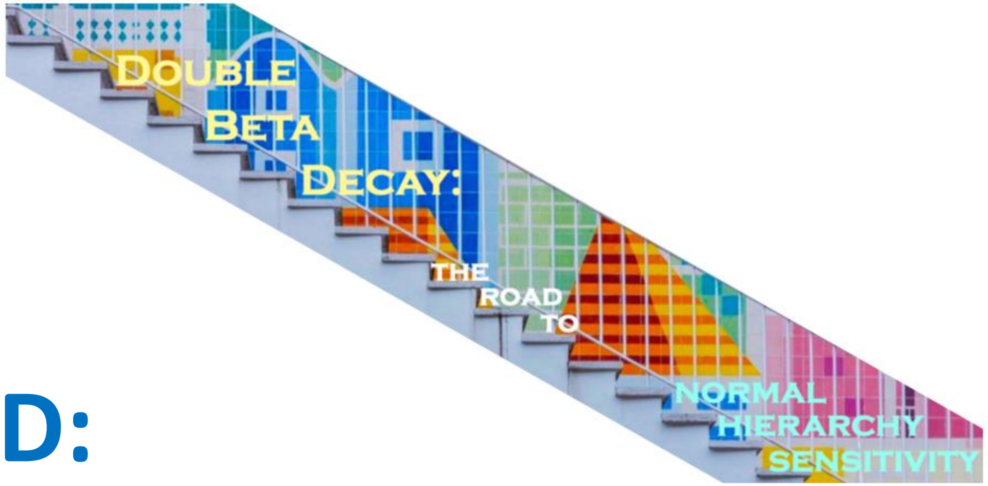
ISCTE



Beyond CUPID: bolometric technological developments toward the exploration of the normal hierarchy

Andrea Giuliani

IJCLab, Orsay, France

Outline

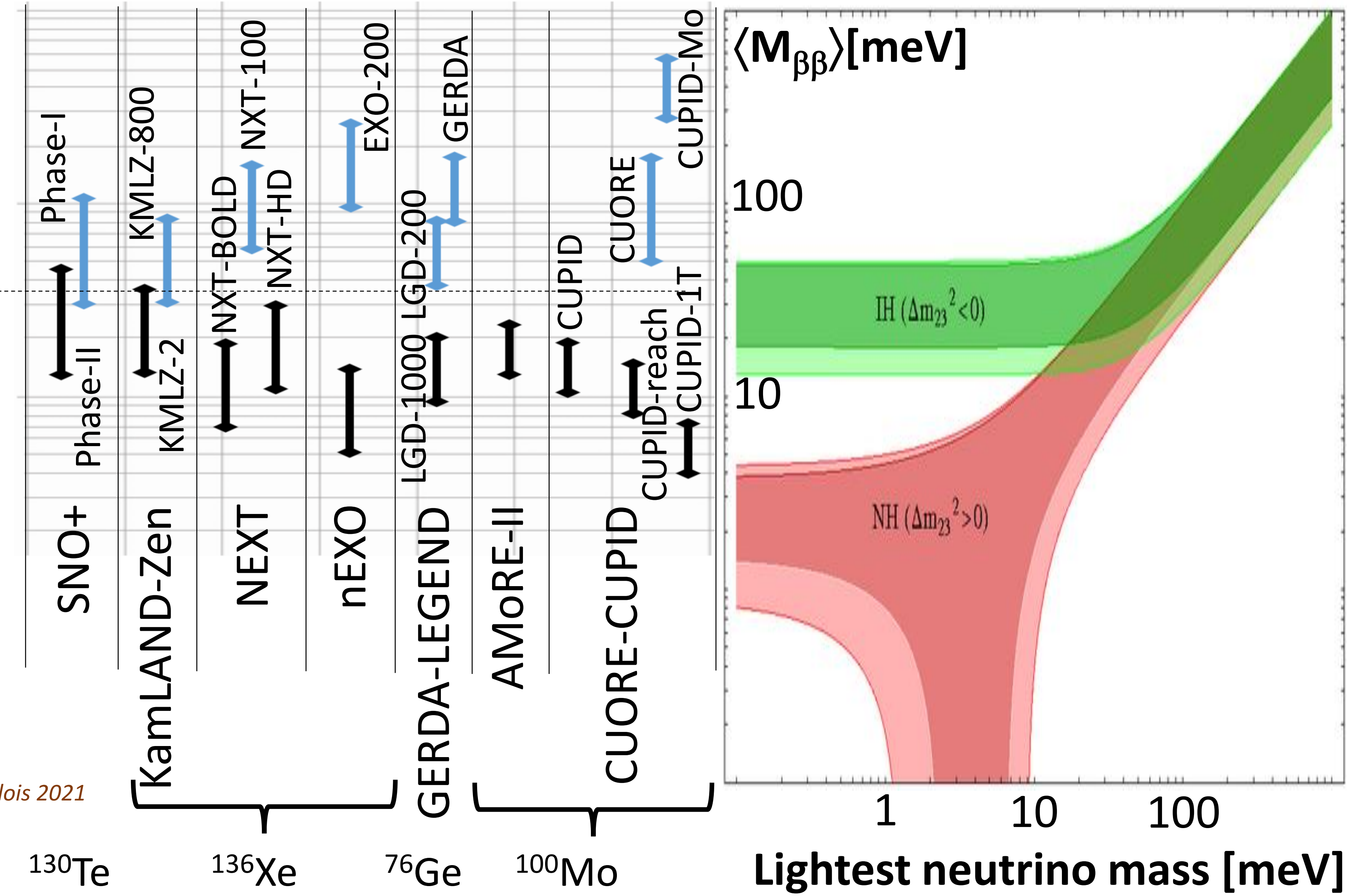
- Prospects in double beta decay search – the bolometric way
- Background components in bolometric experiments: challenges and mitigations
- R&D and solutions aiming at background control
    - CROSS – β surface sensitivity
    - BINGO – set of innovative methods
    - US CUPID-R&D
    - CALDER
    - AMoRE

light detectors with sensors different from the CUPID baseline

Double beta decay: status and prospects

Current generation
(concluded – running – on-commissioning projects)

Next generation
(projects to be started in the next decade)



C. Nones, Rencontres de Blois 2021

Double beta decay: status and prospects

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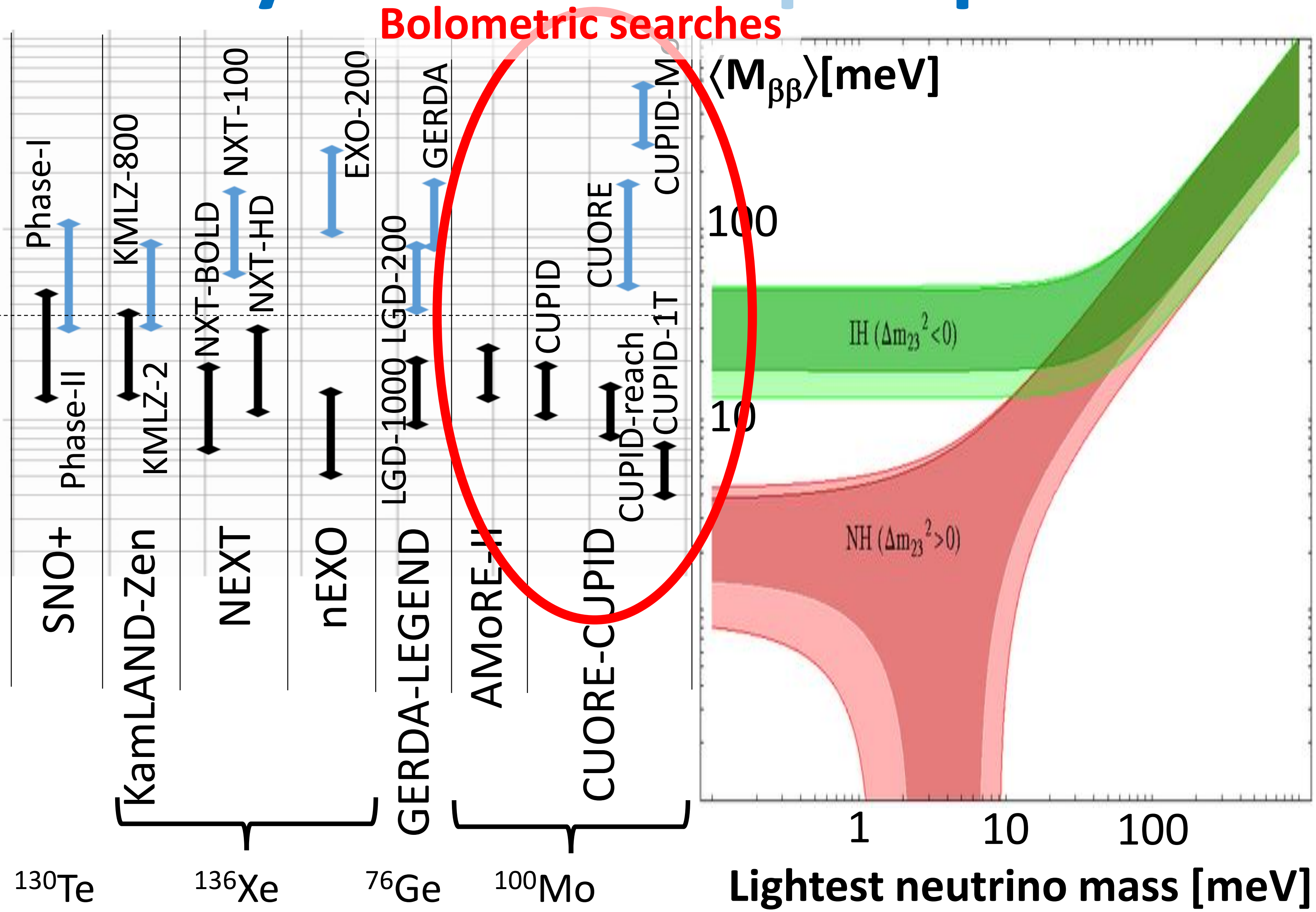
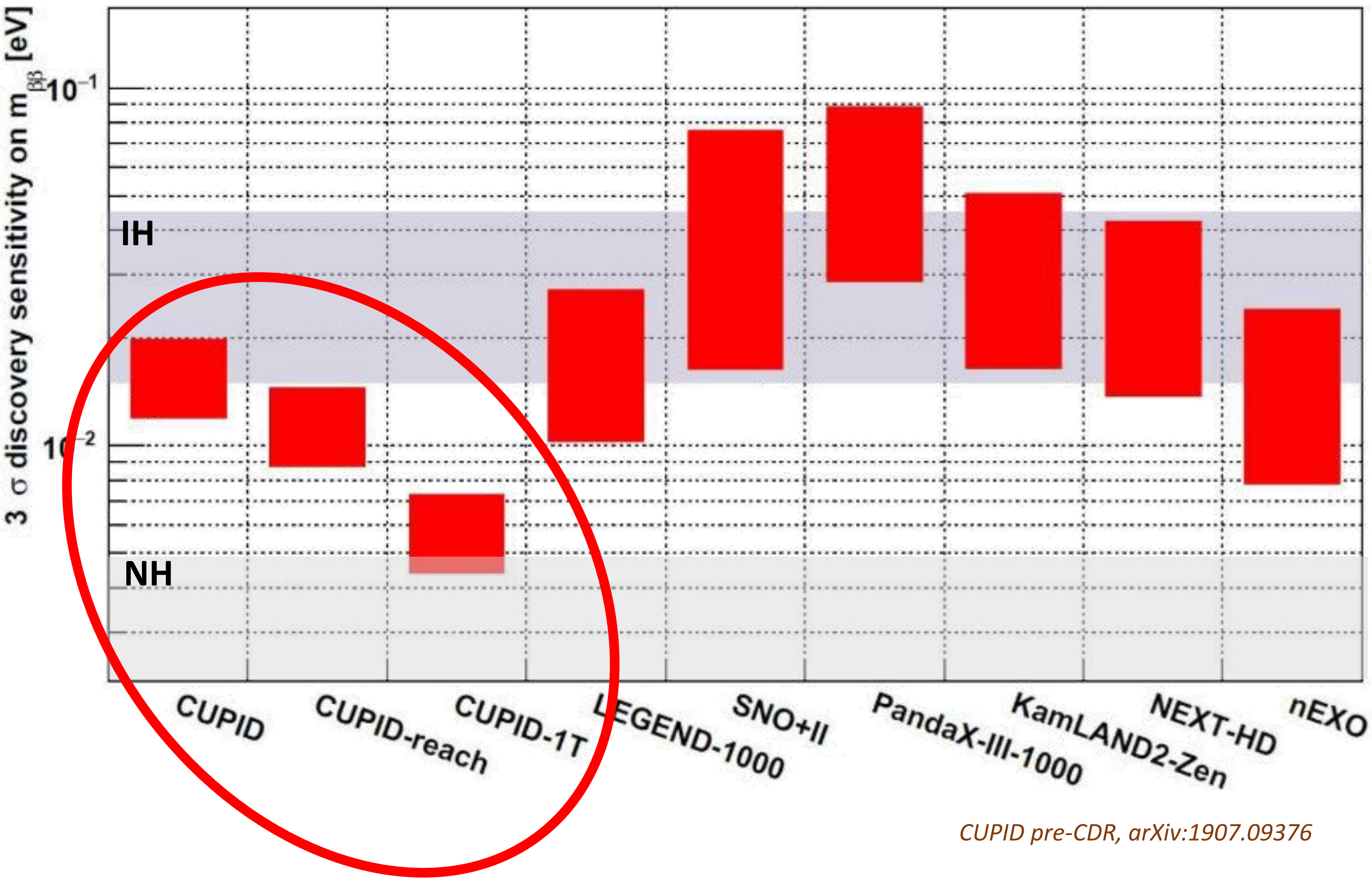


Prospects of some promising projects

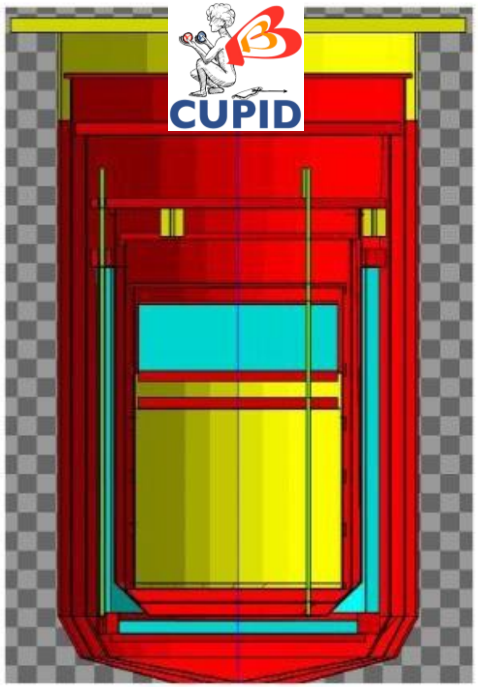


CUPID pre-CDR, arXiv:1907.09376

Prospects of CUPID

Technically ready

CUPID Baseline



240 kg of ^{100}Mo

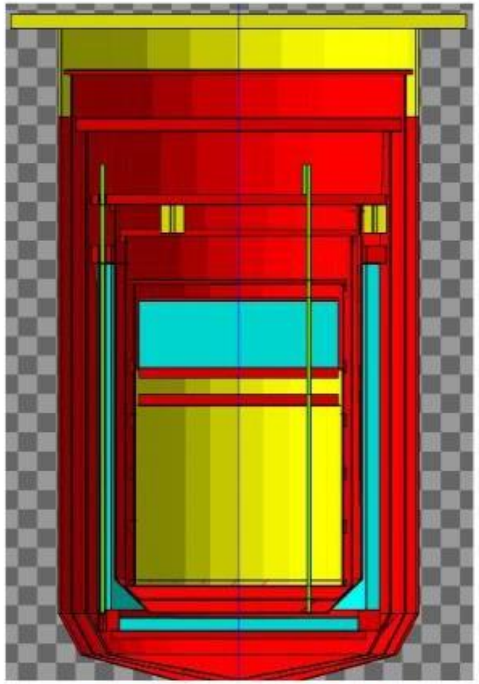
CUORE cryostat

Bkg 1×10^{-4} ckky

Excl. sensitivity:

$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach



240 kg of ^{100}Mo

CUORE cryostat

Bkg 2×10^{-5} ckky

Excl. sensitivity:

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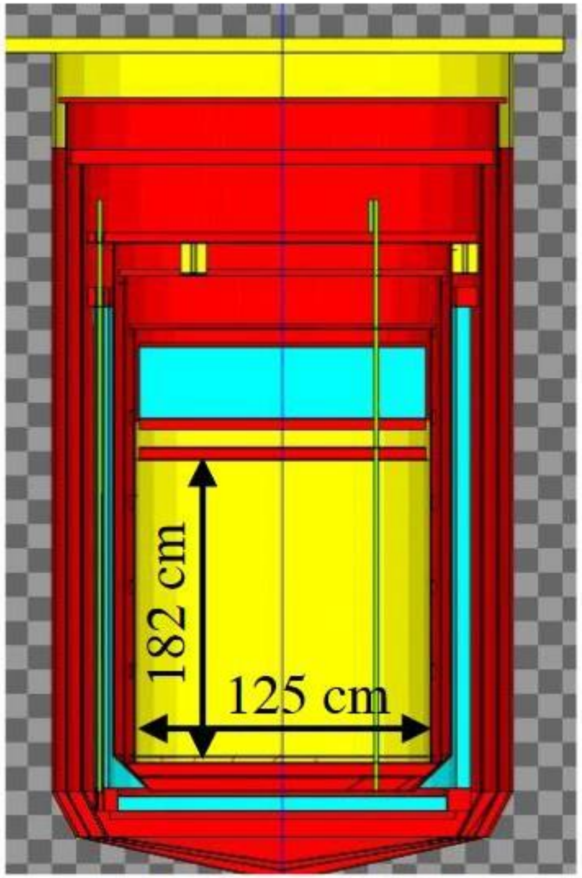
CUPID-1T



1000 kg of ^{100}Mo

New cryostat

Bkg 5×10^{-6} ckky

Excl. sensitivity:

$T_{1/2} > 9.1 \times 10^{27}$ y

F. Bellini, this workshop

Prospects of CUPID

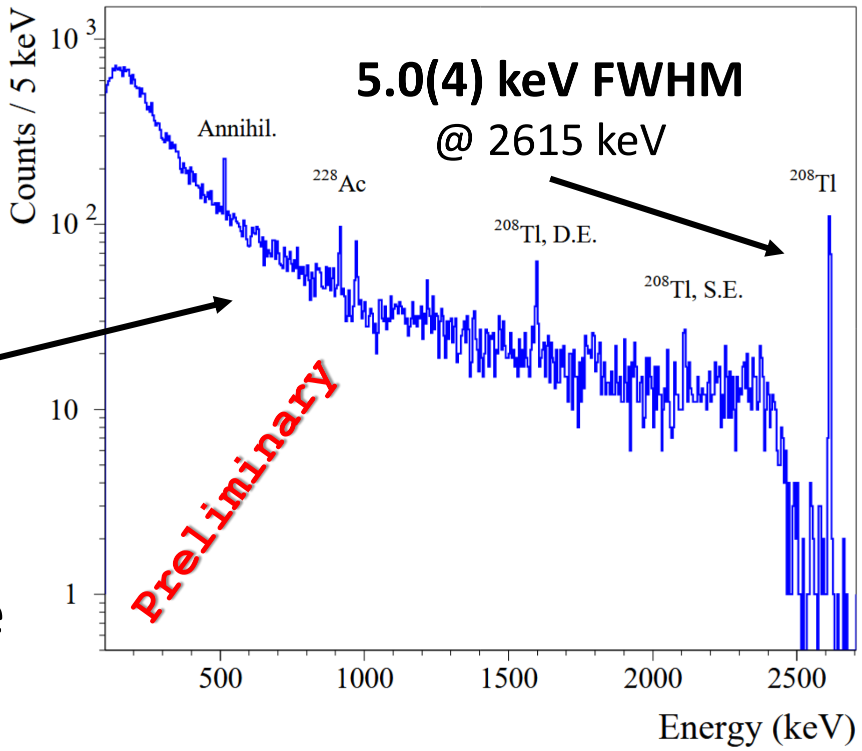
Technically ready

Unlike liquid-helium-bath cryostat ("wet"), current **pulse-tube cryostats ("dry")** – like the CUORE system – have **no cryogenic intrinsic constrain** on the **cryostat diameter**

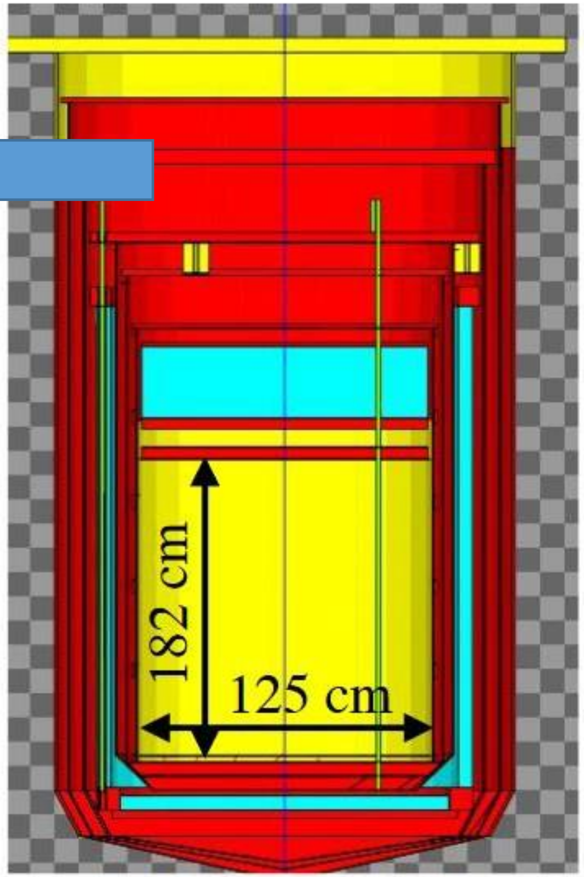
→ **Very large cryostats are possible**

New available technologies allow for **control of vibrations induced by pulse-tubes**

Record energy resolution achieved on a 45x45x45 mm^3 Li_2MoO_4 CUPID-like crystal in the Canfranc laboratory in the CROSS **pulse-tube cryostat**



CUPID-1T



1000 kg of ^{100}Mo

New cryostat

Bkg 5×10^{-6} ckky

Excl. sensitivity:

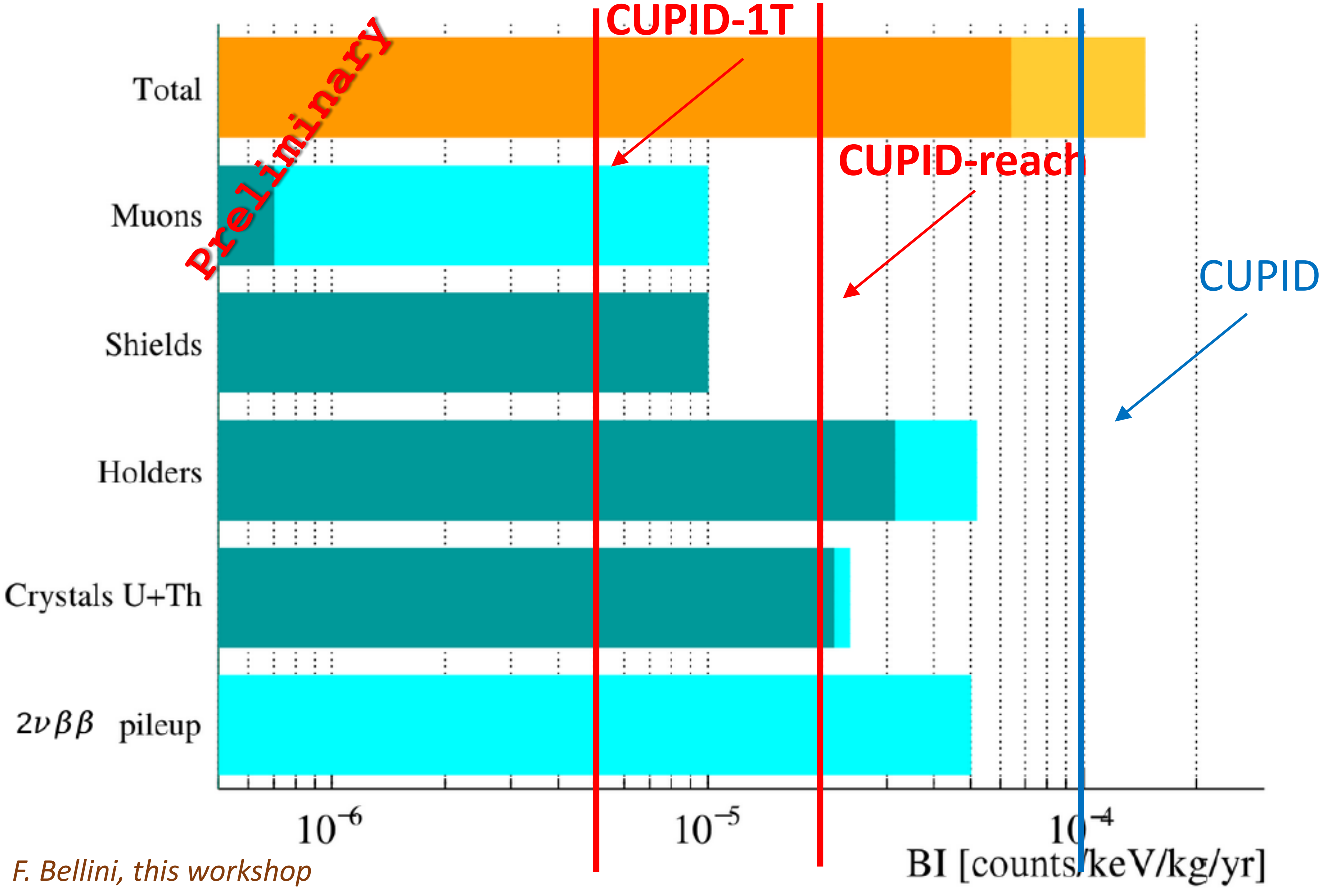
$T_{1/2} > 9.1 \times 10^{27}$ y

Background for ^{100}Mo: status

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo

[Other technically mature isotopes: **^{130}Te in TeO_2 – ^{116}Cd in $CdWO_4$**]



F. Bellini, this workshop

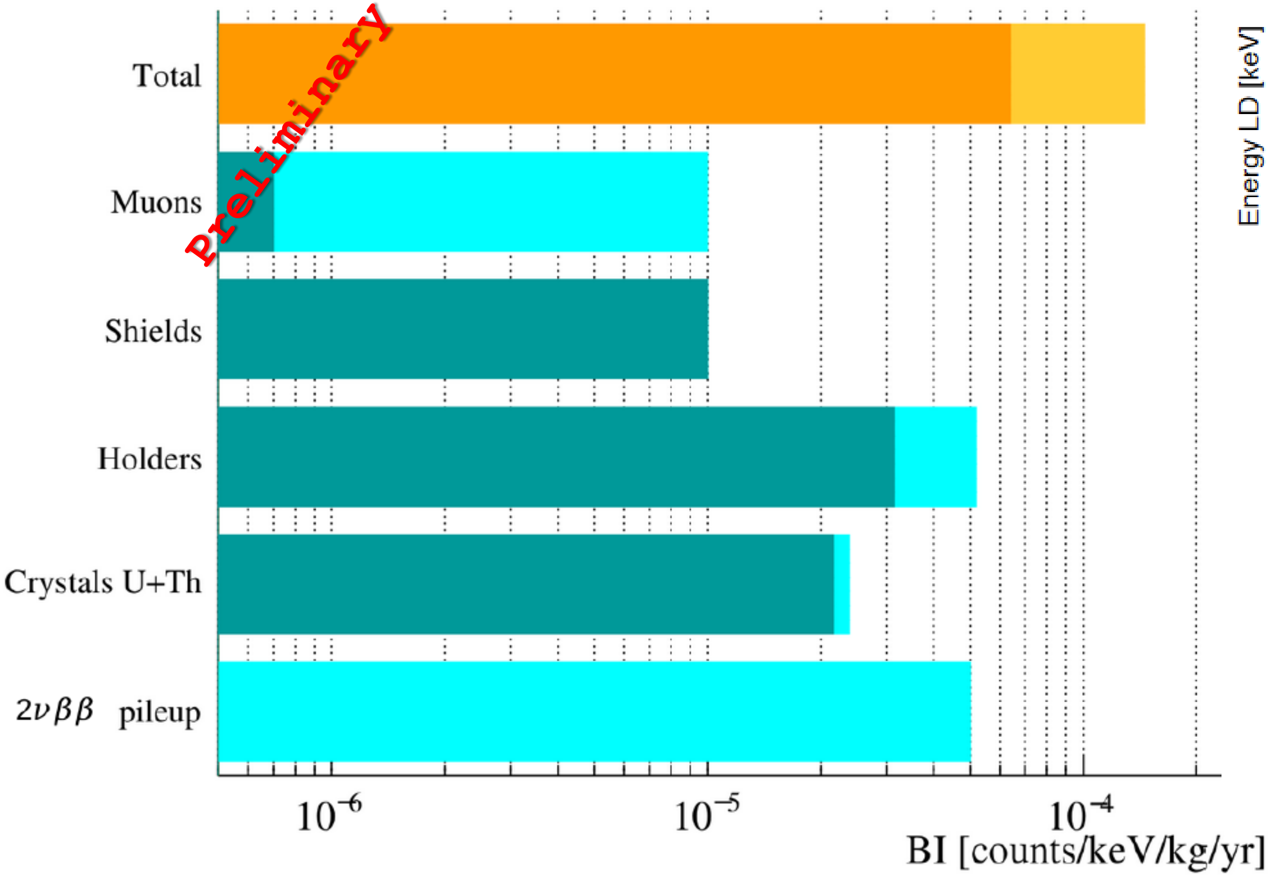
ROI: **3034 keV – ^{100}Mo**

Full α rejection down to BI < 10^{-5} counts/keV/kg/y is assumed

Background for ^{100}Mo: status

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



ROI: **3034 keV – ^{100}Mo**

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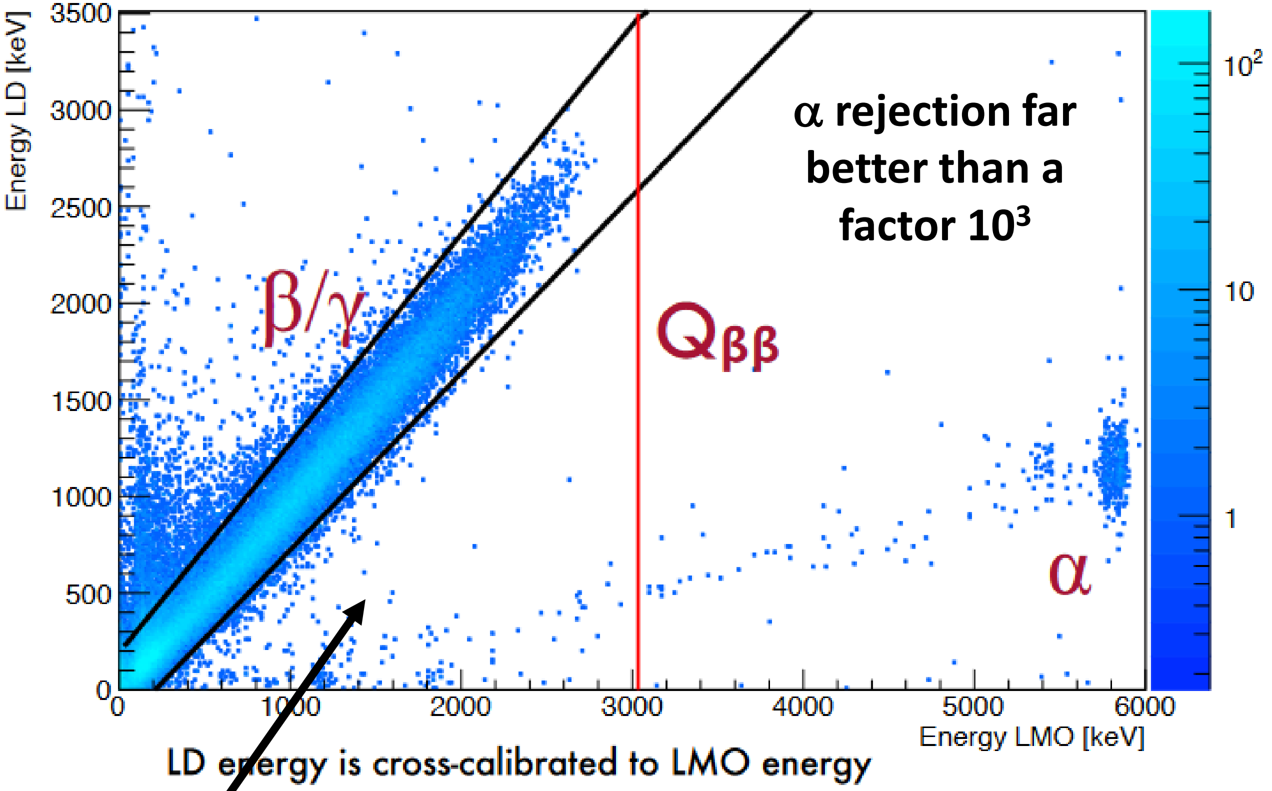
α/β **separation** by light cut



EPJC 80, 44 (2020)

CUPID-Mo data

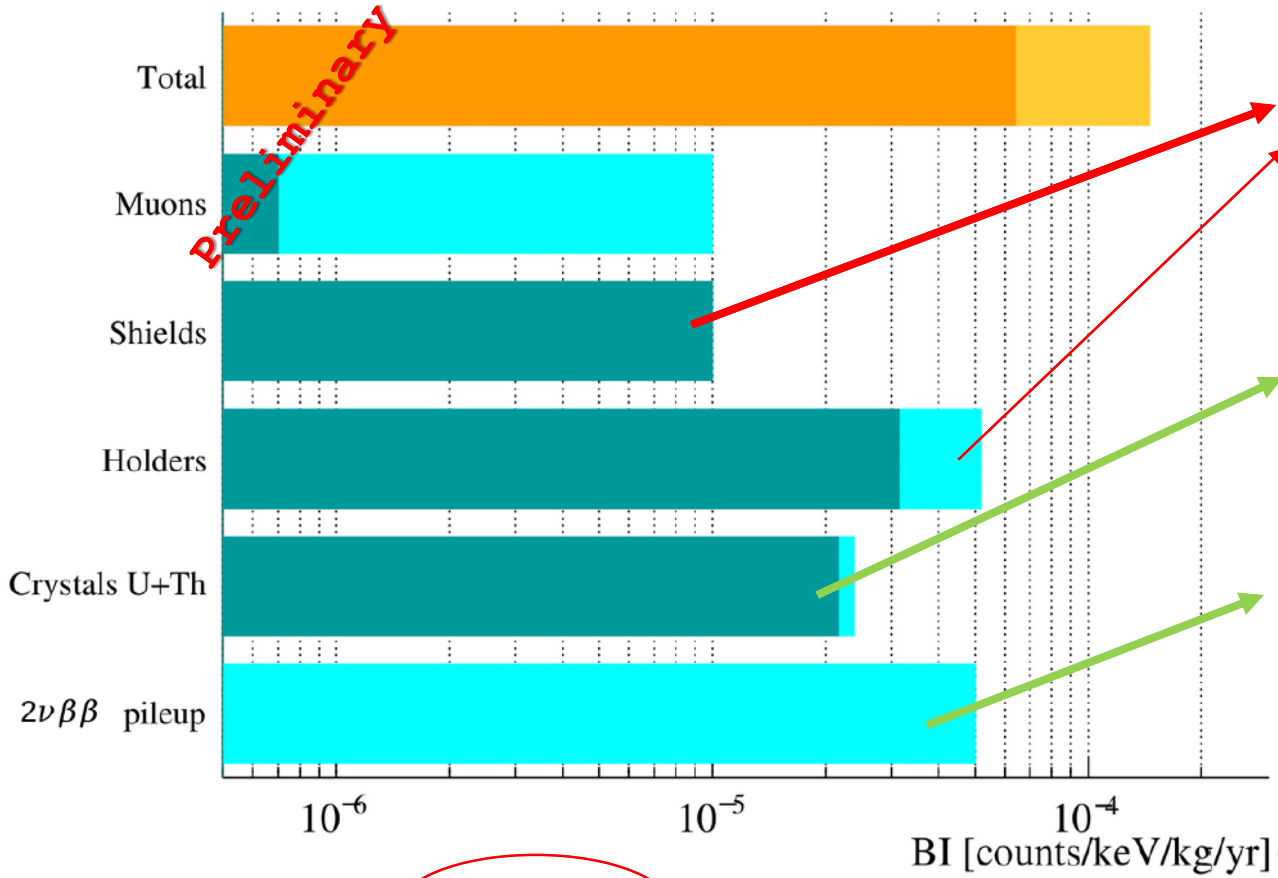
19 channels

Year-scale stability

^{130}Te: complications and advantages

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



ROI: **2527 keV** – ^{130}**Te**

Full α rejection down to BI < 10^{-5} counts/keV/kg/y is assumed

Main advantage: 34% nat. I.A.

Q < 2615 keV (enpoint of most of γ background)
Much more sensitive to shield contamination
Also holder contamination is more critical

Well-established commercial large-scale production of TeO_2 crystals with demonstrated high purity (CUORE)

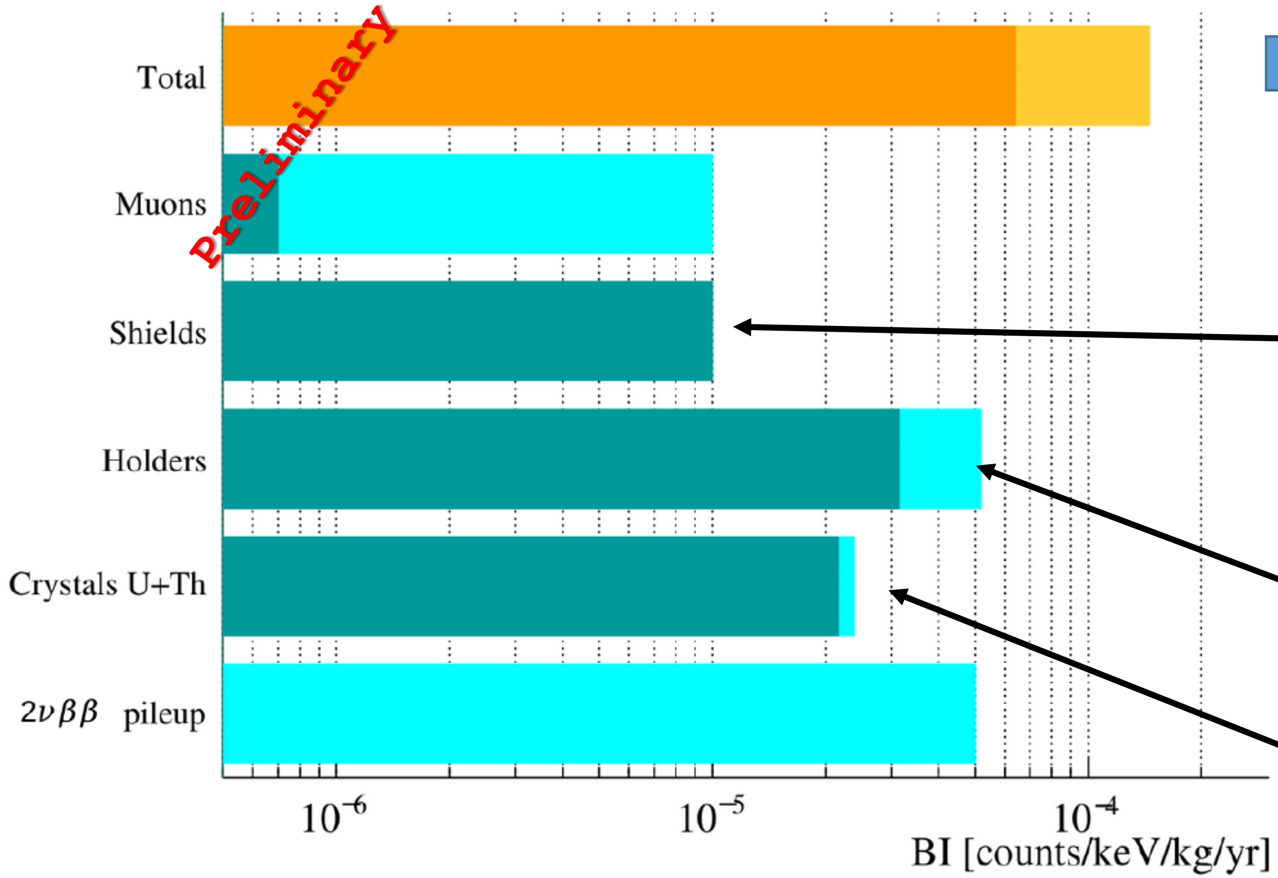
$2\nu2\beta$ rate in ^{130}Te is ~ 100 times lower than in ^{100}Mo
$\rightarrow$ pile-up background is ~ 10^4 times lower

Cherenkov-dominated **light emission in TeO_2 crystals is ~ 10 times lower than in Li_2MoO_4**
α rejection at the set level requires new technologies

Paths for improvement: radiopurity

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



Solutions for background reduction

This talk is not focused on **higher radiopurity**, but on **detector technology**

However, improvements can be obtained in the following items:

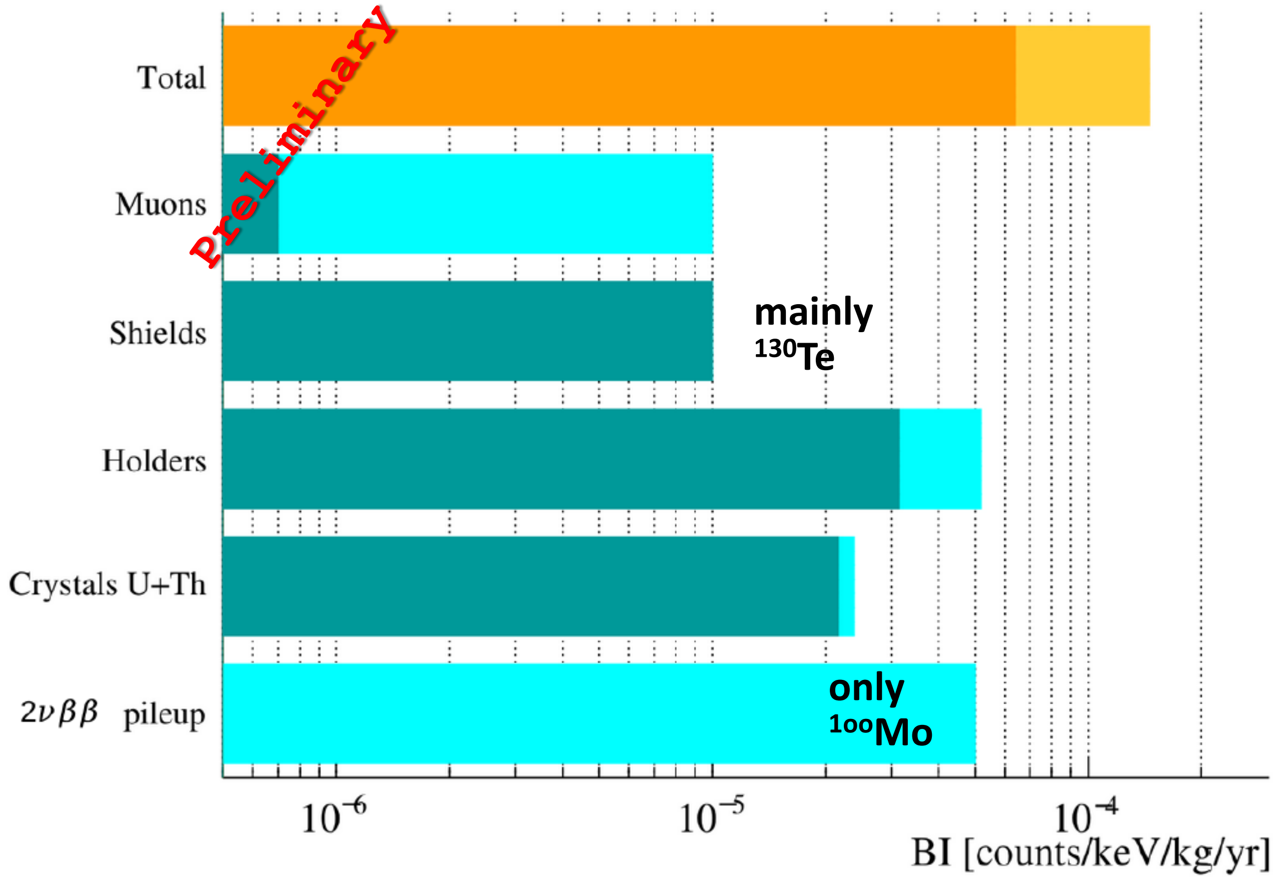
- Replace part of the internal lead shield with **high purity copper** in the existing CUORE cryostat – **Redesign the shields with radiopure materials** in new cryostats
- **Improve copper radiopurity** using advanced techniques (**electroforming**)
- Improve **purification processes of Li_2CO_3 and MoO_3 powders** used to form the Li_2MoO_4 molecule to be crystallized (R&D ongoing)

Full α rejection down to BI < 10^{-5} counts/keV/kg/y is assumed

Paths for improvement: detector technology

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



mainly ^{130}Te

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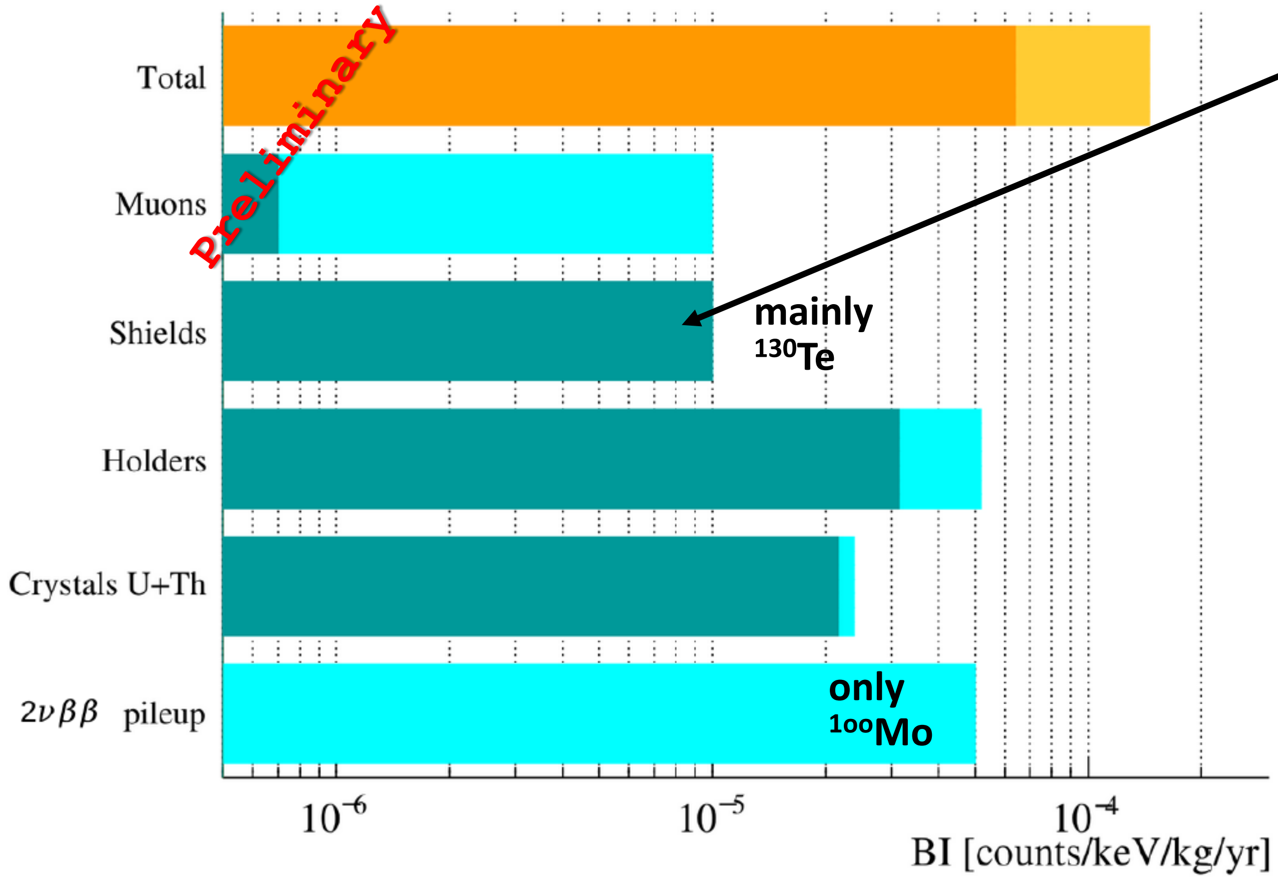

mainly ^{130}Te

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Solutions for background reduction

- **Active veto** immediately around the detectors in the millikelvin region - BINGO

Paths for improvement: detector technology

CUPID background model
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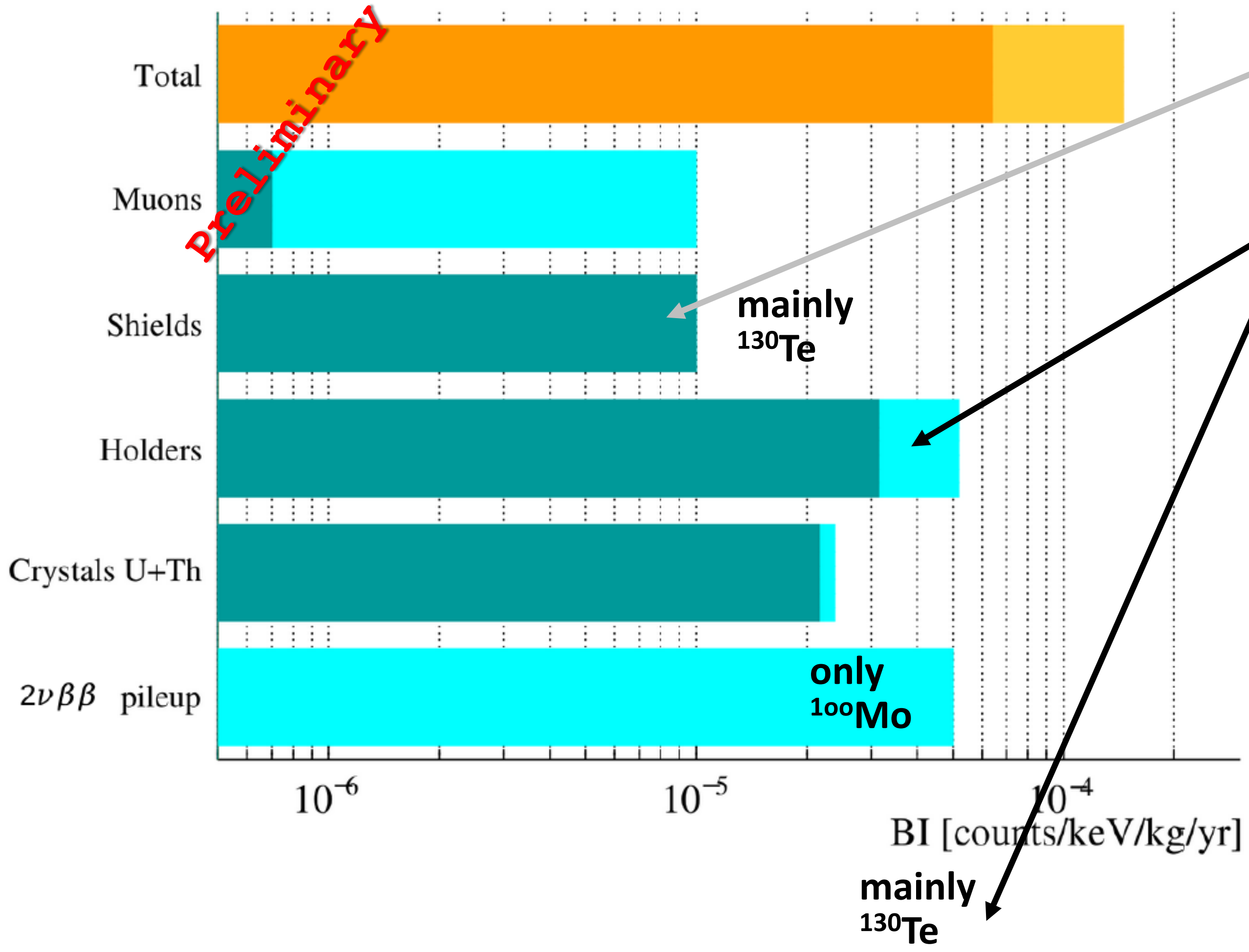

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- **Surface sensitive detectors** to reject **both α and β** surface radioactivity from holders - CROSS

Paths for improvement: detector technology

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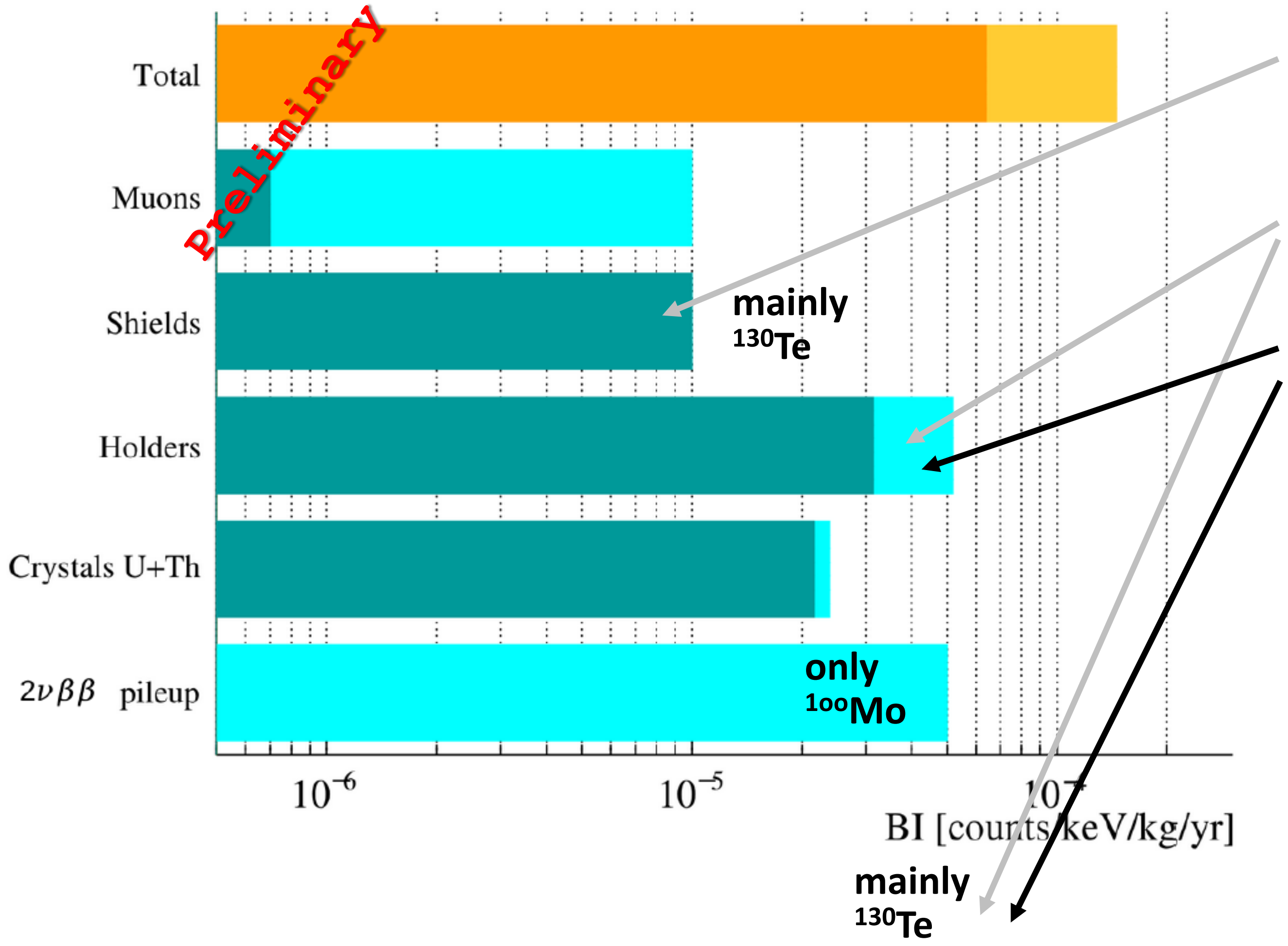

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Paths for improvement: detector technology

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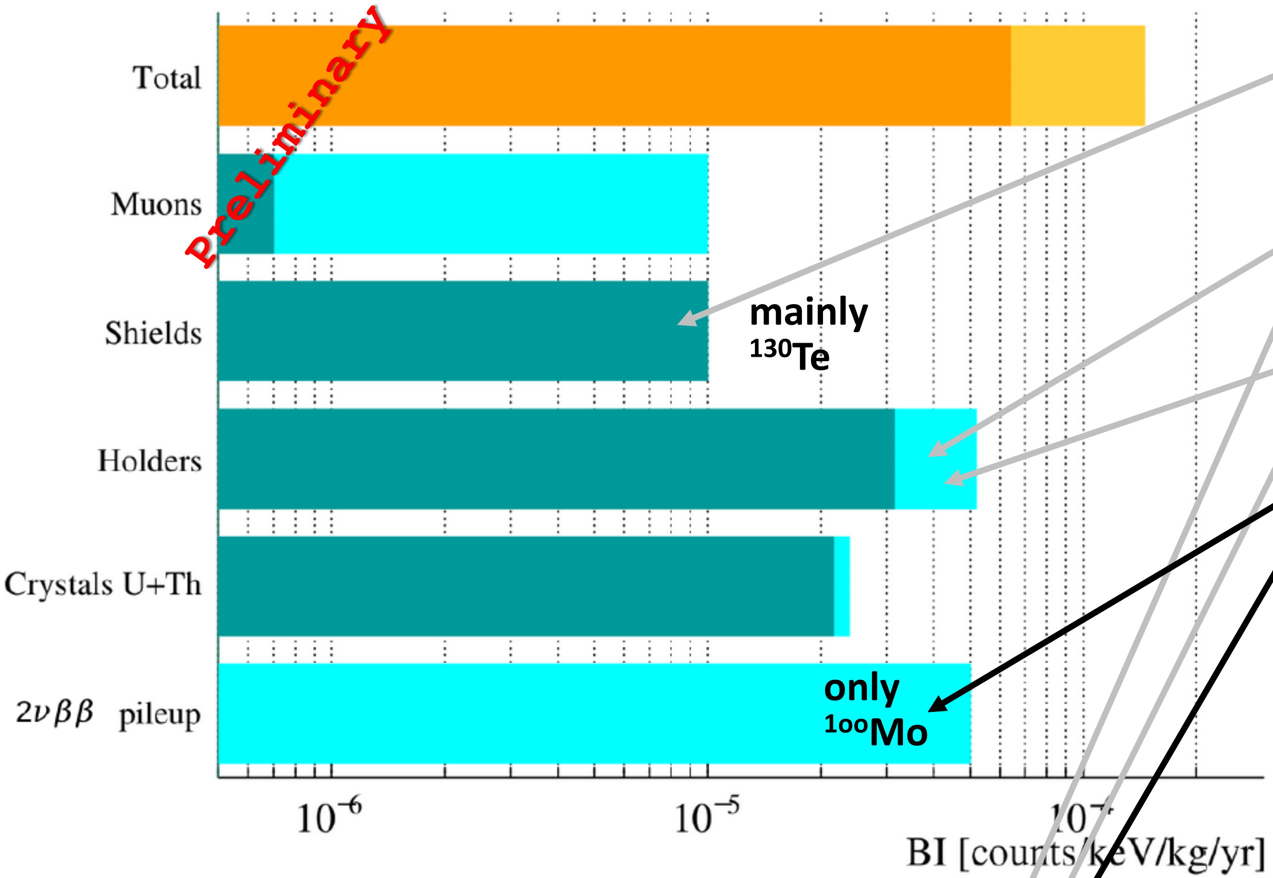

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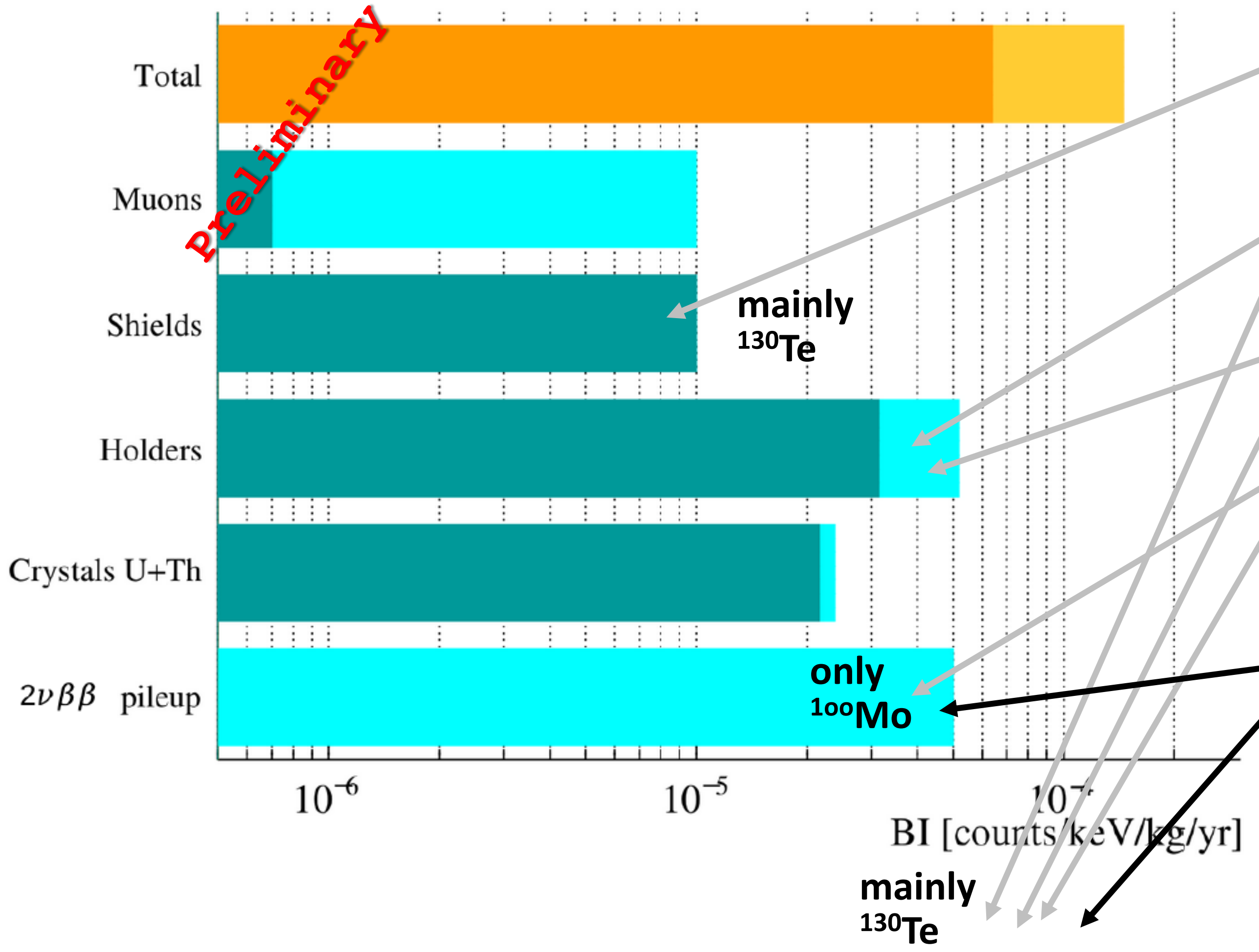

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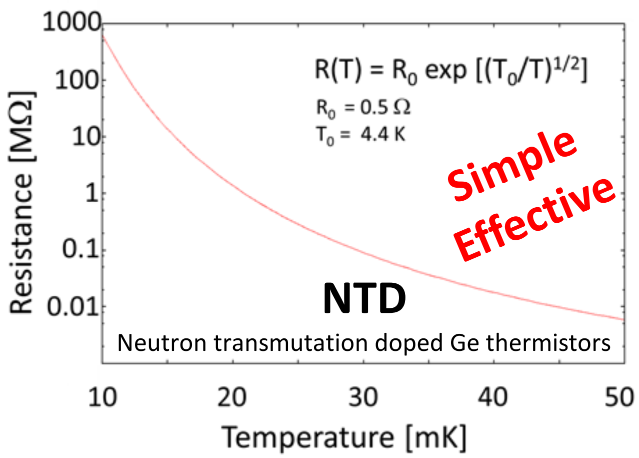
Paths for improvement: detector technology



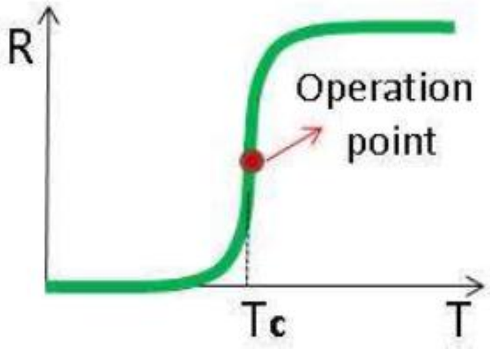
NTD

Neutron transmutation doped Ge thermistors

Solution adopted in CUORE, CUPID

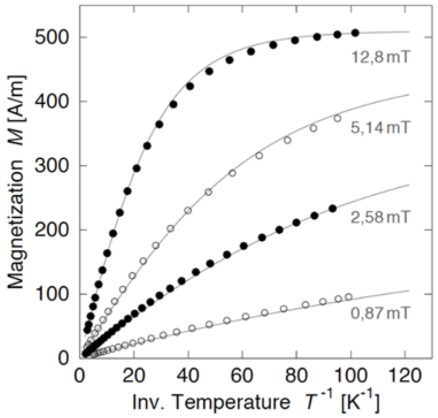
- High impedance
- Gluing

→ **1-20 ms** rise-times



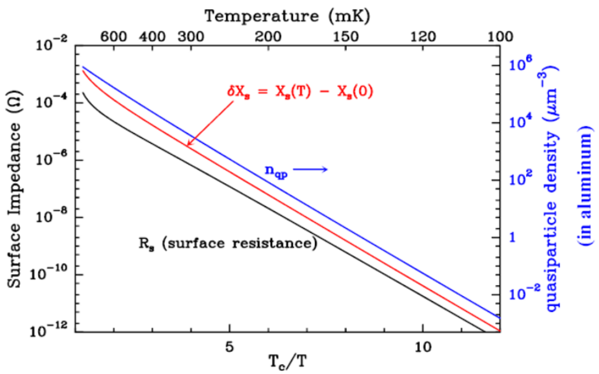
TES

Transition edge sensors



MMC

Metallic magnetic calorimeters

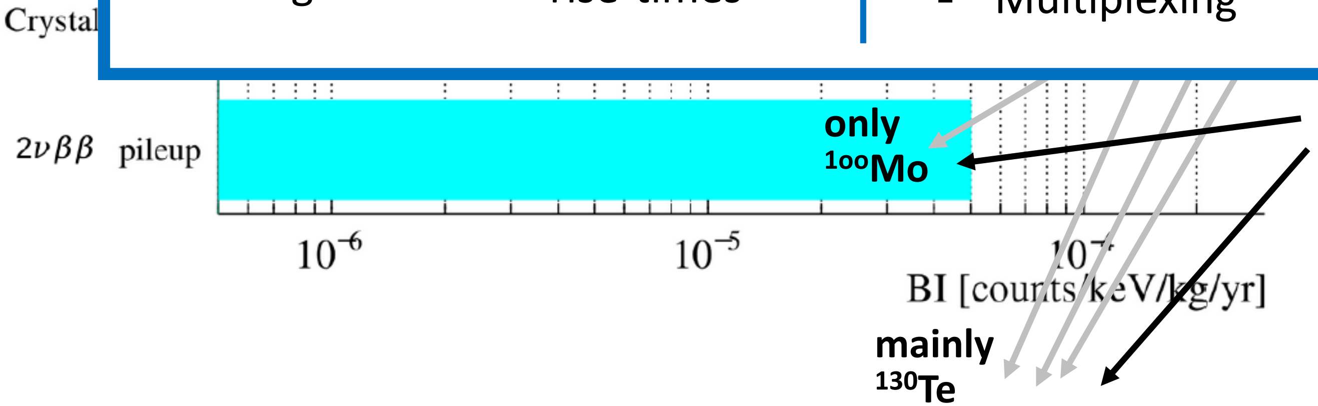


KID

Kinetic inductance detectors

- Better coupling to the absorber
- Low impedance – SQUID readout
- Multiplexing

→ **0.1-1 ms** rise-times



- **Increase light detector speed and signal-to-noise ratio** using **better couplings** and/or **faster sensors** – US CUPID R&D – AMoRE – CALDER

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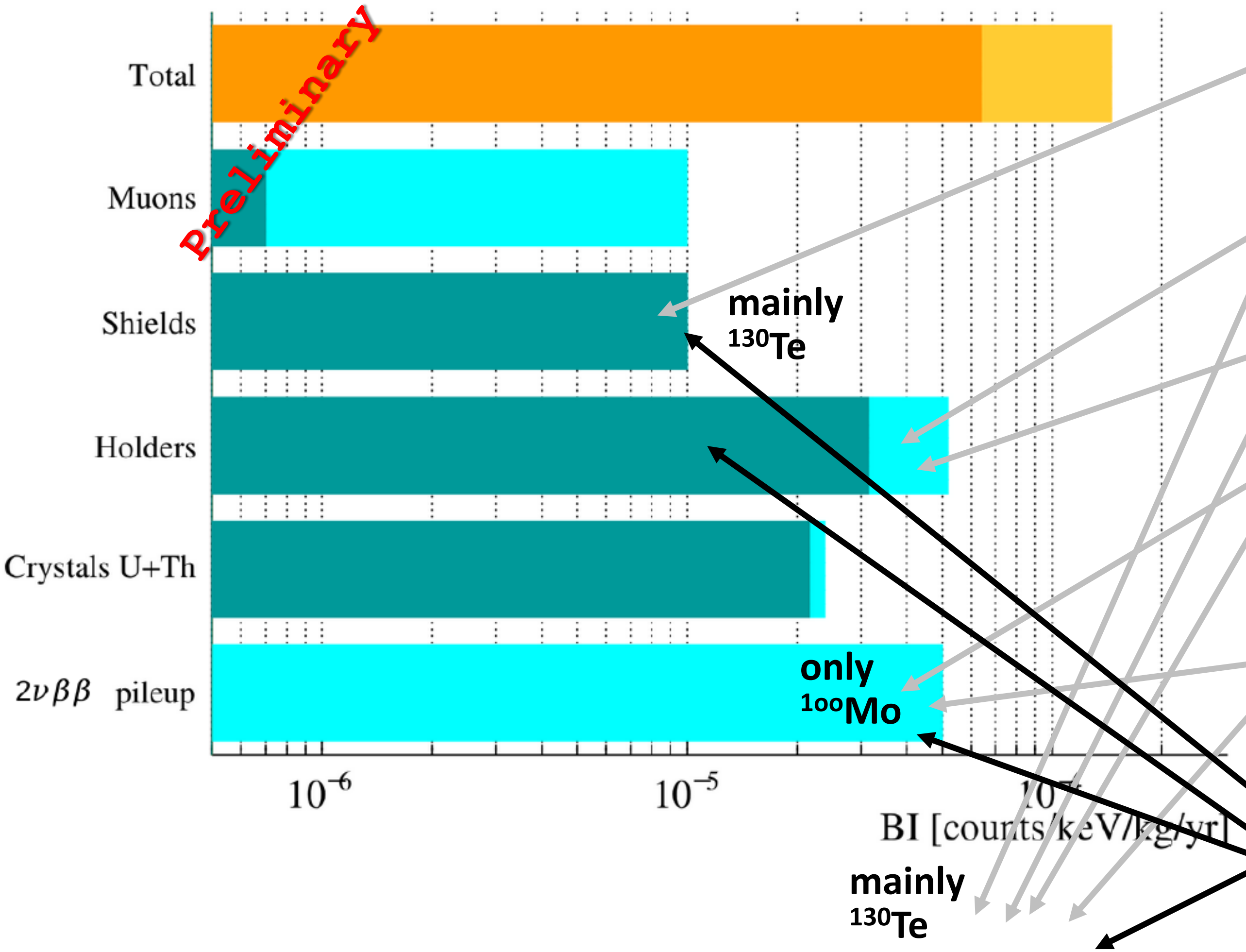
Paths for improvement: detector technology

CUPID background model
Data driven: based on CUORE, CUPID-0, CUPID-Mo



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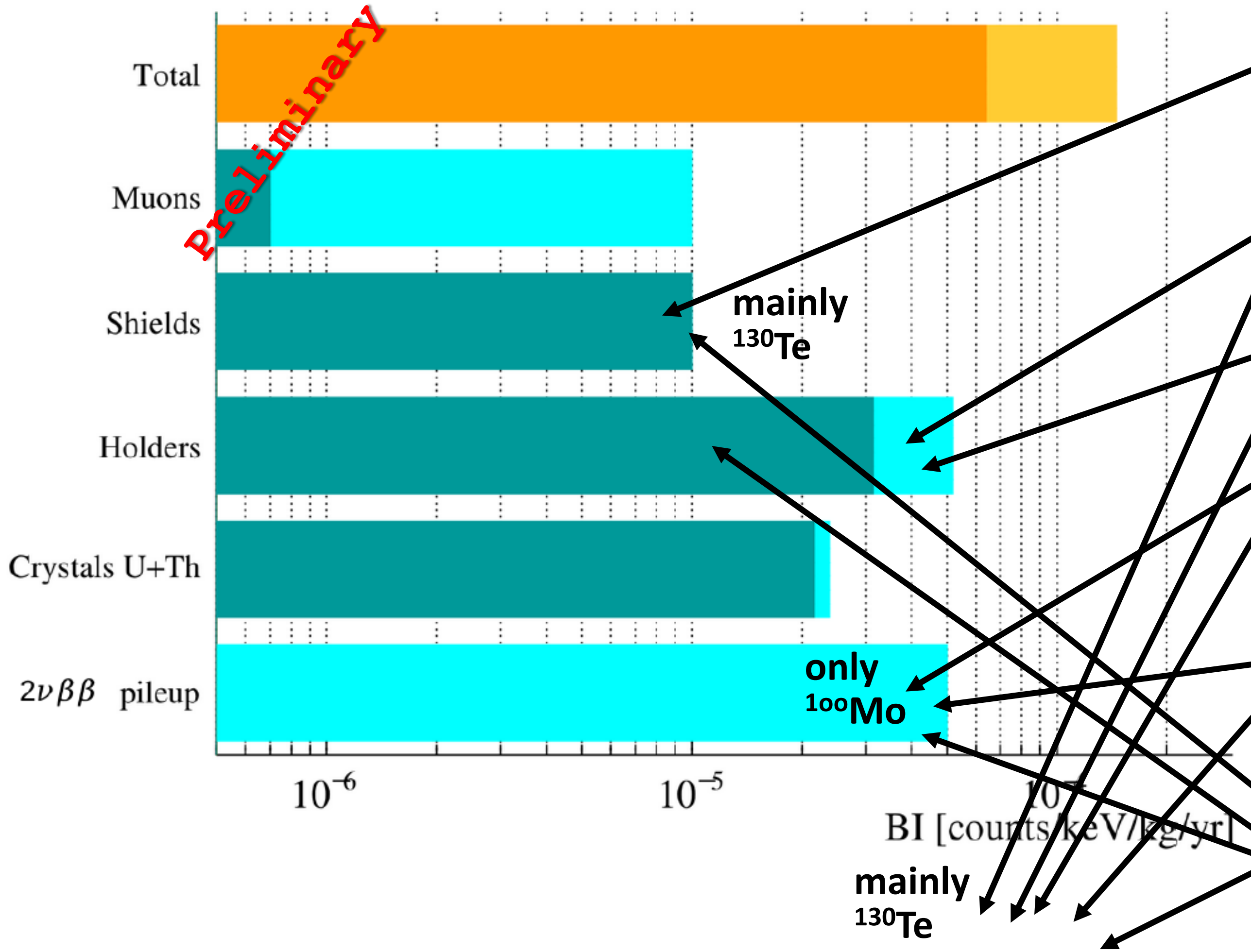

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β surface radioactivity from holder/crystals

^{238}U chain ⟶ ^{214}Bi Q_β = 3.3 MeV
(^{210}Tl Q_β = 5.5 MeV; 0.02% ^{214}Bi)

$$^{214}\mathrm{Bi} \xrightarrow{\beta} {}^{214}\mathrm{Po} \xrightarrow[164\ \mu s]{\alpha} {}^{210}\mathrm{Pb}$$

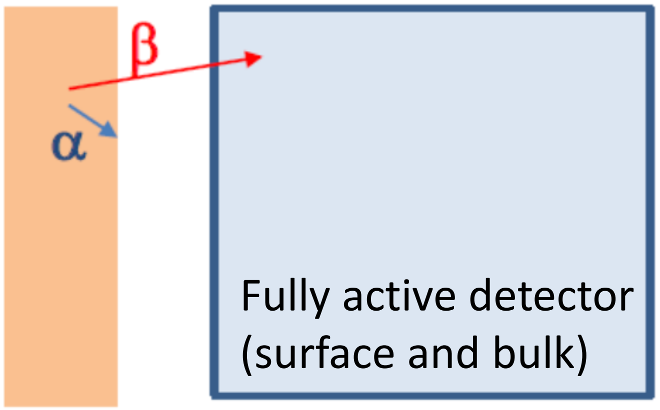
Harmless in the crystal bulk
Mixed α/β event

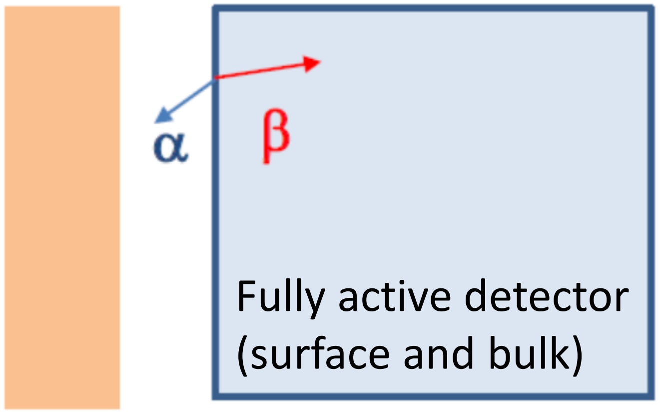
^{232}Th chain ⟶ ^{208}Tl Q_β = 5.0 MeV

$$^{212}\mathrm{Bi} \xrightarrow{\alpha} {}^{208}\mathrm{Tl} \xrightarrow[3.053\ \mathrm{min}]{\beta} {}^{208}\mathrm{Pb}$$

Under control in the crystal bulk
Delayed coincidence

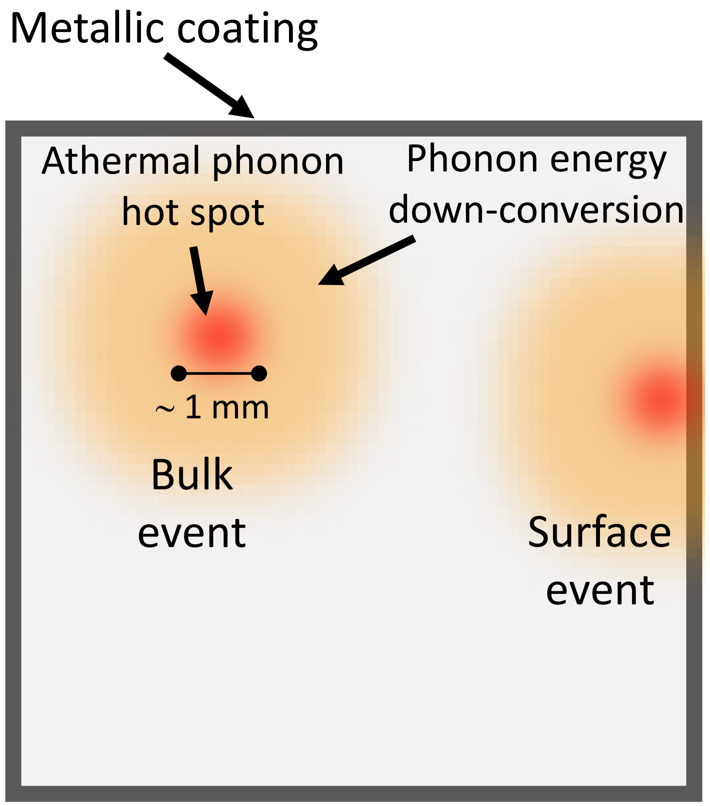
These processes become challenging at the surface ⟶ it may happen that α escapes detection and β is (partially) absorbed





CROSS: tagging surface events

CROSS rationale $\rightarrow$ **metallic film coating** of crystals works as a **pulse-shape modifier** for surface events



First tests with **superconductive films (Al)** to decrease the heat capacity

T_C=1.2 K

$\rightarrow$ **Expectations**: **risetime longer for near-film events**

J. Low Temp. Phys. 167 (2012) 1029

- Al film captures high-energy (30 K) athermal phonons
- Energy is stored in quasiparticles for milliseconds
- Quasiparticles recombine and lower-energy athermal phonons at 1.2 K are emitted
- $\rightarrow$ **delayed component of the signal in near-film events**

Experience: this works only for an **athermal-phonon sensor** (deposited film)

J. High Energ. Phys. (2020) 2020: 18
Appl. Phys. Lett. 118, 184105 (2021

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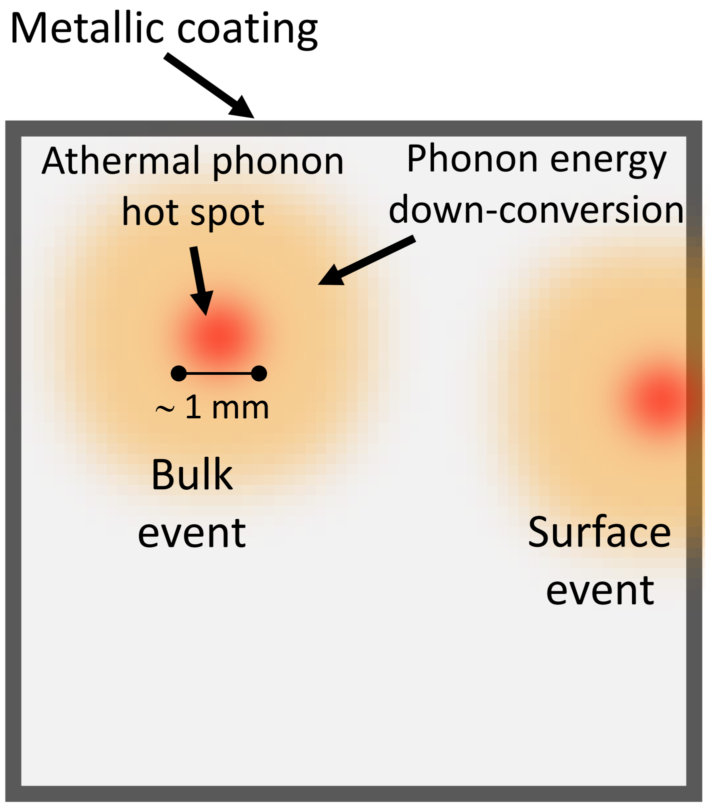

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- $\rightarrow$ **delayed component of the signal in near-film events**

$\rightarrow$ **Experience**: this works only for an **athermal-phonon sensor** (deposited film)

$\rightarrow$ **Reality: risetime shorter for near-film events**!

- Tests were done with CUORE/CUPID readout: **thermal phonon sensors** (NTDs)
- The film converts athermal to low-energy phonons faster than spontaneous phonon decay
- $\rightarrow$ **thermalization is accelerated by the film in near-film events**

To validate this interpretation, we decided to perform a direct test with a **double-sensor device**
Both NbSi film and NTD Ge thermistor on the same Al-coated (one face) TeO_2 crystal

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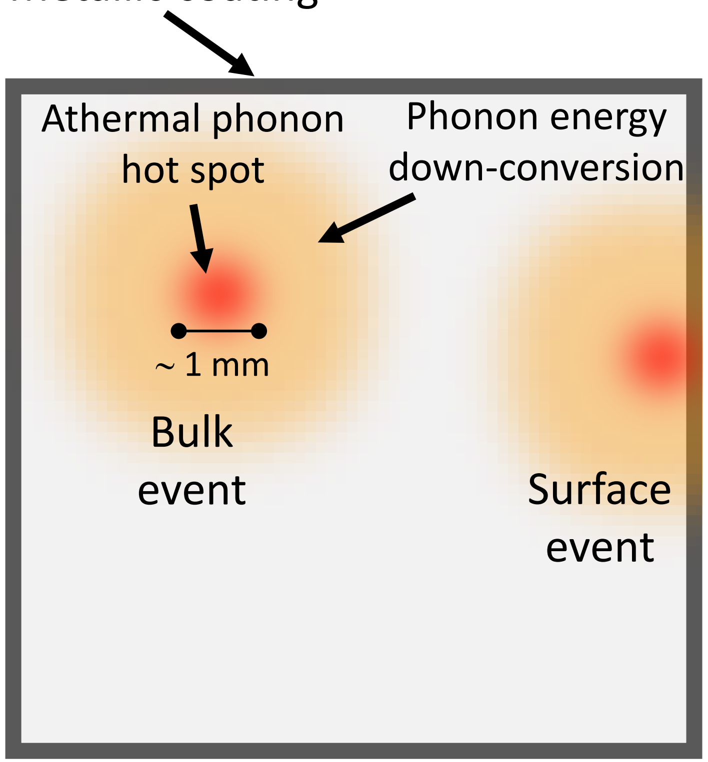
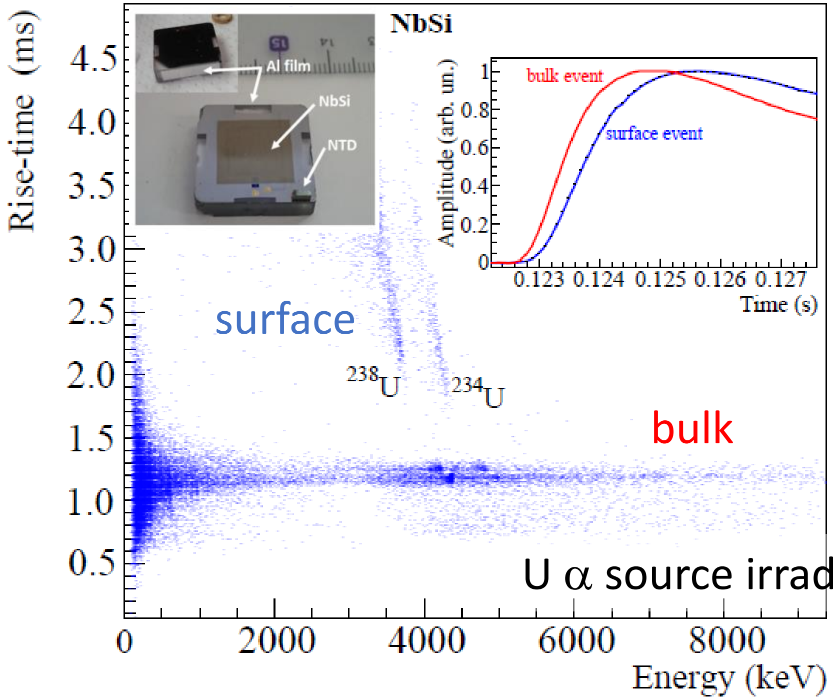
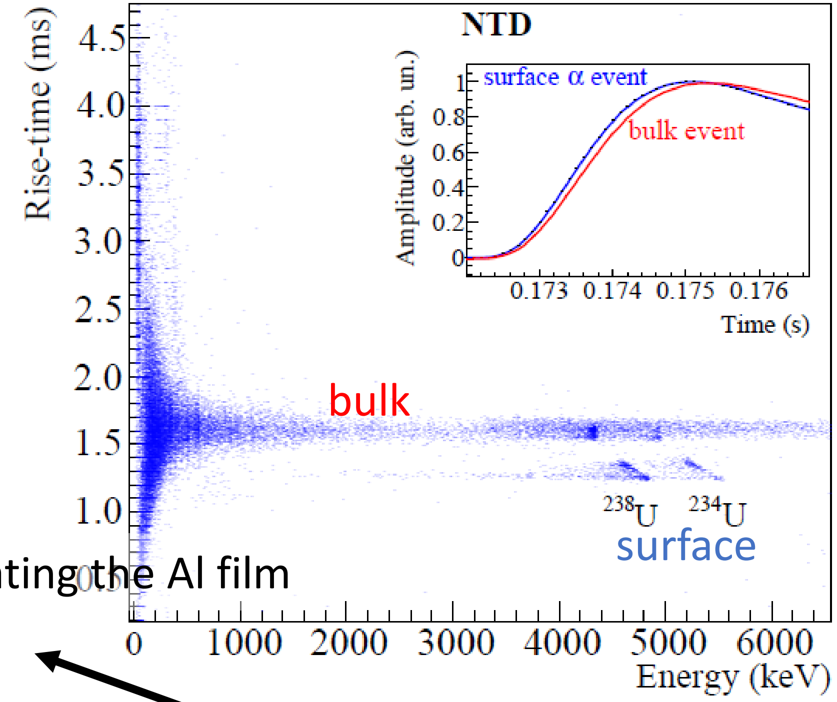


NbSi large-area film (deposited)



NTD Ge thermistor (glued)



U α source irradiating the Al film

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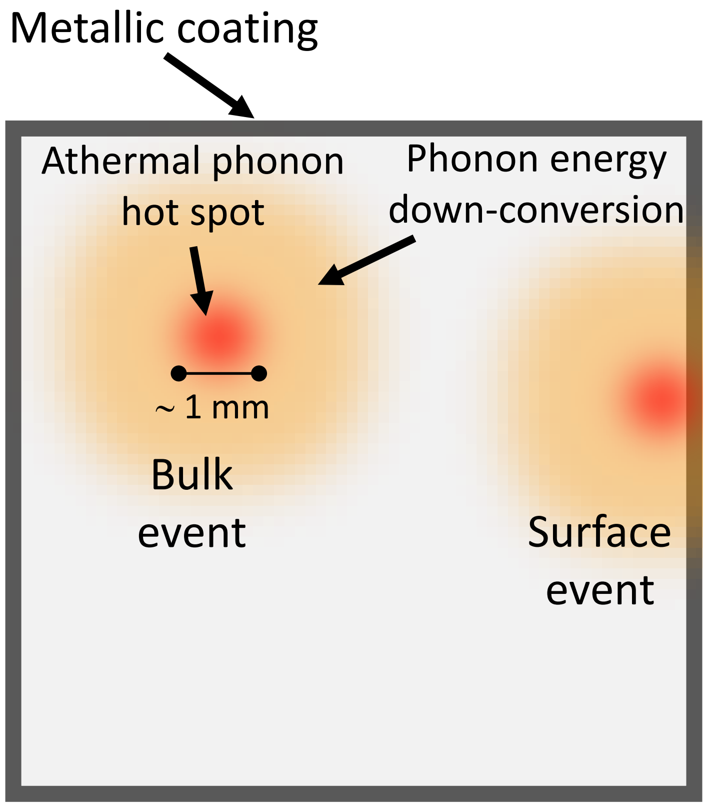

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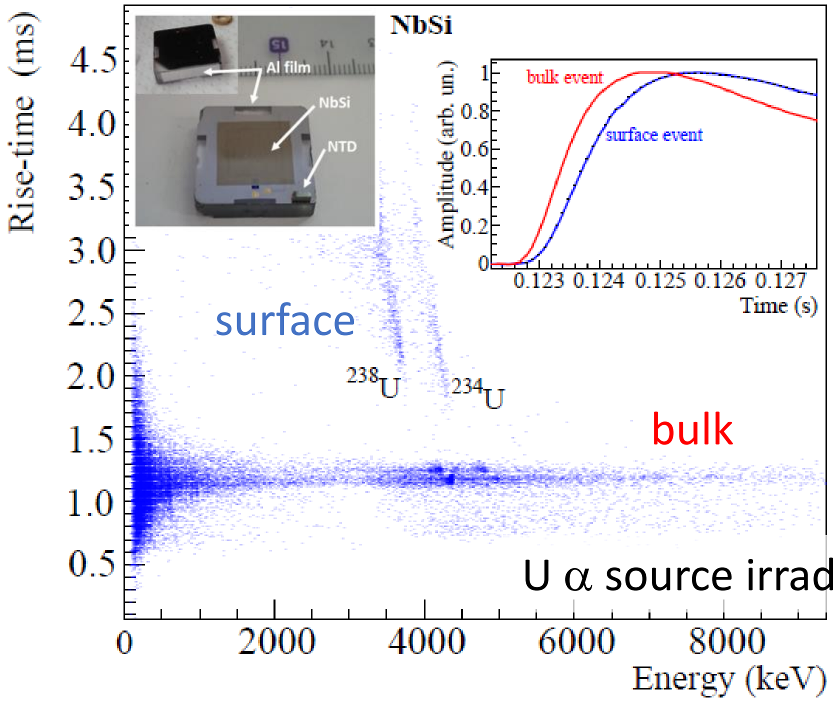
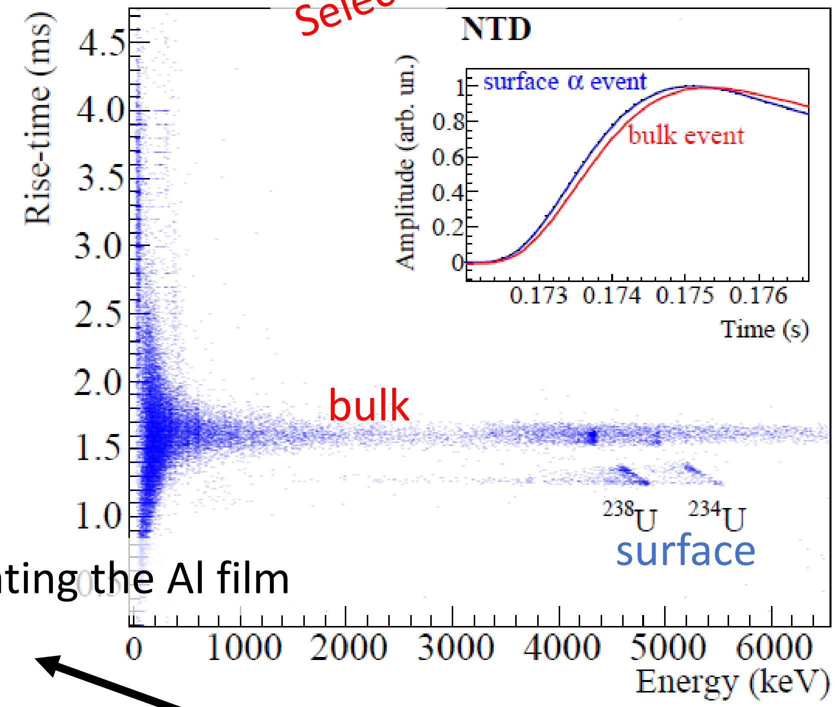


NTD Ge thermistor (glued)

Selected for CROSS



U α source irradiating the Al film

To validate this interpretation, we decided to perform a direct test with a **double-sensor device**
Both NbSi TES and NTD Ge thermistor on the same Al-coated (one face) TeO_2 crystal

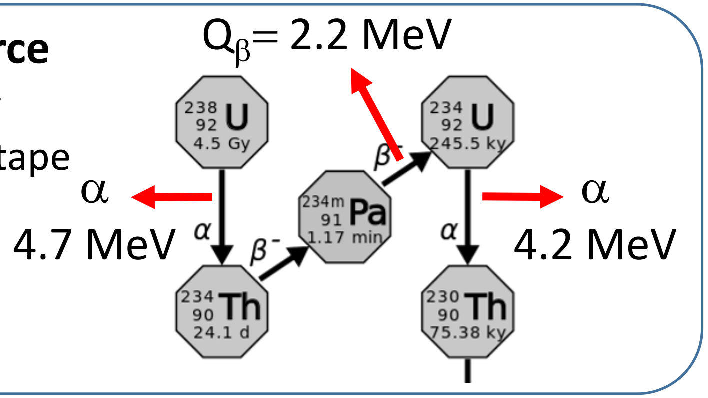
Test on prototypes: the Al way

CROSS selected compounds:
Li_2MoO_4 (CUPID) and **TeO_2** (CUORE)

Preliminary above-ground investigation with 20x20x10 mm crystals **with a** coated 20x20 mm face

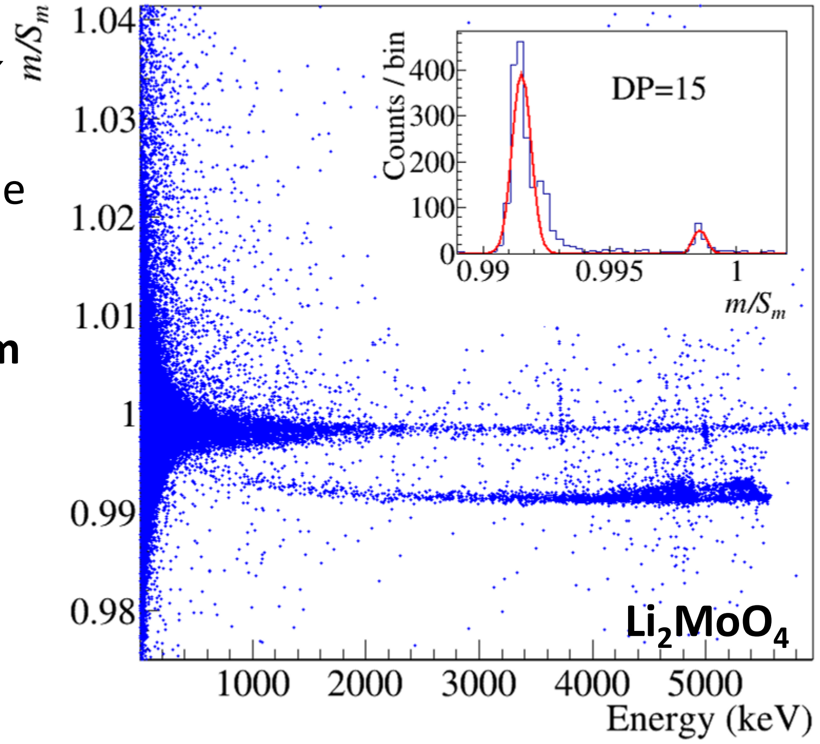
Work **U calibration source** for surface sensitivity
Drop of liquid source on Cu tape

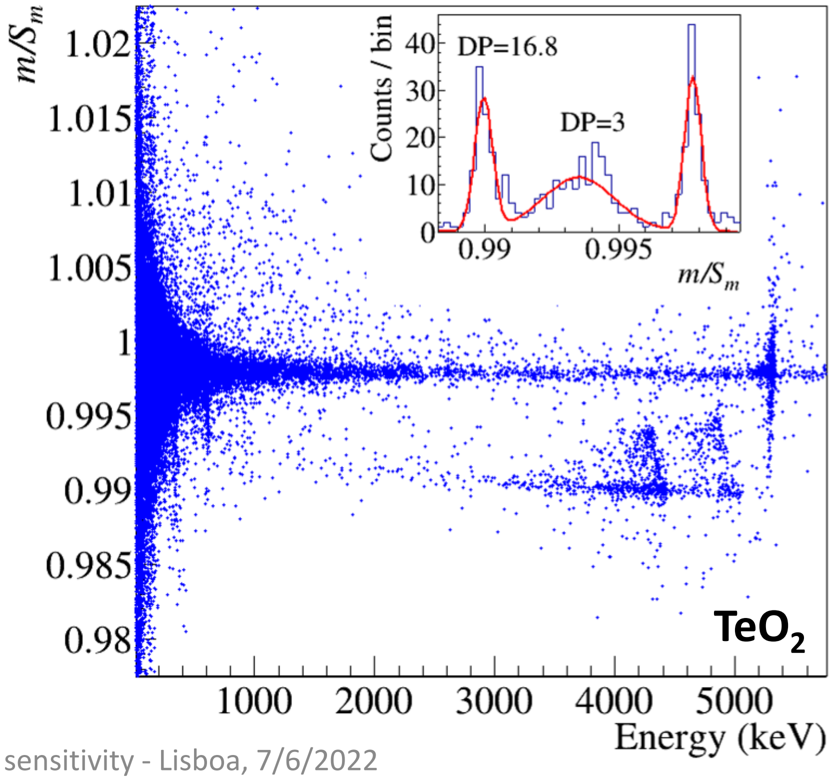
Mixed α/β emission



Special pulse-shape parameter

Al 10 μm thick film





Excellent bulk/surface separation for α particles

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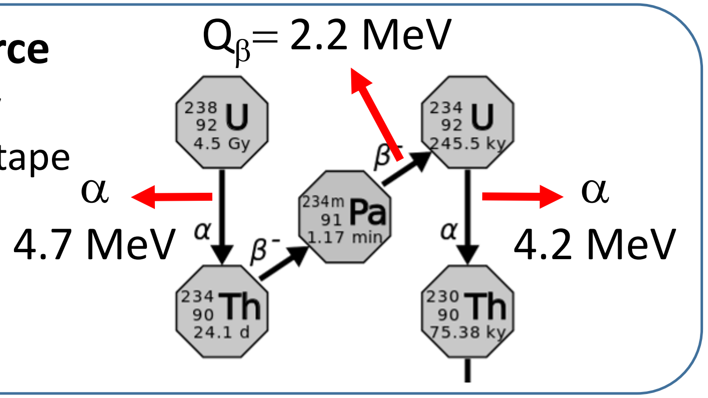
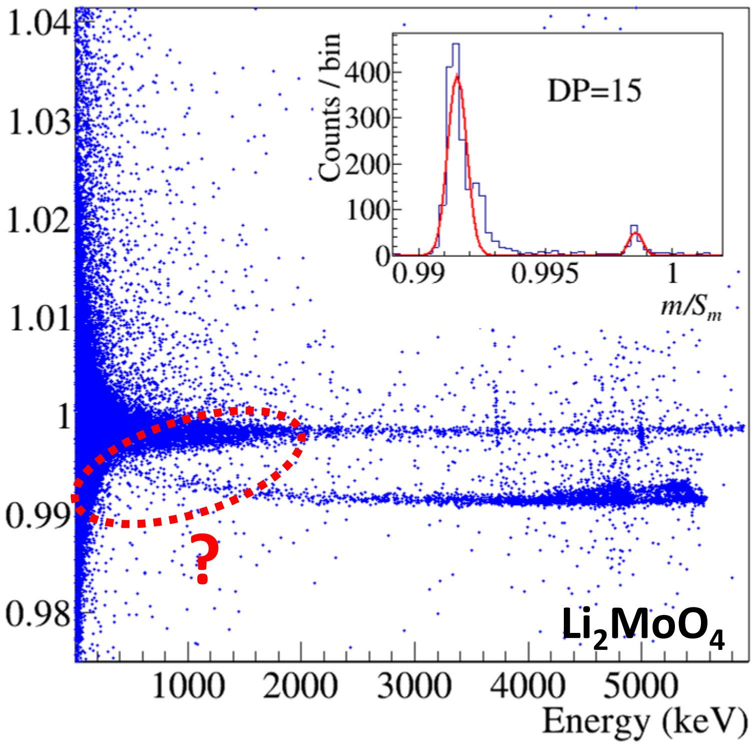
Drop of liquid source on Cu tape

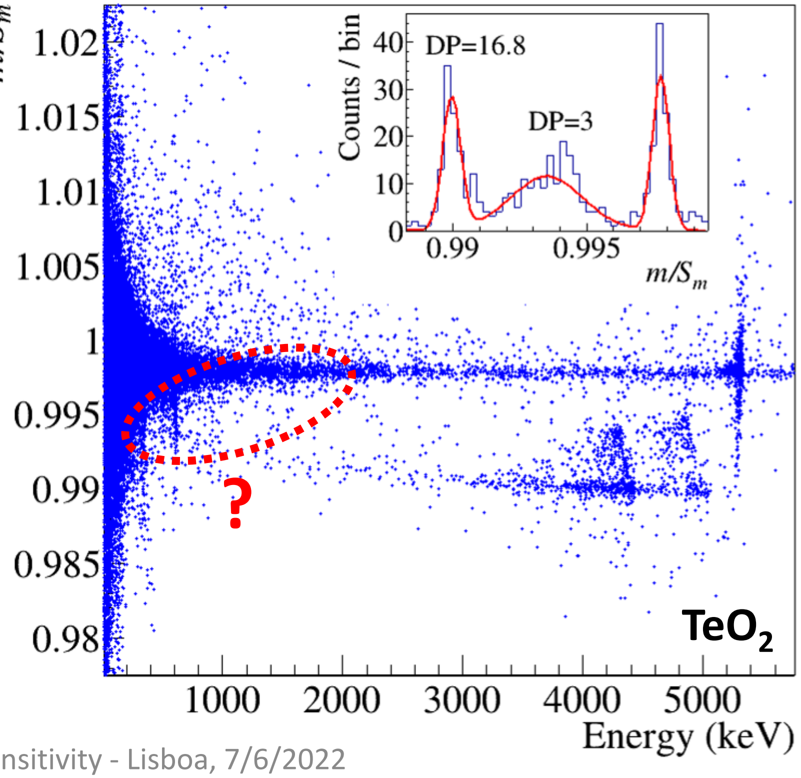
Mixed α/β emission



Special pulse-shape parameter

Al 10 μm thick film





Excellent bulk/surface separation for α particles

No clear hint of identification of surface β's

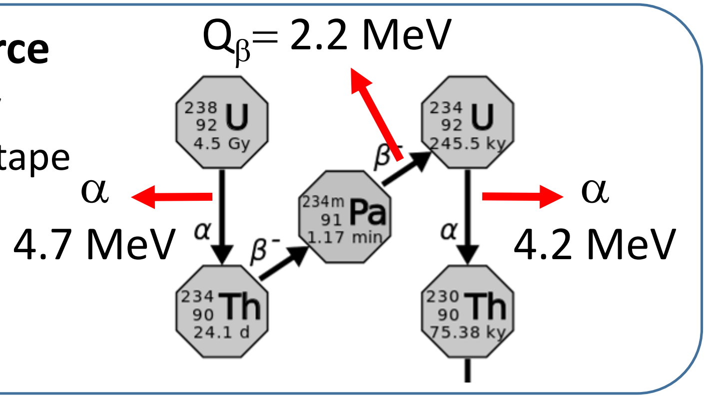
Test on prototypes: the Al way

CROSS selected compounds:
Li_2MoO_4 (CUPID) and **TeO_2** (CUORE)

Preliminary abo
crystals **with a**

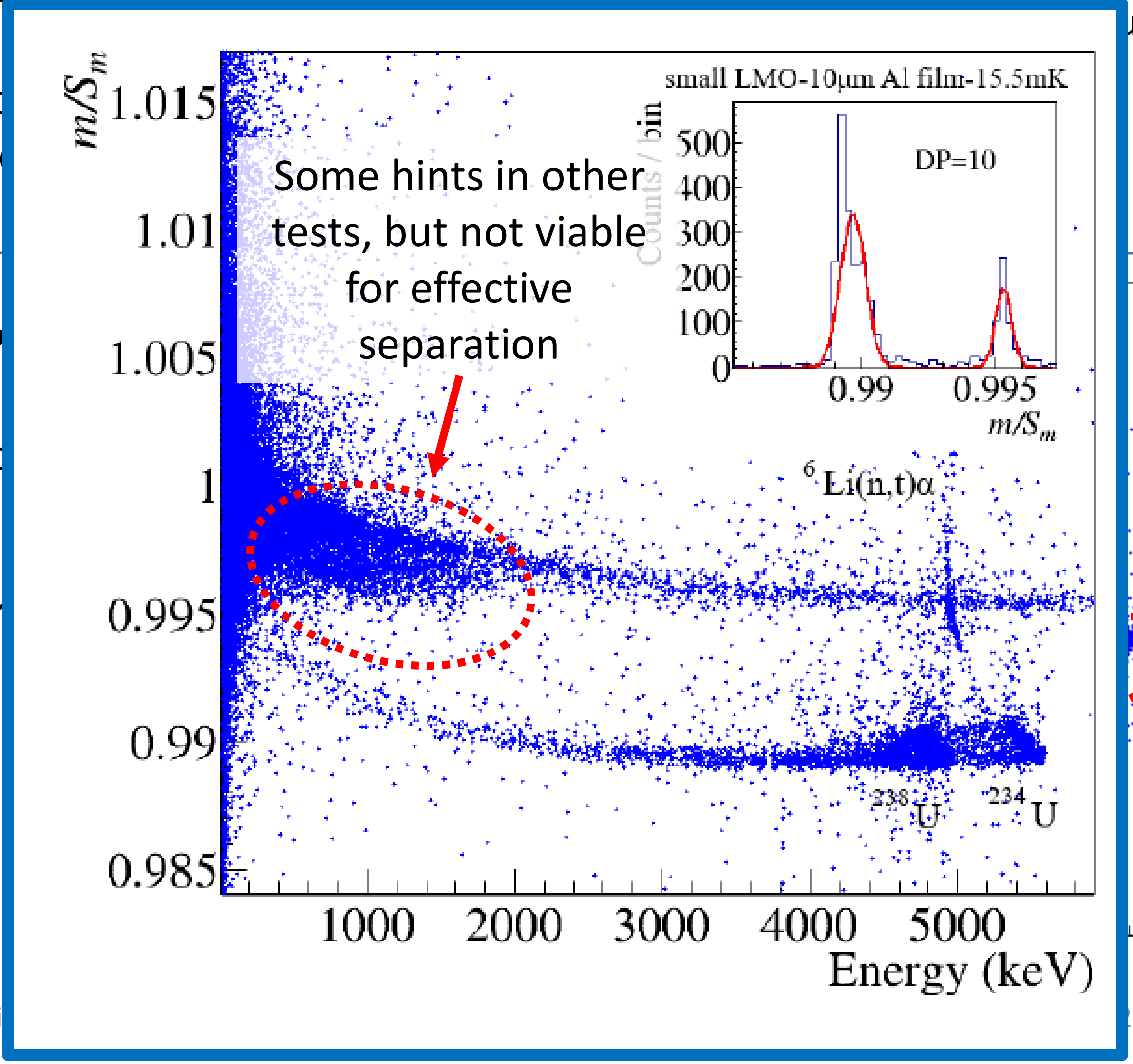
Work **U calibration source** for surface sensitivity
uid source on Cu tape

α/β emission

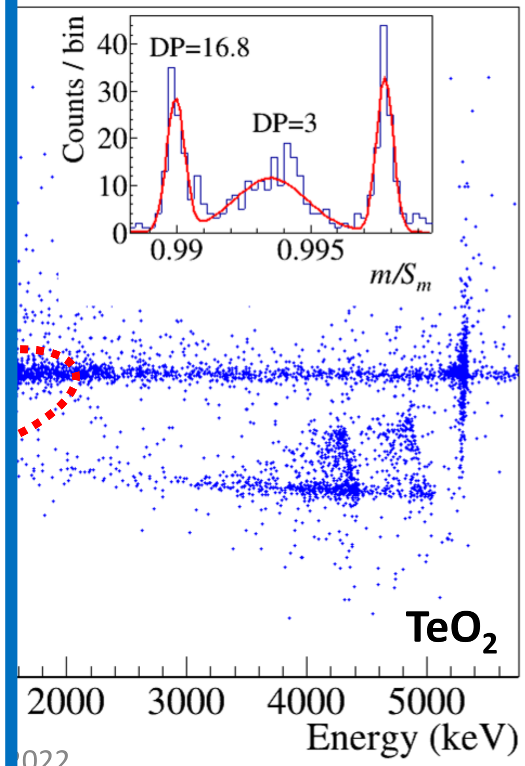


Special pulse-shap
parameter

Al 10 μm thick fil



Some hints in other tests, but not viable for effective separation



Excellent bulk/surface separation for α particles

No clear hint of identification of surface β's

Test on prototypes: the Pd way

Potential **drawback of Al**: competition between accelerated thermalization and slowing quasiparticle trapping

Move to a potentially more efficient thermalizer → a **normal metal** → **Pd** chosen for possibility of thin continuous films

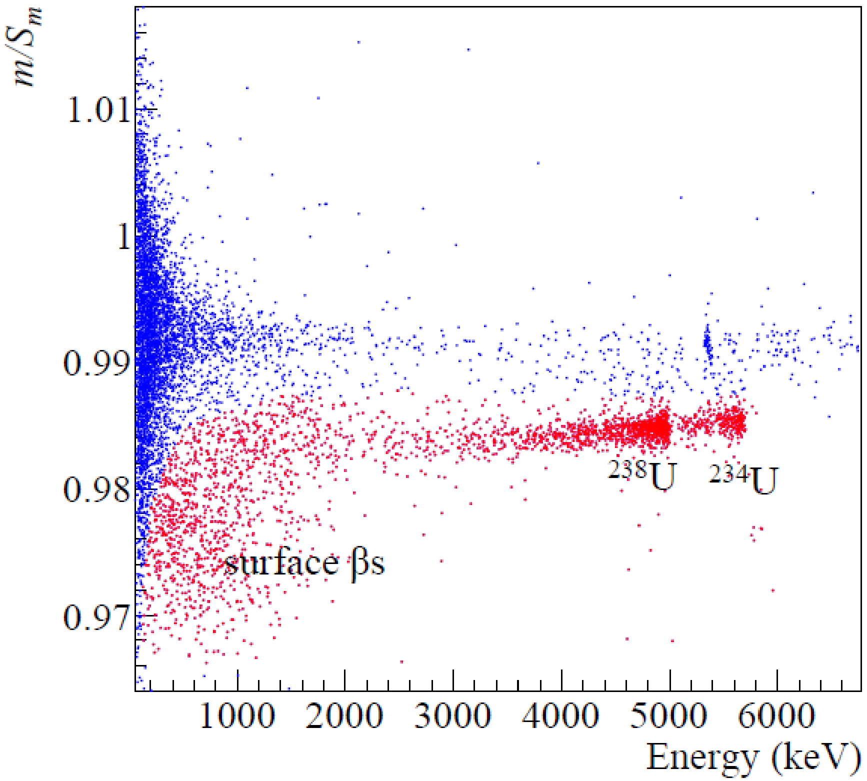
Pd 10 nm thick film → much thinner film in order to reduce the normal electron heat capacity

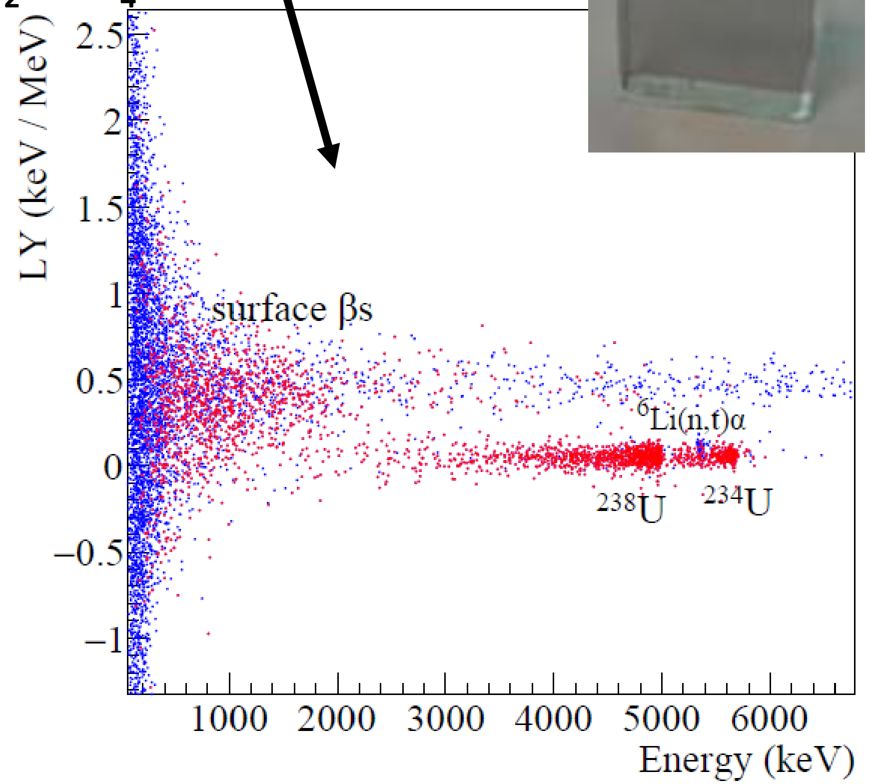
The assembly included also a **light detector**

Li_2MoO_4

Clear **surface β separation** observed at low energy

Drawback Strong reduction of the heat sensitivity due to the Pd specific heat





Test on prototypes: the Pd-Al way

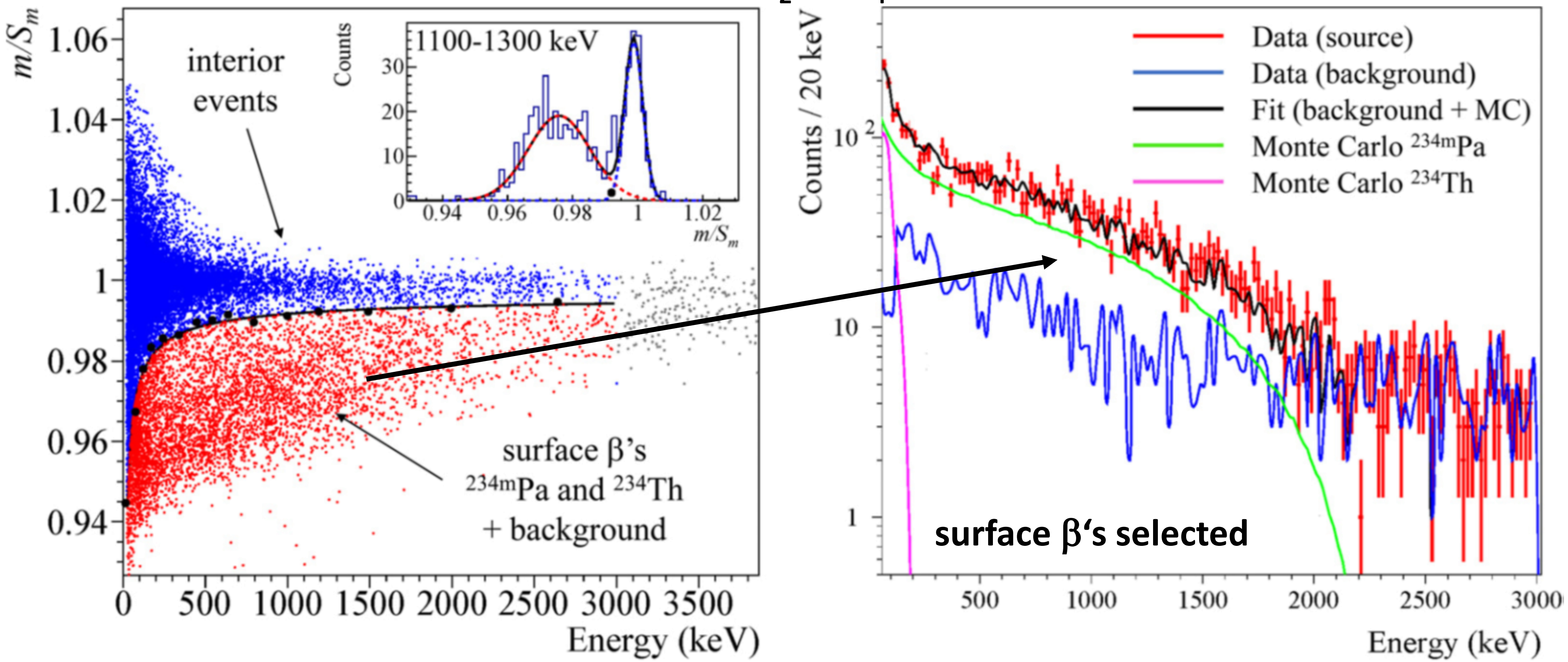
T_C=0.7 K

Pd-Al 10 nm-100 nm bilayer to recover heat sensitivity → superconductivity induced in Pd by **proximity effect**

Quantitative test of the β surface sensitivity

1. Use α peaks to model the source depth profile
2. Generate the expected β spectrum by MonteCarlo
3. Fit real data considering background
4. Evaluate number of β counts contained in spectrum → 3526(81)
5. Estimate this number independently by α counts → 3455(273)

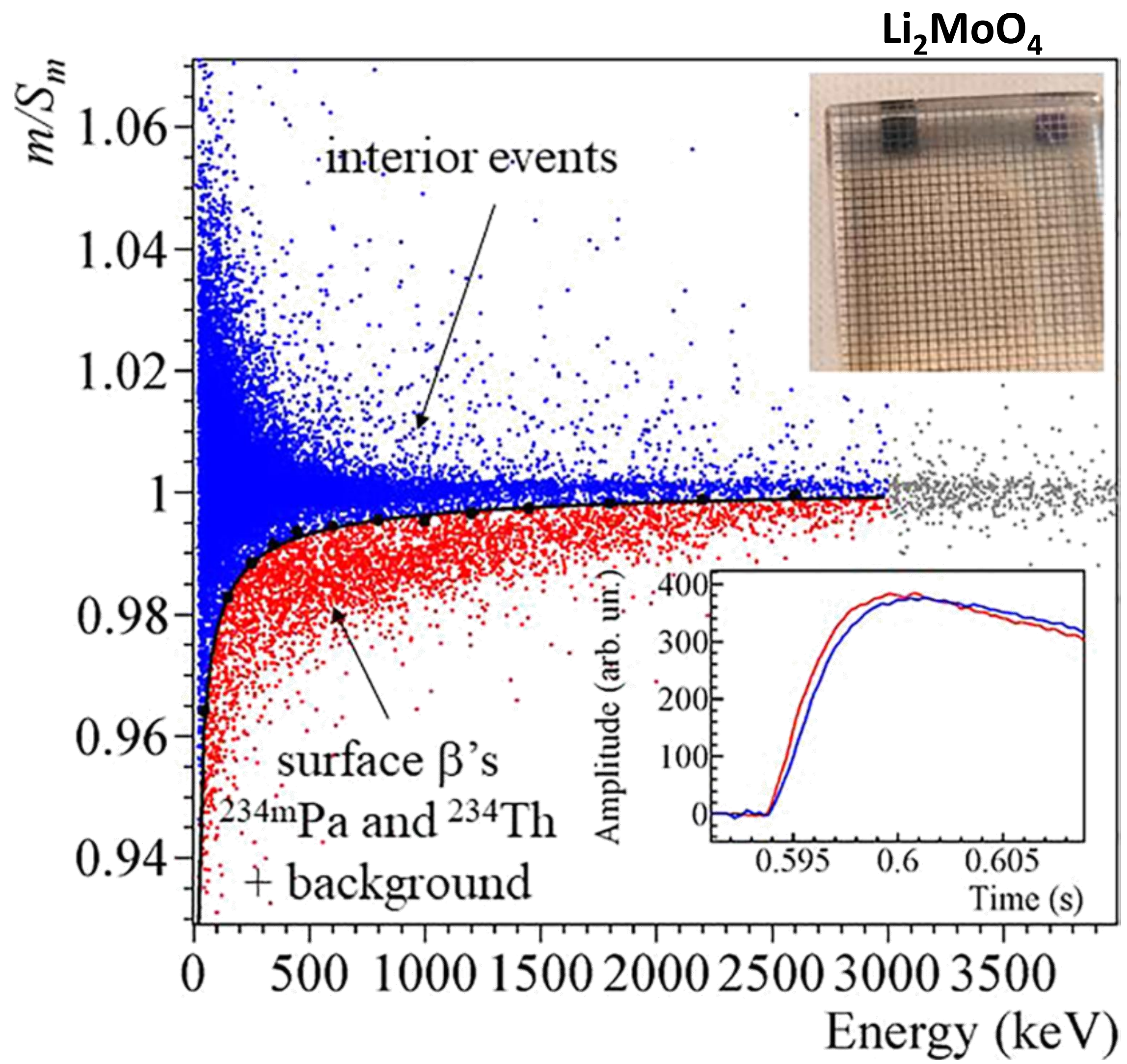
Li_2MoO_4



102(8)% efficiency

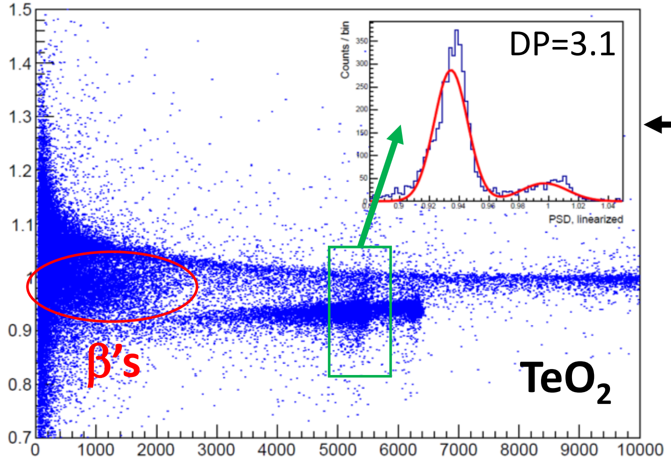
Bulk event acceptance > 99%

Test on prototypes: the Pd-Al way



Move from continuous films to grids

- Further decrease of the heat capacity
- Possibility to extract light → redundancy
- Geometrical parameters to optimize surface sensitivity



Confirmation of the effect in **TeO_2**

Current objectives

- Transfer technology to fully-coated large crystals
- Test reproducibility in the **CROSS demonstrator (Canfranc underground laboratory)**

Bases of the BINGO technology

Isotopes

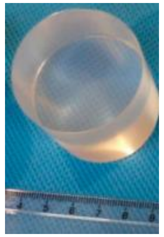
^{100}Mo Q = 3034 keV > 2615 keV – AI: 9.7%

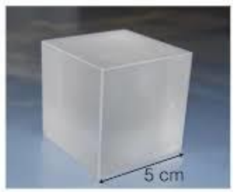
^{130}Te Q = 2527 keV < 2615 keV – AI: 34%

Crystals

Li_2MoO_4

TeO_2





Excellent bolometric properties

High radiopurity → CUPID-Mo, CUORE

Extensively tested

α rejection **heat-light double readout**

Li_2MO_4: scintillator

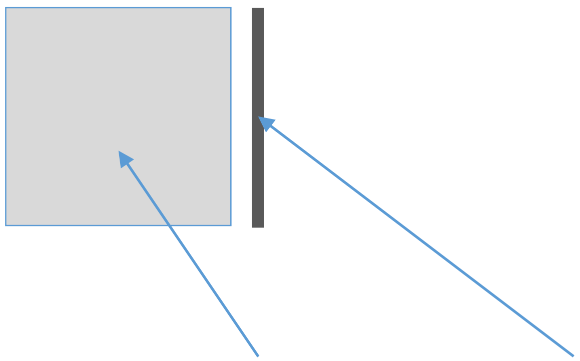
TeO_2: only Cherenkov light → Feeble light yield: **Outstanding light detector required**

NTD readout / Electronics → Keep successful CUORE / CUPID-Mo solutions

Innovative elements in BINGO

arXiv:2204.14161

The BINGO technology is based on **three innovations** in the detector structure and conception



Crystal + light detector (Ge)

(Li_2MoO_4 or TeO_2)

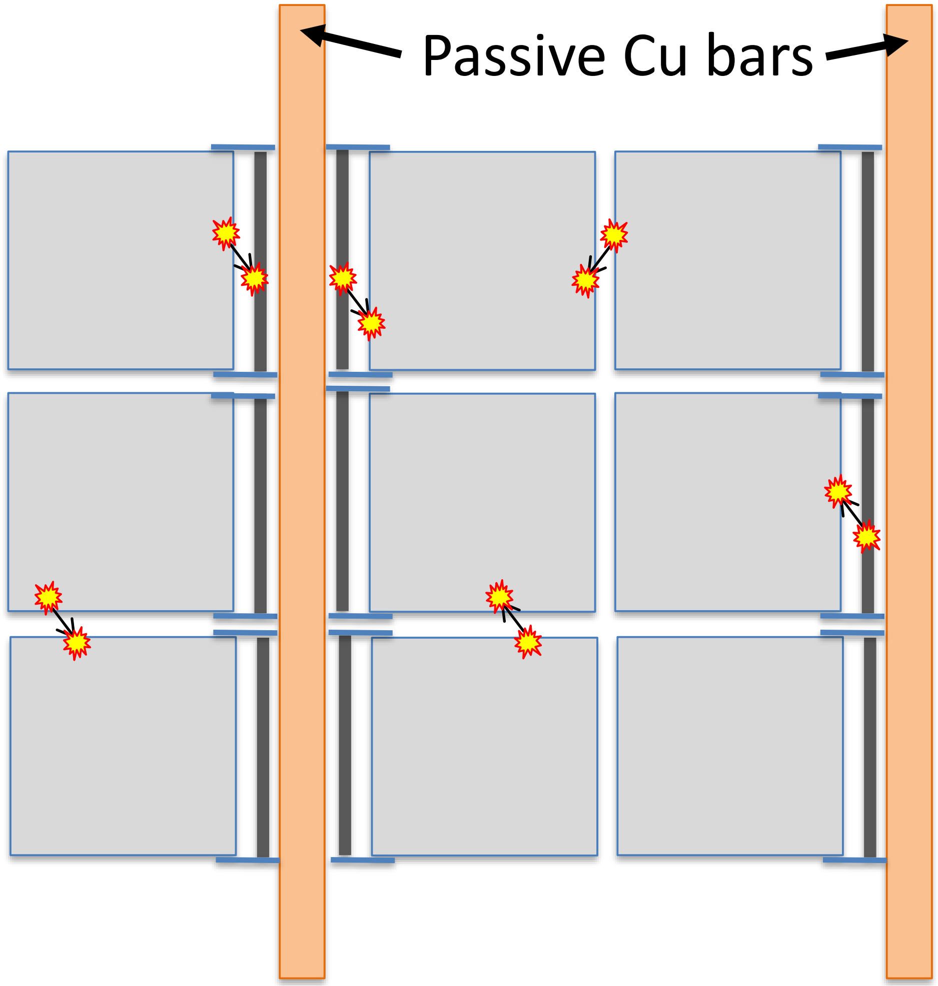
Innovative elements in BINGO

The BINGO technology is based on **three innovations** in the detector structure and conception

① Innovative assembly of the detectors

The crystal will be surrounded only by active elements

→ **Mitigate surface radioactivity by anticoincidence**



Innovative elements in BINGO

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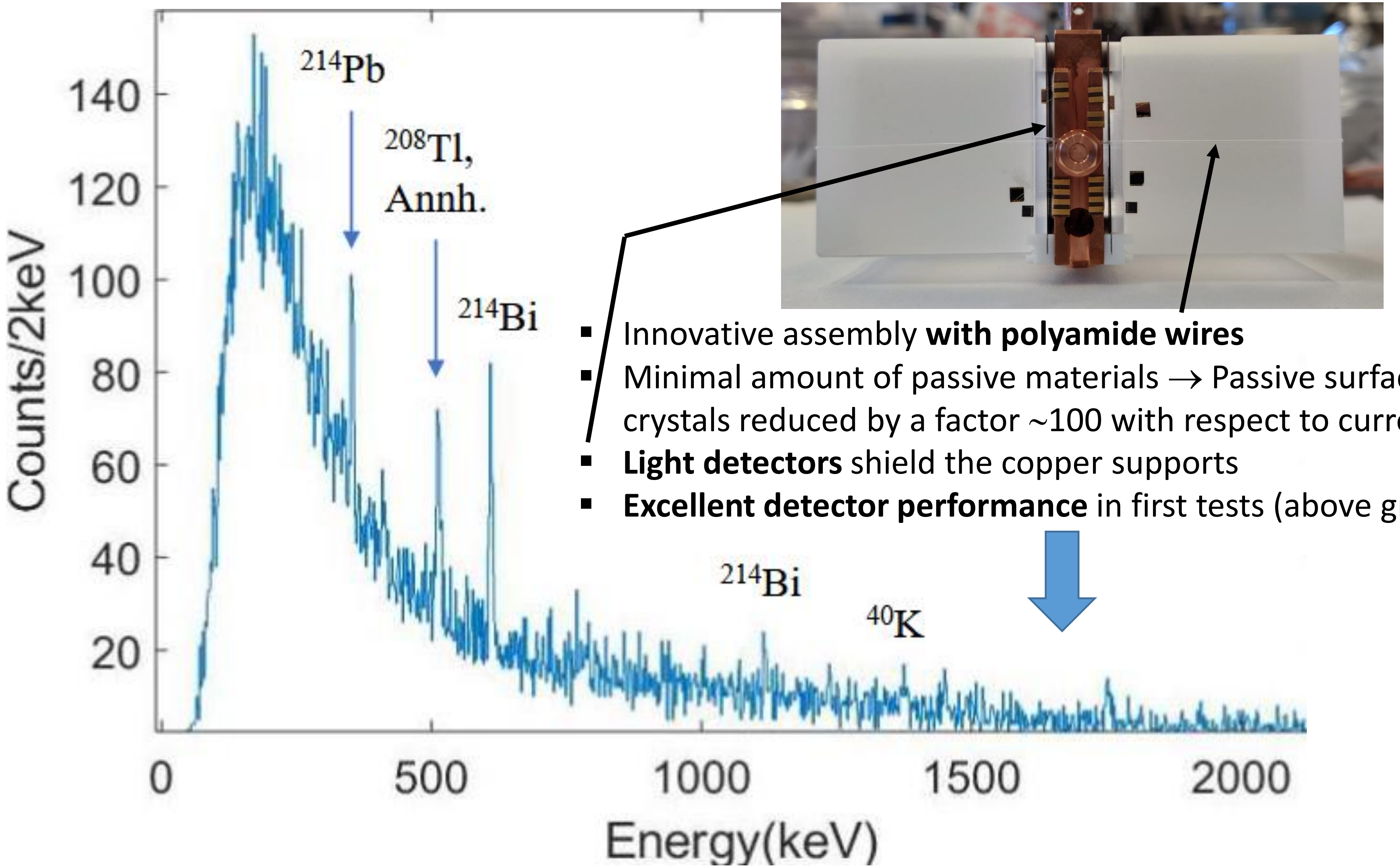
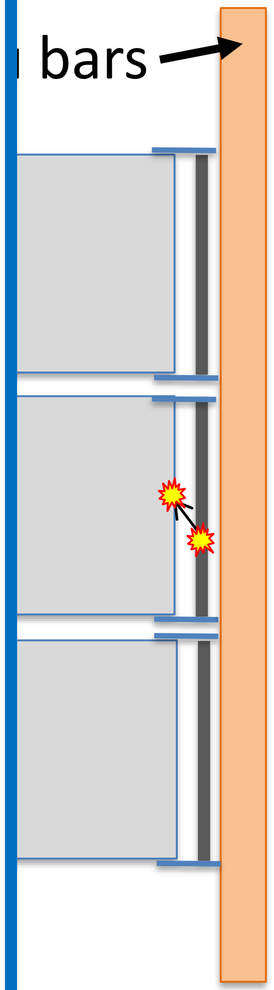


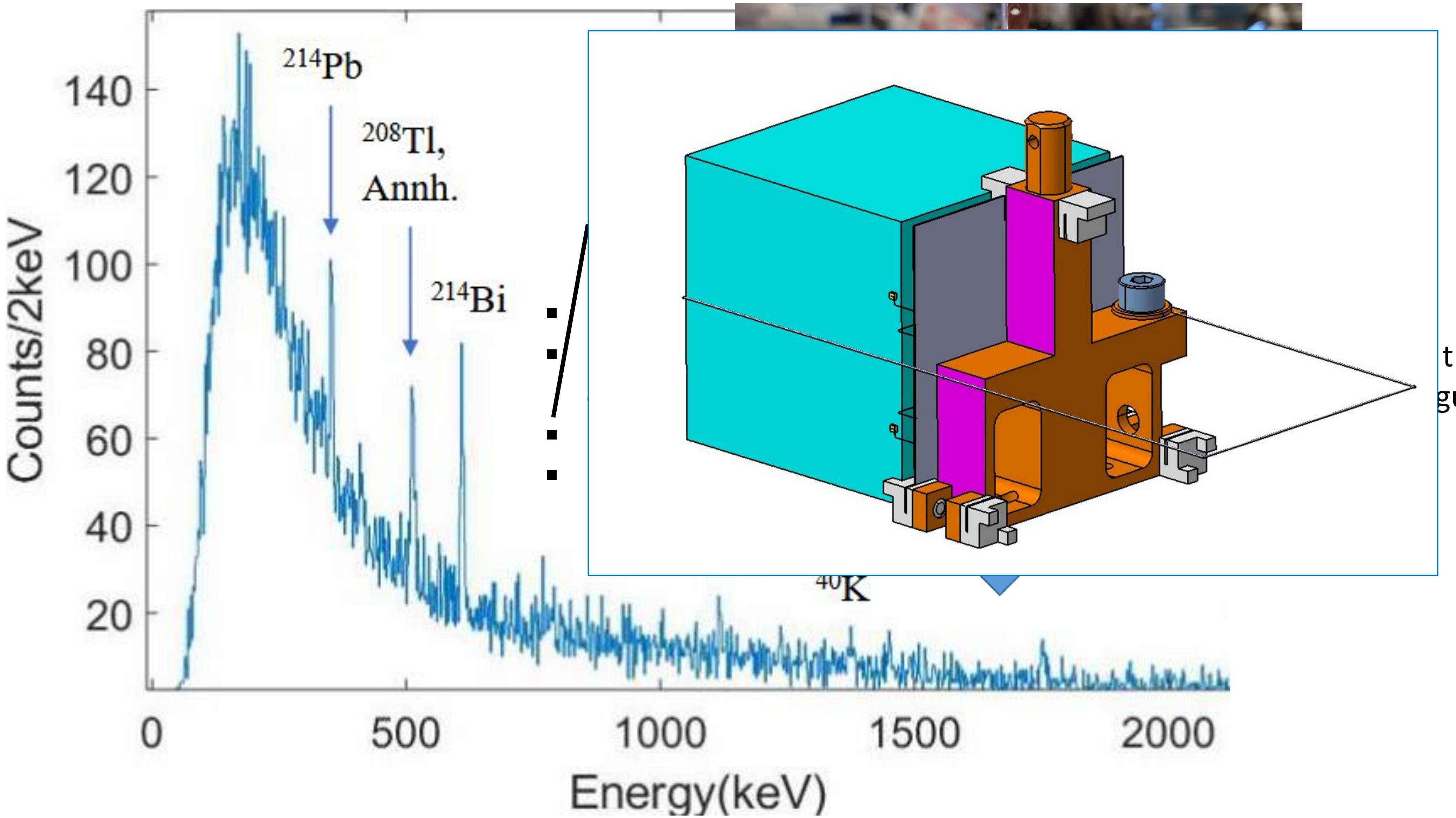
- Innovative assembly **with polyamide wires**
- Minimal amount of passive materials → Passive surface facing the crystals reduced by a factor ~100 with respect to current configuration
- **Light detectors** shield the copper supports
- **Excellent detector performance** in first tests (above ground)

bars

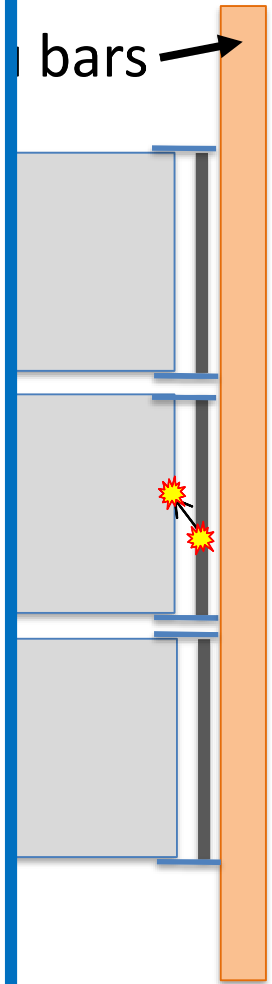


Innovative elements in BINGO

The BINGO technology is based on **three innovations** in the detector structure and conception



bars



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① Innovative assembly of the detectors

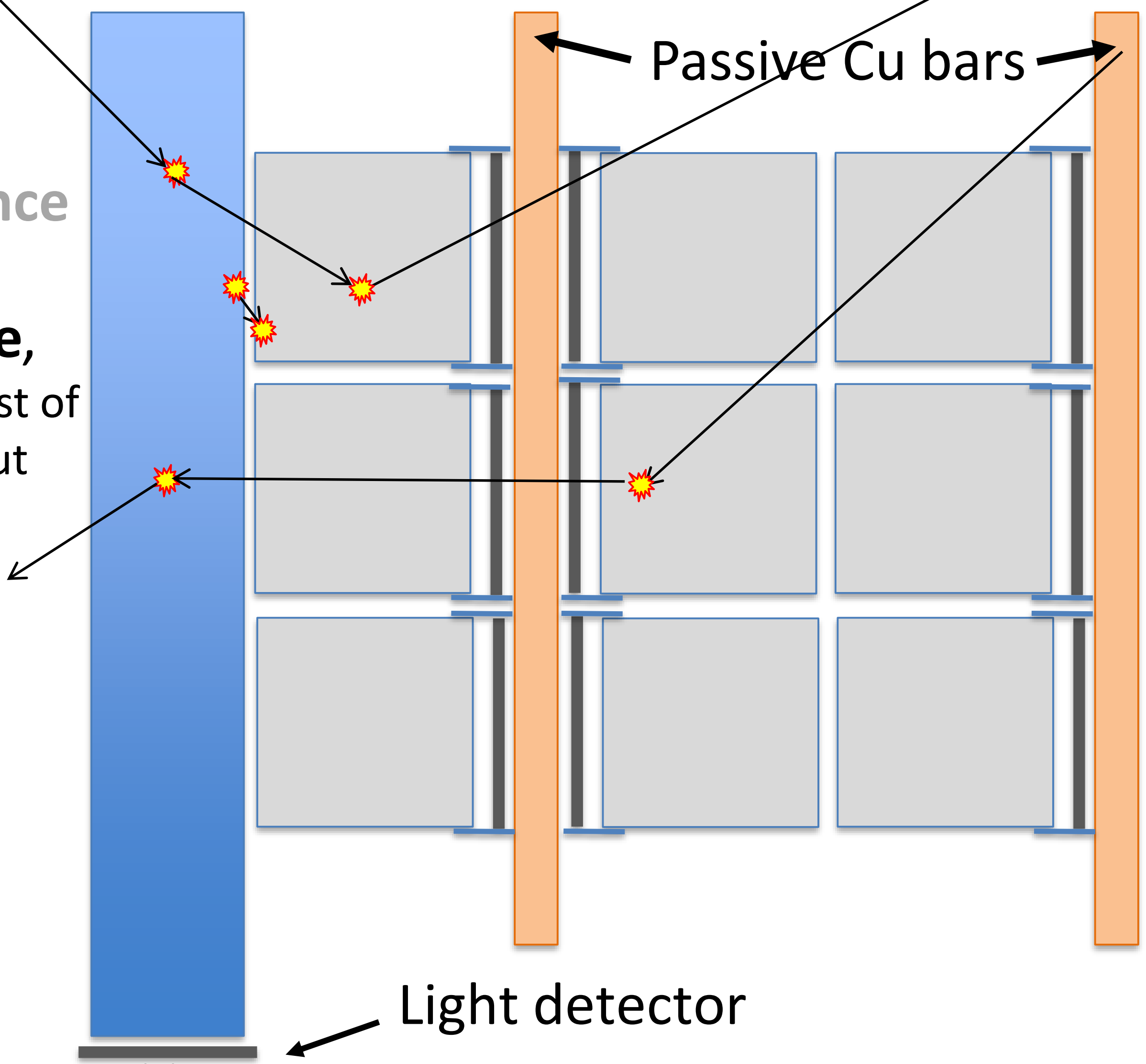
The crystal will be surrounded only by active elements

→ **Mitigate surface radioactivity by anticoincidence**

② Full active shield inside the experimental space,

for the first time in bolometric technology. The shields will consist of BGO/$ZnWO_4$ radiopure scintillators with bolometric light read-out

→ **Mitigate external γ background**



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novations in the detector structure and conception

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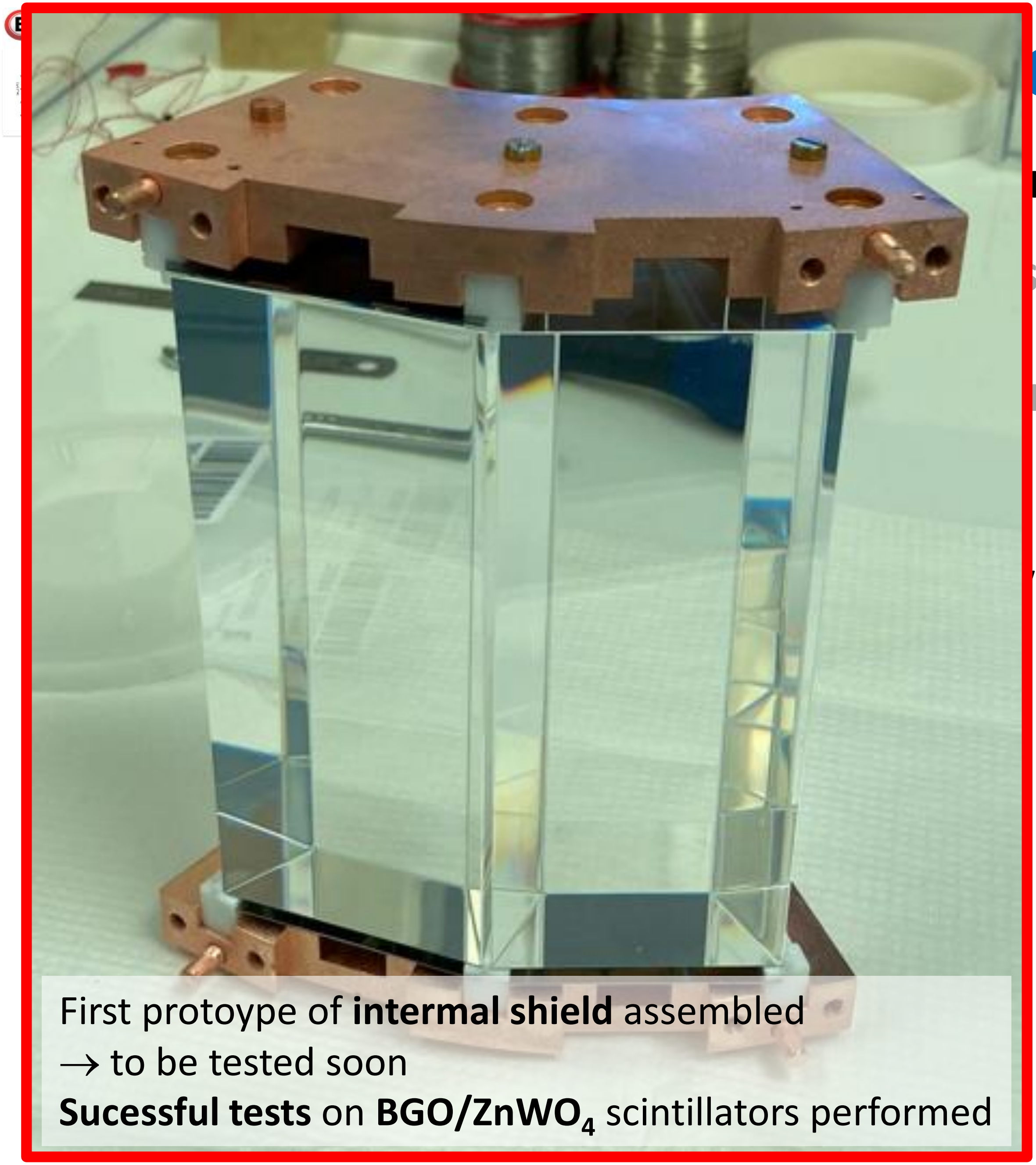
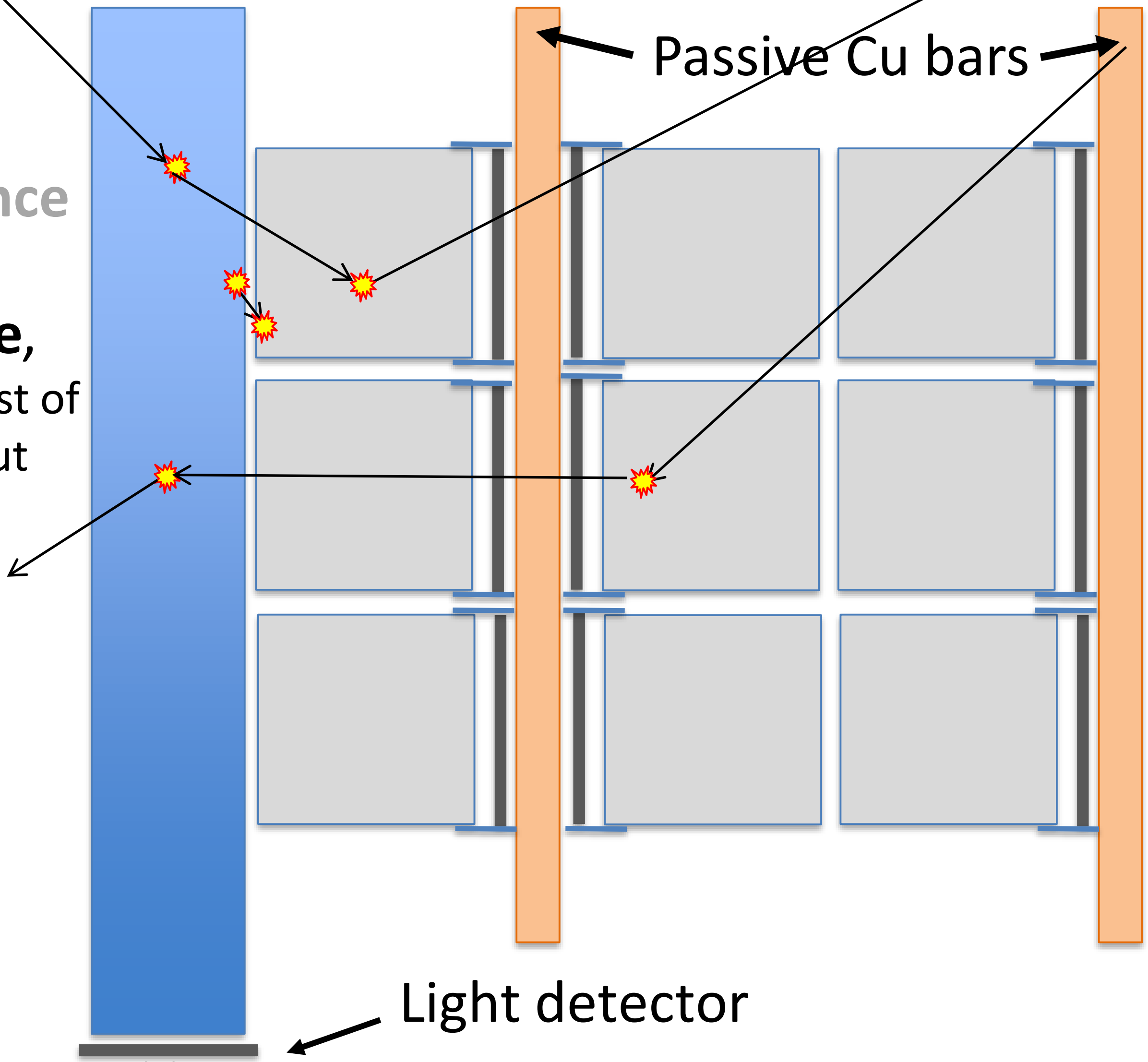
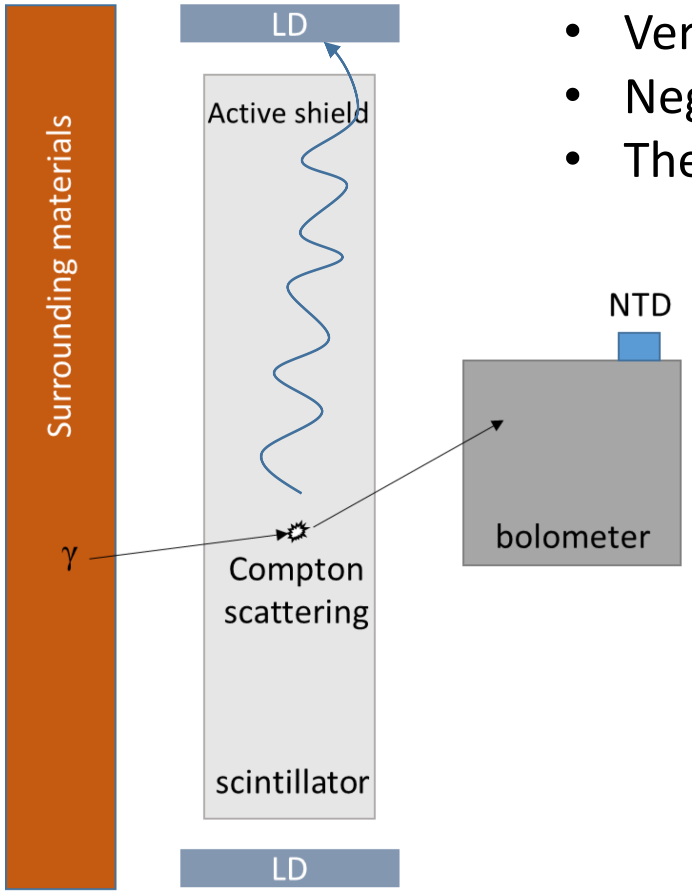




Study on active shield materials

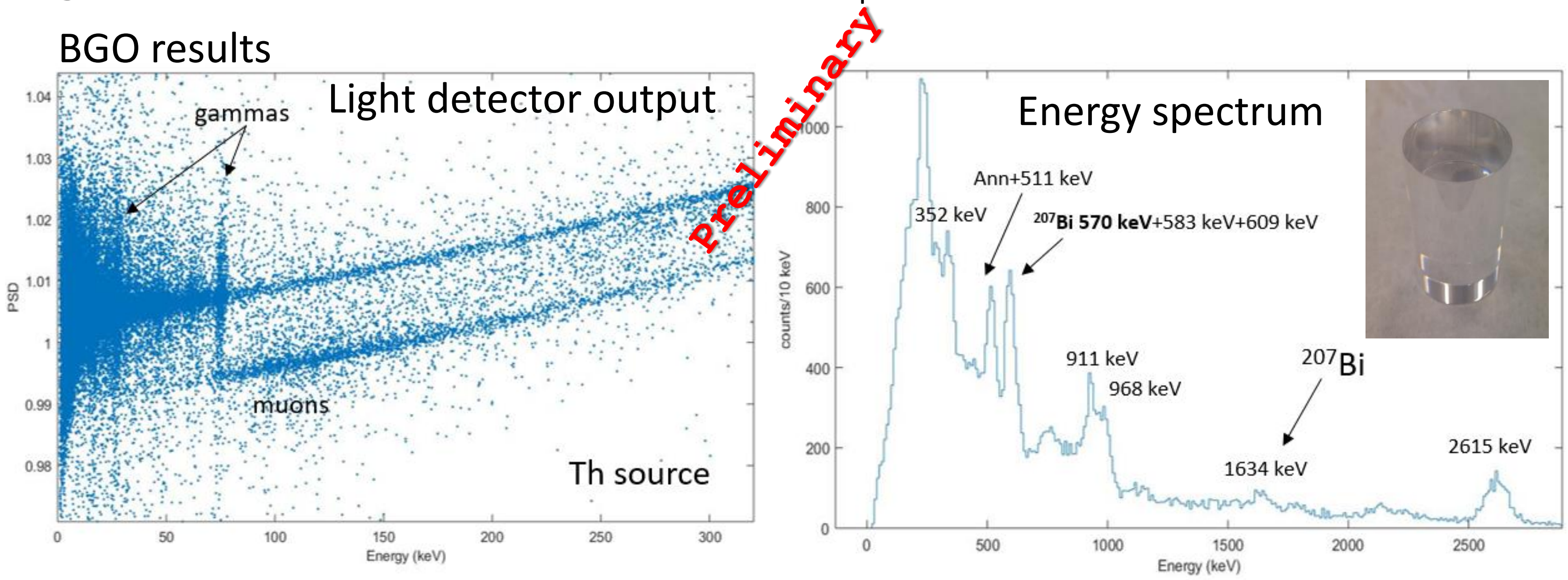
If a 2615 keV γ deposit a small amount of energy in the surrounding material (~80 keV) and the rest in TeO_2 $\rightarrow$ bkg in ROI (2527 keV)



Essential requirements to suppress the background from the ROI of TeO_2:

- Very low energy threshold of the light detector $\rightarrow$ low threshold of $ZnWO_4$ or BGO
- Neganov-Trofimov-Luke LD to increase signal to noise ratio $\rightarrow$ low threshold
- The target BINGO threshold is 50 keV in $ZnWO_4$ and BGO

BGO results



50% efficiency threshold in BGO: ~ 20 keV without NTL effect (< 5 keV feasible)

Light yield in $ZnWO_4$ about ½ of BGO

Innovative elements in BINGO

The BINGO technology is based on **three innovations** in the detector structure and conception

① Innovative assembly of the detectors

The crystal will be surrounded only by active elements

→ **Mitigate surface radioactivity by anticoincidence**

② Full active shield inside the experimental space,

for the first time in bolometric technology. The shields will consist of BGO/$ZnWO_4$ radiopure scintillators with bolometric light read-out

→ **Mitigate external γ background**

③ Innovative light detector based on the Neganov-Trofimov-Luke (NTL) effect

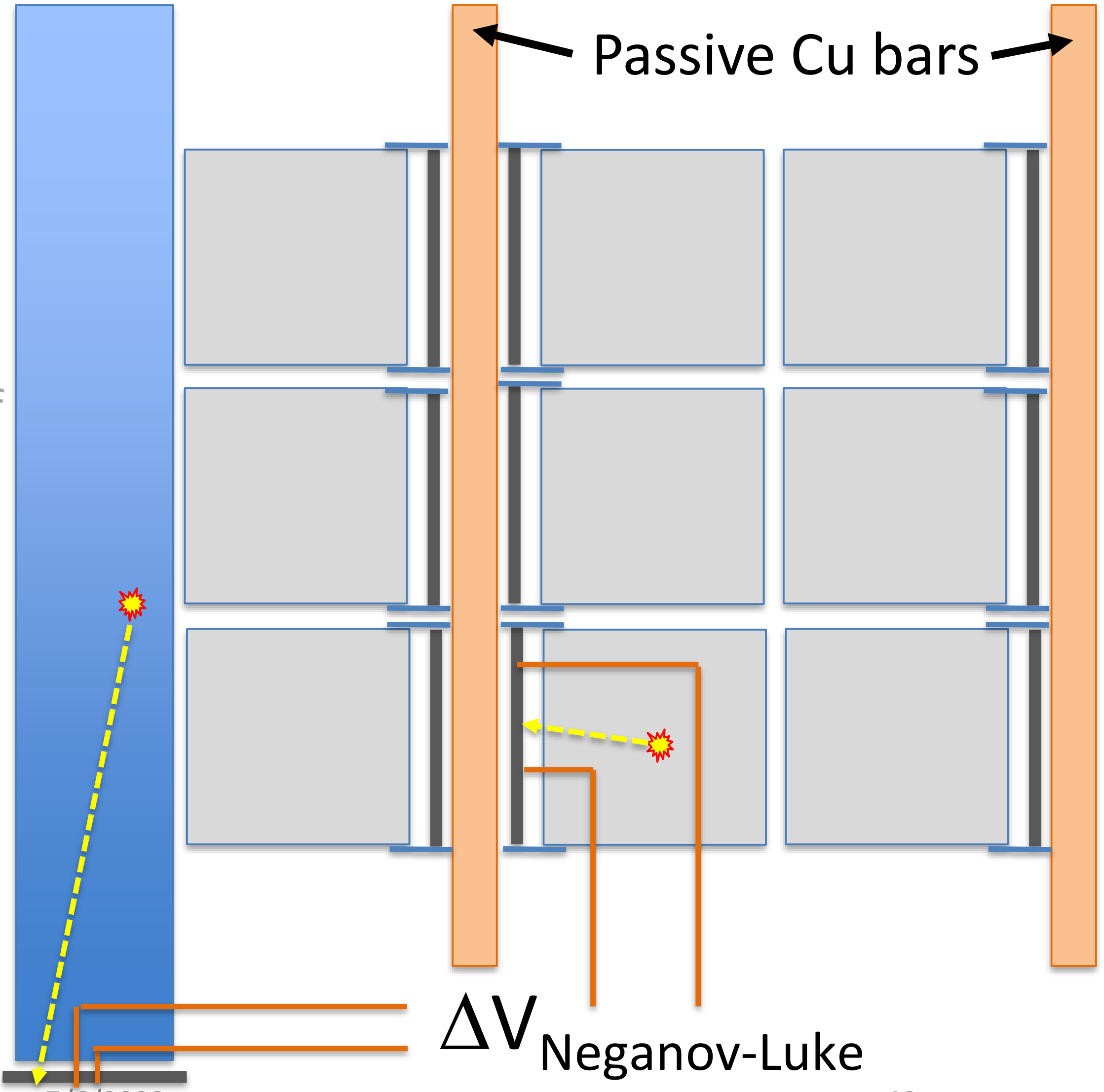
Increase by a factor 10-20 current sensitivity

reach < 10 eV rms baseline width – Multipurpose :

→ **α/β discrimination in TeO_2 by Cherenkov light**

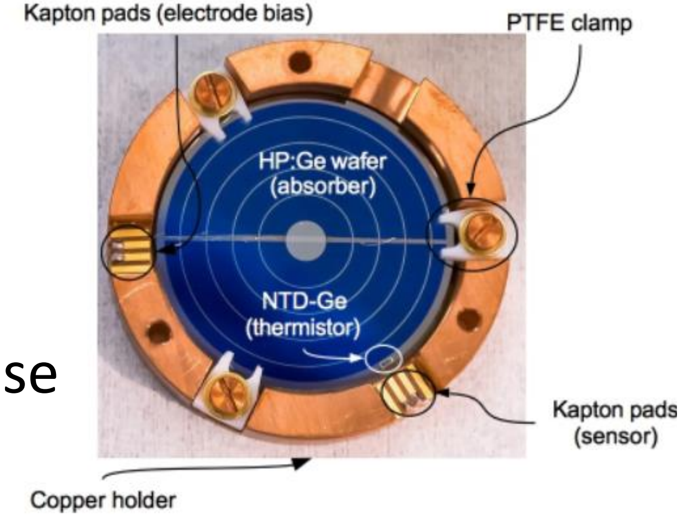
→ **Read-out scintillator light of the active shield**

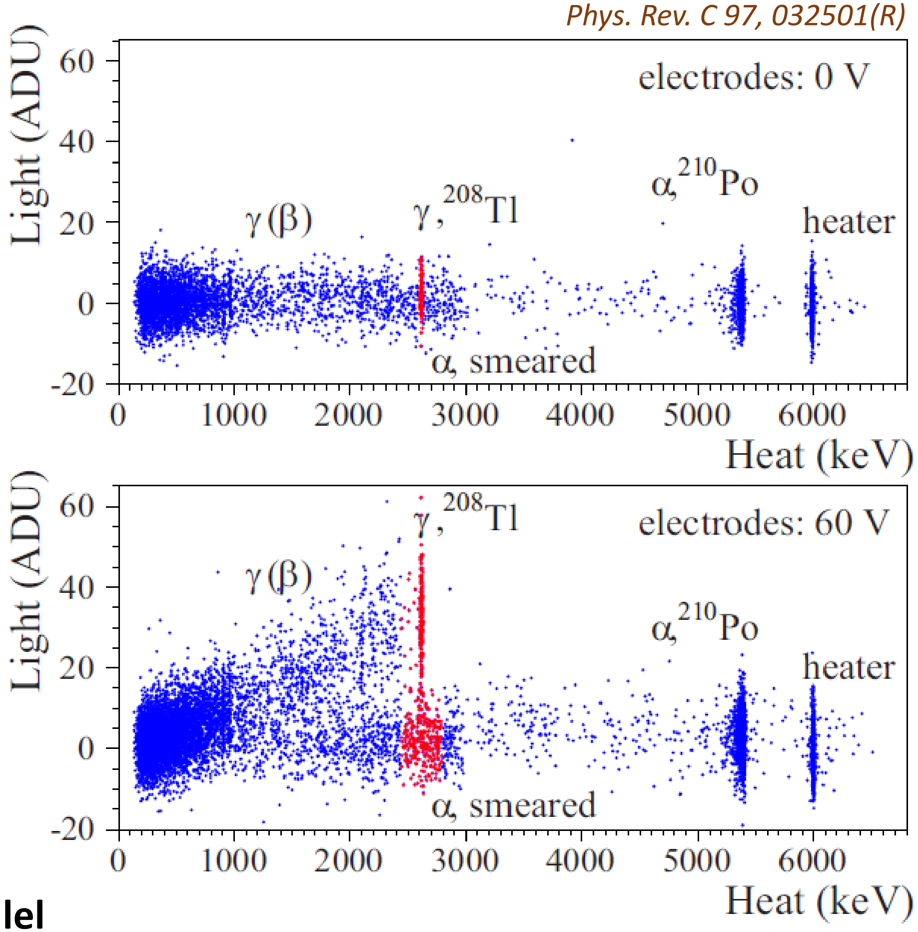
→ **Increase S/N to perform pile-up rejection**



Innovative elements in BINGO

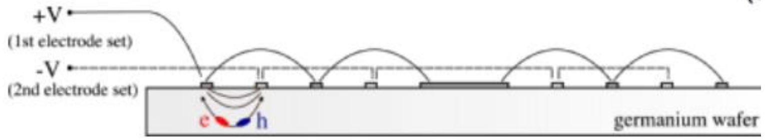
Well established technology capable of detecting **Cherenkov light** in CUORE-like 5x5x5 cm^3 TeO_2 crystal [succesfull test in Modane]





Ge light detectors with sensitivity enhanced by NTL effect

x12 gain – ~25 eV FWHM noise



Possibility to bias **several detectors in parallel**

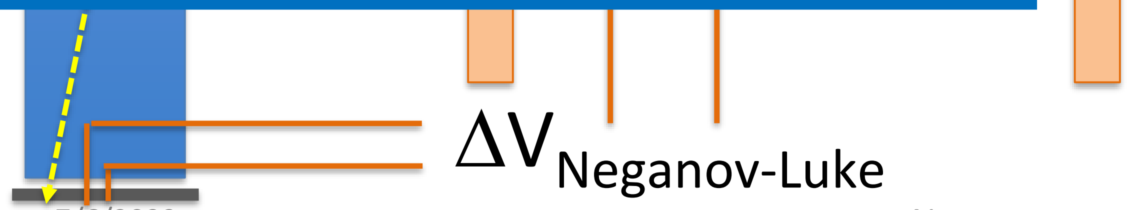
Objetives in BINGO

- Reach the theoretical gain (improve x2)
- Make NTD readout faster (act on size and coupling)

$\rightarrow$ **α/β discrimination in TeO_2 by Cherenkov light**

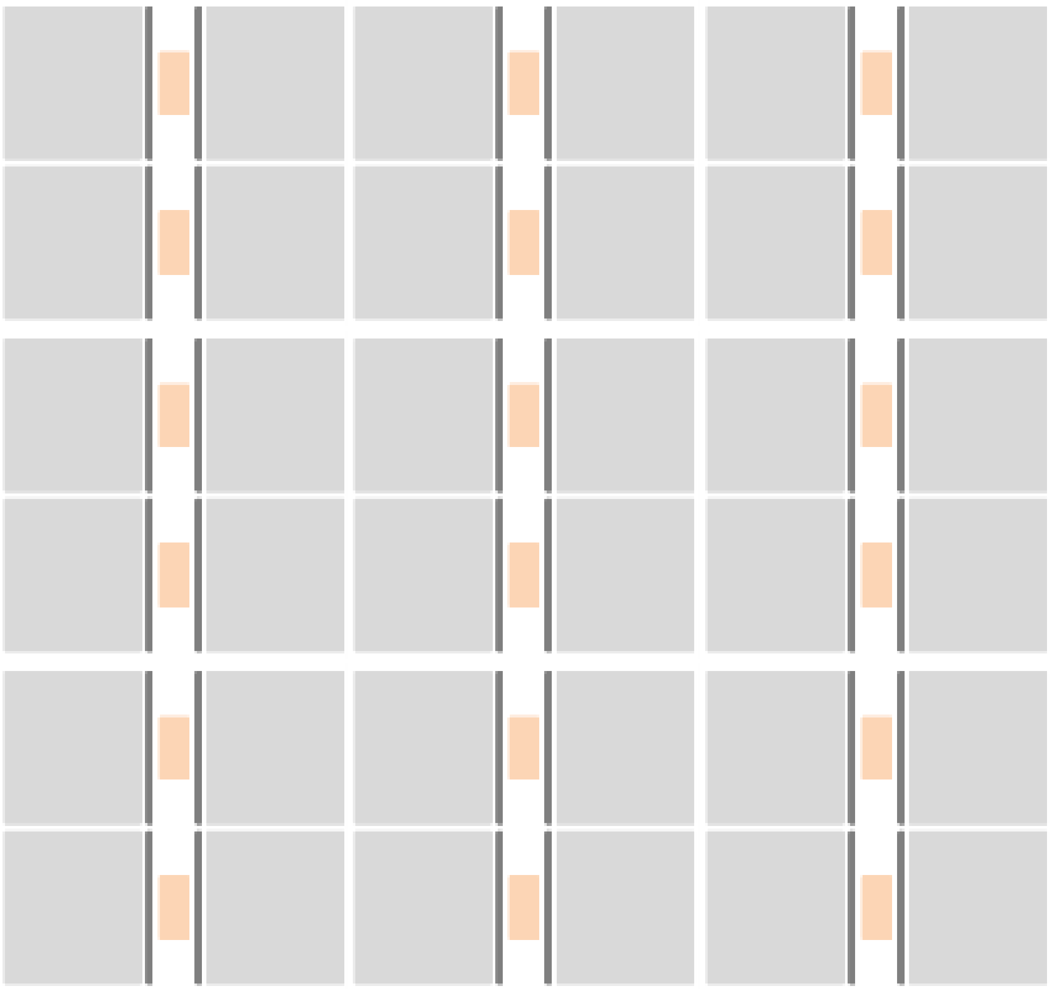
$\rightarrow$ **Read-out scintillator light of the active shield**

$\rightarrow$ **Increase S/N to perform pile-up rejection**

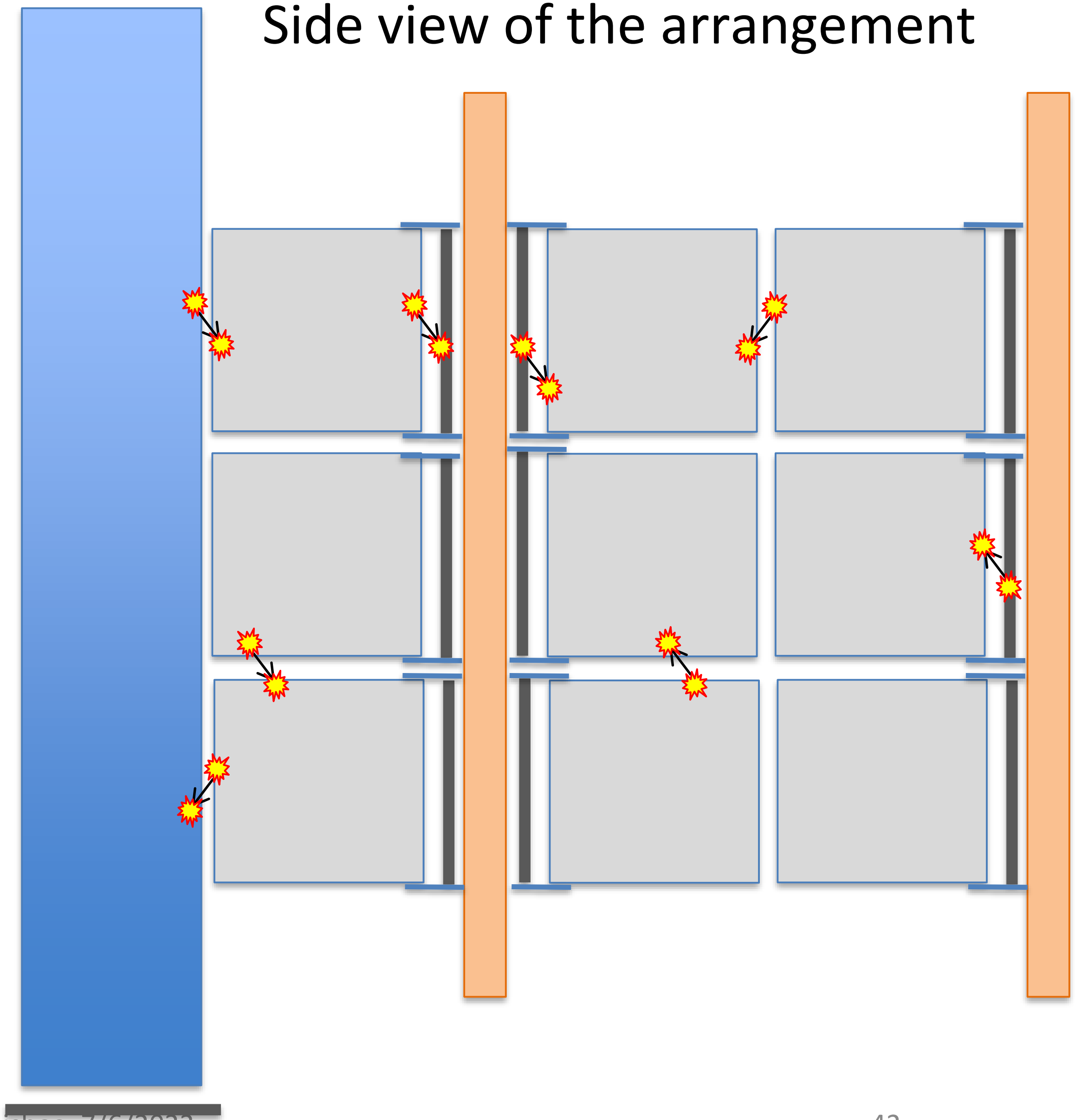


“White” and “grey” zones in BINGO

Top view of the arrangement



Side view of the arrangement



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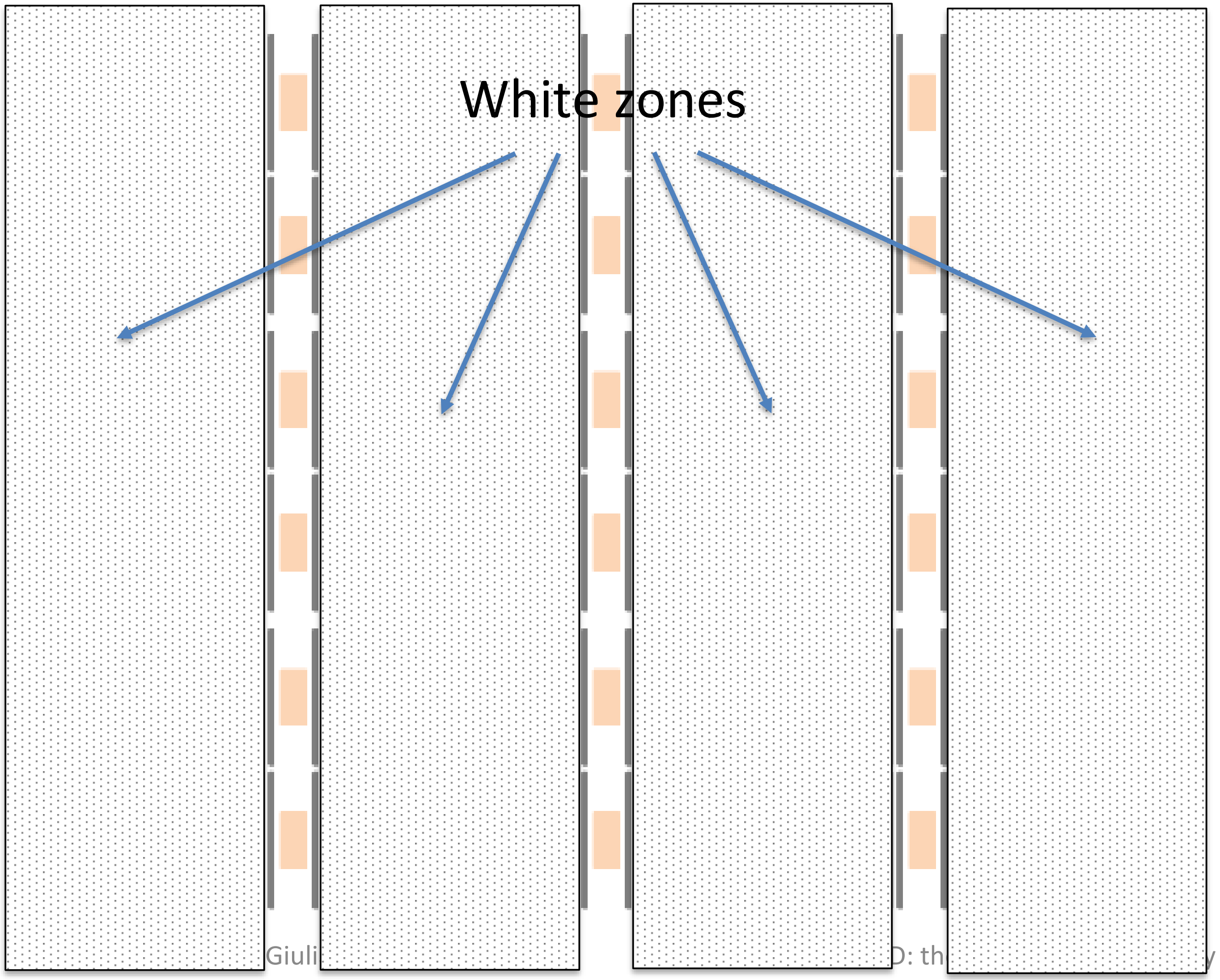
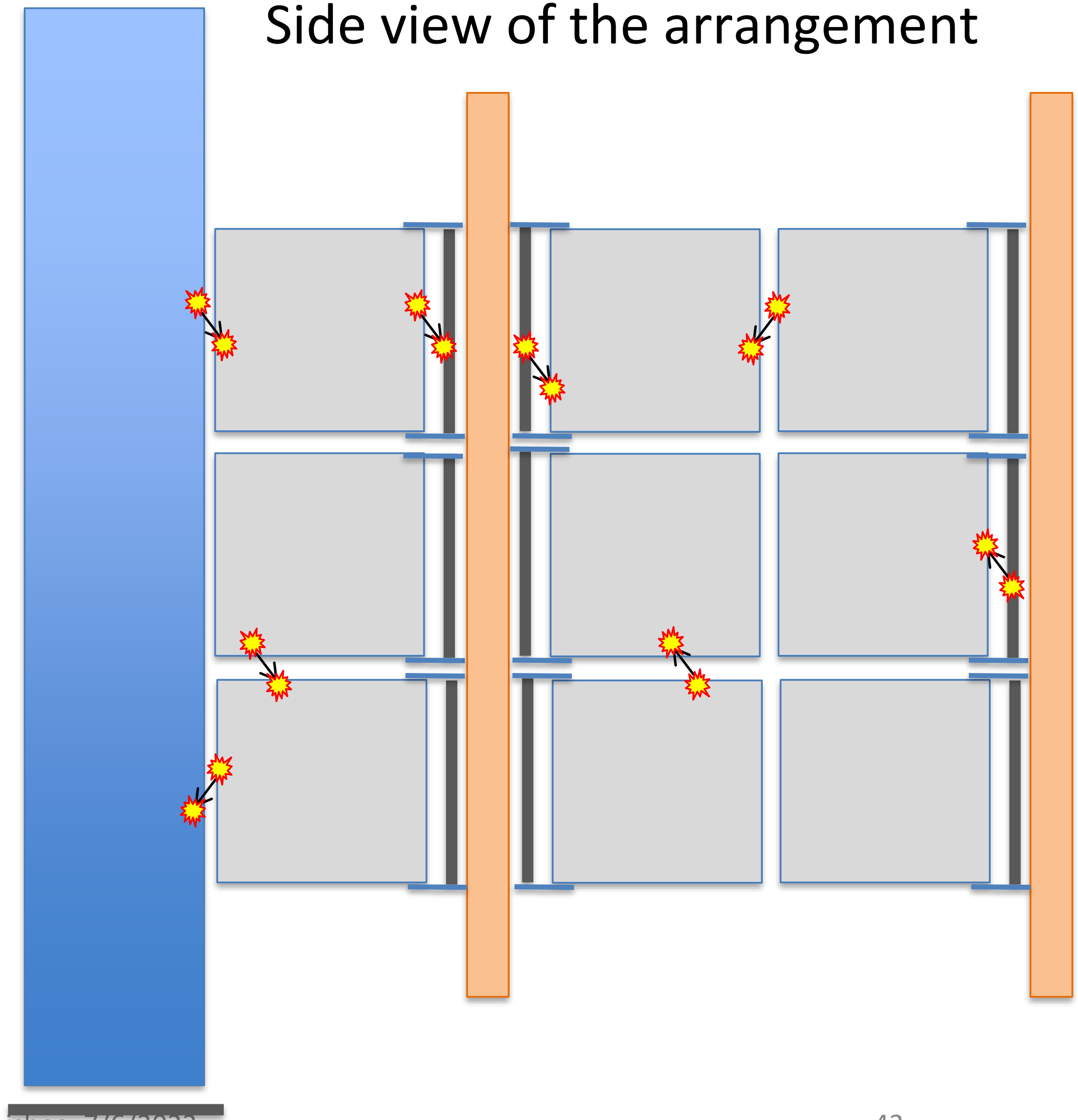
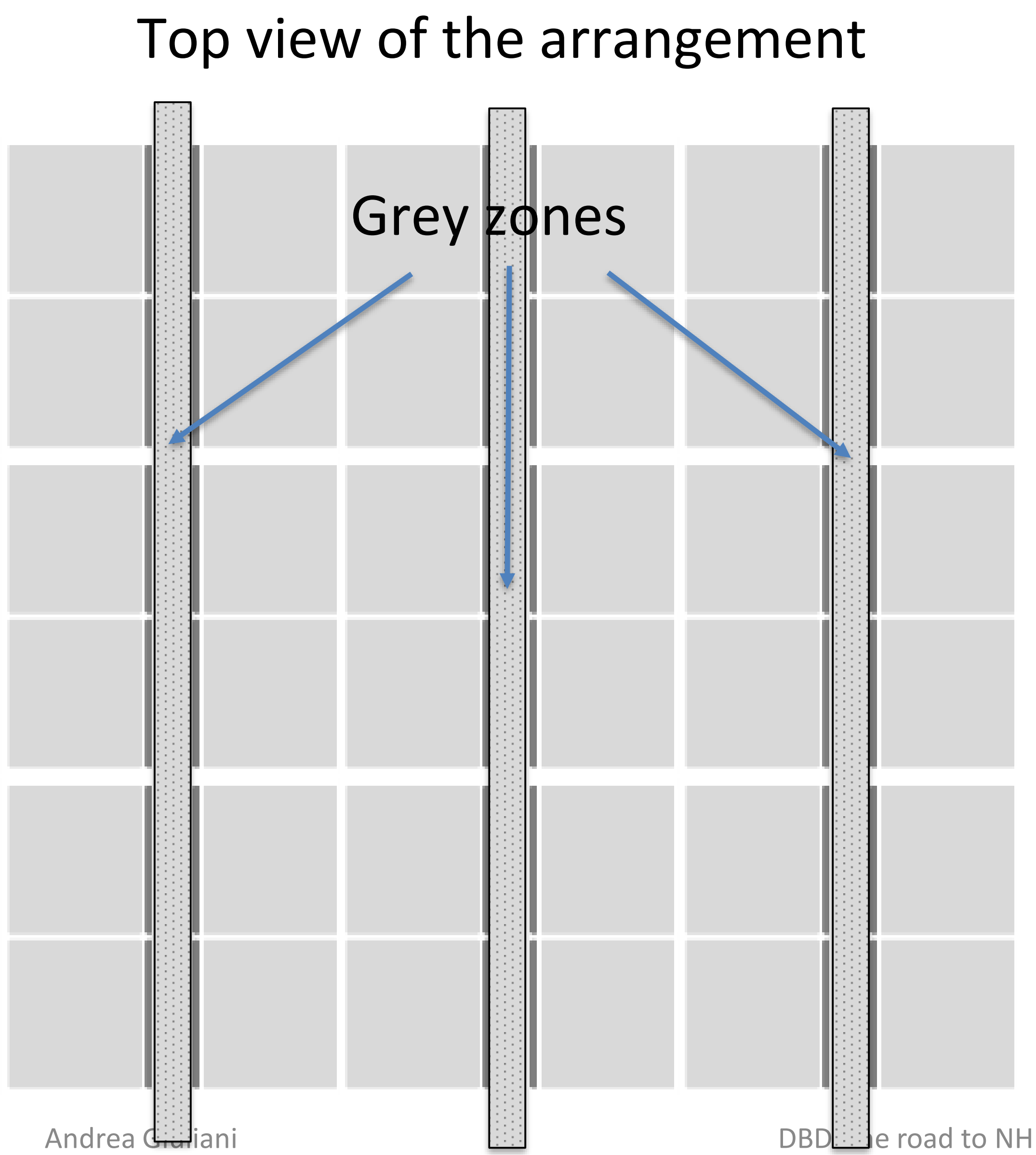
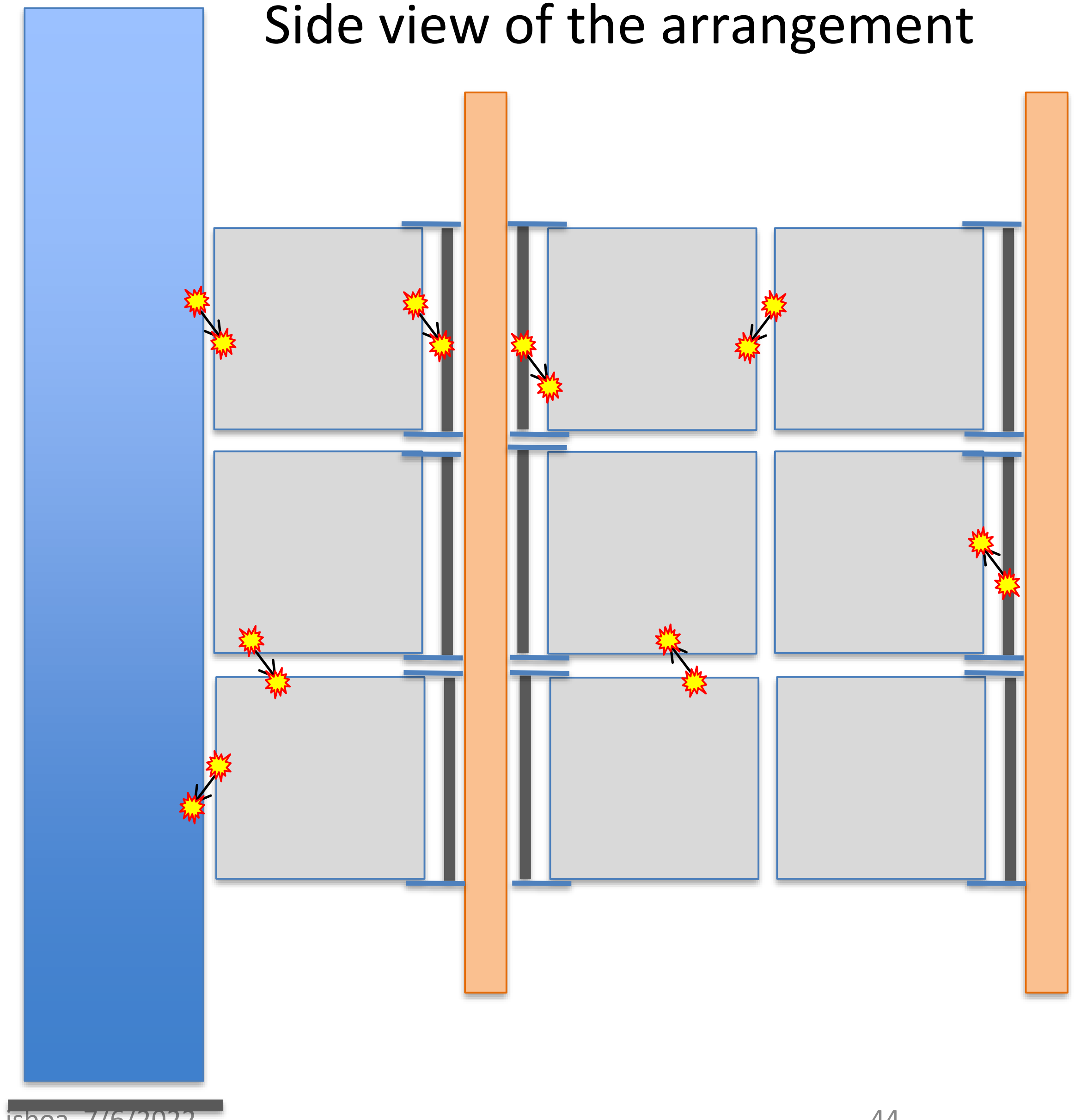


Side view of the arrangement



"White" and "grey" zones in BINGO





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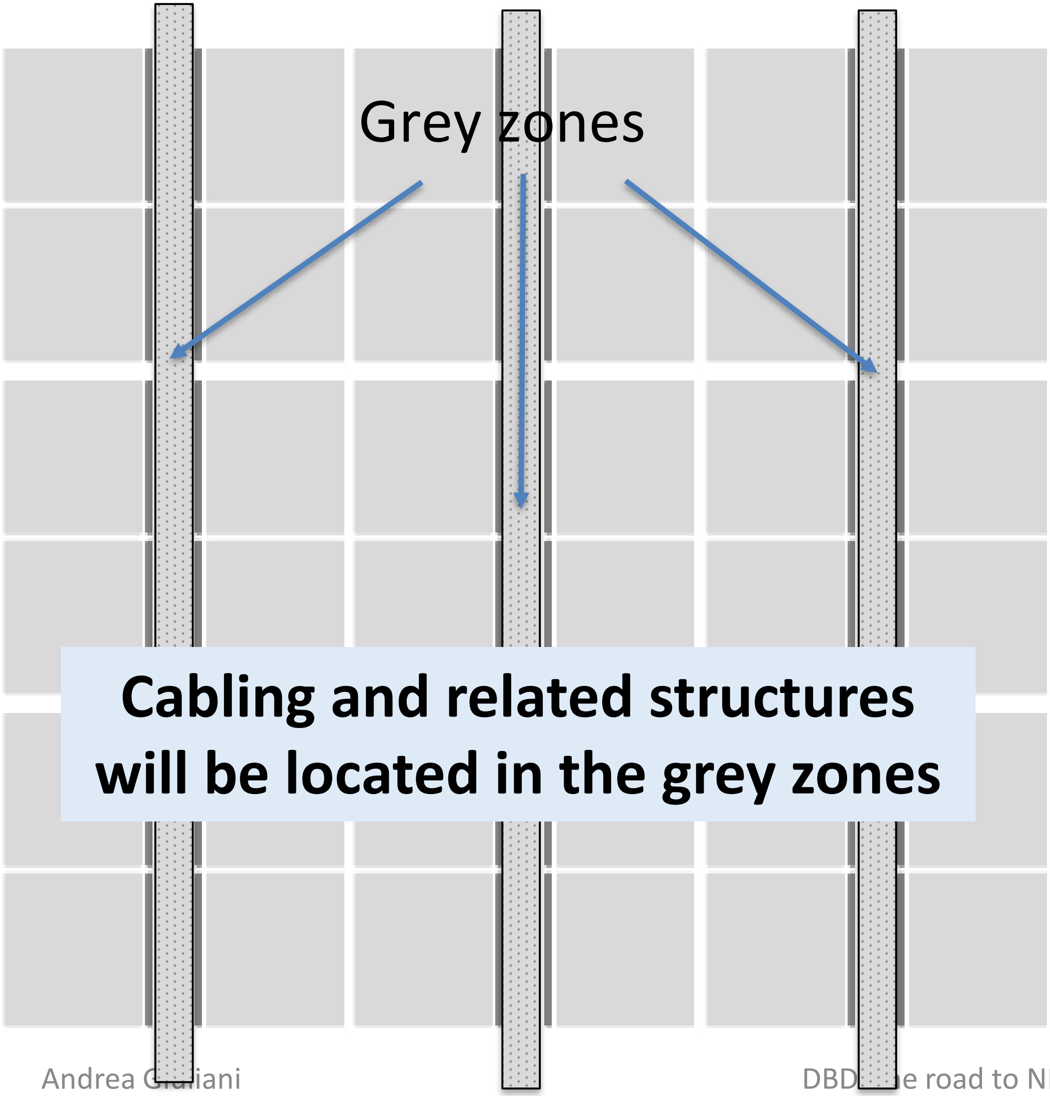
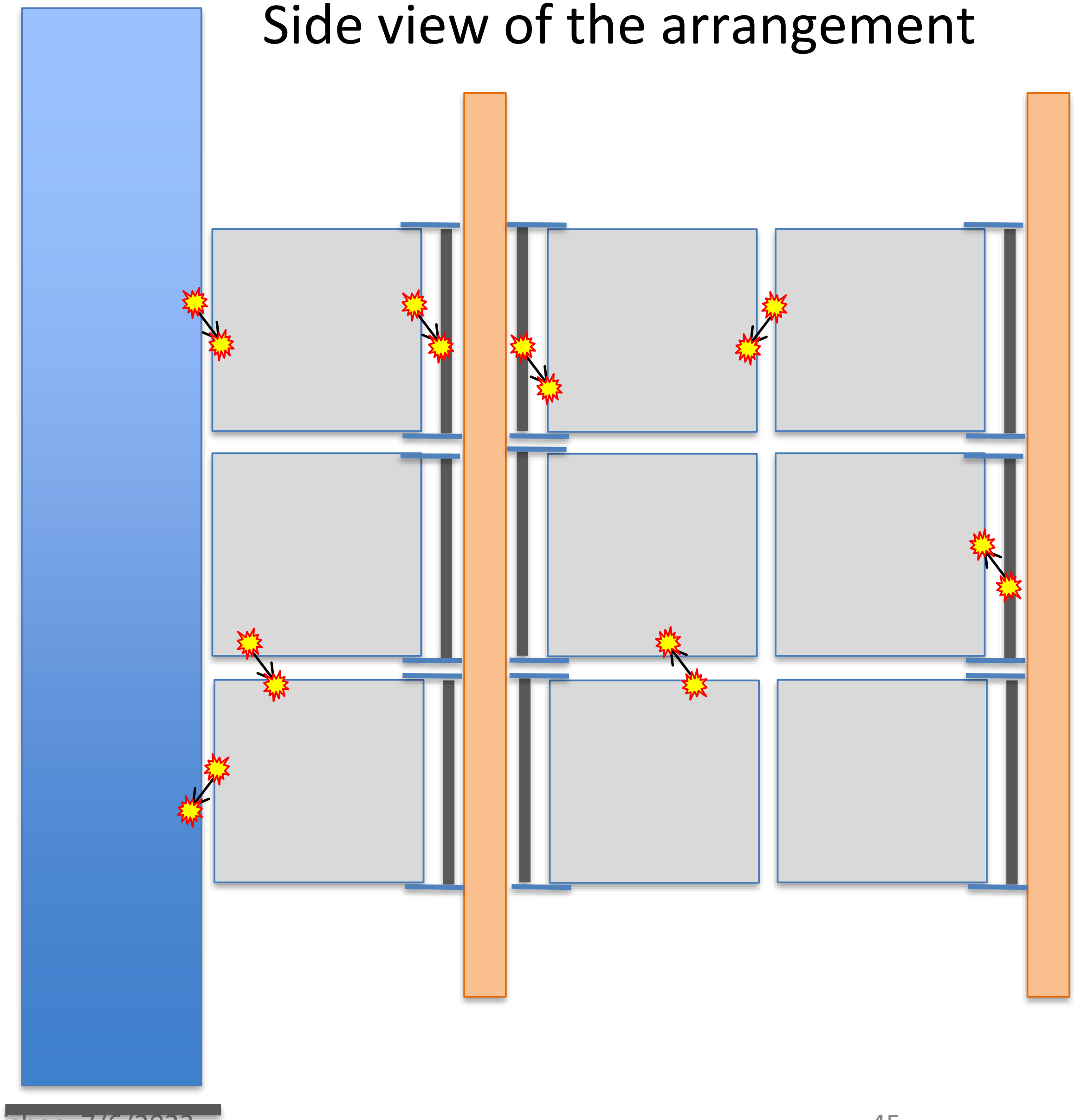
Top view of the arrangement

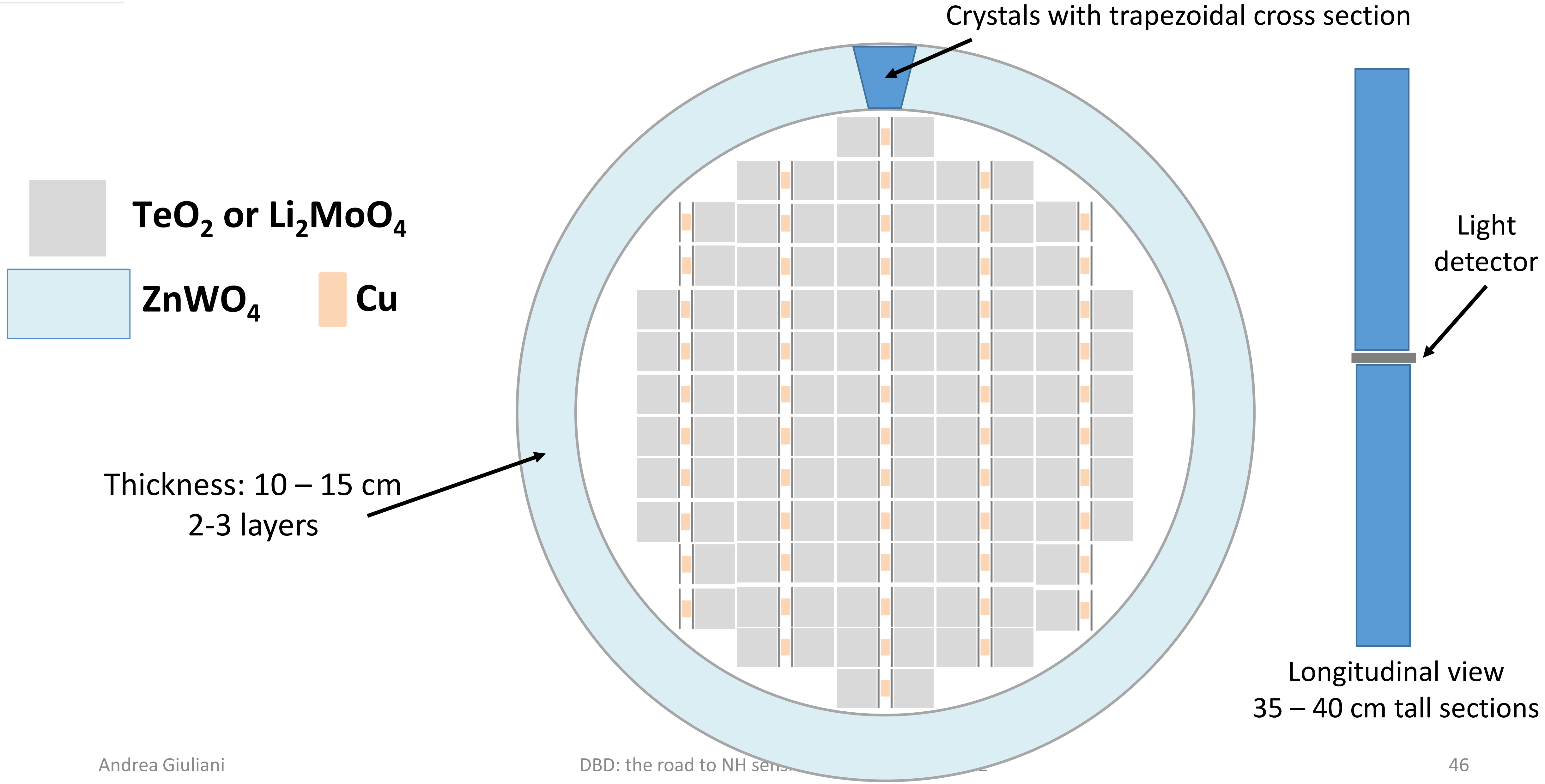


Cabling and related structures will be located in the grey zones

Side view of the arrangement

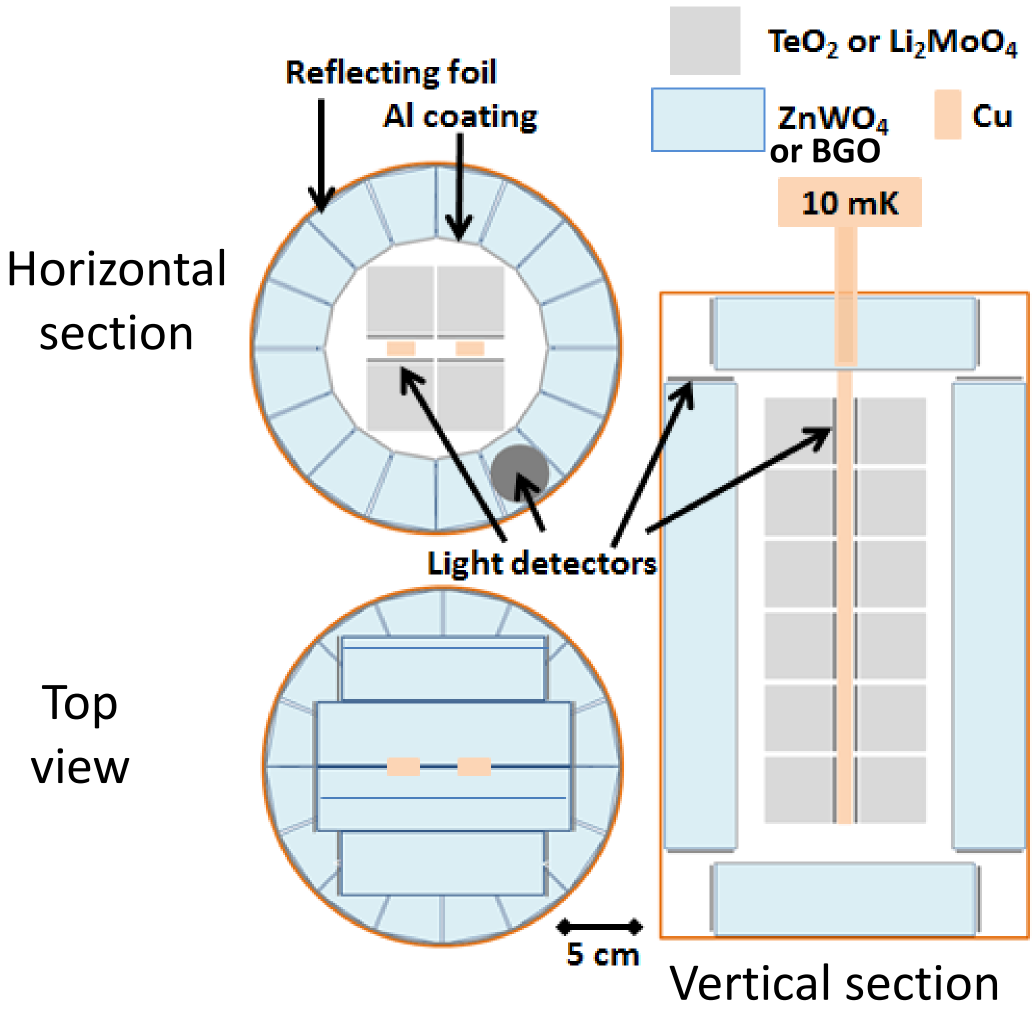


Large scale implementation



MINI-BINGO demonstrator

MINI-BINGO is a **small-scale demonstrator** of the BINGO technology in a dedicated **underground cryostat** **[Modane laboratory]**



Validation of all the BINGO elements

- 2 isotopes: ^{100}Mo and ^{130}Te
- 2 towers of 12 crystals each
- Crystals will see nothing else that is not active
- BGO or $ZnWO_4$ crystals as active shields
- Innovative light detectors

Data taking: 2024

Simulations in progress to evaluate the external background suppression factor in MINI-BINGO and in large-scale experiments
(as a function of threshold, thickness, geometry)

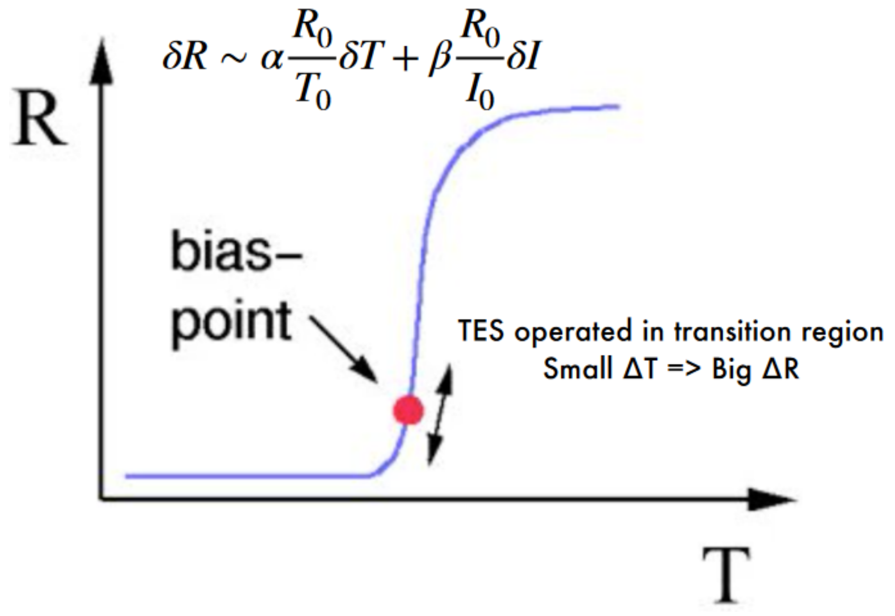
TES-based light detectors: concepts

Current features of **NTD-based light detectors** (CUPID baseline) used in CUPID-Mo, CUPID-0, CUPID tests:
$\rightarrow$ **Rise-times ~ 1-2 ms** – **Baseline width ~ 100 eV FWHM** (improvable by a factor ~ 10 by NTL effect)

→ Limited by gluing, electron-phonon decoupling, high impedance readout

A new phonon-sensor technology can substabtially improve these figures mitigating the 2ν pile-up background

Transition Edge Sensor (TES)



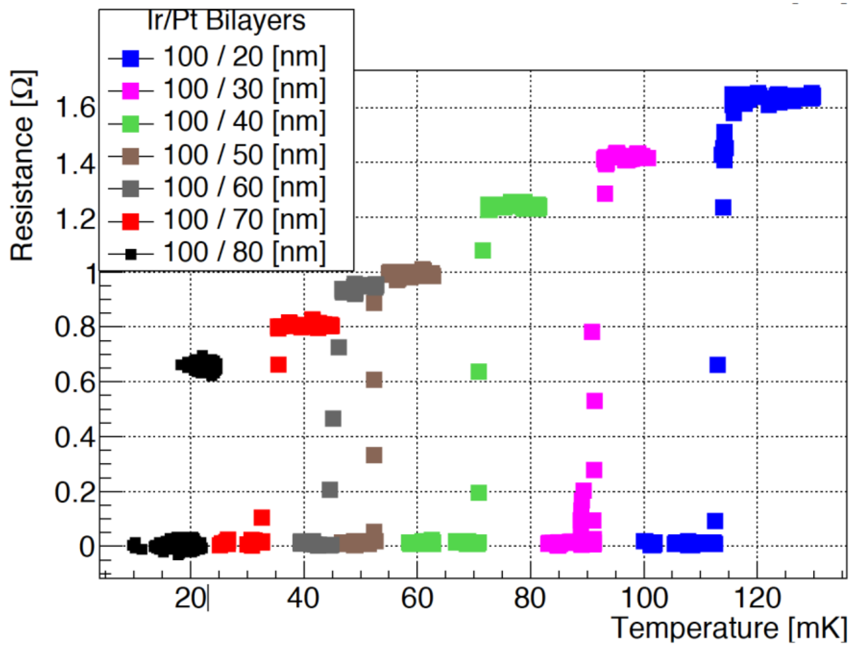
Time resolution with TES can be much better than with NTD

- Low impedance and SQUID readout → **Multiplexing** is possible
- Direct coupling to the wafer without glue
- Technical bolometric feature: negative electrothermal feedback

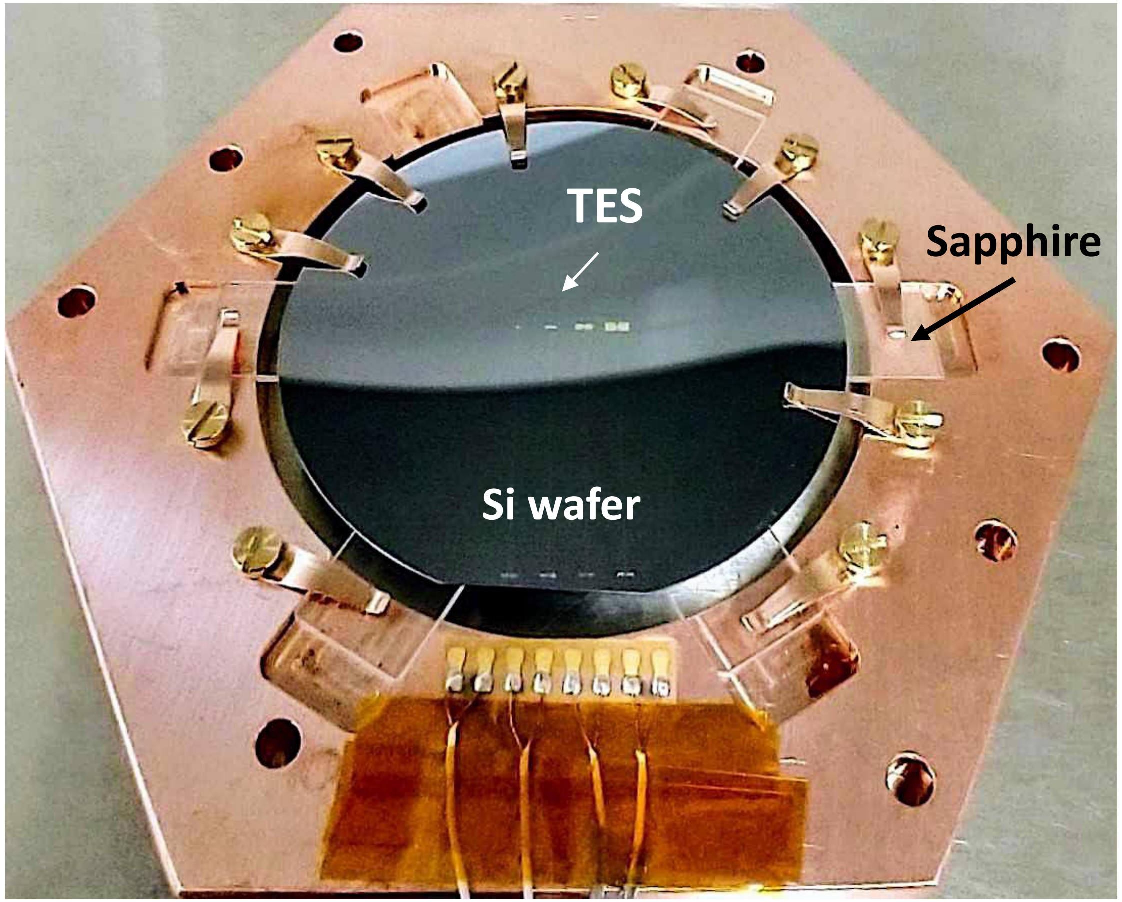
→ Objective: $\leq$ **150 μs rise-time**

TES-based light detectors: devices

- Control of the critical temperature T_C via **proximity effect**
- **IrPt bilayer** $\rightarrow$ T_C in the 20-110 mK range
- Variable TES sizes: **300-500 μm x 300-500 μm**
- **Si wafer** – 5.08 cm ∅

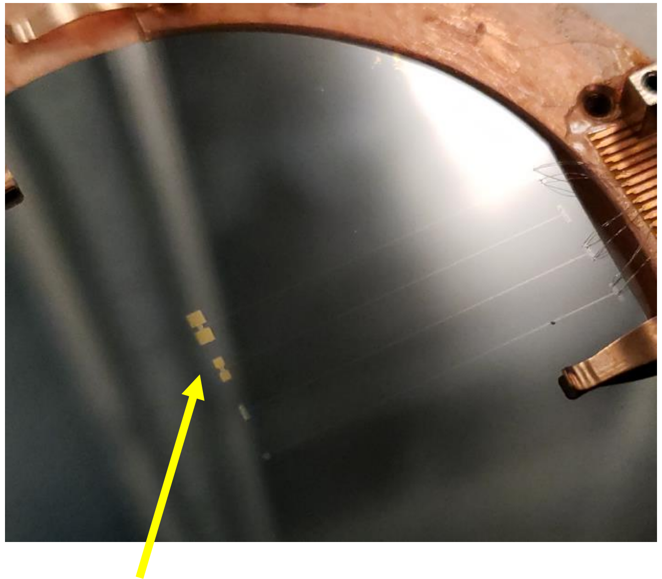


B. Welliwer, 15th Pisa Meeting on Advanced Detectors 2022

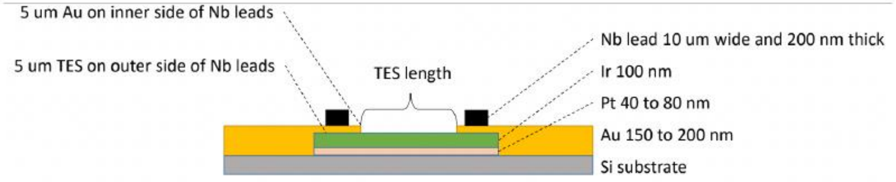


Complex thermal network
Important to **increase TES-wafer coupling**

TES-based light detectors: performance

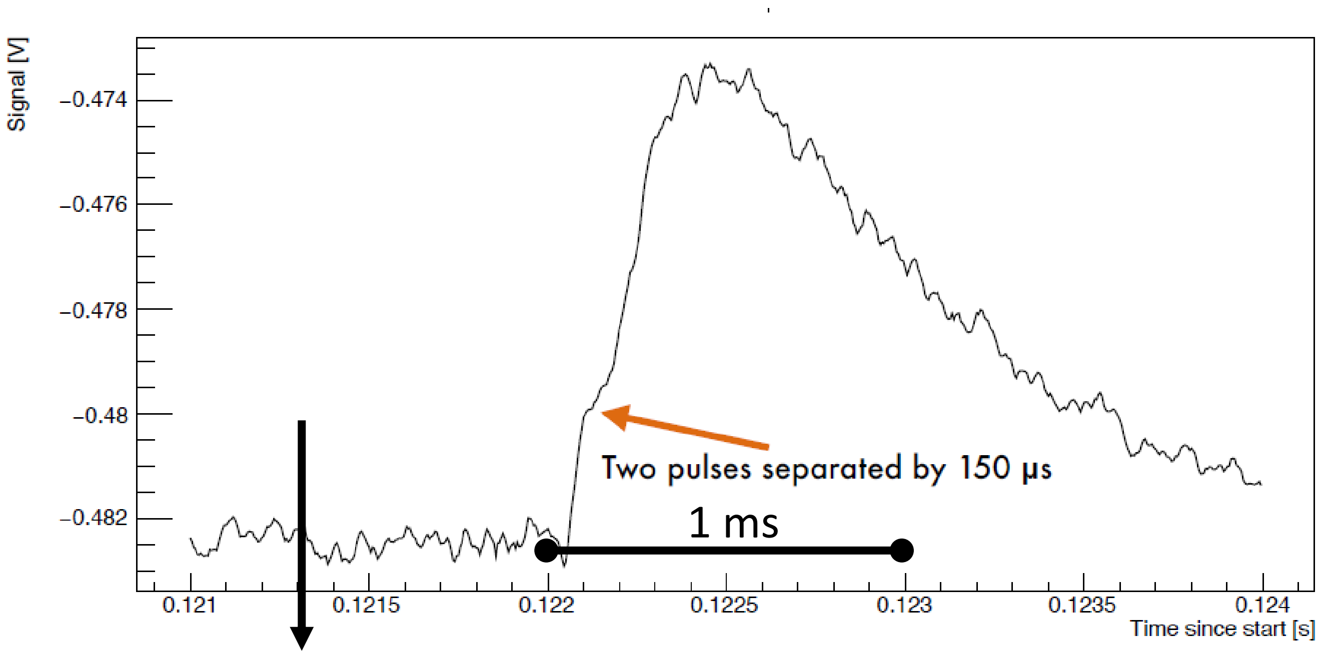


Gold pads to improve the TES **thermal conductance** to the Si wafer



Cross-section view of TES

Test with optical fibers



- Allows for **pulse-shape discrimination** for pile-up events
- Baseline noise measured with photon statistics: ~ **120 eV (FWHM)**

Implementation in CUPID

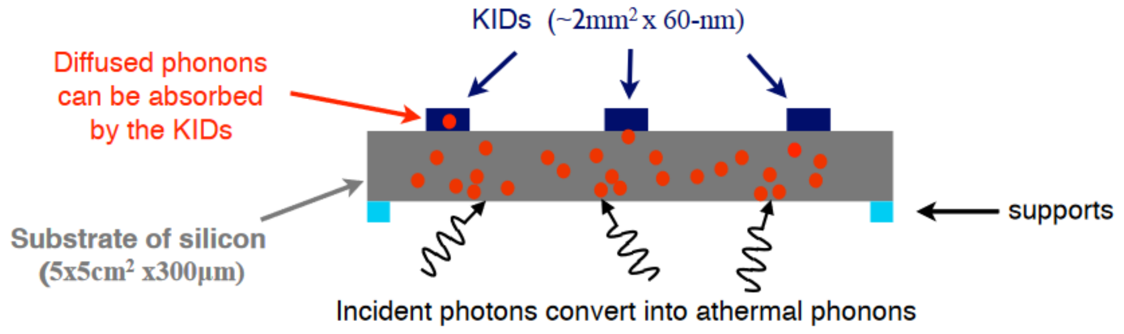
At least 1500 TESs are required for light detector readout
Frequency domain multiplexing → multiplexing factor of the order of 10

MKID-based light detectors in CALDER

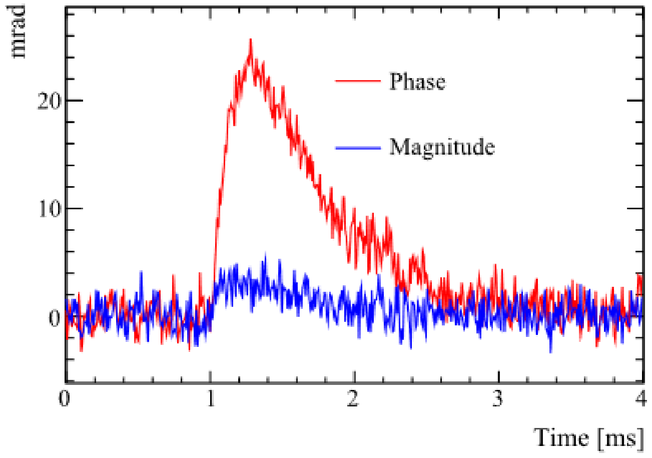
Cooper pairs in a superconductor act as an **inductance**

A KID is a **superconductive devices** that detect **photons** and **phonons** through the **change of its inductance** induced by a change of Cooper pair density

A KID is included in a **resonating circuit** biased with a microwave signal (GHz)

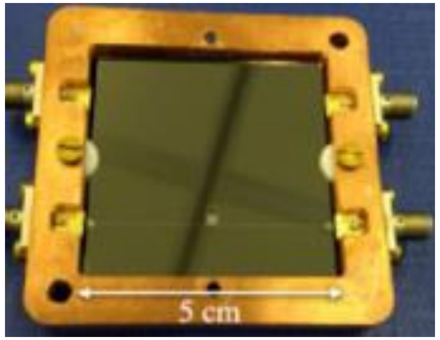


Signal from **amplitude** and **phase shift**



"Natural" multiplexing up to a factor 1000

Final results from CALDER



- **Si wafer** – 5x5 cm^2
- **Single AlTiAl three-layer resonator**

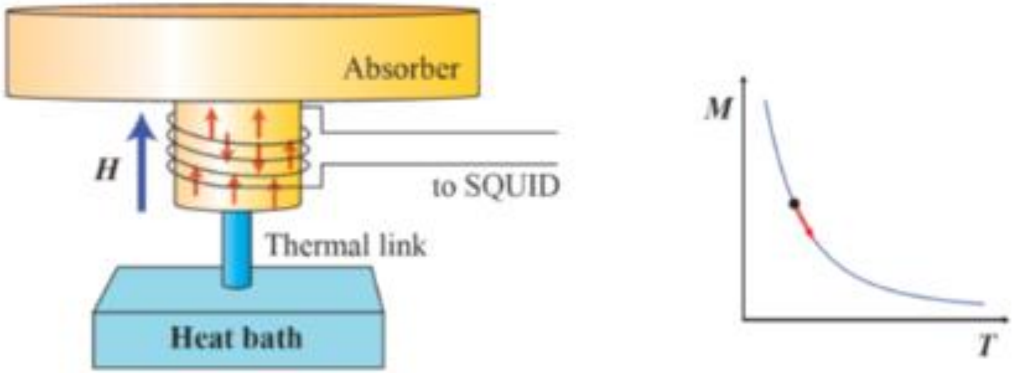
- Baseline noise measured with photon statistics: ~ **210 (FWHM)** → limitied by microphonic noise
- Pulse rise-time: 120 μs

EPJC 81, 636 (2021)

AMoRE approach: MMC readout

AMoRE is a bolometric experiment searching for neutrinoless double beta decay of ^{100}Mo with the **Magnetic Metallic Calorimeter** (**MMC**) technology

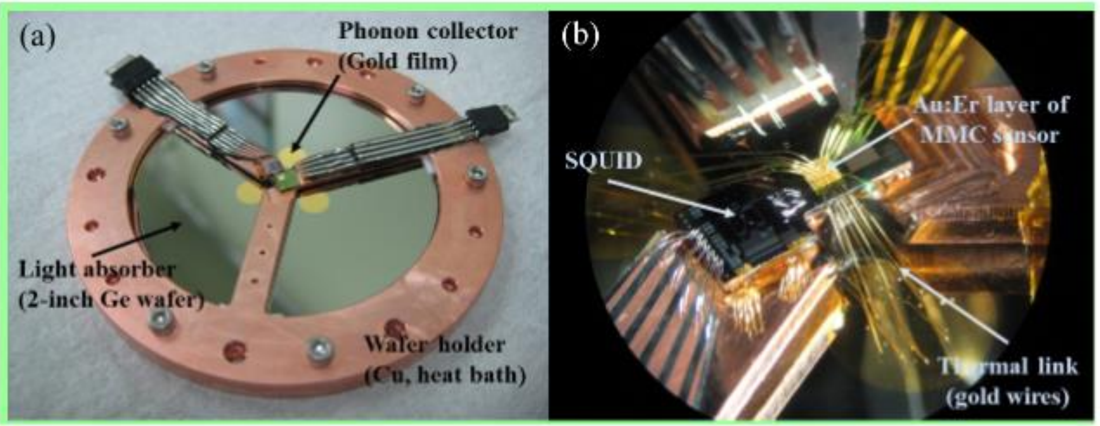
An **MMC** is a device that measures a given amount of heat deposited in it through a **magnetization change**



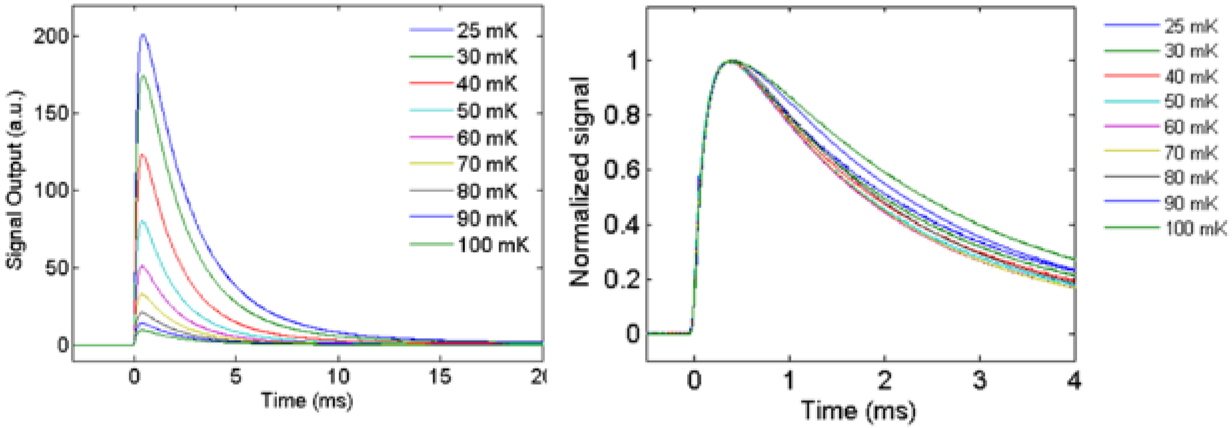
An MMC requires the application of a **magnetic field** and a **SQUID readout**

arXiv:1512.05957

Light detector



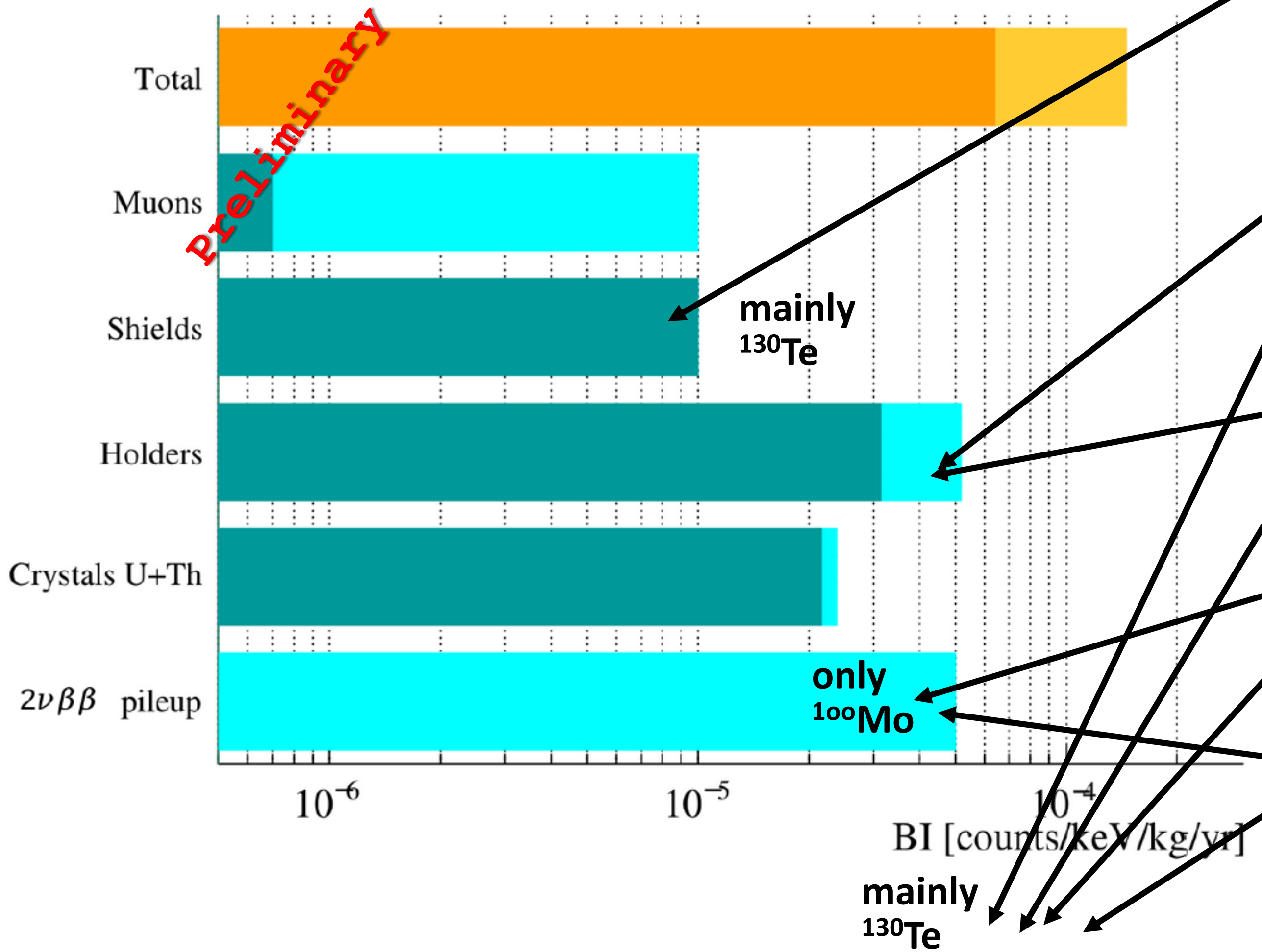
- **Si wafer** – 5.08 cm ∅
- **Rise-time** – 200 μs, independent of operation temperature



Summary

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



- **Active veto**
  Two types of scintillating crystals have been successfully tested at 10 mK with bolometric light detector readout: BGO and $ZnWO_4$
  Prototype barrel under preparation
  [BINGO]
- **Surface sensitive detectors**
  Surface sensitivity to β particles by pulse shape discrimination assisted by film coating proved in small-scale prototypes
  Trasnsfer to final crystals in progress
  [CROSS]
- **Redesign the holder structure**
  Almost full active surrounding for each crystal
  Proof of concept achieved
  [BINGO]
- **Increase light detector signal-to-noise ratio**
  Exploit Neganov-Trofimov-Luke effect + NTD readout
  Proof of concept achieved
  [BINGO]
- **Increase light detector speed**
  Several possible solutions:
  TES – tested in prototype [US CUPID-R&D]
  KIDs – tested in prototypes [CALDER]
  MMC – adopted in [AMoRE]

Full α rejection down to BI < 10^{-5} counts/keV/kg/y is assumed