GRAN SASSO SCIENCE INSTITUTE

First measurements with a NaI(Tl) crystal for the SABRE experiment

2nd year research activity report
October 17th, 2019

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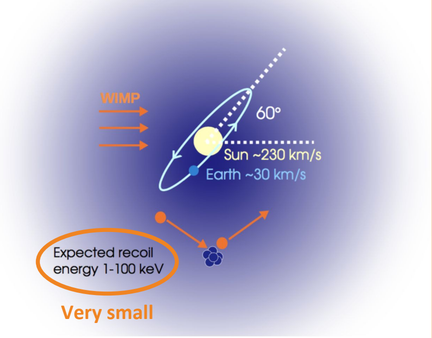
- Conclusions and future perspectives

Dark matter search through annual modulation

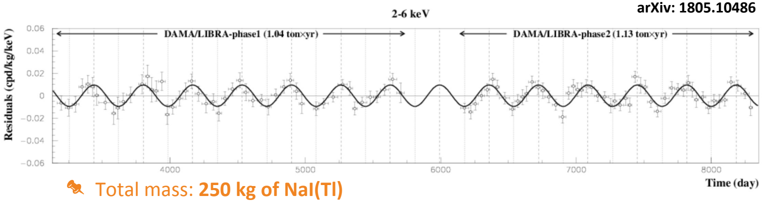
$R \approx S_0 + S_m \cos(\frac{2\pi}{1yr}(t - t_0))$



- **85%** of the matter in the Universe is **"dark"**.
- **WIMPs** (**W**eakly **I**nteracting **M**assive **P**articles) are the most studied candidates for dark matter.
- **Direct detection principle:** dark matter scattering off detector nuclei.
- **Annual modulation of the event rate is a model-independent signature** caused by the combination of Earth and Sun velocities within the dark matter halo
  - ➢ period 1 year;
  - ➢ maximum of the modulation around June 2nd.

A signal has been observed by the DAMA/LIBRA experiment at LNGS, Italy.

arXiv: 1805.10486



- Total mass: **250 kg of NaI(Tl)**
- Exposure of phase-1 + phase-2: **2.17 ton x yr**
- Statistical significance: **11.9σ C.L.**

Experiments with different targets seem to exclude the interpretation of DAMA signal as due to spin-independent WIMPs nuclear scattering in the standard WIMP galactic halo hypothesis.

On the other hand, existing experiments using the same target, do not have sufficiently low background to carry out a model independent verification of DAMA/LIBRA.

A new high sensitivity and low background measurement with NaI(Tl) crystals is needed.

The SABRE strategy - (1)

***SABRE** (**S**odium iodide with **A**ctive **B**ackground **RE**jection) is a direct detection experiment aiming to measure the annual modulation of dark matter interaction rate with NaI(Tl) crystals.*

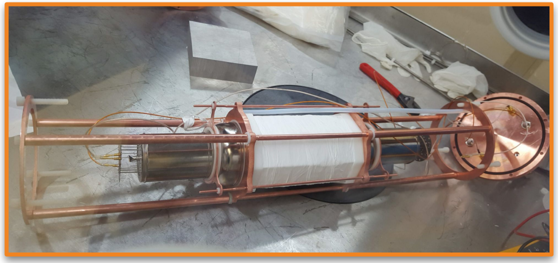
1. **Development of ultra-high purity NaI(Tl) crystals**
   - Main background is due to crystal radioactivity: ^{40}K, ^{87}Rb, ^{232}Th, ^{238}U, ^{210}Pb, ^{3}H
     - ➢ Ultra high purity NaI powder;
     - ➢ Ultra clean crystal growth method.

ICP-MS measurements

Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	$\sim$13	9	$\sim$4
Rb	n.a.	< 0.35	< 0.2	< 0.1
U	$\sim$0.02	$0.5\text{-}7.5 \cdot 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Th	$\sim$0.02	$0.7\text{-}10 \cdot 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$

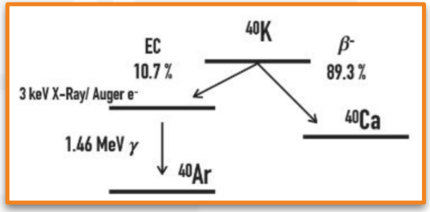
K concentration:
3 times lower compared to **DAMA/LIBRA** (13 ppb)
9 times lower compared to **ANAIS-112** (32 ppb) and **COSINE-100** (42 ppb)

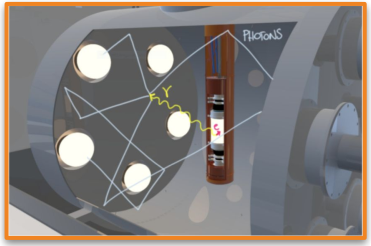
2. **Low energy threshold**
   - Two Hamamatsu R11065-20 3" PMTs directly coupled to the crystal:
     - ➢ high quantum efficiency and light yield;
     - ➢ low radioactivity: ~1 mBq for U, Th; <10 mBq for K.

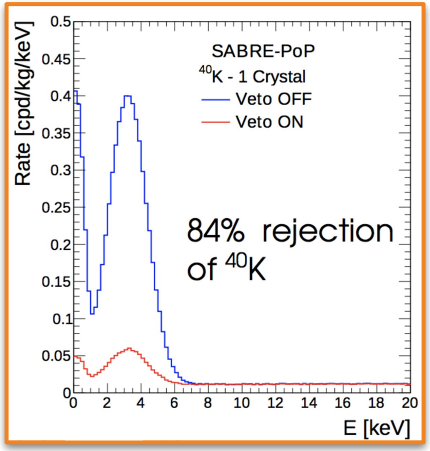


The SABRE strategy - (2)

3. **Active veto**
   - Array of crystals surrounded by liquid scintillator to tag internal and external backgrounds
     - ➢ Unprecedented background rejection and sensitivity with a NaI(Tl) experiment.

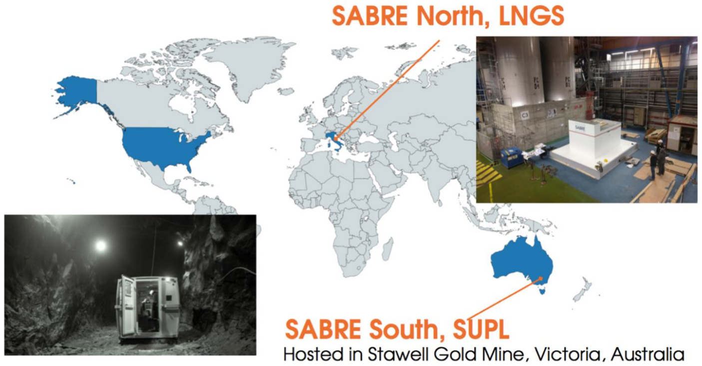




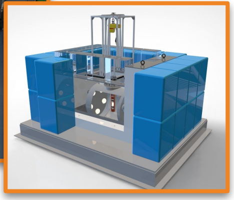


^{40}K represents a consistent fraction of the background in the Region Of Interest (ROI: 2-6 keV) but can be tagged, as well as ^{22}Na.

4. **Double location**
   - Two identical detectors in northern and southern hemispheres
     - ➢ seasonal effects have opposite phases in opposite hemispheres;
     - ➢ dark matter signal has same phase.



The SABRE Proof of Principle (PoP)



Goals:

- Fully characterize SABRE NaI(Tl) intrinsic and cosmogenic backgrounds;
- Test few (≈ 3) crystals;
- Test active veto performance.

Layout:

- 1 NaI(Tl) crystal module per time (but the apparatus is easily scalable up to 3 crystals);
- Crystal mounted inside a copper enclosure and directly coupled to 2 Hamamatsu R11065-20 3” PMTs;
- Active veto: 2 ton PC+PPO (3g/l) scintillator (from Borexino exp) read by 10 Hamamatsu R5912-100 8” PMTs;
- External passive shielding (lead, polyethylene and water) purged with gas nitrogen.

Status:

- The veto vessel, cleaned and internally covered with Lumirror reflector, is in its final position.
- All the veto PMTs have been cleaned and tested.
- All the needed infrastructures are completed.

SABRE PoP setup is ready to be filled with liquid scintillator prior the completion of the laboratory approval procedure.

SABRE crystals

NaI-31

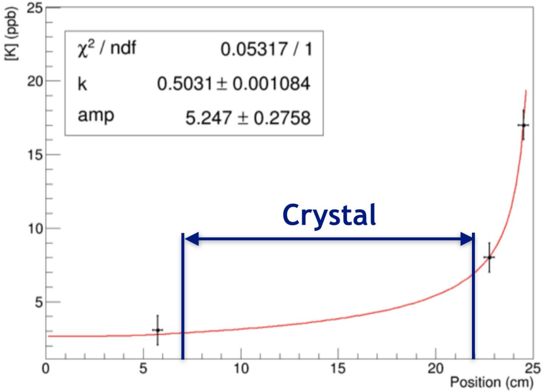
- **Astrograde powder** by Sigma Aldrich.
- Crystal growth completed in June 2018.
- **Octagonal shape, Mass ~ 3 kg** after cut and polishing.
- **Potassium** measurement via ICP-MS: **~ 25 ppb.**

NaI-31 before cut and polishing

Both crystals currently underground at LNGS.

NaI-33

- **Astrograde powder** by Sigma Aldrich.
- Crystal growth completed in October 2018.
- **Octagonal shape, Mass ~ 3.5 kg** after cut and polishing.
- **Potassium** measurement via ICP-MS: **~ 4 ppb.**
  - ➢ Improved powder and crucible handling.



***K content:** fit to data from three samples taken near tip, tail and far-end tail measured by ICP-MS (at Seastar).*

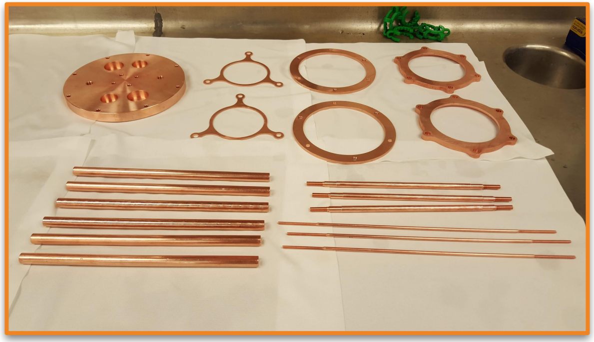
NaI-33 after cut and polishing

Detector module cleaning procedure

- The crystal **detector module** is mainly made of 2 materials: **copper** and **teflon**.
- All the components have been cleaned at Princeton University using the following procedure:
    - ➢ **Ultrasonic bath** with deionized water + 2% of detergent-8 (**both for copper and teflon**), ~ 30 min;
    - ➢ **Ultrasonic bath** with deionized water + 4% of citric acid (**only for copper**), ~ 30 min;
    - ➢ **Vacuum baking**: T ~ 100 °C for copper, T ~ 50 °C for teflon, ~ 1 day.

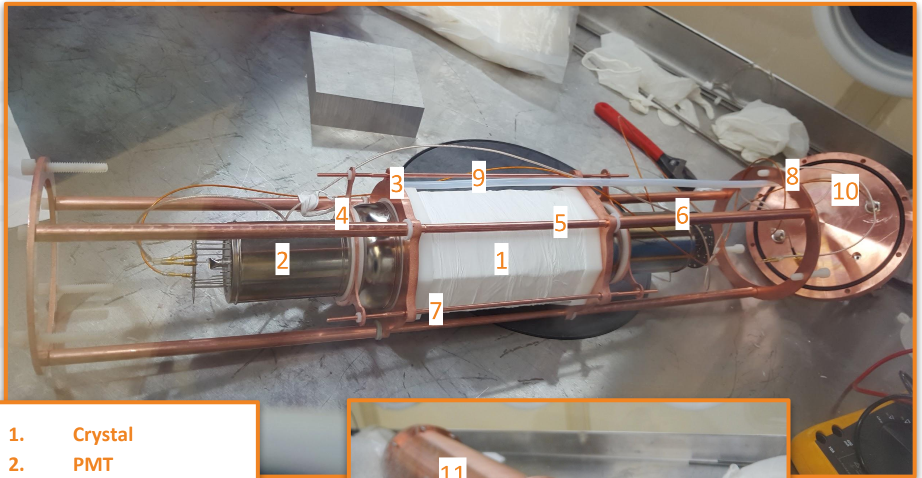
All the components close to the crystal must be extremely clean not to introduce any additional impurity.

NaI(Tl) crystals are highly hygroscopic, so it is very important to eliminate any moisture trace.

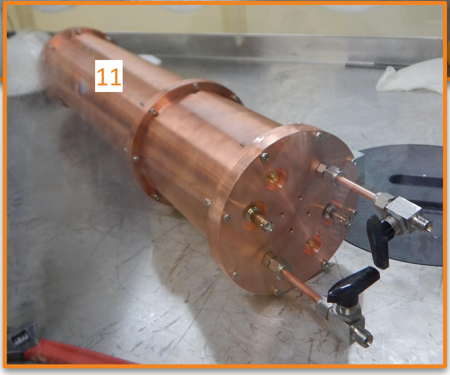


Detector module assembly

- The detector module assembly was done into a **glove box** inside a clean room at Princeton University for both the crystals.



1. Crystal
2. PMT
3. Crystal holder
4. PMT holder
5. Crystal column
6. Rods
7. PMTs column
8. Cu ring
9. Gas tube
10. Top flange
11. Enclosure

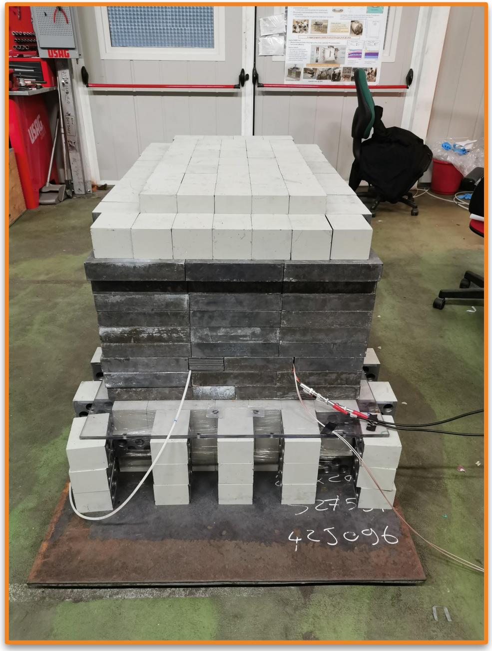


NaI-31 shipped by plane, while NaI-33 shipped by boat to reduce cosmogenic activation.

Data taking at LNGS

- Underground shielding built for preliminary crystal measurements
  - ➢ it can host two crystal enclosures.
- An anti-radon box could be used to flush the setup with nitrogen.

➢ *5/10 cm of low radioactivity copper;*
➢ *≥ 15 cm of lead.*

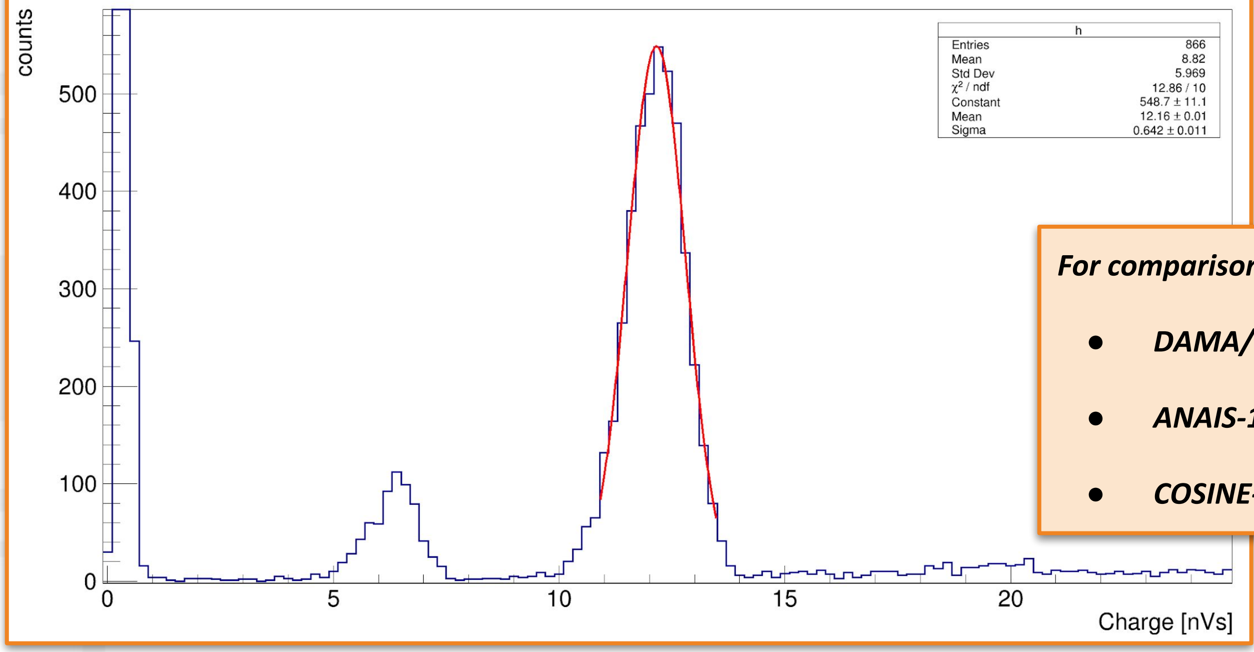


- NaI-31 and NaI-33 data have been collected here.
- Data used to debug and improve the Data Acquisition System (DAQ) and the reconstruction software which will be the same as the PoP.

In the next slides the NaI-33 data analysis will be presented.

NaI-33: energy resolution and light yield

- NaI-33 arrived at LNGS on August 6, 2019.
- ^{241}**Am source** used to measure energy resolution and light yield (LY) on the **59.5 keV** line:
  - ➢ Peak at (12.16 ± 0.01) nVs
  - ➢ σ = (0.64 ± 0.01) nVs



LY
11 phe/keV

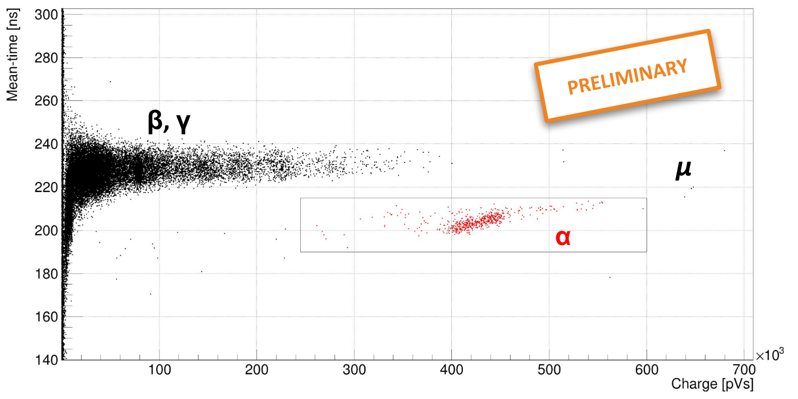
FWHM/E
12.3%

For comparison…

- ***DAMA/LIBRA phase-2:*** *15.8% @59.5 keV*
- ***ANAIS-112:*** *11.2% @59.5 keV*
- ***COSINE-100:*** *11.8% @59.5 keV*

NaI-33: alpha rate

- The spectrum is still dominated by cosmogenic isotopes decays but alpha decays can be easily distinguished.



Pulse charge-weighted mean-time used to distinguish alpha events (shorter τ) from beta/gamma or muon events (longer τ).

$$\tau = \frac{\sum_{t_i<600ns} h_i t_i}{\sum_{t_i<600ns} h_i}$$

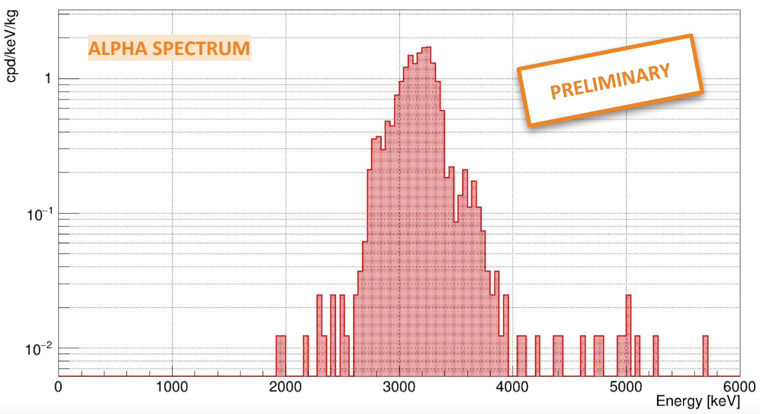
Pulse height at time t_i

Good pulse shape discrimination.

Alpha rate: (0.48 ± 0.01) mBq/kg

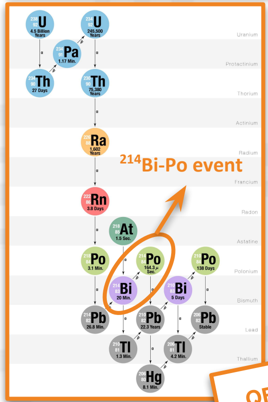
Higher than DAMA but lower than other competitors.

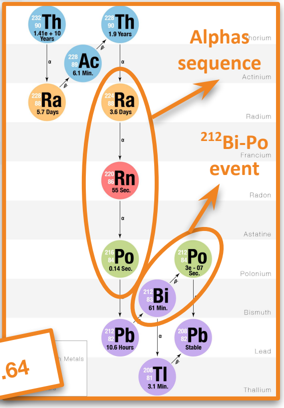
The most part (~ 0.43 mBq/kg) is due to ^{210}Po from a ^{210}Pb contamination out of equilibrium (see next slide).



NaI-33: ^{238}U and ^{232}Th estimation from alphas

β decays from U and Th decay chains are possible background in the ROI for dark matter searches.





QFα = 0.62-0.64

- ^{238}U
  - ➢ **^{214}Bi-Po events:** beta decay followed by an alpha with $T_{1/2}$ = 164.3 μs.

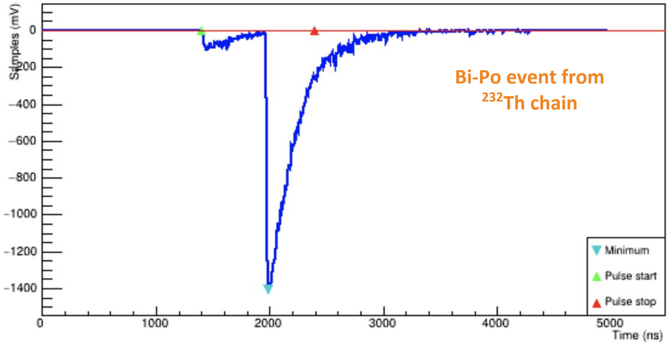
Activity(^{226}Ra) = (5.4 ± 0.9) μBq/kg

If we assume secular equilibrium:
0.45 ppt ^{238}U

- ^{232}Th
  - ➢ **^{212}Bi-Po events:** beta decay followed by an alpha with $T_{1/2}$ = 299 ns (Branching Ratio (BR) = 64%);
  - ➢ **Alphas sequence:** three alpha decays with $T_{1/2}$ = 55.6 s and $T_{1/2}$ = 0.145 s, respectively.

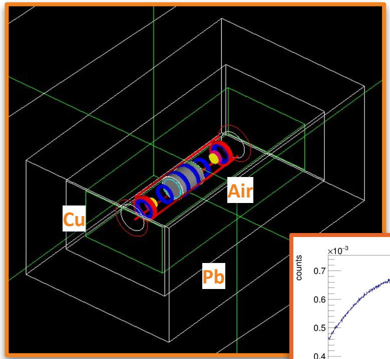
Activity(^{228}Ra) = (1.6 ± 0.5) μBq/kg

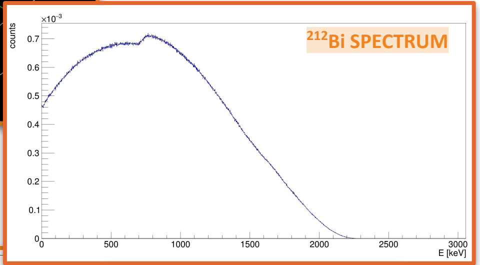
If we assume secular equilibrium:
0.40 ppt ^{232}Th



NaI-33: ^{212}Bi-Po selection efficiency

- **^{212}Bi-Po events selection procedure:**
  1. Selection of alpha events using the charge-weighted mean-time;
  2. Selection of the time-distance between the α and the β event: **$0.03\,\tau < t < 3\,\tau$** where τ = 431 ns is the lifetime;
  3. Trigger on the β event: **E_β > 60 keV** (where trigger efficiency on β is 100%).



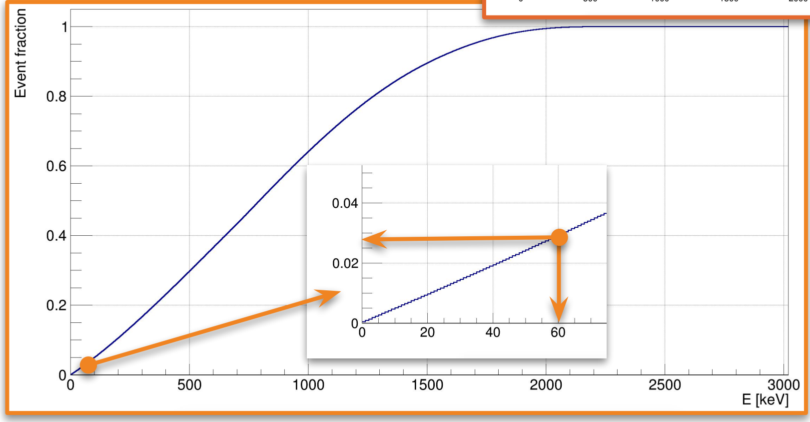


Two efficiencies:

1) ***ε_1*** *from time-distance cut;*
2) ***ε_2*** *from* β energy cut.

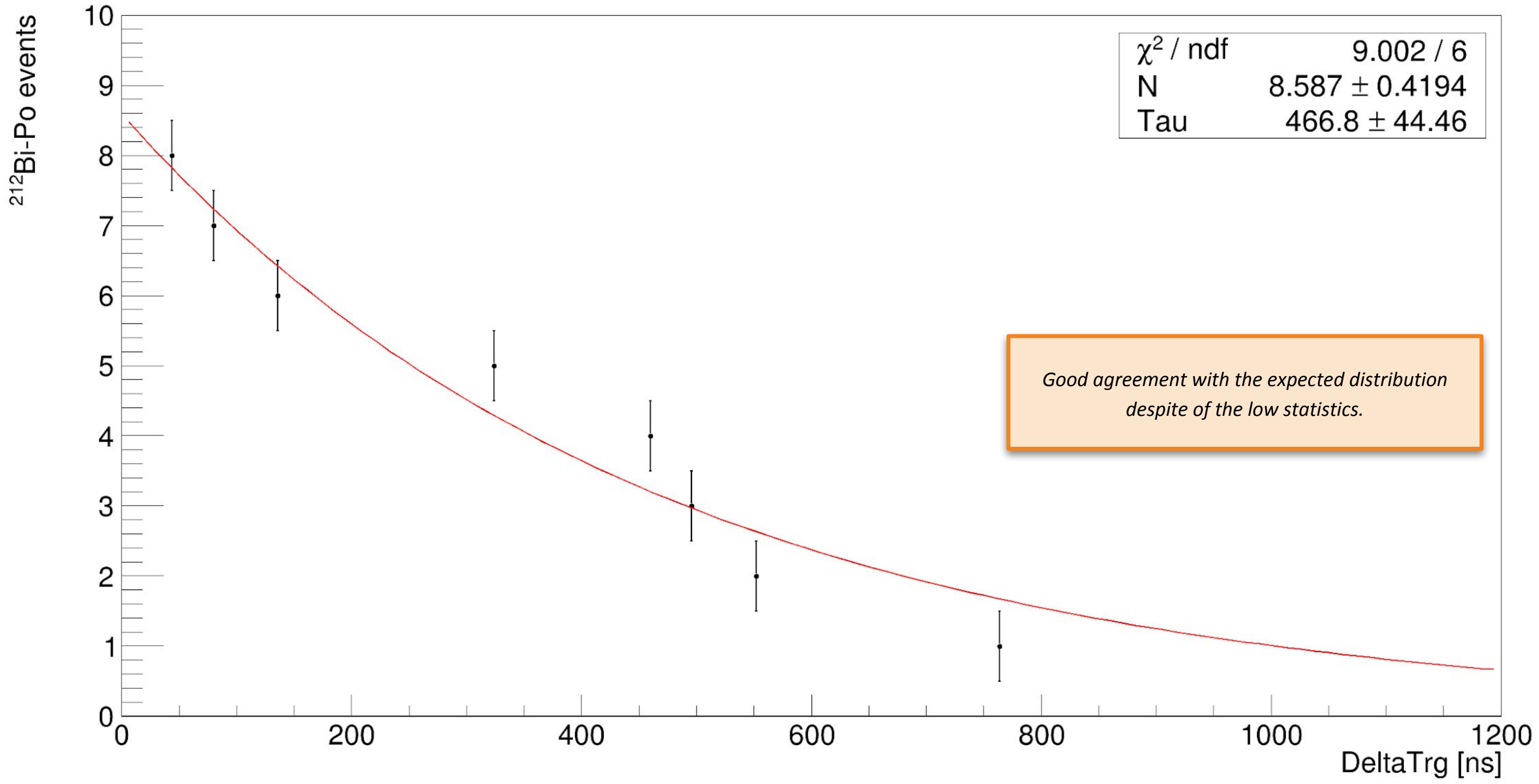
1) $$\varepsilon_1 = \int_{t_{min}}^{t_{max}} \frac{1}{\tau}\, e^{-t/\tau}\, dt = e^{-t_{min}/\tau} - e^{-t_{max}/\tau} = 92\%$$

2) ***ε_2*** = 97% : from Monte Carlo simulation



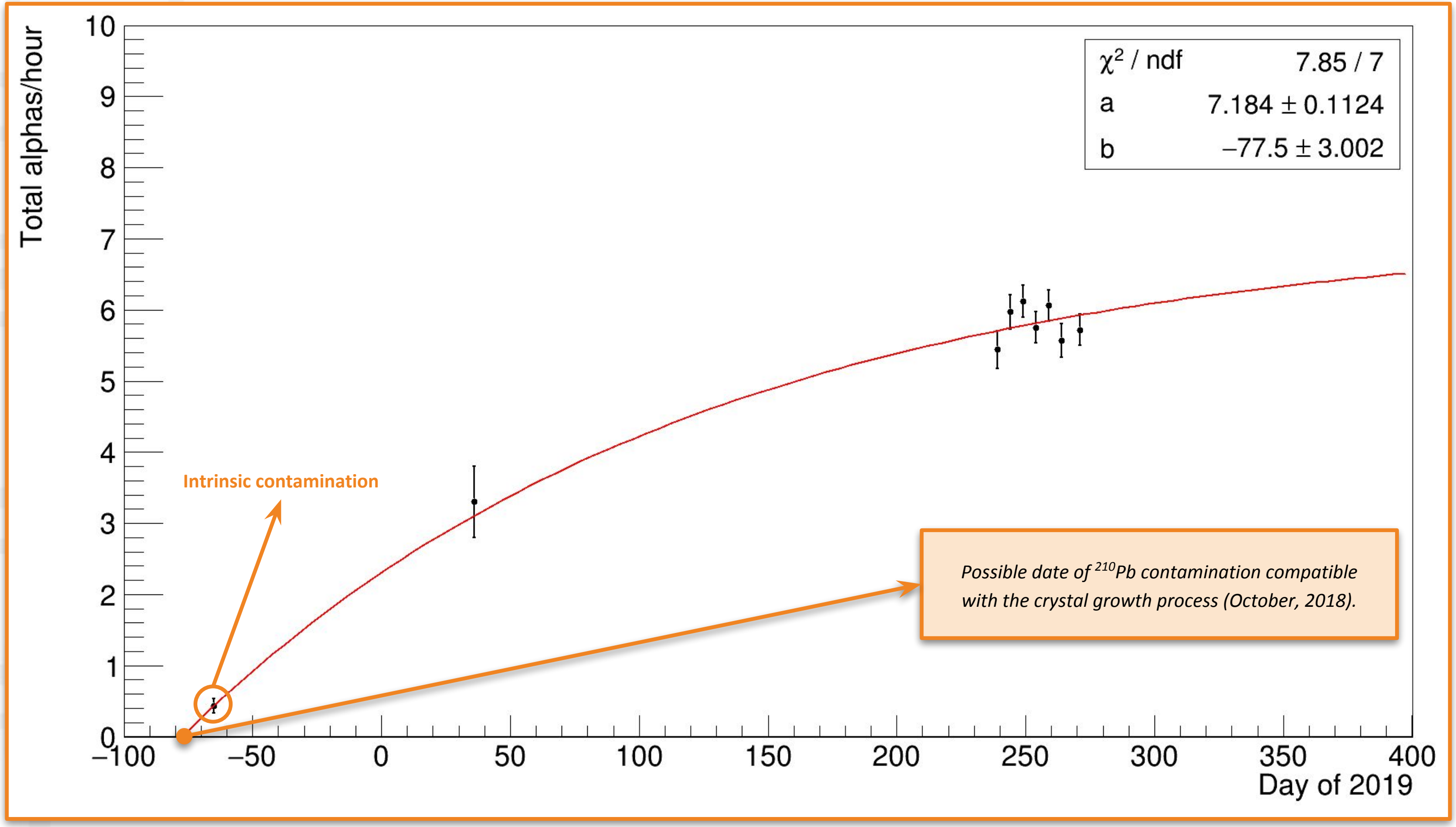
$\varepsilon = \varepsilon_1 \cdot \varepsilon_2 \geq 89\%$

NaI-33: ^{212}Bi-Po time distribution

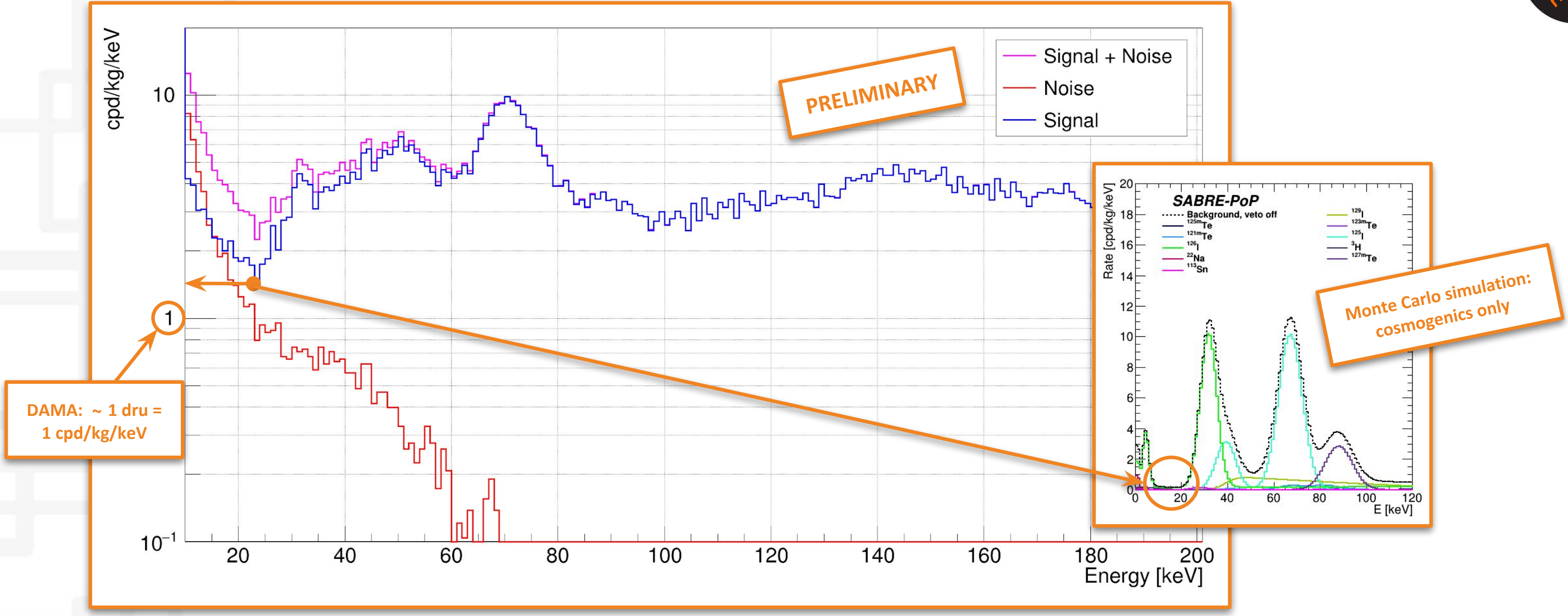


Good agreement with the expected distribution despite of the low statistics.

NaI-33: build-up of ^{210}Po



NaI-33: Low energy spectrum (10-200 keV)



- Looking at a region without cosmogenics (10-25 keV) is possible to extract an upper limit for the background.

Using PMTs noise filter only:
BGK < 1.5 cpd/kg/keV in [10-25] keV.

Conclusions and future perspectives

- All the PoP experimental setup has been cleaned, installed and tested;
- An underground passive shielding has been built for preliminary characterization of SABRE NaI(Tl) crystals;
- NaI-31 and NaI-33 data collected into the passive shielding have been used to debug and improve the SABRE reconstruction software and to develop tools for data analysis;
- First significative results presented at international conferences such as TAUP2019;
- Development of algorithms for noise rejection in progress.

In addition, a research activity for the full-scale experiment is ongoing:

- Test of the new R13444 4” PMTs;
- Definition of the optimal shielding and veto design using new simulations and the SABRE-PoP measurements as reference.

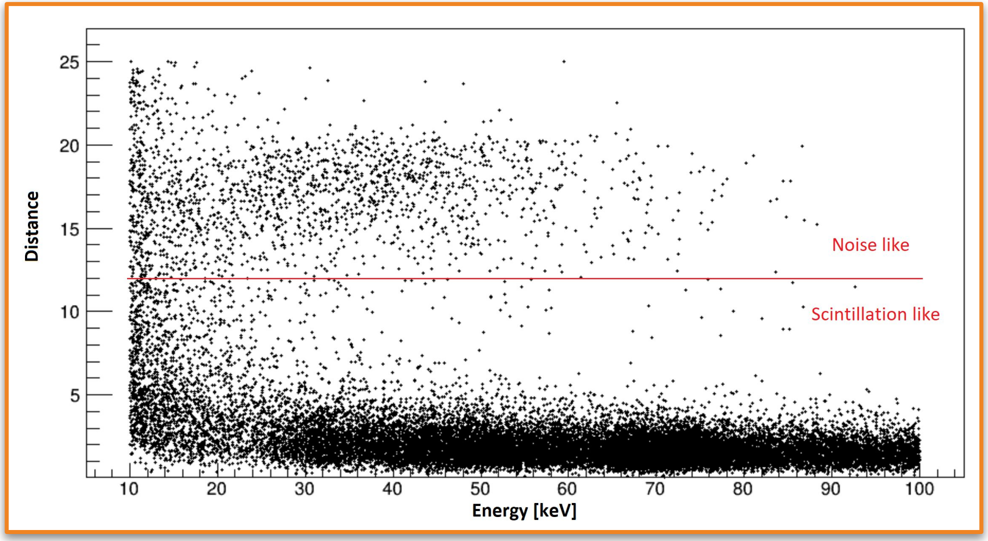
A future perspective of this research project should be a collaboration with the Princeton University dedicated to the development of a facility to grow ultra-pure NaI(Tl) crystals without the industrial partners support.

Backup slides

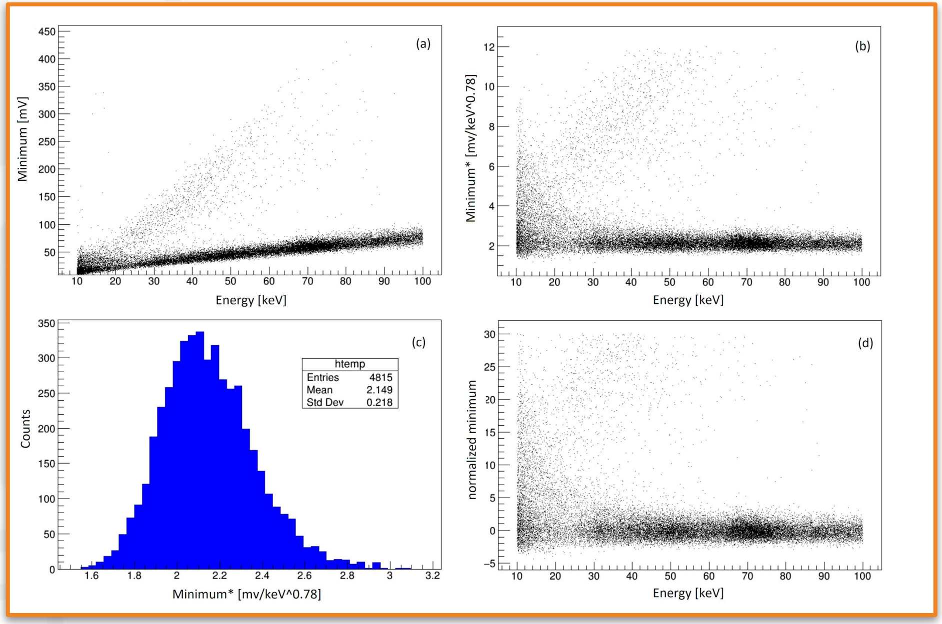
Noise rejection

- **The data selection is based on four parameters:**
  1. Pulse amplitude;
  2. Mean-time;
  3. Ratio of the integrals of the signal's head and tail;
  4. A parameter based on the performance of a compression algorithm on the waveform.
- For each parameter we define a pull with respect to the distribution of its values for "pure" scintillation signals (such as the cosmogenic ^{125}I peak at 70 keV).
- We combine them into a 4-dimensional "distance" from the ideal scintillation pulse.

> ➢ *d ≤ 12: signal;*
> ➢ *d > 12: noise.*



Noise rejection - more in details...



- Each parameter P is divided by a given power *a* of the energy E, such that its mean value for scintillation events becomes independent on the energy: $P^* = P/E^{a}$;
- Events in [65 - 75] keV interval (mainly from ^{125}I) are selected, then mean value and standard deviation are used to define the pull of the parameter:

$$p = (P^* - \overline{P^*}) / \sigma_P.$$

- This leads to a set of parameters p_i whose mean value is expected to be 0 for signal pulses, at every energy.

$$d = \sqrt{\sum_{i=1}^{4} p_i^2}$$

The origin O represents the position of the ideal scintillation pulse and the distance d can be used to select scintillation events.

Signal band - Americium source

- In red a sample of Americium signal events.