The CROSS Experiment:
Rejecting Surface Events with PSD

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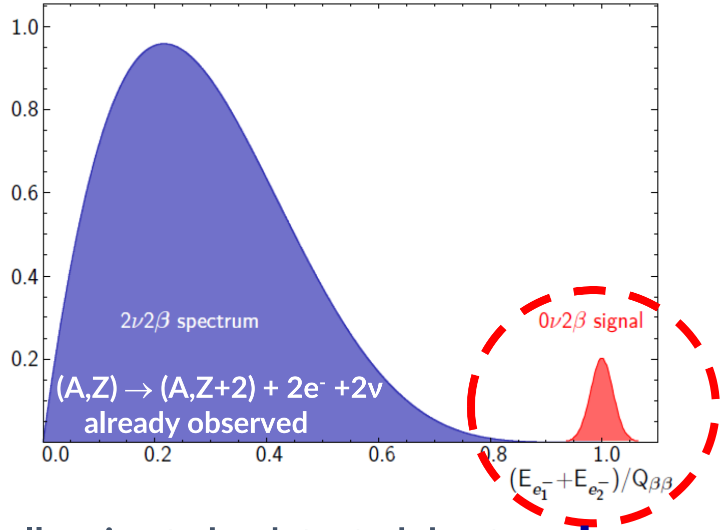
Neutrinoless double beta decay

Double beta decay:

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

- Allowed in the standard model for 35 nuclei (observed for 11 nuclei: ^{76}Ge,^{82}Se,^{100}Mo,^{116}Cd,^{130}Te…)
- Rarest observed nuclear decay: $T_{1/2} \sim 10^{18}$ -10^{24} yr



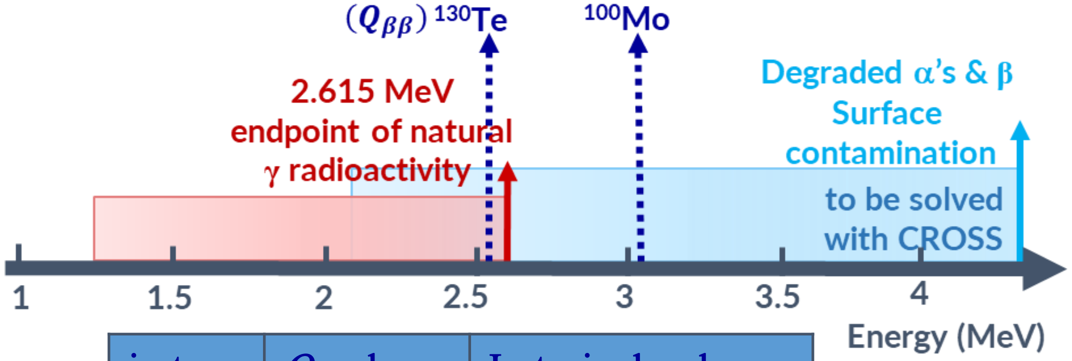
very challenging to be detected due to very low rate of the process

Neutrinoless double beta decay:

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

- Forbidden in the standard model:
  - lepton number violation
- $\nu = \bar{\nu}$ (Majorana particle)
- $T_{1/2} > 10^{26}$ yr

controlling the background is crucial:



isotope	Q-value	Isotopic abundance
^{100}Mo	3034 keV	9.6 %
^{130}Te	2527 keV	34 %

Bolometric technique

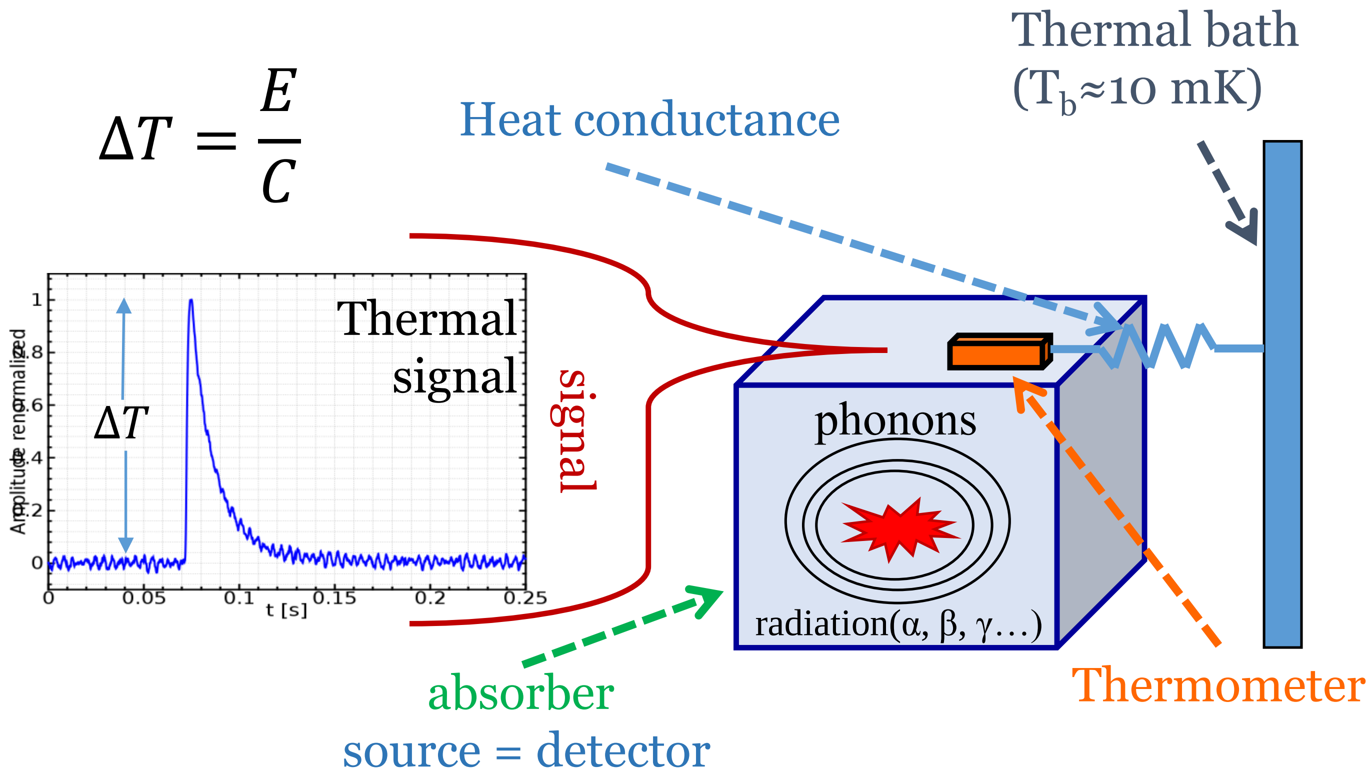
Bolometer

is a low temperature calorimeter which detects particle interaction via a small temperature rise following phonon production in the absorber.

Features

- High energy resolution
- ββ source-embedded detectors
- Full active volume (no dead layer)
- Particle identification capability (hybrid or surface sensitive detectors)
- Flexible material choice (Li_2MoO$_4$, ZnMoO$_4$, CaMoO$_4$, TeO$_2$, …)

$$\Delta T = \frac{E}{C}$$



As in **CUORE**: **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
not a zero background experiment (surface α's & β's)

Check CUORE talk by Giovanni Benato

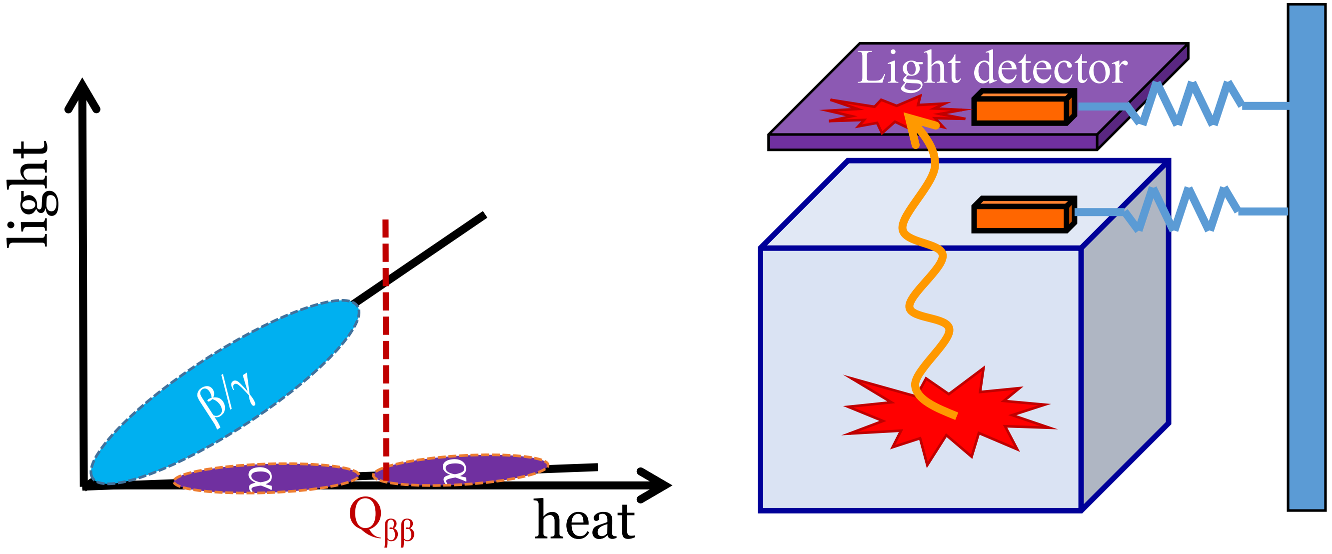
Bolometric detectors

Bolometer
is a low temperature calorimeter which detects particle interaction via a small temperature rise induced by phonons production in the lattice of the absorber

Features

- High energy resolution
- ββ source-embedded detectors
- Full active volume (no dead layer)
- Particle identification capability (hybrid or surface sensitive detectors)
- Flexible material choice (Li_2MoO_4, $ZnMoO_4$, $CaMoO_4$, TeO_2, …)

CUPID (CUORE Upgrade with Particle IDentification) adopts a method to reject surface α events in bolometers exploiting the scintillation (**$Li_2{}^{100}MoO_4$**) or Cherenkov radiation (**$^{130}TeO_2$**) emitted by the absorber, since α & β/γ have different light yield.



CROSS proposes a technique to mitigate surface contamination (α's & β's) via providing bolometers with surface sensitivity

➡ no light detector is needed

Large scale experiments sensitivity

Pure bolometer: CUORE
Background dominated by α's

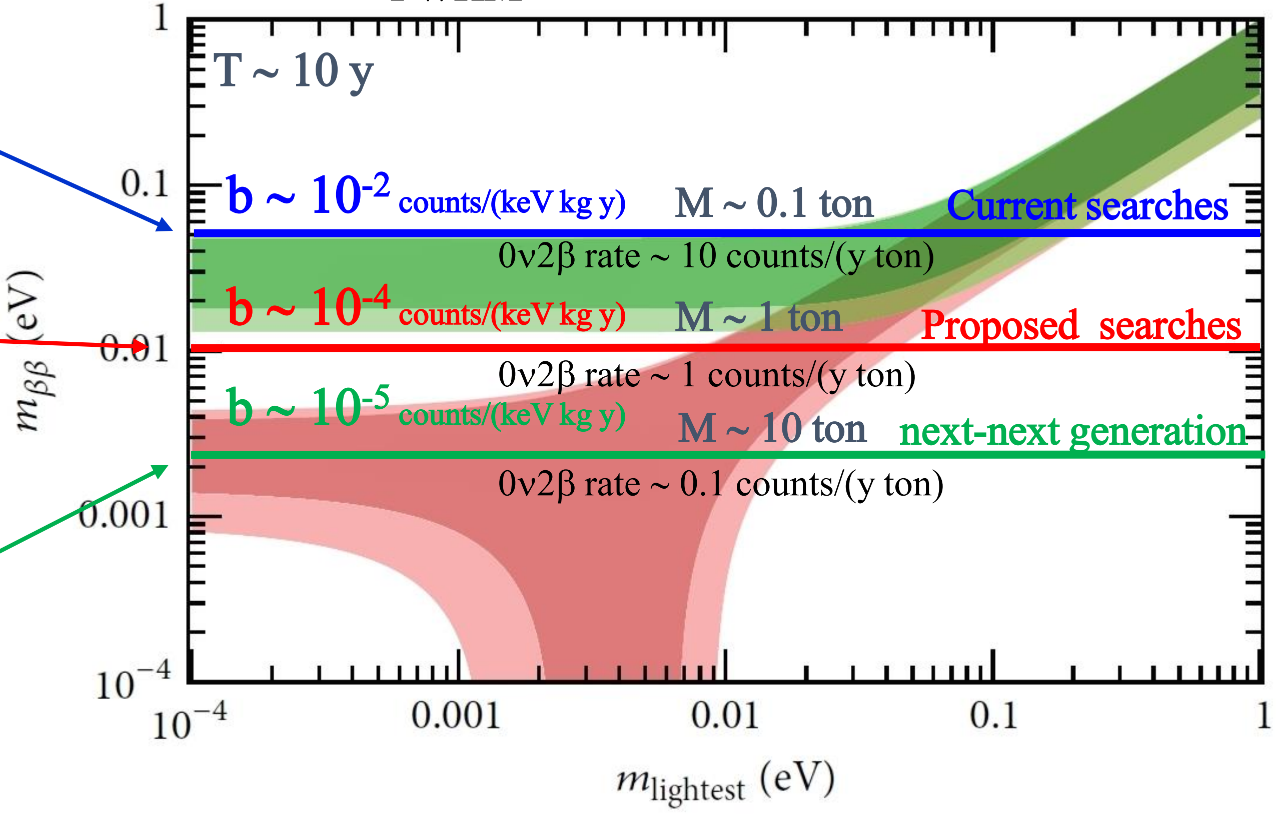
Reject α's

Scintillating bolometer: CUPID
Background dominated by β's

Reject surface α's & β's

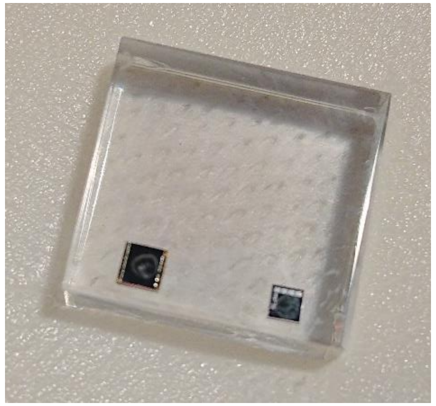
Surface sensitive bolometer: CUPID-like experiment with CROSS technology

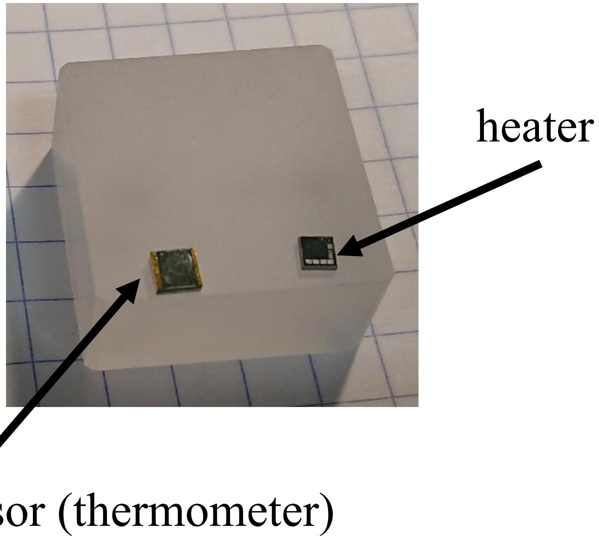
ΔE_{FWHM} ~ 5 keV for bolometers



CROSS Overview

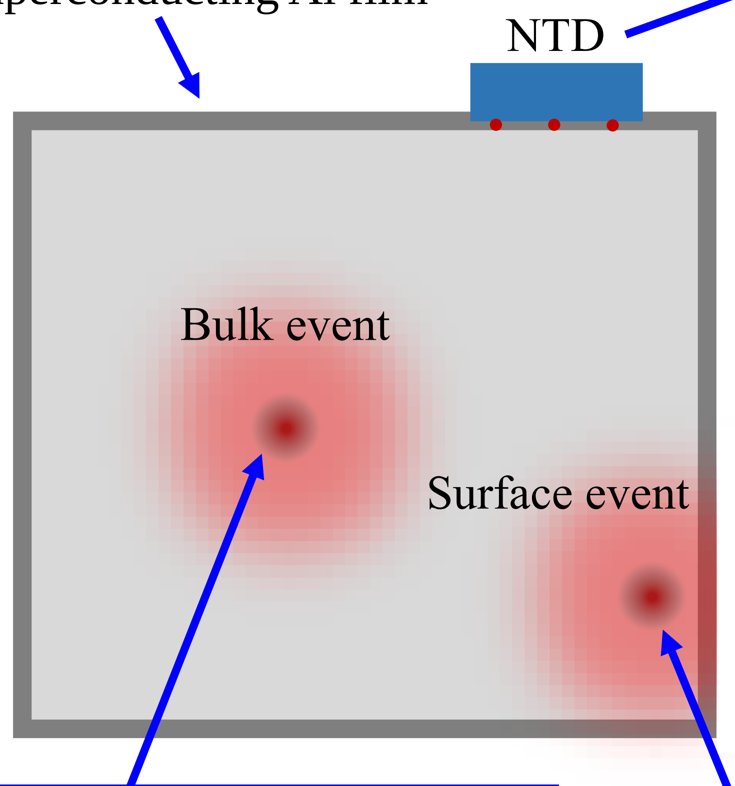
- Main Objective: Rejection of surface events due to surface contamination
  - Effective pulse shape discrimination (PSD) capability
  - The surface sensitivity is achieved by Superconducting Al coating
- Two promising bolometers are used: **$Li_2{}^{100}MoO_4$ and ${}^{130}TeO_2$**





How PSD happens?

Few-µm superconducting Al film



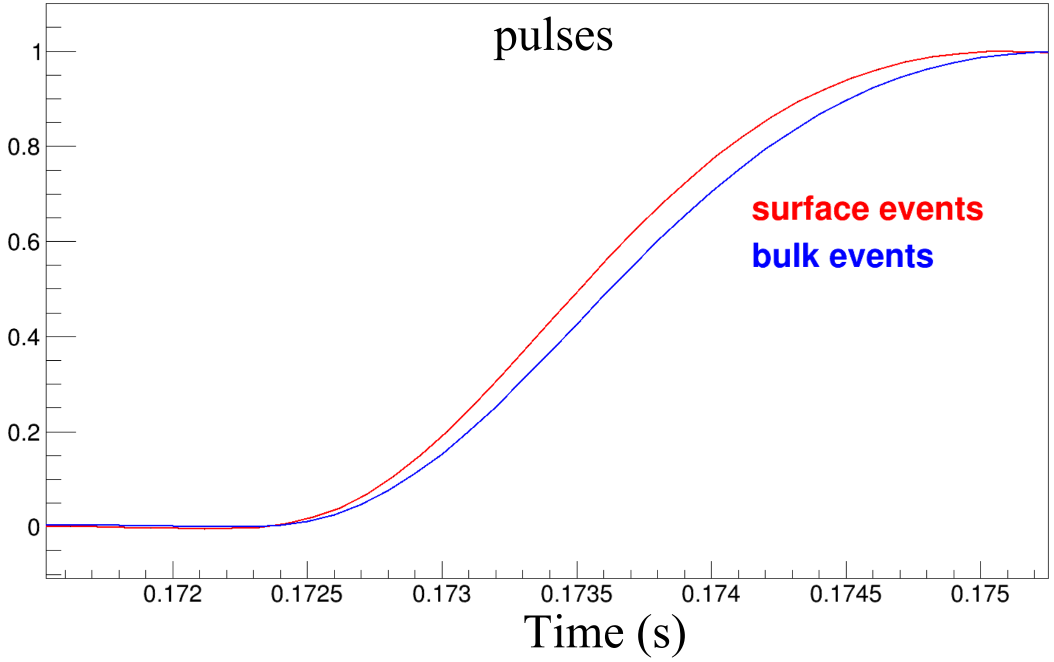
It has an intrinsic slowness in addition to having a glue interface with the surface ➡ sensitive to thermal phonons

Athermal phonons are immediately produced after particle interaction in the crystal.

Athermal phonons will eventually evolve into thermal phonons that are registered in the NTD

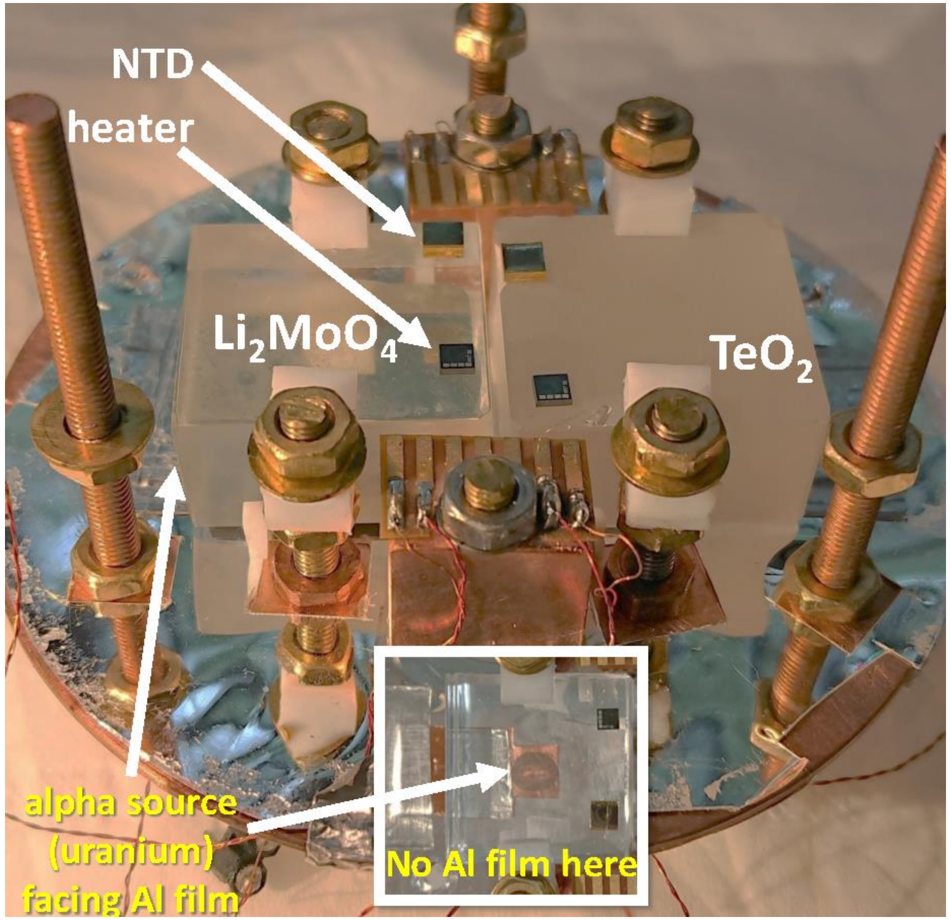
Athermal phonons will break Cooper pairs in superconducting Al-film, and will be trapped for a few ms in the form of quasi-particles that will eventually recombine to give much lower energy phonons.

➡ **Faster thermalization**



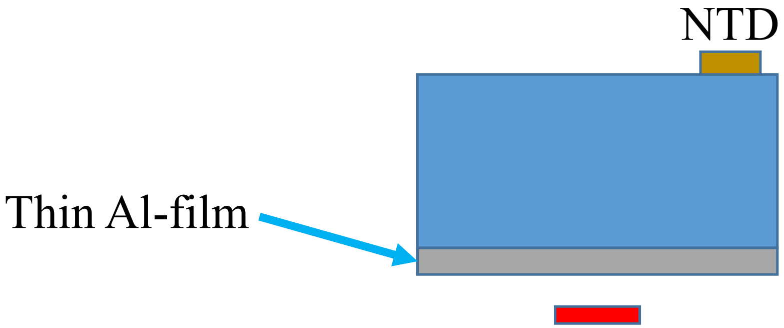
Surface events are faster than bulk events, so it is possible to discriminate pulses by pulse shape comparison (the rise-time for example)

CROSS above-ground prototypes



Heater: injects power periodically to be able to stabilize the bolometric performance offline.

2×2×1 cm³	∅4×2 cm³	2×2×1 cm³
12 g	67 g	25 g
10 μm Al	10 μm Al	1 μm Al
53 nV/keV	37 nV/keV	44 nV/keV

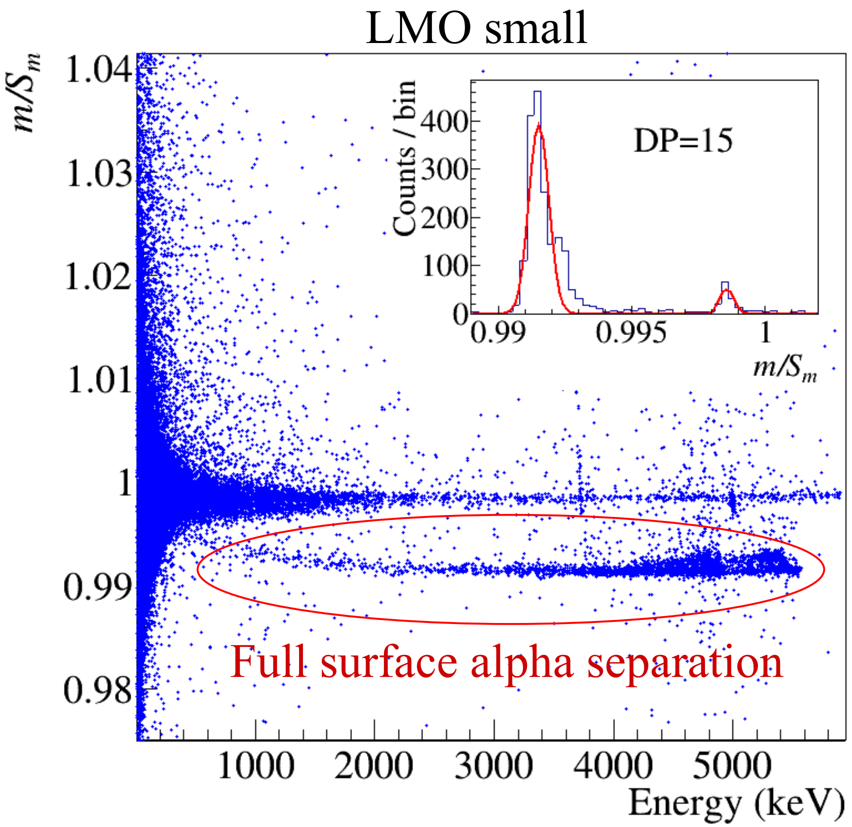


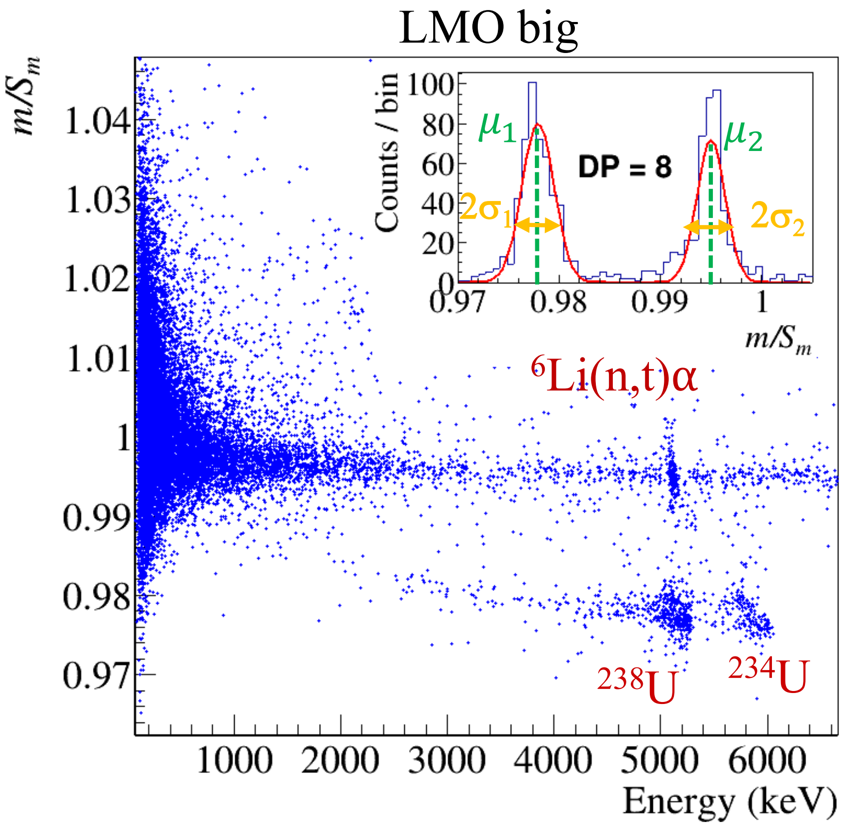
Uranium alpha source
to mimic surface events

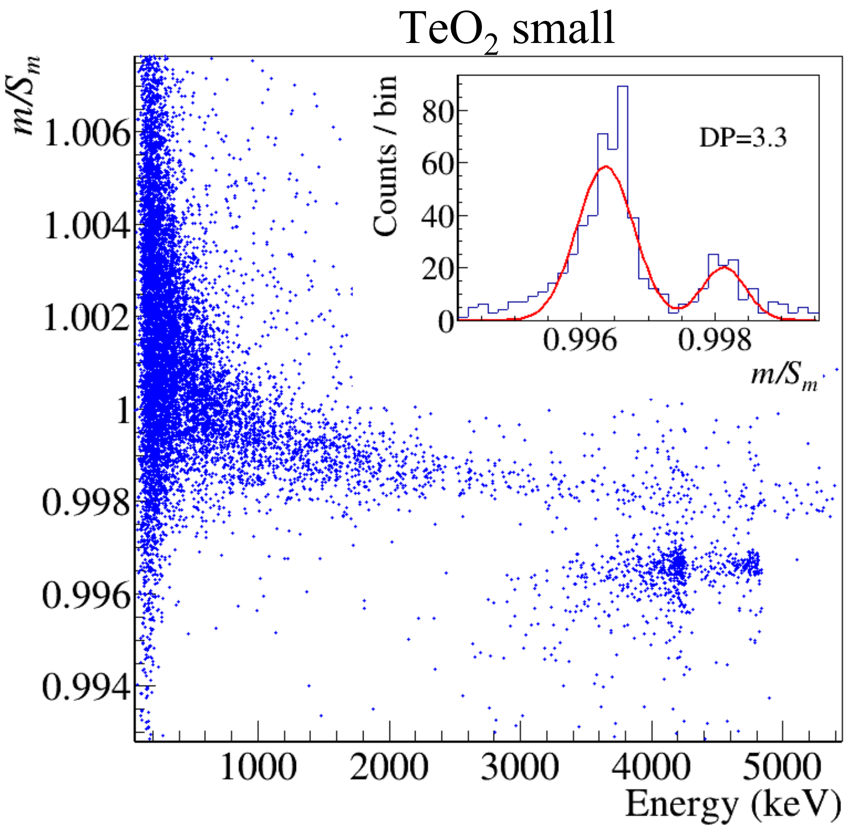
Performing at 22 mK

2 main alpha lines at **4.2 MeV and 4.7 MeV**

Results

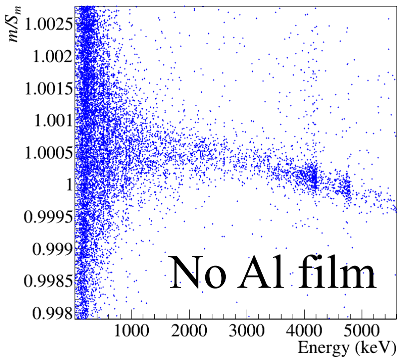






Discrimination power quantifies our ability to separate two populations

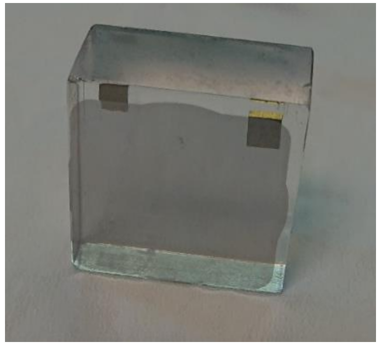
$$DP=\frac{|\mu_2-\mu_1|}{\sqrt{\sigma_2^2+\sigma_1^2}}$$



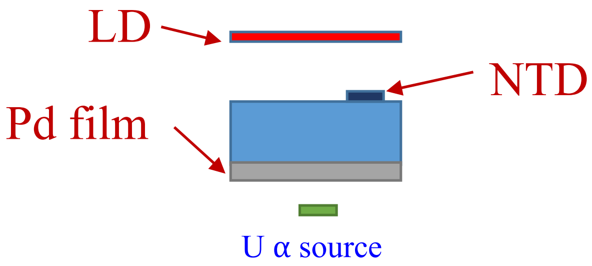
Few-μm-thick aluminum film significantly **improves** the **pulse-shape discrimination** capability for both **bolometers for surface alphas**

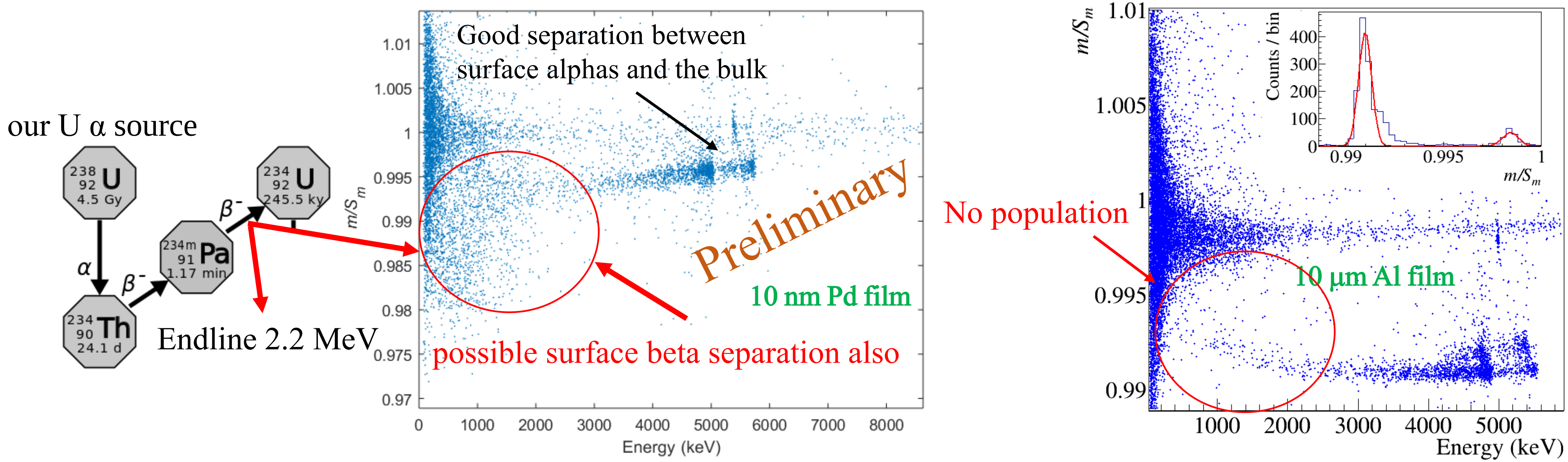
Li_2MoO_4 with Palladium film

In principle, a normal metal should be a better thermalizer for athermal phonons than a superconductor

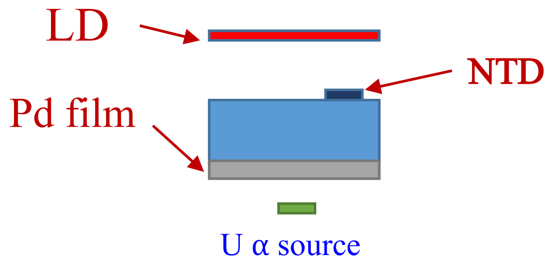


20×20×10 mm^3 Li_2MoO_4 + light detector
10 nm thin Pd film faced by a uranium α source
(nm thickness to reduce specific heat capacity of Pd)

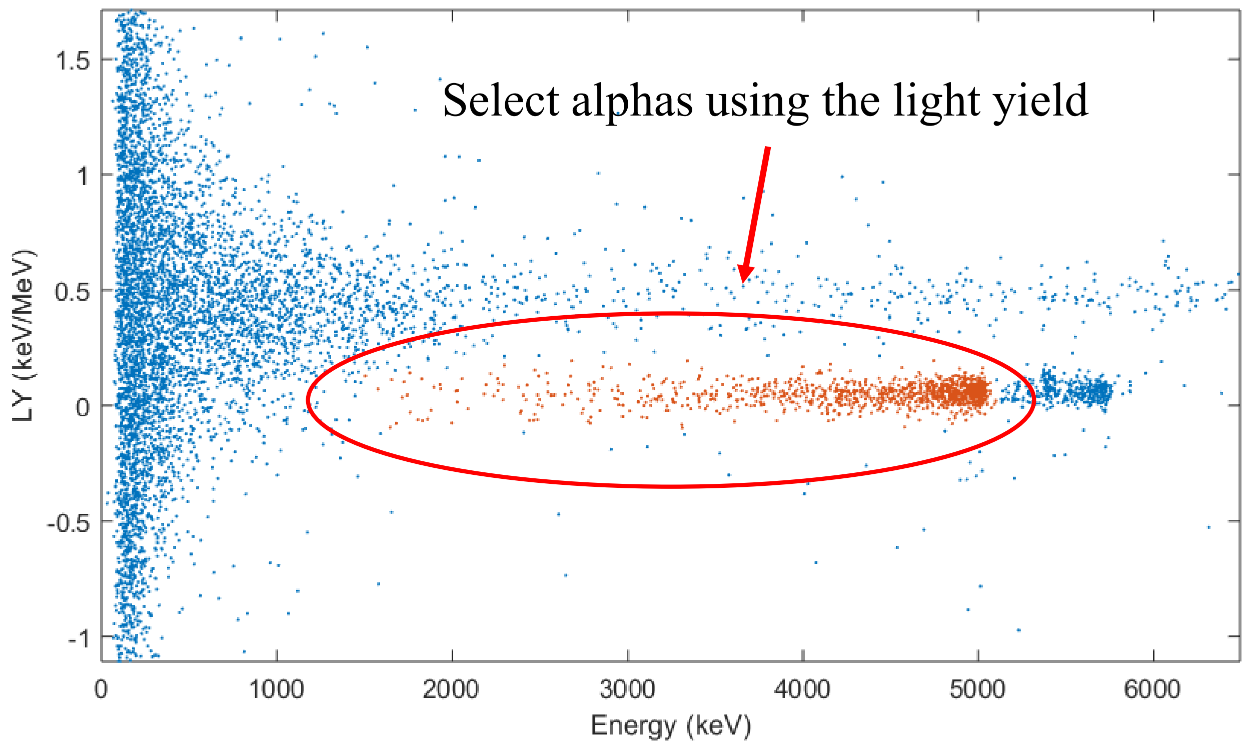




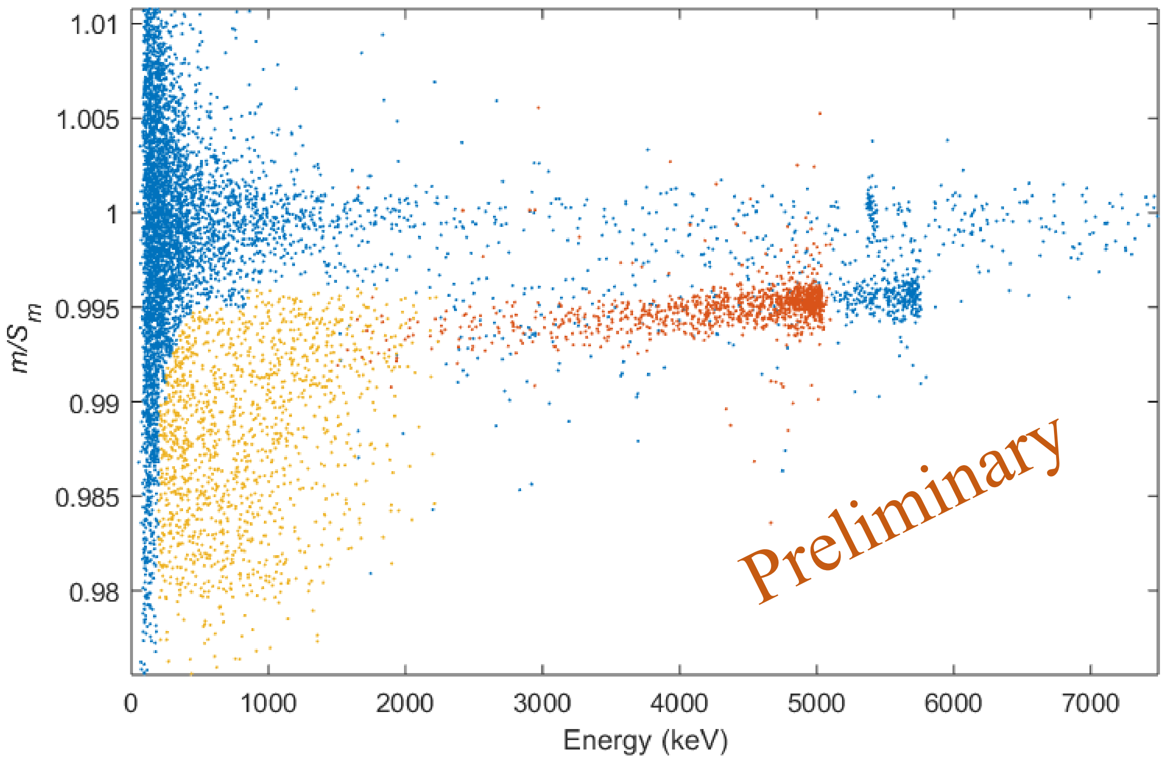
Li_2MoO_4 with Palladium film



Scintillating bolometer (CUPID mode)



Al film bolometer (CROSS mode)



But, a fully Pd-coated crystal showed a big drop in sensitivity which affected PSD due to the high heat capacity

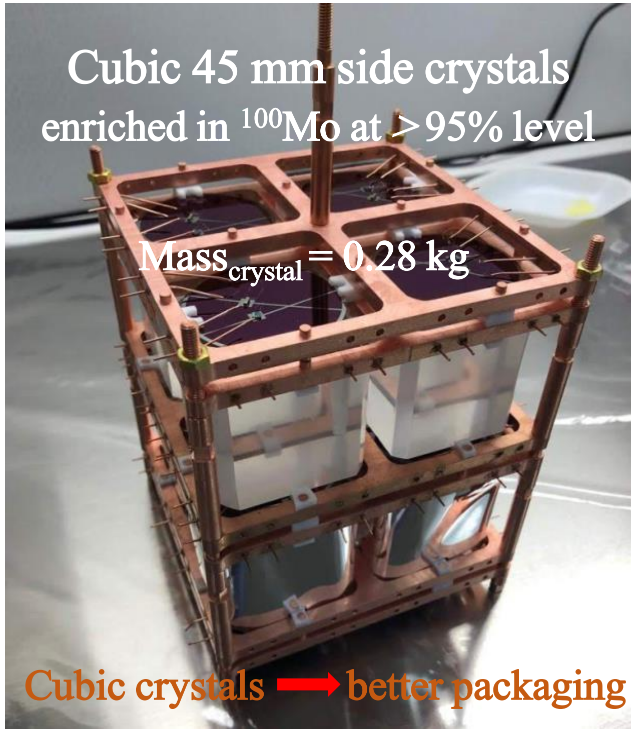
CROSS Demonstrators

First demonstrator: hybrid CUPID-CROSS technology

- 8 $Li_2{}^{100}MoO_4$ crystals: 4 Al-coated crystals coating on four sides
- Coupled to light detectors to test the effect of Al film on the light collection
- First results: April 2020 at CROSS facility at LSC (Canfranc, Spain)

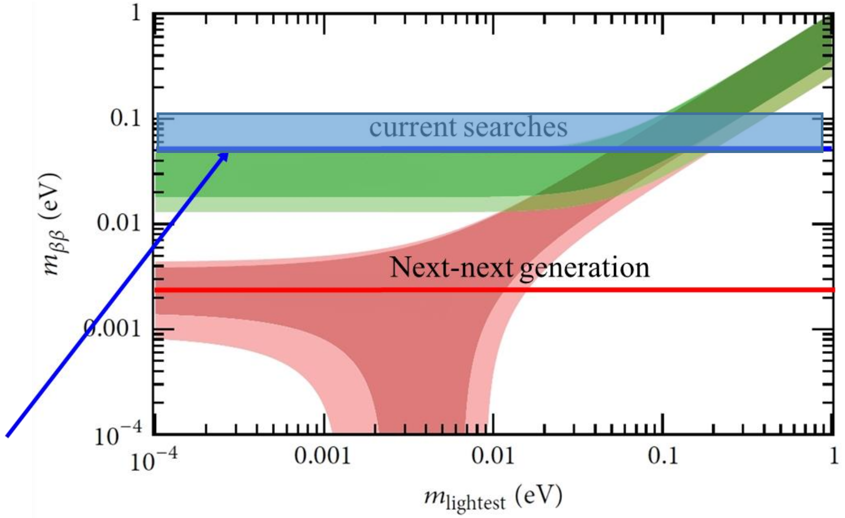
Future demonstrator

- 32 $Li_2{}^{100}MoO_4$ crystals (4.7 kg of enriched ^{100}Mo (>95%) corresponding to $2.9×10^{25}$ ^{100}Mo)
- The planned date of the run: 2021 at CROSS facility at LSC



This will test CROSS technique with high statistics and prove the stability and the reproducibility of the CROSS methods

Background level [counts / (keV kg y)]	Live time [y]	Lim $T_{1/2}$ [y] (90% c.l.)	Lim $m_{\beta\beta}$ [meV] (90% c.l.)
10^{-2}	2	$8.5×10^{24}$	124-222
10^{-3}	2	$1.2×10^{25}$	103-185
10^{-2}	5	$1.7×10^{25}$	88-159
10^{-3}	5	$2.8×10^{25}$	68-122



Conclusions

- Next generation $0\nu2\beta$ searches with cryogenic detectors require an active rejection of surface contamination induced background.
- Most of the present active R&Ds are devoted to the developments of heat-light dual read-out bolometers for $0\nu2\beta$ searches.
- CROSS demonstrated the capability of bolometers to reject near surface interaction exploiting surface coating of superconducting Al or normal metal Pd films.
- Further R&D to reject surface βs. (Pd grid to reduce the heat capacity or another solution?)
- CROSS 32 crystals demonstrator will not only develop a new technique for PSD, but also it will compete with the current experiments.

References:

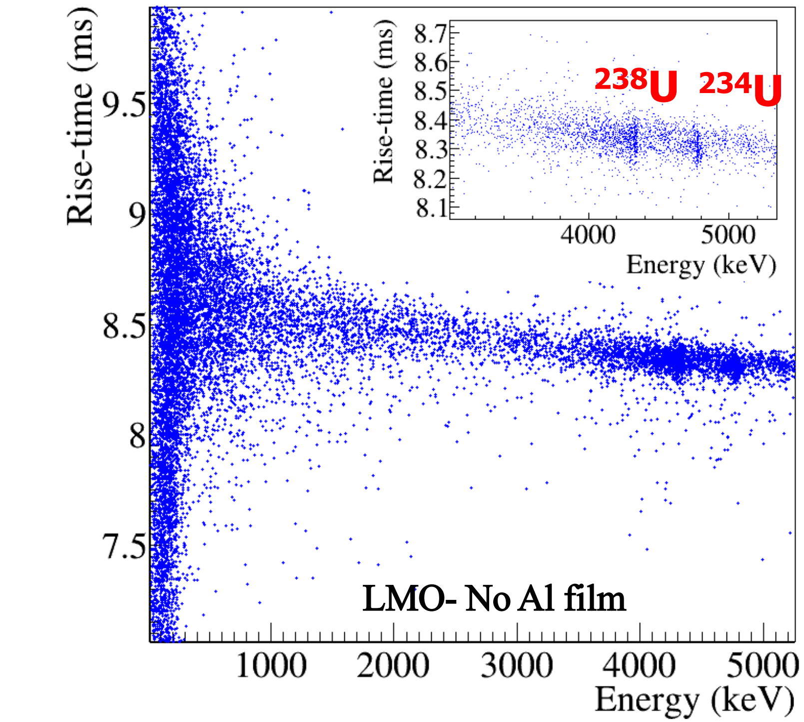
I.C. Bandac et al., *JHEP 01, 018* (2020). https ://doi.org/10.1007/JHEP0 1(2020)018
H. Khalife *et al.*, *J Low Temp Phys* (2020). https://doi.org/10.1007/s10909-020-02369-7

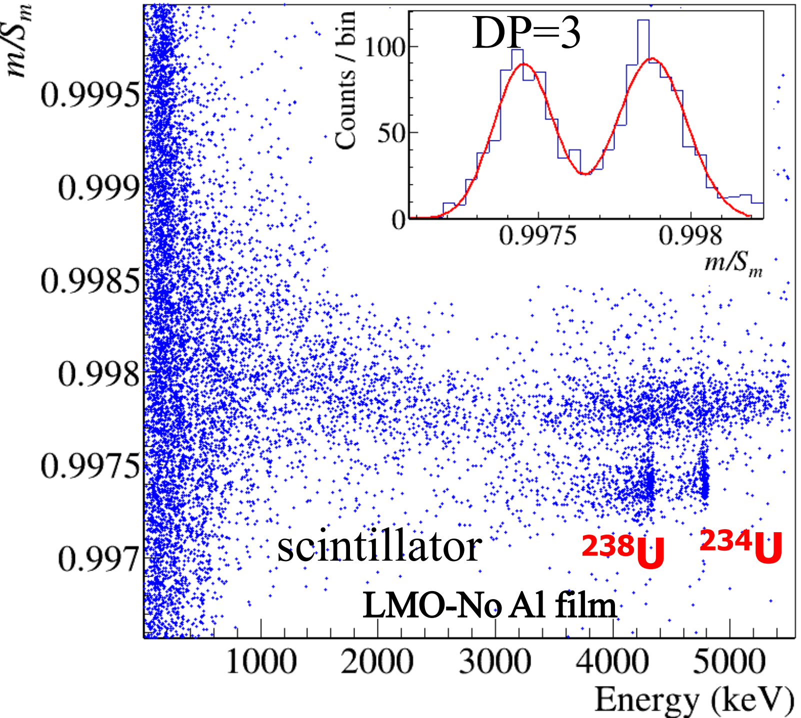
Thank you for your attention

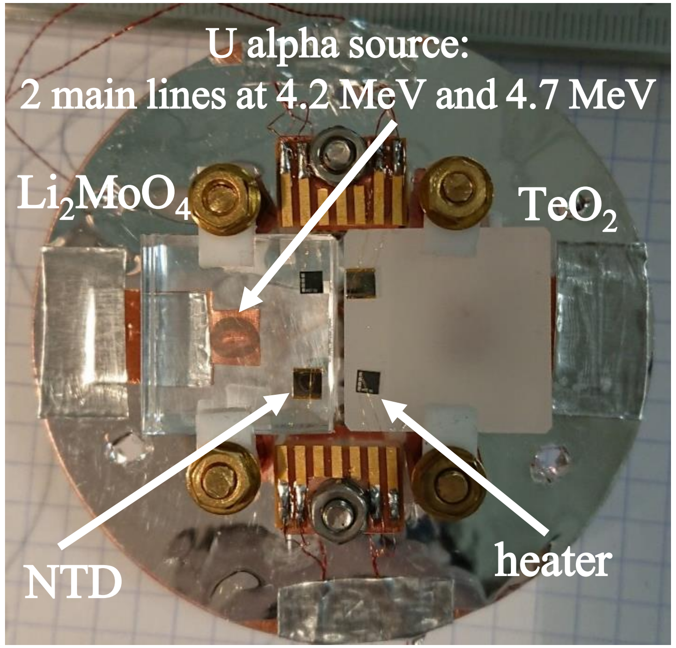
Backups

No Al film

CROSS R&D run	Li_2MoO_4 2×2×1 cm³, 12 g	TeO_2 2×2×1 cm³, 25 g
#1	no Al film	no Al film

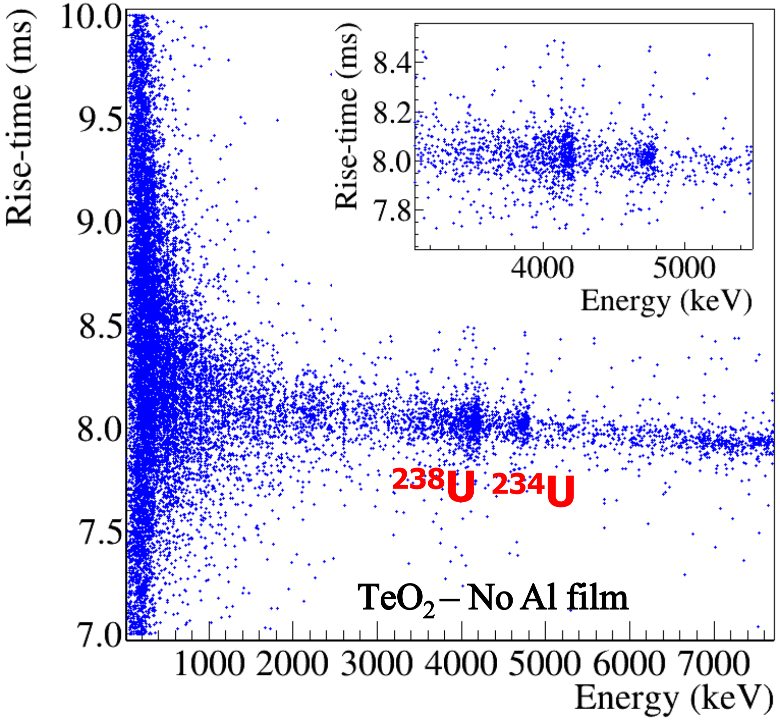


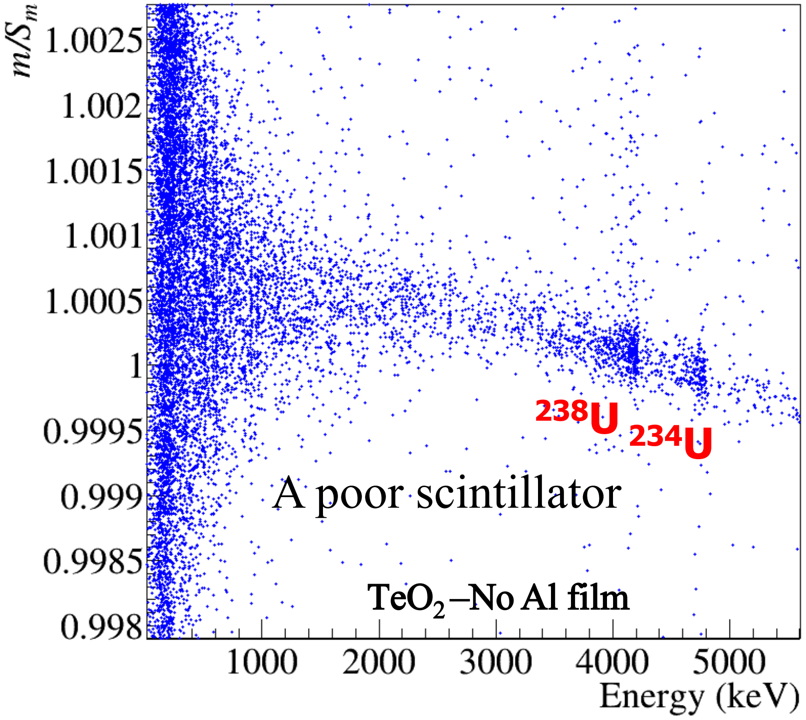




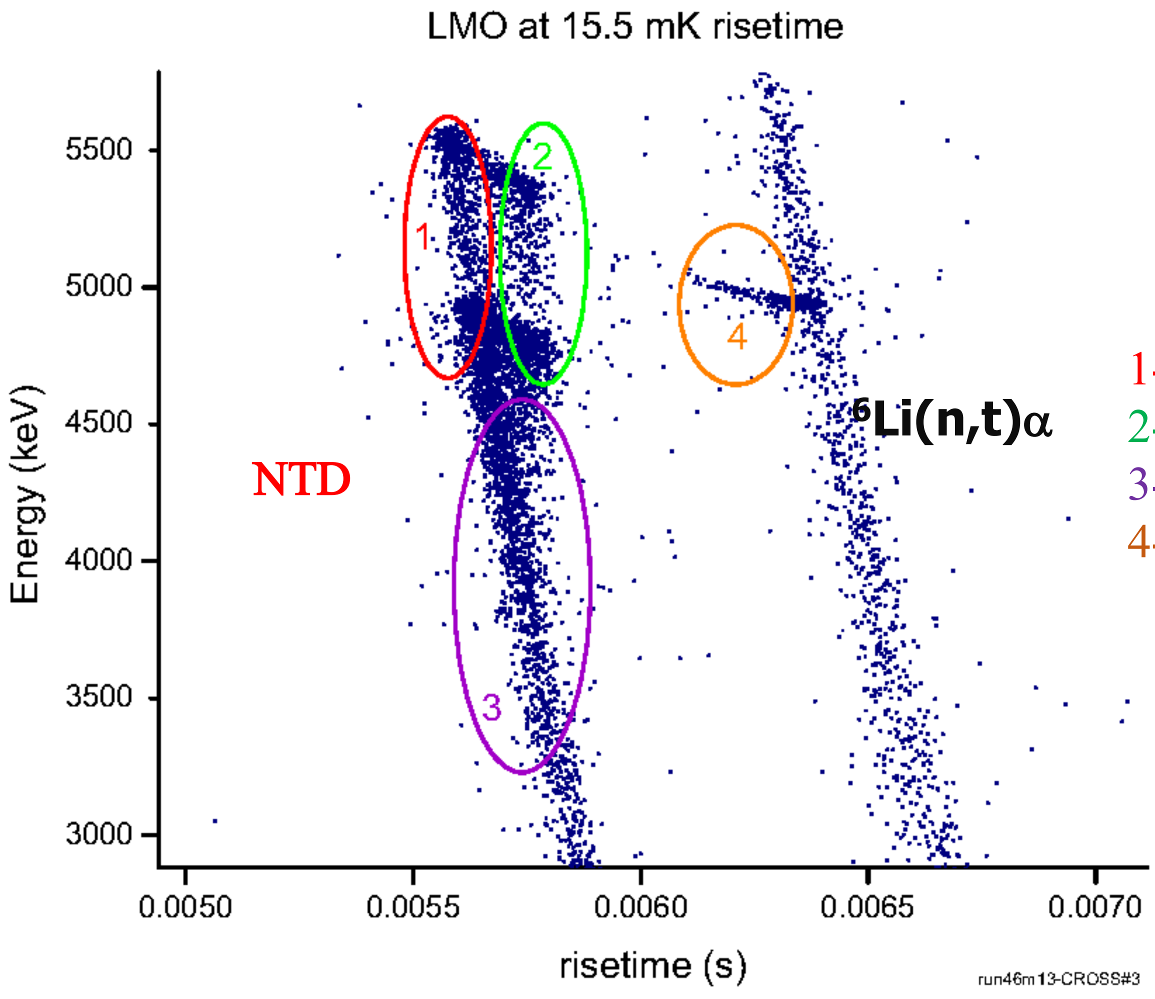
This test was performed to check the intrinsic properties of the crystal:

- Sensitivity
- Energy resolution
- Pulse shape discrimination





Closer view on a pulse-shape difference (Li_2MoO_4)



1- alphas that deposited all of its energy in Al film

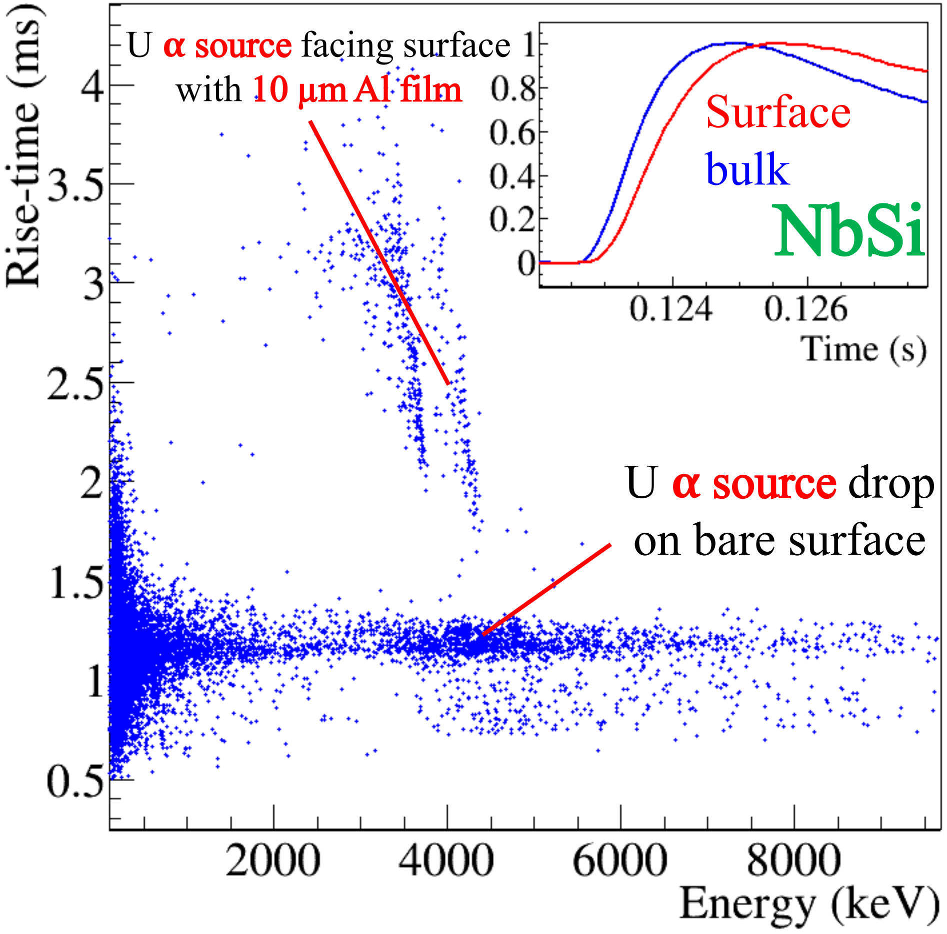
2- alphas that deposited partially its energy in Al

3- degraded alphas that lost some of its energy before reaching Al film

4- neutron capture close to Al film

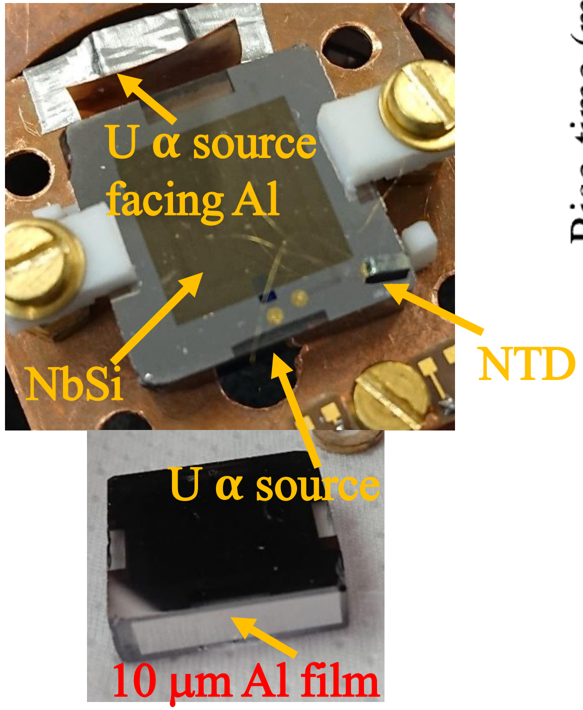
NbSi & NTD on TeO_2

30 mK	Sensitivity (nV/keV)	$FWHM_{baseline}$ (keV)
NTD	70	5.5
NbSi	54	8

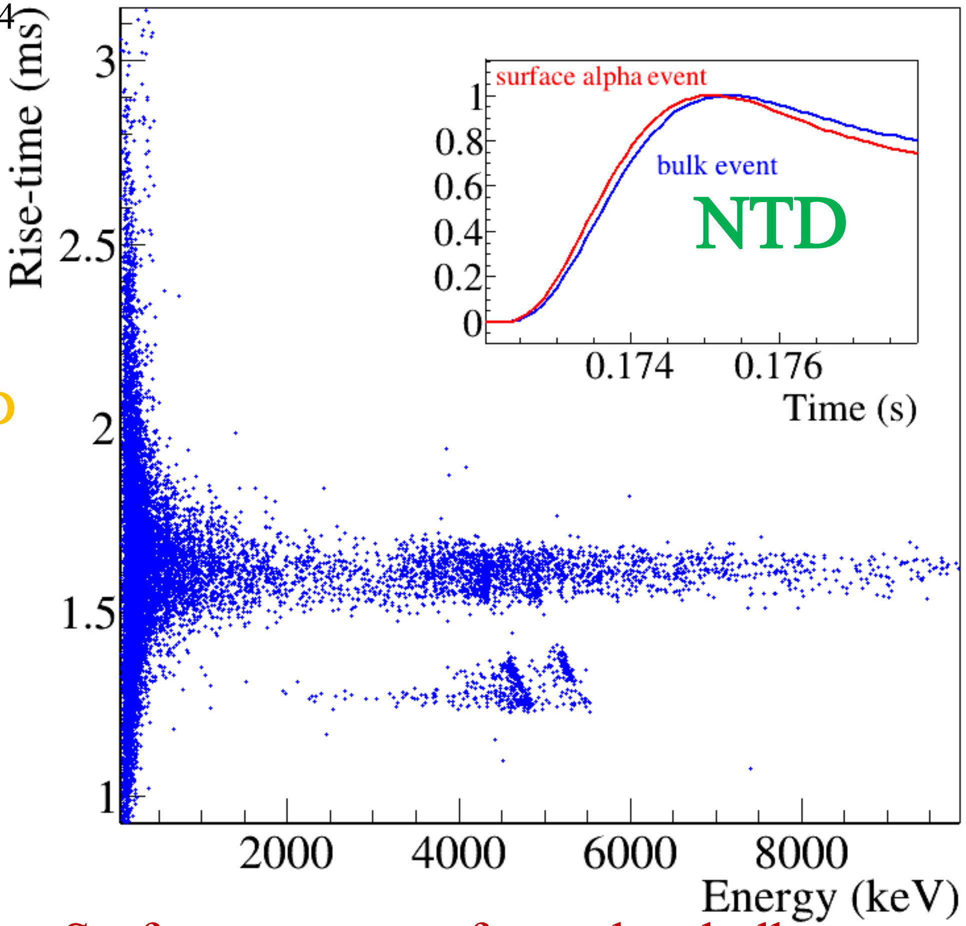


Surface events are slower than bulk events

J Low Temp Phys (2012) 167:1029–1034



U α source
$^{238}U = 4.2$ MeV
$^{234}U = 4.78$ MeV



Surface events are faster than bulk events

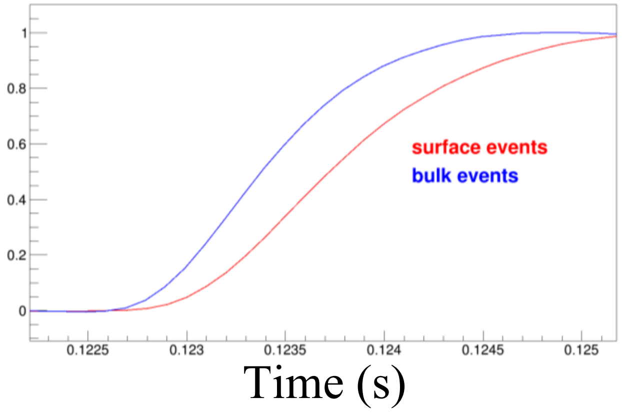
Opposite behavior of NbSi and NTD on the same crystal!

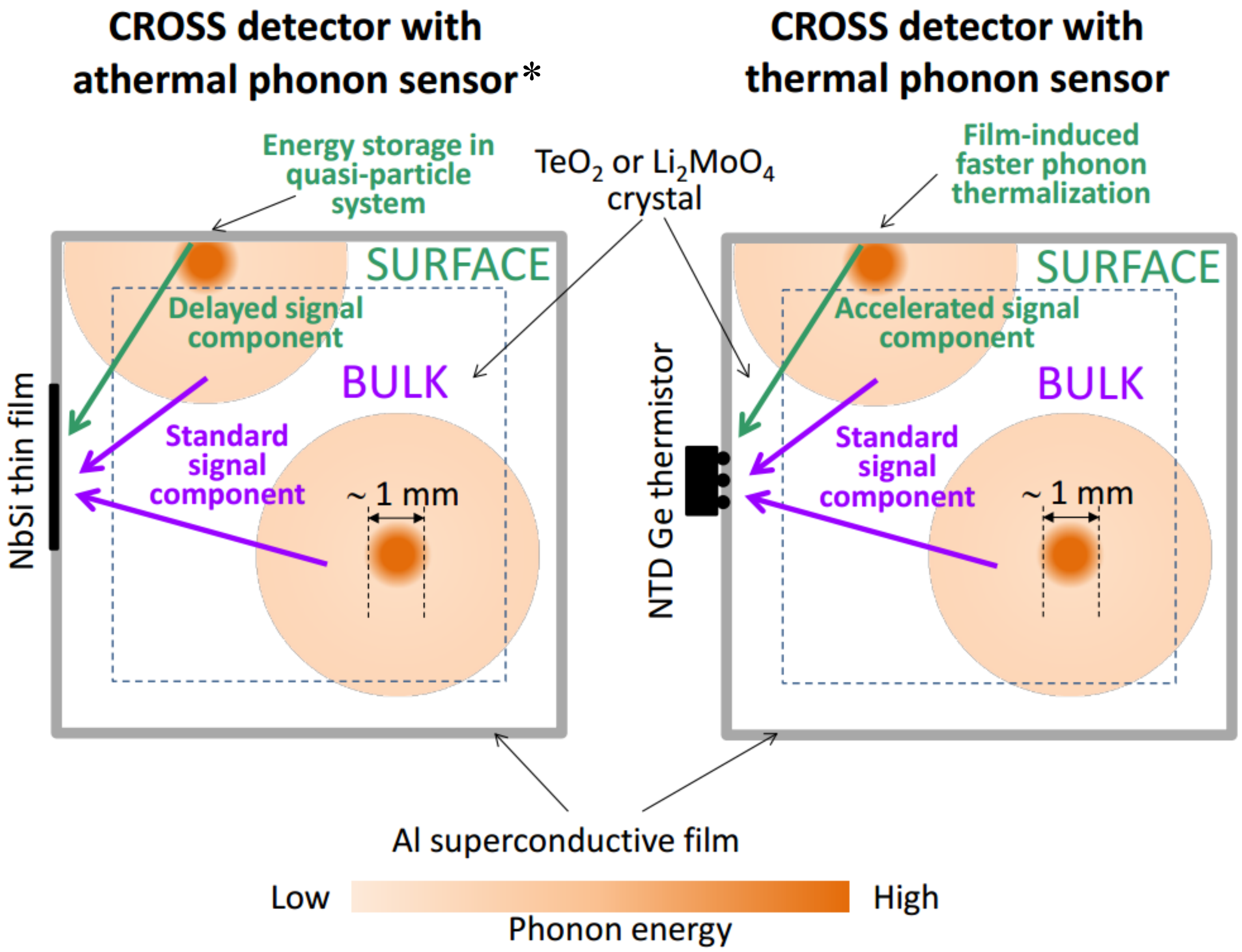
CROSS detector

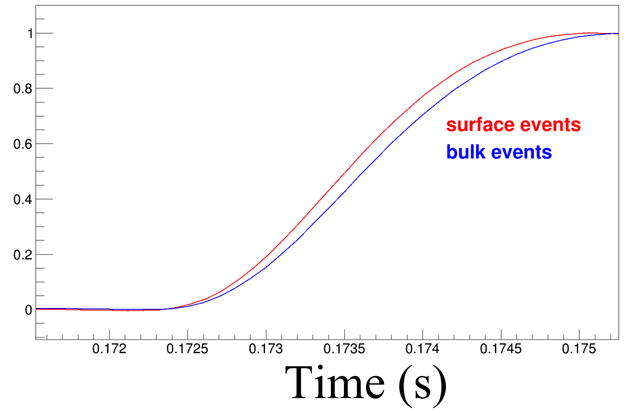
NbSi film (insulator):
Deposited directly on the crystal over a large surface, making them sensitive to the prompt **athermal** component of the phonon population produced by the impinging particle

Athermal phonons are immediately produced after particle interaction in the crystal, and then they evolve toward thermal phonons

NTD (neutron-transmutation-doped):
NTDs are sensitive rather to the **thermal** component due to their intrinsic slowness and the glue interface.





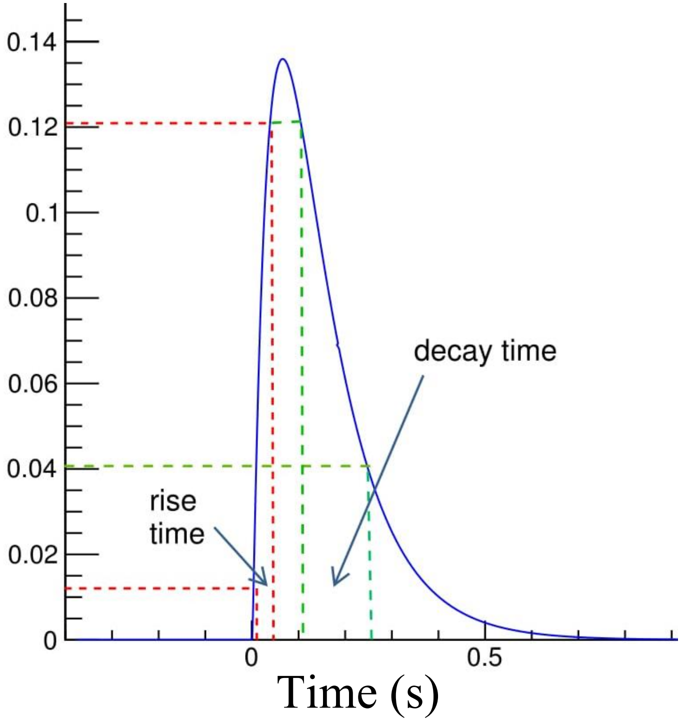


*J Low Temp Phys (2012) 167:1029–1034

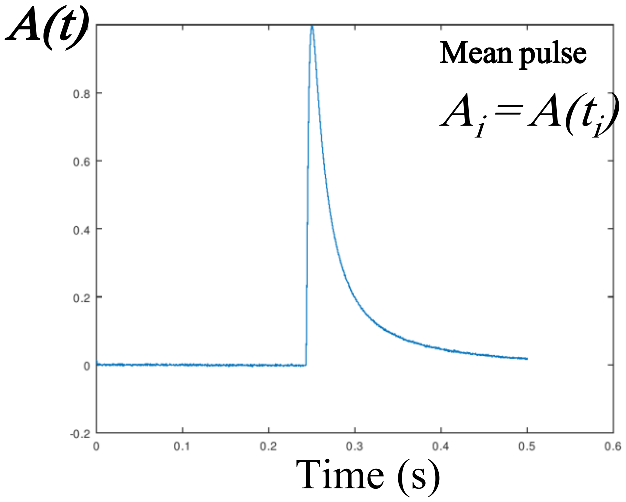
Particle identification parameters

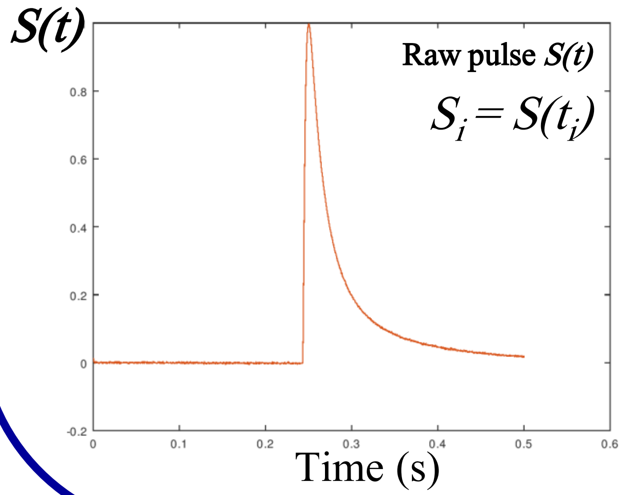
Rise-time

The Rise-time is measured from 10% to 90% of the pulse amplitude

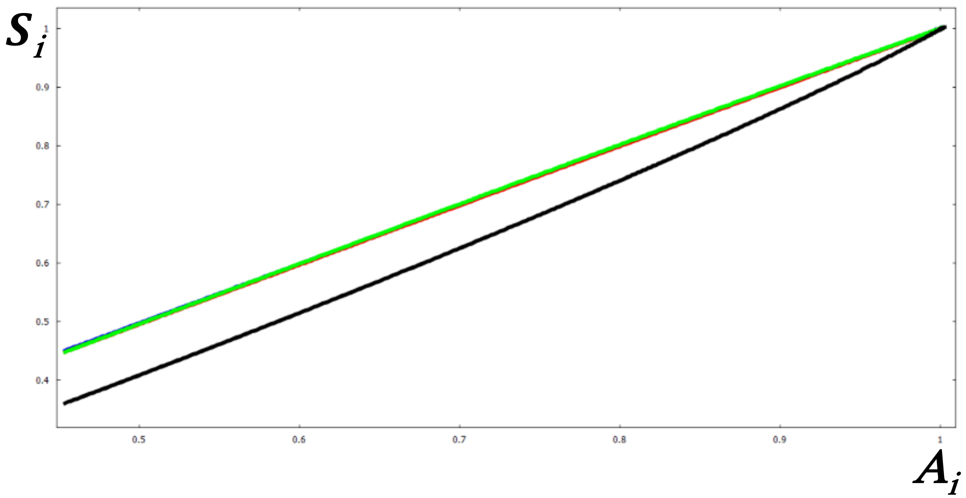


PSD parameter= m/S_m



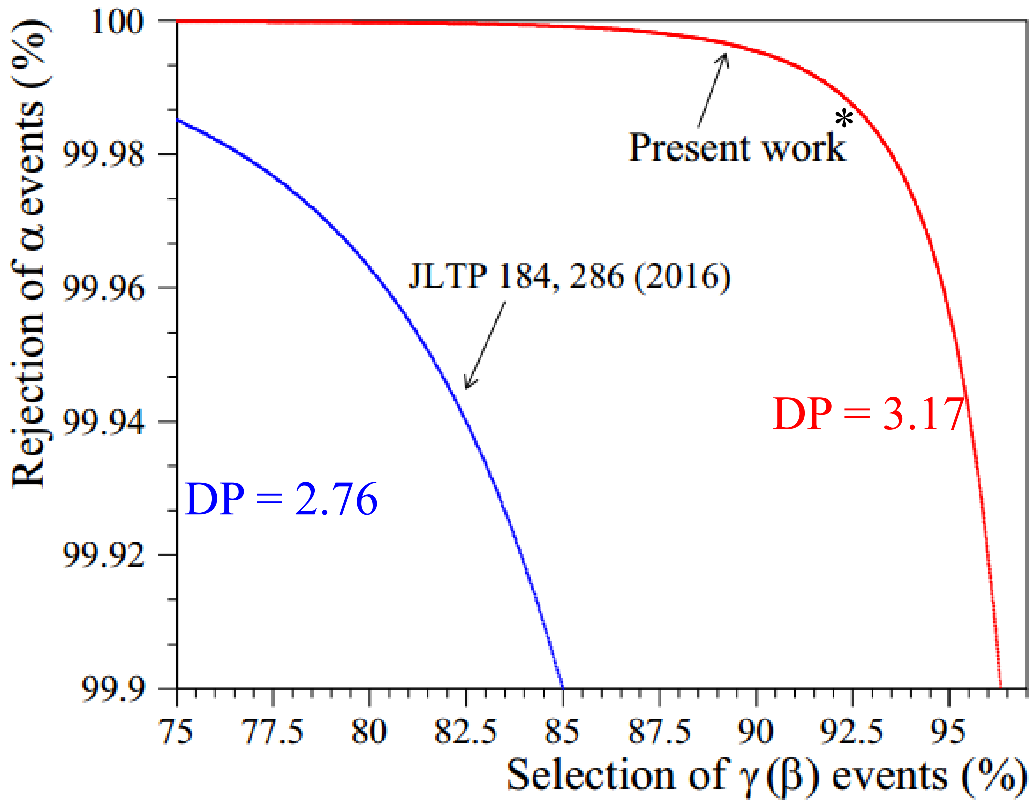


The pulses are synchronized according to their maximum position



Linear fit : $S_i = mA_i + q$

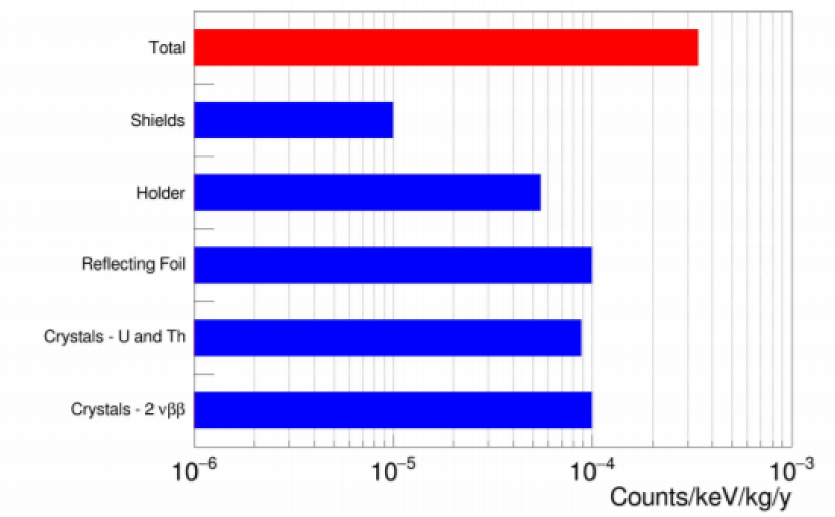
The slope is the PSD parameter



* PHYSICAL REVIEW C **97**, 032501(R) (2018)

CUPID goals and background projection

- Crystals:
  - U/Th bulk → from CUPID-0
  - U/Th surface → from CUORE bkg-model
  - $2\nu\beta\beta$ pile-up ($T_{1/2}^{2\nu} = 7.1\times10^{18}$ yr)
- Crystal holders
  - U/Th surface → CUPID-0 bkg-model
- Cryogenic infrastructure and shielding
  - U/Th bulk → CUORE bkg-model
- Muons → Cut by muon veto



Goals

- ~1500 $Li_2{}^{100}MoO_4$ scintillating crystals (~250 kg of ^{100}Mo)
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via PID
- Goal background: 10^{-4} counts/keV/kg/yr
- Discovery sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr