Dark matter annual modulation with CUORE experiment

DARK SIDE OF THE UNIVERSE 2016

BERGEN, JULY 25-29

LAURA MARINI

UNIVERSITÀ DI GENOVA

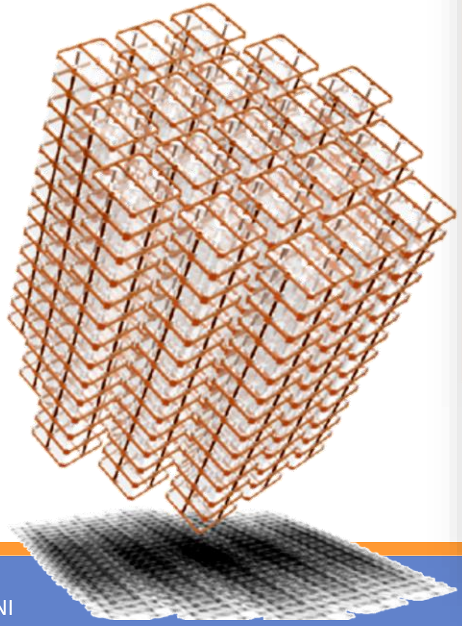
ON BEHALF OF THE CUORE COLLABORATION

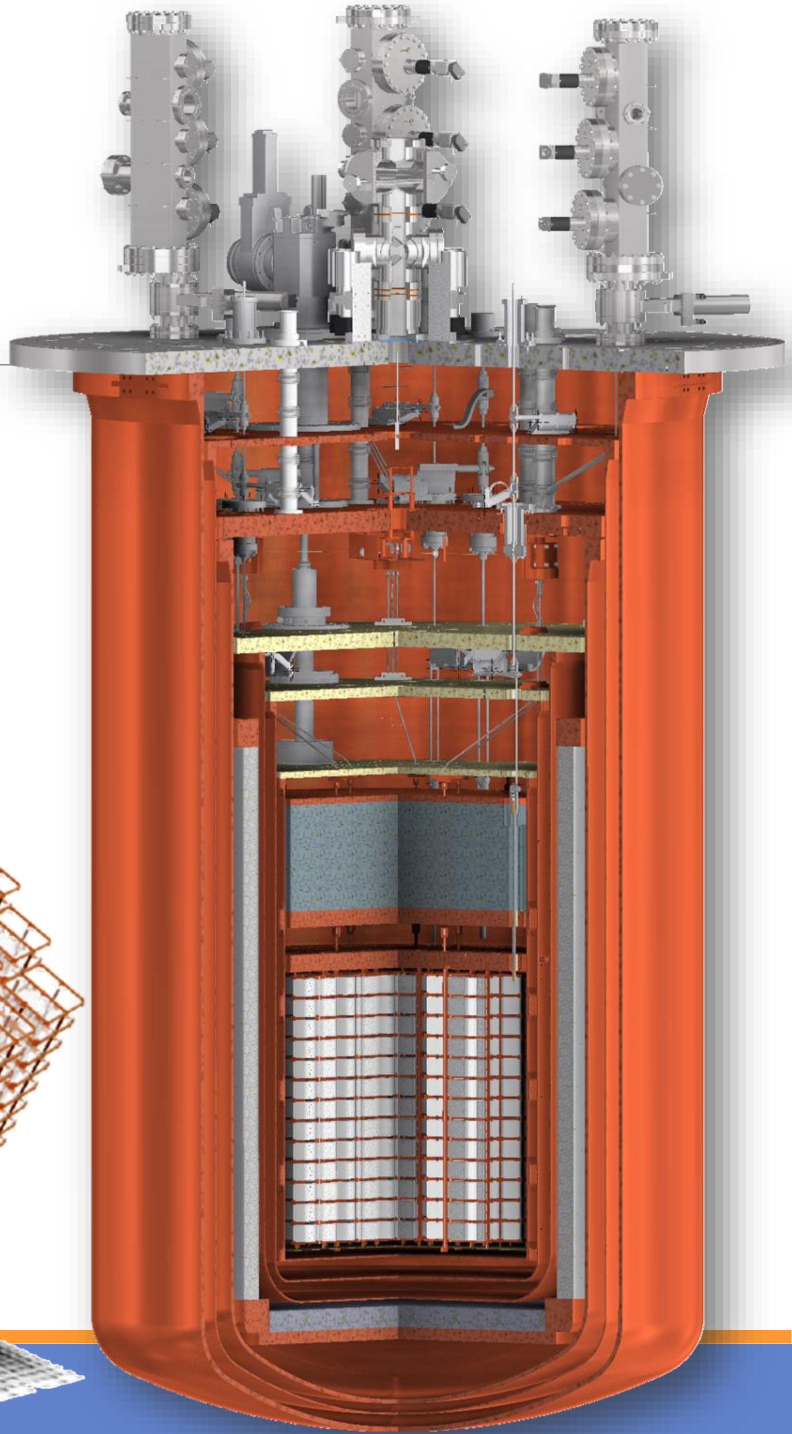
CUORE

Operate a huge bolometric array, in an extremely low radioactivity and low vibrations environment

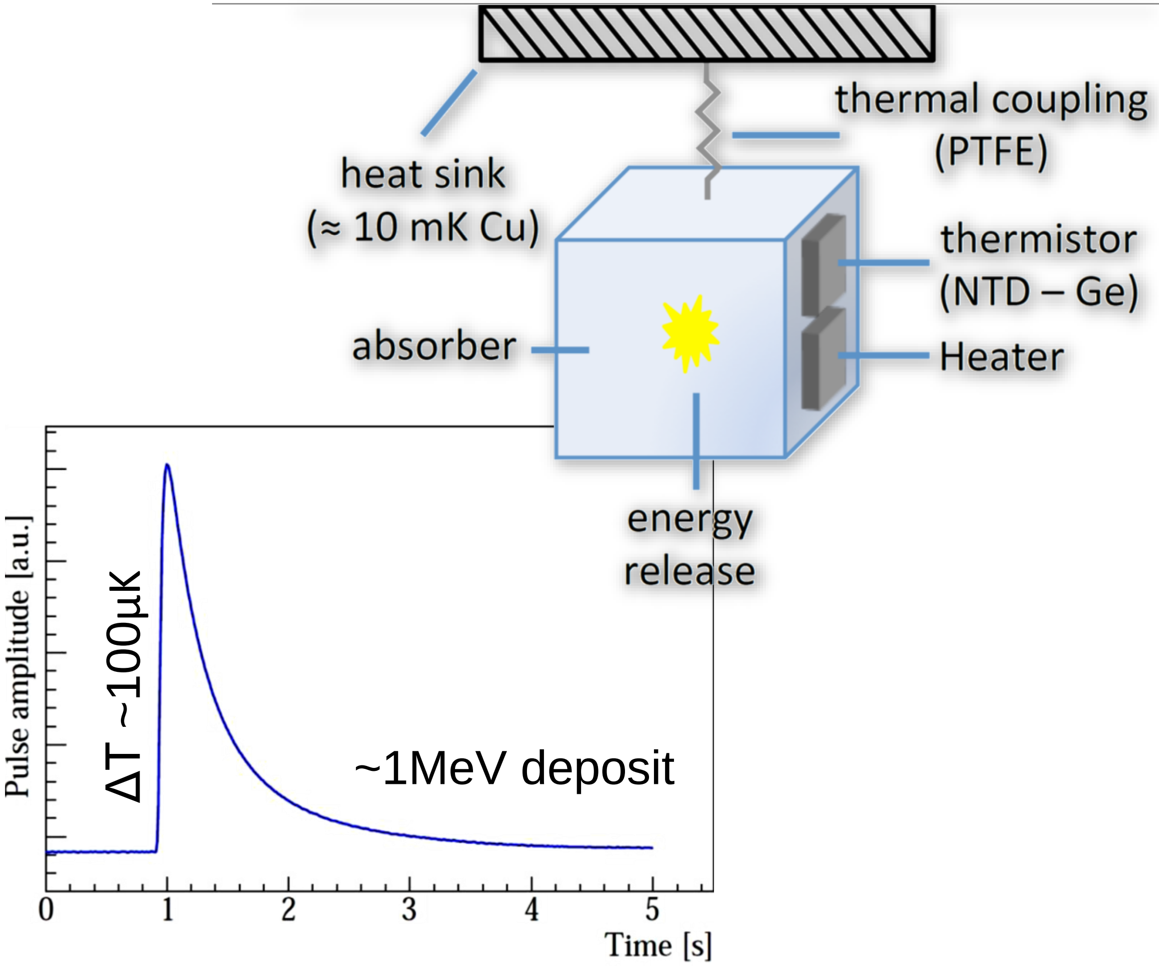
- array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75kg each)
- Energy resolution: 5keV @ 2615keV [FWHM] ($Q_{\beta\beta}$≅2527 keV)
- Stringent radiopurity controls on materials and assembly
- Operating temperature: ~ 10 mK
- Mass to be cooled < 4K: ~ 15 tons (Pb, Cu and TeO_2)

Designed for $0\nu\beta\beta$ of ^{130}Te, but suited for dark matter searches thanks to the low energy threshold and the big exposure





Bolometric technique

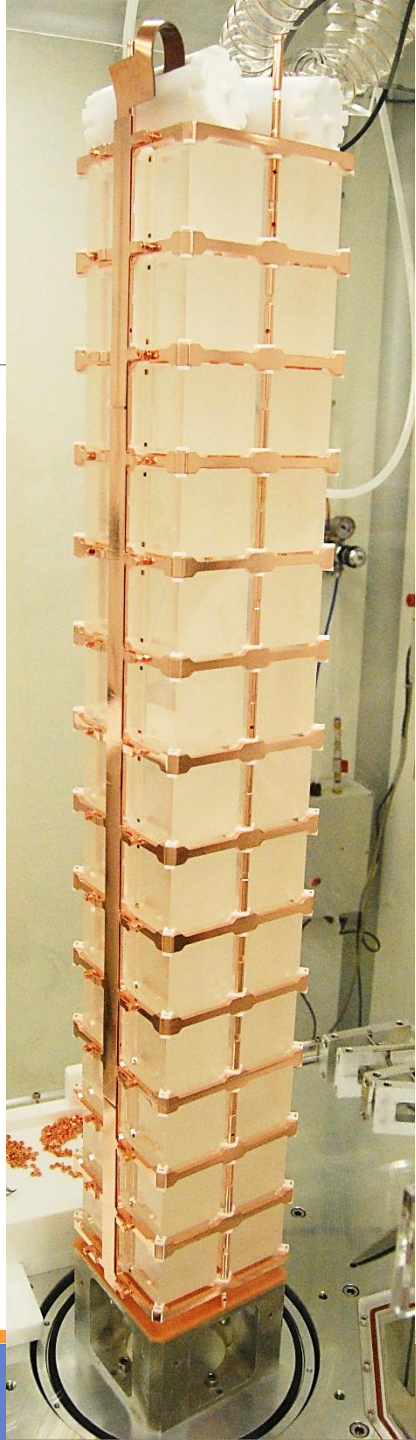


A particle interaction in the absorber causes an increase in temperature, measured by the thermistor

$$\Delta T = \frac{\Delta E}{C} \sim \frac{100\mu K}{MeV}$$

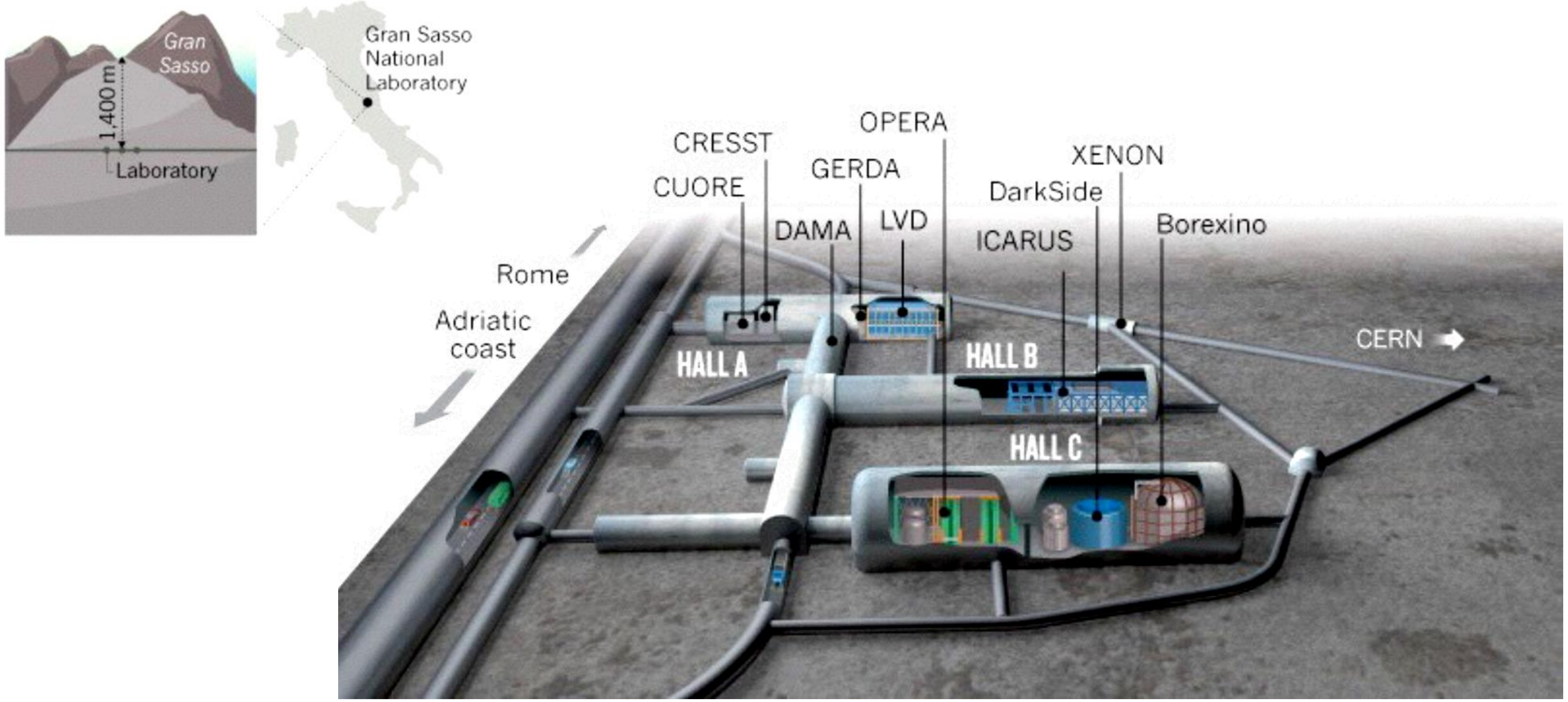
$$\tau = \frac{C}{G} \sim 1s$$

C: absorber capacity
ΔT: temperature variation
ΔE: energy deposition
G: thermal conductance
τ: signal decay time



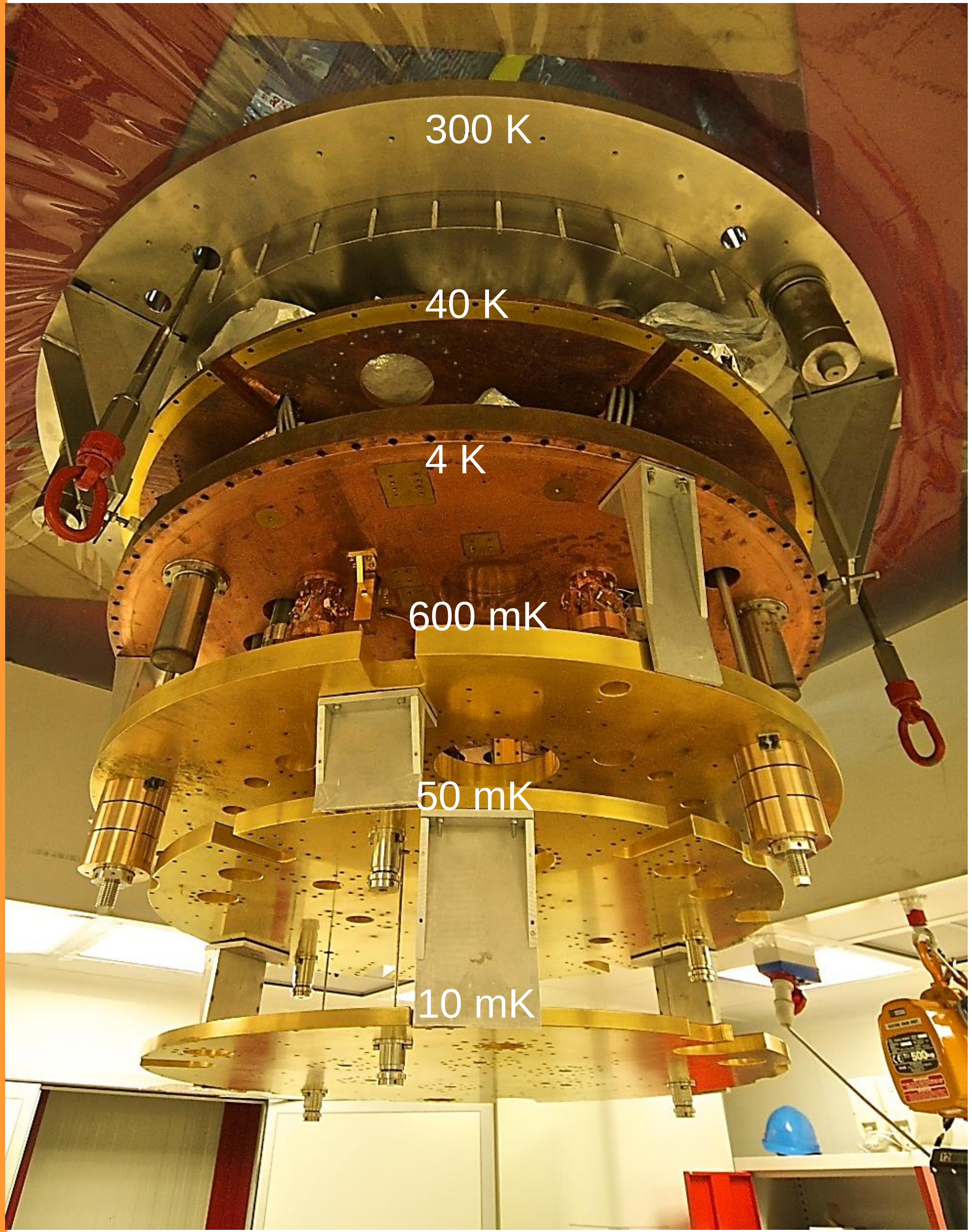
LNGS: LABORATORIO NAZIONALE DEL GRAN SASSO

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



CUORE STATUS: CRYOGENIC SYSTEM COMMISSIONED

Goal was to develop a cryogenic system capable to deliver stable base T (~10mK)



- ✓ Thermalization of all cryostat components – no evident heat leaks
- ✓ Stable base temperature without detector towers: **6.3 mK**
- ✓ Provided nominal cooling power: 3µW @ 10mK
- ✓ Base temperature allows an operating temperature of 10mK for a stable detector response

CUORE STATUS: SHIELDING FROM EXTERNAL BACKGROUND

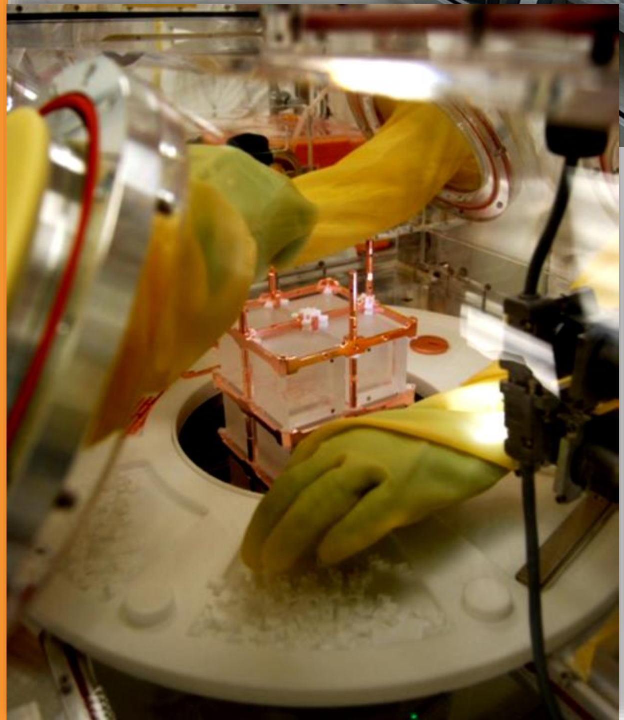
Background aim in $Q_{\beta\beta}$ ROI:

10^{-2} counts/keV/kg/year

- ✓ Cleaning and selection of materials to achive a radio clean envirnoment
- ✓ Lateral and bottom shielding with 6cm of roman lead @4K
- ✓ Top shielding with 30cm of modern lead

CUORE STATUS: TOWERS ASSEMBLY

All 19 towers assembled and ready to be installed starting from July 26



Towers assembled inside N_2-flushed glove boxes, to minimize exposure to Rn

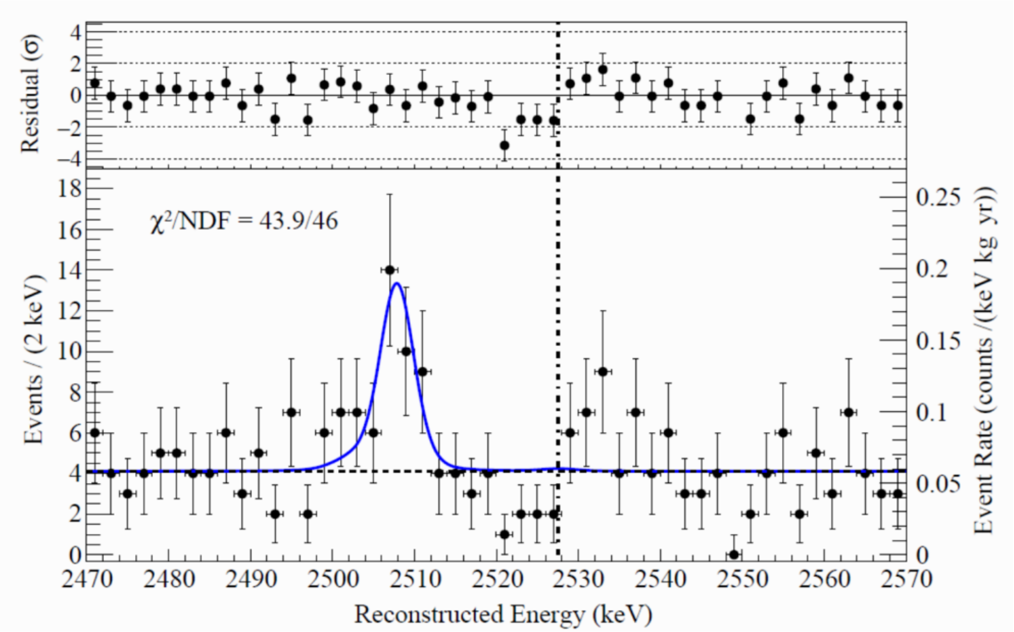
- ✓ gluing of NTD thermistors and heaters to crystals
- ✓ assembly of instrumented crystals into a tower
- ✓ wire bonding of the crystals' chips to the readout cables

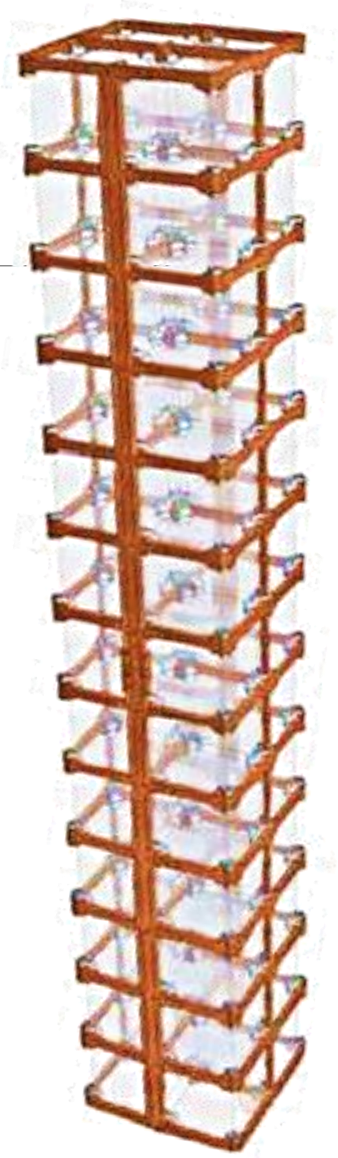
CUORE-0: the first CUORE tower

Single CUORE tower:
- ✓ Test of the assembly procedure
- ✓ Test of the design
- ✓ Measure the background
  - ✓ Low background level achived
- ✓ Measure the energy resolution

Total detector mass: 39kg of TeO_2 (10.9kg of ^{130}Te)
Data taking from March 2013 to September 2015

Reached the CUORE energy resolution:
4.9keV FWHM @ 2615keV





CUORE-0

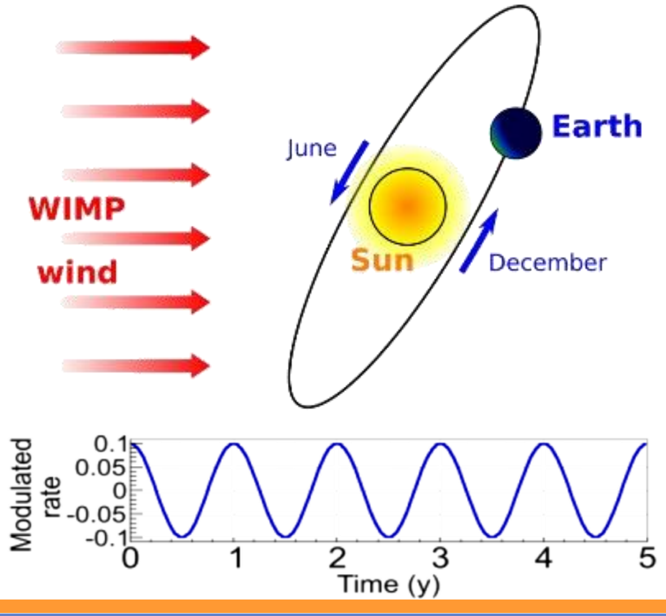
$0\nu\beta\beta$ ANALYSIS
Phys. Rev. Lett. 115 (2015) no.10, 102502
Phys. Rev. C 93, 045503 (2016)

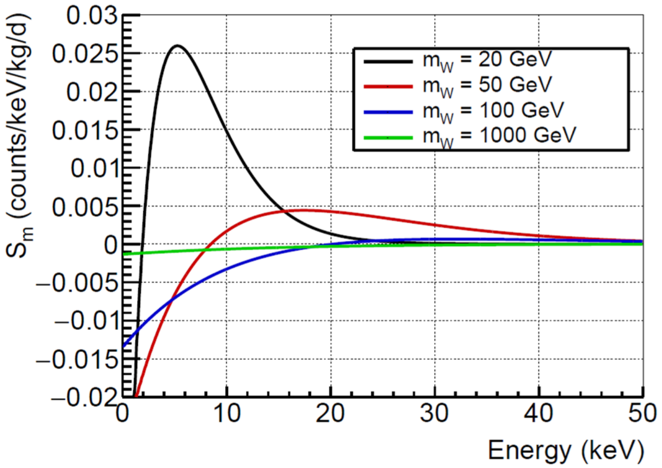
DARK MATTER ANALYSIS
ongoing (this talk)

CUORE bolometers for WIMP detection

- Good energy resolution
- Low energy threshold achievable
- Big exposure (for CUORE only)
- Quenching factor ~1 for nuclear vs electron recoils
- Sensitive to both light and heavy mass WIMPs

- Limited sensitivity to SD interactions
- No particle discrimination
  - ➢ Background in the ROI
    - ➢ **LOOKING FOR ANNUAL MODULATION!**





Expected SI DM modulated rate in a TeO_2 bolometer for different WIMP masses

Signature

- annual modulation of events rate
- model independent approach
- maximum on June 1st

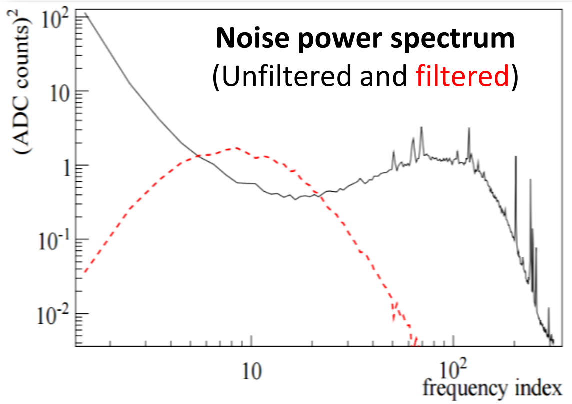
Challenges

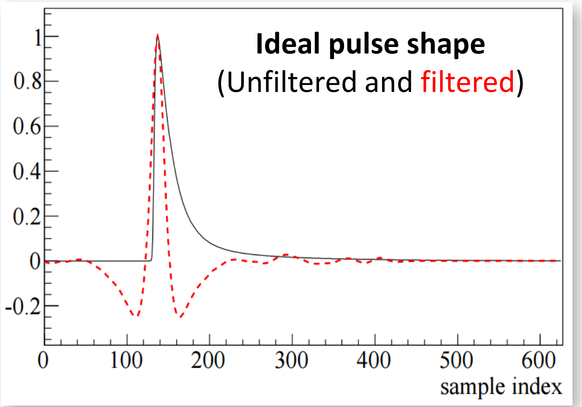
- lower the energy threshold
- high stability of detector parameters

Exploring low energies

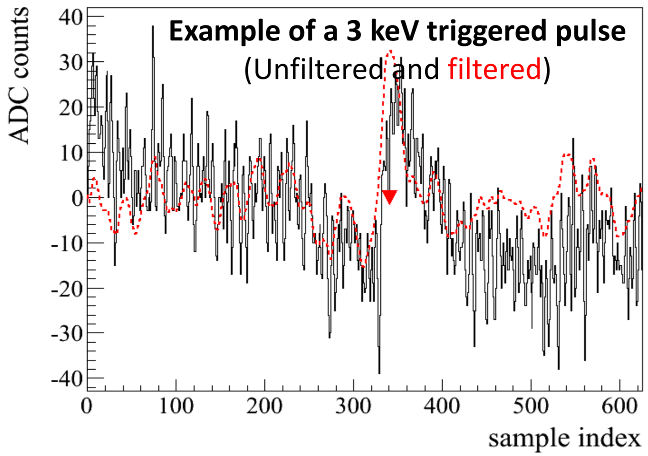
We apply continuously an optimum filter that maximizes the signal to noise ratio

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-j\omega_k i_M}$$

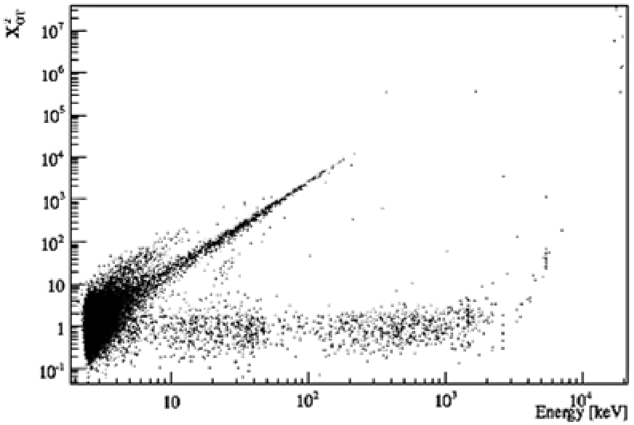




triggering on filtered data which allows to lower the energy threshold



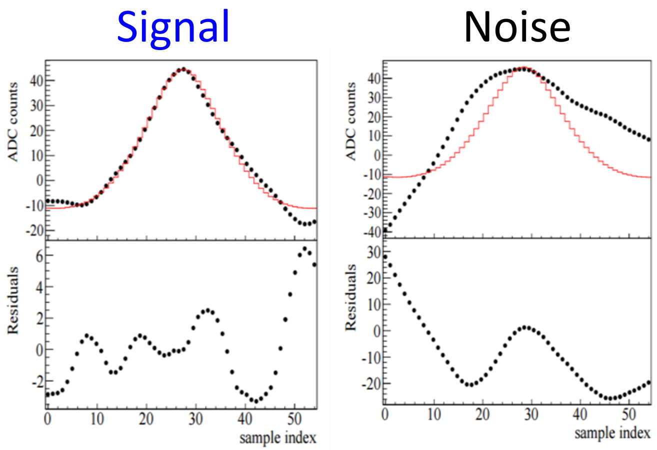
pulse shape parameter to discriminate signal from noise during the analysis, based on the χ^2 between filtered pulse and template

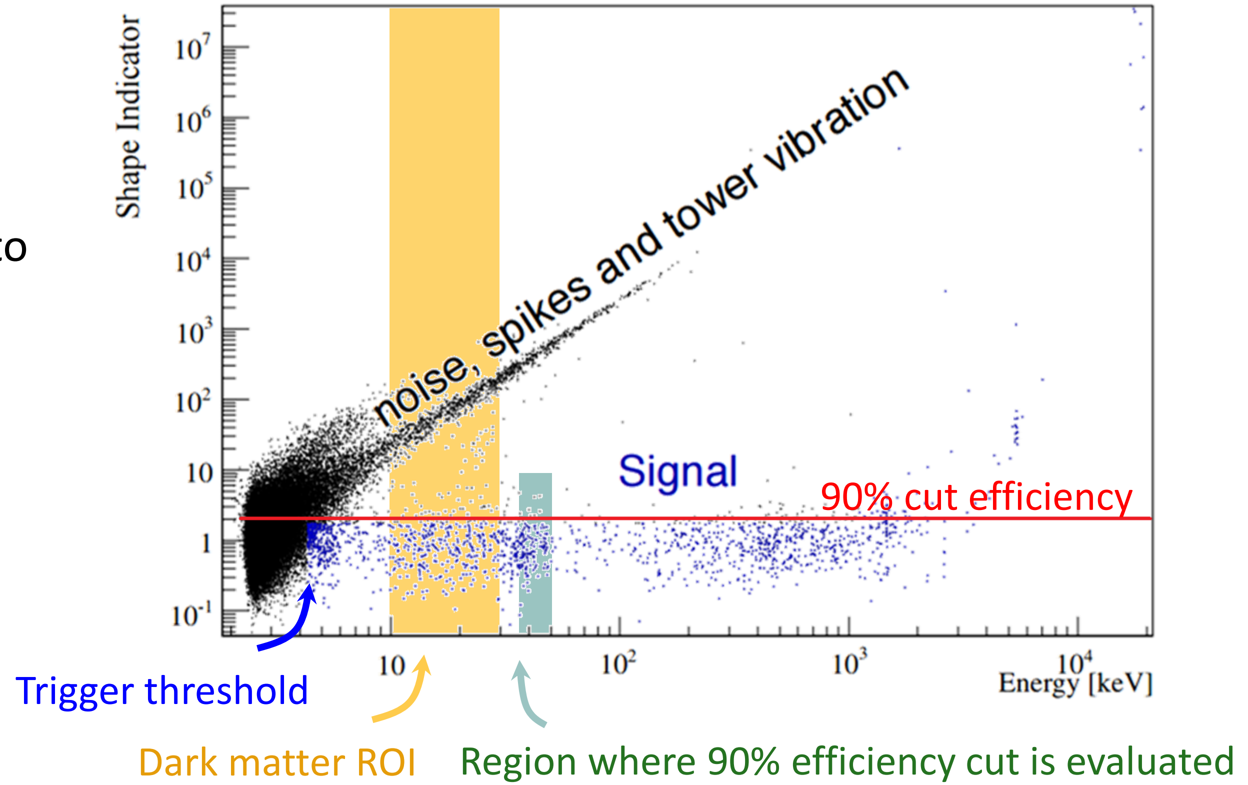


CUORE-0 results: data selection

Strong channel and data selection to reduce noise:

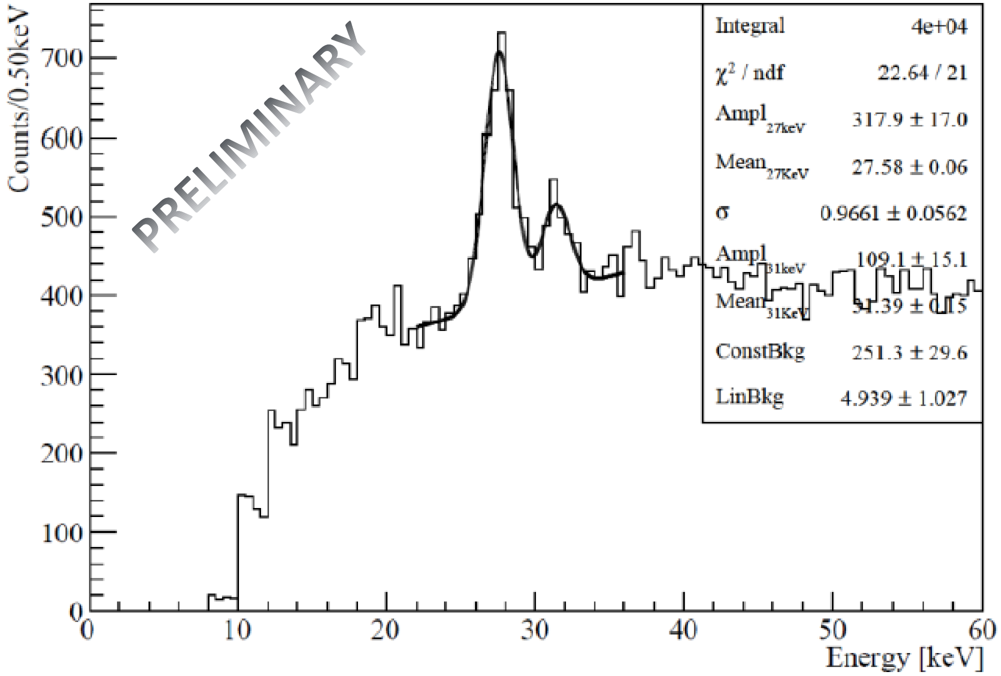
- Cut on pulse shape indicator (signal vs noise)
- Selected only channels where the calibration peak was visible – see next slide (26 channel out of 52)
- Analysis energy thresholds higher than trigger thresholds to be out of the noise band





CUORE-0 results: calibration

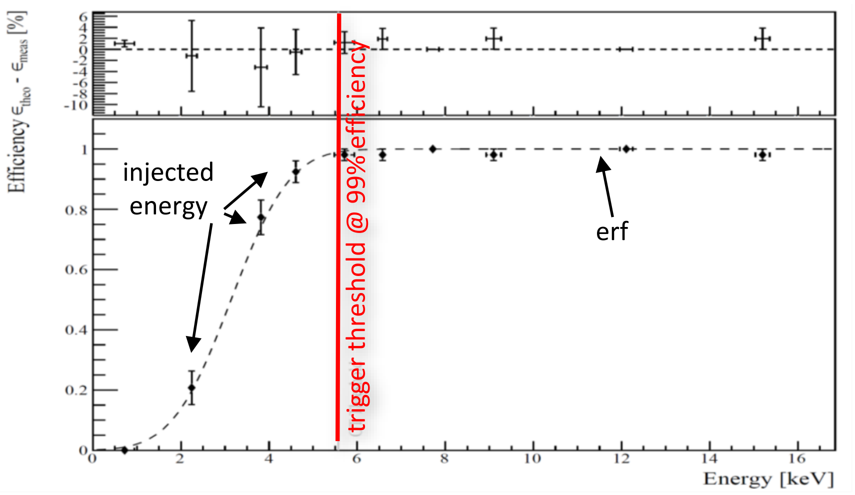
- A calibration run is periodically performed with ^{232}Th. In this way we check the single channel calibration stability
- Two X-ray with mean energy around 27keV and 31keV arise from the Te atomic de-excitation
- These peaks are visible in the total spectrum and can be used to evaluate the overall energy calibration uncertainty



CUORE-0 results: energy thresholds

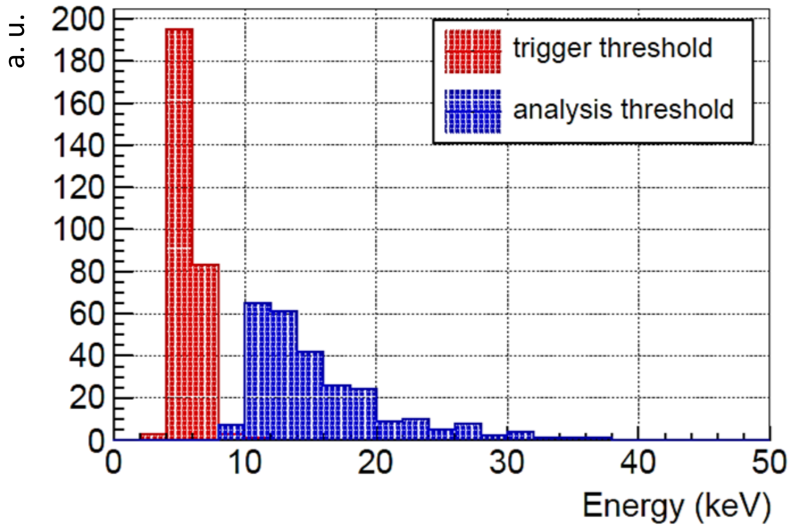
Two methods to evaluate trigger efficiency:

- Injecting precise energy amounts using resistors glued on the crystals
- Analytically predicted using the "error function" and describing noise events distribution with a Gaussian centered on zero and with a certain σ

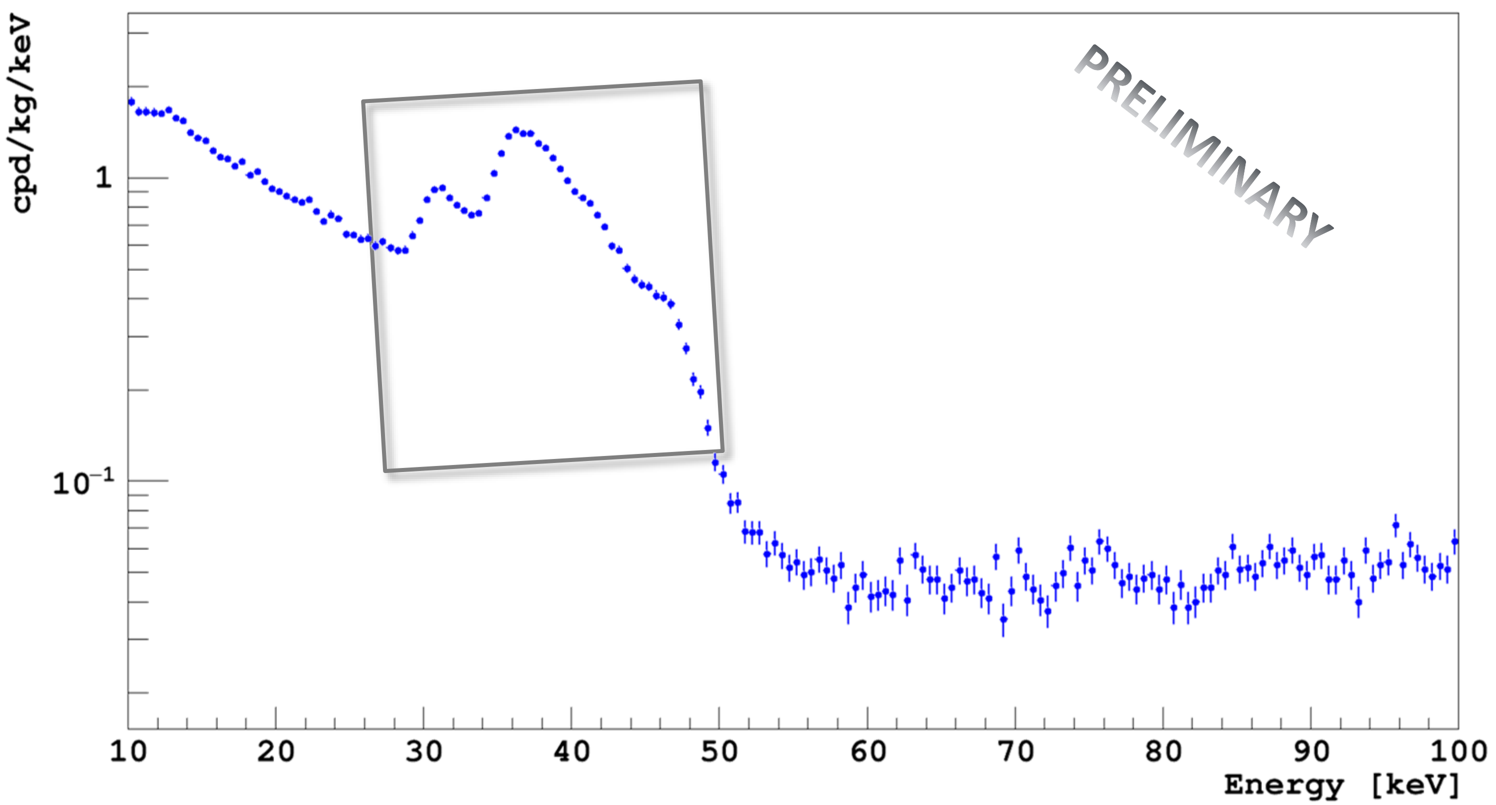


Analysis energy thresholds:

- Higher than trigger threshold in order to minimize the noise contribution to the energy spectrum

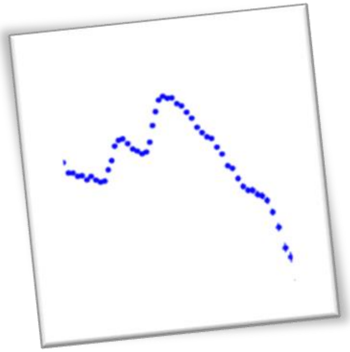


CUORE-0 results: low energy spectrum



Total energy spectrum at low energy obtained with filtered data and strong data selection

The nature of these bumps, very likely due to ^{210}Pb, is still under study



Total Exposure = 10.9 kg·y

CUORE

CUORE-0 results: WIMP sensitivity

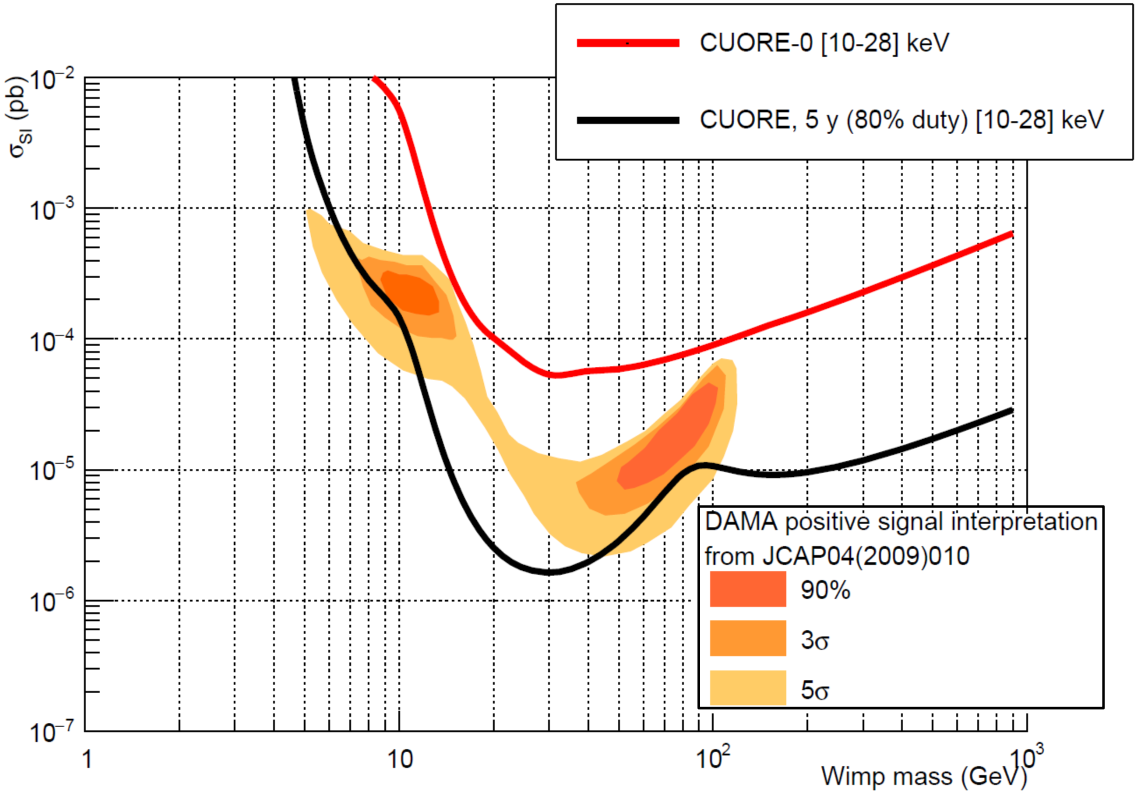
CUORE and CUORE-0 sensitivity to DM annual modulation

The total exposure for CUORE-0 is 10.9 kg yr and the analysis thresholds vary between 10 and 30 keV

CUORE-0 sensitivity to DM annual modulation is very limited due to the low statistics

but…

extrapolating background from CUORE-0 and assuming an analysis energy threshold of 10keV, CUORE could test the DAMA/LIBRA annual modulation positive signal, assuming a WIMP scenario and a standard galactic halo model



Summary

Dark Matter search with CUORE-0 and perspectives for CUORE experiment

- CUORE is a bolometric experiment mainly designed for ^{130}Te $0\nu\beta\beta$ search

- CUORE will also be able to search for WIMPs, thanks to its large mass, good energy resolution and foreseen low background

- CUORE-0 (single CUORE tower prototype) allowed us to develop and tune low energy tools for CUORE

- CUORE-0 achived 10 keV threshold for best crystals and a background ~1 cpd/kg/keV

- Assuming the same CUORE-0 background/threshold (conservative), CUORE will be able to explore the DAMA parameter region obtained assuming that the DAMA annual modulation can be interpreted accordingly to the WIMP scenario and assuming a standard galactic halo model

CUORE

THANKS

CSNSM

Yale

UCLA

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

SINAP

INFN Istituto Nazionale di Fisica Nucleare

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITY OF SOUTH CAROLINA

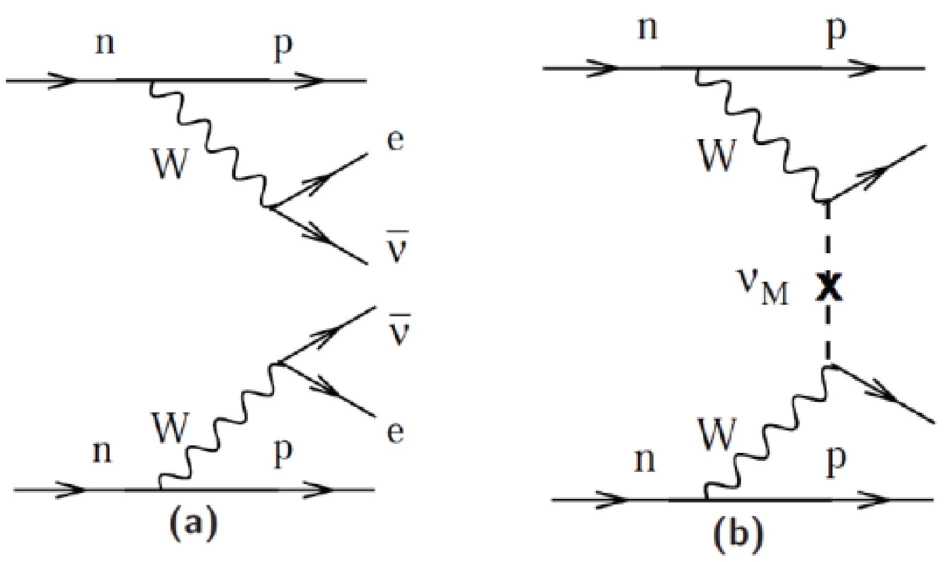
BERKELEY LAB

CAL POLY SAN LUIS OBISPO

Massachusetts Institute of Technology

Lawrence Livermore National Laboratory

Backup - Main goal: $0\nu\beta\beta$



$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Why $0\nu\beta\beta$?

- lepton number violation
- Majorana nature of neutrinos
- constrain of the absolute neutrino mass scale

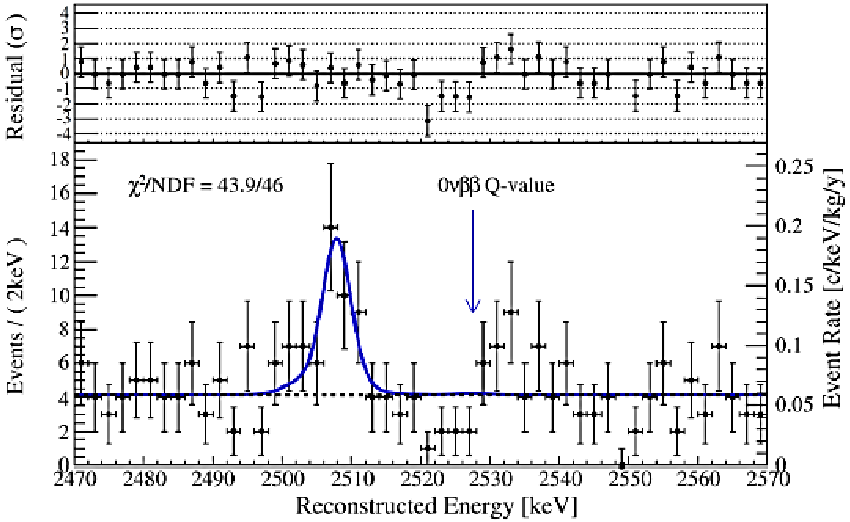
Signature

- peak at the Q-value of ^{130}Te **(**2527keV)

Challenges

- big exposure (mass x time)
- high energy resolution
- low backgroung

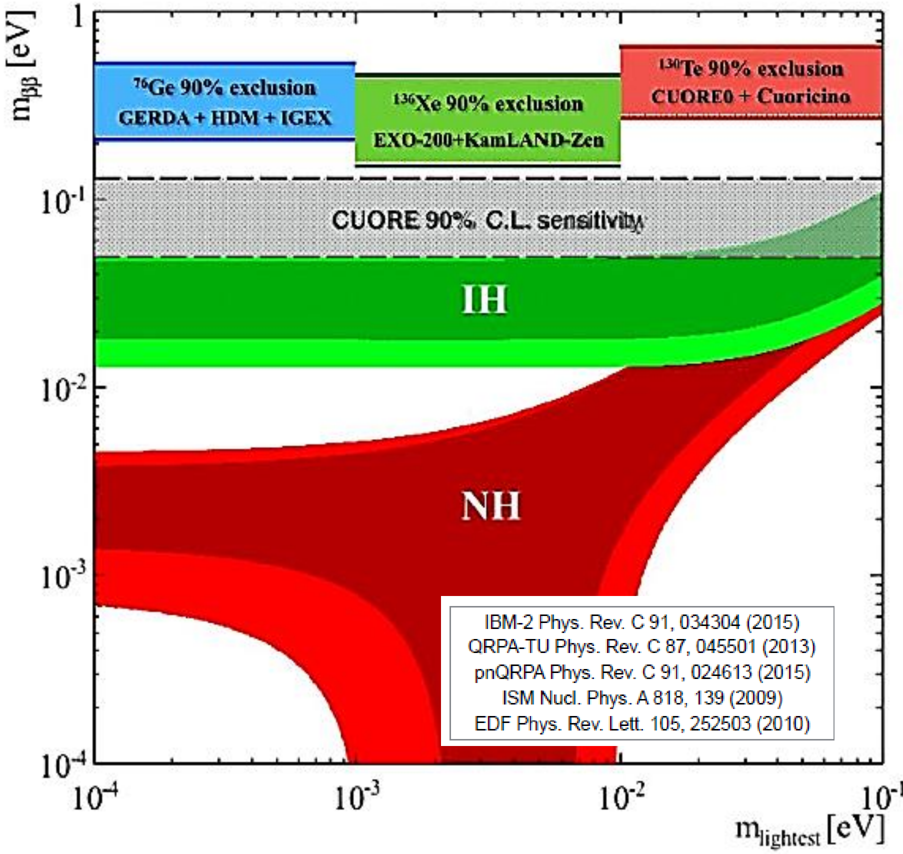
Backup - CUORE-0: results for $0\nu\beta\beta$



Exposure: 9.8 kg yr (^{130}Te)

Fit function in the energy region 2470-2570keV

- signal peak at the Q-value of the transition
- a peak at 2507keV from ^{60}Co double-gammas
- smooth continuum background – multiscatter Compton events from ^{208}Tl and surface decays



Phys. Rev. Lett. 115 (2015) no.10, 102502
doi:10.1103/PhysRevLett.115.102502 [arXiv:1504.02454 [nucl-ex]]

Best-fit values:

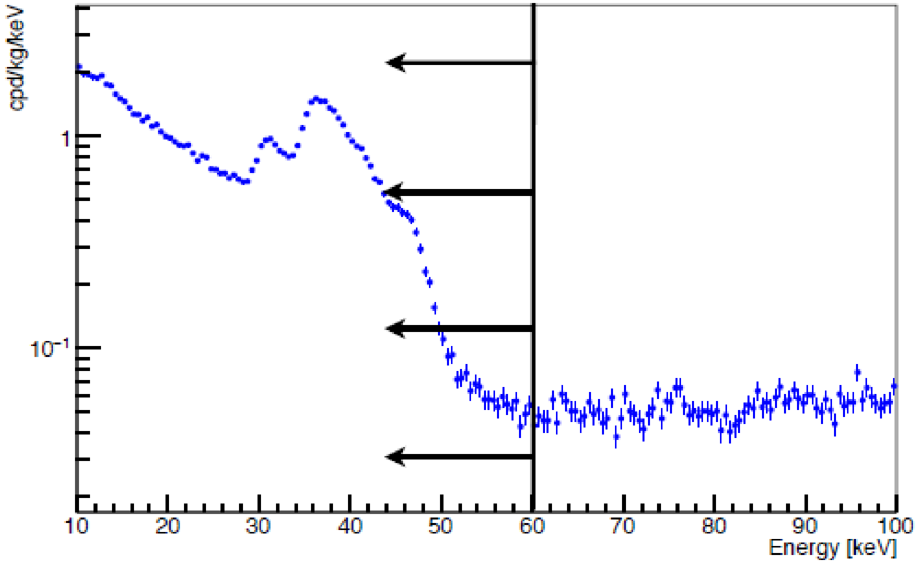
Decay rate $\Gamma^{0\nu\beta\beta}$ **= 0.01 ± 0.12(stat)±0.01(syst) × 10^{-24}yr^{-1}**

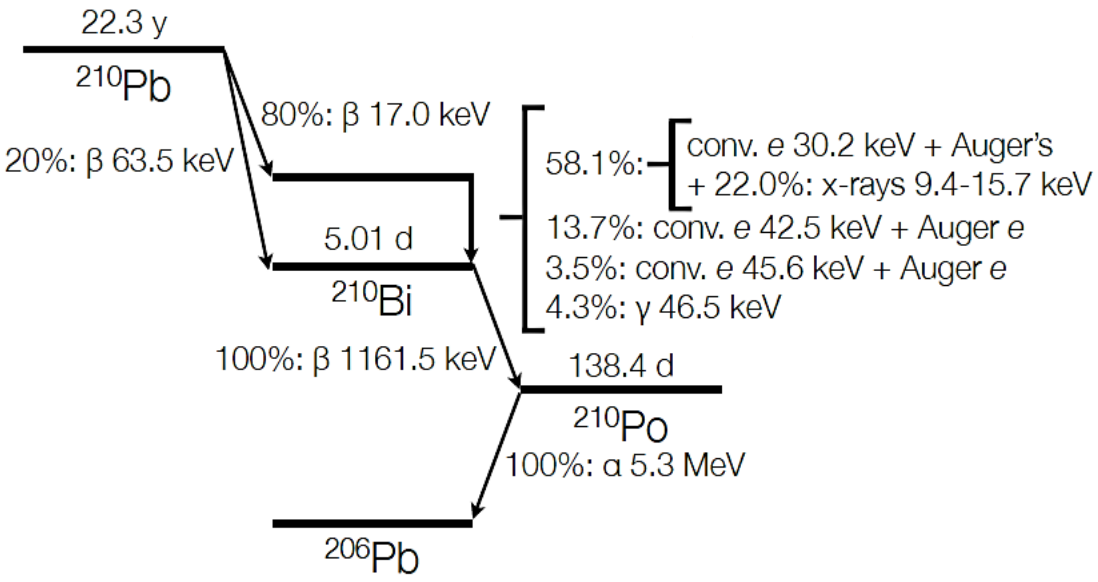
Background index in ROI 0.058±0.004(stat)±0.002(syst) counts/keV/kg/y

Limit on effective Majorana neutrino mass <$m_{\beta\beta}$>: 270-650meV

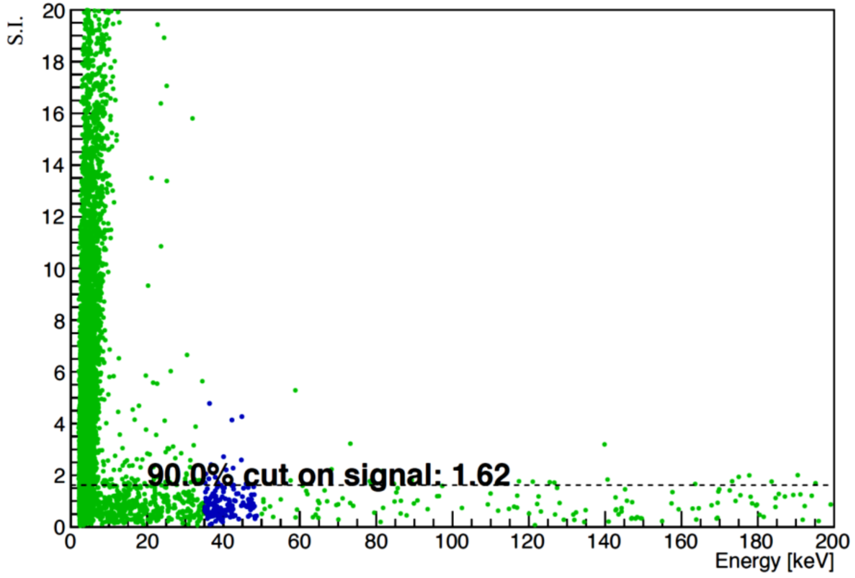
Backup – Low energy bumps

Possible explanation of the bumps and of the rise below 60keV in the energy spectrum: inclusions of ^{210}Pb in the materials facing the crystals or in the crystals themselves



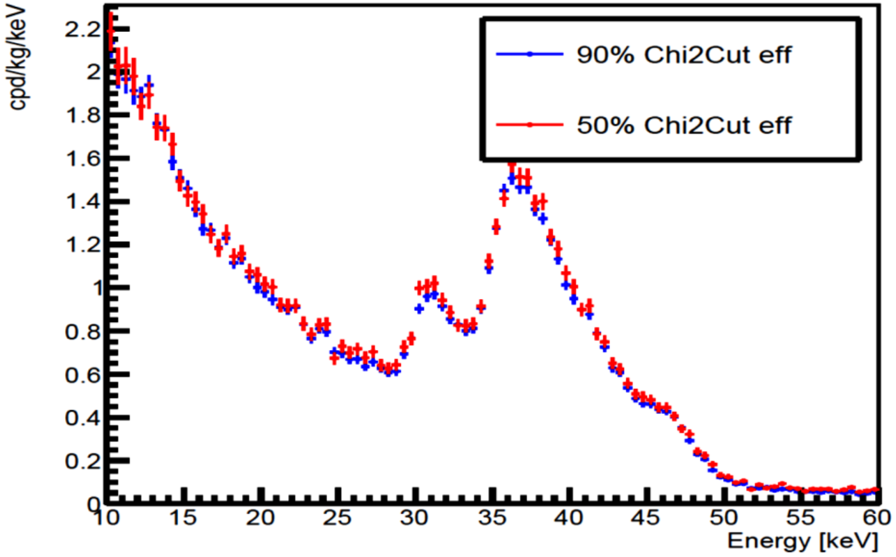


Backup – χ^2 cut efficiency



Comparison of the 90% cut efficiency spectra with the 50% one (smaller cut value → smaller inclusion from the upper noise band) to check goodness and stability of the selection:
the two spectra are compatible

To select good quality events we perform a 90% efficiency cut on the Shape Indicator for events in the [35,50] keV interval



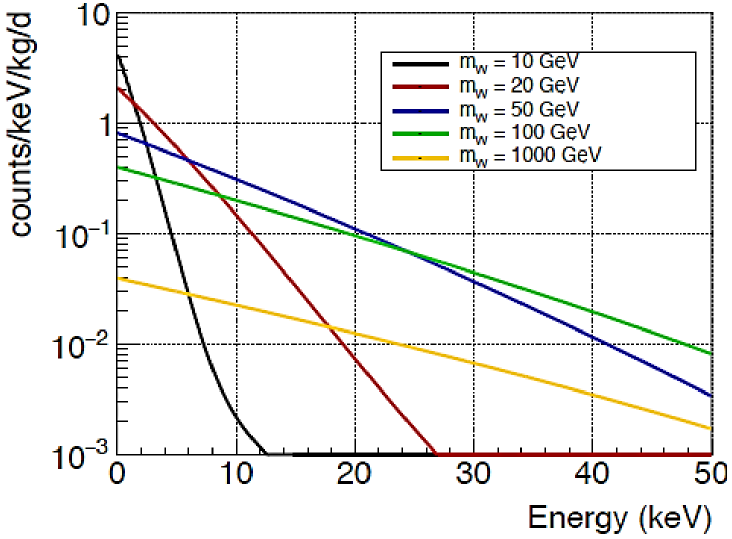
Backup – WIMP event rate in TeO_2

Expected WIMP event rate in TeO_2 for different WIMP masses.

Parameter	Value
ρ_W	0.3 GeV/cm^3
v_{esc}	650 km/s
v_0	220 km/s
Quenching	1

Expected DM modulation rate in TeO_2 for different WIMP masses.

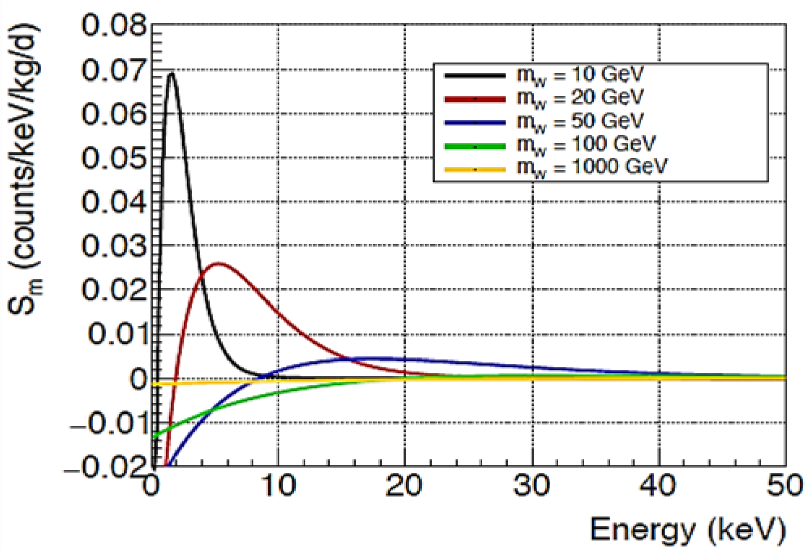
$$S_m \sim (5-7\%)S_0$$



Only SI interaction was considered with $\sigma_{SI} = 10^{-5} pb$ and Standard Halo Model

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) cos\omega(t-t_0)$$

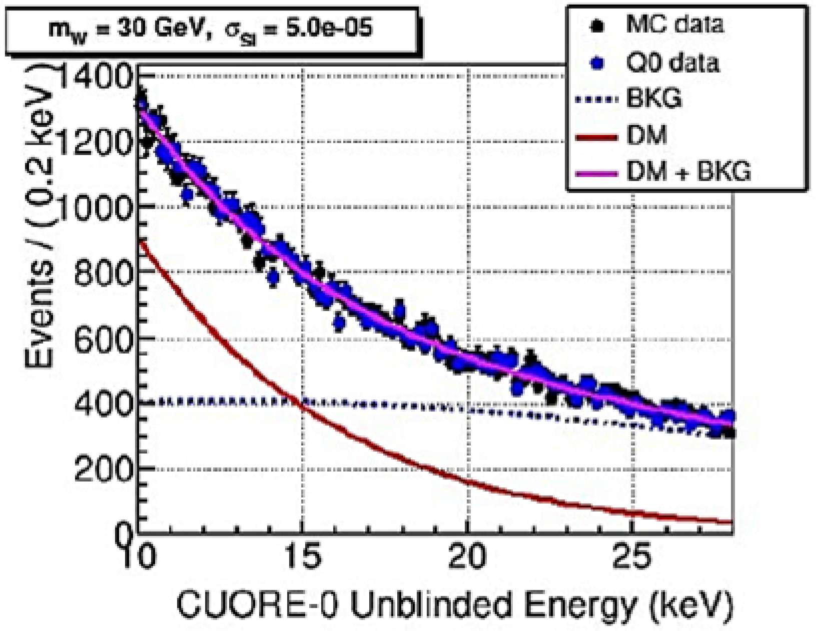
One year period with maximum around June 1st

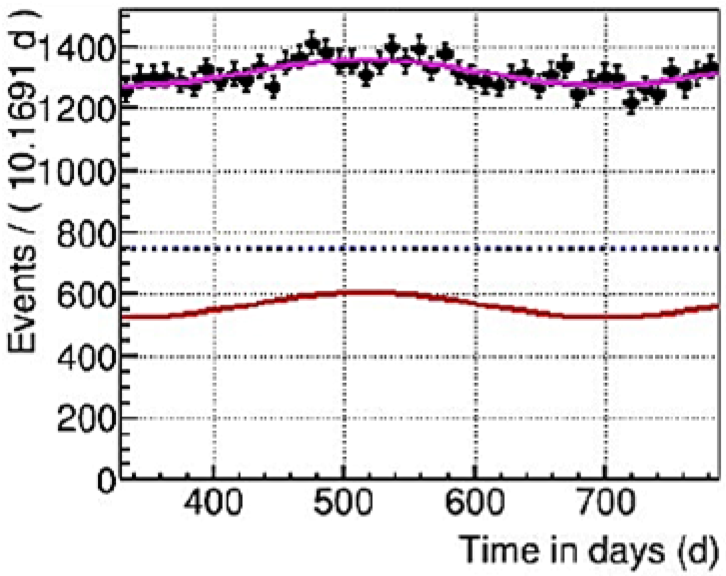


Backup – Sensitivity study (I)

Significance of the annual modulation hypothesis relative to the null hypothesis:

$$2\log\left(\frac{\mathcal{L}_{AM}}{\mathcal{L}_{null}}\right) = 2(NLL_{null} - NLL_{AM})$$





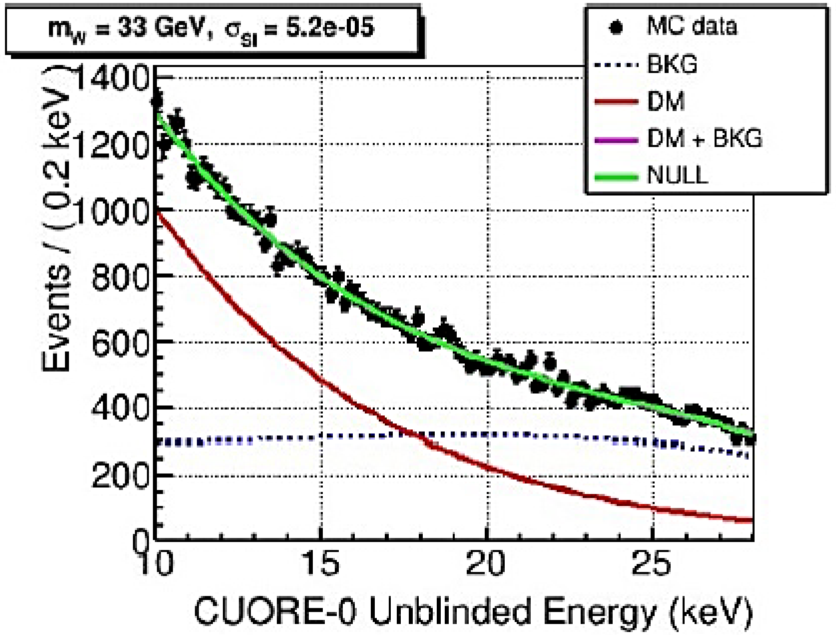
1. Fit the CUORE-0 energy spectrum to bkg + DM signal and determine the best fit background coefficients

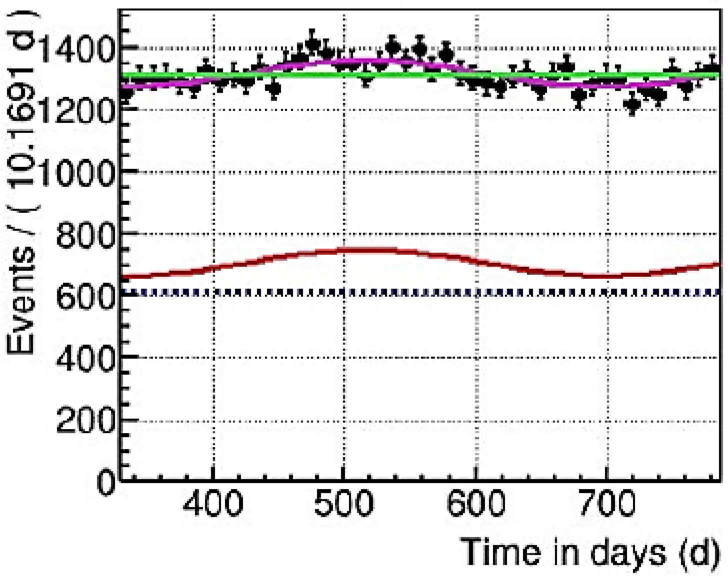
2. Generation of 100 toy MC experiments (bkg + DM) from the coefficients extracted from the previous fits

Backup – Sensitivity study (II)

Significance of the annual modulation hypothesis relative to the null hypothesis:

$$2\log\left(\frac{\mathcal{L}_{AM}}{\mathcal{L}_{null}}\right) = 2(NLL_{null} - NLL_{AM})$$





3. Maximization of $\mathcal{L}_{AM}$ and $\mathcal{L}_{null}$ for every toy MC and calculate the maximum likelyhood ratio

4. Experimental sensitivity as (m_W, σ_{SI}) pairs for which at least 90% of experiments prefer the modulation hypothesis at 90% C.L.