Universidad Zaragoza

LSC

Dark Matter searches at Canfranc with NaI: The ANAIS experiment

M. Martínez, Fundacion ARAID, Univ. de Zaragoza – Laboratori Nazionali del Gran Sasso, February 2013

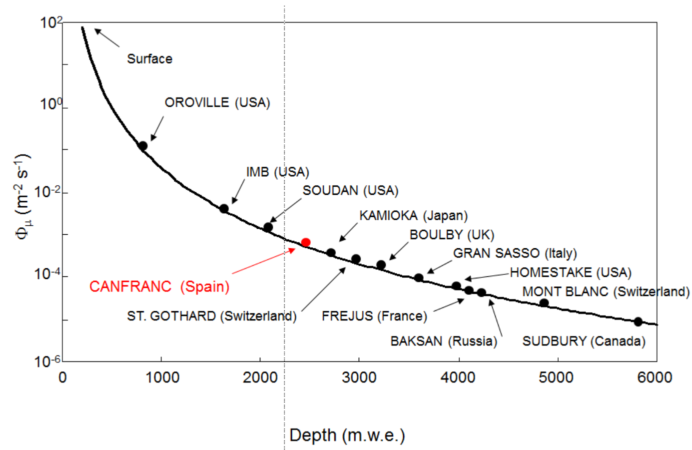
Outline

- The Canfranc Underground Laboratory
- DM detection by Annual Modulation
- The ANAIS experiment
- R&D NaI for bolometric applications

The Canfranc Underground Laboratory

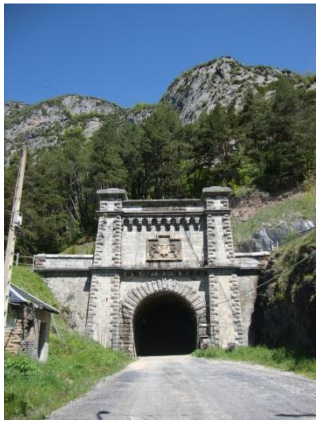
Laboratorio Subterráneo de Canfranc

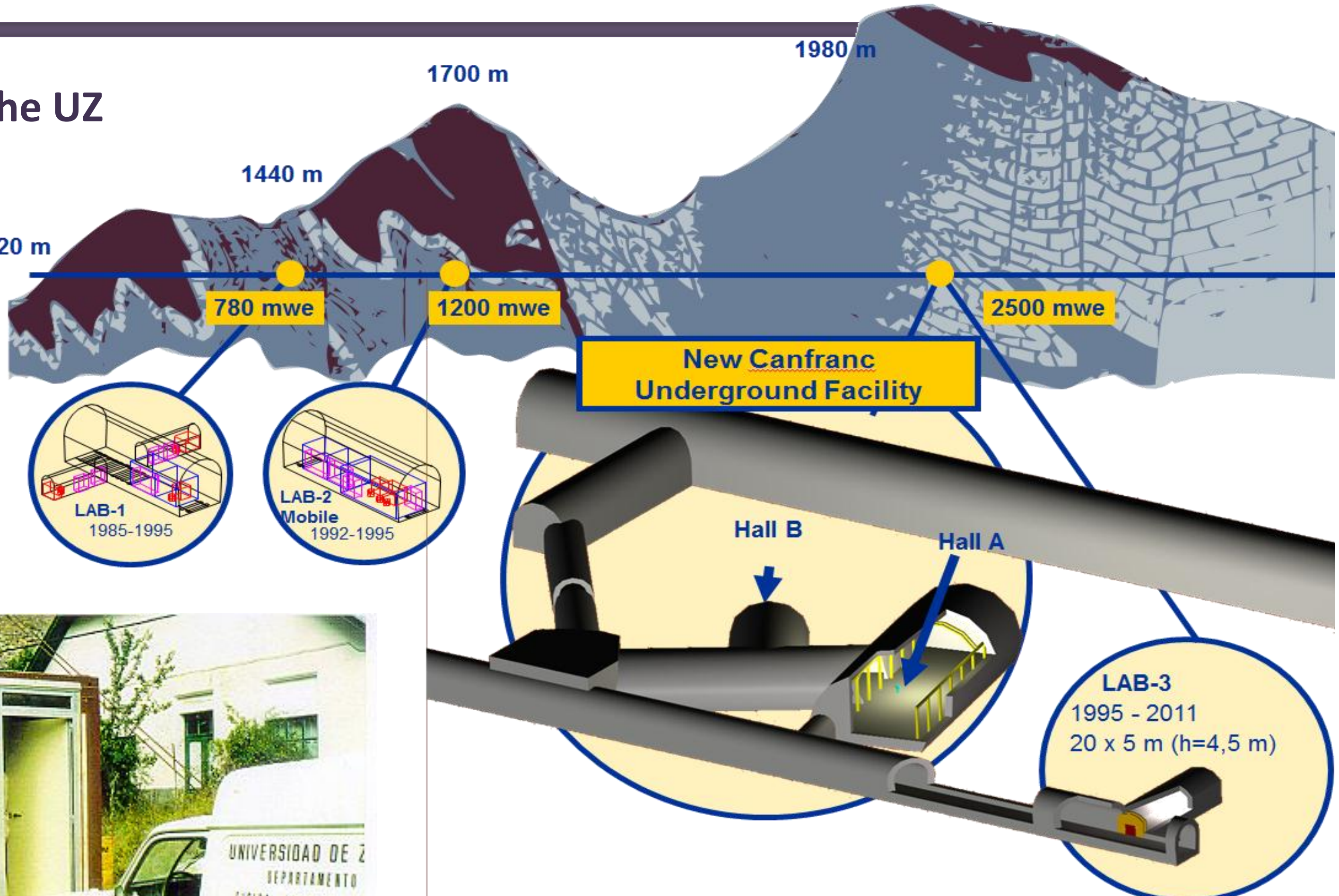
http://www.lsc-canfranc.es



The history of the LSC

… a laboratory of the UZ





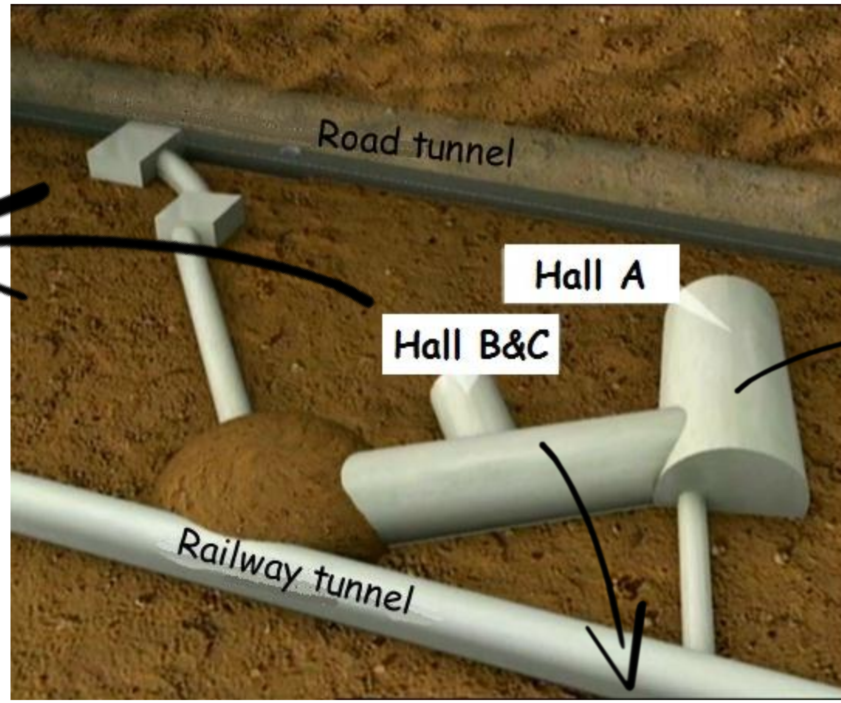
<u>**Experiments**</u>:

COSME, IGEX, IGEX-DM, NAI-32, ROSEBUD, ANAIS…

Underground facilities

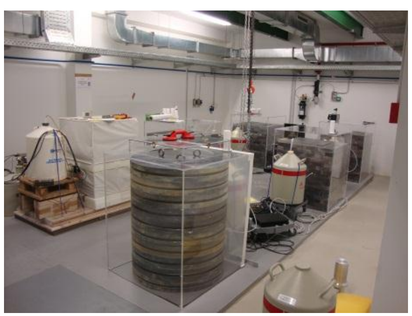
The new laboratory is run by a Consortium between the Spanish Ministerio de Economía y Competitividad, the Government of Aragon and the University of Zaragoza.

Hall B
15 x 10 m², h = 8 m



Hall A
40 x 15 m², h = 10 m

Hall C
HPGe farm

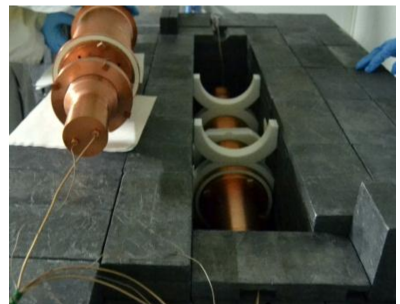


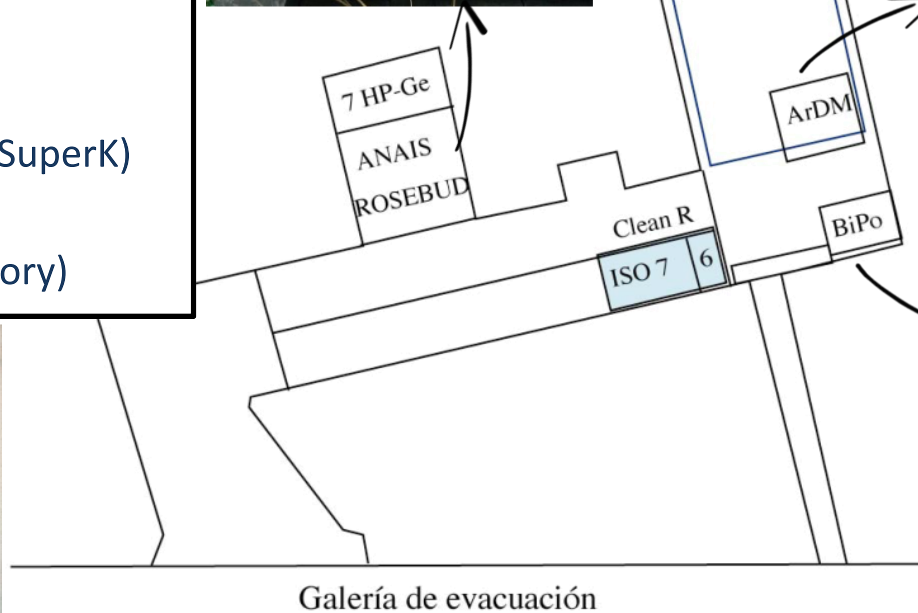
Service facilities: offices, workshop, clean room…

Experiments at LSC

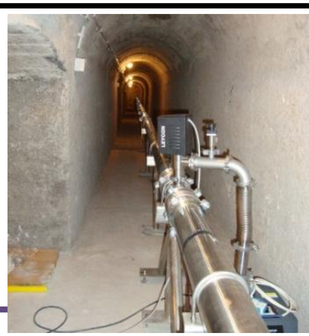
APPROVED EXPERIMENTS

- **ANAIS**
  (DM Annual Modulation with NaI)
- **ROSEBUD**
  (DM scintillating bolometers)
- **BiPo**
  (DBD, Super-NEMO prototype)
- **NEXT**
  (DBD, Enriched ^{136}Xe TPC)
- **ArDM**
  (DM, Liquid Argon TPC)
- **SuperK-Gd**
  (Material screening for SuperK)
- **GEODYN**
  (Geodynamics observatory)



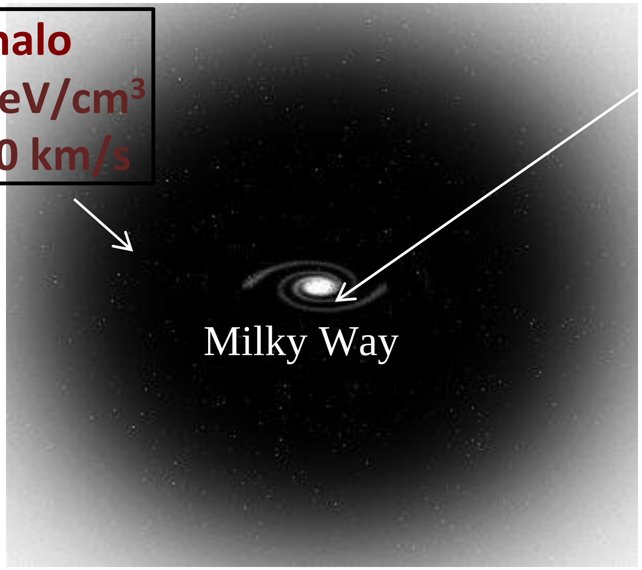


GEODYN



DM direct detection rate

Dark halo
ρ_0 = 0.3 GeV/cm^3
V_{rms} = 270 km/s



Earth (8.5 kpc from galactic center)
DM flux: $10^8 - 10^{10}$ wimps/m^{-2} s^{-1}

Standard approach:
χ Elastic scattering with nuclei

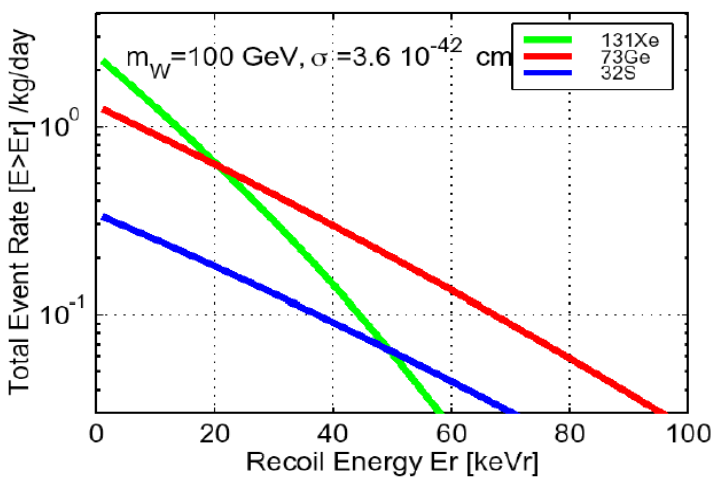
Expected rate:

Halo model

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2\right)$$

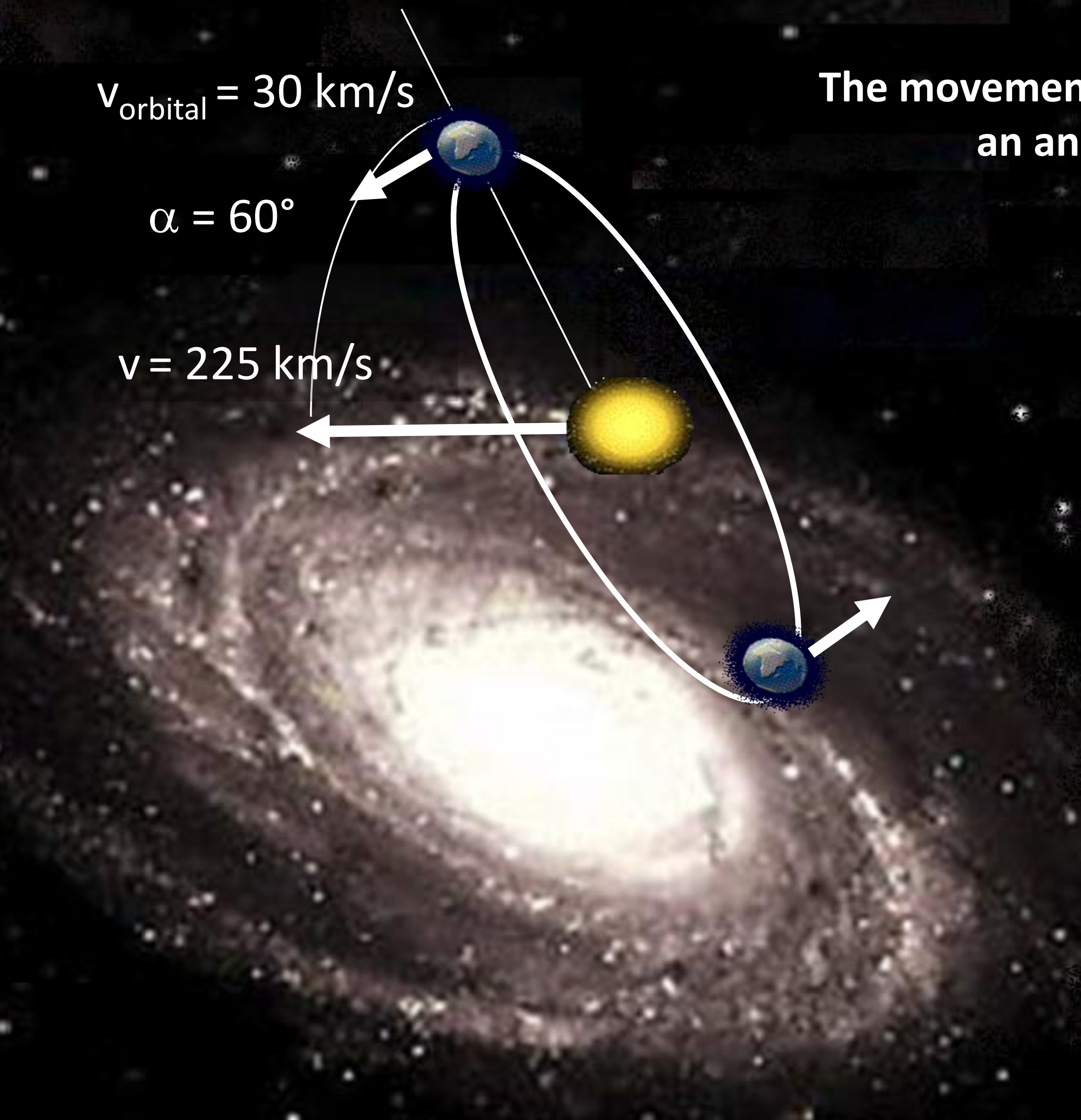
Spin Independent: $\sigma_{SI}^0 \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 \sigma_{SI}^{nucleon}$

Spin Dependent: $\sigma_{SD}^0 \propto \frac{m_{WN}^2}{m_{Wn}^2} \sigma_{SD}^{nucleon} \frac{4}{3} \frac{(J+1)}{J} \frac{1}{\bar{a}^2} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$



But also .... Inelastic scattering, Inelastic dark matter, interaction with e$^-$ ...

Distinctive signal: annual modulation

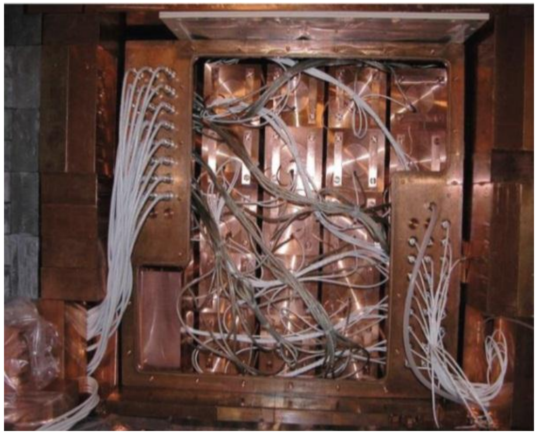


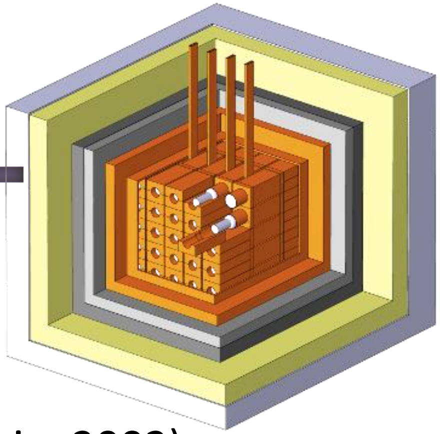
The movement of the Earth around the Sun induces an annual modulation in the expected rate.

$$S_k(t) = S_{0,k} + S_{m,k}\cos[w(t - t_0)]$$

- ✓ **Cosine behaviour**
- ✓ **1 year period**
- ✓ **Maximum around June 1st**
- ✓ **Weak effect (<7%)**
- ✓ **Only noticeable at low energy**
- ✓ **(For NaI, E<6 keVee)**

DAMA/LIBRA @ LNGS





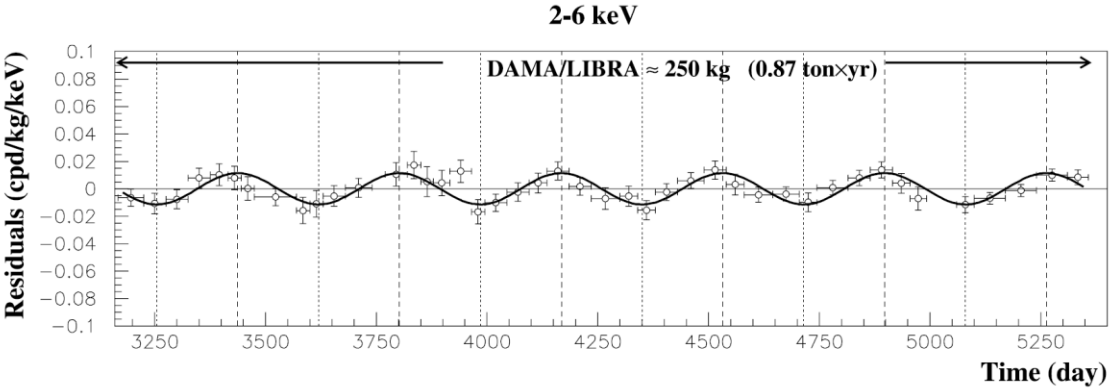
~250kg NaI scintillators @ LNGS

Total exposure:

DAMA/NaI (100 kg NaI, 7 years, completed in 2002)

+ DAMA/LIBRA (250 kg NaI, more than 9 years, ongoing)

→ total exposure reported so far: 425428 kg×day = 1.17 ton×yr

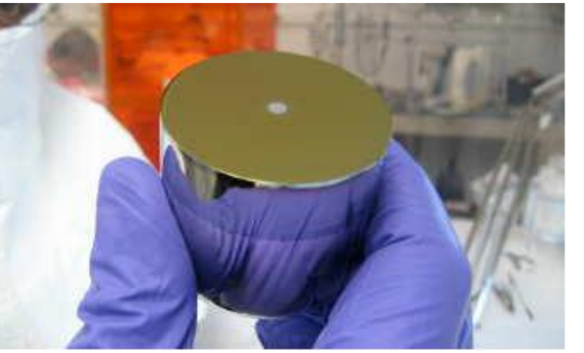


A_m = 0.0116 ±0.0013 cpd/kg/keV
T = (0.999 ±0.002) y
T_0 = (146 ±7) d (2^{nd} June=153)
No modulation above 6 keV

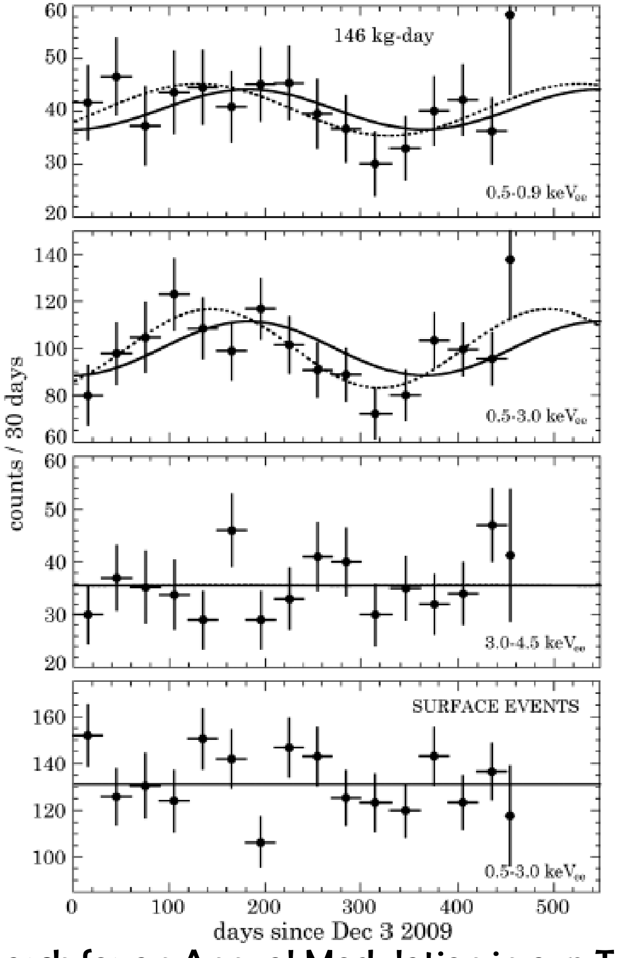
« New results from DAMA/LIBRA » Eur. Phys. J. C (2010) 67: 39

Evidence (8.9 σ C.L.) of an annual modulation of the *single-hit* events in the (2–6) keV energy region satisfying all the requests of a DM component in the galactic halo

CoGeNT @ Soudan



PPC HPGe (p-type point contact high purity Ge detector)



Reported so far: 15 months of data collection

"Presently available data support the presence of a modulated component of unknown origin, with parameters prima facie compatible with a galactic halo composed of light-mass WIMPs" (2.8 σ C.L.)

"Search for an Annual Modulation in a *p*-Type Point Contact Germanium Dark Matter Detector" PRL 107, 141301 (2011)

Comparison between DAMA and CoGeNT results is model dependent

PRD 84 (2011) 055014
JCAP 1108 (2011) 008
PRD 85 (2012) 043515
arXiv:1106.6241
arXiv:1302.0796
…

and also the comparison with other experiments with negative results (Xenon, CDMS..)

NaI Scintillators for DM search

- ↑ I -> σ_{SI} (α A^2)↑
- ↑ Na -> sensitive to light WIMPS
- ↑ Sensitive to SD-proton interaction

  ^{23}Na (i.a. 100%) : J=3/2 (unpaired proton)
  ^{127}I (i.a. 100%): J=5/2 (unpaired proton)

- ↑ High light yield (420 nm, well matched with PMTs)
- ↑ Particle discrimination by pulse shape analysis

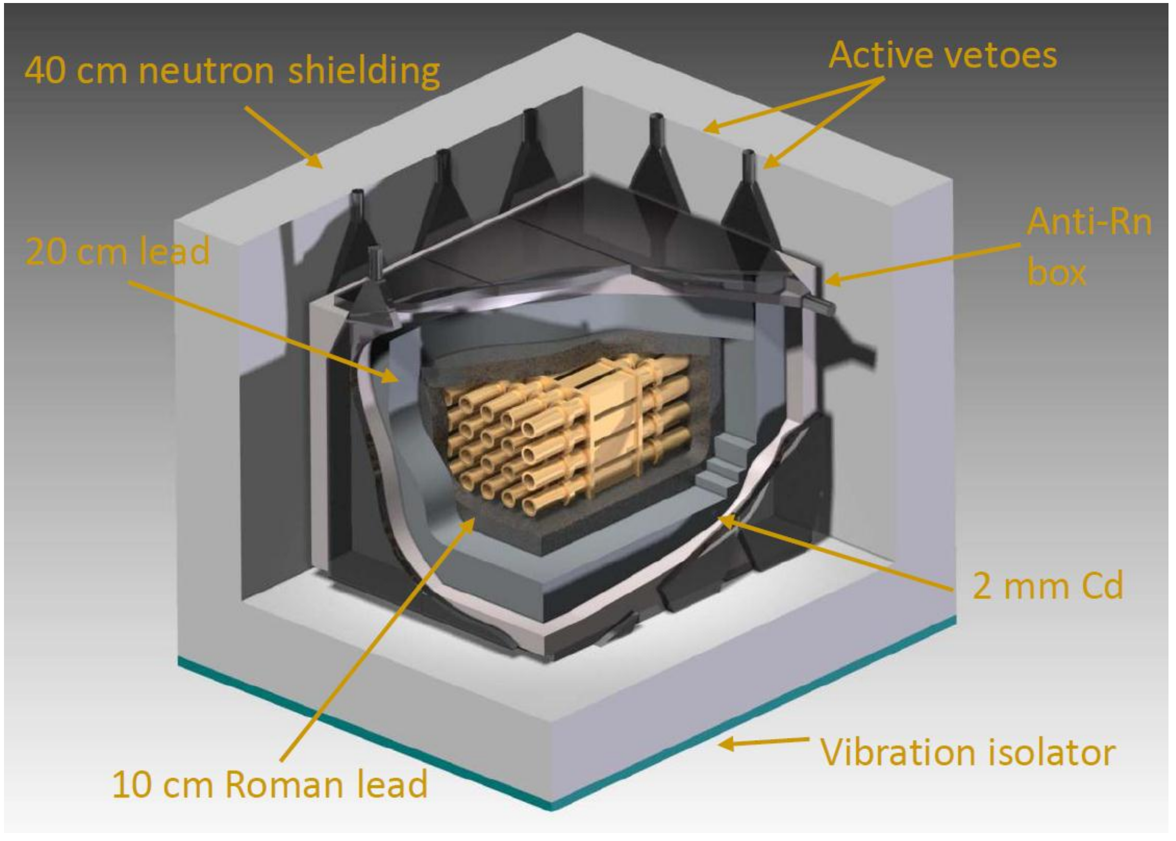
- ↓ Low quenching factor NR/$\beta\gamma$ (Na ≈ 0.3, I ≈ 0.1)
- ↓ Hygroscopic character
- ↓ No particle discrimination ($\beta\gamma$/NR) at very low energy

The ANAIS experiment

Annual Modulation with NaI Scintillators

Universidad Zaragoza 1542

J. Amaré, S. Cebrián, C. Cuesta, E. García, C. Ginestra, M. Martínez, M. A. Oliván, Y. Ortigoza, A. Ortiz de Solórzano, C. Pobes, J. Puimedón, M. L. Sarsa, P. Villar and J. A. Villar.

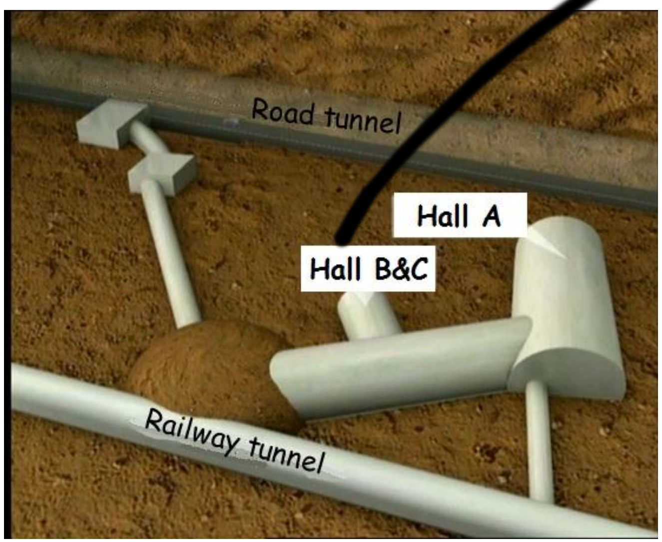


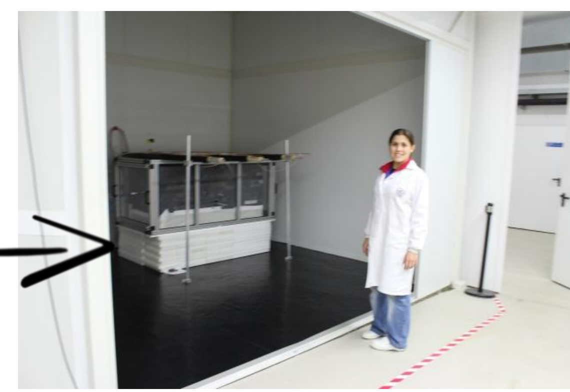
- **Looking for DM annual modulation with 250 kg NaI(Tl) scintillators**
- **To be installed at the new Canfranc Underground Laboratory (start data-taking expected: end 2013)**

Same target and technique as DAMA/LIBRA

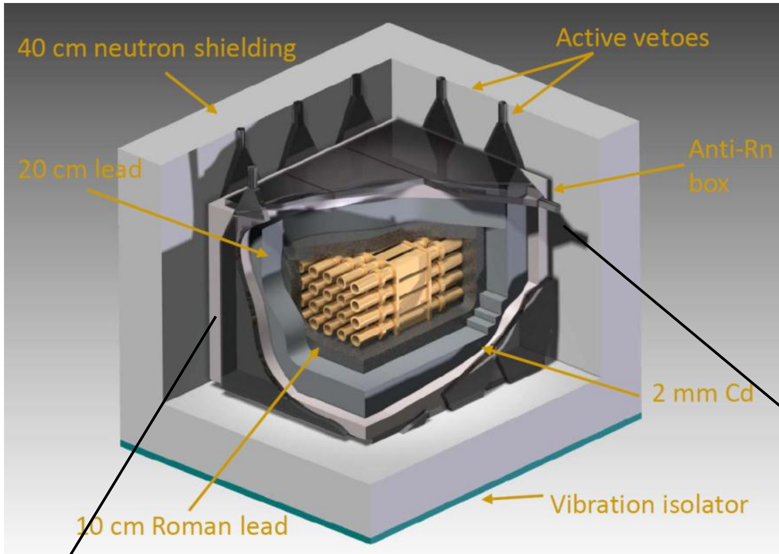
ANAIS @ LSC (Hall B)

The ANAIS Hut and the control room already constructed @ LSC Hall B



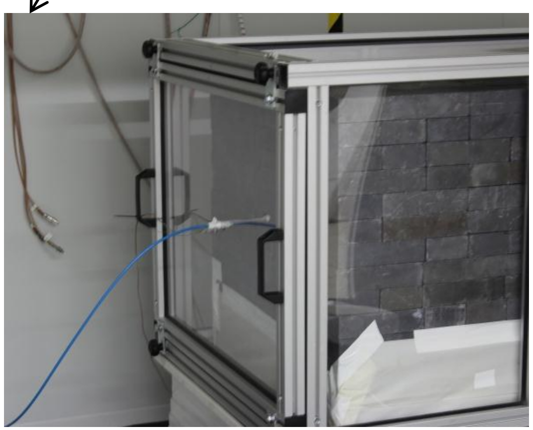


Shielding



Mechanical isolation, polyethylene, archaeological and low activity lead required for the whole ANAIS shielding are ready for the mounting.

Active muon vetoes: plastic scintillators to cover maximally the ANAIS shielding
12 1000x500x50 mm (lateral faces)
4 750x700x50 mm (top face)
(awaiting delivery)



Anti-Radon box recently mounted in LSC Hall B (expandable to house the whole ANAIS shielding)

PMTs Selection

Several models have been considered so far. We have selected **Hamamatsu VLB** based on the radioactivity levels (measured at LSC by HPGe spectroscopy) and quantum efficiency

	^{40}K (mBq/PMT)	^{232}Th (mBq/PMT)	^{238}U (mBq/PMT)	^{60}Co (mBq/PMT)	
Low background Electron Tubes Limited 9302B	420 ± 50	24 ± 4	220 ± 12	-	↓ radioactivity too high
Low background (LB) Hamamatsu R6233-100	678 ± 42	68 ± 3	100 ± 3	-	↓ radioactivity too high
Ultra low background (ULB) Hamamatsu R11065SEL	12 ± 7	3.6 ± 1.2	^{238}U - 47 ± 28 ^{226}Ra – 8.0 ± 1.2	4.1 ± 0.7	↑ Very low background level ↓ Relatively low Q.E. ↓ Very expensive
Very low background (VLB) Hamamatsu R6596MOD	97 ± 19	20 ± 2	^{238}U - 128 ± 38 ^{226}Ra – 84 ± 3	-	↑ Q.E. > 33 % @ 420 nm

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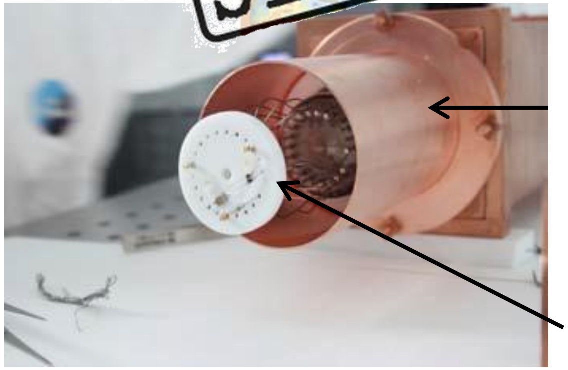
Very low background (VLB) Hamamatsu R6596MOD	97 ± 19	20 ± 2	^{238}U - 128 ± 38 ^{226}Ra – 84 ± [illegible]	-	↑ Q.E. > 33 % @ 420 nm

SELECTED

42 units of the Hamamatsu R6956 MOD SEL model have been purchased

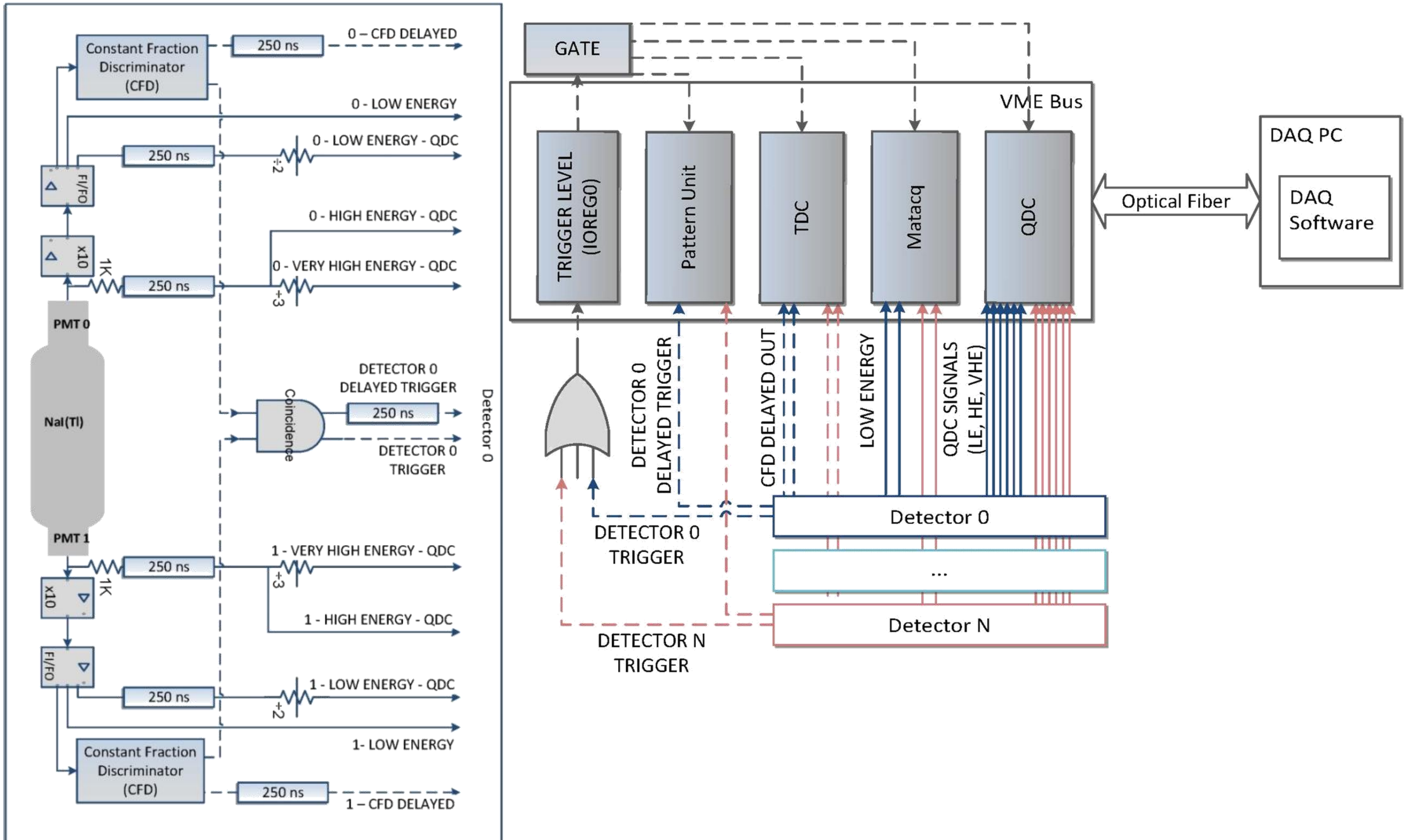


OFHC copper housing

Voltage divider (with Teflon support)

Electronic chain

- 20 detectors x 2 PMTS = 40 channels
- (almost) fully commissioned.



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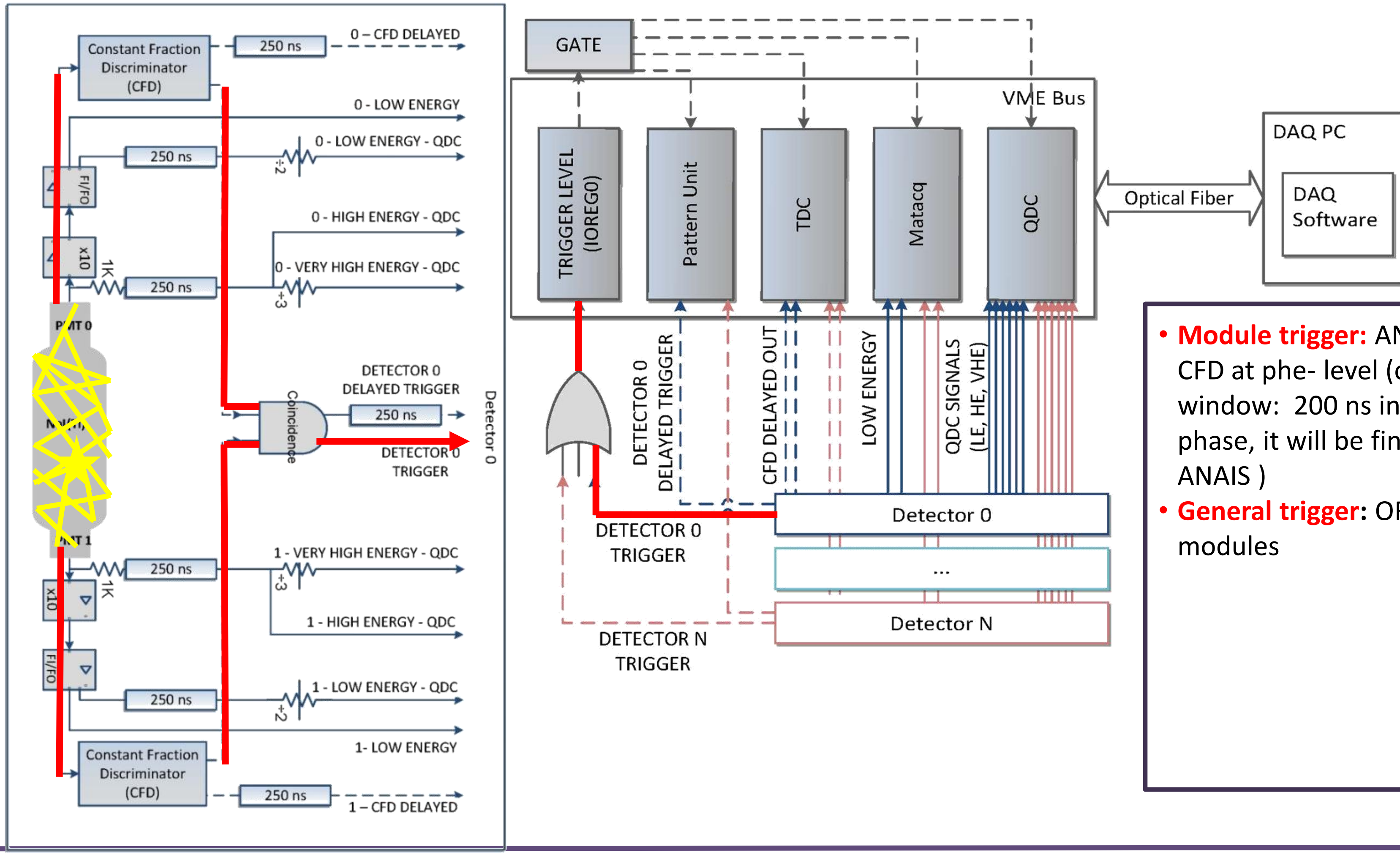

- **Module trigger:** AND of two CFD at phe- level (coincidence window: 200 ns in the test phase, it will be fine tuned for ANAIS)
- **General trigger:** OR of 20 modules

Electronic chain

- 20 detectors x 2 PMTS = 40 channels
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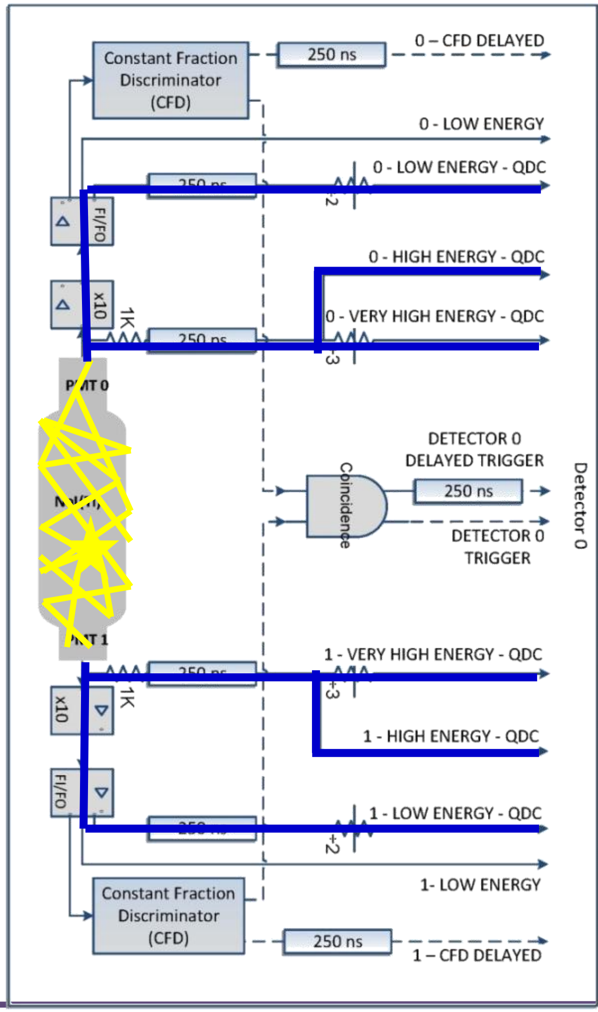

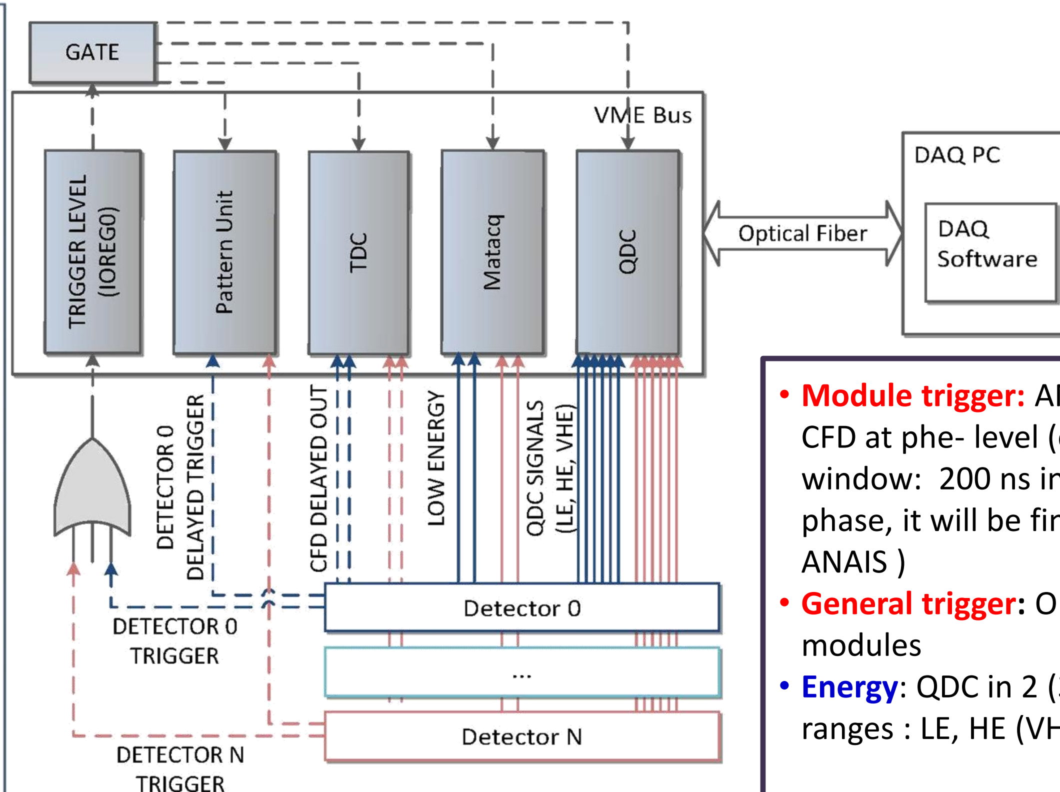

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Electronic chain

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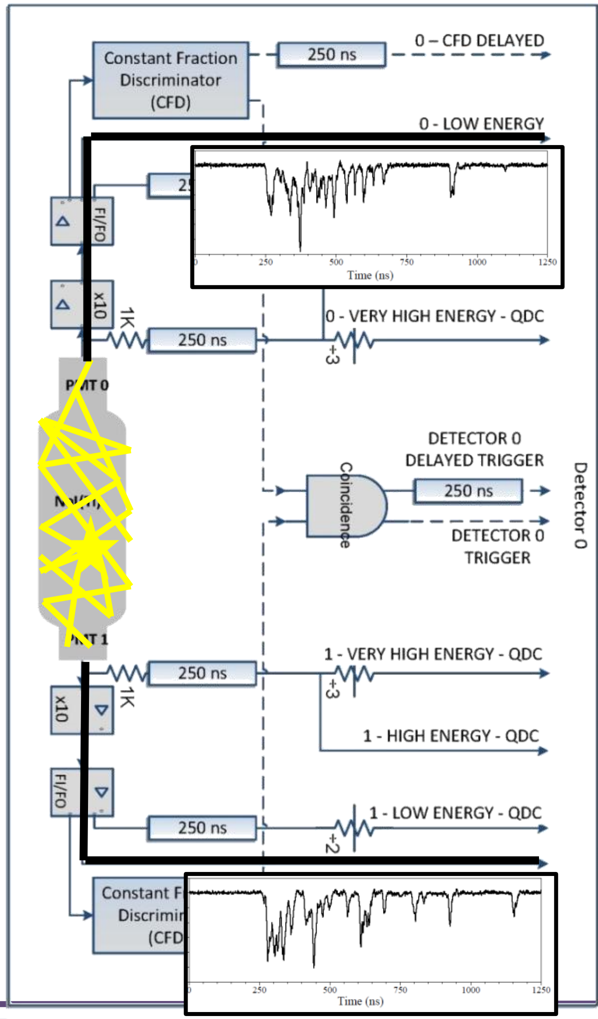

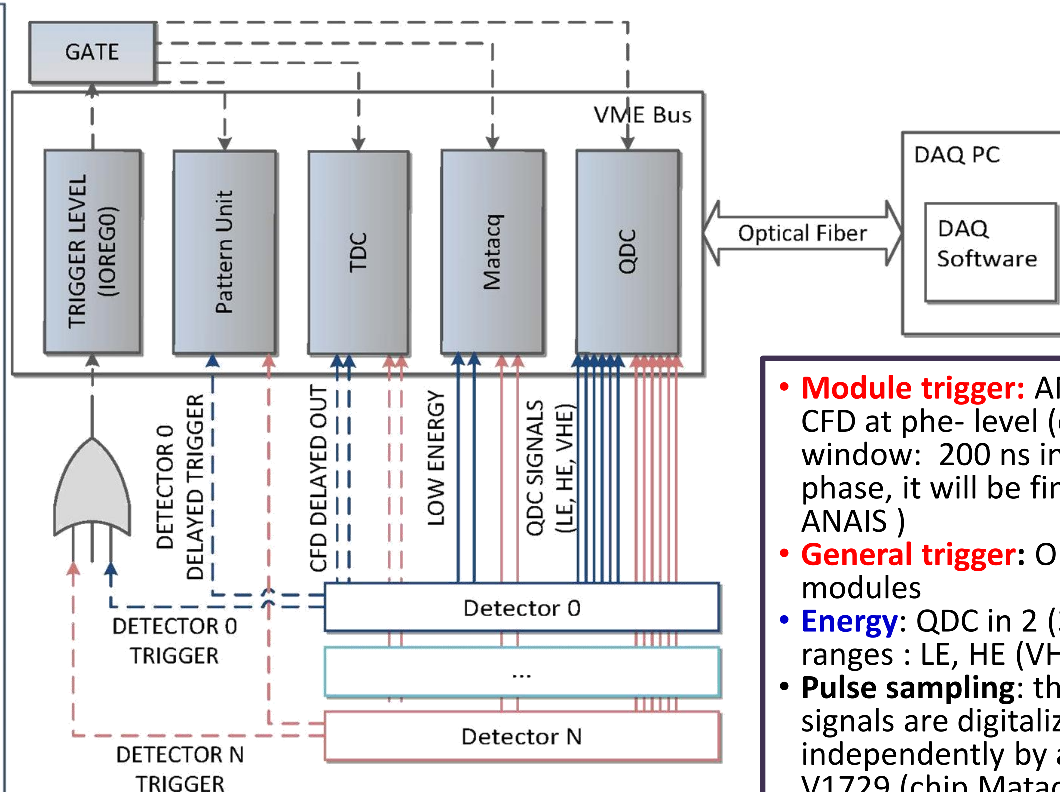

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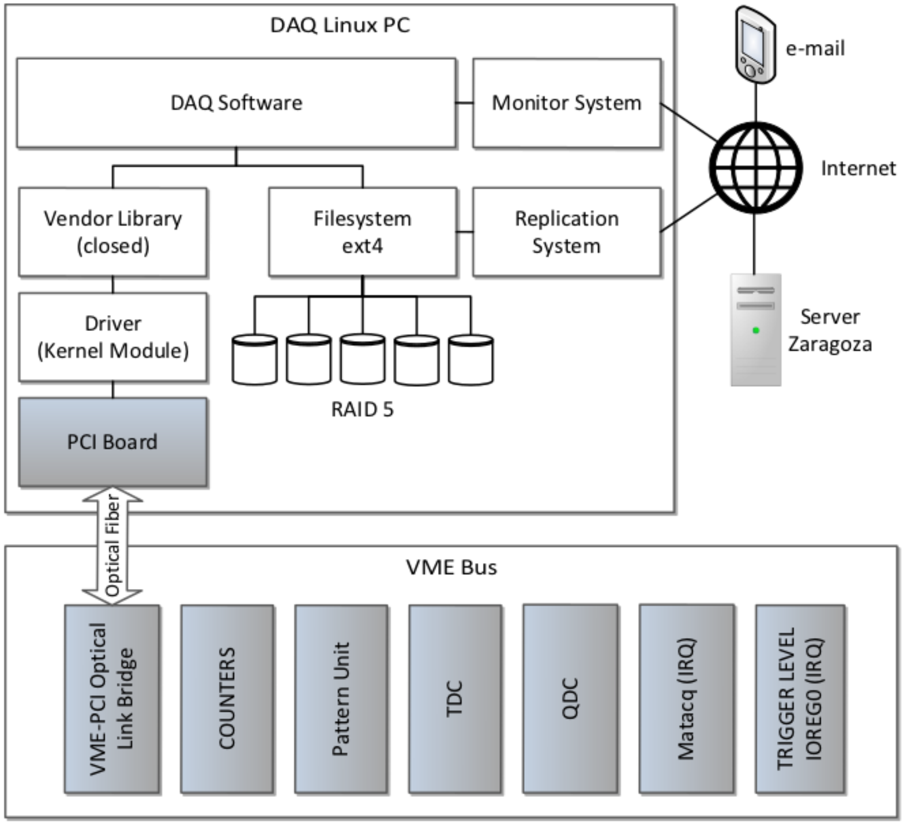
- **General trigger:** OR of 20 modules
- **Energy**: QDC in 2 (3) dynamic ranges : LE, HE (VHE)
- **Pulse sampling**: the two PMT signals are digitalized independently by a CAEN V1729 (chip Matacq) @ 2 GS/s, 12 bit vertical resolution, 1.25 μs window
- **Dead time:** 2.1 ms/event

Good low energy estimator: Sum(area of the peaks)

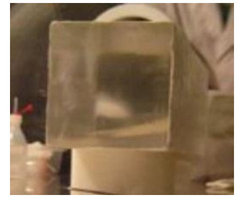
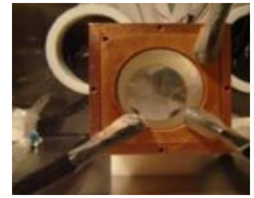
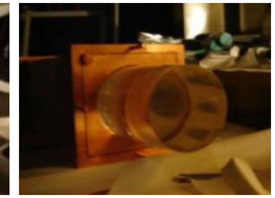
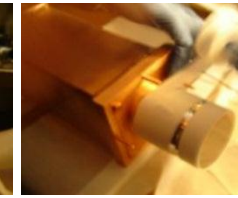
Acquisiton & analysis software and Slow control system



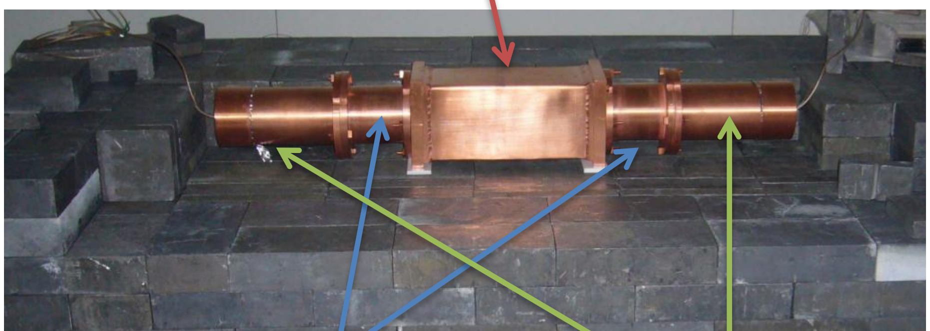
- Linux 3.0.0, multithread, root integrated
- Raid5 (2.7 TB) with replication system (rsync)
- Monitor system with alerts via e-mail/sms
- Slow control system monitoring:
  - Temperature (Hut/electronics/Hall B) ✓
  - N_2 flux ✓
  - HV supply ✓
  - Radon concentration @ Hall B ✓
  - Baseline noise
  - Muon rate
  - …

ANAIS-0 @ LSC

- A 9.6 kg NaI(Tl) (St Gobain) Crystal
- Encapsulated at UZ with ETP copper
- @ LSC from Sep 2011 to Dec 2012

25.4 x 10.2 x 10.2 cm^3 NaI(Tl) crystal



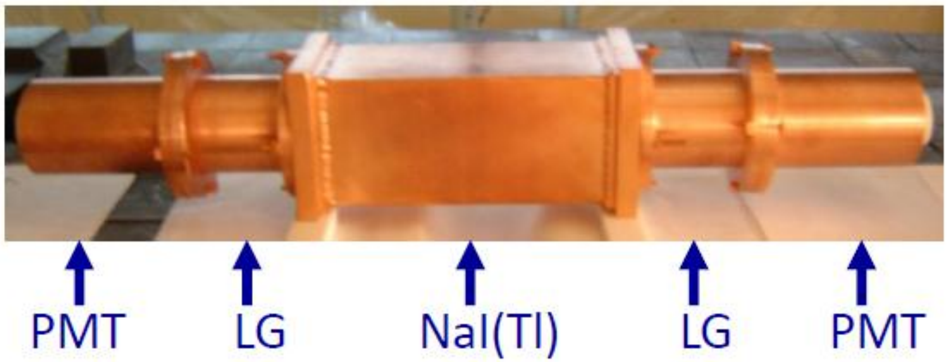
(removable) light guides

PMTs (several models tested)

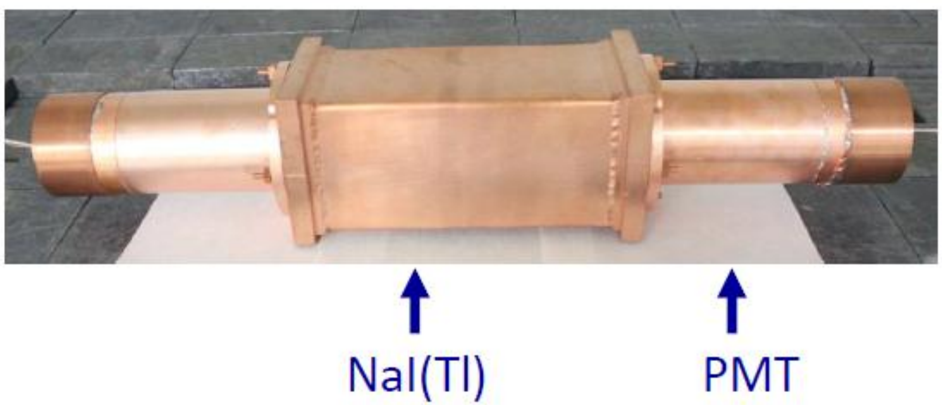
Goals:
- Test ANAIS DAQ (electronic chain & software)
- PMT/guides test
- Fine tuning analysis algorithms
- Background model

Shielding:
- 10 cm roman lead + 20 cm low activity lead.
- 3 active vetoes anti-muons.
- Anti-radon box, adaptable to the complete ANAIS experiment.

ANAIS-0: light collection in different configurations



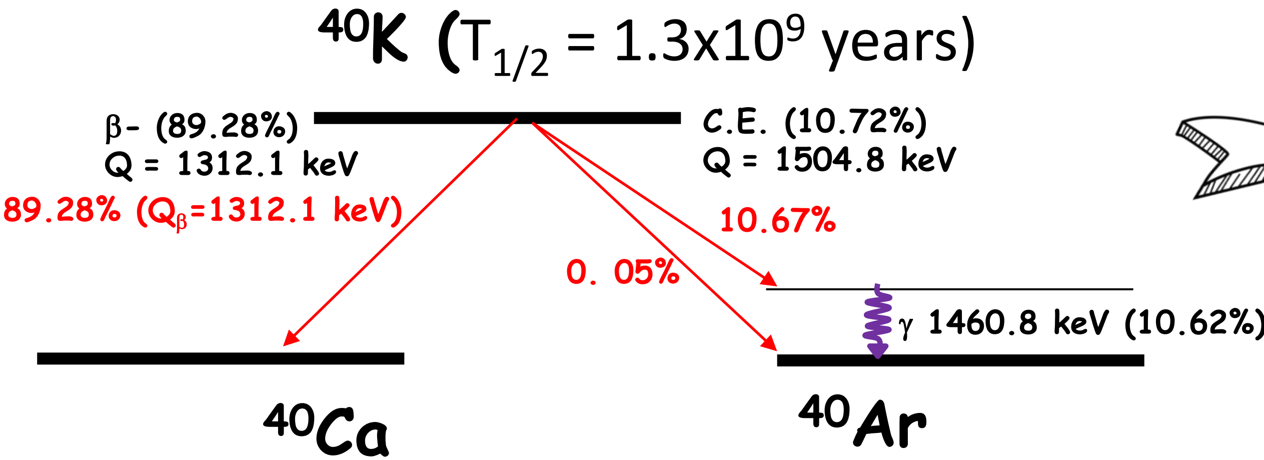
Set-up	PTM	Light guides	Resolution (%) 14.4 keV	Resolution (%) 122.1 keV	Phe$^-$/keV
1	ET LB	No	17.6	7.8	6.5
2	Ham LB	Yes	22.3	6.6	4.9
3	Ham ULB	Yes	17.6	7.2	4.1
4	Ham ULB	No	14.4	6.3	5.5
5	Ham VLB	No	15.2	5.9	7.5

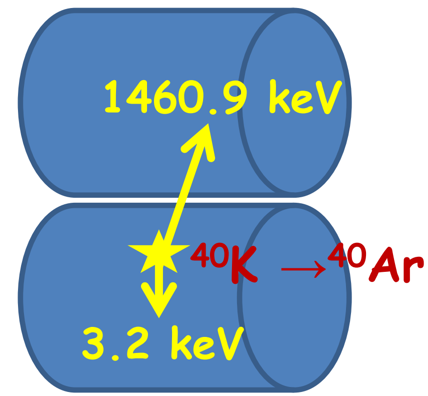


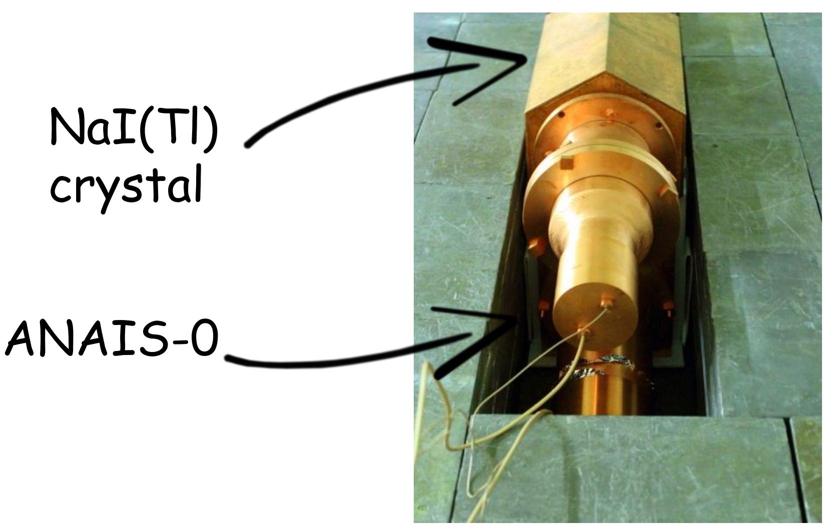
10 cm length light guides worsen ~30 % resolution and light collection

ANAIS-0 ^{40}K internal contamination

^{40}K : especially harmful at low energy





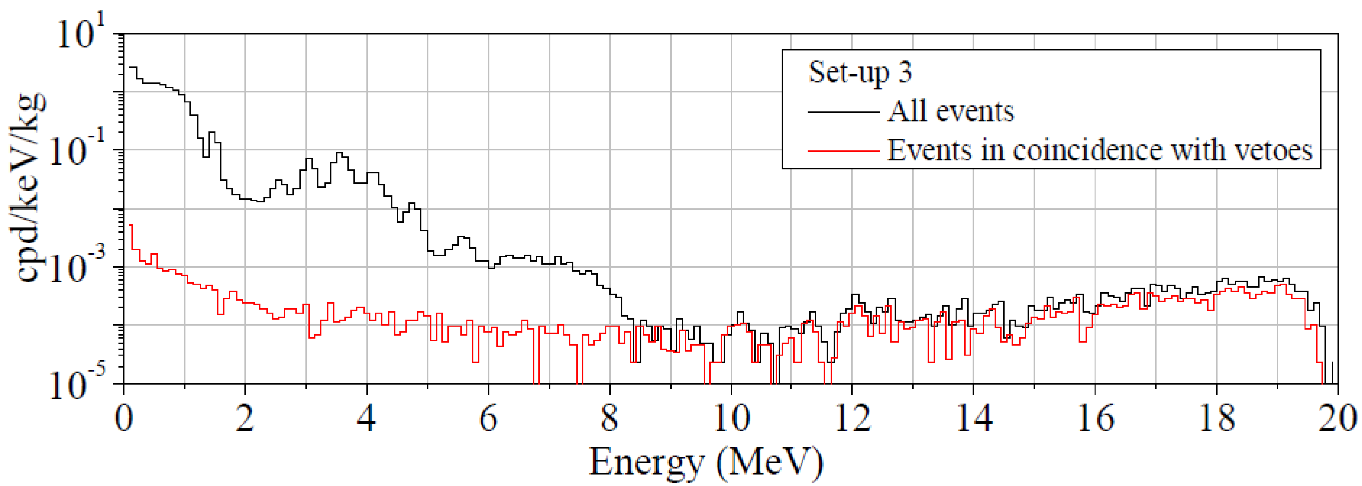


^{40}K bulk activity in ANAIS-0:
12.7 ± 0.5 mBq/kg

ANAIS-0 Event selection

Reject events based on:

- Periods of high rate (after calibrations)
- Cut 0.5 s after a muon (high energy event) in crystal
- **Muon veto to coincidence**



ANAIS-0 Event selection

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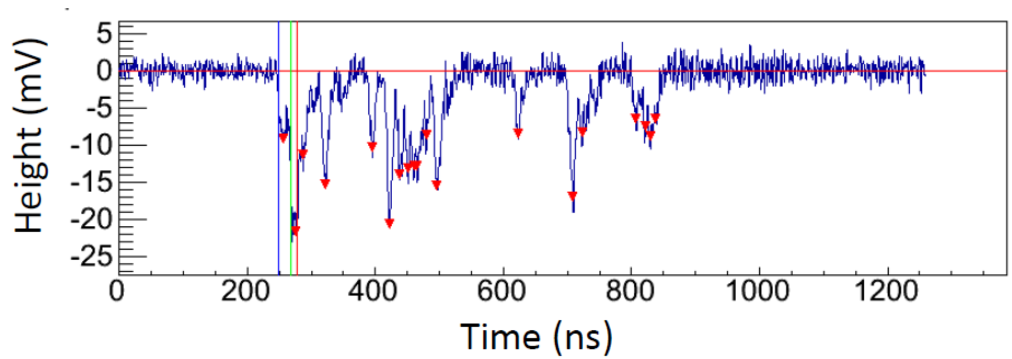
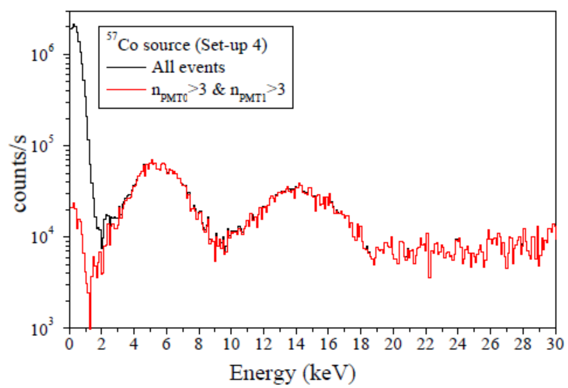
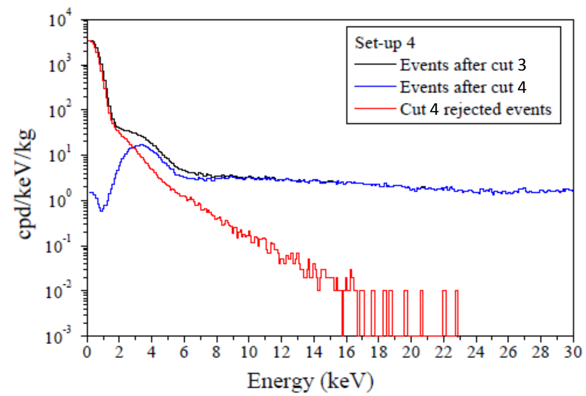
- Muon veto to coincidence
- **Number of photoelectrons**

  PMT1< 3 && PMT2<3

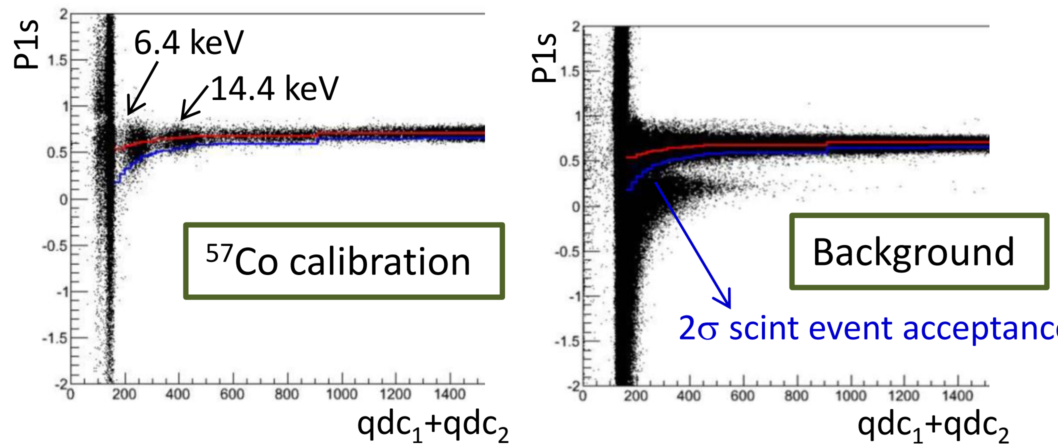






ANAIS-0 Event selection

Efficiency checked with calibrations down to 2 keVee



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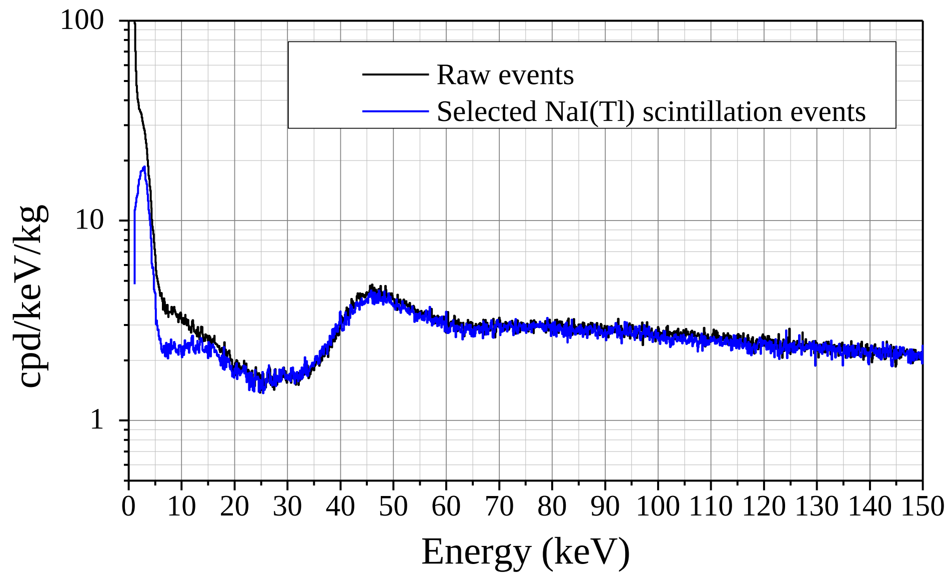
- Cut 0.5 s after a muon (high energy event) in crystal
- Muon veto to coincidence
- Number of photoelectrons
  PMT1< 3 && PMT2<3
- **Cut on the scintillation time (P1 parameter):**

$$P1s = \frac{area1(100-600\,ns) + area2(100-600\,ns)}{area1(0-600\,ns) + area2(0-600\,ns)}$$



Rejection of non bulk events: surface events or scintillation of other materials

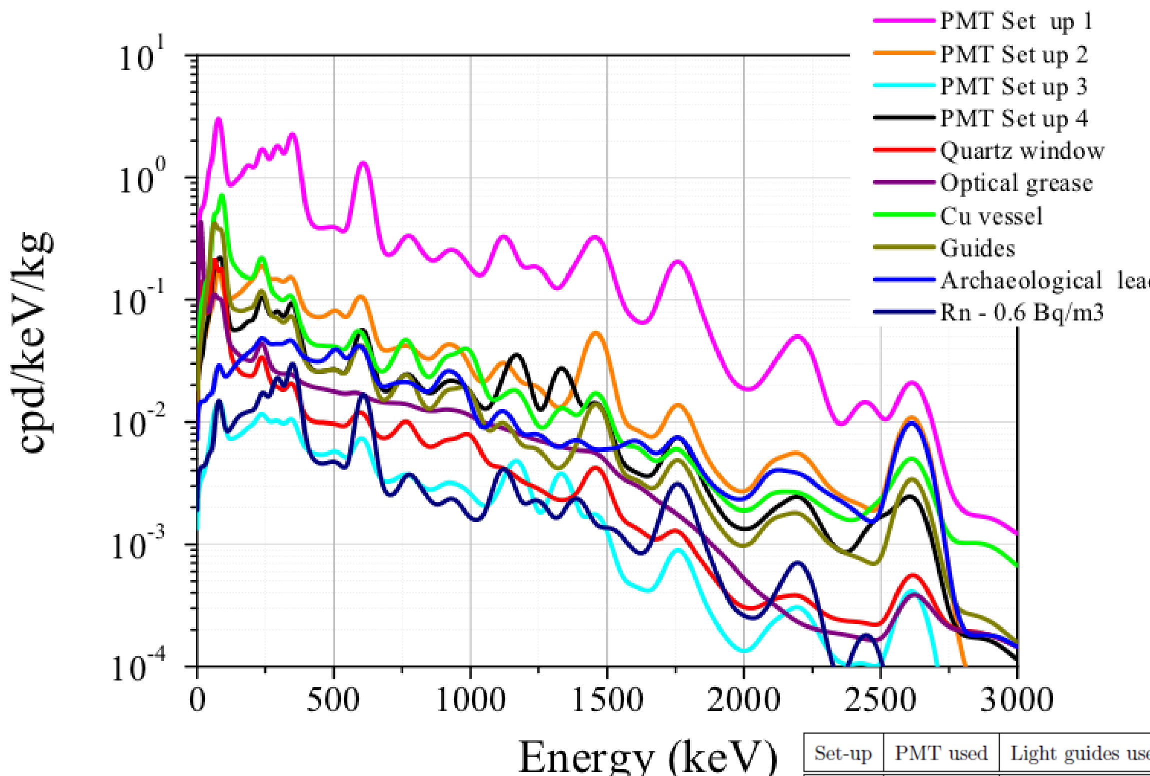
ANAIS-0 Background model

All the materials used in ANAIS-0 have been screened with a HP-Ge . Apart from the PMTs, only upper limits (95% CL) have been found:

Simulated component	Isotope	Activity
Copper encapsulation	^{40}K	< 11 mBq
	^{232}Th	< 4.1 mBq
	^{238}U	< 140 mBq
	^{226}Ra	< 2 mBq
	^{60}Co	< 0.94 mBq
Quartz optical window	^{40}K	< 12 mBq/kg
	^{232}Th	< 2.2 mBq/kg
	^{238}U	< 100 mBq/kg
	^{226}Ra	< 1.9 mBq/kg
Light guides	^{40}K	< 21 mBq/guide
	^{232}Th	< 4.1 mBq/guide
	^{238}U	< 120 mBq/guide
	^{226}Ra	< 4.7 mBq/guide
Optical coupling grease	^{40}K	< 200 mBq/kg
	^{232}Th	< 200 mBq/kg
	^{238}U	< 2000 mBq/kg
	^{226}Ra	< 30 mBq/kg
Archaeological Lead	^{210}Pb	< 20 mBq/kg
	^{232}Th	< 0.3 mBq/kg
	^{238}U	< 0.2 mBq/kg

+ reflectant, mylar, glue, teflon…

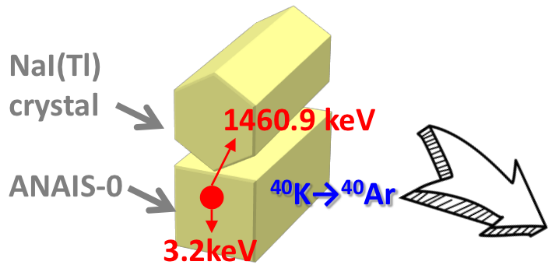
Contribution to background (Geant4 simulation):



Set-up	PMT used	Light guides used
1	ET LB	No
2	Ham LB	Yes
3	Ham ULB	Yes
4	Ham ULB	No

ANAIS-0 Background model

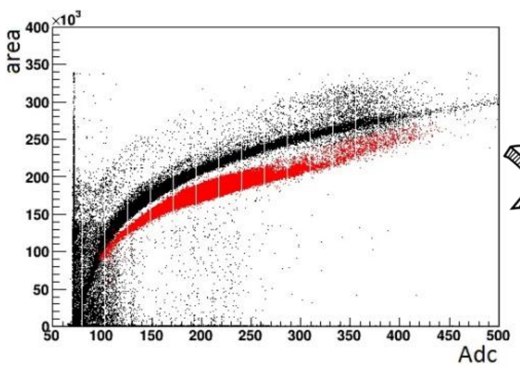
Crystal internal contamination determined by several methods:

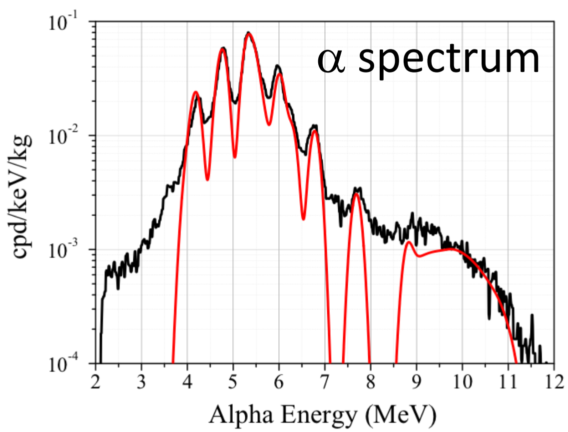


Isotope	bulk activity (mBq/kg)
^{40}K	12.7 ± 0.5
^{238}U / ^{234}U	0.075 ± 0.005
^{230}Th	0.023 ± 0.007
^{226}Ra	0.098 ± 0.004
^{210}Pb	0.188 ± 0.005
^{232}Th	0.013 ± 0.005
^{228}Th	0.035 ± 0.003

<u>^{232}Th and ^{238}U chains:</u>

- PSA α / $\beta\gamma$ discrimination:





- Identification of Bi-Po sequences

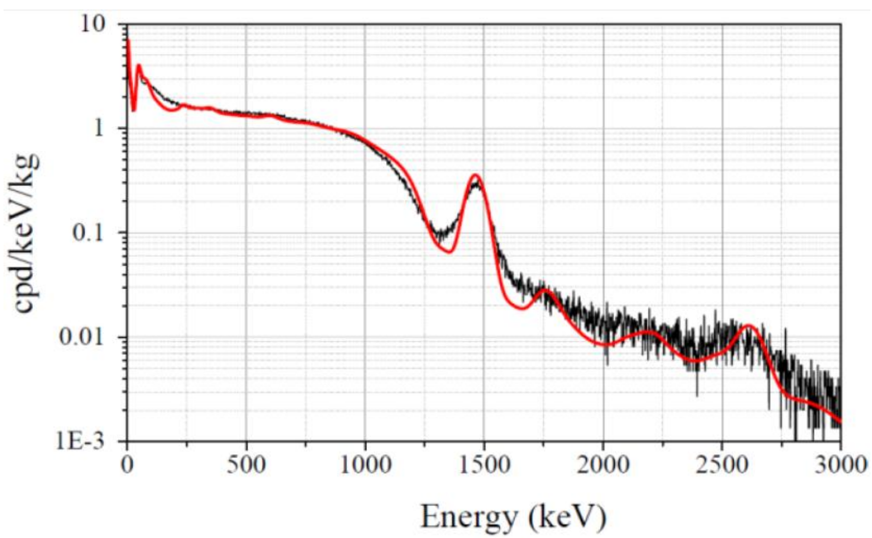
ANAIS-0 Background model

MC simulation of known background components

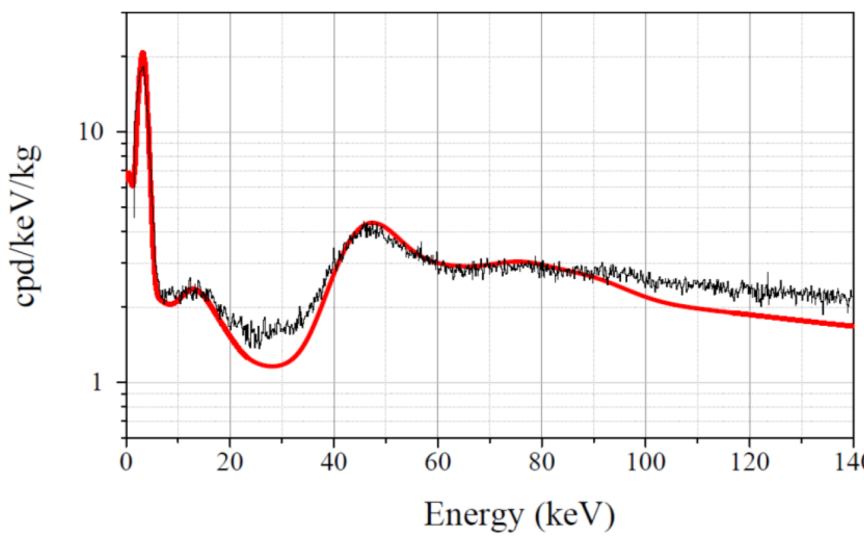
- PMT and adjacent materials contamination (measured by HPGe)
- internal crystal contamination (estimated by alpha discrimination, Bi-Po events identification and coincidence measurement)

plus some plausible hypotheses (^{210}Pb surface contamination in NaI and copper, cosmogenic ^{3}H and ^{129}I in NaI)
successfully explain the measured background :

High energy:



Low energy:



"Background model for a NaI (Tl) detector devoted to dark matter searches" Astrop. Phys. 37 (2012) 60

NaI(Tl) Powder selection

- **Goal: <20 ppb of ^{nat}K (0.6 mBq/kg)**
- **Contacts with several scintillator suppliers**
- **Powder selection based on HPGe measurements at LSC**

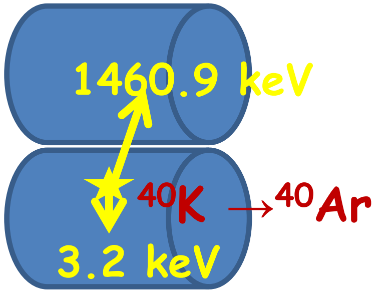
SELECTED POWDER (AS):

K (ppb)	U (ppb)	Th (ppb)
< 90	< 0.055	< 0.13

assuming equilibrium in U and Th chains

UPPER LIMITS AT 95% C.L.

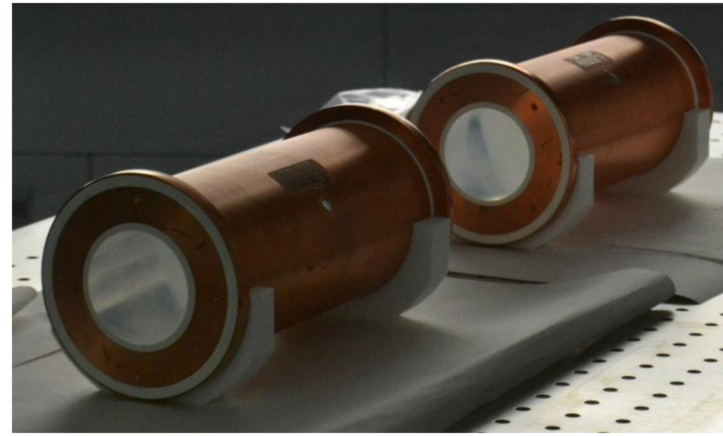
- **Next step: Measure K content by coincidence between two crystals grown with the selected powder**



NaI(Tl) Crystals encapsulation

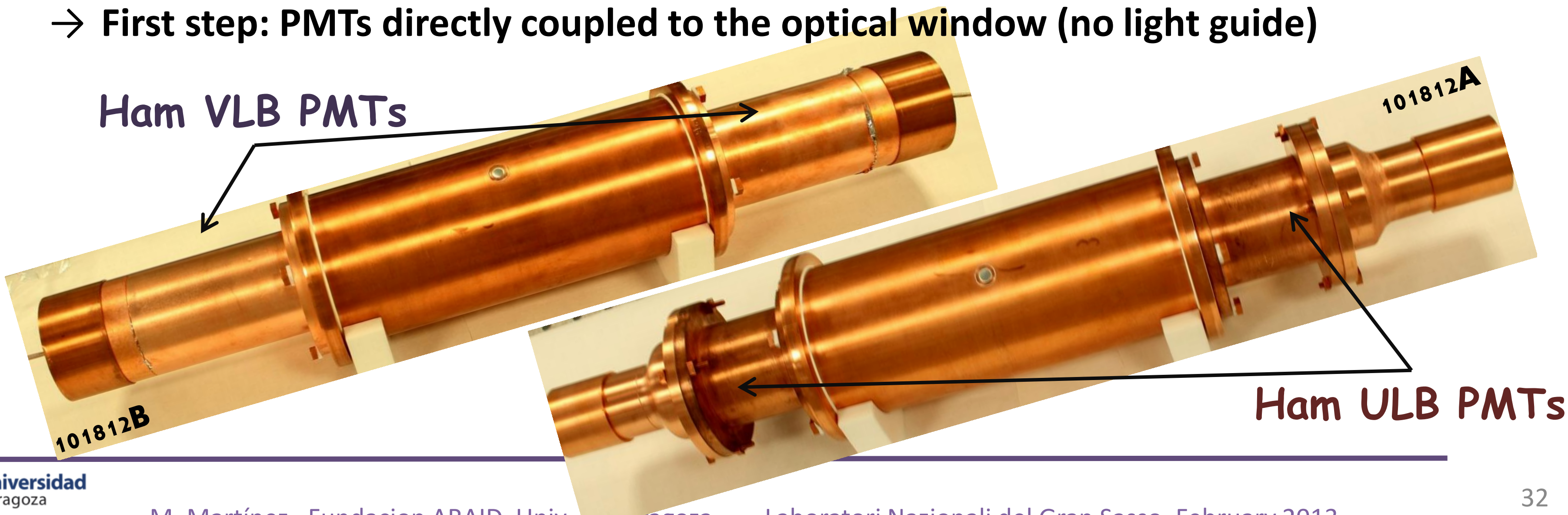
12.5 kg NaI(Tl) prototypes:

- 4.75” ϕ x 11.75” length cylindrical shape
- OFHC copper encapsulation
- Teflon diffusor
- Mylar window for low energy calibration
- Two optical windows



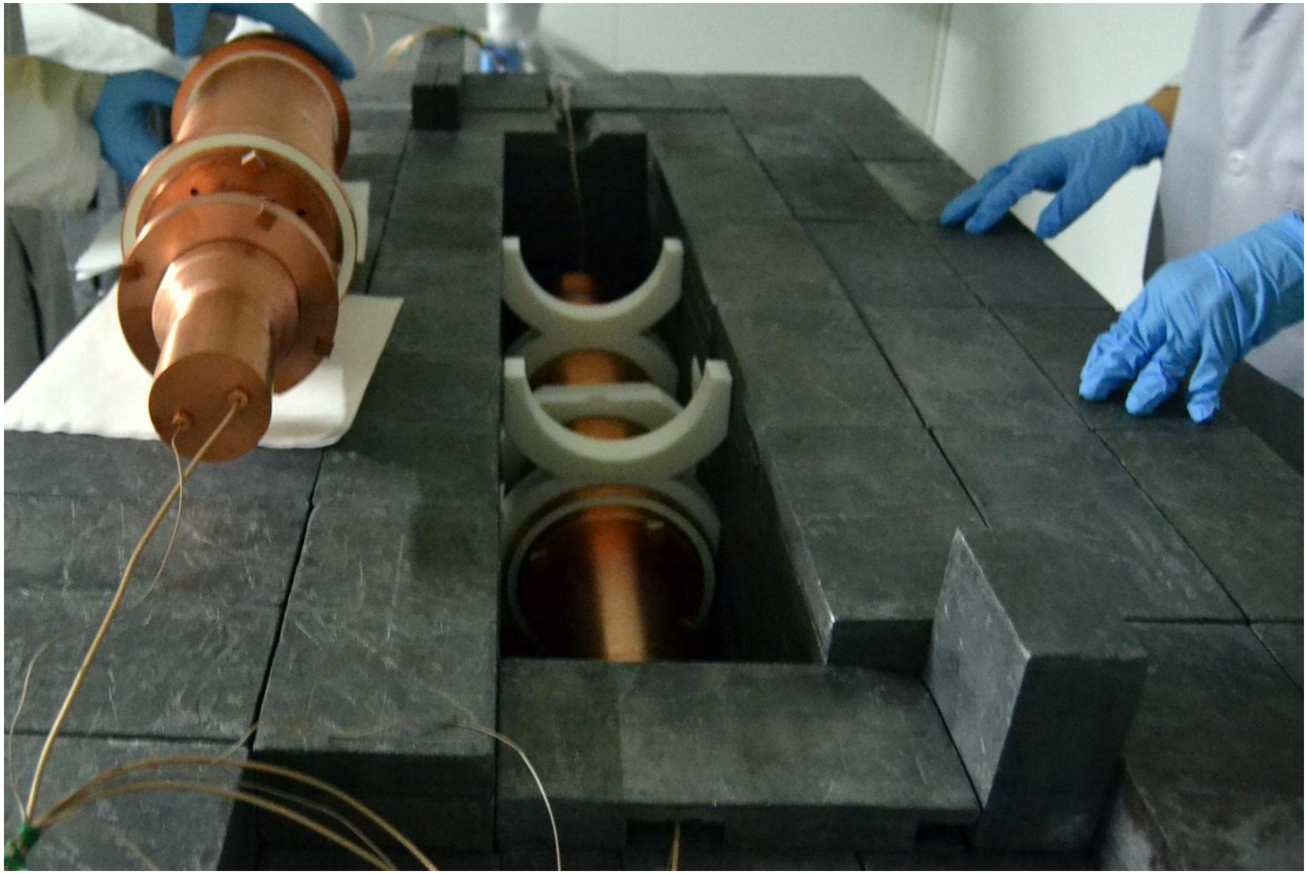
- ➢ Two first prototypes arrived to LSC in December 2012 for a low background measurement
- ➢ The PMT have been coupled at LSC by the ANAIS team:

→ **First step: PMTs directly coupled to the optical window (no light guide)**



ANAIS-25 prototypes @ LSC

From December 2012



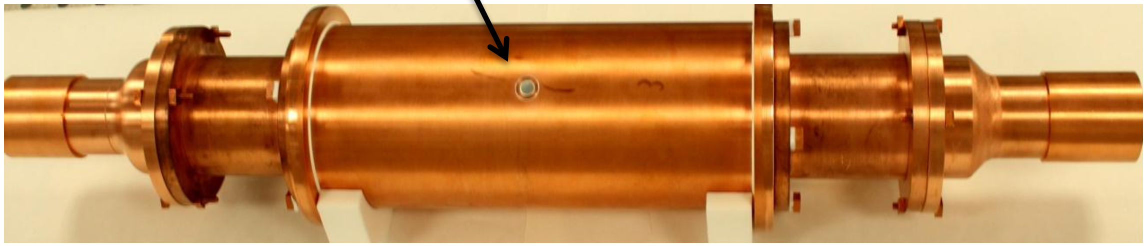
Shielding:

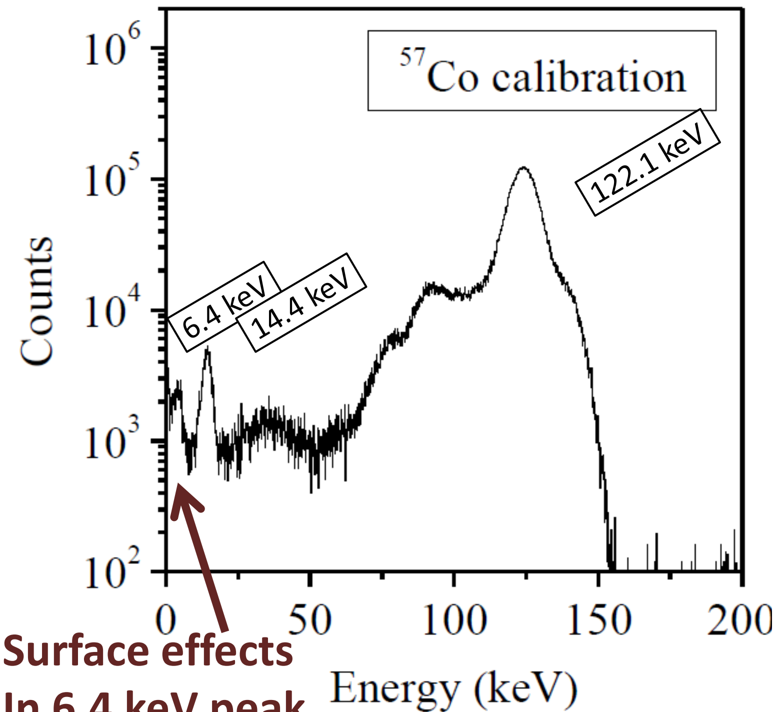
- 10 cm roman lead
- 20 cm low activity lead
- 3 active vetoes anti-muons.
- Anti-radon box

At least 3 months of data taken will be needed to estimate the ^{40}K bulk content

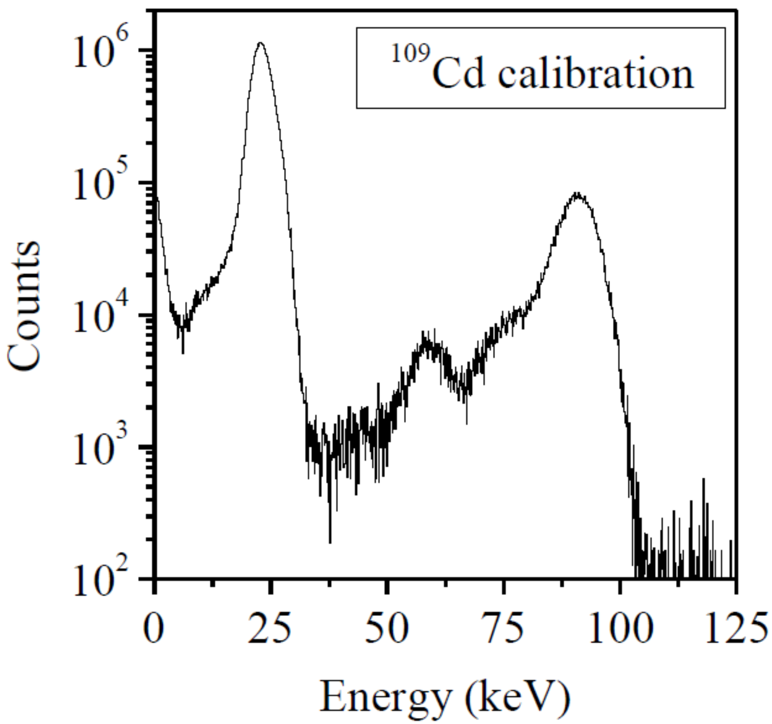
ANAIS-25 Low energy calibration

A Mylar window for low energy calibration with external sources



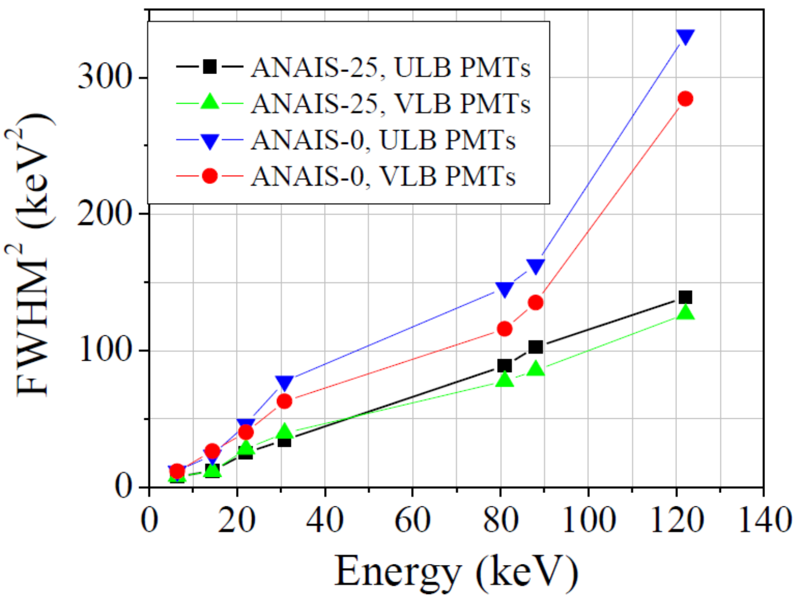


Surface effects
In 6.4 keV peak



+ other sources (^{55}Fe, ^{137}Cs, ^{133}Ba)

ANAIS-25 prototypes: Resolution



Energy (keV)	Res_{FWHM} (%)	
	ULB PMTs	VLB PMTs
6.4	43.5	43.9
14.4	24.0	23.5
22.1	22.6	24.0
30.8	19.0	20.4
81	11.5	10.8
88	11.5	10.6
122.1	9.6	9.2

ANAIS-25 prototypes: Light collection

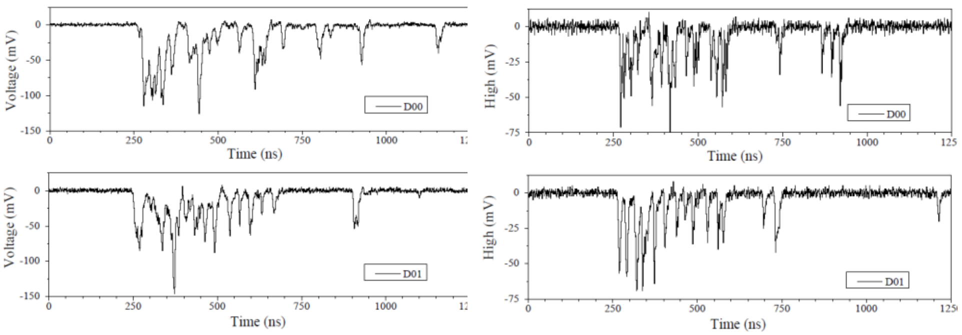
- Number of phe⁻/keV (no light guides)

Preliminar analysis

Nphe⁻ /keV	ANAIS-0 Ham VLB	ANAIS-25 Ham VLB	ANAIS-25 Ham ULB
Via 1	3.66 ± 0.02	7.77 ± 0.04	5.82 ± 0.08
Via 2	3.71 ± 0.07	8.36 ± 0.66	6.76 ± 0.1
Total	7.38 ± 0.07	**16.13 ± 0.66**	**12.58 ± 0.13**

Examples of 4.7 keV pulses (selected by coincidence with ^{121}Te 573 keV γ in the other crystal)

Ham VLB **Ham ULB**



- **With 10 cm length light guides we expect a decrease in light collection of ~30%**
(final decision will depend on background measurements)

ANAIS-25 prototypes: Cosmogenic activation

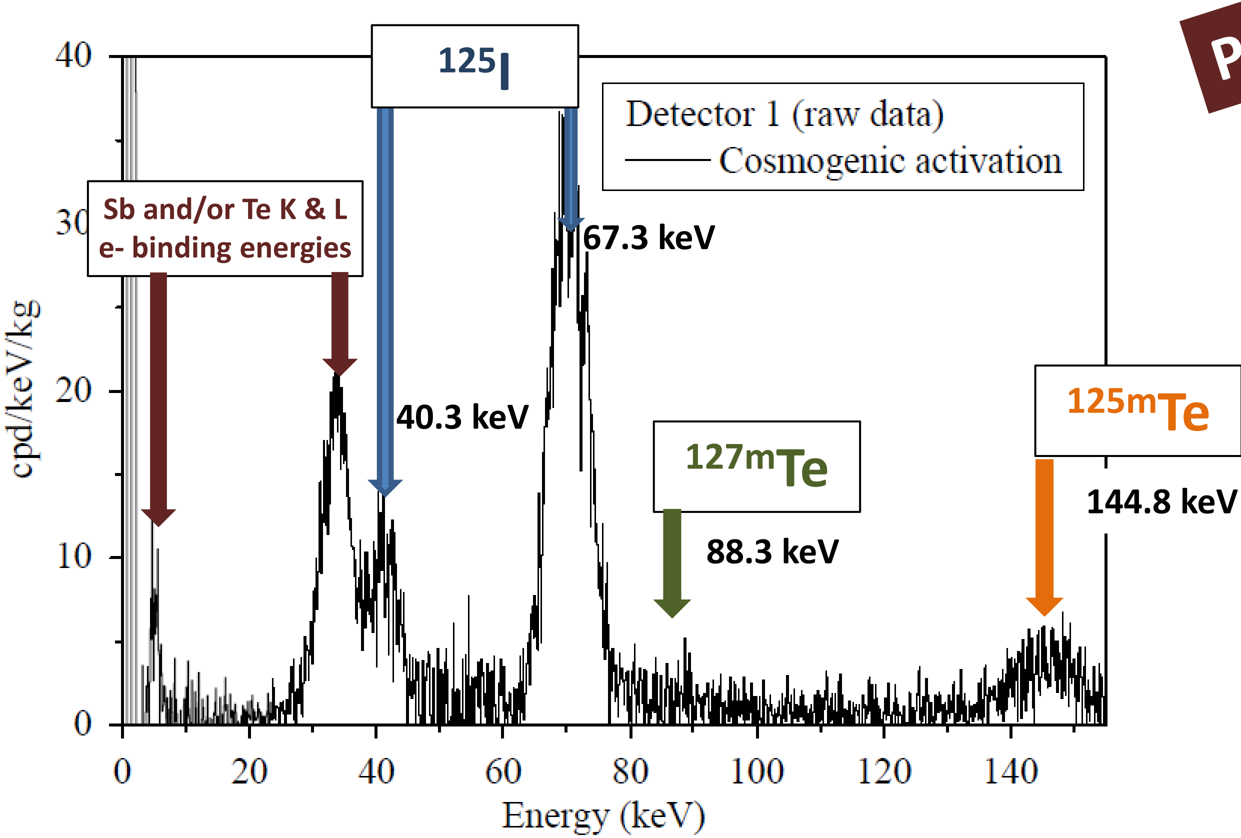
We started measuring underground very fast after the arrival of the prototypes → valuable information on cosmogenic activation

Production in	Isotope	Half life	Decay mode
^{127}I	^{126}I	13.11 d	CE, b-
	^{125}I	59.4 d	CE
	^{124}I	4.18 d	CE, b+
	^{121m}Te	154 d	IT, CE
	^{121}Te	16.8 d	CE
	^{123m}Te	119.7 d	IT
	^{123}Te	>10^{19} y	CE
	^{125m}Te	57.4 d	IT
	^{127m}Te	109 d	IT, b-
	^{127}Te	9.35 h	b-
^{23}Na	^{22}Na	949.7 d	CE, b+

ANAIS-25 prototypes: Cosmogenic activation

Differential background:

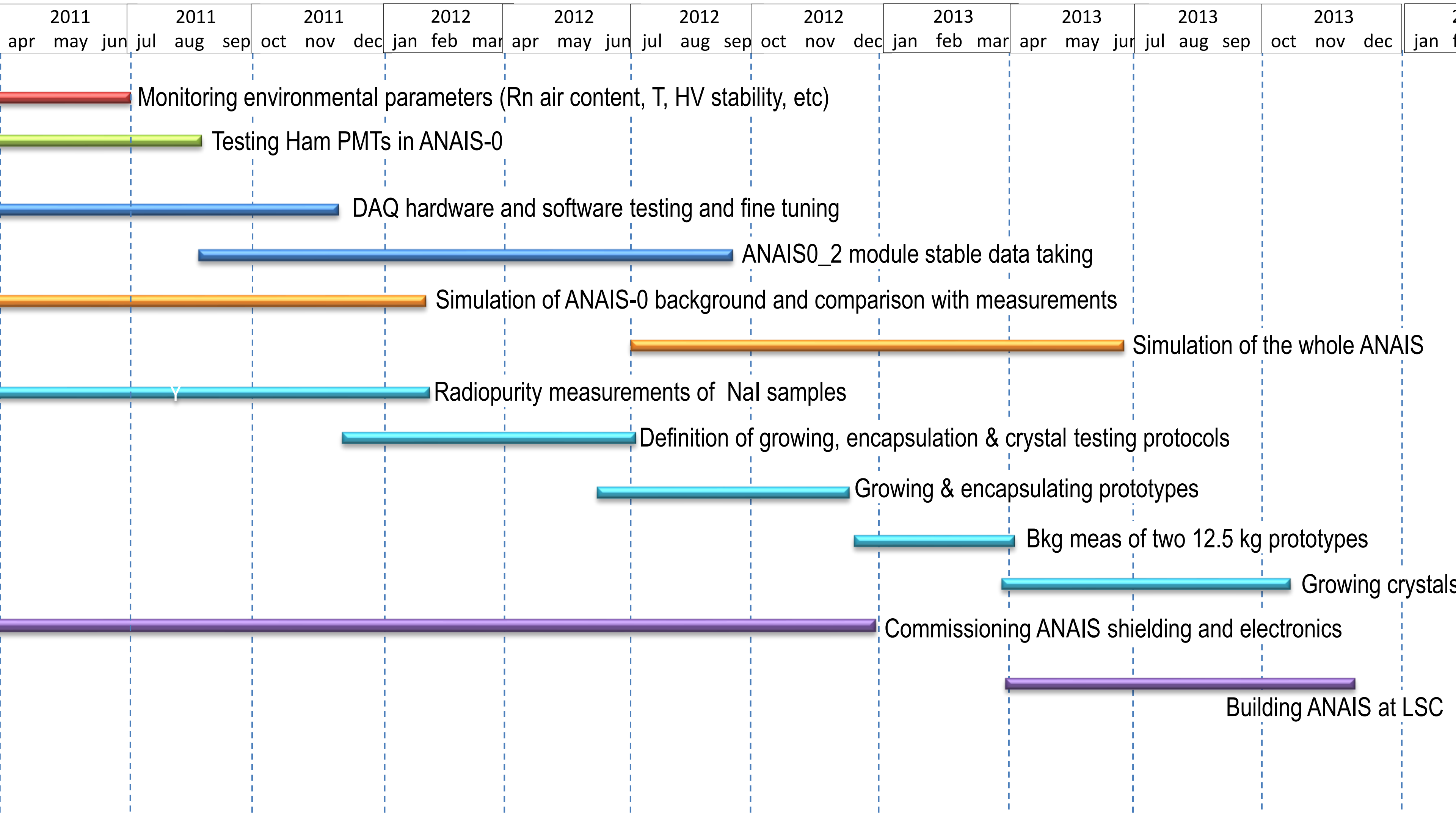
First week (04/12/12 – 12/12/12)
minus last week (31/01/13 – 06/02/13)



Preliminar analysis

- We are still working in the adaptation of the event selection algorithms
- Some cosmogenic isotopes have been identified so far. The lines are decreasing as expected.

ANAIS Schedule



R&D: NaI for bolometric applications

Motivation: Same target, but: NR/γ discrimination

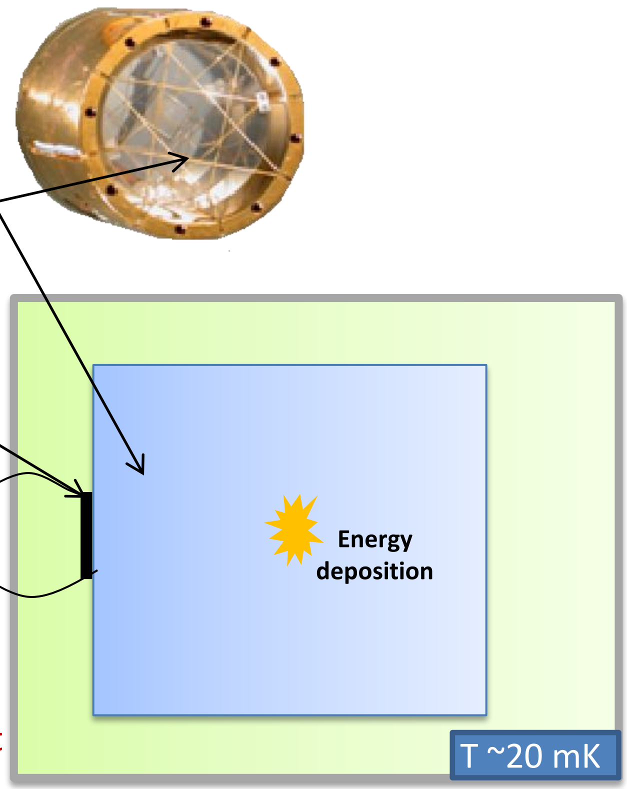
$Q_{NR/\gamma} \approx 1$

In collaboration with the Advanced Detectors Group (ADG) of the Lisbon Universtity and the Institute d'Astrophysique Spatial (IAS), Orsay (France)

The bolometric technique

crystal
(absorber)

Thermometer



HEAT CHANNEL

The energy deposition is measured as a temperature increment

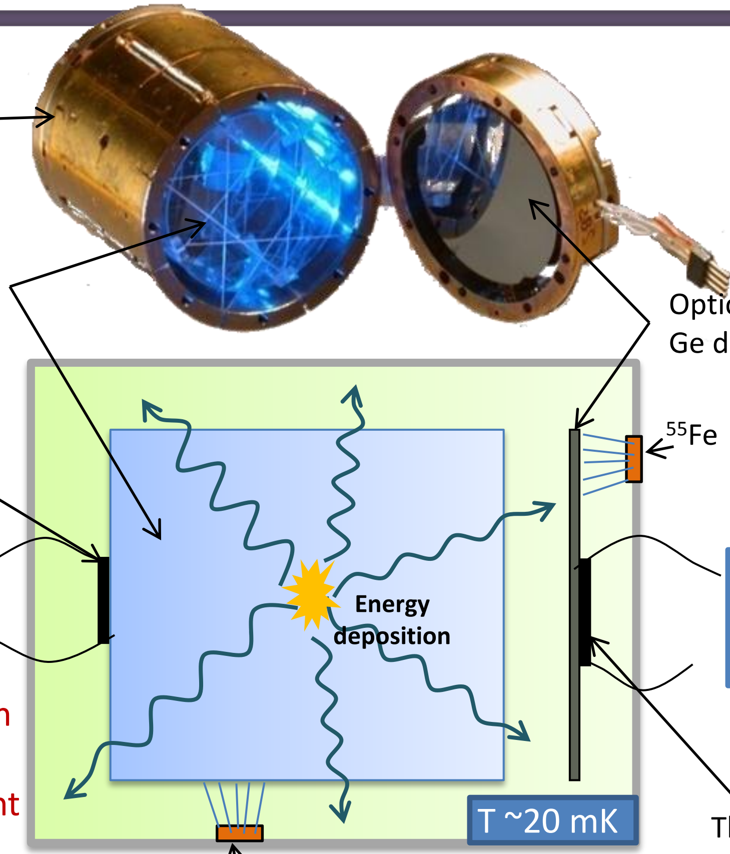
$\Delta T = E/C$

Ultimate energy resolution: internal energy statistical fluctuation

$$\Delta U_{rms} = \sqrt{K_B T^2 C}$$

Very good energy resolution

Scintillating bolometers



HEAT CHANNEL

LIGHT CHANNEL

The energy deposition is measured as a temperature increment

ΔT = E/C

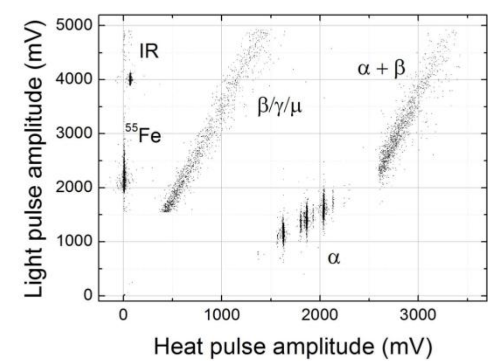
Ultimate energy resolution: internal energy statistical fluctuation

$$\Delta U_{rms} = \sqrt{K_B T^2 C}$$

Very good energy resolution

The light yield depends on the ionizing power of the incident particle

Particle discrimination by the ratio HEAT/LIGHT



Target SrF_2

NaI for bolometric applications

Scintillating bolometers are excellent detectors for dark matter (and other rare event) searches:

- **Very good energy resolution**
- **Low energy threshold achievable**
- **Quenching factor close to 1**
- **Particle discrimination (γ/α and γ/NR) down to several keV (or several tens of keV)**
- **Wide target choice**

NaI is a very interesting DM target!, but….

- **Relatively high specific heat (θ_{Debye}=164 K)**
- **Large coefficient of thermal expansion (1% between 300 K and 4 K)**
- **High hygroscopicity**

A possible solution:

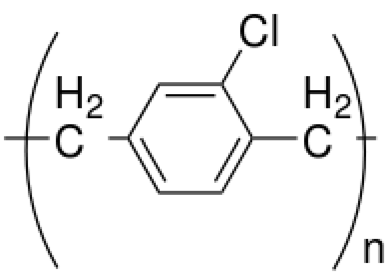
Coat the NaI crystal with an appropriate material acting as humidity barrier

Parylene coating

The coating material has to be:

- Transparent in the λ of NaI emission
- Resistant to thermal cycles
- Radiopure
- Low heat capacity (→ very thin films!)
- …

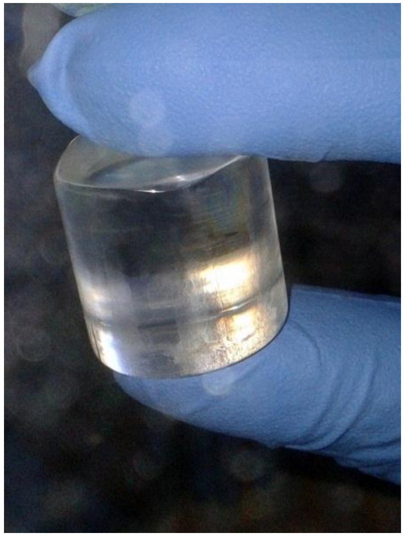
A possibility: PARYLENE



<u>Parylene C</u>
Good humidity barrier!

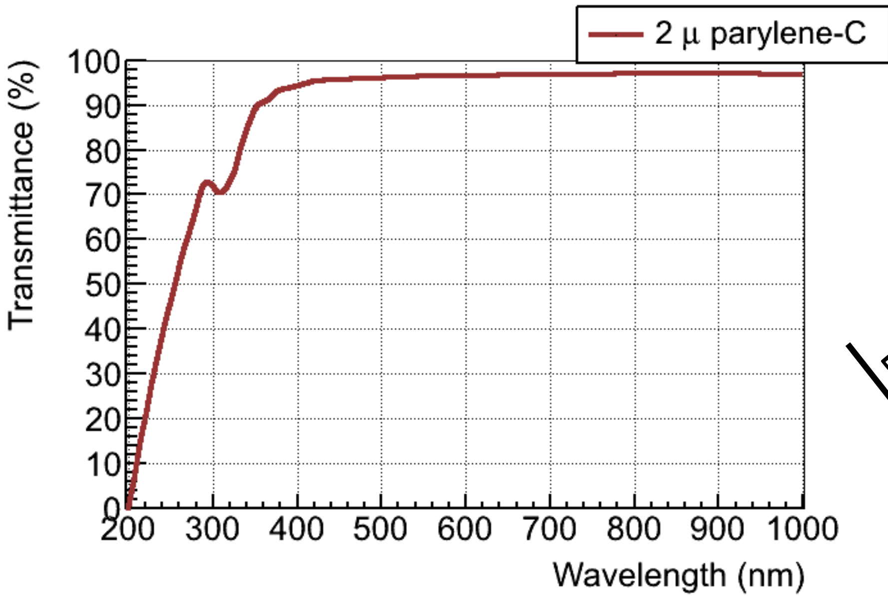
It can be deposited in very thin films by vapor-phase condensation polymerization

NaI pure



parylene-C coated NaI

Parylene transmission in NaI emission bands



Adapted from Jeong et al., Synthetic Metals 127 (2002) 189

Better match

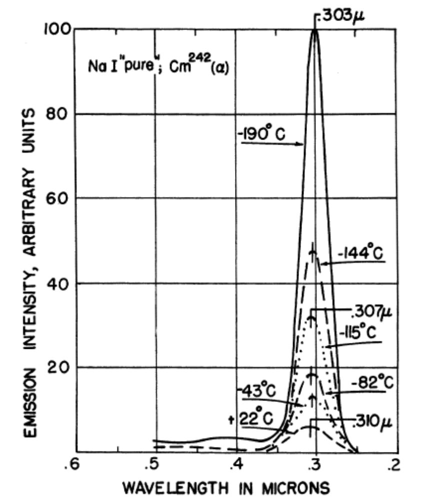


Fig. 9—Emission spectra of NaI ("pure") excited by Cm^{242} alpha

NaI pure

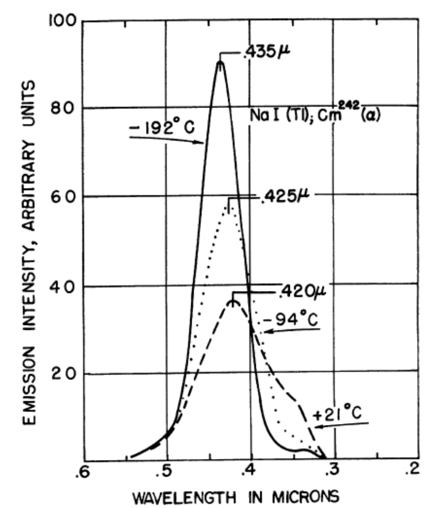


Fig. 5—Emission spectra of NaI(Tl) excited by Cm^{242} alpha particles.

Na(Tl)

Sepctra from "Alkali Halide Scintillators" W.J. Van Sciver, IRE Trans. Nucl. Sci. 3 (1956) 39.

Parylene radiopurity

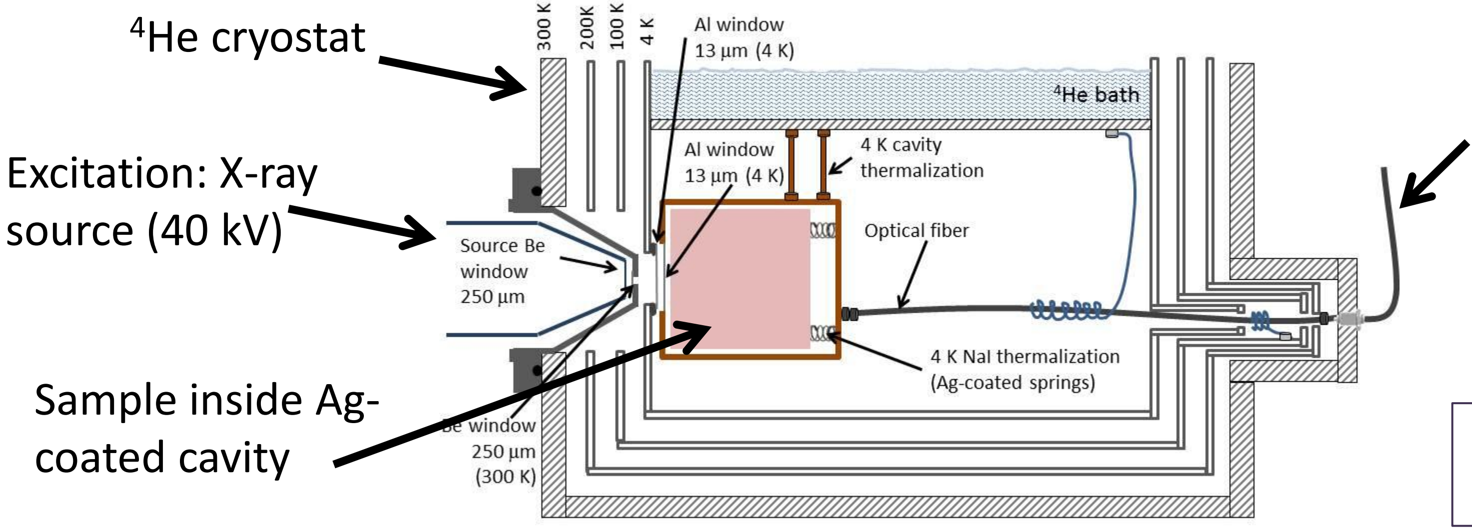
HPGe measurement at LSC on dimer (dichloro-p-cylophane) samples

Activity (mBq/kg)					
^{232}Th	^{226}Ra	^{238}U	^{40}K	^{60}Co	^{137}Cs
26 ± 8	<12	<370	<100	<4.5	<6.2

UPPER LIMITS AT 90% C.L.

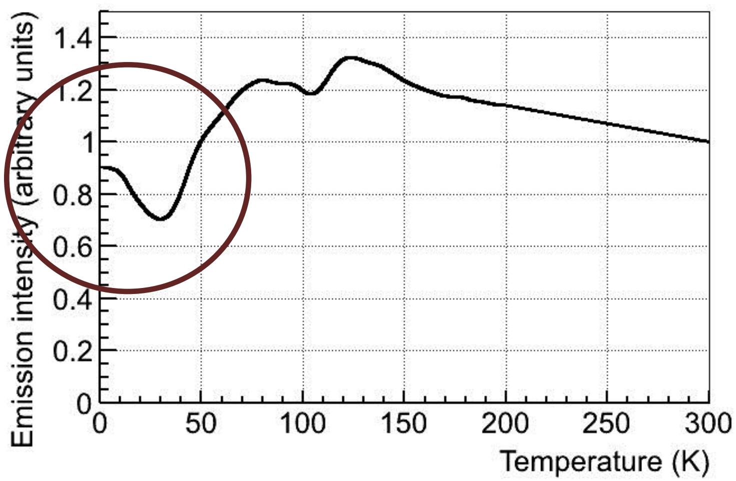
0.05 counts/cm^2/μm/year → very low contribution to the background for thin parylene layers

Parylene-coated NaI(Tl)
Low temperature X-ray scintillation

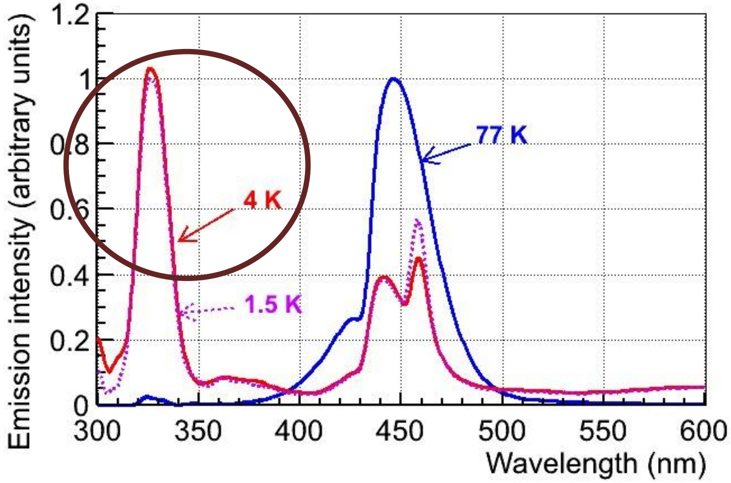


Measurements done at IAS (Orsay)

- Light output vs Temperature (Si photodiode)



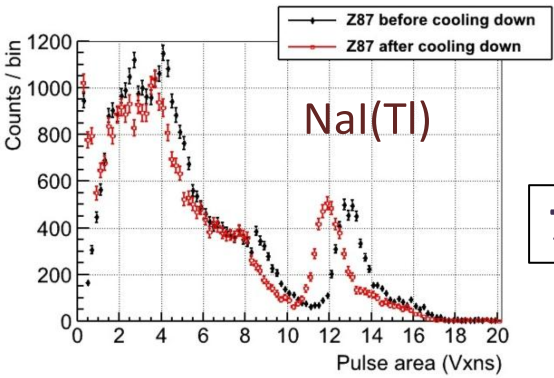
- Light output vs wavelength (fiber spectrometer)



Parylene resistance to thermal cycles

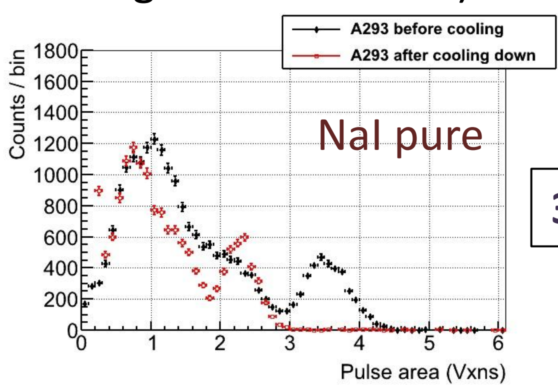
Light output measurement before and after the thermal cycle

- Cooling down to 100 K (with a N_2 bath)



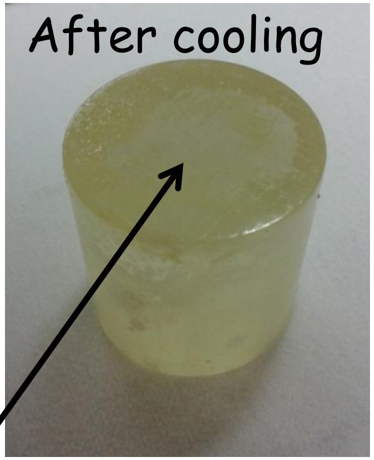
7.5 % decrease

- Cooling down to 80 mK (with a dilution unit) (Mounting time one week)



35 % decrease

Light detector: PMT faced to the crystal
Excitation: ^{137}Cs



loss of adherence in certain areas

Parylene resistance to RH

In any case, 2-5 μm parylene allow some days handling but it is not a permanent coating

If the crystals are not kept in dry atmosphere, after one month…

We have not succeeded yet in doing a bolometric measurement with parylene-coated NaI

In parallel we are studying other coating materials

Summary

- The Canfranc Underground laboratory hosts a multidisciplinary scientific program, with focus on rare events physics. The approved experiments are being installed in the new facilities.
- ANAIS is a UZ project that will look for dark matter annual modulation with 250 kg of NaI(Tl) at LSC
  - PMTs, shielding, electronics and software are (almost) ready.
  - Two 12.5 kg NaI(Tl) prototypes have been constructed with selected NaI(Tl) powder (^{nat}K < 90 ppb at 95% C.L.) and radiopurity is being checked underground. The good light collection allow us to expect an energy threshold below 2 keV. If background requirements are fulfilled, the 250 kg production will start .
- R&D is in progress to study coated NaI and NaI(Tl) crystals at low temperature for bolometric applications. Test of light output and resistence to thermal cycles of parylene-coated NaI samples have been performed. The results are not completely satisfactory and other coating materials are being studied.

Grazie!