ICHEP 2022 BOLOGNA

CUORE

Latest results from the CUORE experiment

A search for $0\nu\beta\beta$ of ^{130}Te

Stefano Dell'Oro, *on behalf of the CUORE Collaboration*

Dipartimento di Fisica G. Occhialini, Università di Milano-Bicocca

INFN, Sezione di Milano-Bicocca

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XLI International Conference on High Energy Physics (ICHEP)

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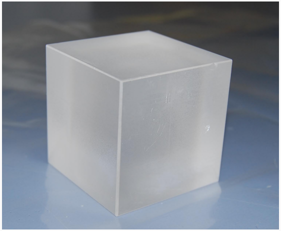
A powerful search has to aim at the optimal
isotope + detector technique combination

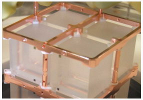
- ^{130}Te is an ideal candidate for the 0νββ search
  - $Q_{\beta\beta}$ moderately high: (2527.515 ± 0.013) keV (between the ^{208}Tl peak and Compton edge)
  - large natural abundance: $(34.167 \pm 0.002)\%$
- Tellurium dioxide, TeO_2, suitable for the use in cryogenic particle detectors
  - high Debye temperature: $\Rightarrow$ small heat capacity
  - thermal expansion close to copper
- production of **high-quality crystals**
  - large mass: ~ 750 g ($5 \times 5 \times 5$ cm^3)
  - scalability of detector arrays
- very **low radioactive contamination**
  - bulk: 10^{-14} g/g for both U and Th
  - surface: $< 10^{-9}$ Bq cm^{-2} for both U and Th



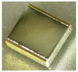
CUORE crystal

Working principle

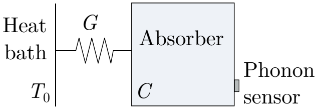
- bolometers detect the **phonon** contribution of the energy release
  - large fraction of the total energy
  - ionization/excitation $\rightarrow \cdots \rightarrow$ phonons
  - measured via **temperature variation**



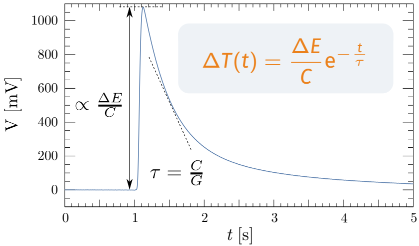
- $\Delta T = \Delta E / C$
  - **low C**: $C \downarrow \quad \Rightarrow \quad \Delta T \uparrow$
  - **very low T**
    - Debye law: $C \propto (T/\Theta_D)^3$
    - thermal fluctuations $\propto T^2\, C$
- temporal evolution: $\tau = C/G$
- Neutron Transmutation Doped Ge thermistor
  - $R = R_* \ \exp\left(T_*/T\right)^{1/2}$



Simplified thermal model

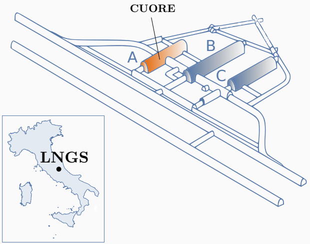


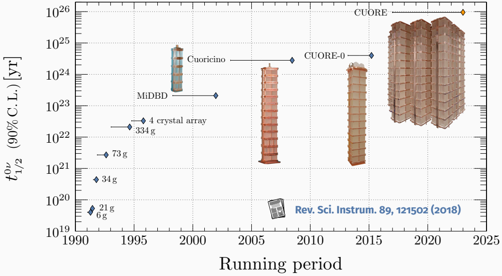
- an absorber with heat capacity C
- (connected to) a heat bath @ constant T_0
- (through) a thermal conductance G



- LNGS $\rightarrow$ ideal place to search for $0\nu\beta\beta$
  - $\sim$ 3600 m w. e. overburden
  - μ: $3 \cdot 10^{-8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  - n: $< 4 \cdot 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ below 10 MeV
- dedicated facilities to run bolometric detectors
  - Hall A dilution refrigerator (1989)
    - crystals (1991 – 1995)
    - MiDBD (1998 – 2001)
    - Cuoricino (2003 – 2008)
    - CUORE-0 (2013 – 2015)
  - CUORE cryostat (2016)
    - **CUORE** (from 2017)

30-year-long history of measurements





CUORE detector

CUORE: Cryogenic Underground Observatory for Rare Events

- largest bolometric detector ever built by a factor 10
  - 19 towers $\times$ 13 floors $\times$ 4 crystals = 988 bolometers
  - 1 tonne detector mass: 330 kg Cu + 742 kg TeO_2

    $\rightarrow$ 206 kg of ^{130}Te
- design goals on performance
  - 5 keV FWHM energy resolution @ 2615 keV
  - 0.01 counts $keV^{-1}\,kg^{-1}\,yr^{-1}$ in the $0\nu\beta\beta$ region
- primary goal: **search for $0\nu\beta\beta$ of ^{130}Te**
  - measurement of $2\nu\beta\beta$ half-life + Te rare decays
  - search for DM candidates (WIMPs, axions, ...)
  - study of the bolometric thermal behavior
  - investigation of background for next generation $0\nu\beta\beta$ experiments

CUORE requires a **dedicated cryogenic system** in order to be operated as a bolometer

A 10-mK infrastructure for large bolometric arrays

- the **design** of the CUORE cryostat had to satisfy **very tight requirements**
  - large **experimental volume** for detector + shielding of $\sim 1\,m^3$
  - **base temperature** for optimal operation of NTDs, i. e. down to 10 mK
  - **low radioactive background** from the cryogenic apparatus,
    compatible with goal of 0.01 counts $keV^{-1}\,kg^{-1}\,yr^{-1}$ at $Q_{\beta\beta}$
  - **high system reliability** to guarantee long-term operation
  - **response to seismic events**
    (LNGS are located in a seismic sensitive area)

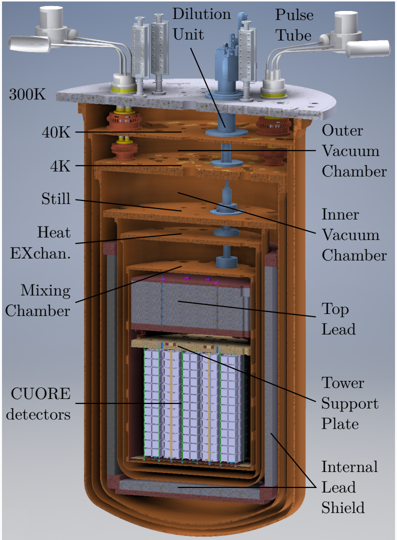
- custom cryogen-free cryostat
- only a few construction materials acceptable
  - use of Cu OFE/Cu NOSV for plates and vessels
  - more than 6.5 t of lead shielding integrated in the structure

CUORE cryostat

- 6+1 thermal stages
  - 300 K @ ambient temperature
  - 40 K @ PT first stage temperature
  - 4 K @ PT second stage temperature
  - Still @ 800 mK
  - HEX @ 50 mK
  - MC @ base $T < 10$ mK
  - TSP @ stabilized working T
- 2 vacuum chambers
- Fast Cooling System +

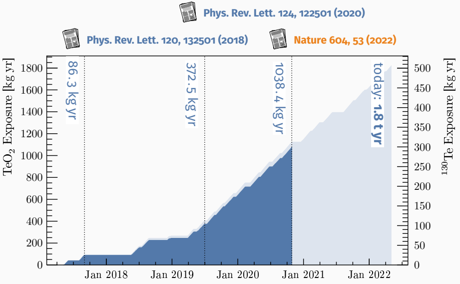
  5 Pulse Tubes + custom Dilution Unit
- 2 internal lead shields
  - use of ancient **Roman lead**
  - Spanish ingots from I century BCE
  - ^{210}Pb activity $<$ **4 mBq kg^{-1}**

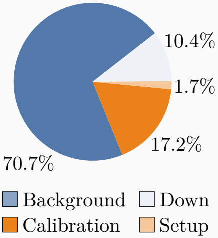
Cryogenics 102, 9 (2019)



CUORE data-taking

- start of data-taking in April 2017
  - initial period of detector optimization
- *full-speed* data collection since 2019
  - exposure increase of $\sim$ 60 kg yr per month
- goal: 3 t yr of TeO_2 (**1 t yr of ^{130}Te**)





Operational performance

- operating $T = 11 - 15$ mK
  - year-long cryogenic stability
- uptime of close to 90%
- 99.5% of channels active (984/988)
- energy resolution at $Q_{\beta\beta}$ of **7.8 keV** FWHM
- $0\nu\beta\beta$ signal efficiency of $\sim$ **80%**

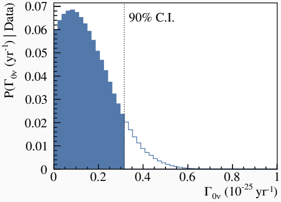
Results on the search for 0νββ

- **no peak** found at $Q_{\beta\beta}$ of ^{130}Te
  - 1038.4 kg yr of TeO_2 / 288 kg yr of ^{130}Te
- **bkg index** in line with expectations:

  $(1.49 \pm 0.04) \cdot 10^{-2}$ counts $keV^{-1}\, kg^{-1}\, yr^{-1}$
- **limit** on decay half-life:

  $\Gamma_{0\nu}^{best} = (0.9 \pm 1.4) \times 10^{-26}\, yr^{-1}$

  $t_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr @ 90% C. I.

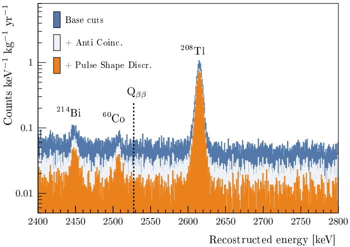


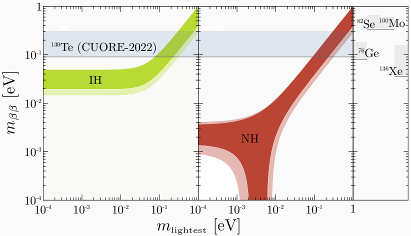
- bound on effective Majorana mass:

  $m_{\beta\beta} > (90 - 305)$ meV

Nature 604, 53 (2022)

ROI spectrum





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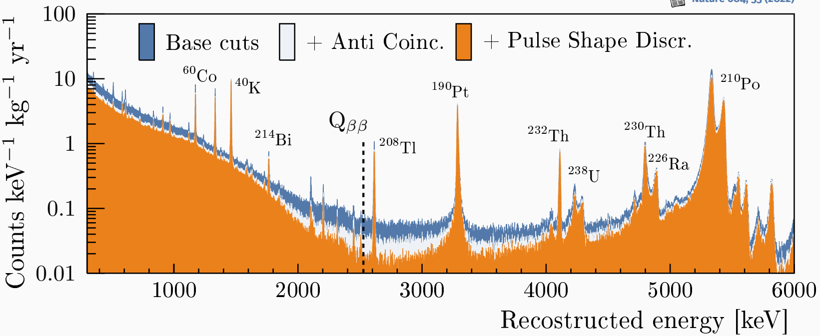
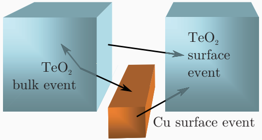


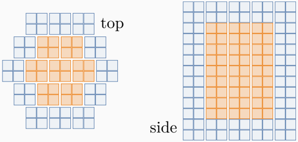
- different contributions in different regions of the energy spectrum
  - γ continuum + peaks up to 2.7 MeV
  - degraded α's in (2.7 — 3.9) MeV
  - α region from 4 MeV
- construction of an extensive **background model**
  - large effort ongoing since predecessors of CUORE
  - ultimate validation by CUORE data

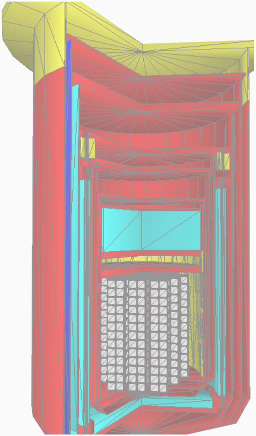


Modeling the background

- simulation of contamination from different cryostat components with **Geant4 MC**
- background sources identified/ascribed to different locations in experimental setup
- inputs of MC
  - coincidence analysis, gamma peaks, alpha peaks
  - radio-assay measurements, data from neutron activation
- split data → exploit detector granularity
  - multiplicities: sensitive to different event topologies

  - inner and outer layers (benefit from self-shielding)

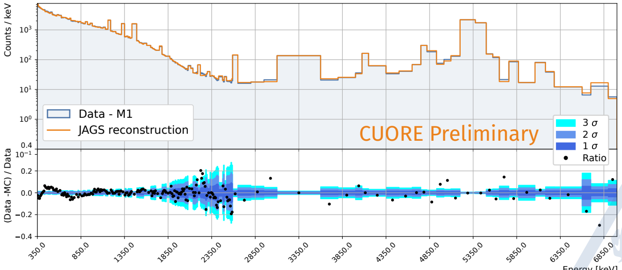




Fit to CUORE data

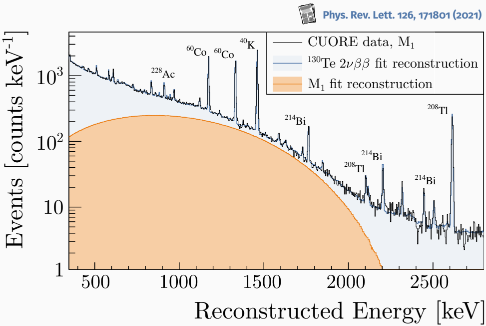
- validation with whole $0\nu\beta\beta$ dataset (1038.34 kg yr of TeO_2)
- $\sim$ 60 independent parameters for possible contamination contributing to bkg model
  - bulk and surface (for near elements) contamination
- large Bayesian Fit to data
  - flat priors on all parameters (except muons which come from cosmogenic analysis)

Multiplicity 1



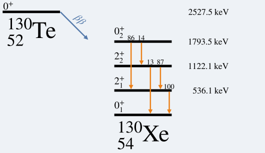
S. Ghislandi, *poster @Neutrino2022*

WORK IN PROGRESS



- 2vββ spectrum dominates in (1 — 2) MeV range
    - accounts for $\sim$ 50% of M_1 events
- most precise measurement of 2vββ of ^{130}Te
    - TeO_2 exposure: 300.7 kg yr
    - $t^{2\nu}_{1/2} = \left(7.71 \ ^{+0.08}_{-0.06} \text{ (stat.) } ^{+0.12}_{-0.15} \text{ (syst.)}\right) \times 10^{20}$ yr

Decay to excited states

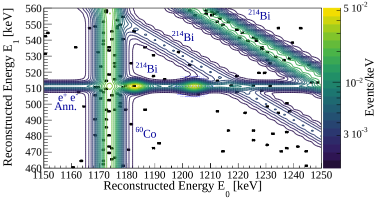


- search for de-excitation γ's
- multi-site signatures
- no peak was found
- limits @ 90% C. I.
    - TeO_2 exposure: 372.5 kg yr
    - $(t_{1/2})^{0\nu}_{0^+_2} > 5.9 \times 10^{24}$ yr
    - $(t_{1/2})^{2\nu}_{0^+_2} > 1.3 \times 10^{24}$ yr

Other searches

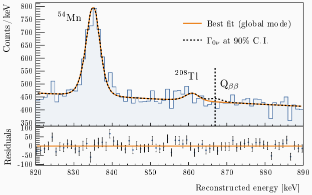
- $0\nu\beta^+EC$ of ^{120}Te $\quad (Q_{\beta\beta} = 1714.8$ keV)
  - $^{120}\text{Te} + e_b^- \rightarrow {}^{120}\text{Sn}^* + \beta^+$
    $\rightarrow {}^{120}\text{Sn} + X + \beta^+$
    $\rightarrow {}^{120}\text{Sn} + X + 2\,\gamma_{511}$
  - multiple signatures in M1, M2 and M3
  - limit: $t_{1/2}^{0\nu} > 2.9 \times 10^{22}$ yr @ 90% C. I.
    - 355.7 kg yr of TeO_2 / 0.2405 kg yr of ^{120}Te $\quad (^{120}\text{Te}/^{nat}\text{Te} = 0.09\%)$

Phys. Rev. C 105, 065504 (2022)



- $0\nu\beta\beta$ of ^{128}Te $\quad (Q_{\beta\beta} = 866.7$ keV)
  - limit: $t_{1/2}^{0\nu} > 3.6 \times 10^{24}$ yr @ 90% C. I.
    - 309.33 kg yr of TeO_2 / 78.56 kg yr of ^{120}Te

arXiv:2205.03132 [nucl-ex]



- broad-band investigations
  - low-E search for DM (WIMPS, axions, ...)
  - high-mulitplicity event reconstruction for exotic processes
  - spectral-shape studies of $2\nu\beta\beta$ for CPT violation, Majoron emission, ...

Summary & Outlook

- CUORE has been collecting data since 2017
  - the current limit on the 0νββ of ^{130}Te is: $t^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr @ 90% C. I.
  - multiple analyses are ongoing
- the goal is to collect 1 t yr of ^{130}Te

Looking ahead…

See G. Fantini's talk

- **CUORE** is sharing in the efforts, together with the **CUPID-0** and **CUPID-Mo** Collaborations, to bulid the next-generation bolometric experiment searching for 0νββ
  - **CUPID** = CUORE Upgrade with Particle IDentification
    - enhanced sensitivity, aimed at probing the *IH* of the neutrino mass region
    - a rich R&D program is already underway… consider joining

Thank you!

CUORE Collaboration – LNGS (Italy), June 2022

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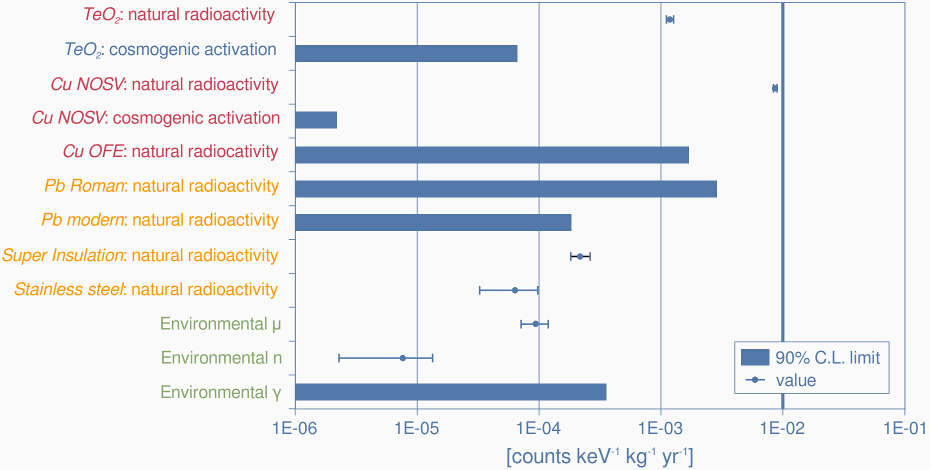
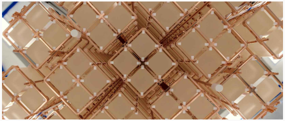
Eur. Phys. J. C, 77, 543 (2017)



cosmogenic activation Te   CUORE-0 bkg model   material screening   environmental fluxes

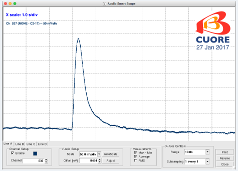
- tower assembly (Sep 2012 – Jul 2014)
- cryostat commissioning

  (Aug 2012 – Mar 2016)
- detector installation (Jul – Aug 2016)

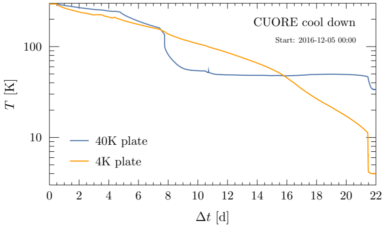


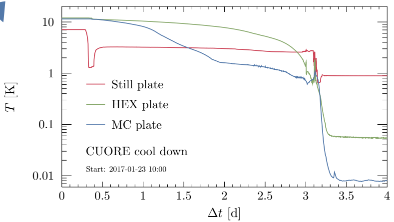
- cool down: $\boldsymbol{T_{MC}}$ **= 6.8 mK**

First events @ Jan 2017



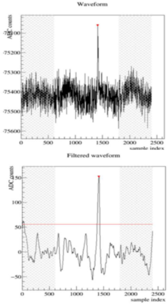
CUORE cool down

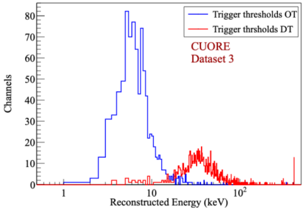




Triggering pulses

- Online Derivative Trigger (DT): threshold on the derivative of the data-stream
- Offline Optimal Trigger (OT): identification of pulses in the filtered data-stream (template filter: expected pulse shape wrt to expected noise)



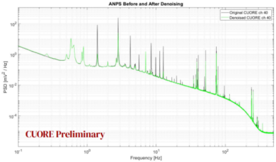


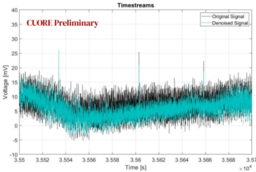
Thresholds: DT ~50 keV, OT <10 keV

CUORE low thresholds

Denoising the continuous data

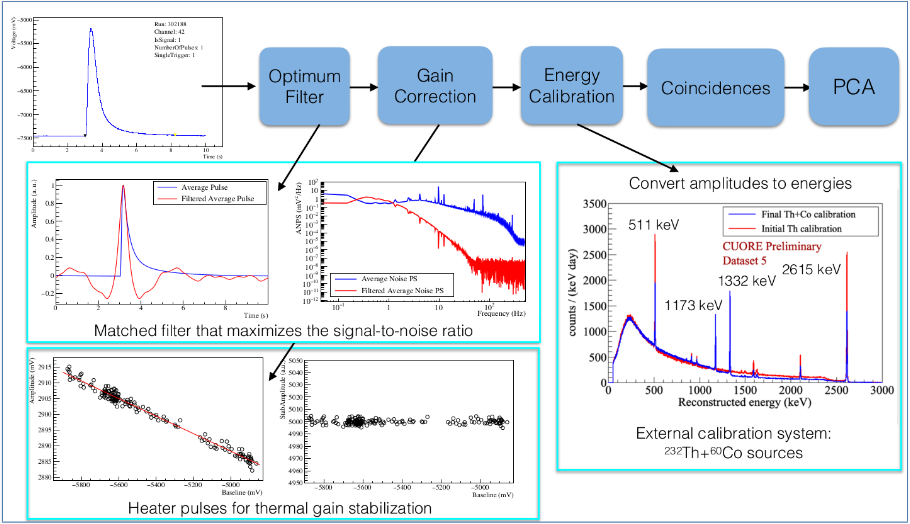
Remove noise from calorimeter channels utilising diagnostic devices (accelerometers, antennae, microphones) which can identify and measure the noise sources.





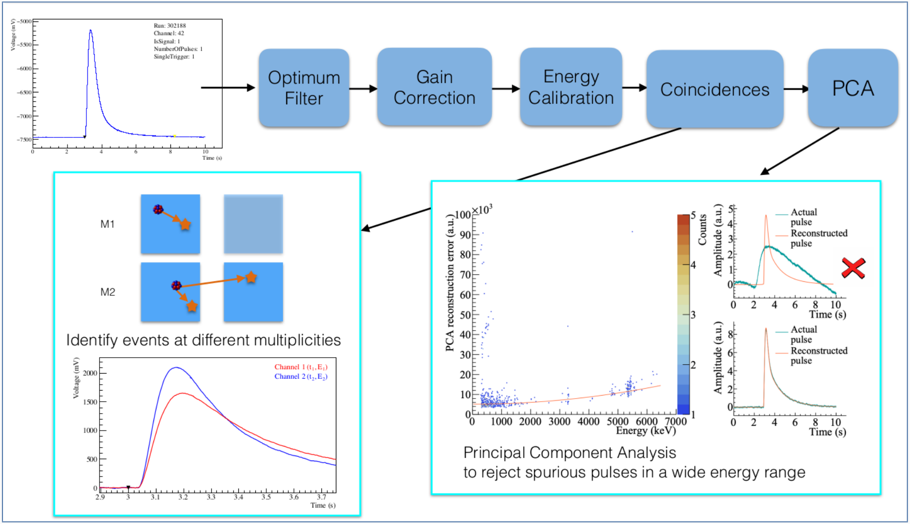
CUORE denoising @DNP 2021

By courtesy of I. Nutini, *CUORE talk @Neutrino2022*



By courtesy of I. Nutini, *CUORE talk @Neutrino2022*

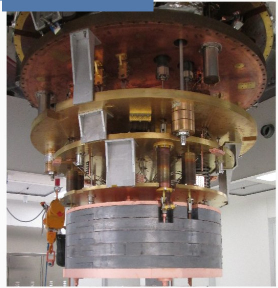
CUORE data processing III



By courtesy of I. Nutini, *CUORE talk @Neutrino2022*

Some pictures from the CUORE cryostat

Plates + Top Lead



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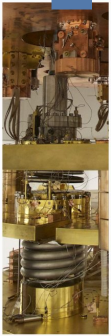
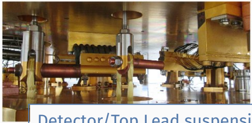


PT

Superinsulation



Detector/Top Lead suspensions

Inside the IVC

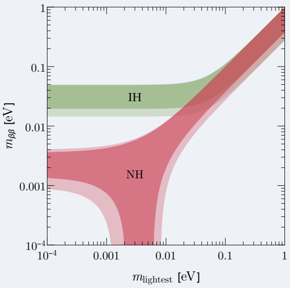
Vessels

Effective Majorana mass

- $m_{\beta\beta}$ is the key quantity in the 0νββ
  - absolute value of **ee-entry** of ν mass matrix
  - $m_{\beta\beta} \equiv |M_{ee}| = \left| \sum_{i=1,2,3} e^{i\xi_i} \, |U_{ei}^2| \, m_i \right|$
  - $U \equiv U|_{osc.} \cdot \text{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
    - 1 CP-violating + 3 **Majorana phases**
    - U **mixing matrix** of oscillation analysis
  - only two phases play a *physical* role
- $m_{\beta\beta} = \left| e^{i\alpha_1} \cos^2\theta_{12} \cos^2\theta_{13} m_1 + e^{i\alpha_2} \cos^2\theta_{13} \sin^2\theta_{12} m_2 + \sin^2\theta_{13} m_3 \right|$

$m_{\beta\beta}$ vs. m_{lightest}

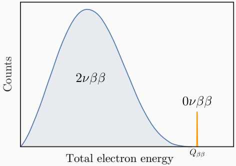
Phys. Rev. D 90, 033005 (2014)



An **experimental measurement** of the 0νββ half-life corresponds to a **horizontal band** in the ($m_{\beta\beta}$ vs. m_{lightest}) plot.

The band width is due to **theoretical uncertainties** from atomic and nuclear physics

Experimental search for 0νββ



- the **search** relies on detection of the 2 emitted e^-
  - monochromatic peak at $Q_{\beta\beta}$
  - smearing due to finite energy resolution
- the **observable** is the decay half-life $t^{0\nu}_{1/2}$ of the isotope
  - the experimental sensitivity corresponds to the maximum signal that can be hidden by the background fluctuations $n_B = \sqrt{M\,T\,B\,\Delta}$

$$t^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \sqrt{\frac{M\,T}{B\,\Delta}}$$

M = detector mass T = measuring time
B = background level Δ = energy resolution

- the **information on the neutrino mass** can be extracted

$$\left[t^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,\frac{m^2_{\beta\beta}}{m^2_e}$$

  - $G_{0\nu}$ = **Phase Space Factor** (atomic physics)
  - $\mathcal{M}$ = **Nuclear Matrix Element** (nuclear physics)
  - $m_{\beta\beta}$ = **effective Majorana mass** (particle physics)

$$m_{\beta\beta} \leq \frac{m_e}{\mathcal{M}\sqrt{G_{0\nu}\,t^{0\nu}_{1/2}}}$$