Capabilities of the CIEMAT Nuclear Innovation Unit in relation to a Nuclear Astrophysics Program at the LSC

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Unidad de Innovación Nuclear – CIEMAT

The Nuclear Innovation Unit

We are a group with four main research lines:

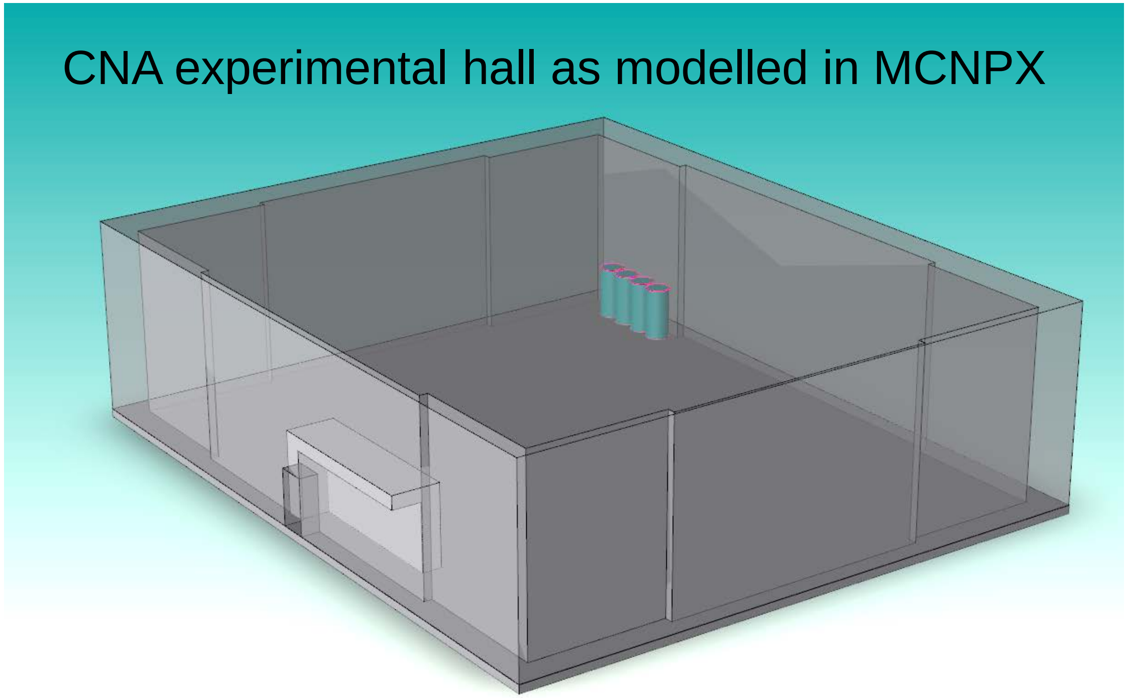
- Advanced reactor design: Generation IV (ASTRID), accelerator driven systems (MYRRHA)
- Integral experiments with experimental nuclear reactors
- **Experimental nuclear physics**: neutron induced reaction cross sections (n_TOF at CERN) and nuclear structure (neutron spectroscopy)
- Development of **neutron detectors**.

We share most of the tools and facilities with nuclear astrophysicists and have overlapping goals (nucleosynthesis inside human made nuclear reactors).

Solid experience in **Monte Carlo simulation**:

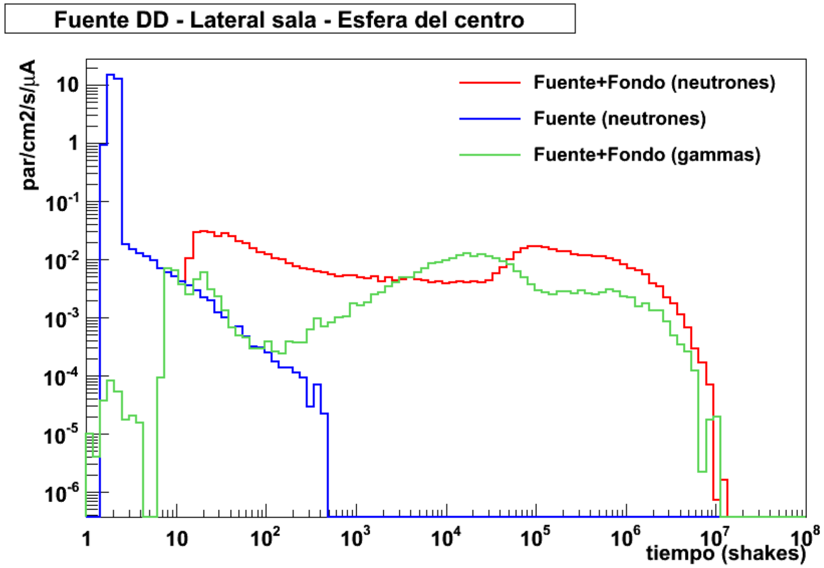
- MCNPX, MCNP6 for reactors and design of nuclear installations with **neutrons**
- GEANT4 for the simulation of detectors and complete experiments. We are members of the GEANT4 collaboration.

Neutron beam line at the Centro Nacional de Aceleradores



CNA experimental hall as modelled in MCNPX

CIEMAT is doing the Monte Carlo simulations (with MCNPX) of a new neutron beam line at CNA in Sevilla. Collaboration CNA – CIEMAT – IFIC – UGR – UPC – USE – USC



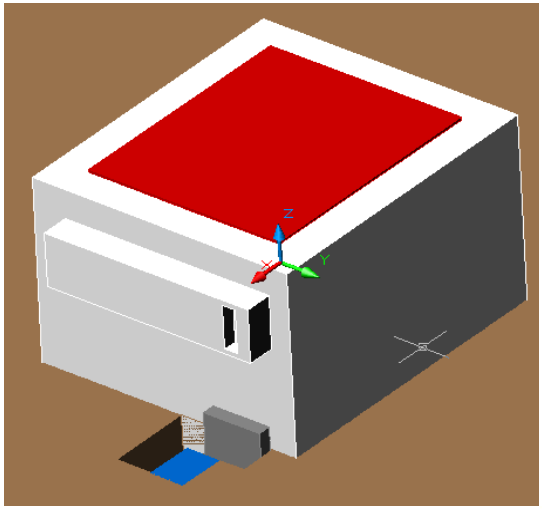
Fuente DD - Lateral sala - Esfera del centro

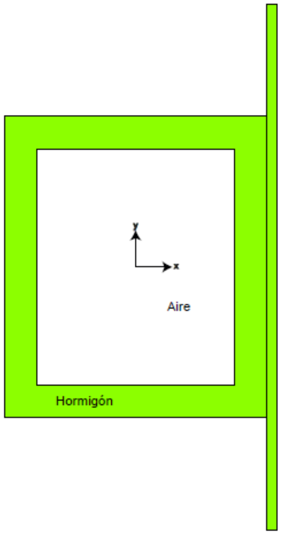
Very **time consuming calculations** for determining the characteristics of the neutron beams and backgrounds due to:

- DD source at various incident energies. Both D(d,n)^{3}He and D(d,pn)d.
- ^{7}Li(p,n) at various energies

Complete calculation for the design of a metrology laboratory at CIEMAT with a ^{252}Cf source

The entire building has been modelled in detail

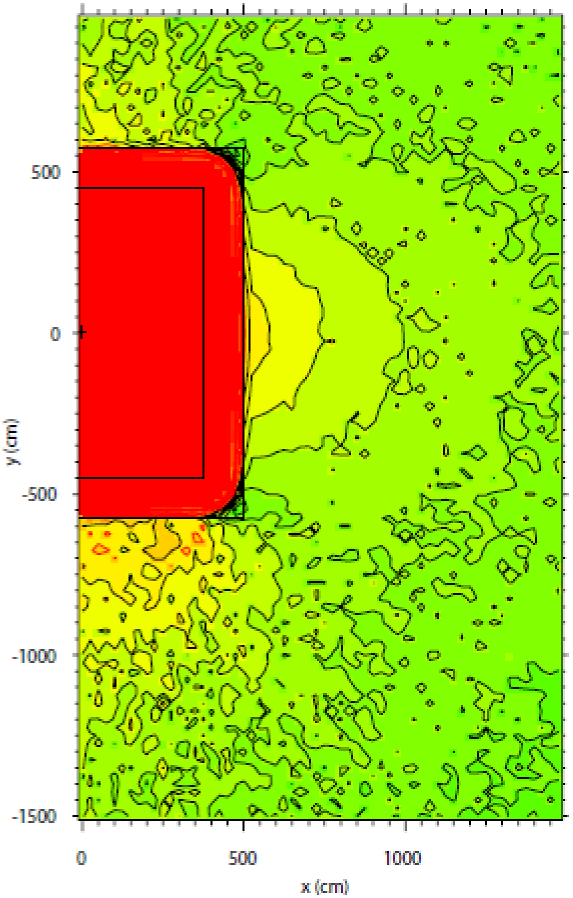




Optimisation of the shielding for minimising the neutron and gamma dose.

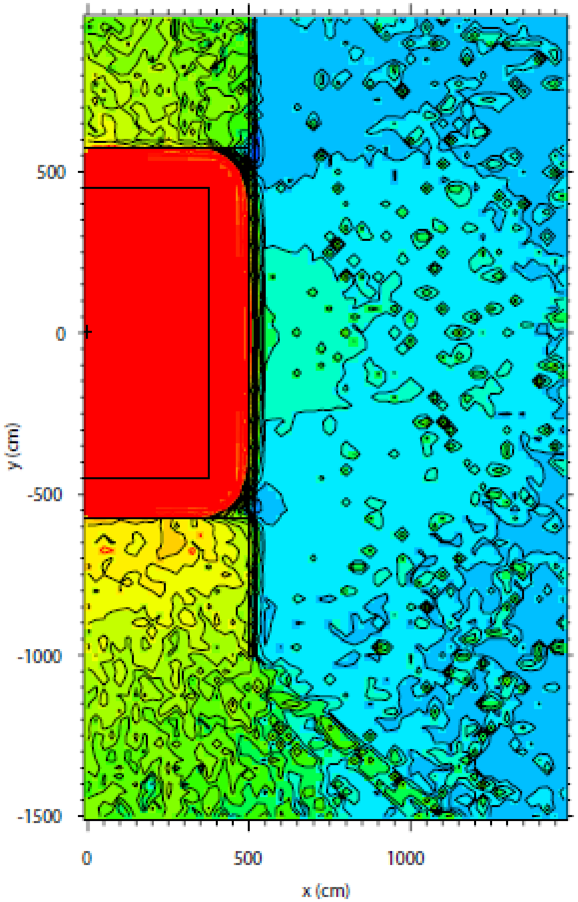
LPN reference case

Neutron dose - Horizontal view at Cf source level



LPN with polyethylene above and extra concrete shielding

Neutron dose - Horizontal view at Cf source level



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IR-33. Laboratorio de patrones neutrónicos

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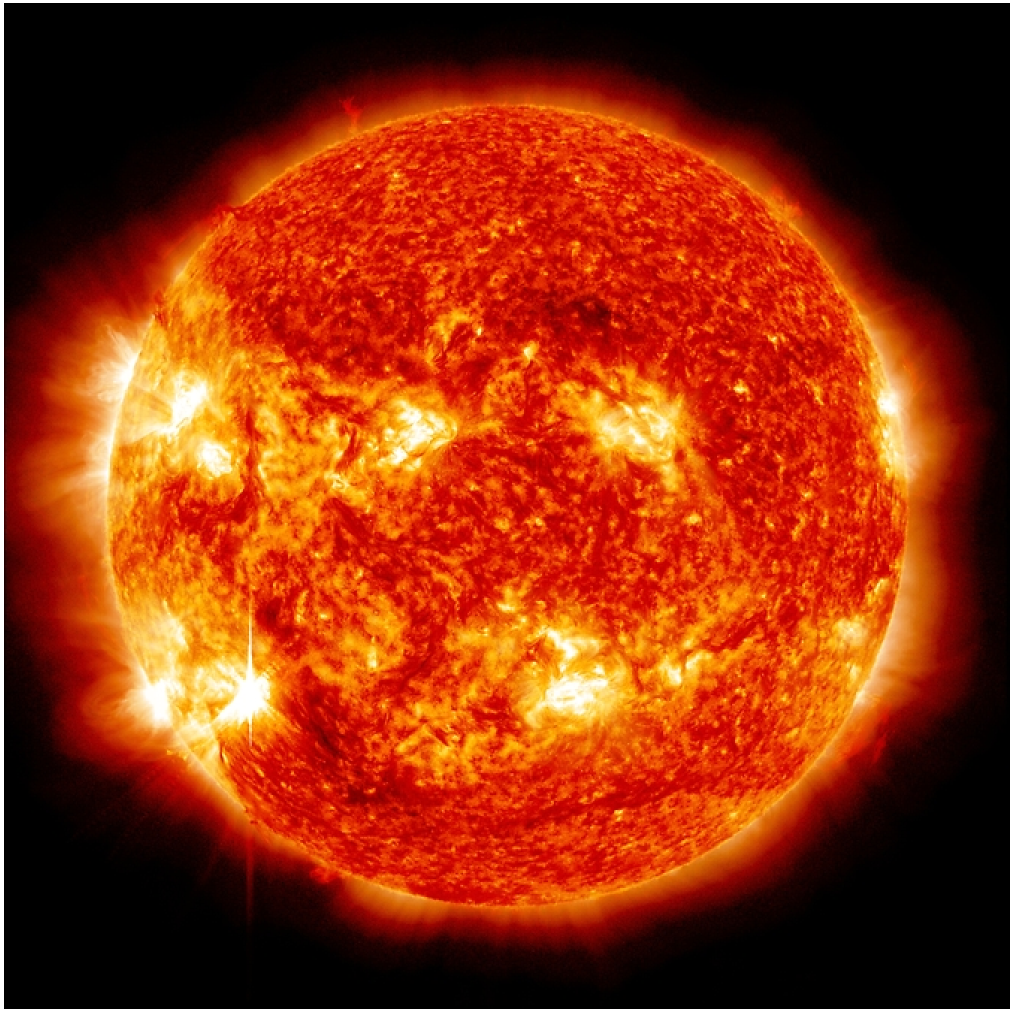
Designing a star is easy: not need of authorisation from the nuclear regulatory body

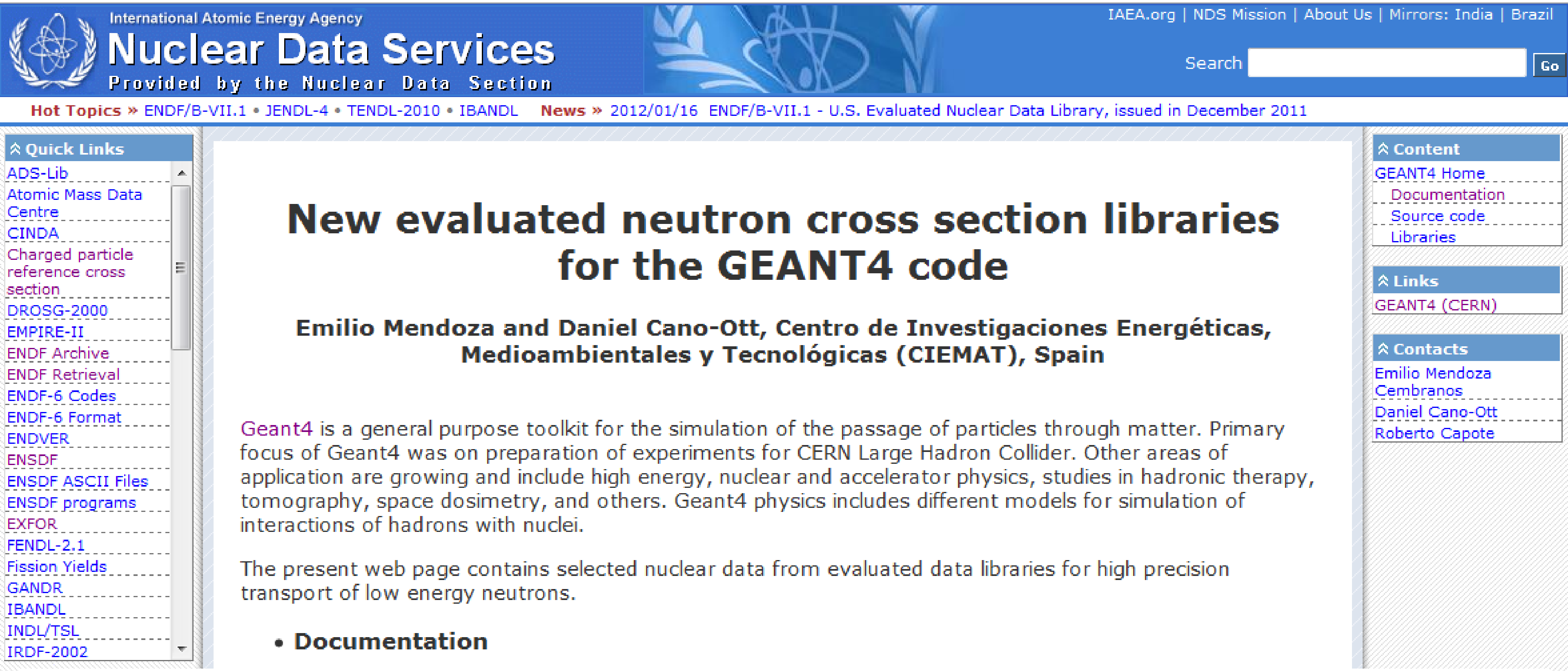


- No licensing is required.
- No environmental impact study is needed.
- Also no de-commissioning and dismantling studies.
- Also no nuclear waste management path.
- Nuclear reaction data have no impact in the budget.

Accurate reaction cross sections are welcome but not compulsory. The typical required accuracy in reactor calculations << 1% for the most relevant isotopes.

Evaluated cross section files!

Production of nuclear data libraries for Geant 4



New evaluated neutron cross section libraries for the GEANT4 code

Emilio Mendoza and Daniel Cano-Ott, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain

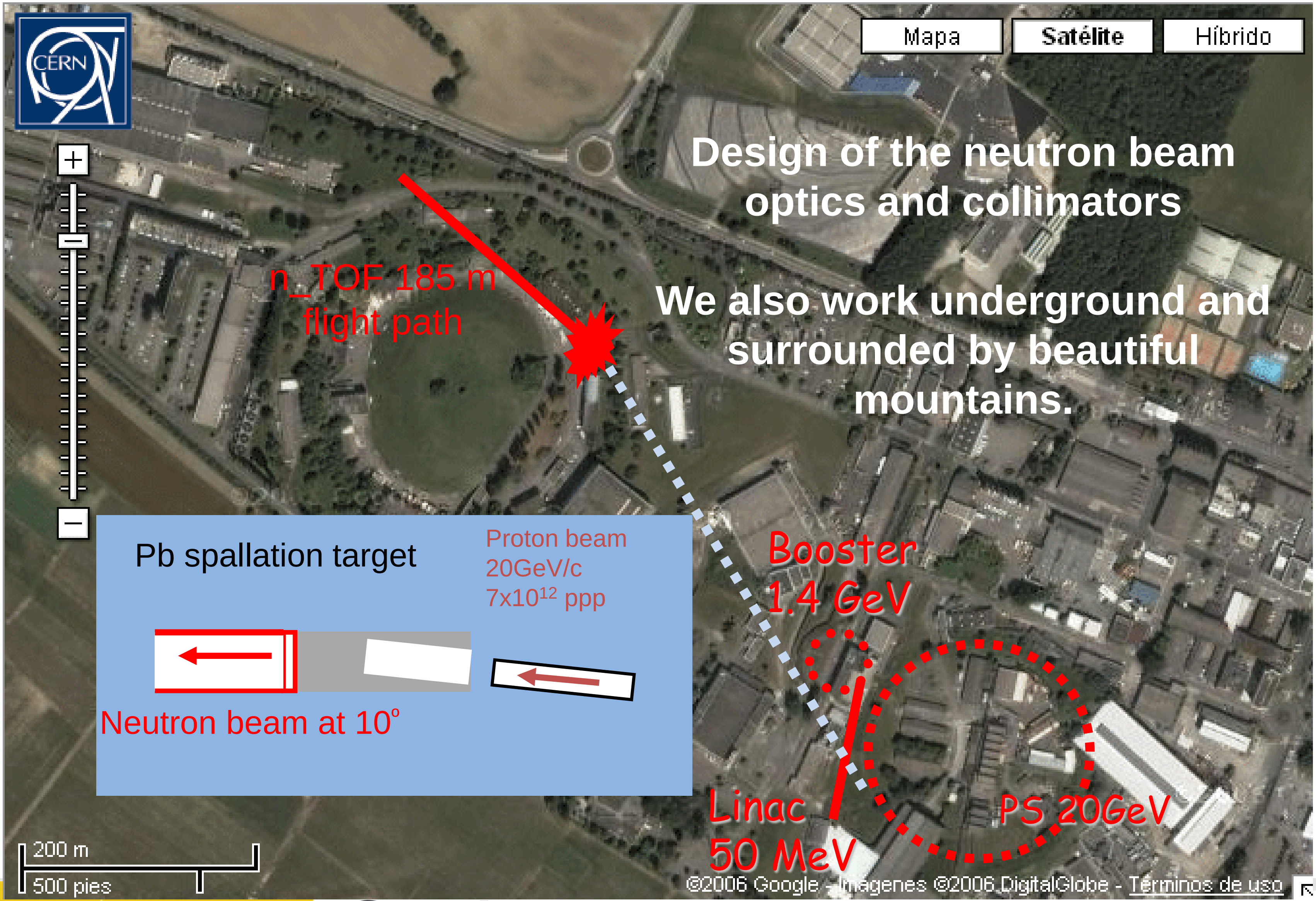
Geant4 is a general purpose toolkit for the simulation of the passage of particles through matter. Primary focus of Geant4 was on preparation of experiments for CERN Large Hadron Collider. Other areas of application are growing and include high energy, nuclear and accelerator physics, studies in hadronic therapy, tomography, space dosimetry, and others. Geant4 physics includes different models for simulation of interactions of hadrons with nuclei.

The present web page contains selected nuclear data from evaluated data libraries for high precision transport of low energy neutrons.

- **Documentation**

Theory can not predict “usable” neutron induced reaction cross sections. Need of standard evaluated neutron cross sections. CIEMAT is responsible for the production of “complete” evaluated neutron data libraries for GEANT4 at the IAEA site.
http://www-nds.iaea.org/geant4/
Recent development: evaluated libraries (TENDL) for charged particle nuclear induced reactions. Soon available at the IAEA site (partial libraries distributed with GEANT4).

The n_TOF facility



Design of the neutron beam optics and collimators

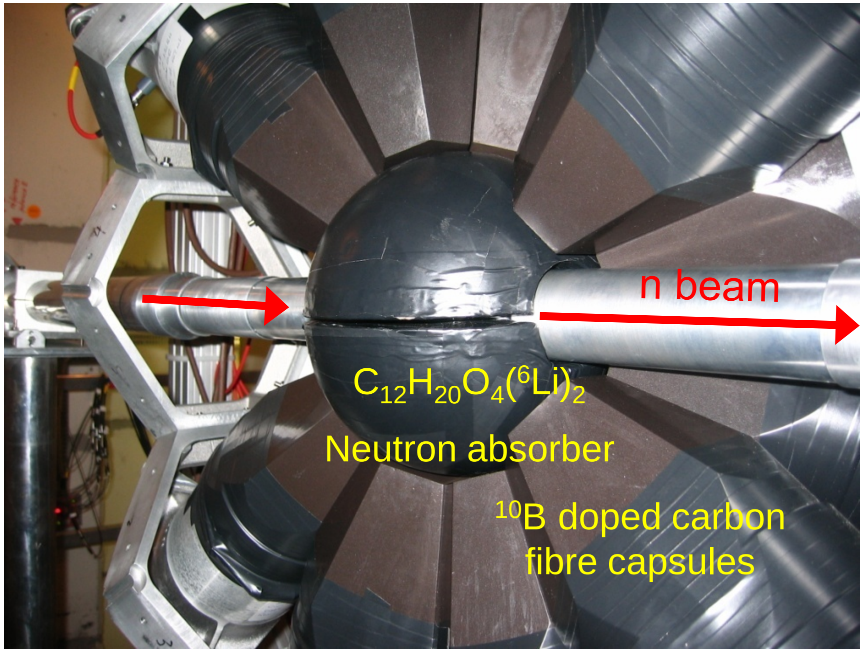
We also work underground and surrounded by beautiful mountains.

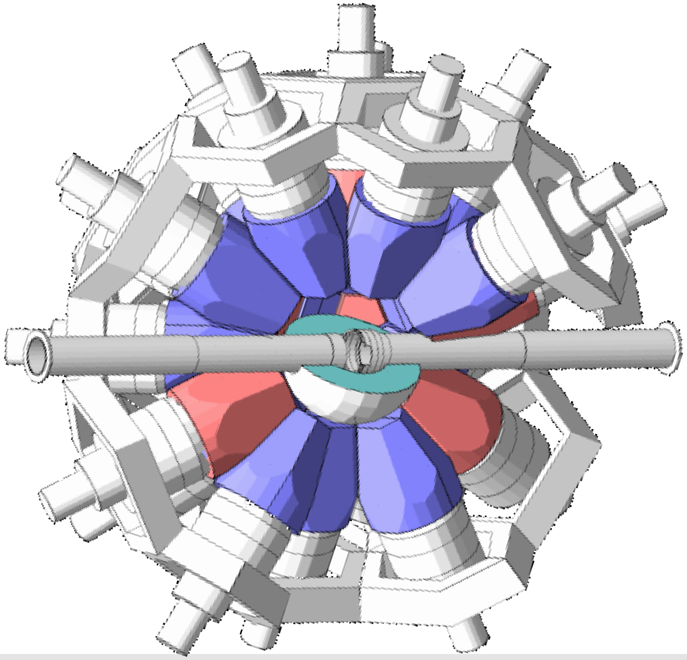
Neutron capture cross section measurements at n_TOF

Doing experiments with the 40 crystals BaF_2 Total Absorption Calorimeter

- Very high detection efficiency for (n,γ) cascades >95%
- Excellent time resolution < 1ns
- Adequate energy resolution

Our scientific program consists in the **measurements of (n,γ) cross sections of actinides**: responsible of the **^{237}Np, ^{240}Pu, ^{241}Am, ^{243}Am and ^{235}U** measurements

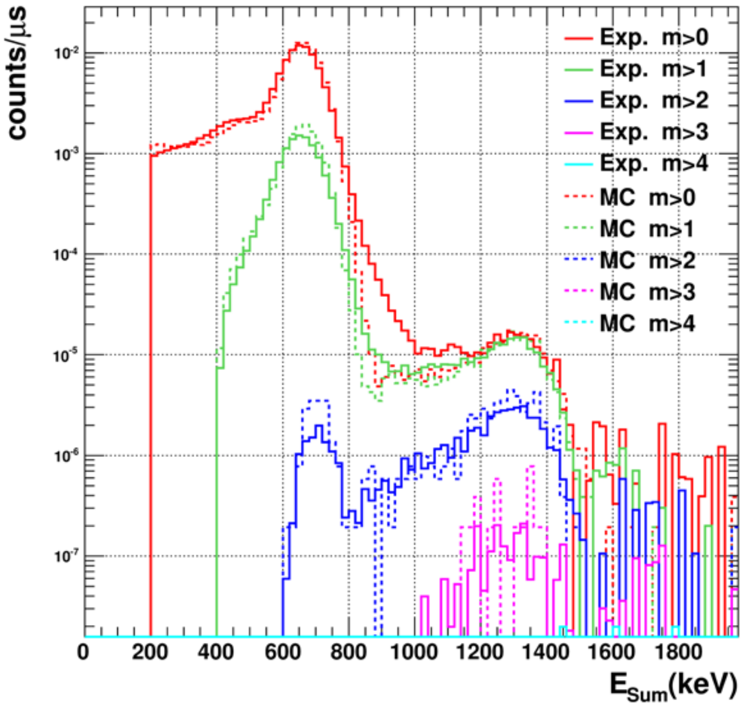




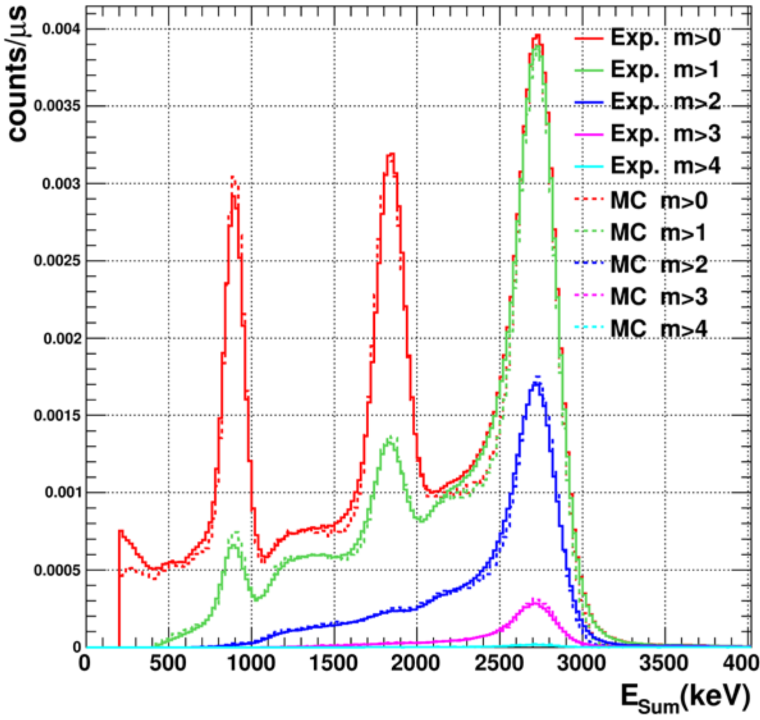
Determination of the efficiency by Monte Carlo simulation

Very accurate Monte Carlo simulations (energy deposition, pileup model) with GEANT4 of the detector response function.

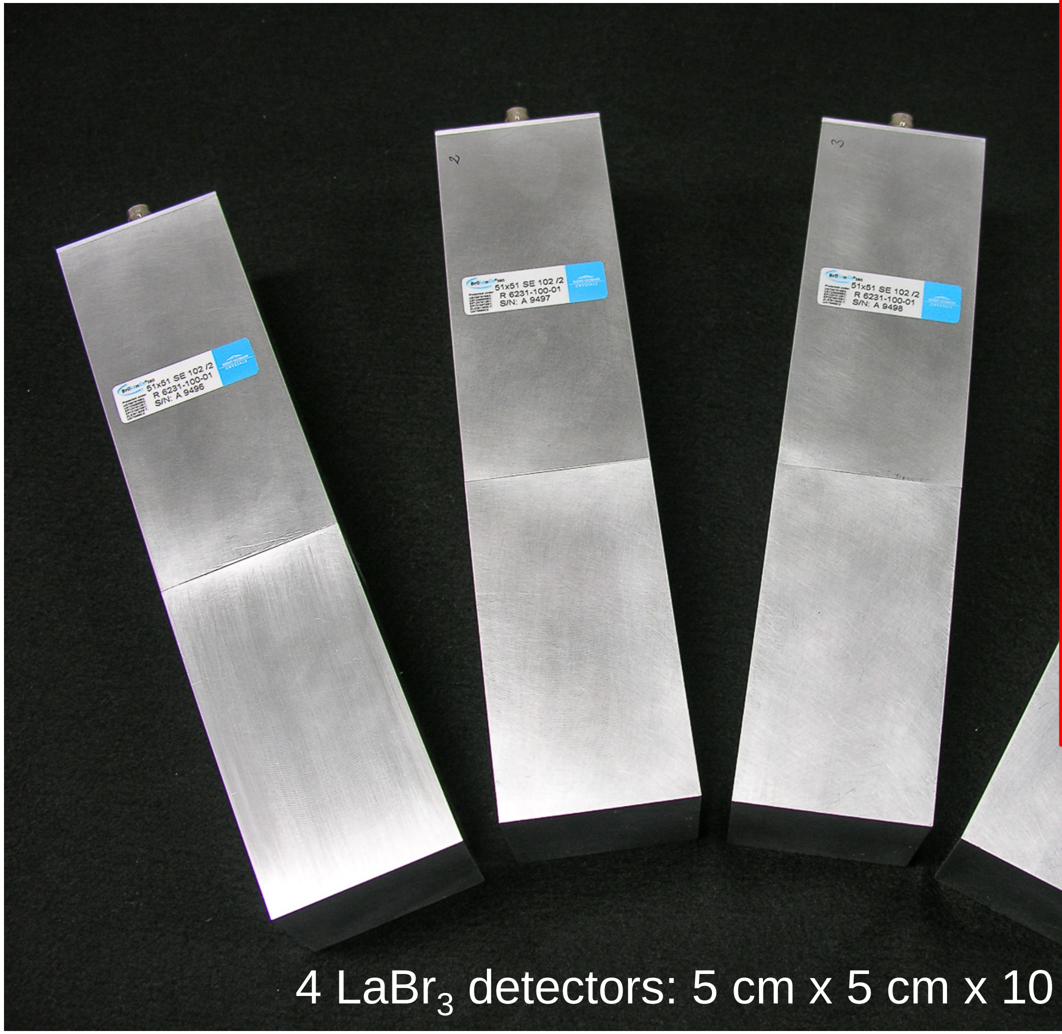
^{137}Cs

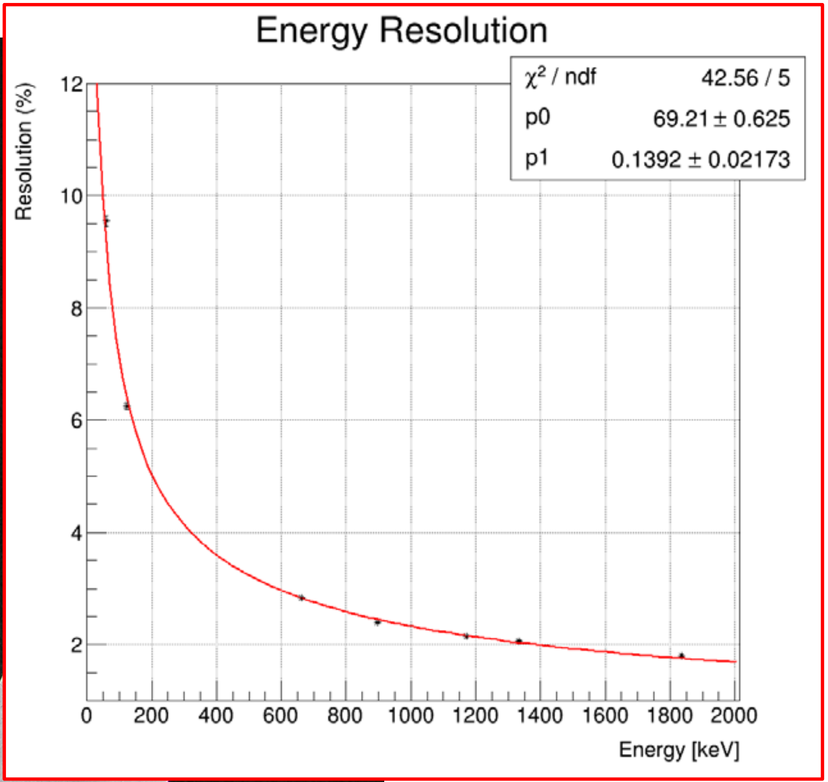


^{88}Y



Development of new calorimeters for (n,γ) measurements


4 $LaBr_3$ detectors: 5 cm x 5 cm x 10 cm



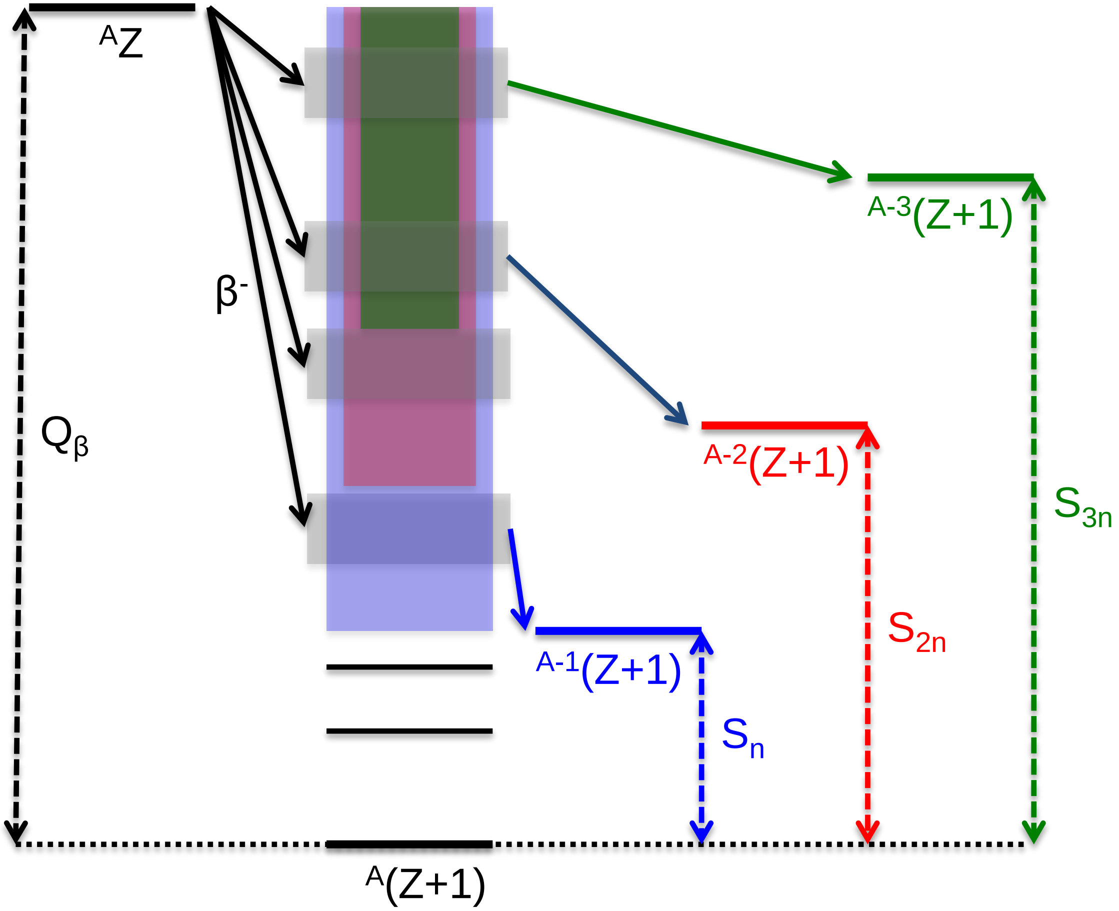
β-delayed neutron measurements

Delayed neutrons $E_n \leq 10$ MeV

Measure E_n, I_β, J_π

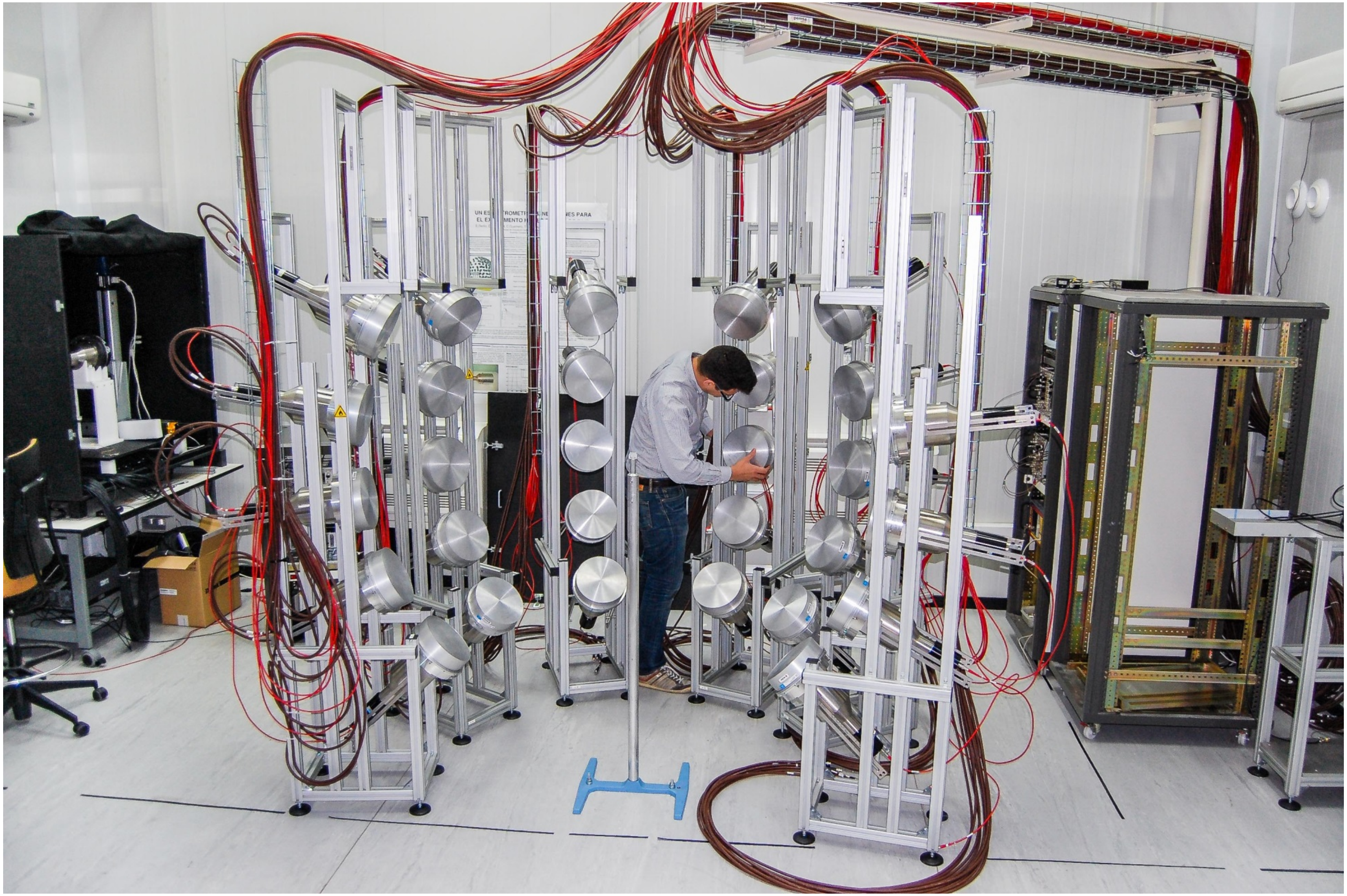
Possible β-2n, β-3n for large Q_β

nn correlations: sequential/direct



The Modular Neutron SpectromeTER (MONSTER)

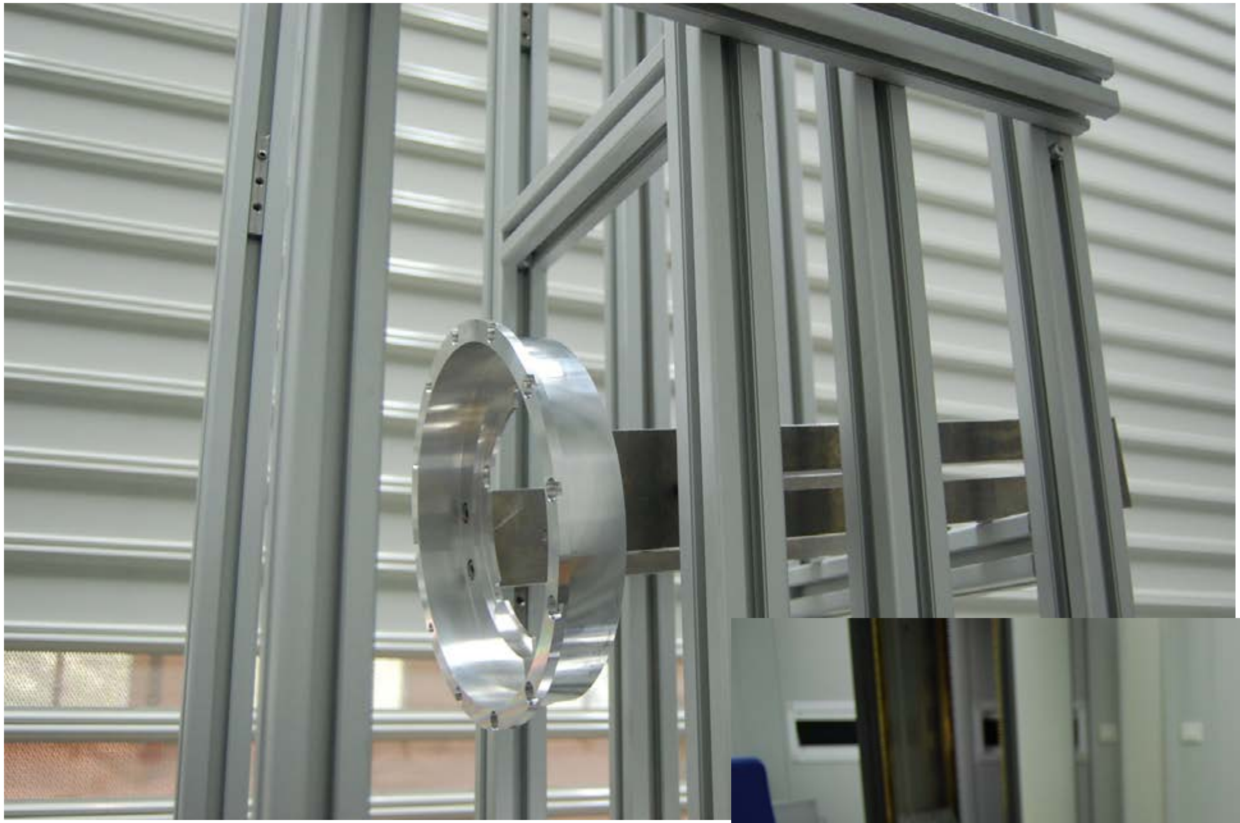
CIEMAT (coordinator), IFIC, UPC, U. Jyväskylä (Finland), VECC – Calcatta (India)



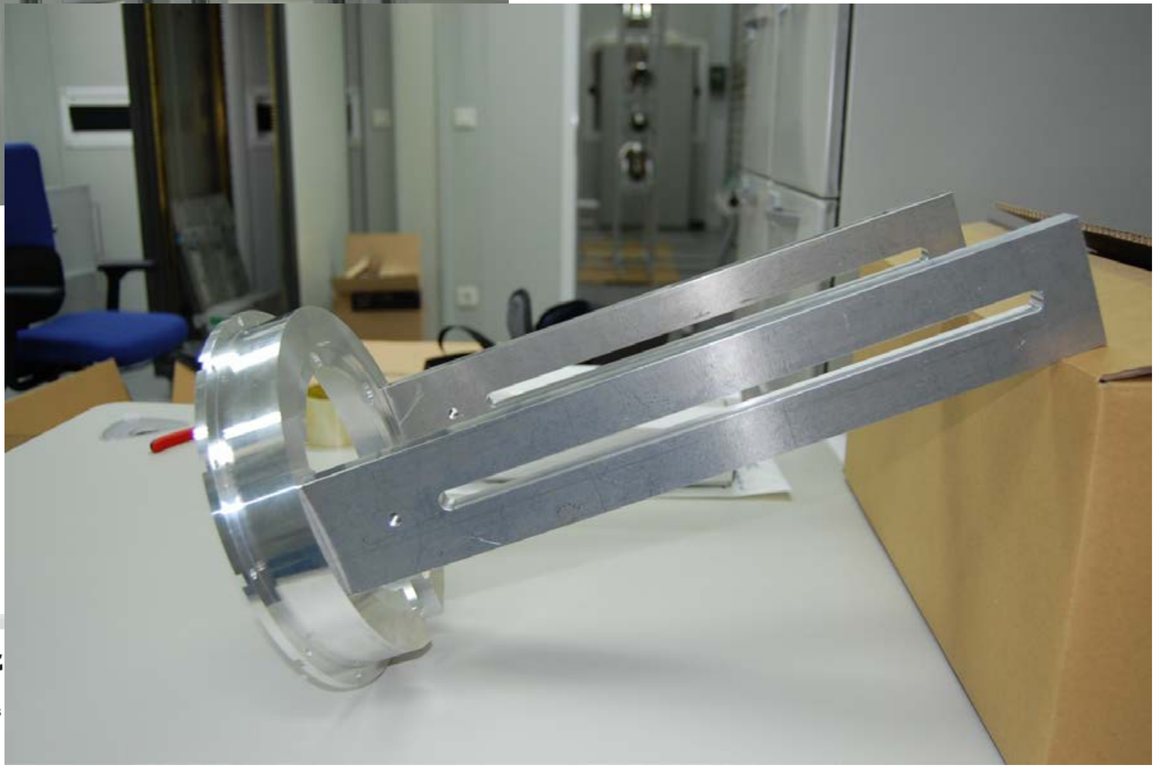
MONSTER-related facilities @ CIEMAT

New laboratories set up for the development of detectors (MONSTER). Next to the facility with a ^{252}Cf with ~5x10^8 n/s.

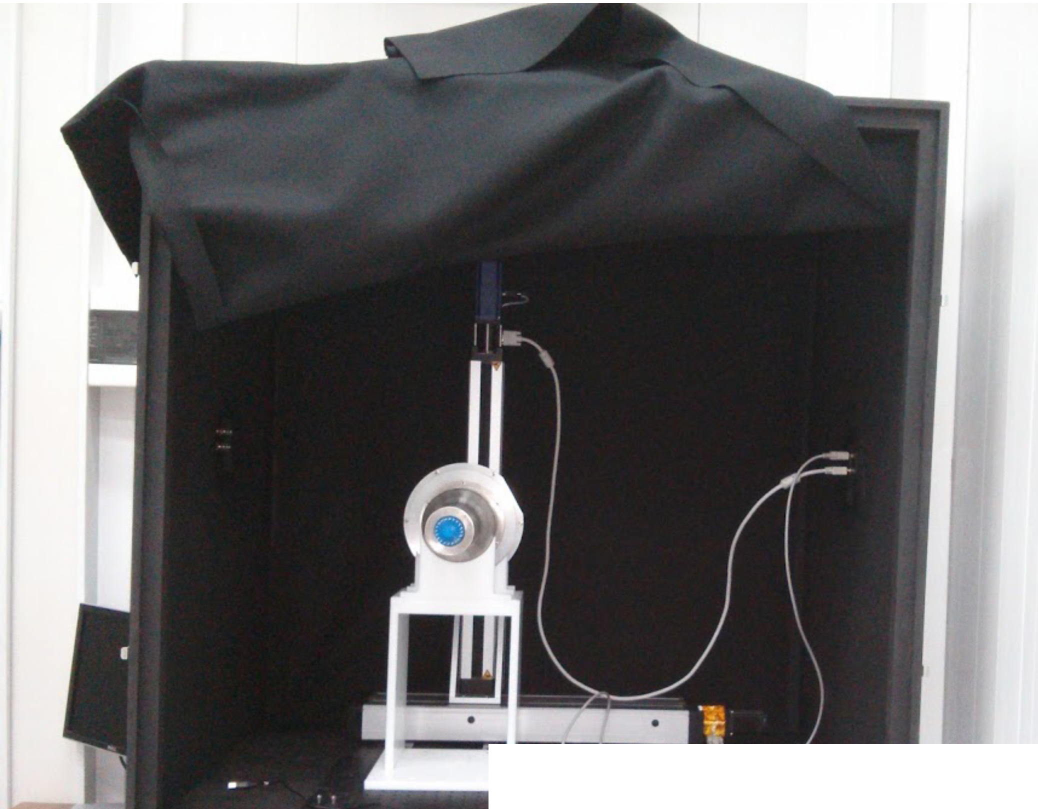
Glove box for the manipulation of liquid scintillators in a N_2 (or Ar) atmosphere.



Very important: access to the CIEMAT workshop which can machine mechanical parts with high precision.

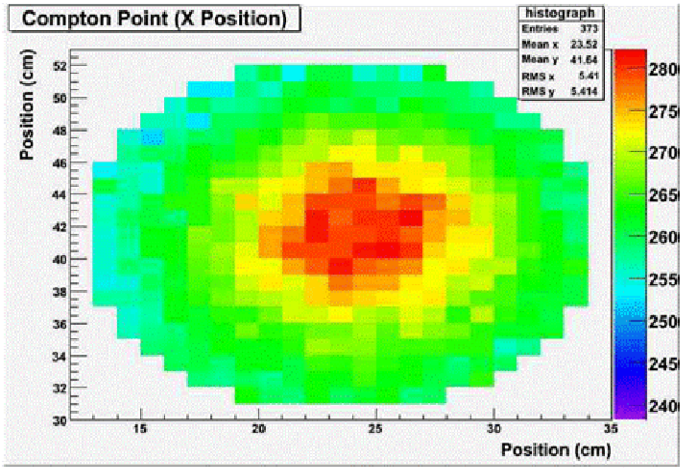


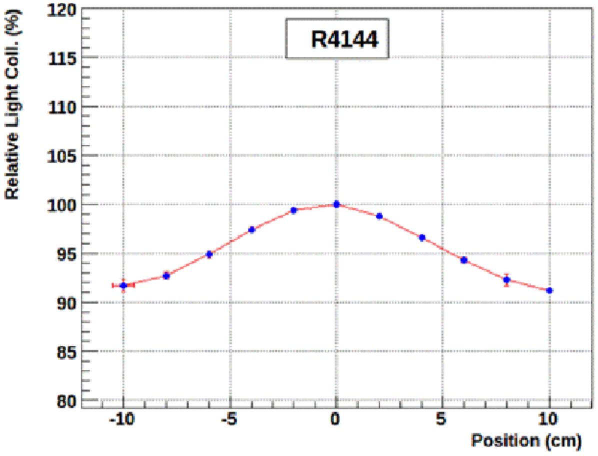
Neutron and gamma detector test bench



Scanning system for characterising photomultipliers (inside dark box) and detectors (with collimated sources).

Laser source for the characterisation of PMTs and the stability monitoring of the liquid scintillators (as a reference pulse).





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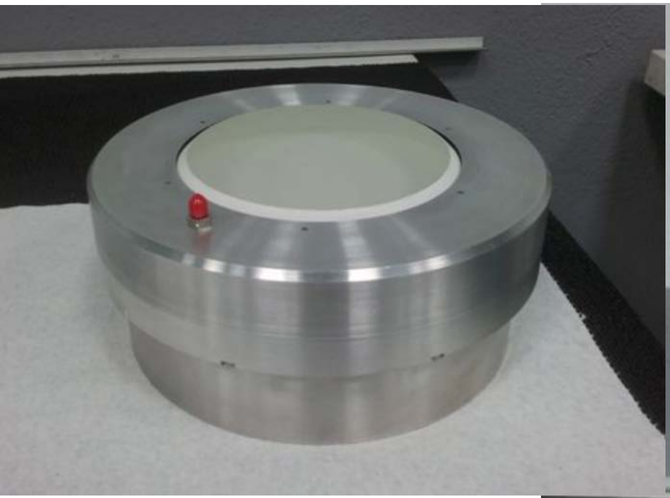
Development of neutron detectors with the Spanish company **Scientifica Internacional S.L.**



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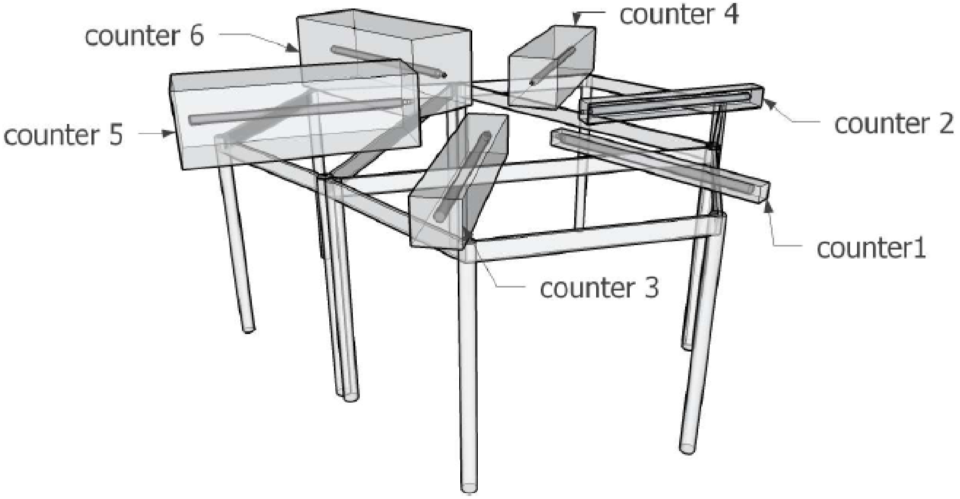
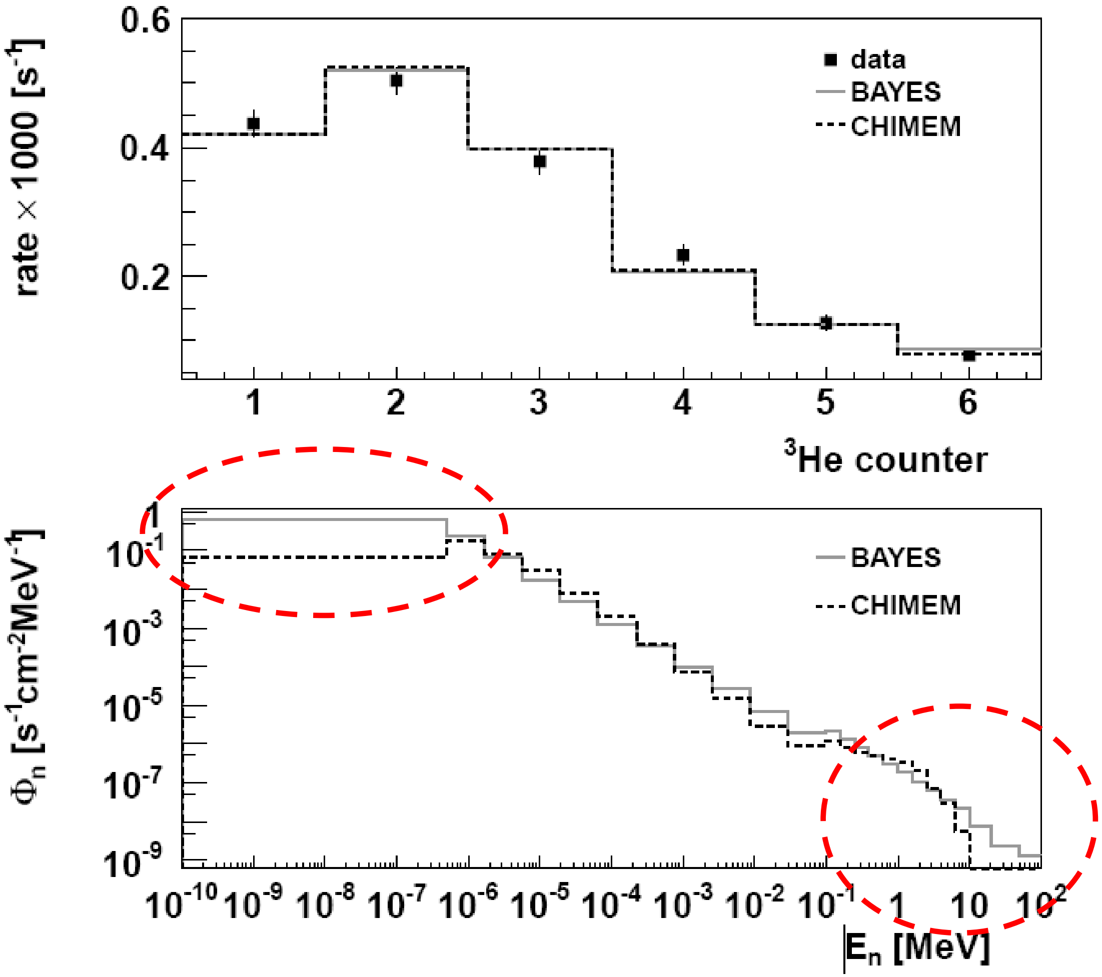
The neutron background at the LSC

D. Jordan et al. Astroparticle Physics 42 (2013) 1–6. have measured the neutron background at CANFRANC with a detector array based on ^{3}He long counters (See J.L. Taín previous talk)



Set of ^{3}He long counters with different polyethylene moderator thickness, thus making the detector sensitive to different energies (*paralelepipedic* Bonner spheres).

Detection principle: thermalisation of the neutrons and ^{3}He(n,p) reactions inside the counter, detection of secondary charged particles. No direct information on the incident neutron energy.



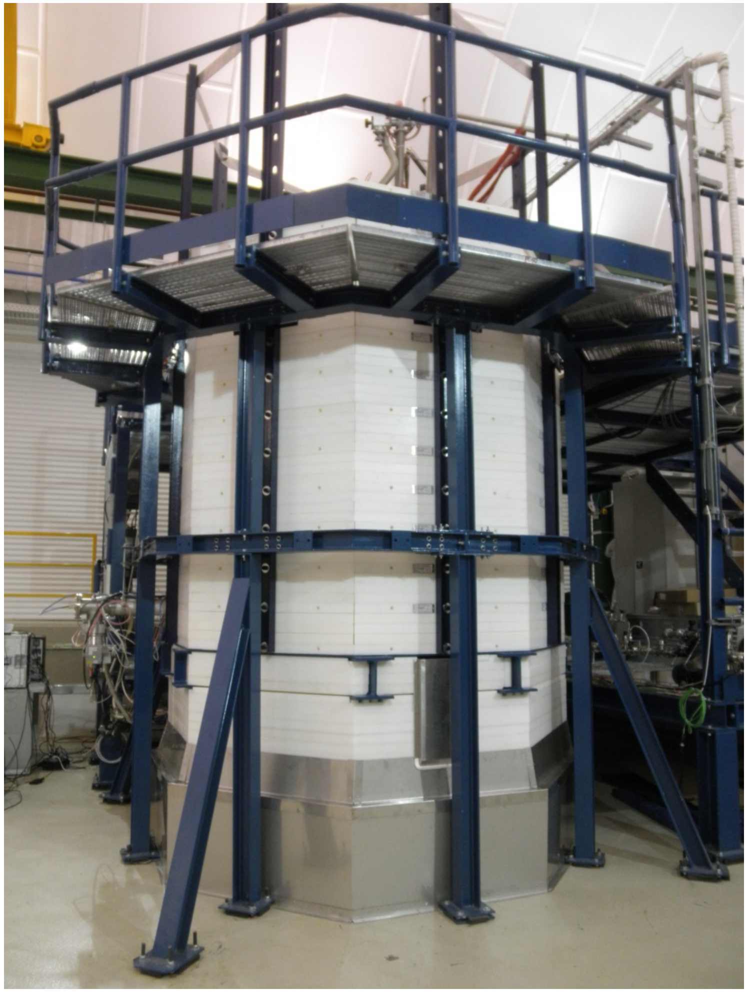
Upper panel: reconstructed counting rate compared with data. In gray the result of the BAYES (Bayesian reconstruction) code and the dashed black line corresponds to the result of CHIMEM (maximum entropy) code.

J.L. Tain and D. Cano, Nucl. Instrum Meth. A571 (2007) 728

Neutron flux obtained using the two codes.

Discrepancies at thermal (E_n < 1 eV) and high energies (E_n > 1 MeV)

Collaboration with the ArDM experiment at LSC



D. Cano-Ott, T. Martínez, E. Mendoza, A. García Ríos – Nuclear Innovation / CIEMAT

B. Montes, R. Santorelli, L. Barajas – Group of Astroparticle Physics / CIEMAT

The CUNA collaboration

Problem: WIMP induced nuclear recoils can not be distinguished from neutron induced recoils. **Signals in the range from 30 keV to 100 keV can be produced by elastic and inelastic scattering of neutrons in Ar with energies above 1.2 MeV**.

Our experience with organic scintillators has driven us to propose a complementary measurement with BC501 detectors and try to improve the measurement for $E_n > 1$ MeV.

Neutron detectors available at CIEMAT

CIEMAT has a large variety of organic scintillators available:

- BC501A: 20 cm ϕ x 5 cm (30 units, used as TOF spectrometer),
- **10 cm ϕ x 10 cm (1 unit low γ-ray background, can be borrowed for a long period)**
- EJ301: 10 cm ϕ x 10 cm (1 unit)
- EJ309: 5 cm x 5 cm (2 units, with and without ^{10}B)
- New plastic EJ299 – 33 with a (not really fantastic) neutron/ γ-ray discrimination
  Anthracene: 3 cm x 3 cm (1 unit)
- + various plastics (BC400), ^{3}He and BF$_3$ tubes.

Neutron spectroscopy with organic liquid scintillators

Organic scintillators (liquid and plastics) are excellent fast neutron detectors.

Detection principle: (n,p) reactions in the Hydrogen rich material

-High intrinsic efficiency (50% to 20% in the 1 MeV – 10 MeV range for 3”x3” detectors) due to the large (n,p) cross section and reasonable density (~1 g/cm^3). Sensitive to neutrons at all energies above the detection threshold (100 keVee).

-Low sensitivity to high energy γ-rays (large compared to gaseous)

-Some liquids offer excellent neutron/γ pulse shape discrimination capabilities.

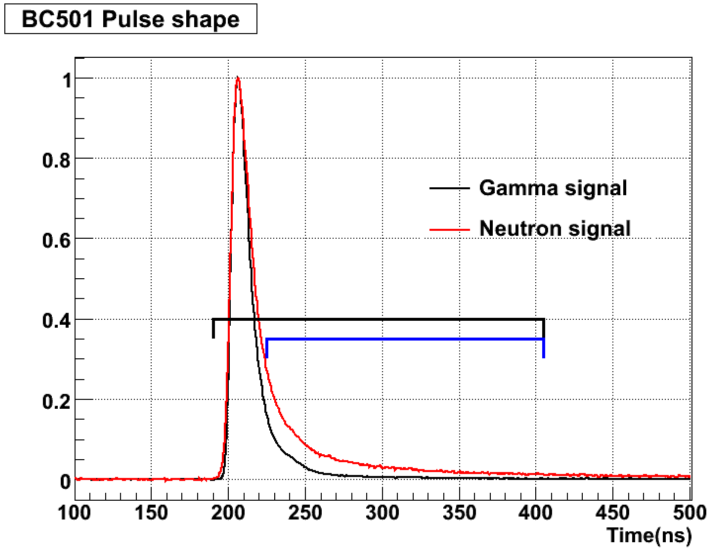
Drawbacks:

-poor energy resolution

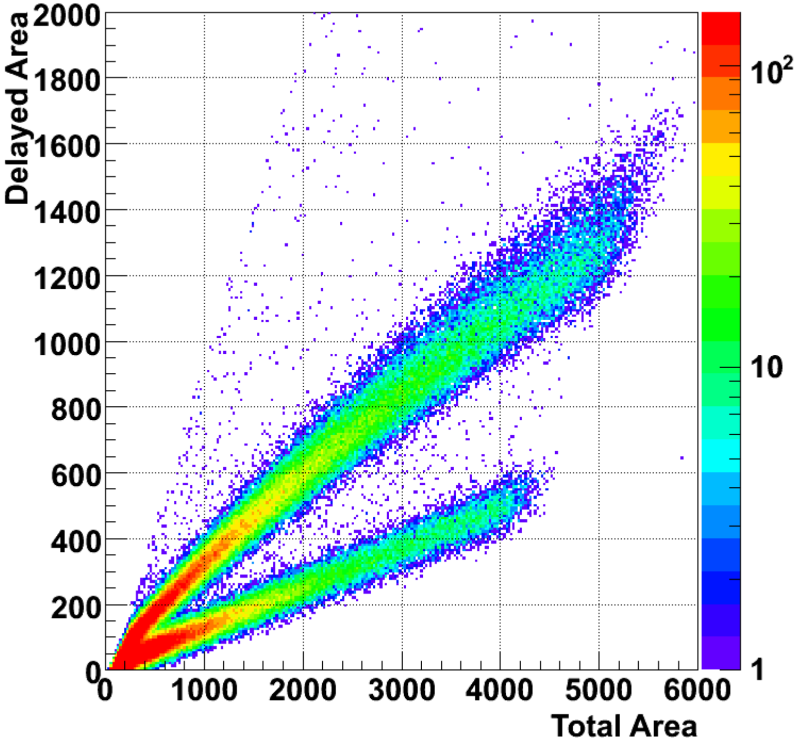
-particle dependent and non-linear light output (e$^-$, protons, D, T, a, ^{12}C...)

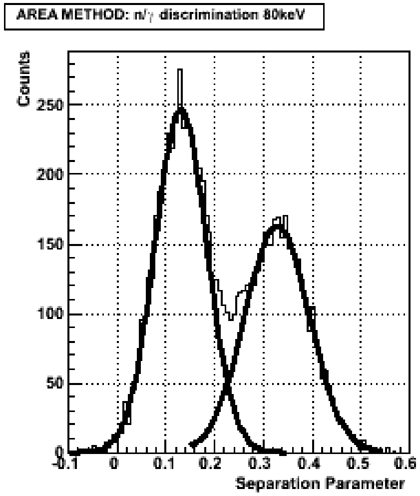
-high intrinsic threshold E_n>100 keV due to the quenched light output

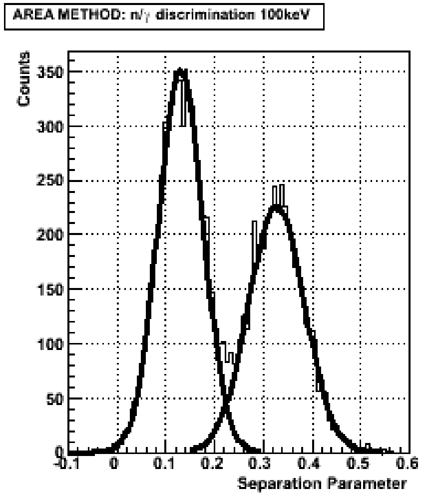
-the information of the incident neutron energy can not be recovered by spectral analysis. TOF or unfolding techniques are necessary for extracting the information on the incident neutron energy.

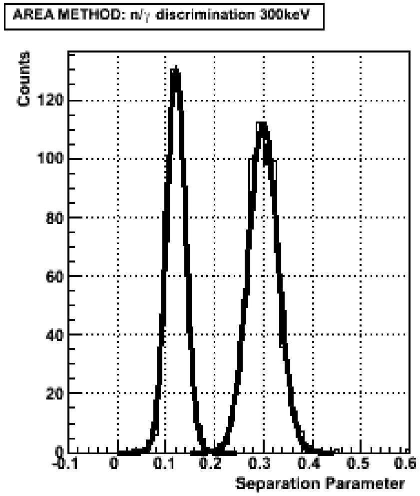


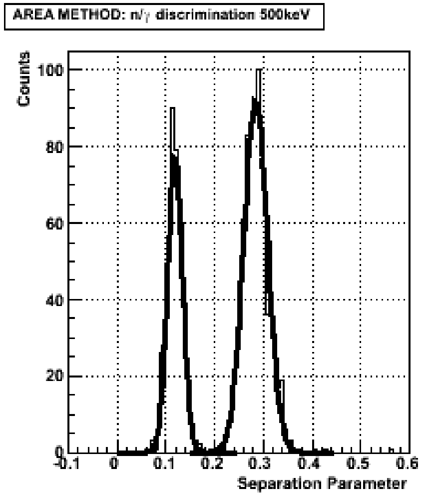
The BC501A scintillator offers good overall n/γ pulse shape discrimination capabilities. At E_n > 1 MeV the separation is really excellent.



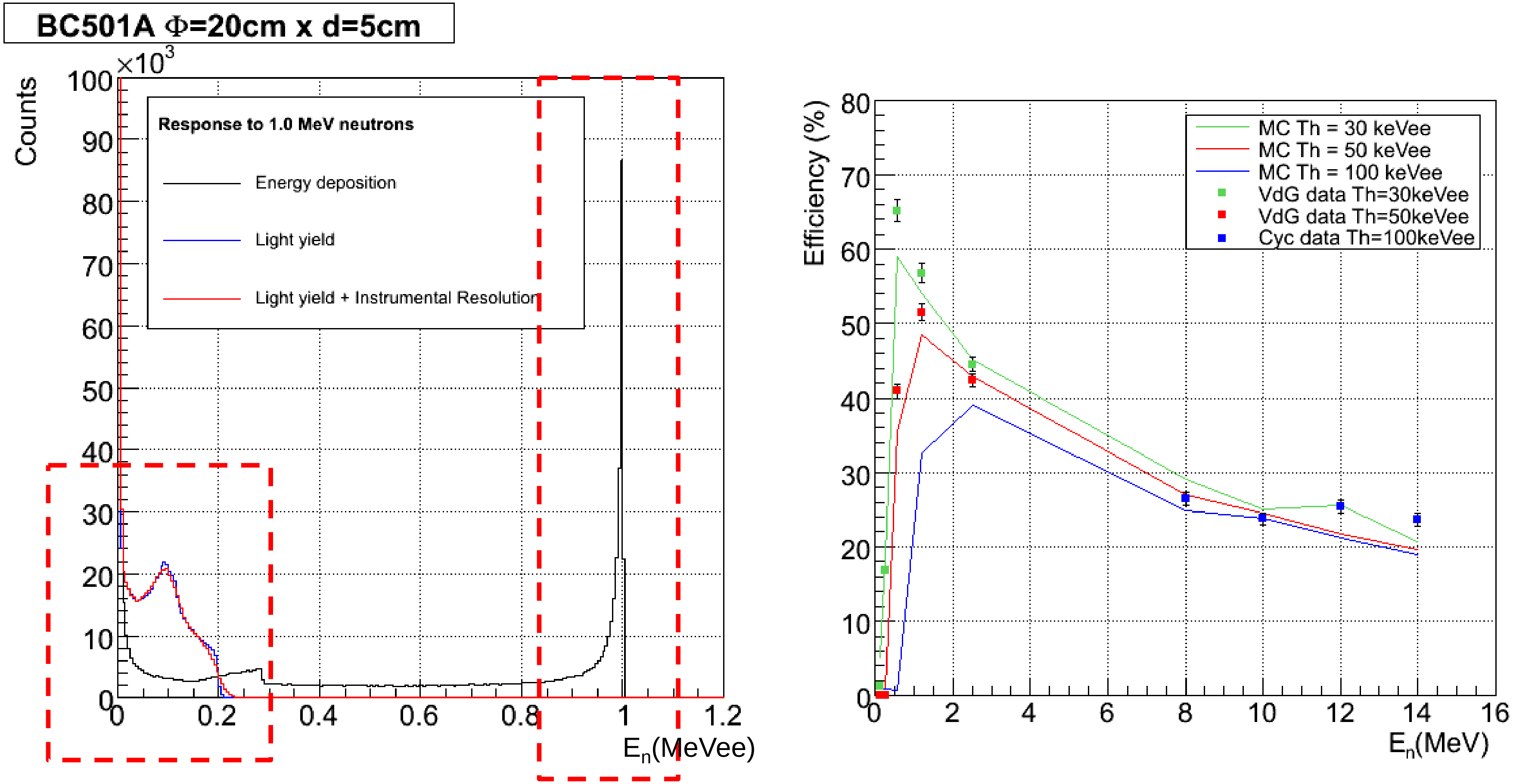






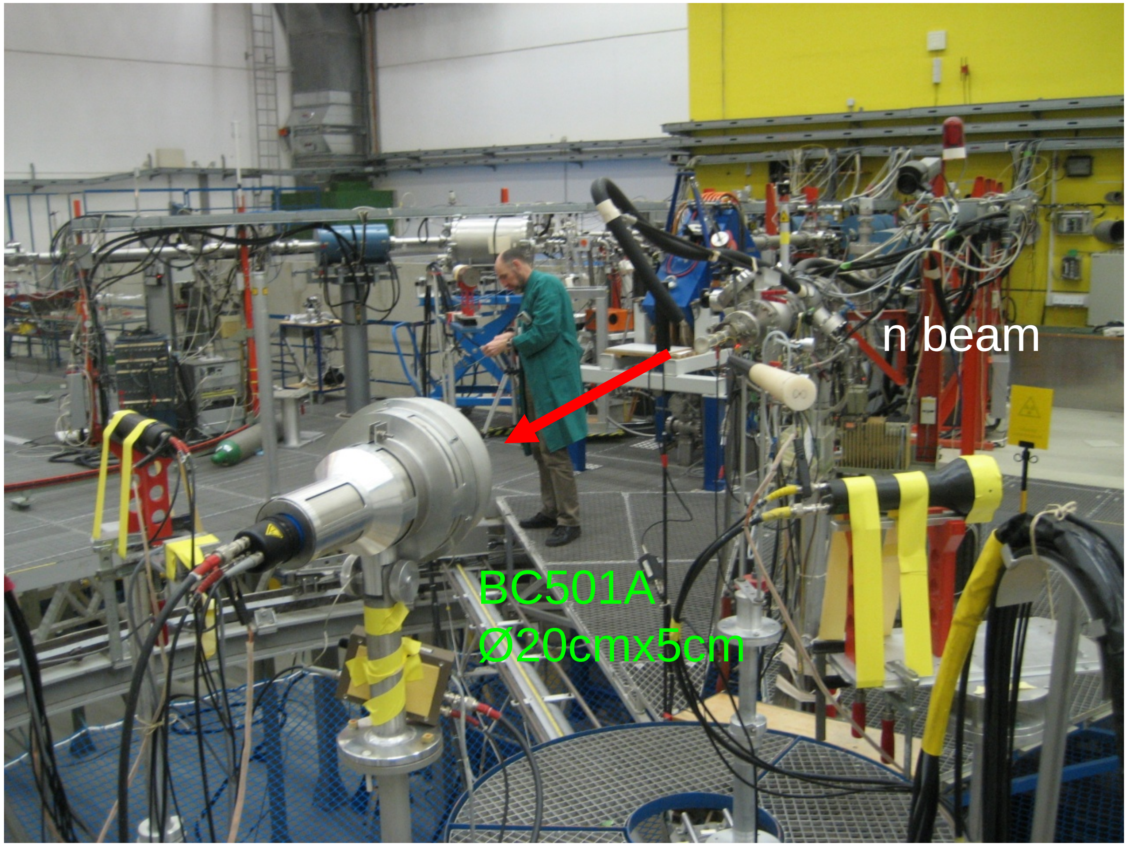


Response function of BC501A



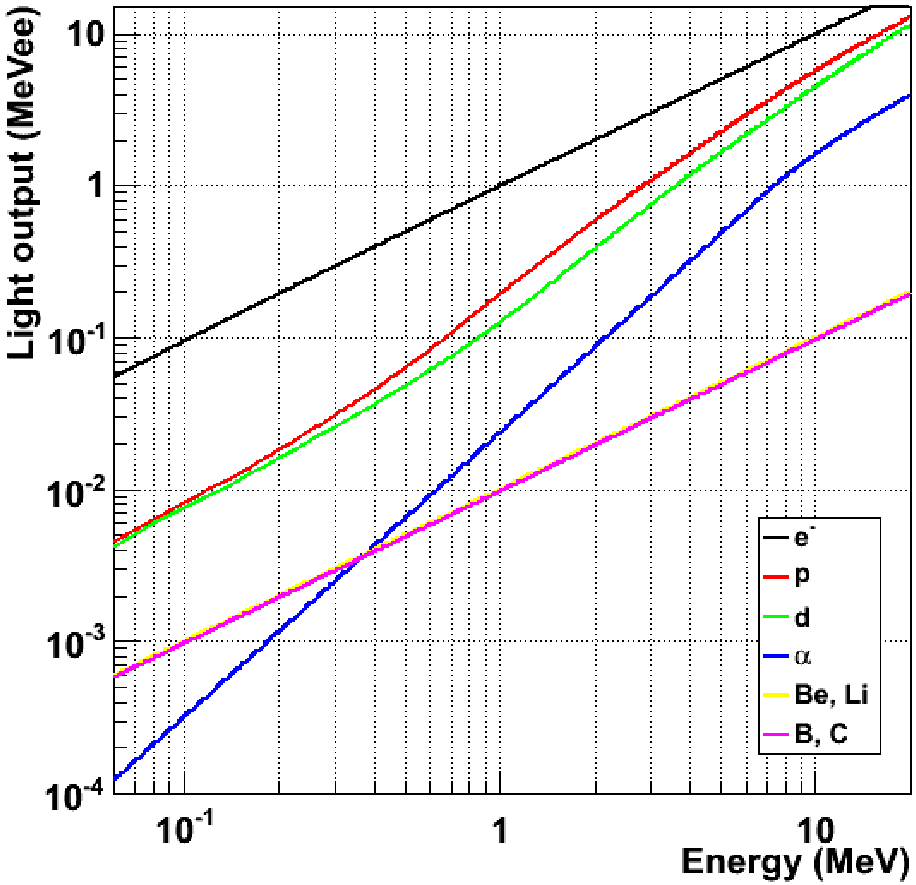
The shape of the efficiency curve depends largely on the light yield and on the threshold. A good Monte Carlo modelling is mandatory.

Metrologic characterisation of the organic scintillator



Characterisation of the detector cells at PTB-Braunschweig (Cyclotron and VdG)

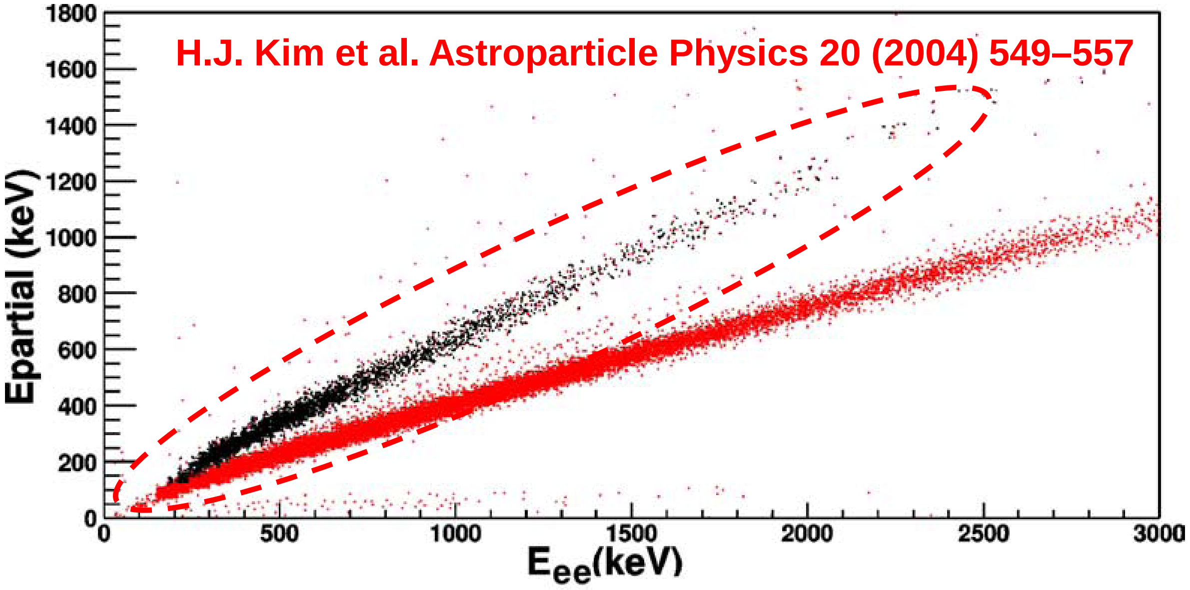
- Deuterium-Deuterium and Deuterium-Tritium reactions for E_n>5 MeV
- ^{7}Li(p,n) reaction, E_n= 0.144, 0.250, 0.565, 1.2, 2.5 MeV
- Pulsed beam (1.25MHz) for TOF background discrimination
- TOF measurement at L=1 - 2 m
- Energy calibration with sources (^{137}Cs, ^{22}Na, ^{207}Bi)

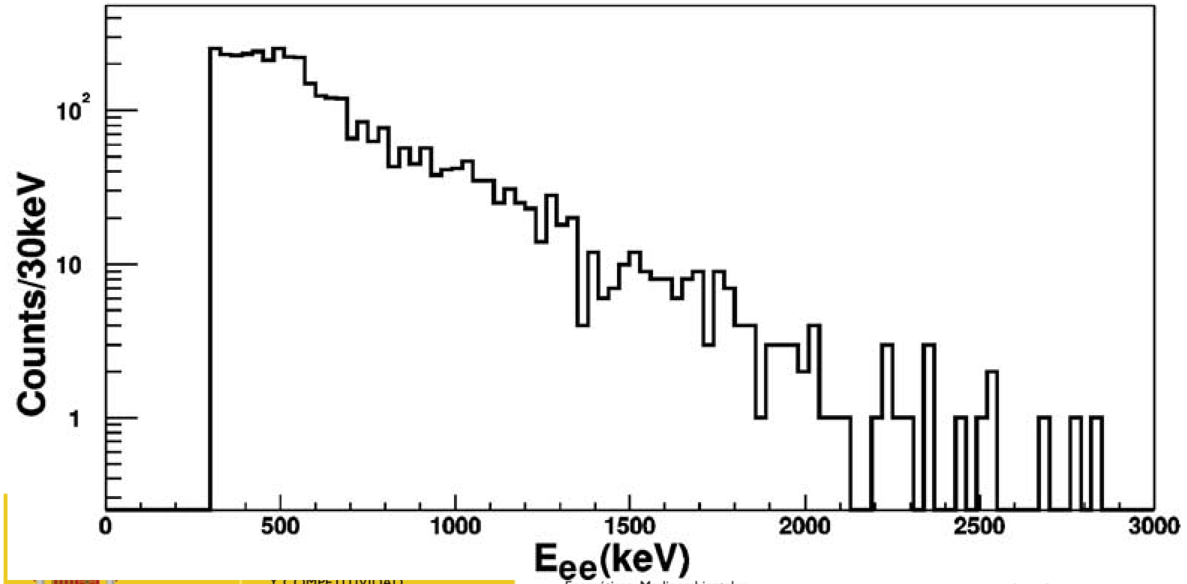


An adequate modelling of the light yield L(E) has to be implemented into the simulation codes. The light output depends on the ionising particle. The L(E) depends largely on the specific detector material and even for identical detectors 5% variations are expected.

It is not possible to characterise a large number of detectors with reference neutron beams. Monte Carlo simulation tools are essential…

Neutron background measurements with liquid scintillators


H.J. Kim et al. Astroparticle Physics 20 (2004) 549–557



This experimental technique has been applied with the same type of detector at the **CheongPyung underground laboratory (CPL) - South Korea.**

-measurement with **sufficient** statistics
-**Neutron/γ-ray separation** – good **background subtraction**
-Monte Carlo simulation of the **response functions**.
-**Unfolding of the experimental spectrum** by different methods (systematic uncertainty due to the unfolding method).

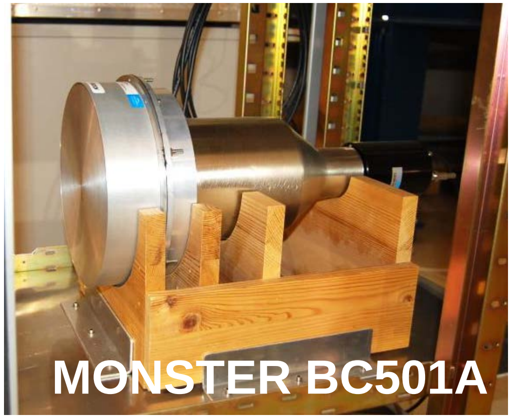
Expected high energy neutron count rates at CANFRANC

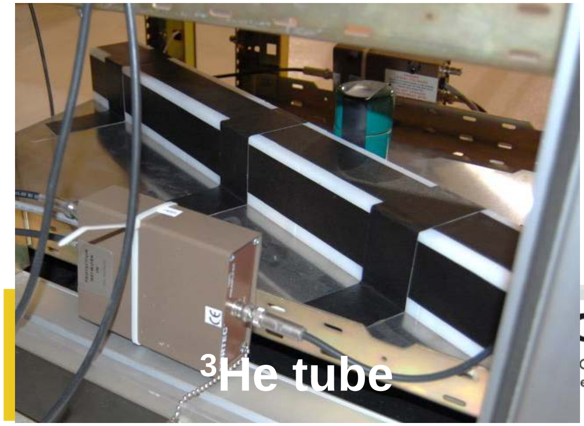
		Φ (n hr^{-1})			
Low E_n	**High E_n**	**Bayes**	**Chimem**	**Gravel**	**Maxed**
0,4	0,63	1,23E+00	1,24E+00	1,39E+00	1,40E+00
0,63	1	1,21E+00	1,59E+00	1,59E+00	2,40E+00
1	1,58	1,16E+00	2,14E+00	1,61E+00	3,88E+00
1,58	2,51	1,09E+00	2,14E+00	9,91E-01	1,45E+00
2,51	3,98	1,01E+00	1,14E+00	7,21E-01	5,20E-01
3,98	6,31	9,26E-01	7,42E-01	5,30E-01	1,84E+00
6,31	10	8,52E-01	2,39E-01	3,84E-01	6,10E-02
10	20	7,94E-01	4,56E-02	6,58E-01	9,75E-02
20	50	7,32E-01	6,83E-03	1,19E+00	8,70E-01
50	100	6,73E-01	2,58E-03	0,00E+00	0,00E+00
		8,45E+00	**8,04E+00**	**7,68E+00**	**1,11E+01**
Th 150keVee		**4,22E-01**	**4,02E-01**	**3,84E-01**	**5,56E-01**

Neutron flux (x4) values taken from ***D. Jordan et al. Astroparticle Physics 42 (2013) 1–6***

Assuming a liquid scintillator efficiency in the range 1 MeV<E_n<100 MeV of ~ 30%, we can expect about **12 counts/day – 0.5 counts · hr^{-1}** in our single detector.

The experimental setup at LSC





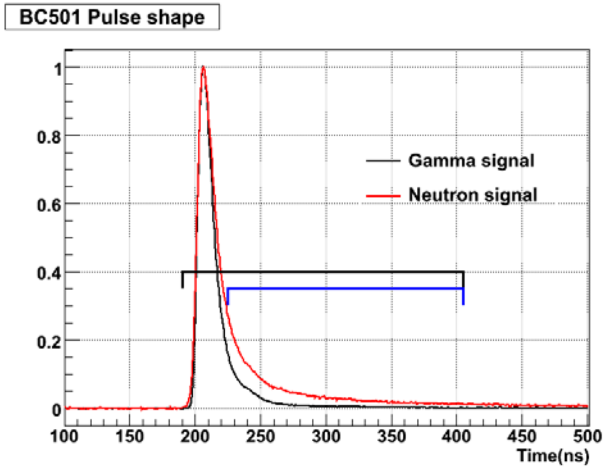
Digital pulse shapes are digitised with a N6720 de CAEN, de 250 MS/s, 2V flash ADC.

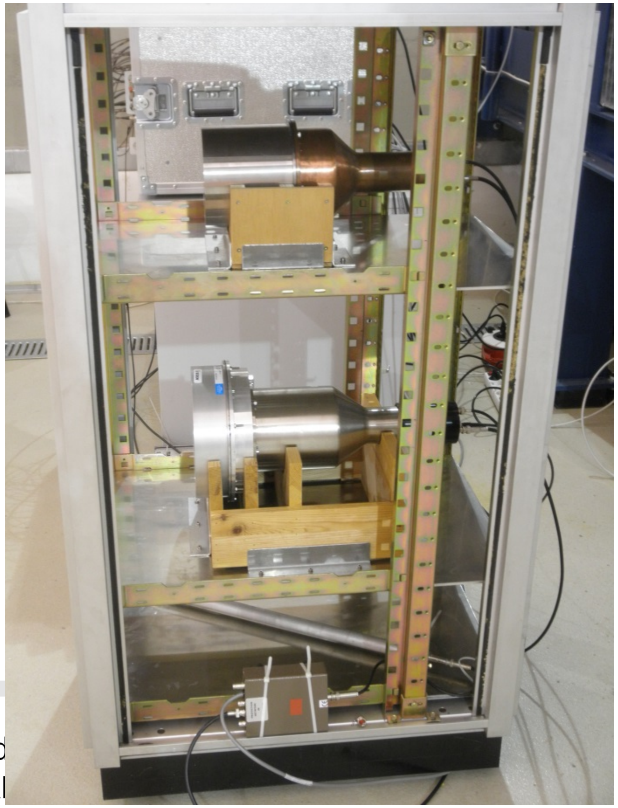
The pulse shape analysis is done shortly quase on-line.

3 (later only two) detectors are being used:

- Low background BC501A, 10 cm x 10 cm
- Standard MONSTER module, 20 cm x 5 cm
- ^{3}He detector used as a monitor.

7 + 7 months of statistics have been collected and are being analysed.





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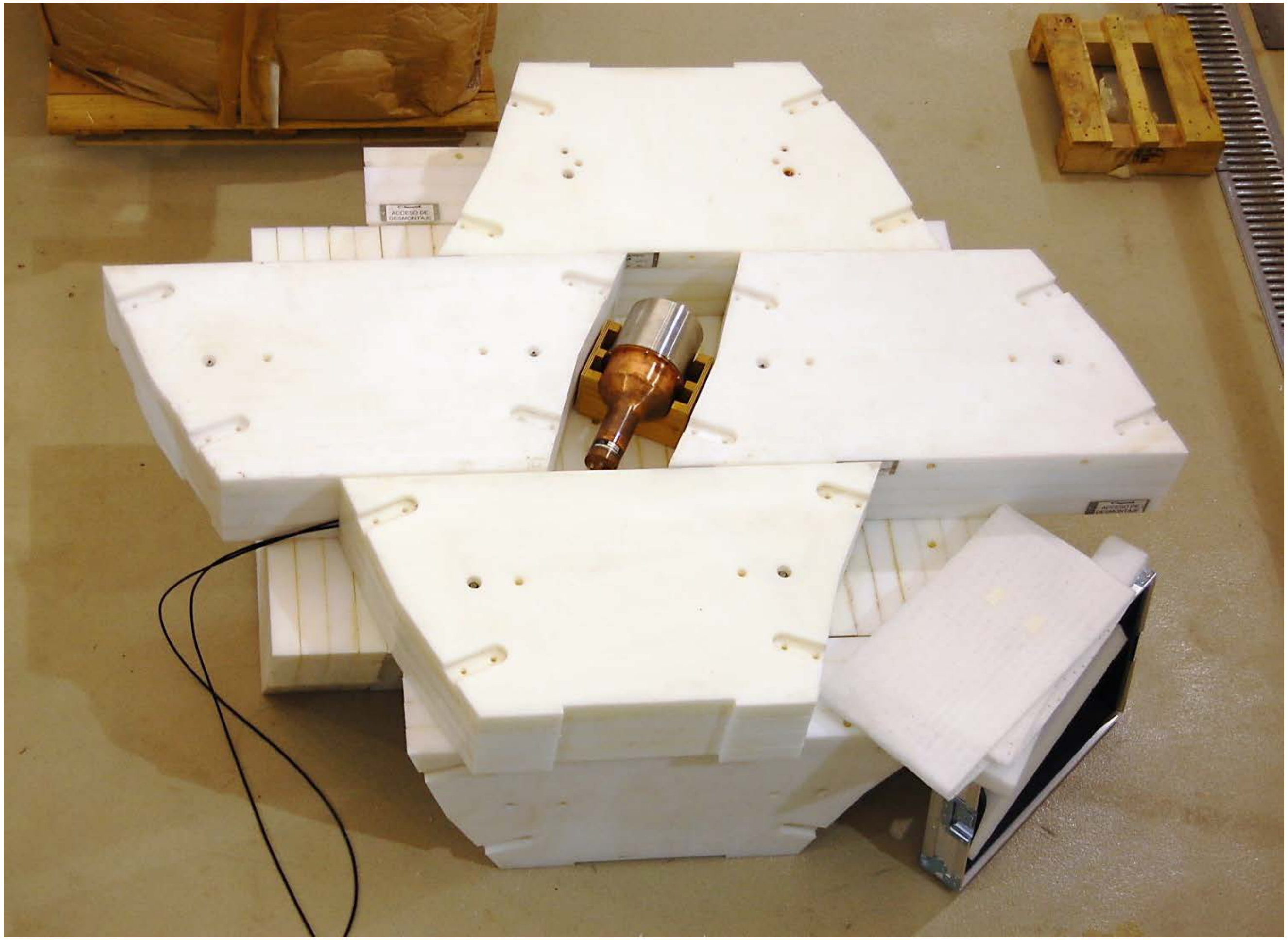
Screening of the detector by the CANFRANC ULBS

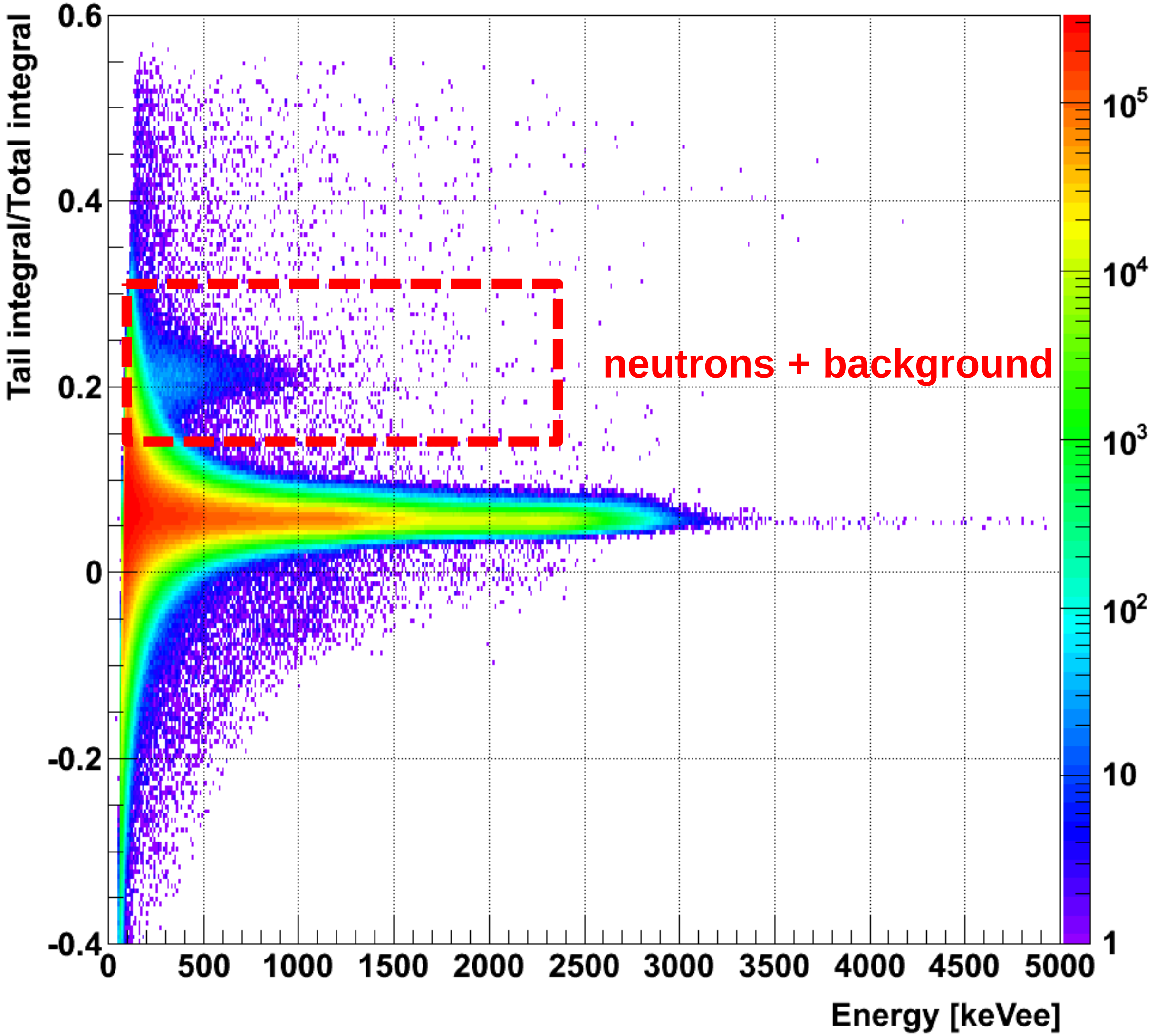
Thanks to Iulian Bandac for his work and support.

Measurement inside the ArDM polyethylene shielding



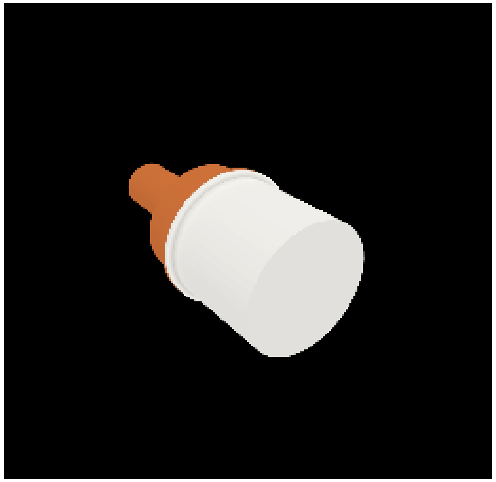
Measurement under the background conditions inside the ArDM neutron shielding.

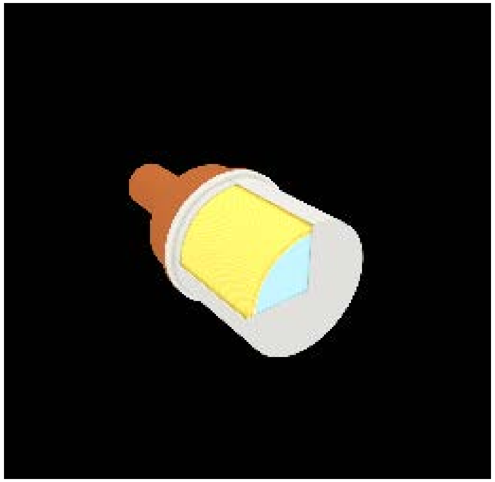
Real data

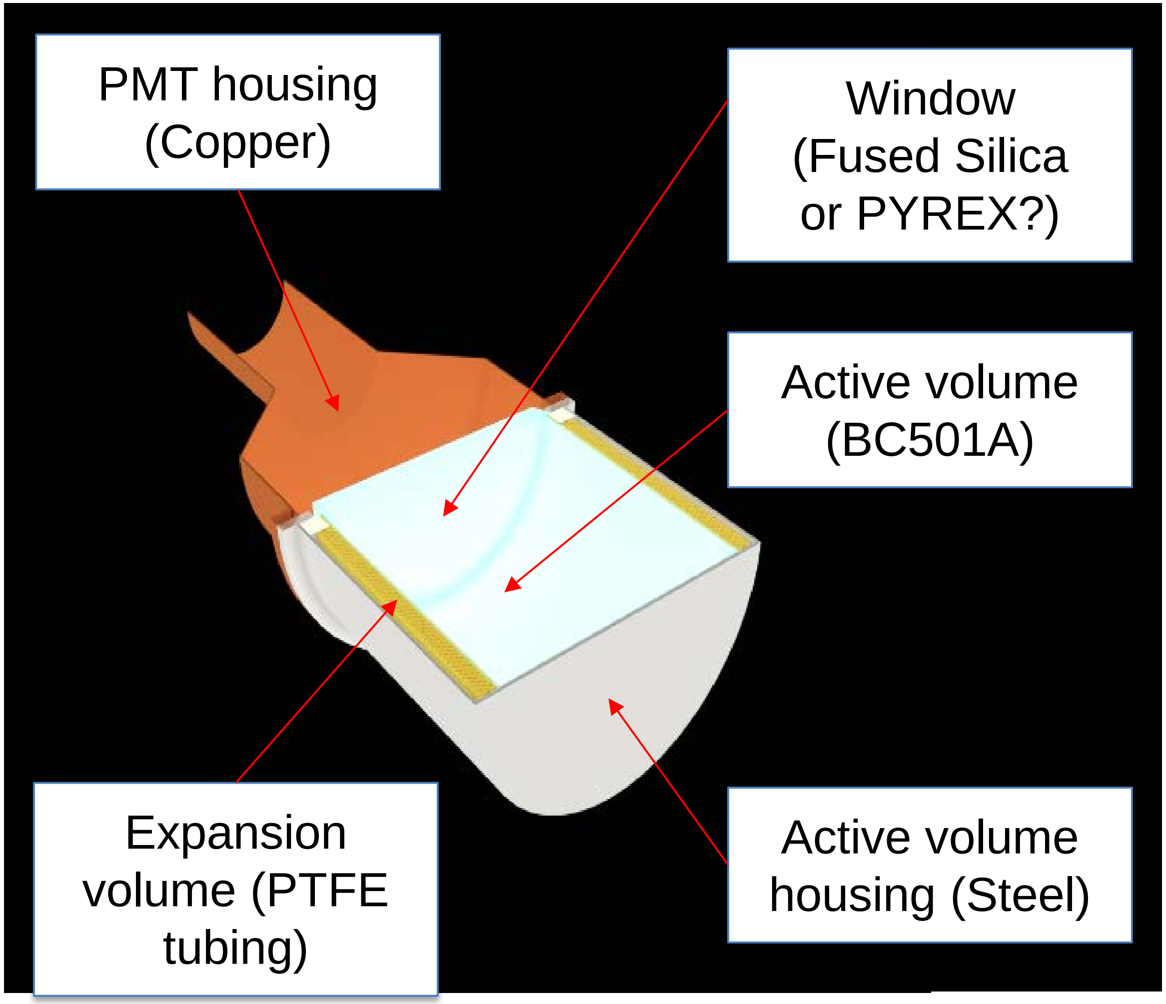


neutrons + background

Detector geometry implemented in GEANT4







PMT housing (Copper)

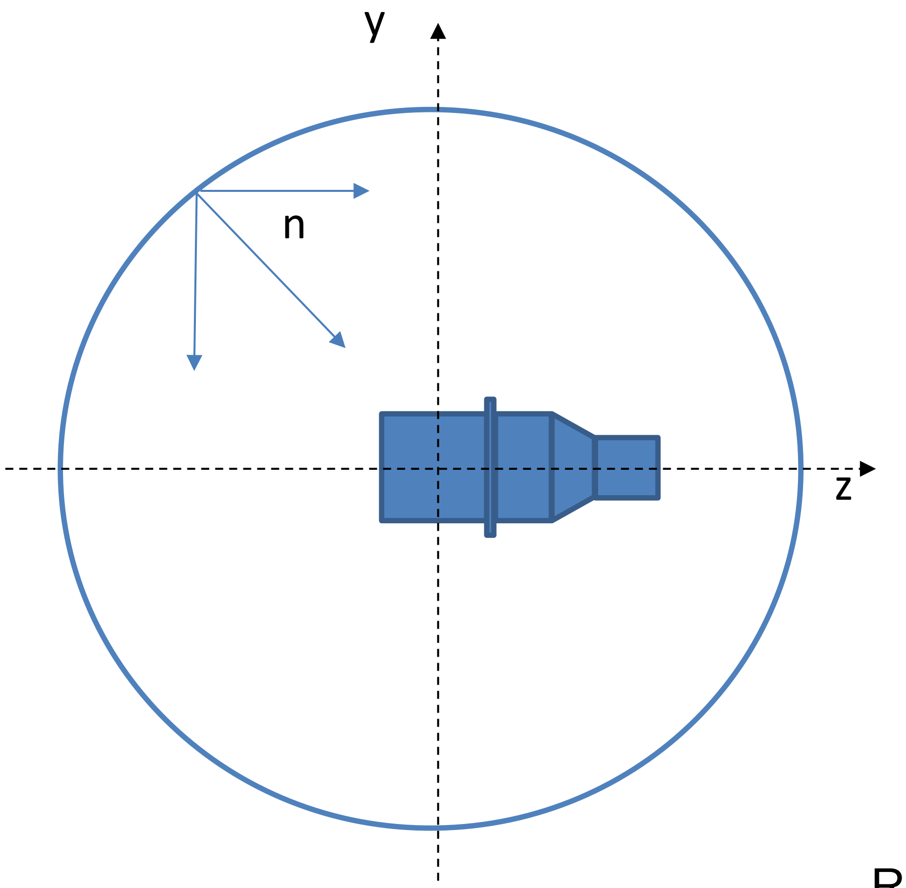
Window (Fused Silica or PYREX?)

Active volume (BC501A)

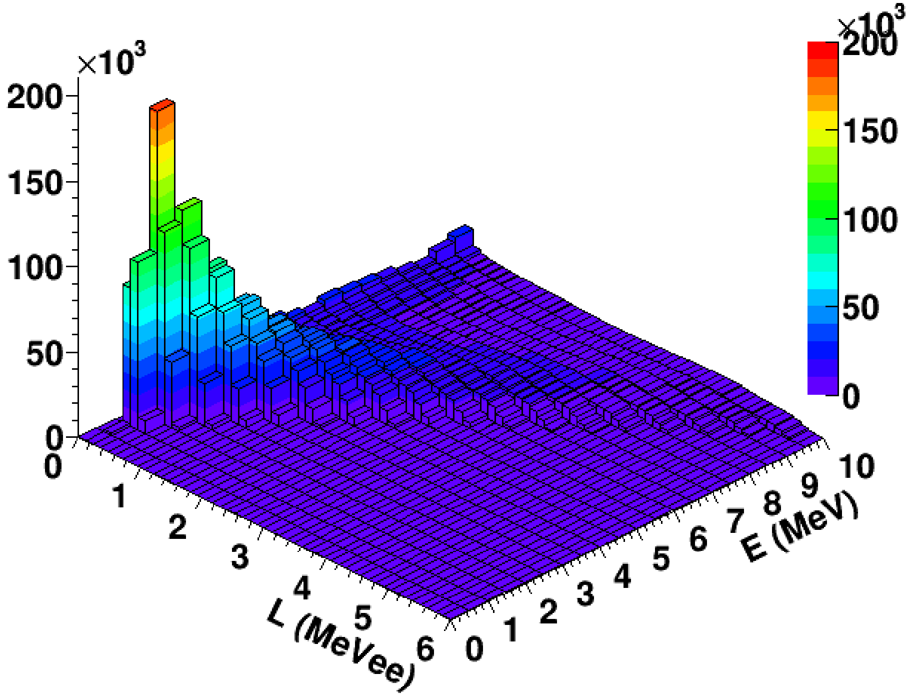
Expansion volume (PTFE tubing)

Active volume housing (Steel)

Determination of the response to neutrons



Determination of the Monte Carlo response functions for an isotropic neutron source. Calculation of the detection efficiencies.



Response matrix calculated for the BC501A detector.

(*) The figure is produced with 20 bins in the initial neutron energy range between 0 and 10 MeV (500 keV per bin) and 50 bins in the produced light range between 0 and 6 MeVee (120 keVee per bin).

Status of the data taking and analysis

- 2 large data taking periods in 2014 and 2015 (7 months each) in various configurations. 1.5 years of ”almost” continuous operation experience.
- The preliminary data analysis reveals a signal of **0.5 counts/hr** in the region where neutrons are expected after the subtraction of the intrinsic background of the detector.
- A very careful analysis is ongoing to guarantee the correctness of the results. Several sources of systematic uncertainties are being evaluated: gain variations, effect of the calibration and threshold, background subtraction, light output, contaminations in the detector.
- The last step will consist in the de-convolution of the energy deposition spectrum in order to produce a neutron energy distribution. All the tools are ready.

Summary and conclusions

In relation to a nuclear astrophysics programme at the LSC, CIEMAT can offer:

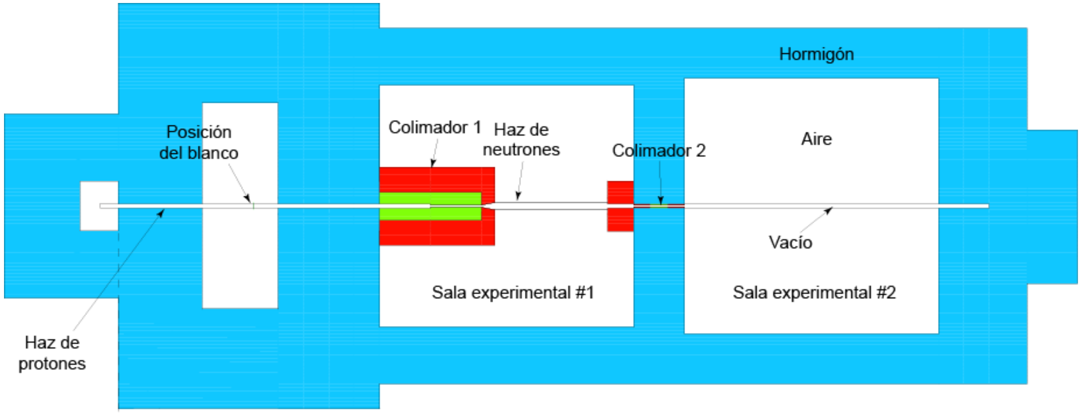
- Experience in Monte Carlo simulations for the design of the facility and determination of backgrounds. Experience in the improvement of GEANT for the simulation of problems involving neutrons. Possible contribution to the design of the accelerator cave (work already done in collaboration with IFIC) and the simulation of experimental setups.

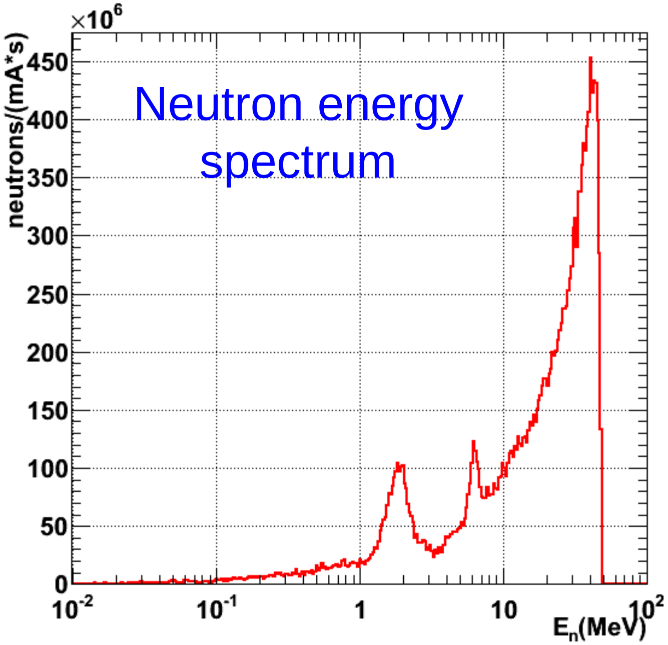
- Experience in the design, operation and data analysis of large calorimeters used in (n, γ) measurements. Possible contribution to the design and construction of a calorimeter for (p, γ) and (α,γ) cross section measurements.

- Experience in the design, construction and operation of neutron detectors based on liquid scintillators. Possible contribution to the design of a neutron background monitor and, if convenient, a neutron TOF spectrometer.

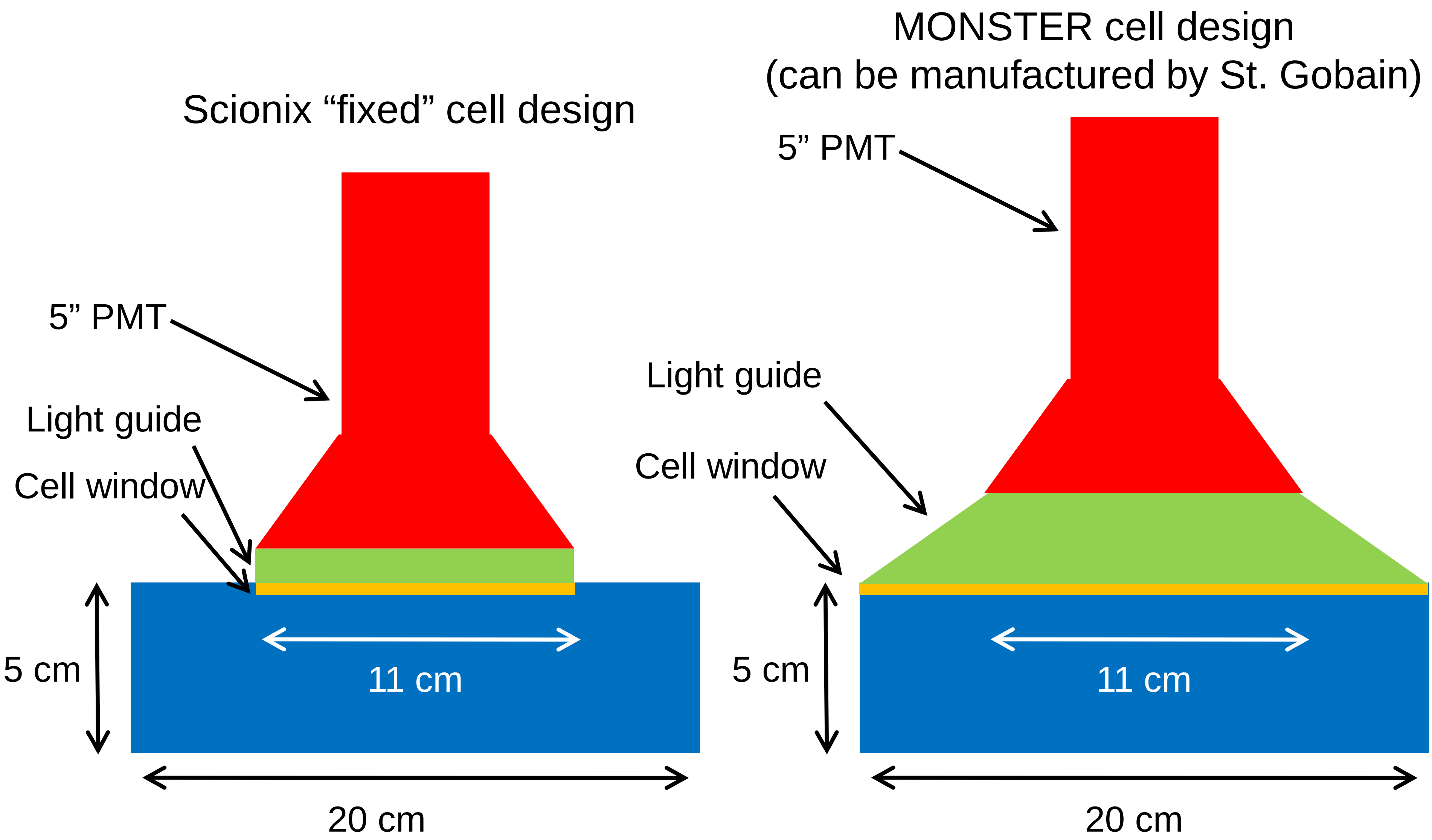
Experience in the design of neutron facilities

Conceptual design of a neutron TOF facility in Spain (former ESS – Bilbao site). (p,n) neutron source on beryllium. **30 x 10^9 source particles**





Complete conceptual design of the cell: optics, effiency, materials



Monte Carlo simulation of detectors and light output

Excellent agreement except in the low energy region of response functions for neutrons above 8 MeV due to (n,3α) reactions on carbon not implemented in GEANT4.

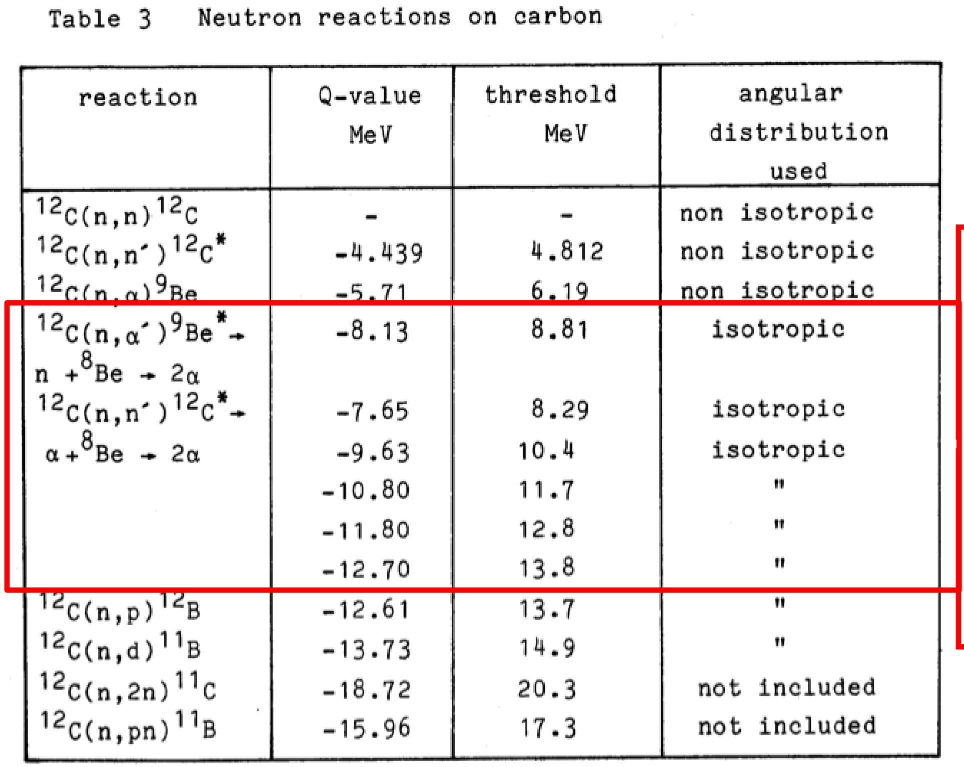
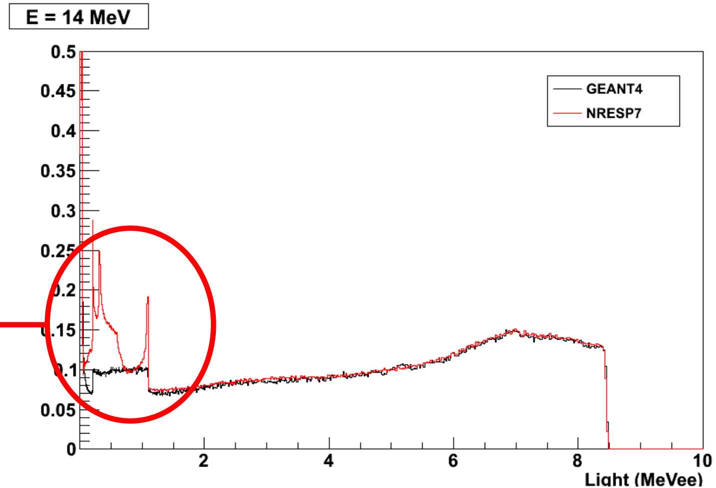
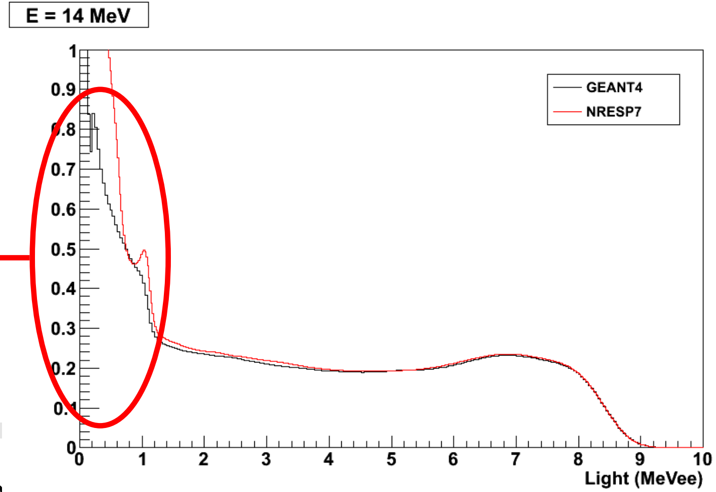


Table 3 Neutron reactions on carbon

reaction	Q-value MeV	threshold MeV	angular distribution used
$^{12}C(n,n)^{12}C$	-	-	non isotropic
$^{12}C(n,n')^{12}C^*$	-4.439	4.812	non isotropic
$^{12}C(n,\alpha)^9Be$	-5.71	6.19	non isotropic
$^{12}C(n,\alpha')^9Be^* \rightarrow n + {}^8Be \rightarrow 2\alpha$	-8.13	8.81	isotropic
$^{12}C(n,n')^{12}C^* \rightarrow \alpha + {}^8Be \rightarrow 2\alpha$	-7.65	8.29	isotropic
	-9.63	10.4	isotropic
	-10.80	11.7	"
	-11.80	12.8	"
	-12.70	13.8	"
$^{12}C(n,p)^{12}B$	-12.61	13.7	"
$^{12}C(n,d)^{11}B$	-13.73	14.9	"
$^{12}C(n,2n)^{11}C$	-18.72	20.3	not included
$^{12}C(n,pn)^{11}B$	-15.96	17.3	not included





E_n=12 MeV

The physics of the NRESP code (PTB, calculation of detector efficiencies with 2% accuracy) has been implemented in GEANT4.