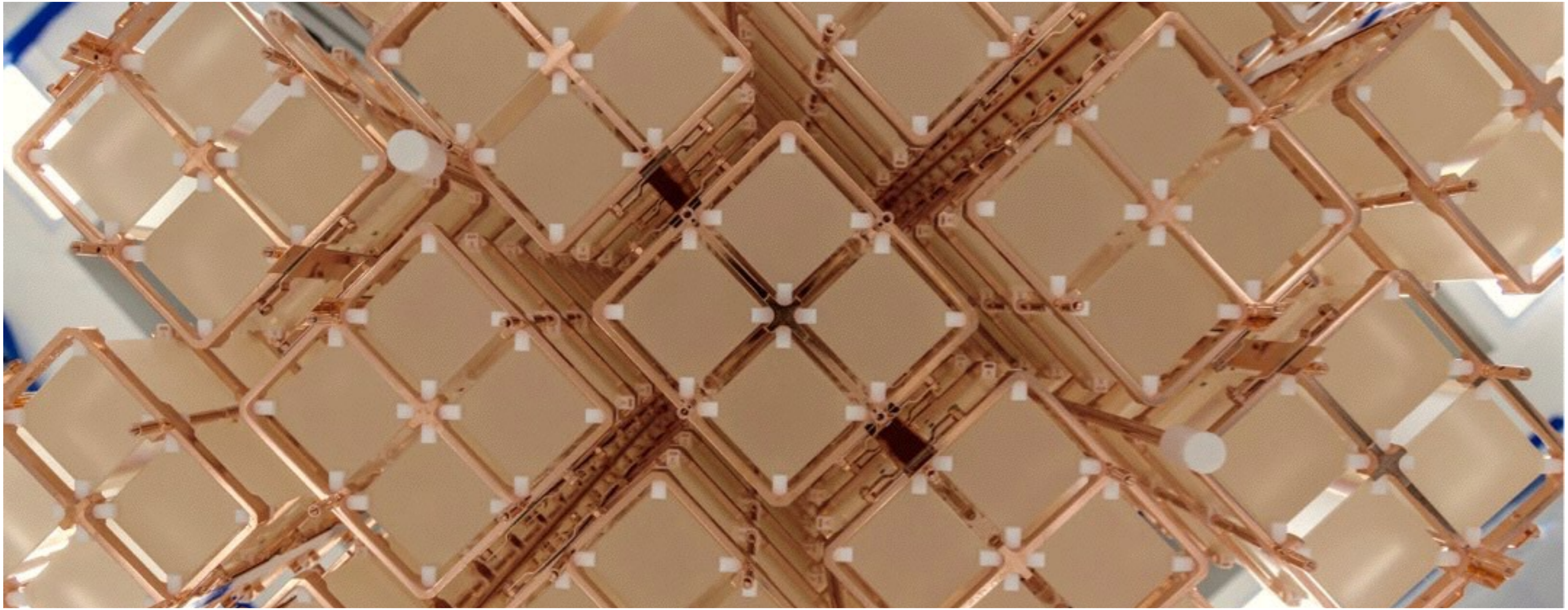


The science program of CUORE

Oliviero Cremonesi
INFN - Sez. Milano Bicocca
on behalf of the CUORE Collaboration

October 23, 2017 - CUORE inauguration, LNGS

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Milano Bicocca · Lawrence Livermore National Laboratory · Università di Padova · Massachusetts Institute of Technology · Virginia Tech Invent the Future® · INFN · Alma Mater Studiorum Bologna · Università degli Studi di Cassino e del Lazio Meridionale · Yale · Shanghai Jiao Tong University · Cal Poly San Luis Obispo · Berkeley Lab · University of South Carolina · Sapienza Università di Roma · UCLA · University of California

CUORE

Outline

- Neutrinoless double beta decay
- Why Tellurium?
- CUORE
- Conclusions

Acknowledgements

The experiment we are going to celebrate today would have not been possible without

- the support of the funding agencies
  - Istituto Nazionale di Fisica Nucleare (INFN)
  - National Science Foundation (NSF)
  - US Department of Energy (DOE)

- the contribution o all the institutions and private foundations

- the hospitality, availability and support of the directors and staff of
  - Laboratori Nazionali del Gran Sasso (LNGS)

Acknowledgements (2)

- the careful analysis of the scientific review committees
  - CUORE Review Committee (CRC)
  - INFN Commissione Scientifica 2 (CSN2)
  - LNGS Scientific committee (DOE)
- the professional work of many companies, large and small, near and far
- the help and understanding of the administrative offices
- the devotion and hard work of CUORE scientific and technical staff

CUORE MoU

Memorandum of Understanding (MOU)

for the Construction and Operation of the CUORE Experiment
between
the Istituto Nazionale di Fisica Nucleare, INFN, Italy and

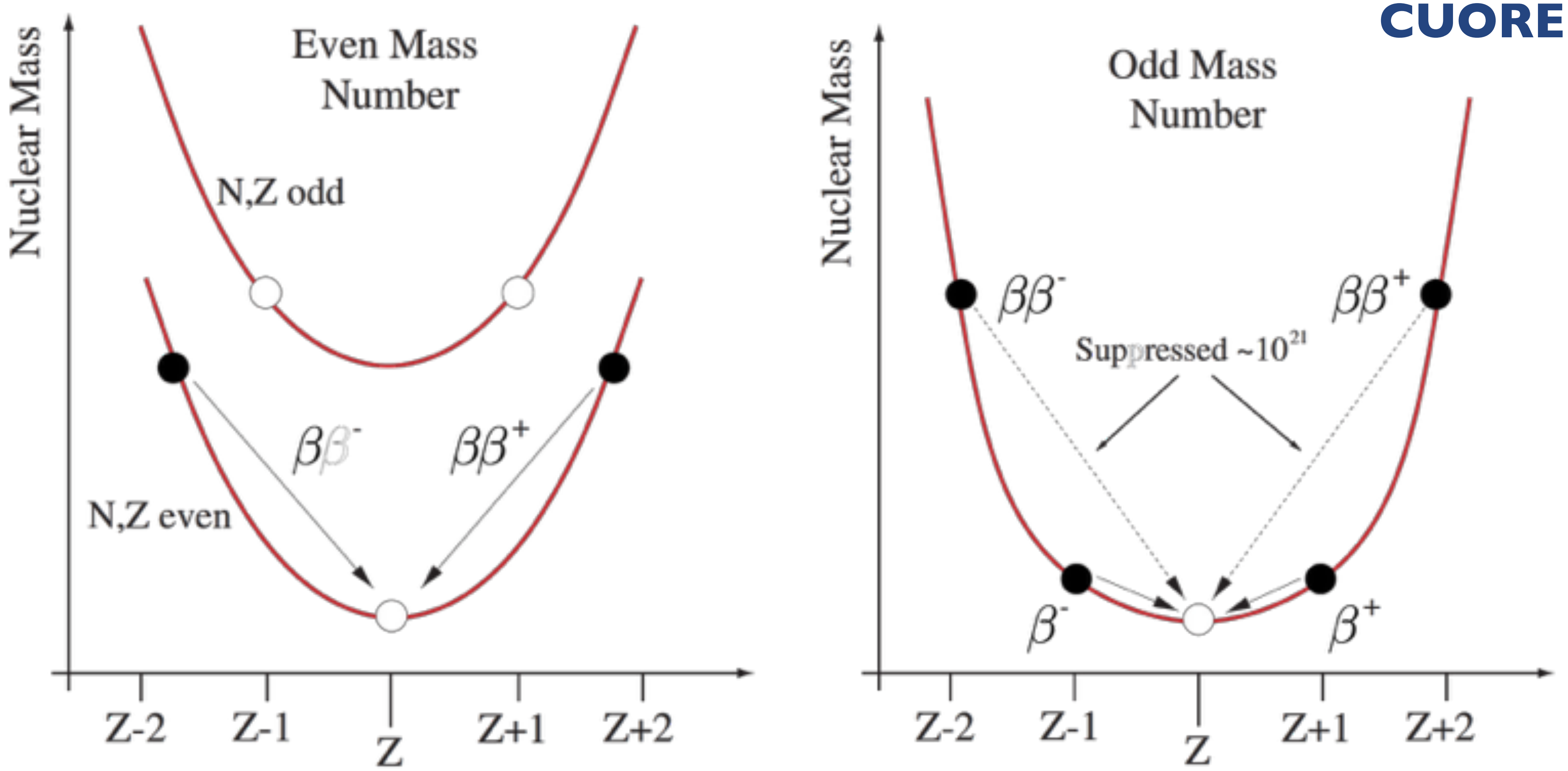
the University of California, UC, as the Management and Operating contractor for the Lawrence Berkeley National Laboratory, LBNL, USA

August 13, 2010

Article 1.2

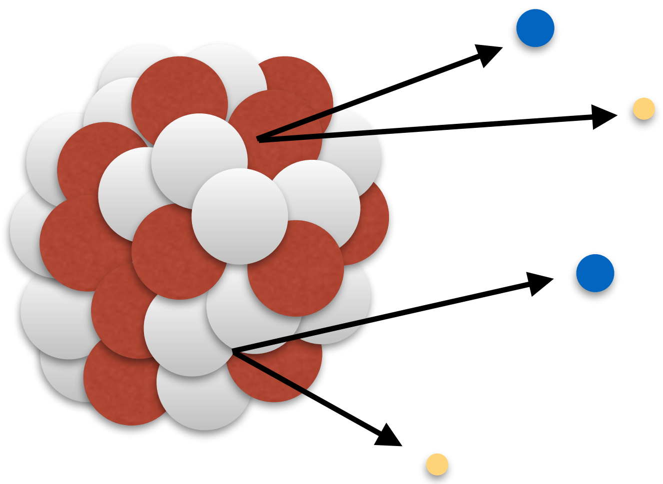
The aim of the CUORE experiment is to explore the nature of the neutrino by searching for neutrino-less double beta decay of ^{130}Te. CUORE is a bolometric detector consisting of crystals of TeO_2 operated at low temperature. The experiment will be deployed and operated in Hall A of the Gran Sasso National Laboratory (in the following "The Site"). It is expected that other studies will be possible once CUORE is in operation.

Double Beta Decay



1935 Maria Goeppert-Mayer anticipates double beta decay observing the trend of nuclear binding energies

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



The neutrino

1930 W.Pauli invents a new elusive particle to explain the observed features of nuclear beta decays in terms of the existing physics principles and avoid very exotic interpretations

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Physics Institute Zürich, Dec. 4, 1930
of the ETH Gloriastrasse
Zürich

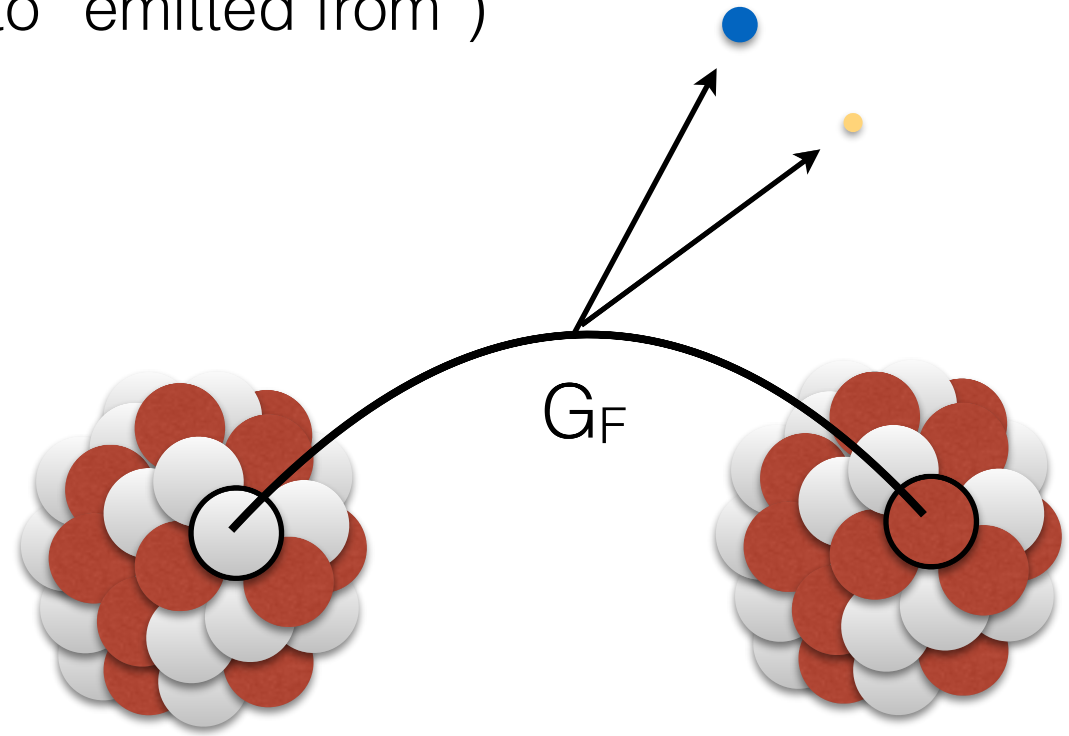
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Fermi's revolution

1934 E.Fermi completes his famous theory of Weak Interactions and names "neutrino" the particle of W.Pauli

- Electrons and neutrinos are created in nuclear beta decay (as contrasted to "emitted from")



- The probability of the processes mediated by the Weak Interaction can be eventually calculated
- It is really very low

A slightly different point of view

1937 Ettore Majorana introduces a symmetric description for particles (fermions) and anti-particles. Neutrino is immediately recognised as an important actor

1937 Giulio Racah understands that Majorana theory can give rise to new processes

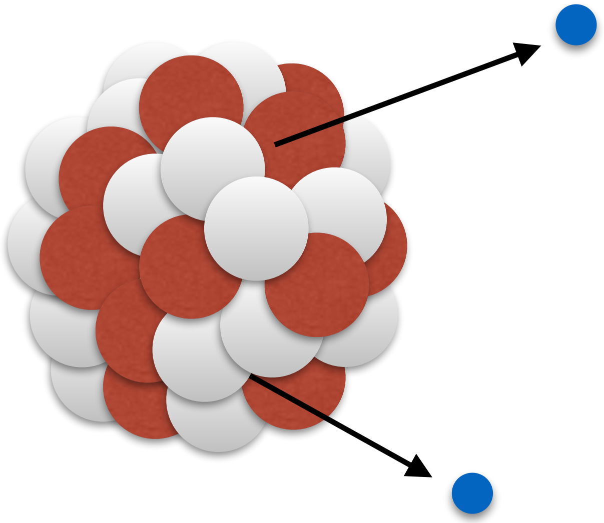
Nella seconda parte si considera l'ipotesi (che dovrà essere un giorno verificata sperimentalmente) che nel caso particolare dei neutrini non si abbia una semplice simmetria, ma addirittura una identità fisica tra neutrini ed antineutrini, e si mostra come questa ipotesi porti automaticamente al formalismo di E. MAJORANA [4]. Si rende così evidente il contenuto fisico assolutamente nuovo della teoria di E. MAJORANA, e si indica come l'esperienza potrà decidere della sua validità.

1939 Wendell H. Furry introduces neutrino-less double beta decay (ββ0ν)

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

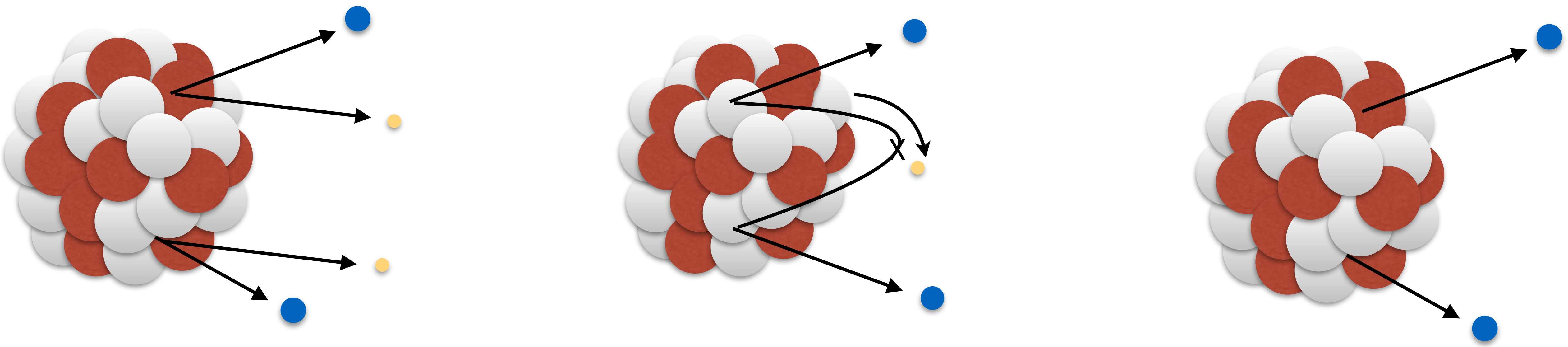
B=A, L=0 B=A, L=2

ββ0ν first of all violates lepton number



Neutrino mass mechanism

- Neutrino offers the most direct interpretation of neutrino less double beta decay

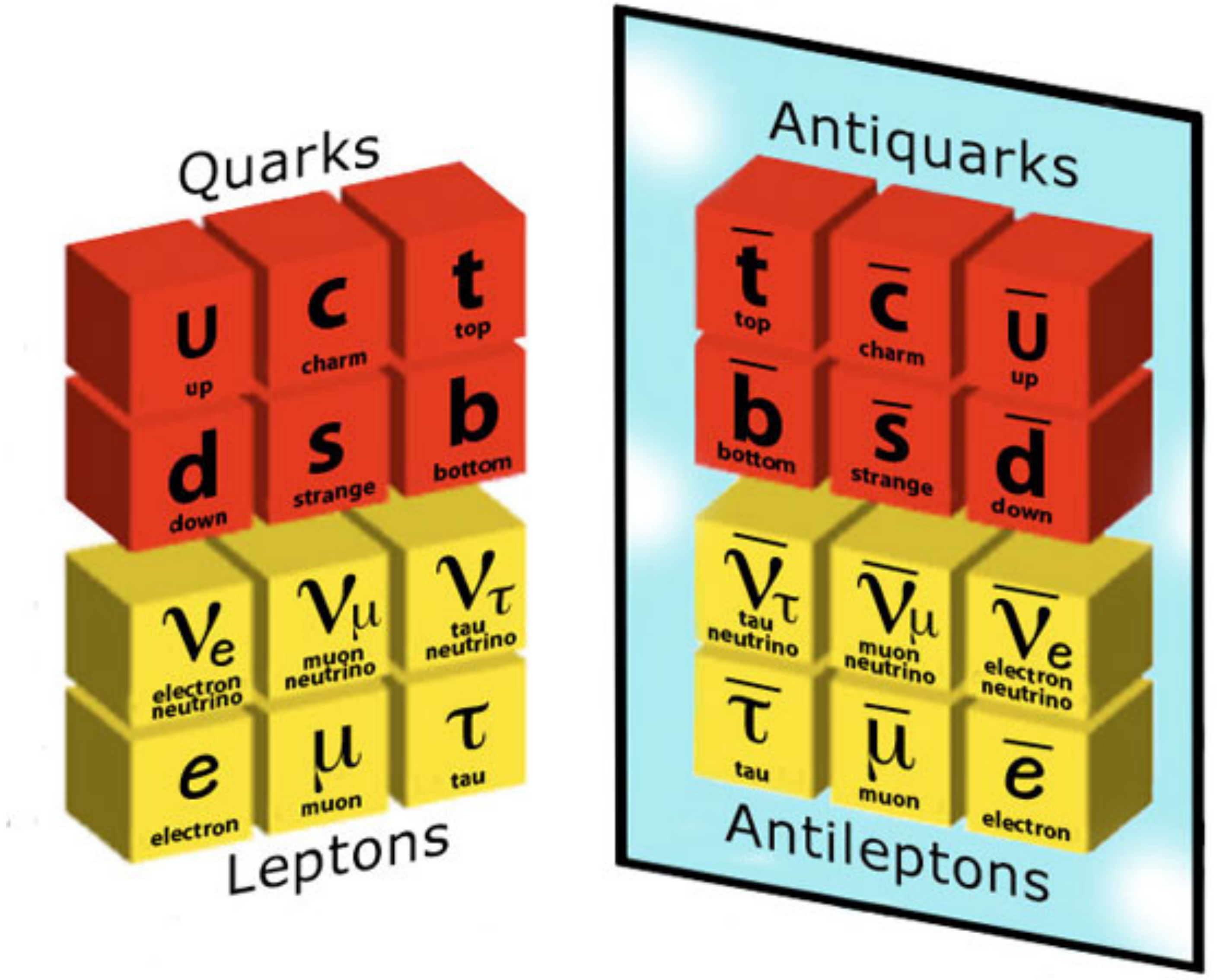


- In this process a neutrino is emitted at the first vertex but only an antineutrino can be absorbed at the second!
    - Neutrino = Anti-neutrino
    - Neutrino is a Majorana particle

→ Mechanisms to explain the cosmic asymmetry between matter and anti-matter are possible

Nowadays

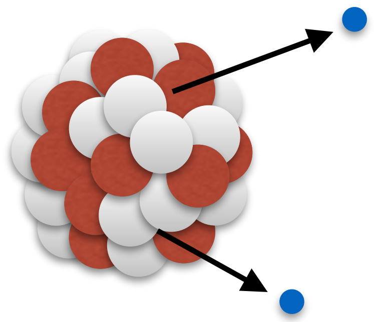
Standard Model (SM) is the best theory of matter we have



- Few particles can explain all observed processes
- Neutrinos look different from other fundamental particles

Standard Model

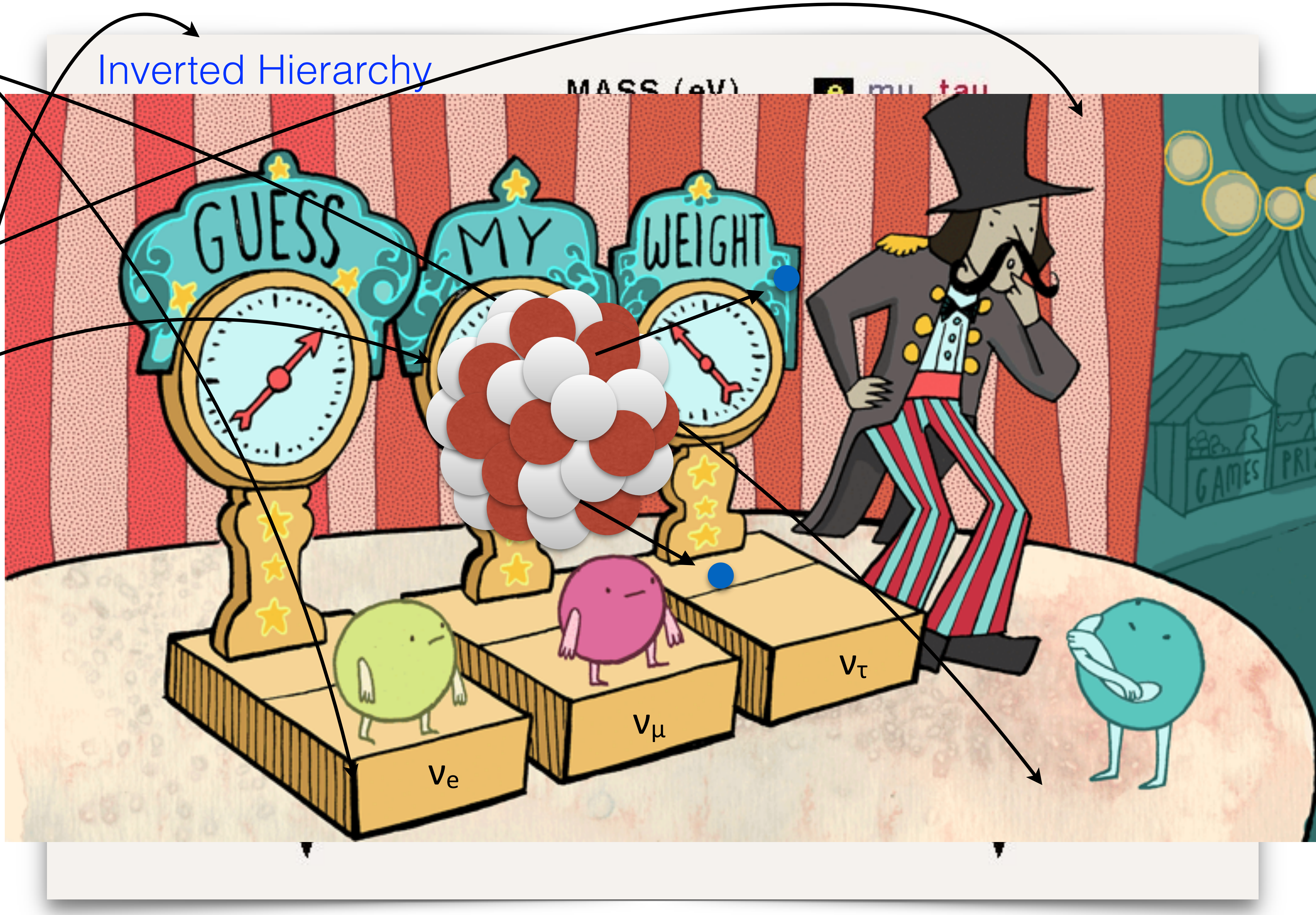
- neutrino masses are zero [FALSE]
- B-L , L_e-L_μ , L_e-L_τ , L_τ-L_μ are exactly conserved;
- B , L , L_e , L_μ , L_τ only perturbatively [MOSTLY FALSE]
- matter ≠ antimatter, neutrinos included [UNCERTAIN]
- (no explanation of cosmic matter unbalance)



ββ0ν: a unique opportunity to solve an 80 year old mystery

The neutrino open questions

- **What is the absolute neutrino mass scale?**
  - Is the lightest ν massless? Hierarchical or degenerate?
- **What is the neutrino mass ordering?**
  - Normal ($m1<m2 \ll m3$) or inverted ($m3 \ll m1 <m2$)?
- **Are neutrinos Dirac or Majorana particles?**
  - Lepton number violation, neutrinoless double beta decays
- What is the origin of neutrino masses and flavor mixing?
  - See saw mechanisms, flavor symmetries, ...
- Is there CP violation in the lepton sector?
  - What is the value of the Dirac CP-violating phase δ?



ββ0ν and the neutrino

- Neutrinos are important probes of the Standard Model

- ββ0ν observation would imply that:
  - lepton number L is violated (by two units)
  - neutrinos and antineutrinos are different states of the same particle (Majorana particle)

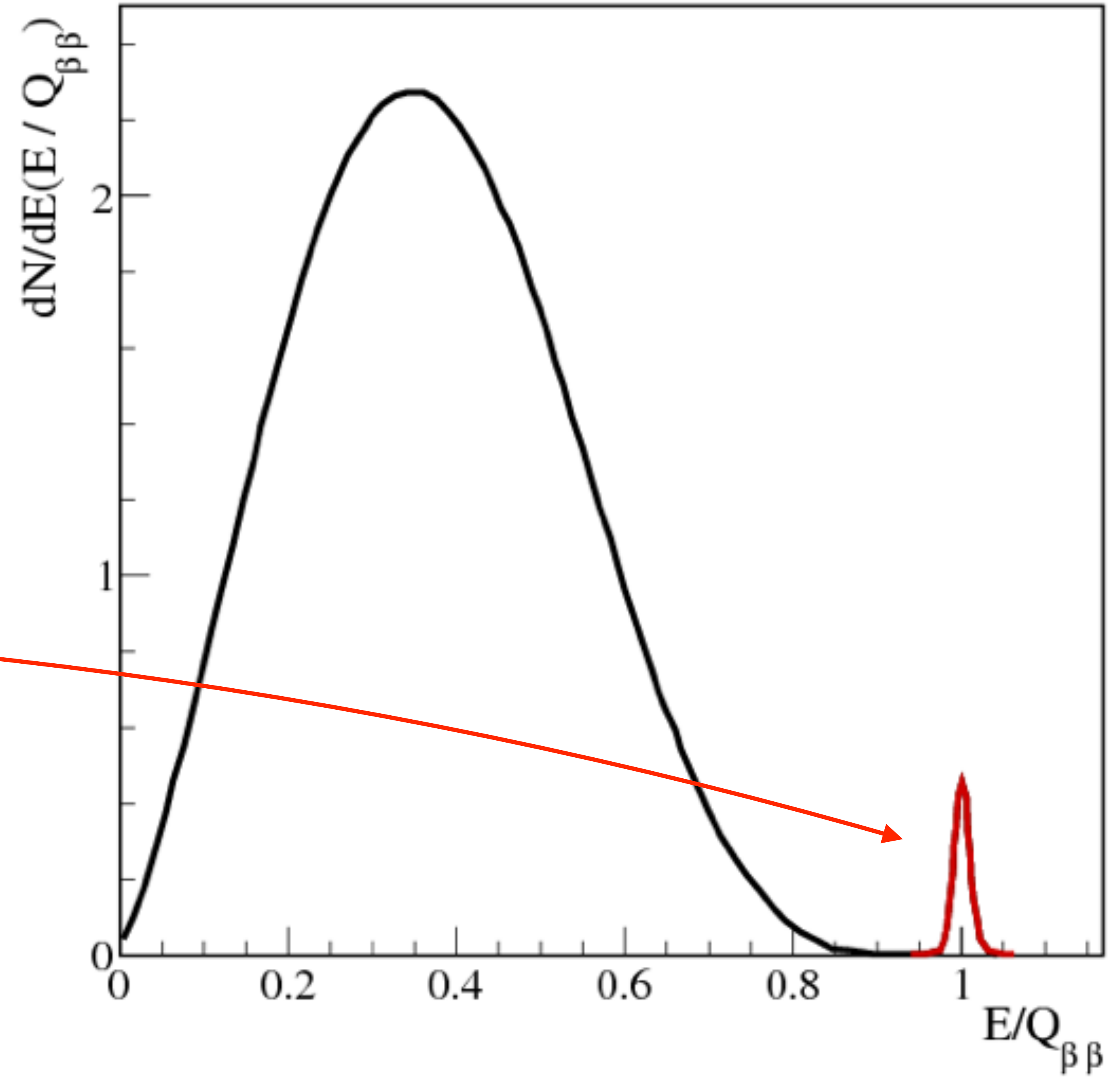
  - and moreover that:
    - neutrinos are massive particles (this actually is already known!)
    - neutrino masses are measurable
    - new mechanisms for CP violations are possible
    - explanations of the cosmic asymmetry between matter and antimatter exist (leptogenesis)

The experimental search

- A very complex interpretation for a quite simple reaction

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

- Few actors: a recoiling nucleus and two freshly produced electrons
- A quite simple signature: the two electrons carry always the same energy
  → a sharp peaks in the sum spectrum of the electron energies



Additional signatures:
- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

ββ0ν sensitivity master formula

CUORE

The sensitivity (minimum observable activity) of an experiment like CUORE can be derived under very simple assumptions

$$S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

where:

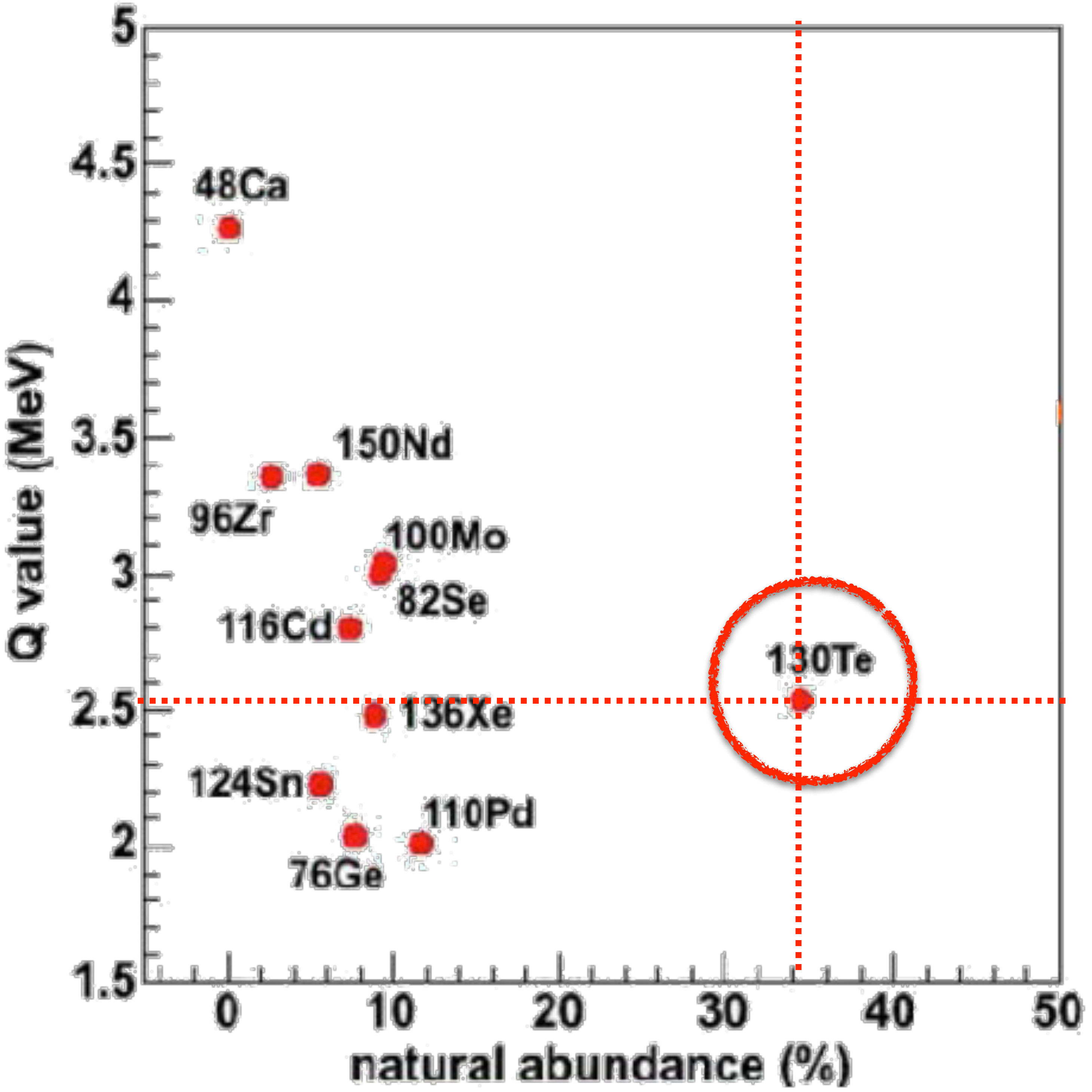
N_{nuclei} number of active nuclei in the experiment
t_{meas} measuring time [y]
M detector mass [kg]
ε detector efficiency
i.a. isotopic abundance
A atomic number
ΔE energy resolution [keV]
bkg background [c/keV/y/kg]

Despite its simplicity this formula outlines the dependence of the sensitivity on the critical experimental parameters:

- **Isotope properties**
- **Detection efficiency**
- **Mass**
- **Energy resolution**
- **Background**
- **Measure Time**

Why Tellurium?

Isotope	i.a.(%)	Q [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.1	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371



Lifetime achievement award

- In the ’60’s Ettore Fiorini understands the importance of the homogeneous approach to increase the efficiency ε

- Almost exactly 50 years have passed since the first experiment on ^{76}Ge

Volume 25B, number 10 PHYSICS LETTERS 27 November 1967

A SEARCH FOR LEPTON NON-CONSERVATION IN DOUBLE BETA DECAY WITH A GERMANIUM DETECTOR

E. FIORINI and A. PULLIA
Istituto di Fisica dell'Università and INFN, Milano, Italy

G. BERTOLINI, F. CAPPELLANI and G. RESTELLI
Euratom, CCR, Ispra, Italy

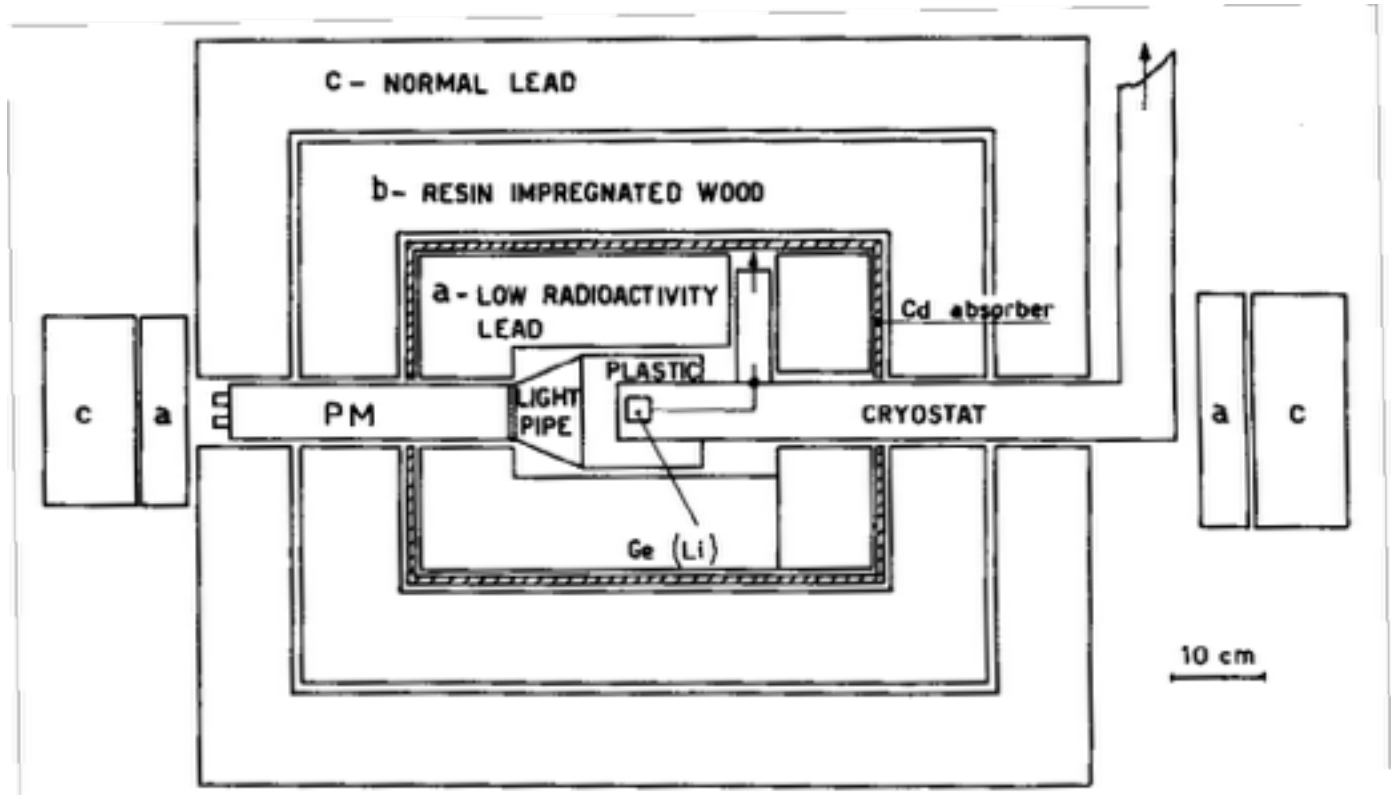


Fig. 1. Experimental setup.

Direct searches in Tellurium become a reality

CUORE

- In 1984 E.Fiorini and T.Niinikoski propose the use of low temperature detectors for rare event searches
- This opens completely new perspectives in the field since any constraint on the choice of the element of interest seems to vanish
- In principle any ββ0ν decaying isotope can be studied with this technique

Nuclear Instruments and Methods in Physics Research 224 (1984) 83–88
North-Holland, Amsterdam

LOW-TEMPERATURE CALORIMETRY FOR RARE DECAYS

E. FIORINI

Dipartimento di Fisica dell'Università and INFN, Milano, Italy

T.O. NIINIKOSKI

CERN, Geneva, Switzerland

Received 27 December 1983

The recent developments in underground low-counting experiments give limits to rare decays which are hard to improve since scaling the size and the resolution of the combined source–detector is difficult with the existing techniques. We explore here the possibility of low-temperature calorimetry to improve the limits on processes such as neutrinoless double-beta decay and electron decay.

- Later in th 80's, Giorgio Benedek suggests the use of TeO_2
- The adventure begins ….

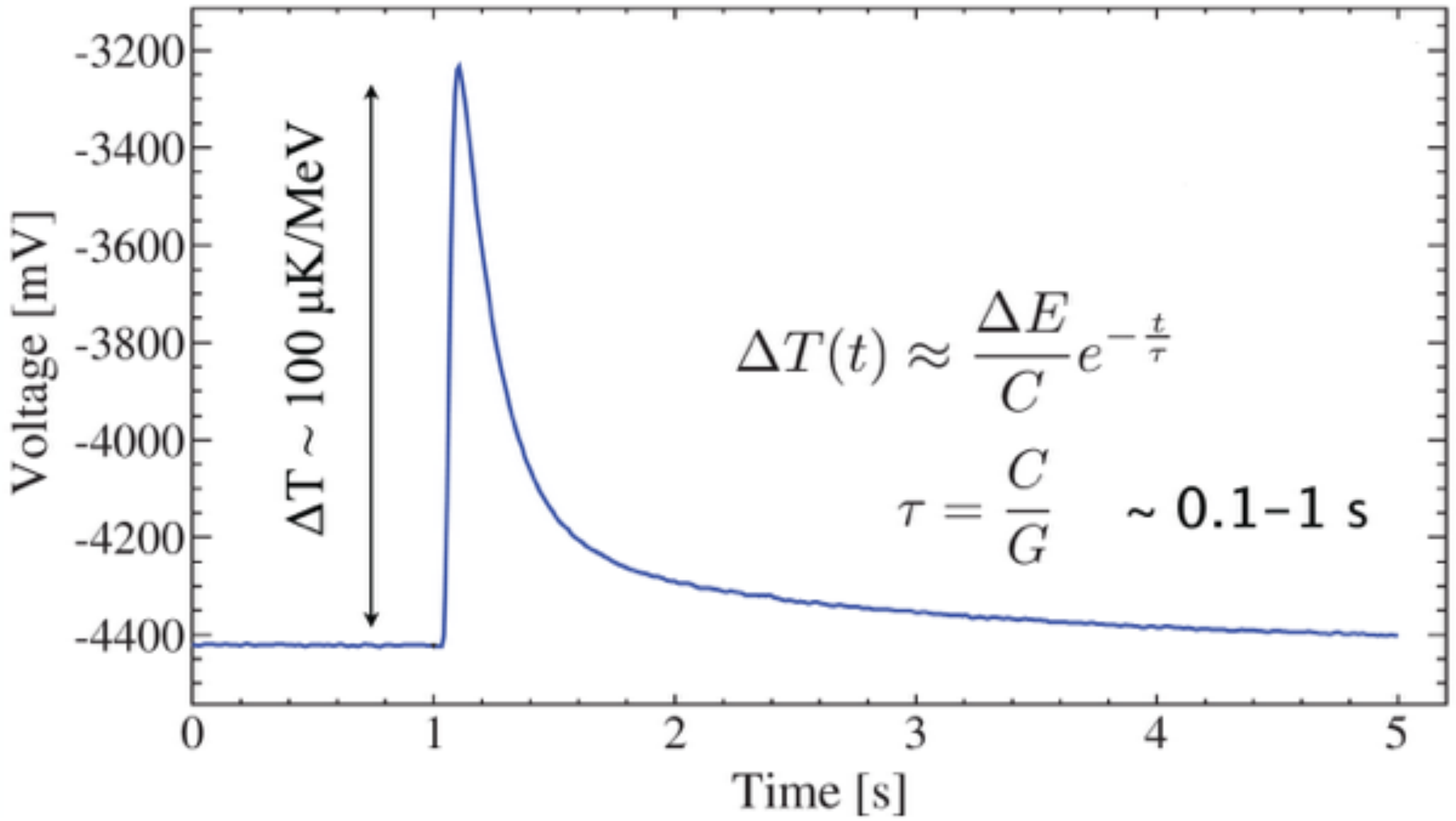
The CUORE detectors

Large array of thermal detectors

- low heat capacity @ T_{work} ($C \sim T^3$)
- excellent energy resolution (~0.2% FWHM)
- same detector response for different particles
- slowness (suitable for rare event searches)

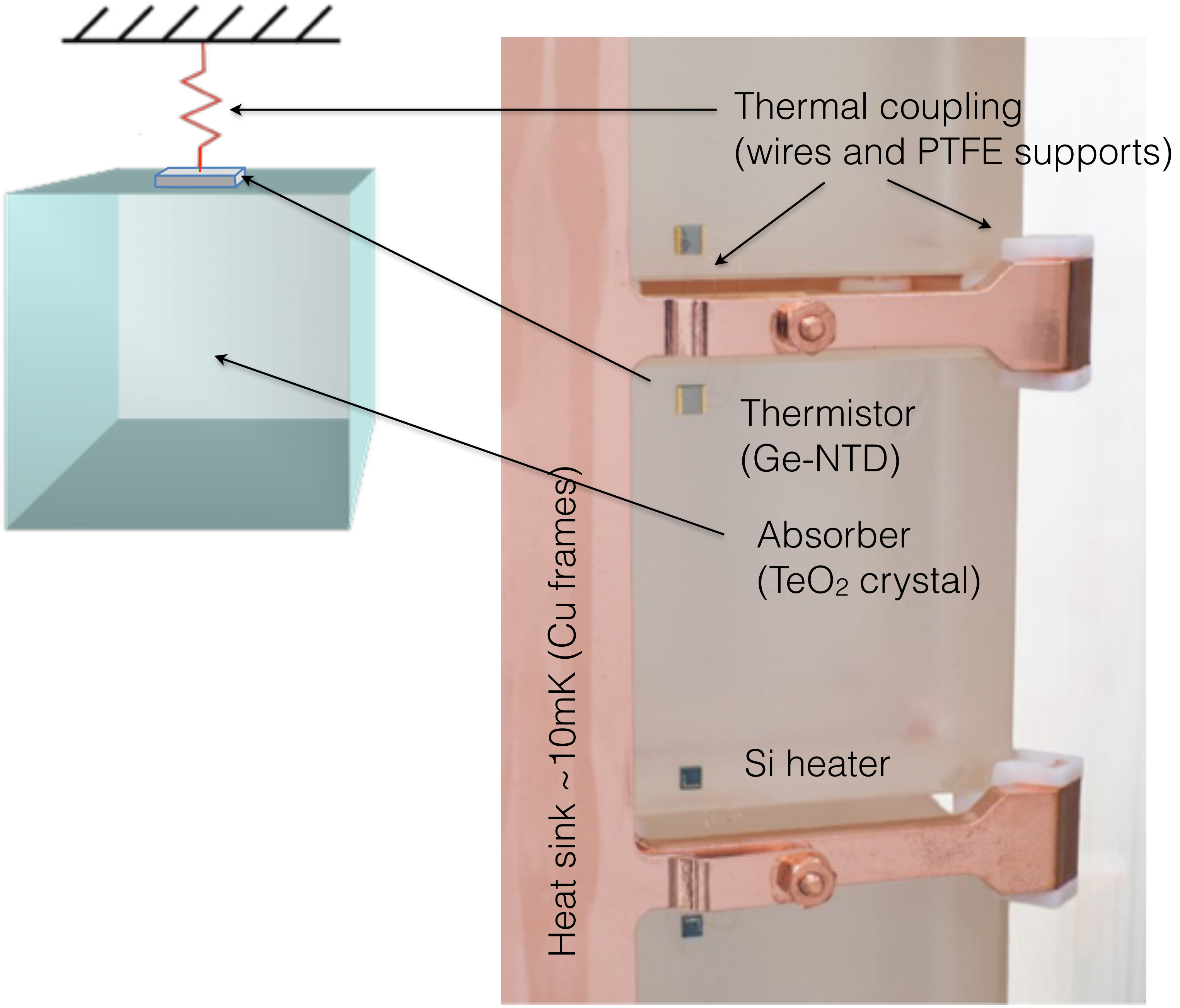
The concept: a pure calorimeter

The absorbed energy is converted into a variation of the crystal temperature, measured by the thermistor



$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G} \quad \sim 0.1\text{–}1\text{ s}$$



CUORE

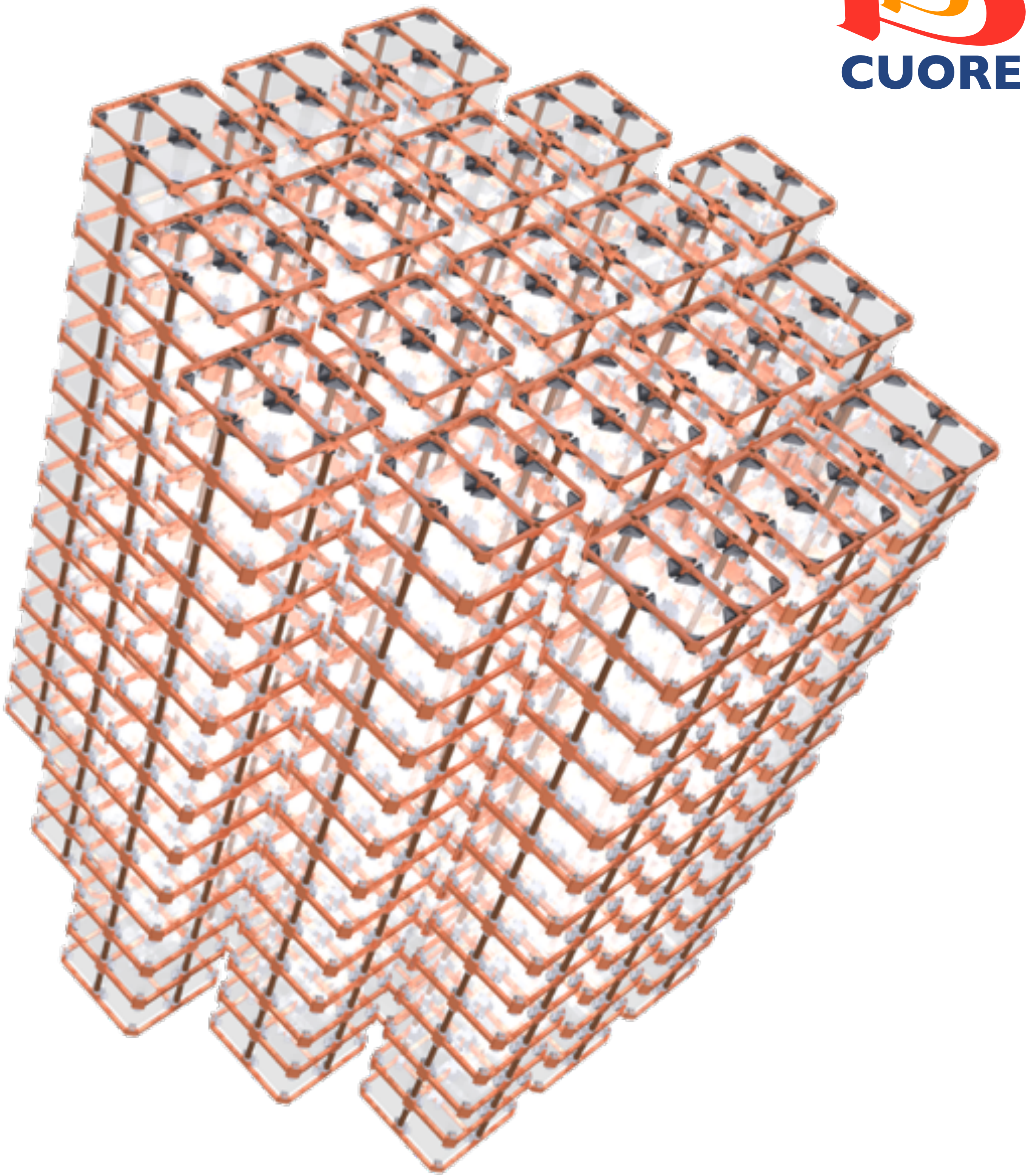
(Cryogenic Underground Observatory for Rare Events)

Primary goal: search for ββ0ν decay in ^{130}Te

- 988 TeO_2 crystals
- 19 towers

CUORE design parameters:

- mass of TeO_2: **742 kg** (206 kg of ^{130}Te)
- low background aim: **10^{-2} c/(keV·kg·yr)**
- energy resolution: **5 keV** FWHM in the Region Of Interest (ROI)
- high granularity
- deep underground location
- strict radio-purity controls on materials and assembly



CUORE projected sensitivity (5 years, 90% C.L.):

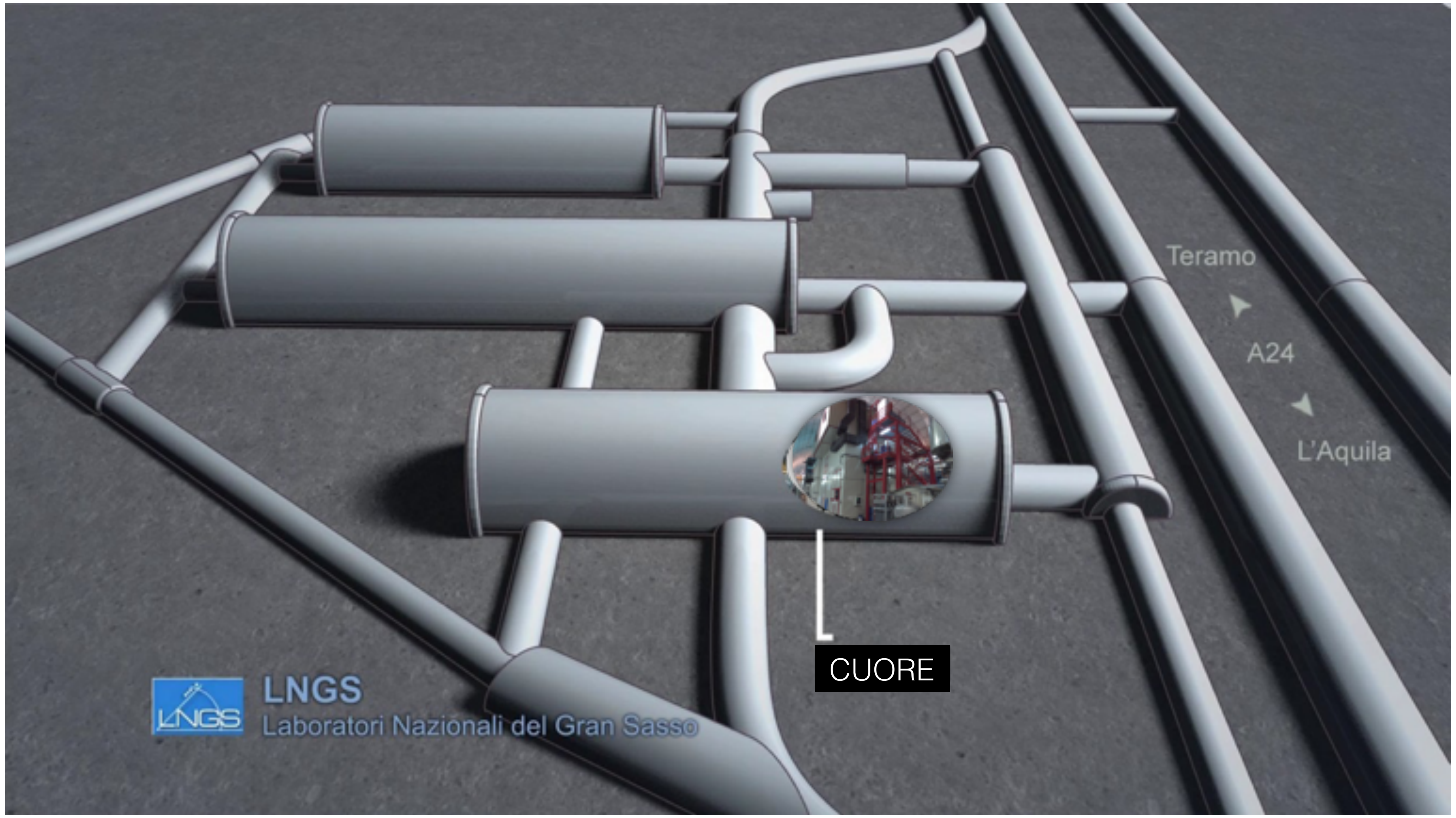
$$T_{1/2} > 9 \times 10^{25}\ yr$$

CUORE @ LNGS

1400 m of rock (~3600 m.w.e.) deep

- μ's: ~3 × 10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4 × 10^{-6} n/(s·cm^2) below 10 MeV

CUORE @ LNGS

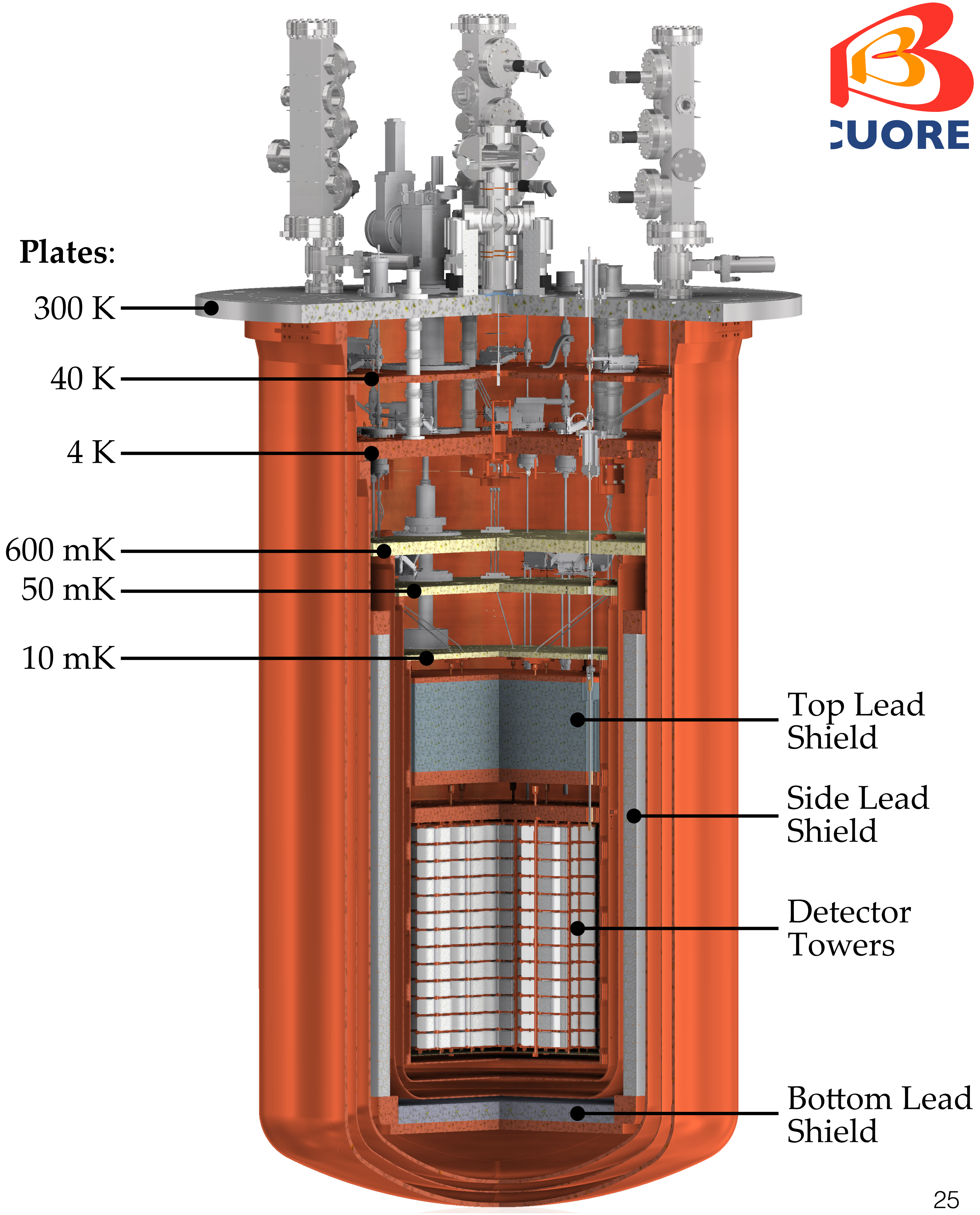

Teramo
A24
L'Aquila
CUORE
LNGS
Laboratori Nazionali del Gran Sasso

Underground lab

- Three-story building
  - Ground floor: service area
  - First floor: clean room & cryostat
  - Second floor: Readout systems

The CUORE cryostat

- Designed to cool down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- Low background environment

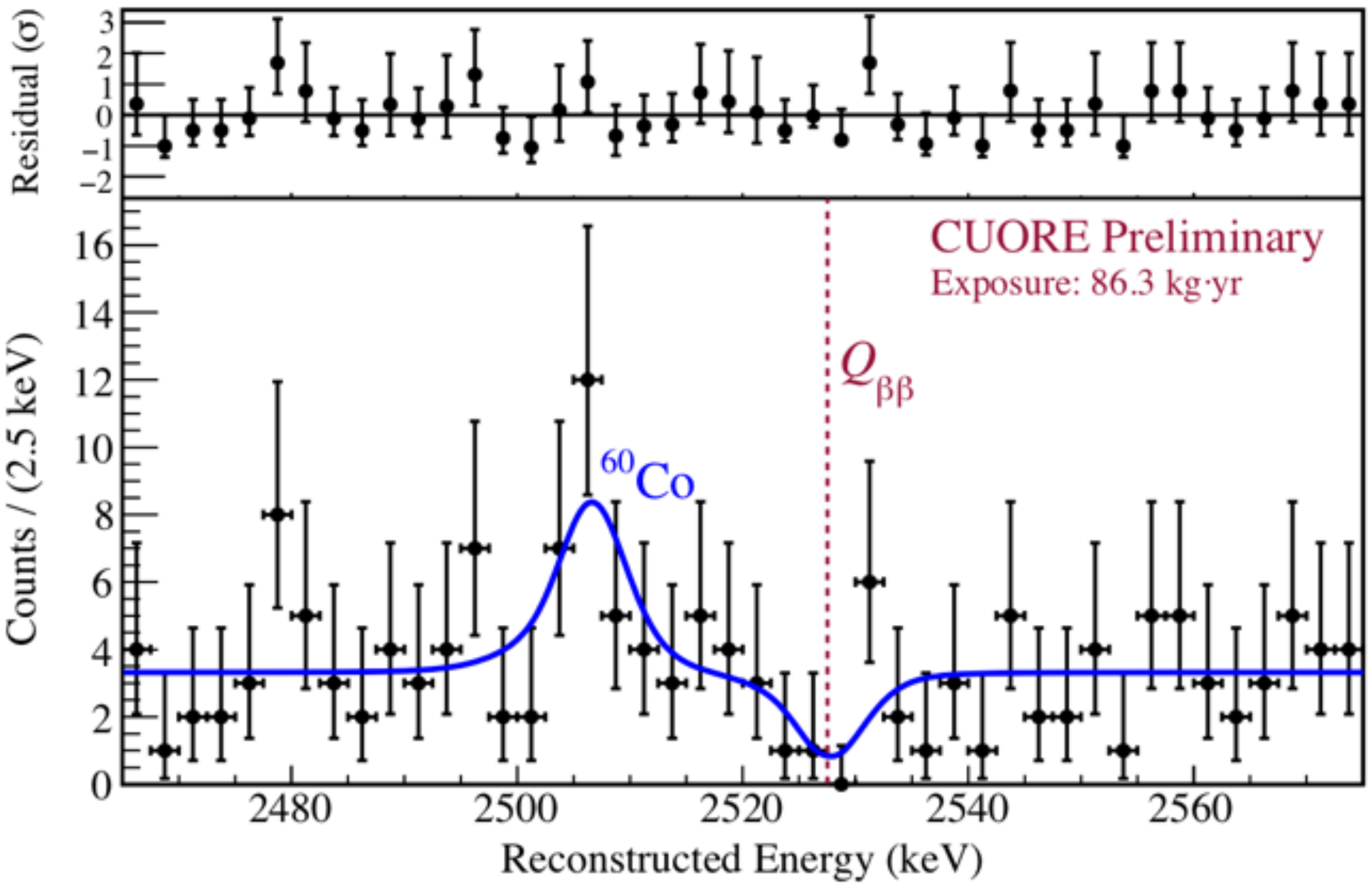


CUORE operation and present results

- CUORE has started taking data in April 2017
- System performance is excellent and preludes to a long and stable operation
- Performance parameter are consistent with design parameters

- Seven weeks of useful physics data have been so far collected
- No evidence for ββ0ν of ^{130}Te has been observed
- The corresponding limit on the ^{130}Te ββ0ν half-lifetime already surpasses the results of its predecessors (CUORE-0 and Cuoricino) which were operated for years:

$$T_{1/2} > 1.3 \times 10^{25}\ \text{yr}$$



Results & perspectives

- Combining CUORE result with the existing ^{130}Te
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0

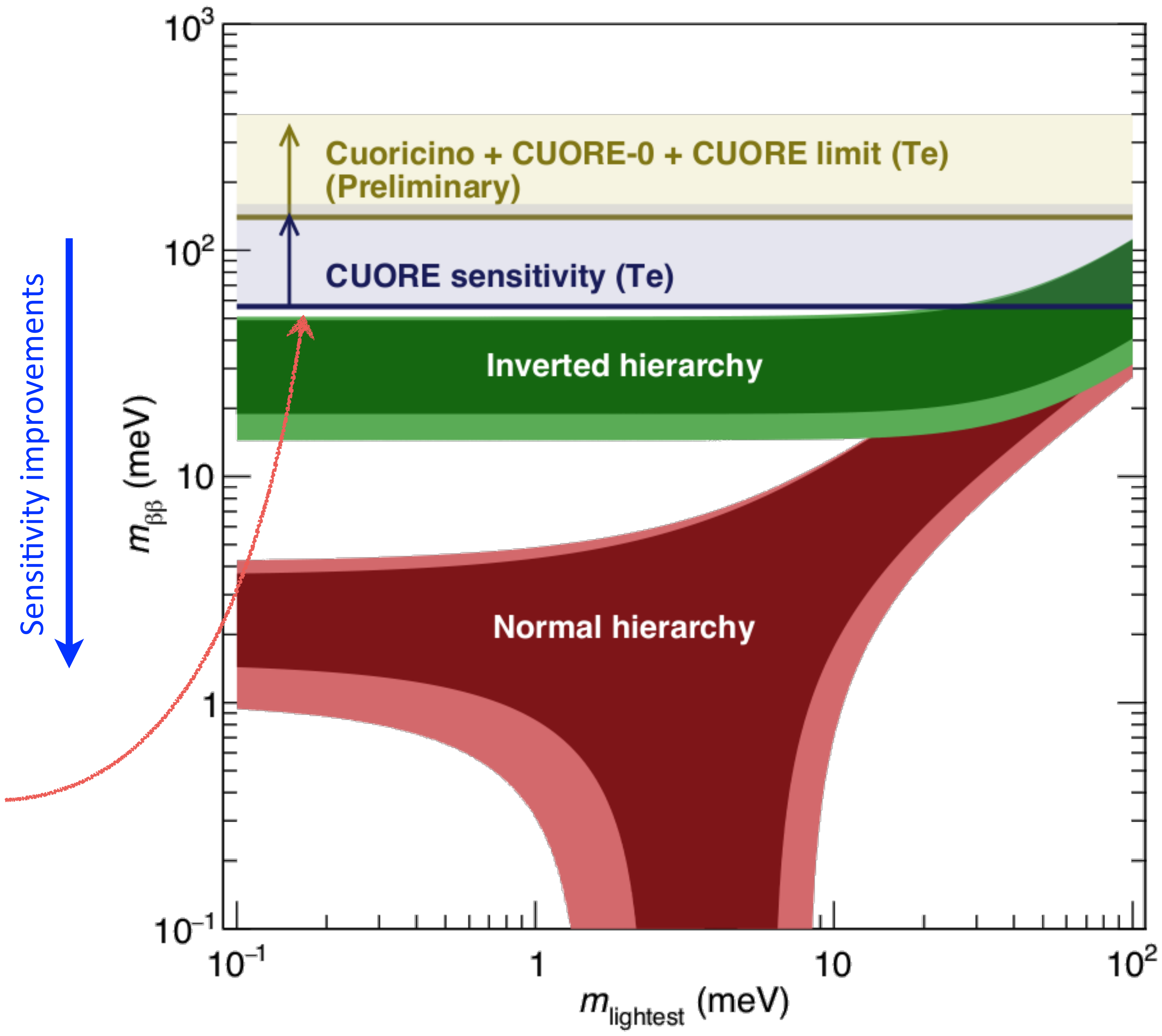
we get a 90% C.L. limit

$T_{0\nu} > 1.5 \times 10^{25}$ yr

corresponding to

$m_{\beta\beta} <$ 140 – 400 meV

- **The estimated in 5 years of data taking make CUORE the most sensitive experiment for the search of $\beta\beta0\nu$ of ^{130}Te**



Other BDB studies

Tellurium has three isotopes of interest for double beta decay

^{130}Te	$\beta^-\beta^-$	34.08%	2527.51
^{120}Te	β^+/EC,EC/EC	0.09%	1714.81
^{128}Te	$\beta^-\beta^-$	31.74%	865.87

We have so far considered only transitions to the ground state of the daughter nucleus but transitions to excited states are equally important and can provide unique informations

The relevance of these studies has already been demonstrated in Cuoricino and CUORE-0, but the experimental sensitivity can be enormously amplified by exploiting the huge mass of CUORE

Other physics studies

The increased mass of the detector opens new horizons for the study of a number of physics processes

- supernovae neutrinos
- dark matter candidates
- exotic processes (electron stability, CPT/Lorentz invariance, …)

Preliminary studies carried out with CUORE-0 can become competitive measurements with CUORE

Conclusions

- CUORE is the first ton-scale cryogenic detector array in operation, more than an order 440 of magnitude larger than its predecessors

- The successful commissioning and operation of this large-mass, low-background cryogenic bolometer array represents a major advancement in the application of this technique to $\beta\beta0\nu$ decay searches and demonstrates the feasibility of future large-mass bolometer arrays for rare-event searches.

- Thanks to the increased mass of the detector a number of physics processes can be studied with a high precision

Experiment Provides Deeper Look into the Nature of Neutrinos

23 October 2017 - Lawrence Berkeley National Laboratory

CUORE expected to reveal – or rule out – a possible explanation for why the universe favors matter over antimatter

The first glimpse of data from the full array of a deeply chilled particle detector operating beneath a mountain in Italy sets the most precise limits yet on where scientists might find a theorized process to help explain why there is more matter than antimatter in the universe.

This new result, submitted today to the journal *Physical Review Letters*, is based on two months of data collected from the full detector of the CUORE (Cryogenic Underground Observatory for Rare Events) experiment at the Italian National Institute for Nuclear Physics' (INFN's) Gran Sasso National Laboratories (LNGS) in Italy. CUORE means "heart" in Italian.

The Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) leads the U.S. nuclear physics effort for the international CUORE collaboration, which has about 150 members from 25 institutions.

CUORE is considered one of the most promising efforts to determine whether tiny elementary particles called neutrinos, which interact only rarely with matter, are "Majorana particles" – identical to their own antiparticles. Most other particles are known to have antiparticles that have the same mass but a different charge, for example. CUORE could also help us home in on the exact masses of the three types, or "flavors," of neutrinos – neutrinos have the unusual ability to morph into different forms.

"This is the first preview of what an instrument this size is able to do," said Oliviero Cremonesi, a senior faculty scientist at INFN and spokesperson for the CUORE collaboration. Already, the full detector array's sensitivity has exceeded the precision of the measurements reported in April 2015 after a successful two-year test run that enlisted one detector tower. Over the next five years CUORE will collect about 100 times more data.

DATE ISSUED:

October 23rd, 2017

SOURCE:

Lawrence Berkeley National Laboratory

CONTENT:

Press Release

CONTACT:

Glenn Roberts Jr.,
Public Affairs, Lawrence Berkeley National Laboratory
geroberts@lbl.gov
http://newscenter.lbl.gov/

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SI INAUGURA CUORE: IL GIGANTE FREDDO CHE STUDIA NEUTRINI

Pubblicato: 23 Ottobre 2017

Si inaugura oggi, 23 ottobre, ai Laboratori Nazionali del Gran Sasso (LNGS) dell'INFN l'esperimento CUORE (Cryogenic Underground Observatory for Rare Events), il più grande rivelatore criogenico mai costruito, concepito per studiare le proprietà dei neutrini. Nei primi due mesi di presa dati, l'esperimento ha funzionato con una precisione straordinaria, soddisfacendo pienamente le aspettative dei fisici che lo hanno realizzato. Grazie alla notevole precisione raggiunta in questa prima fase, CUORE è già riuscito a restringere significativamente la regione in cui cercare il rarissimo fenomeno del doppio decadimento beta senza emissione di neutrini, principale obiettivo scientifico dell'esperimento. Rivelare questo processo consentirebbe non solo di determinare la massa dei neutrini, ma anche di dimostrare la loro eventuale natura di particelle di Majorana, fornendo una possibile spiegazione alla prevalenza della materia sull'antimateria nell'universo.

"Questa è solo l'anteprima di ciò che uno strumento di queste dimensioni è in grado di fare" commenta Oliviero Cremonesi, ricercatore INFN e responsabile scientifico dell'esperimento CUORE. "Abbiamo grandi aspettative per il futuro. Nei prossimi cinque anni, infatti, CUORE registrerà una quantità di dati 100 volte superiore a quelli acquisiti in questo primo periodo di attività" conclude Cremonesi.

"CUORE ha rappresentato un'incredibile sfida tecnologica il cui successo apre la strada a sviluppi impensati fino a pochi anni fa" dichiara Carlo Bucci, responsabile nazionale INFN e coordinatore tecnico dell'esperimento CUORE. "Grazie alle sue eccezionali

The CUORE Collaboration

CUORE

UCLA

Yale

INFN LNGS

Berkeley Lab

Cal Poly San Luis Obispo

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