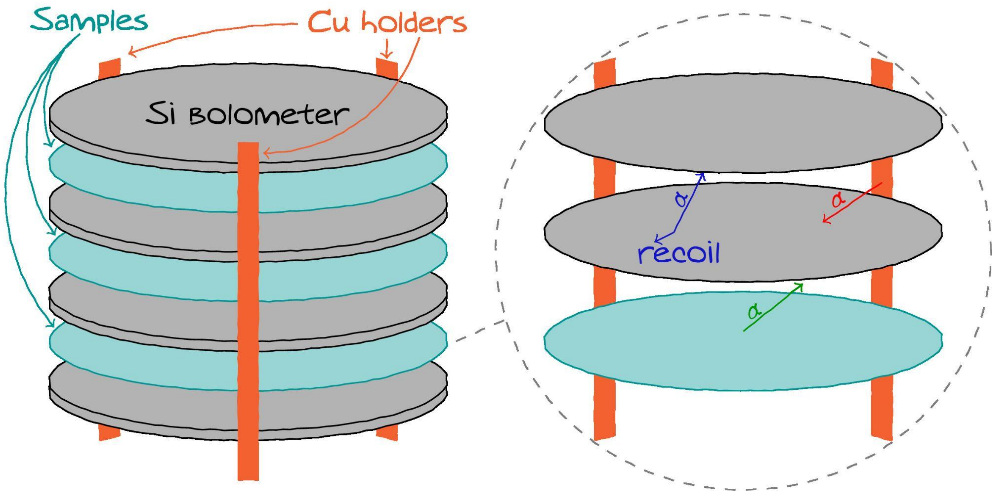
Silicon
Underground
Radiopure
Finder
of **α**
Contamination
Excesses



Giovanni Benato for SURFαCE
Low Radioactivity Techniques 2026
Funded by *Fondo Italiano per la Scienza*

MUR Ministero dell'Università e della Ricerca
FONDO ITALIANO PER LA SCIENZA
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

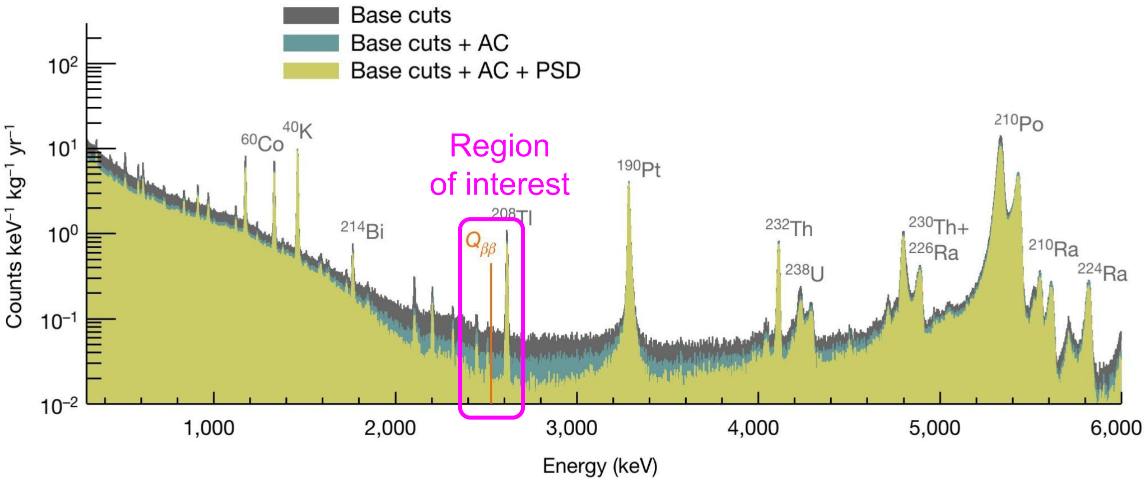
The need for low-background α spectroscopy

CUORE experiment for 0νββ decay

- Main background1: α's from ^{238}U and ^{232}Th on copper surface
- Contamination level: **~10 nBq/cm^2**
  →Measured by CUORE itself over few years

CUPID: CUORE + particle discrimination

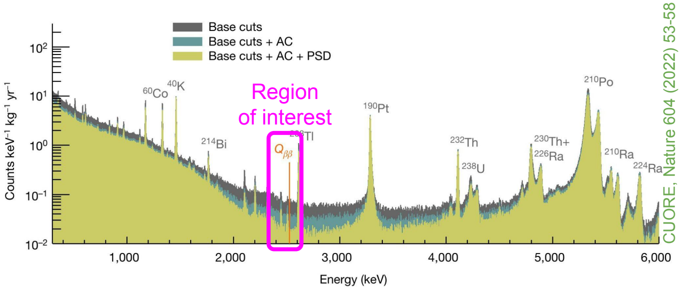
- Readout of scintillation light to suppress α's
- Reducing surface contamination to **1 nBq/cm^2** would significantly improve the sensitivity



The need for low-background α spectroscopy

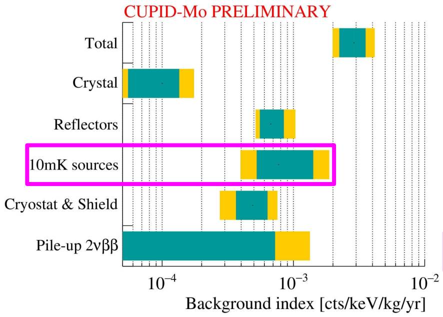
Bolometric searches for 0νββ decay

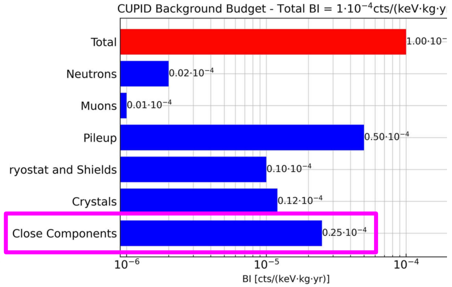
CUORE data (no particle identification)



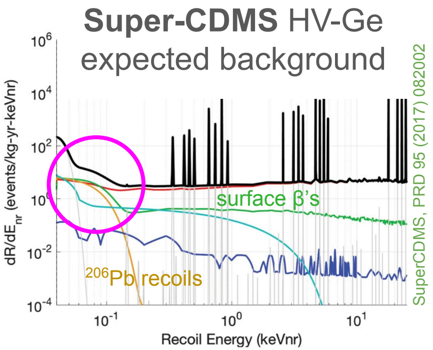
CUPID (with particle identification)

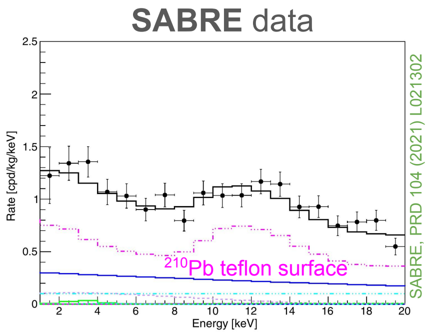
→ Residual β's from ~10 nBq/cm^2 surface contamination



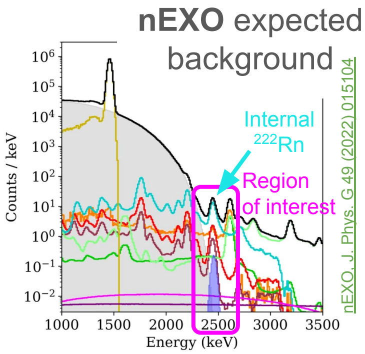


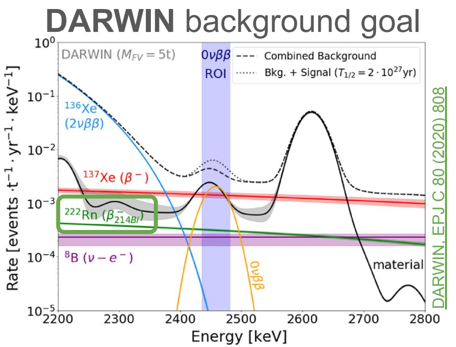
Direct Dark Matter searches w/ crystals





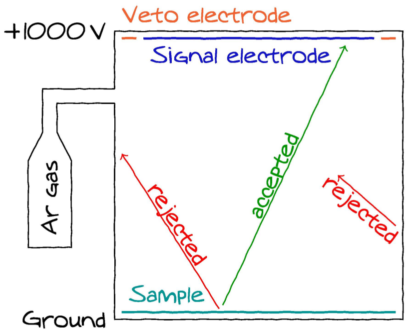
TPCs for 0νββ decay and Dark Matter searches





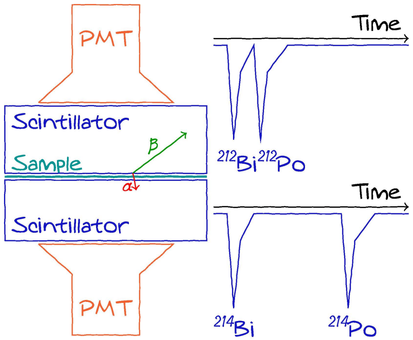
State of the art

XIA UltraLo-1800



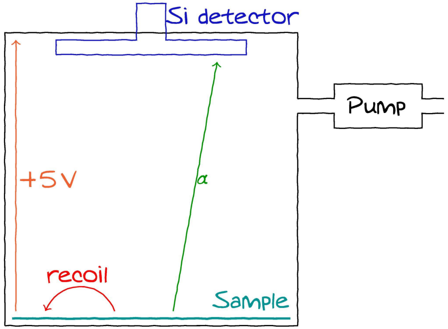
- Ionization chamber
- Area 0.18 m^2
- Sensitivity ~30 nBq/cm^2
- Resolution ~400 keV

BiPo



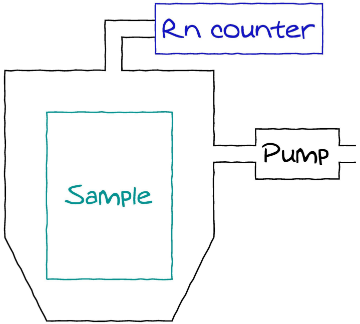
- Area 3.6 m^2
- Sensitivity 0.1 nBq/cm^2
- Only ^{212}Bi–^{212}Po and ^{214}Bi–^{214}Po pairs
- Thin samples ≤100 μm

Ion-implanted silicon detectors



- Area of O(10) cm^2
- Sensitivity ~10 μBq/cm^2
- Resolution 20-60 keV

Radon-emanation detectors



- Area up to 60 m^2
- Sensitivity ~0.1 nBq/cm^2 but highly dependent on sample thickness
- Only measures ^{222}Rn

State of the art

Name	Producer or location	Background level [10^{-9}counts/s/cm^2]	Background region [MeV]	FWHM @5 MeV [keV]	Active area [m^2]	Sensitivity [nBq/cm^2]
UltraLo-1800	XIA	$\sim$250	2.5–10	$\sim$400	0.18	$\sim$30
PIPS	LNGS	$\sim$15 000	1–10	$\geq$20	0.0012	$\sim$10 000
BiPo-3	LSC	0.1			3.6	$\sim$0.1
Rn emanation	LNGS	0.25			$\leq$60	$\geq$0.1
TPCs	various	1–30	2.5–10	150–300	$\leq$0.24	1–30
SURFαCE	LNGS	$\leq$ 10	2.5–10	$\lesssim$10	2	1

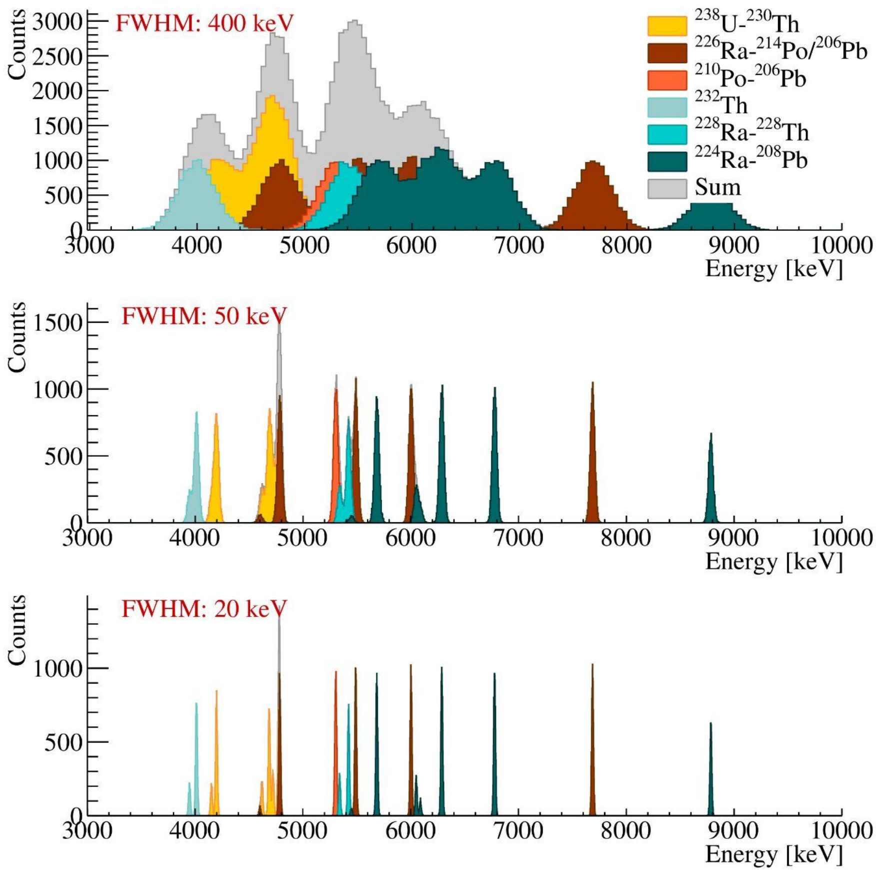
- All technologies limited by sensitive area, background or resolution
- BiPo-3 and Rn emanation suitable only for a part of ^{238}U chain and only for thin foils
- TPCs at early design phase so far

SURFαCE goal: α spectroscopy with 1 nBq/cm^2 sensitivity

Requirements

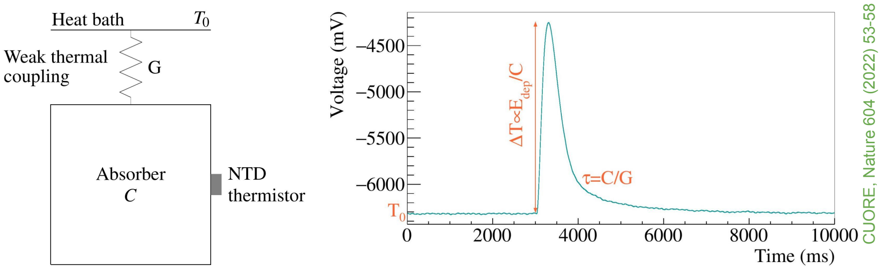
- **Sensitivity of ~1 nBq/cm^2** with a few weeks of measurement
  → **Area ≥ 1m^2**
  → **α background ≲ 10^{-8} counts/s/cm^2**
- Measure all parts of the ^{238}U and ^{232}Th chain that are out of secular equilibrium
  →**Energy resolution ≲ 20 keV (FWHM)**
- Easy operation of sample insertion/removal
- Possibility to clean or replace the detector

None of the current technologies satisfies all the requirements!



Proposed solution: large-area bolometers

Bolometric detectors



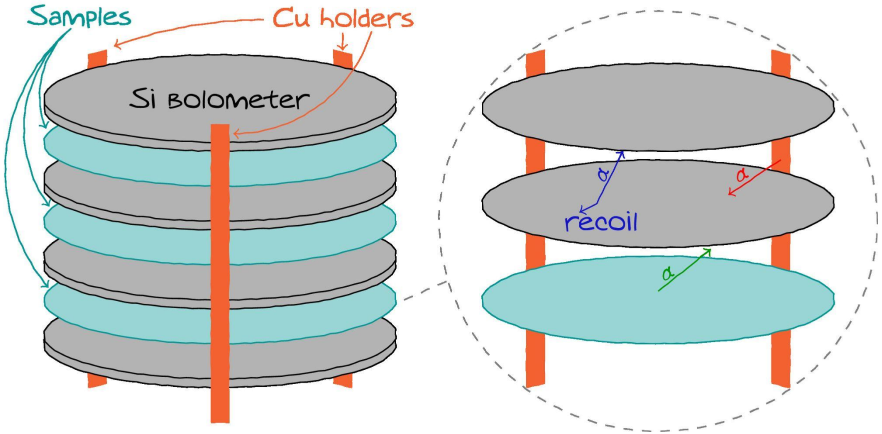
- Crystal absorber coupled to phonon or temperature sensor
  → ΔT ∝ # of phonons ∝ deposited energy
- ΔT of the order of 0.1 mK
  → Must operate at 10-30 mK

Bolometers for α spectroscopy

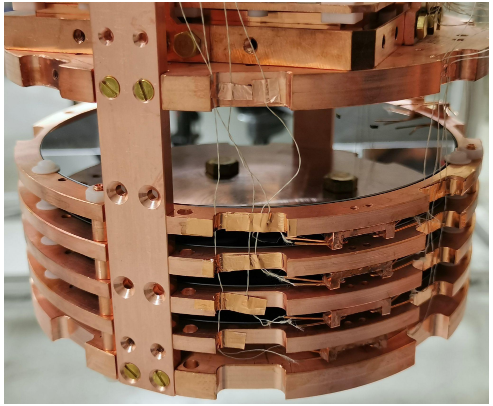
- Many materials suitable as absorbers
  → Can use commercially available ones
  → Backup solutions also available
- Energy resolution ≤10 keV FWHM
- No dead layer
  → Sensitivity to contamination depth profile
- **Never used for α spectroscopy so far**

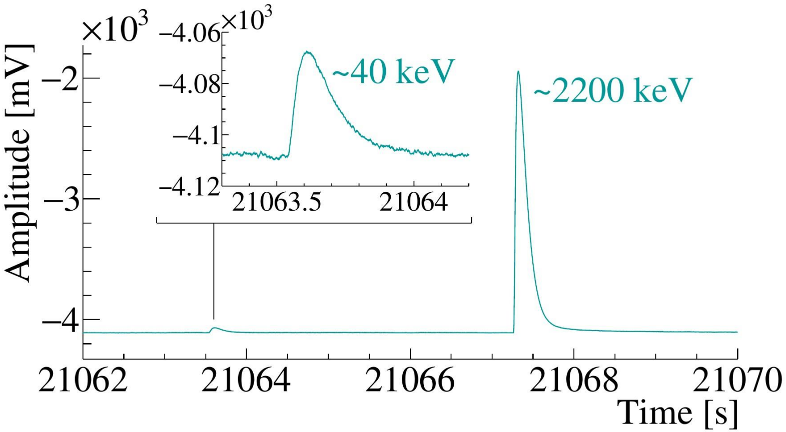
The SURFαCE concept

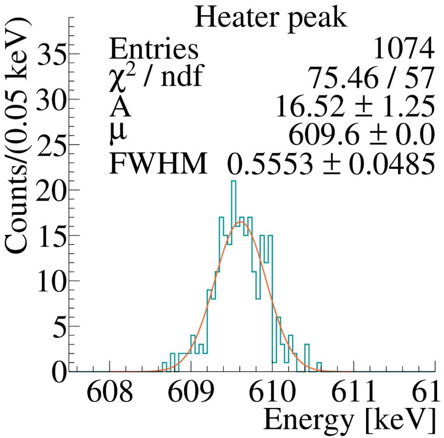
- Array of **large-area silicon bolometers with 1 nBq/cm^2 sensitivity**
  → Among the cleanest materials
  → 15cm ∅ commercially available
- Interleave Si detectors with material samples
  → ≥1 m^2
  → Allow samples of up to 5 mm thickness
- Background: 10^{-8} counts/s/cm^2 in full α range
  →Minimize area of copper support frame
  →Active suppression of silicon background
  →Underground operation to suppress event rate



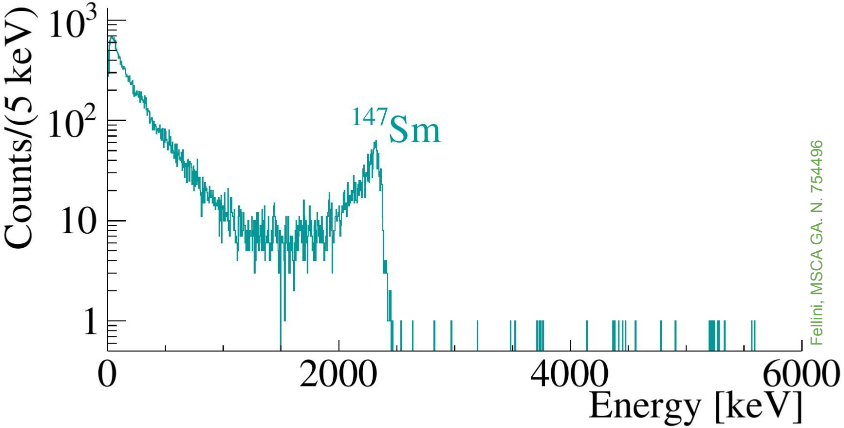
The first SURFαCE prototype



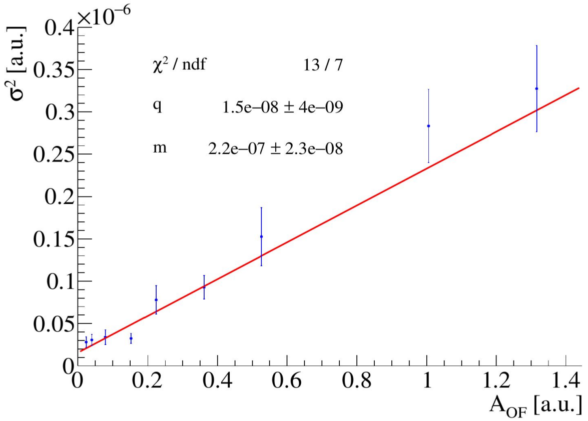


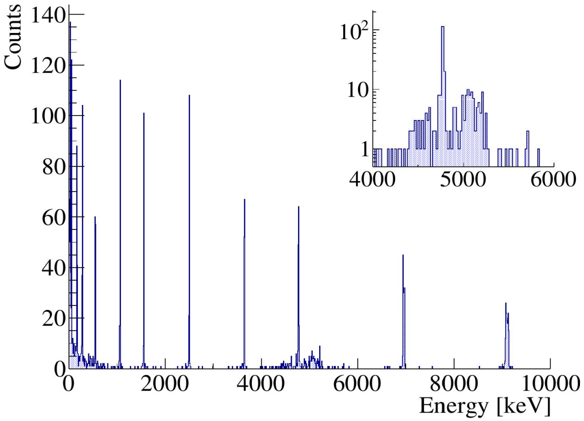


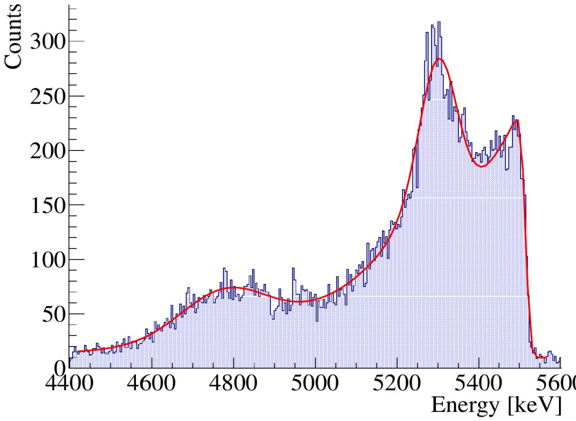
- Operated underground @ LNGS in fall 2021
- High-purity silicon suitable for use as bolometer
- Integrated α background: ≤10^{-7} counts/s/cm^2
  → **Lowest α background ever!**



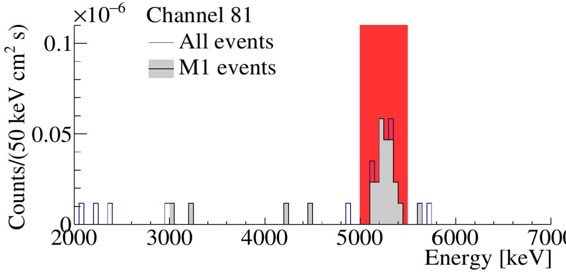
The second SURFαCE prototype







- Operated underground @Canfranc in Jan-Mar 2024
- Proof of principle for LED-based calibration in [10 keV, 10 MeV] range
- Resolution on α peak from ^{222}Rn-irradiated sample ~110 keV FWHM
  →Space dependence of detector response? Self-absorption?
- Lowest background: $6\cdot10^{-8}$ events/cm^2/s excluding ^{210}Po peak
  →**Lowest α background ever!**



Challenges: detector performance

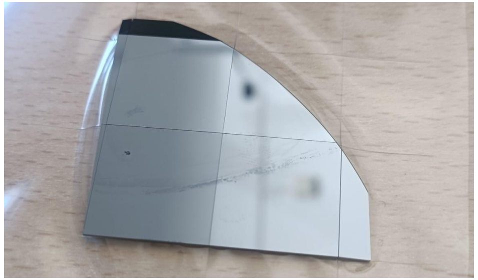
Reproducibility of detector performance

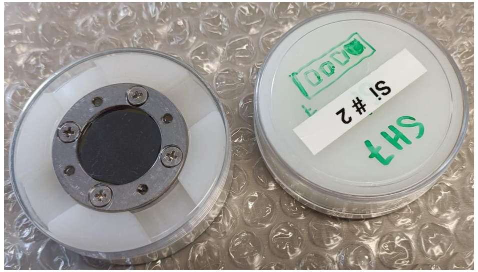
- Final goal: setup with up to 60 detectors to be operated repeatedly with minimal intervention
- In both prototypes, some detector failed or underperformed due to faulty wiring or noise
- Strategies:
  - Automate detector assembly to ensure robustness
  - Optimize design of mechanical structure to allow for an easy detector replacement

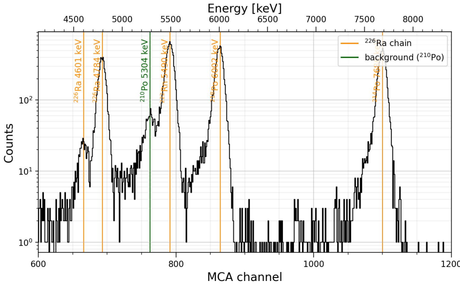
Understanding detector response

- Final goal: 10 keV resolution on α peaks (starting from the current 110 keV)
- Strategy: instrument single detector with 2 NTDs and face it to:
  - 2 LED-coupled optic fibers shining light close to the NTDs
  - 2 ^{226}Ra-implanted samples
- Develop pulse-shape dependent energy reconstruction?
- Dedicated tests to be performed in Yeti cryostat during first year

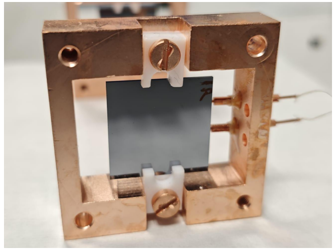
Challenges: detector performance

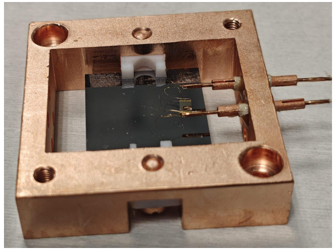


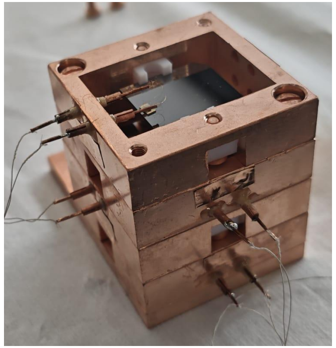




- 2 Si samples (20×20mm^2) implanted with ^{226}Ra @ISOLDE
  →0.24 and 2.4 Bq activity
- Samples measured with α detector, HPGe, and Rn-emanation
  →See L. Ascenzo presentation
- Currently assembled as bolometers
  →Validate intrinsic Si resolution as bolometer and evaluate need to switch to sapphire
  →Study ^{226}Ra implantation profile
  →Use as calibration source for SURFαCE detectors
  →Use as collimated source to study space dependence of detector response

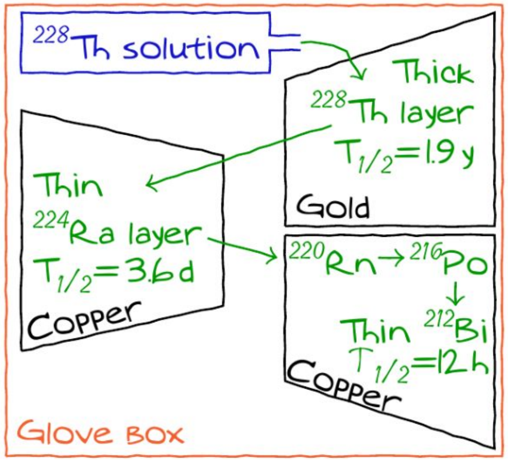


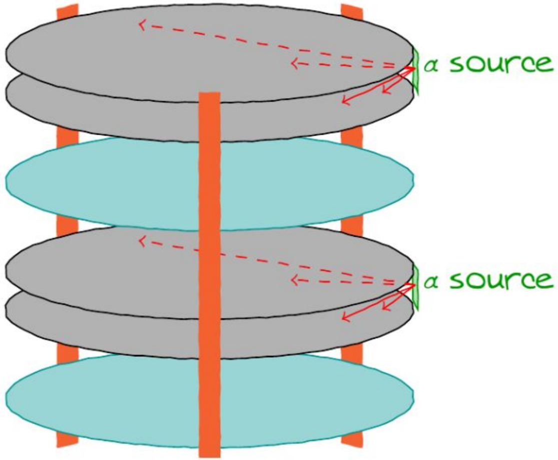


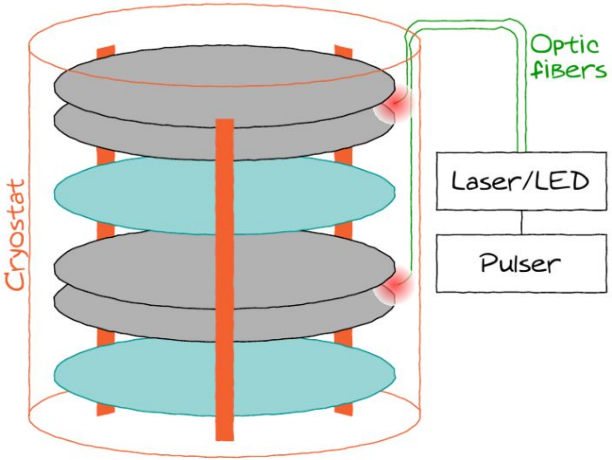


Challenges: energy calibration

- Requirements: calibrate 2–10 MeV range within same cooldown of sample/bkg measurement without contaminating the detector
- Solutions:
  - Implant α-emitting ^{212}Pb isotopes on a metal plate to be placed in front of each detector →Requires to double irradiation of ^{224}Ra and ^{220}Rn before each cooldown
  - Absolute calibration with light source exploiting Poisson photon statistics →Promising preliminary results, fine-tuning required







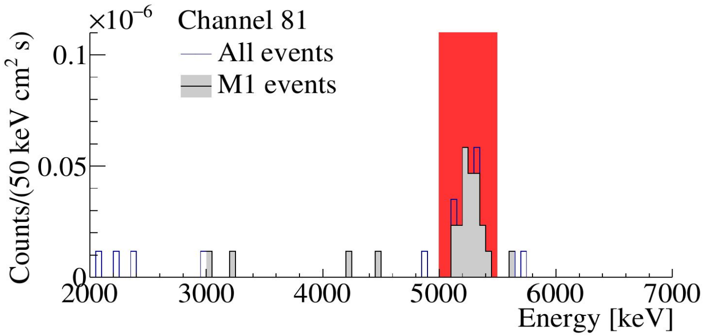
Challenges: background control

Background control

- Goal: 10^{-8} events/cm^2/s on full α spectrum
- Current status: $6 \cdot 10^{-8}$ events/cm^2/s excluding ^{210}Po peak (obtained without working in clean room)
  - Too low statistics to identify backgrounds
- Strategies:
  - Clean copper via electropolishing
  - Boil-off nitrogen storage
  - Assembly in Rn-free air
  - Staged approach: evaluate background on 10–20 detectors, then optimize bkg-minimization strategy for final setup

Choice of absorber material

- Silicon as first choice due to availability and price
  - However, poor resolution and evidence for ^{210}Po contamination
- Strategies:
  - Bake Si wafers prior to detector fabrication
  - Replace Si with e.g. sapphire



The SURFαCE team

Institution	Tasks
INFN/GSSI	Detector design, fabrication and operation, cryogenics, data analysis and simulations
UnivAQ	^{212}Pb-implanted samples
UniMIB/INFN-MIB	Electronics
LBNL/UCBerkeley	NTD production, data reconstruction software
INFN-LNL	Material cleaning
IJCLab	LED-based calibration, data analysis and simulations
MPI-HD	^{226}Ra-implanted samples

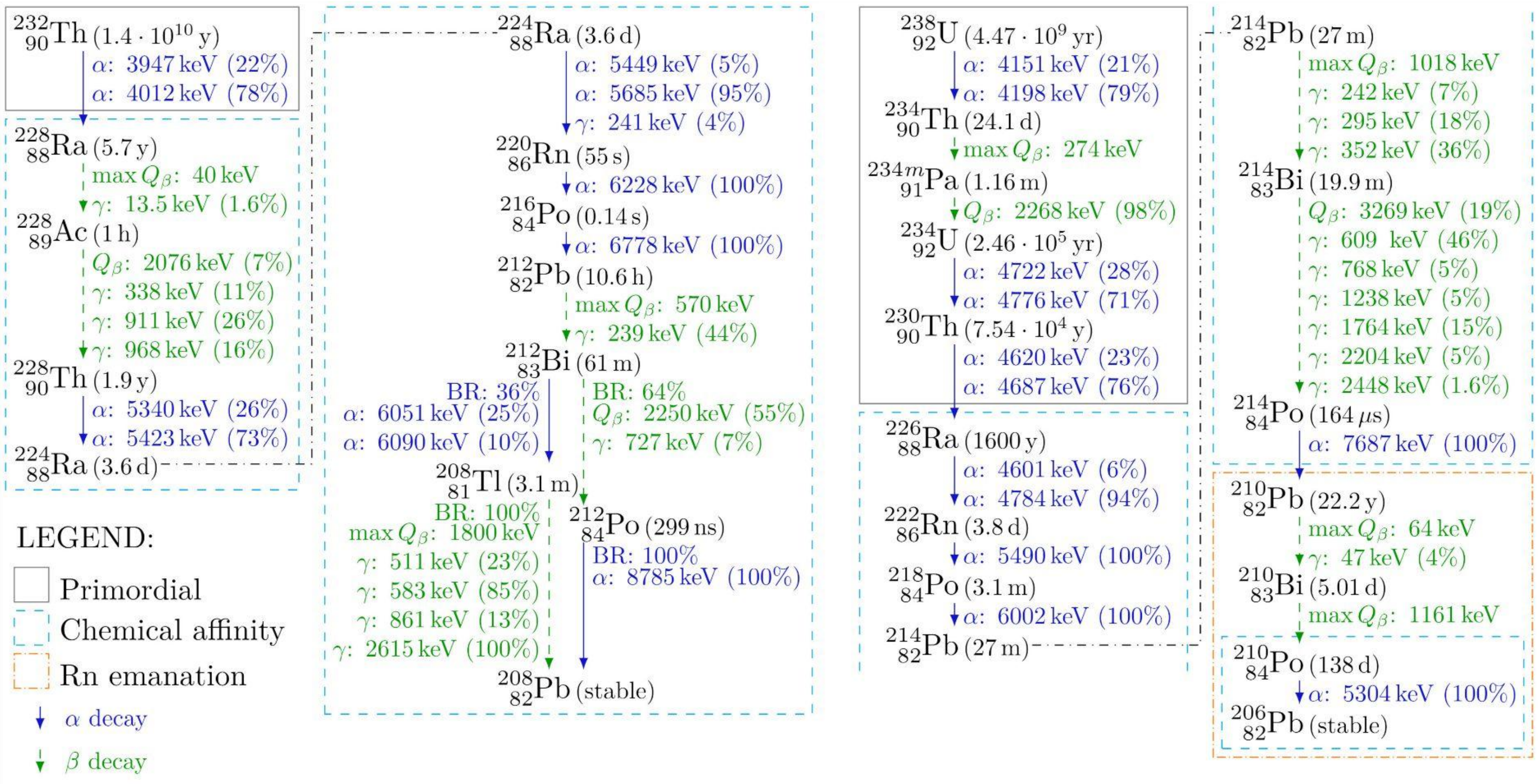
Summary

Silicon
Underground
Radiopure
Finder
of **α**
Contamination
Excesses

Impact

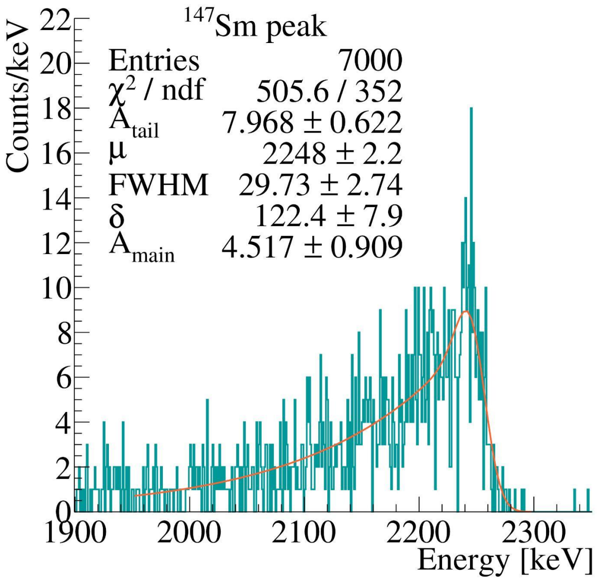
- Empower the measurement of surface contamination down to 1 nBq/cm^2, required by next-generation experiments, in few weeks of measurement
- If successful, SURFαCE would complement germanium detectors for γ screening and ICP-MS/LA-MS and significantly strengthen the screening capabilities of LNGS

Backup: ^{232}Th and ^{238}U decay chains



Backup: Prototype detector performance

- Selected 4 channels with best performance and working pulser
- **^{147}Sm source smeared on porous nylon foil** placed around the detectors
  → ^{147}Sm peak visible, low energy tail as expected
- Non-linearity of the energy spectrum above ~3 MeV
  → Energy of α events not reliable
  → With the current data, just count events above ^{147}Sm peak
- Integrated background in the [2.5,10] MeV region: ~10^{-8} counts/s/cm2
  → detector fabrication and installation NOT performed
  in clean room or glove box!
  → Quick copper cleaning with soap + passivation
  → Space for improvement!



Backup: detector calibration

Requirements

- Calibrate energy scale in 3-8 MeV region
  → γ sources are of no use
  → Need **sharp α lines**
- Combine calibration and background/sample measurement
  → α lines from source should not overlap with those from background/sample
  → Do **NOT contaminate the detector**!
- Possibly, also calibrate at few keV

Solutions

1. Use an α source with a half-life of ~1 day
   - Create a master source, and implant (radioactive) recoiling nuclei into the actual calibration source
   - **First few days for calibration, followed by background/sample measurement**
   - Combine with e.g. ^{55}Fe source for low-energy calibration
2. Irradiate detectors with laser/LED light New!
   - Optic fiber from room temperature to detectors
   - Inject laser pulses of different amplitudes
   - Linearity proven, precision to be verified
   - Continuous calibration
   - **Simultaneous calibration and stabilization**

Backup: ion-implanted α sources

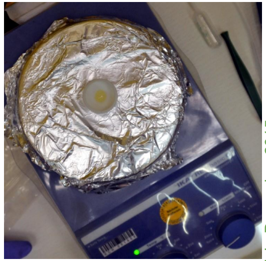
Starting point: GERDA recipe

- Commercial $ThCl_4$ dissolved in 1M HCl
- Deposit Th on gold to suppress (α,n) reactions:

$3ThCl_4 + 16HNO_3 \rightarrow [3Th(NO_3)_4]_s + [4NOCl+8H_2O+4Cl_2]_g$

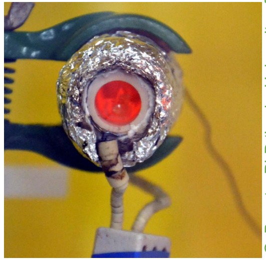
$3Th(NO_3)_4 \rightarrow [3ThO_2]_s + [12NO_2+3O_2]_g$

$ThCl_4$ solution



Chlorine evaporation

HNO_3 evaporation

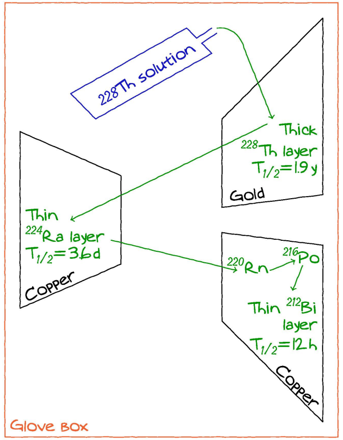


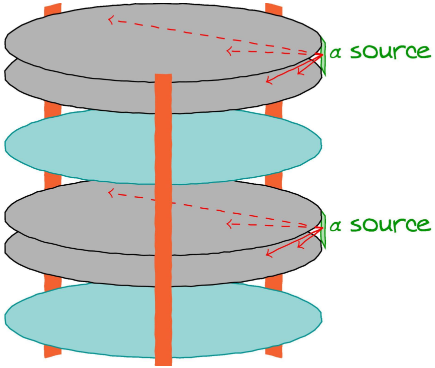
$Th(NO_3)_4 \rightarrow ThO_2$

G. Benato, PhD thesis, University of Zurich, December 2015

Plan of action

- Fabricate ^{228}Th source(s) using GERDA recipe
  → Use dedicated glove box
- Implant ^{224}Ra recoils on copper plates
- Replicate with $^{220}Rn \rightarrow {}^{216}Po \rightarrow {}^{212}Bi$
- Fine-tune implantation recipe with commercial ion-implanted silicon detector

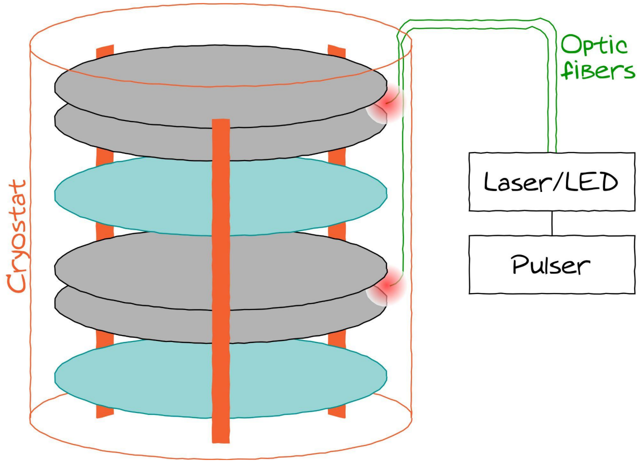




Backup: calibration with light pulse

Concept

- Drive light to detectors with optic fibers
- Periodic light pulses of different amplitudes for amplitude stabilization and linearization
  → **No more need for stabilization heaters**
- Combine with low-energy γ or X-ray source for energy calibration



Open questions

- LED or laser?
- Precision (<0.1% @ 5 MeV) to be verified
- Absolute calibration?
- Stability?

Advantages

- No risk to contaminate detectors
- **No need to periodically produce recoil-implanted α sources**
- Amplitude of light pulses **can be tuned during runtime** at room temperature
- 100% of cooldown time available for background/sample measurement (no calibration needed)