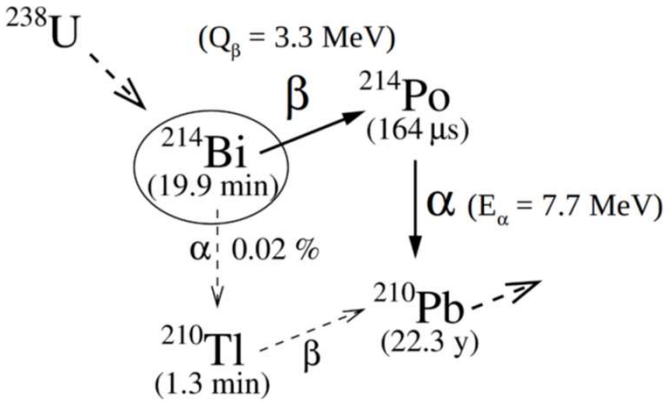
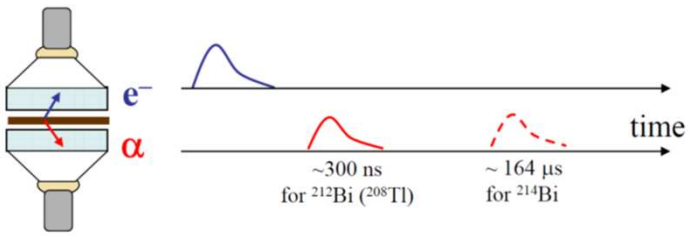
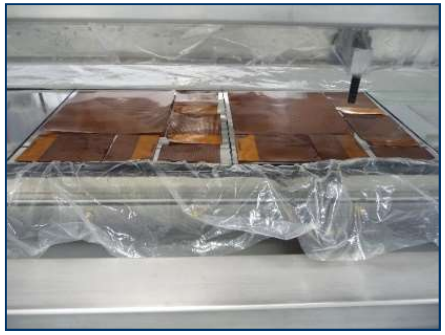


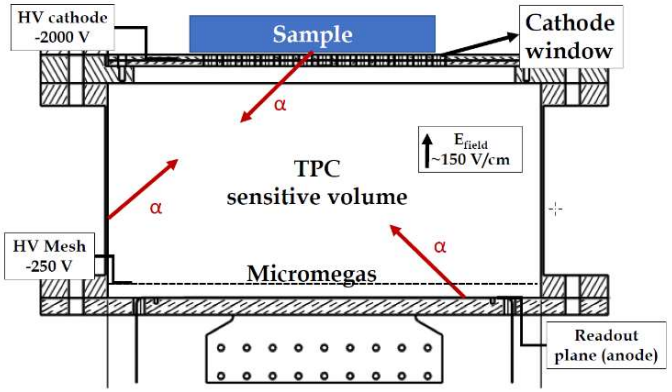




Upper limits on Micromegas samples below 0.1 μBq/cm^2

Control of radiopurity: special detectors

AlphaCAMM (Alpha CAMera Micromegas) detector being built by the TREX-DM collaboration: a gaseous chamber read with a segmented Micromegas to measure **^{210}Pb surface contamination** of flat samples down to **100 nBq/cm^2**



K. Altenmuller et al, 2022 JINST 17 P08035

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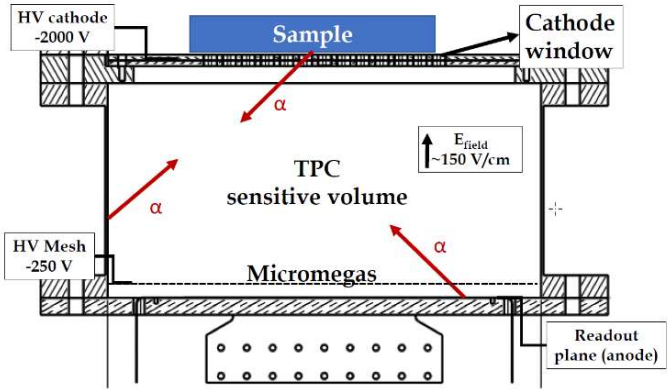

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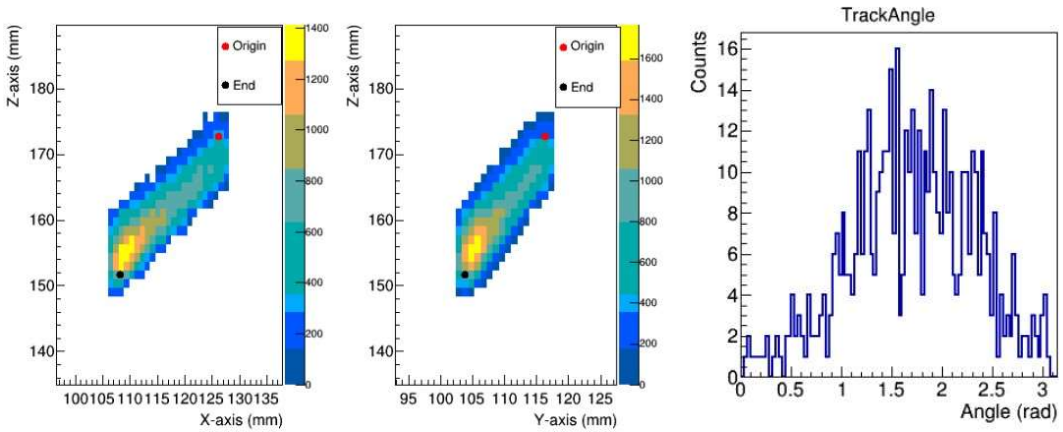
Micromegas provides topological information to reconstruct origin and end of α tracks from **^{210}Po**



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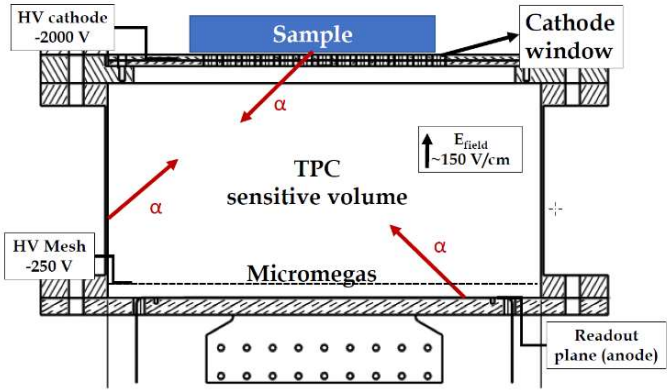
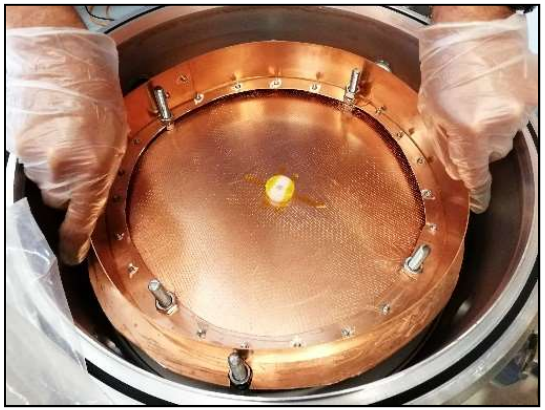


K. Altenmuller et al, 2022 JINST 17 P08035

After proof-of-concept with a non-radiopure prototype, a radiopure detector is being commissioned



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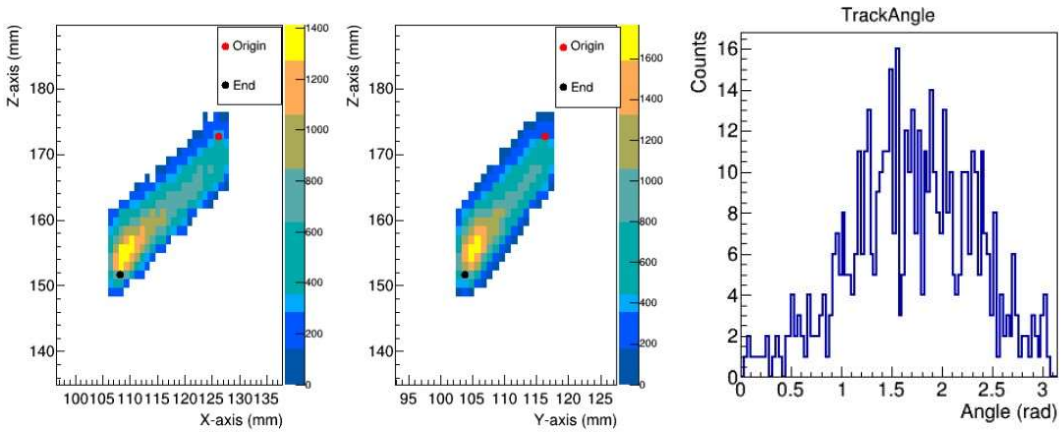
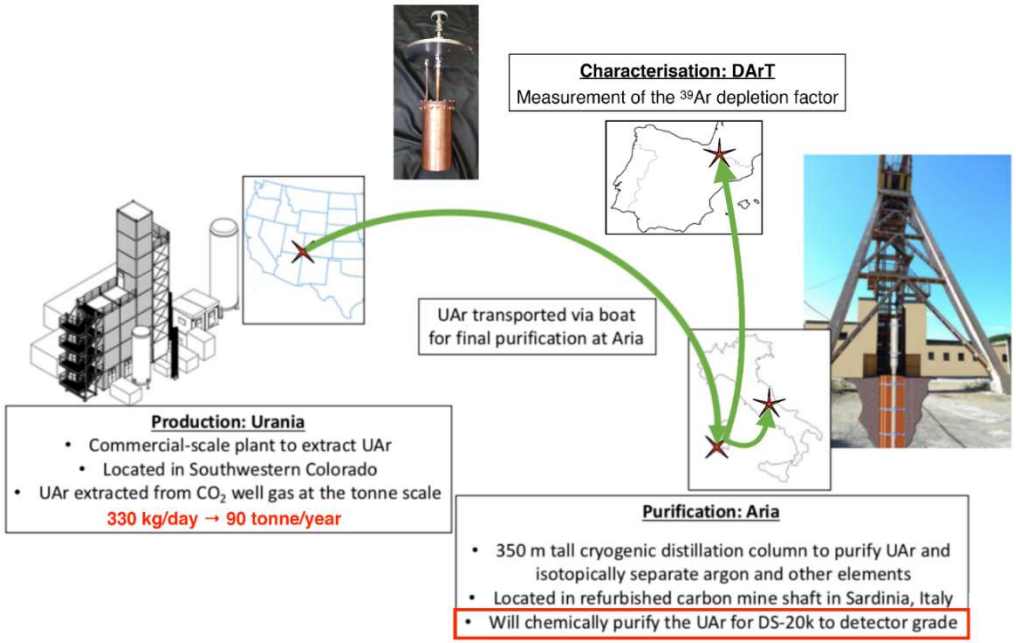


Control of radiopurity: special detectors

Procurement of **low-radioactivity Underground Ar for** DarkSide-20k

- Urania: extraction from CO_2 wells in Colorado (as DarkSide-50)
- Aria: purification in a criogenic distillation column in Sardinia
- DArT: quantification of **^{39}Ar** (pure beta emitter) in Canfranc



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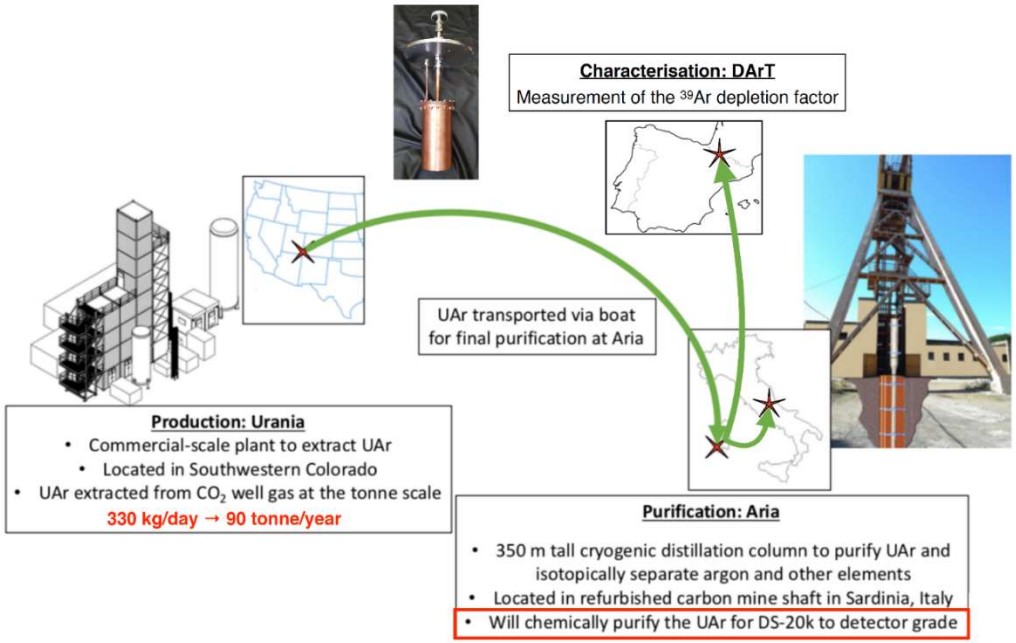

DArTinArDM (Depleted Argon Target) detector is intended to measure **<1 mBq/kg of ^{39}Ar** with statistical accuracy better than 10% in one week of counting time

C.E. Aalseth et al, 2020 JINST 15 (2020) P02024

Control of radiopurity: special detectors

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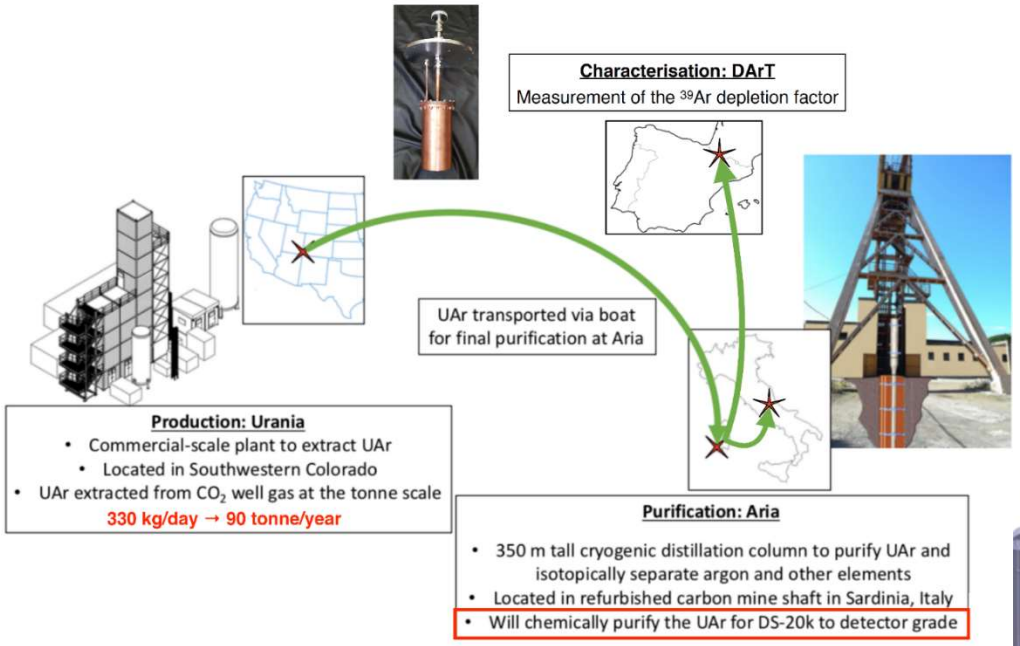

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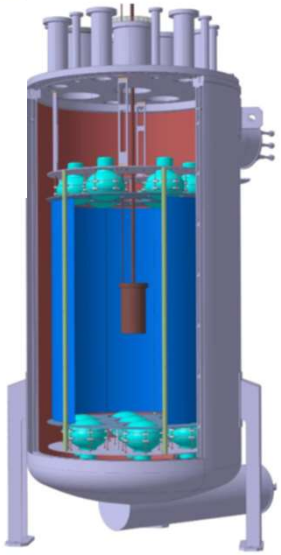

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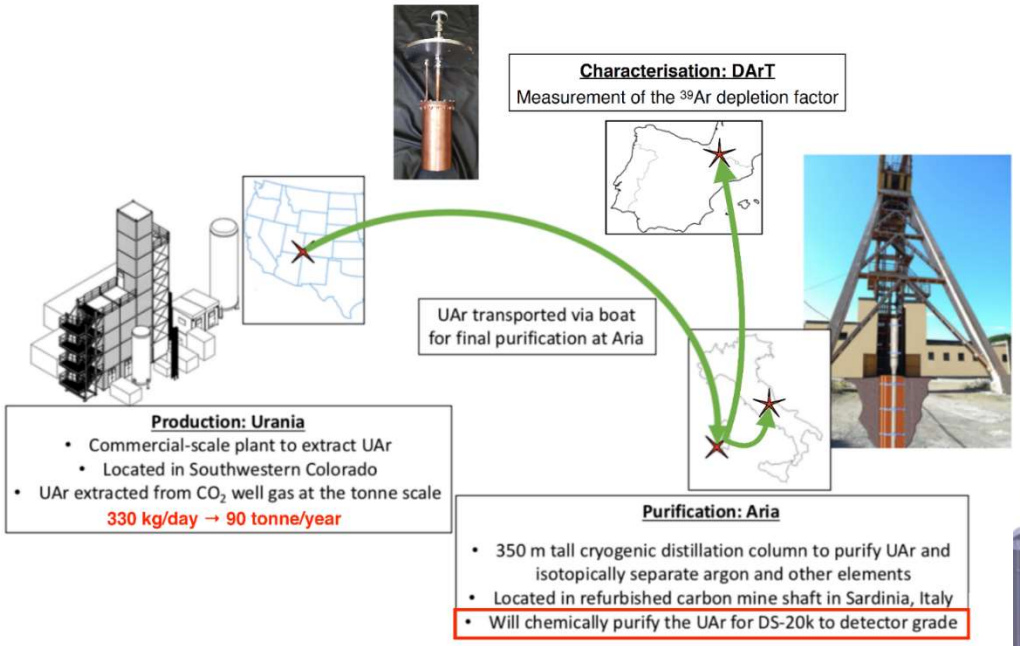

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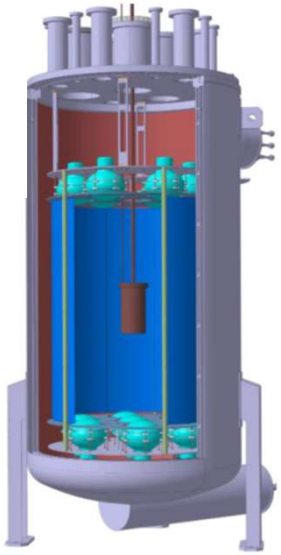
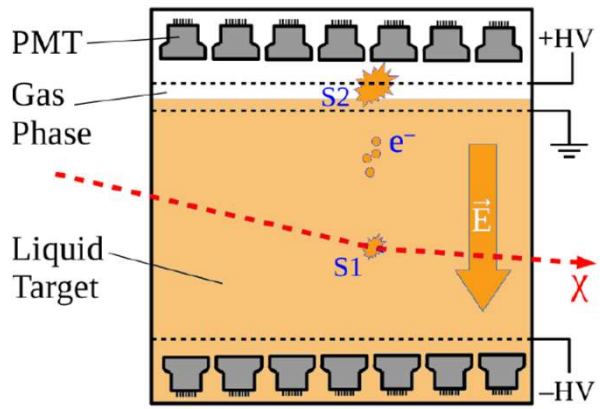


Test set-up

Techniques for background rejection

- **S1/S2 discrimination for dark matter experiments**

Dual-phase TPCs of liquid scintillators (Xe, Ar): detection of a primary scintillation signal in liquid (**S1**) and a secondary signal in gas from the drift and extraction of ionization electrons (**S2**).



M. Schumann, J. Phys. G46 (2019)103003

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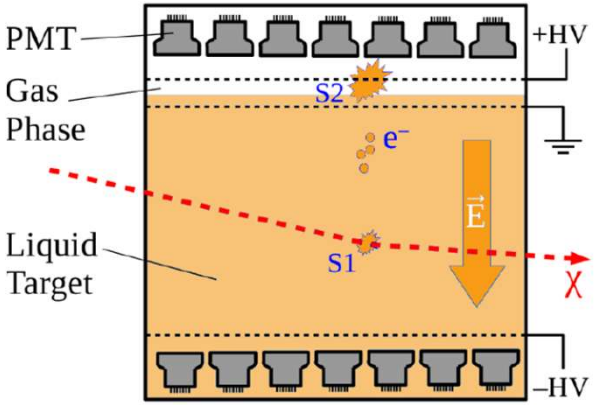

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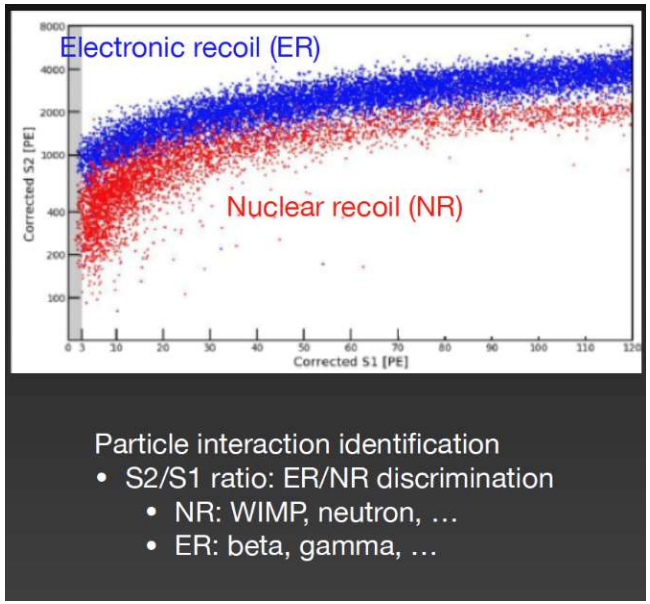

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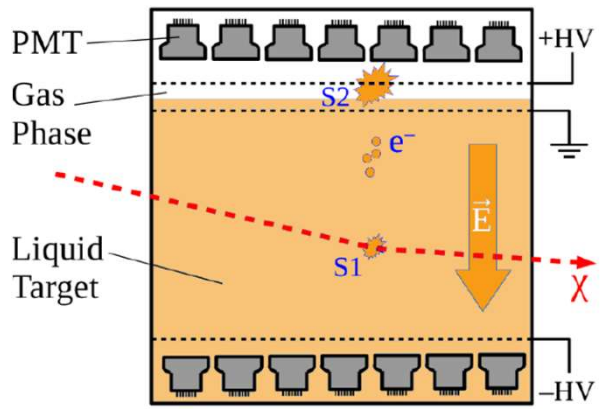

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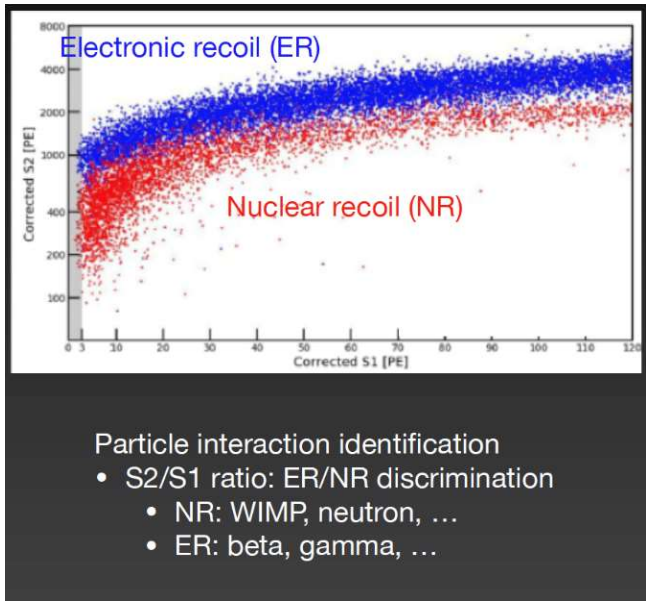
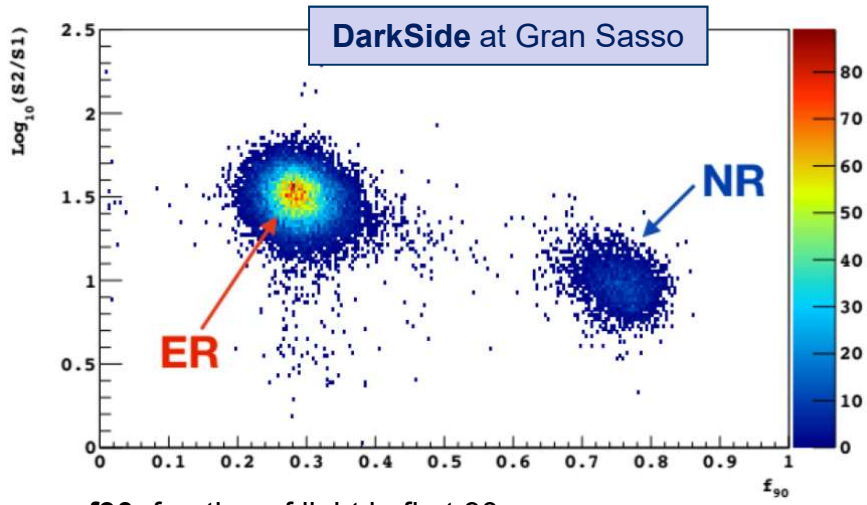


- Combined with very efficient **PSD** in **liquid Ar**



f90: fraction of light in first 90 ns

Techniques for background rejection

- **Topology of events for double beta decay experiments**

Tracks of two electrons from a common vertex can be discriminated from background

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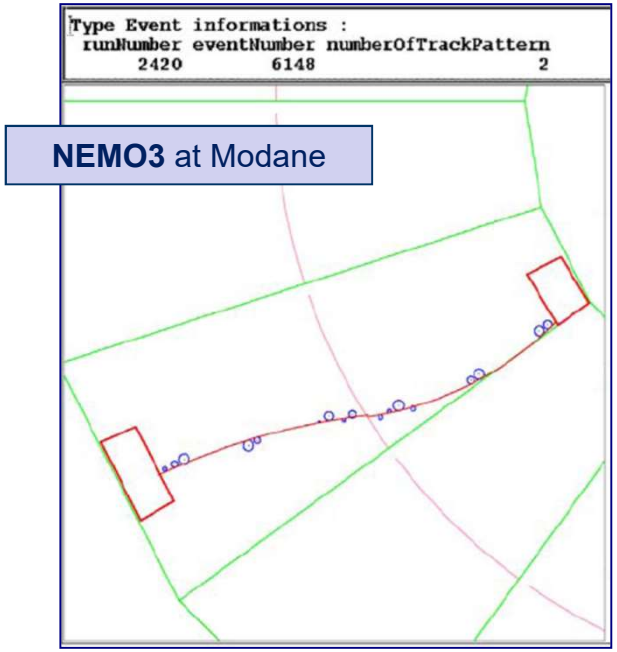

NEMO3 at Modane

Plastic scintillators +
Geiger cells

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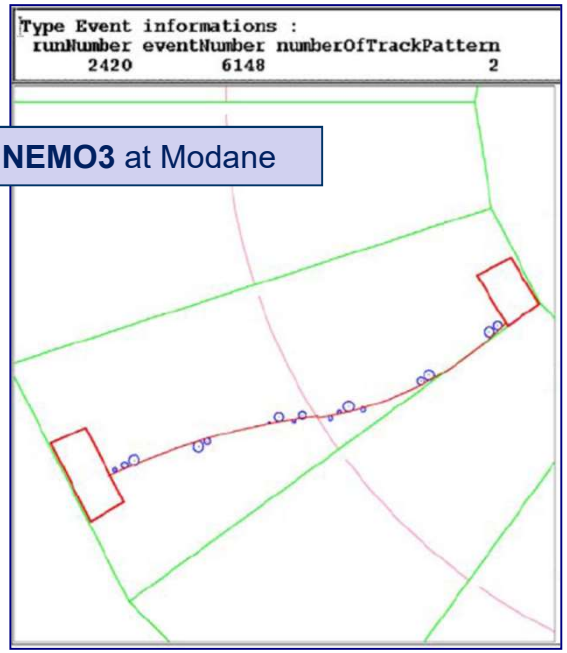

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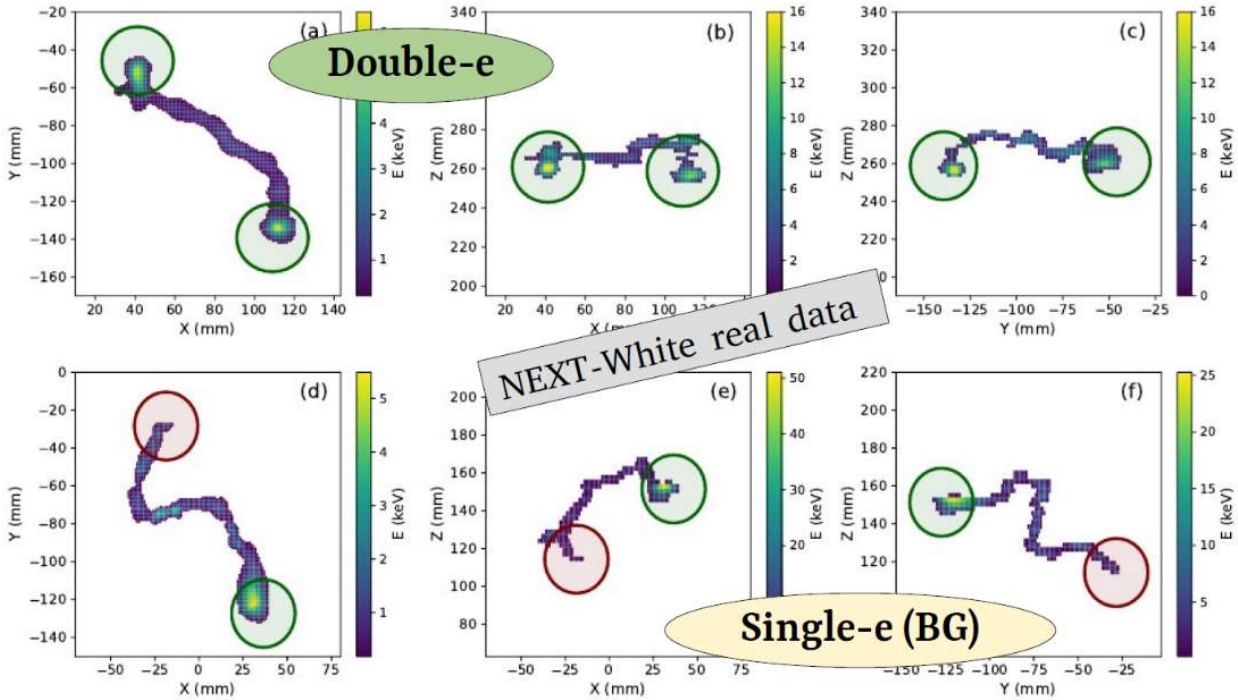
NEXT at Canfranc

High Pressure Xe-Electroluminiscence gas TPC with separate energy / tracking readout



Simulation and codes

Monte Carlo simulations of the interaction of background radiation in matter are extremely useful to:

- Assessment of effect of background **reduction strategies**: shieldings, vetoes, discrimination, …
- Evaluation of expected **counting rates** and **sensitivity** of future experiments
- Understanding of measured data → **background models**

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Tools: **general-purpose packages**
GEANT4 (GEometry ANd Transport), **FLUKA**, **MCNPX**

- To define: primary particles + physical processes + set-up + outputs
- Geant4 environments created for particular technologies: MaGe, G4DS, ImpCRESST, …

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- Integration of **detector response** by specific codes/modules:

  NEST (Noble Element Simulation Technique) for Xenon detectors
  https://nest.physics.ucdavis.edu/about

  G4CMP (Condensed Matter Physics with Geant4) for solid-state detectors

  http://geant4-resources.com/G4CMP/G4_CMP.html

  REST-for-Physics (Rare Event Searches Toolkit for Physics) for gas TPCs
  https://doi.org/10.1016/j.cpc.2021.108281

Simulation and codes

Specific tools (codes, libraries, databases) focused on particular backgrounds

EXPACS (EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum)
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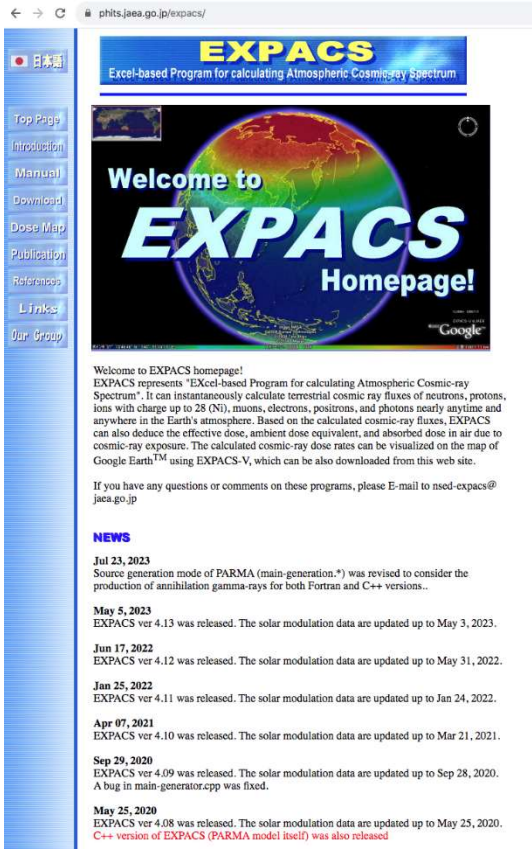
To calculate terrestrial **cosmic ray** fluxes of **neutrons, protons**, light ions, **muons,** electrons, positrons, and photons nearly **anytime** and **anywhere** in the Earth's atmosphere.



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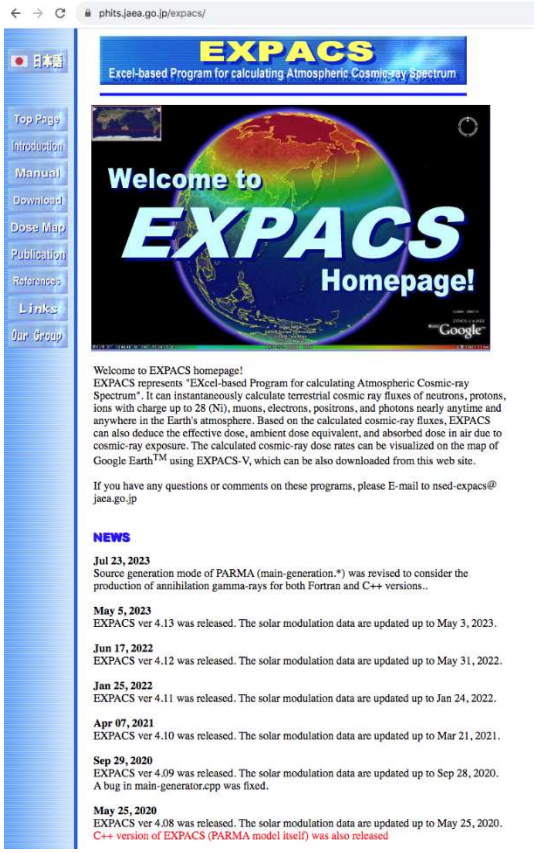

MUSUN, MUSIC, MUTE (MU inTensity codE)

https://github.com/wjwoodley/mute

To obtain **muon intensity** and distributions (E, θ)

Simulation and codes

Yields of radiogenic neutrons

Allow to set requirements on α activity of materials

$$Y_i(E_\alpha) = \frac{\eta_i}{\eta} \int_0^{E_\alpha} \frac{\sigma^i_{(\alpha,Xn)}(E)}{\varepsilon(E)} dE$$

E_α is the initial energy of the α particle;
η_i is the number density of nuclide i;
η is the number density of the material;
$\sigma^i(\alpha,Xn)(E)$ is the neutron production x-sec for the nuclide i
$\varepsilon(E) = -\frac{dE}{dx}$ is the stopping power of the material

SOURCES4A(C)

(α, n) reaction cross-sections using EMPIRE2.19

V. Tomasello et al., Nucl. Instrum. Methods A 595, 431 (2008)

V. A. Kudryavtsev et al, NIMA 972 (2020) 164095

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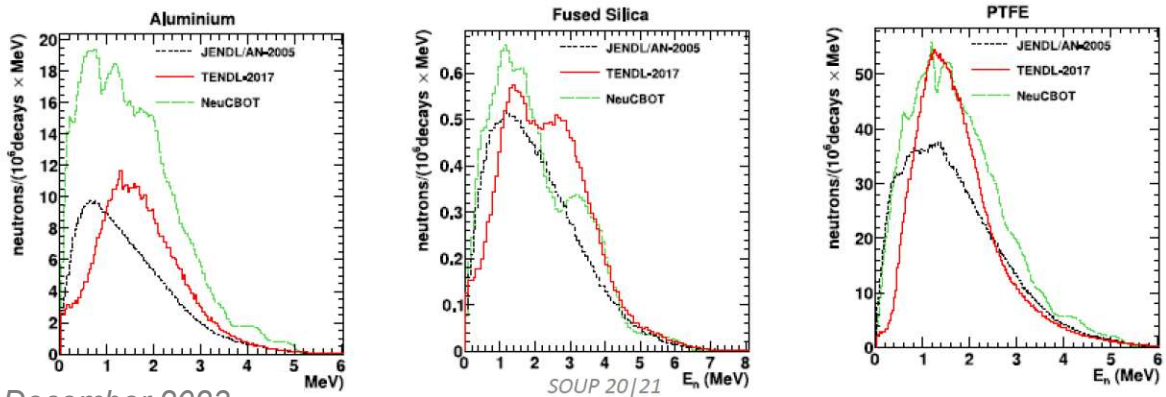


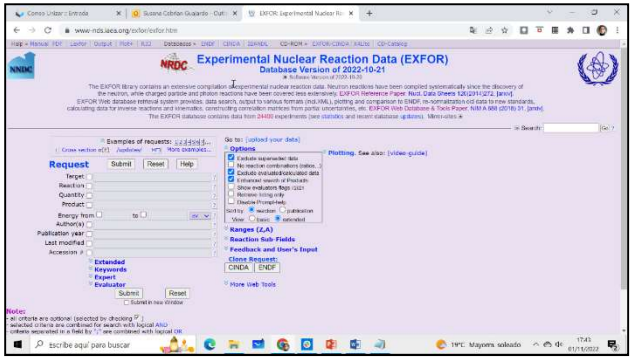
Simulation and codes

Production cross sections for cosmogenic activation

Experimental data from beam experiments, few data for **n**

EXFOR (Experimental Nuclear Reaction Data) database

http://www-nds.iaea.org/exfor/exfor.htm



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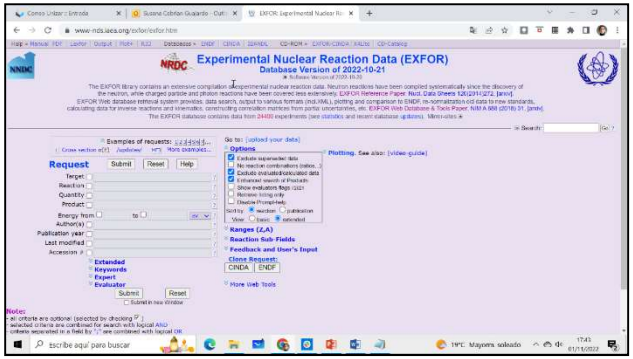
Semiempirical formulae (Silberberg&Tsao equations)

targets A ≥3, products A ≥ 6 and E>100 MeV

COSMO, YIELDX, ACTIVIA codes



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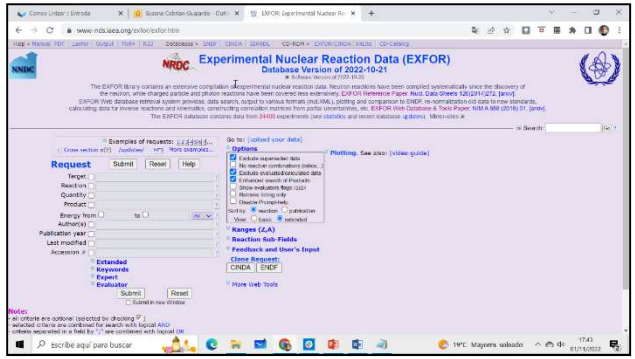

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Monte Carlo simulation: formation and decay of compound nuclei, de-excitation processes like **fission, fragmentation, spallation, or breakup**

TENDL (TALYS-based Evaluated Nuclear Data Library)

https://tendl.web.psi.ch/tendl_2019/tendl2019.html

Using the TALYS code for **n and p up to 200 MeV**

HEAD-2009 (High Energy Activation Data) library: only for Z≥12

https://doi.org/10.1016/j.nima.2010.08.110

Using a selection of models and codes (CEM, ...)

for **p from 150 MeV to 1 GeV**

JENDL (Japanese Evaluated Nuclear Data Library)

https://wwwndc.jaea.go.jp/jendl/j40/j40.html

Using GNASH code for **n and p up to 200 MeV,** from **20 MeV to 3 GeV**

Summary

Rare event searches demand ultra-low background conditions achieved mitigating all known **background sources**: cosmic **muons,** radiogenic, cosmogenic **neutrons** and **radioactivity**.

- Deep **underground laboratories** provide not only shelter but different support facilities.
- **Passive** and more sophisticated **active shieldings** are a must.
- Specific **background rejection techniques** based on different appraches are in continuous development.
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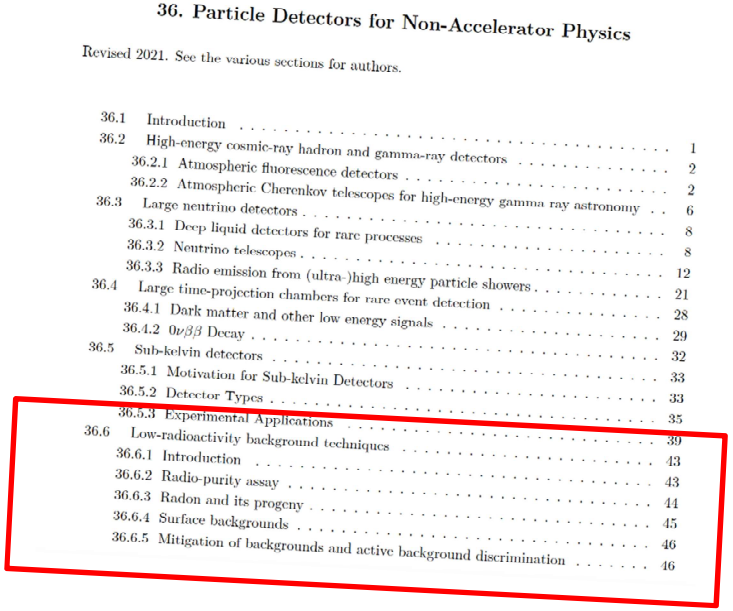
https://arxiv.org/abs/2203.07623

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Snowmass2021 Cosmic Frontier White Paper: Calibrations and backgrounds for dark matter direct detection

arXiv:2203.07623v2 [hep-ex] 1 May 2022

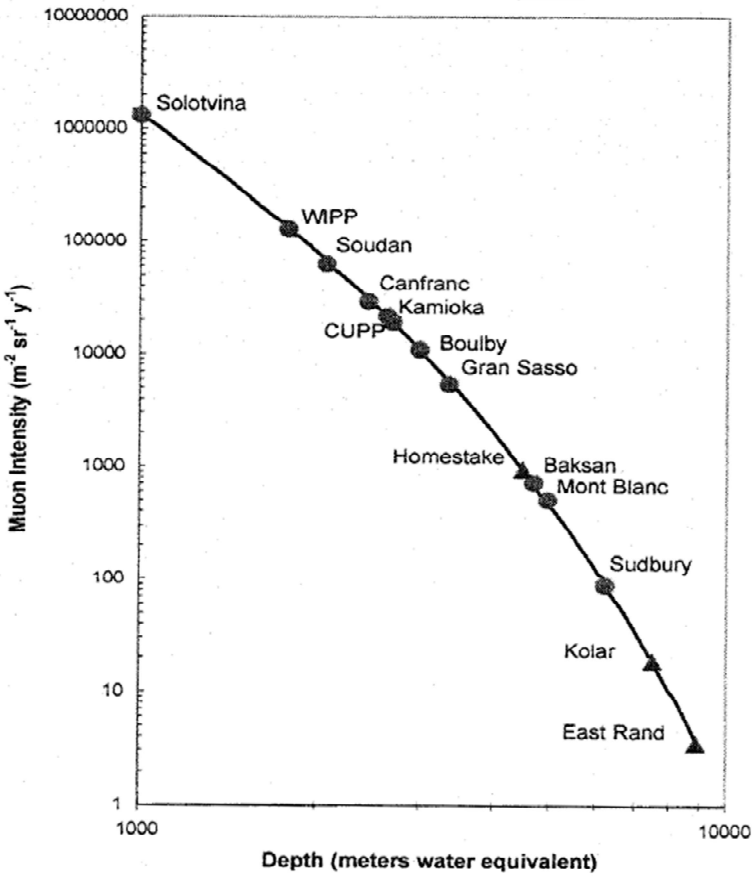
https://pdg.lbl.gov/2022/reviews/contents_sports.html



36. Particle Detectors for Non-Accelerator Physics

Revised 2021. See the various sections for authors.

Extra material



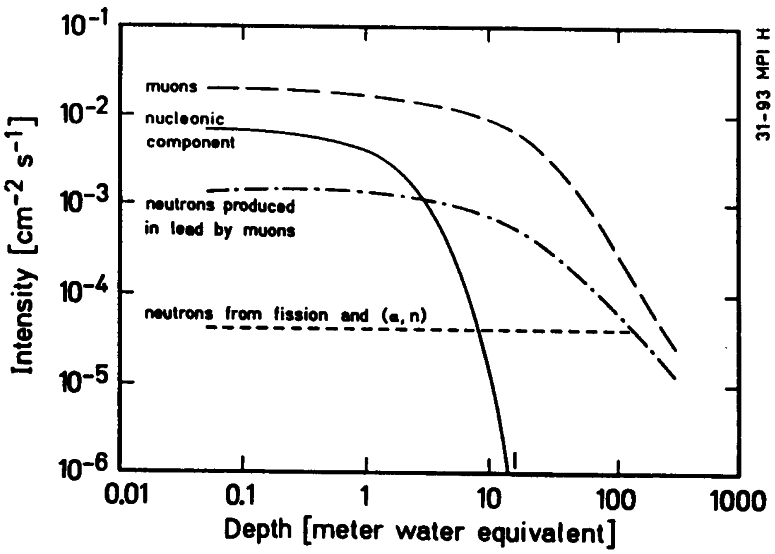


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.

G. Heusser, Ann. Rev. Part. Sci. 45 (1995) 543

Radon

Many **dangers for experiments:**

M. Wojcik, G. Zuzel, "*Review of high-sensitivity Radon studies*", *Int.J.Mod.Phys.A* 32 (2017) 30, 1743004.

Radon is soluble in water and even more so in organic solvents. For large liquid scintillation detectors, radon mobility due to convection and diffusion is a concern.

Radon diffuses readily through thin plastic barriers, with different permeability. Due to its intrinsic U content, materials can produce **Rn outgassing**.

Prolonged exposure of materials to air leads to the accumulation of the long-lived radon daughter ^{210}Pb on surfaces (**plate-out** electrostatically)

Strongly enhanced on statically charged surfaces such as plastic or glass

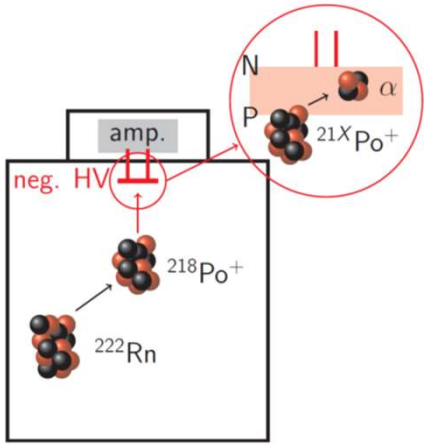
Large spread of effective radon daughter collection distances ranging from a few cm to a few m in air

→ limit the allowable air exposure time

In case raw materials (e.g. in the form of granules) were exposed to air at the production site, the bulk (instead of the surface) of the finished components may be loaded with ^{210}Pb and its daughters.

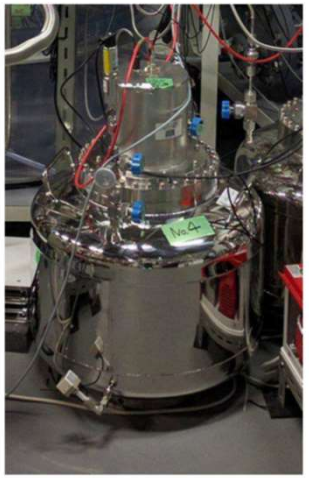
Radon detectors

Based on alpha spectroscopy (using scintillation, silicon or gas detectors)
Commercial monitors (AlphaGuard): sensitivity of a **few Bq/m³**

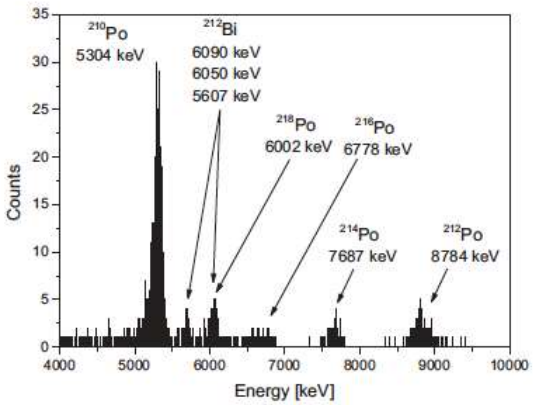


Special systems having efficiency boosted by **electrostatic collection** of radon ions (^{218}Po and ^{214}Po for ^{222}Rn) from a large gas volume onto a small detector

- Electro-polished inside stainless steel vessel shaped to maximize the collection of ions to an alpha counter installed on the upper part.
- Sensitivities of the order of **mBq/m³** and even below

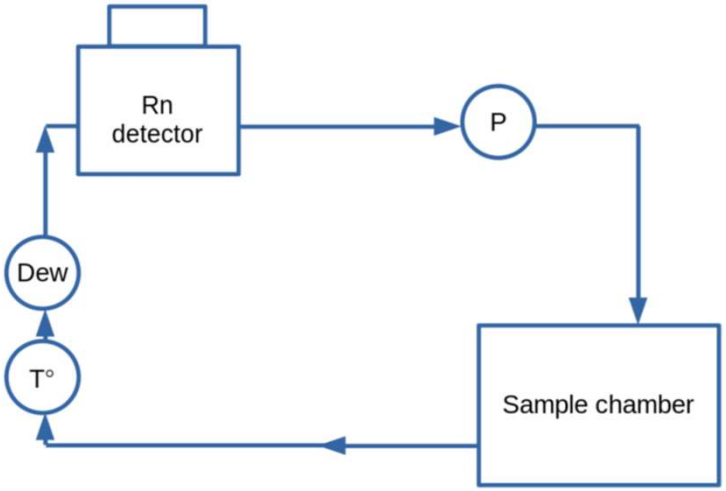


High-sensibility 80L detector

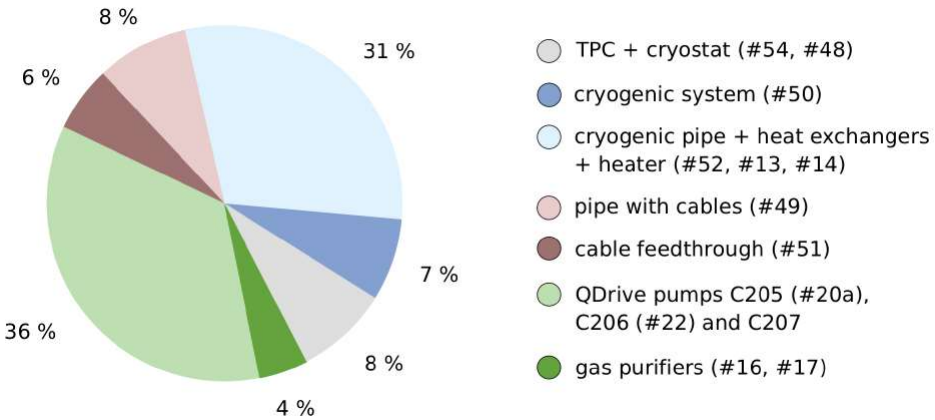


Radon emanation measurements: based on the **pre-concentration of ^{222}Rn on a charcoal trap** and subsequent counting of alpha decays with miniaturized proportional detectors

- ^{222}Rn atoms are collected inside an exhalation chamber for several half-lives before adsorption and counting.
- Emanation of large vessels (cryostats, storage tanks, purification columns) can be determined by collecting exhaled radon into transportable charcoal traps.



Extensive study of radon emanations made by XENON1T to achieve 4.5 mBq/kg in the target Xe



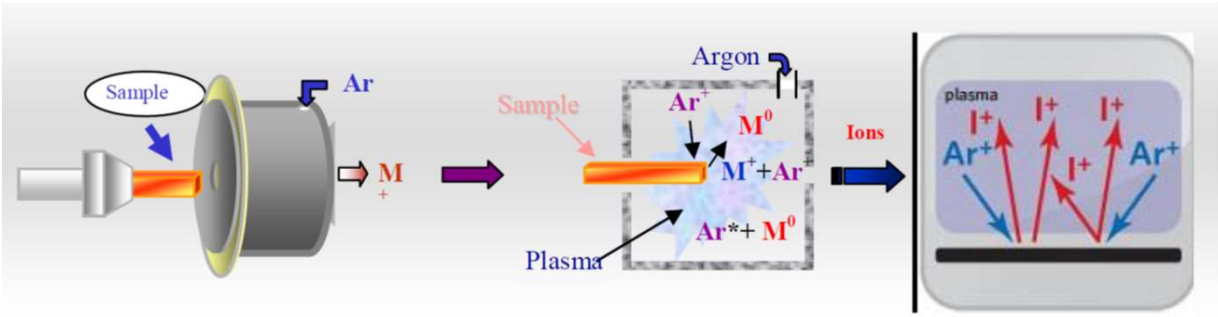
E. Aprile et al, Eur. Phys. J. C 81 (2021) 337

Mass spectrometry

Glow Discharge Mass Spectrometry (GDMS)

Consists in creating a low pressure Ar plasma which allows the ionisation of elements by sputtering.

- A 1KV DC Voltage is applied between anode (body cell) and cathode (sample) creating the plasma.
- Ar+ ions thus formed sputters the surface of the sample.
- Particles issued of the sample are ionized forming elemental ions.



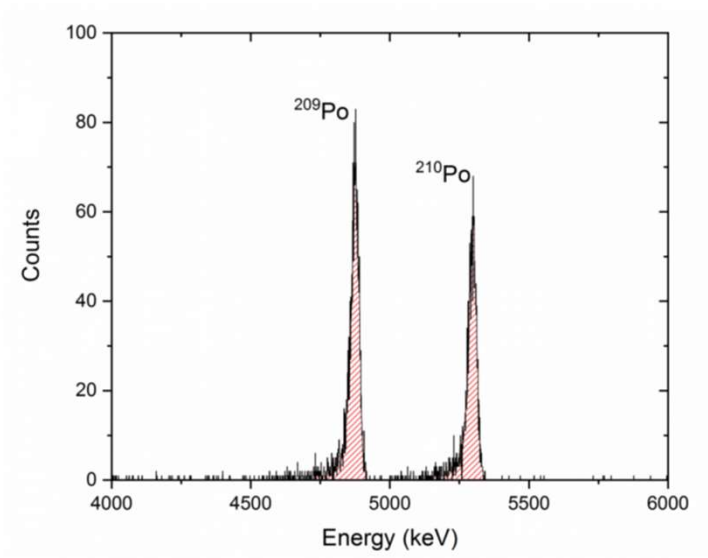
Alpha spectroscopy

- Very useful if the decay of some radionuclides is not accompanied by a gamma ray emission of significant intensity
- **Alpha spectrometry** uses very thin samples of low mass, since the range of alpha particles is very short → measurements have to be carried out in a vacuum chamber so that the energy loss of the alpha particles is minimized.

The detectors are usually based on **silicon detectors** with a flat and very thin shape.

Due to the very small detector volumen the interaction probability of gamma rays is very low; in combination with the relatively high energy of alpha particles of approximately 4 MeV to 9 MeV, very **low background count rates** in the order of few cts/d, depending on the detector size, can be reached.

Alpha spectrometry combined with **radiochemical methods** to extract ^{210}Po offers best sensitivity to quantify the lower part of the ^{238}U chain



Control of radiopurity: cosmogenic activation

Example: many activation studies are available for **Cu**, a material widely used in experiments

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Production rates in $kg^{-1}d^{-1}$

	^{46}Sc	^{48}V	^{54}Mn	^{56}Co	^{57}Co	^{58}Co	^{59}Fe	^{60}Co
Half-life[27,108]	83.787(16)	15.9735	312.19(3)	77.236	271.81(4)	70.85(3)	44.494	5.2711(8)
units	d	d	d	d	d	d	d	y
Measurement [202]	2.18 ± 0.74	4.5 ± 1.6	8.85 ± 0.86	9.5 ± 1.2	74 ± 17	67.9 ± 3.7	18.7 ± 4.9	86.4 ± 7.8
Measurement [184]	$2.33^{+0.95}_{-0.78}$	$3.4^{+1.6}_{-1.3}$	$13.3^{+3.0}_{-2.9}$	$9.3^{+1.2}_{-1.4}$	$44.8^{+8.6}_{-8.2}$	$68.9^{+5.4}_{-5.0}$	$4.1^{+1.4}_{-1.2}$	$29.4^{+7.1}_{-5.9}$
ACTIVIA (MENDL-2P) [36]	3.1		12.4	14.1	36.4	38.1	1.8	9.7
ACTIVIA [36,184]	3.1		14.3	8.7	32.5	56.6	4.2	26.3
COSMO [184]	1.5	3.1	13.5	7.0	30.2	54.6	4.3	25.7
ACTIVIA [46]	4.1		30.0	20.1	77.5	138.1	10.5	66.1
ACTIVIA [99]	3		16	9	34	60	2	29
GEANT4 [46]	1.2		12.3	10.3	67.2	57.3	8.8	64.6
TALYS [94]			16.2		56.2			46.4
MENDL+YIELDX [43]	2.7		27.7	20.0	74.1	123.0	4.9	55.4
CONUS [99]	3		14	10	50	76	5	92

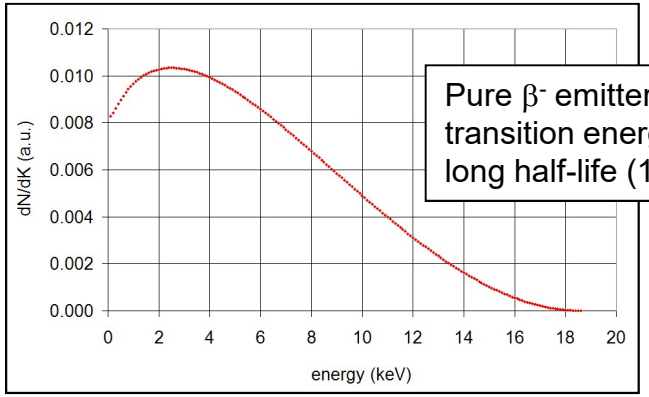
S. Cebrián, Universe 2020, 6, 162

Measured rates from sensitive screening after exposing large samples in controlled conditions at Gran Sasso for long time

Control of radiopurity: cosmogenic activation

Example: specific study of tritium production rates induced in dark matter detectors (Ge, Si, NaI, Ar, Ne)

J. Amare et al., Astropart. Phys.97 (2018) 96



Pure β^- emitter, with very low transition energy (18.591 keV) and long half-life (12.312 y)

Production rates in $kg^{-1}d^{-1}$

Target	Ref. 55	TENDL+HEAD[71]	TALYS[59]	GEANT4[37]	GEANT4[36]	ACTIVIA[37]	ACTIVIA[36]	ACTIVIA	Others
^{nat}Ge	178/210	75 ± 26	27.7	48.3	47.4	52.4	52.4	46/43.5 (Ref. 65)	82 ± 21 (Ref. 65)
									76 ± 6 (Ref. 70)
^{enr}Ge	113/140	94 ± 34	24.0		47.4		51.3		140 ± 10 (Ref. 66)
Si		120 ± 23		27.3		108.7			125 (Ref. 52)
TeO_2			43.7						
NaI		83 ± 27	31.1	42.9		36.2			
CsI			19.7						
$CaWO_4$			45.5						
Ar		146 ± 31	44.4	84.9		82.9			
Ne		228 ± 16							
Xe			16.0	31.6		35.6			
Quartz									
C_2H_6				279.5					

New measurements with LANSCE beam:

Si: 112 ± 24

R. Saldanha et al, Phys. Rev. D 102 (2020) 102006

NaI: 80 ± 21

R. Saldanha et al, Phys Rev. D 107 (2023) 022006