Results from the CUORE experiment
DOUBLE BETA DECAY

Processes explained by the Standard Model

- Lepton number not conserved
- Occurs if neutrinos have mass and are their own antiparticle

2\textsuperscript{nd} order weak interaction

Normal beta decay suppressed by Q value or J^\pi

\begin{align*}
\beta^- & \rightarrow e^- + \bar{\nu} \\
2\nu \beta^- & \rightarrow e^- + \bar{\nu} + \bar{\nu} \\
0\nu \beta^- & \rightarrow e^- + \bar{\nu}
\end{align*}
\[ T_{1/2}^{0\nu}(n\sigma) = \frac{\ln 2}{n\sigma} \frac{N_A i \varepsilon}{A} f(\Delta E) \sqrt{\frac{M t}{B \Delta E}} \]

- Sum energy of emitted electrons: Peak at Q value of the decay.

Sensitivity of the search
IMPLICATIONS

- Neutrinos are Majorana fermions.
- Physics beyond standard model.
- Constraints on absolute mass scale.
- Probes the mass hierarchy of the neutrinos.
- Constraints on CP violating phases?

\[ \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \left( \frac{m_{\beta\beta}}{m_e^2} \right)^2 \]

- Past and present (~10 kg)
- Present and near future (~100 kg)
- Future (~1000 kg)
- Dreams (~10000+ kg?)
The Cryogenic Underground Observatory for Rare Events

- Search for $0\nu\beta\beta$ in $^{130}$Te at LNGS, Italy (depth $\sim 3600$ m.w.e.)
CUORE

- $Q_{\beta\beta} = 2527.515$ keV
- Isotopic mass of $^{130}$Te : 206 kg
- 988 TeO$_2$ crystals (arranged in 19 towers with 13 floors each)
- Massive thermal calorimeters operated at $\sim$10 mK
- Goal:
  - $\triangle E_{\text{FWHM}} \leq 5$ keV @ 2615 keV
  - $B = 0.010$ cnts/(keV·kg·yr)
  - $T_{1/2}$ (90% C.L.) $> 9 \times 10^{25}$ y
    5 yrs of live time ;
  - $<m_{\beta\beta}> \sim 45 - 210$ meV.
DETECTOR PRINCIPLE: THERMAL CALORIMETERS

- Electron events mostly contained in the bulk: Large detection efficiency.
- The calorimeter cannot discriminate background from signal events easily.

\[ \Delta E_{TFN} = \sqrt{k_B T^2 C(T)} \]

- Thermodynamic limit for energy resolution can be made small by operating the detectors at a very low temperature.
- Requires ultra-low temperature facility with ultra-stable operating conditions.
DETECTOR PRINCIPLE

- 750 g (5x5x5 cm\(^3\)) crystal
- \(\Delta T \approx 100 \mu K\) for 1 MeV energy deposit
- NTD-Ge thermistor read out
  - \(R(T) \approx R_0 \exp \left[ (T_0/T)^{1/2} \right]\)
    (large sensitivity at low T)
- Energy response calibrated using known gamma sources
- Note:
  - Signal ➔ thermal channel only
  - No active background rejection
DETECTOR ASSEMBLY

- Strict material selection
- Stringent surface cleaning procedures for detectors and materials nearby the detectors
- Minimize radon contamination at every step of the detector assembly.
DETECTOR ARRAY

CUORE Assembly efficiency
- 984/988 NTD-Ge thermistors connected
- > 99.5% functional detectors.
- 942/988 heaters connected
CUORE CRYOSTAT

- Experimental Conditions
  - Low radioactivity environment
  - Stable ultra-low temperatures
  - Extremely low vibrations
EXTERNAL SHIELDING

External lead: 25 cm thick

Neutron shield: 18 cm of PET + 2 cm of H$_3$BO$_3$
SCIENCE RUNS

Science operations:
Very short commissioning run (identified issue with the thermistor bias on about 1/3 of the channels)
- First optimization of the detector working point
- **Dataset 1**: 3 weeks of physics data (May - June 2017)
- Second optimization campaign
- **Dataset 2**: 4 weeks of physics data (August - September 2017)

Operational performance:
- 984/988 operational channels
- Improved detector stability, compared to Cuoricino/CUORE-0
- Calibrations/physics ratio data to be optimized to maximize $0\nu\beta\beta$ sensitivity

Acquired statistics used for this $0\nu\beta\beta$ decay search (Dataset 1 + Dataset 2):
- $^{nat}\text{TeO}_2$ exposure: **86.3 kg yr** (37.6 + 48.7)
- $^{130}\text{Te}$ exposure: **24.0 kg yr**
CUORE: ENERGY RESOLUTION IN ROI

Calibration resolution at 2615 keV

- Dataset 1: 9 keV FWHM
- Dataset 2: 7.4 keV FWHM
- Effective (exposure-weighted): 8 keV FWHM

Physics data Resolution@ Q-value

- Dataset 1: $(8.3 \pm 0.4)$ keV FWHM
- Dataset 2: $(7.4 \pm 0.7)$ keV FWHM
- Effective (exposure-weighted): $(7.7 \pm 0.5)$ keV FWHM
CUORE: EFFICIENCIES FOR $0\nu\beta\beta$ ANALYSIS

- First we remove events from periods of low-quality data (~1% of total live time)
- Base cuts (number of pulses in the window, baseline stability)
- Anti-coincidence: accept/reject events based on a multiplicity cut.
- Pulse shape analysis and cuts: reject deformed events

<table>
<thead>
<tr>
<th></th>
<th>DATASET 1</th>
<th>DATASET 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>$(99.766 \pm 0.003)$ %</td>
<td>$(99.735 \pm 0.004)$ %</td>
</tr>
<tr>
<td>Energy reconstruction</td>
<td>$(99.168 \pm 0.006)$ %</td>
<td>$(99.218 \pm 0.006)$ %</td>
</tr>
<tr>
<td>Base cuts</td>
<td>$(95.63 \pm 0.01)$ %</td>
<td>$(96.69 \pm 0.01)$ %</td>
</tr>
<tr>
<td>Anti-coincidence</td>
<td>$(99.4 \pm 0.5)$ %</td>
<td>$(100.0 \pm 0.4)$ %</td>
</tr>
<tr>
<td>Pulse Shape Analysis</td>
<td>$(91.1 \pm 3.6)$ %</td>
<td>$(98.2 \pm 3.0)$ %</td>
</tr>
<tr>
<td>$0\nu\beta\beta$ containment</td>
<td>$(88.345 \pm 0.085)$ %</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$(75.7 \pm 3.0)$ %</td>
<td>$(83.0 \pm 2.6)$ %</td>
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</table>
**CUORE: $0\nu\beta\beta$ RESULTS**

**Limits combining CUORE with CUORE-0 and Cuoricino:**

- **Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$):**
  \[1.5 \times 10^{25} \text{ yr}\]

- **Profile likelihood ("frequentist") limit @ 90% CL:**
  \[2.2 \times 10^{25} \text{ yr}\]

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Region of interest: [2465..2575] keV
Overall efficiency: (75.7 ± 3.0)%
  (83.0 ± 2.6)%

ROI background index: (1.49 −0.17 +0.18) \(\times\) \(10^{-2}\) counts/(keV·kg·yr)
  (1.35 −0.18 +0.20) \(\times\) \(10^{-2}\) counts/(keV·kg·yr)

Events in the ROI: 155

Best fit for $^{60}$Co mean: (2506.4 ± 1.2) keV

Best fit decay rate: [−1.0−0.3+0.4 (stat.) ± 0.1 (syst.)] \(\times\) \(10^{-25}\) yr\(^{-1}\)
CUORE: $<m_{\beta\beta}>$ SENSITIVITY

CUORE Nuclear Transition Matrix Element (NTME) calculations from:
- JHEP02 (2013) 025
- Phys. Rev. C 87, 064302 (2014)

Half-life limits:
- $^{136}$Xe: $1.1 \times 10^{26}$ yr from Phys. Rev. Lett. 117, 082503 (2016)
- $^{136}$Te: $1.5 \times 10^{25}$ yr from PRL 120, 132501 (2018)
- $^{76}$Ge: $8.0 \times 10^{25}$ yr from PRL 120, 132503 (2018)
- $^{100}$Mo: $1.1 \times 10^{24}$ yr from Phys. Rev. D 89, 111101 (2014)
- CUORE sensitivity: $9.0 \times 10^{25}$ yr

$m_{\beta\beta} < 110 - 520$ meV
• Relevant reduction in the $\gamma$ region, compared to CUORE-0
• Spectrum is consistent with the background expectations

• 2615 keV in calibration normalized to physics data
• Shows background in ROI dominated by alphas
BACKGROUND EXPECTATION

CUORE-0 Bkg Model
- Surface of TeO2
- Surface of near elements
- Bulk of TeO2
- Bulk of near elements
- Cosmogenic Activation of CuNOSV elements
- Cosmogenic Activation of TeO2
- Far Bulk: CuOFE elements
- Far Bulk: Roman Pb
- Far Bulk: Modern Pb
- Far Bulk: Superinsulation
- Far Bulk: Stainless steel parts
- Environmental muons
- Environmental neutrons
- Environmental gammas

Energy spectra for different backgrounds:

Bkg Goal

CUORE Goal: 0.01 counts/keV/kg/y

90% CL limit

Value

Major background sources identified and ascribed to different locations in the experimental setup using

- Coincidence analysis
- Gamma peaks
- Alpha peaks
- Radio-assay measurements
- Data from neutron activation

**Bayesian Fit:**
- Split data into inner and outer layers: utilize self shielding by the outer layers.
- Split data by Multiplicities: different multiplicities are sensitive to different types of backgrounds
Excellent agreement of the data with the $2\nu\beta\beta$ background model

**CUORE**: $T_{1/2} = [7.9 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (syst.)}] \times 10^{20} \text{ y}$

- **CUORE-0**: $T_{1/2} = [8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \times 10^{20} \text{ y}$
- **NEMO**: $T_{1/2} = [7.0 \pm 0.9 \text{ (stat.)} \pm 1.1 \text{ (syst.)}] \times 10^{20} \text{ y}$
In CUORE-0, 20% of the counts in the region of 1 - 2 MeV were from $2\nu\beta\beta$.

In CUORE, almost all the counts in the region of 1-2 MeV are accounted by $2\nu\beta\beta$.
CUORE : STATUS

• We found a small leak into the cryostat in the previous phase of data taking and had to warm up the cryostat to 100 K.

• We cooled down to the base temperature in March 2018.

• We spent quite some time in optimizing the detector performance (towards 5 keV FWHM goal)

• May 2018 - Back to the data taking mode!

DEVELOPING ANALYSIS TECHNIQUES

• Signal separation using multi-channel decorrelation.

• Thermal model to describe the pulse template and noise in bolometers.

• Possibility of using delayed coincidences to develop a better background model.

Finding optimal working temperature for the best Signal-to-noise ratio

More updates at TAUP 2019
LIFE BEYOND CUORE

CUPID = CUORE UPGRADE WITH PARTICLE IDENTIFICATION

- Increase Sensitive mass ➞ Enrichment
- Active background rejection ➞ $\alpha / (\beta - \gamma)$ separation
- Goal:
  - $\Delta E_{FWHM} \leq 5$ keV @ 2615 keV
  - $B = 0.1$ c/ton/y in ROI
  - $<m_{\beta\beta}> \sim 10$ meV discovery sensitivity
    (10 yrs of live time)
CUPID = CUORE UPGRADE WITH PARTICLE IDENTIFICATION

Li$_{2}^{100}$MoO$_{4}$ bolometers have been recognized as the baseline for next generation high sensitivity background experiment

- Large scale enriched crystal production feasible.
- Internal radio-purity targets met.
- Demonstrated active background rejection.
- Energy resolution of $\sim 5$ keV demonstrated.
- Total background of 0.1 c/ton/y achievable.
SUMMARY:

- CUORE a ton scale cryogenic experiment will be able to probe $<m_{\beta\beta}> \sim 45 - 210$ meV
- CUORE → Limited by the surface $\alpha$ background near the detector.
- Natural successor → CUPID, one tonne experiment with particle identification
  - $B = 0.1$ c/ton/y in ROI
  - $<m_{\beta\beta}> \sim 10$ meV discovery sensitivity (covers IHE)
- Heat + Light channel most favorable technique for particle ID.
- $\text{Li}_2^{100}\text{MoO}_4$ bolometers have been recognized as the baseline for next generation high sensitivity background experiment
- $\text{TeO}_2$ with enrichment and Cherenkov is a viable alternative.
- Extensive ongoing R&D on crystal production and sensor technology.
- CUPID collaboration to be formed soon.
COLLABORATION
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BACK UP
CUORE Preliminary

130Te

100Mo