Direct Dark Matter and Axion Detection with CUORE

Europhysics Conference on High-Energy Physics 2011

Cecilia G. Maiano on behalf of CUORE collaboration

Contents

- The Bolometric Technique
- The CUORE experiment
- The pilot experiment CUORICINO
- CUORE-0 and CUORE
- The main scientific goal of CUORE: $\beta\beta 0\nu$
- Other rare physics events
- Potentiality of CUORE to Dark Matter and Axion searches.

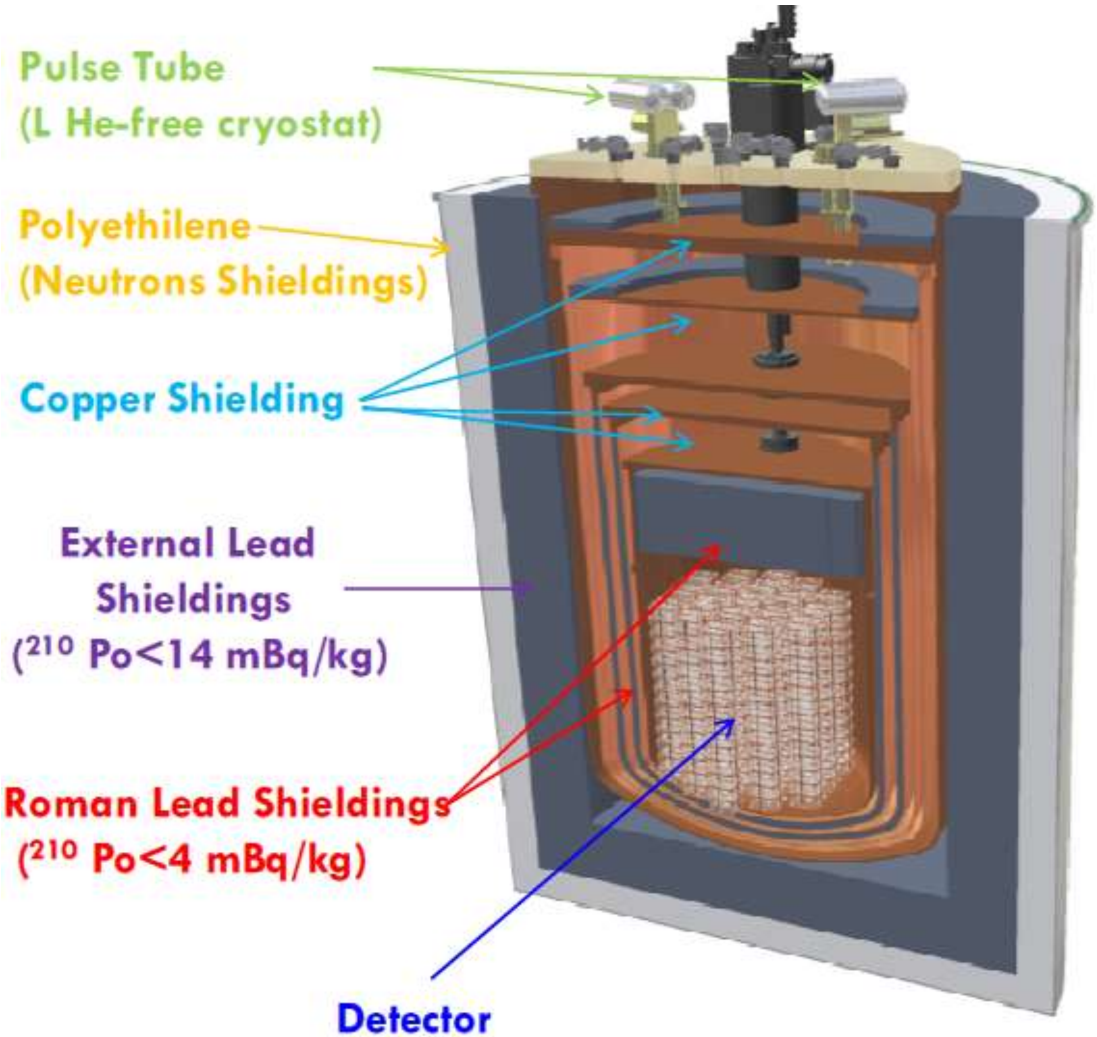
CUORE

Cryogenic Underground Observatory for Rare Events Array of 988 TeO2 crystals 5X5X5 cm^3 (750 g each) ⇨ total **mass 741 kg** TeO2 **granular calorimeter**

* Proposed for ββ0υ search
* Crystlas operate as bolometers @10 mK
* Well known technique, used for CUORICINO (stopped in June 2008)
* CUORE-0 (the first tower of CUORE) will start in 2011
* Background aim: 0.01/0.001 c/keV/kg/y

⇩

* **Stringent controls on radioactivity are mandatory**



CUORE

CUORE will be located in the Hall A
of the Gran Sasso national laboratories
(L'Aquila – Italy)

* Depth: 3650 m.w.e.
* Muon flux: (2.58±0.3)x10-8 m/s/cm2
* Neutron flux @ 4x10/6n/s/cm2
* Gamma flux: 0.73 g/s/cm2

Cosmic rays are not a problem!

Laboratori Nazionali del Gran Sasso – **LNGS** -
a natural shield of 1500 m of rock
(3650 meters of water equivalent.
Average depht)

CUORICINO

The Cuoricino experiment (LNGS, 2003-2008) is the result of years of research on bolometers containing ^{130}Te, by using TeO_2 energy absorbers

I Tower 62 crystals M ≈ **11 kg** of ^{130}Te Bkg @ Q-vallue 0.17 c/keV/kg/yr

Pilot experiment

* intermediate size ββ0υ experiment
* important test for
  * radioactivity
  * performance of large LTD arrays

Installed in Hall A @ LNGS since middle of 2003

-decomissioned in June 2008-

TeO2 thermal calorimeters

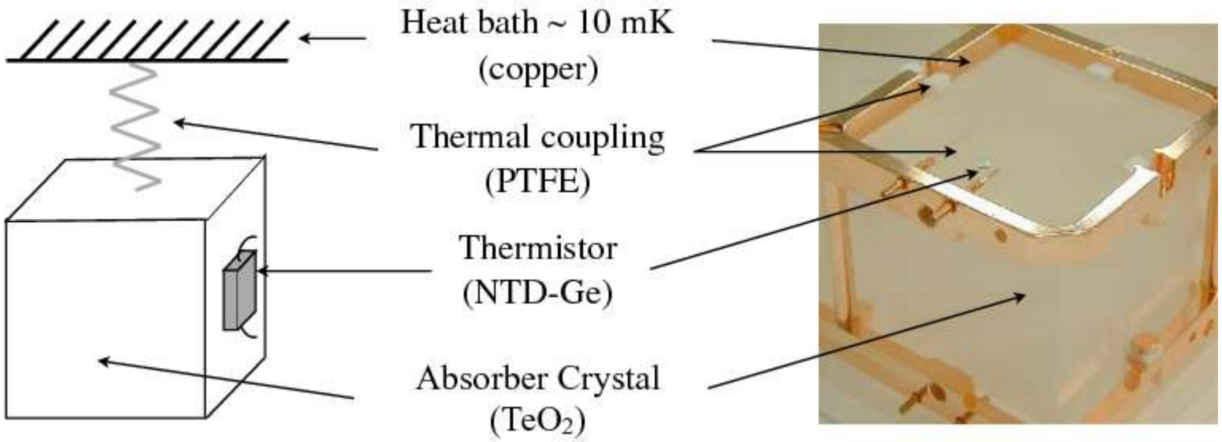
•11 modules
4 detectors each
Dimension: 5x5x5 cm3
TeO2 crystal mass: 790 g

•2 modules
9 detectors each,
Dimension: 3x3x6 cm3
TeO2 crystal mass: 330g

CUORE-0: on the way to CUORE

- A single CUORE tower, realized with the same procedure as CUORE:
- same assembly line;
- same Crystals and PFTE;
- same copper and surface cleaning.
- The CUORE-0 detector will replace the CUORICINO tower in the Hall A dilution refrigerator.
- CUORE-0 will be assembled during the summer and data taking will start before the end of the year.

The bolometric technique



* **Thermal bath** (copper) @ 10mK
* **Weak thermal coupling** (Teflon)
* NTD Ge **thermistor** R@10 MΩ
*TeO 2 **Crystal Absorber** C @ 10 $^{-9}$ J/K

✔ All the deposited energy is measured
✔ The detector is fully sensitive
x Slow signals
x No particle distinction

Detection Principle

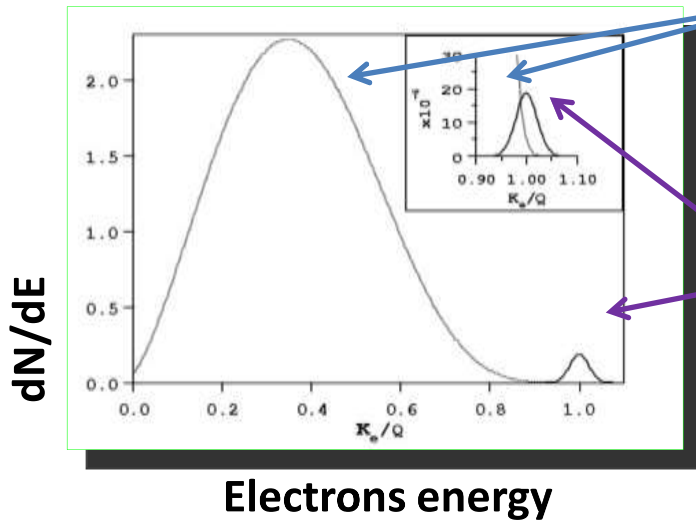
ΔT=E/C C: thermal capacity
Dielectric and diamagnetic crystals: low thermal capacity
@ low temperature
FWHM ~ 5 keV @Q-value (2527 keV)

Temperature variation ~0.1 mK/MeV ➡ Resistance variation ~3 MΩ/MeV ➡ Voltage variation ~0.1 mV/MeV

The CUORE physics

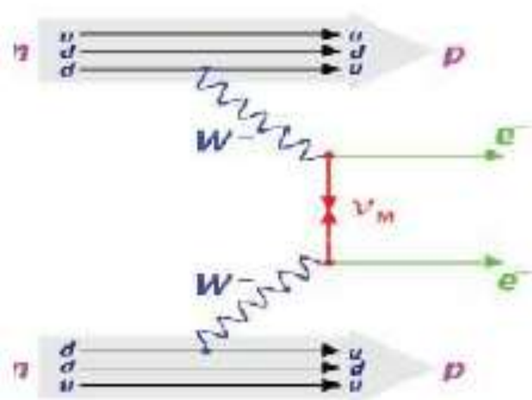
CUORE : proposed for ββ0υ search – main scientific goal –

In a source=detector approach we expect a peak at the Q-value of the transition (energy sum of the two electrons)



ββ2υ: continuum with maximum at ~1/3 Q.
Allowed in SM
Already observed
$\tau < 10^{19}$y

ββ0υ: peak enlarged only by the detector energy resolution
Forbidden in SM $\Delta L=2$



$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$

0ν-DBD rate — Phase space — Nuclear Matrix Elements — Effective Majorana mass

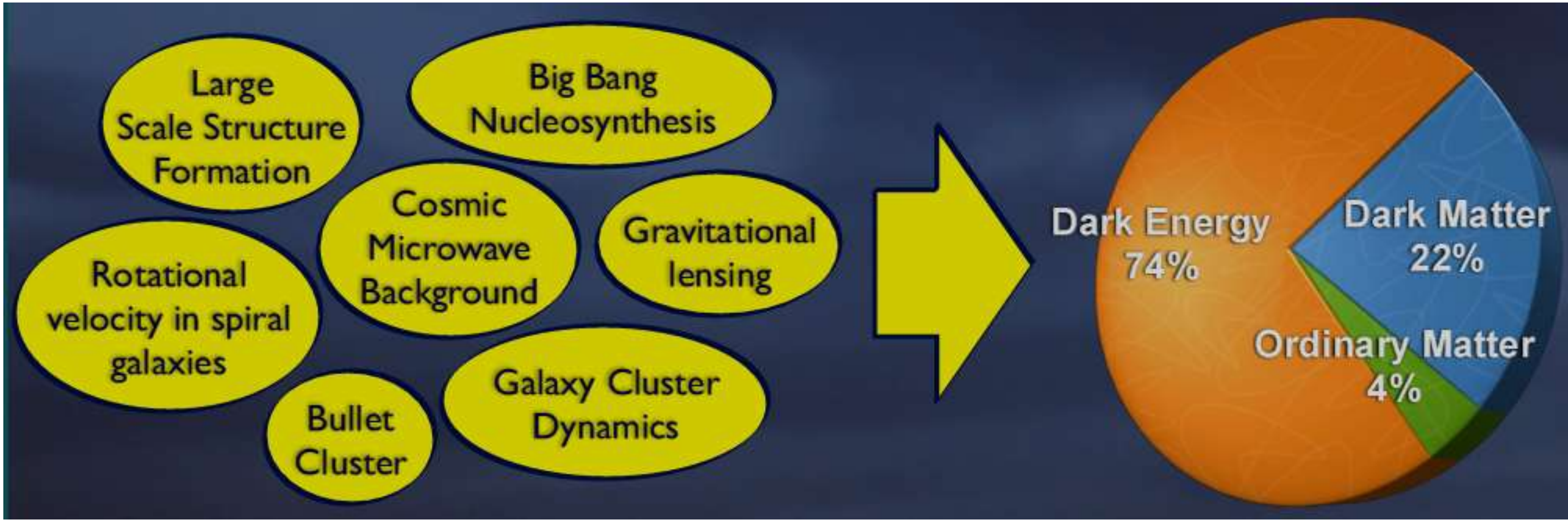
$m_\upsilon \neq 0$
$\upsilon = \overline{\upsilon}$

The CUORE physics

Due to the low background level achievable with CUORE other rare physics events are available:

- Rare nuclear transitions (^{209}B alpha decay)
- Electron decay e- → $\upsilon_e + \gamma$
- Dark Matter

The Dark Matter Problem



Weak Interacting Massive Particles (WIMPs)
are the most likely candidates

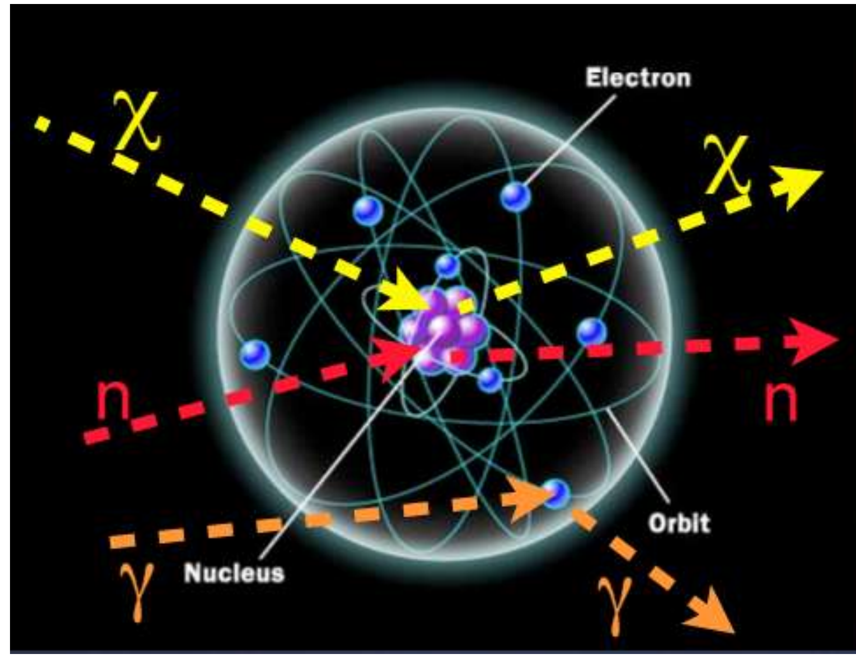
Data favor cold non-baryonic Dark Matter:
- Non-relativistic velocities
- Gravitational and weak interactions
- Stable particles

Event signature

Detect matter recoil after WIMP elastic scattering

Signal:
$\chi + N \rightarrow \chi + N$

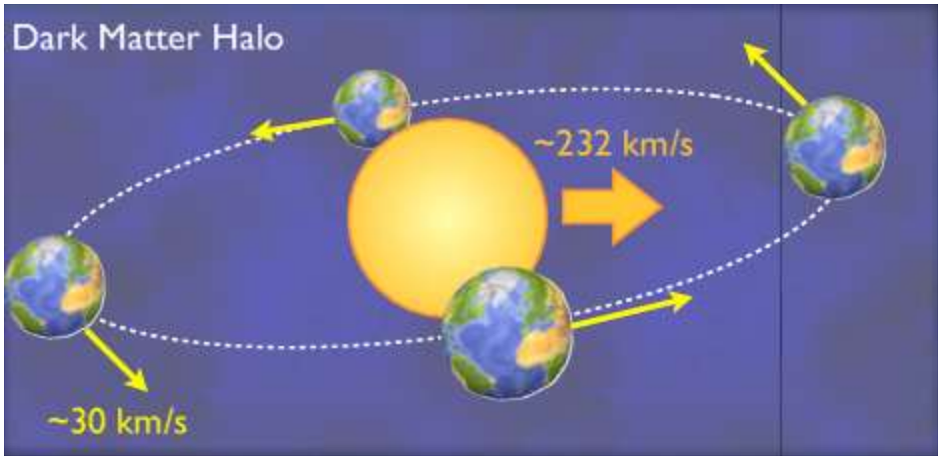
Background:
$n + N \rightarrow n + N'$
$\nu + N \rightarrow \nu + N'$
$\gamma + e^- \rightarrow \gamma + e^-$
$N \rightarrow N' + a, e^-$



Need of extremely
low energies (few keV) **thresholds**

Much background
Several different techniques
Several target materials
Several experiments

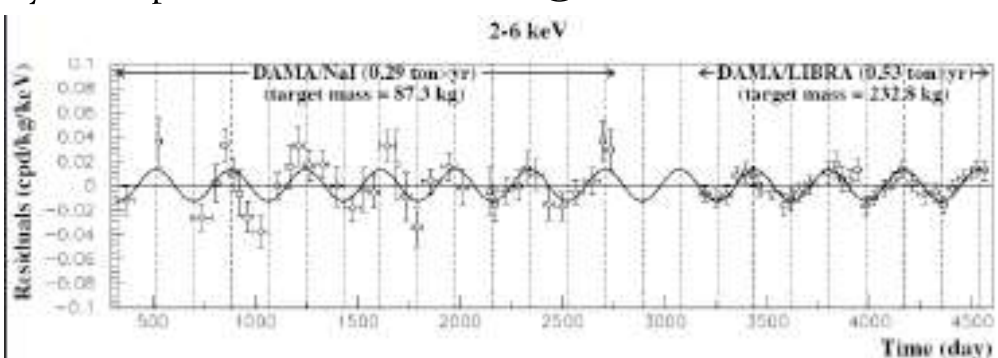
The annual modulation



Detector-WIMP relative velocity has an annual modulation

Event rate
must be
modulated

DAMA experiment: Highly radiopure NaI scintillators @LNGS

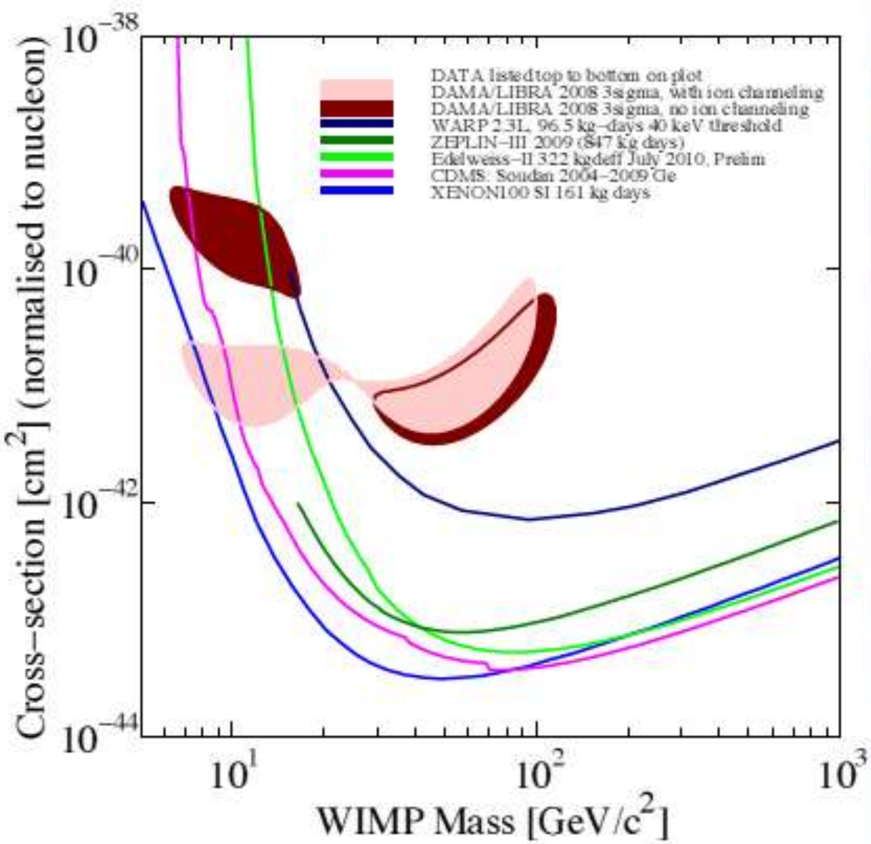


The state of the art

The DAMA detection claim

Several limits excluding the claim

Many theoretical models and many assumptions



Still too many open questions

Thresholds

CUORE TRIGGER

Standard
Thresholds ~ 20 keV

Optimized
Thresholds ~ 10 keV

The region of interest is below 10 keV!
Need of **lowering the thresholds**

Development of

- New Trigger
- New Pulse Shape parameter

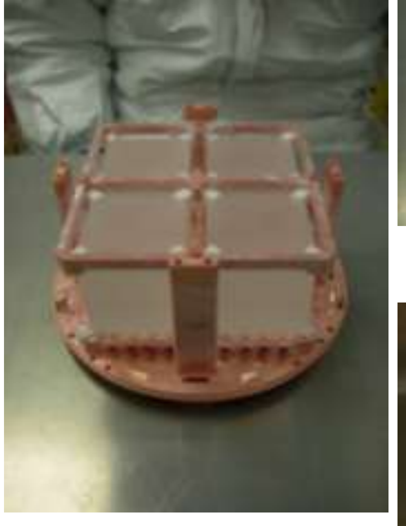
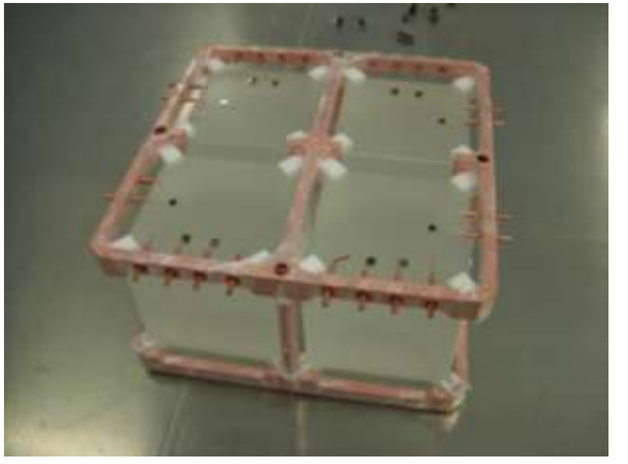
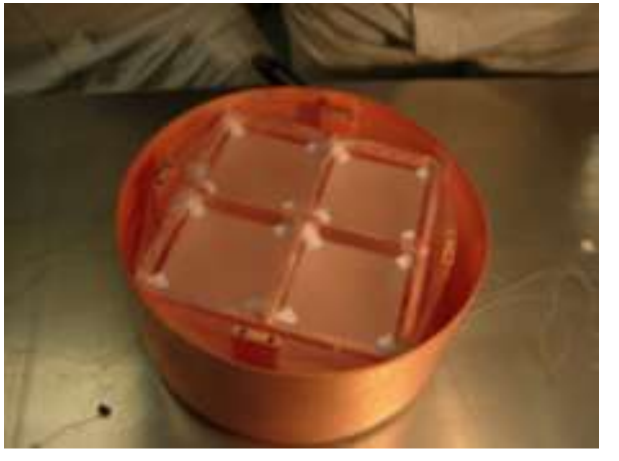
Based on Optimum Filter

Application on **CCVR-2** data let to lower the thtresholds down to few keV's

The test detector

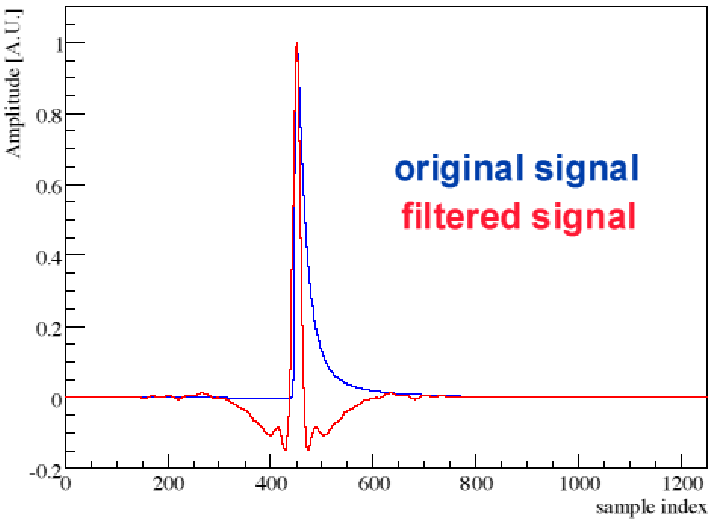
CUORE Crystal Validation Run 2 CCVR-2

- 4 crystals CUORE-like
- 2 thermistors per crystal
- Live time of **19.4** days
- Operated in Hall C @LNGS

Best resolutions ever **~3.5 keV** FWHM
@ ββ0υ Q-value (2527 keV)

Data filtering and triggering



Data are divided in slices and then filtered in the frequency domain using the optimum filter algorithm, maximizing the signal to noise ratio

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

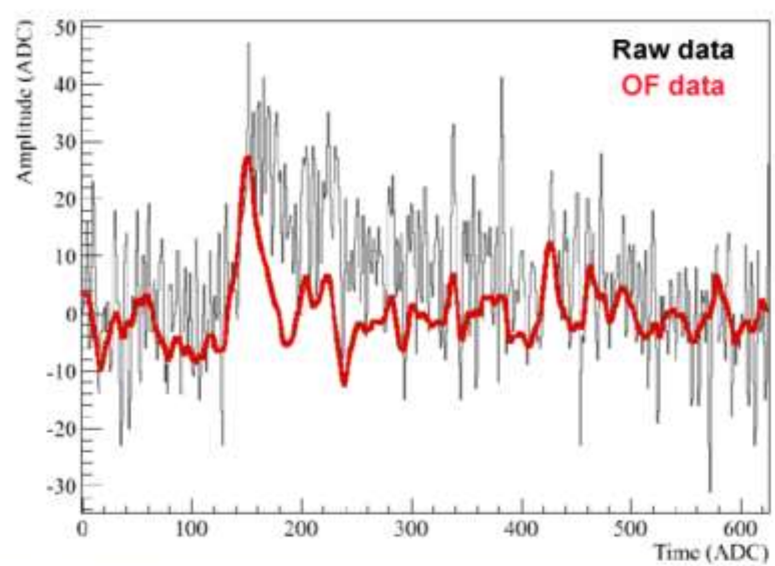
average signal shape (estimated from data)

noise power spectrum (estimated from data)

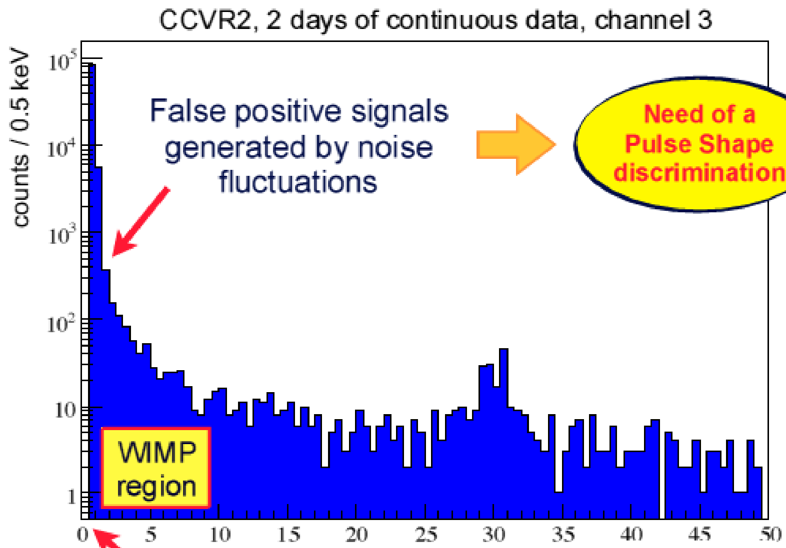
maximum position s_i

The trigger is implemented as a simple **threshold** trigger on the filtered samples, with debounce time related to the width of the filtered average pulse

The threshold is set a priori in terms of the OF Theoretical resolution

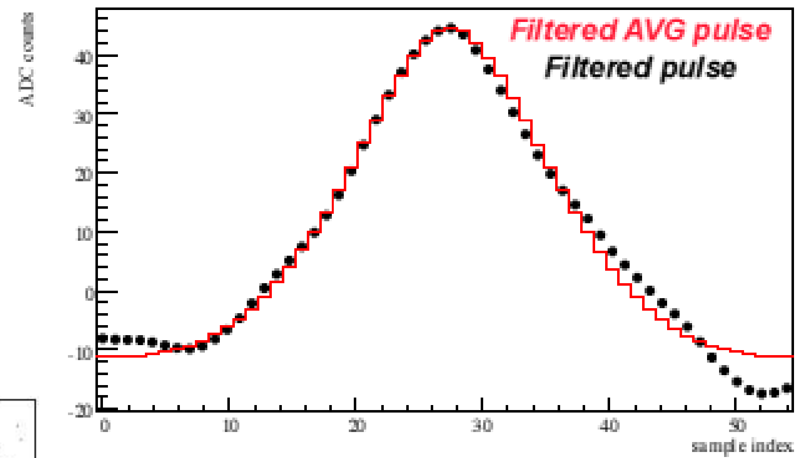


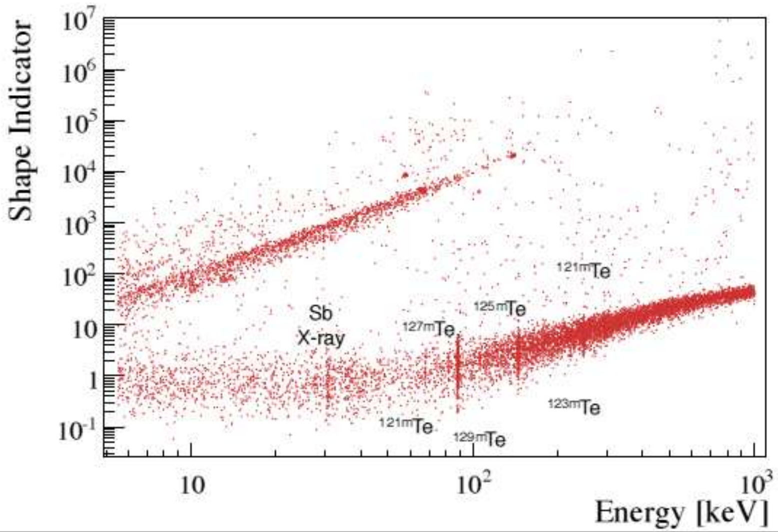
Lowering the thresholds



Threshold ≅ 0.65 keV

Filtered average pulse is used as a **fit function** of the central part of the pulse





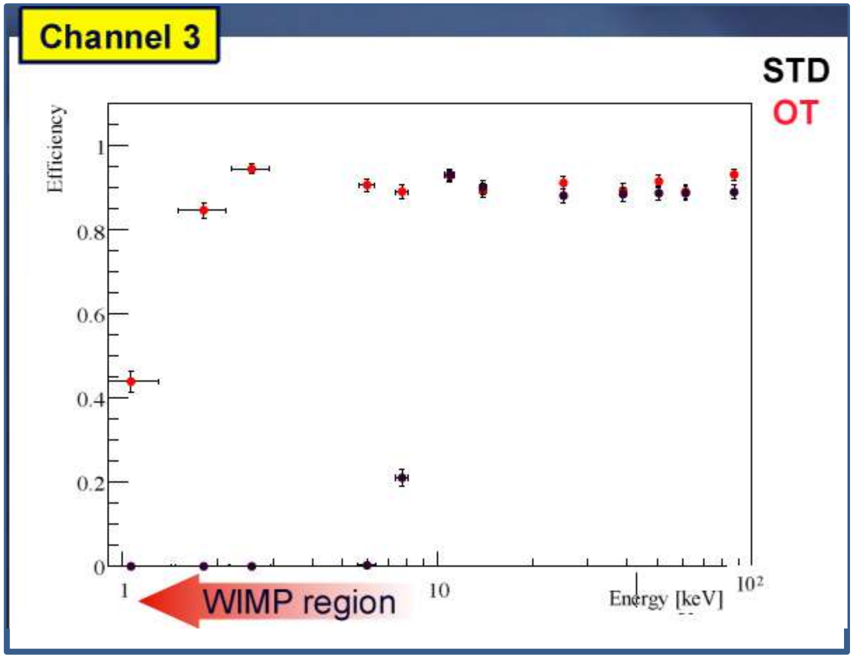
- To remove non-physical pulses we fit the filtered pulses with the known shape of physical pulses
- The χ^2/**ndf** is used as shape parameter.

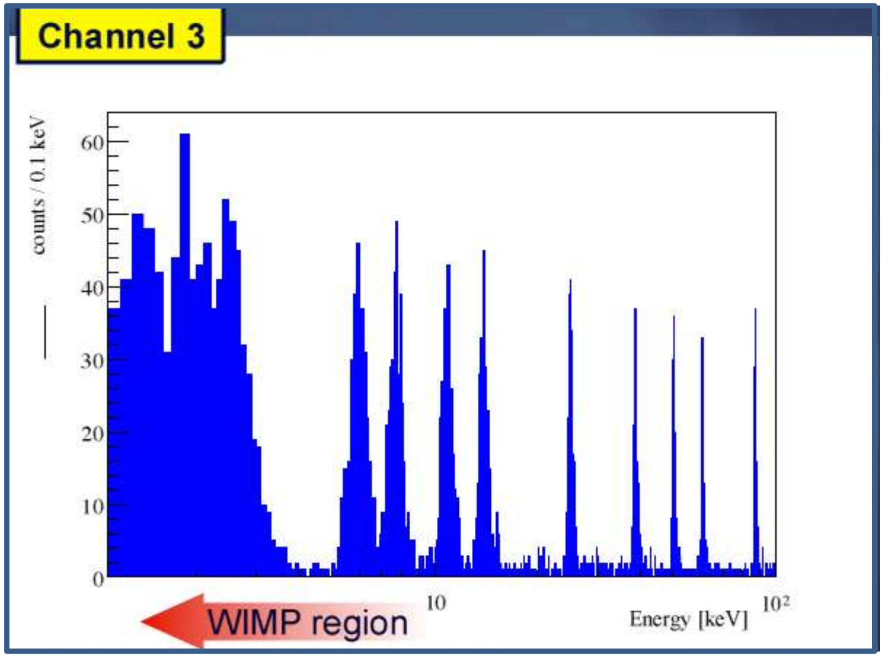
Trigger efficiency

Dedicated measurement the end of CCVR2 run

* External heater glued on crystal, which mimic particle interactions

* Possibility to scan all the low energy range





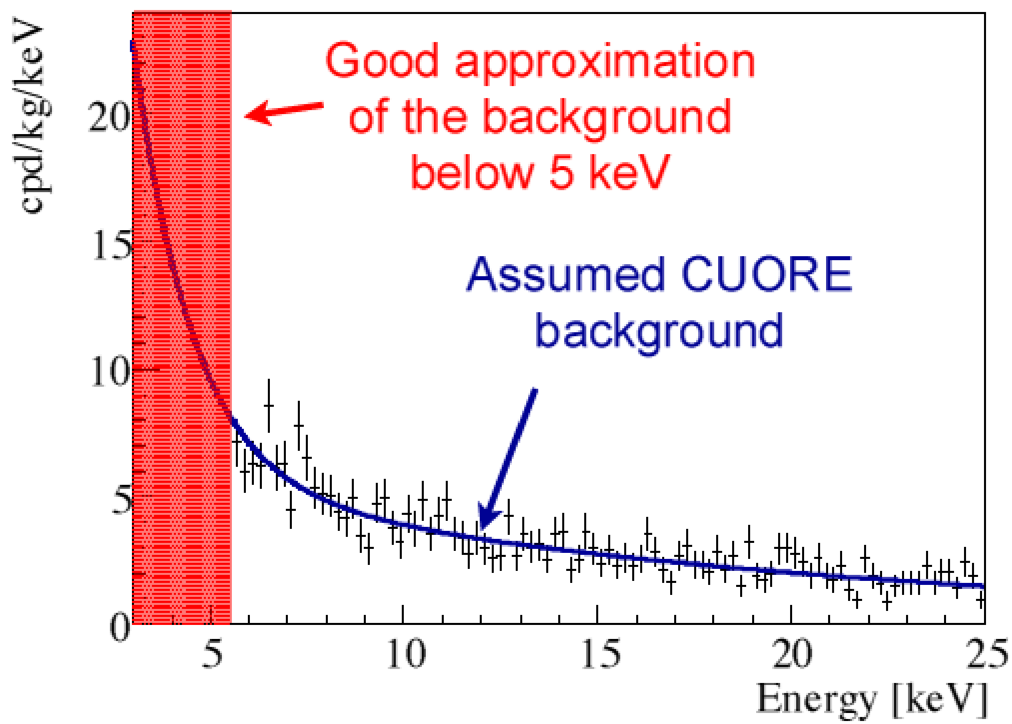
Energy thresholds ~2-3 keV
Efficiencies bigger than **80%**

Dark Matter sensitivity study

The background, averaged over the three good crystals, can be projected to CUORE-0 and CUORE, assuming that it will be the same

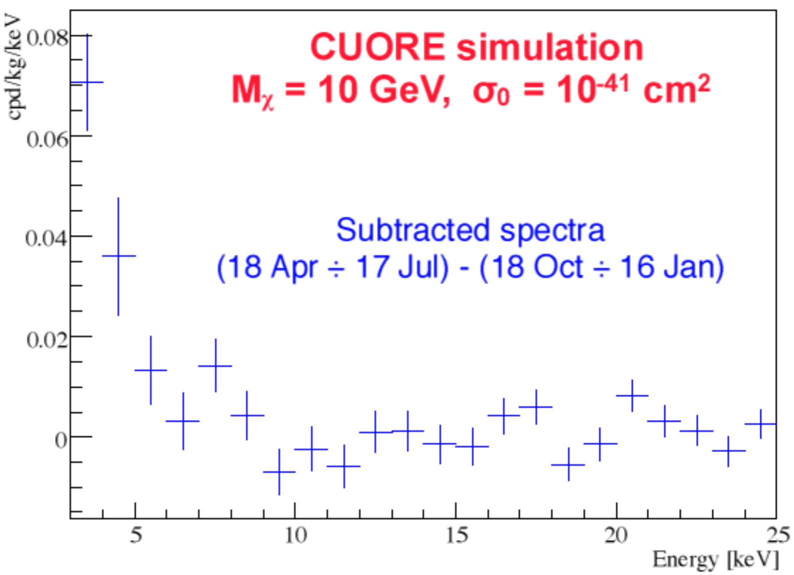
The background is too high to put stringent limits on Dark Matter interactions

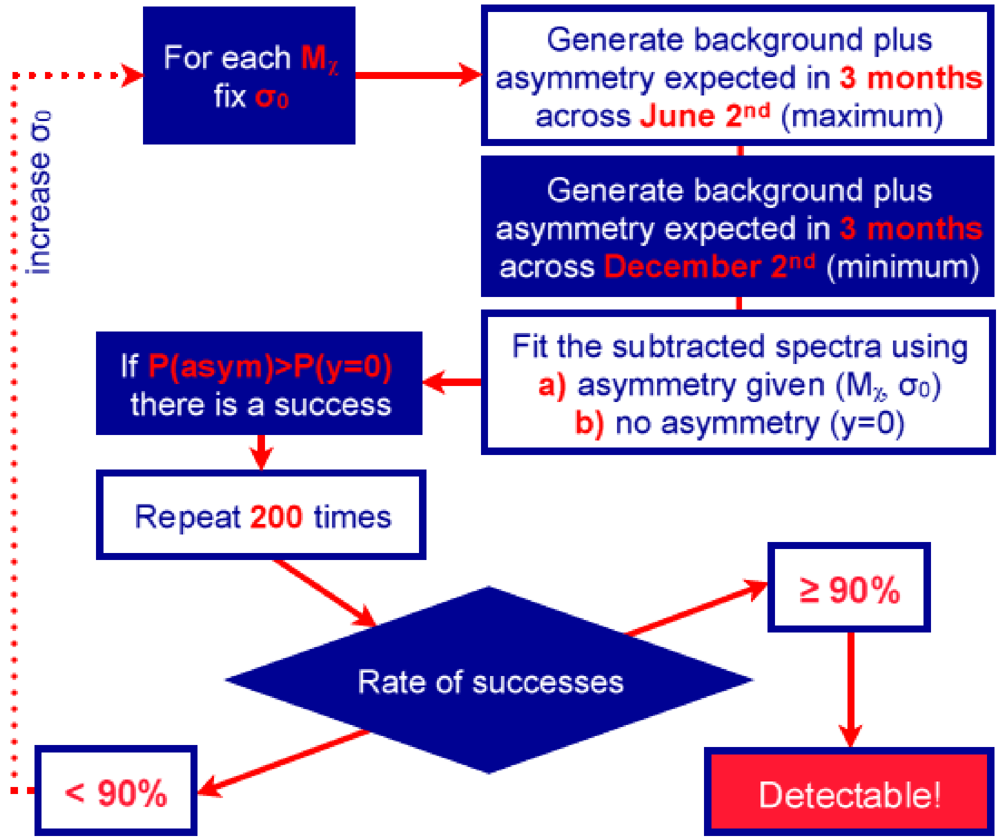
Even if the background is too high to give stringent limits on Dark Matter interactions, the effect of a Dark Matter modulation signal can be simulated.



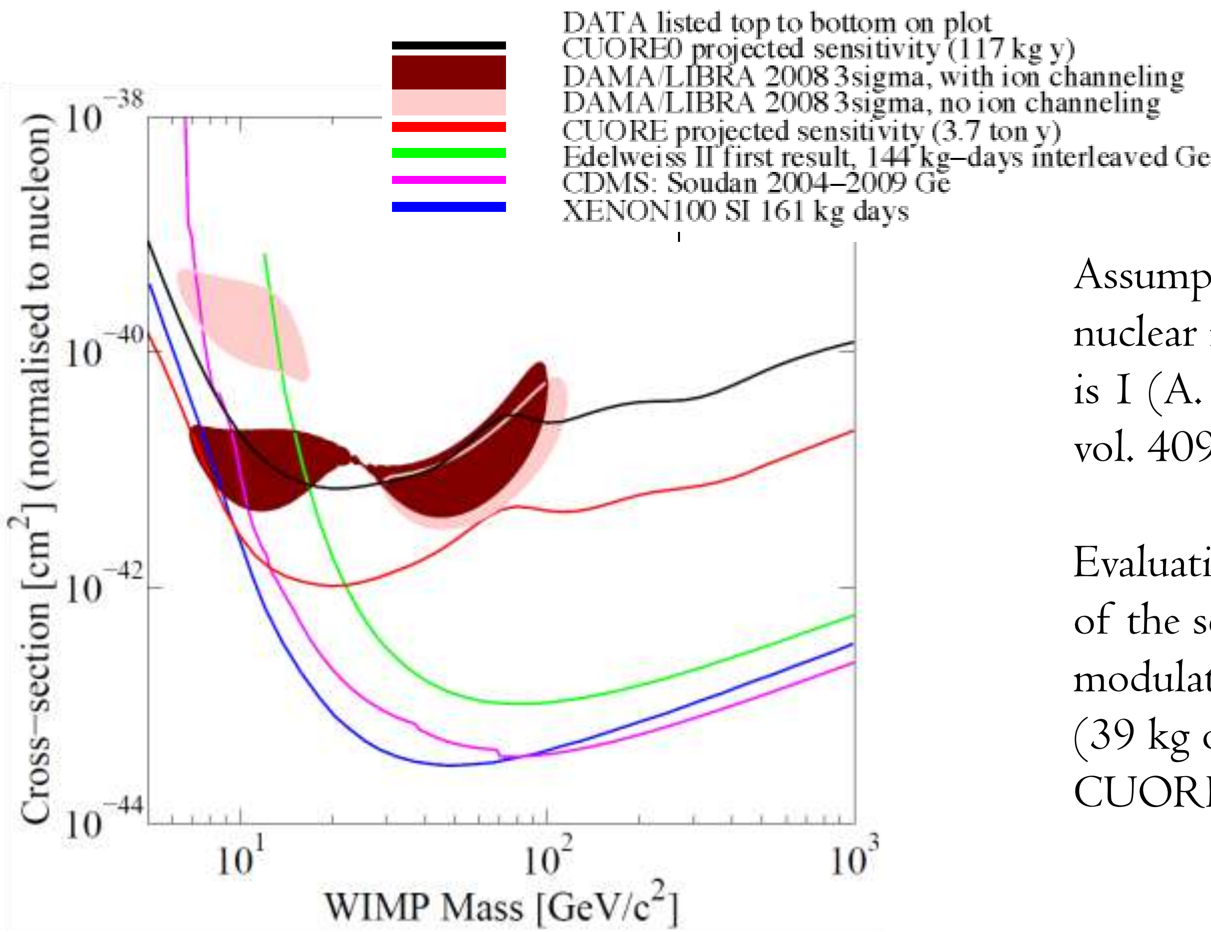
Dark Matter sensitivity study

The sensitivity to a WIMP modulation signal in CUORE-0 (39 kg of TeO_2, 3 y) and in CUORE (741 kg of TeO_2, 5 y) is evaluated with toy MonteCarlo's.





Sensitvity to WIMPs @90%C.L.

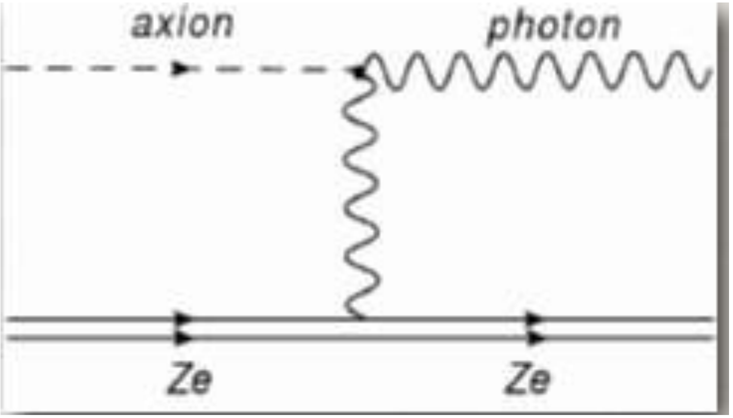


Assumption: quenching factor for nuclear recoils in TeO2 bolometers is 1 (A. Alessandrello et al., NIM A, vol. 409, pp. 451–453,1998).

Evaluation, via toy MonteCarlo's, of the sensitivity to a WIMP modulation signal in CUORE-0 (39 kg of TeO2 , 3 years) and in CUORE (741 kg of TeO2, 5 years).

Solar axion detection

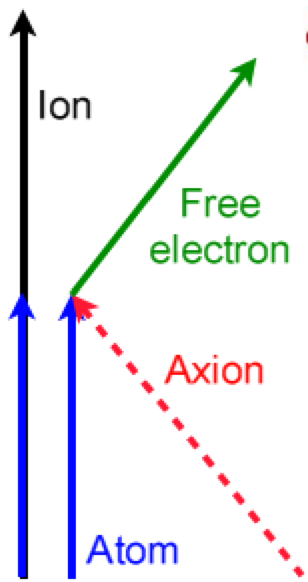
✤ Axion: a neutral pseudo-scalar particle, light and weakly coupled to matter.
✤ The axion has been postulated to solve the strong CP problem in QCD.
✤ Experimental approach: detection of solar axions through the **Primakoff coherent conversion** into photons via **Bragg scattering in the TeO2 crystals.**



✤ Requirements:
- ✤ low threshold;
- ✤ low background;
- ✤ crystal orientation must be known;
- ✤ time series analysis techniques to detect the modulation.

Solar axion detection

✤Other axion detection possibility: axio-electric effect in the Sun on ^{57}Fe M1 line at 14.4 keV:

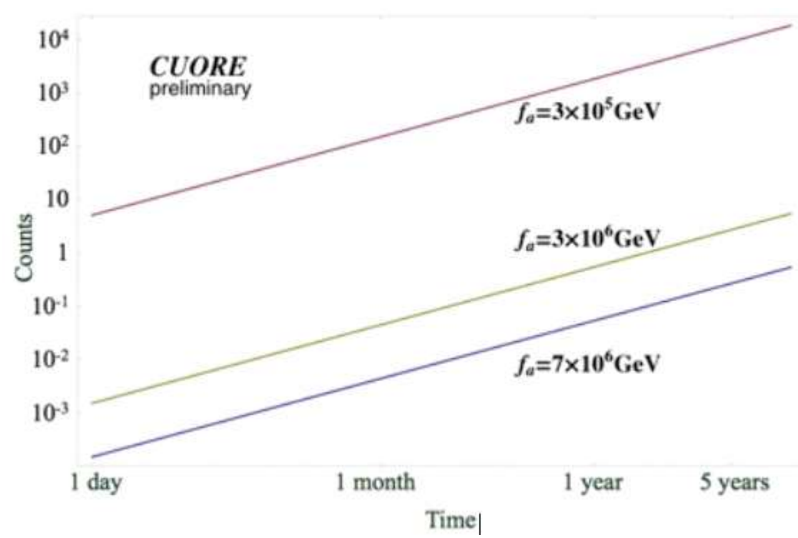


$$\Phi_a(14.4\,keV) = 1.0\times 10^{11}\,cm^{-2}s^{-1}\left(\frac{10^6\,GeV}{f_a}\right)^2 C(F,D,S,z)^2$$

$$C(F,D,S,z) = -1.19\left(\frac{3F-D+2S}{3}\right) + (D+F)\frac{1-z}{1+z}$$

where F=0.48, D=0.77, z=0.56, 0.15 = S = 0.55
(F. T. Avignone, Phys. Rev. D 79, 035015 (2009)).

CUORE Axion detection rates (S=0.55)



Ongoing analysis on a CUORE test detector of 1786 kg·days. Stay tuned!

CONCLUSION

* A new trigger for the CUORE experiment that is sensitive to the pulse shape with detection efficiency in excess of 80% above 3 keV.

* Its application to the CCVR2 data pushed the energy threshold from tens of keV down to the few keV region, an energy range that has never been available in TeO_2 bolometers.

* We estimated the sensitivity of CUORE and CUORE-0 to a Dark Matter modulation signal, showing that CUORE will be able to test the DAMA claim and play an important role in the Dark Matter quest.

* An analysis on the potentiality of CUORE for solar axion detection is under development.