Analysis of the Response of Silicon Photomultipliers to Optical Light Fields

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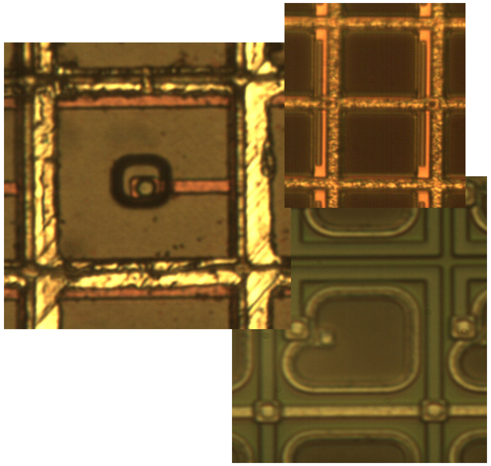
Outline

- ➔Main Features of SiPMs
- ➔Characterization Protocol
- ➔Experimental Setup
- ➔Theoretical Model
  - Detection
  - Dark Count Rate
  - Optical Cross-Talk
- ➔Data Analysis
- ➔Conclusions



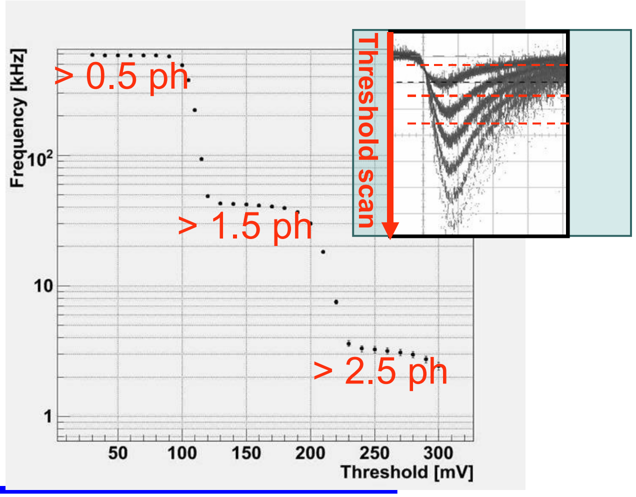
SiPMs: Main Features

Array of parallel diodes
Common output
Avalanche Mode

High Gain
High Photon number resolution
High speed (T_{fall} ~ 50 ns)
Low dead time

Producer	Area (mm²)	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	77	~0.4 MHz	2 x 10^6	65
CPTA	1 x 1	30 x 30	500	24	~3 MHz	10^6	30

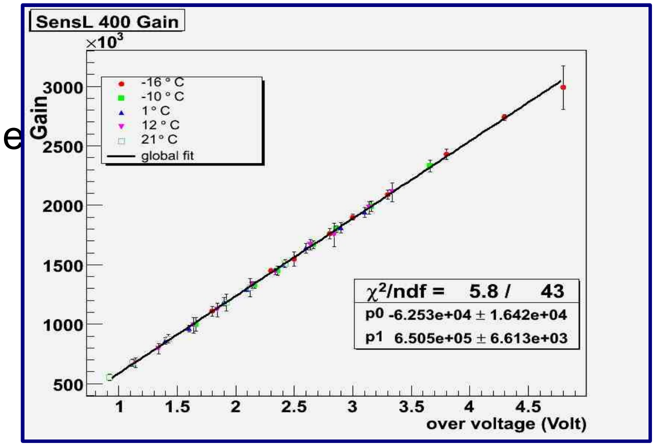
High Dark Count Rate (DCR): 100 kHz – 5 MHz
High optical cross-talk (X_T): up to 40%



Need for Characterization

Within RAPSODI

–***I-V measurements*** (leakage current, quenching resistor, breakdown voltage



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–***Noise measurements*** (vs over voltage and vs temperature):

•dark counting rate (DCR) vs bias voltage

•optical cross-talk (DCR vs threshold)

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–***linearity*** & ***dynamic range***

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–***Spectral response*** (PDE vs λ, PDE vs temperature)

•

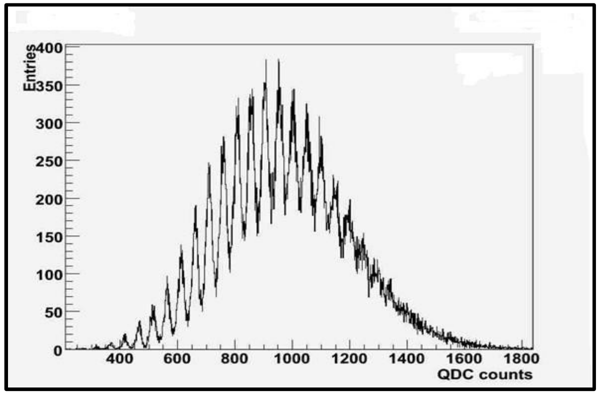
–timing properties and time resolution (not relevant for RAPSODI but in progress)

–***Analysis of*** (Poissonian photon) ***spectrum*** (vs temperature)

•resolution power (how many photons can I distinguish?) & gain

•working point optimization (at low and large flux)

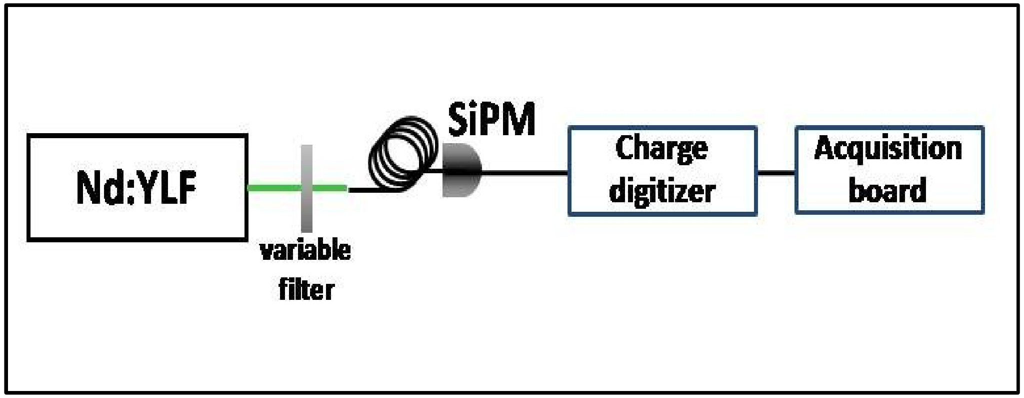
•optical cross-talk (deviations from the Poissonian distribution)



M. Bondani, A. Allevi, A. Agliati, A. Andreoni "Self-consistent characterization of light statistics", J. Mod. Opt. 56, 226-231 (2009)

Experimental Setup

Poissonian Light Setup



Nd:YLF mode-locked laser amplified at 500 Hz - pulse duration 5.4 ps second-harmonics (523 nm)

Hamamatsu MPPC S10362 11 100C

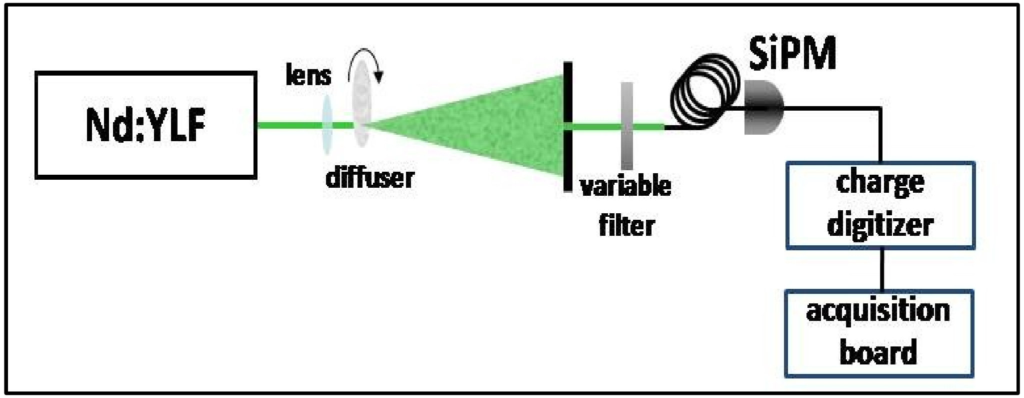
General Purpose Amplifier (GPA)

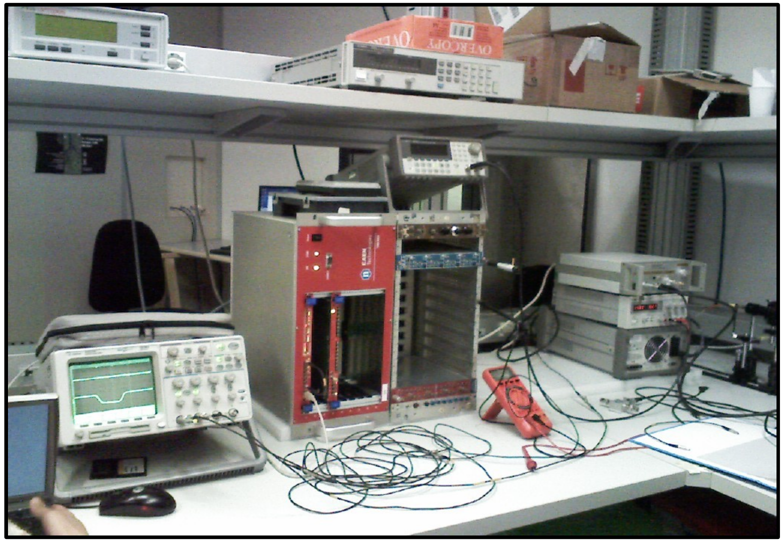
USB-VME Bridge CAEN

V171816ch QDC CAEN V792N

Pulse Generator Agilent 33250A [50 MHz]

Thermal-like Light Setup





The Model

What we Measure:
Geiger – Müller Avalanches

generated by:

Detection of impinging photons

Thermally Generated (DCR)

Optical Cross-Talk

Model the contributions
parameters

What we Want:
Light Field Statistics

Modeling the response: Detection

$P_{n,ph}$ - probability distribution of the light field

$P_{m,el}$ - distribution of avalanches triggered by impinging photons

$$P_{m,\mathrm{el}} = \sum_{n=m}^{\infty} B_{m,n}(\eta) P_{n,\mathrm{ph}} .$$

$$B_{m,n}(\eta) = \binom{n}{m} \eta^m (1-\eta)^{n-m} .$$

key parameter!

η - PDE

m_{el} expect. value of triggerd cells

Modeling the response: DCR

DCR modeled as a poissonian event during the integration time

$$P_{m,dc} = \frac{\overline{m}_{dc}^{m}}{m!} e^{-\overline{m}_{dc}} \qquad \overline{m}_{dc} = \nu_{dc} \times t_{gate}$$

key parameter!

The distribution of the avalanches is now given by the convolution

$$P_{m,\mathrm{el+dc}} = \sum_{k=0}^{m} P_{k,\mathrm{dc}} P_{m-k,\mathrm{el}}$$

Modeling the response: Cross-talk

Avalanche triggering in neighbour cells by other avalanches had been modeled with a bernoullian-like process:

$$C_{k,m}(\epsilon) = \begin{pmatrix} m \\ k-m \end{pmatrix} \epsilon^{k-m}(1-\epsilon)^{2m-k}$$

key parameter!

and the distribution of avalanches becomes

$$P_{k,\mathrm{cross}} = \sum_{m=0}^{k} C_{k,m}(\epsilon) P_{m,\mathrm{el+dc}}$$

X_T a cascade phenomenon: more than one stage

Data Analysis Outlook

1) Multi-peak fit of spectrum → Peak Areas

2) Fit of curve of $P_{k,cross}$ → Parameters

<u>Pros</u>

$P_{k,cross}$ no need to be explicit analytic expression

<u>Cons</u>

Limited to peak resolving spectra

Resolved peaks greater than free parameters of $P_{k,cross}$

Multi-fit procedure

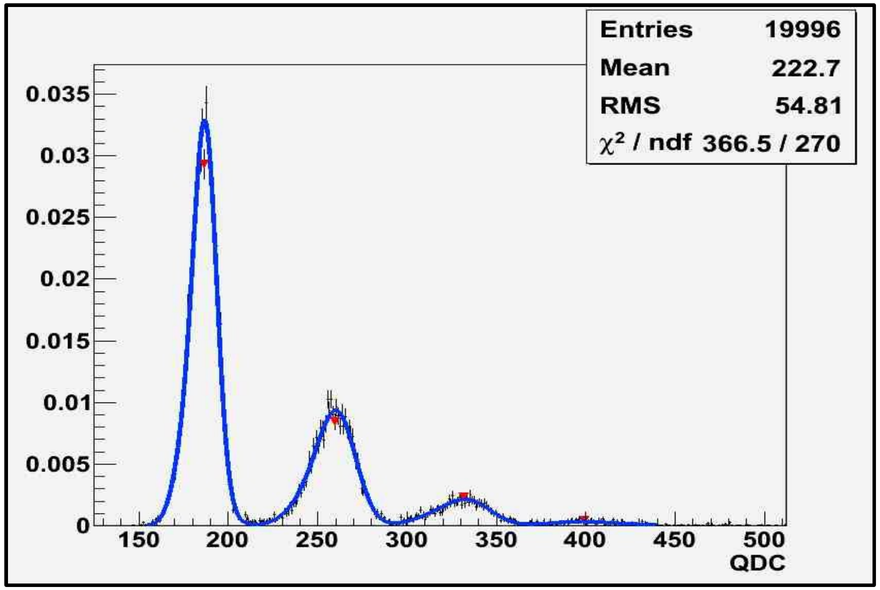
Total area of spectrum normalized

Multi-peak fit performed

Each peak described by a Gauss-Hermite Function

$$\mathrm{GH} = N e^{-w^2/2} \left(1 + {}^{3}h H_3(w) + {}^{4}h H_4(w)\right)$$

$$w = \frac{x - \bar{x}}{\sigma}$$



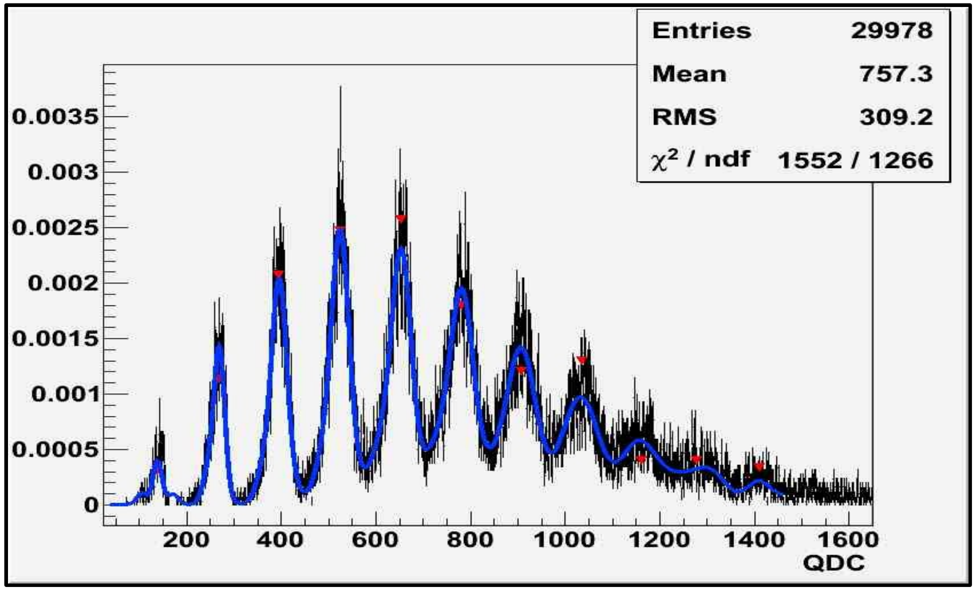
Peak areas *A* calculated from fit parameters

$$A = N\,\sigma\,(\sqrt{2\pi} + {}^{4}h)$$

Results: Poissonian Light

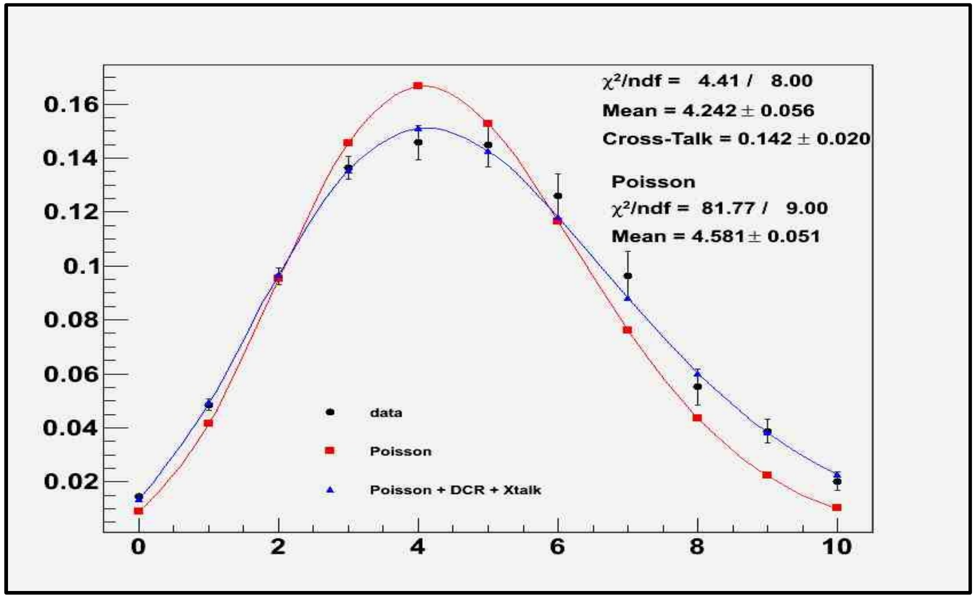
$P_{m,el}$ is poissonian
$P_{m,dc}$ is poissonian

$P_{k,el+dc}$ is poissonian too



Three free parameters:

- $m_{el+dc} = m_{el} + m_{dc}$
- X_T
- Prefactor



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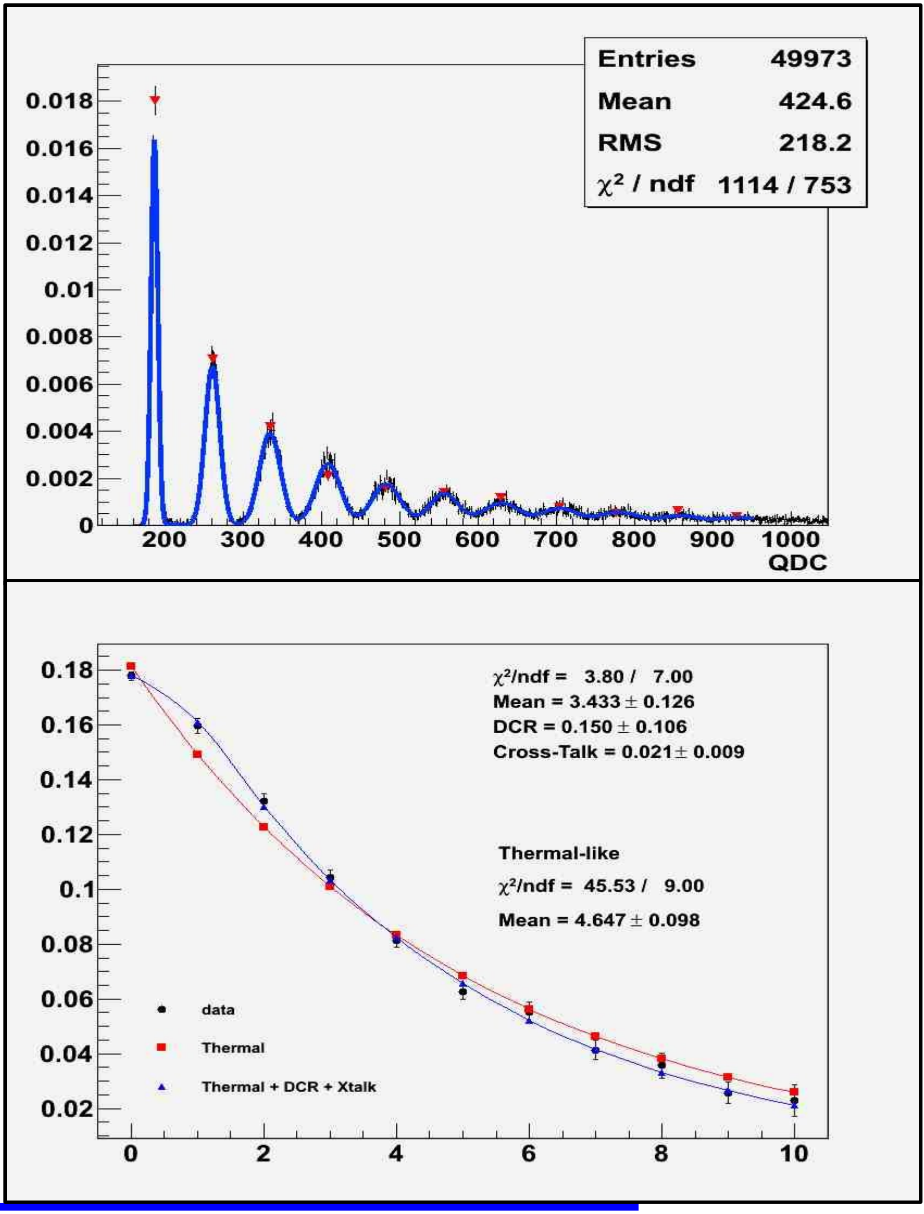
Results: Thermal-like Light

Probability distribution of single mode thermal light is described by

$$P_{m,el} = \frac{\overline{m}_{el}^{m}}{(\overline{m}_{el}+1)^{m+1}}$$

Four free parameters:

- $\rightarrow m_{el}$
- $\rightarrow m_{dc}$
- $\rightarrow X_T$
- $\rightarrow$ Prefactor



Cui Prodest?

Example: *Photon Counting Histogram* tecqniques

Acquisition of spectra of stimulated fluorophore emission

Biophysical parameter obtained from

measure of

deviation from poissonian distribution

knowledge of other sources of deviation needed!!!

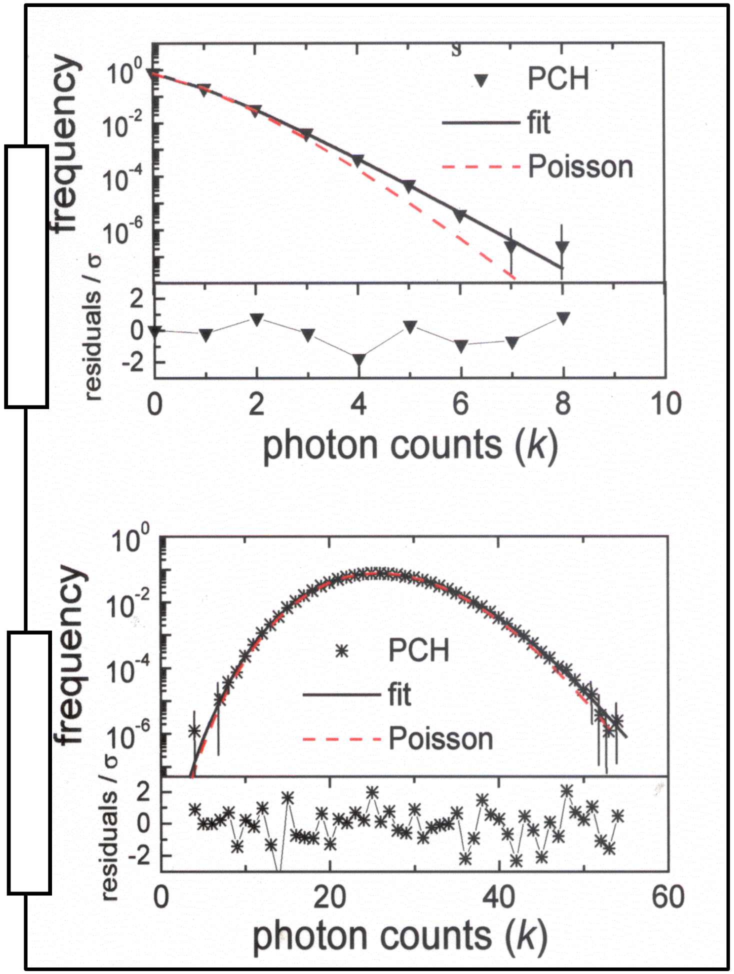


Image from an E. Gratton lecture

Conclusions

- Provided a mathematical model for cross-talk and DCR effects;
- Developed a procedure to analyzed data taking these contributions into account;
- Tested the model
  - Poissonian light
  - Thermal-like light
- *Full description of Self-Consistent Method in upcoming paper!*
- Example of possible applications of the procedure

Backup Slides

Self-Consistent Approach

Several spectra at varying η
Final explicit analytic expression of $P_{k,cross}$
Momenta from analytic expression

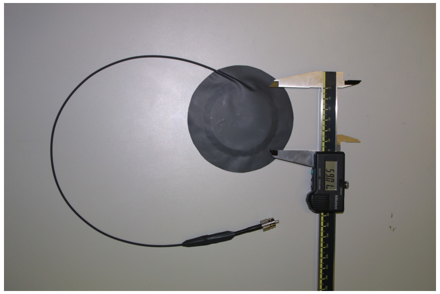
Fit of the “Fano Factor” and “Skewness”

Pros
Not limited by peak resolution
Self-Consistent

Cons
Several acquisitions
Explicit analytic expression to calculate momenta

Some Application

Real time dosimetry in mammography



Sensitivity
High dynamic range

Illicit radiocactive material detector

Low flux sensitivity
Stability vs Environmental Condition variations

Radon detector

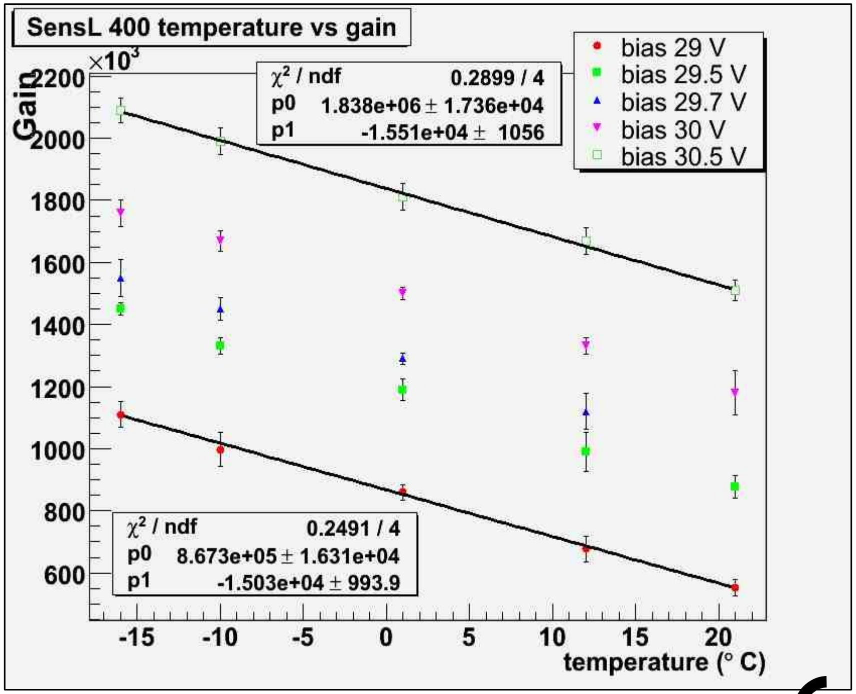
Zero Dark Count
Stability vs Environmental Condition variations

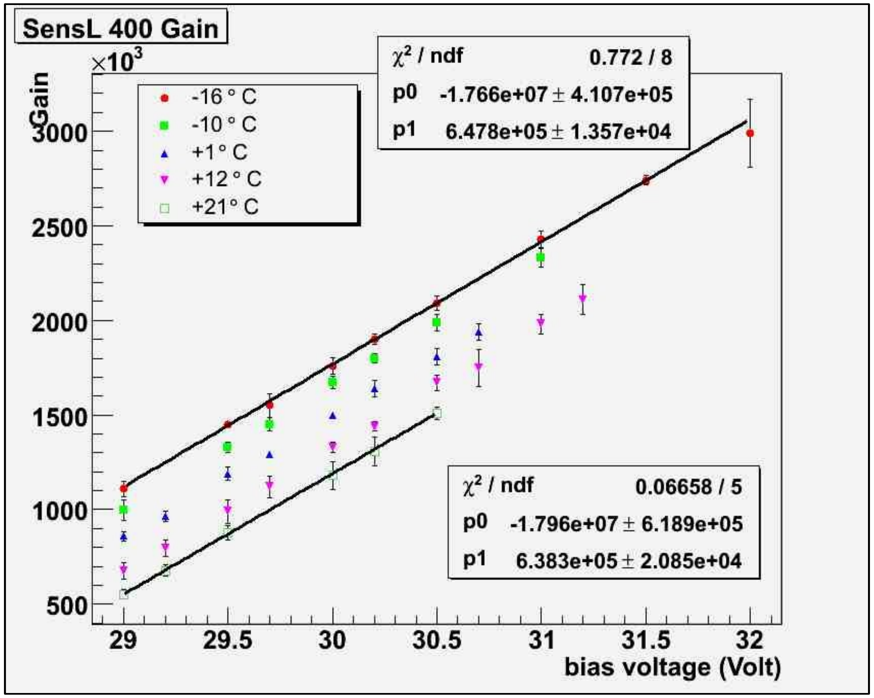
Temperature Dependence

- Pico Quant PDL 800 – light @ ~ 510 nm
- Cooling Box + Temperature control

Gain vs bias voltage

Gain vs temperature





$$\frac{dV}{dT} = -\frac{dG}{dT}\frac{1}{\frac{dG}{dV}}$$

- SensL 9k: 23.2 mV/°C ± 1.4 mV/°C
- SensL 04k : 23.6 mV/°C ± 0.9 mV/°C