DRTBT2012 :
7ème école thématique
Perspectives nouvelles des détecteurs cryogéniques

Le neutrino : histoire et perspectives, science et défis technologiques (2)

Claudia Nones

CEA/DSM/IRFU/SPP

Outline

- Les neutrinos aujourd'hui
- Détecteurs a basse températures pour les neutrinos
  - Mesures directes de la masse
  - La diffusion cohérente neutrino-nucleus
  - La double décroissance bêta → Claudia Nones
- Conclusions

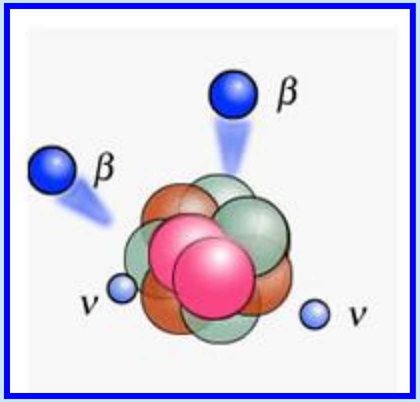
Decay modes for Double Beta Decay

$2\nu\beta\beta$

Two decay modes are usually discussed:

$0\nu\beta\beta$

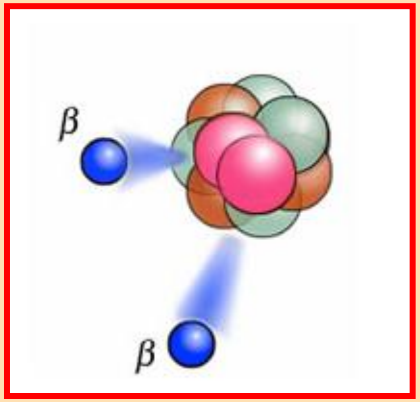
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$



2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \geq 10^{19}$ y

$[T_{1/2}(2\nu)]^{-1} = G_{2\nu}(Q, Z)|M_{2\nu}|^2$

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



Neutrinoless Double Beta Decay
never observed (except a discussed claim)
$\tau > 10^{25}$ y

$[T_{1/2}(0\nu)]^{-1} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 m_{\beta\beta}^2$

New physics beyond the Standard Model
⬇
Violation of lepton number conservation
Possible only if ν is a Majorana particle

Let's join the pieces

Observation of $0\nu\beta\beta$ → $m_\nu \neq 0$, $\nu \equiv \bar{\nu}$

To be more quantitative:

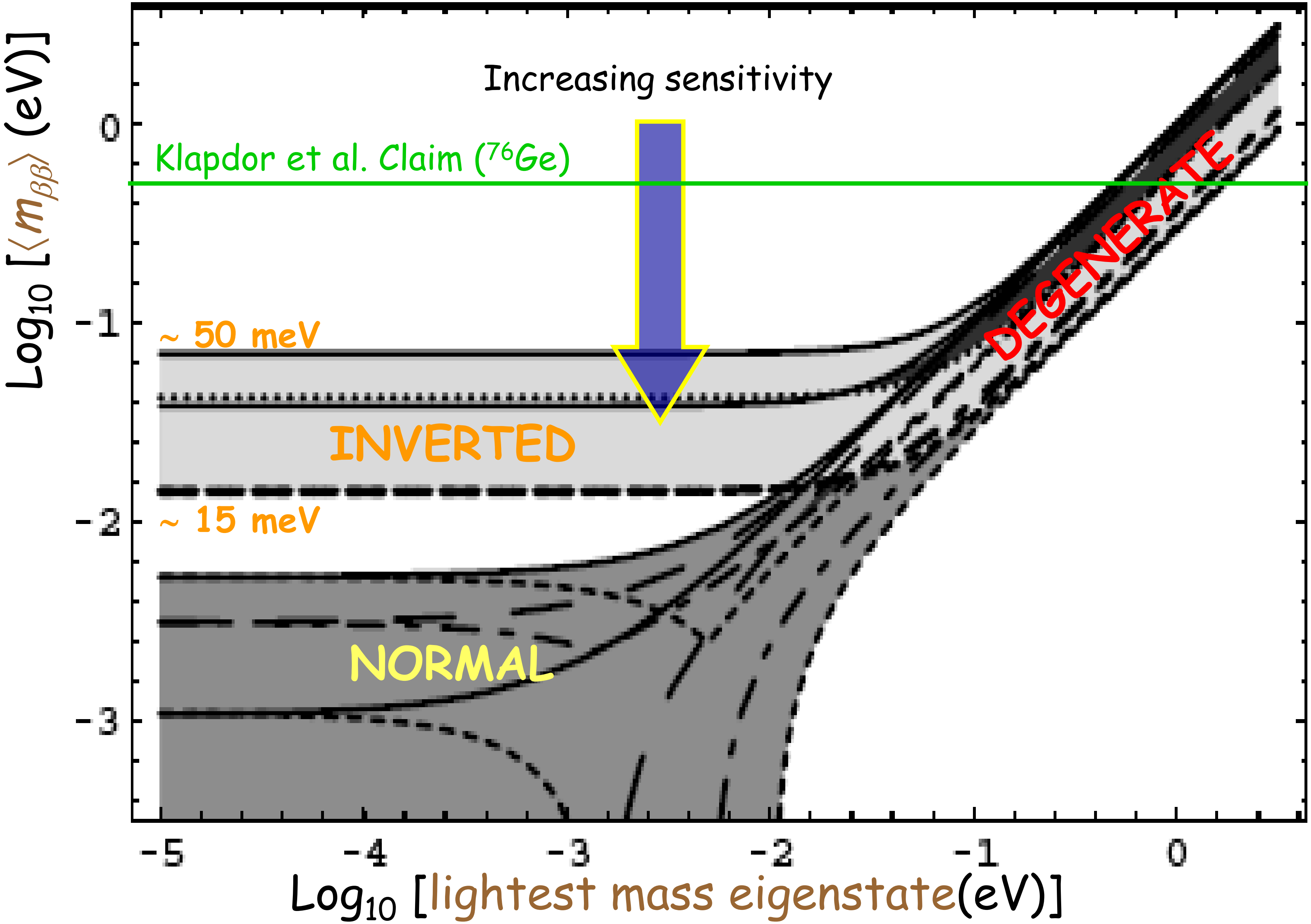
$$\frac{1}{\tau} = G(Q,Z) \cdot |M|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

- $\frac{1}{\tau}$: neutrinoless Double Beta Decay rate
- $G(Q,Z)$: Phase space
- $|M|^2$: Nuclear matrix elements
- $\langle m_{\beta\beta} \rangle$: Effective Majorana mass

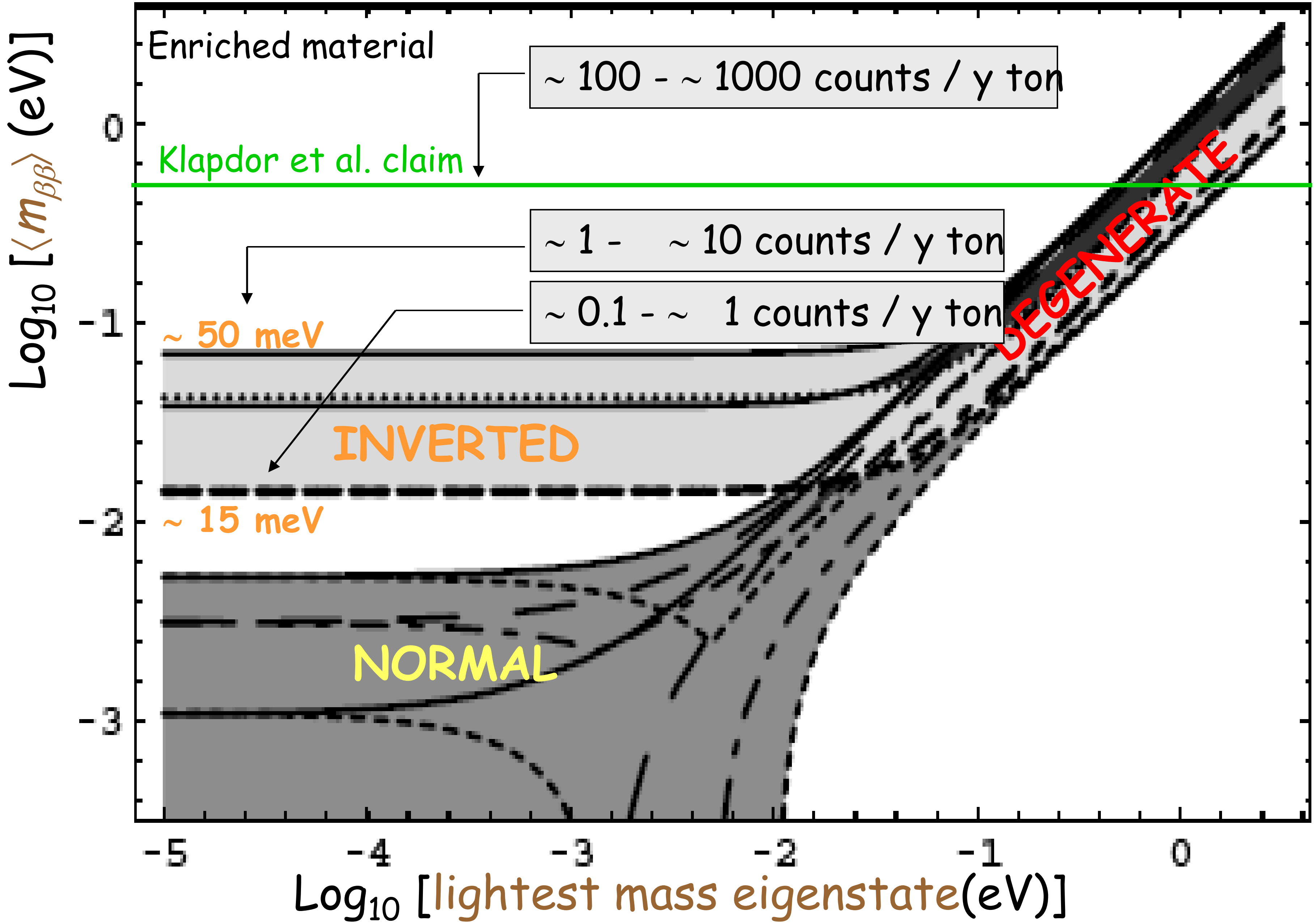
$$\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

→ can be of the order of ~ 50 meV in case of inverted hierarchy

The physics reach of 0νββ

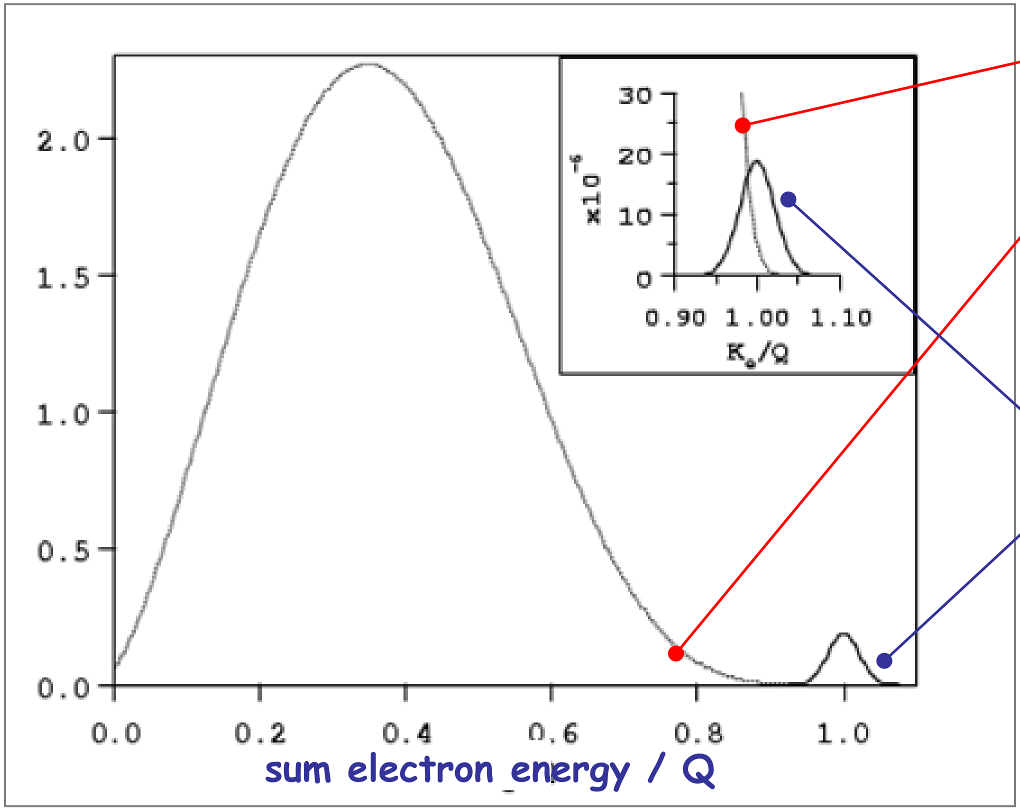


How difficult is it?



The experimental signatures

The shape of the two electron sum energy spectrum enables to distinguish among the two different discussed decay modes



2ν double beta decay
continuum with
maximum at ~1/3 Q

0ν double beta decay
peak enlarged only by
the detector energy resolution

An ideal experiment

SENSITIVITY $S_{0\nu}$: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

Maximize Rate + Minimize Background

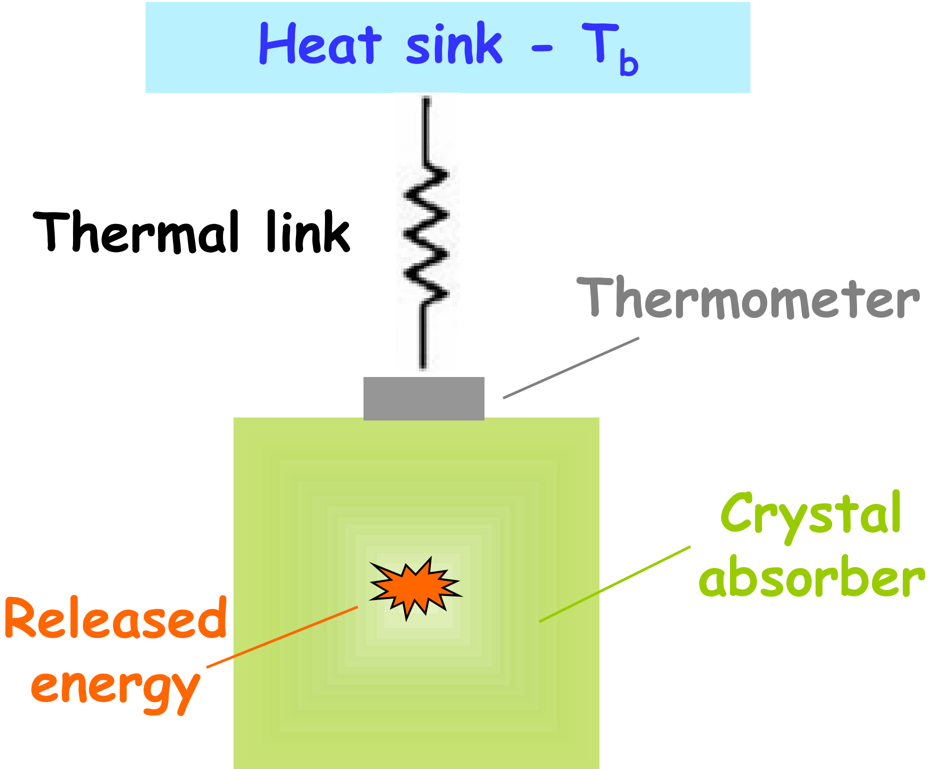
$$S_{0\nu} \propto \left(\frac{M t_{live}}{b \Delta E} \right)^{\frac{1}{2}}$$

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b \Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

Desirable features

Large Mass (~ 1 ton)
Large Q value, fast $0\nu\beta\beta$
Good source radiopurity
Demonstrated technology
Ease of operation
Natural isotope
Small volume, source = detector
Good energy resolution
Slow $2\nu\beta\beta$ rate
Identify daughter in real time
Event reconstruction
Nuclear theory

The bolometric technique



Signal: $\Delta T = E/C$

Time constant $= C/G$

-> to develop high pulses the detector has to work at **low temperatures** (10 – 50 mK).

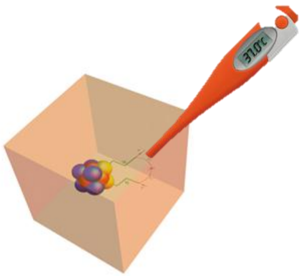
Desirable features

- Large Mass (~ 1 ton)
- Large Q value, fast $0\nu\beta\beta$
- Good source radiopurity
- Demonstrated technology
- ~~Ease of operation~~
- Natural isotope
- Small volume, source = detector
- Good energy resolution
- Slow $2\nu\beta\beta$ rate
- ~~Identify daughter in real time~~
- ~~Event reconstruction~~
- Nuclear theory

Bolometers for 0νββ

E. Fiorini, T.O. Niinikoski (1983)

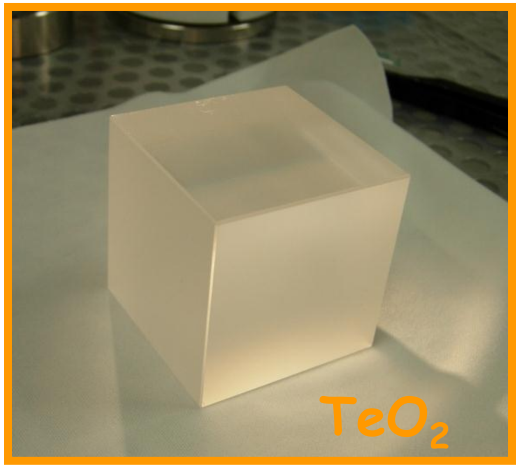
Nucleus	I. A.	Q-value [keV]	Materials successfully tested as bolometers in crystalline form
^{76}Ge	7.8	2039	Ge
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $ZnMoO_4$, Li_2MoO_4, $MgMoO_4$
^{96}Zr	2.8	3350	ZrO_2
^{150}Nd	5.6	3367	NONE → many attempts
^{48}Ca	0.187	4270	CaF_2, $CaMoO_4$



→ Cuoricino, CUORE

TeO_2 bolometers: the main ingredients

MAIN ABSORBER



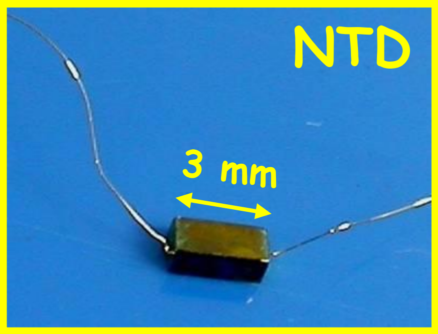
DBD source ≡ absorber

Why TeO_2

It contains a good isotope, ^{130}Te, that among the possible $0\nu\beta\beta$ candidates presents several nice features:

- high natural isotopic abundance (33.87 %)
- high transition energy (Q ~ 2527 keV)
- reasonably favourable theoretical calculations of NME

THERMISTOR



Sensitive to thermal phonons

The thermal signal is measured by means of a NTD Ge Thermistor working in the Variable Range Hopping regime:

$$R = R_0 \cdot \exp\left(\frac{T_0}{T}\right)^{\gamma}$$

An electrical read-out converts resistance changes into voltage pulses

The Cuoricino experiment

Neutrinoless DBD

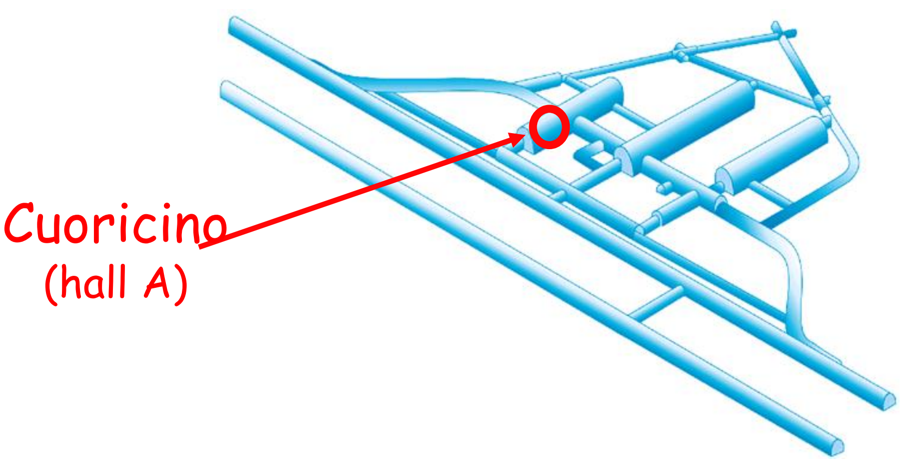
Underground National Laboratory of Gran Sasso

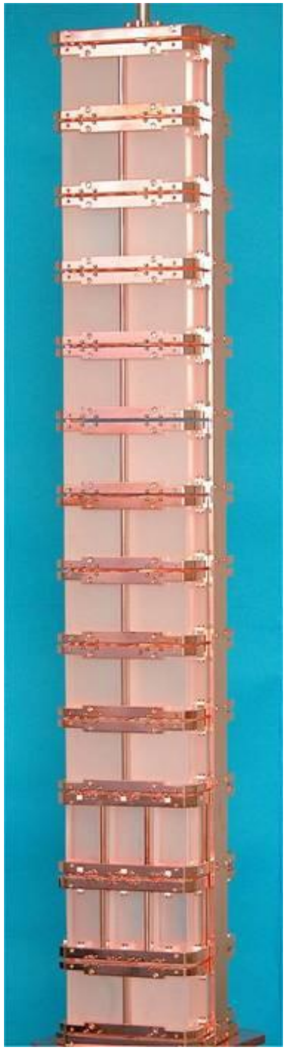
located in the highway tunnel

3500 m.w.e.

24μ /m²/d

ITALY





T= 10 mK

62 TeO_2 bolometers

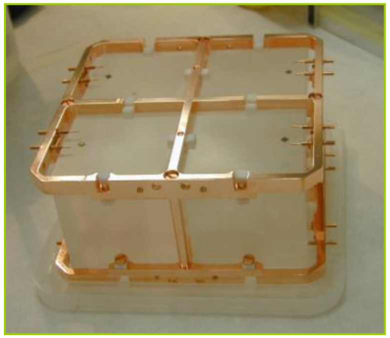
total active mass

- TeO_2 : 40.7 kg
- ^{130}Te : 11.3 kg
- ^{128}Te : 10.5 kg

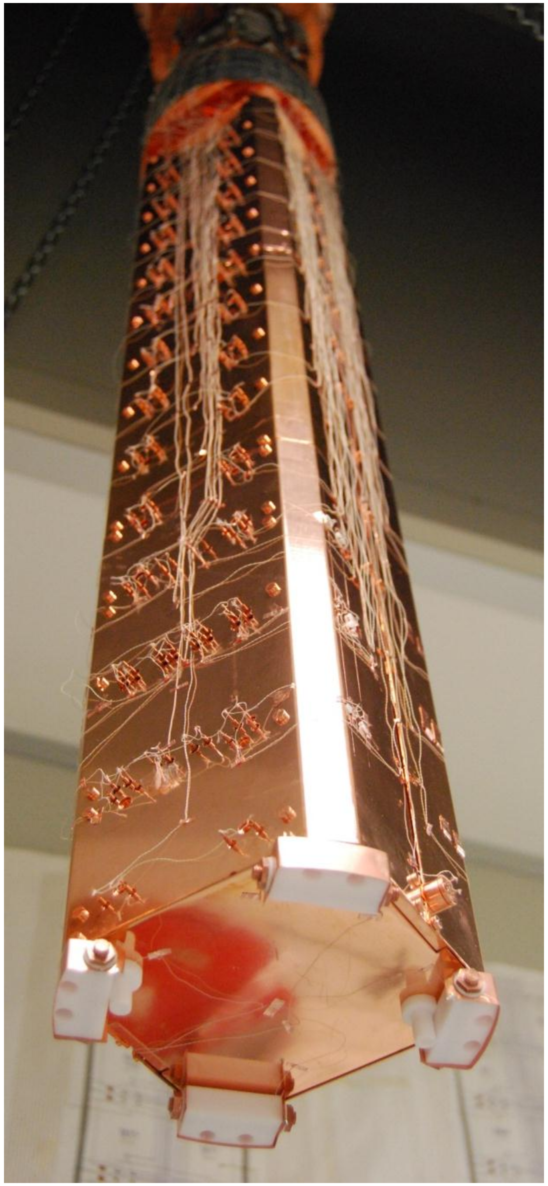
- 11 modules with 4 *big* detectors
  - 44 TeO_2 crystals
  - 5×5×5 cm^3 ⇒ 790 g
  - TeO_2 mass ⇒ 34.76 kg

- 2 modules with 9 *small* detectors
  - 18 TeO_2 crystals
  - 3×3×6 cm^3 ⇒ 330 g
  - TeO_2 mass ⇒ 5.94 kg
- 4 crystals are enriched
  - 2×$^{130}TeO_2$ + 2×$^{128}TeO_2$

- **Heat** @ 10 mK with Ge/NTD thermometer



In Cuoricini sempiterna memoria

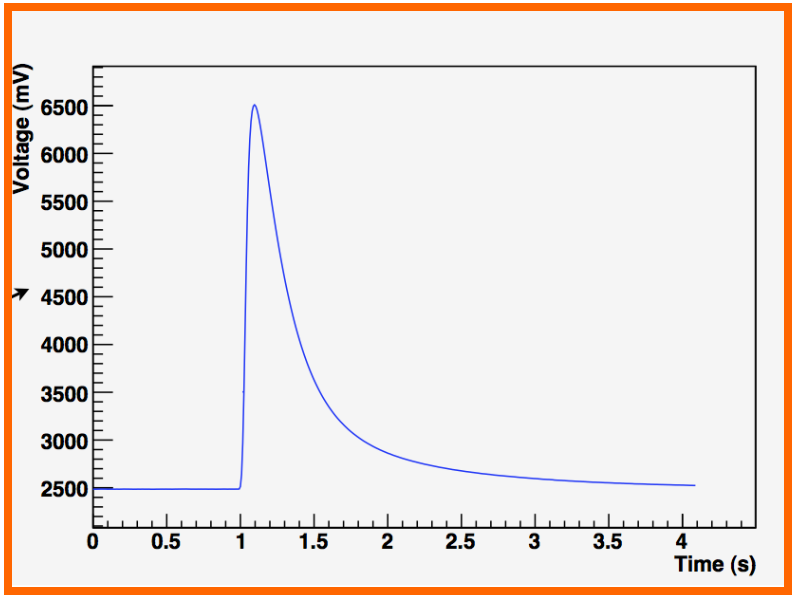


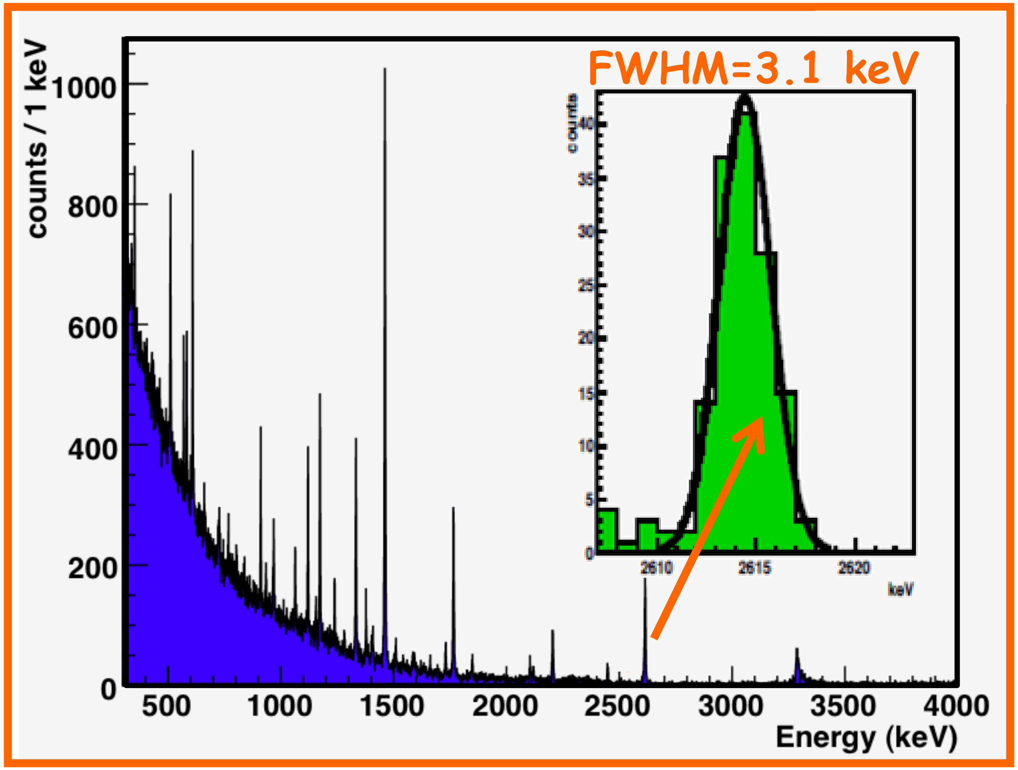
Data taking started in April 2003 and ended in June 2008. The data are separated in two runs (RUN I and RUN II), due to a major maintenance interruption

End of June 2008:
Cuoricino has been shut down

Saturation of sensitivity
Need of experimental space in hallA for further tests

Cuoricino/CUORE: the performance





$C = 2 \times 10^{-9}$ J/K
$\Delta T = 0.1$ mK/MeV
τ_{rise} 50ms - τ_{decay} 300 ms

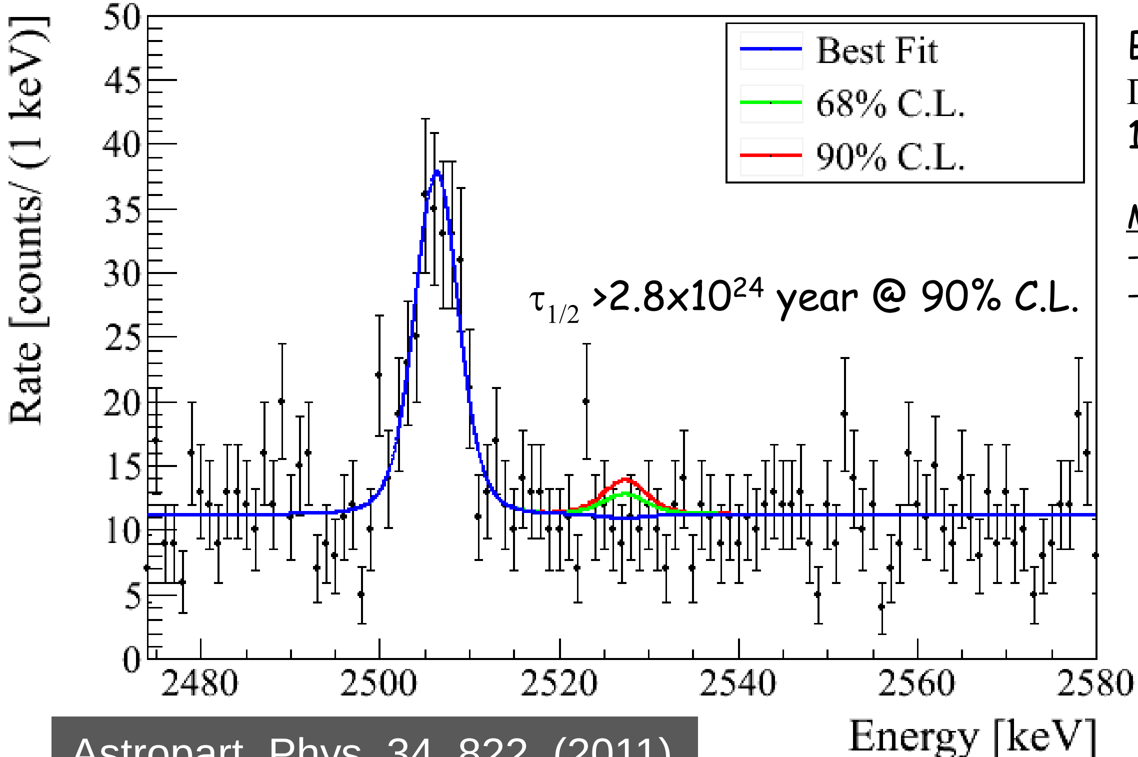
R ~ 100 MΩ
$\Delta R = 3$ MΩ/MeV
$\Delta V = 0.3$ mV/MeV

CUORE R&D test: $FHWM_{2615keV} = 4.6 \pm 1.2$ keV

Excellent energy resolution on the internal alphas from ^{210}Po: $FHWM_{5407keV} =$ 2.4 KeV

Cuoricino 0νββ results

MT = 19.75 kg ^{130}Te × y
b @ Q-value = 0.17 counts/(keV kg y)



Astropart. Phys. 34, 822, (2011)

BEST FIT:
Γ = (-0.2 +/- 1.4 (stat) +/- 0.3 (syst)) x 10^{-25} year $^{-1}$

<u>METHOD:</u>
- BEST FIT: MAXIMUM LIKELIHOOD
- LIMIT : BAYESIAN (flat prior on the rate)

Maximum likelihood fit with 8 free parameters:
OnuDBD rate (same on all the detectors)
3 FLAT BACKGROUND rates (for BIG, SMALL and ENRICHED)
3 ^{60}Co rates (for BIG, SMALL and ENRICHED)
^{60}Co sum energy value (same on all the detectors)

$m_{\beta\beta}$	< (300 – 570) meV	(R)QRPA	*Phys. Rev. C 77, 045503 (2008)*
	< (360 – 580) meV	pnQRPA	*J. Phys. Conf. Ser. 173, 012012 (2009)*
	< (570 – 710) meV	ISM	*Nucl. Phys. A 818, 139-151 (2009)*
	< 370 meV	IBM-2	*Phys. Rev. C 79, 044301 (2009)*

From Cuoricino to CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

Main improvements

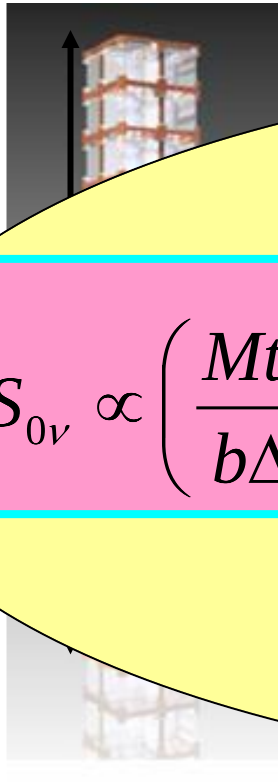
$$S_{0\nu} \propto \left(\frac{M t_{live}}{b \Delta E} \right)^{\frac{1}{2}}$$

$$M = 20 \cdot M_{Cuoricino}$$

$$\Delta E = \Delta E_{Cuoricino} / 1.6$$

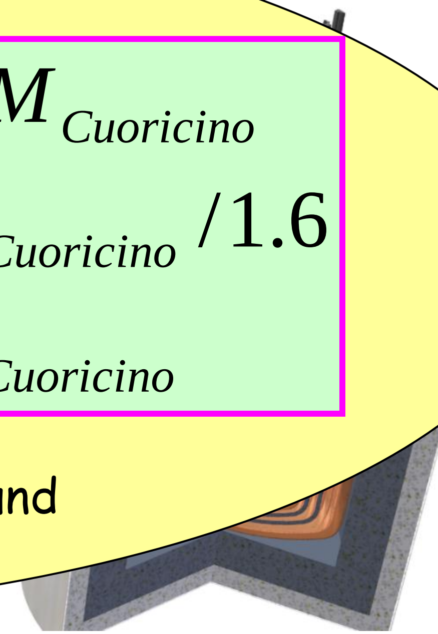
$$t_{live} = 4 \cdot t_{Cuoricino}$$

…the crucial parameter is the background



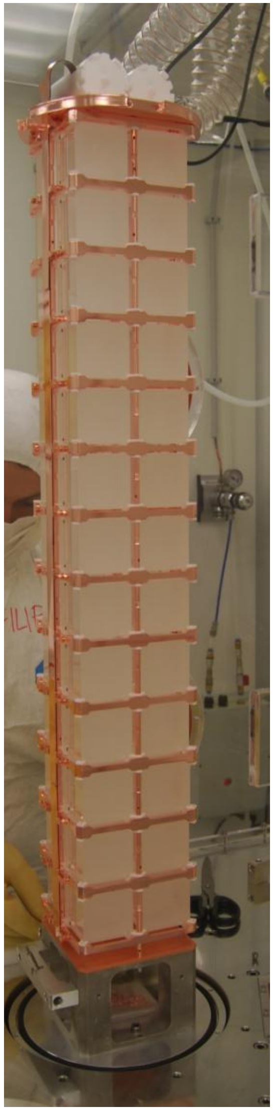
19 Cuoricino-like towers with 13 planes of 4 crystals each

… a tightly packed array of **988 bolometers** M ~ 200 kg of ^{130}Te…



… placed in a special dilution refrigerator

From Cuoricino to CUORE through CUORE-0



CUORE-0

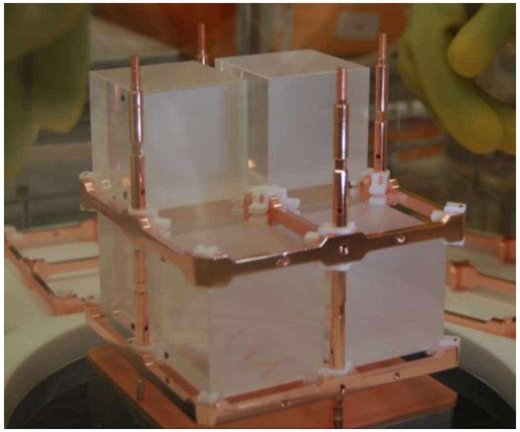
the first step of CUORE experiment

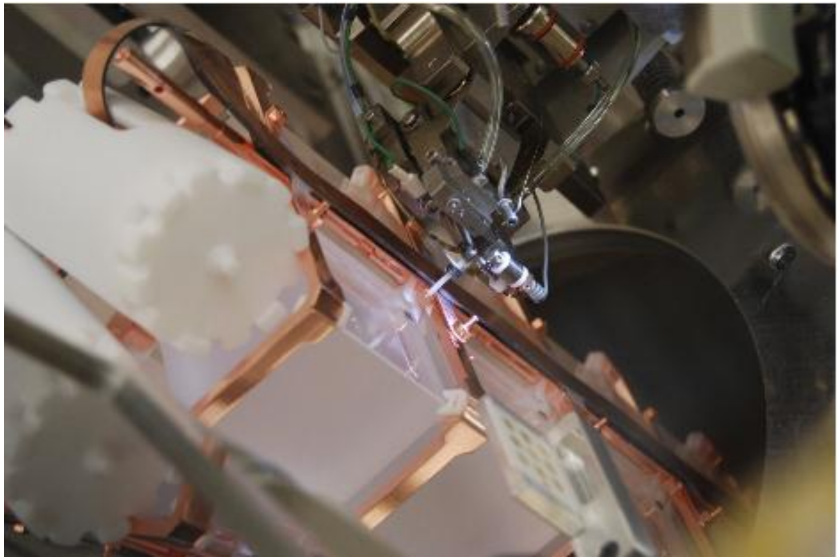
CUORE-0 will be assembled with the same procedures foreseen for CUORE (totally different from those adopted for Cuoricino) and operated in the old Cuoricino dilution refrigerator.

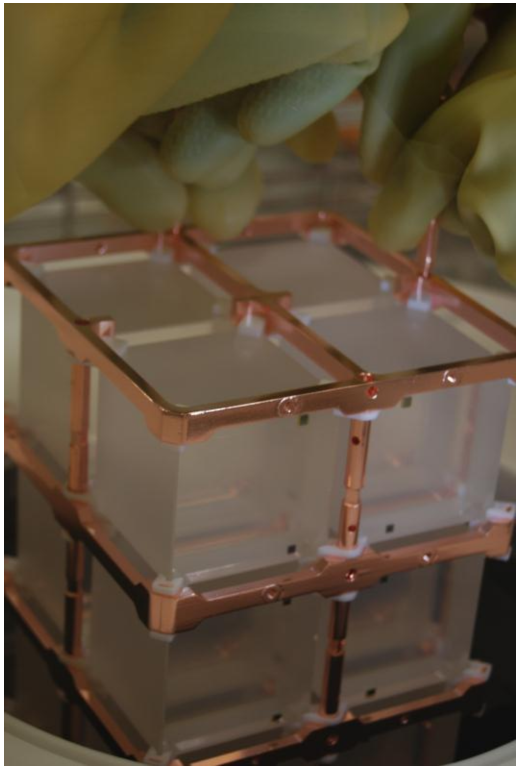
Main goals:

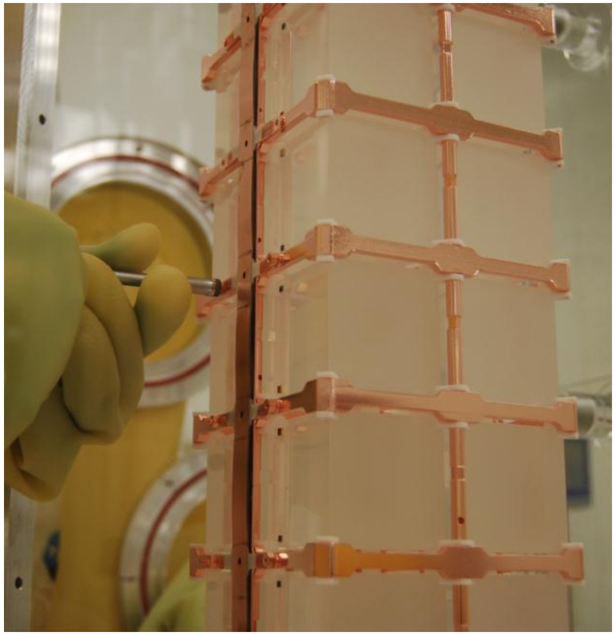
- full test and debug of the new CUORE assembly line
    - high statistics check of the improved uniformity of bolometric response
    - identify which operations are critical for the success of CUORE
    - reveal flaws and inefficiencies in the assembly procedures
- permit a thorough exercise of the analysis framework
- provide an opportunity to test the skill sets necessary within the collaboration

CUORE-0: detector assembly

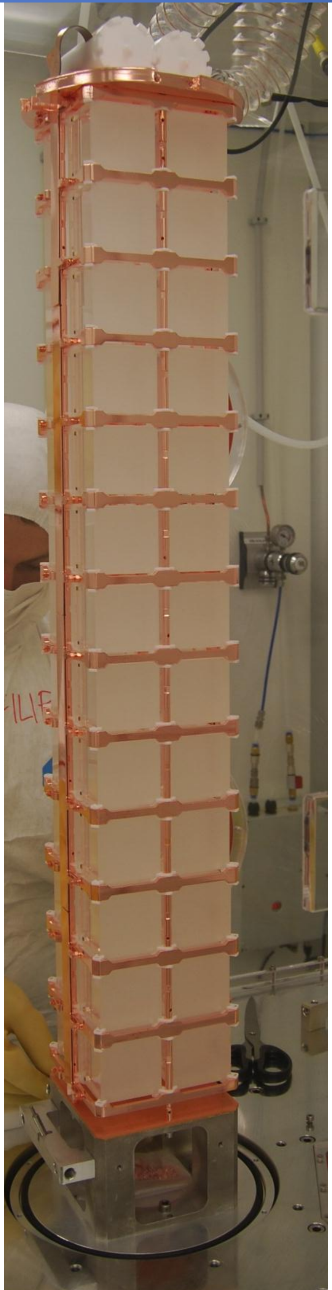


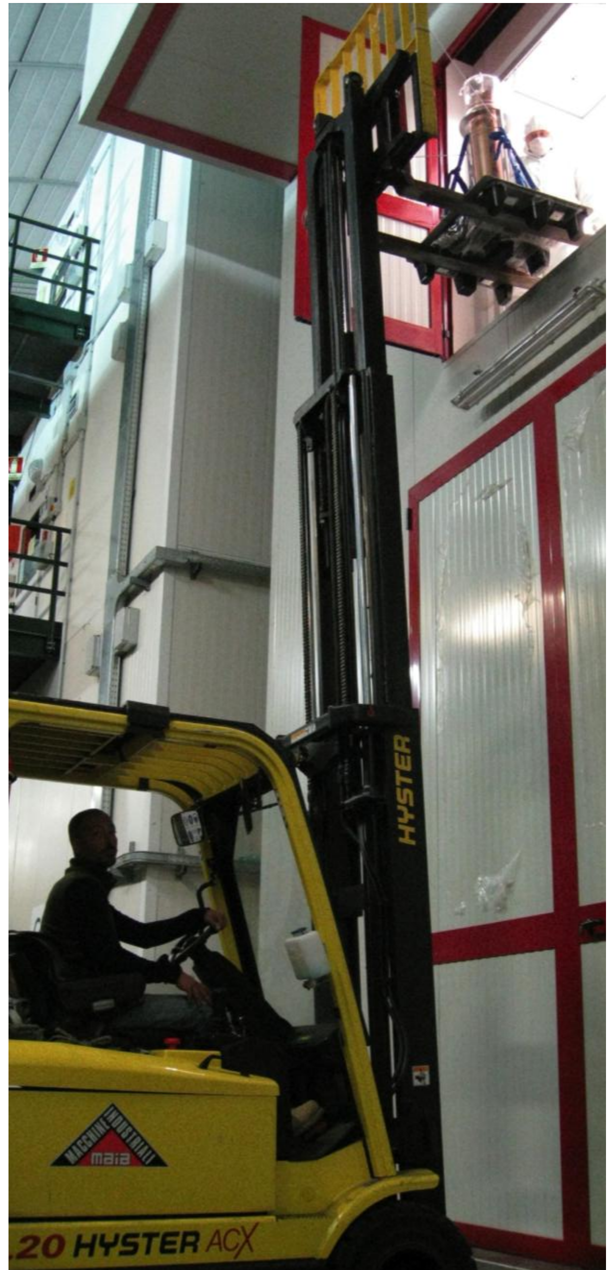




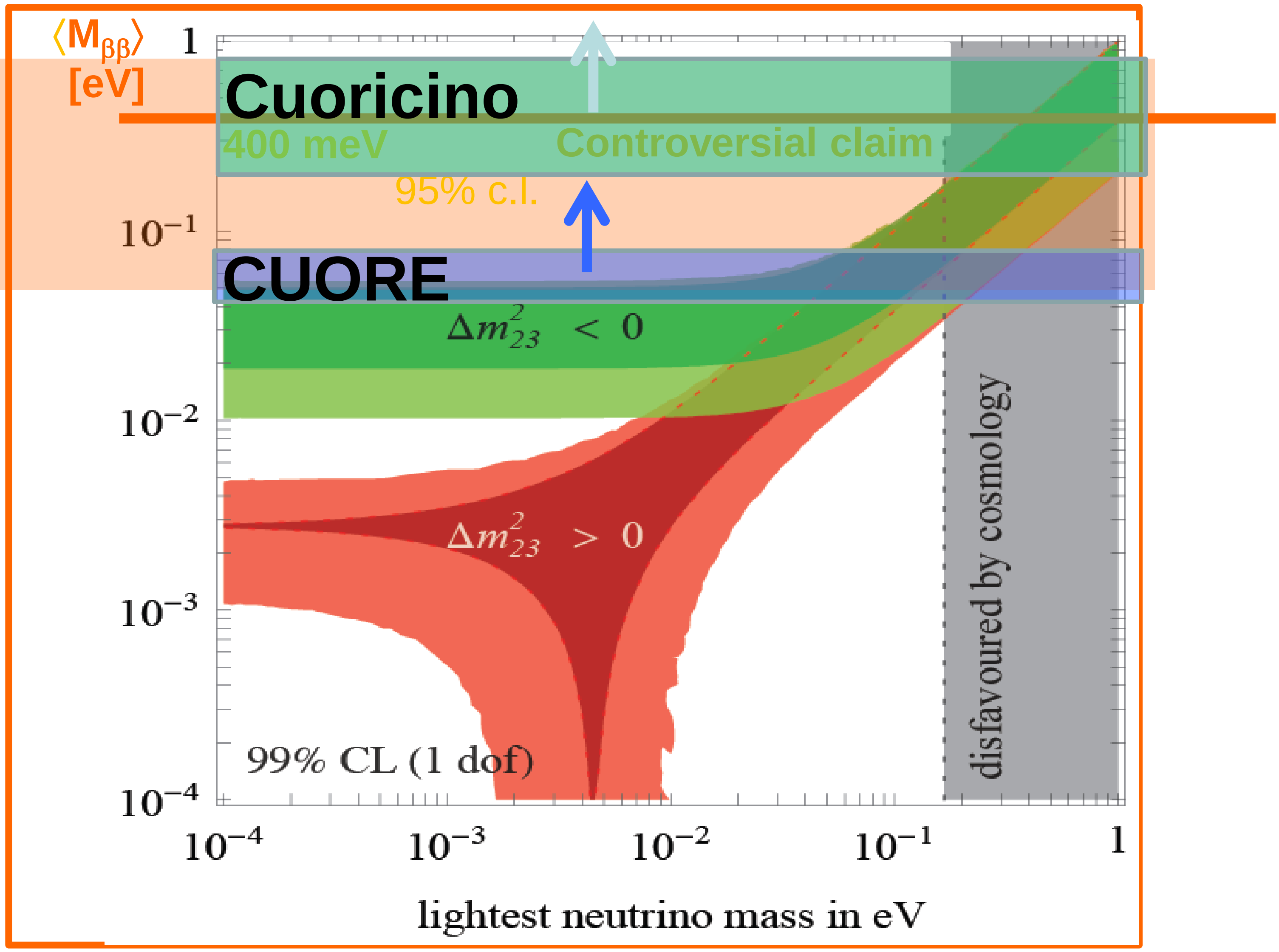


CUORE-0: the tower is ready

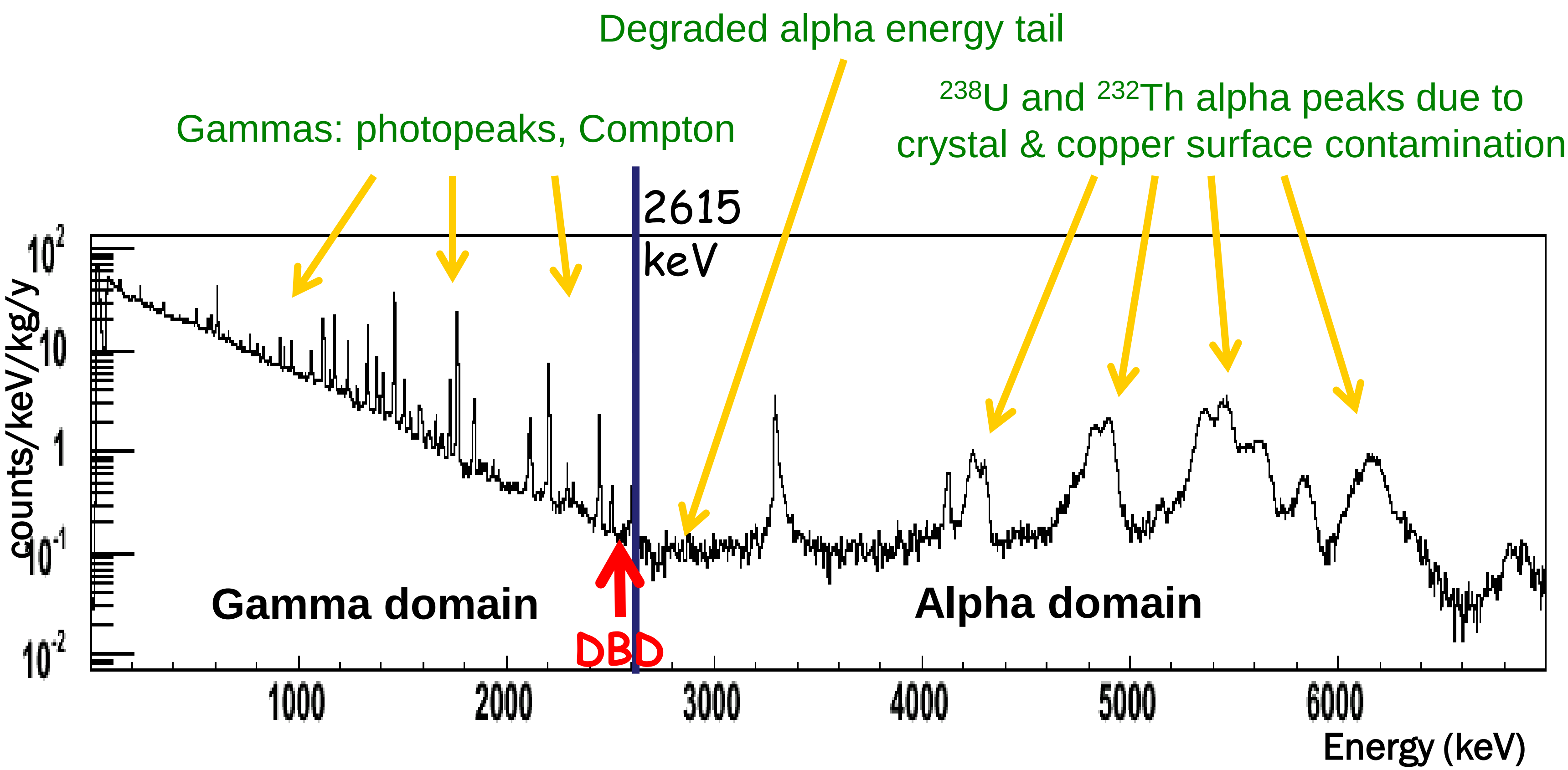




Role of ^{130}Te bolometric experiments

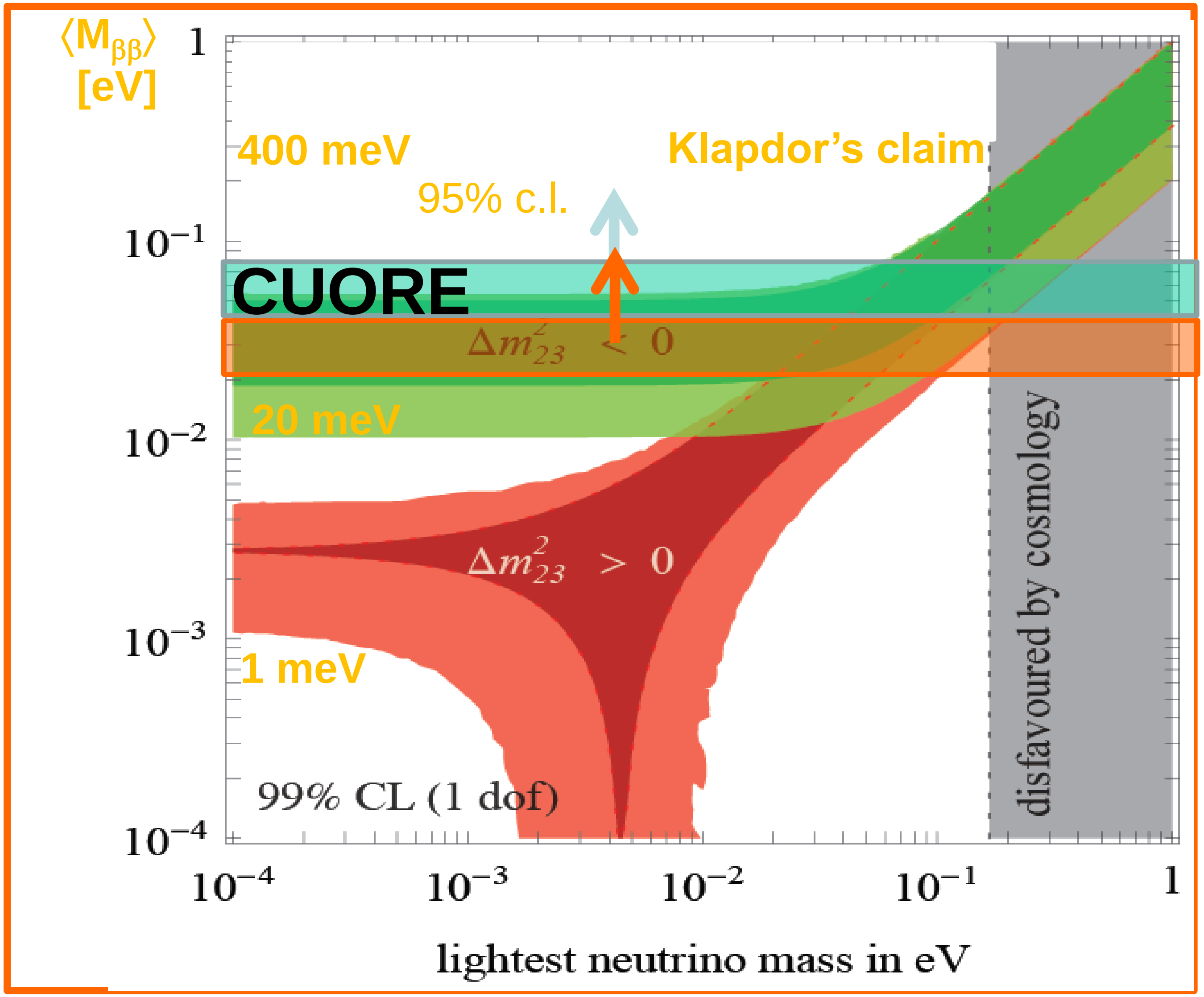


Cuoricino/CUORE: the dominating background



1. Get rid of surface (alpha) contamination
2. Move DBD peak above 2615 keV → change isotope

If surface events are rejected…



BKG ~ 10^{-2} c/keV/kg/y

↓

BKG ~ 10^{-3} c/keV/kg/y

↓

$\langle M_{bb} \rangle$ [eV] improves by $10^{1/4} \sim 1.8$

Pulse shape discrimination in TeO_2

No detectable difference between α/β pulses in pure TeO_2 bolometers

Three methods were proposed to make TeO_2 bolometers sensitive to surface events and all them work at the prototype level.

① **Surface sensitive composite bolometers**

Astropart. Phys. 34, 809, (2011)

② **Use of thin NbSi films (as Anderson insulators) as phonon sensors**

J. Low Temp. Phys. 151, 871, (2008)

③ **Coat all the crystal with a passive SC film and use an ordinary sensor**

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

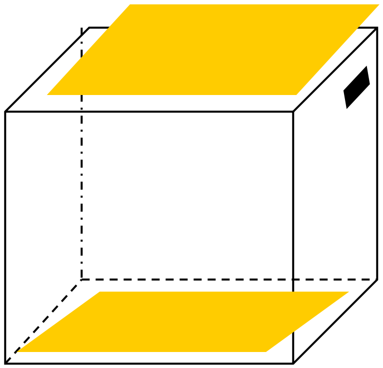
Surface Sensitive Composite Bolometers

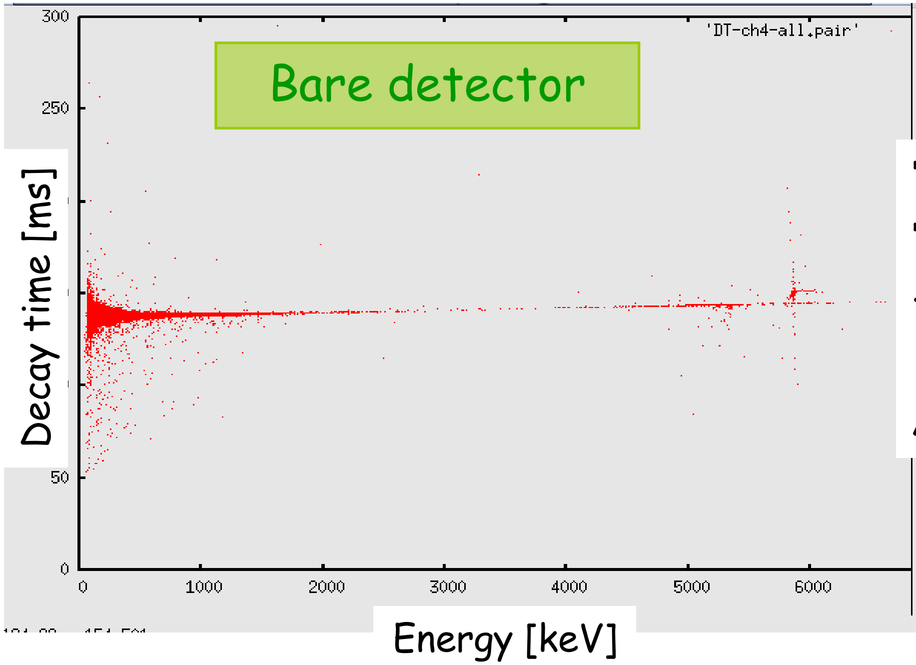
① Surface sensitive composite bolometers

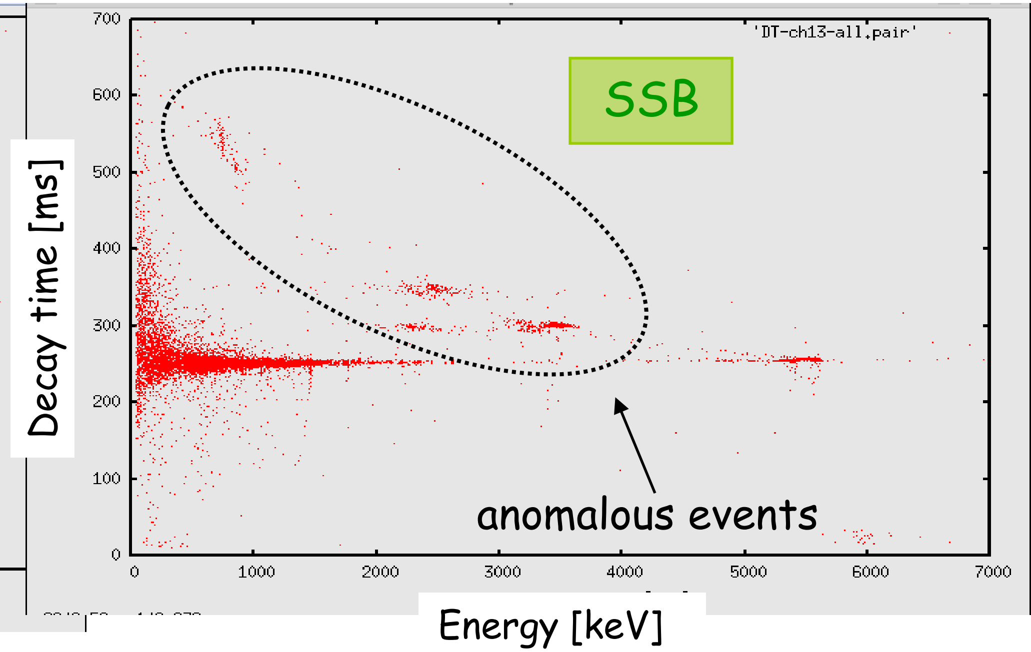
Astropart. Phys. 34, 809, (2011)

Protect each crystal face with a thin TeO_2 slab working as pulse shape modifier.

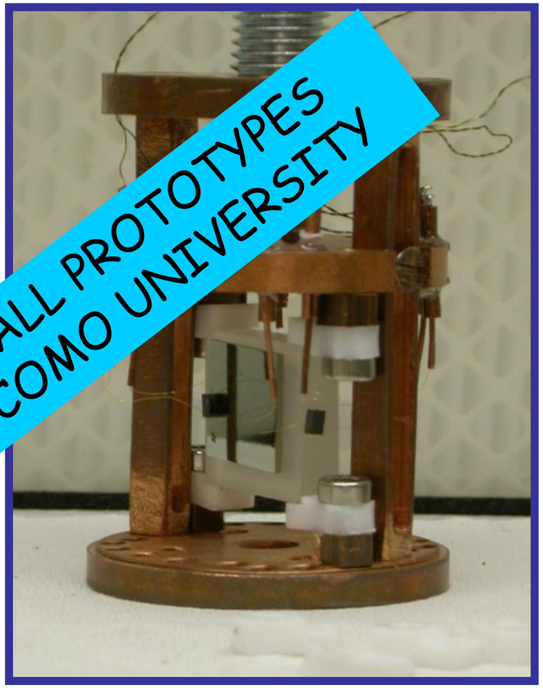
It worked in real size prototype, but would require important modification in the CUORE structure and relevant assembly complications.

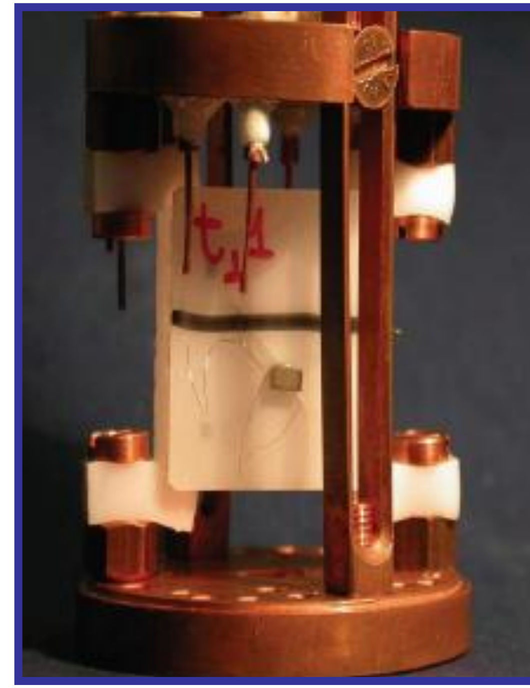




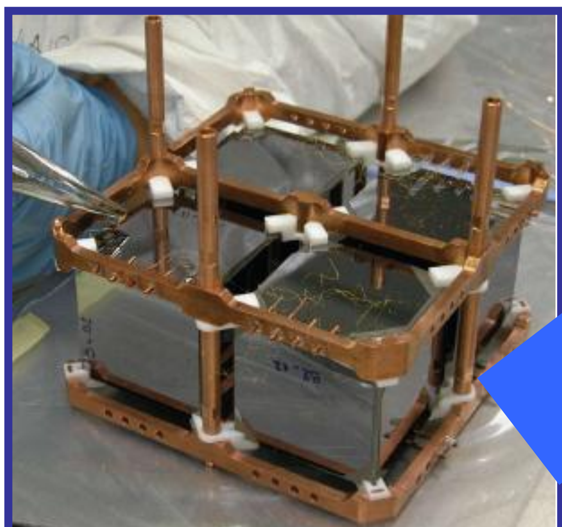


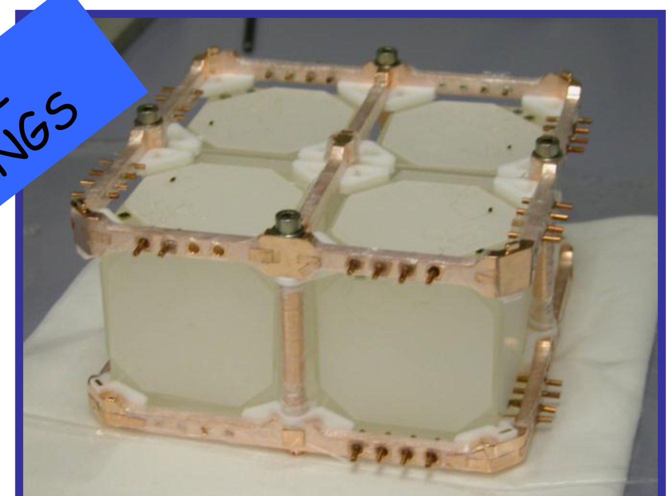
Surface Sensitive Composite Bolometers





SMALL PROTOTYPES @ COMO UNIVERSITY





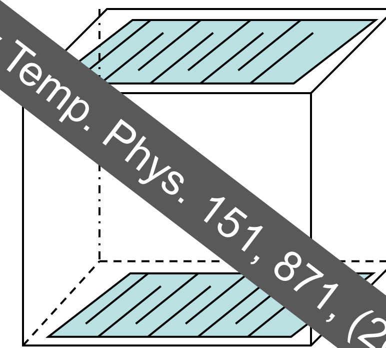
CUORICINO SIZE PROTOTYPES @ LNGS

NbSi film equipped bolometers

② Use of thin NbSi films (as Anderson insulators) as phonon sensors

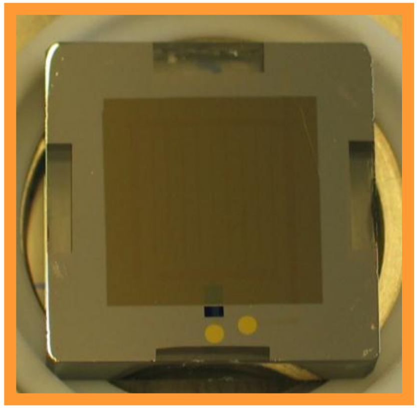
Technique first developed in the framework of Dark Matter by the EDELWEISS collaboration.

J. Low Temp. Phys. 151, 871, (2008)



Events depositing energy close to surface are distinguishable thanks to an enhanced athermal component.

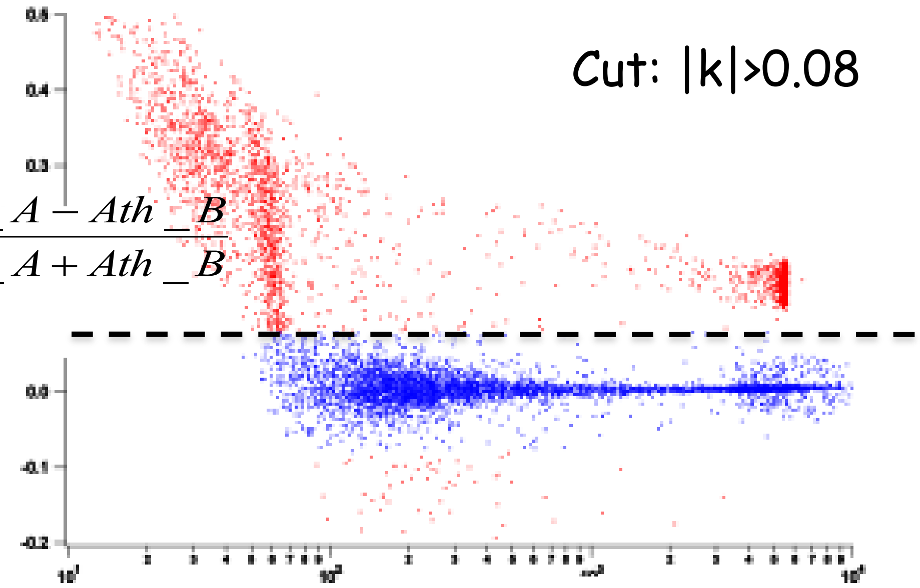
Small size prototype detectors were successful, but they would require sensitive films covering all the faces, and nuclear NbSi film heat capacity would be huge at 15 mK.



TeO_2 bolometers for 0νββ

$$k = \frac{Ath\_A - Ath\_B}{Ath\_A + Ath\_B}$$

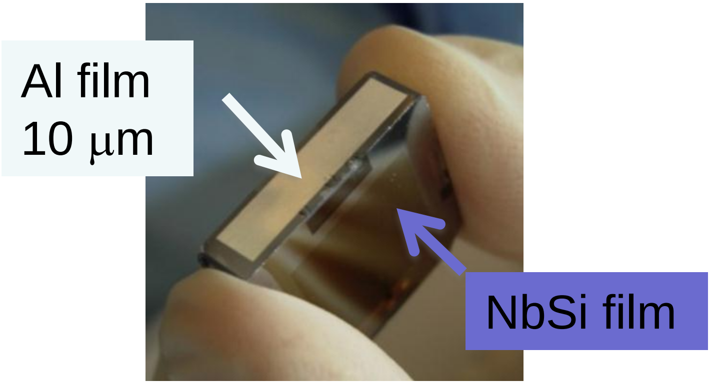
Cut: |k|>0.08



Al film equipped bolometers

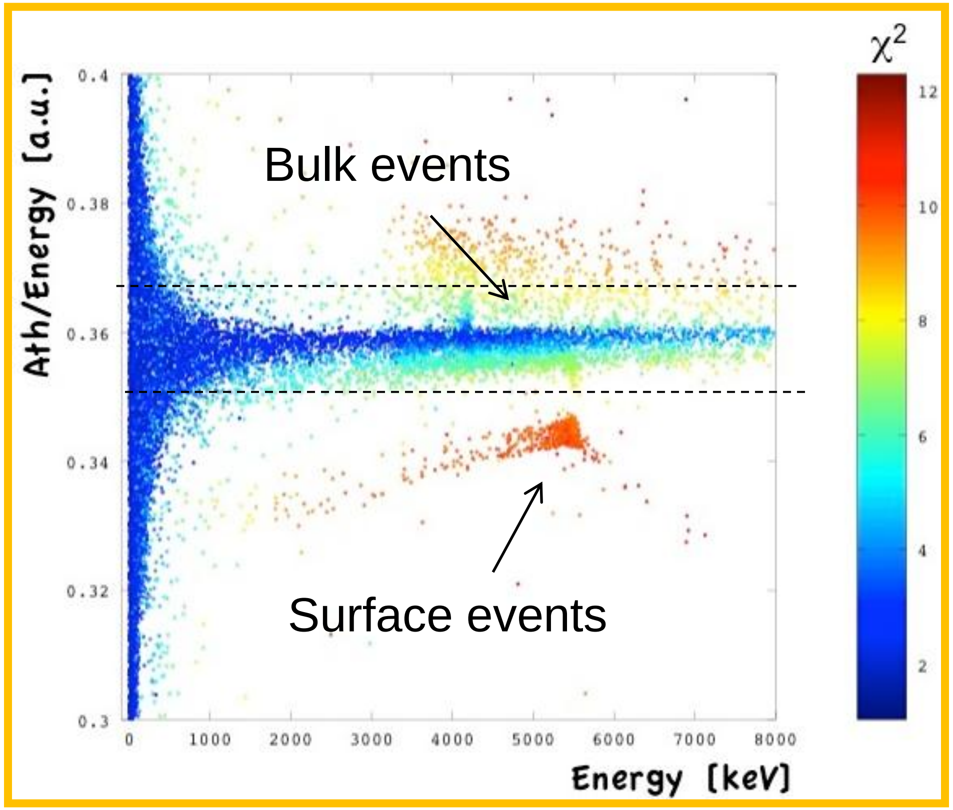
③ Coat all the crystal with a passive SC film and use an ordinary sensor

- Events close to surface determine a large population of quasiparticles in the film due to absorption of out-of-equilibrium phonons
- Exploit **quasi-particle life-time** in superconductive Al.
- Delayed component in the phonon pulse (pulse shape discrimination).



Fast sensor (NbSi film)
+
TeO_2 crystal
+
Al film
(pulse shape modifier)

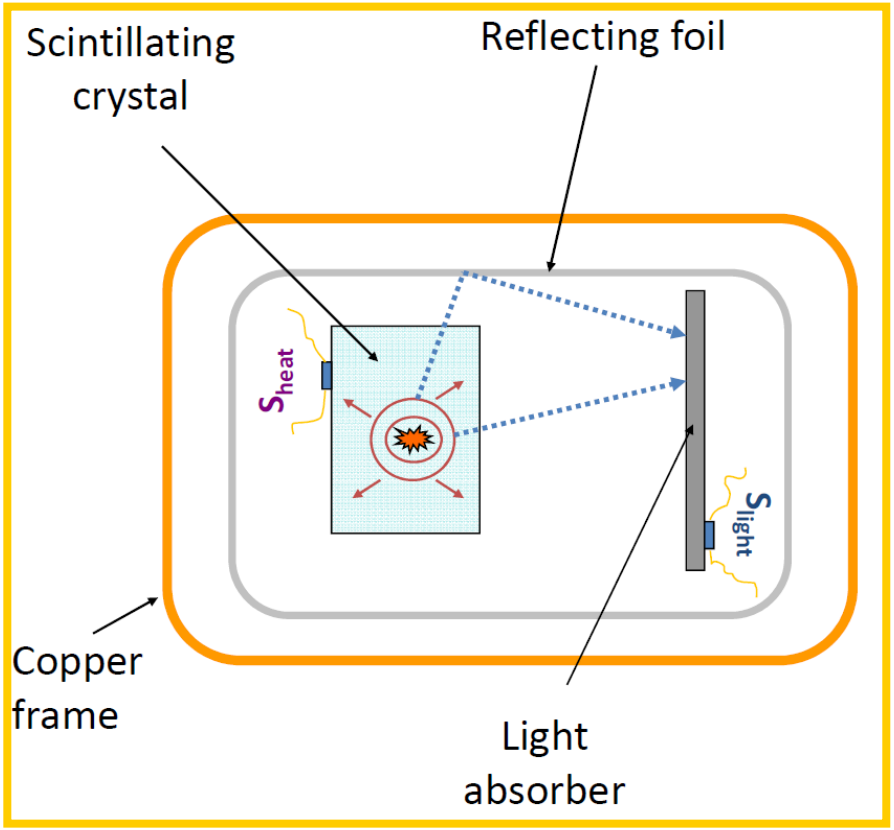
J. Low Temp. Phys. 167, 1029, (2012)

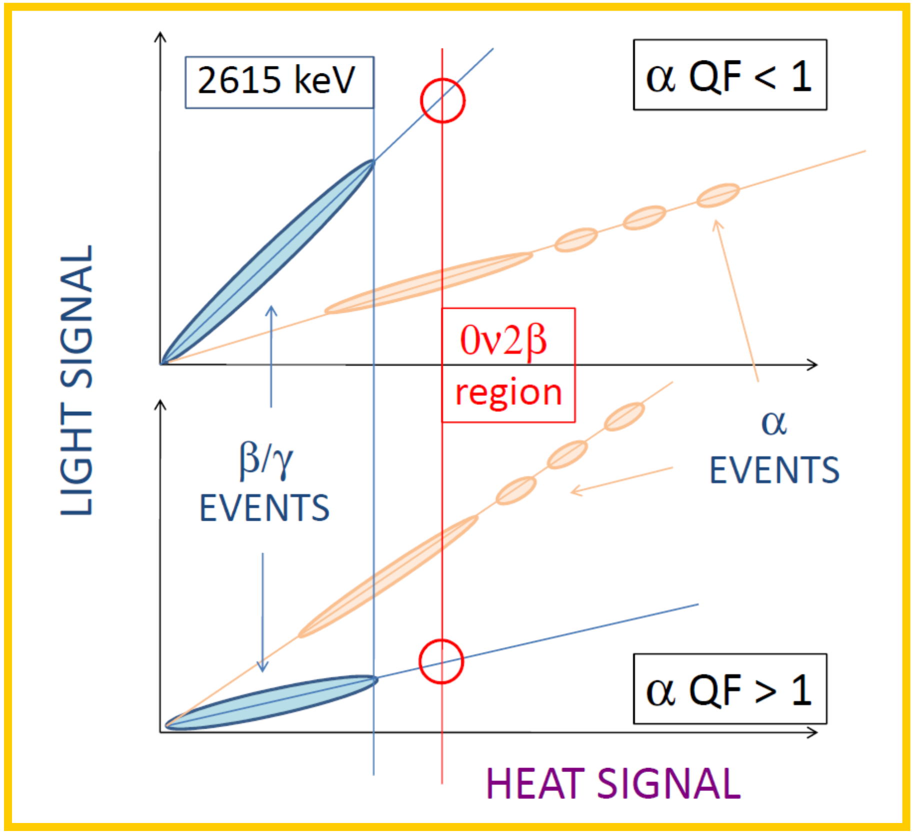


Demonstration of the rejection power for surface events in a TeO_2 crystal equipped with an Al layer as pulse shape modifier.

Scintillating bolometers

L. Gonzalez-Mestres, D. Peret-Gallix



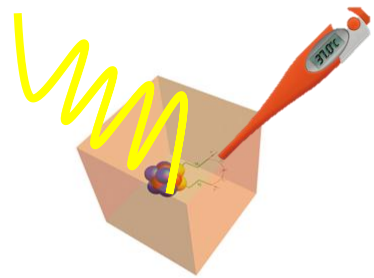


"Easy" with scintillating materials

Intense R&D in LNGS in the last years
Since 2011, a group in CSNSM work on this subject

Which absorber?

Nucleus	I. A. [%]	Q-value	Underlined materials are good scintillators
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$ $ZnMoO_4$, Li_2MoO_4, $MgMoO_4$
^{96}Zr	2.8	3350	ZrO_2
^{150}Nd	5.6	3367	NONE → many attempts
^{48}Ca	0.187	4270	CaF_2, $CaMoO_4$



LUCIFER - ZnSe (LNGS, Rome, Orsay)

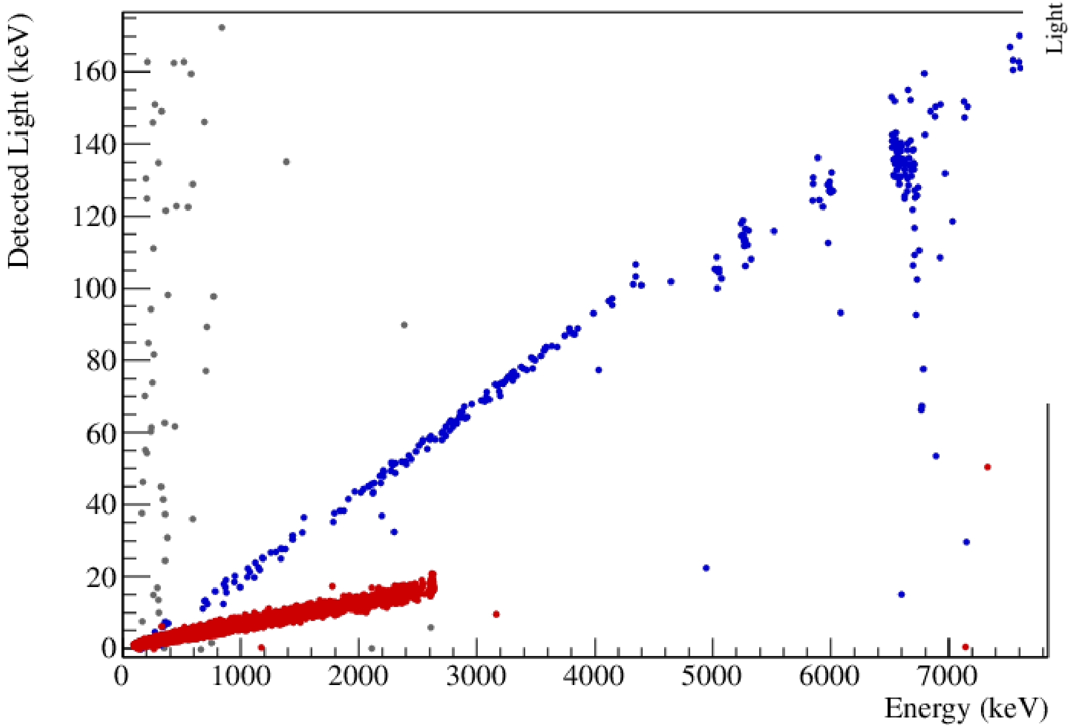
$ZnMoO_4$ program (Orsay, Kiev, Novosibirsk, LNGS, Rome)

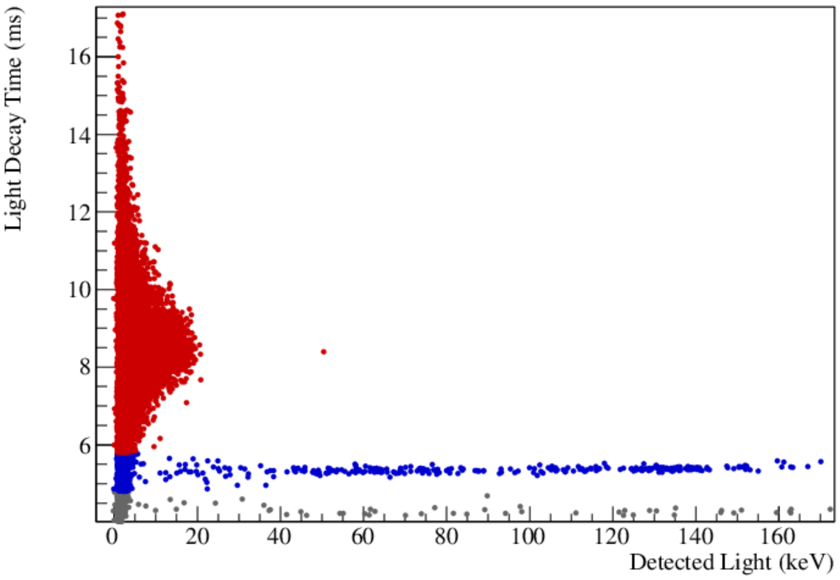
$CaMoO_4$ program (Korea)

Scintillating bolometers – ZnSe

Astropart. Phys. 34 (2011) 344B

ZnSe (LNGS, Milano-Bicocca)





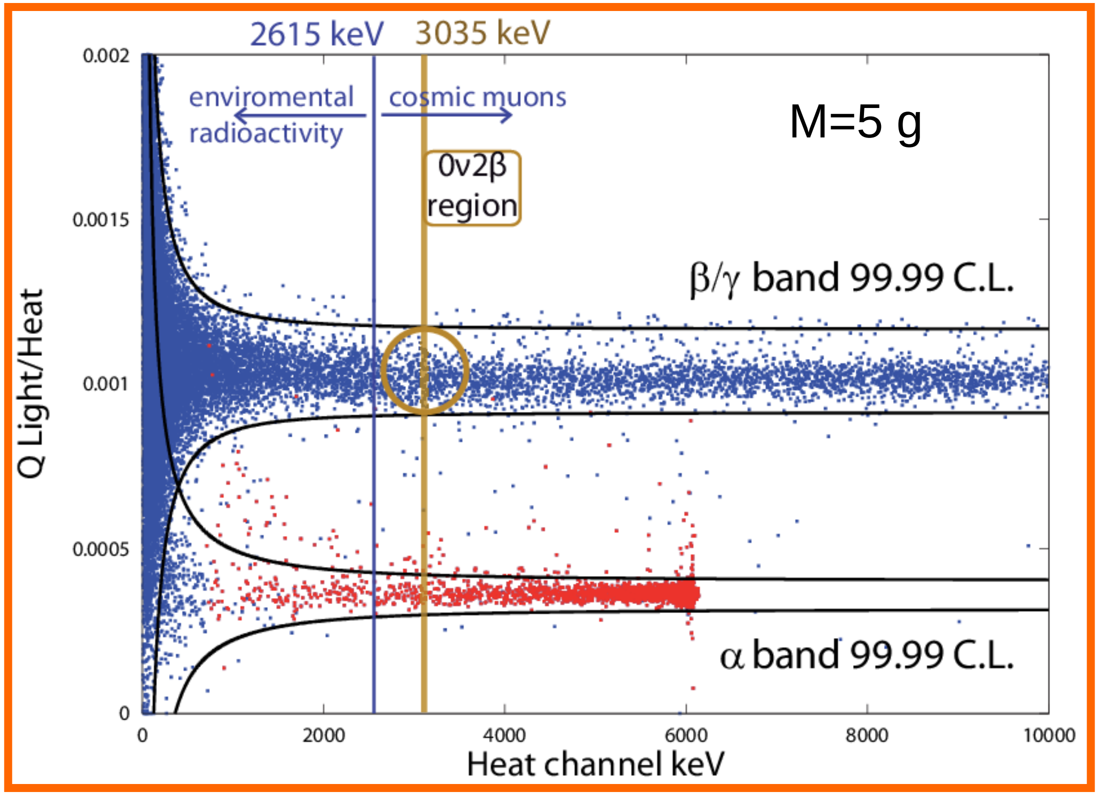
Pulse shape discrimination in the light signal

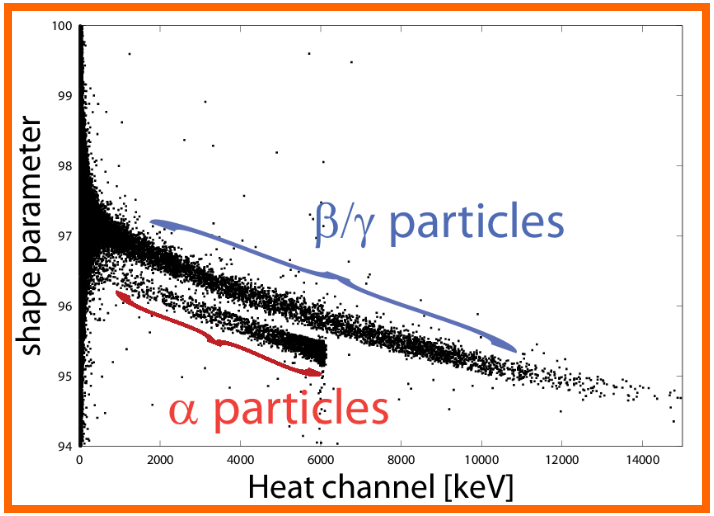
JINST 5 (2010) 11007

Astropart. Phys. 34 (2010) 143

Scintillating bolometers – $ZnMoO_4$ (1)

$ZnMoO_4$ (Orsay, Como)



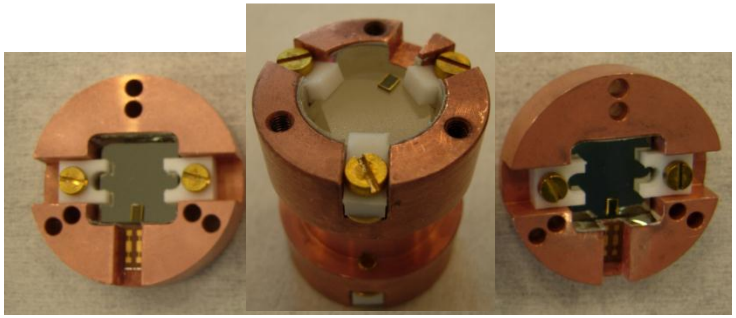


Pulse shape discrimination in the heat signal

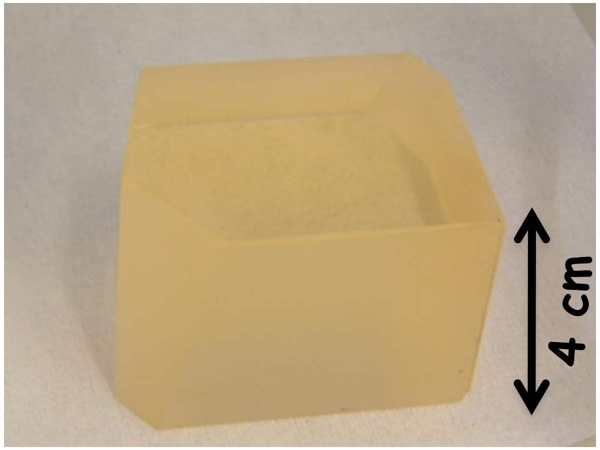
Phys. Lett. B 70 (2012) 318

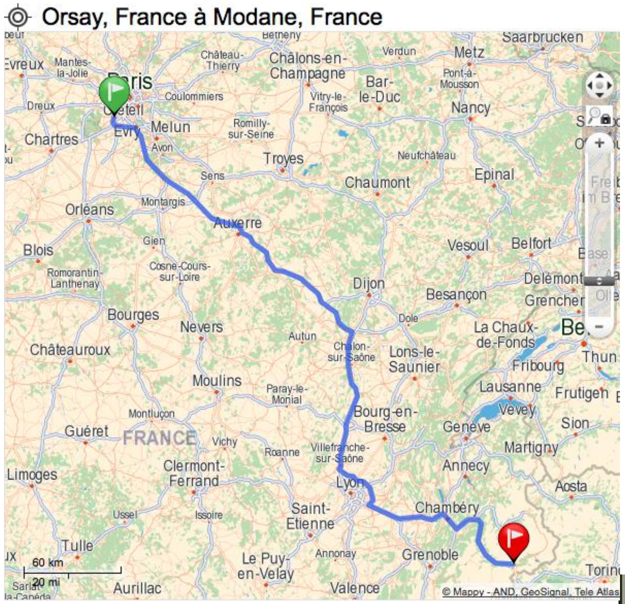
Scintillating bolometers – $ZnMoO_4$ (2)

A detector of **24 g** has operated at CSNSM

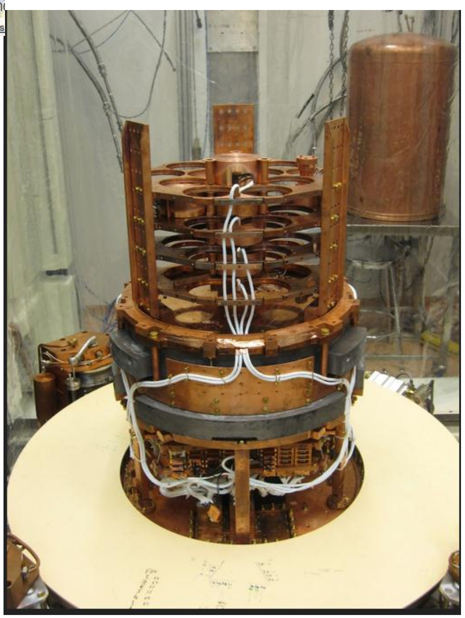


A big $ZnMoO_4$ of about 400 g is already at CSNSM and will be cooled down soon.



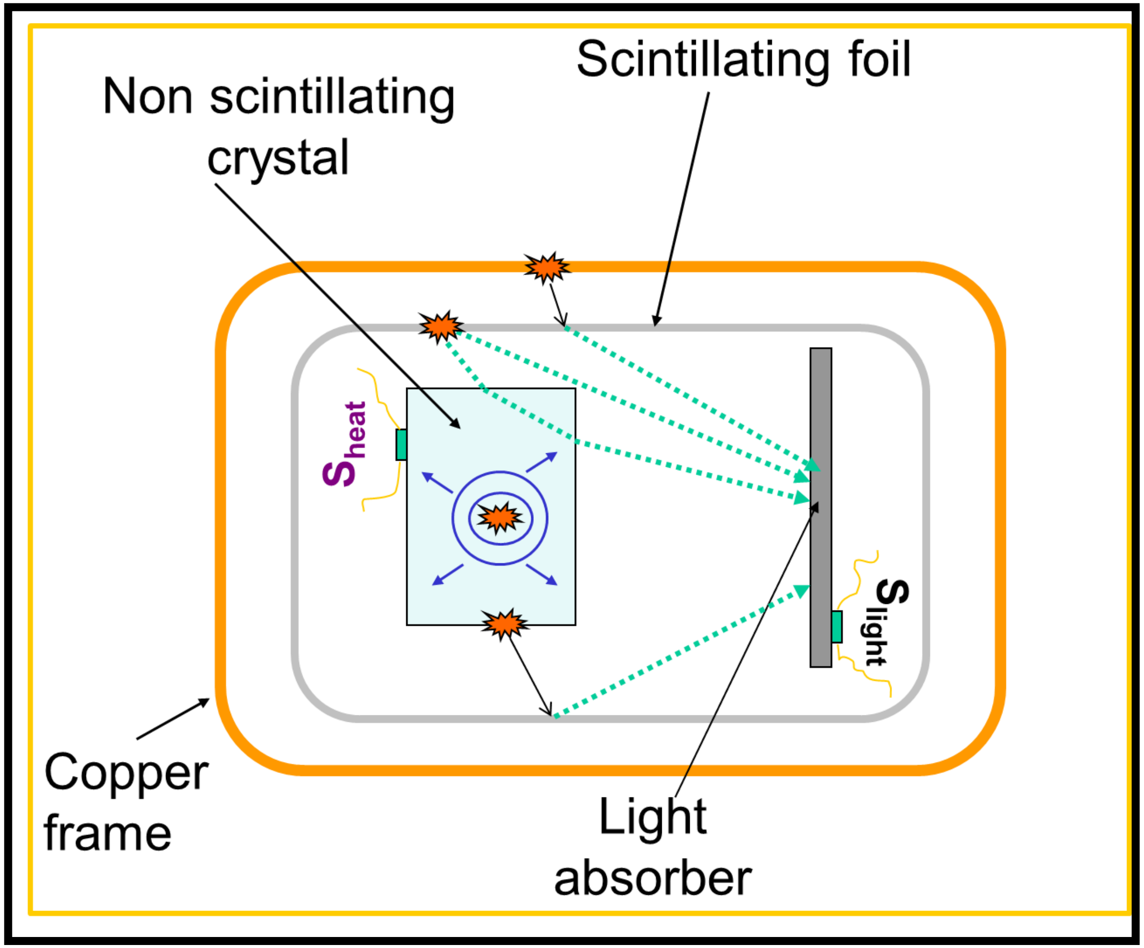


It is now at LSM



ABSURD: A Background SUrface Rejection Detector

Luminescent envelope for TeO_2



TeO_2 crystal is equipped with a light detector as if it were scintillating

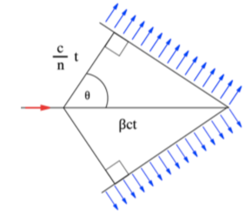
TeO_2 crystal is enveloped by a high efficient scintillating foil

Only surface events produce scintillation, read out by the light detector

↓

arXiv:1103.5296v1

Is TeO_2 luminescent (1) ?



Indication of weak luminescence of TeO_2 traces back to several years ago

NIM A 520, 159, (2004)

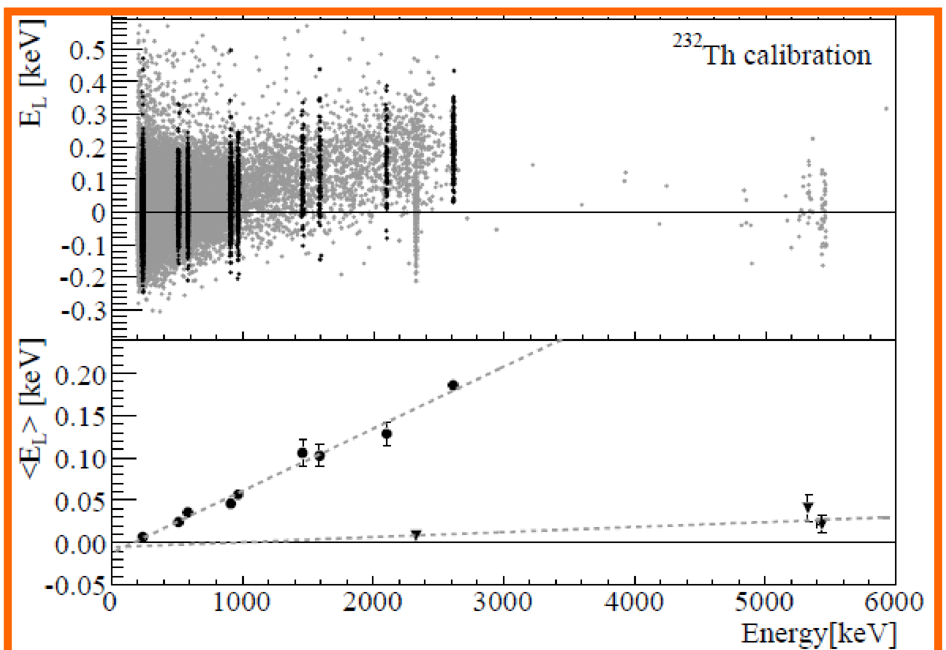
Optical properties of TeO_2 crystals

- Transparent from **350 nm to infrared**
- **n=2.4**

Threshold for Čerenkov emission:
50 keV for an **electron**
400 MeV for an **alpha particle**

Eur. Phys. J. C 65 (2010) 359

~ **125 photons** for a 0νββ decay event in the 2-3.5 eV range



First observation of luminescence light from TeO_2 on an event by event basis (LNGS, Rome)

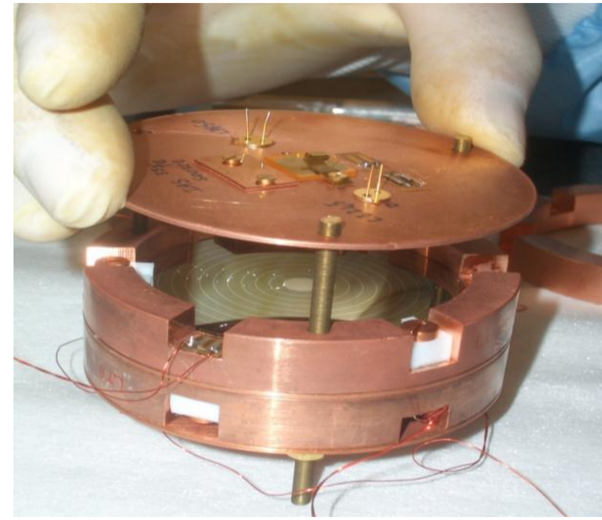
Light emission:

For beta/gamma: 73±2 eV/MeV
For alpha: 6±3 eV/MeV

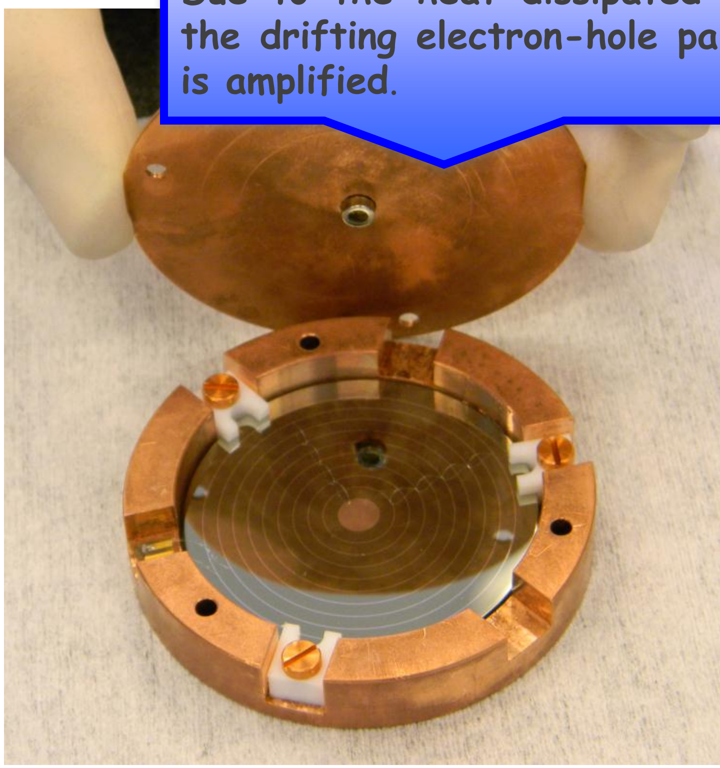
→ arXiv:1106.6286v1

Is TeO_2 luminescent (2) ?

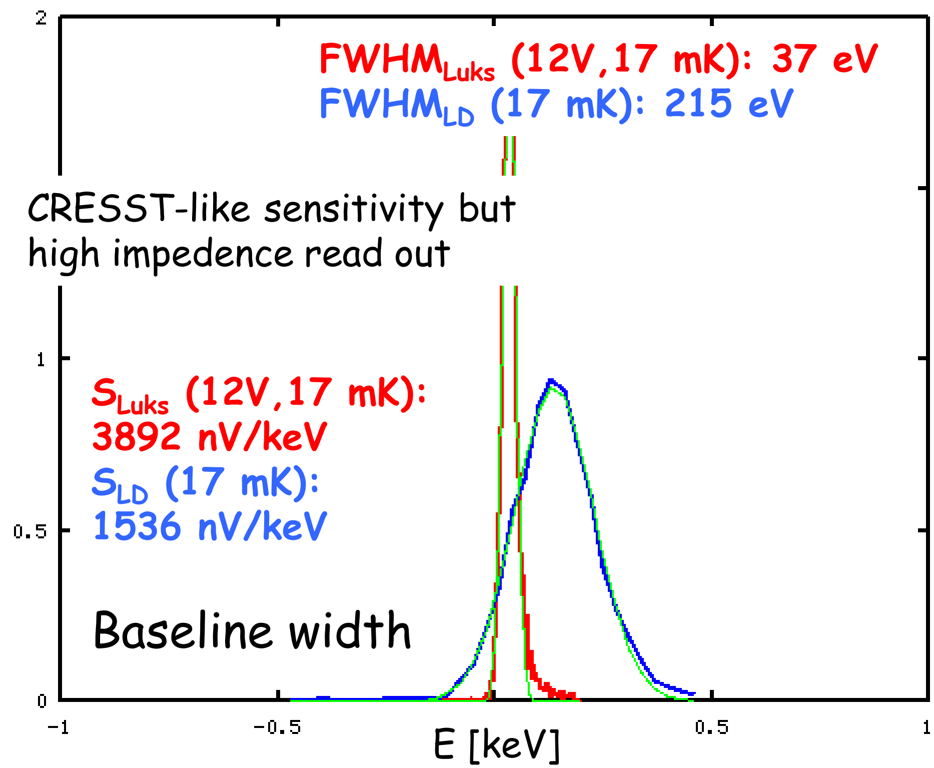
Light detector with Luke effect – Luks @ CSNSM



The energy threshold of a low- temperature light detector employing a semiconducting substrate can be improved by drifting the photon-induced electron-hole pairs by an applied electric field. Due to the heat dissipated in the substrate by the drifting electron-hole pairs the phonon signal is amplified.



Concentric electrodes done with the same technology of EDW-FID detectors.



Conclusions

➢0νββ is a crucial tool for neutrino physics.

➢The role of low-temperature detectors is extremely relevant for future developments on neutrino physics