The bolometric way towards the inverted hierarchy of the neutrino mass: CUORE-0 → CUORE → CUPID

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CEA/IRFU/SPP

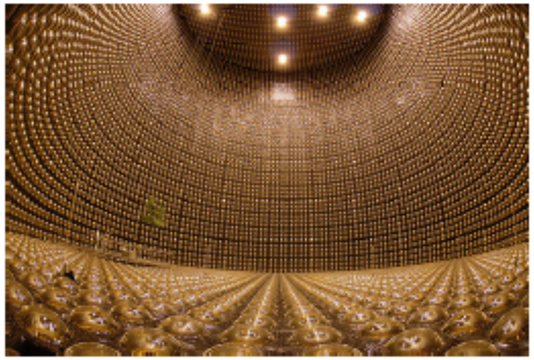
GDR Neutrino Meeting – Saclay – 4/11/15

Outline

- Neutrinos and Double beta decay in a nutshell
- The bolometric technique and TeO_2 detectors
- CUORE-0: detectors, background, results
- CUORE: state of the art and sensitivity
- CUPID: Next-generation bolometric tonne-scale experiment
- 3 ongoing CUPID-related R&Ds and results
- Conclusions

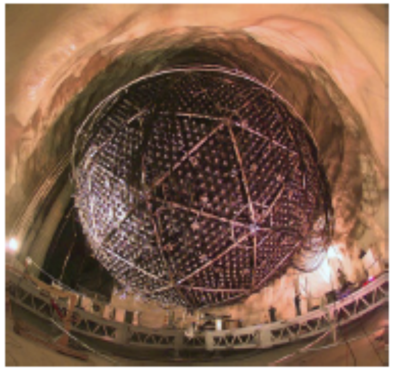
Neutrino physics

T. Kajita



Super-Kamiokande exp.

The Nobel Prize in Physics, 2015



SNO exp.

A. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

What we do know

Neutrinos are massive fermions
There are 3 active neutrino flavors
Neutrino flavor states are mixture of mass states
We have measured 2 independent squared mass splittings (Δm_{ij}^2)
The moduli of the elements of the mixing matrix have been measured

What we do not know

What is the neutrino mass hierarchy?
What about the CP violating phases?
Are neutrinos Dirac or Majorana particles?
What is the absolute neutrino mass scale?

Double Beta Decay

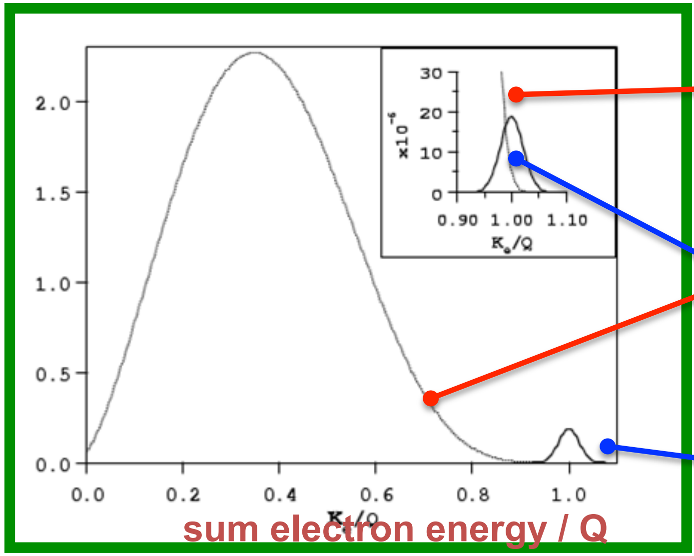
Double beta decay in a nutshell

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ → 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ → Neutrinoless Double Beta Decay (0ν-DBD)
never observed
$\tau > 10^{25}$ y

Process ② would imply new physics beyond the Standard Model

violation of total lepton number conservation



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

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

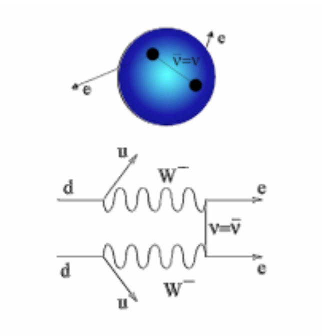
The rate in the mass mechanism

neutrinoless Double Beta Decay rate

Phase space

Nuclear matrix elements

Effective Majorana mass



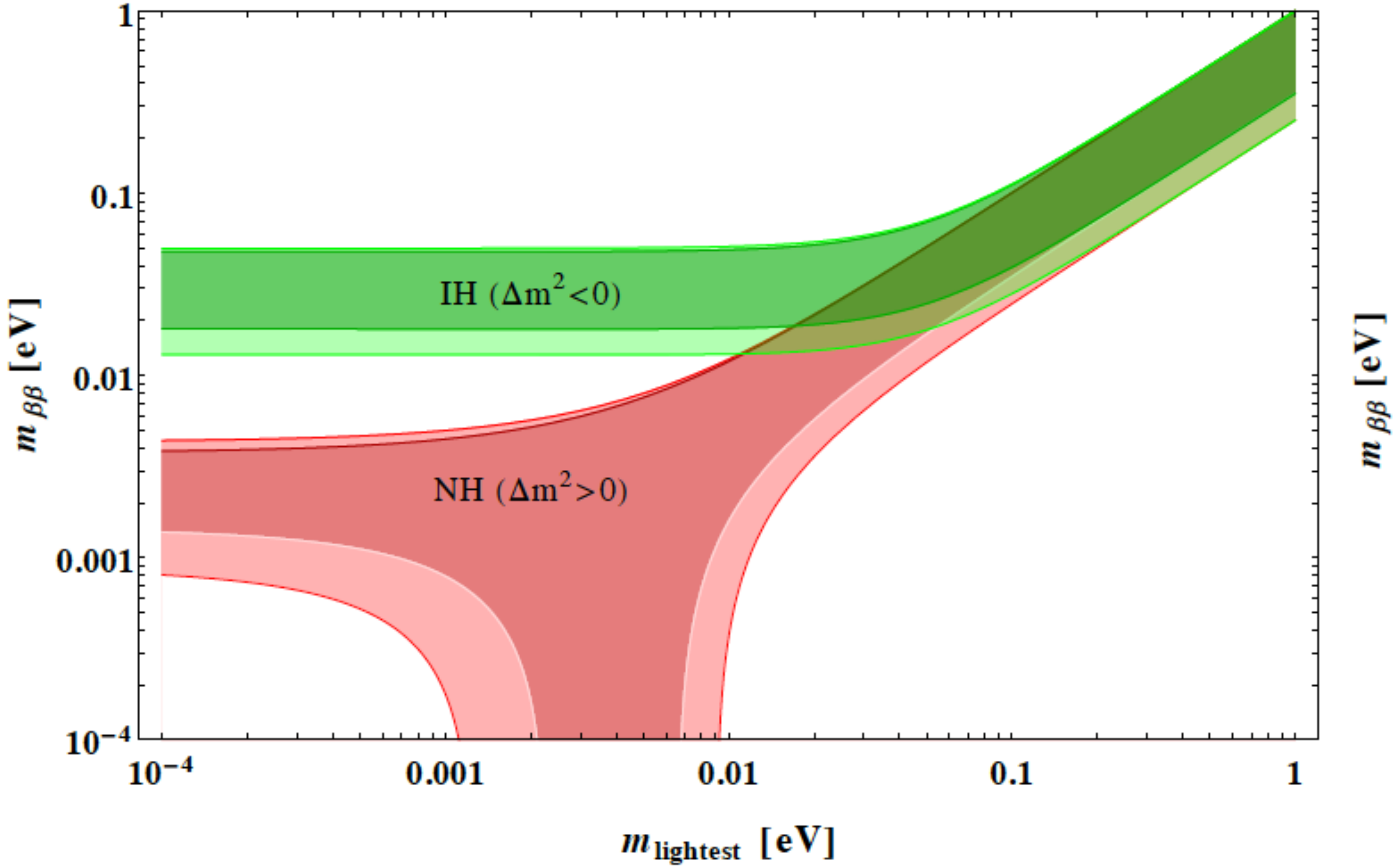
$$\frac{1}{\tau} = G(Q,Z)\cdot\left|M\right|^2\cdot\left\langle m_{\beta\beta}\right\rangle^2$$

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

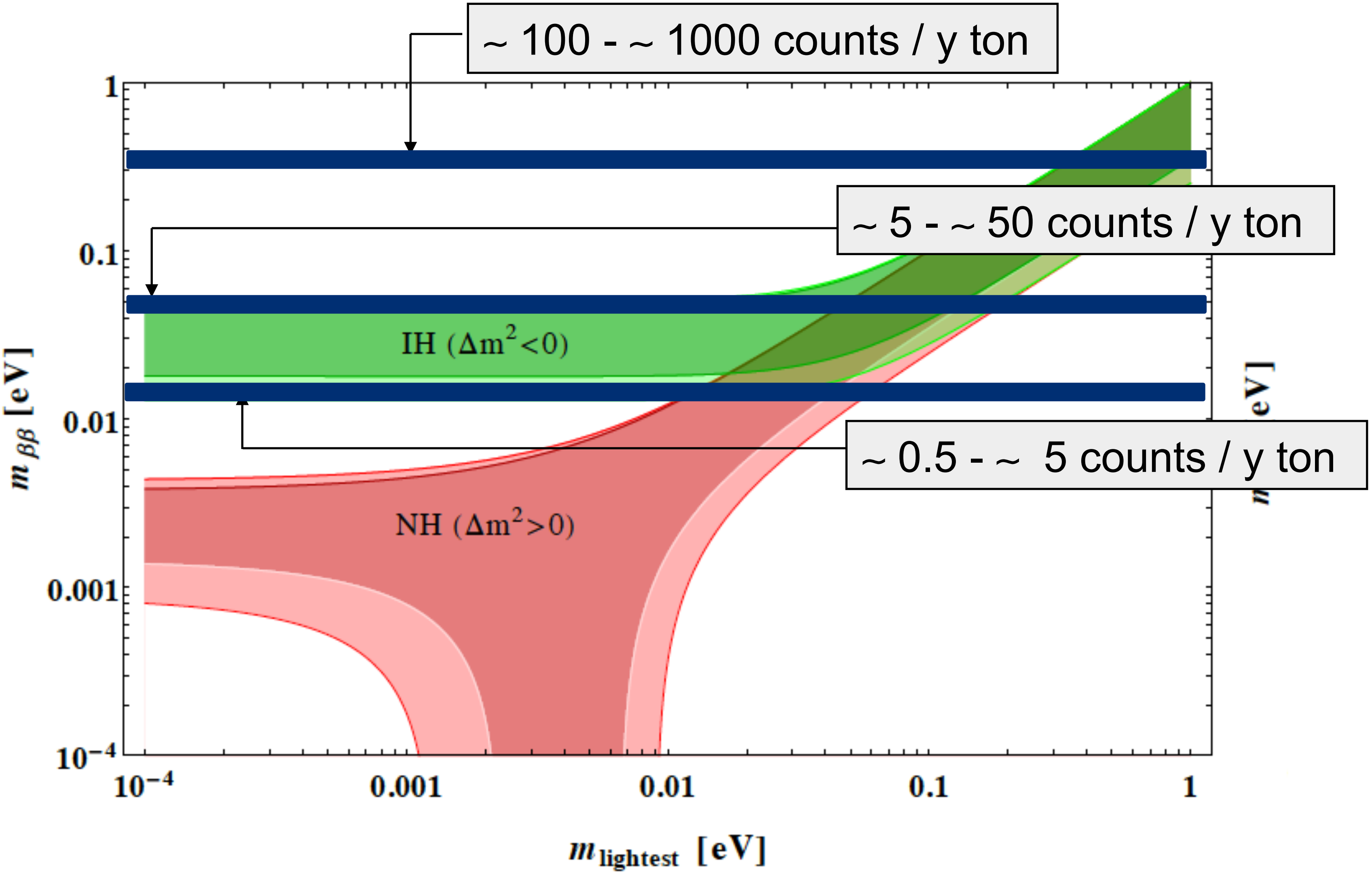
can be of the order of ~ 50 meV in case of inverted hierarchy

An important plot for 0νββ

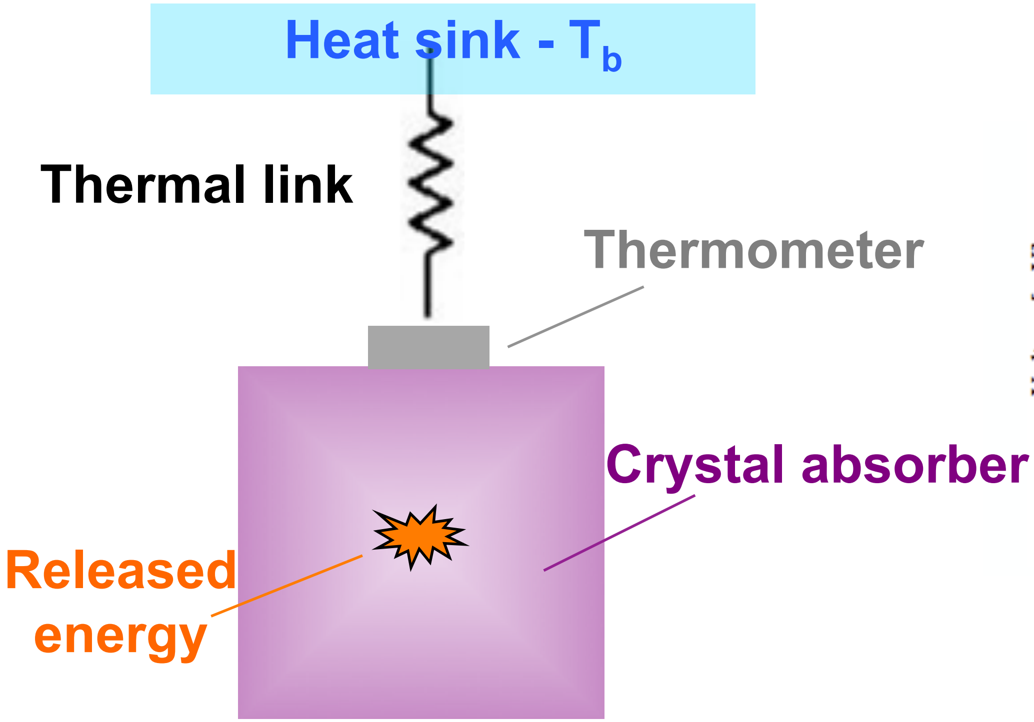
$$\langle m_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

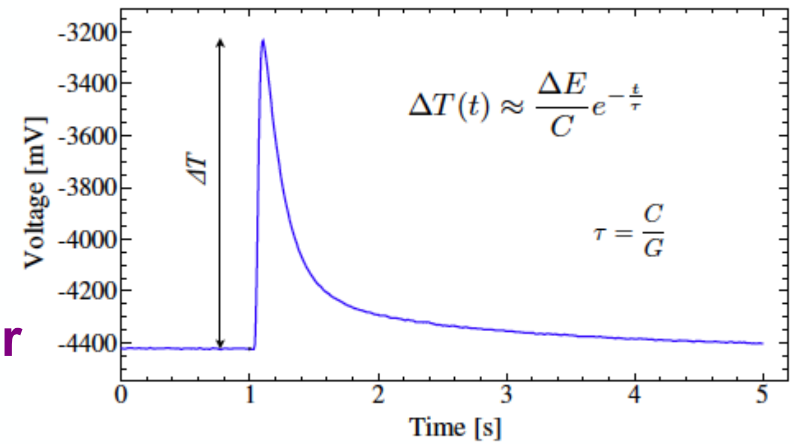


How difficult is it?



The bolometric technique





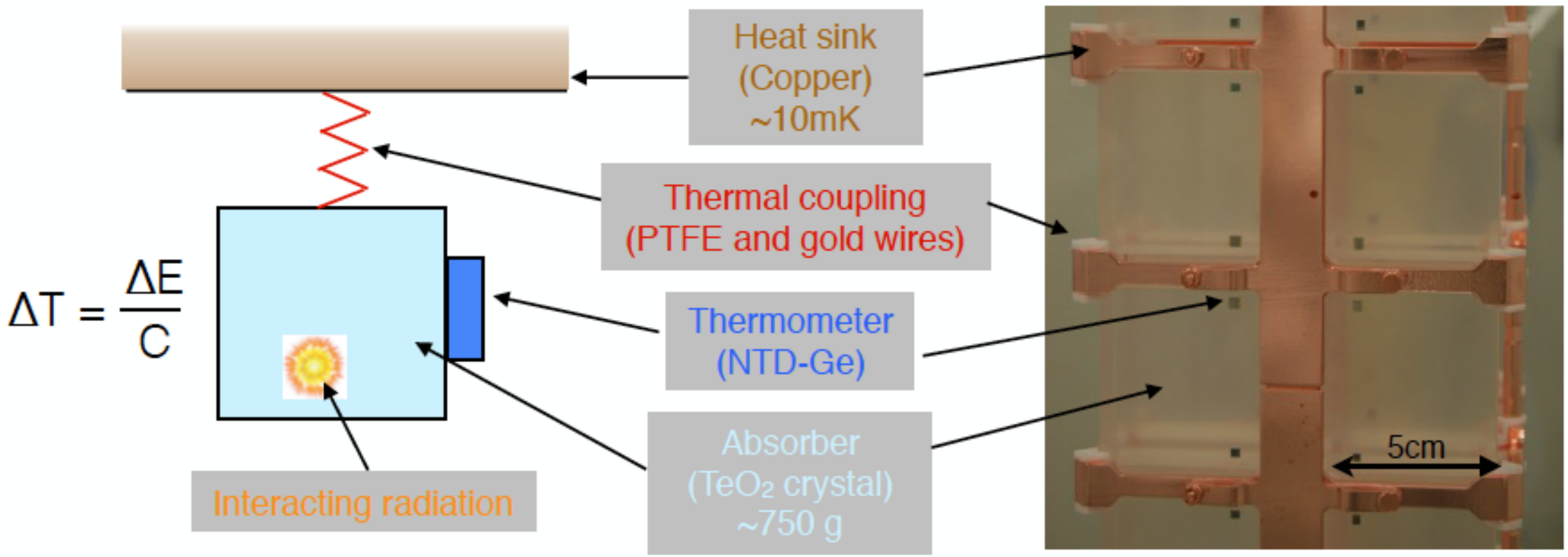
Main features:

- high energy resolution
- wide versatility (few constrains on absorber material)
- the detector is fully sensitive (no dead layer)

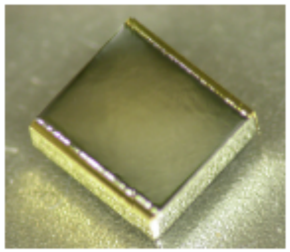
To develop high pulses the detector has to work at very low temperatures.

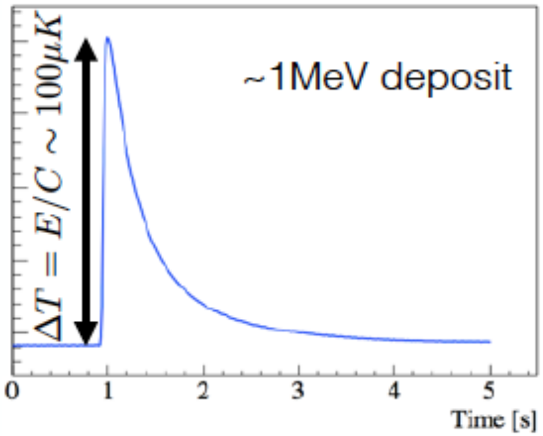
TeO_2 bolometers

Source=detector approach
Candidate: ^{130}Te – A.I. 34%



- $^{nat}TeO_2$ crystals: low heat capacitance
- NTD-Ge thermistor (R~50MΩ)
- Resolution @ ~2528 keV:
  ΔE = 5-7 keV FWHM





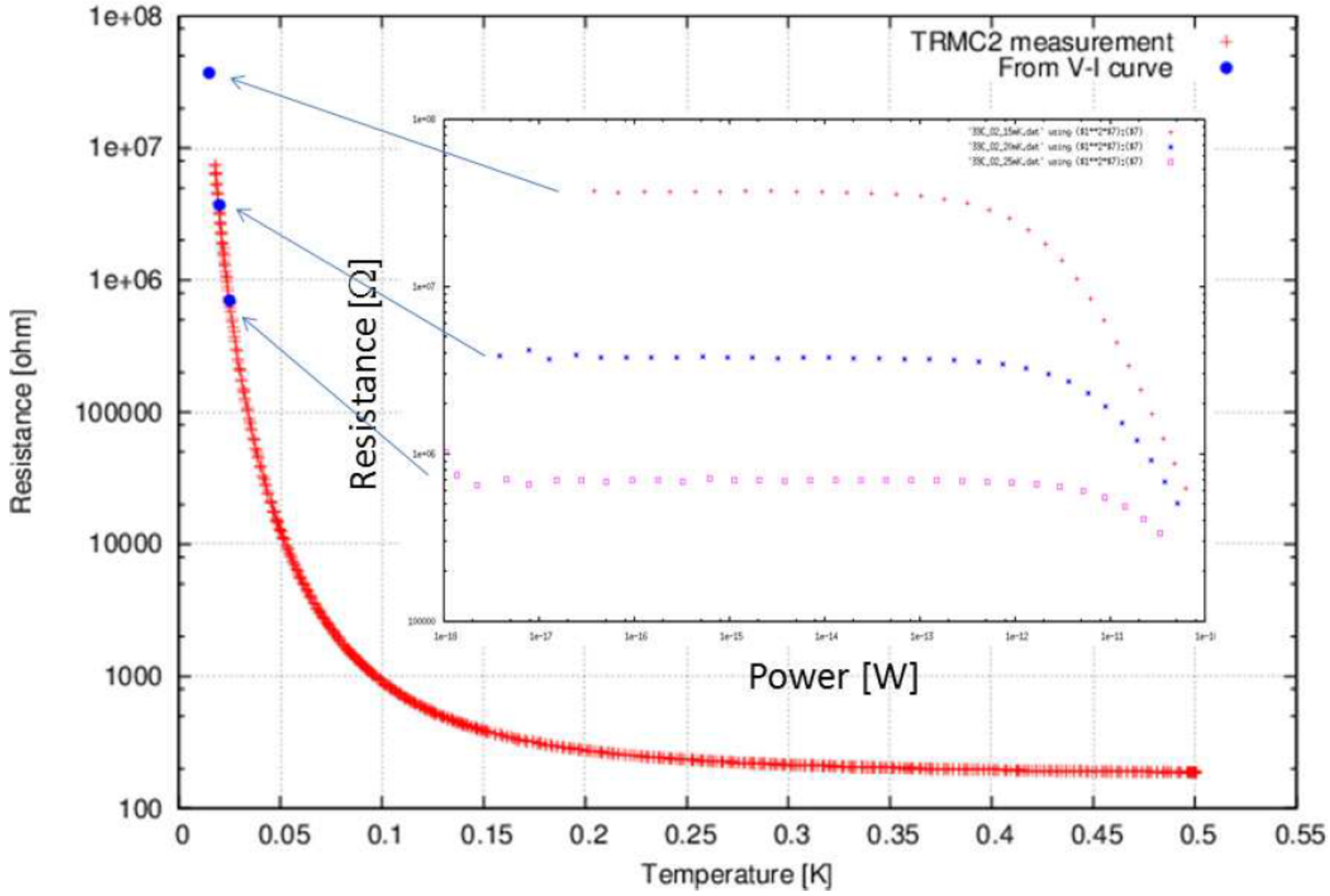
TeO_2 bolometers: the thermometer

Characterization of the CUORE NTD-Ge thermistors at CSNSM (Orsay)

$R(T) = R_0 \exp[(T_0 / T)^{0.5}]$

$T_0 = 4.5$ K

$R_0 = 0.9\ \Omega$

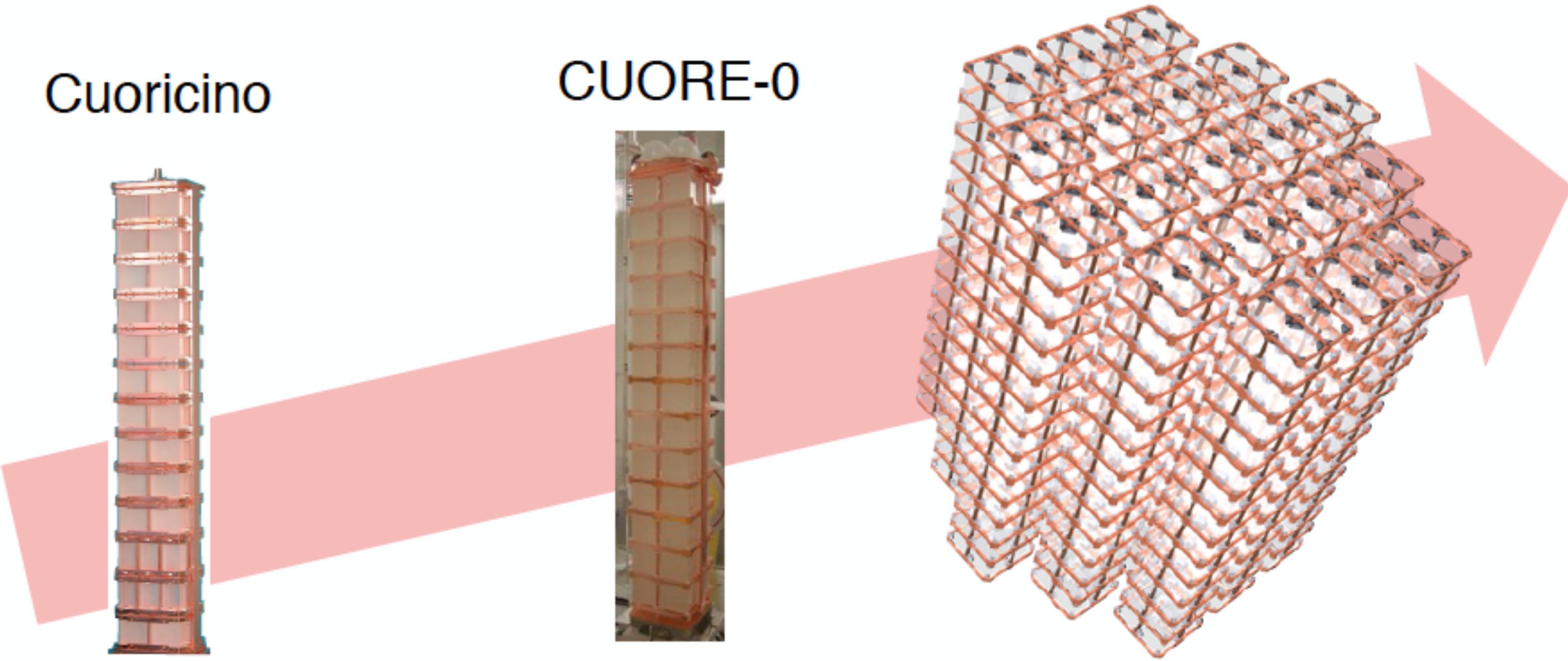


The TeO_2 bolometer history

CUORE

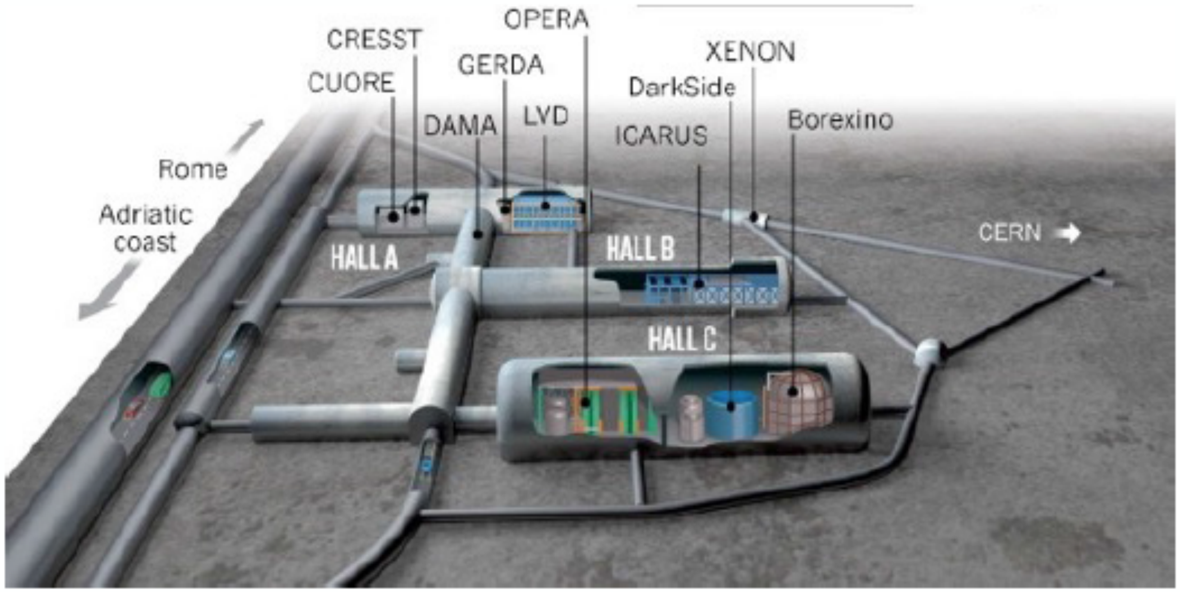
Cuoricino

CUORE-0

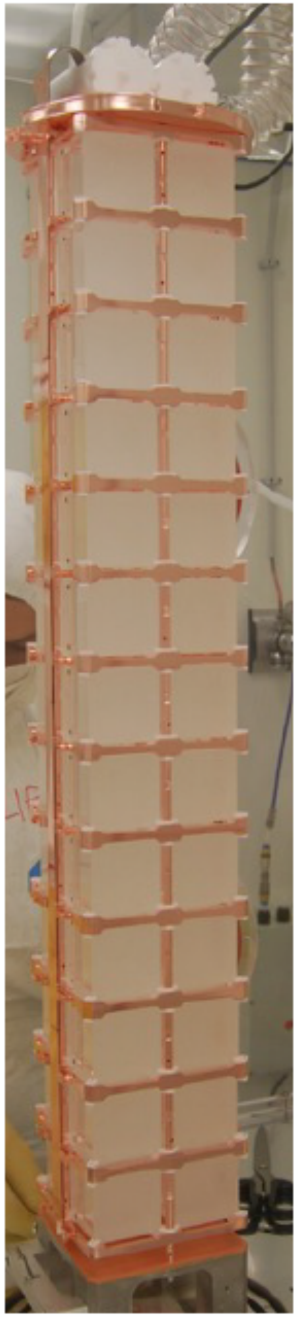


2003-2008	2013- running	2015-2020
$M = 11.3kg\ ^{130}Te$	$M = 10.9\ kg\ ^{130}Te$	$M = 206\ kg\ ^{130}Te$

CUORE-0 & CUORE at LNGS



- ~3600 m.w.e. deep
- μs: ~3×10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4×10^{-6} n/(s cm^2)



CUORE-0

CUORE-0 is the first tower produced out of the CUORE assembly line.

- 52 TeO_2 5x5x5 cm^3 crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)

CUORE-0 has been taking data since March 2013 in the 25 year old Cuoricino cryostat.

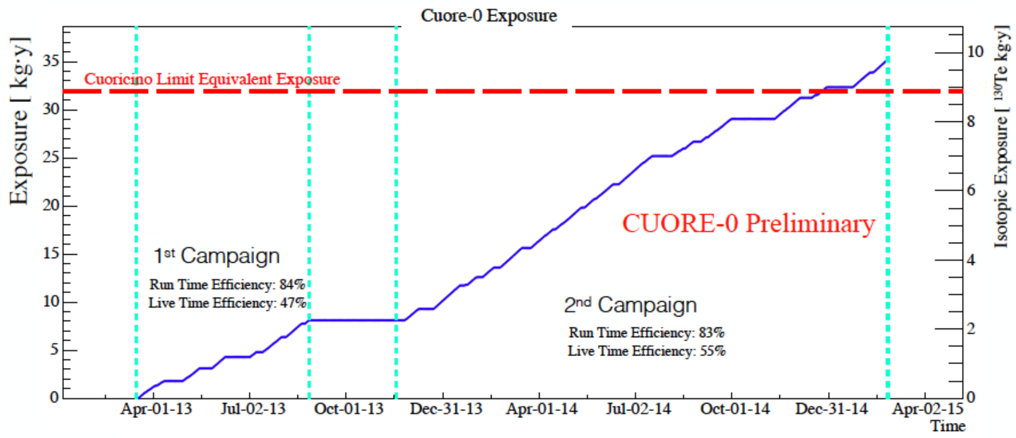
- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Check of the radioactive background reduction
- Sensitive 0vDBD experiment

Experimental setup & exposure

Same cryostat as Cuoricino experiment

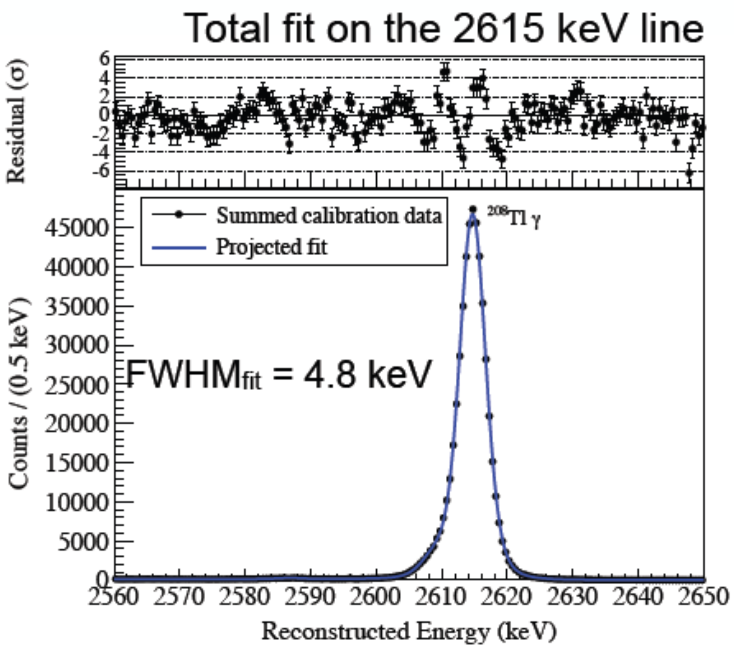
- Inner shield: 1 cm of Roman Lead (4 < mBq/kg)
- External shield: 20 cm of Modern Lead
- Nitrogen flushing

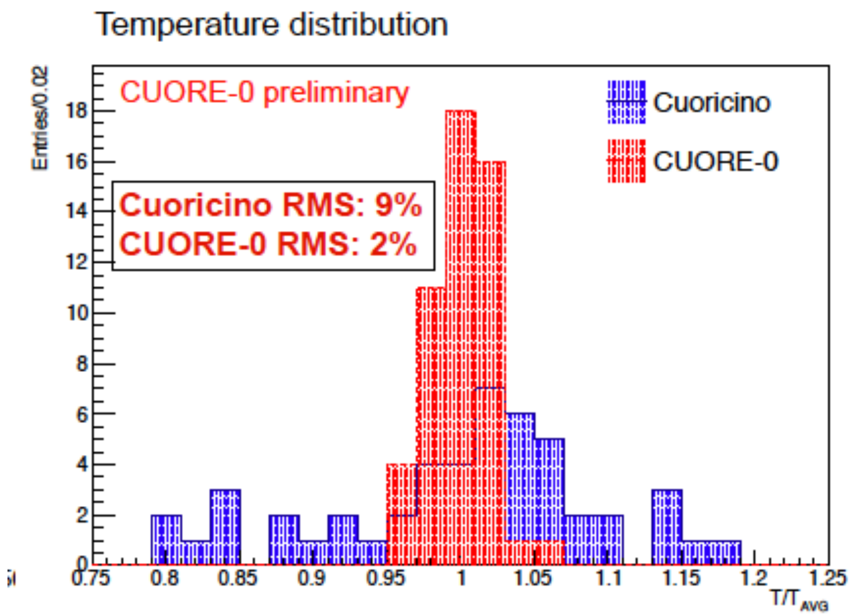
Gamma backgorund from cryostat shields not expected to change
(test of alpha background)



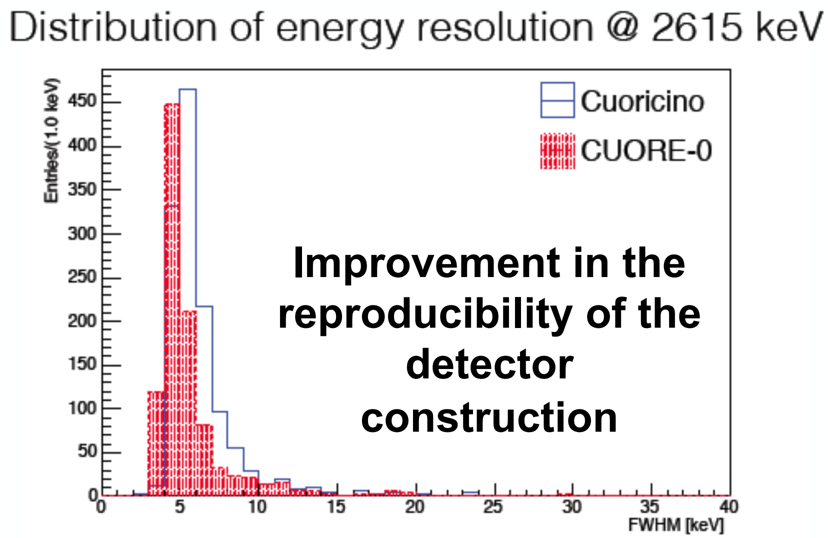
Acquired statistics
for $0\nu\beta\beta$ search:
35.2 kg y TeO_2
9.8 kg y ^{130}Te

CUORE-0: calibration energy resolution





The 5 keV CUORE goal has been reached



Physics-exposure-weighted harmonic mean

	Average FWHM [keV]	RMS of FWHM [keV]
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

CUORE-0 background (1)

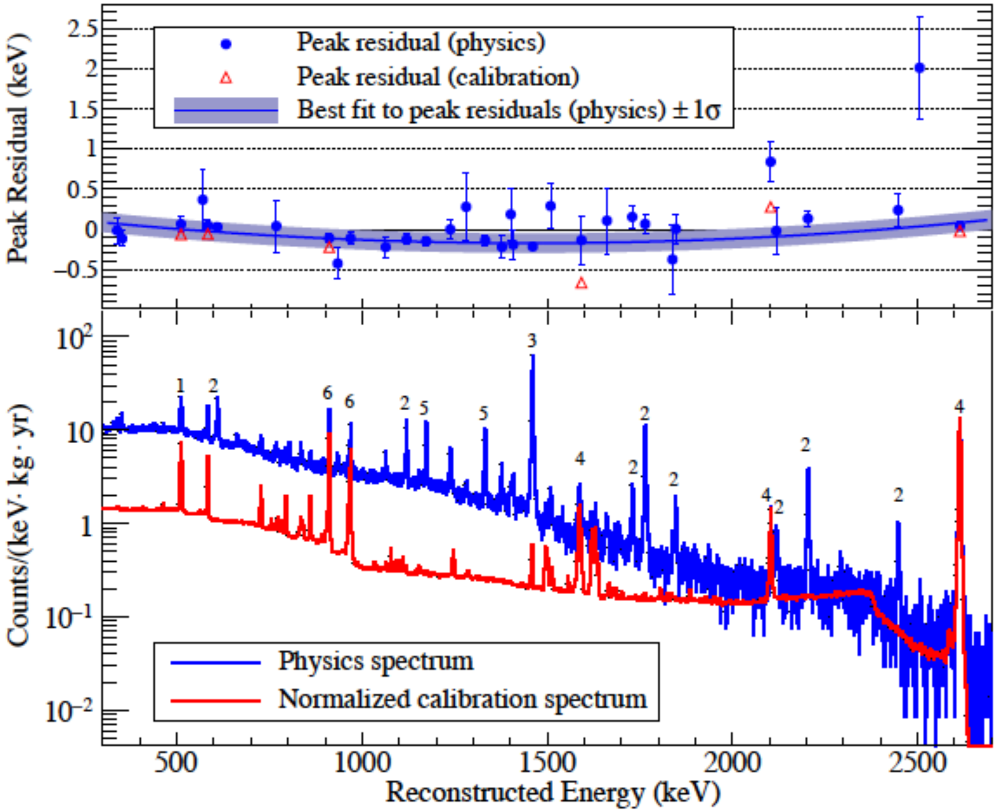


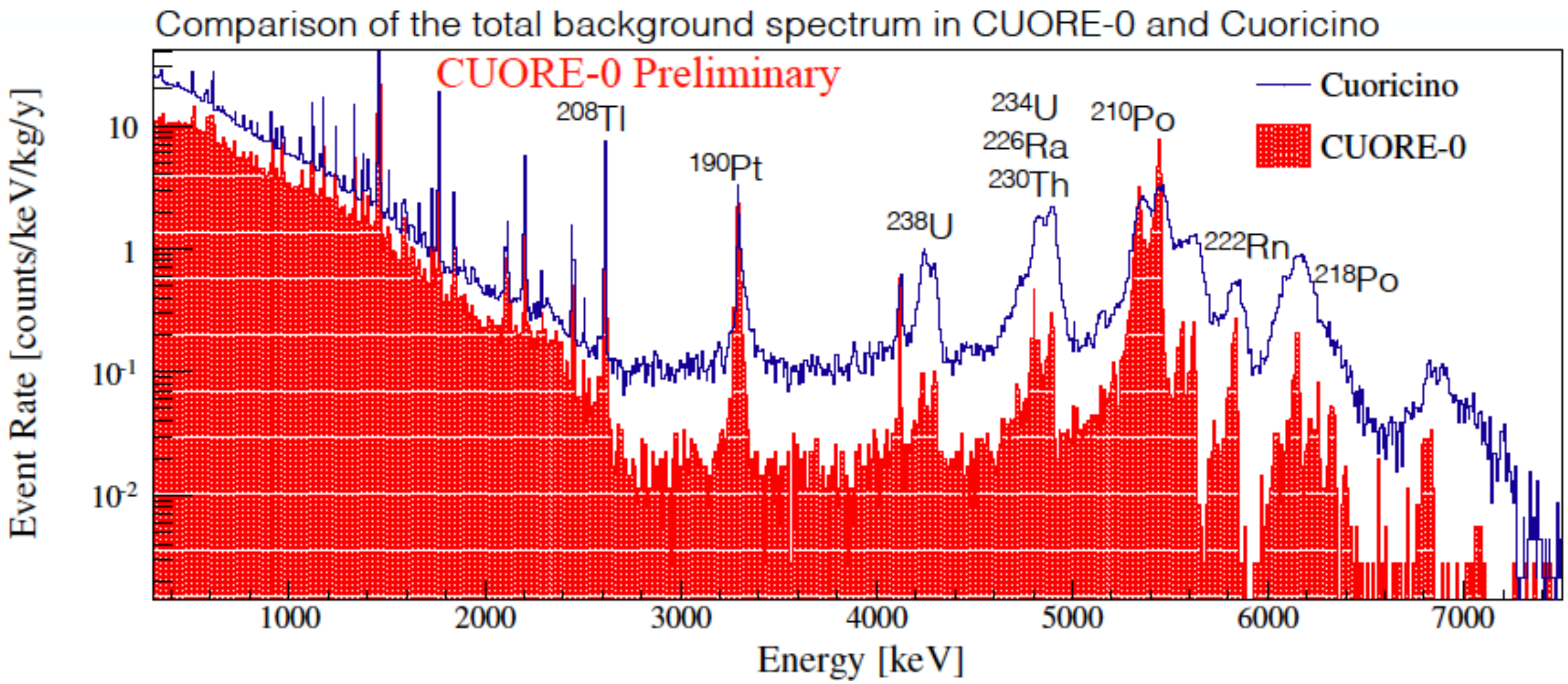
FIG. 1. Bottom: Energy spectra of physics (blue) and calibration (red) data; the latter is normalized relative to the former at 2615 keV. The peaks are identified as: (1) e^+e^- annihilation, (2) ^{214}Bi, (3) ^{40}K, (4) ^{208}Tl, (5) ^{60}Co, and (6) ^{228}Ac. Top: Difference of best-fit reconstructed peak energy and expected peak-energy for physics (blue points) and calibration (red) data. The blue line is the best-fit function to the physics peak residuals; the shaded band is its 1σ uncertainty.

- Detectors have been calibrated using two thoriated tungsten wires source placed in between the outermost cryostat shield and the external lead shield.

- Typical event rate per crystal:
  - 1 mHz during physics data taking
  - 60 mHz during calibrations

- Calibration function: quadratic function with zero intercept

CUORE-0 background (2)



- ^{238}U and ^{232}Th α lines reduced thanks to the new surface treatement of detectors
- ^{238}U γ lines reduced by a factor 2 (better control of Radon)
- ^{232}Th γ lines not reduced (they come from the cryostat which is the same in both cases)

	2.7-3.9 MeV	ROI
CUORE-0	0.016 ± 0.001	0.058 ± 0.004
Cuoricino	0.110 ± 0.001	0.169 ± 0.006

Factor 6 reduction in the α continuum region

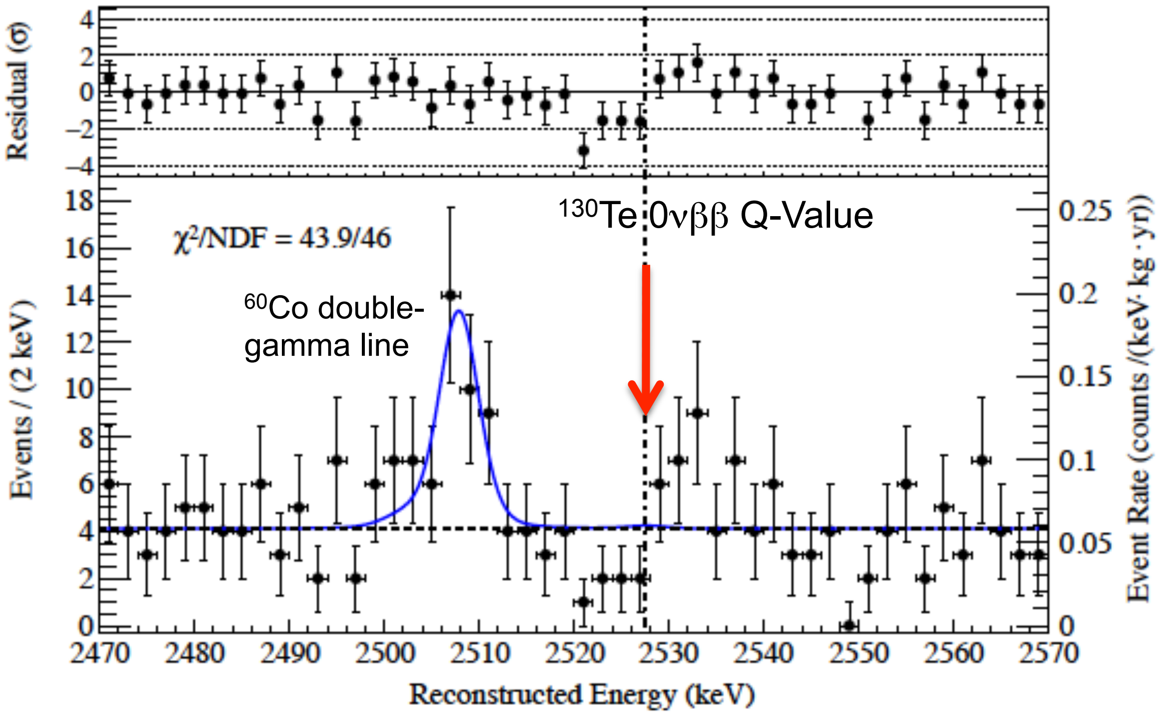
CUORE-0: ROI fit

- The best fit value of the 0vDBD decay rate is

$$\Gamma_{0\nu} = 0.01 \pm 0.12\,(\mathrm{stat.}) \pm 0.01\,(\mathrm{syst.}) \times 10^{-24}\mathrm{yr}^{-1}$$

- The background index in the ROI is:

$$0.058 \pm 0.004\,(\mathrm{stat.}) \pm 0.002\,(\mathrm{syst.})\ \mathrm{c/keV/kg/yr}$$



The yield of 0νββ events has been determined by performing a simultaneous unbinned extended maximuum likelihood fit in the region 2470-2570 keV.

The used fit has 3 components:

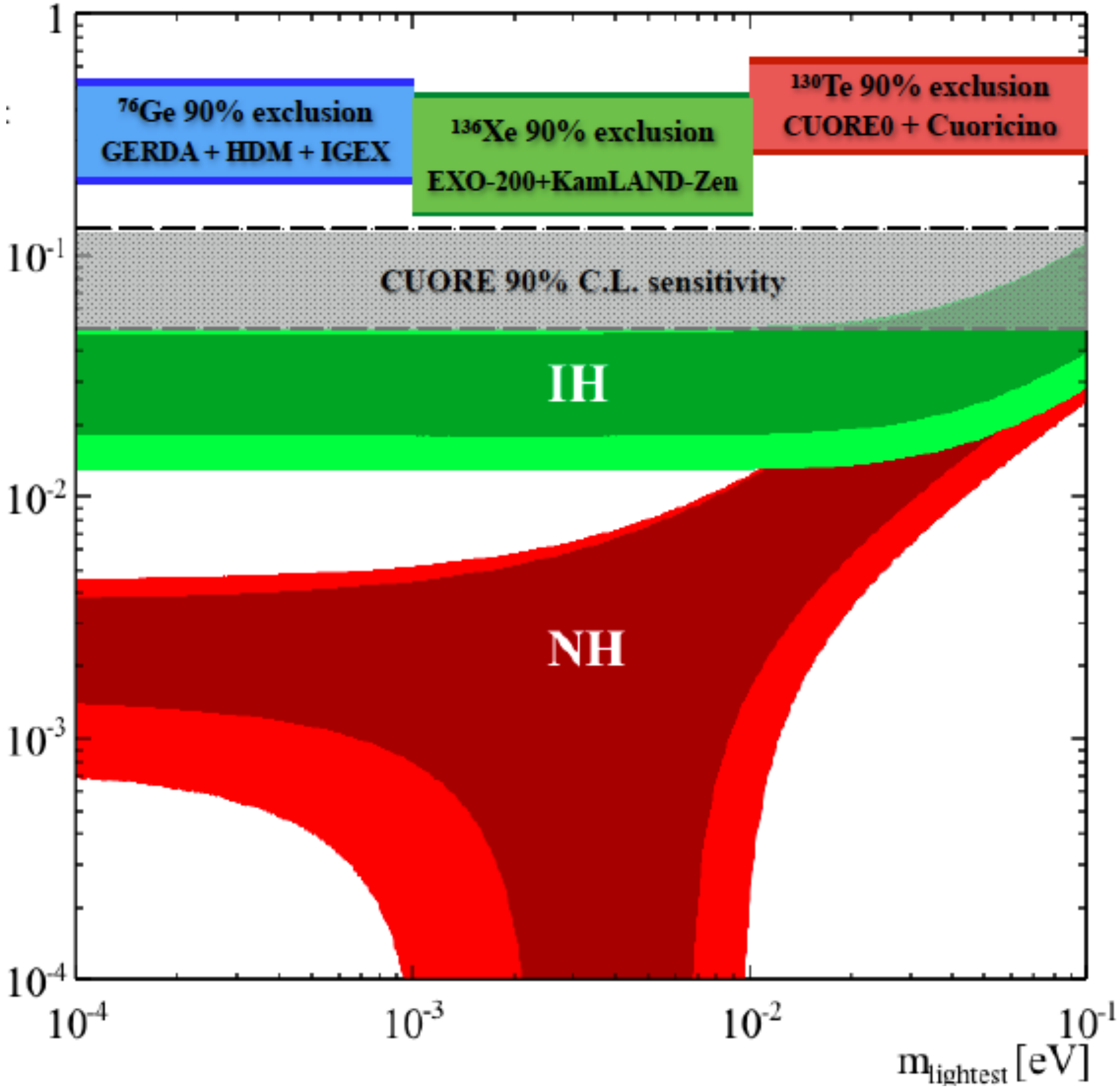
1. The hypothetical 0νββ peak at the Q-value of 130Te (2527 keV)
2. A peak floating around 2505 keV due to sum of gamma events from ^{60}Co in the nearby copper
3. A flat continuum bkg, attributed to multi scatter Compton events from ^{208}Tl and surface α events.

0νββ 130Te Bayesian 90% C.L. limit: **2.7×10^{24} y**

Phys. Rev. Lett. 115, 102502

When combining the CUORE-0 result with the existing 19.75 kg · yr of ^{130}Te exposure from Cuoricino, we obtain a 90% C.L. limit of: **$T_{1/2} > 4.0 \times 10^{24}$ yr**.

Limit on $m_{\beta\beta}$



The combined result gives a limit on the effective Majorana neutrino mass:

$\langle m_{\beta\beta} \rangle < (270\text{-}650)$ meV

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

CUORE

• Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals $5x5x5\ cm^3$, 0.75 kg each)

• TeO_2 total mass: 741 kg (~ 206 kg of ~^{130}Te)

• Energy resolution: 5 keV @ 2615 keV

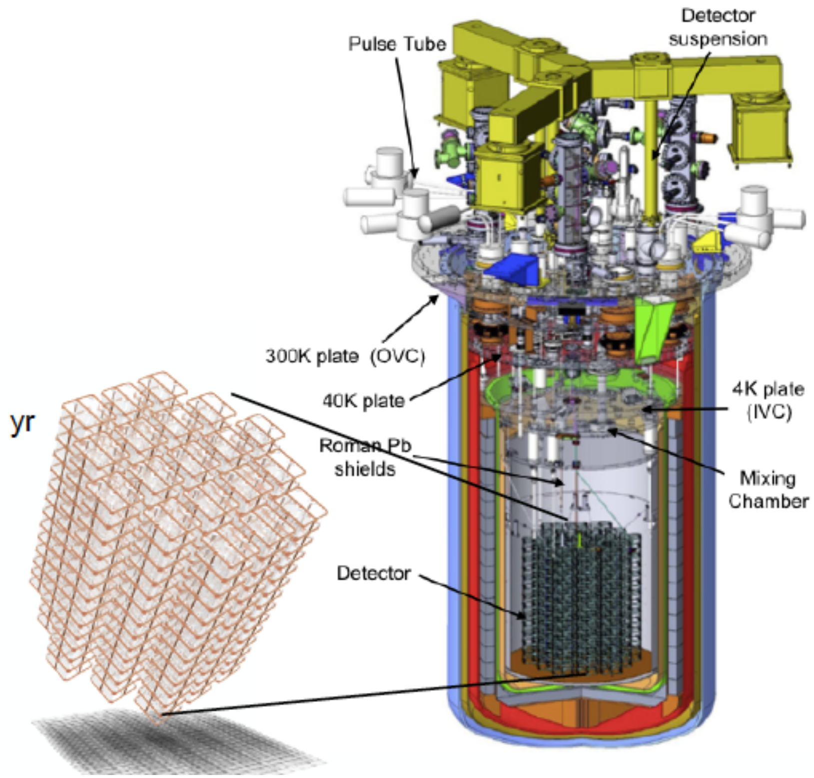
• Operating temperature: ~ 10 mK

• Total mass to be cooled down: ~ 15 tons

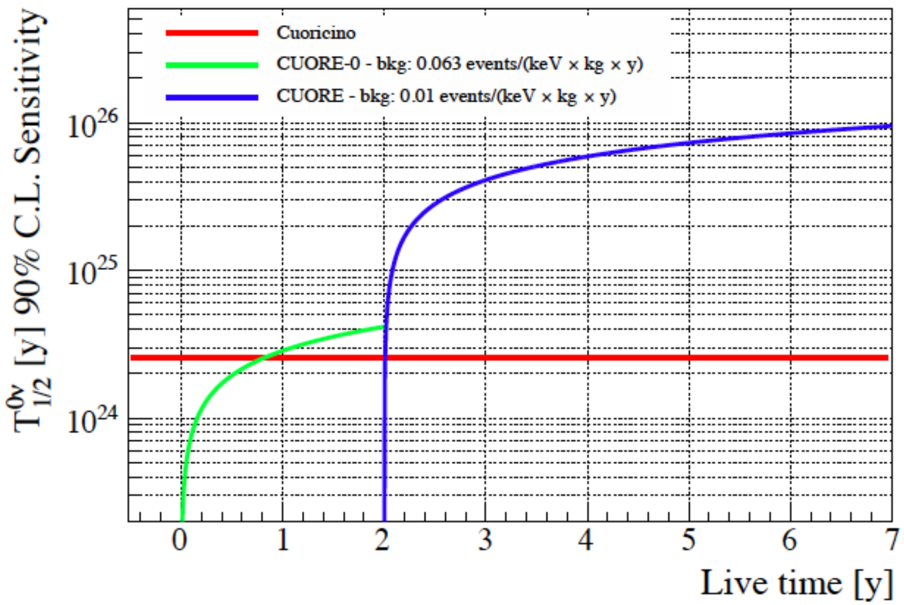
• Stringent radiopurity controls on materials and assembly

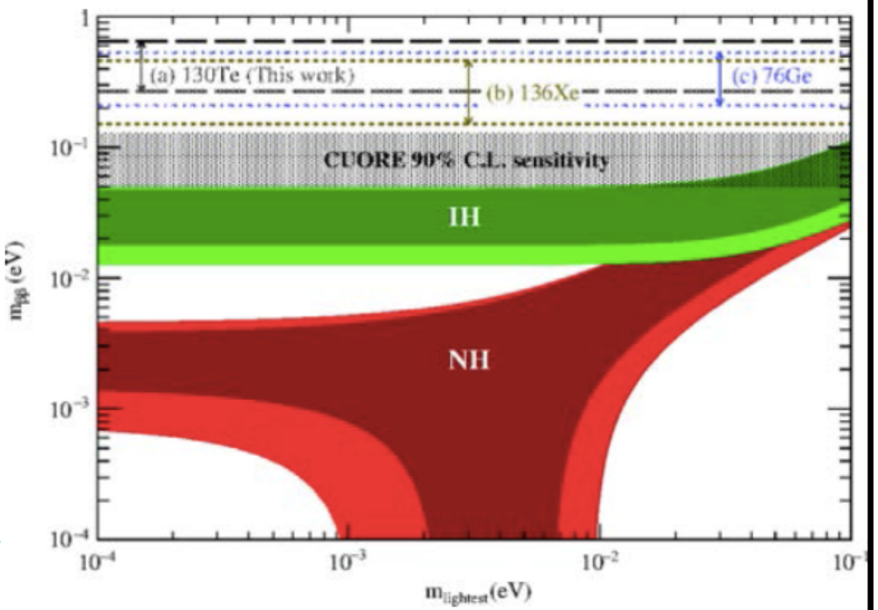
• Stable ultra-low temperatures

• Extremely low vibrations



CUORE sensitivity





<u>**Main goals:**</u>

- Background rate: 10^{-2} counts/ (keV kg y) dominated by surface α background
- 5 keV FWHM
- 5 years of live time

CUORE projected sensitivity (90% C.L.)

$S_{1/2}(0\nu\beta\beta)$= 9.5 x 10^{25} y

$m_{\beta\beta}$: 50-130 meV

Physics cases:

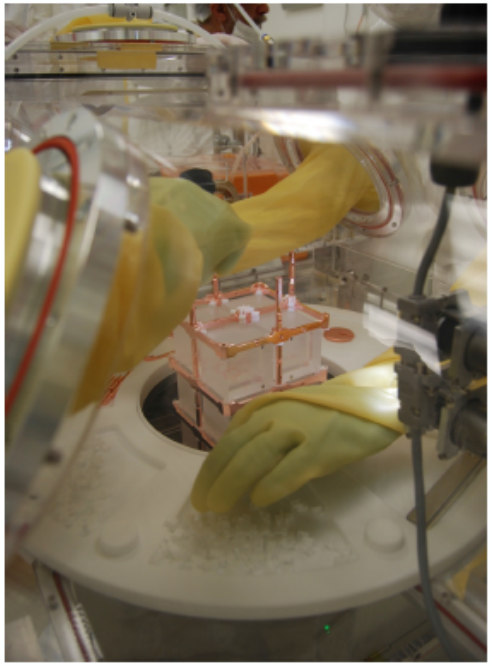
$0\nu\beta\beta$

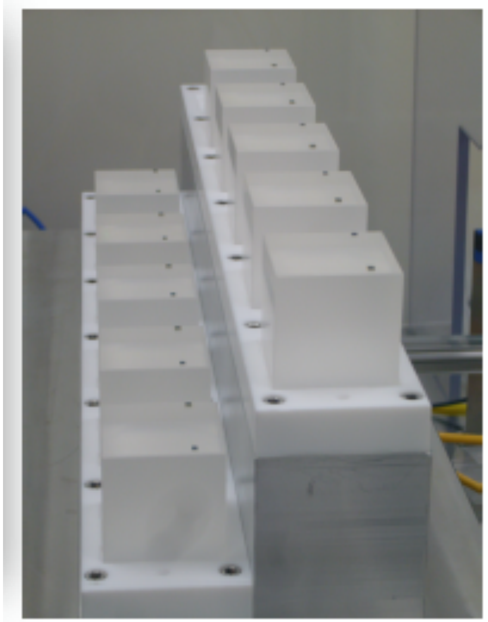
Dark Matter

Axions

Rare nuclear decays

CUORE status (1)

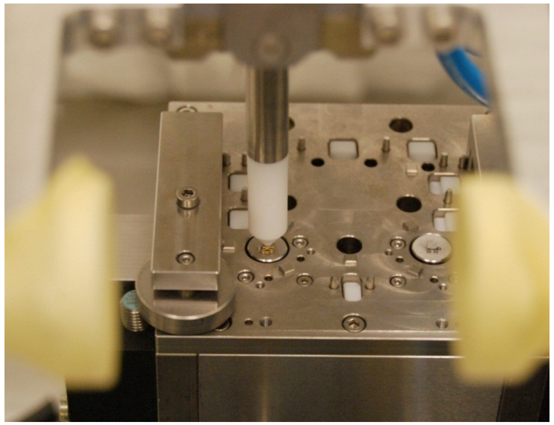




Assembly line improved thanks to CUORE-0 experience

988/988 NTD connected
988/988 heaters connected

- New semi-automatic system
- Highly-reproducible
- Fully performed under N_2 atmosphere to minimize radioactive recontamination.



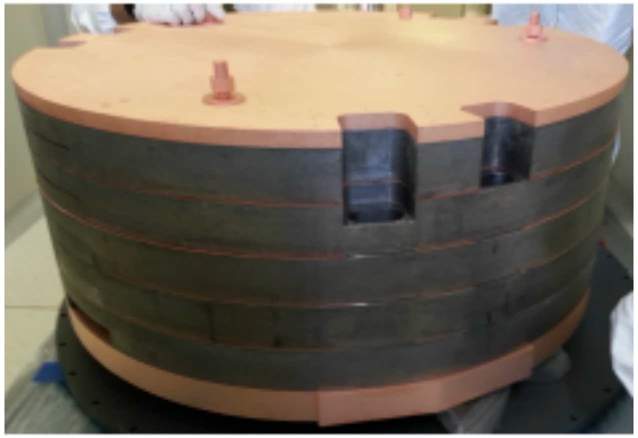
Assembly of all the 19 CUORE towers completes in 2014

CUORE status (2)

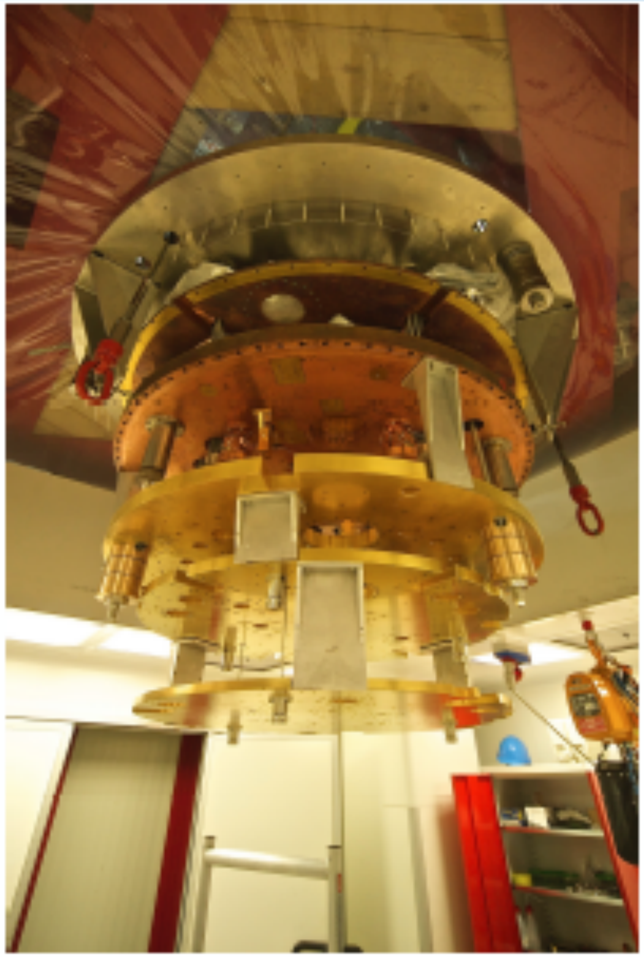
The commissioning of the cryogenic system has been done adding complexity at each step.

Phase1: tests on individual systems
- Outer/inner vacuum chamber
- Cryostat
- Dulition unit

Phase2: system integration

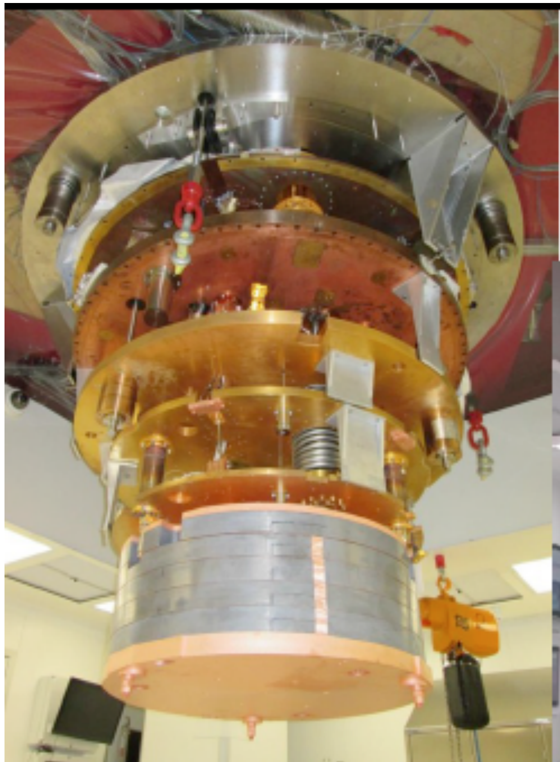


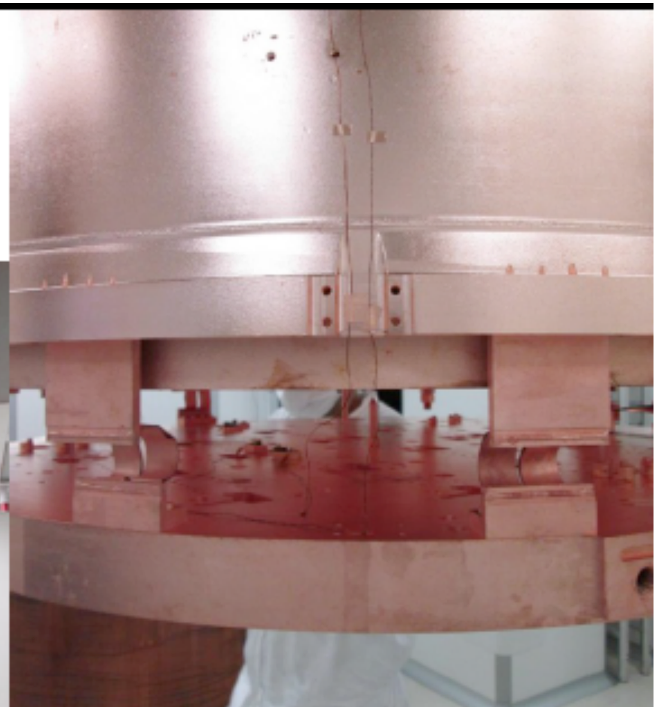
Wiring
Top Pb shield
Detector calibration System
Tower support plate

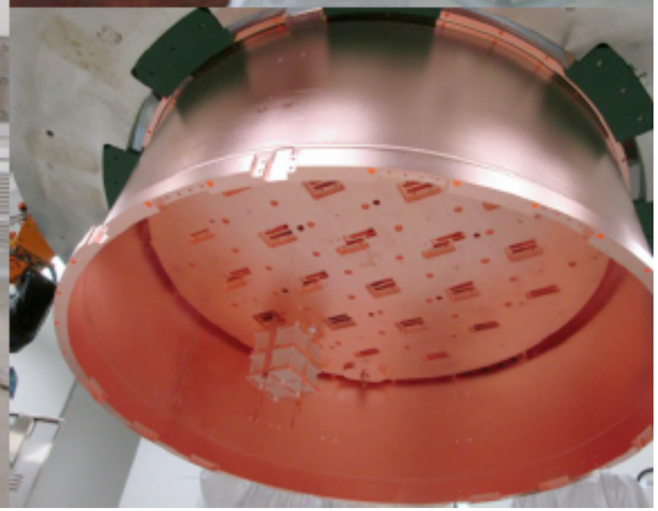


Some pictures from last tests

Top lead shield & suspension
Thermalizers
Top ferrule (10 mK)







The coldest place in the Universe

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21 October 2014 http://www.interactions.org
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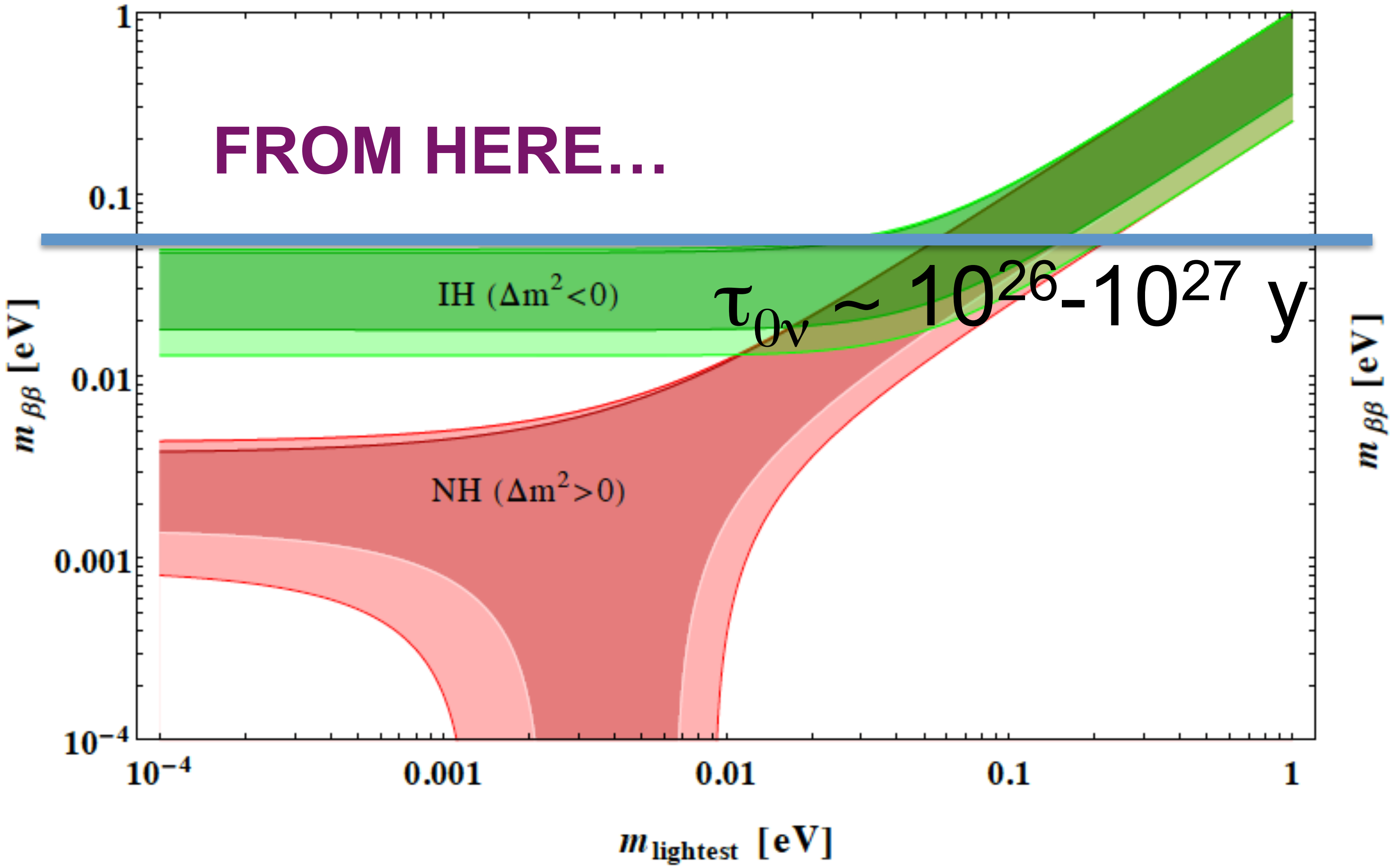
Source: INFN
Content: Press Release
Date Issued: 21 October 2014
****

CUORE: The Coldest Heart in the Known Universe

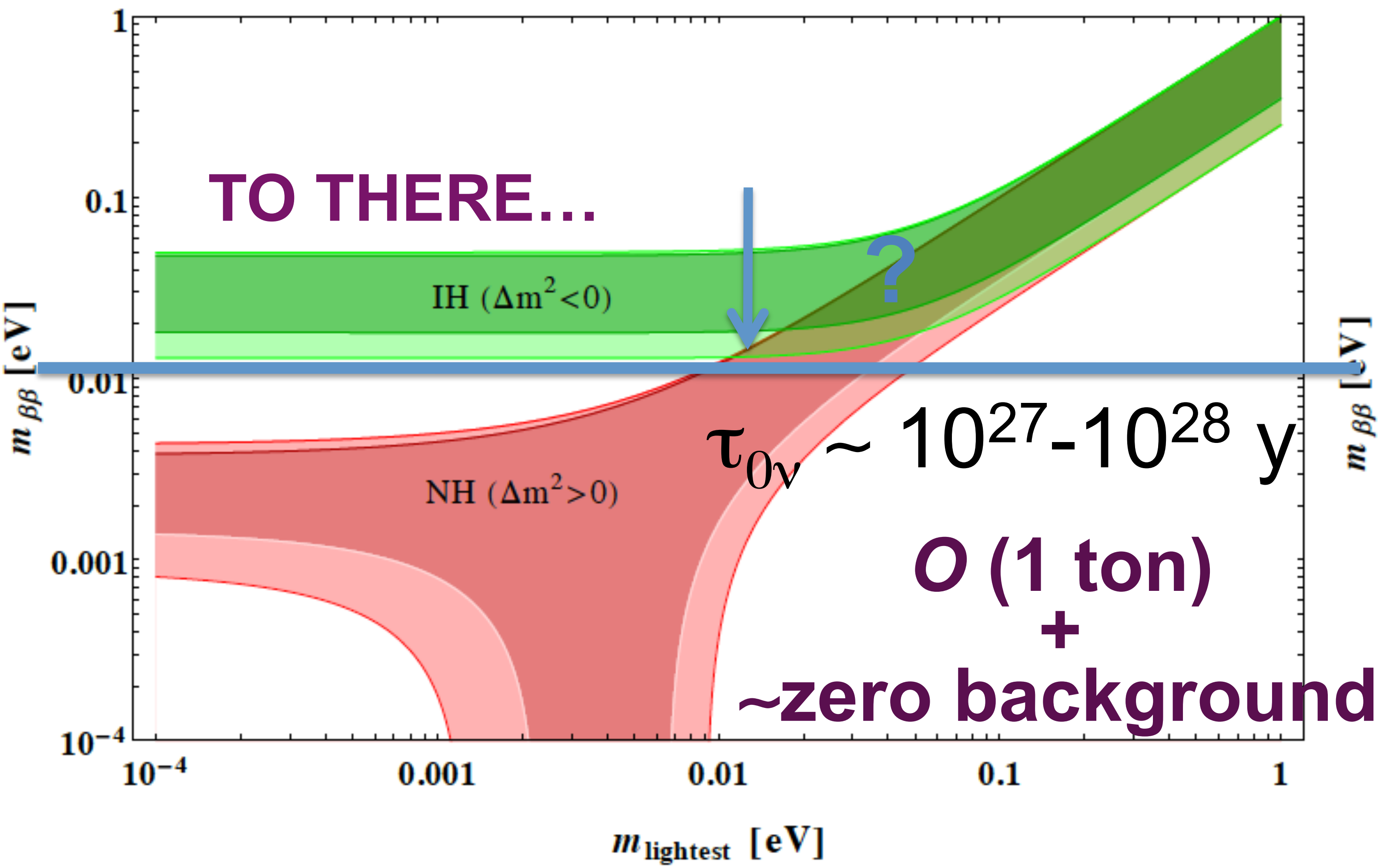
The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.

Current-generation experiments

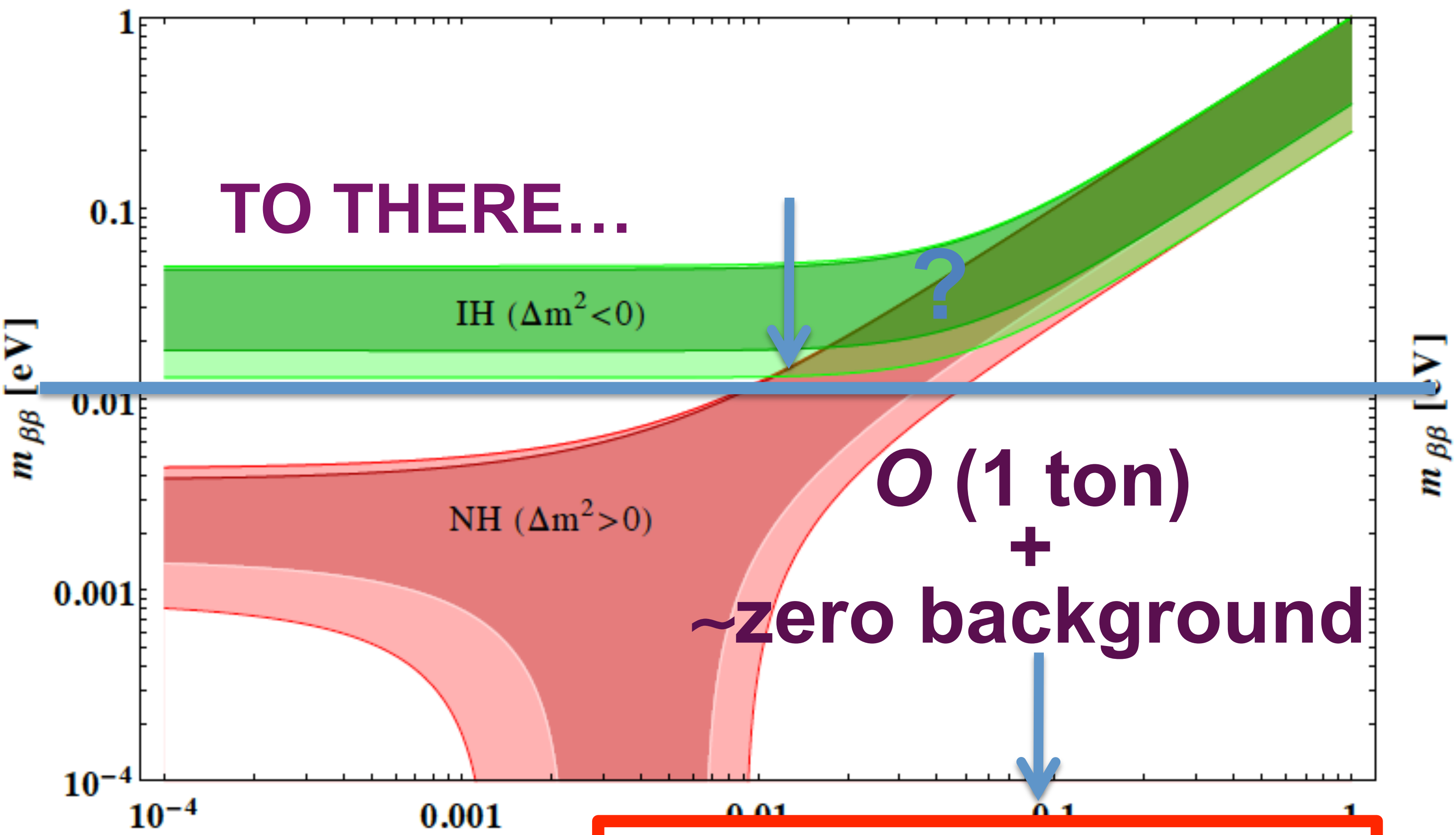


What's next…



TO THERE…
?
IH ($\Delta m^2<0$)
NH ($\Delta m^2>0$)
$\tau_{0\nu} \sim 10^{27}\text{-}10^{28}$ y
O (1 ton)
+
~zero background
$m_{\beta\beta}$ [eV]
m_{lightest} [eV]
1
0.1
0.01
0.001
10^{-4}

What's next…



A bolometric approach:
CUPID

CUPID

CUORE Upgrade with Particle IDentification

Main idea:

Use CUORE infrastructure (after completion of CUORE programme) with:

- **enriched crystals** (sensitive mass: 210 kg – 550 kg)
- upgraded technology to get **0 background at ton × y scale** (**10-15 meV sensitivity**)

Technology selection +
CDR in ~two years

The CUPID group of interest

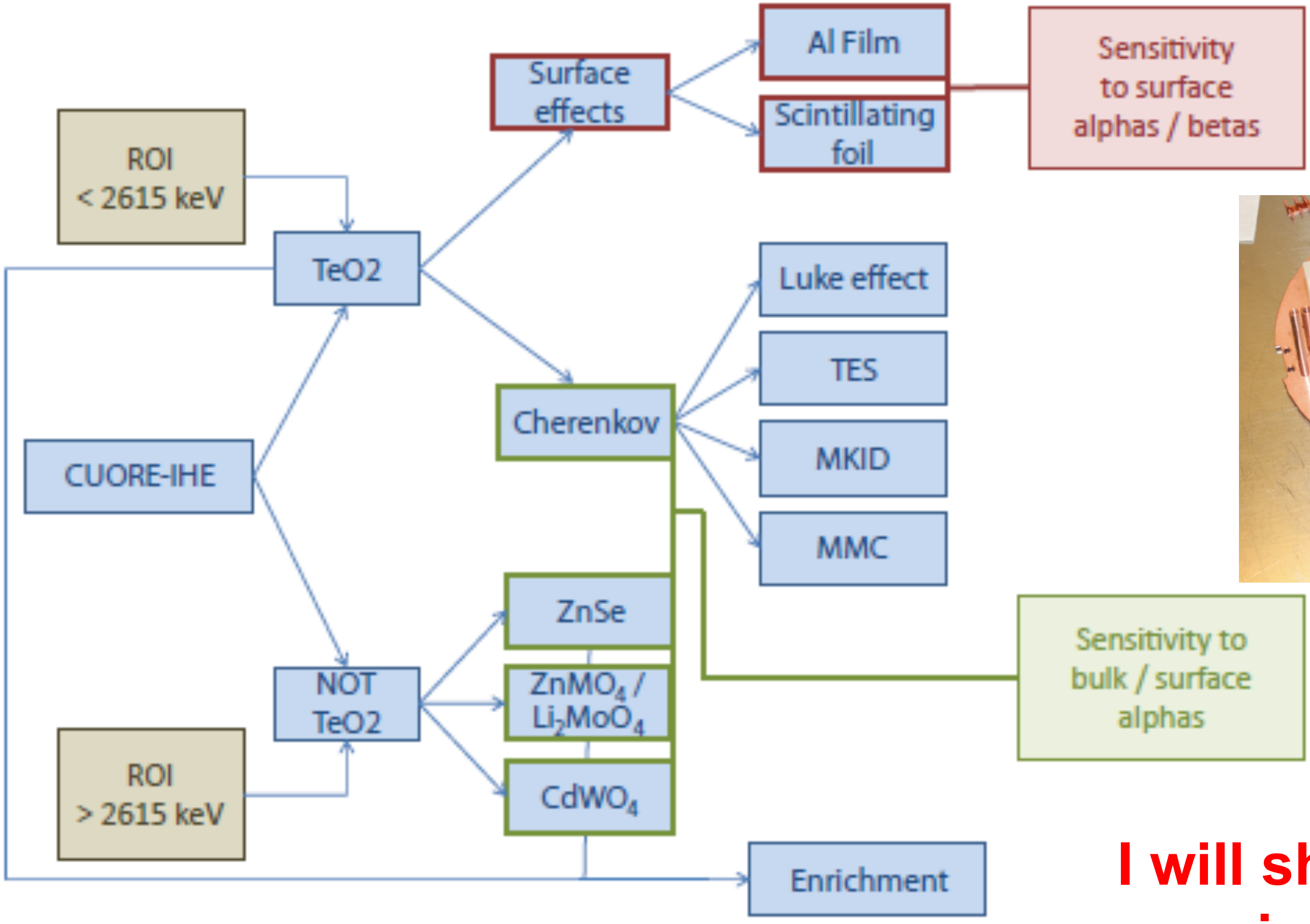
High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA!
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
!Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
Department of Physics, University of California, Berkeley, USA
Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
Lawrence Livermore National Laboratory, Livermore, CA, USA
Department of Physics and Astronomy, University of California, Los Angeles, CA, USA
INFN sez. di Milano Bicocca and Dipartimento di Fisica, Università di Milano Bicocca, Italy
State Scientific Center of the Russian Federation - Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
Max-Planck-Institut für Physik, D-80805 München, Germany
Nikolaev Institute of Inorganic Chemistry, SB RAS, Novosibirsk, Russia
Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk, Russia
Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), CNRS/IN2P3, Orsay, France
INFN - Sezione di Padova, Padova, Italy
Institut de Chimie de la Matière Condensè de Bordeaux (ICMCB), CNRS, 87, Pessac, France
Dipartimento di Fisica, Università di Roma “La Sapienza” and INFN - Sezione di Roma, Roma, Italy
IFN-CNR, Via Cineto Romano, I-00156 Roma, Italy!
Service de Physique des Particules, DSM/IRFU, CEA-Saclay, France
!Physics Department, California Polytechnic State University, San Luis Obispo, CA, USA
Shanghai Institute of Applied Physics (SINAP), China
Institut de Physique Nuclèaire de Lyon, Universitè Claude Bernard, Lyon 1, Villeurbanne, France
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA!
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain)

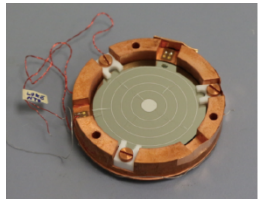
8 countries
~ 30 laboratories
~ 100 persons from CUORE
~ 30 persons from outside

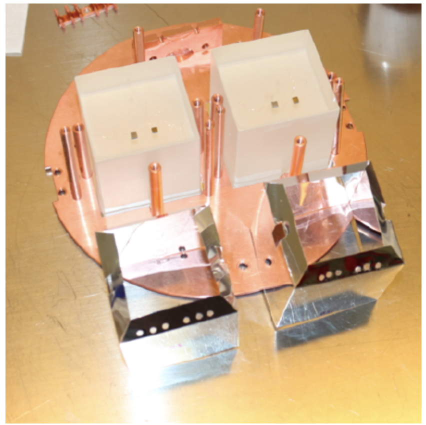
White papers:
arXiv: 1504.03599
arXiv:1504.03612

R&D for 1-ton bolometric experiment

Important goal: get rid of the currently dominant surface α background

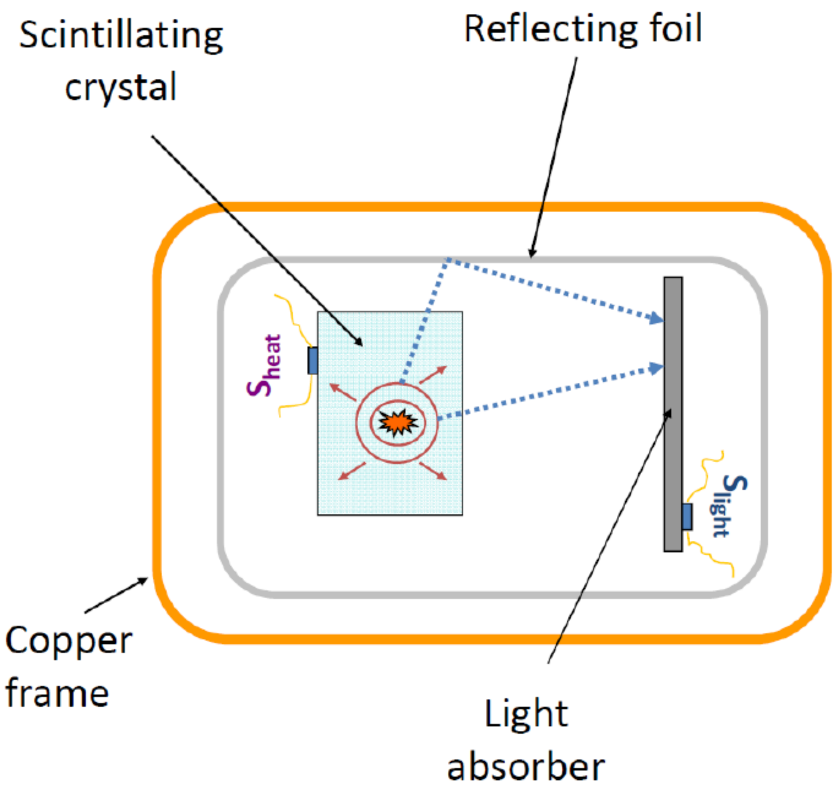


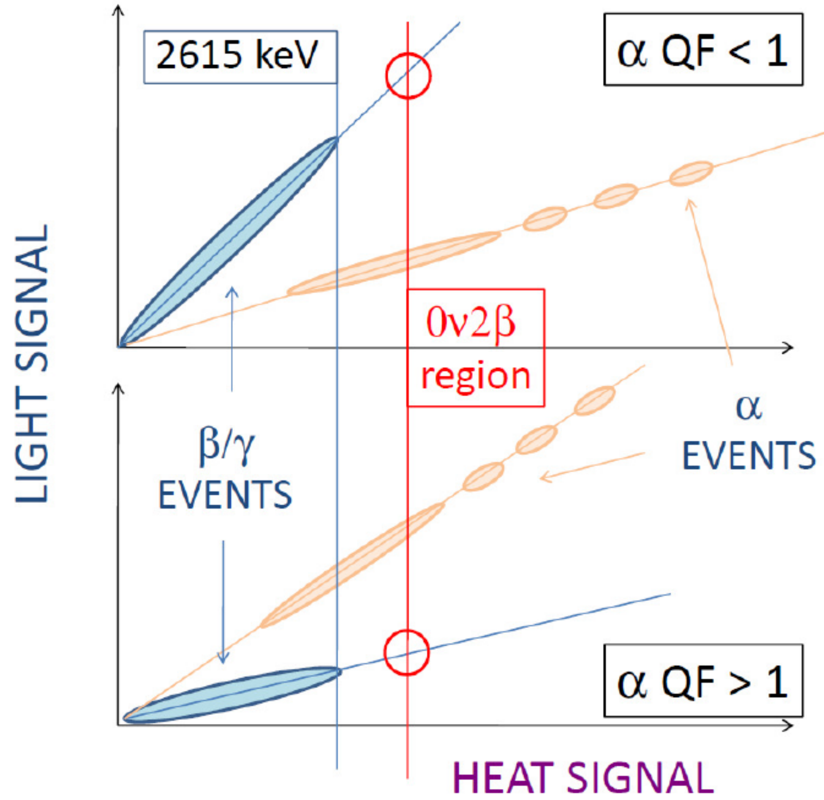




I will show three main results

Central role of luminescent bolometers in CUPID





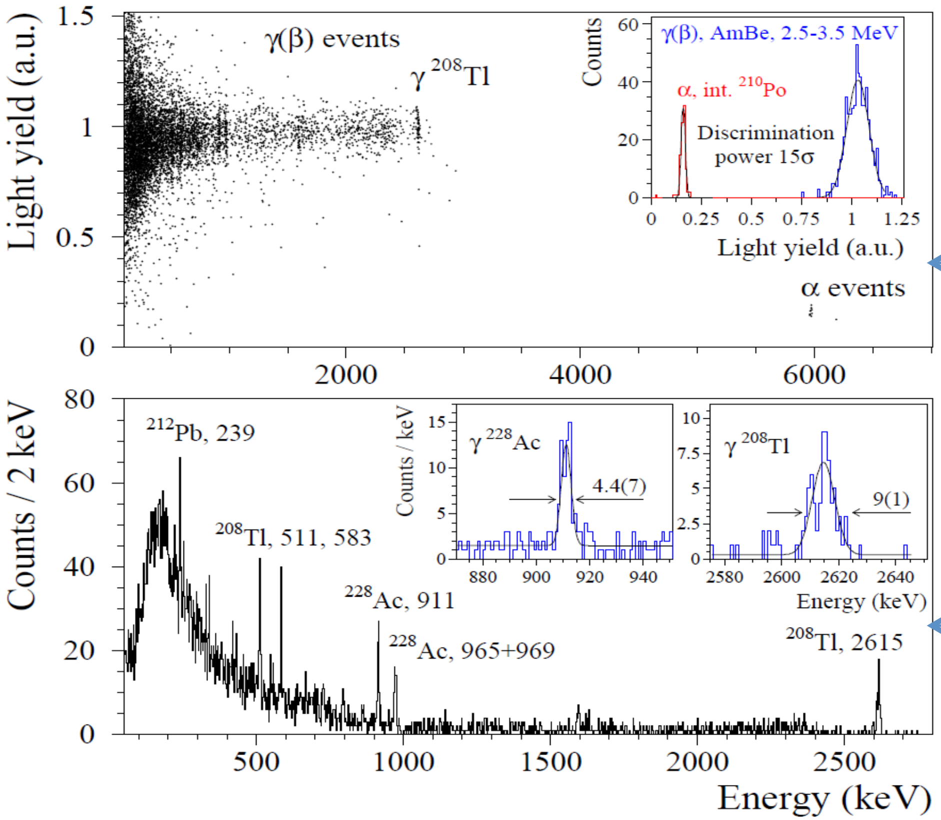
ANR

LUMINEU & LUCINEU

Scintillating bolometers with **$ZnMoO_4$ crystals** and simple pure **NTD light detectors**

Very promising results – mature technology (**LUMINEU, LUCIFER-ZMO** achievements)

High sensitive CUPID demonstrator with **7 kg of Mo** in preparation (**LUCINEU**)
(IN2P3-CEA-INFN-ITEP-KINR-Heidelberg) (in **LNGS** and **LSM**) (**$M_{\beta\beta}$ < 90 – 300 meV**)



334 g detector tested in Modane (in the EDELWEISS setup)

JINST 10 (2015) P05007

Excellent α/β separation

Satisfactory energy resolution

Excellent crystal radiopurity
< 4 μBq/kg in ^{228}Th
compatible with background index
< 0.3 counts/(keV ton y)

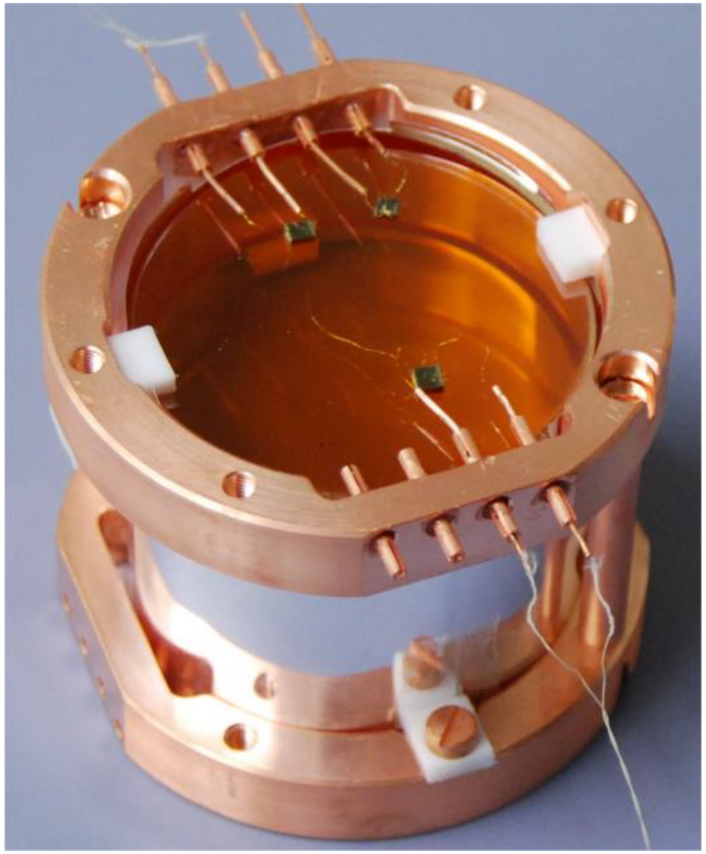
Advanced successful protocol for enrichment – purification – crystallization chain → < 4 % of irrecoverable losses of Mo

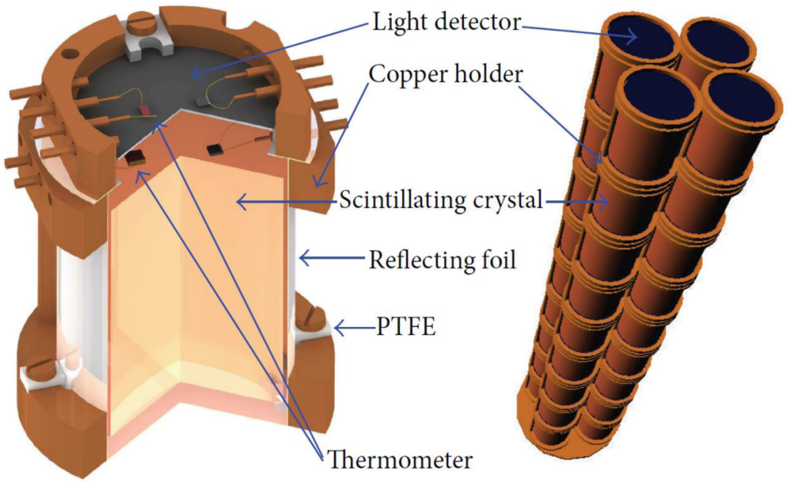
JINST 9 (2014) P06004

Eur. Phys. J. C74 (2014) 3133

LUCIFER

Scintillating bolometers with **ZnSe crystals** and simple pure **NTD light detectors**
Intense R&D for detector optimization – complicate crystallization technology
Technique now mature for **demonstrator experiment (LNGS)**
15 kg of chemically **pure ^{82}Se** (enriched in western Europe) available for crystals





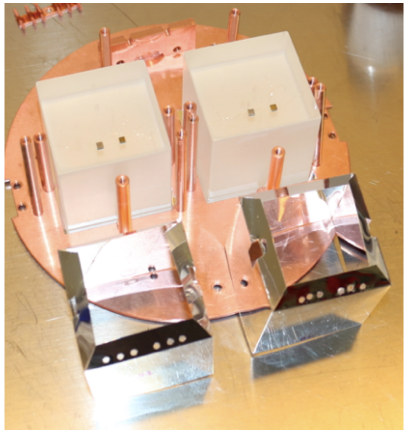
Array of 32 enriched (96%) $Zn^{82}Se$ crystals
Expected background index ~ 1-2 c/(keV ton y)
Energy resolution: ~ 10-20 keV FWHM
$M_{\beta\beta}$ < 100 – 300 meV

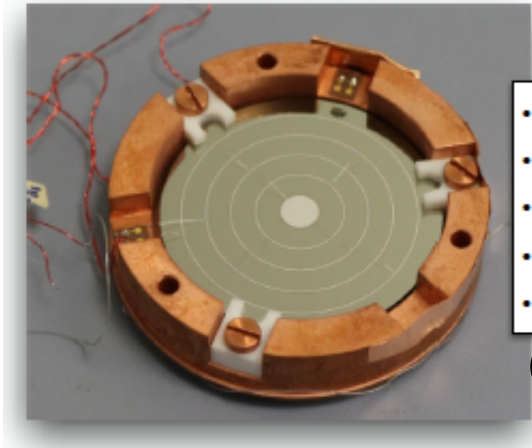
Adv. High En. Phys. 2013 (2013) ID 237973
JINST 8 (2013) P05021

TeO_2 Cherenkov light emission (1)

Cherenkov threshold	@ ^{130}Te $Q_{\beta\beta}$ (2.5 MeV)
$E_{e^-} > 50$ keV	~220 Cherenkov photons (300-900 nm) → 600 eV
$E_\alpha > 400$ MeV	No Cherenkov photons from natural radioactivity

Light detector produced at CSNSM (France)





- HP-Ge wafer (44 mm X 180 um)
- Al electrodes (EDELWEISS-like)
- IR LED faced to LD
- ^{55}Fe X-ray calib. source
- Thermal sensor: Ge-NTD

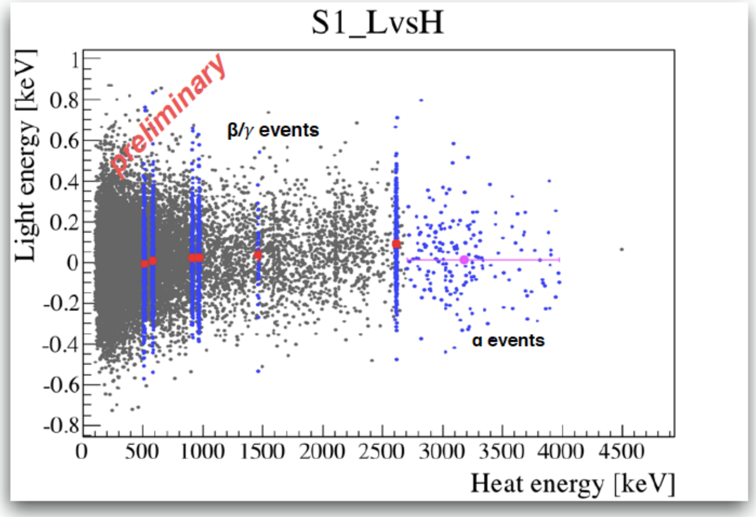
(Same sensor as in CUORE)

Luke amplification of the thermal signal: electron-hole pairs generated by Cherenkov light drift in the electric field and produce additional heat

Tested with a real size CUORE TeO_2 crystal: 5 x 5 x 5 cm^3

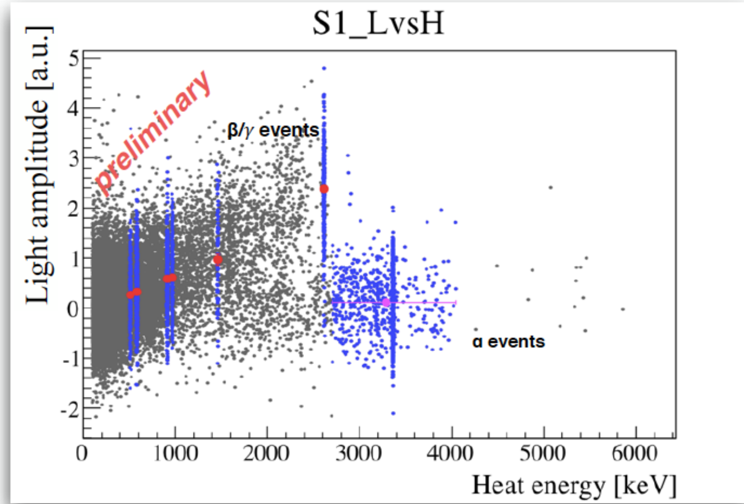
TeO_2 Cherenkov light emission (2)

V_{grid} OFF



GeLuke baseline σ: **0.48 mV**
Light @ 2615 keV: **0.24 mV**

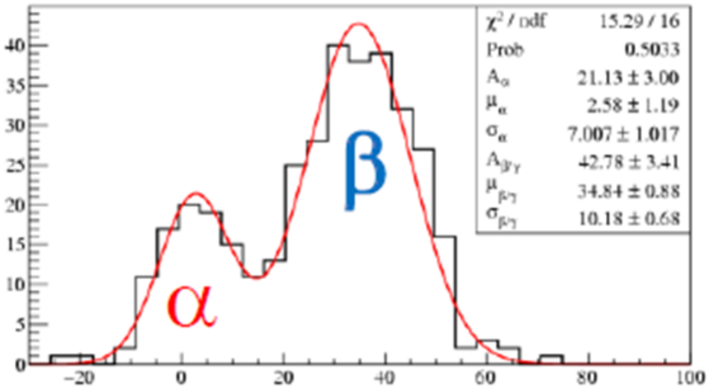
V_{grid} ON : 90 V



Gain = 1
S/N = 0.5

GeLuke baseline σ: **0.65 mV**
Light @ 2615 keV: **2.33 mV**

Baseline energy resolution
@ 0 V σ = 185 eV
@ 90 V σ = 19 eV



Discrimination power in the region of interest:

2.7 σ

http://arxiv.org/pdf/1510.03266v1.pdf

Conclusions

- TeO_2 bolometers are a well-established and competitive technique for the search of $0\nu\beta\beta$
- CUORE-0 has achieved its goals in terms of energy resolution and background level
- CUORE-0 data has significantly improved the limit set by Cuoricino, without any evidence of a $0\nu\beta\beta$ peak
- CUORE will be able to probe the region $m_{\beta\beta}$ ~ 50-130 meV
- CUORE data-taking beginning 2016
- CUPID, successor of CUORE, will be a one tonne experiment with particle identification ($m_{\beta\beta}$ ~ 6-15 meV)
- Extensive ongoing R&D for a down-selection
- STAY TUNED!!!