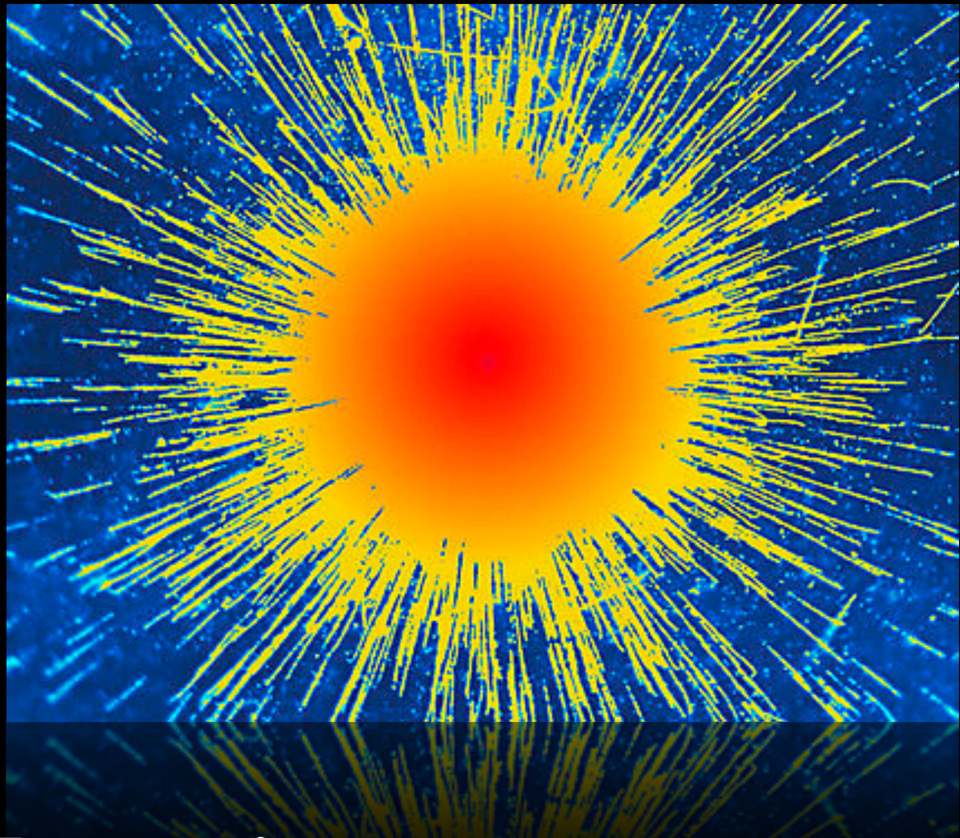

A new Experimental upper limit on the λ parameter

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Overlook

- Introduction to the Collapse theories and the Spontaneous Emission Phenomenon
- present λ upper limits
- The pioneering work of Q. Fu
- The reliability of the earlier analysis
- The new analysis on data published by the IGEX collaboration
- Results and outlook
- Dedicated experiment

Collapse theories and Spontaneous X-ray emission

An introduction

Collapse Theories and Spontaneous Emission

Collapse Theories aim:

To describe MICRO and MACRO world within the same theory

Based on:

Modification of the Schrödinger equation to obtain

Dynamical Reduction (DR) mechanism

$$|\psi, t=0\rangle = a_1(0)|\psi_1\rangle + a_2(0)|\psi_2\rangle$$

evolves into

$$|\psi, t\rangle = e^{i\vartheta_k}|\psi_k\rangle \ (k = 1 \vee 2)$$

Continuos Spontaneous Localisation (CSL) model [1]

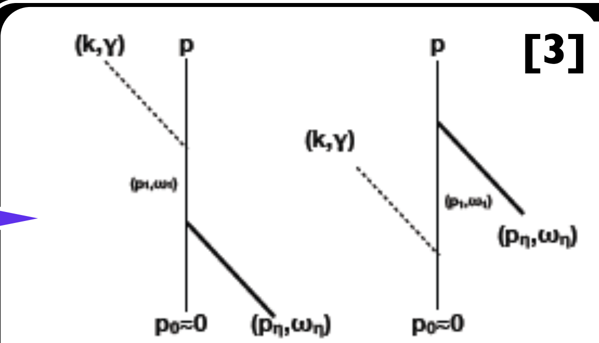
Developed from GRW model [2]

Trigger Problem solution [3]

A non - Hermitian interaction between a fluctuating scalar field (η) and the particle in the Hamiltonian causes the collapse [1]

Spontaneous Emission

The interaction between a free electron and η is the basis of the Spontaneous X-ray emission by free electrons phenomenon



$$\sigma(e^- + \eta \to e^- + \gamma) = f(\lambda, a)$$

λ,a are fundamental parameters of the Collapse theories class

It is possible to fix an upper limit on λ searching for this phenomenon

Expected X-ray Rate for Ge low-activity experiments

The Rate of the radiated photons of energy k is :

$$\frac{d\Gamma(k)}{dk} = 4\pi k^2 \frac{e^2\lambda}{16\pi^3 k^3 a^2 m^2} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 k}$$ [3]

$\lambda_{GRW} = 10^{-16} s^{-1}$

$a_{GRW} = 10^{-7}$ m [2]

Application to the Ge case: 4 Valence Electrons (VE) "quasi-free"

Binding Energy ~ 10 eV ⇔ Energy of emitted γ: 4-49 keV (our case)

Ge VE **1 day**

$$R_{theory}(k) = (2.74\times10^{-31})\times 4\times(8.29\times10^{24})\times(8.6\times10^{4})\times\frac{1}{k[keV]}$$ [3]

$e^2\lambda/(4\pi^2a^2m^2)$ **atoms/Kg[Ge]** **γ energy [keV]**

Upper bounds on the λ parameter

Present Status

CSL parameters upper bounds

In ref [4] Adler present different upper bounds for CSL parameters:

Fullerene Diffraction	$\lambda < 5 \times 10^{12} \lambda_0$
Supercurrent Persistence	$\lambda < 10^{14} \lambda_0$
Proton Decay	$\lambda < 10^{18} \lambda_0$
Spontaneous Radiation from Ge	$\lambda < 10^{6} \lambda_0$

Lab Experiments

Only 1 paper in litt.!

Cosmic IGM heating effects	$\lambda < 10^{8\pm1} \lambda_0$
Dissociation of cosmic hydrogen	$\lambda < 10^{17} \lambda_0$
Heating of protons in the universe	$\lambda < 10^{12} \lambda_0$
Heating of Interstellar dust grains	$\lambda < 10^{15} \lambda_0$

Cosmological data

Correlation lenght: $r_c = 10^{-5}$cm [1]

Standard CSL parameter: $\lambda_0 = 10^{-17} s^{-1}$ [1]

The strongest upper bound is set by the spontaneous X-ray emission!

The pioneering work of Q Fu

About the analysis done

Fu analysis

To get an experimental upper bound Fu used data taken (in 1990) by two twin Ge diodes at Homestake mine (looking for ^{76}Ge $\beta\beta2\nu$: E^{theo}_{max} = 700÷800 KeV [5]):

The reconstruction of the experimental history is a crucial point to understand the analysis results, as we'll point out!

Basics of the analysis

Energy (keV)	Expt. upper bound (counts/keV/kg/day)		Theory (counts/keV/kg/day)
11	0.049	ANOMALY	0.071
101	0.031		0.0073
201	0.030		0.0037
301	0.024		0.0028
401	0.017		0.0019
501	0.014		0.0015

Evaluation of $R_{theory}(k)$ at six different energies, then a simple comparison with the observed data

[5]

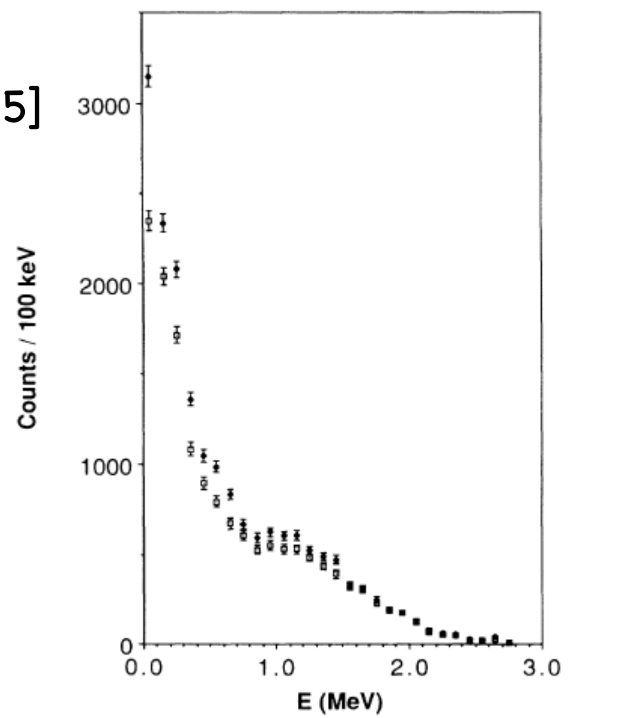


FIG. 1. 1.92 kg yr of raw data (solid diamonds) from the present experiment and corrected (open squares) for the γ-ray peaks and associated Compton distributions.

Fu Results and the anomaly

The ANOMALY: more expected counts than the observed

There is something WRONG!

Experimental side

Detector Performances → **Sistematic Errors**

Analysis Done → **Bias**

This work

WHERE?

Theoretical side

Rescale $\lambda_{GRW} \Rightarrow \lambda < 0.55 \times 10^{-16} s^{-1}$

Results:

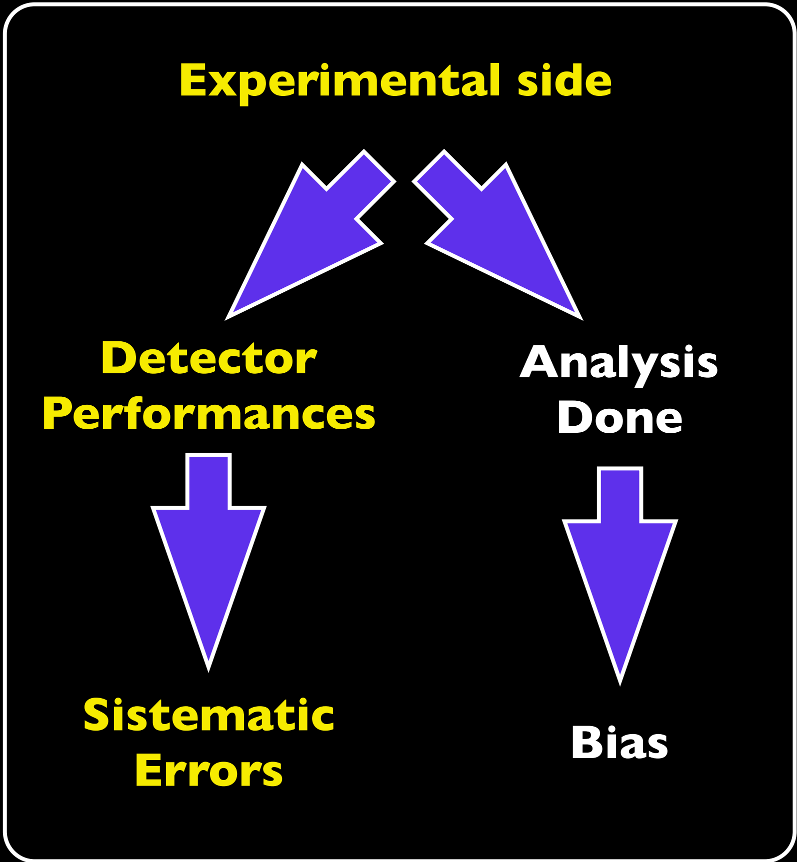
Historically:

The original GRW and CSL models were ruled out!

Mass-proportional models to restore the compatibility and solve the anomaly

FU's work

Detector Performances

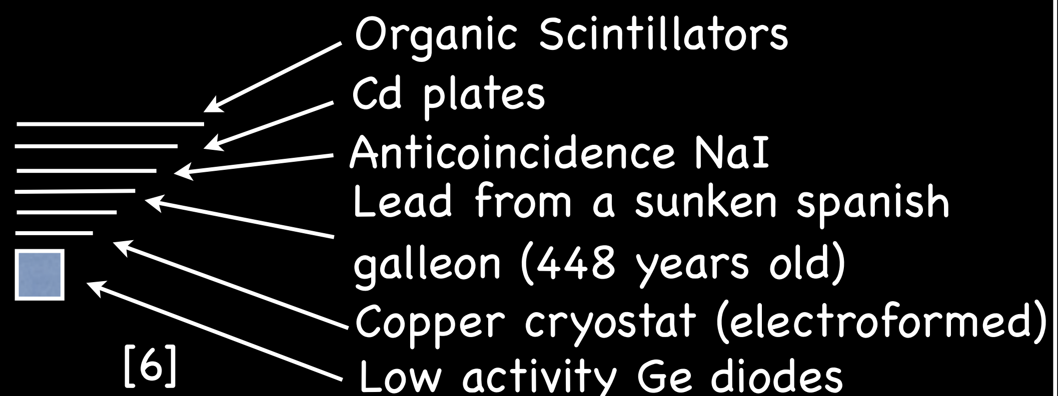


Experimental lack

- Highly hydrogenated material to slow down the neutrons maximising the capture in Cd plates
- Control on Radon contamination

I) Experimental Setup Configuration

Two Ge (naural-isotopic-abundance) **diodes** of **1116 g and 1105 g** (∅=67 mm, l=67 mm) [6]

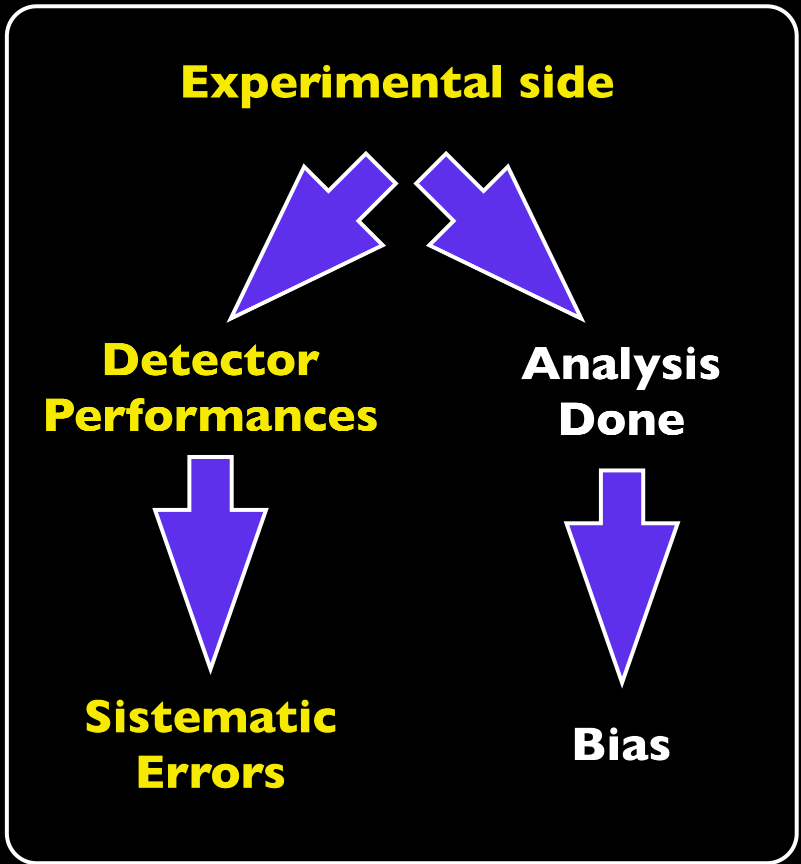


Homestake mine: 1438m underground (standard rocks) [7]

Removal of the solder electrical connection (^{115}In beta emitter)

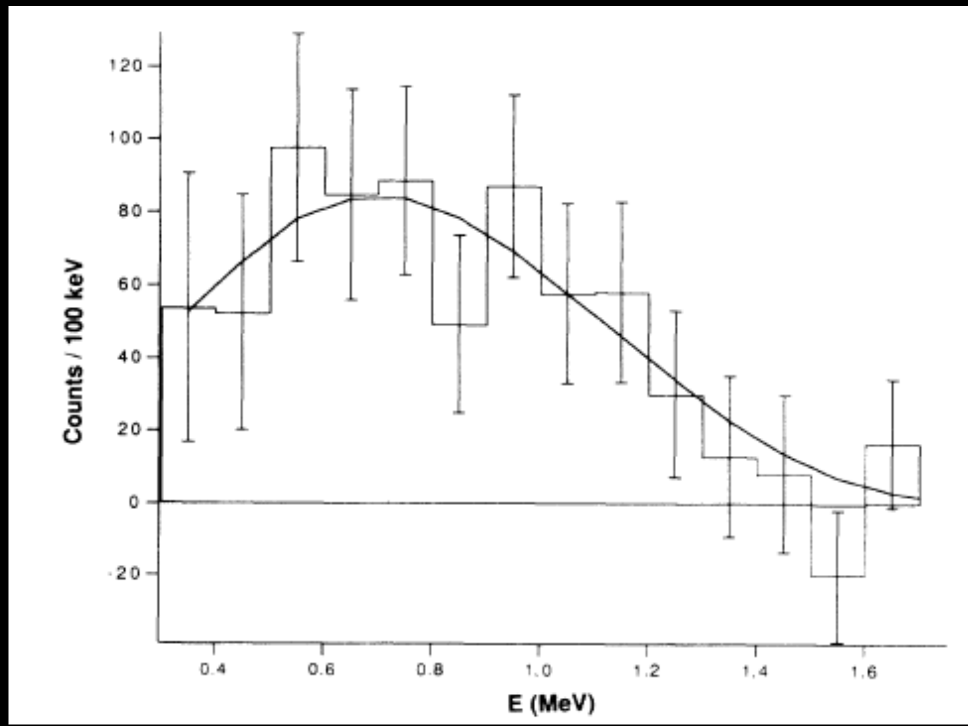
Not an highly radiopure apparatus, but could be used to set the upper bound

Detector Performances



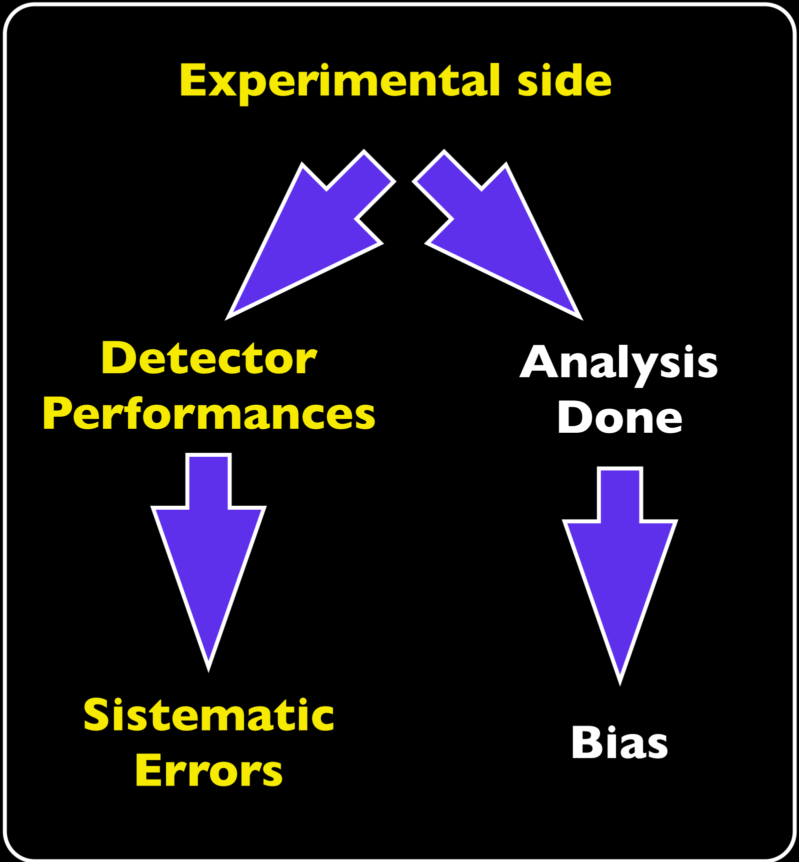
2) Characterization of the Ge diodes at low energies

- lack of an evaluation of the detector resolution at lowest energy
- lack of a detector efficiency study in the very low energy region of the spectrum (quite far from the Q value - the anomaly could be originated by an inefficiency of the detector at very low energy)



- Used-spectrum for the analysis in [6] ($\beta\beta2\nu$), starts from 300 KeV
- This lower limit is due to the type of analysis presented in [6]

Detector Performances



- The Homestake data were affected by gain stability problem
- A systematic in Fu's work seems to be reliable…

3) reconstruction of the experimental history

- Without other informations, any claim about a systematic error is only an inference
- But, we reconstructed the experimental history of these two Ge diodes:
- They were two Ge diodes of the IGEX experiment!

IGEX story

Homestake gold mine (4K mwe) ← Fu ^{76}Ge $\beta\beta 2\nu$

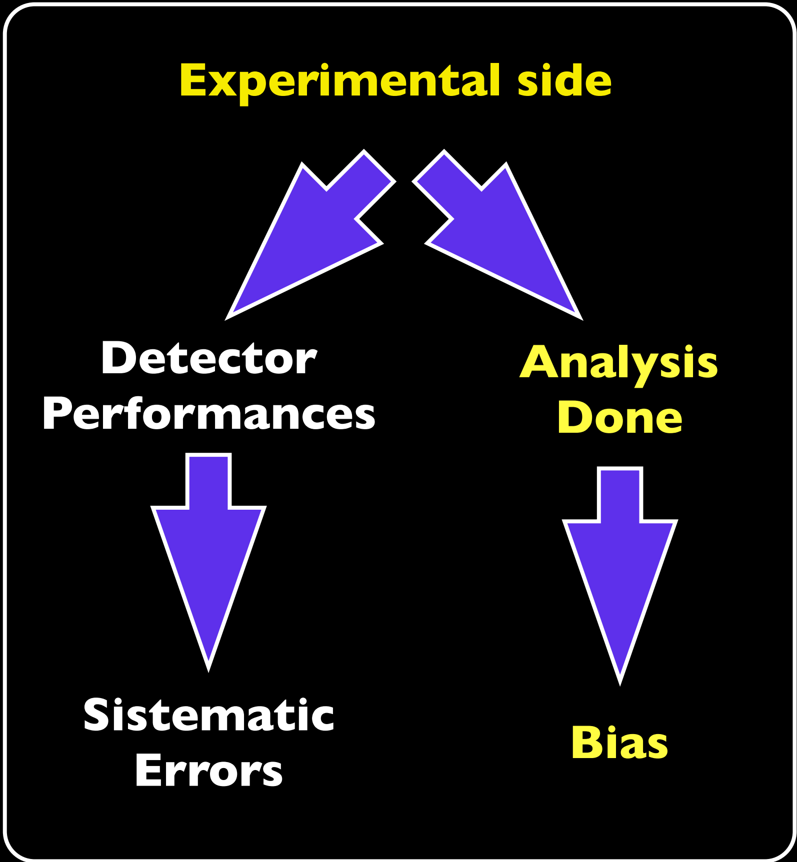
The Canfranc Tunnel (2450 mwe)

Big Improvement in the experimental apparatus

Backsan Neutrino Observatory (660 mwe) → Today IGEX is looking for ^{76}Ge $\beta\beta 0\nu$ and Dark Matter

[8]

Analysis done



A biased analysis to estimate an order of magnitude, not a real upper limit

Energy (keV)	Expt. upper bound (counts/keV/kg/day)	Theory (counts/keV/kg/day)
11	0.049	0.071
101	0.031	0.0073
201	0.030	0.0037
301	0.024	0.0028
401	0.017	0.0019
501	0.014	0.0015

The "punctual" evaluation of the rate at six different energies brings a bias:

The bias

choice as the only reliable experimental observable the counts at 11 keV

Lack of information: evaluation of a free parameter using a single bin (d.o.f.=0)

In case of a systematic error in an energy region (or a bin) of the spectrum, it will affect the results of such analysis in a strong way (we have seen that this systematic could be present)

Lack of an error estimation (CL on the limit)

Fu's result: not a reliable limit, and not a limit!

The new analysis

Using data published by the IGEX collaboration

Looking for DM with the IGEX experiment

- Data published by the IGEX collaboration used in this work are related to the experimental search of DM using the IGEX apparatus
- A big Improvement in the shielding and in general in the low-background techniques is achieved
- No gain stability problem

Improvements

- 1 Ge diode with an active mass of about 2 Kg and its cryostat fabricated following the state-of-the-art ultralow background techniques, with selection of the radiopure material
- The detector is fitted in a precision-machined chamber minimizing the empty spaces available for the radon
- Nitrogen gas flushed into the chamber creating a positive pressure minimizing the radon contamination
- Innermost shielding: 2.5 tons of 2000-year-old archeological lead (roman), surrounded by 20 cms of lead brick made from 70-year-old-activity (about 10 tons)
- 2mm thick Cd sheets surrounded by a plastic scintillator (muon veto) surrounded by polyethylene bricks and borated water thanks ends the shielding


[8]

- FWHM = 800 eV @75keV (Pb line) [9]
- Energy threshold = 4 keV [9]

Published data

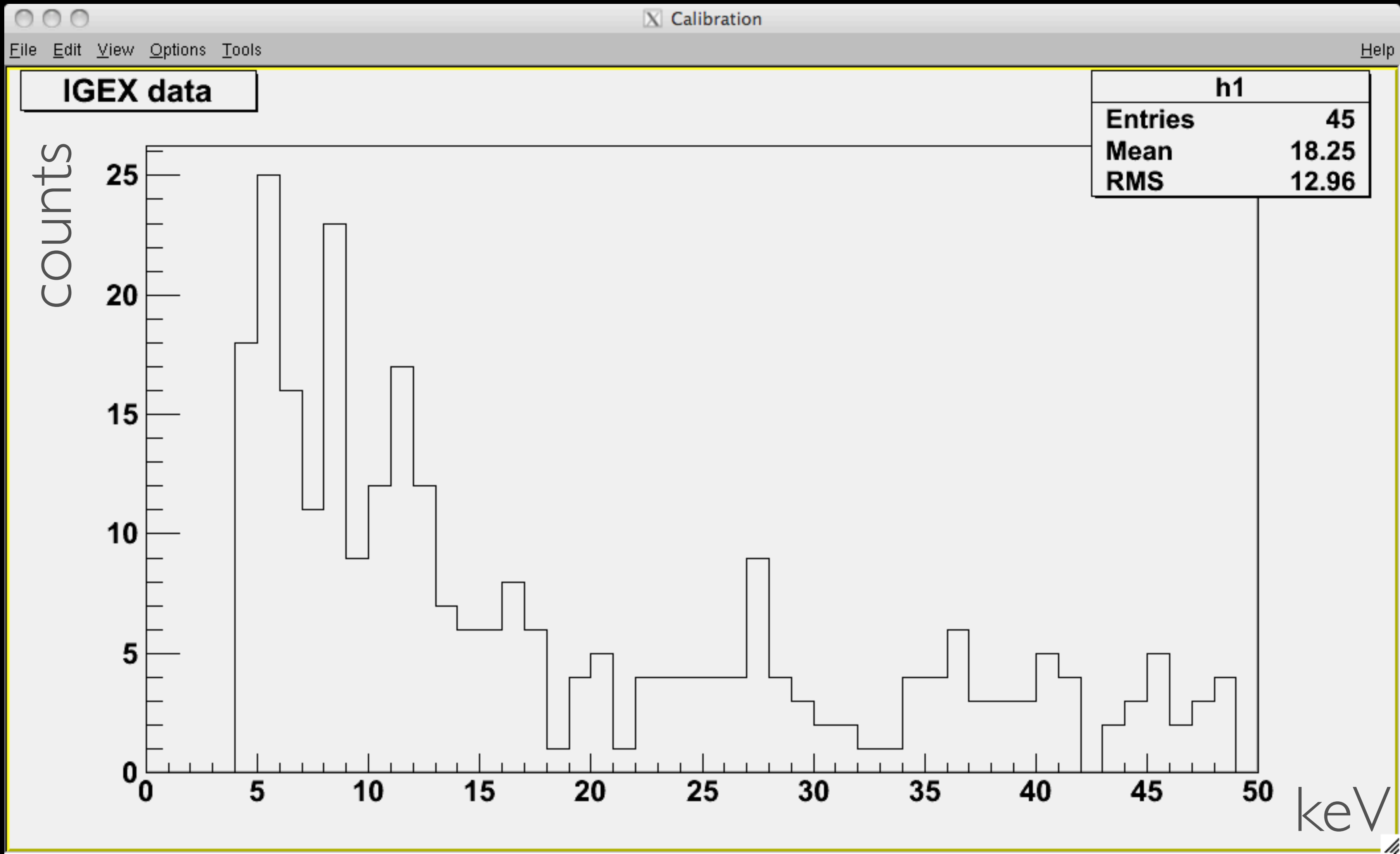
Low-energy data from the IGEX RG-II detector (Mt = 80 kg day)

E (keV)	Counts	E (keV)	Counts	E (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	5
16.5	8	31.5	2	46.5	2
17.5	6	32.5	1	47.5	3
18.5	1	33.5	1	48.5	4

Exposure: 80 Kg day

It is possible to reconstruct the histogram to analyze

The Histogram



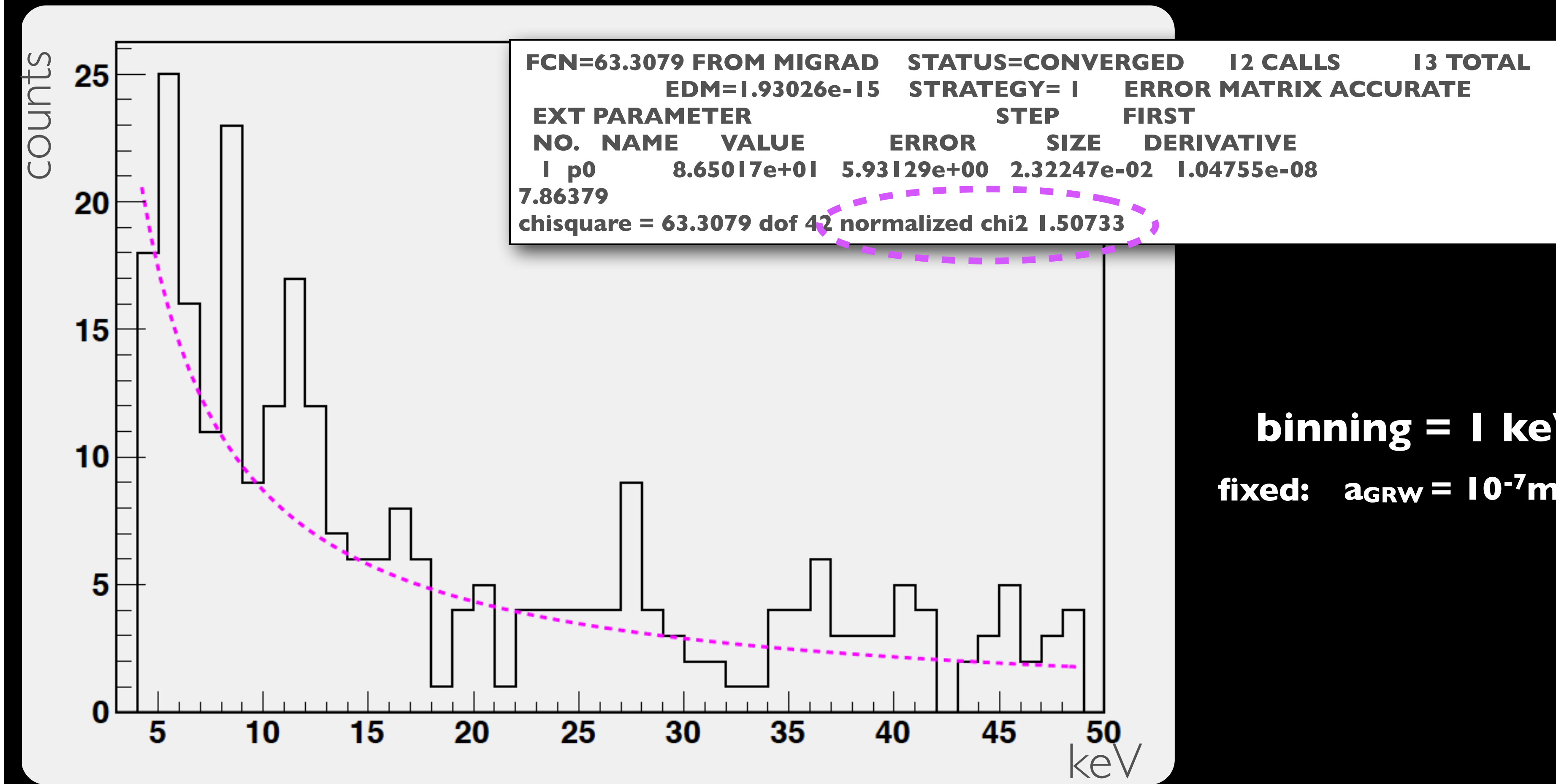
binning = 1 keV

A Simple fit

Exposure

Fit Function

$$R_{theory}(k) = (2.74\times10^{-15})\times4\times(8.29\times10^{24})\times(8.6\times10^{4})\times\frac{\lambda}{k[keV]}\times80[Kg][day]$$

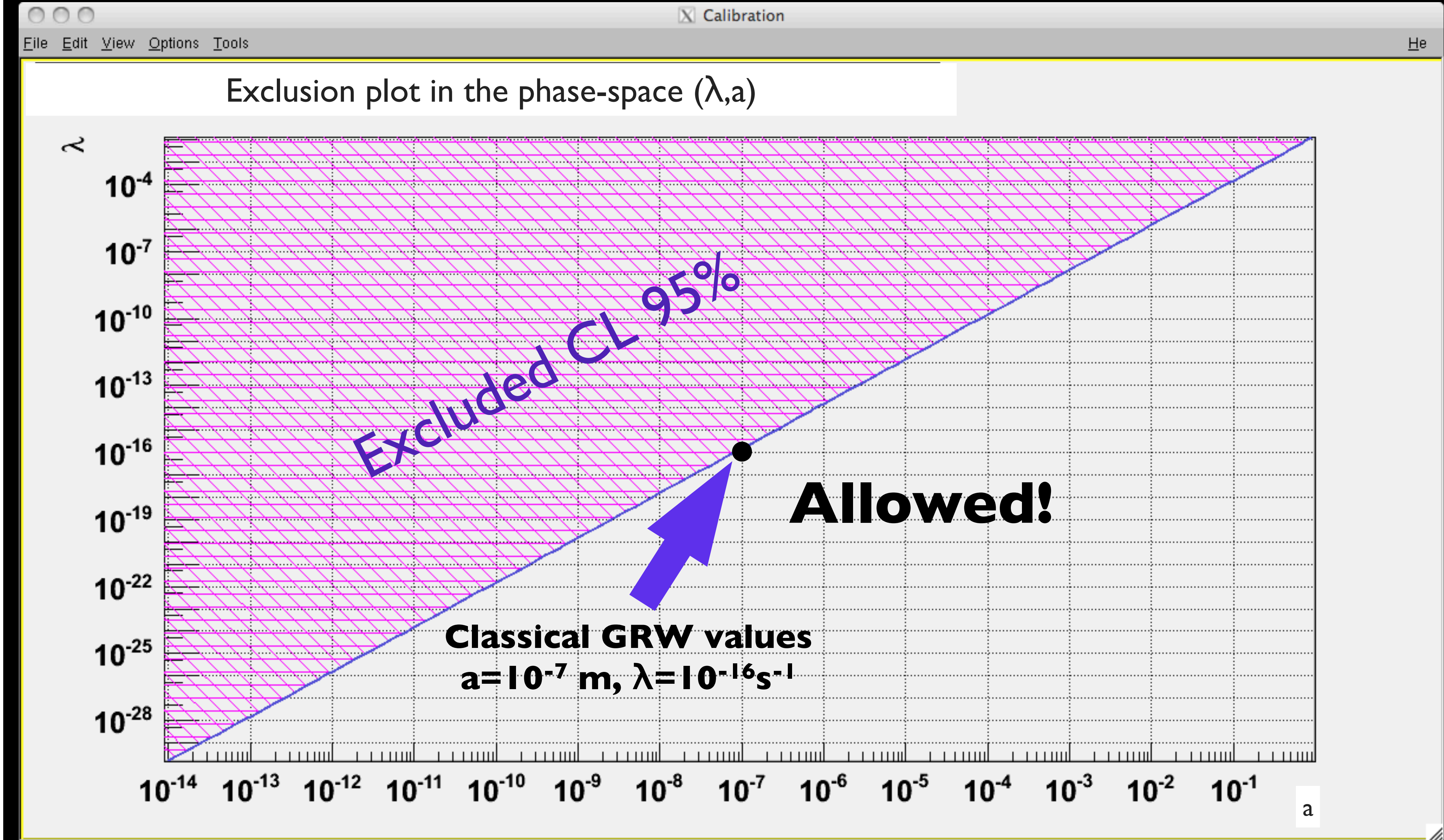


binning = 1 keV

fixed: $a_{GRW} = 10^{-7}$m [3]

$\lambda < 1.5\times10^{-16} s^{-1}$ (C.L. = 95%)

A Plot in the (λ,a) space



Conclusion

- The result of this work on the upper limit of λ parameter is going to fill the gap present up to now in scientific literature about the experimental search of Spontaneous Collapse Theories in Ge-based experiment (only 1 article)
- Our critical analysis of the pioneering work of Q. Fu ruled out the previous result, recognising it as a rough estimation of the order of magnitude of λ parameter
- This result is the first real upper limit on the lambda parameter coming from Ge-based experiment
- Today this result sets the strongest upper bound on the lambda parameter

Limitations of this work

Main limitation of this work: the use of a published data

- We cannot perform analysis to characterize the detector and use the results to obtain a more precise result
- We cannot evaluate in the analysis the known background sources

But this work shows that this search is feasible nowadays

So we have started to think about a future dedicated experiment...

A Dedicated Experiment

The Idea: → **Reduce the mass of the detector** → **Dimensions Reduced**

smallest Shielding

less material

Less Costs → **Problem: Less Statistic More time** → **Solution:**

lowering

$$\text{Counts} = 4\pi k^2 \frac{e^2\lambda}{16\pi^3 k^3 a^2 m^2} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 k} \times \text{exposure}(M_{tot}, t)$$

lowering

Available Technology

PPCs

p-type point contact (PPC) germanium detectors.

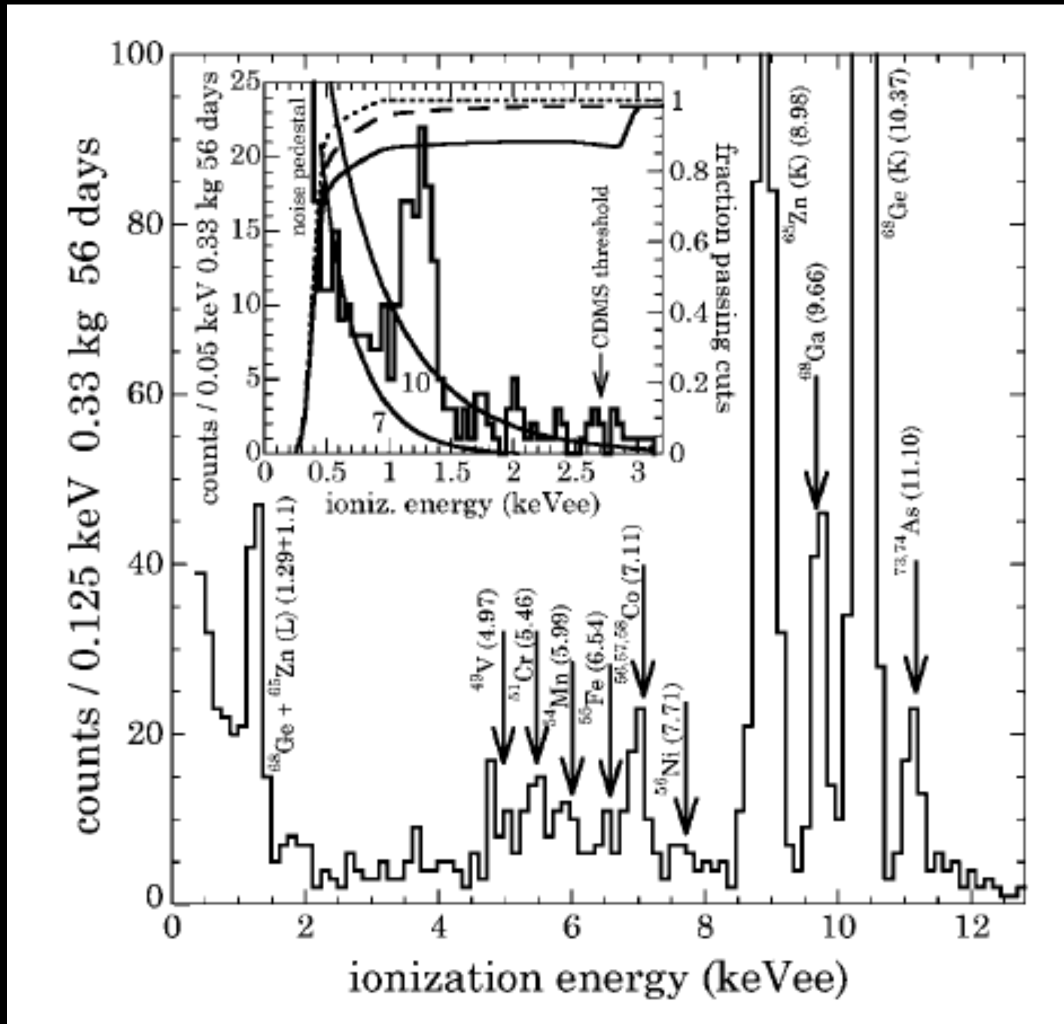
mass~500g [10] (used by CoGent experiment)

Energy resolution (σ)~140 eV @59.5keV (^{241}Am) [10] [11]

[11] - C. E. Aalseth et al., PRL 106, 131301 (2011)

[10] - P. S. Barbeau et al., J. Cosmol. Astropart. Phys. 09 (2007) 009

CoGent Spectrum



Studies about the CoGent detector and spectrum are started

Thank you for your attention