The CUORE experiment for 0vββ research: status and perspectives



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Rencontres du Vietnam

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## Outline



- Brief introduction to  $0\nu\beta\beta$
- Experimental strategies
- Bolometric technique
- $0\nu\beta\beta$  with TeO<sub>2</sub> bolometers
- Cuoricino result
- CUORE project and status
- The background issue
- First CUORE phase: CUORE-0
- Conclusions

## Ονββ



- Channel for  $\beta\beta$  decay forbidden by SM ( $\Delta$ L=2)
- Extremely rare process (T<sub>1/2</sub> > 10<sup>22</sup> 10<sup>24</sup> y)
- Never observed (but Ge<sup>76</sup> claim<sup>[1]</sup>)
- It's observation would prove v Majorana nature





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### **Experimental search**



Main signature: 0vββ exhibits a peak at Q over 2vββ tail enlarged only by detector resolution



Defining the **experimental sensitivity S**<sup>ov</sup> as the lifetime corresponding to the minimum detectable number of events over background at a given C.L.

- M: total active mass
- $\epsilon$ : detector efficiency
- a.i.: isotopic abundance
- **b**: background in c/keV/kg/y
- $\Delta E$ : detector resolution @ ROI
- T: total live time

$$S^{0\nu} \propto \frac{\epsilon a.i.}{A} \left( \frac{MT}{b\Delta E} \right)^{1/2} b \neq 0$$

Qualitative expression in the Gaussian approximation (not fully accurate for very low background experiments)

#### $0\nu\beta\beta$ status of the art





## **Experimental Strategies**



#### Additional signatures can be looked for:

Single electron energy spectrum Angular correlation between the two electrons Track and event topology Time Of Flight Daughter nuclear specie

**Two** main approaches: **calorimetric** (source ≤ detector) or **external-source** detector



## **Bolometric technique**







## $0\nu\beta\beta$ research with TeO<sub>2</sub>





## Cuoricino final 0vßß result



90% CL

 $T_{1/2}^{0v}$  > 2.8 x 10<sup>24</sup> y <sup>[5]</sup>

 $< m_{\beta\beta} > < 0.3 \div 0.7 \text{ eV}^{[5]}$ 

Statistics: Mxt = 19.75 kg (130Te)xyEnergy resolution:  $\Delta E = 6.3 \pm 2.5 \text{ keV FWHM}$ Background:  $b = 0.169 \pm 0.006 \text{ c/keV/kg/y}$ 



### The Background in the Cuoricino ROI



The main issue are degraded  $\alpha$  and  $\beta$  from crystal and copper surfaces

## From Cuoricino to CUORE



**988 TeO**, 5x5x5 cm<sup>3</sup> crystals (750 g each)

**Detector Mass:** ~741 kg TeO<sub>2</sub>

<sup>130</sup>Te mass (natural i.a.) : ~206 kg of <sup>130</sup>Te

Array: 19 towers, each with 13 planes of 4 crystals each

Sensitivity improvement:

$$S^{0\nu} \propto \frac{\epsilon a.i.}{A} \left(\frac{MT}{b\Delta E}\right)^{1/2}$$

 $(Mx20) + (\Delta E/1.5) + (Tx2) + (b/20)$ 

=> CUORE  $S^{0\nu} \sim 35$  Cuoricino  $S^{0\nu}$ 





the most challenging issue is background reduction

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## **Background reduction**



**Passive methods adopted for CUORE** while testing different active methods (i.e. Surface sensitive bolometers, scintillating bolometers) for future improvements

- Shields design and materials selection
- New holder design to reduce the amount of copper facing the crystals
- TeO, crystals bulk contamination control: strict protocol for TeO<sub>2</sub> production
- Crystals surface contamination reduction: new treatment developed
  - => bolometric tests on 4 sample crystals from each batch: CCVR<sup>[9]</sup> tests
- Surface contamination of the copper facing the crystals reduction:
  - => bolometric tests of three different surface treatments: Three Tower Test (TTT)
- Further improvement thanks to detector granularity

## **Background from TeO<sub>2</sub>: CCVR test**

**CUORE Crystal Validation Run**: a dedicated cryogenic setup in C Hall at LNGS to test crystal radioactivity and performances (4 crystal samples from each CUORE batch since 2008 – 8 runs)





- Improved performance with respect to CUORICINO: ∆E FWHM @2615 = 4.6±1.2 keV
- Background in the 2.7-3.9 MeV region reduced by a factor of ~2 with respect to CUORICINO

Bulk/surface activities within contract specifications: Bulk activity 90% C.L. upper limits: 8.4E-07 Bq/kg (<sup>232</sup>Th), 6.7E-07 Bq/kg (<sup>238</sup>U), 3.3E-06 Bq/kg (<sup>210</sup>Po) Surface activity 90% C.L. upper limits: 2E-09 Bq/cm<sup>2</sup> (<sup>232</sup>Th), 1E-08 Bq/cm<sup>2</sup> (<sup>238</sup>U), 1E-06 Bq/cm<sup>2</sup> (<sup>210</sup>Po)

# Background from Cu: TTT test

Bolometric test to compare the effect in the ROI of **3 different copper surface treatments Crystals** from Cuoricino array **fully reprocessed** according to the new CUORE standards



## **CUORE** location





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## **CUORE HUT**







Developed a low-noise, cryogen-free, low-radioactivity cryostat able to reach ~ 6 mK

- 6 nested copper vessels (300K, 40K, 4K, 600mK, 50mK, 10mK)
- Cryogen free
   => better duty cycle
- Detector suspensions indipendent of refrigerator => less vibrational noise
- Material selection
   => low radioactivity
- Shields for neutrons
   (18cm PET + 2 cm H<sub>3</sub>B0<sub>3</sub>)
- External+Internal Pb shields (~35 cm minimum thickness)



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## **CUORE background budget**



Source Element	Contamination level Bulk [Bq/kg]; Surf [Bq/cm <sup>2</sup> ]	Source Data	c/keV/kg/y		
Environmental $\gamma$	0.73 γ/s/cm <sup>2</sup>	LNGS Meas. [14] [15]	< 3.9E-05 <sup>[15]</sup>		
Environmental n	4E-06 n/s/cm <sup>2</sup>	LNGS Meas. [12] [13]	(8.56±6.06)E-06 <sup>[15]</sup>		
Environmental $\mu$	3E-06 μ/s/cm <sup>2</sup>	MACRO Meas. [11]	(1.04±0.22)=04 <sup>[15]</sup>		
Far bulk: Cu OFE and	<6.4E-5 (Th), <5.4E-5 (U)	HPGe	22E-03		
Far bulk: Steel parts	<1E-2 (Th), <5E-3 (U)	HPGe FI	<3E-04		
Internal Roman Lead	Roman:<4.3E-5 (Th), <4.6E-5 (U)	HPG	<4E-03		
Internal Roman Lead	COMETA: <1.2E-4 (Th), <1.4E-4 (U)	C NHPGe	<5E-05		
Small near parts	Depending on the material	HPGe, NAA, bolo	< 3E-03		
Cosm. Activation: TeO <sub>2</sub>	~ 1.5E-08 ( <sup>60</sup> Co) ~ 4E-07 ( <sup>110</sup> Ag, <sup>110</sup> Ag)	Calculations	~ 1E-03		
Cosm. Activation: Cu	< 5 <b>5 (</b> <sup>\$0</sup> Co)	Calculations	< 5E-04		
Near bulk: Cu NOSV	< 25-00 (Th), < 6.5E-05 (U)	NAA (Th), HPGe (U)	< 7E-04		
Near bulk: TeO	< 8.4E-07 (Th),< 6.7E-07 (U) <3.3E-06 (Pb)	CCVR <sup>[9]</sup>	< 1E-04		
Near Surface: GN NOSV	Cu: <7E-08(Th / U), <7E-07(Pb) PTFE: <7E-06 (Pb)	From TTT 2.7-3.9 MeV rate	< (2-3)E-02 if Cu <6E-02 if PTFE		
Near surface:TeO <sub>2</sub>	<2E-09(Th),<1E-8 (U),<1E-06 (Pb)	CCVR <sup>[9]</sup>	< 4E-03		

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### **CUORE Status**







- Hut and clean room: fully equipped
- Detector assembly line: almost ready
- Radon abatement system: installed
- Cryostat: commissioning of first 3 shields will start soon at LNGS
- Calibration system: construction started
- Copper parts: are being machined and cleaned, delivered by end 2013
- Crystals: 90% stored underground at LNGS (100% by end 2012)
- Thermistors: production on-going, final delivering in early 2013



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## **CUORE first phase: CUORE-0**

**1 CUORE-like tower** of 13 planes - 4 crystals each **52 TeO**<sub>2</sub> 5x5x5 cm<sup>3</sup> crystals (750 g each)

**Detector Mass:** ~39 kg TeO<sub>2</sub>

<sup>130</sup>Te mass (natural i.a.): ~11 kg of <sup>130</sup>Te

- All detector components manufactured, cleaned and stored with protocols defined for CUORE
- Assembled with the same procedures foreseen for CUORE
- In old CUORICINO cryostat

#### GOALS:

- Test of proof for CUORE at all stages
- Test and debug of the new CUORE assembly line
- Test of the whole new CUORE analysis framework
- Surpass CUORICINO in physics reach while CUORE is being assembled
- Demonstrate potential for DM and Axion detection (see S. Di Domizio talk in parallel session)







## CUORE-0: assembly procedure



CUORE-0 assembly was performed in the new CUORE clean room following all the stages and using all the equipment developed for CUORE



## **CUORE-0: thermistor gluing**



The gluing of CUORE-0 thermistor to crystals was performed with the **new CUORE gluing semi-automatic machine** (in a  $N_2$  flushed glove box): fast, operator independent, minimizes radioactive contaminations, makes this stage more reproducible thus improving detector uniformity.



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## **CUORE-0: tower assembly**



The assembly of the tower was done with the CTAL (CUORE Tower Assembly Line) provided of a sealed and flushed stainless steel chamber (Garage) supporting a working plane where 4 different glove boxes switch allowing 4 operations to be performed (mounting, bonding, cabling and tower storage) with radioactivity control and reproducible protocols



#### CUORE-0: shield installation and transportation



After shield installation the tower has been closed in a flushed Plexiglas box, then moved to the special opening door of the **CUORE clean room** with a trans-pallet. It has then been lifted with a fork-lift to the **CUORICINO clean room** where it has been joined to the cryostat dilution unit (operations not necessary for CUORE).



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- The CUORE-0 cryostat and tower have been closed the first time on the 24<sup>th</sup> of April
- A leak in the dilution unit has then been discovered forcing to dismount and storage the tower
- The leak has been repaired by a technician from Oxford Instruments in the 1<sup>st</sup> week of June
- Cryostat was reassembled in mid-June
- Room temperature and low temperature tests on-going
- Data taking foreseen in middle August

## **CUORE-0 and CUORE sensitivity**



	CUORE-0	CUORE	data
M [kg]	39 (~11 of <sup>130</sup> Te)	741 (~206 of <sup>130</sup> Te)	
∆E [keV]	~5	~5	CCVR <sup>[9]</sup>
b [c/keV/kg/y]	0.05	0.01	Measured contaminations + bkg model
Т [у]	2	5	

$$S^{0\nu} \propto \frac{\epsilon a.i.}{A} \left( \frac{MT}{b\Delta E} \right)^{1/2}$$

ε = 87.4% i.a. (<sup>130</sup>Te) = 34.167 %



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### CUORE sentitivity to <m<sub>ββ</sub>>



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## Conclusions



- TeO<sub>2</sub> bolometers represent since many years a competitive detector for  $0\nu\beta\beta$  research
- After the CUORICINO lesson a strong R&D has been developed in order to reduce the background in the ROI (the main challenge being surface contaminations of detector and facing parts)
- Bolometric tests after improving surface treatments demonstrate that the CUORE goal of 0.01 c/keV/kg/y is just behind the corner. Copper/PTFE surface is the most crucial issue
- CUORE is under construction: LNGS hut and clean room ready, cryostat commissioning almost starting, crystal production and storage foreseen by 2012, other parts on schedule
- CUORE cool down foreseen for end 2014
- First CUORE tower, CUORE-0, will soon start data taking in the CUORICINO cryostat
- Positive result and optimization in view of CUORE of all production/cleaning and assembly stages

# Bibliography



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#### **The CUORE Collaboration**





- INFN LNGS Laboratories
- INFN & University Milano Bicocca
- INFN Roma & Sapienza University
- INFN Roma Tor Vergata
- INFN & University Genova
- INFN & University Firenze
- INFN LNL Laboratories
- INFN LNF Laboratories
- INFN Padova
- INFN and University Bologna

- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- University of California Berkeley
- University of Califoria Los Angeles
- · University of South Carolina
- · California Politechnic state University
- University of Wisconsin Madison
- CNRS CSNSM Orsay
- Shanghai Institute of Applied Physics
- University of Zaragoza

![](_page_30_Picture_24.jpeg)

## **Back-up slides**

## **TeO<sub>2</sub> bolometer parameters**

![](_page_32_Picture_1.jpeg)

**Detector working temperature:** T ~ 10 mK

**Mixing chamber temperature:**  $T_{MC} \sim 5 \text{ mK}$ 

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Heat capacity of crystal: C ~ 2 x 10-9J/K
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**Thermal conductance of thermal coupling to heat bath:** G ~ 2 x 10-9 W/K

Time constant of bolometer: T ~ C/G ~ 1 s

**Rise time of pulse:** ~ 50 ms

Decay time of pulse: ~ 200 ms

**Resistance of thermistor:**  $R \sim 100 M\Omega$ 

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

R<sub>0</sub>: nominal values ~0.9-1.2 Ω T<sub>0</sub>: nominal values ~3-4 K γ is considered to be = 0.5 **Detector Response:** 

 $\Delta V$ thermistor ~ 0.3 mV/MeV

 $\Delta$ Rthermistor ~ 3 M $\Omega$ /MeV

 $\Delta$ Tthermistor ~ 0.03 mK/MeV

ΔTcrystal ~ 0.1 mK/MeV

A representative set of reasonable parameters that reproduces R ~ 100 M $\Omega$  is: R<sub>0</sub> ~ 1.1  $\Omega$ , T<sub>0</sub> ~ 3.35 K,  $\gamma$  = 0.5

# CUORE-0: Sensitivity to <sup>76</sup>Ge claim

![](_page_33_Figure_1.jpeg)

•The inner band corresponds to the best-fit value of the claim; the range arises from the "1o" range of QRPA NME calculations in A. Faessler et al., Phys. Rev. D79 (2009) 053001

•The outer band also includes the  $1\sigma$  error on the  $^{76}$  Ge claim

### **CUORE schedule**

![](_page_34_Picture_1.jpeg)

Instance         Part	D	Task Name	Start	Finish	Fst	2010	2011	2012	2013	2014	2015
1       0-10 Hu       20 Hu       0-20 Hu       0-20 Hu         2       Cean Room Takon Sea & Abuerrent       20 Hu       4512         3       Facady Cage       11/212       62 Statu         2       Ober Sont       61/07       12/12       60/07         3       Facady Cage       13/07       20 Hu       60/07         4       0.00 Hu       0.00 Hu       12/11       60/07         5       Organization       81/07       13/014       20/0         6       10/07 Hou       42/08       31/014       20/0         8       Orgonoles       81/07       12/013       0       0         10       Orgonoles frait       81/07       12/012       0       0         2       Ocolong Unis an Test Howar       81/07       12/012       0       0         3       Dacok - 4K Chamber Fais       51/010       61/183       0       0       0         3       Dacok - 4K Chamber Fais       51/010       2/04/13       0       0       0       0         3       Dacok - 4K Chamber Fais       61/01/13       2/04/13       0       0       0       0       0       0       0       0	-		Start	THIS I	Float	Otr 1 Otr 2 Otr 3 O	tr 4 Otr 1 Otr 2 Ot	r 30tr 40tr 10tr 20tr 3	Otr 4 Otr 1 Otr 2 Ot	r 3 Otr 4 Otr 1 Otr 2 Otr 3	Otr 4 Otr 1 Otr 2
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Immission         91/011         22/01         2mo           Struct-Cealing         4/2000         31/12/4         2mo           3 db Cryogenic         6/107         12/013           1         Cryogenic Procuments         6/107         2/2412           2         Cooling Unisand Test Dewar         6/107         2/2412           2         Cooling Unisand Test Dewar         6/107         1/2412           2         Cooling Unisand Test Dewar         6/107         1/2412           3         2000-44 (Chamber Fab         5/1010         6/1012         1/2412           5         Detector Suspension         3/110         2/2413	5	Crystal Procurement	6/30/10	12/7/12	6 mo						
7         Structure - Design, Prod.         8/107         1/19/2           8         Structore - Design, Prod.         8/107         1/19/2           9         20 Cryopenics         8/107         1/20/13           0         1/107/000000000000000000000000000000000	6	Thermistors	3/16/11	3/25/13	2 mo		6		2		
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Internal Corrogenic Procurements         B/107         1/22412         Construction           2         Cooling Units and Test Dowar         B/107         7/212         2 no           3         900K - 4K Chamber Fab         5/1010         6/1012         0           4         600mK - MC Fab         7/1012         12/2412         0           5         Deeccor Supension         3/110         2/2412         0           6         Internal Lad Stheding         12/206         12/1013         0           7         2 Catibration Design         4/110         32/211         0         0           9         Catibration Design         4/110         32/211         0         0         0           11         12/209         2/2013         7/100         0         0         0         0           12         Etc. Production & Testing         11/22/09         2/2013         7/100         0 </td <td>10</td> <td>3.1 Cryo Design &amp; Construction</td> <td>8/1/07</td> <td>2/4/13</td> <td></td> <td></td> <td></td> <td></td> <td><b></b></td> <td></td> <td></td>	10	3.1 Cryo Design & Construction	8/1/07	2/4/13					<b></b>		
2       Cooling Units and Test Dewar       0/107       7/2/12       2 mo         3       2000-44 Chamber Fab       5/10/10       1/2/11       1/2/2/12         4       600mK - MC Fab       3/11/0       2/4/13       1         5       Detector Suspension       3/11/0       2/4/13       1         6       Internal Lads Shielding       1/11/0       2/4/13       1         7       2.2 Calibration System       4/22/09       1/2/10/13       1         6       Calibration Construction       7/11/1       1/2/0/13       1         7       2.2 Calibration Dosign       4/2/209       7/2/12       1         10       Calibration Construction       7/11/1       1/2/0/13       1         12       CEC. Production & Testing       1/2/200       2/2/2/14       7       0         12       Cootism Agental Into Hut       6/19/12       2/2/14       7       0       1         13       Cootast Assembly Integration & Test       6/19/12       2/2/14       1       1       1         14       Decervice Insertion & System Test - Futil Load       1/9/13       1/9/13       1       1       1         12       Assemble Towers 1 to 5       10/2/12	1	Cryogenic Procurements	8/1/07	12/24/12							
3       300K-4K Chamber Fab       5/10/10       0/10/12       12         4       060mK-MC Fab       7/10/12       12/10/12       1         6       Internal Lad Shekding       12/108       11/16/12       1         7       2.2 Calibration System       4/209       12/10/13       1         6       Calibration Proteypes       4/209       12/10/13       1         7       2.2 Calibration Construction       17/11       12/10/13       1         10       Calibration Construction       17/11       12/10/13       1         12       Deteorolis       12/2209       2/28/13       1         12       Deteorolis       12/2209       2/28/13       1         12       Deteorolis       12/2209       2/28/13       1         12       Deteorolis       6/19/12       2/29/13       1         12       Deteorolis fistill       0/19/12       2/2/14       1         13       Assembly Integration & Testing       0/12/12       2/18/13       1         14       Deteorolis Install Acomissionall       0/19/13       1       1       1         14       Assemble Towers 10 is       10/29/12       1/14/14       2 mo	12	Cooling Units and Test Dewar	8/1/07	7/2/12	2 mo				1		
44       000mk - MC Fab       7/1012       12/24/12         5       Detector Suspension       3/110       2/413         7       3.2 Calibration System       4/2009       12/1013         8       Finatz calibration Design       4/110       3/2311         9       Calibration Construction       7/1011       1/10112         10       Calibration Construction       7/1011       1/1012         11       42209       2/2813       7         12       Celeconos       12/209       2/2813         12       Celeconos       12/2209       2/2813         13       Obasamistanos A Test       6/1912       5/2214         15       Crostas Imégration Into Hut       6/1912       5/2214         16       Install mégration       10/2312       4/1414         13       Assembé Towers 1 to 5       10/2313       10/2313         14       Assembé Towers 1 to 5       10/2314       1/2014	13	300K - 4K Chamber Fab	5/10/10	6/18/12		-					
5       Detector Suspension       31/10       2/413         6       Internal Laad Shielding       12/10/13	4	600mK - MC Fab	7/10/12	12/24/12							
6         Internal Lad Shielding         12/108         11/16/12         Image: Shielding         12/108         11/16/12         Image: Shielding         12/108         Image: Shielding         12/108         Image: Shielding         12/108         Image: Shielding         Image: Shielding         12/108         Image: Shielding         Image: Shielding         12/108         Image: Shielding         11/118         12/108         Image: Shielding         11/118         12/108         Image: Shielding         11/118         12/108         Image: Shielding         11/118	15	Detector Suspension	3/1/10	2/4/13		C					
7       3.2 Calibration System       4/2009       12/10/13         8       Finalize Calibration Design       4/10       3/23/11         9       Calibration Construction       7/111       12/10/13         10       Calibration Construction       7/111       12/10/13         12       Ebec. Production & Testing       12/20/9       2/28/13         12       Ebec. Production & Testing       12/20/9       2/28/13         14       0.0 bata Analysis Tools       1/0/14       4/22/14       7 mo         14       0.0 bata Analysis Tools       1/0/14       4/22/14       7 mo         15       Cryostat Integration No Huit       6/19/12       2/28/13	6	Internal Lead Shielding	12/1/08	11/16/12							
38       Finaltze Calibration Design       4/1/10       328/11       Calibration Prototypes       4/2009       7/2/12         40       Calibration Construction       7/1/11       12/10/13       Calibration Construction       7/11/1       12/10/13       12/2209       22/21/3       To	17	3.2 Calibration System	4/23/09	12/10/13							
9       Calibration Prototypes       4/2099       7/2712       Image: Calibration Construction       1/2712       2/2913       7/11       Image: Calibration Construction	8	Finalize Calibration Design	4/1/10	3/23/11		C	-				
0       Calibration Construction       7/111       12/10/13         1       40 Ebe tronics       12/200       22/2013       7         2       Ebe. Production & Testing       12/22/09       22/2013       7       7         3       60 Data Analysis Tools       11/61/4       40/22/14       7       7       7         4       7.0 Assembtly Inegration in to Hut       6/19/12       2/25/15         7         5       Cryostat Infegration Into Hut       6/19/12       2/21/4            6       Initial Installation & 4K Test       6/19/12       2/21/4            7       Base Tempurature Test - Partial Load       10/9/13       10/9/13            10       Assemble Towers 16 to 11       10/9/13       10/22/12       4/9/13           12       Assemble Towers 12 to 19       10/30/13       4/1/14       2            13       A.4 Ebetroninestioning       5/21/4       2/25/15             14       T.5 Detector Insention       6/27/14       1/2/21/4       1	19	Calibration Prototypes	4/23/09	7/27/12					3		
14       0 Electronics       12/2209       2/28/13       T         12       Elec. Production & Testing       12/2209       2/28/13       T         13       6.0 Data Analysis Tools       11/14       7       Tool         14       7.0 Assembty Integration & Test       6/19/12       2/25/15       T         15       Cryostat Integration into Hu       6/19/12       2/21/13       T         16       Initial Installation & 4K Test       6/19/12       2/21/14       T         17       Base Tempurature Test - Parila Load       1/19/13       5/22/14       T         19       7.3 Tower Assembly & Integration       10/22/12       4/14/14       2         10       Assemble Towers 16 to 1       5/19/13       10/29/13       T         11       Assemble Towers 16 to 1       5/19/14       10/29/13       T         12       Assemble Towers 12 to 19       10/29/13       T       T         13       7.4 Electronics Install & Commissioning       3/1/14       10/29/14       T         14       7.5 Detector Insertion & Sys. Testing       5/22/14       T       T         16       Detector Insertion & Sys. Testing       5/22/14       T       T         16	20	Calibration Construction	7/1/11	12/10/13				C			
22       Elec. Production & Testing       12/22/9       22/813       7 mo         33       6 Data Analysis Tools       1/814       8/2214       7 mo         44       7.0 Assembly Integration & Testing       6/1912       22/2515       5         55       Cryostas Integration Into Hut       6/1912       5/2214       5         10       Assembly Integration Into Hut       6/1912       2/2913       6         10       Base Tempurature Test - Partial Load       1/913       5/2214       5         10       Assemble Towers 1 to 5       10/2212       4/1414       2 mo         10       Assemble Towers 1 to 5       10/2212       4/1414       2 mo         11       Assemble Towers 6 to 11       5/913       10/2913       -         12       Assemble Towers 6 to 11       5/913       10/2913       -         13       7.4 Electronics Install & Commissioning       5/2314       22515       -         15       Open and prepare for Installation       5/2314       22515       -         16       Detector Insertion & System Check       9/9/14       11/20/14       1 mo         17       Initial Cooldow and System Check       9/9/14       11/20/14       1 mo	21	4.0 Electronics	12/22/09	2/28/13		<b>v</b>					
33       0.0 bita Analysis Tools       1/6/14       9/22/14       7 mo         44       7.0 Assembly Integration & Test       6/19/12       2/25/15       0         45       Cryostat Integration into Hut       6/19/12       5/22/14       0         47       Base Tempurature Test - Partial Load       2/19/13       10/19/13       0         48       Base Tempurature Test - Partial Load       2/19/13       10/19/13       0         49       7.3 Tower Assembly Integration       10/22/12       4/14/14       2 mo         10       Assemble Towers 1 to 5       10/22/12       4/14/14       2 mo         11       Assemble Towers 1 to 5       10/29/13       10/29/13       0         12       Assemble Towers 12 to 19       10/20/13       4/14/14       2 mo         13       7.4 Electronics Install & Commissioning       3/12/13       9/22/14       1         14       7.5 Detector Insertion & Sys. Testing       5/23/14       0/25/15       0         15       Open and prepare for Installation       5/23/14       0/29/14       1 mo         16       Detector Insertion & Sys. Testing       5/23/14       1/2/01/4       1 mo         17       Initital Cooldowm and System Check       9/9/14       <	22	Elec. Production & Testing	12/22/09	2/28/13	7 mo	C			2		
44       7.0 Assembly Integration & Test       6/1912       2/25/15         55       Gryosiat integration into Hui       6/1912       5/221/4         166       Initial installation & 4K Test       6/1912       2/1913         177       Base Tempurature Test - Partial Load       10/913       5/221/4         178       Base Tempurature Test - Partial Load       10/913       5/221/4         179       7.3 Tower Assembly & Integration       10/2212       4/14/14       2 mo         179       Assemble Towers 1 to 5       10/2212       4/19/13       1         170       Assemble Towers 1 to 5       10/2212       4/19/13       1         171       Assemble Towers 1 to 5       10/2212       4/19/13       1         172       Assemble Towers 1 to 5       10/2212       4/19/13       1         172       Assemble Towers 1 to 5       10/2212       4/19/14       1         172       Assemble Towers 1 to 19       10/30/13       8/22/14       1         173       Open and prepare for Installation       5/22/14       2/25/15       1         174       Detector Insertion & System Check       9/9/14       11/20/14       1 mo         174       Initial Cooldown and System Check       9/	23	6.0 Data Analysis Tools	1/6/14	8/22/14	7 mo					E	2
135       Cryostat Integration Into Hut       6/1912       5/2214         16       Initial Insuilation & 4K Test       6/1912       2/1813         17       Base Tempurature Test - Partial Load       2/1913       10/813         18       Base Tempurature Test - Full Load       10/913       5/2214         19       7.3 Tower Assembly & Integration       10/2212       4/1913         10       Assemble Towers 1 to 5       10/2212       4/1913         11       Assemble Towers 1 to 5       10/2212       4/1913         12       Assemble Towers 1 to 5       10/2212       4/1913         13       7.4 Electronics Install & CommissionIng       3/1/13       8/2214         14       7.5 Detector Insertion & Sys. Testing       5/2314       2/2515         15       Open and prepare for Installation       5/2314       2/2614         16       Detector Insertion & System Check       9/314       11/20/14       1 mo         17       Initial Cooldown and System Check       9/314       11/20/14       1 mo         18       System Test Complete       1/2/3014       2 mo       12/2         19       CD 4- US Deliverables Complete       2/2515       2/2515       12/2	24	7.0 Assembly Integration & Test	6/19/12	2/25/15							
Initial installation & 4K Test       6/19/12       2/19/13         Base Tempurature Test - Partial Load       2/19/13       10/9/13         Base Tempurature Test - Full Load       10/9/13       5/22/14         Base Tempurature Test - Full Load       10/9/13       5/22/14         7. Tower Assemble Towers 1 to 5       10/22/12       4/14/14       2 mo         10       Assemble Towers 1 to 5       10/22/12       4/14/14       2 mo         11       Assemble Towers 6 to 11       5/9/13       10/29/13	25	Cryostat Integration Into Hut	6/19/12	5/22/14					)		
Rase Tempurature Test - Partial Load       2/19/13       10/9/13       10/9/13         Rase Tempurature Test - Full Load       10/9/13       5/22/14       10/23/12         Pg       7.3 Tower Assembly & Inegration       10/23/12       4/14/14       2 mo         Assemble Towers 1 to 5       10/23/12       4/9/13       10/29/13       10/29/13         Assemble Towers 6 to 11       5/9/13       10/29/13       10/29/13       10/29/13         Assemble Towers 12 to 19       10/30/13       4/14/14       2 mo       10/30/13       4/14/14         Assemble Towers 12 to 19       10/30/13       4/14/14       2       10/23/14       2/25/14         Assemble Towers 12 to 19       10/30/13       4/14/14       2       10/23/14       2/25/14         Assemble Towers 12 to 19       10/30/13       4/14/14       2       10/23/14       2/25/14         Assemble Towers 12 to 19       10/30/13       8/22/14       2       10/23/14       2/25/14       10/23/14         Assemble Towers 12 to 19       0/21/14       2/25/14       2/25/14       10/20/14       10/20/14         Assemble Towers 6 installation       6/27/14       7/24/14       1mo       10/20/14       1mo         Assystem Test Complete       12/30/14	26	Initial Installation & 4K Test	6/19/12	2/18/13							
Base Tempurature Test - Full Load       10/913       5/22/14         10       7.3 Tower Assembly & Integration       10/23/12       4/14/14       2 mo         10       Assemble Towers 1 to 5       10/23/12       4/9/13	27	Base Tempurature Test - Partial Load	2/19/13	10/8/13							
9       7.3 Tower Assembly & Integration       10/29/12       4/14/14       2 mo         00       Assemble Towers 1 to 5       10/29/12       4/9/13          11       Assemble Towers 6 to 11       5/9/13       10/29/13          12       Assemble Towers 12 to 19       10/30/13       4/14/14          13       7.4 Electronics Install & Commissioning       3/1/13       8/22/14          14       7.5 Detector Insertion & Sys. Testing       5/23/14       2/25/15          15       Open and prepare for Installation       5/23/14       2/25/15          16       Detector Insertion       6/27/14       1/20/14       1 mo         17       Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         18       System Test Complete       12/30/14       2/25/15          19       CD 4- US Deliverables Complete       2/25/15	28	Base Tempurature Test - Full Load	10/9/13	5/22/14							
10       Assemble Towers 1 to 5       10/29'12       4/9'13          11       Assemble Towers 6 to 11       5/9'13       10/29'13          12       Assemble Towers 12 to 19       10/30'13       4/14'14          13       7.4 Electronics Install & Commissioning       3/1'13       8/22'14          14       7.5 Detector Insertion & Sys. Testing       5/23'14       2/25'15          15       Open and prepare for Installation       5/23'14       2/25'15          16       Detector Insertion       6/27/14       7/24'14       1 mo         17       Initial Cooldown and System Check       9/9'14       11/20'14       1 mo         18       System Test Complete       12/30'14       2/20'15          19       CD 4- US Deliverables Complete       2/25'15       2/25'15	29	7.3 Tower Assembly & Integration	10/23/12	4/14/14	2 mo				<b></b>		
Assemble Towers 6 to 11       5/9/13       10/29/13       10/29/13         Assemble Towers 12 to 19       10/30/13       4/14/14       10/20/13         7.4 Electronics Install & Commissioning       3/1/13       8/22/14       10/20/13         7.5 Detector Insertion & Sys. Testing       5/23/14       2/25/15       10/20/14         7.6 Detector Insertion & Sys. Testing       5/23/14       6/26/14       10/20/14         7.6 Detector Insertion       6/27/14       7/24/14       1 mo         7.6 Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         7.7 Initial Cooldown and System Check       9/9/14       11/20/14       2 mo         7.8 System Test Complete       12/30/14       2/25/15       2/25/15         7.9 CD 4- US Deliverables Complete       2/25/15       2/25/15       1	80	Assemble Towers 1 to 5	10/23/12	4/9/13							
Assemble Towers 12 to 19       10/30/13       4/14/14       Image: Complete Comp	81	Assemble Towers 6 to 11	5/9/13	10/29/13							
33       7.4 Electronics Install & Commissioning       3/1/13       8/22/14          44       7.5 Detector Insertion & Sys. Testing       5/23/14       2/25/15          45       Open and prepare for Installation       5/23/14       6/26/14          46       Detector Insertion       6/27/14       7/24/14       1 mo         47       Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         48       System Test Complete       12/30/14       12/30/14       2 mo         49       CD 4- US Deliverables Complete       2/25/15       2/25/15	32	Assemble Towers 12 to 19	10/30/13	4/14/14							
14       7.5 Detector Insertion & Sys. Testing       5/23'14       2/25'15         15       Open and prepare for Installation       5/23'14       6/26'14         16       Detector Insertion       6/27'14       7/24'14       1 mo         17       Initial Cooldown and System Check       9/9'14       11/20'14       1 mo         18       System Test Complete       12/30'14       12/30'14       2 mo         19       CD 4- US Deliverables Complete       2/25'15       2/25'15       0	33	7.4 Electronics Install & Commissioning	3/1/13	8/22/14							3
315       Open and prepare for Installation       5/23/14       6/26/14         316       Detector Insention       6/27/14       7/24/14       1 mo         317       Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         318       System Test Complete       12/30/14       12/30/14       2 mo         319       CD 4- US Deliverables Complete       2/25/15       2/25/15	34	7.5 Detector Insertion & Sys. Testing	5/23/14	2/25/15						<b>Q</b> =	
Bit       Detector Insention       6/27/14       7/24/14       1 mo         Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         Initial Cooldown and System Check       12/30/14       12/30/14       2 mo         Initial Cooldown and System Test Complete       12/25/15       2/25/15       2/25/15	35	Open and prepare for Installation	5/23/14	6/26/14							
37       Initial Cooldown and System Check       9/9/14       11/20/14       1 mo         38       System Test Complete       12/30/14       12/30/14       2 mo         39       CD 4- US Deliverables Complete       2/25/15       2/25/15	86	Detector Insention	6/27/14	7/24/14	1 mo						
System Test Complete         12/30/14         12/30/14         2 mo           19         CD 4- US Deliverables Complete         2/25/15         2/25/15         4	37	Initial Cooldown and System Check	9/9/14	11/20/14	1 mo						
9 CD 4- US Deliverables Complete 2/25/15 2/25/15	38	System Test Complete	12/30/14	12/30/14	2 mo						¢ 12/1
	9	CD 4- US Deliverables Complete	2/25/15	2/25/15							

## What beyond CUORE?

![](_page_35_Picture_1.jpeg)

$$S^{0\nu} \propto \frac{\epsilon a.i.}{A} \left(\frac{MT}{b\Delta E}\right)^{1/2}$$

Extensions beyond CUORE are possible in order to increase sensitivity to cover the inverted hierarchy region of the neutrino mass spectrum

#### Relatively inexpensive isotopic enrichment of <sup>130</sup>Te

- No change needed to the experimental infrastructure
- > 500 kg of <sup>130</sup>Te
- A factor 3 increase in i.a. => S<sup>0v</sup><sub>enr</sub> ~ 3 S<sup>0v</sup><sub>nat</sub>

#### Particle discrimination (R&D is being developed)

signal shape, surface sensitive detectors [16], Cherenkov light detection [17] or scintillating bolometers (i.e. ZnSe, CdWO<sub>4</sub>, CdMoO<sub>4</sub>...)