CUORE

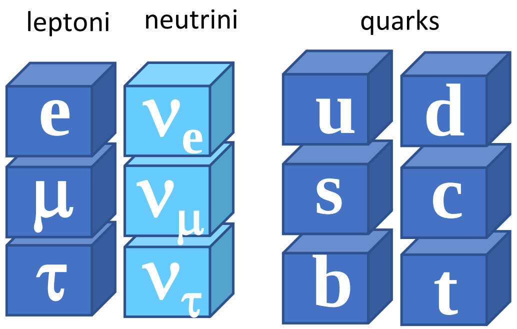
Cryogenic Underground Observatory for Rare Events

Una ricerca del doppio decadimento beta senza neutrino $(0\nu2\beta)$

Bologna – Assemblea di sezione

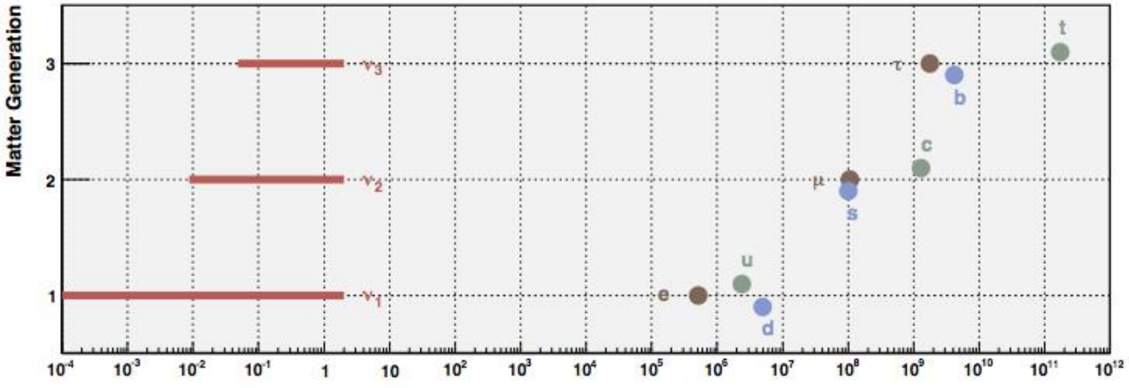
Febbraio 2020

Motivazioni



e' ormai consolidato che i neutrini possiedono massa, seppure molto piccola, e dato che hanno massa possono ''mischiarsi'' tra loro, neutrino's oscillations and mixing

ma restano ancora aperte numerose questioni :



- **quale e' la scala assoluta di massa ?**
- **quale e' la gerarchia di massa ?**

  la misura delle masse richiede la conoscenza

  - della scala assoluta di massa m_{min} - e -

  - della struttura della gerarchia di massa (NH, IH o QD)

- **violazione di CP nel settore dei neutrini ?**
- **neutrino '' sterili '' ?**

Normal Hierarchical Spectrum

(NH) $m_1 << m_2 < m_3$

$m_1 = m_{min}$

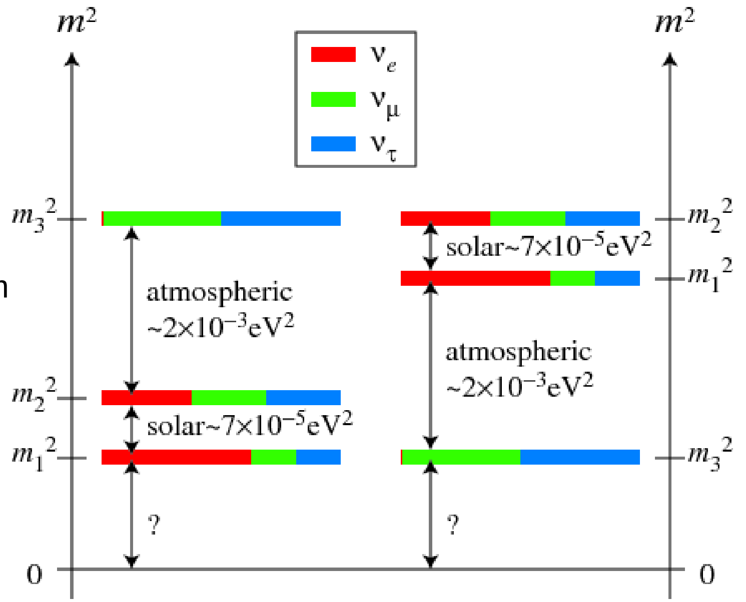
Inverted Hierarchical Spectrum

(IH) $m_3 << m_1 < m_1$

$m_3 = m_{min}$

Quasidegenerate Spectrum

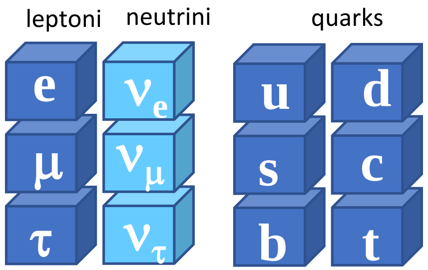
(QD) $m_1 \simeq m_2 \simeq m_3$



e tra le piu' rilevanti:

- **quale e' la natura dei neutrini ?**

i neutrini potrebbero essere femioni (particelle di spin semintero) di Dirac, come assunto nello SM, oppure potrebbero essere particelle identiche alla loro antiparticella (di Maiorana)

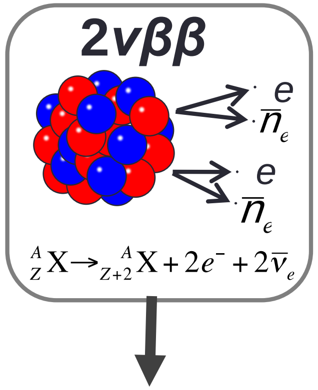


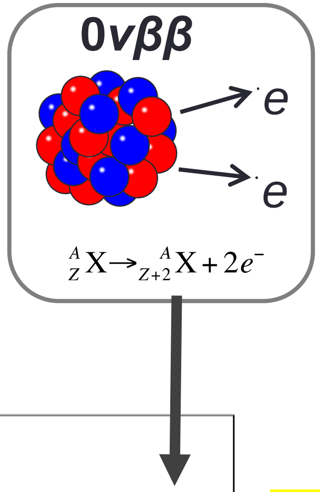
e se fossero fermioni di Majorana ?

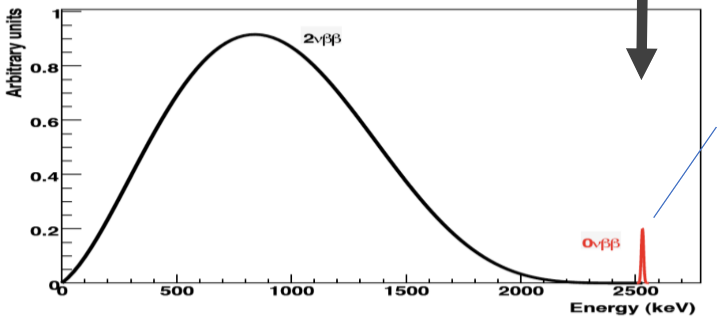
nello SM soltanto i neutrini potrebbero essere particelle di Majorana perche' sono gli unici costituenti fondamentali elettricamente neutri

- potrebbe avvenire il "decadimento doppio β privo di neutrini" (0νββ)
- due neutroni di un nucleo instabile potrebbero simultaneamente decadere trasformandosi in protoni con l'emissione di due elettroni, ma senza emissione di antineutrini

un processo che viola la conservazione del numero leptonico e che crea materia senza l'emissione bilanciante dell'antimateria







picco artificialmente evidenziato

processo estremamente raro

^{232}Th	10^{10} years
The Universe	10^{10} years
Two Neutrino Double Beta	10^{20} years
Neutrinoless Double Beta	$>10^{26}$ years
Proton Decay	$>10^{34}$ years

decadimento 0νββ nel ^{130}Te

$$^{130}\mathrm{Te} \to \; ^{130}\mathrm{Xe} + 2e^-$$

osservabile: una riga nello spettro alla energia dei due elettroni:

$E_{\beta\beta} = E_{\beta 1} + E_{\beta 2}$ $Q(^{130}\mathrm{Te}) \simeq 2528$ keV

CUORE

tratto da ***GERDA,*** ***2109 Science,*** Vol. 365 **p. 1445**

Significati se scoperto

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M_{nucl}^{0\nu}|^2 \frac{\langle m_{\beta\beta}^2 \rangle}{m_e^2}$$

semivita

Spazio delle fasi (calcolato)

elemento di matrice nucleare (calcolato)

massa "effettiva" di Majorana

$$\langle m_{\beta\beta} \rangle = \left| \sum_{j=1}^{3} |U_{e,i}^2|\, e^{i\phi_j} m_j \right|$$

elementi della riga del ν_e della matrice di mixing

- lepton number violation ΔL=2
- $\nu = \bar{\nu}$
- indicazioni sulla gerarchia di massa
- limiti al valore assoluto della massa

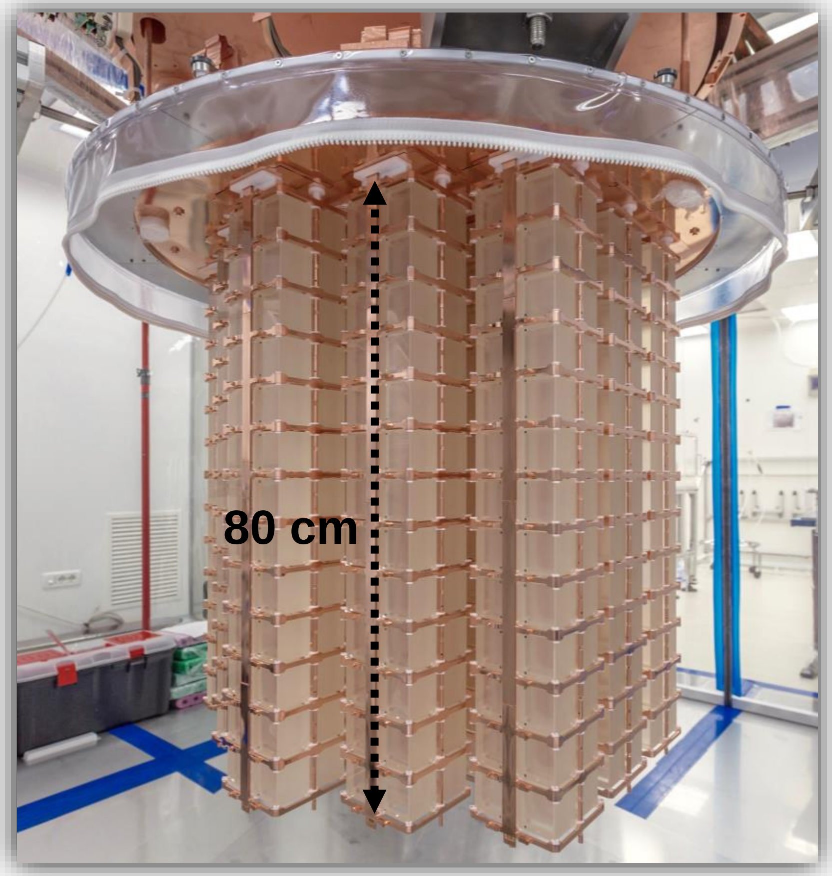
limite inferiore alla massa del ν

L'esperimento

1- rivelatore: 988 cristalli di TeO_2 (bolometri)

2- criostato: raffredda fino a 10 mK

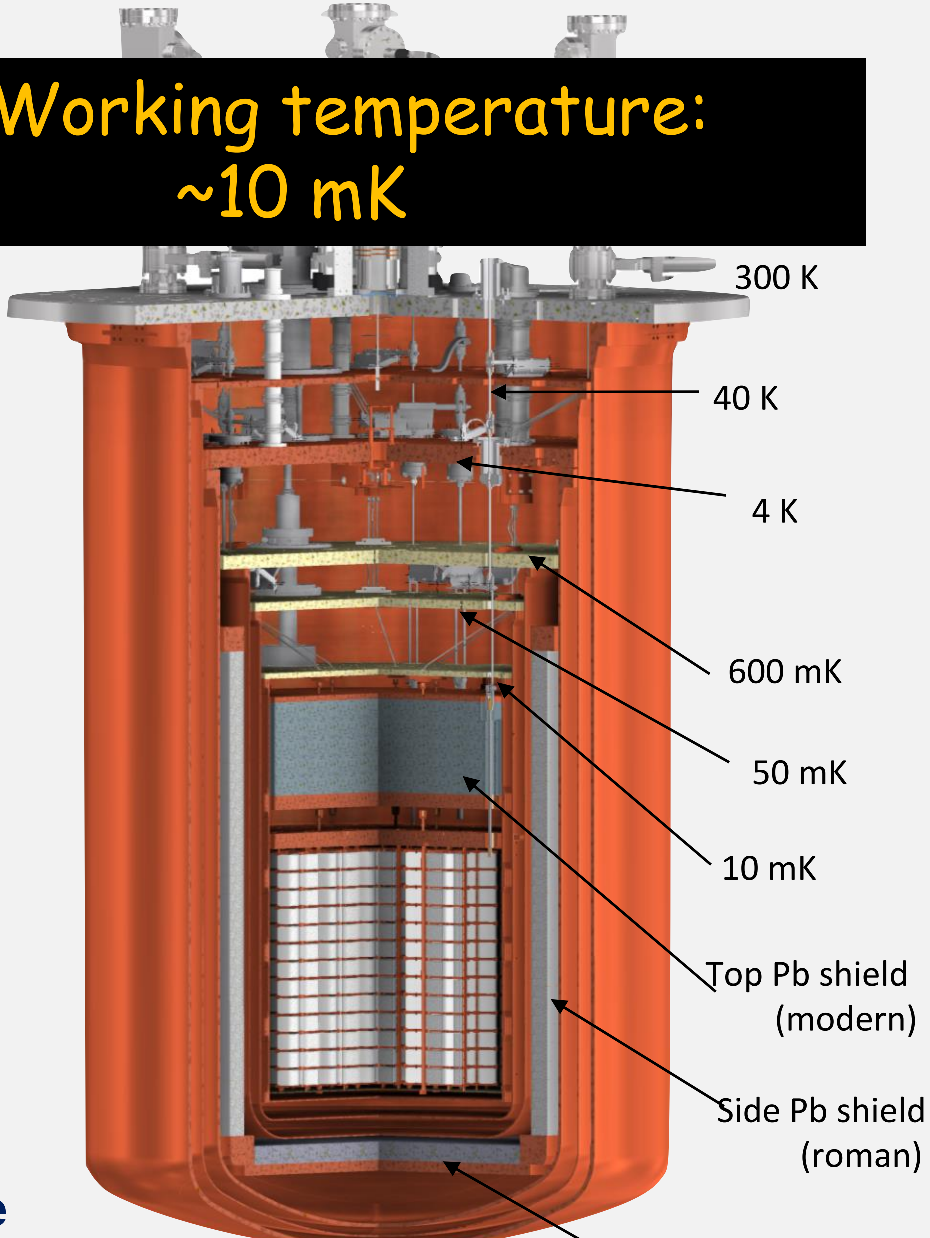
3- schermi: (in piombo romano) per riduzione fondo



- 988 cristalli 5x5x5 cm
- 742 kg (206 kg ^{130}Te)
- background: 0.01 counts/(kg keV yr) (obiettivo)
- Risoluzione in energia: 5 keV FWHM nel ROI (obiettivo)

ogni cristallo è un rivelatore indipendente

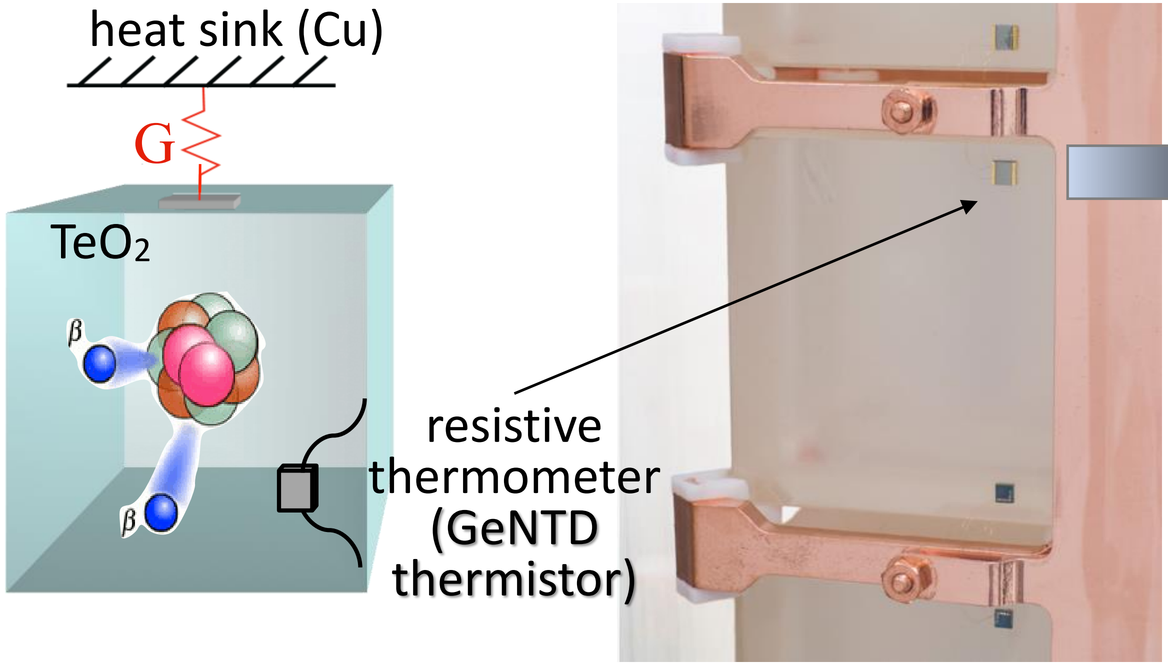
Working temperature: ~10 mK

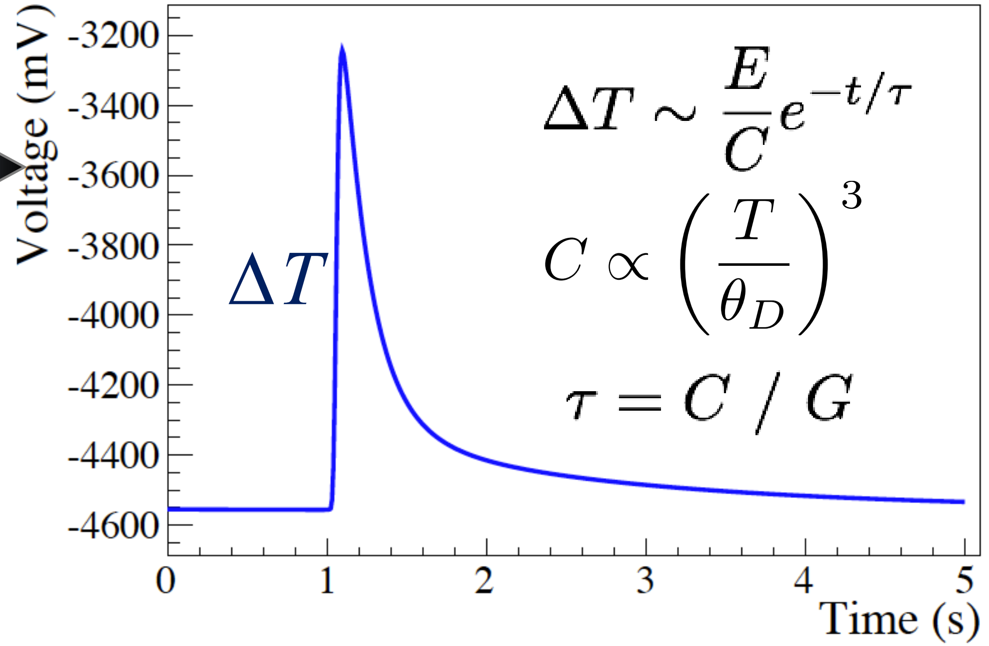


@LNGS, hall A

La tecnica bolometrica

Ogni bolometro: 1) contiene isotopo 2) assorbe energia 3) aumenta di temperatura





- Eccellente efficienza e risoluzione in energia
- Non distingue segnale da background (per es. il segnale dovuto a contaminazioni esterne è simile a quello del 0νββ)

$T \approx 10 \quad mK$

$C \approx 10^{-9} J/K$

$E = 1 MeV \qquad \Delta T = 0.1 \frac{mK}{MeV}$

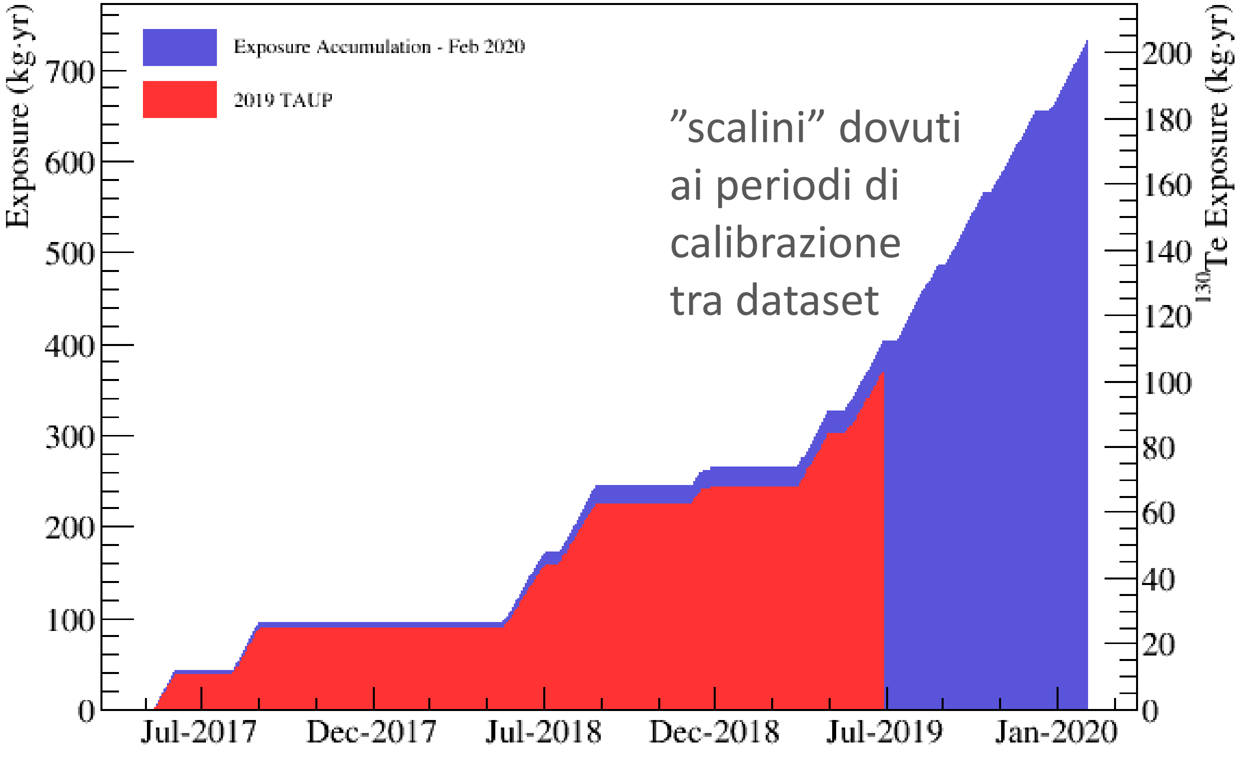
Detector performance

in presa dati per tutto il 2019 e 2020

← almeno si spera

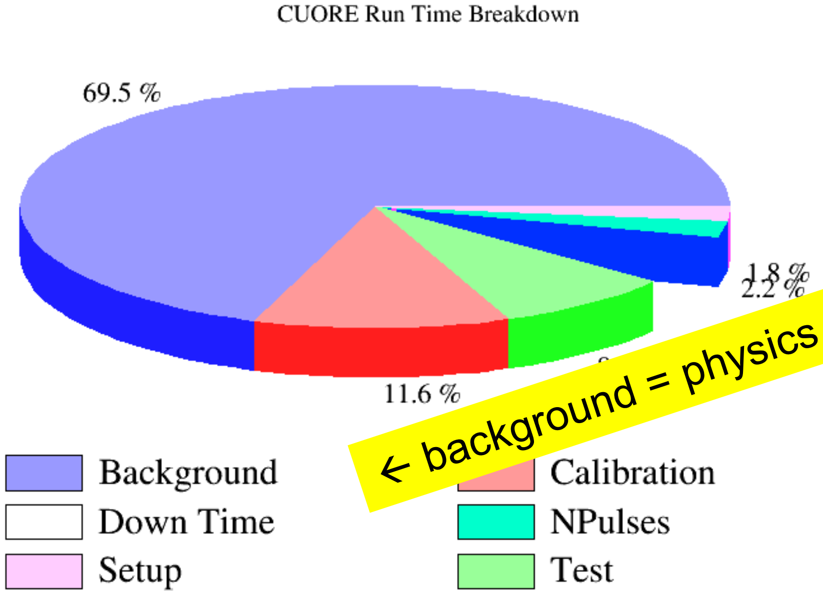
Efficienza: (87.54 ± 0.17)%
Risoluzione in energia: 7.0 ± 0.4 keV @$Q_{\beta\beta}$
Background: (1.369±0.069) x10^{-2} cnts/keV/kg/yr

Esposizione accumulata: ~700 kg*yr



"scalini" dovuti ai periodi di calibrazione tra dataset

Duty cycle



← background = physics data

Fit and results

- First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te - **Phys. Rev. Lett. 120, 132501 (2018)**
- Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE - **arXiv:1912.10966, 23 Dec 2019**

Extended maximum likelihood fit in 2465-2575 keV:
- ^{60}Co peak 2506 keV (floating position)
- peak at $Q_{\beta\beta}$ (fixed position, floating rate)
- flat background (dataset dependent)

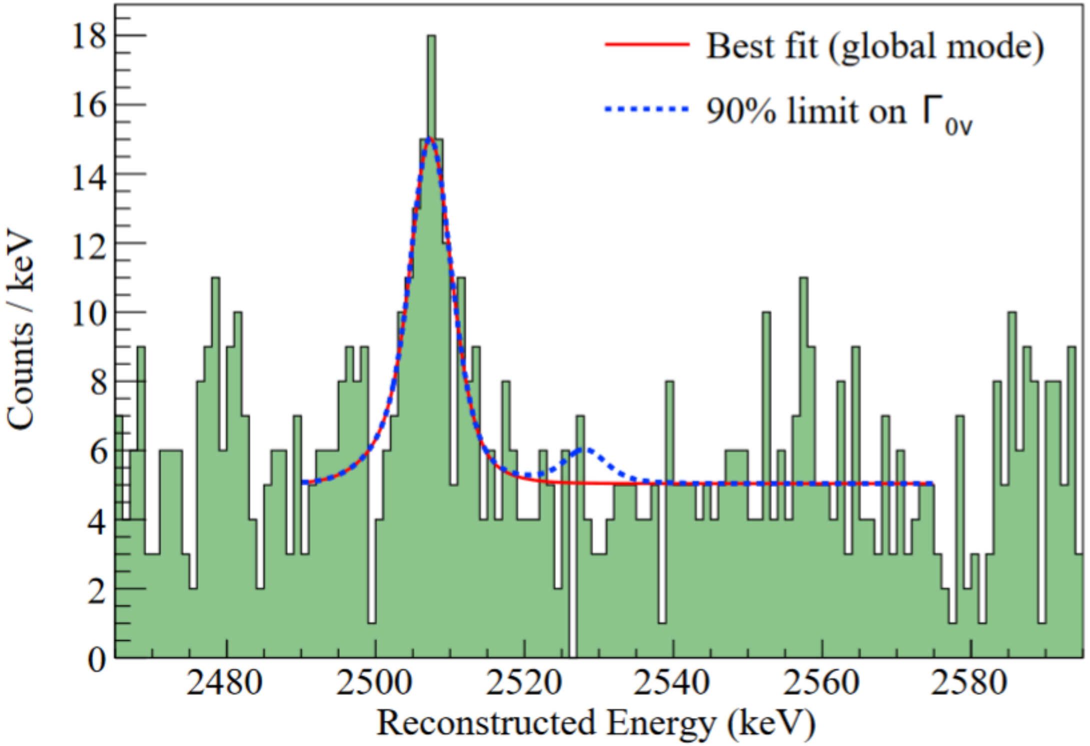


FIG. 4. ROI spectrum with the best-fit curve (solid red) and the best fit-curve with the $0\nu\beta\beta$ decay component fixed to the 90% CI limit (dashed blue).

nessuna evidenza di segnale
si pone un limite inferiore:

$$T_{1/2} > 3.2\text{x}10^{25} \text{ yr}$$

$$m_{\beta\beta} < 75\text{-}350 \text{ meV}$$

(90% C.I. including syst.)

altri risultati recenti :

Double-beta decay of Xe with CUORE-0
EUROPEAN PHYSICAL JOURNAL C Volume: 79 Issue: 9 (**SEP 2019**)

Search for neutrinoless beta(+) EC decay of Te-120 with CUORE-0
PHYSICAL REVIEW C Volume: 97 Issue: 5, 055502 **(2018)**

Measurement of the two-neutrino double-beta decay half-life of ^{130} Te with the CUORE-0 experiment Eur. Phys. J. C 77, no.1, 13 **(2017)**

La collaborazione

109 ricercatori da 4 paesi:

- ✓ 61 italia
- ✓ 41 USA
- ✓ 4 Cina
- ✓ 3 Francia

Bologna:
Giacomo Bari
Niccolò Moggi
Stefano Zucchelli
Marco Guerzoni
Antonio Chiarini
Francesca Del Corso
Mauro Lolli
Cristina Guandalini

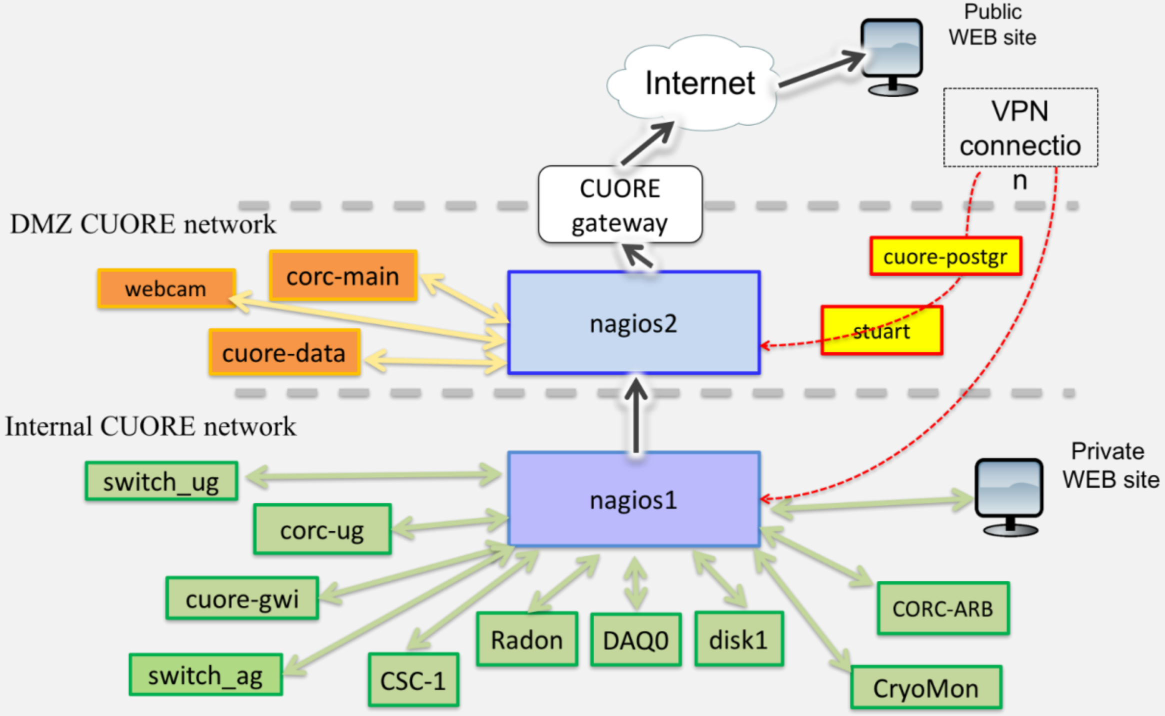
Ruoli ufficiali nella gestione dell'esperimento:
S. Zucchelli ……responsabile locale, ex chair Publication Board
N. Moggi ………shift coord., resp. slow monitor, ex chair Vetting Board
F. Del Corso ….. resp. local network

Attività di Bologna

- Realizzazione “Permanent Storage Area”
- Monitor dei devices e dei servizi
- Sistema sismometrico: 2 sismometri
- Sistema di backup dell’azoto
- Sistema sollevamento vessel criostato

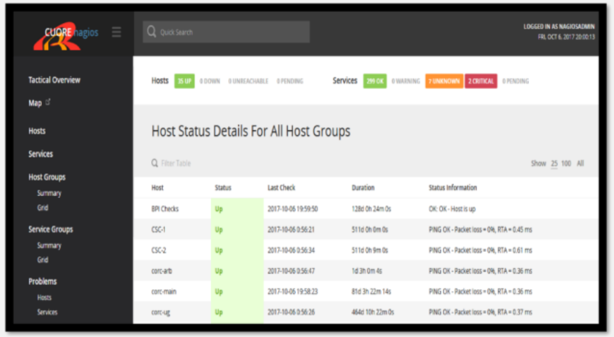
PSA

sistema di sollevamento dei vessel criogenici



- 300 servizi

Db
DAQ
Run Control
Radon system
CryoMon
Network
UPS
Nitrogen storage
…



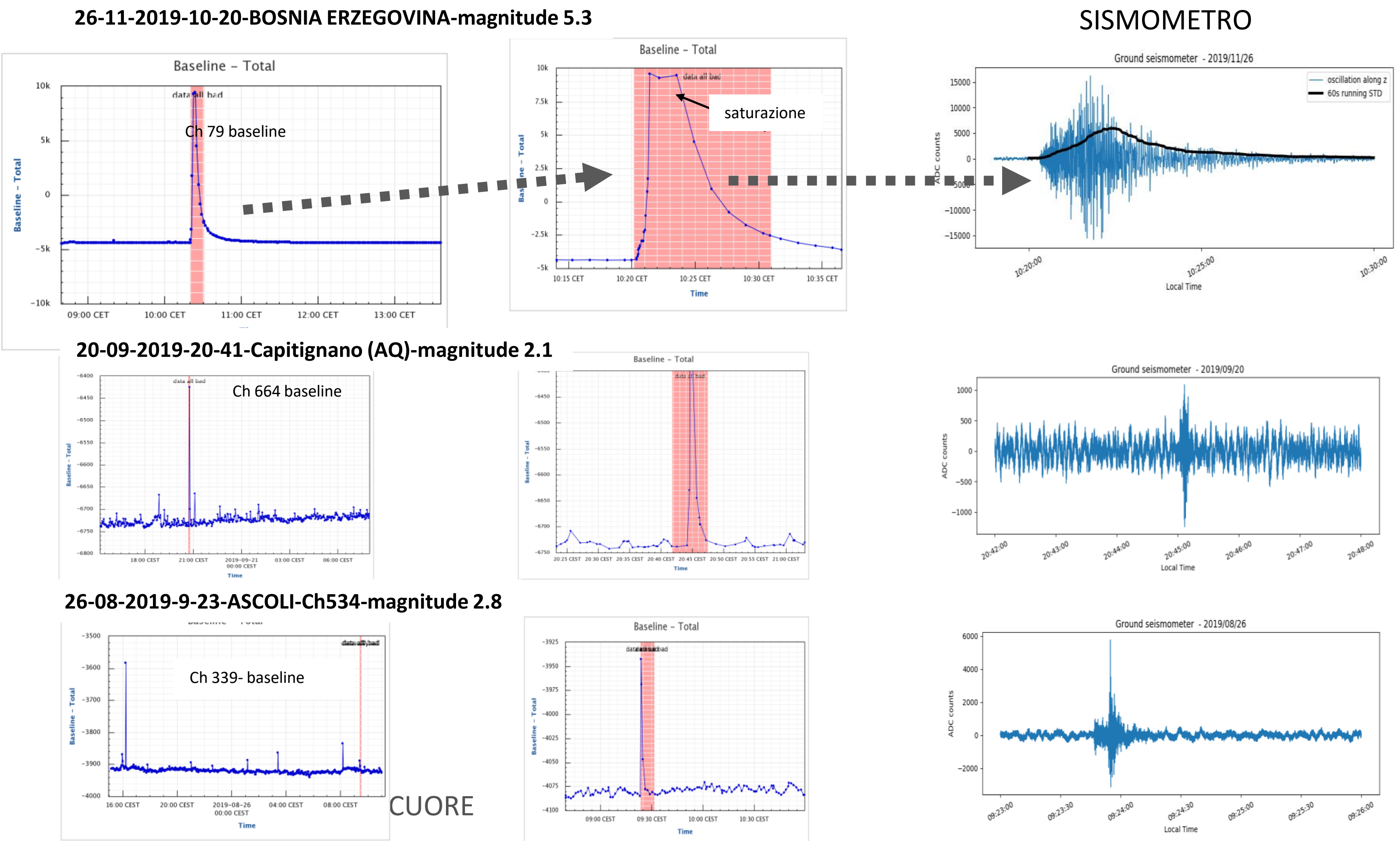
Inaugurazione Cuore a LNGS - Ottobre 2017

Sismometri

CUORE è uno strumento sensibilissimo: ogni sorgente di rumore altera la baseline della temperatura e contribuisce alla risoluzione in energia

In collaborazione con INGV abbiamo installato un sistema sismometrico che permette di:

1. monitorare le vibrazioni esterne e identificare le sorgenti antropiche (lavori in galleria, microterremoti, vibrazioni delle pompe etc) riconoscendo lo spettro caratteristico prodotto da questi tipi di attività
2. segnalare in tempo reale (~1s) i dati di cattiva qualità sullo SlowControl
3. analizzare i modi di vibrazione del criostato: ''denoising'' del rivelatore



Risultati di CUORE

$$T_{1/2}^{0\nu} > 3.2\times10^{25}\ yr \quad \text{e} \quad m_{\beta\beta} < 75-350\ meV$$

e' il limite piu' stringente per il decadimento $0\nu2\beta$ in ^{130}Te

e' un risultato competitivo con quanto ottenuto degli esperimenti piu' avanzati in questo settore di ricerca

Expected Cuore Sensitivity : 9 10^{25} yr with 5 years of live time
attuale "exposure" totale di ~ **700 kg·yr**
attuale rapidita' di raccolta dati ≈ **50 kg·yr**
risoluzione energetica FWHM: **7.0 KeV** (attesa ~ 5)
fondo: **$(1.38 \pm 0.07)\cdot10^{-2}$ cnts/(keV·kg·yr)** (atteso ~ 10^{-2})

c'e' margine di miglioramento ?

Risoluzione energetica — Limite inferiore sulla emivita — **- milli - eV e non MeV !**

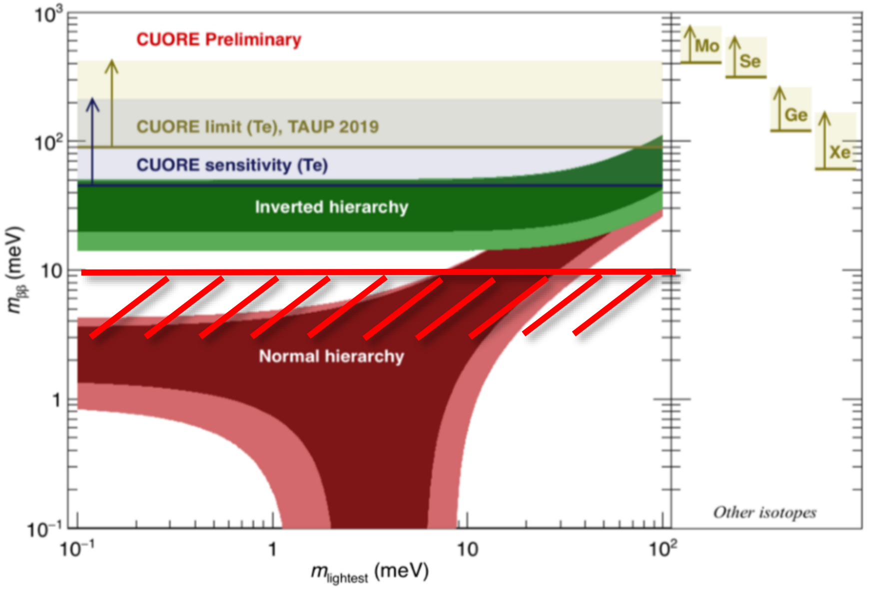
Experiment	Isotope	FWHM (keV)	$\Gamma(T_{1/2})$ (10^{25} yr)	$m_{\beta\beta}$ (meV)
GERDA	^{76}Ge	3.3	9	104 - 228
Majorana	^{76}Ge	2.5	2.7	157 - 346
CUPID-0	^{82}Se	23	0.24	394 - 810
CUORE	**^{130}Te**	**7.0**	**3.2**	**75 – 350**
EXO-200	^{136}Xe	71	1.8	93 - 287
KamLAND-Zen	^{136}Xe	270	10.7	76 - 234

Tabella comparativa estratta dalla recente pubblicazione di GERDA
Probing Majorana neutrinos with double-β decay *Science* 27 Sep 2019: Vol. 365, Issue 6460
e aggiornata

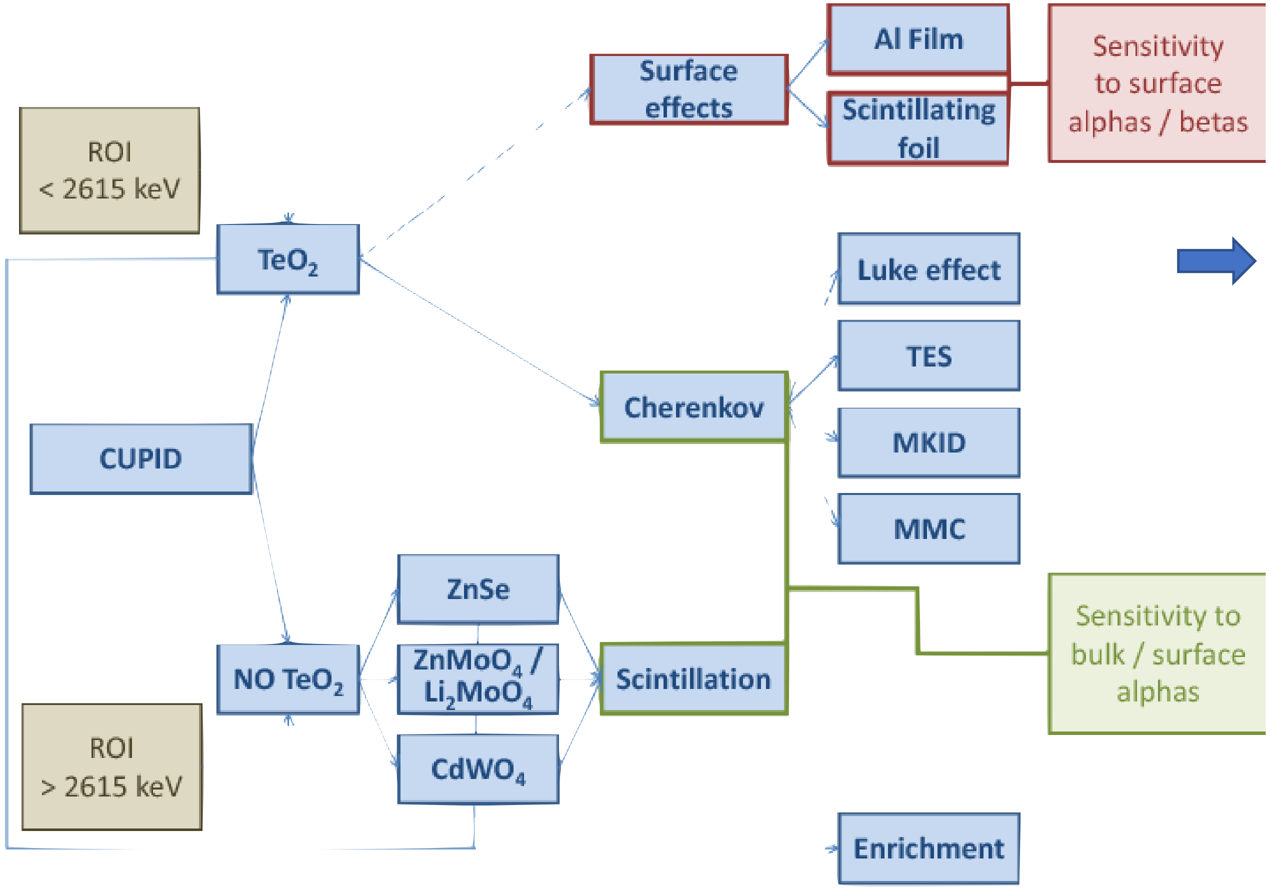
$$m_{\beta\beta} = \frac{1}{g_A^2\,|M_{0\nu}|\,\sqrt{G_{0\nu}T_{1/2}^{0\nu}}}$$

Effective Majorana mass — Axial vector coupling — Nuclear matrix element — Phase space factor — 0νββ decay rate

a cio' puntano una serie di esperimenti di nuova generazione ⇨



CUORE R&D's



Cuore
Upgrade with
Particle
IDentification

→ **CUPID**

Cupid-preCDR arXiv : 1907.09376 Jul 22, 2019

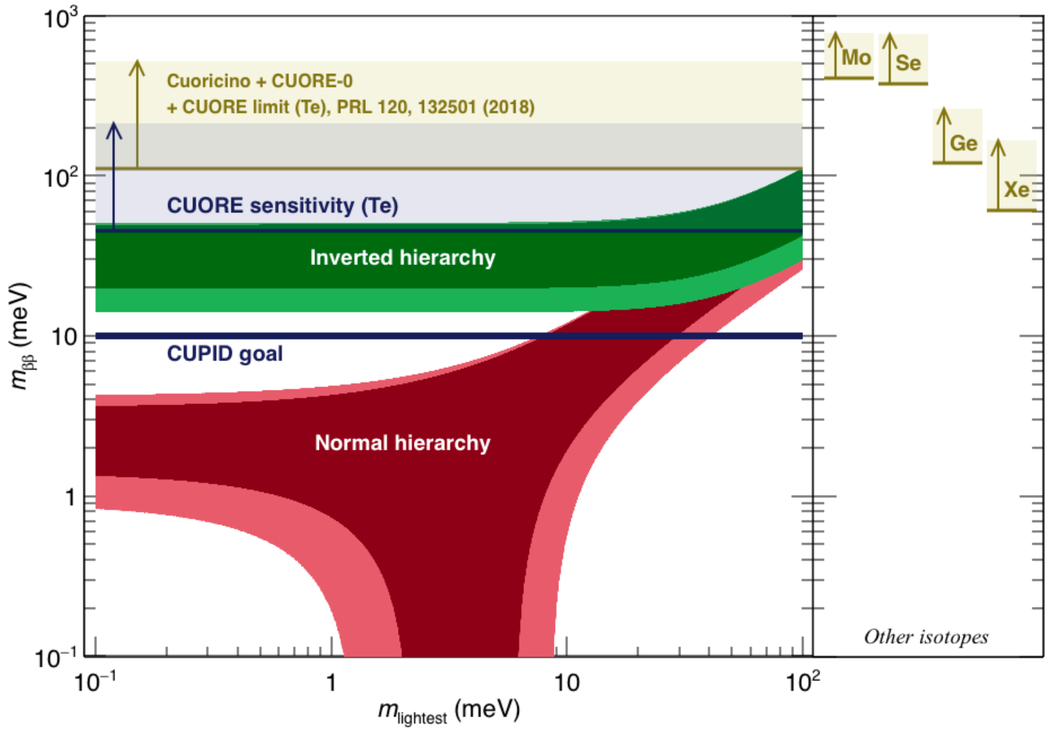
~ 170 firmatari, 7 paesi

Bologna:

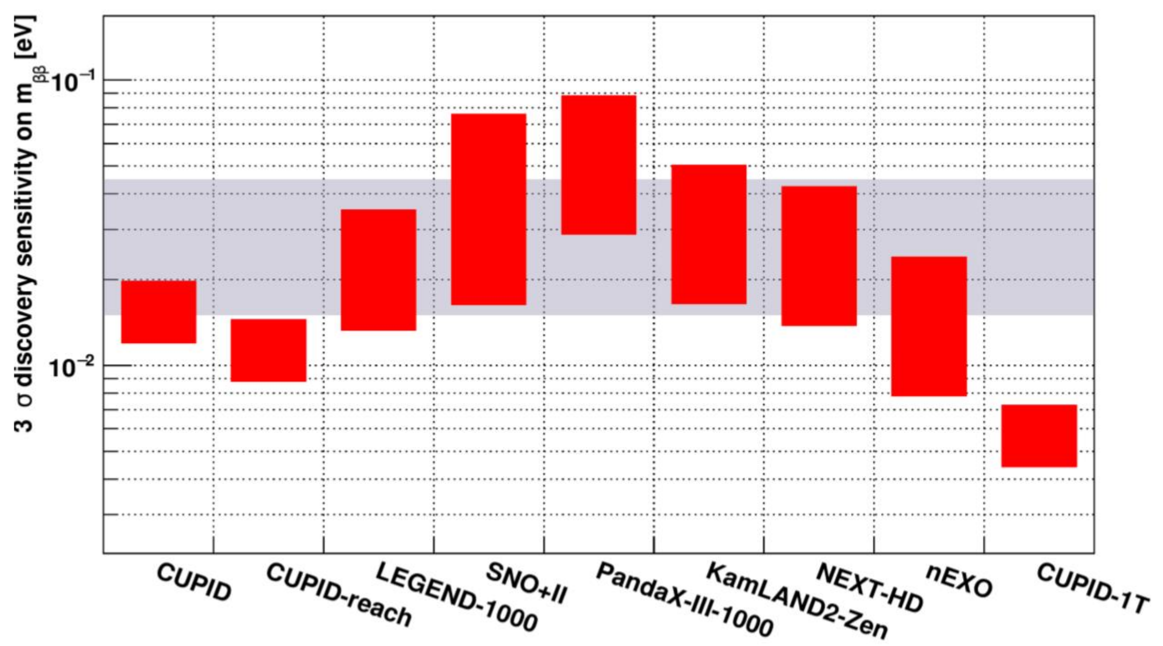
S. Zucchelli , G. Bari, N. Moggi

Fulvio Mancarella e Rita Rizzoli, Istituto per la Microelettronica e Microsistemi (IMM) del CNR di Bologna

CUPID



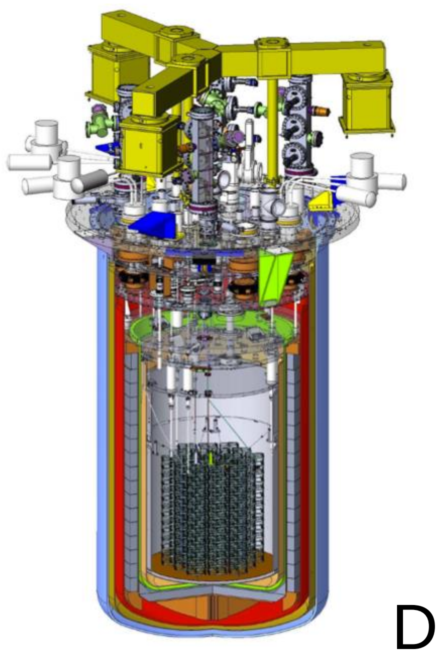
Next Generation 0νββ sensitivity



The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects
arXiv:1909.02994 6 Sep 2019

Final Result of CUPID-0 Phase-I in the Search for the ^{82}Se Neutrinoless Double-β Decay
Phys. Rev. Lett. 123, 032501 – Published 15 July 2019

CUPID



Infrastruttura di CUORE

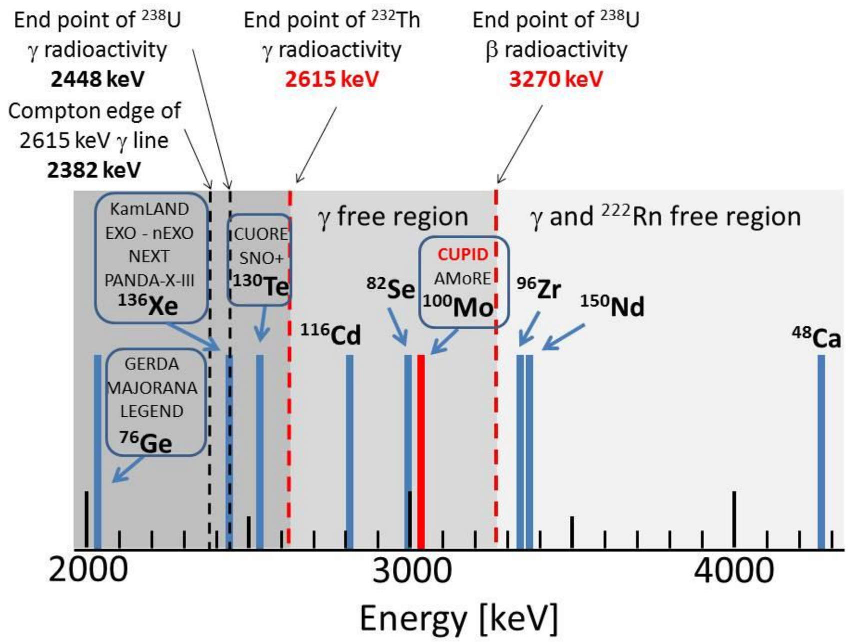
+

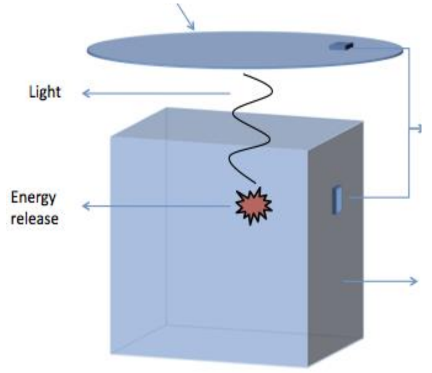
CUPID-0/CUPID-Mo : Nuovo rivelatore

$Li_2{}^{100}Mo\ O_4$

$Q_{\beta\beta}$ 3034 KeV

Discriminazione α vs β/γ

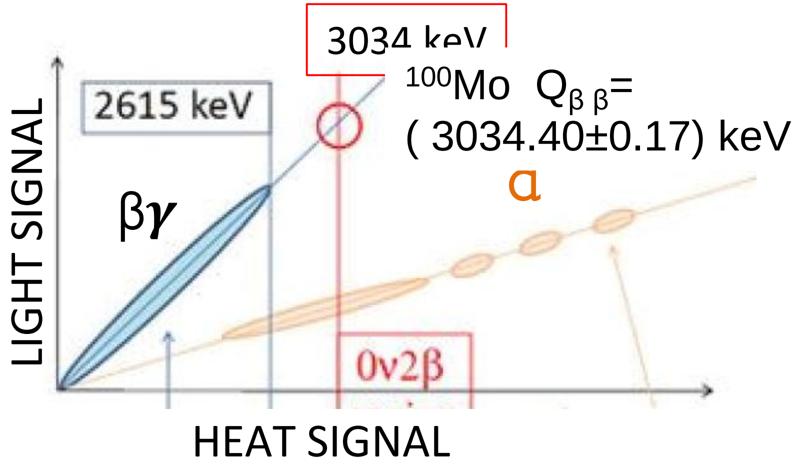




Re-use CUORE cryogenic infrastructure at LNGS

- $Li_2{}^{100}MoO_4$ scintillating crystals
- ~1500 crystals for 270kg of ^{100}Mo
- Active background rejection using light and heat signals
- Phased deployment option foreseen
- Options for multiple isotopes possible
- TDR and construction readiness by 2021

la diversa produzione di luce permette la separazione del segnale di α vs β/γ



CUPID

Thermistor Readout: ΔT → ΔV

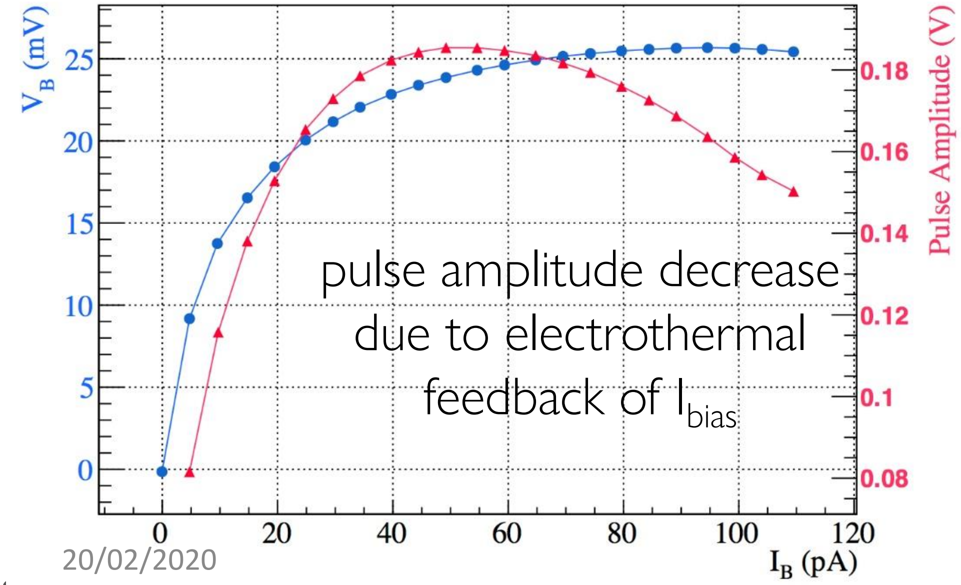
Crystals are read out by a ``Neutron Transmutation Doped'' Germanium transistor (NTD)

$$R_{th} = R_0 e^{\left(\frac{T_0}{T}\right)^{\gamma}} = \frac{V_{th}}{I_{bias}}$$

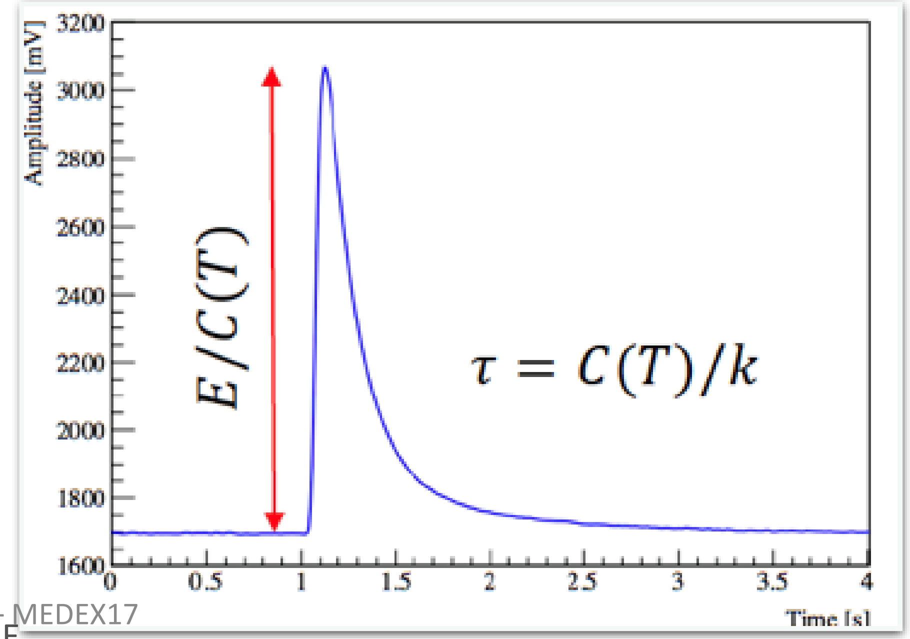
Readout ΔV

Maintain a constant current

Set I_{bias} working point where signal amplitude is maximum

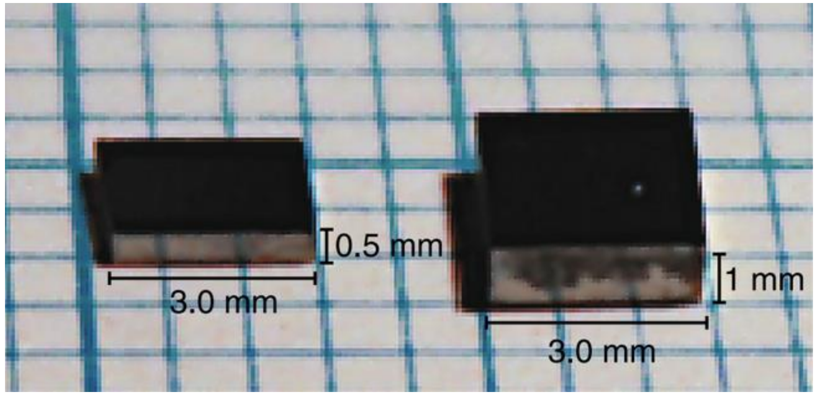


Typical signal pulse shape

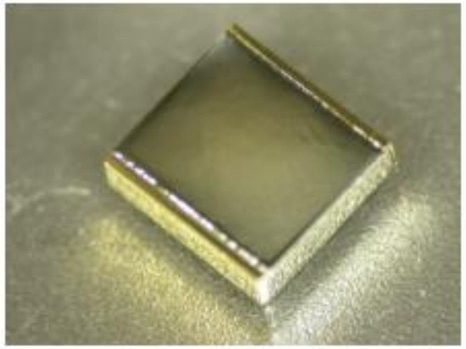


CUPID

Germanio irraggiato



termistore finito



Dimensions for CUPID0 thermistors
Bolometer thermistor : 3 × 2.8 × 1 mm3
Light detector : 2 × 2.8 × 0.5 mm3

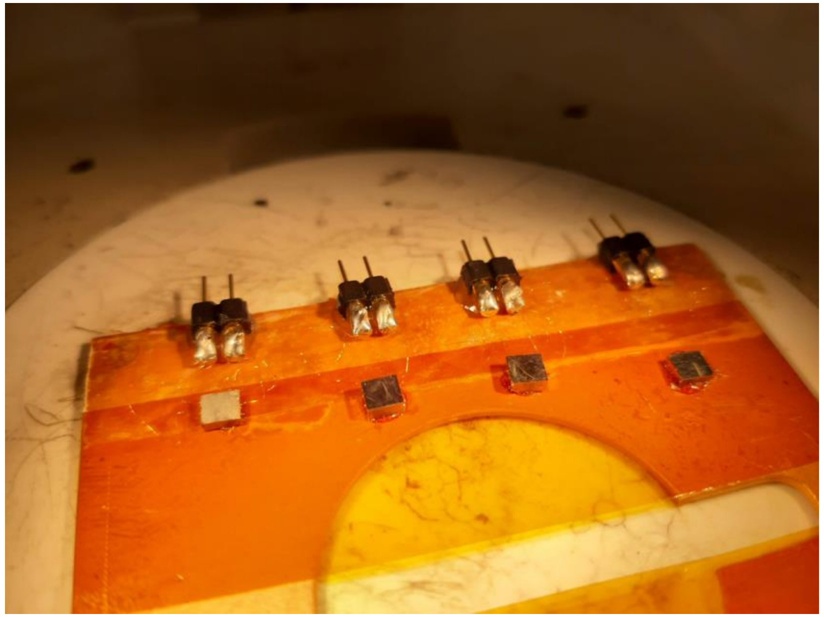
- Define a robust post-processing procedure in order o obtain good implant+bonding pads

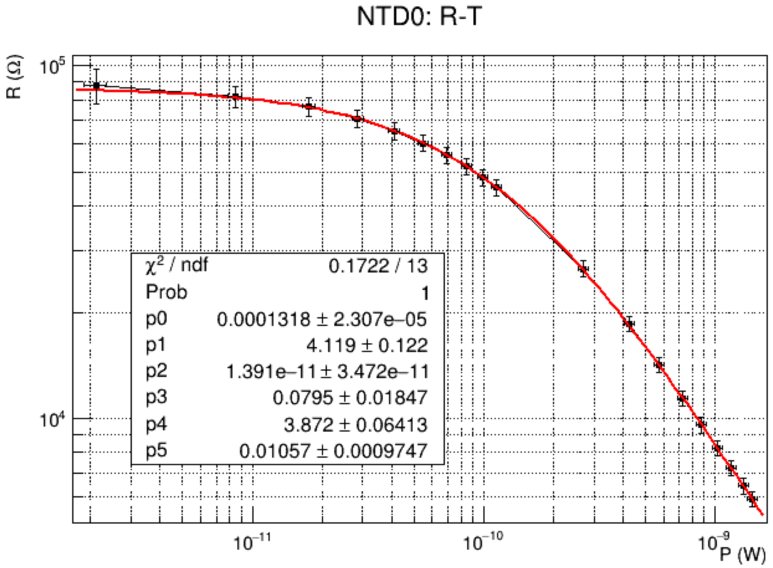
Implantation tests at CNR-Bo: ^{11}B (higher efficiency) and ^{10}B-only test (2019-2020)

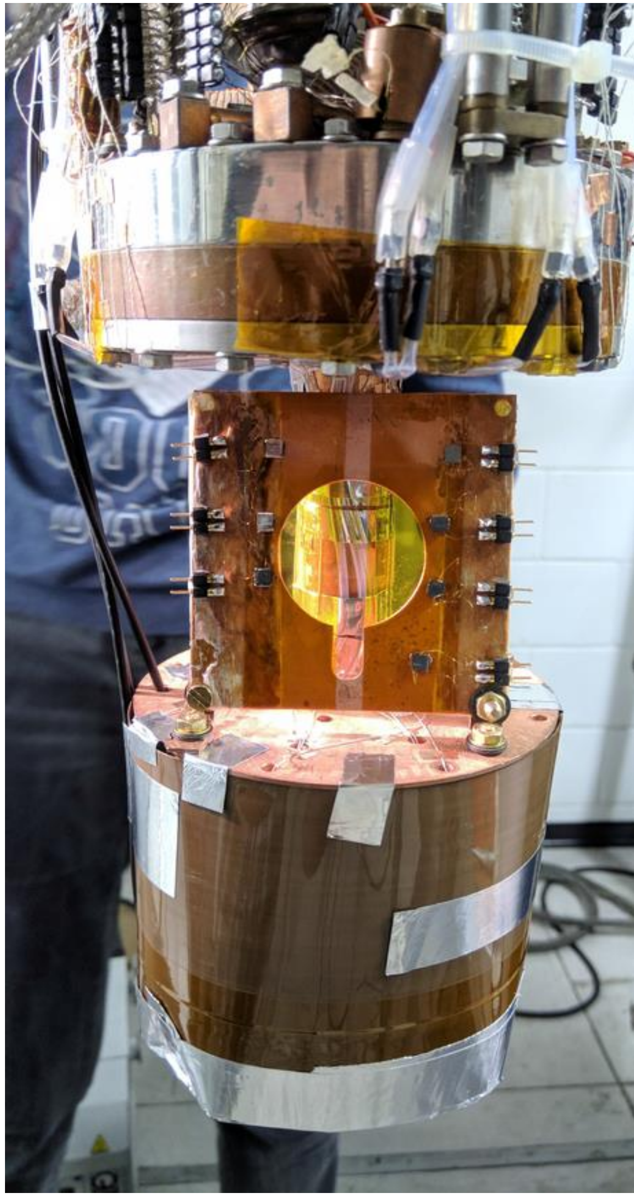
Test on first Pd and Au deposition at CNR Bologna → feedback establishing next steps towards a final process flow for implantation and contact deposition

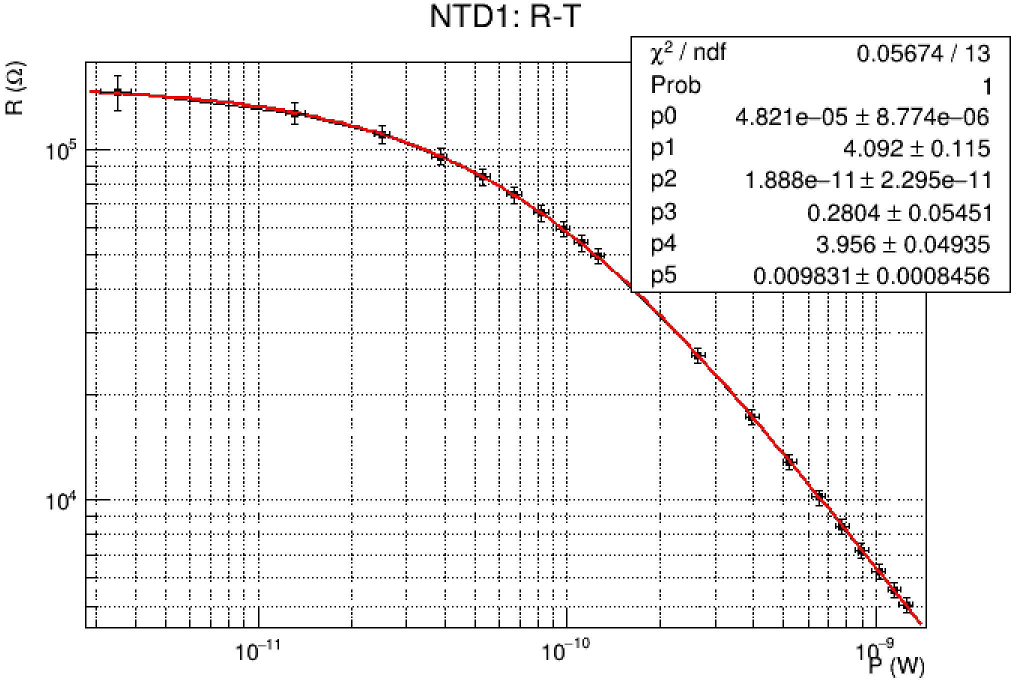
Targe valuest: T_0 = 4.2 K; ρ_0 = 1.5 Ohm

For reaching 1 MΩ/mK sensitivity









T_0 = 4.1 K
compliant with the measurements at LNGS for CUPID-0

Future goals:

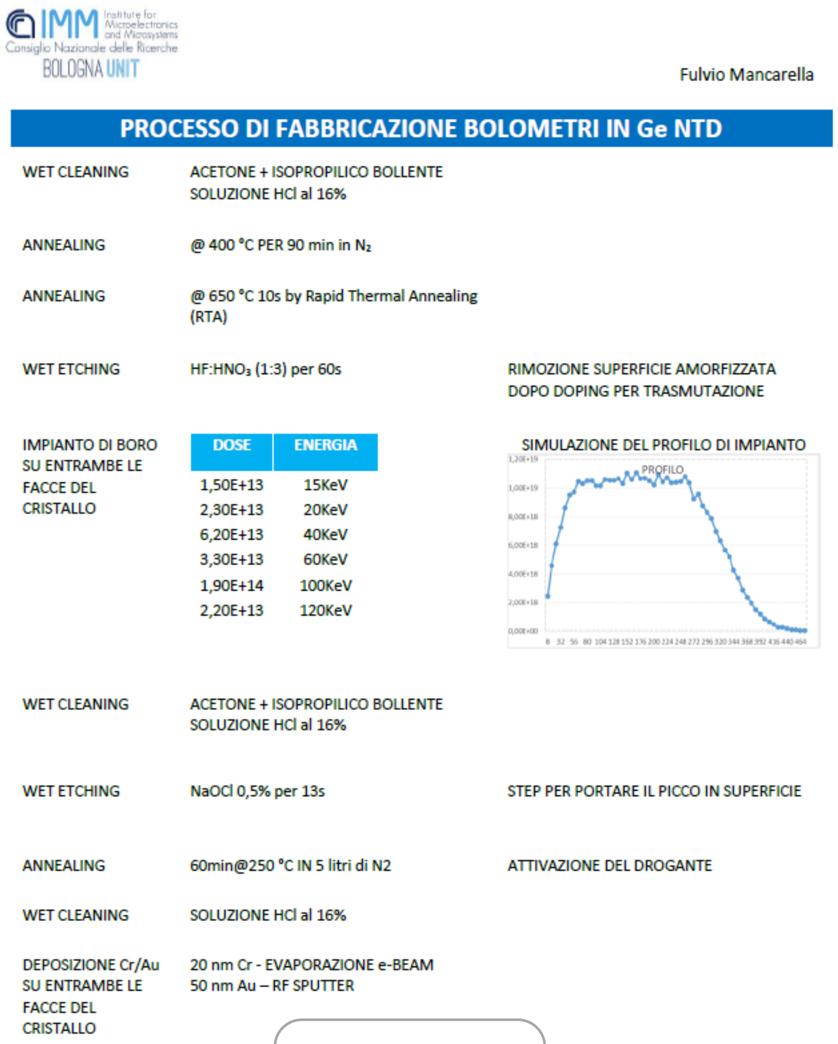
Fine tuning and precise control of T_0 using MIT reactor + Pavia Triga reactor (low flux)

Define a robust post-processing procedure in order to obtain good implant+bonding pads

Test at CNR Bologna for ^{11}B implantation, Pd and Au deposition

Establishing the Bologna procedure for Ge contacts (2020)

^{10}B test, implantation



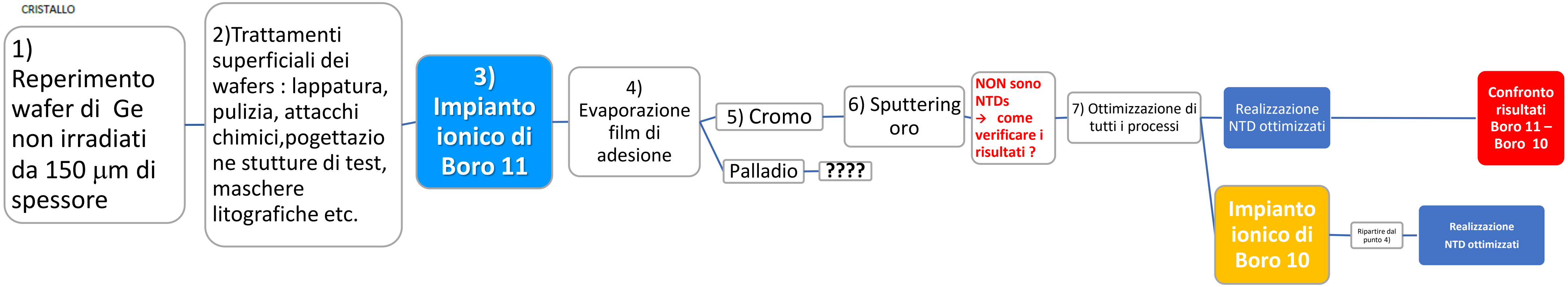
IMM Institute for Microelectronics and Microsystems – Consiglio Nazionale delle Ricerche – BOLOGNA UNIT

Fulvio Mancarella

PROCESSO DI FABBRICAZIONE BOLOMETRI IN Ge NTD

WET CLEANING	ACETONE + ISOPROPILICO BOLLENTE SOLUZIONE HCl al 16%	
ANNEALING	@ 400 °C PER 90 min in N_2	
ANNEALING	@ 650 °C 10s by Rapid Thermal Annealing (RTA)	
WET ETCHING	HF:HNO_3 (1:3) per 60s	RIMOZIONE SUPERFICIE AMORFIZZATA DOPO DOPING PER TRASMUTAZIONE
IMPIANTO DI BORO SU ENTRAMBE LE FACCE DEL CRISTALLO	see table below	SIMULAZIONE DEL PROFILO DI IMPIANTO
WET CLEANING	ACETONE + ISOPROPILICO BOLLENTE SOLUZIONE HCl al 16%	
WET ETCHING	NaOCl 0,5% per 13s	STEP PER PORTARE IL PICCO IN SUPERFICIE
ANNEALING	60min@250 °C IN 5 litri di N2	ATTIVAZIONE DEL DROGANTE
WET CLEANING	SOLUZIONE HCl al 16%	
DEPOSIZIONE Cr/Au SU ENTRAMBE LE FACCE DEL CRISTALLO	20 nm Cr - EVAPORAZIONE e-BEAM 50 nm Au – RF SPUTTER	

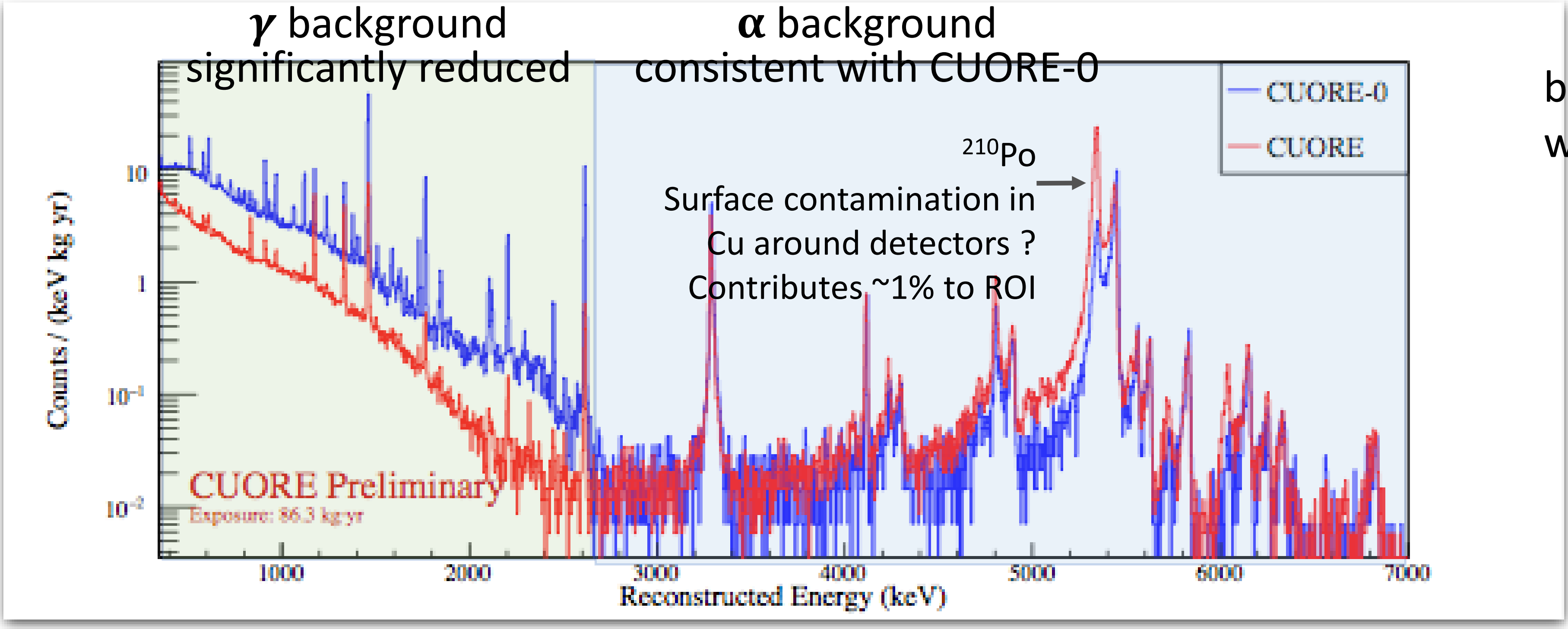
DOSE	ENERGIA
1,50E+13	15KeV
2,30E+13	20KeV
6,20E+13	40KeV
3,30E+13	60KeV
1,90E+14	100KeV
2,20E+13	120KeV



BACKUP SLIDES

CUORE background

Compare to CUORE-0 (first CUORE tower tested in older cryostat)



background consistent with expectations

Origin of background:

- contamination of cryostat, shields and detector parts:
  - ^{232}Th, ^{238}U, ^{40}K natural contaminations
  - environmental ^{222}Rn resulting in ^{210}Pb surface implantation
- environmental muons and neutrons

Dominating background in ROI:

- α from surface of crystal and copper close-parts

Search for neutrinoless double-β decay in 76Ge with 26 kg yr of exposure from the Majorana Demonstrator S. I. Alvis *et al.* (Majorana Collaboration)

Phys. Rev. C **100**, 025501 – Published 23 August 2019

The Majorana Collaboration is operating an array of high-purity Ge detectors to search for the neutrinoless double-β decay of 76Ge. The Majorana Demonstrator consists of 44.1 kg of Ge detectors (29.7 kg enriched to 88% in 76Ge) split between two modules constructed from ultraclean materials. Both modules are contained in a low-background shield at the Sanford **Underground Research Facility in Lead, South Dakota**. We present updated results on the search for neutrinoless double-β decay in 76Ge with 26.0±0.5 kg yr of enriched exposure. With the Demonstrator's energy resolution of 2.53 keV FWHM at Qββ, which is the best among all neutrinoless double-β decay experiments, we observe one event in the region of interest with 0.65 events expected from the estimated background, resulting in a lower limit on the 76Ge neutrinoless double-β decay half-life of 2.7×1025 yr [90% confidence level (CL)] with a median sensitivity of 4.8×1025 yr (90% CL). Depending on the matrix elements used, a 90% CL upper limit on the effective Majorana neutrino mass in the range of 200–433 meV is obtained. The measured background in the configurations with full shielding and optimized grounding is 11.9±2.0 counts/(FWHM t yr).

DOI:https://doi.org/10.1103/PhysRevC.100.025501

Search for Neutrinoless Double-β Decay with the Complete EXO-200 Dataset
G. Anton *et al.* (EXO-200 Collaboration)
Phys. Rev. Lett. **123**, 161802 – Published 18 October 2019
In the EXO-200 detector, a common cathode splits the LXe TPC

Enriched Xenon Observatory

Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico.

A search for neutrinoless double-β decay (0νββ) in ^{136}Xe is performed with the full EXO-200 dataset using a deep neural network to discriminate between 0νββ and background events. Relative to previous analyses, the signal detection efficiency has been raised from 80.8% to 96.4±3.0%, and the energy resolution of the detector at the Q value of ^{136}Xe 0νββ has been improved from σ/E=1.23% to 1.15±0.02% with the upgraded detector. Accounting for the new data, the median 90% confidence level 0νββ half-life sensitivity for this analysis is 5.0×1025 yr with a total ^{136}Xe exposure of 234.1 kg yr. No statistically significant evidence for 0νββ is observed, leading to a lower limit on the 0νββ half-life of 3.5×1025 yr at the 90% confidence level.

DOI:https://doi.org/10.1103/PhysRevLett.123.161802

A. Gando et al. (KamLAND-Zen), Phys. Rev. Lett. 117, 082503 (2016), [Addendum: Phys. Rev. Lett.117,no.10,109903(2016)].

We present an improved search for neutrinoless double-beta (0νββ) decay of 136Xe in the KamLAND-Zen experiment. Owing to purification of the xenon-loaded liquid scintillator, we achieved a significant reduction of the 110mAg contaminant identified in previous searches. Combining the results from the first and second phase, we obtain a lower limit for the 0νββ decay half-life of T0v1/2>1.07×1026 yr at 90% C.L., an almost sixfold improvement over previous limits. Using commonly adopted nuclear matrix element calculations, the corresponding upper limits on the effective Majorana neutrino mass are in the range 61–165 meV. For the most optimistic nuclear matrix elements, this limit reaches the bottom of the quasidegenerate neutrino mass region.

Final Result of CUPID-0 Phase-I in the Search for the ^{82}Se Neutrinoless Double-β Decay
O. Azzolini *et al.*
Phys. Rev. Lett. **123**, 032501 – Published 15 July 2019

CUPID-0 is the first pilot experiment of CUPID, a next-generation project for the measurement of neutrinoless double beta decay (0vDBD) with scintillating bolometers. The detector, consisting of 24 enriched and 2 natural ZnSe crystals, has been taking data at Laboratori Nazionali del Gran Sasso from June 2017 to December 2018, collecting a 82Se exposure of 5.29 kg×yr. In this Letter we present the phase-I results in the search for 0vDBD. We demonstrate that the technology implemented by CUPID-0 allows us to reach the lowest background for calorimetric experiments: (3.5+1.0−0.9)×10−3 counts/(keV kg yr). Monitoring 3.88×1025 82Se nuclei×yr we reach a 90% credible interval median sensitivity of T0v1/2>5.0×1024 yr and set the most stringent limit on the half-life of 82Se 0vDBD: T0v1/2>3.5×1024 yr (90% credible interval), corresponding to mββ<(311–638) meV depending on the nuclear matrix element calculations.