Development of an ultralow-background bolometric alpha detector for the measurement of surface contamination

G. Benato, E. Celi, M. Olmi, S. Ghislandi, and S. Quitadamo
Low Radioactivity Techniques, Rapid City, June 2022

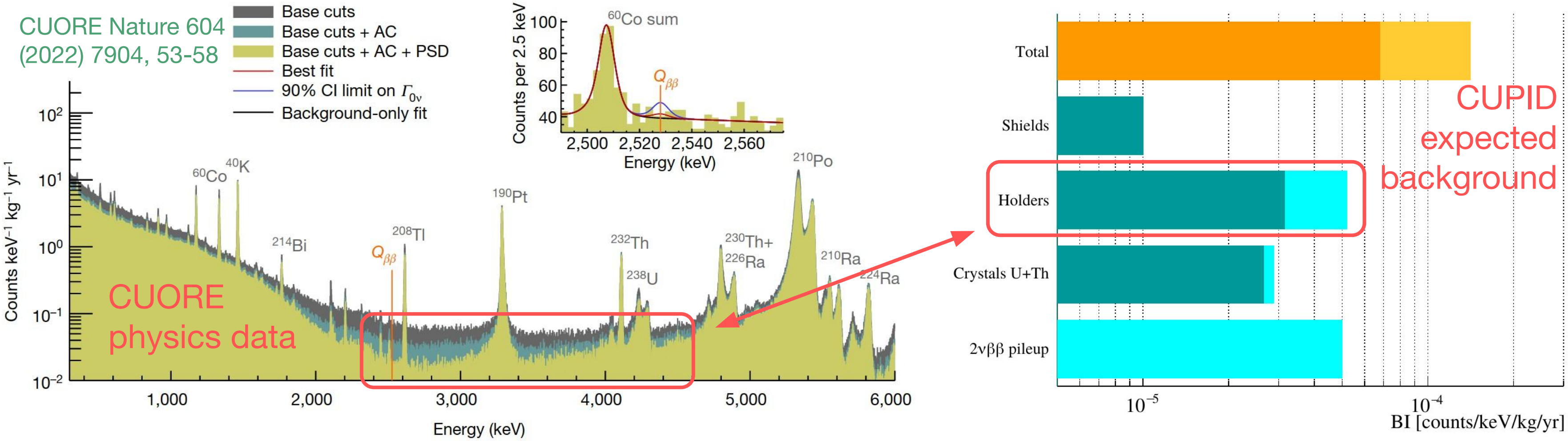
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Fellini
Fellowship for Innovation at INFN

Work supported by the EU Horizon 2020 research and innovation program under the MSCA GA No. 754496

Surface α’s as background - 0νββ bolometric searches

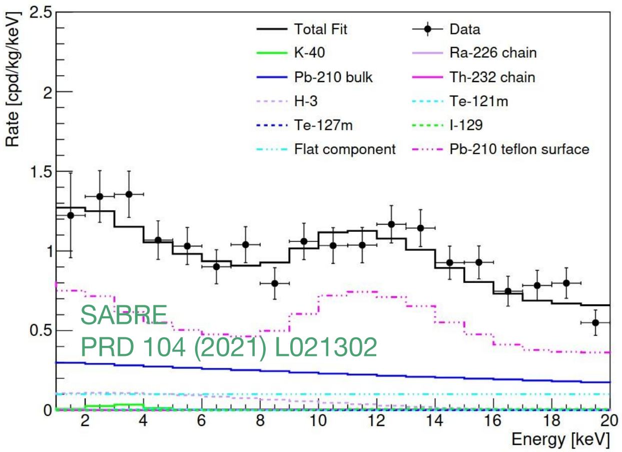
CUORE Nature 604 (2022) 7904, 53-58

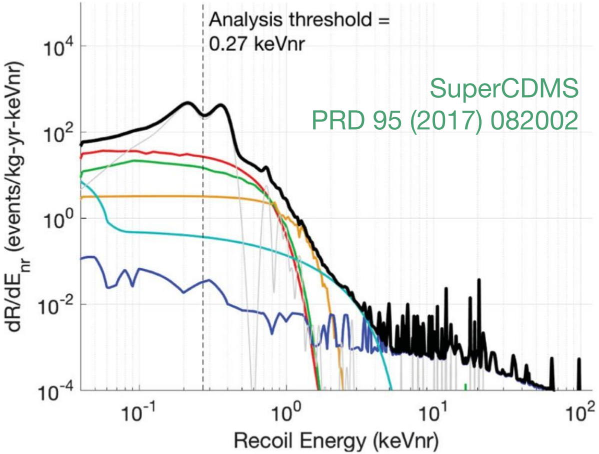


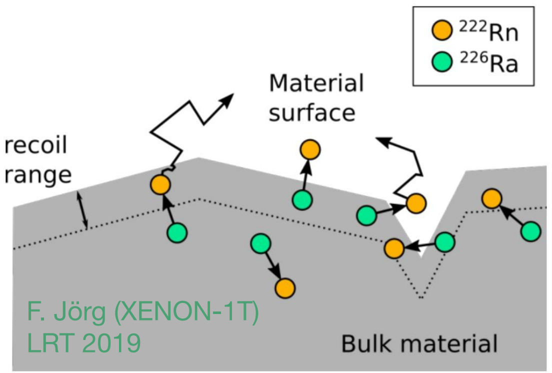
- Bolometric experiments for 0νββ decay (e.g. CUORE) have the highest background from degraded α particles emitted by the passive support materials (mainly copper)
- Next-generation experiments (CUPID, AMoRE) will use scintillating crystals for particle identification → Surface β’s from e.g. ^{214}Bi still a significant source of background

Surface α's as background - WIMP searches

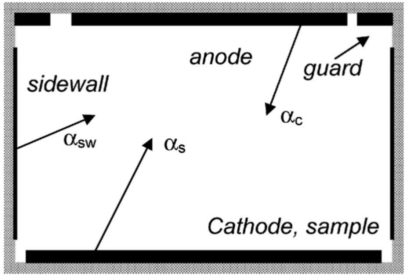
- WIMP searches with scintillating crystals are highly sensitive to the surface contamination of the reflector
- WIMP searches with bolometers subject to β's and nuclear recoil background from surface radioactive contamination
- WIMP searches using TPCs are subject to the diffusion of ^{222}Rn into the sensitive volume
  → Rn outgassing can be measured just for a subset of materials







Current technologies for measuring surface contamination

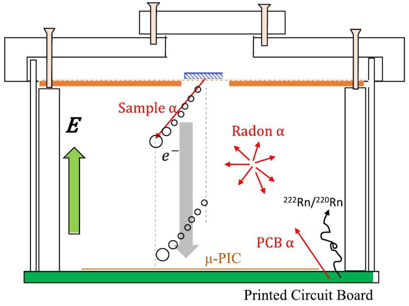


XIA UltraLo-1800

- Large area
- Lowest background
- Easy operation
- Poor resolution

Ion-implanted Si detectors

- Easy operation
- High resolution
- Small area
- High background

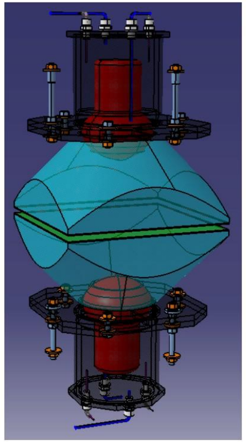


TPCs

- Large area
- Not plug&play
- Poor resolution
- R&D still ongoing

BiPo

- Large area
- Only thin foils
- Measures only BiPo’s



Requirements for next-generation α detector

- Sensitivity to surface ^{232}Th or ^{238}U contamination down to few nBq/cm^2
  → Area ≥ 1 m^2
  → Background ≤ 10^{-8} cts/s/cm^2 in the full α range
- Capability to distinguish different parts of the ^{232}Th and ^{238}U chain that are out of equilibrium
  → Energy resolution ≤ 20 keV FWHM to distinguish different α peaks
- Sensitivity to depth profile of surface contamination
  → No deformation induced by e.g. dead layers
  → Energy resolution of few keV FWHM

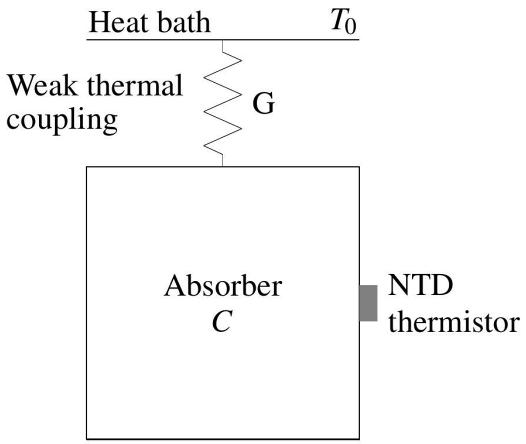
None of the existing technologie satisfies all these requirements!

Name	Producer or location	Background level [10^{-9} cts/s/cm^2]	Background region [MeV]	FWHM @5 MeV [keV]	Active area [m^2]	Sensitivity [nBq/cm^2]
UltraLo-1800	XIA	~250	2.5-10	~400	0.18	~30
PIPS	various	~10^4	1-10	≥20	0.0012	~10^4
Bi-Po	LSC	0.1			3.6	~0.1
TPCs	various	1-30	2.5-10	150-300	≤0.24	1-30

Cryogenic calorimeters

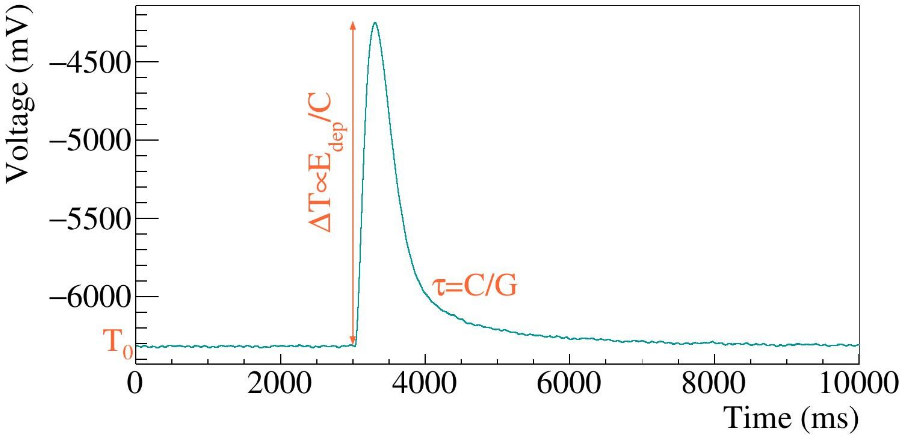
Highly sensitive calorimeter operated at cryogenic temperature (~10 mK).
Energy measured as temperature variation of the absorber:

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau}\right) \qquad \tau = C/G$$



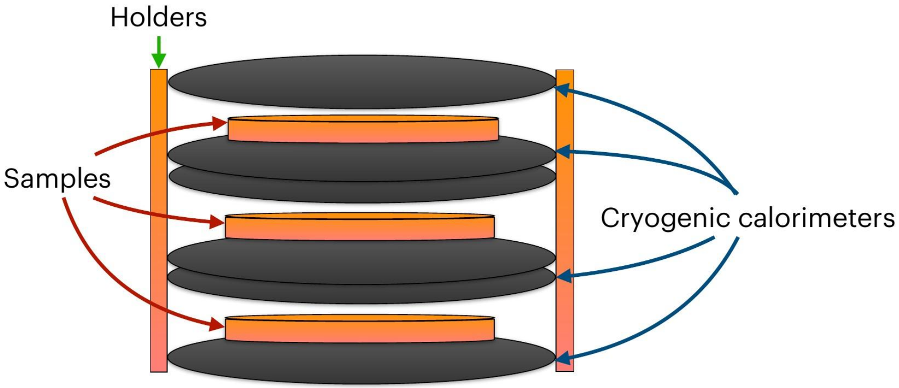
Main advantages:

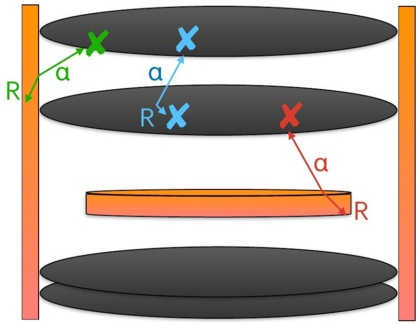
- Detector modularity
- Stable long-term operation possible
- Great dynamic range, few keV to 10 MeV
- Excellent energy resolution (≤10 keV FWHM)
- Possibility to use different absorber crystals and select the one with the lowest radioactive contamination



The *SURFACE* detector concept

- Array of disk-like material samples interleaved with thin, disk-like absorbers
  → Samples of thickness up to ~5 mm possible
- Operated as bolometer
  → No dead layer!
  → Can be sensitive to the contamination depth profile
- Intrinsic backgrounds:
  - α particles from detector holder
    → Minimize area of passive material
  - α particles from absorbers
    → Can be rejected with coincidence analysis
- Thermal variation measured with Ge-NTD thermistors
  → Great linearity (if you operate them properly…)
- 20 keV resolution would allow to distinguish most α lines from ^{232}Th and ^{238}U chains





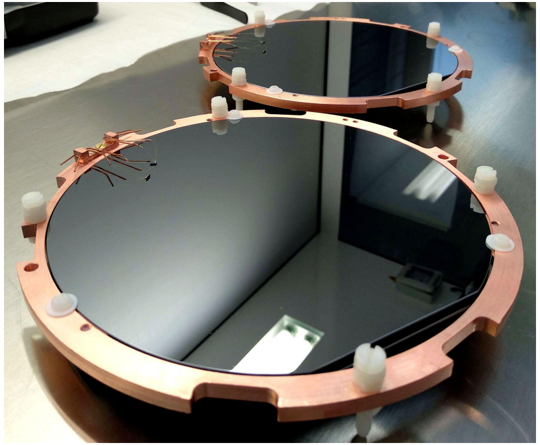
First SURFACE prototype

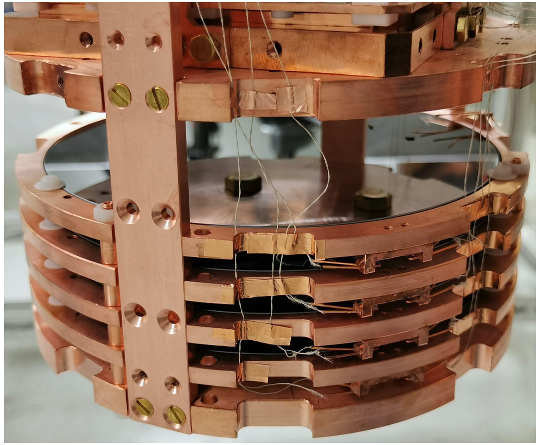
Detector components:

- 8 intrinsic high-resistivity silicon wafers operated as bolometer
- 15 mm diameter, 1 mm thickness
- 4 copper frames, 2 wafers per frame
- Temperature readout with leftover Cupid-Mo Ge-NTD thermistors
- Leftover CUORE Si heaters to inject artificial pulses for thermal stabilization

Experimental setup and operation

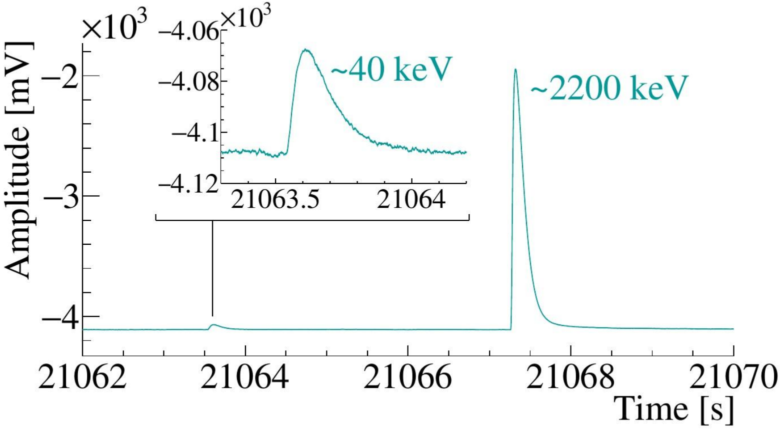
- ^{147}Sm source smeared on nylon foil wrapped around holders
  → Expect α peak at 2.2 MeV
  → Combined calibration and background measurement
- Operated in wet R&D dilution refrigerator @LNGS
  → 6.5 days of calibration+background data
  → Few hours of linearity studies with pulser scan data



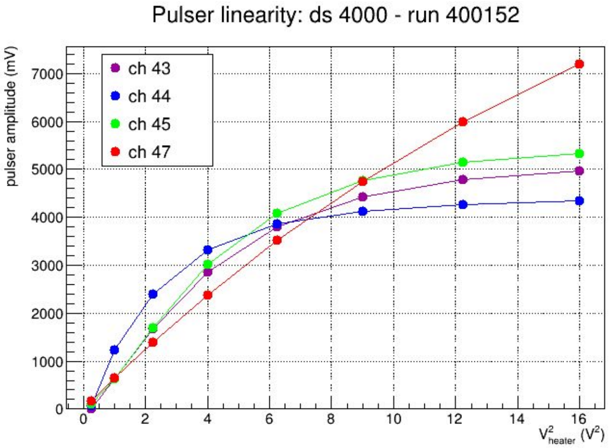


Detector performance

- 1 dead channel, 1 noisy channel, 2 without pulser
- Resolution computed only on pulser peak
- 1 keV threshold on multiple channels
  → Can definitely see nuclear recoils and X-rays!
- Non-homogeneous time profile of event pulses
  → Different thermalization and/or NTD gluing
- Non-linearity of energy scale
  → Suboptimal NTD working points

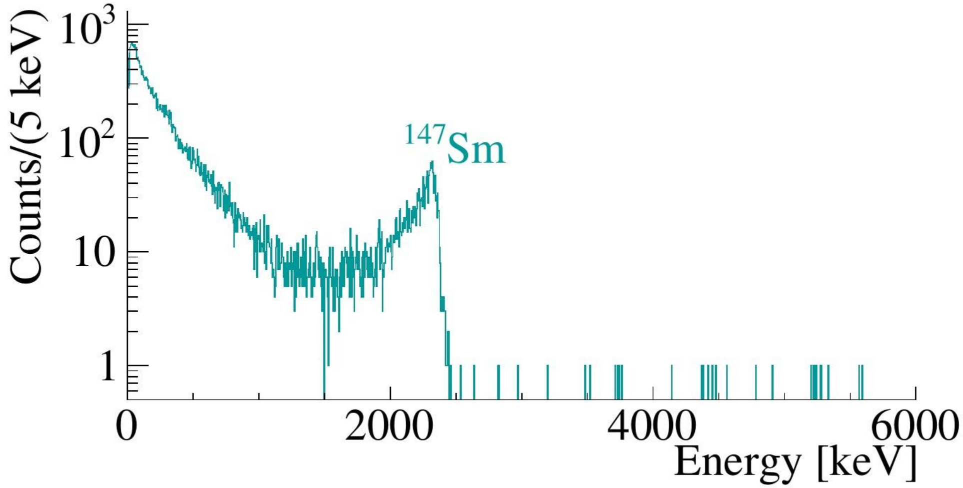


Channel	Pulser resolution FWHM [keV]	Risetime [ms]	Decay time [ms]	Threshold [keV]
41	no pulser	166±3	1182±35	2.2
43	0.80±0.02	60±3	106±3	1.4
44	0.51±0.02	31±1	44±1	1.1
45	0.79±0.04	65±3	217±4	1.3
47	3.56±0.17	63±3	106±3	6.3
48	no pulser	34±1	62±2	1.0



Background

- Selected 4 channels with best performance and working pulser
- ^{147}Sm peak visible, low energy tail as expected
- Large continuum below 1 MeV due to γ source used for other detectors present in the setup
- 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^{-7} events/s/cm^2**
  → detector fabrication and installation NOT performed in clean room or glove box!
  → Space for improvement!



Next steps

1. Fix non-linearity issue
    a. Optimize NTD working point
    b. Correct using pulser events, validate with α source
2. Find out a smarter way to calibrate
    a. Shining optical photons with fiber?
    b. Use implanted ^{224}Ra or ^{212}Pb source?
3. Long background run with ≥ 20 channels
    a. Full background model using MC simulations
    b. Evaluate impact of clean room or glove box operations
    c. Compare frame and detector background
4. Measure samples