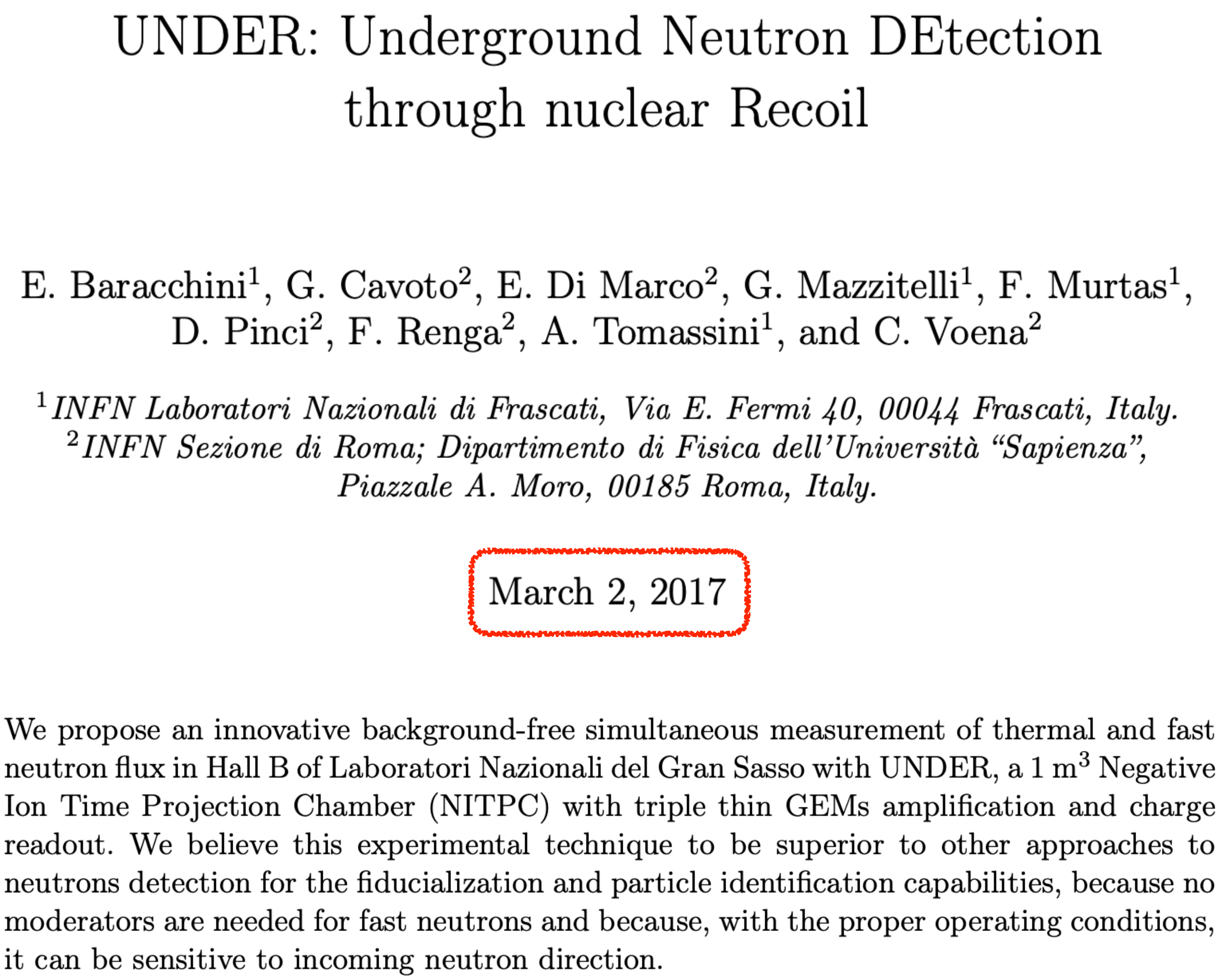
Motivation and prospects for underground neutron flux measurement with LIME

Elisabetta Baracchini

A little history…



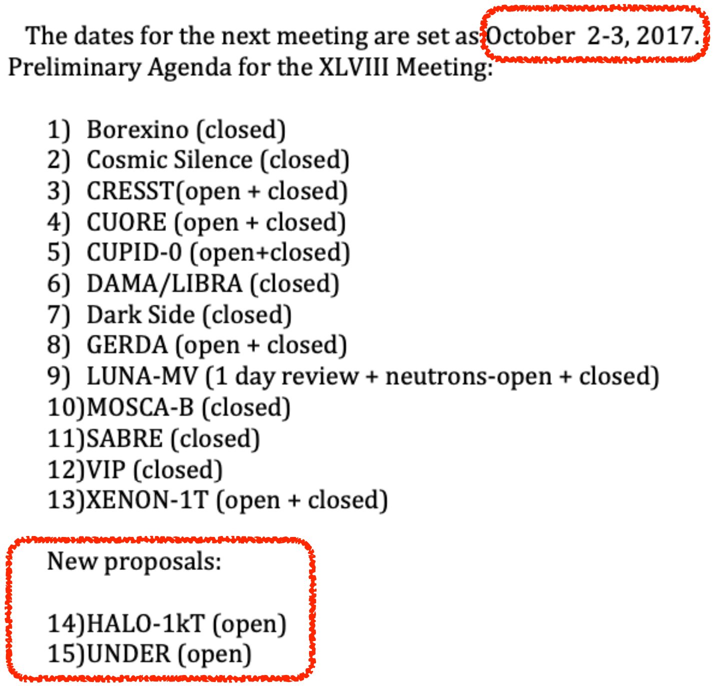
UNDER: Underground Neutron DEtection through nuclear Recoil

E. Baracchini[1], G. Cavoto[2], E. Di Marco[2], G. Mazzitelli[1], F. Murtas[1], D. Pinci[2], F. Renga[2], A. Tomassini[1], and C. Voena[2]

[1] INFN Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, Italy.
[2] INFN Sezione di Roma; Dipartimento di Fisica dell'Università "Sapienza", Piazzale A. Moro, 00185 Roma, Italy.

March 2, 2017

We propose an innovative background-free simultaneous measurement of thermal and fast neutron flux in Hall B of Laboratori Nazionali del Gran Sasso with UNDER, a 1 m^3 Negative Ion Time Projection Chamber (NITPC) with triple thin GEMs amplification and charge readout. We believe this experimental technique to be superior to other approaches to neutrons detection for the fiducialization and particle identification capabilities, because no moderators are needed for fast neutrons and because, with the proper operating conditions, it can be sensitive to incoming neutron direction.



The dates for the next meeting are set as October 2-3, 2017.
Preliminary Agenda for the XLVIII Meeting:

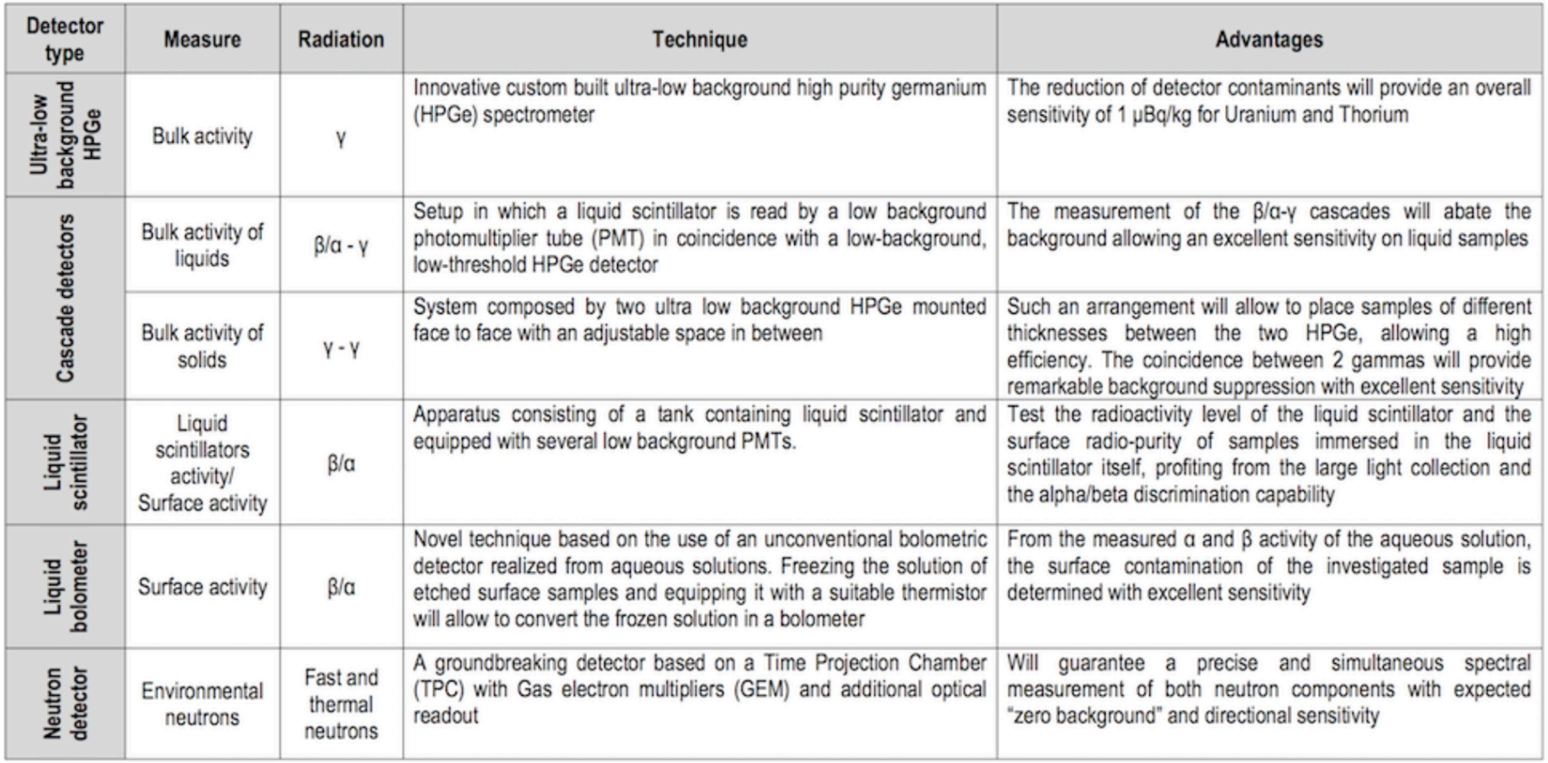
1) Borexino (closed)
2) Cosmic Silence (closed)
3) CRESST(open + closed)
4) CUORE (open + closed)
5) CUPID-0 (open+closed)
6) DAMA/LIBRA (closed)
7) Dark Side (closed)
8) GERDA (open + closed)
9) LUNA-MV (1 day review + neutrons-open + closed)
10)MOSCA-B (closed)
11)SABRE (closed)
12)VIP (closed)
13)XENON-1T (open + closed)

New proposals:

14)HALO-1kT (open)
15)UNDER (open)

UNDER became CYGNO in Summer 2018

PRIN 2017

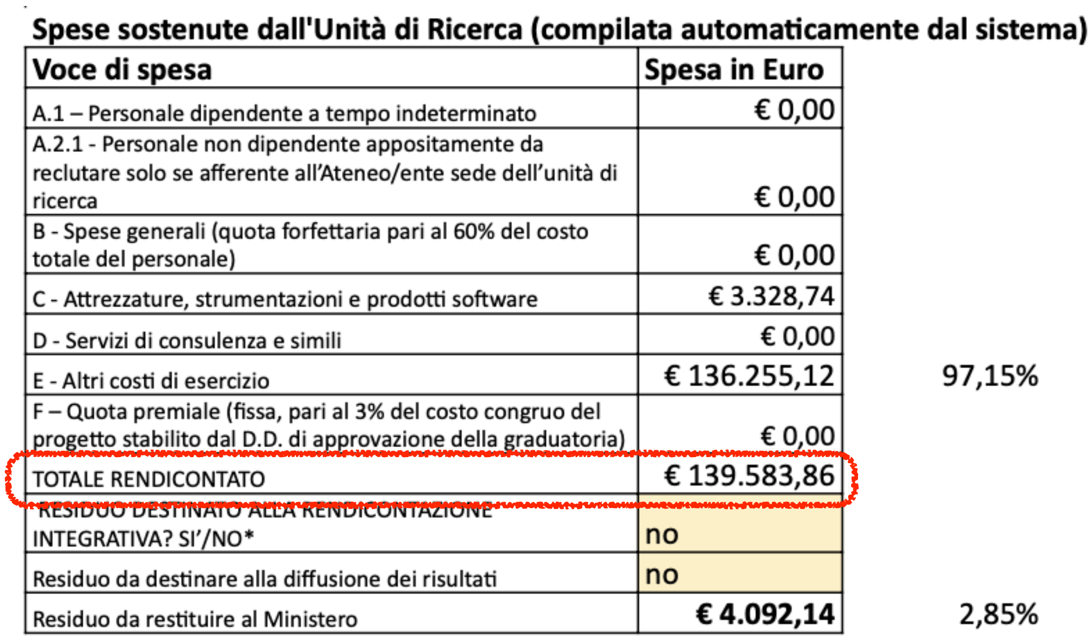


Detector type	Measure	Radiation	Technique	Advantages
Ultra-low background HPGe	Bulk activity	γ	Innovative custom built ultra-low background high purity germanium (HPGe) spectrometer	The reduction of detector contaminants will provide an overall sensitivity of 1 μBq/kg for Uranium and Thorium
Cascade detectors	Bulk activity of liquids	β/α - γ	Setup in which a liquid scintillator is read by a low background photomultiplier tube (PMT) in coincidence with a low-background, low-threshold HPGe detector	The measurement of the β/α-γ cascades will abate the background allowing an excellent sensitivity on liquid samples
	Bulk activity of solids	γ - γ	System composed by two ultra low background HPGe mounted face to face with an adjustable space in between	Such an arrangement will allow to place samples of different thicknesses between the two HPGe, allowing a high efficiency. The coincidence between 2 gammas will provide remarkable background suppression with excellent sensitivity
Liquid scintillator	Liquid scintillators activity/ Surface activity	β/α	Apparatus consisting of a tank containing liquid scintillator and equipped with several low background PMTs.	Test the radioactivity level of the liquid scintillator and the surface radio-purity of samples immersed in the liquid scintillator itself, profiting from the large light collection and the alpha/beta discrimination capability
Liquid bolometer	Surface activity	β/α	Novel technique based on the use of an unconventional bolometric detector realized from aqueous solutions. Freezing the solution of etched surface samples and equipping it with a suitable thermistor will allow to convert the frozen solution in a bolometer	From the measured α and β activity of the aqueous solution, the surface contamination of the investigated sample is determined with excellent sensitivity
Neutron detector	Environmental neutrons	Fast and thermal neutrons	A groundbreaking detector based on a Time Projection Chamber (TPC) with Gas electron multipliers (GEM) and additional optical readout	Will guarantee a precise and simultaneous spectral measurement of both neutron components with expected "zero background" and directional sensitivity

Fast and thermal neutron detector (Sub-project 5)

- WP 5.1 (Detector design and gas optimization studies - GSSI+INFN): With an already existing detector prototype (LEMOn) we will study gas properties and detector design, testing various GEM layouts to optimize gain and energy resolution. In parallel, we will develop the needed DAQ and gas system and test them on LEMOn.
- WP 5.2 (Detector construction and underground installation – GSSI + INFN): the goal is to build and install the detector in the LNGS underground laboratories.
- WP 5.3 (Detector commissioning and physics run – GSSI+INFN): This working package will be dedicated to the underground commissioning and calibration followed by the neutron flux measurement physics runs.
- WP 5.4 (Data analysis, calibrations and simulation – GSSI +INFN): We will develop all the necessary analysis and simulation tools to interpret the prototype and experimental data, to optimize the detector configuration and to evaluate the measured neutron flux.

LIME and PRIN2017 fundings



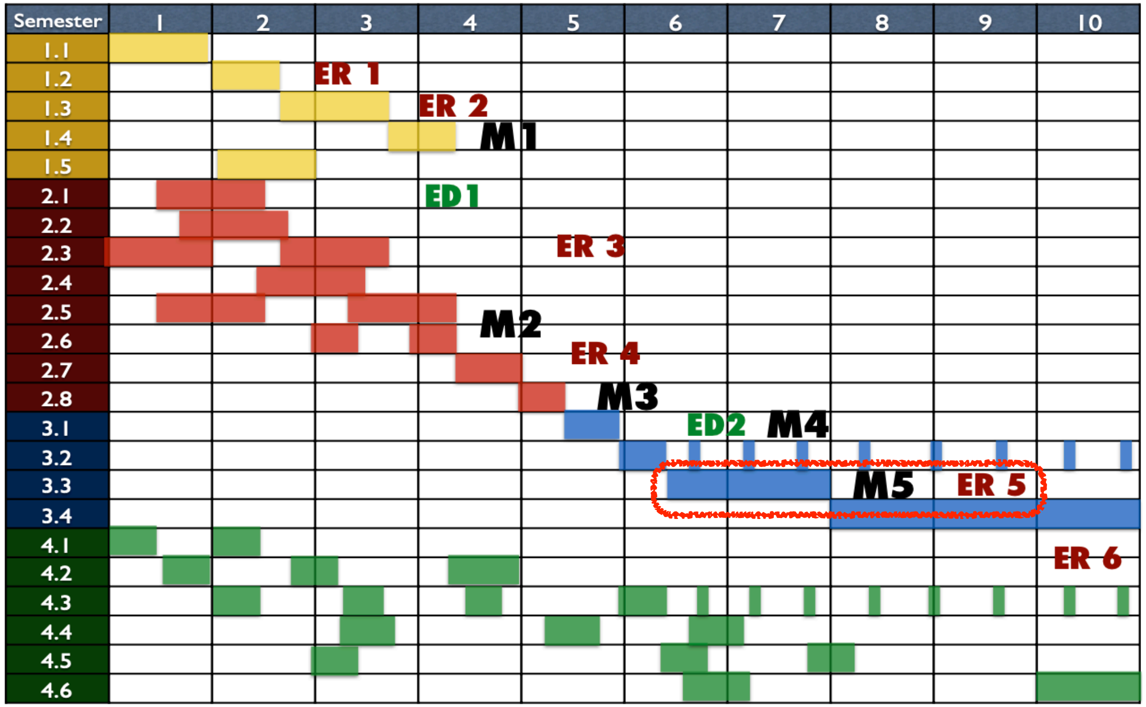
Spese sostenute dall'Unità di Ricerca (compilata automaticamente dal sistema)

Voce di spesa	Spesa in Euro	
A.1 – Personale dipendente a tempo indeterminato	€ 0,00	
A.2.1 - Personale non dipendente appositamente da reclutare solo se afferente all'Ateneo/ente sede dell'unità di ricerca	€ 0,00	
B - Spese generali (quota forfettaria pari al 60% del costo totale del personale)	€ 0,00	
C - Attrezzature, strumentazioni e prodotti software	€ 3.328,74	
D - Servizi di consulenza e simili	€ 0,00	
E - Altri costi di esercizio	€ 136.255,12	97,15%
F – Quota premiale (fissa, pari al 3% del costo congruo del progetto stabilito dal D.D. di approvazione della graduatoria)	€ 0,00	
TOTALE RENDICONTATO	€ 139.583,86	
RESIDUO DESTINATO ALLA RENDICONTAZIONE INTEGRATIVA? SI'/NO*	no	
Residuo da destinare alla diffusione dei risultati	no	
Residuo da restituire al Ministero	**€ 4.092,14**	2,85%

- **Lens + sCMOS Orca Fusion**
- **Highly performing Teledyne Oscilloscope**
- **^{55}Fe calibration source**
- **Compressor, air purificator, oxygen/ moisture filters**
- **About 30k of gases**
- **Vacuum pump**
- **Water shielding**
- **Cu cutting for gamma shielding**
- **Total of ±140k EUROs invested on LIME from PRIN2017**

ERC COG 2018

- 3.3 Fast and thermal environmental neutron flux seasonal measurement, to investigate potential temporal variations (without polyethylene shielding).



—WP III

In order to be better able to mitigate unexpected contingencies, LIME will be tested underground before finalising INITIUM design. To this aim, an hut in underground LNGS Tir Tunnel has been adapted to host LIME set up, with detector installation foreseen by December 2021. Since LIME is identical to each of the modules that will comprise INITIUM, this will allow to study underground performances (WP 3.2) and, with dedicated shielding (see WP IV), characterise internal and external backgrounds and perform a preliminary measurement of environmental neutron flux (WP 3.3).

At the 36 months ERC report, given the status of the project and what discussed so far at that time within the CYGNO collaboration (see also initial Flaminia's thesis goal), a preliminary neutron flux measurement was promised with LIME

From 2017 slides…

Natural neutron backgound

- **Neutron background limits the maximum achievable sensitivity in most deep underground nuclear, astroparticle and double-beta decay experiments**
  - Fast neutrons background to current experiments
  - Thermal neutrons: able to activate detector material, background for future large volume experiments

- **At a typical depth of 3000-4000 m.w.e. neutron flux from the environment is about 2-3 order of magnitude larger than from cosmogenic muon activation**
  - Dominant source from ^{238}U fission from rocks, (alpha,n) reaction on light nuclei and experimental setup activity

From 2017 slides…

Current knowledge of LNGS undergound neutron flux

Thermal neutrons

^{3}He BF$_3$ ^{3}He ^{3}He

E interval (eV)	Thermal Neutron Flux (10^{-6}cm^{-2}s^{-1}) Ref. [1]	Ref. [2]	Ref. [3]	Ref. [4]
0 - 0.05	5.3 ± 0.9	1.08 ± 0.02 (1.07 ± 0.05)	0.54 ± 0.13	0.32 ± 0.09
0.05 - 1000		1.84 ± 0.20 (1.99 ± 0.05)		

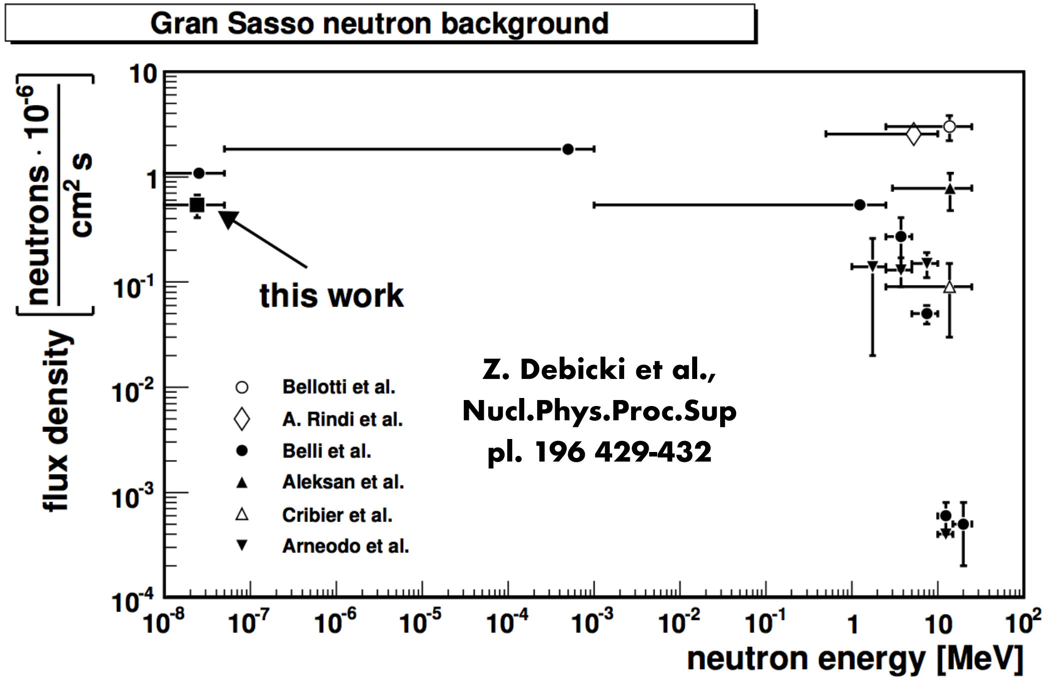
Fast and thermal neutron measurements varying widely

Fast neutrons

BF$_3$ ^{3}He ^{3}He

E interval (MeV)	Fast Neutron Flux (10^{-6}cm^{-2}s^{-1}) Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
0.1 – 1	Liquid scintillator		0.54±0.01 (0.53±0.08)			2.56±0.27
1 – 2.5		0.14±0.12				
2.5 – 3		0.13±0.04	0.27±0.14 (0.18±0.04)	3.0±0.8	0.09±0.06	
3 – 5	0.78±0.3					
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)			
10 – 15		$(0.4 \pm 0.4) \cdot 10^{-3}$	$(0.6 \pm 0.2) \cdot 10^{-3}$ ($(0.7 \pm 0.2) \cdot 10^{-3}$)			UL
15 – 25	UL		$(0.5 \pm 0.3) \cdot 10^{-6}$ ($(0.1 \pm 0.3) \cdot 10^{-6}$)			

Fast neutron flux measurement more than 20 years old



Z. Debicki et al., Nucl.Phys.Proc.Suppl. 196 429-432

- [1] Bellotti 1985
- [2] Belli 1989
- [3] Debicki 2009
- [4] Best 2015
- [5] Aleksan 1989
- [6] Arneodo 1999
- [7] Cribier 1995
- [8] Rindi 1988

Very poor knowledge of actual neutron spectrum shape

From 2017 slides…

LNGS Hall A, Hall B and Hall C

Wulandari et. al., Astropart.Phys. 22 (2004) 313-322

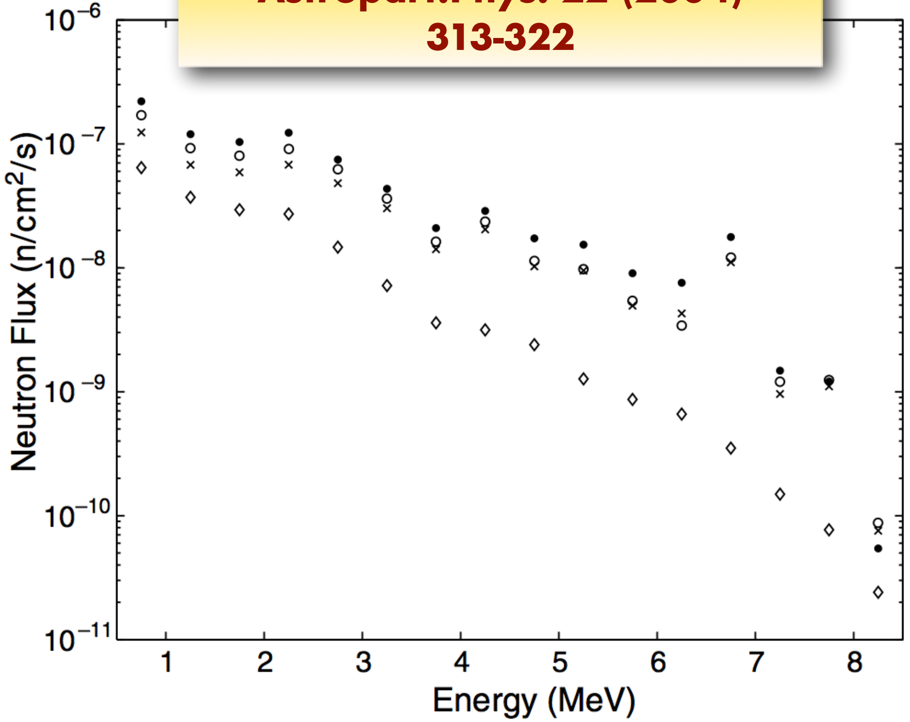


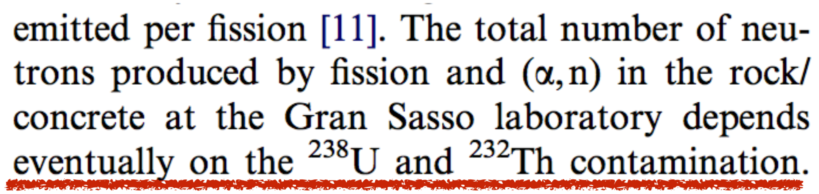
Fig. 3. Neutron flux at the Gran Sasso laboratory, ●: hall A, dry concrete, ×: hall A, wet concrete, ◇: hall A, dry concrete, fission reactions only and ○: hall C, dry concrete. Each point shows the integral flux in a 0.5 MeV energy bin.

NEUTRON BACKGROUND HIGHLY DEPENDENT ON CONCRETE WATER CONTENT!!!

..something that can change over a year…

The flux is dominated by neutrons produced in the concrete layer and therefore does not vary much from hall to hall

At higher energies, the contribution of (alpha,n) reaction becomes larger introducing the difference


emitted per fission [11]. The total number of neutrons produced by fission and (α,n) in the rock/concrete at the Gran Sasso laboratory depends eventually on the ^{238}U and ^{232}Th contamination.

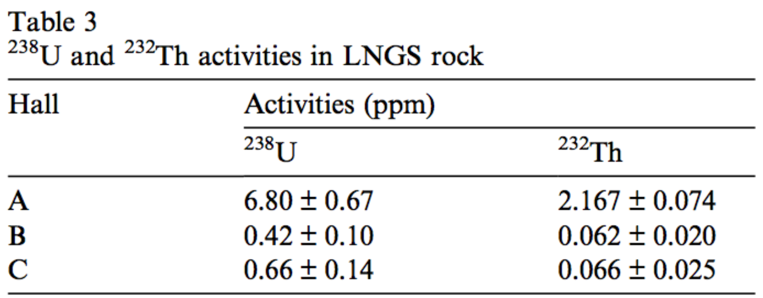


Table 3
^{238}U and ^{232}Th activities in LNGS rock

Hall	Activities (ppm)	
	^{238}U	^{232}Th
A	6.80 ± 0.67	2.167 ± 0.074
B	0.42 ± 0.10	0.062 ± 0.020
C	0.66 ± 0.14	0.066 ± 0.025

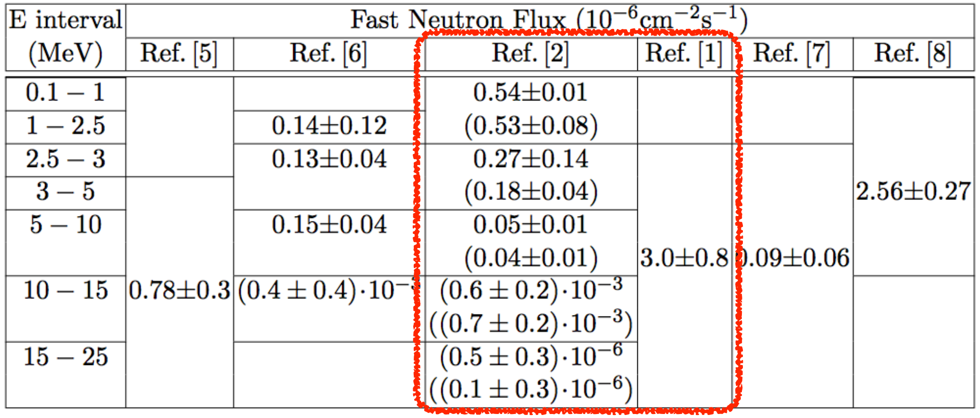
	Hall A	Hall B	Hall C
rock	3.54	0.22	0.34
concrete	0.55	0.55	0.55

n/year/g

Comments on ^{3}He and BF$_3$ counters technique results

From 2017 slides…

- **^{3}He and BF$_3$ measurements**
  - Thermal neutron through capture: a peak over a large background of internal radioactivity (alphas mainly), to be estimated and subtracted to obtain the final result
    - NOTE that several other laboratories felt the need to perform ^{3}He measurements with low-radioactivity background detectors
  - Fast neutron (Belli, Bellotti): only through Cadmium and Polyethylene moderators, complicating detector efficiency and introducing additional uncertainty on yield and energy range



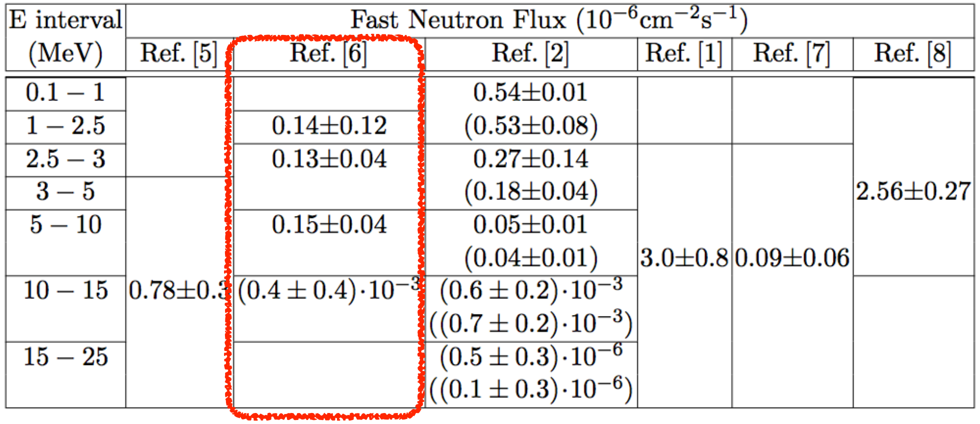
E interval (MeV)	Fast Neutron Flux (10^{-6}cm^{-2}s^{-1})					
	Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
0.1 – 1			0.54±0.01 (0.53±0.08)			2.56±0.27
1 – 2.5		0.14±0.12				
2.5 – 3		0.13±0.04	0.27±0.14 (0.18±0.04)	3.0±0.8	0.09±0.06	
3 – 5	0.78±0.3					
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)			
10 – 15		$(0.4 \pm 0.4)\cdot 10^{-}$	$(0.6 \pm 0.2)\cdot 10^{-3}$ $((0.7 \pm 0.2)\cdot 10^{-3})$			
15 – 25			$(0.5 \pm 0.3)\cdot 10^{-6}$ $((0.1 \pm 0.3)\cdot 10^{-6})$			

Fast neutron measurement through counters is not a direct measurement!

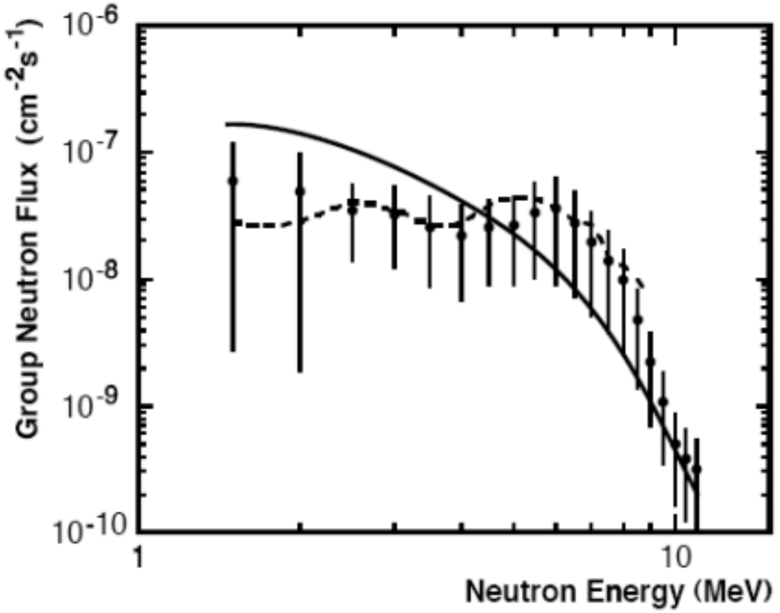
From 2017 slides…

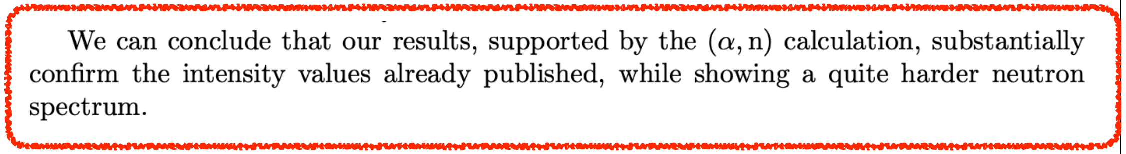
Comments on proton recoil technique results

- Proton recoil technique is similar to nuclear recoil
- >1 MeV energy threshold due to the need for PSD ER/NR discrimination
- Large contamination of alphas from internal radioactivity
- For this reasons, pure p recoils spectrum CAN NOT BE USED
- Scintillators surrounded by Cd foils: neutrons thermalised and detected in coincidence with photons (detected as ERs) from capture on Cd (e+p sample)
- Energy calibration with internal alpha particles but had to estimate the contaminants from simulation (unable to resolve alpha lines)
- All of these significantly complicates and introduces large uncertainties the unfolding of the actual neutron spectrum



E interval (MeV)	Fast Neutron Flux (10^{-6}cm^{-2}s^{-1})					
	Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
0.1 – 1			0.54±0.01 (0.53±0.08)			2.56±0.27
1 – 2.5		0.14±0.12				
2.5 – 3		0.13±0.04	0.27±0.14 (0.18±0.04)	3.0±0.8	0.09±0.06	
3 – 5	0.78±0.3					
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)			
10 – 15		$(0.4 \pm 0.4) \cdot 10^{-3}$	$(0.6 \pm 0.2) \cdot 10^{-3}$ $((0.7 \pm 0.2) \cdot 10^{-3})$			
15 – 25			$(0.5 \pm 0.3) \cdot 10^{-6}$ $((0.1 \pm 0.3) \cdot 10^{-6})$			

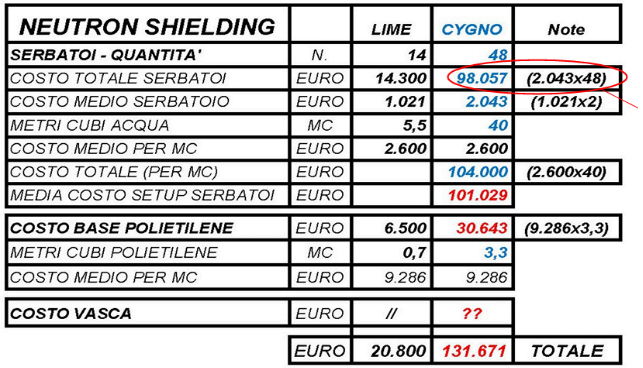




We can conclude that our results, supported by the (α, n) calculation, substantially confirm the intensity values already published, while showing a quite harder neutron spectrum.

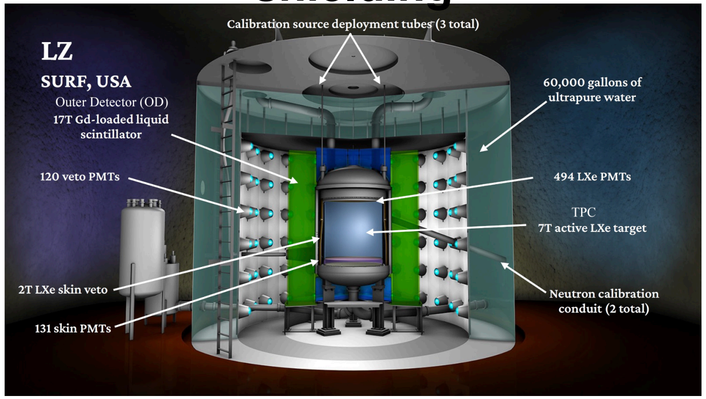
An harder neutron spectrum requires LESS neutron shielding

130k EUROs for CYGNO-04
40 cm H_2O neutron shielding

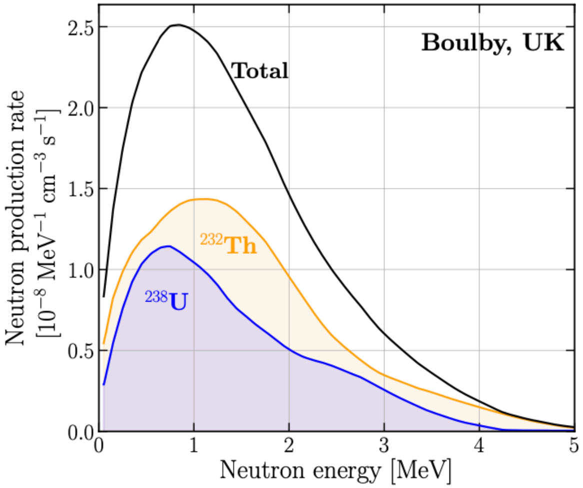


NEUTRON SHIELDING		LIME	CYGNO	Note
SERBATOI - QUANTITA'	N.	14	48	
COSTO TOTALE SERBATOI	EURO	14.300	98.057	(2.043x48)
COSTO MEDIO SERBATOIO	EURO	1.021	2.043	(1.021x2)
METRI CUBI ACQUA	MC	5,5	40	
COSTO MEDIO PER MC	EURO	2.600	2.600	
COSTO TOTALE (PER MC)	EURO		104.000	(2.600x40)
MEDIA COSTO SETUP SERBATOI	EURO		101.029	
COSTO BASE POLIETILENE	EURO	6.500	30.643	(9.286x3,3)
METRI CUBI POLIETILENE	MC	0,7	3,3	
COSTO MEDIO PER MC	EURO	9.286	9.286	
COSTO VASCA	EURO	//	??	
	EURO	20.800	131.671	TOTALE

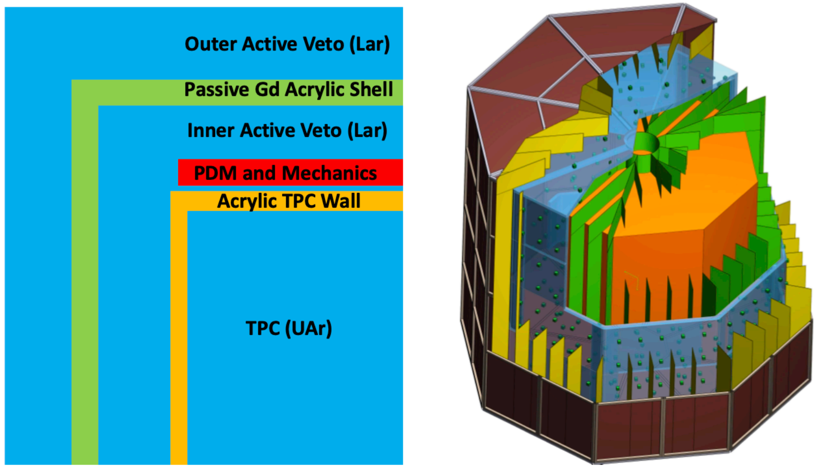
17 Ton of Gadolinium for LZ neutron shielding



75 cm H_2O neutron shielding for 1000 m^3 CYGNUS detector



40 cm AAr + 10 cm Gd + 40 cm AAr from MC simulation for DarkSide20k



Neutron shielding is optimised starting from knowledge of neutron flux spectrum as from before

What do we know from Flamina's thesis

Events in LIME

External backgrounds

10 cm of Cu	Gammas	Neutrons	
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
0-1 keV	0.025 ± 0.005	1970 ± 40	210 ± 10
1-20 keV	0.47 ± 0.02	1360 ± 30	550 ± 20
20-50 keV	0.5 ± 0.02	1270 ± 30	200 ± 10
50-3000 keV	0.99 ± 0.03	2930 ± 50	180 ± 10

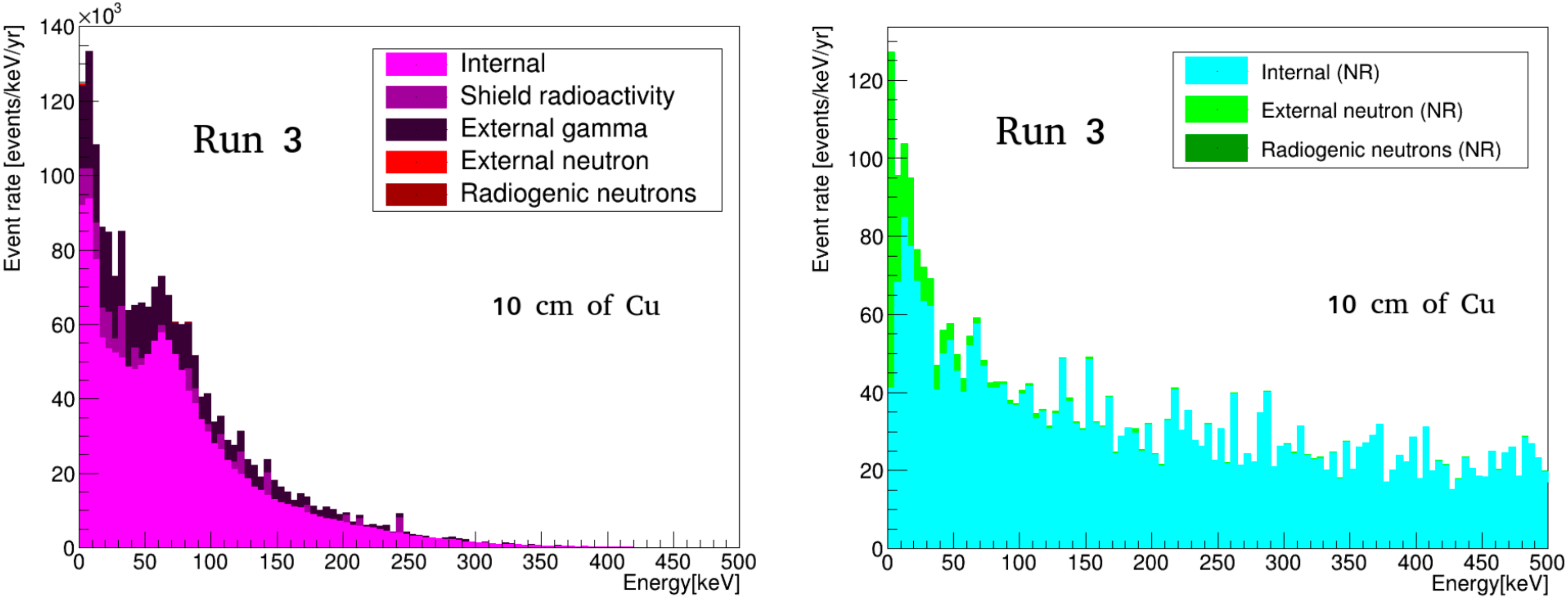
Internal backgrounds

Energy range [keV]	ER+NR [10^5 counts/yr]	NR [counts/yr]
0-1 keV	0.87 ± 0.01	10 ± 2
1-20 keV	15.35 ± 0.06	1360 ± 90
20-50 keV	14.95 ± 0.06	1690 ± 90
50-3000 keV	43.1 ± 0.1	76000 ± 450

About 32 signal events/month above 20 keV
About 200 signal events in 6 months > 20 keV

ER background to be rejected with PID
Internal NR to be reject with fiducialization

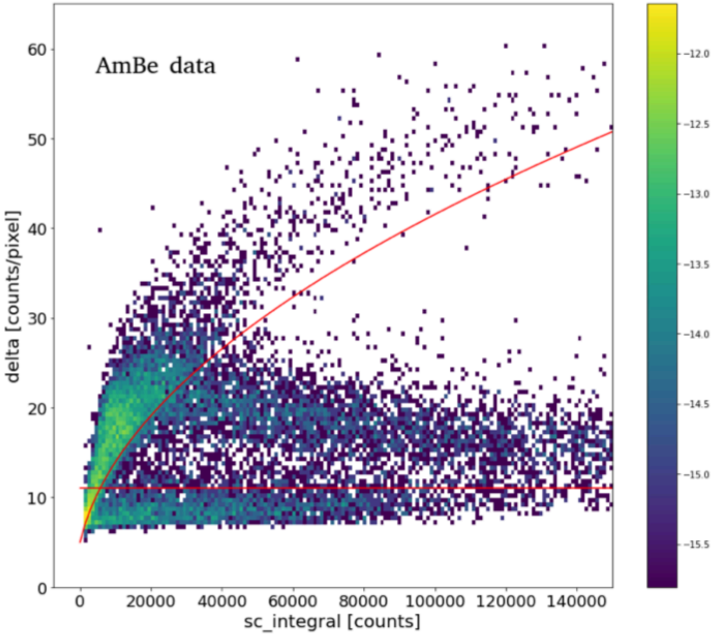
External backgrounds

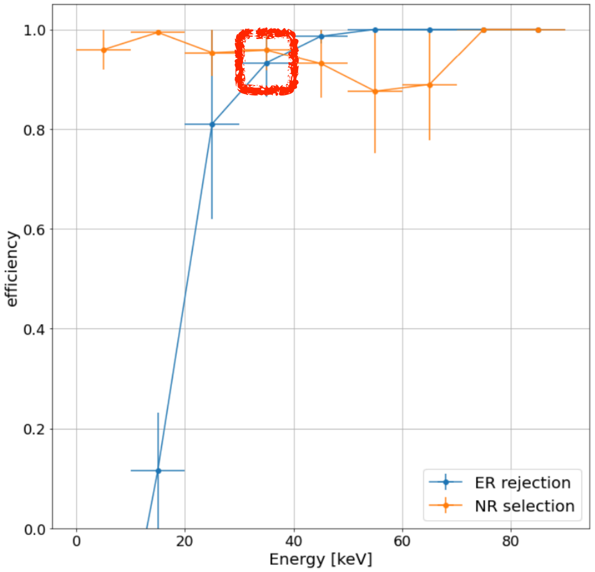


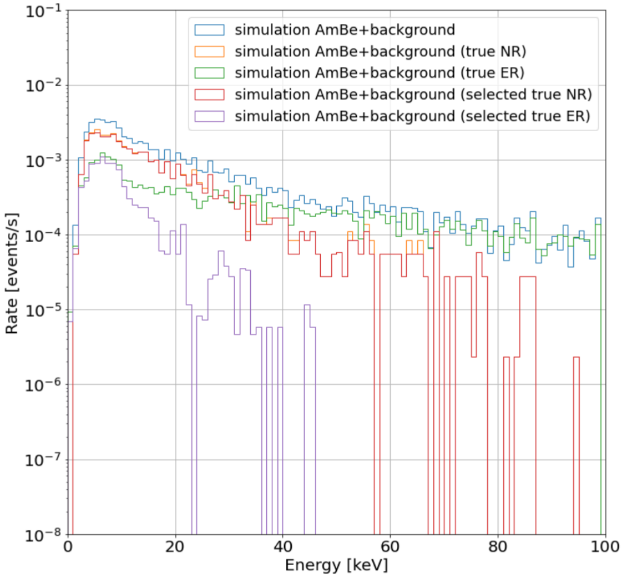
Shield	Energy range [keV]	Gammas	Neutrons	
		ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
10 cm Cu	0-1 keV	0.07 ± 0.01	1240 ± 30	190 ± 10
	1-20 keV	0.90 ± 0.04	720 ± 20	450 ± 20
	20-50 keV	1.14 ± 0.04	510 ± 10	190 ± 10
	50-3000 keV	2.72 ± 0.06	1030 ± 20	280 ± 10

Events from external backgrounds

ER backgrounds rejection and NR identification in AmBe data



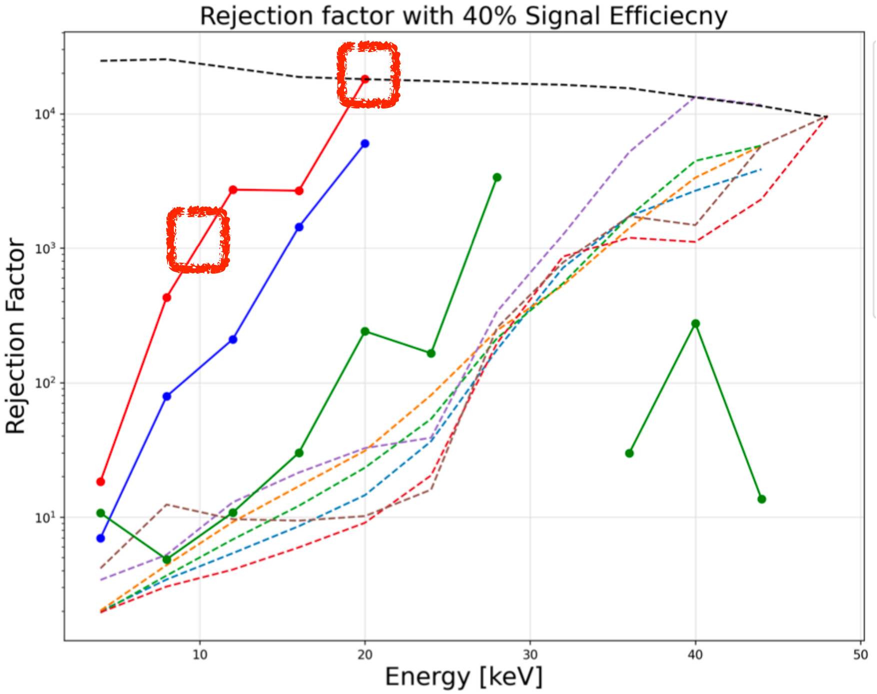




Simple cuts on track energy density and slimness yields good **ER rejection** efficiency (>80% at 20 keV)

Full background discrimination qith 100% signal efficiency (from MC simulation) achieved on AmBe data at ± 30 keV

ER rejection with ML



10^4 rejection/keV @ 20 keV
likely 10^5 rejection/keV @ 25 keV

Background free sample appears achievable at >20-25 keV

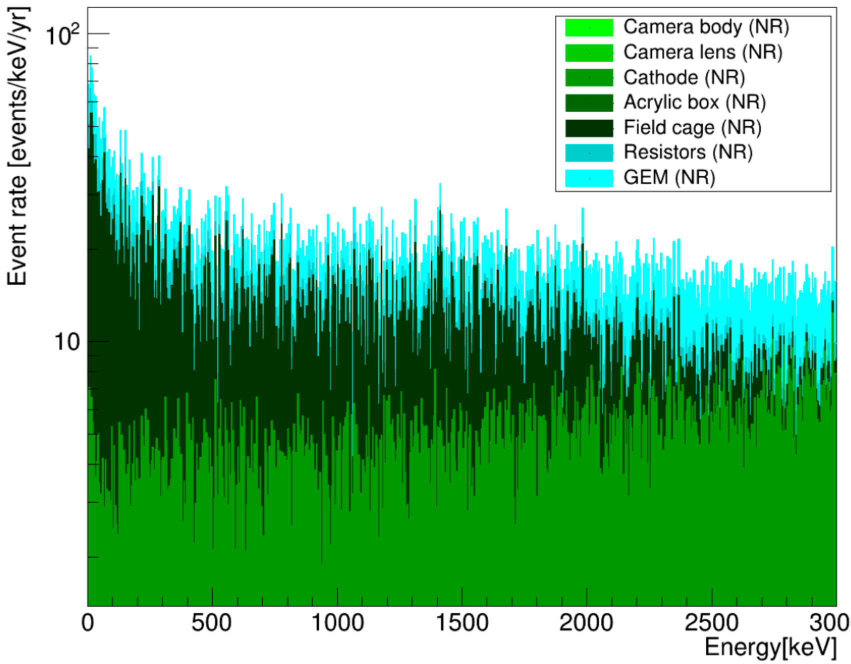
assuming flat spectrum…

	External	Internal	Total	Total
10 cm of Cu	Gammas		[10^6 counts/year]	[10^6 counts/year/keV]
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [10^5 counts/yr]		
0-1 keV	0.025 ± 0.005	0.87 ± 0.01		
1-20 keV	0.47 ± 0.02	15.35 ± 0.06	± 2	± 0.1
20-50 keV	0.5 ± 0.02	14.95 ± 0.06	± 2	± 0.07
50-3000 keV	0.99 ± 0.03	43.1 ± 0.1	± 5	± 0.002

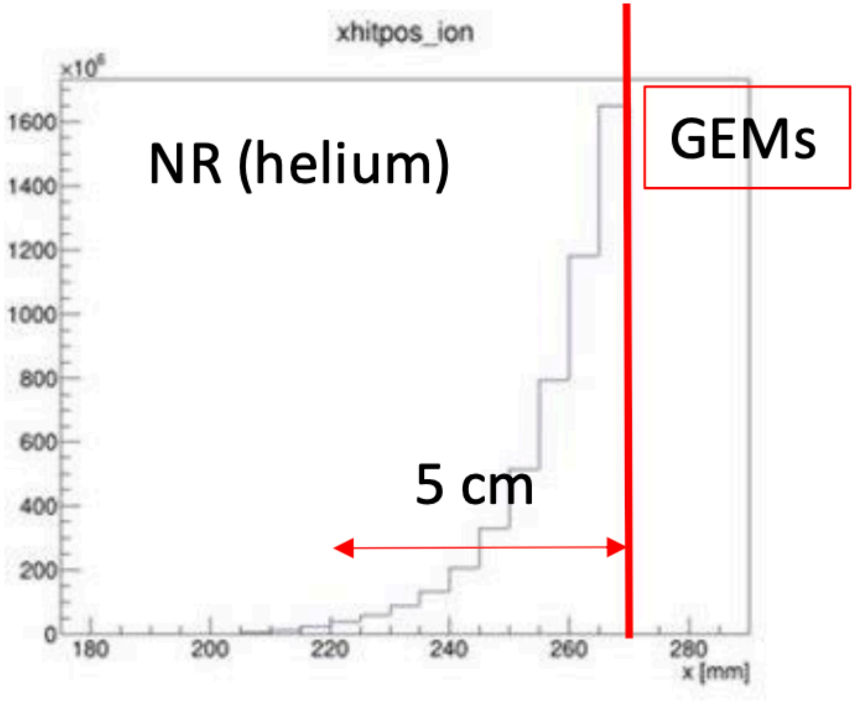
Pessimistic

Internal NR background

Mainly alphas



Worse case (other materials "contain" better NRs)



	cathode	field cage	resistors	GEMs	total
0-1 keV	3 ± 2	1.5 ± 0.5	2 ± 1	3.7 ± 0.3	10 ± 2
1-20 keV	120 ± 10	770 ± 90	150 ± 20	319 ± 3	1360 ± 90
20-50 keV	130 ± 10	890 ± 90	210 ± 20	457 ± 4	1690 ± 90
50-3000 keV	22100 ± 200	22700 ± 400	6590 ± 80	24600 ± 30	76000 ± 450

"Fair" fiducialisation could be enough to reject these
i.e. need to know only if close to GEM or cathode

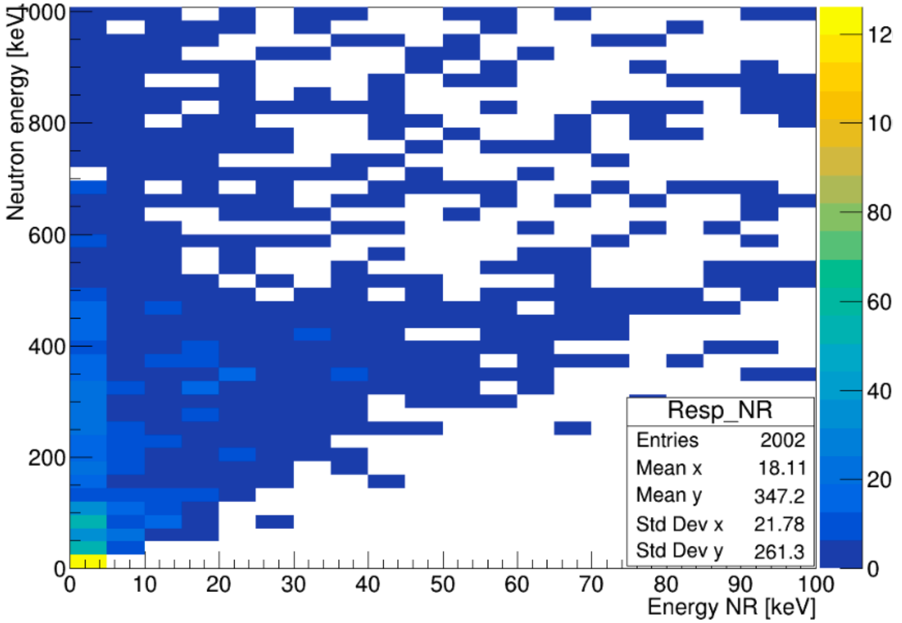
Unfolding technique

$$N(E_{NR}) = \int R(E_{NR}, E_n)\Phi(E_n)dE_n$$

NR spectrum
(measured)

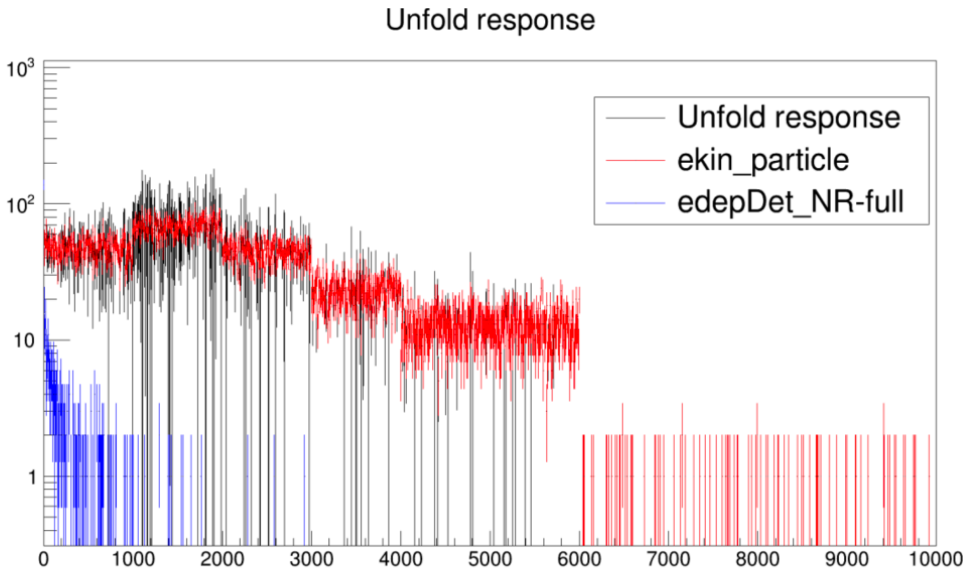
Detector response
(from MC
simulations)

Neutron spectrum
(true distribution)



An AmBe calibration in Run5 would be paramount, and possibly sooner than later in order to have time to throughly analyse it during Run5

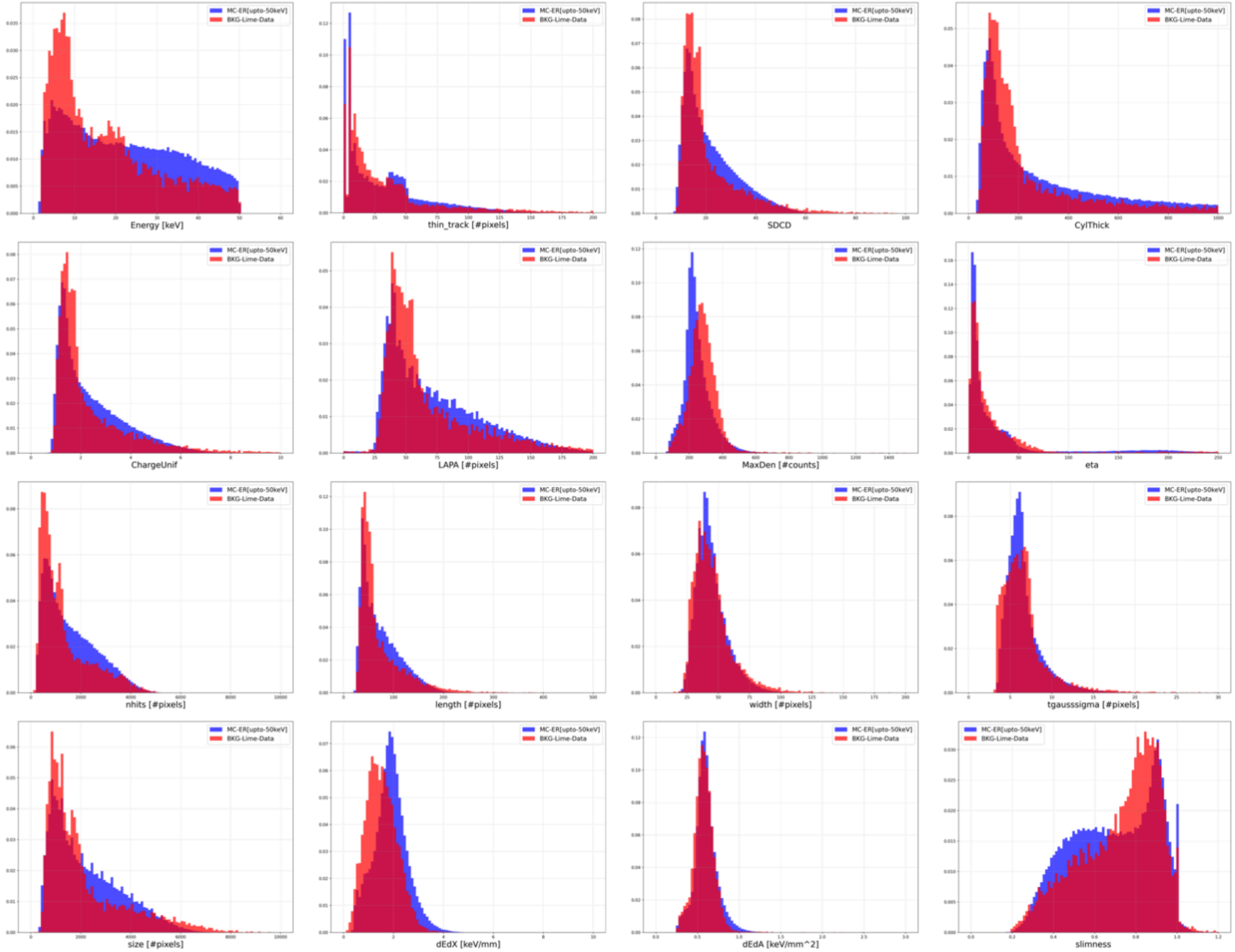
- Detector response simulation exists
- Preliminary unfolding algorithm developed by Flaminia
- Will test the algortihm with different input spectra/input statistic to assess the capability of precision of the measurement as a function of exposure



NOTE: 440 V with 800 V/cm LIME simulation

How much can we trust detector response simulation?

- Standard LIME operating configuration (i.e. high gain)
- Study to be repeated on low gain (everything ready, possibly need to increase MC statistics)
- ER data (in red) compared to ER simulated (in blue)
- 16 different shape variables
- Pretty satisfactory agreement



NOTE: 440 V with 800 V/cm LIME simulation

How much can we trust detector response simulation?

- Standard LIME operating configuration (i.e. high gain)
- In order to repeat this comparison for low gain, AmBe calibration needed
- NR data (in red) compared to NR simulated (in blue)
- 16 different shape variables
- Fair agreement: mismatch likely due to saturation, which was never optimised for NR recoils
- Agreement should improve for low gain data