SILICON PHOTOMULTIPLIER READOUT OF A SCINTILLATING NOBLE GAS DETECTOR FOR HOMELAND SECURITY

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Advancement in Nuclear Instrumentation Measurement Methods and their Applications

ANIMMA, Marseille, June 26, 2013

INFIERI, Oxford, July 10-16, 2013

- Valery Chmill - Insubria
- Sasha Martemiyanov - Insubria
- Romualdo Santoro - Insubria
- Giovanna Davatz - ARKTIS
- Ulisse Gendotti - ARKTIS
- Rico Chandra - ARKTIS

activities & results presented here are part of

modes SNM

a project approved by the European Commission within the FrameworkProgram 6 call SEC-2011.1.5-1, having as a main goal the

Development of detection capabilities of difficult to detect radioactive sources and nuclear materials

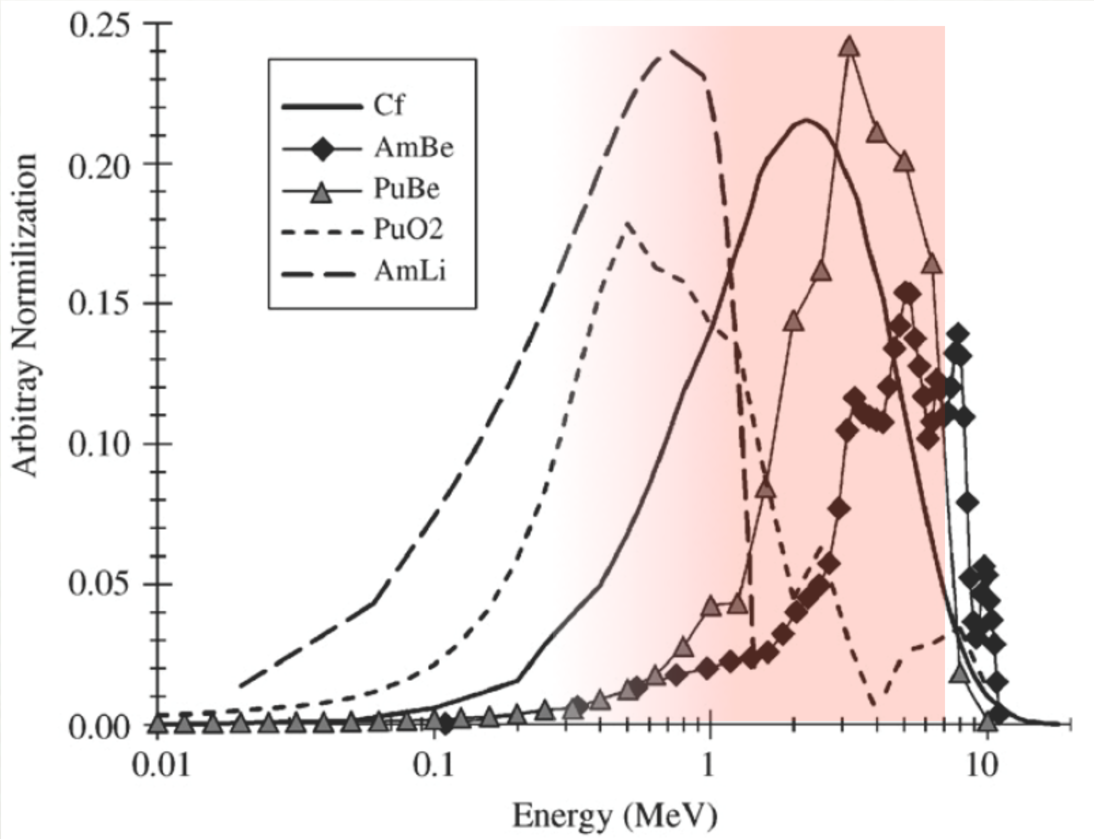
namely solutions for the improvement of detection and enhancement of the portability and mobility of detection solutions, which could be used also by emergency responders in the field or for the detection of a radiation source in large crowds.

Proposed solutions are expected to:
1. be easy to relocate
2. end-user oriented
3. implement detection and localization of sources
4. improve the detection capability of "difficult sources"
5. integrate the identification of the source

the focus is on SPECIAL NUCLEAR MATERIAL (SNM), defined by U.S. Nuclear Regulatory Commission as the primary ingredients of nuclear explosives, namely:

- Plutonium (^{239}Pu)
- ^{233}U or U enriched in the ^{233}U and ^{235}U isotopes (Highly Enriched Uranium, HEU)

The capability of detecting FAST neutrons is essential in this game ⇒



and the possibility to do it without thermalization enhances the discrimination power against natural bckg (from cps to counts/ hour as you move away from thermal n).

Moreover:

- γ detection with spectroscopic capabilites is essential for HEU
- n detection shall not be fooled by the presence of γ, otherwise masking through NORM (Naturally Occurring Radioactive Material) or medical/ industrial sources the SNM

MODULAR DETECTION SYSTEM FOR SPECIAL NUCLEAR MATERIAL

is a consortium

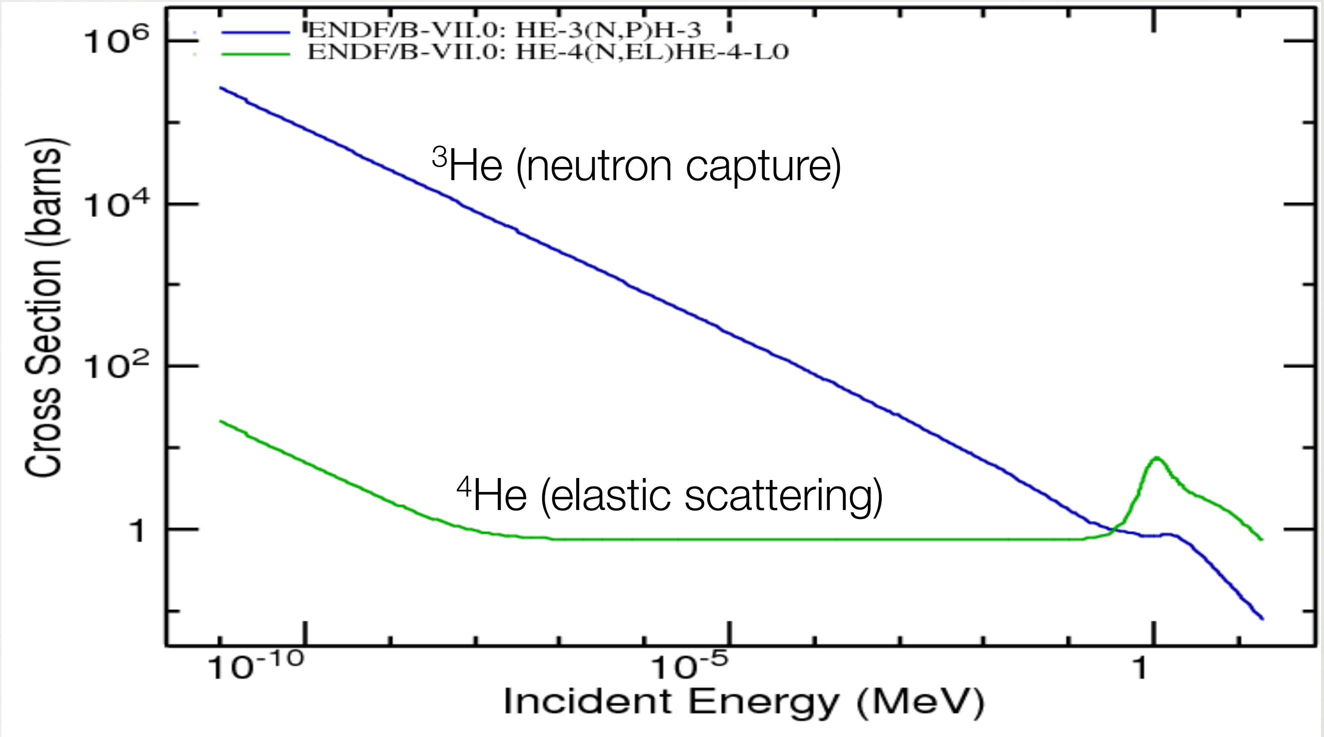
U. Padova, coordinator

which submitted a proposal based on the ARKTIS technology.

Apparently we were good enough, since the project was retained for funding....

Basics of the ARKTIS technology*; 3 key features of ^{4}He:

1. a reasonably high cross section for n elastic scattering



	Z	Photons/ MeV	Peak emission
^{4}He	2	15'000	70 nm
^{40}Ar	18	40'000	128 nm
^{131}Xe	54	46'000	175 nm
NaI(Tl)	11,53	40'000	415 nm

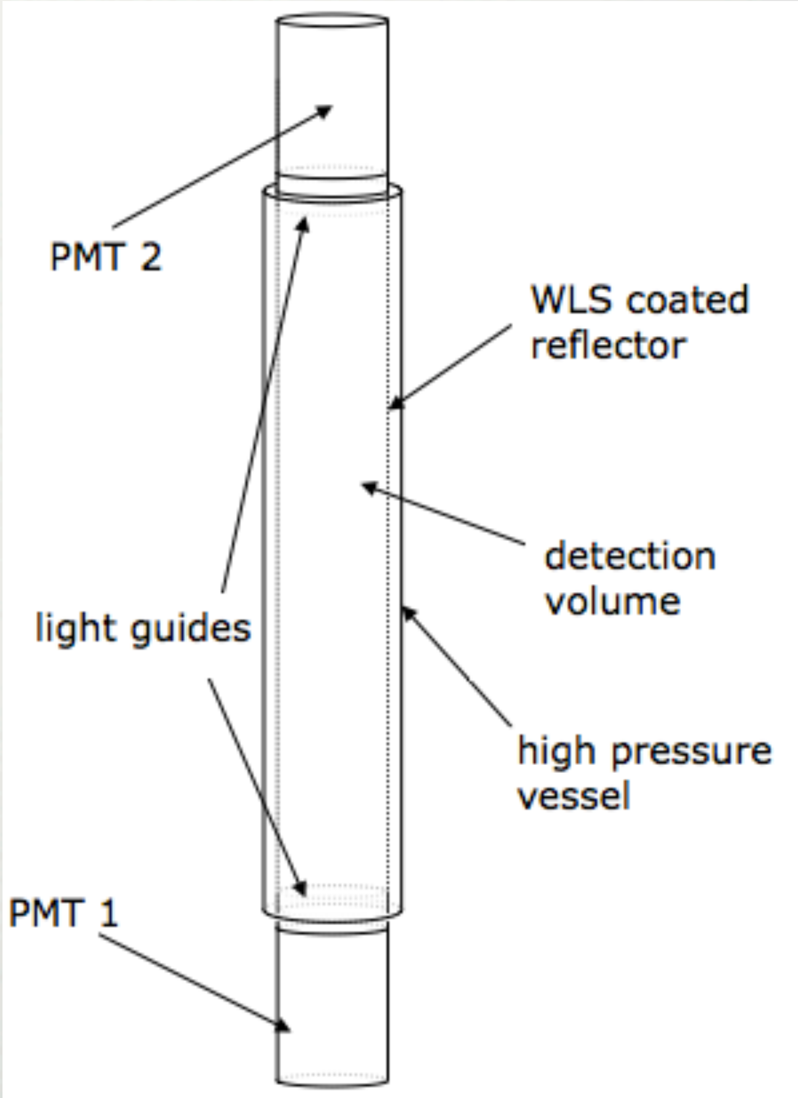
2. good scintillating properties

3. Two component decays, with τ at the ns and μs levels

* R. Chandra et al., 2012 JINST 7 C03035

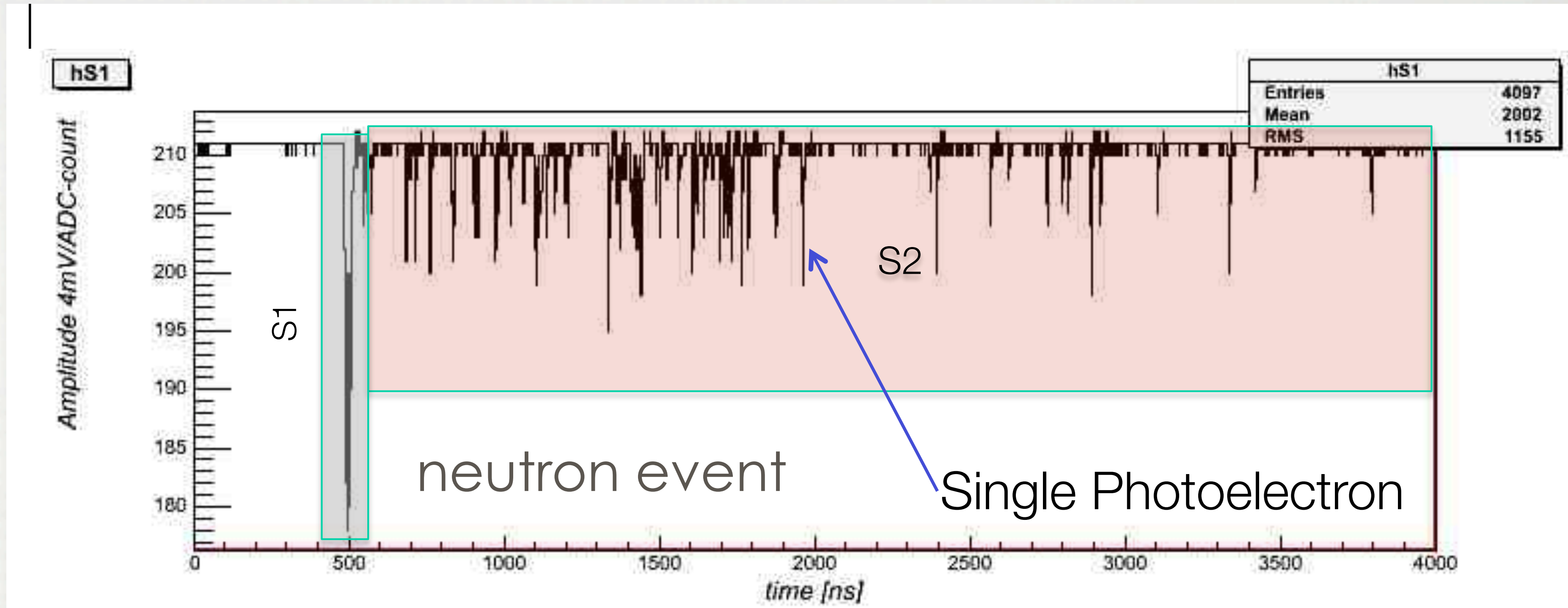
The ARKTIS baseline detector: The Tube

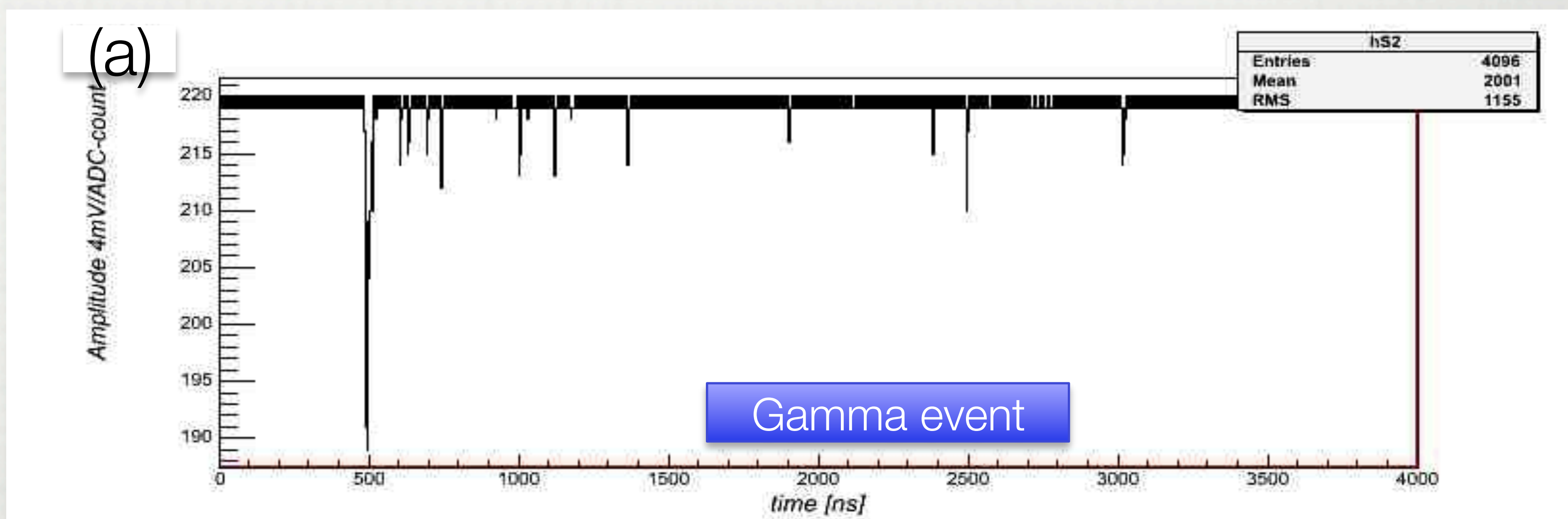
- 2" diameter x 47 cm sensitive length
- 180 bar ^4He
- sealed system maintaining gas purity



Ultimate performance:
5% efficiency over 125 cm^2 for fission neutron while rejecting ^{60}Co rates ~1 mSv/hr to better than 0.03 cps

Neutron/γ discrimination is based on the difference between the fast/slow component of the scintillation light:





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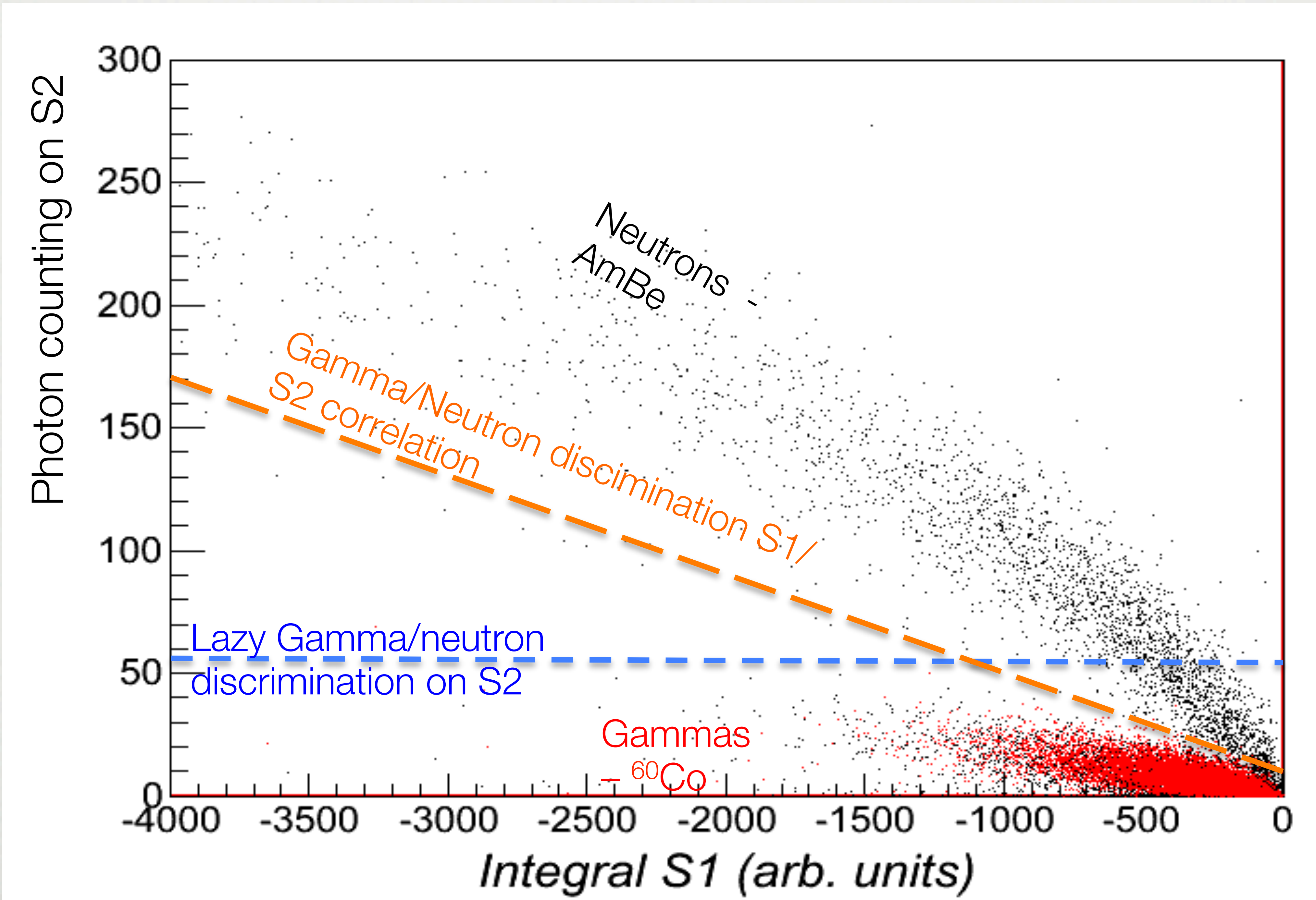


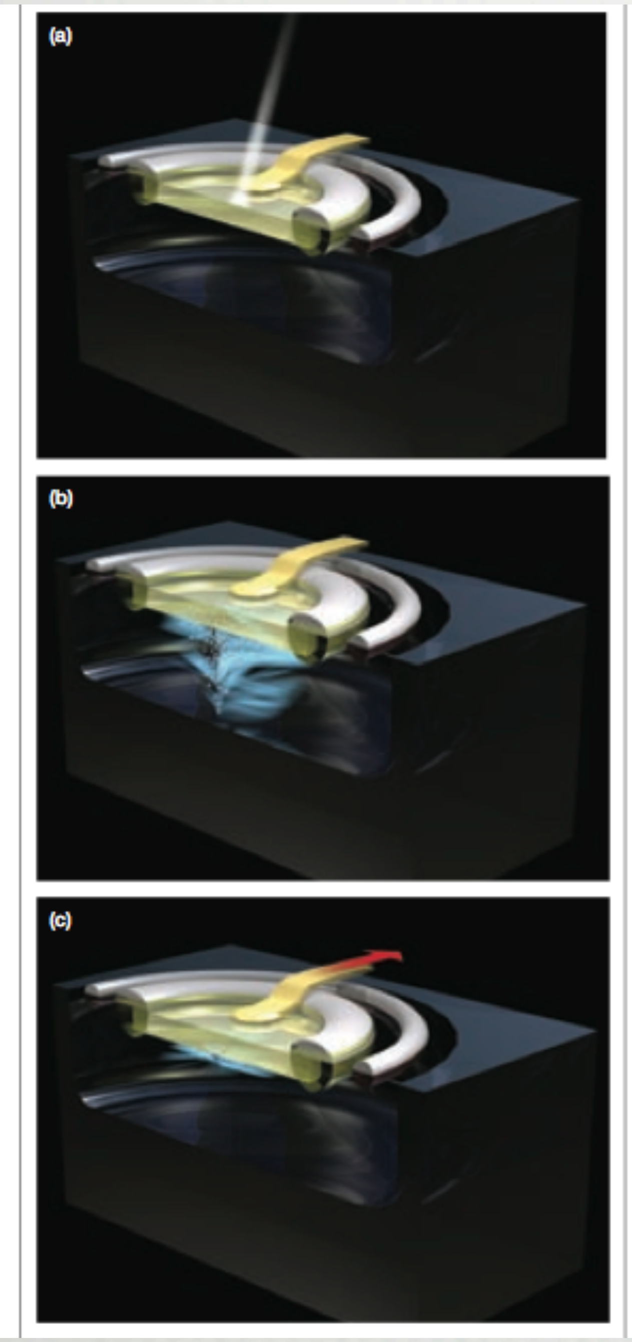
One Tube fits all; what is envisaged within MODES-SNM:

	State of the art	This proposal	Comment
Thermal neutron detection	He-3 proportional counter (until 2009) Replacement technology candidates under evaluation	Noble gas scintillation detector lined with neutron capturing material such as Gd	He-3 proportional counters have become obsolete due to the high cost of the filling gas. This proposal will develop a novel thermal neutron detector based on Arktis technology
Fast neutron detection (new concept, see below)	No such detectors included in current radiological screening systems	Pressurized He-4 scintillation detector The Original Tube	Detection of fast neutrons allows larger standoff distances and increased sensitivity for highly shielded SNM [4]
Gamma detection	PVT or NaI(Tl)	Pressurized Xe scintillation detector	Improved energy resolution, less temperature dependence, lower cost, better ruggedness [13]

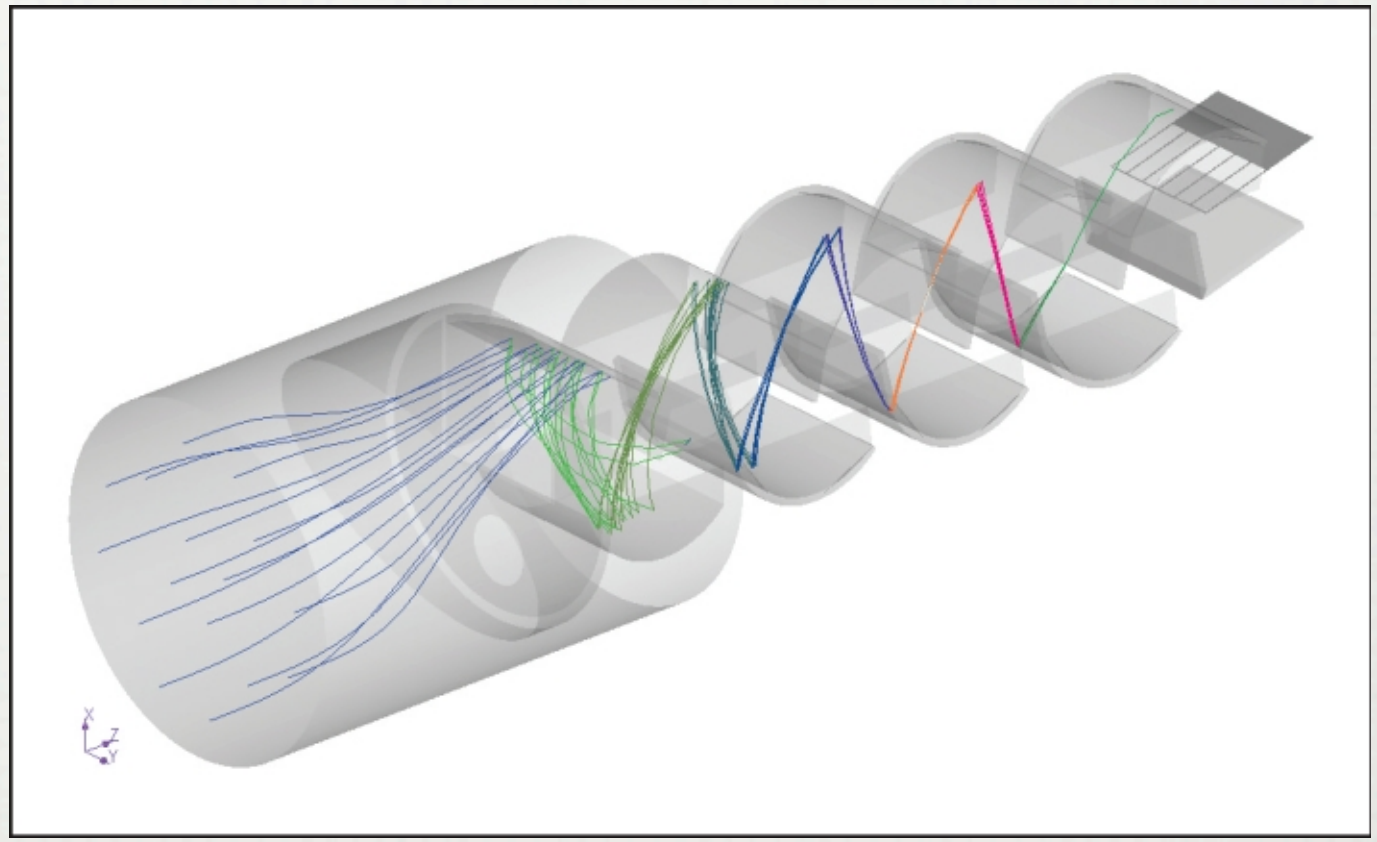
+ optimization of the design, in terms of mechanics, services AND PHOTOSENSOR

STEPPING IN THE DIGITAL ERA

(with a bit of care...)



move away from the good old PMT technology...



...and rely on charge multiplication by impact ionization in a matrix of junctions operated beyond the breakdown voltage

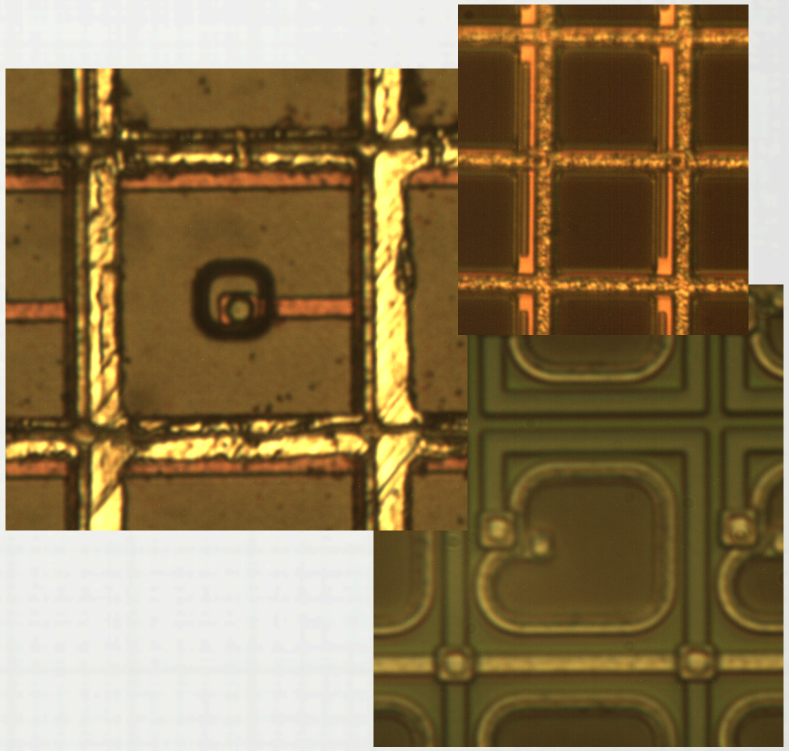
Photon absorption and avalanche ignition in a Single Photon Avalanche Photodiode: an artist's view

E. Charbon & S. Donati, OPN Optics & Photonics News, February 2010

SILICON PHOTO-MULTIPLIERS

genuine *Photon Number Resolving Detectors...*

SiPM = High density (~10^3/mm^2) matrix of diodes with a common output, working in Geiger-Müller regime



advantages over traditional photo-detectors:

- high sensitivity (single photon discrimination)
- high speed (T_{rise}~ 1 ns; T_{fall} ~ 50 ns)
- compactness, robustness,
- low operating voltage and power consumption, low cost

Producer	Area (mm^2)	Pixel size (μm)	No. cells	$V_{working}$	DCR	GAIN	PDE (%) (peak λ)
SensL	3 x 3	20 x 20	8640	30	~4 MHz	~10^6	10
Hamamatsu	1 x 1	100 x 100	100	70	~0.4 MHz	~2 x 10^6	65
CPTA	1 x 1	30 x 30	500	24	~3 MHz	~10^6	30
Possibly the key players a few years ago...							

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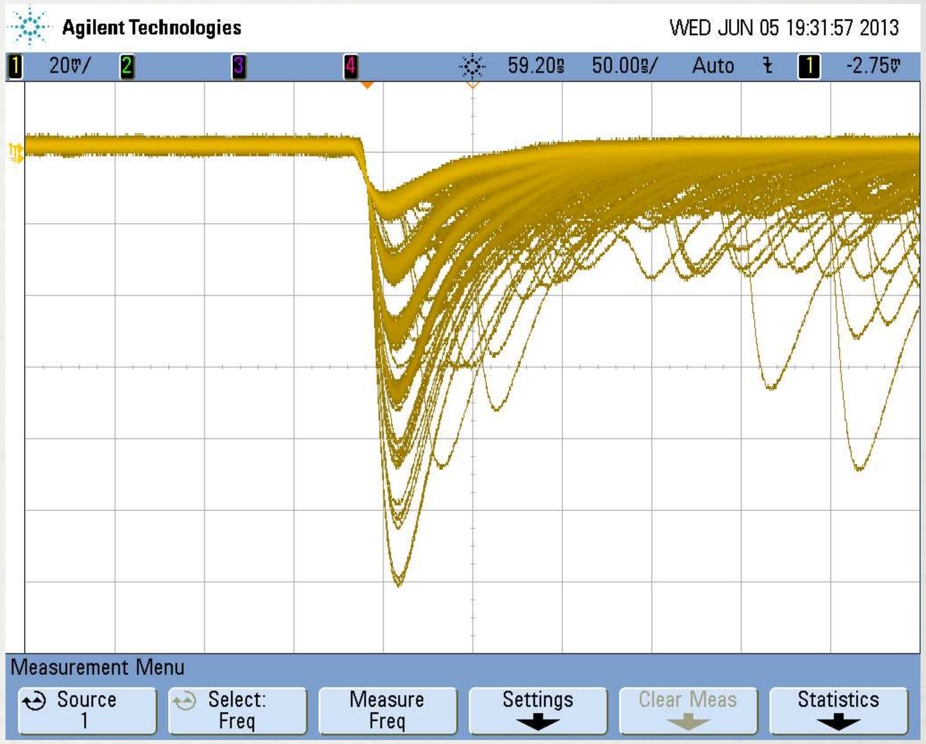

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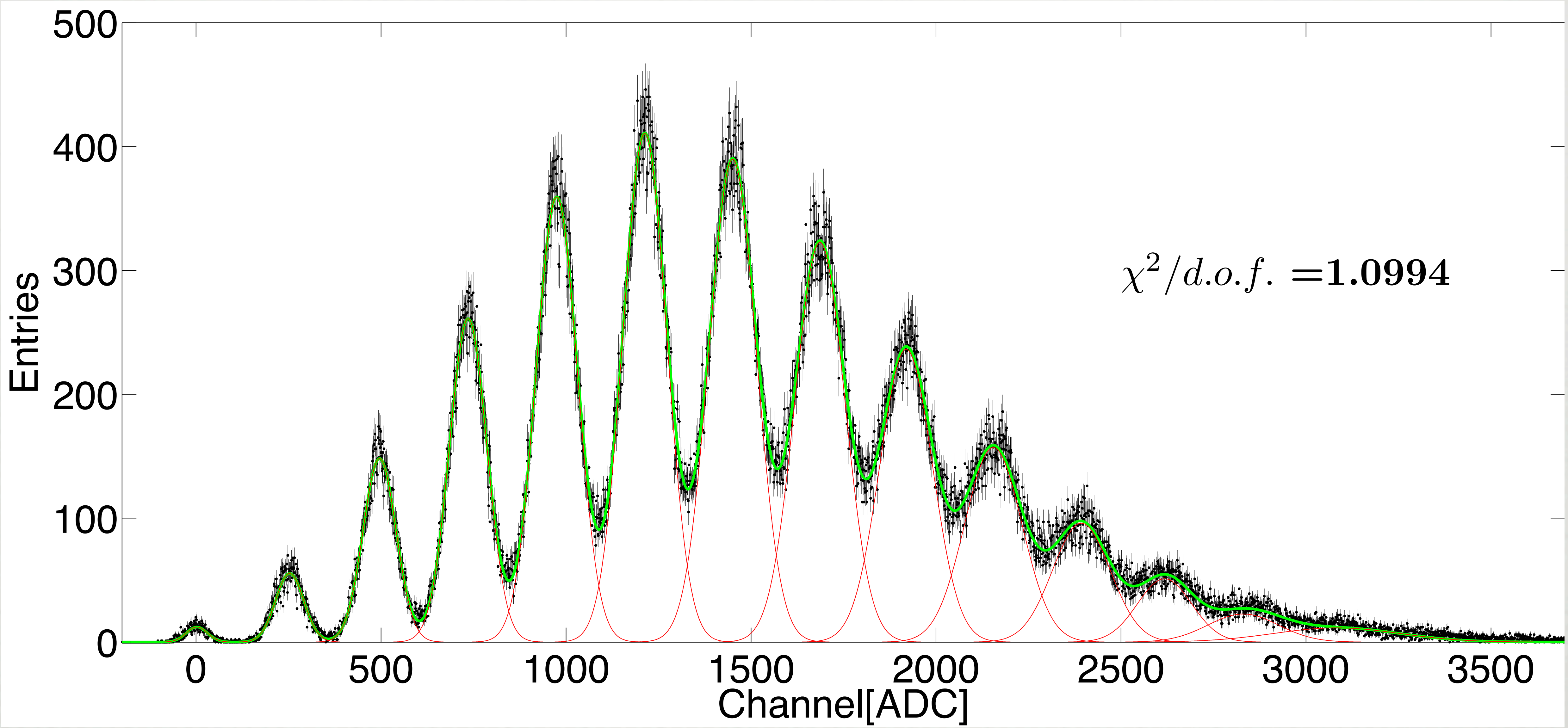
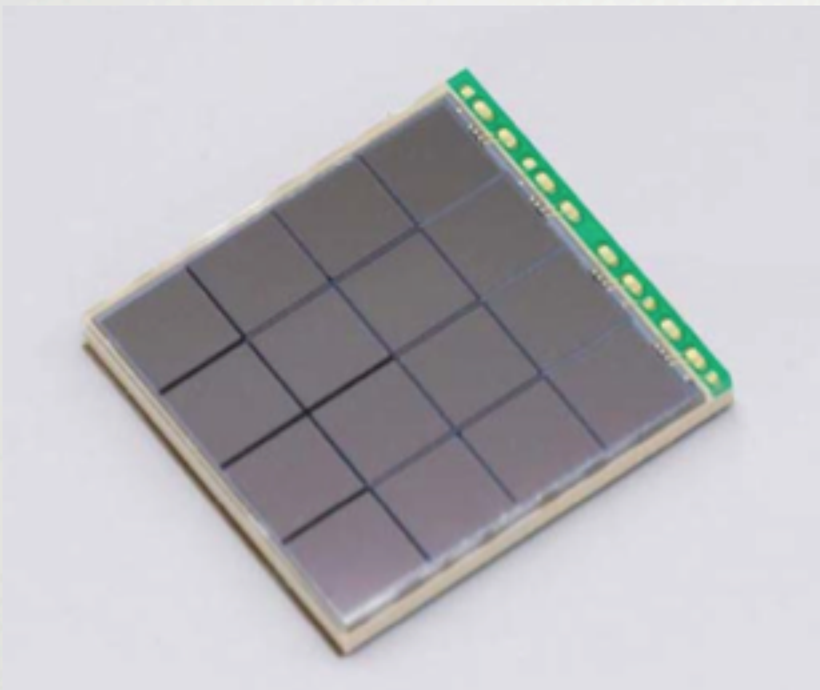
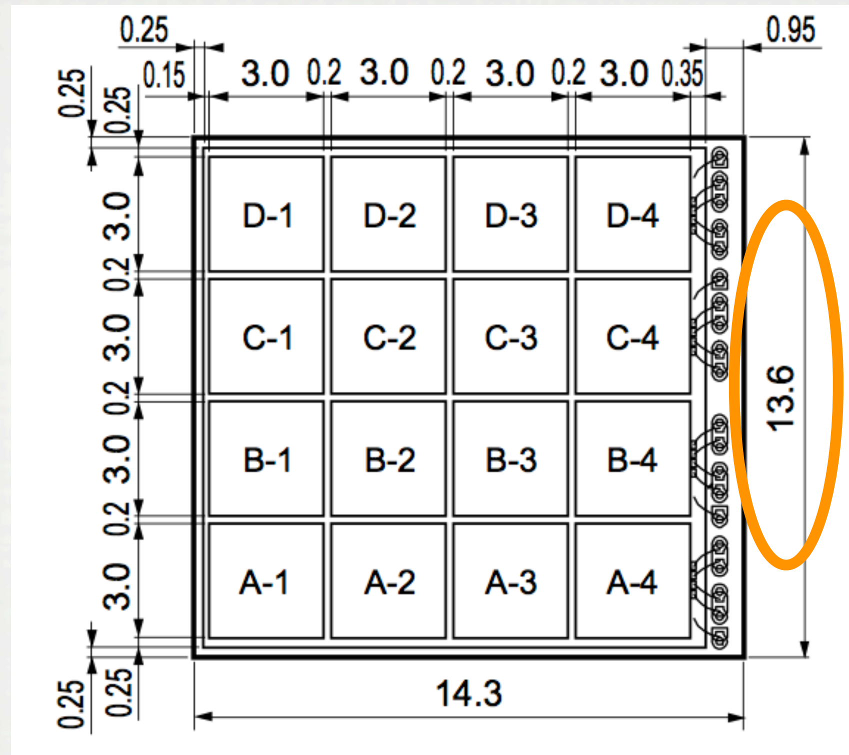


Photo-electron spectrum of the light emitted by a LED

GROWING UP...





The S11829-3344MF
monolithic array of SiPM units

■Specifications

Parameter	Condition	Value	Unit
Number of elements		16 (4 x 4)	elements
Effective active area / channel		3 x 3	mm
Pixel pitch		50	µm
Number of pixels / channel		3600	-
Number of pixels / device		57600	-
Fill factor		61.5	%
Photon detection efficiency *	λ=440 nm	50	%
Dark current / channel	per channel	3	µA
Terminal capacitance / channel		320	pF
Gain		7.5×10^5	-

* Includes cross-talk and after-pulse

The availability of large area SiPM is opening up interesting perspectives for *The Tube* upgrade:

Benefits / Risks

arktis
RADIATION DETECTORS

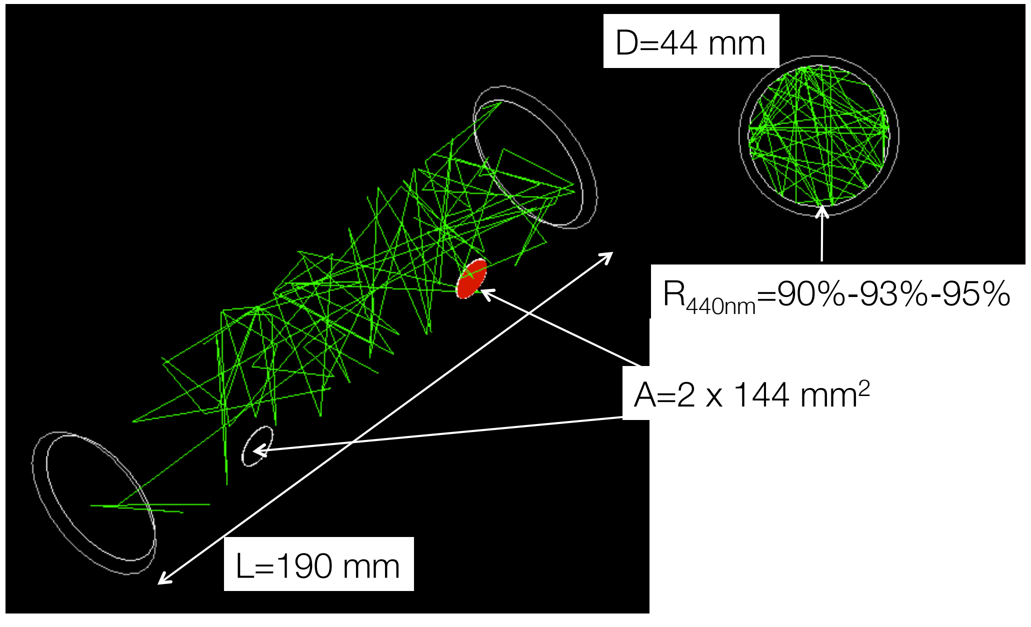
Benefits:

- Improved light collection and uniformity
- No need for optical windows
- Improved robustness
- Compactness

Risks:

- Fast gas purity degradation (material compatibility)
- Need feed throughs
- Operation of SiPM in HP gas: functionality

Preliminary analysis by ARKTIS:



Simplified model that allows to study the light collection:

- Short detector
- Study the amount of 440 nm light detected vs produced
- No WLS simulated (no WLS efficiency included, but required that optical photons are reflected at least once)
- No cabling etc.
- End-cap are reflective
- 90% to 95 % internal tube reflectivity
- Active area of the MPPC (144 mm^2) – Modeled as circle

Reflectivity	MPPC hits (actually photons)
95 %	17%
93 %	12%
90 %	8%

⇒ 240-480 photons @100 KeV deposited energy

Step 1: THE QUEST FOR SENSITIVITY (a lab activity)

provided the boundary conditions from the simulation, the system was initially characterized in terms of

- minimum detectable light
- sensitivity (i.e. S/N or capability to discriminate an “event” against noise)

Basic equipment (1/2), for signal amplification & digitization

+

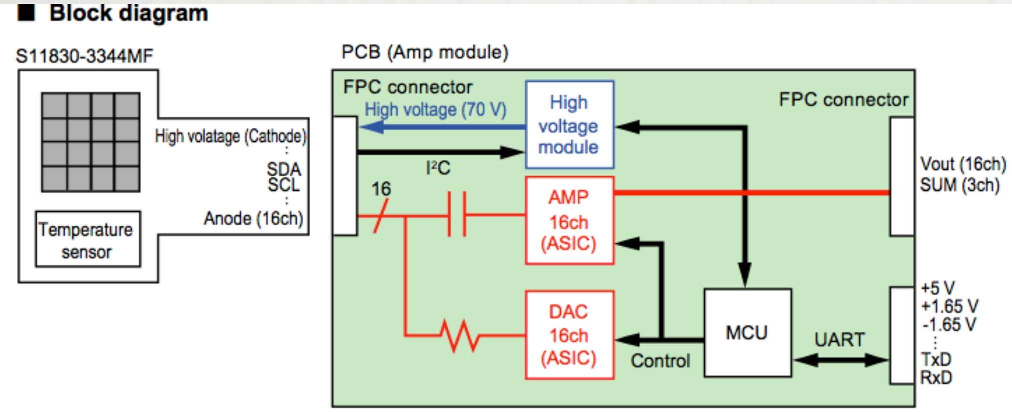
+

- The CAEN V720 Digitizer

- the CAEN SP5600 Power supply and amplification unit

- the HAMAMATSU front-end:

■ Block diagram



■ Specifications

Parameter		Specification
MPPC		S11830-3344MF
Preamp		16ch preamp array
Bias offset		16ch DAC array
High voltage power supply module	Bias voltage	70 V typ.
	Compensate temperature characteristic	Digital processing
	External control	UART
Dimension		30 × 80 mm + S11830-3344MF
Power		Power for analog circuitry: ±1.65 V Power for digital circuitry: +5.0 V

SP5600 Main characteristics:

- 2 channels
- 3 stage amplification
[500 MHz bandwidth, gain up to ~ 50 db]
- Leading edge discri &coincidence

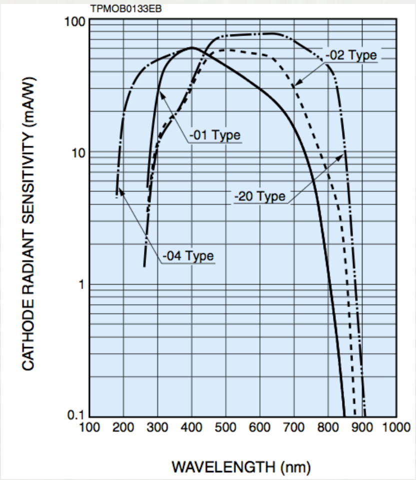
V720:

- sampling rate 250 Ms/s
- 12 bit digitization
- 2 channels

Basic equipment (2/2), providing a “standard candle” for the calibration of the response to light

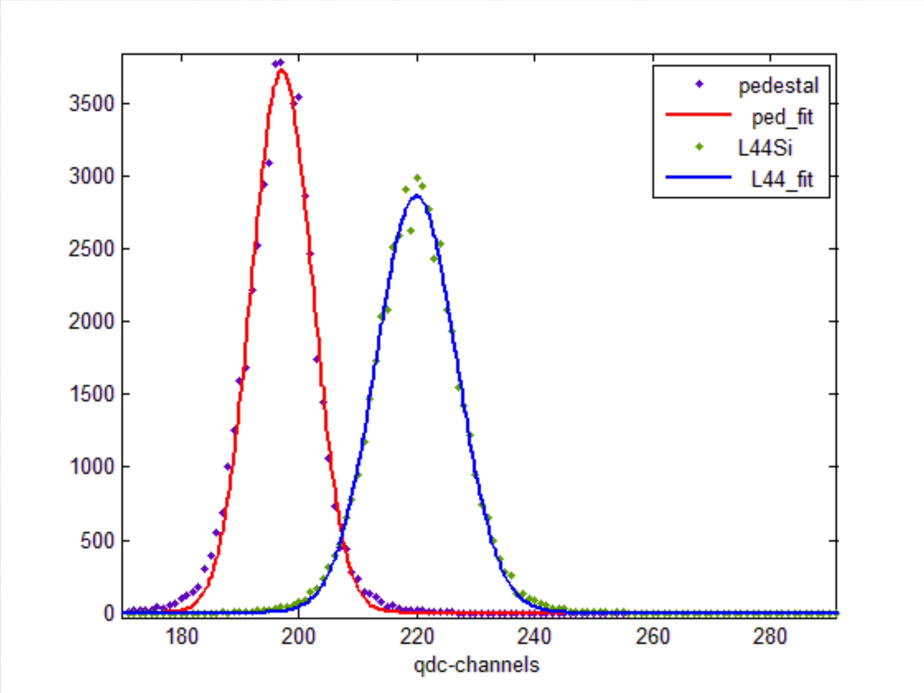
- PicoQuant PDL 800B LED driver

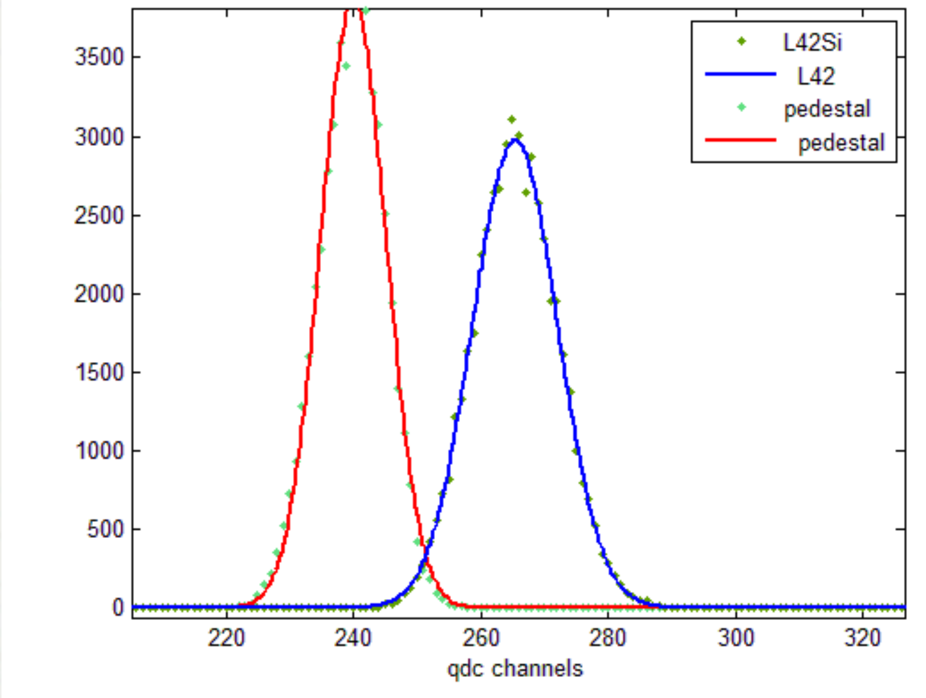
- HPK H5783P PMT module



- V792N QDC
  - 16 channels
  - 12 bits
  - 400 pC range
  - granularity: 100 fC/(ADC Channel)

Response of the matrix to a known light pulse in charge integration mode:





25 °C, 250 photons

21.6 °C, 60 photons

⇐ a combined effect of gain drift & noise increase

"sensitivity" well above what is expected according to the simulation, also at "non optimal" temperatures

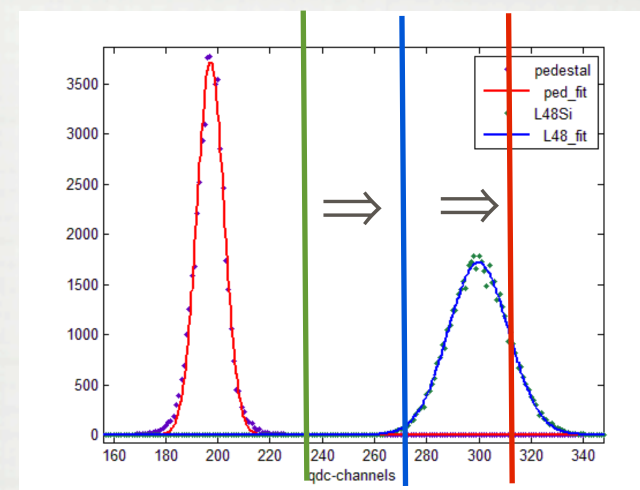
Reflectivity	MPPC hits (actually photons)
95 %	17%
93 %	12%
90 %	8%

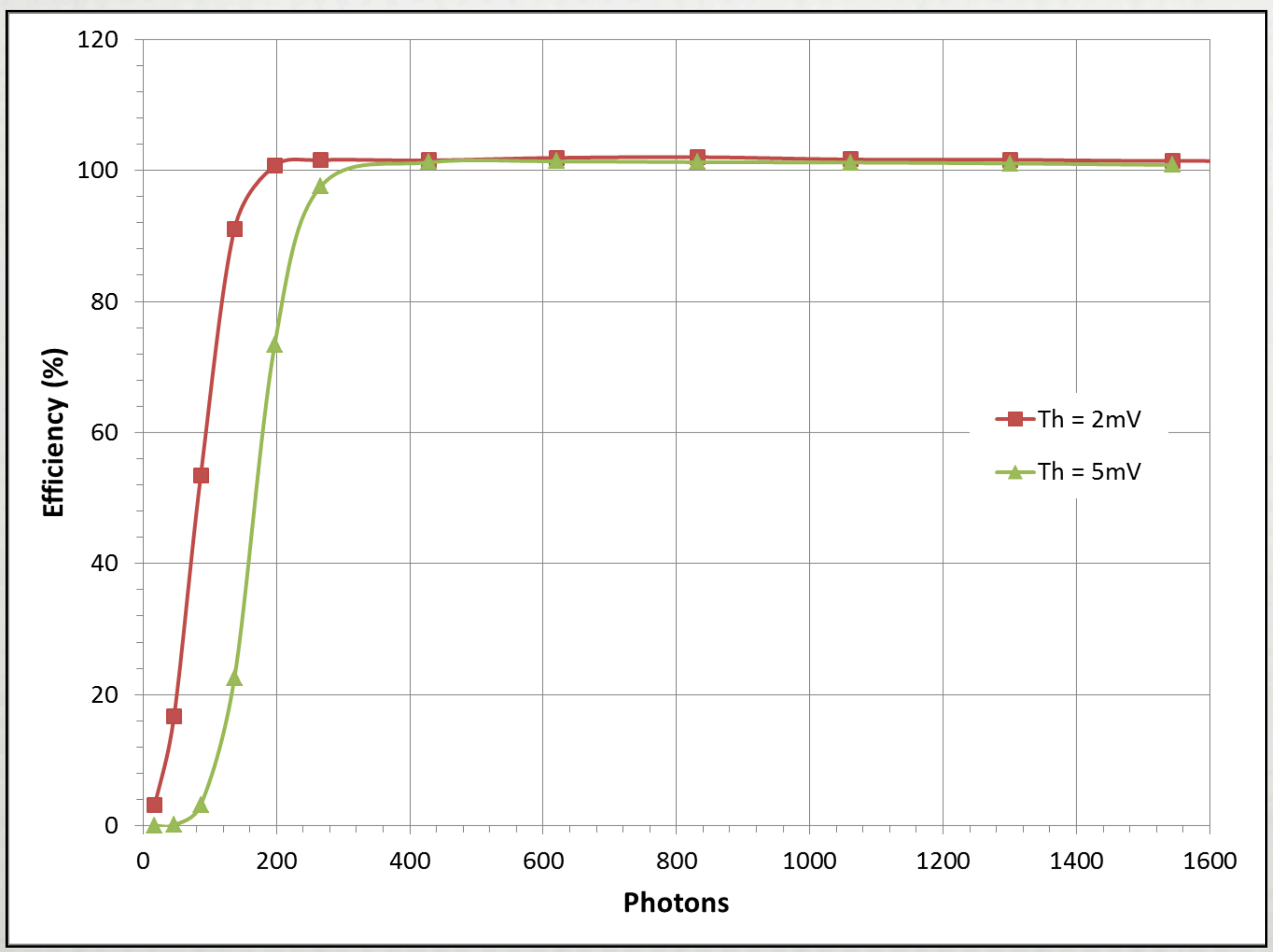
⇒ 240-480 photons @100 KeV deposited energy

Response of the matrix in counting mode:

- use a simple triggering scheme based on a leading edge discrimination of the summed output from the 16 channels in the array

- set a threshold value, pulse the LED at a well defined frequency (1 KHz and evaluate the triggering frequency as the intensity is lowered (i.e. the detection efficiency vs light intensity)





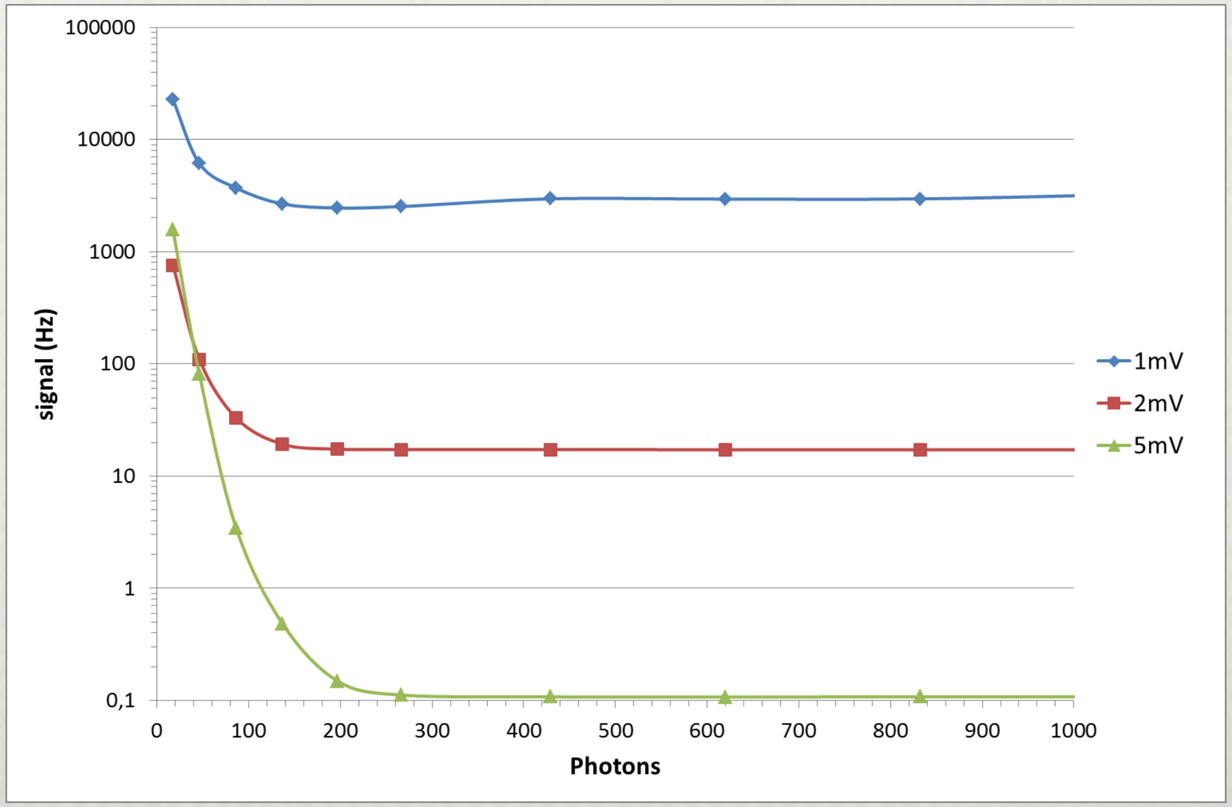
Thr [mV]	# photons (ε=50%)
2	85
5	168

measure the noise count rate for every threshold (after digital noise suppression):

Thr [mV]	Noise count rate
1	2.647 KHz
2	10 Hz
5	< 1 Hz

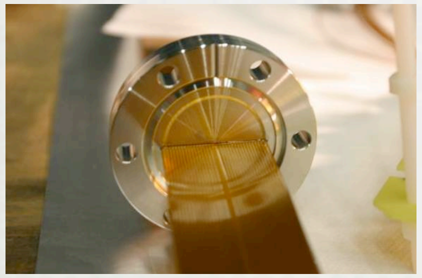
measure the interaction rate which is required to have a detected event rate 5σ away from the noise level, accounting for the efficiency drop as the light pulse approaches the threshold:

where to move on this plot is not trivial (e.g. 100 Hz and 10 Hz...) and only THE EXPERIMENTS will tell the true story...



Step 2: INTO *The Tube* (@ARKTIS, Jan. 2013 & June 2013)

- 2 SiPM arrays integrated, signal routed trough a vacuum feedthrough across a CF40 flange



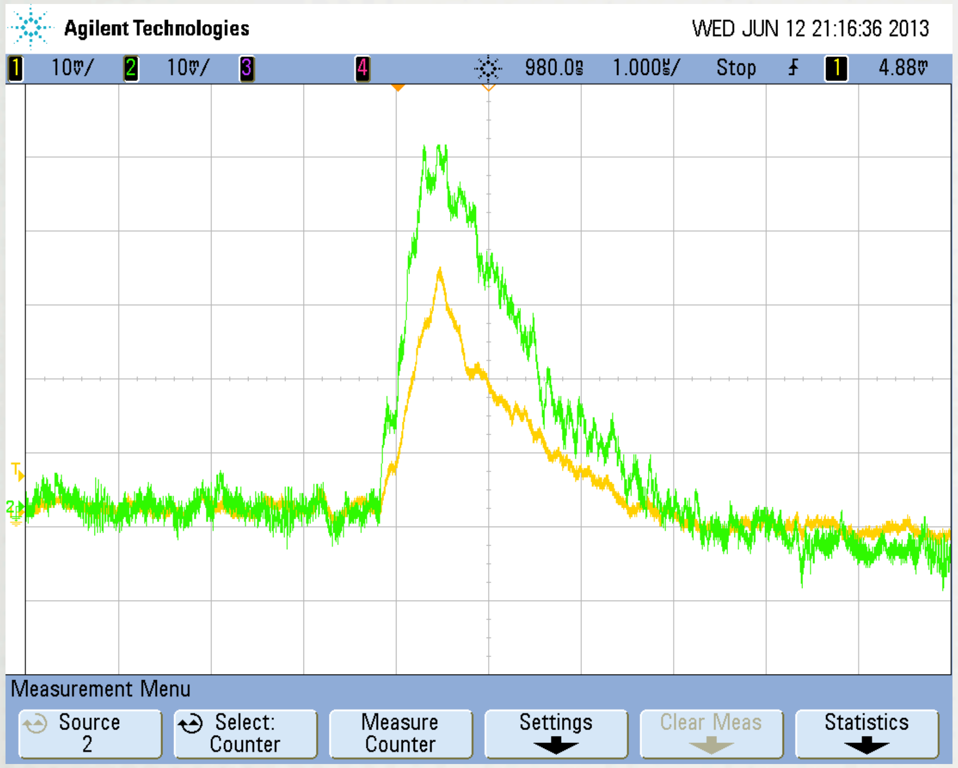
- "short" tube ~ 19 cm long

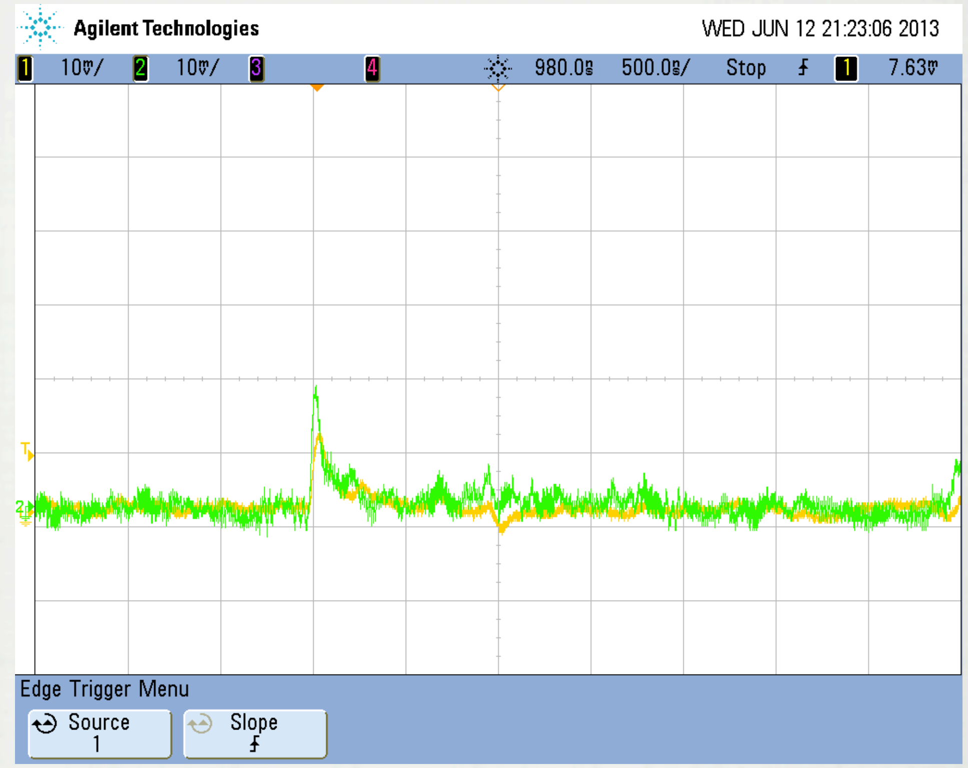
- tests performed with high pressure ^{4}He (140 bar) and Xenon (45 bar)

- runs with no source, ^{60}Co, ^{137}Cs and ^{252}Cf

ONLY PRELIMINARY RESULTS FOR THE ^{4}He ARE REPORTED HERE

Telling the difference between a n and a γ:





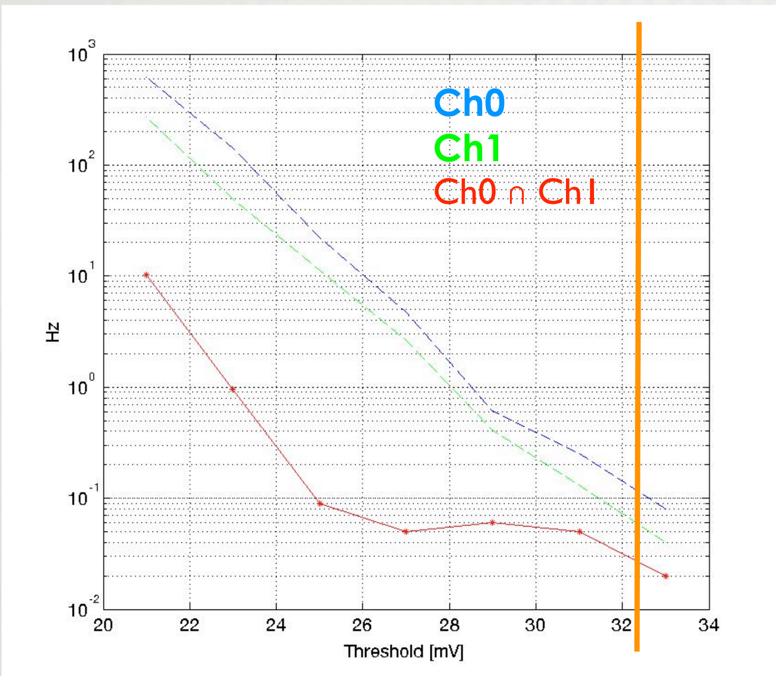
γ's appear to be:

- **smaller** $\Rightarrow$ play with the peak [leading edge discrimination]
- **shorter** $\Rightarrow$ play with the duration [a more sophisticated trigger and an input to pulse shape discrimination algorithms]
- **thinner** $\Rightarrow$ another input to pulse shape discrimination

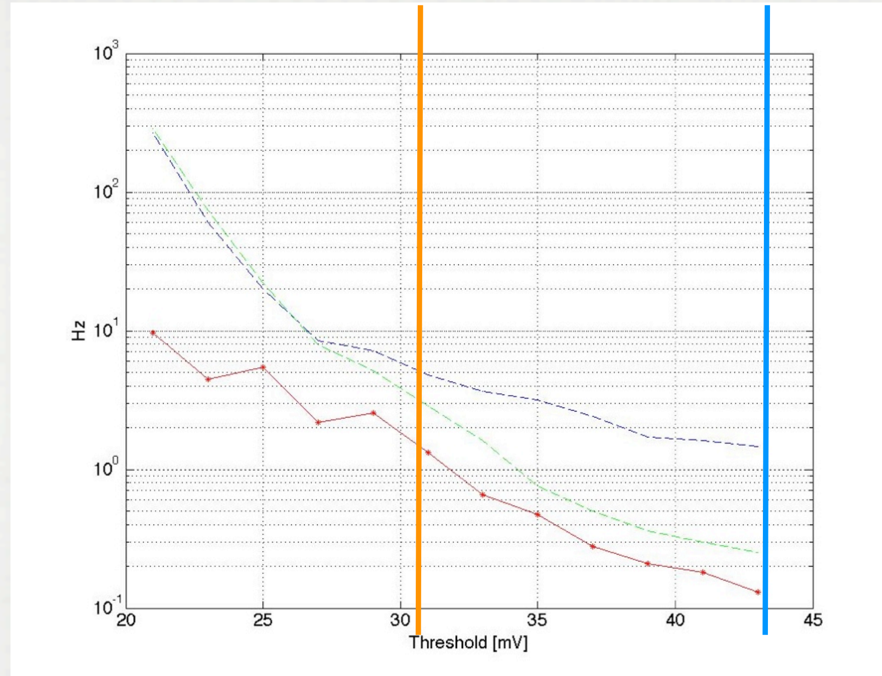
A FIRST GLIMPSE AT THE DATA, ON-LINE

⇒goal: study different triggering schemes

Indications by a counting exercise with a simple leading edge triggering scheme [peak discrimination] (data taken at 28°C!)

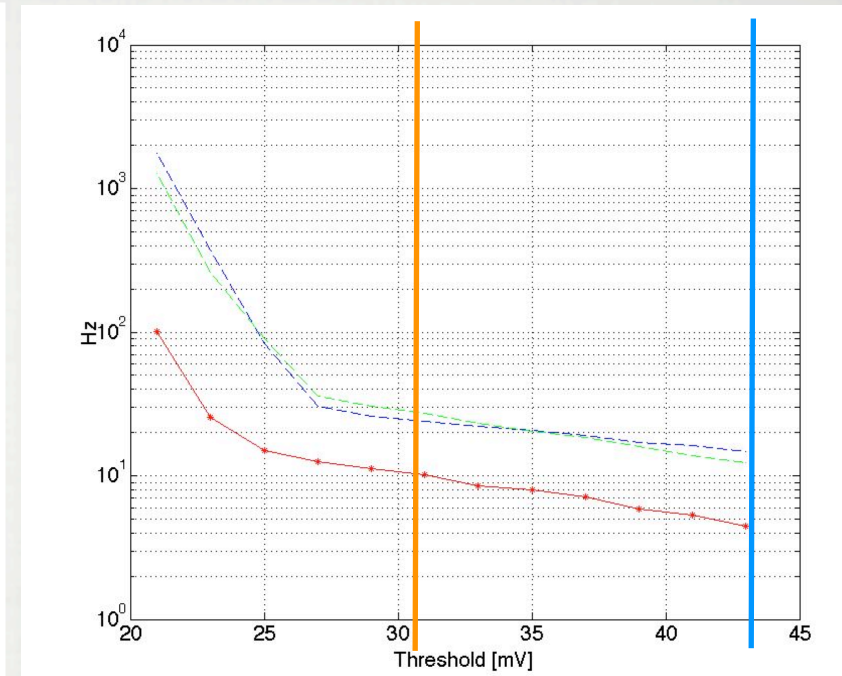


No source



^{60}Co [in contact]

40.4 kBq on 15/05/2011

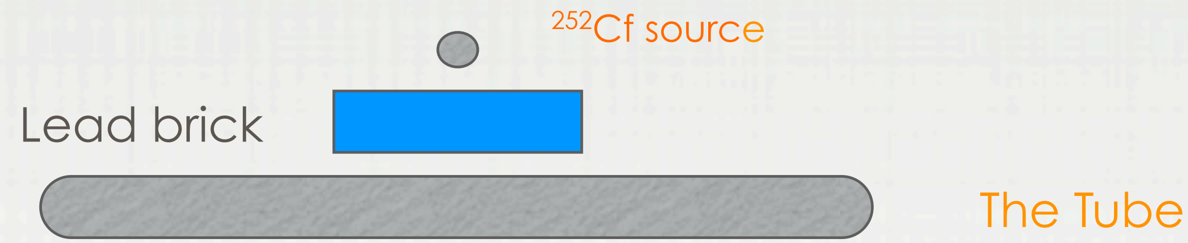


^{252}Cf [in contact]

37 kBq on 15/12/2011

Counting rate (Ch0 ∩ Ch1) @31mV [Hz]	0.05 [0.02 @23°C]	1.32 [1.17 @23°C]	10.18 [19.92 @23°C]
ν_{43mV}/ν_{31mV} (Ch0 ∩ Ch1)	NA	0.20	0.43
$\nu_{Ch0 \cap Ch1}/\nu_{(0.5*(Ch0+Ch1))}$ @31 mV	NA	0.35	0.39

An estimate of the ratio between n and γ detection efficiency **[very rough...]**



- assume you have ~4 n/fission and 8 γ/fission
- assume the lead brick masks all of the γ's
- assume the scattering of neutrons by the lead brick is "*negligible*"
- record the counting frequency **(Ch0 ∩ Ch1) with and without the brick**

then:

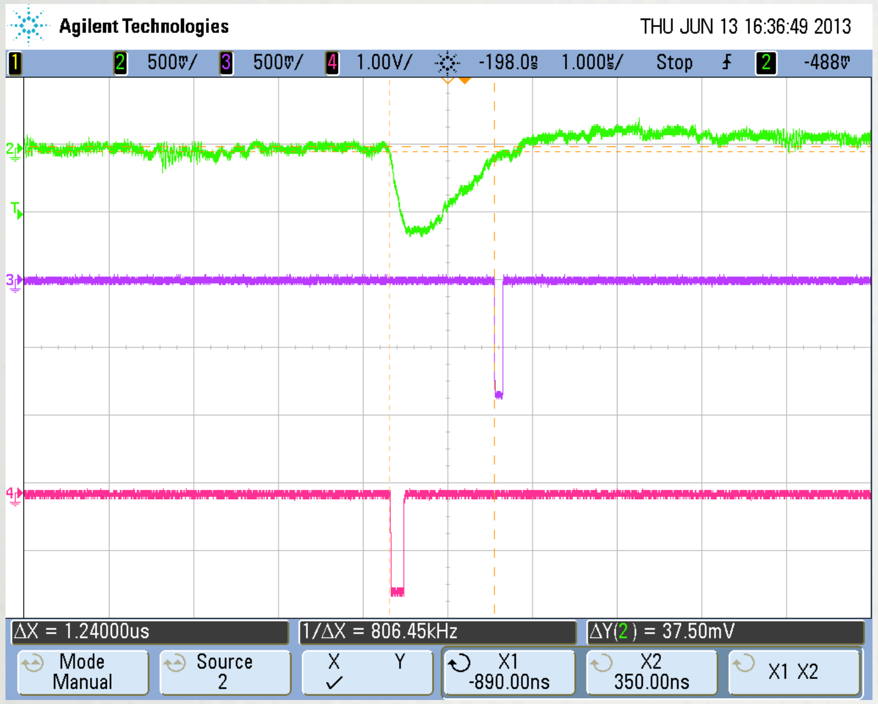
$$\frac{\nu(n+\gamma)_{brickless}}{\nu(n)_{+brick}} = \frac{\varepsilon_n \times 4 + \varepsilon_\gamma \times 8}{\varepsilon_n \times 4}$$

$$\Rightarrow \quad \frac{\varepsilon_n}{\varepsilon_\gamma} \sim 4.2$$

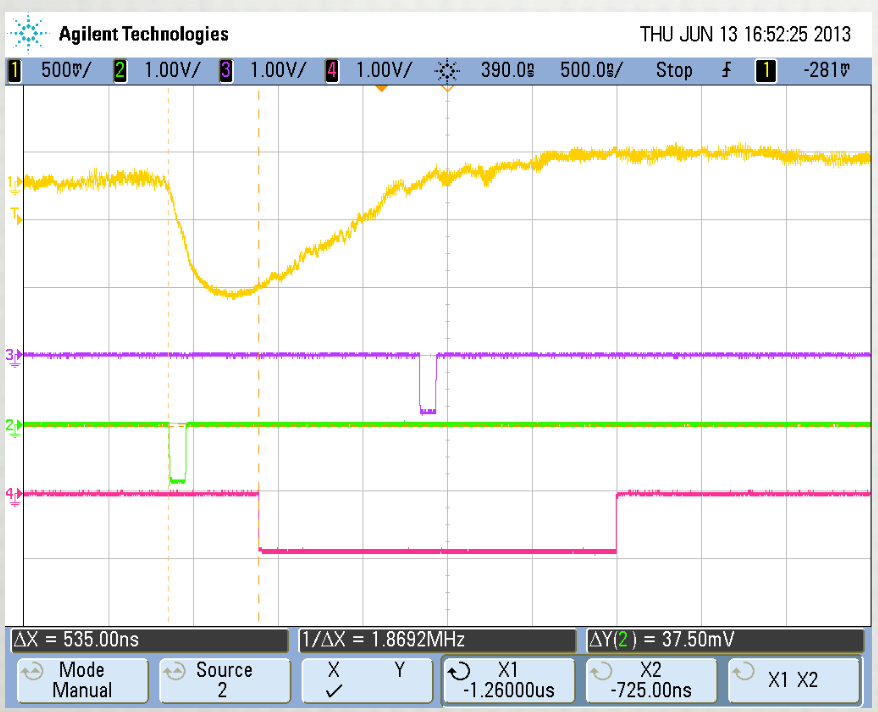
a very good ratio, close to the value for the "standard tube"

note: $\varepsilon = \varepsilon_{\text{selection}} \times \varepsilon_{\text{interaction}}$

A more advanced counting exercise, accounting for the time development of the signal *[a delayed coincidence scheme]*



1. define 2 thresholds (parameters 1 & 2), on the leading and trailing edge

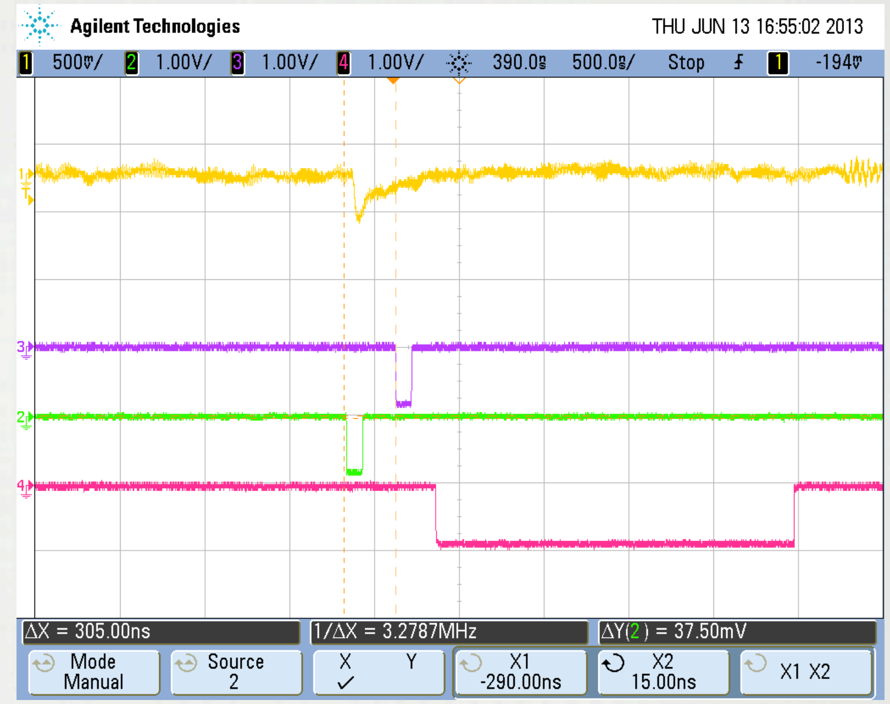


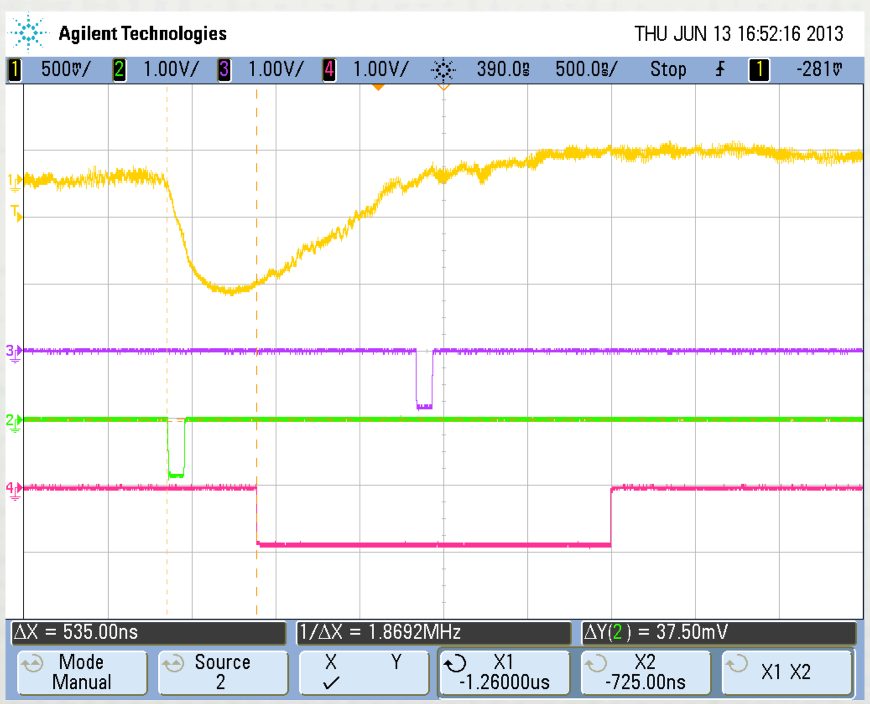
A typical neutron event

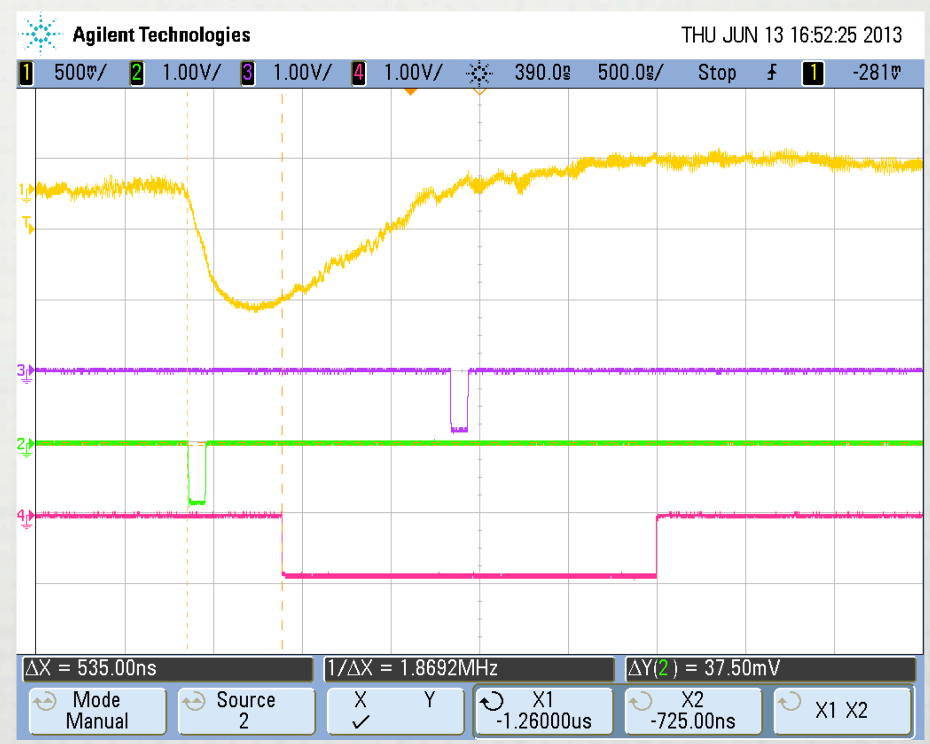
2. delay (parameter 3) *conveniently* the leading edge threshold crossing and open a long gate (parameter 4)

3. count the rate of coincidences between a short gate opened at the trailing edge crossing and the delayed long gate

A gallery of n and γ events:







To be more quantitative (@28°C):

Counting rate [Hz]	no source	^{60}Co in contact	^{252}Cf in contact
Leading edge discrimination (Ch0 ∩ Ch1) @31mV [Hz]	0.05	1.32	10.18
Delayed trigger, single detector [delay 700 ns, long gate 2 μs]	0.02	0.05	12.27
Delayed trigger, Ch0 ∩ Ch1	0.01	**0.01**	8.61

⇓

An amazing result, corresponding to a γ rejection power at the 10^6 level

[10 counts in 1000s, for a number of γ given by acceptance*activity*time = $1/3 * 3 * 10^4 * 10^3 \sim 10^7$]

Two complementary interesting figures:

- counts by a ^{137}Cs [3.7 MBq] in contact: 3 in 100s

- count rate by a ^{252}Cf source of 370 kBq:
  - in contact: 61.9 Hz
  - @20 cm distance: 2,7 Hz
  - @50 cm distance: 0.5 Hz

... actually indicating the *SiPM tube* is close to fulfill the requirements!

A MORE ADVANCED DATA ANALYSIS, OFF-LINE

⇒goal: evaluate the interacting γ rejection power and the interacting neutron selection efficiency

... yes, yet another pulse shape discrimination study

Three data sets recorded with a minimum bias trigger condition [soft request on the slope of the trailing edge on either of the signals from the 2 arms]:

- bckg (no source around): 400 triggers, essentially electronics noise events.
- ^{60}Co: 5800 triggers, a mixture of noise & γ events
- ^{252}Cf: 10 000 triggers, a mixture of noise, γ and n events

waveforms were sampled at 125 MS/s, for a total duration of 4μs.

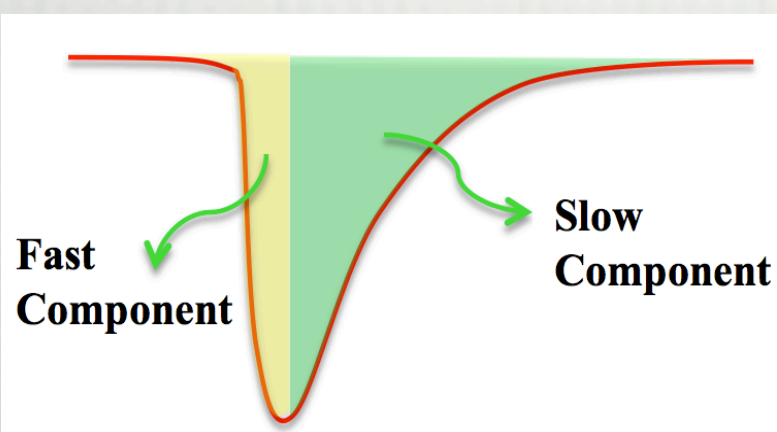
Modus operandi:

1. identify an observable allowing to measure the ratio between noise & particle induced triggers in samples 2 & 3
2. filter through a multivariate analysis noise from particle induced events
3. identify the ratio between γ and n events in sample 3
4. filter through a multivariate analysis γ from n
5. measure the rejection power of interacting γ and the selection efficiency of interacting neutrons

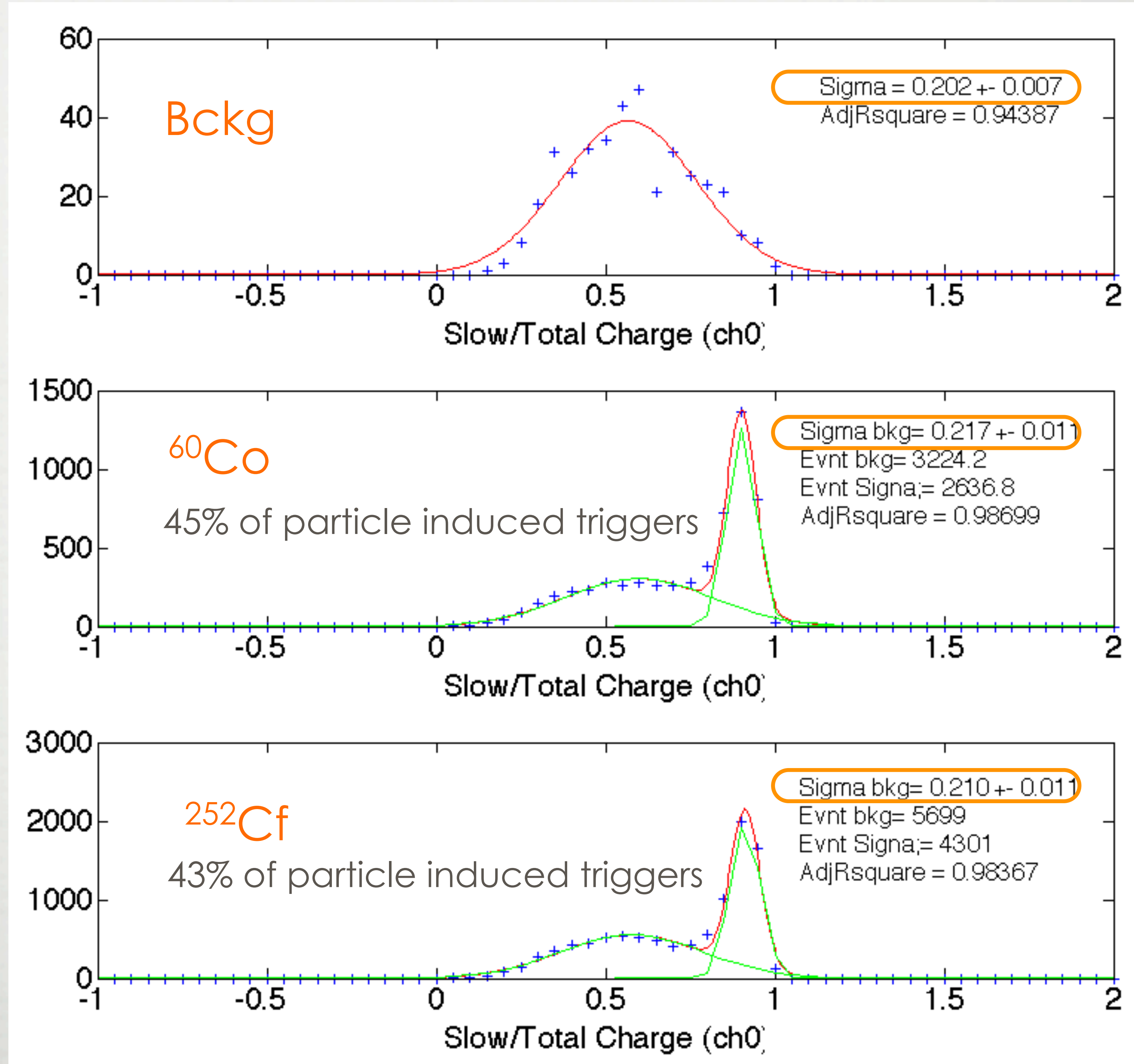
1. sample composition (% noise and particle induced triggers in the 3 data sets)

For every recorded waveform:

- the baseline is calculated
- the longest series of samples below the baseline in the recorded time window is classified as the signal
- a FAST and SLOW component is calculated as the integral of the signal to the LHS and RHS of the peak

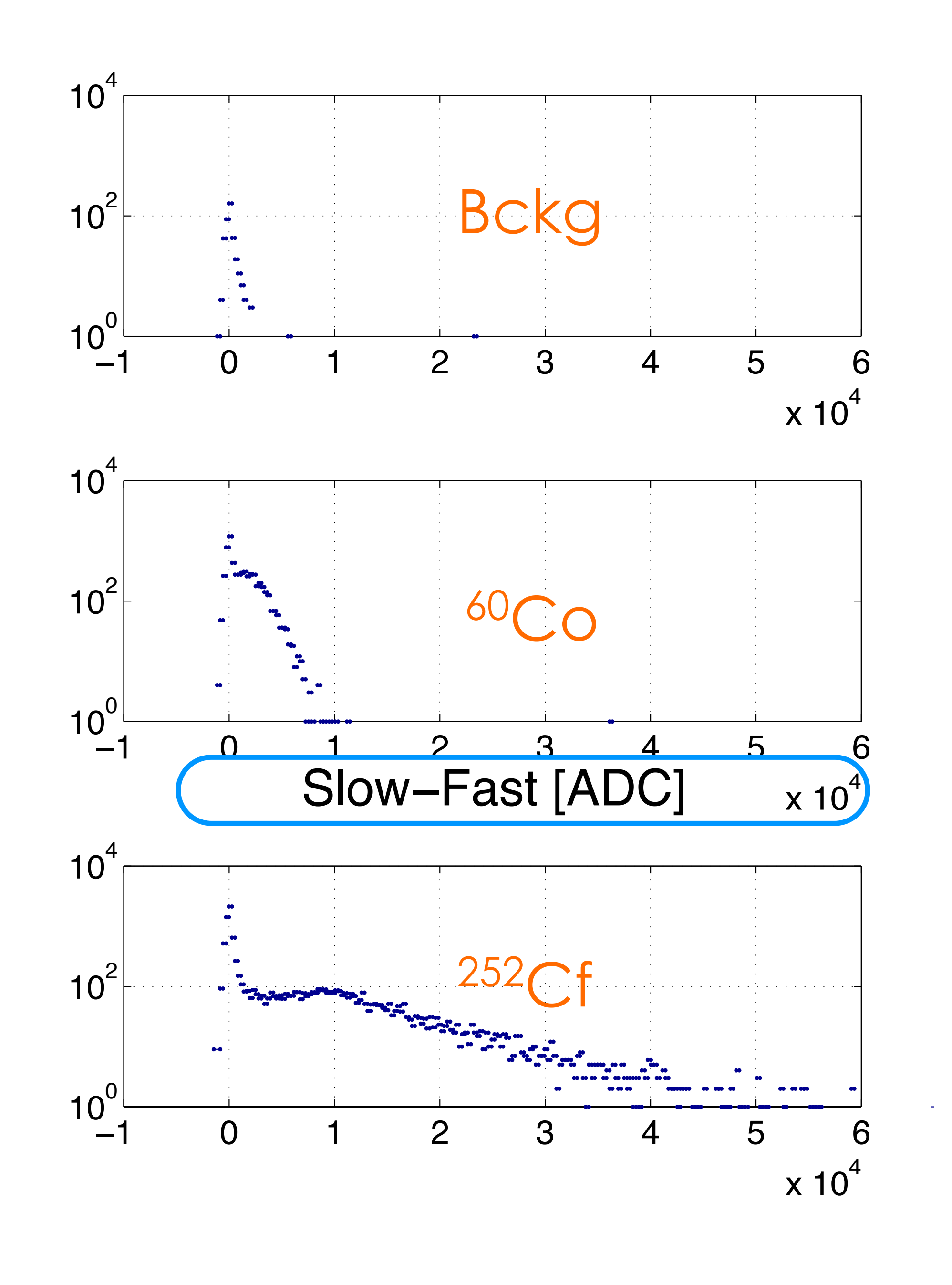


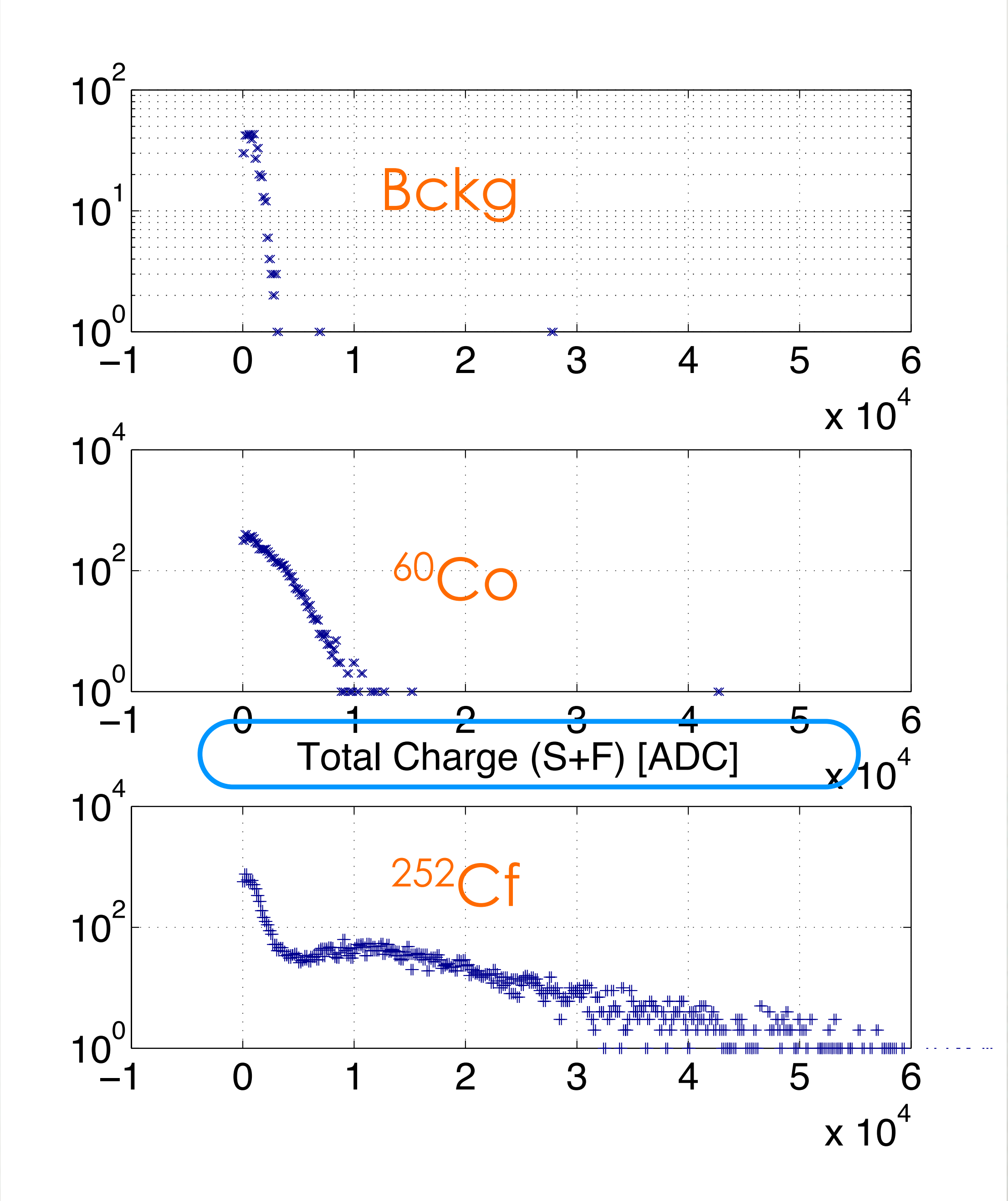
S/(S+F)



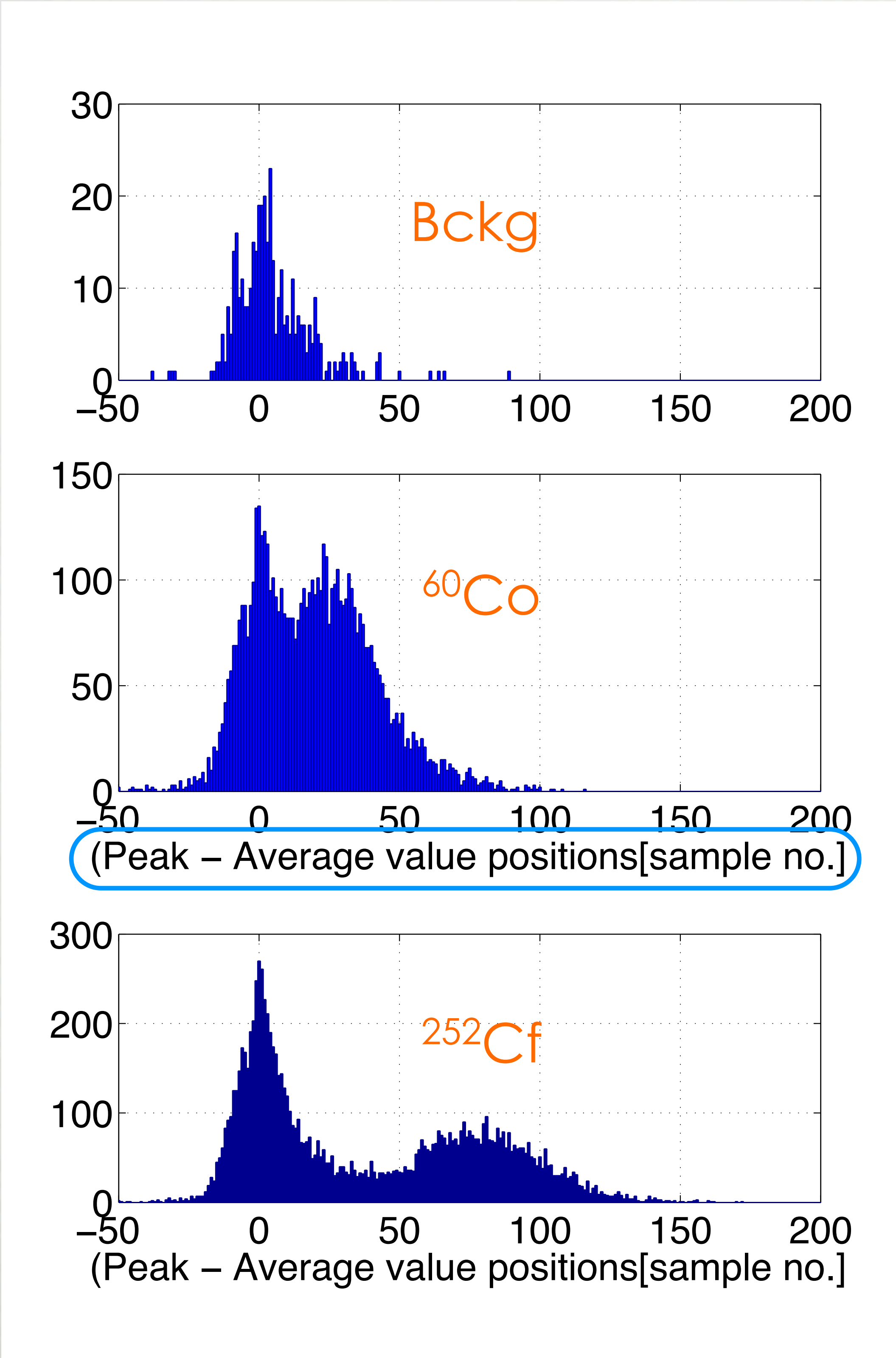
2a. choose a set of variables were noise signals, γ and n appear to be "reasonably" different

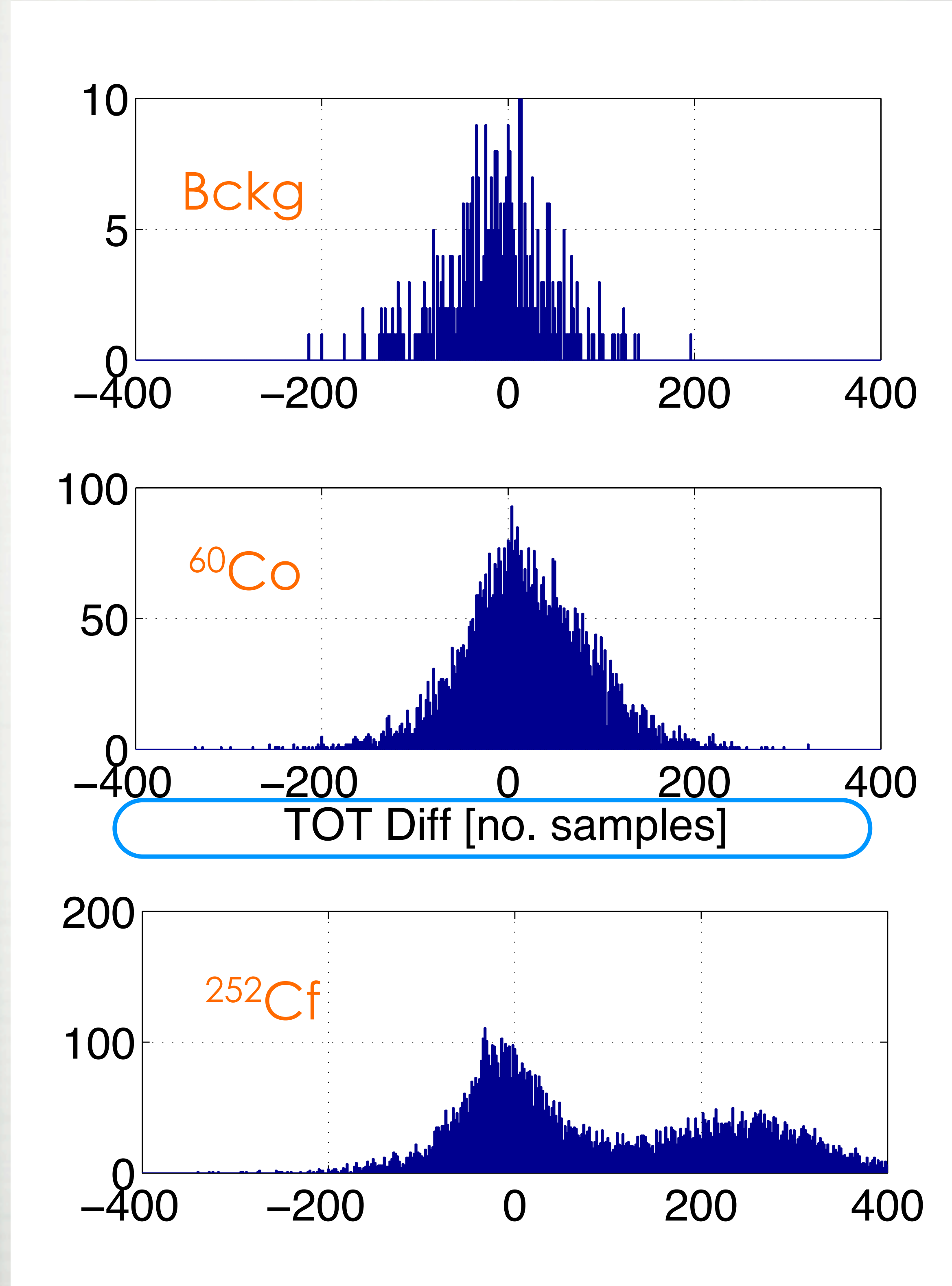
- 2 "deposited energy" related quantities:





2 “time development” related quantities:



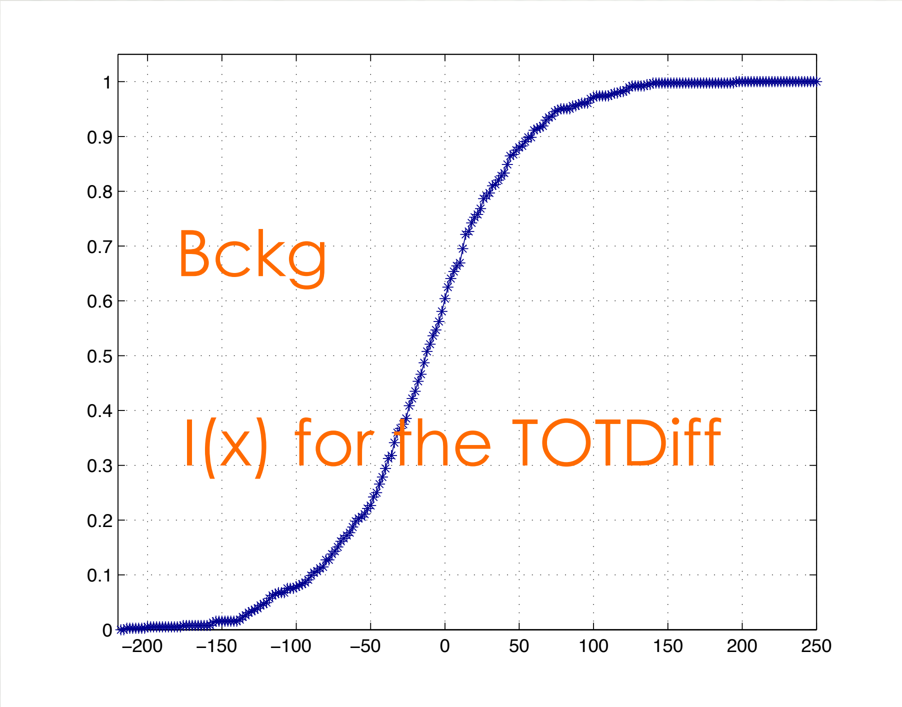


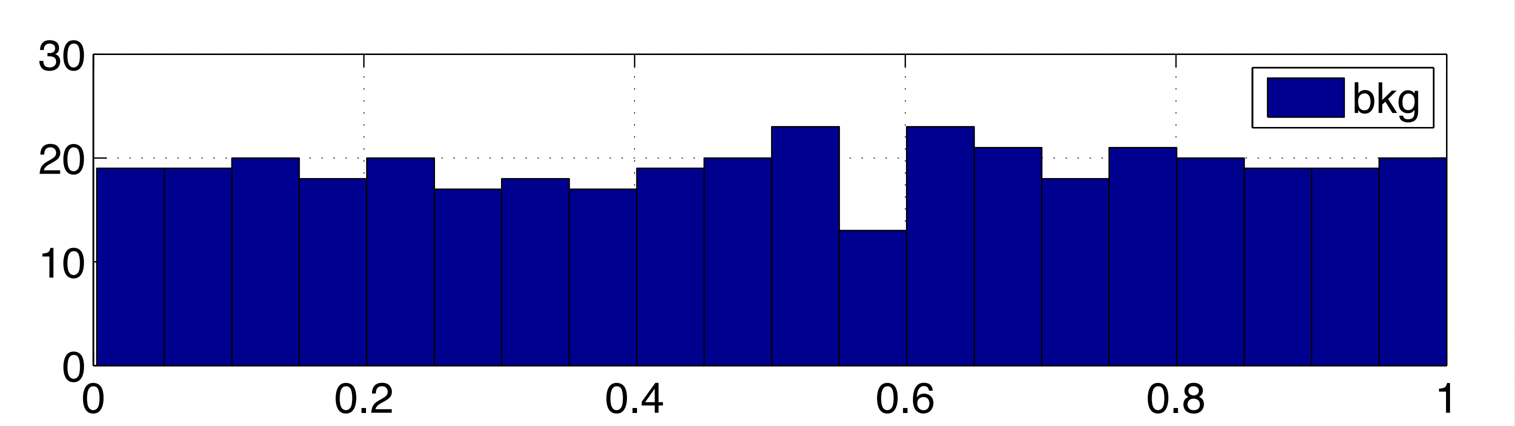
2b. combine them according to the Bayesian recipe developed by the LEP collaborations* @CERN for discriminating c,b quark final states from light quark (u,d,s) states of the Z° decay resulting from e^+e^- annihilations:

*Phys. Lett. B 313 (1993) 535-548 - NIM A417 (1998) 384-390

look at the experimental probability density functions (p.d.f) (i.e. the spectra) $h_i(x_i)$ for the selected quantities in the bckg set and build up the cumulative distribution functions $I_i(x_i)$ (c.d.f.):

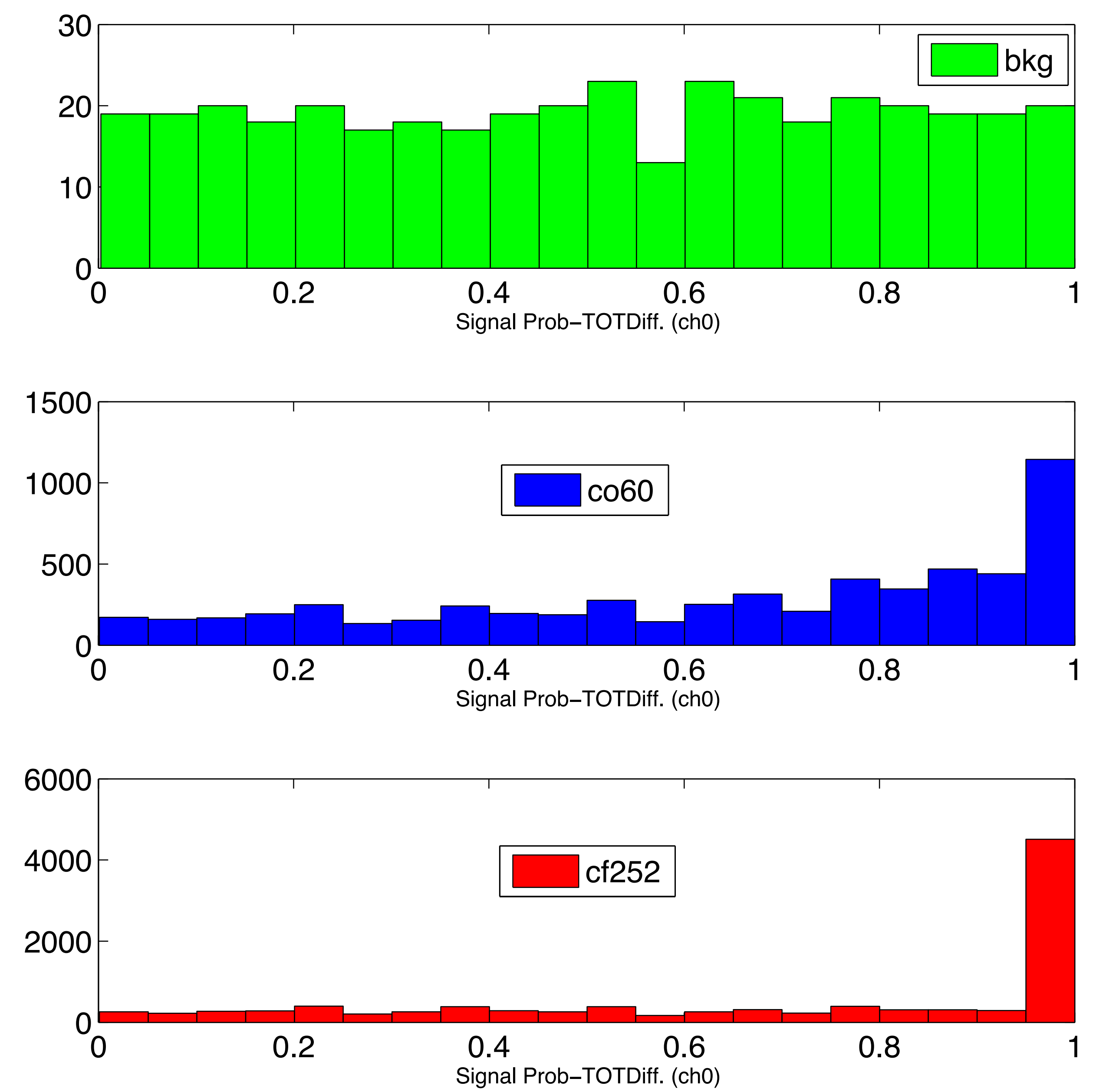
$$I_i(\tilde{x}_i) = \int_{-\infty}^{\tilde{x}_i} h_i(x_i)dx_i$$





$I_i(x)$ is a random quantity, with a flat distribution in [0;1] for the bckg but as long as you move to a different p.d.f. as of the ^{60}Co and ^{252}Cf, you can expect the c.d.f. to look very different, offering the possibility to select what is NOT bckg (null hypothesis rejection):

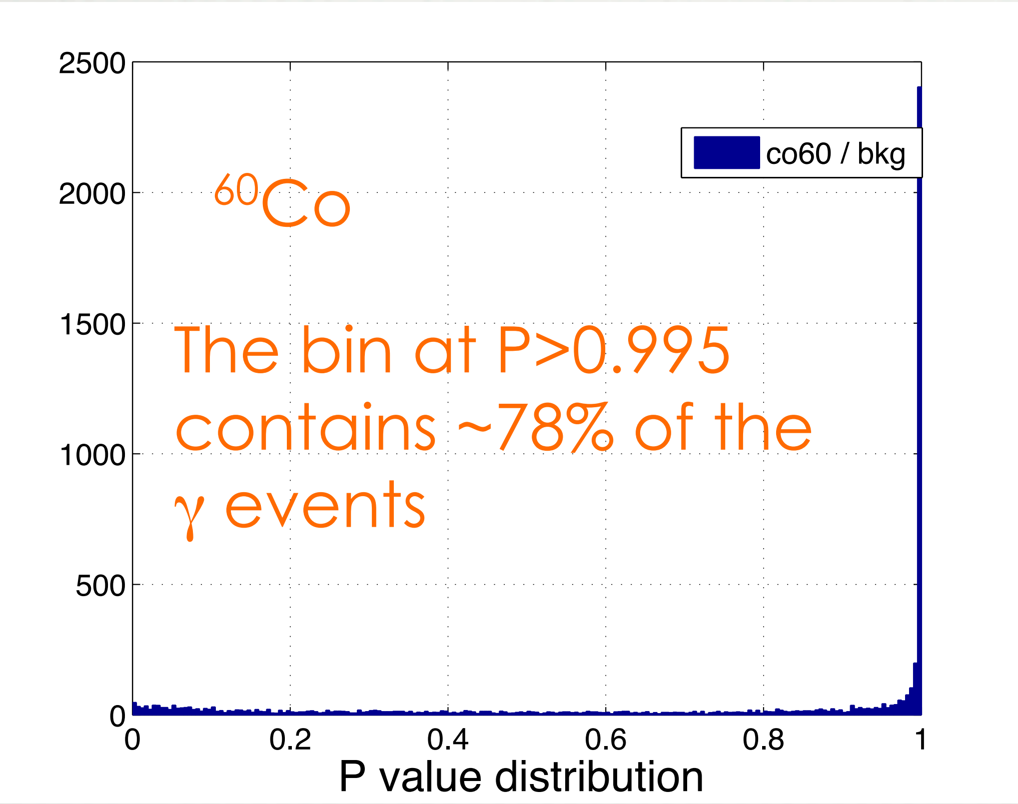
I_{TOT} distributions

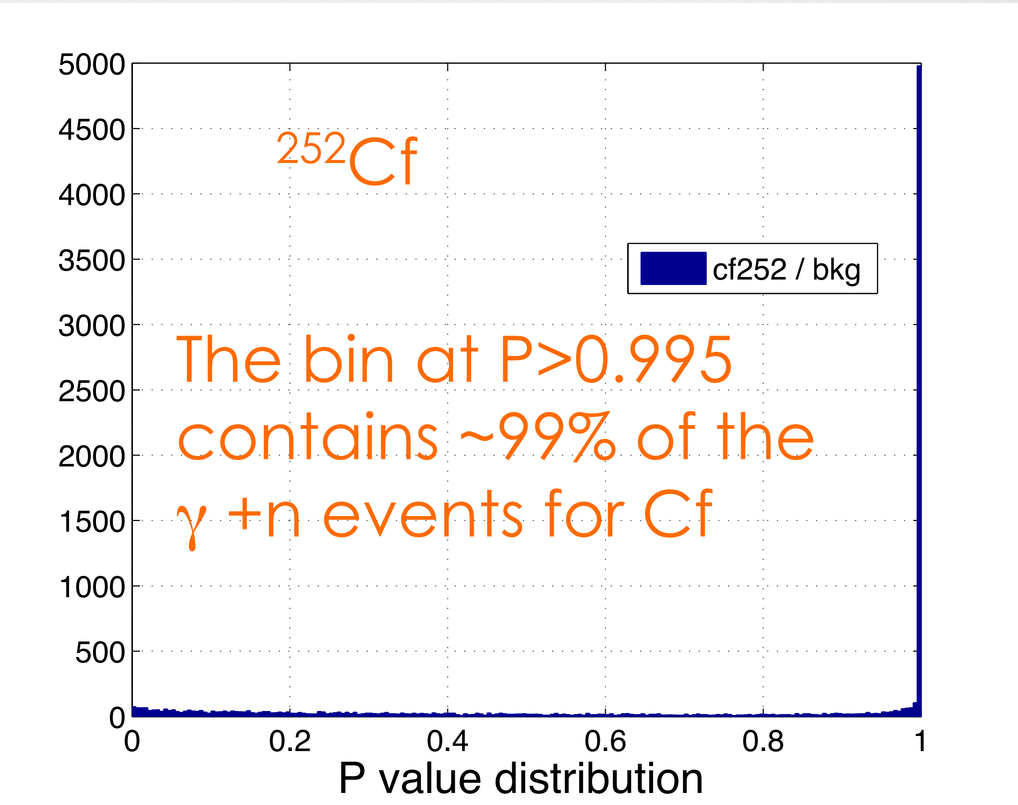


2c. repeat the exercise with each of the 4 quantities and combine the corresponding c.d.f. as follows:

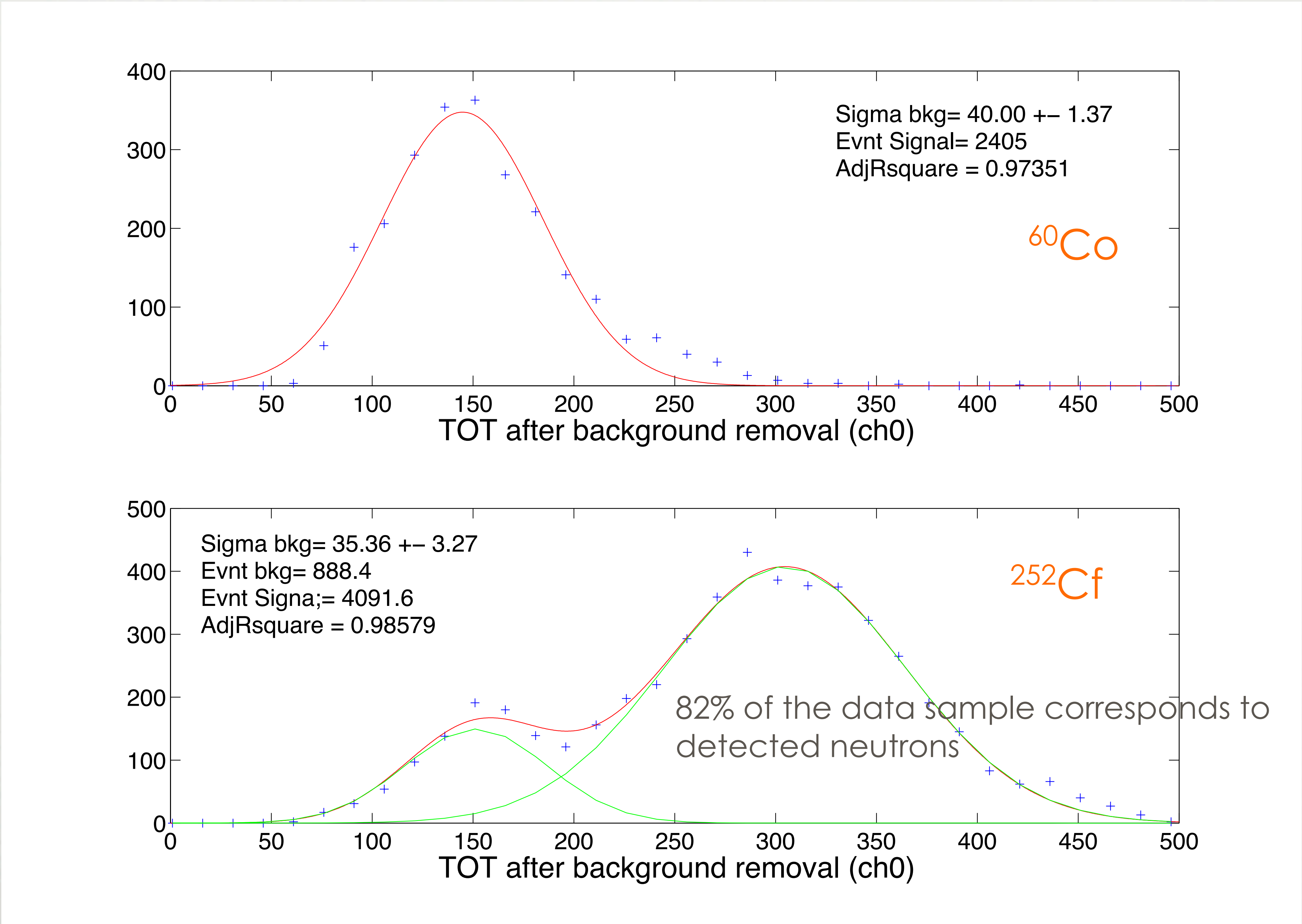
$$P = \Pi \cdot \sum_{i=0}^{3} \frac{(-\log \Pi)^i}{i!}, \Pi = I_1 \cdot I_2 \cdot I_3 \cdot I_4$$

as long as the I_i are not correlated, P has a flat distribution as well and it is the final single quantity upon which the selection is applied TWICE, against the Bckg in a first step and against γ in a second step:

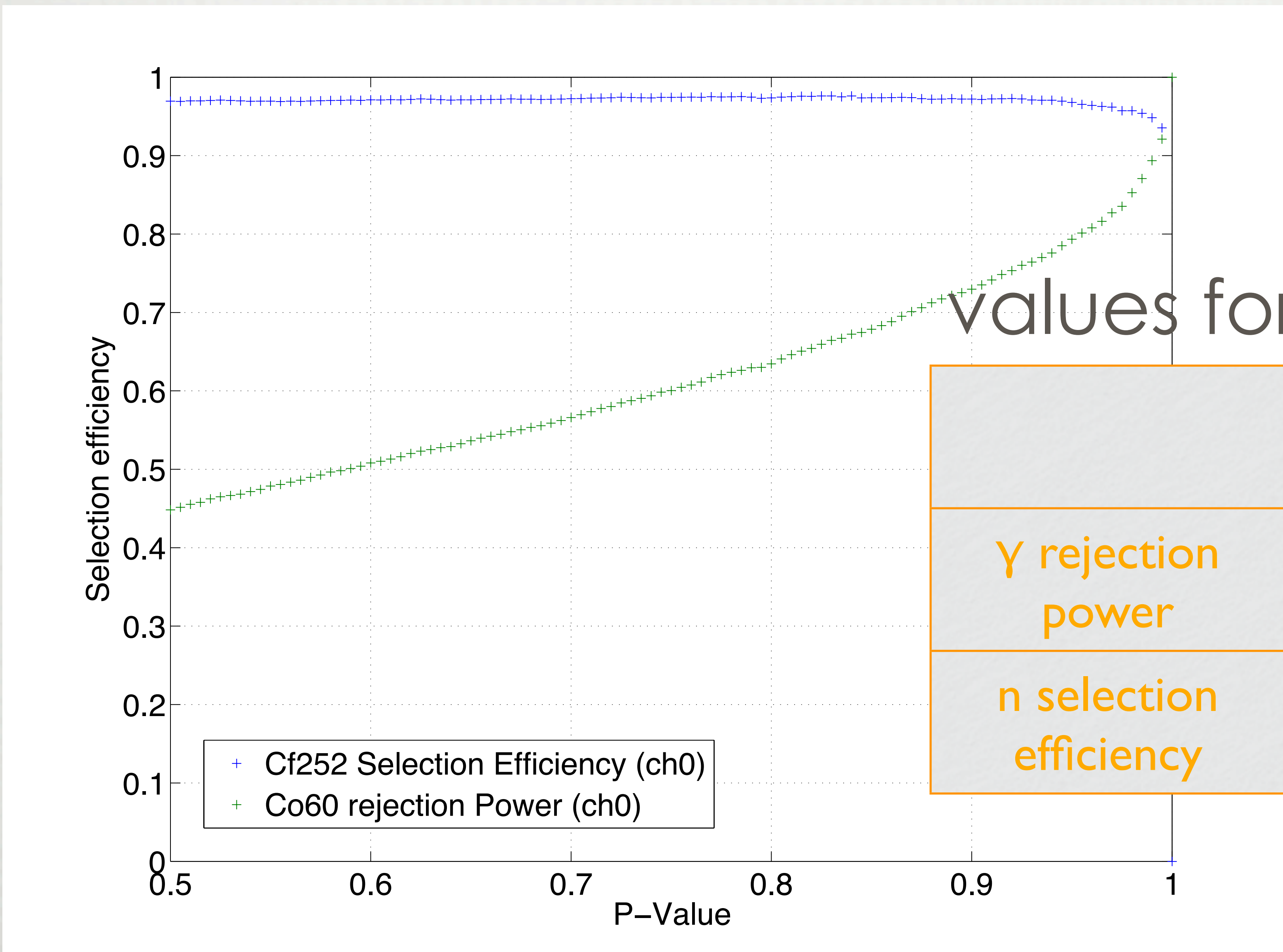




3. after the Bckg has been filtered out, the ratio between γ and n events in sample 3 (252Cf) can be measured:



3. and applying again the same procedure but building up the reference distribution from the ^{60}Co data, every event in the ^{252}Cf can be qualified against the hypothesis of being originated by a γ, getting to the following result:



values for a P > 0.995 cut

	single arm	coincidence
γ rejection power	92%	99%
n selection efficiency	94%	88%

CONCLUSIONS

- The Proof of Concept about using SiPM arrays in the Tube has been successfully completed
- Optimization of the design is certainly required
- A new front-end electronics (custom designed at Uni. Insubria) is being characterized at the moment
- Optimization of the on-line and off-line analysis is on the way
- Results are even beyond expectations and give us a strong push to continue.