Unveiling the Mysteries of Neutrinos by Superconductivity Methods

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What's a neutrino?

- **Elementary particle**
- **Three flavors of neutrinos**: electron (ν_e), muon (ν_μ), and tau (ν_τ).

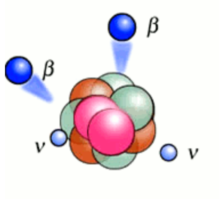
- **Neutral** (zero charge)
- **Tiny but unknown mass**
- **Rarely interact with matter** (flux of solar neutrino 10^{11} neutrino/cm^2/s, a light-year of lead would stop only about half of the neutrinos coming from the Sun).
- **Oscillate** (they change flavor)
- **Unknown neutrino nature:**
    - Dirac (as other fermions): particle $\neq$ anti-particle
    - Majorana: particle = anti-particle
- **Clue for matter-antimatter asymmetry**

  They could be the reason that matter exists in the universe.

Double-decay in a nutshell

Double beta decay

- 2ν2β: (A,Z) → (A,Z+2) + $2e^-$ + $2\bar{\nu}_e$

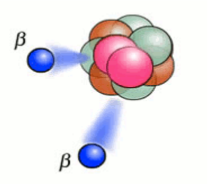


  - Allowed in the standard model for 35 nuclei

    (observed for 11 nuclei: ^{76}Ge,^{82}Se,^{100}Mo,^{116}Cd,^{130}Te…)

  - Rarest observed nuclear decay: $T_{1/2}$ ~ 10^{19} -10^{24} yr

Neutrinoless double beta decay



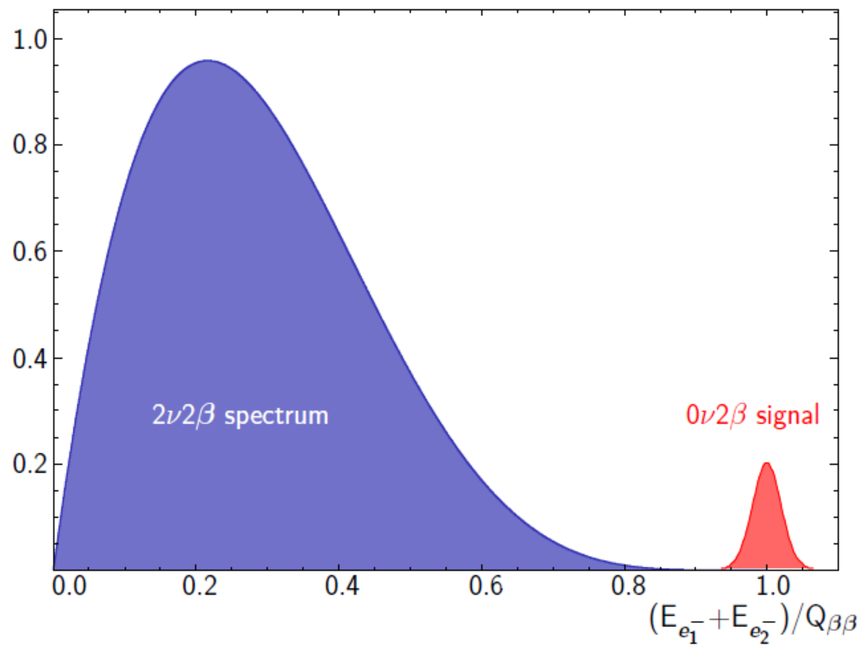
- 0ν2β: (A,Z) → (A,Z+2) + $2e^-$

  - Forbidden in the standard model:

    - lepton number violation

    - $\nu = \bar{\nu}$ (Majorana particle)

  - $T_{1/2} > 10^{26}$ yr (….very long, e.g. ^{238}U $T_{1/2}$~ 10^9 yr)



This makes any experiment aiming at searching for this rare decay very difficult:

An experiment has to be performed with radiopure large-mass detectors and no radioactivity from anything except the nucleus under study

Otherwise

The signal will be hidden in the background…

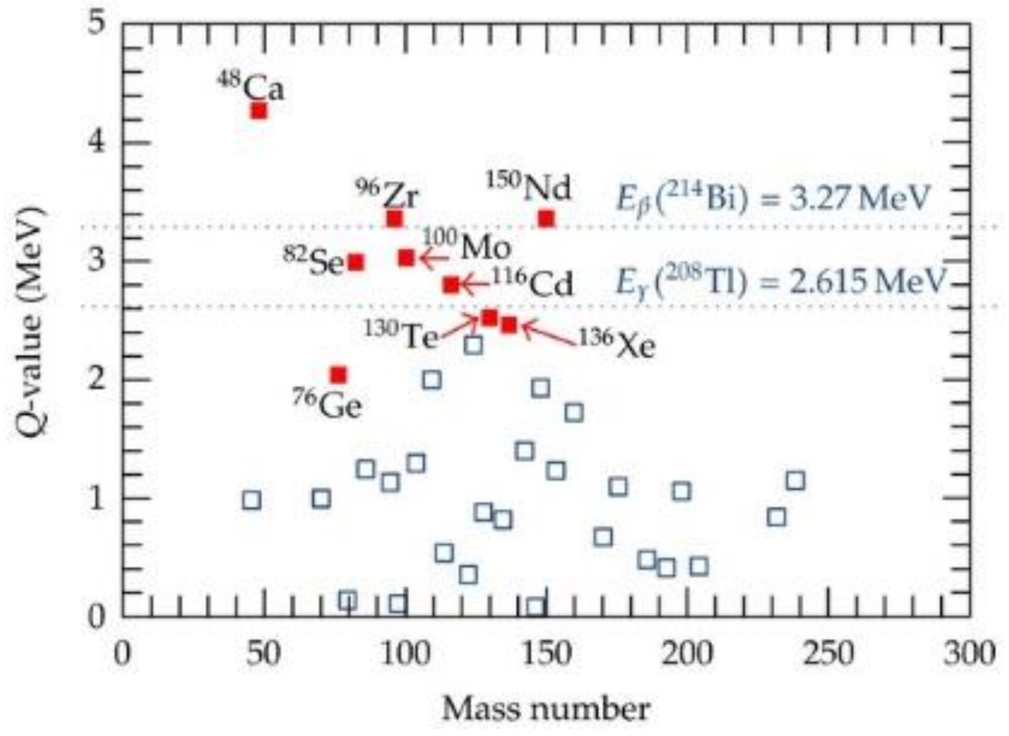
Most promising isotopes for 0ν2β search

The choice is based on:

- **High transition energy $Q_{\beta\beta}$-value** (above endpoint of natural γ radioactivity => lower background)
- **Favorable theoretical predictions**
- **High isotopic abundance + the possibility of enrichment**
- **Existing detector technology**

The candidates chosen:

- ^{100}Mo: $Q_{\beta\beta} = 3034$ keV, 10% isotopic abundance embedded in **Li_2MoO_4** crystal
- ^{130}Te : $Q_{\beta\beta} = 2527$ keV, 34% isotopic abundance embedded in **TeO_2** crystal



Viable detection technique

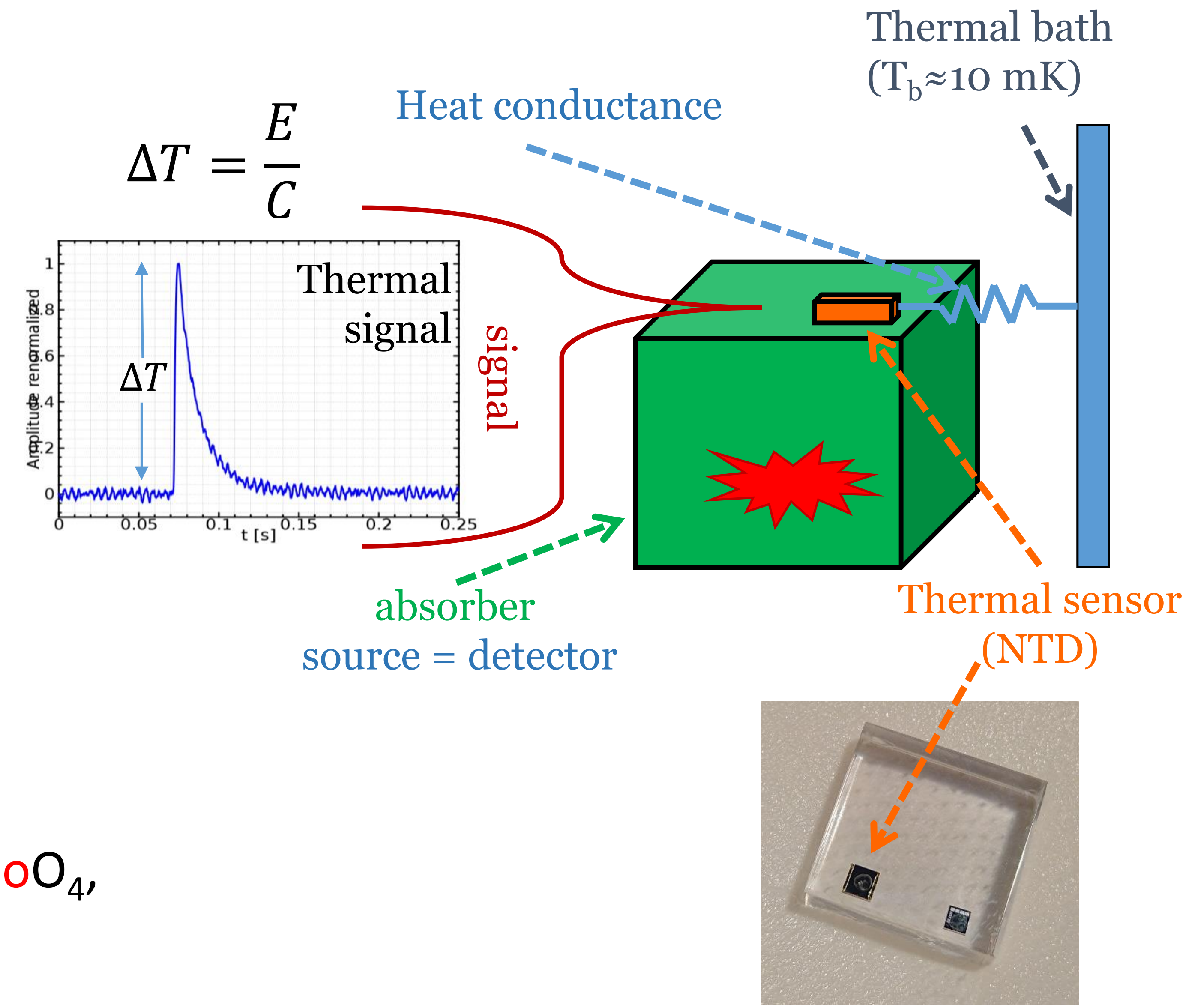
Bolometer

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
- Detector = source
- Full active volume (no dead layer)
- Flexible material choice (Li_2MoO_4, $ZnMoO_4$, $CaMoO_4$, ZnSe, TeO_2 …)

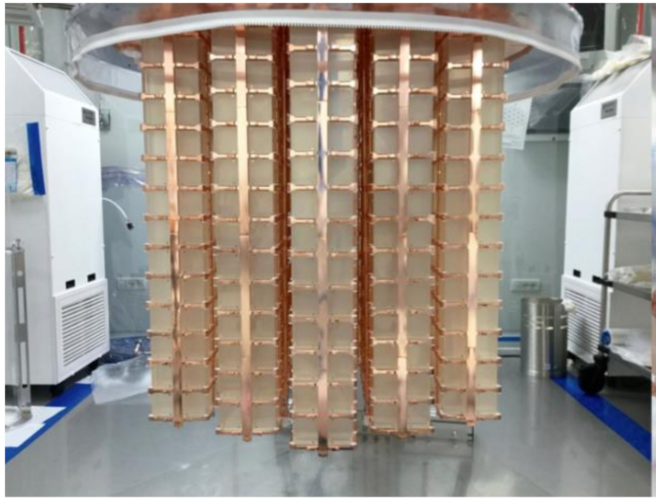
$$\Delta T = \frac{E}{C}$$

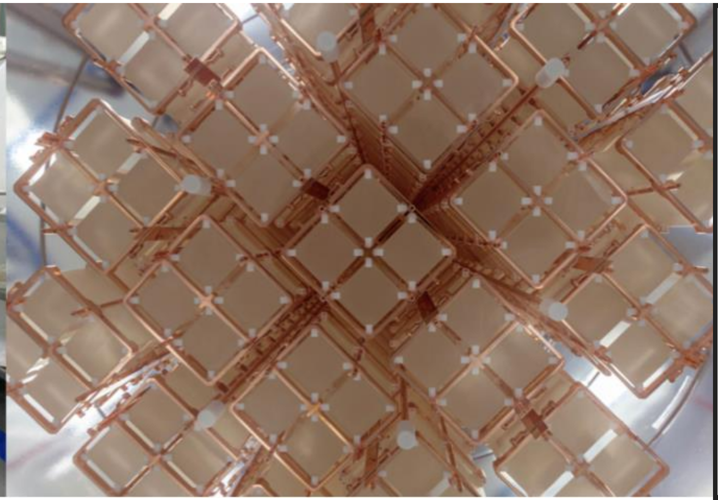


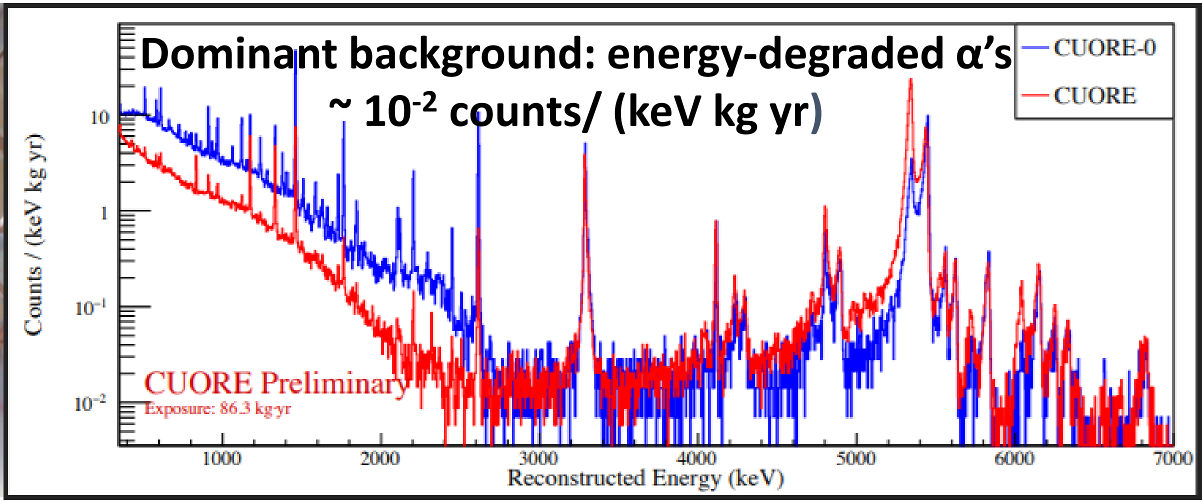
CUORE: 1st ton-scale cryogenic $0\nu2\beta$ experiment

(Cryogenic Underground Observatory for Rare Events)

- Gran Sasso underground laboratory (LNGS), Italy
- Candidate isotope: **^{130}Te** (high natural abundance 34.2%)
- **988 TeO_2** bolometers ($5\times5\times5$ cm^3), **742 kg** (206 kg ^{130}Te)
- High energy resolution at $Q_{\beta\beta}$ = 7.7 keV FWHM







CUORE is not a zero background experiment.
The dominant background in the region of interest is caused by the degraded in energy α's from the residual contamination of the detector surface.

CUPID: Beyond CUORE

(CUORE Upgrade with Particle IDentification)

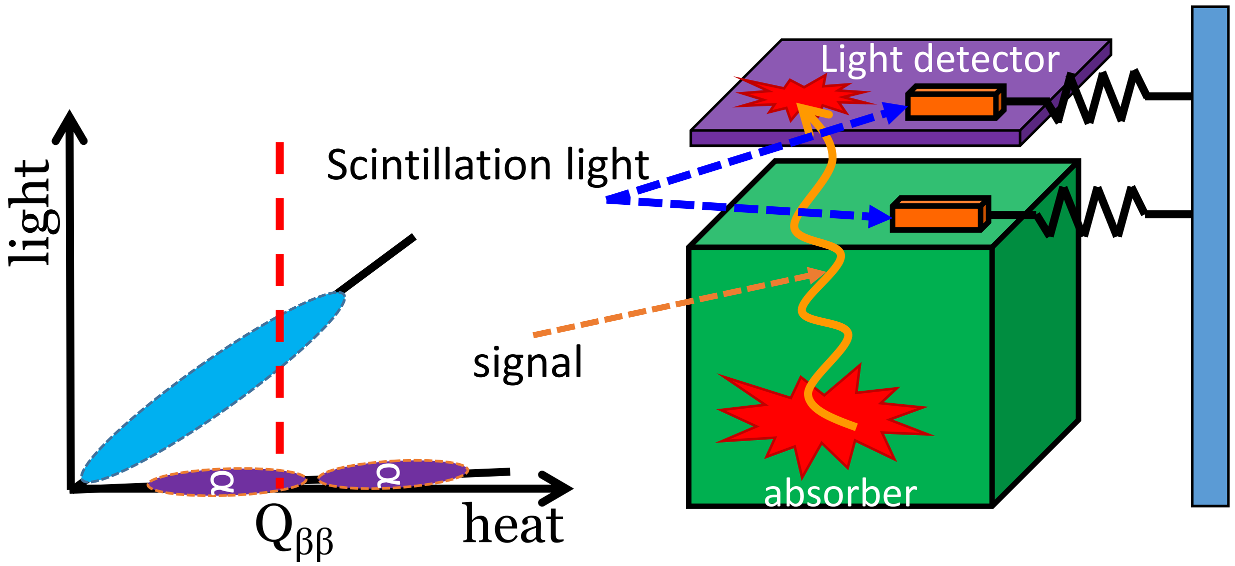
Goals:

- Increase the source mass (via enrichment).
- Reduce background in ROI (close to zero ton×yr exposure scale)

For a common scintillator alpha light yield is ~15-20% of beta light yield at the same energy.

It requires upgrading the detector technology:

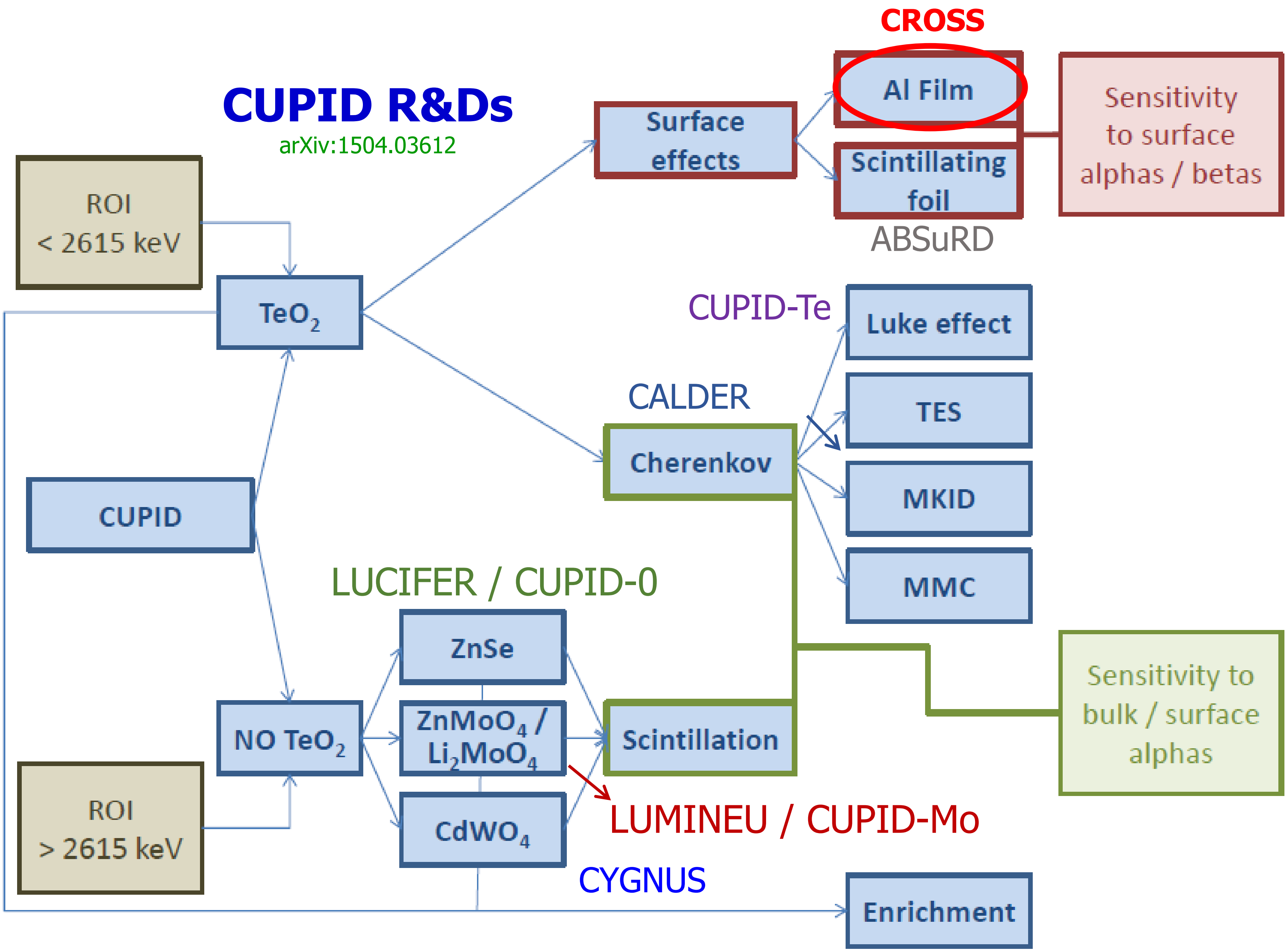
Alphas and betas have different light yield. This feature can be exploited to reject alpha background by reading simultaneously the heat and the light signal.



Getting rid of alpha surface contamination is not enough to have background < 10^{-4} counts / (keV kg yr). It is mandatory to reject beta surface contamination too.

CUPID R&Ds

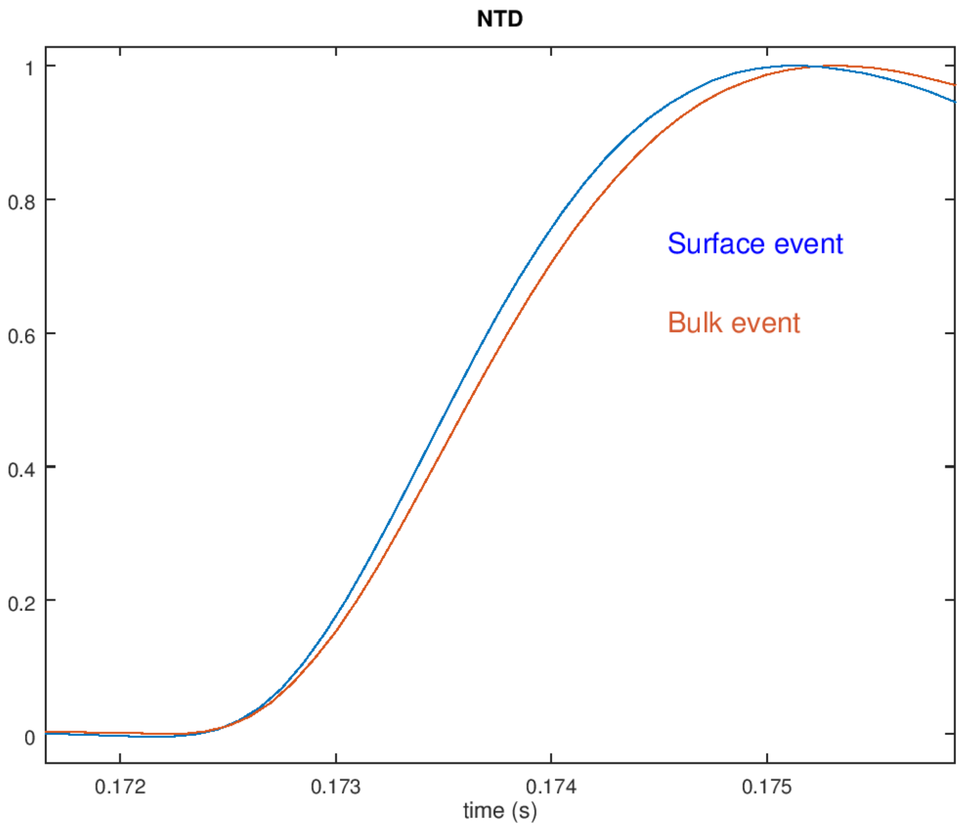
arXiv:1504.03612

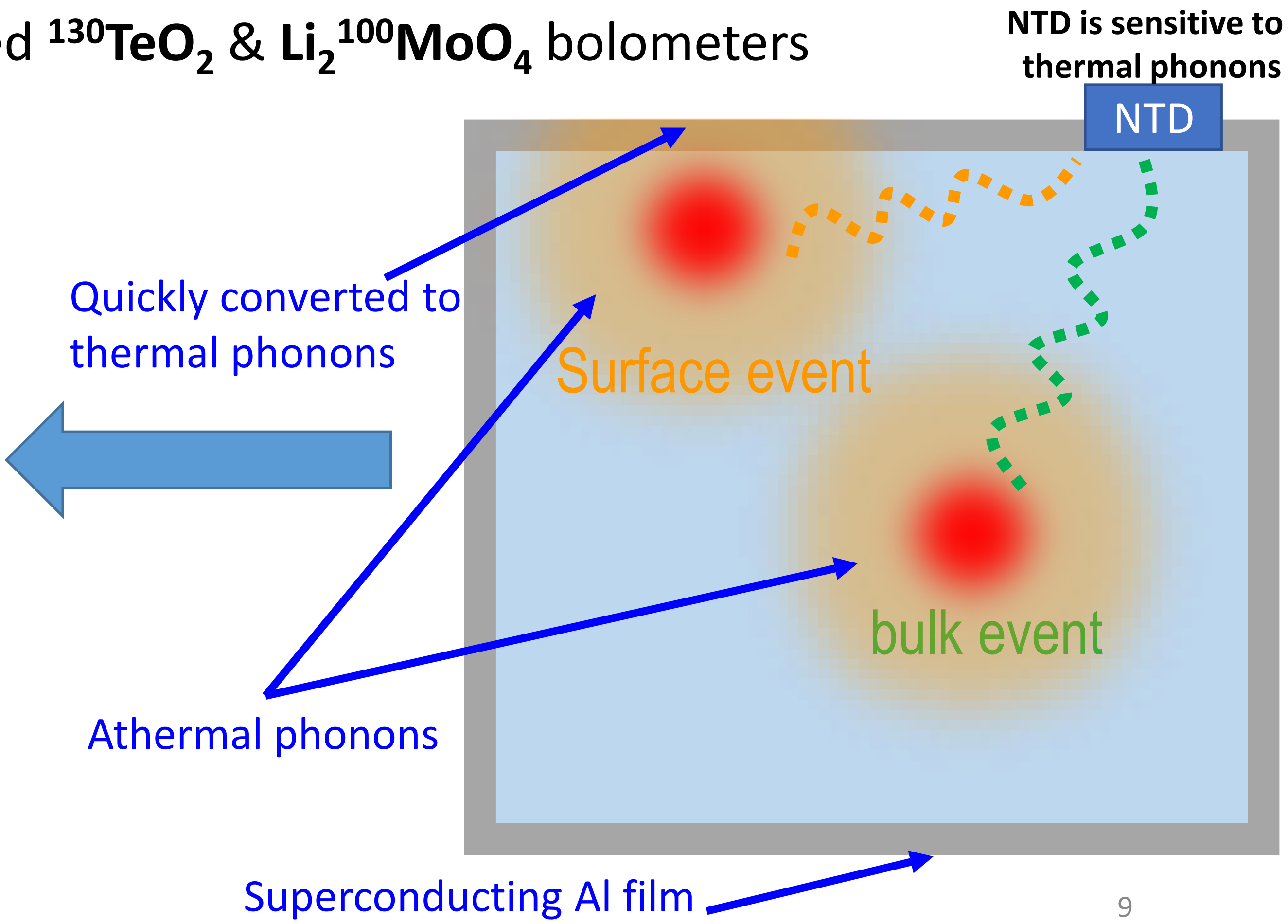


CROSS

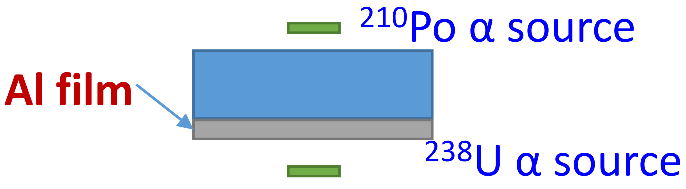
Cryogenic Rare-event Observatory with Surface Sensitivity

- Bolometers with superconducting covering to identify near surface events → no LD is needed
- Prototype tests of Al-coated **TeO_2** & **Li_2MoO_4** crystals
- CUPID demo with 90-crystall array of enriched **$^{130}TeO_2$** & **$Li_2{}^{100}MoO_4$** bolometers

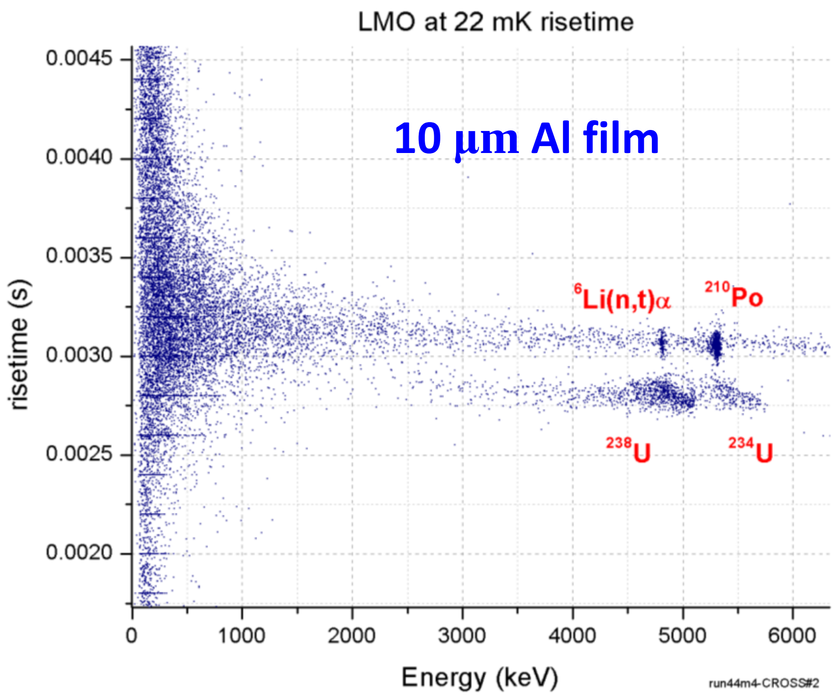


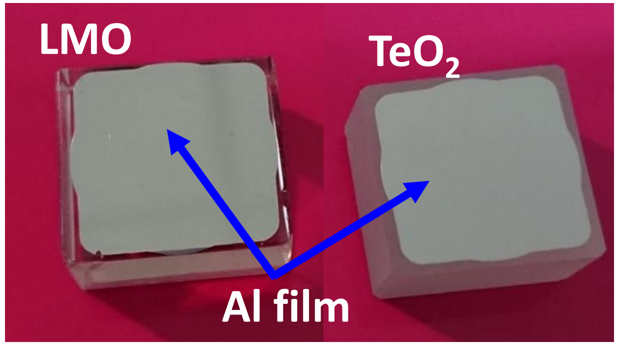


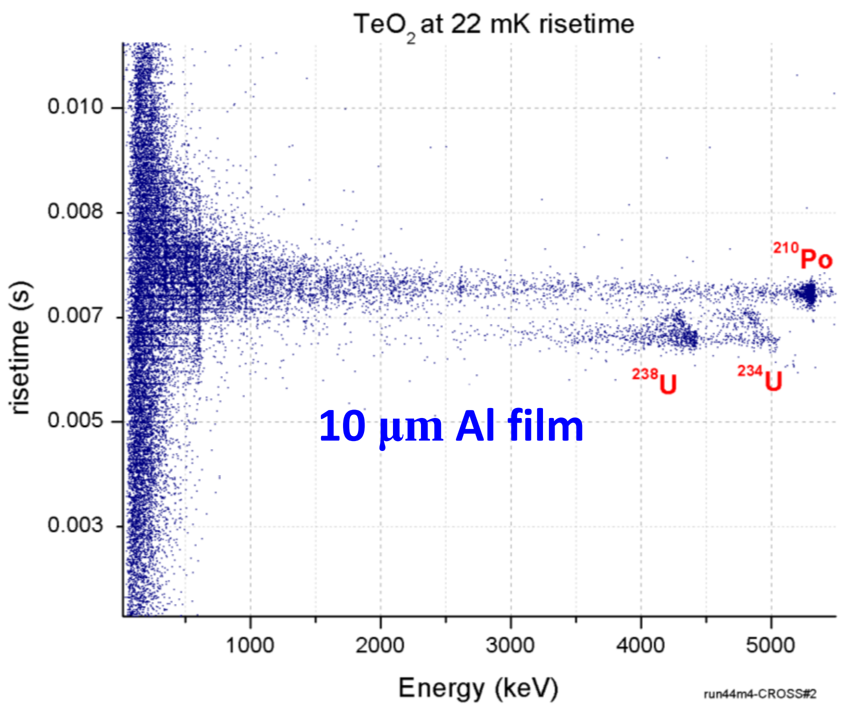
First CROSS prototypes

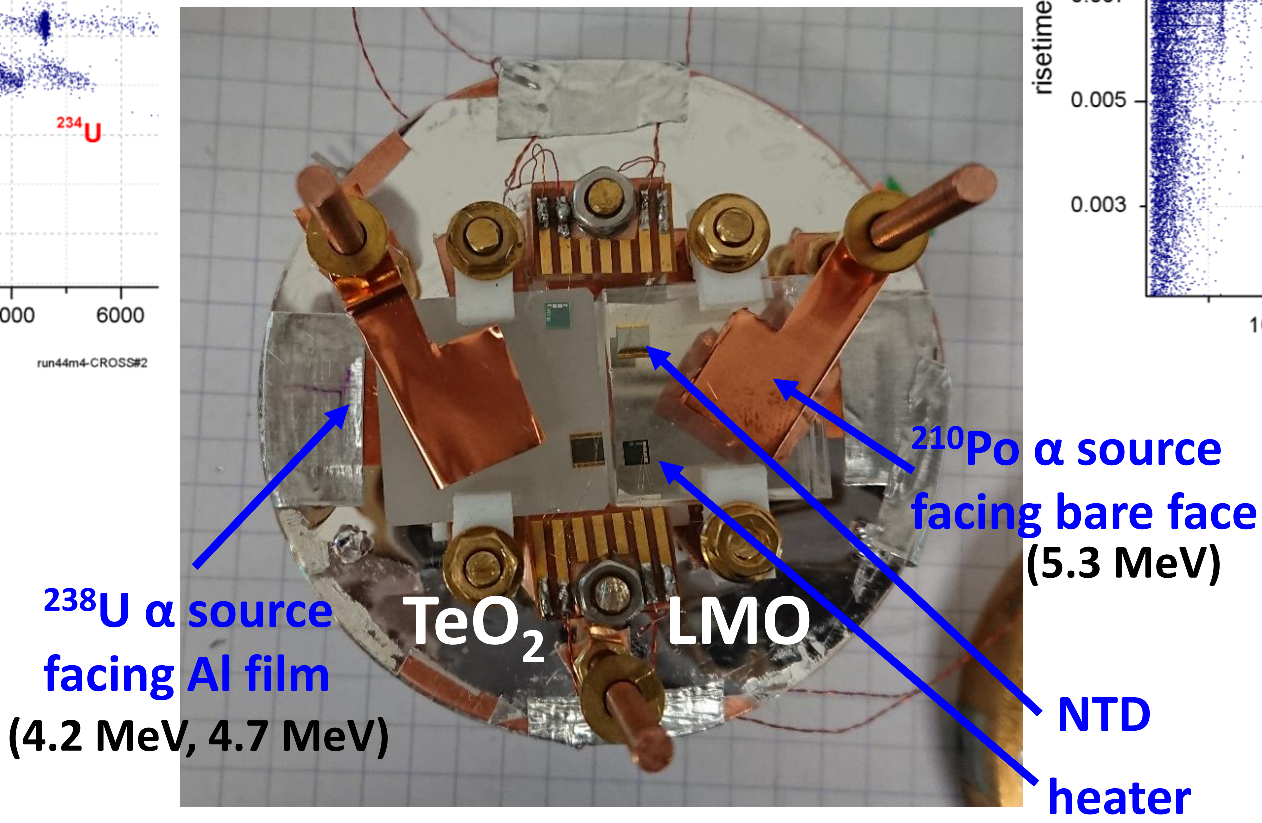


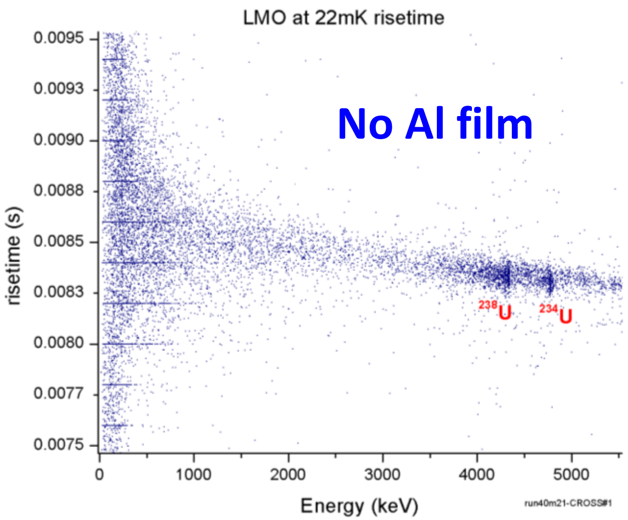
Performed at CSNSM (Orsay, France)

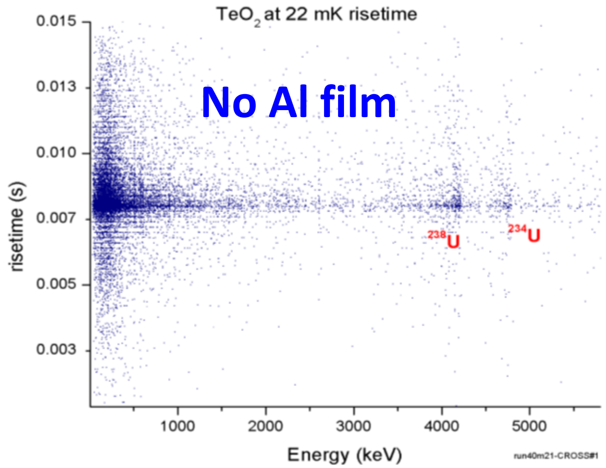








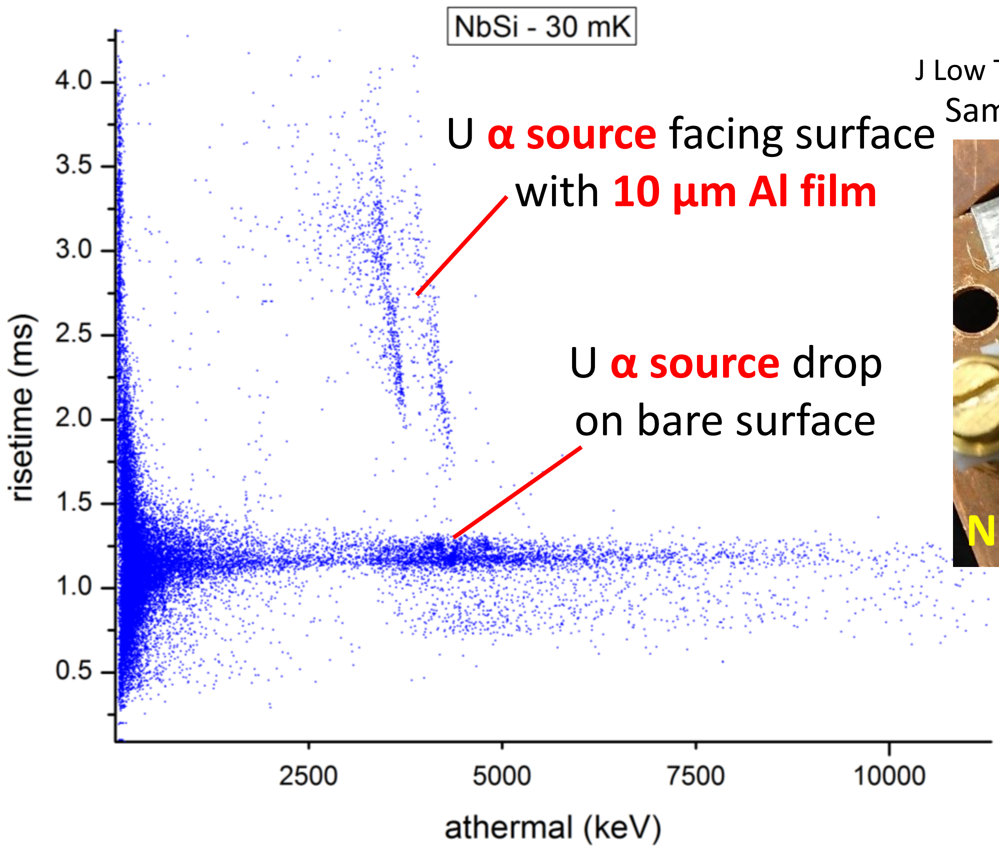


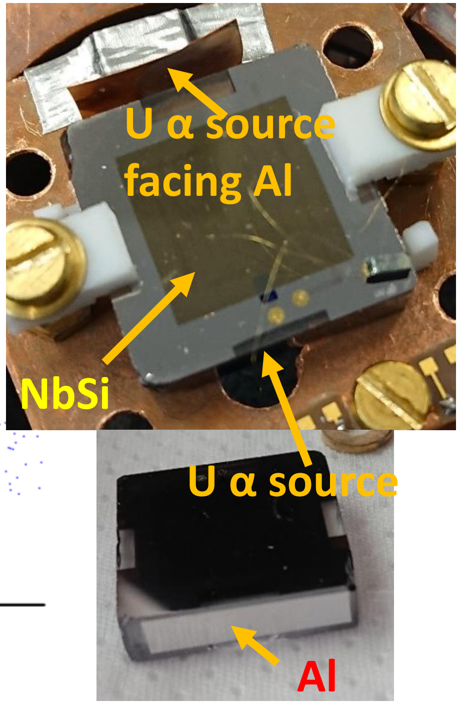


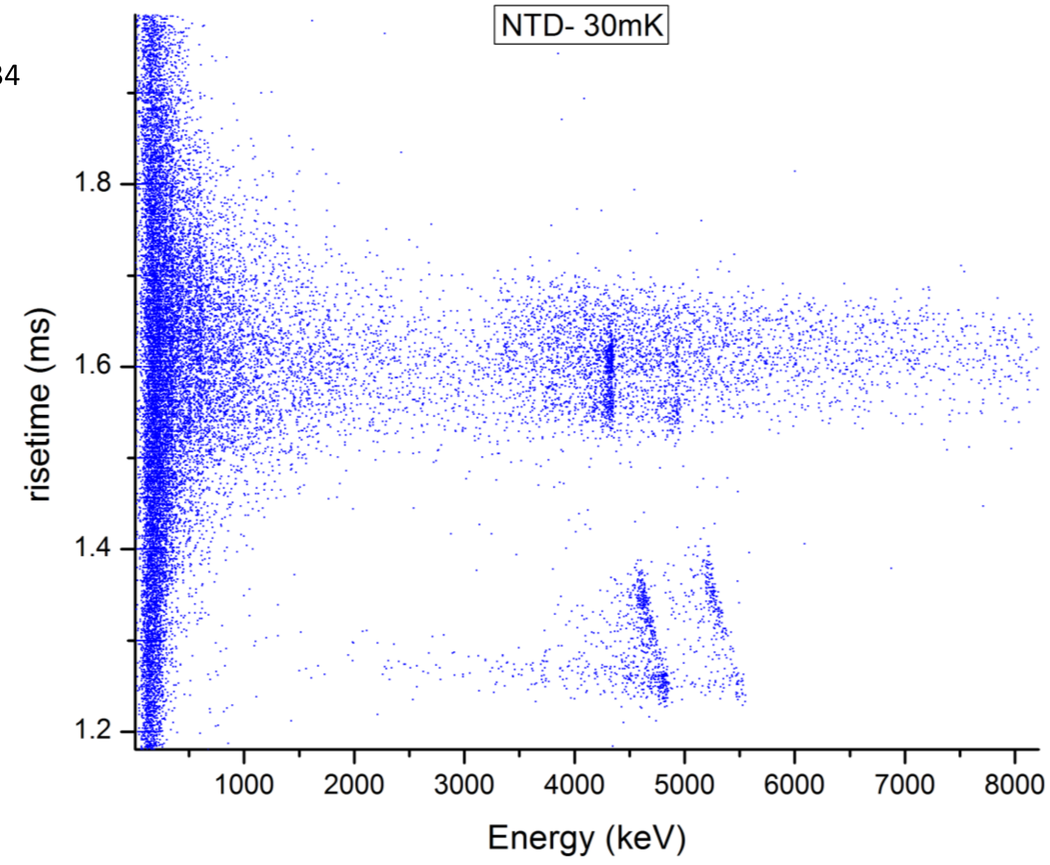
bulk events are slower than surface events

NbSi & NTD on TeO_2

J Low Temp Phys (2012) 167:1029–1034
Same detector tested in 2010





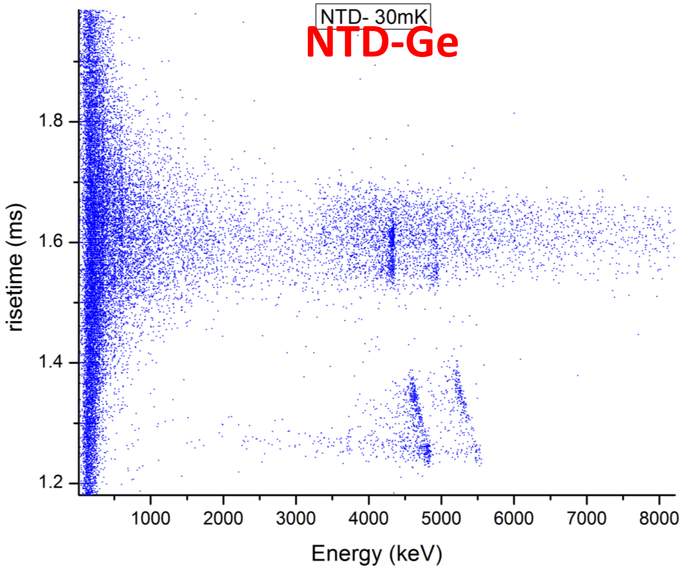


Surface events are slower than bulk events

Surface events are faster than bulk events

Opposite behavior of NbSi and NTD on the same crystal!

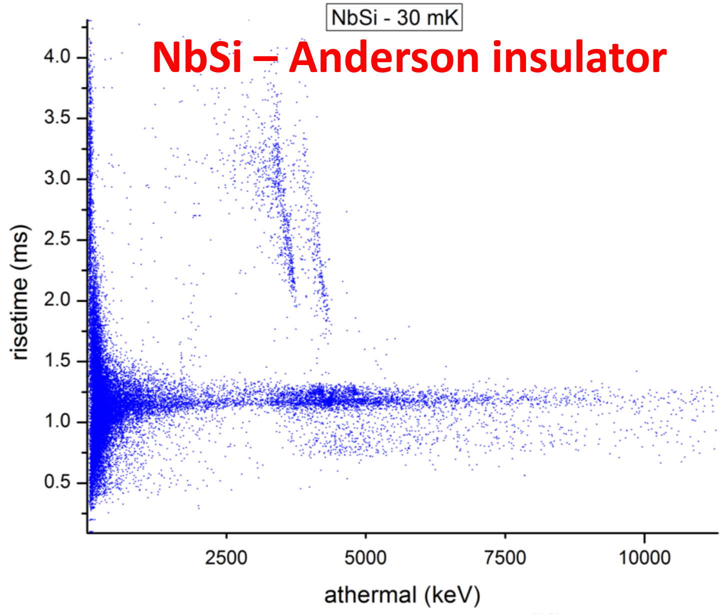
Solid-state-physics phenomena in superconducting Al

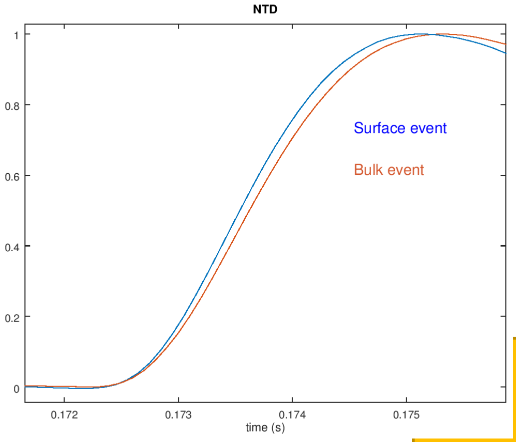


Particle release energy within few mm from the **surface**
high energy phonons are generated

Breaking Cooper pairs

Long lived quasi-particles (QPs)
Subsequent recombination of QPs gives lower energy phonons ($E=E_g=1.2K$)

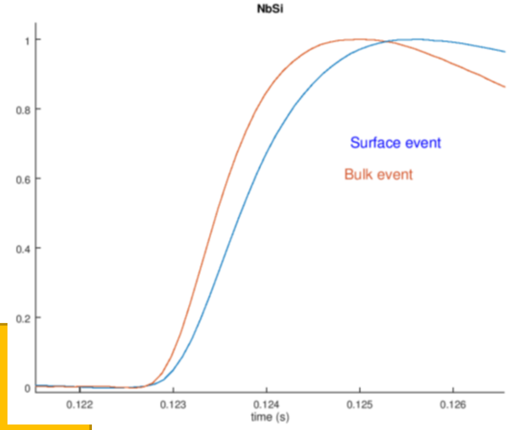




NTD
Slow

Phonons generated from **bulk** events reach the Al film with energy insufficient to break Cooper pairs

NbSi
fast



Sensitive to thermal phonons
events close to Al film are thermalized faster than bulk events
Surface events are faster than bulk events

Sensitive to athermal phonons
the subsequent emission of the trapped energy in Al film gives a delayed thermal component for the athermal pulse
Surface events are slower than bulk events

Summary and perspective

- Neutrinoless double beta decay plays a unique role in understanding fundamental neutrino properties
- Next generation $0\nu2\beta$ searches with cryogenic detectors (CUPID project) require an active rejection of surface contamination induced background (at least α's)
- Most of the present CUPID R&Ds are devoted to the developments of heat-light bolometers
- CROSS aims at the development of bolometers capable to reject near surface interaction exploiting superconducting properties of an Al film surface covering
- First CROSS prototypes ($2\times2\times1$-cm Li_2MoO_4 and TeO_2 with ¼ of surface covering by 10- or 1-μm-thick Al) show high detector performance and a highly efficient pulse shape discrimination of alpha interaction near the Al-covered surface (no hint yet of beta rejection)
- R&D and study of fully covered detectors is ongoing to fulfill the CROSS project goals

Thank you for your attention ☺

CROSS

Canfranc undergoing laboratory (Spain)

Majorana or Dirac?

Dirac particle: particle is different from its anti-particle

e.g. electron e^- and positron e^+

they can be distinguished by charge, baryon or lepton number

There are particles that are identical to their anti-particles

e.g. photon and π^0

Majorana particles are fermions where the particle is the anti-particles

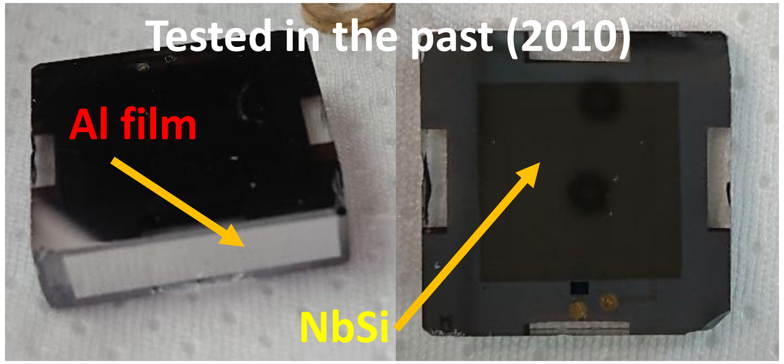
But there is no known Majorana fermion yet…

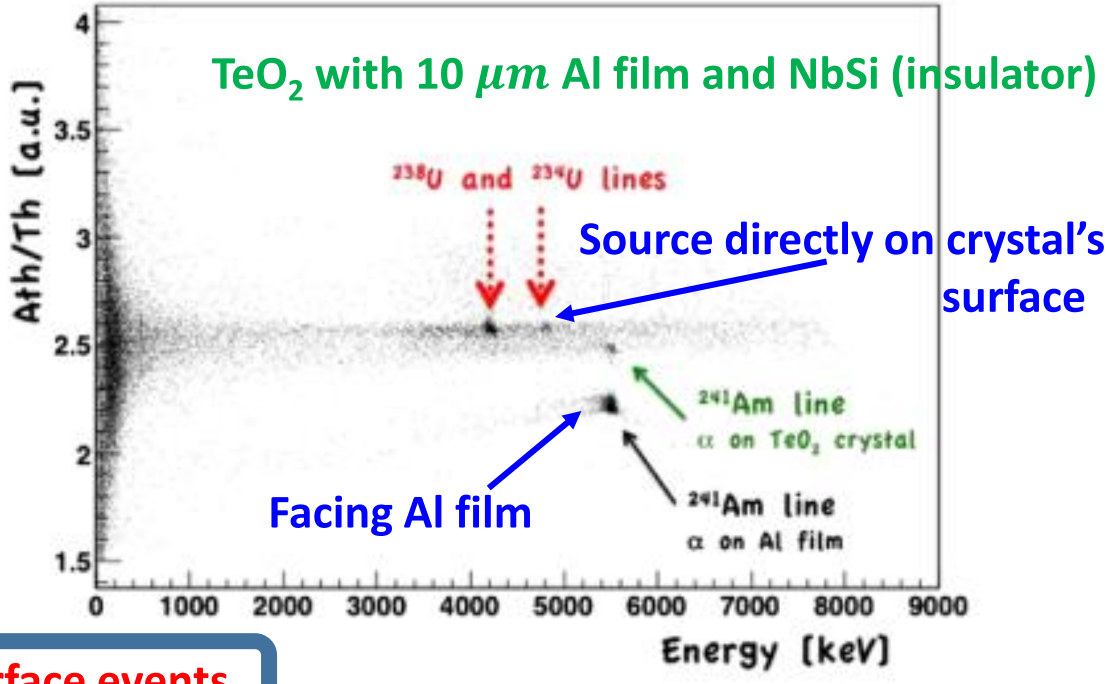
Is neutrino Majorana or Dirac?

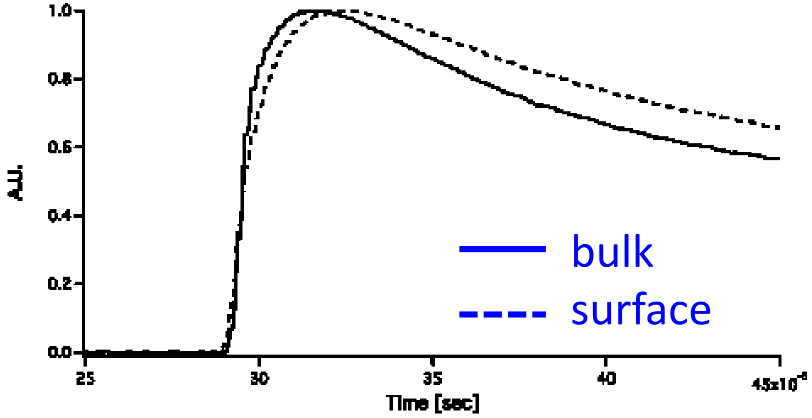
Idea behind CROSS

J Low Temp Phys (2012) 167:1029–1034

- A few μm thickness of Al film is deposited using a dedicated evaporator
- Al film is a superconductor at low temperature (Tc ≈ 1.2 K)
- Energy deposited in or close to the Al film (~ 1mm) will break Cooper pairs and produce quasiparticles which store energy for a few ms and recombine afterwards to provide a delayed component of the signal which is not foreseen for the bulk events.

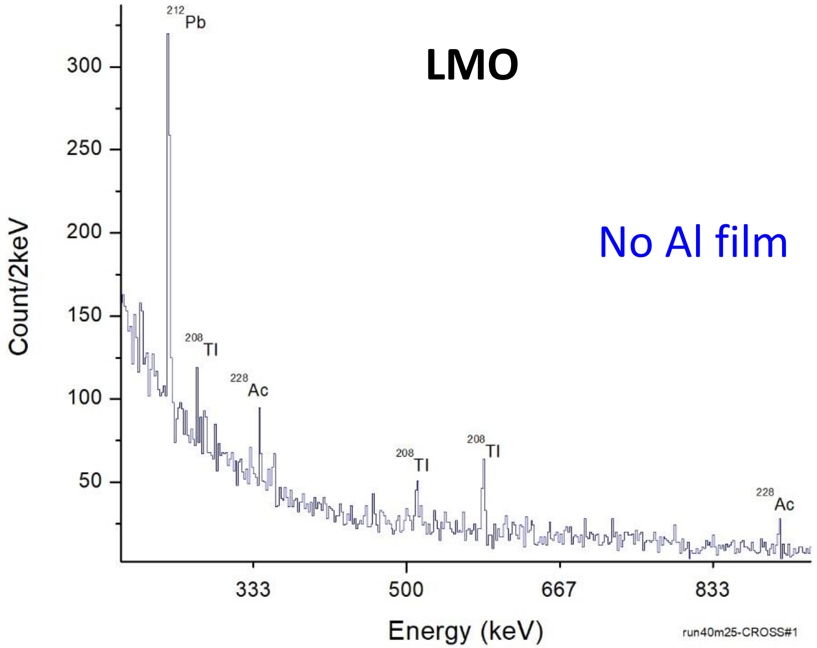


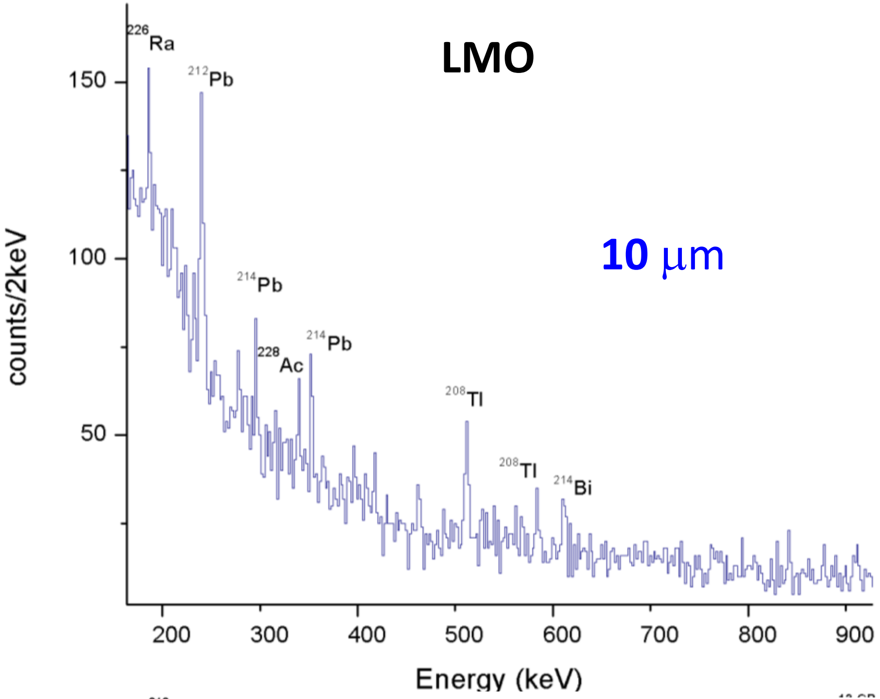


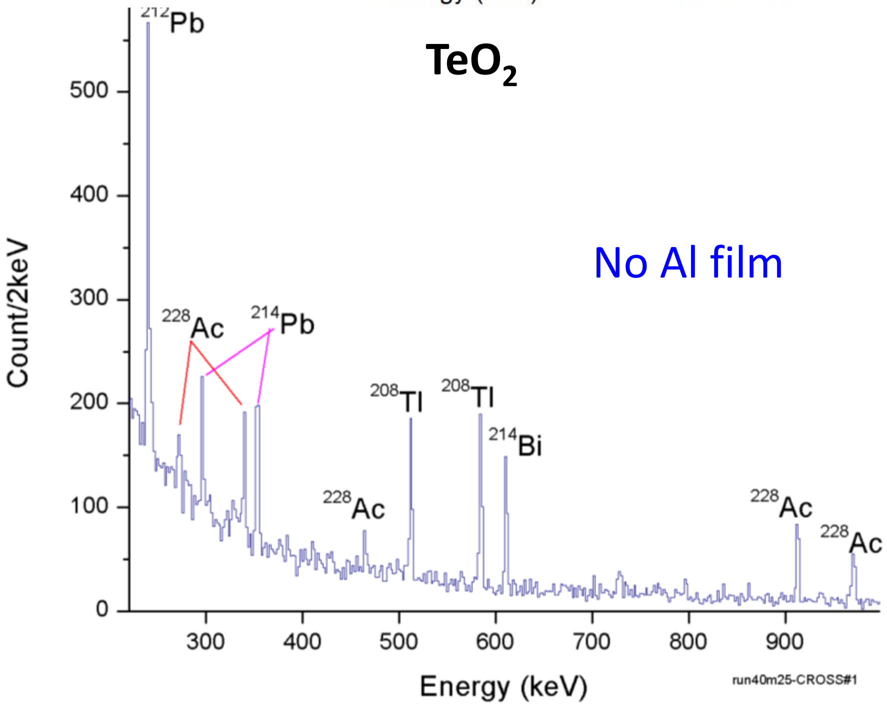


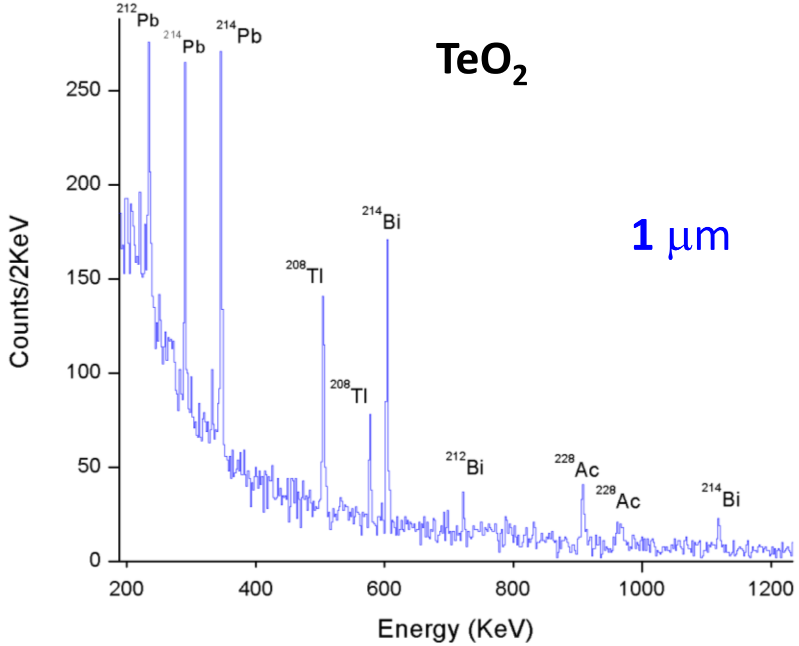
bulk events are faster than surface events

Energy Spectrum



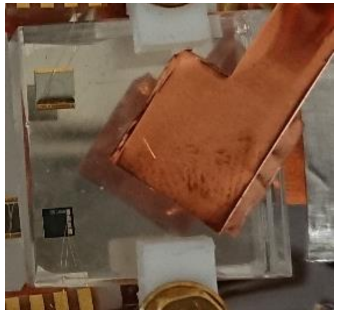






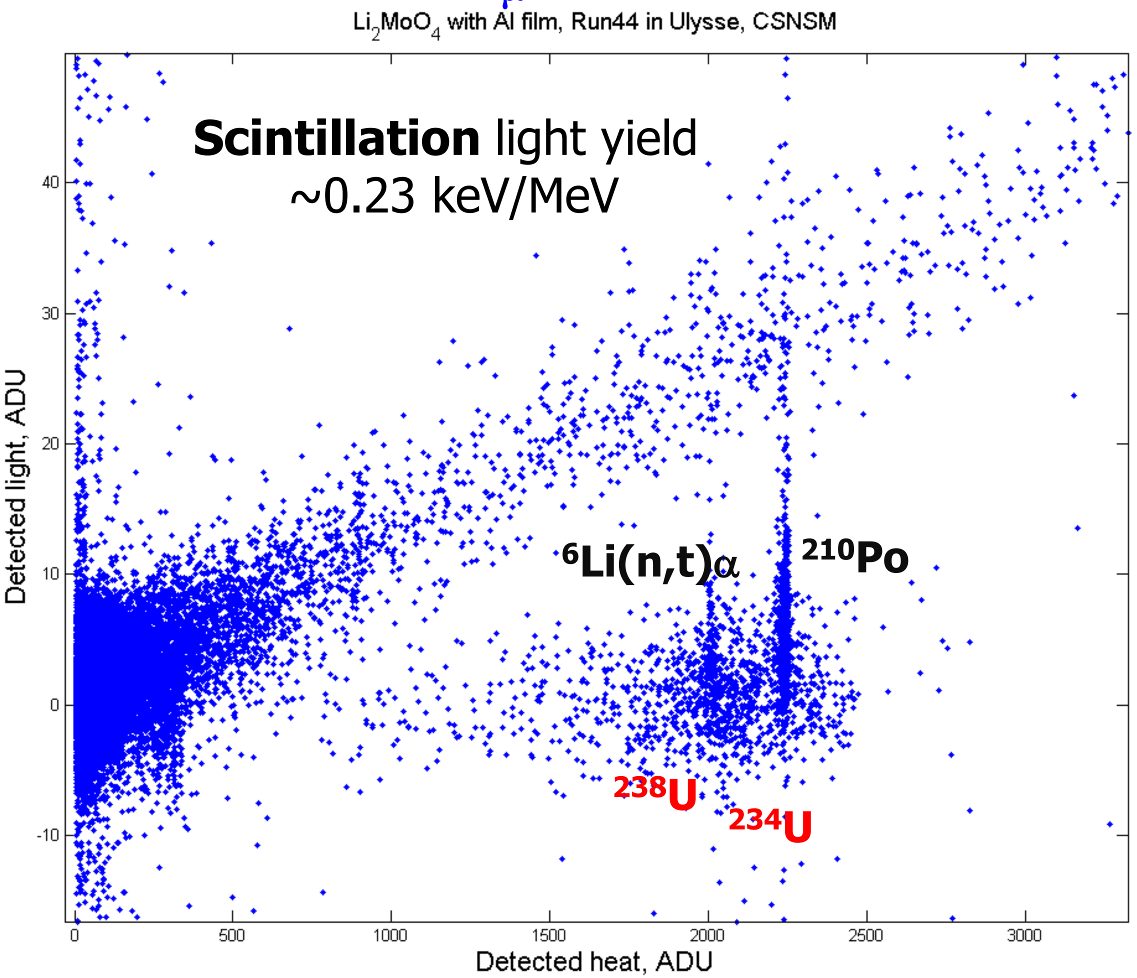
no impact of Al film on energy resolution

Light-assisted particle ID with CROSS prototypes

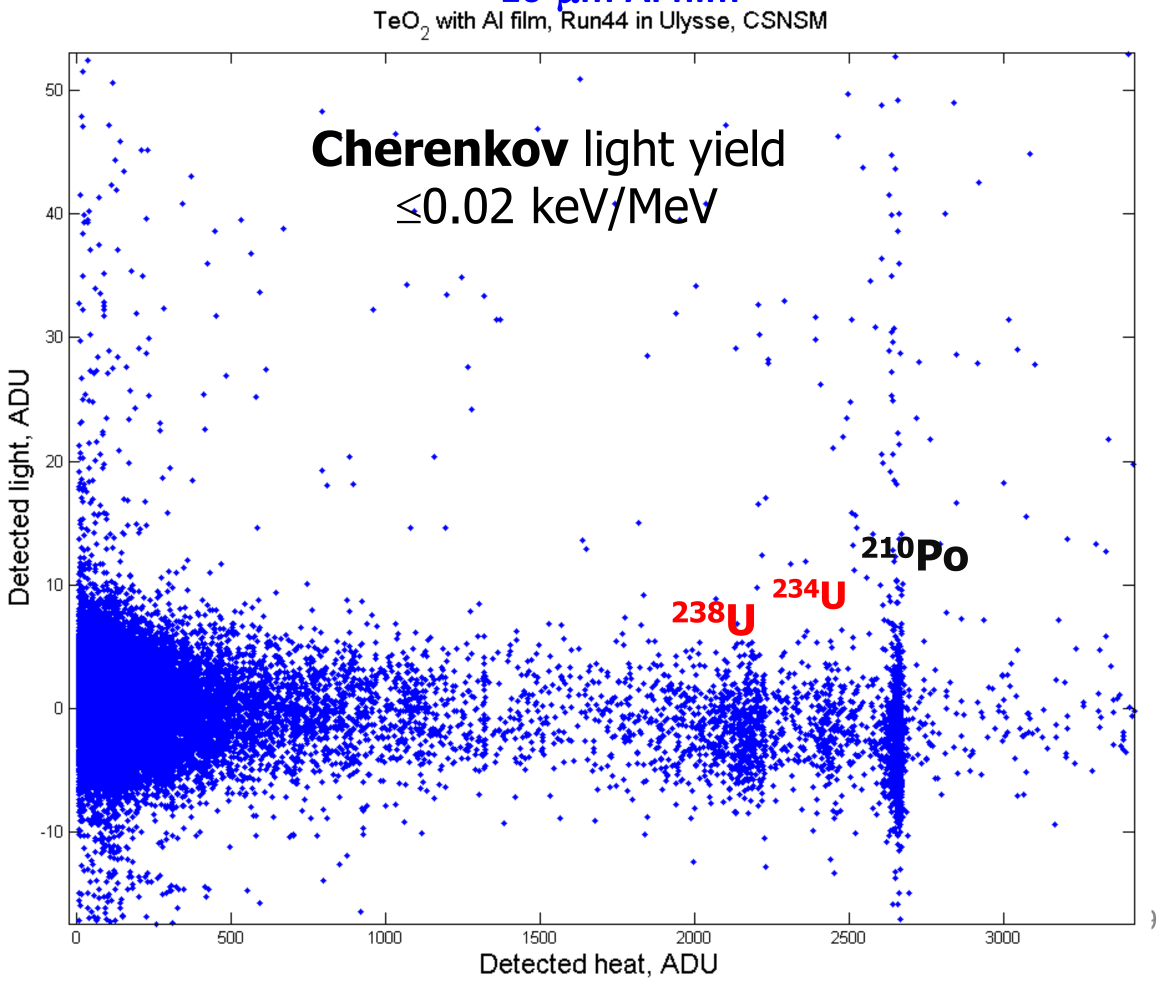


- **"Standard" performance ∅44-mm Ge bolometric photodetector** (0.42 μV/keV & 0.32 keV FWHM baseline noise @ 22 mK)
- **Poor light collection** (crystals were shadowed by the ^{210}Po sources)

Li_2MoO_4
10-μm Al film

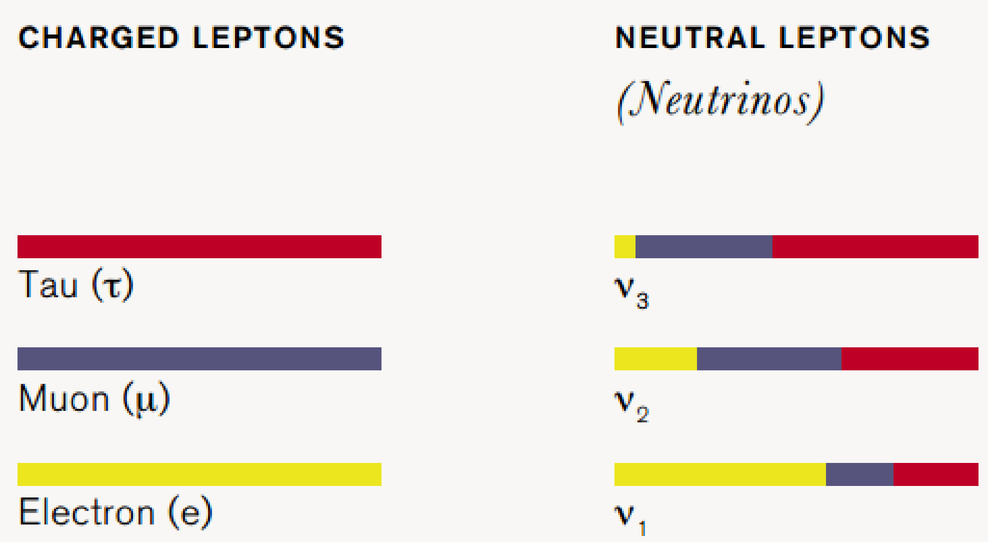


TeO_2
10-μm Al film



Neutrino oscillation

- Any neutrino flavor (ν_e , ν_μ , ν_τ) is actually a superposition of three massive neutrino types (ν_1 , ν_2 , ν_3)



$$[T_{1/2}^{0\nu}]^{-1} = |m_{\beta\beta}|^2 |M^{0\nu}|^2 G^{0\nu}$$

- $m_{\beta\beta}$: effective Majorana mass
- $M^{0\nu}$: nuclear matrix element
- $G^{0\nu}$: phase space factor

- Normal hierarchy: $m_1<m_2<<m_3$
- Inverted hierarchy: $m_3<<m_1<m_2$