



Towards a new generation of photodetectors: the VSIPMT (Vacuum Silicon PhotoMultipliер)

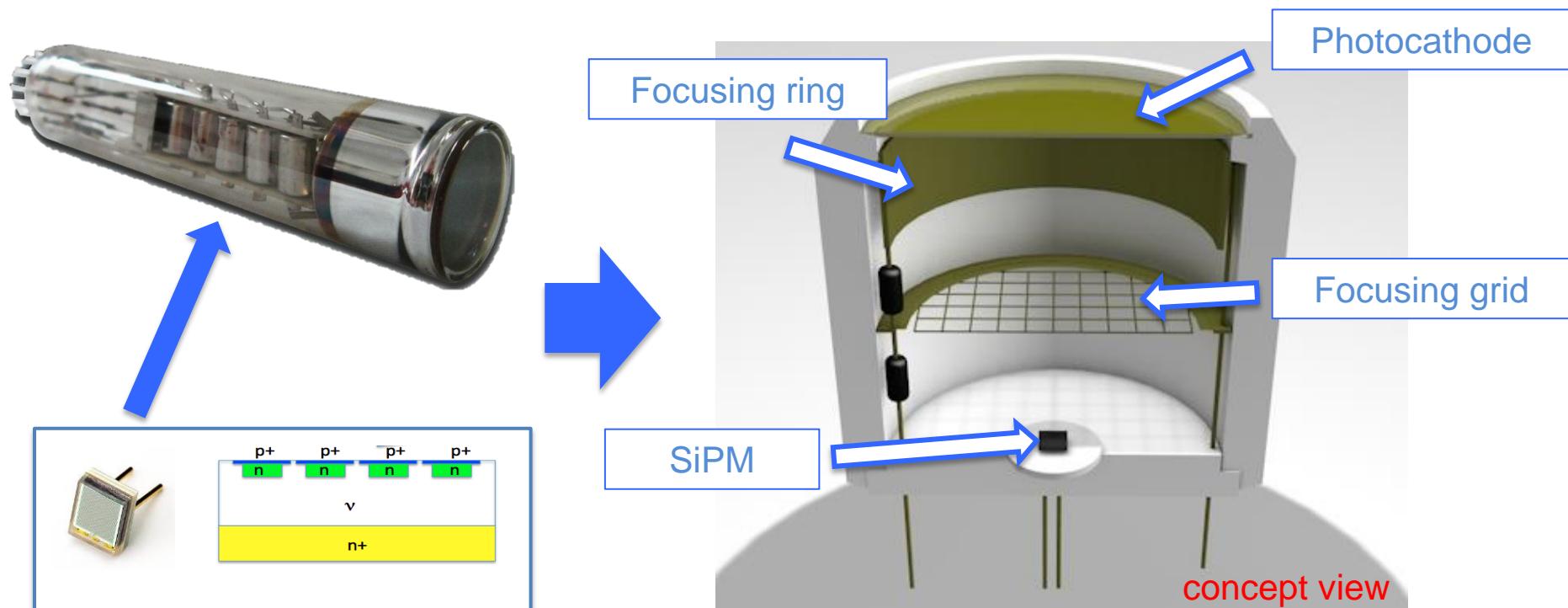
Gianfranca De Rosa

Università degli Studi di Napoli “Federico II” and INFN Napoli

Introduction

Vacuum Silicon PhotoMultiplier Tube (VSiPMT)

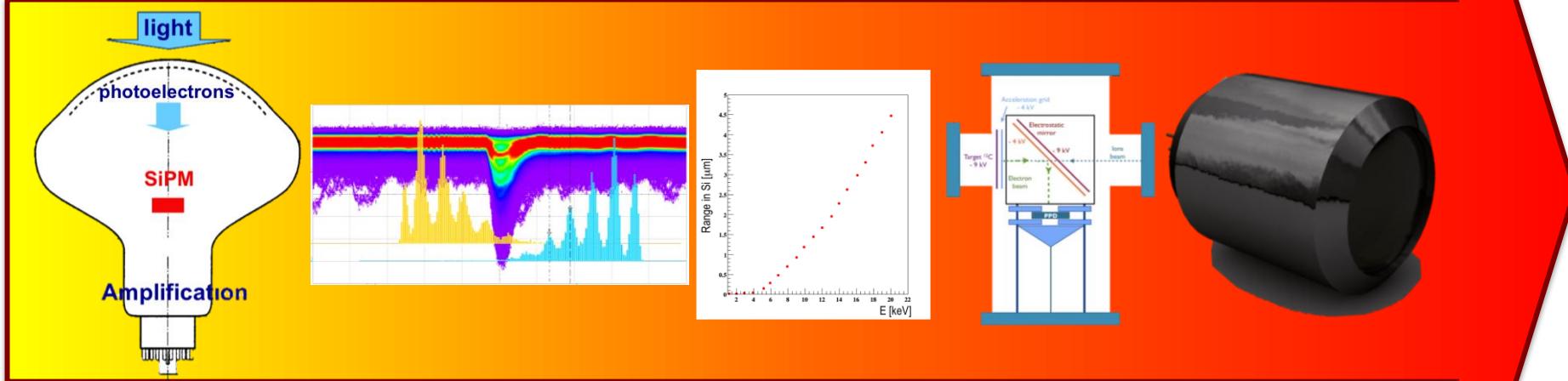
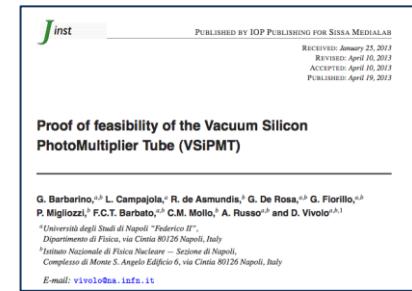
An innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope



The classical dynode chain of a PMT is replaced with a SiPM,
acting as an electron multiplying detector.

(NIM, G. Barbarino, R. de Asmundis, G. De Rosa, G. Fiorillo, V. Gallo, S. Russo (2008))

Timeline



2007

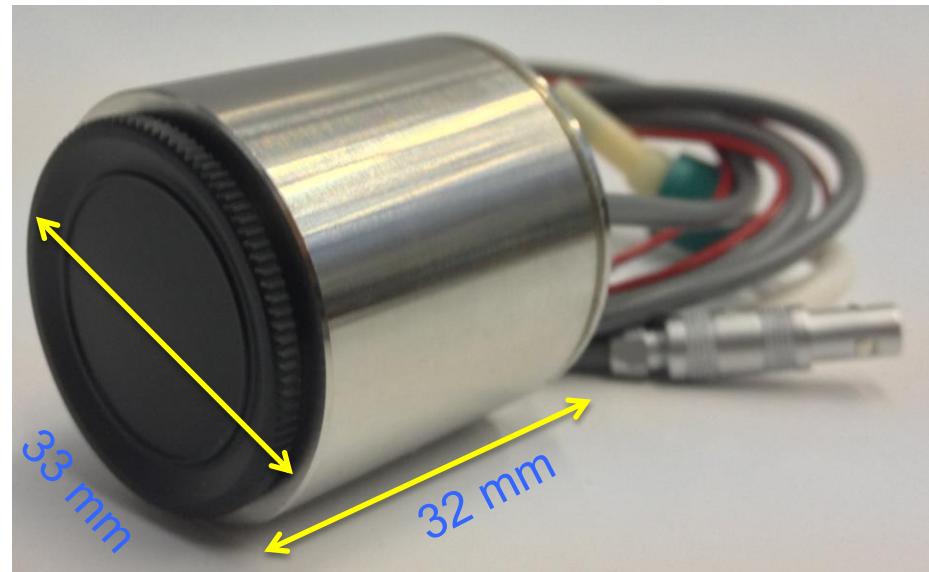
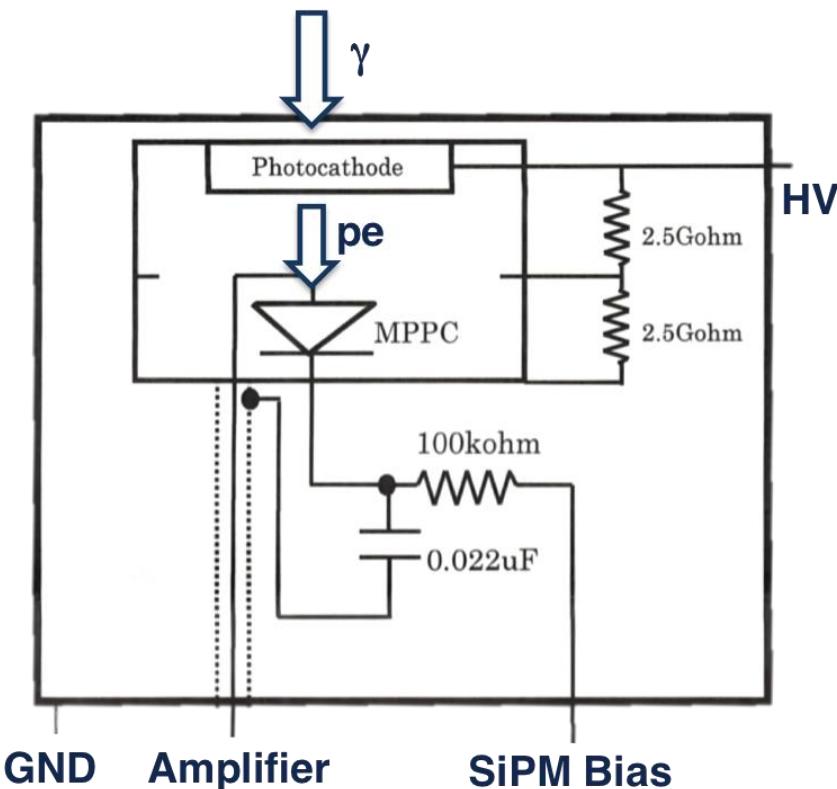


2013

The prototypes

HAMAMATSU

PHOTON IS OUR BUSINESS

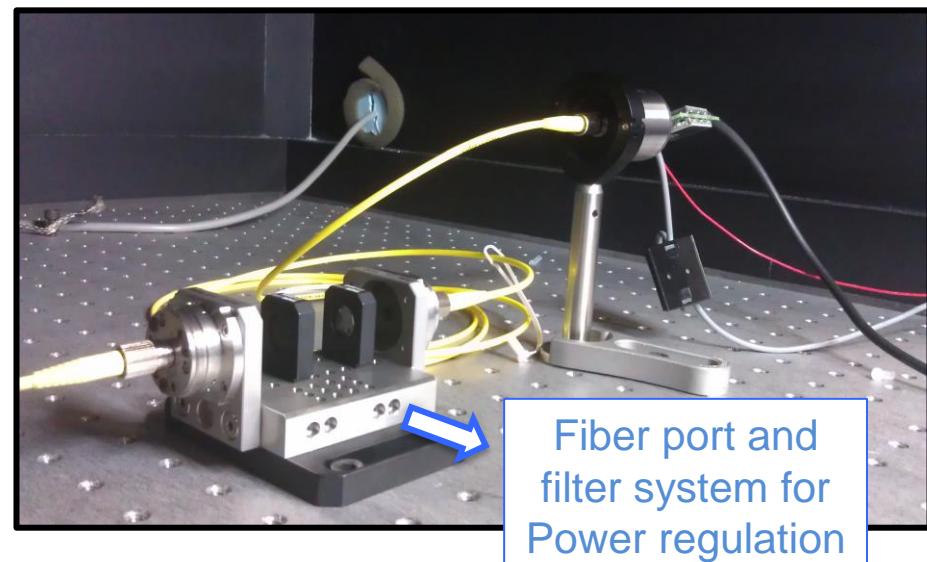
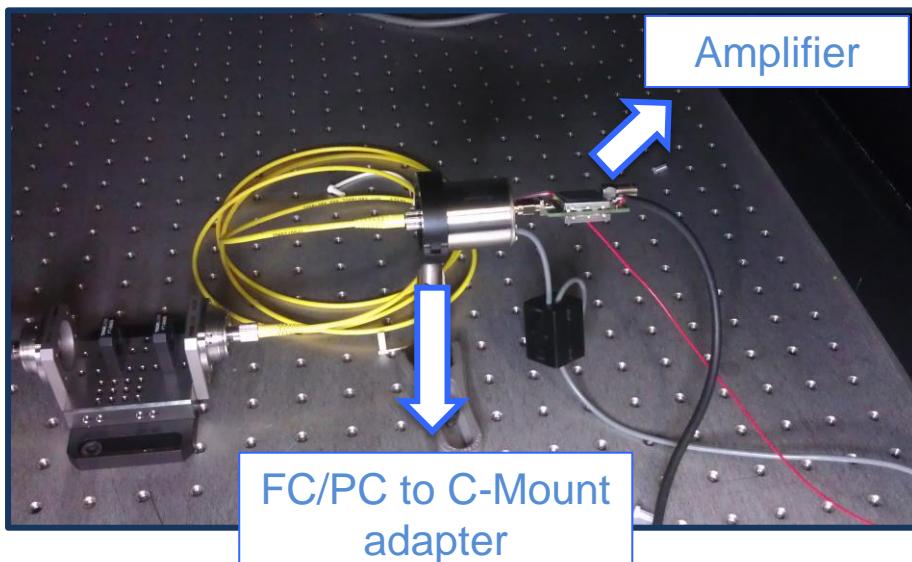
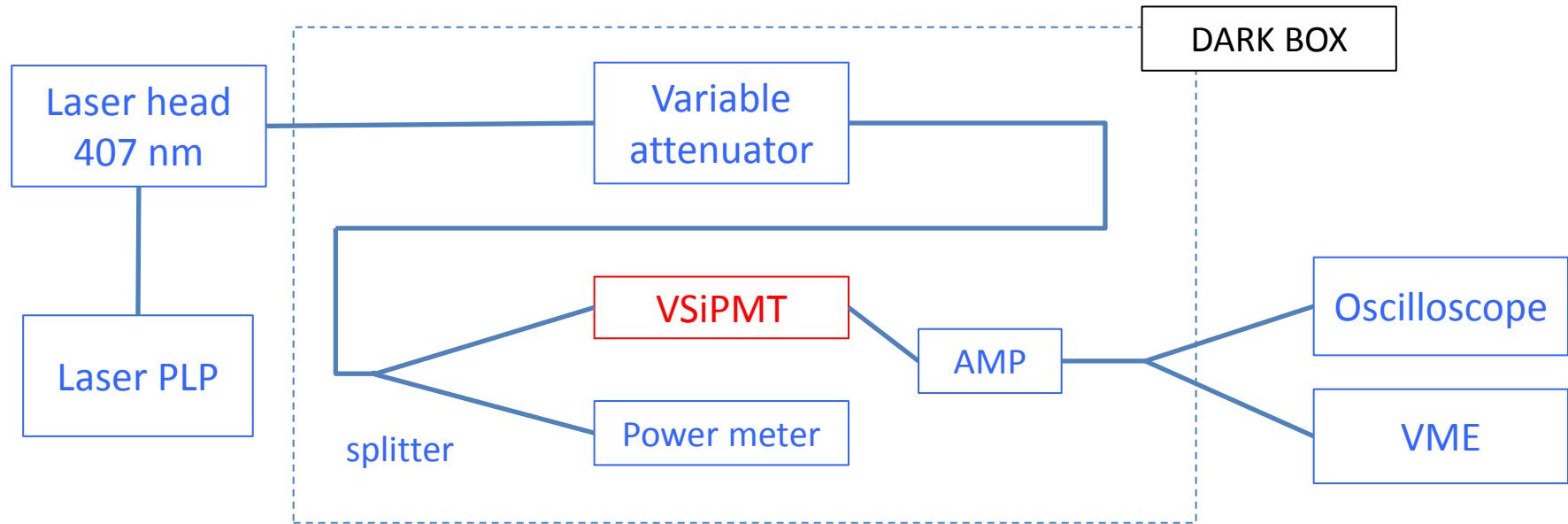


7x7 mm² entrance window
3 mm diameter GaAsP photocathode
2 prototypes:
MPPC 1 mm² / 50 μ m / 400 cells
MPPC 1 mm² / 100 μ m / 100 cells

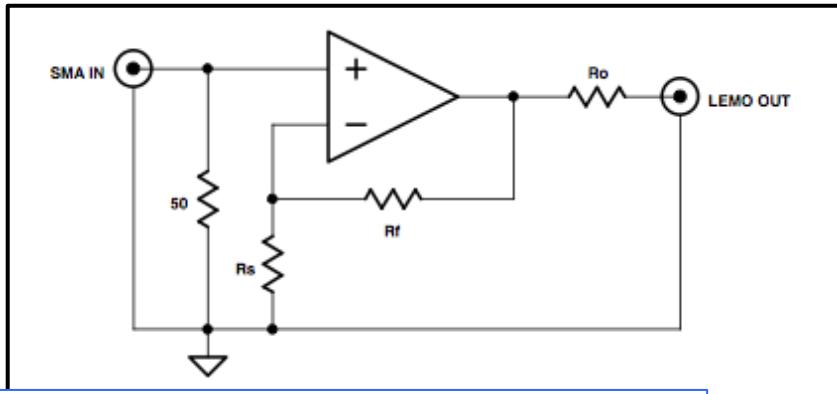
p^+nvn^+ configuration, special non-windowed series for ϵ optimization.
Lower voltage required (-2,5/3 kV expected).

No voltage divider: no power dissipation nor complicated circuits to reduce the dissipation
Only a very simple amplifier is required (typ. < 5mW).

Experimental setup



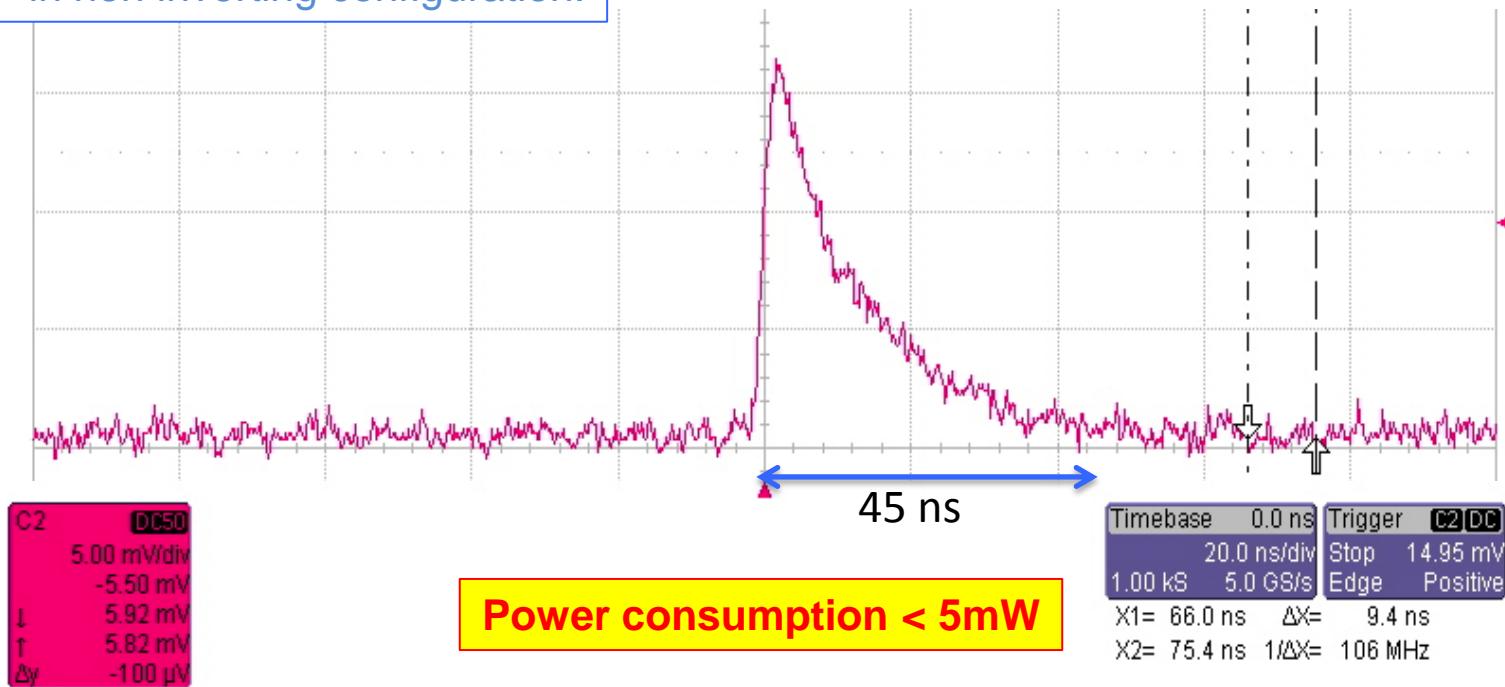
Amplification



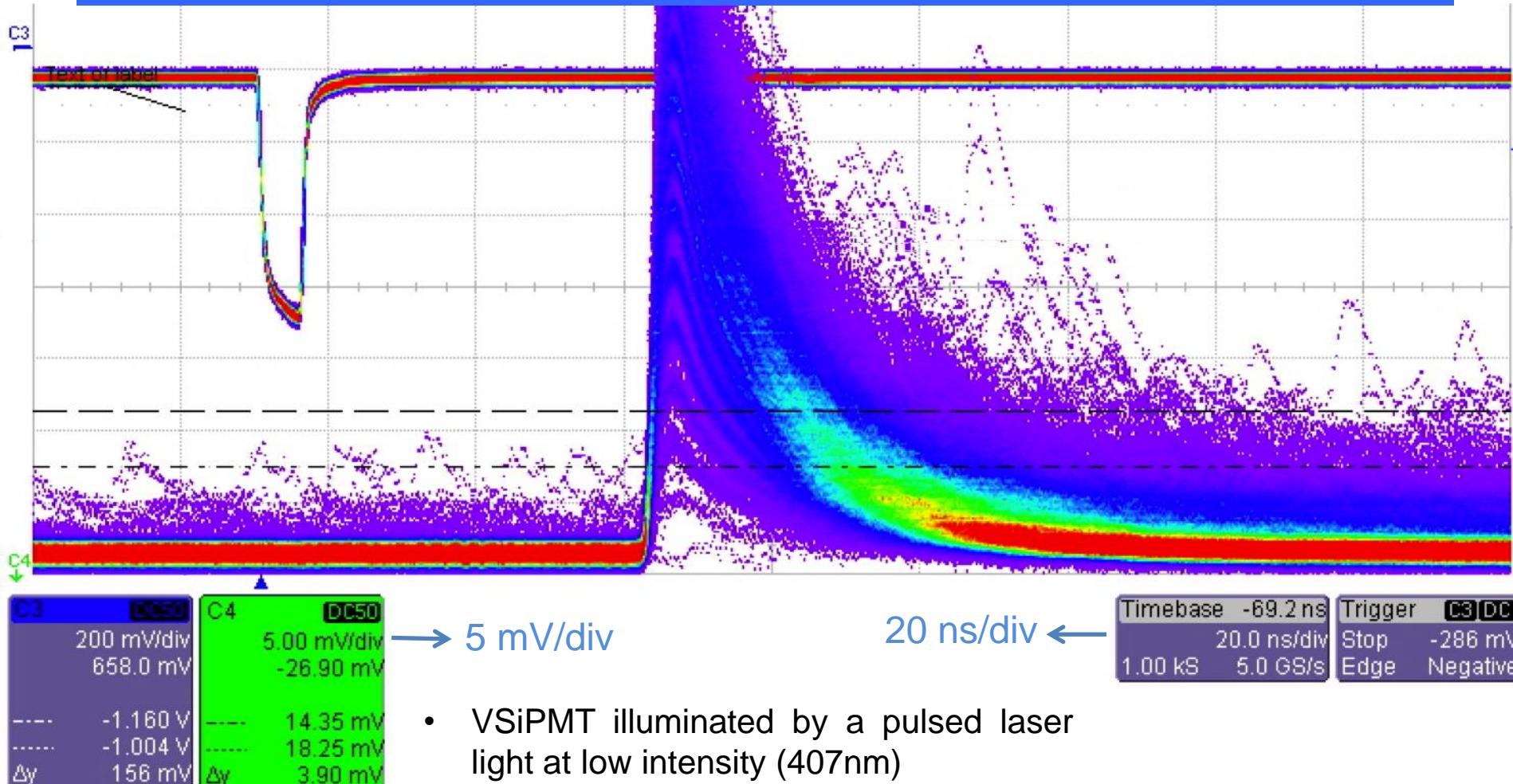
Single-state amplifiers based on an OP-AMP in non inverting configuration.



Three different gains: 10, 15, 20.

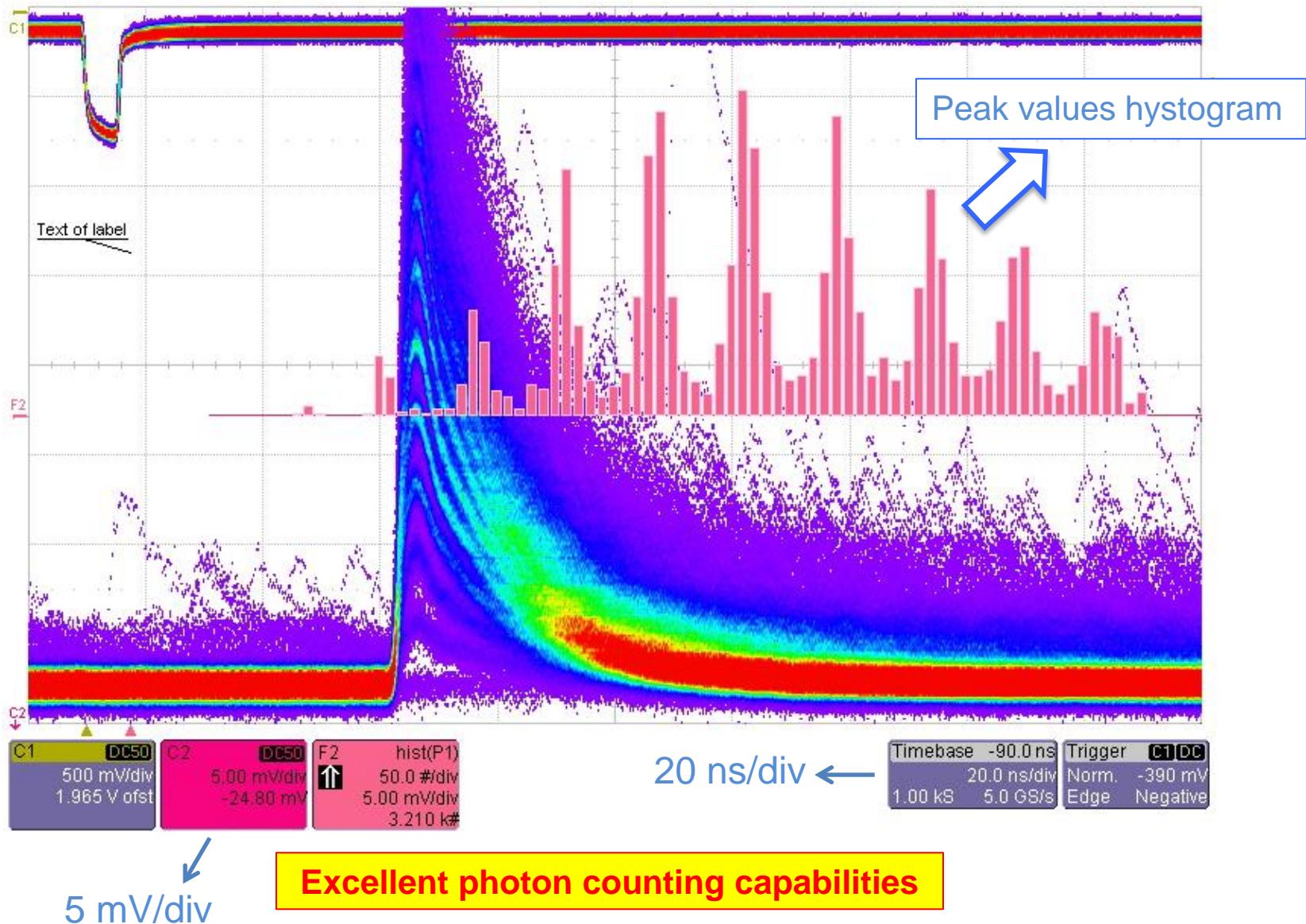


Waveforms



- VSIPMT illuminated by a pulsed laser light at low intensity (407nm)
- oscilloscope triggered in synch with the laser
- Responses for multiple triggers are overlaid

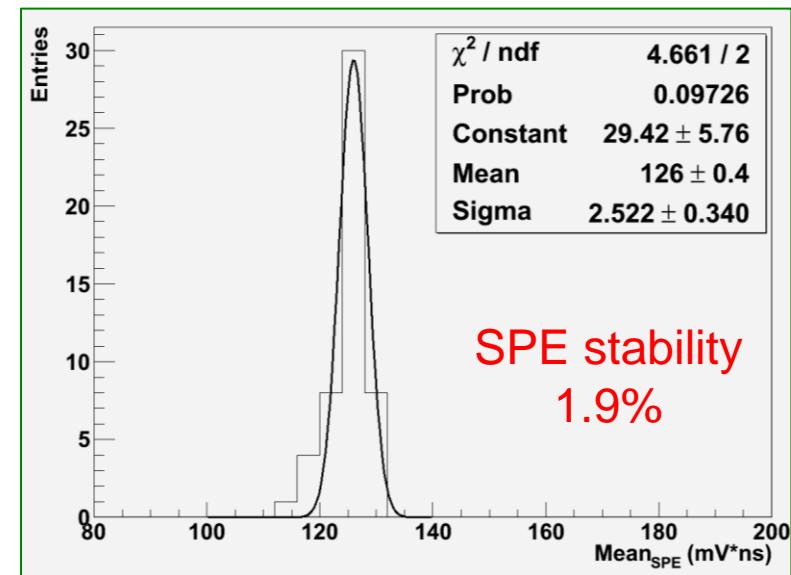
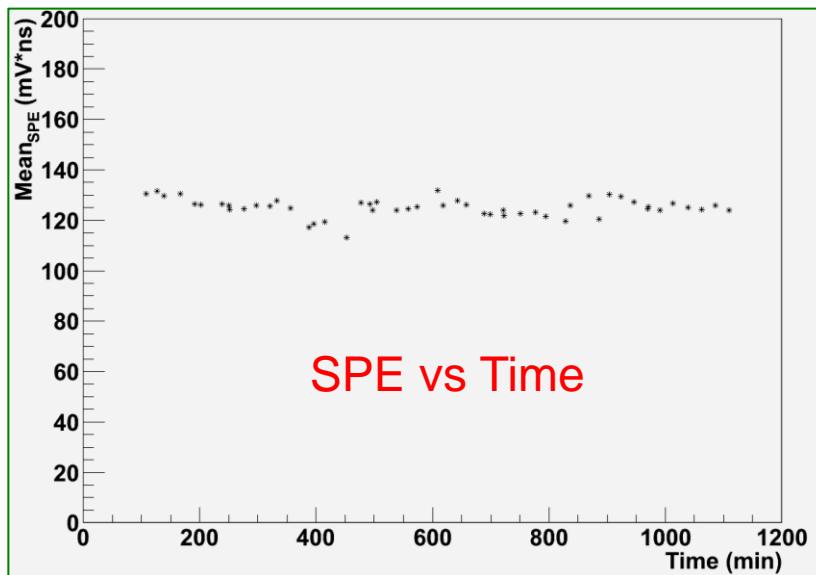
Waveforms



Time stability

100.000 waveforms with low intensity laser light have been acquired every 20 min for 20 hours to study the stability in time of the following parameters:

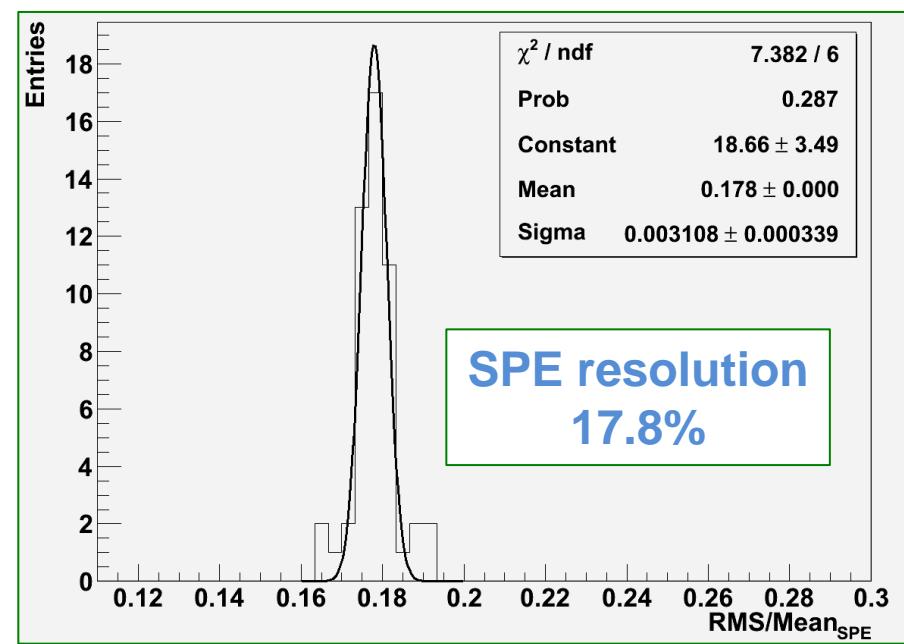
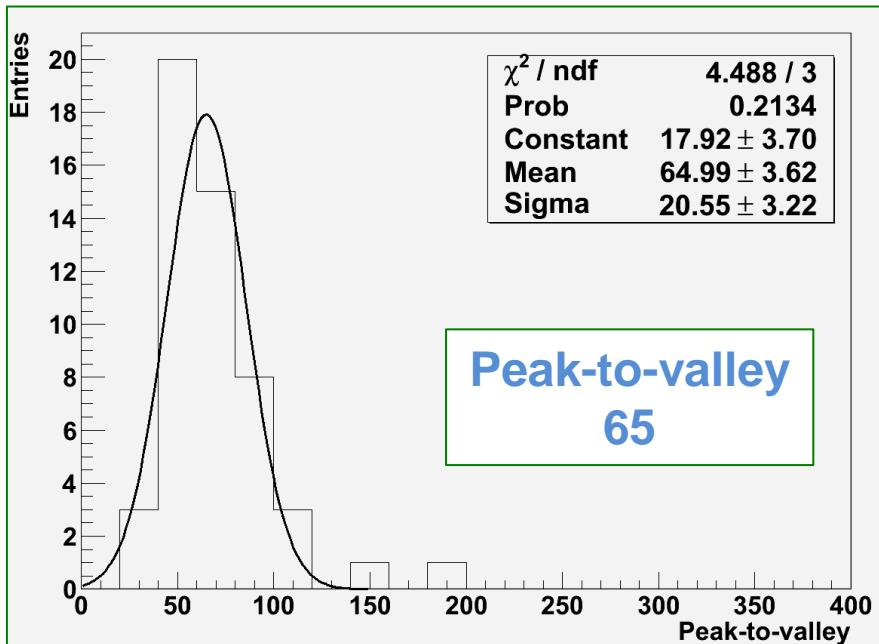
1. Single photo electron response (Mean_{SPE})
2. Resolution of the SPE ($\text{RMS}_{\text{SPE}}/\text{Mean}_{\text{SPE}}$)
3. Peak-to-Valley ratio



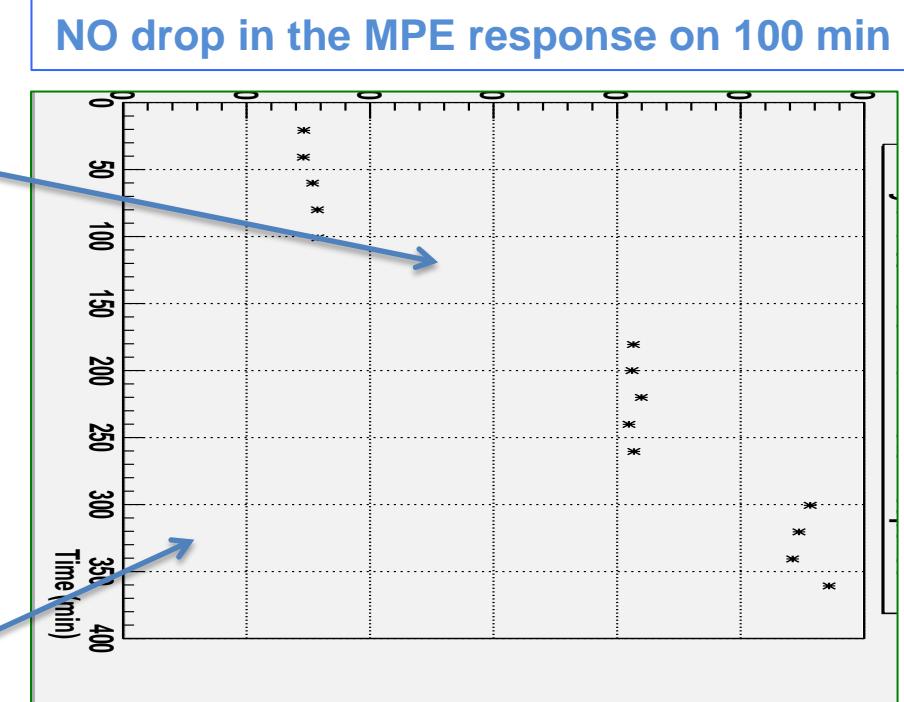
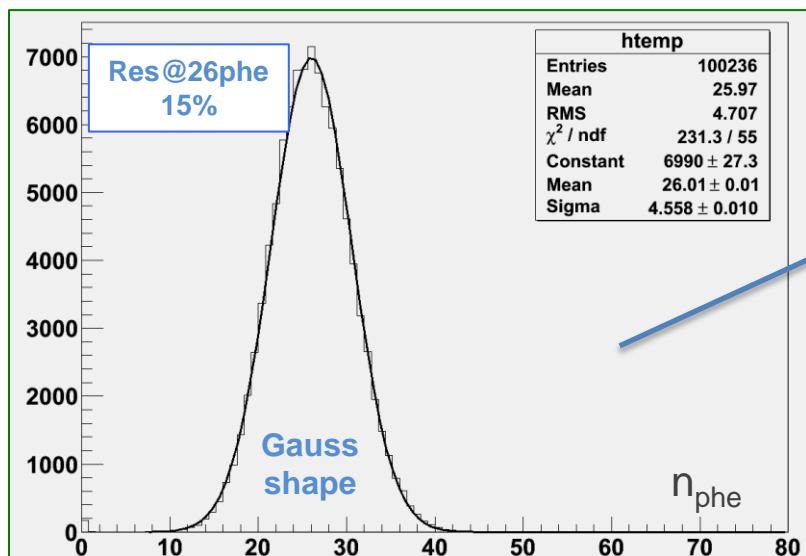
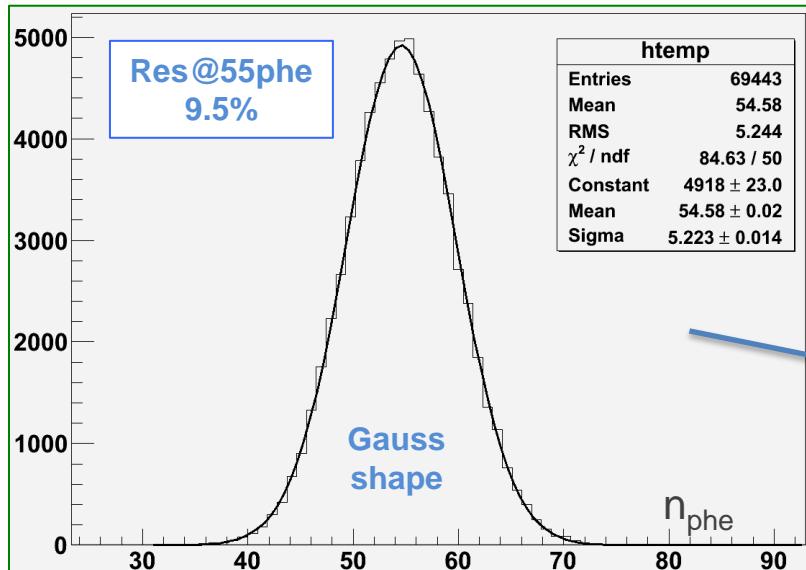
Time stability

100.000 waveforms with low intensity laser light have been acquired every 20 min for 20 hours to study the stability in time of the following parameters:

1. Single photo electron response (Mean_{SPE})
2. Resolution of the SPE (RMS_{SPE}/Mean_{SPE})
3. Peak-to-Valley ratio

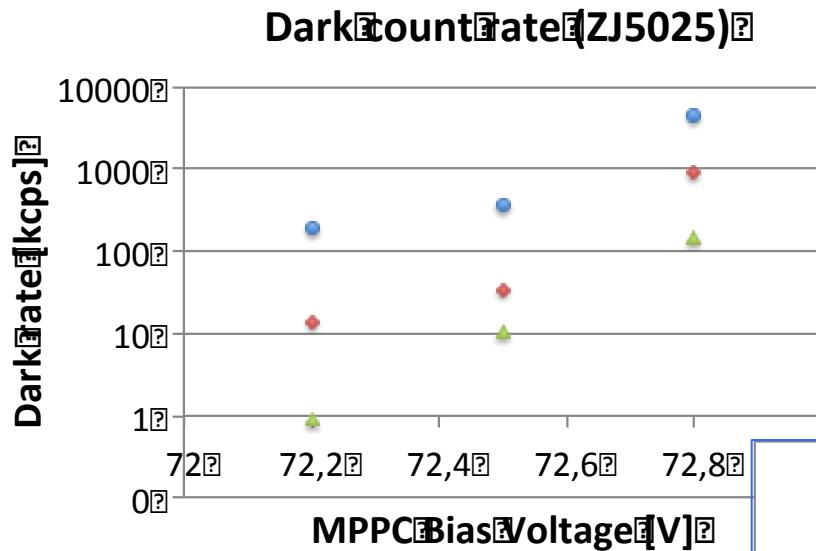


Multi photon response and stability

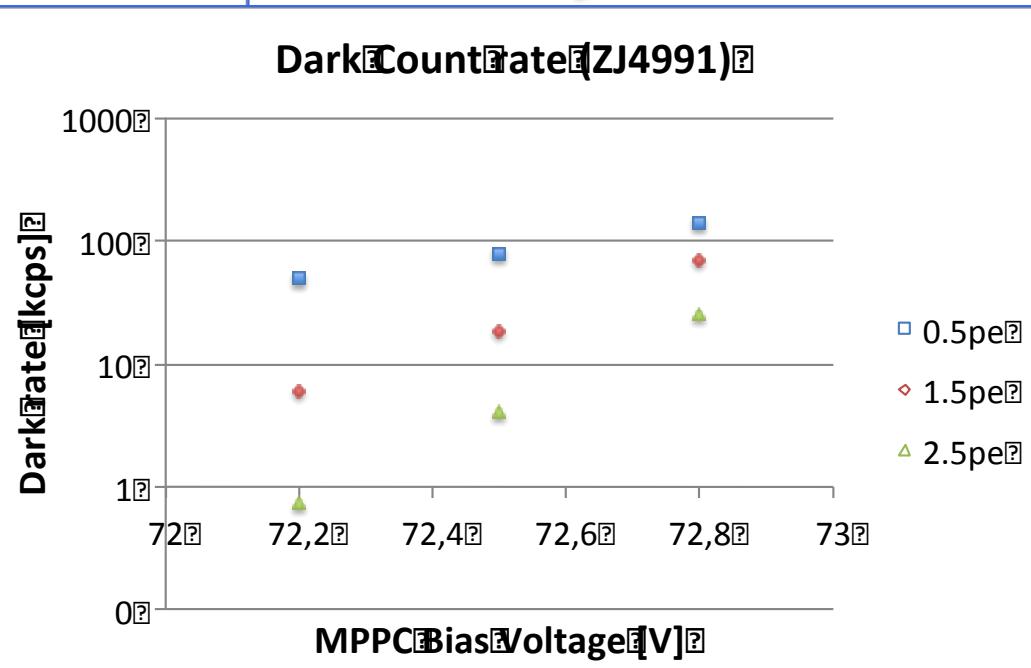


NO fatigue effect on high illumination

Dark counts/1



High DC rates
100 – 1000 kcps

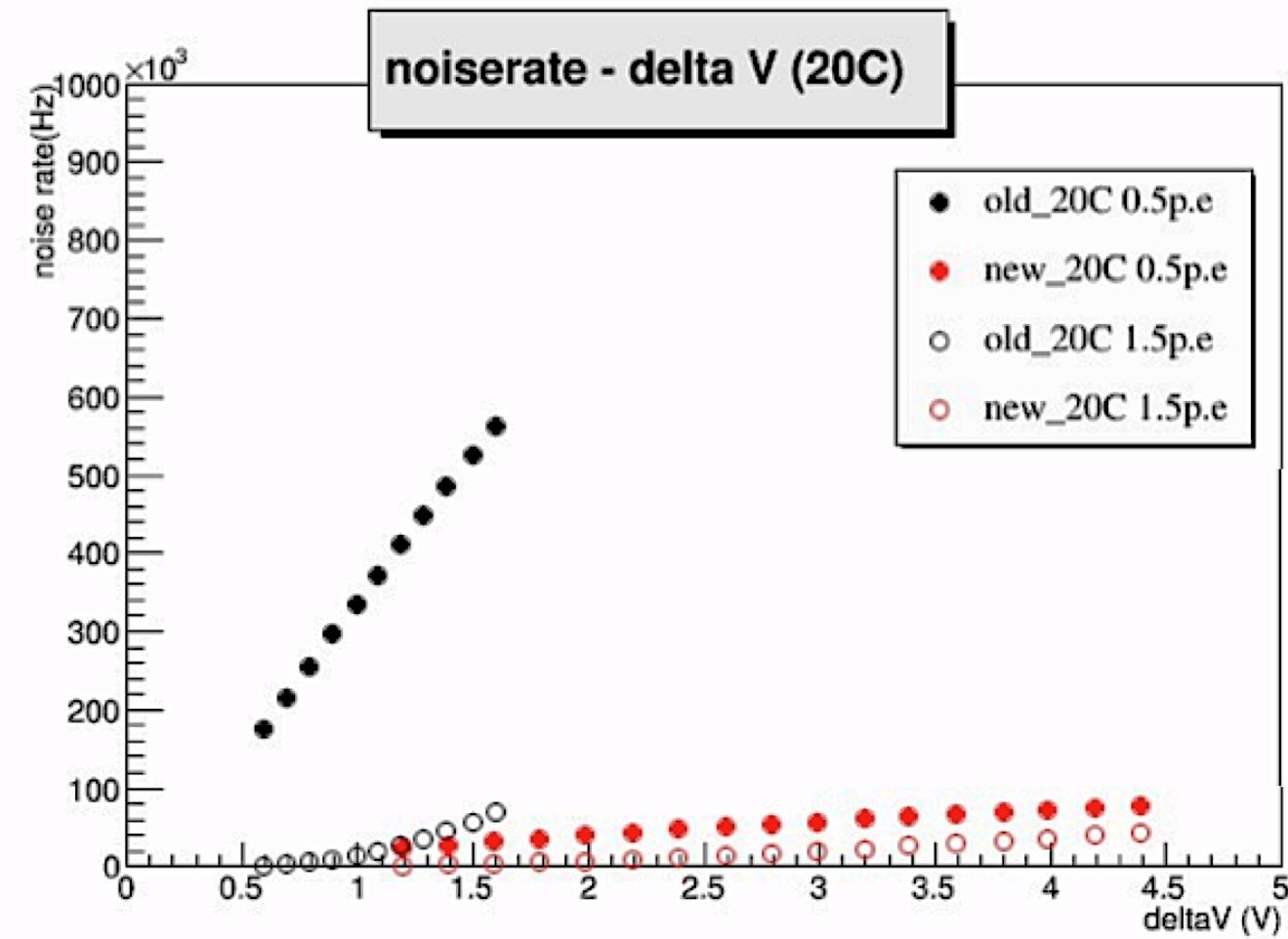


Decisively looks like a weak figure

However...

Dark counts/2

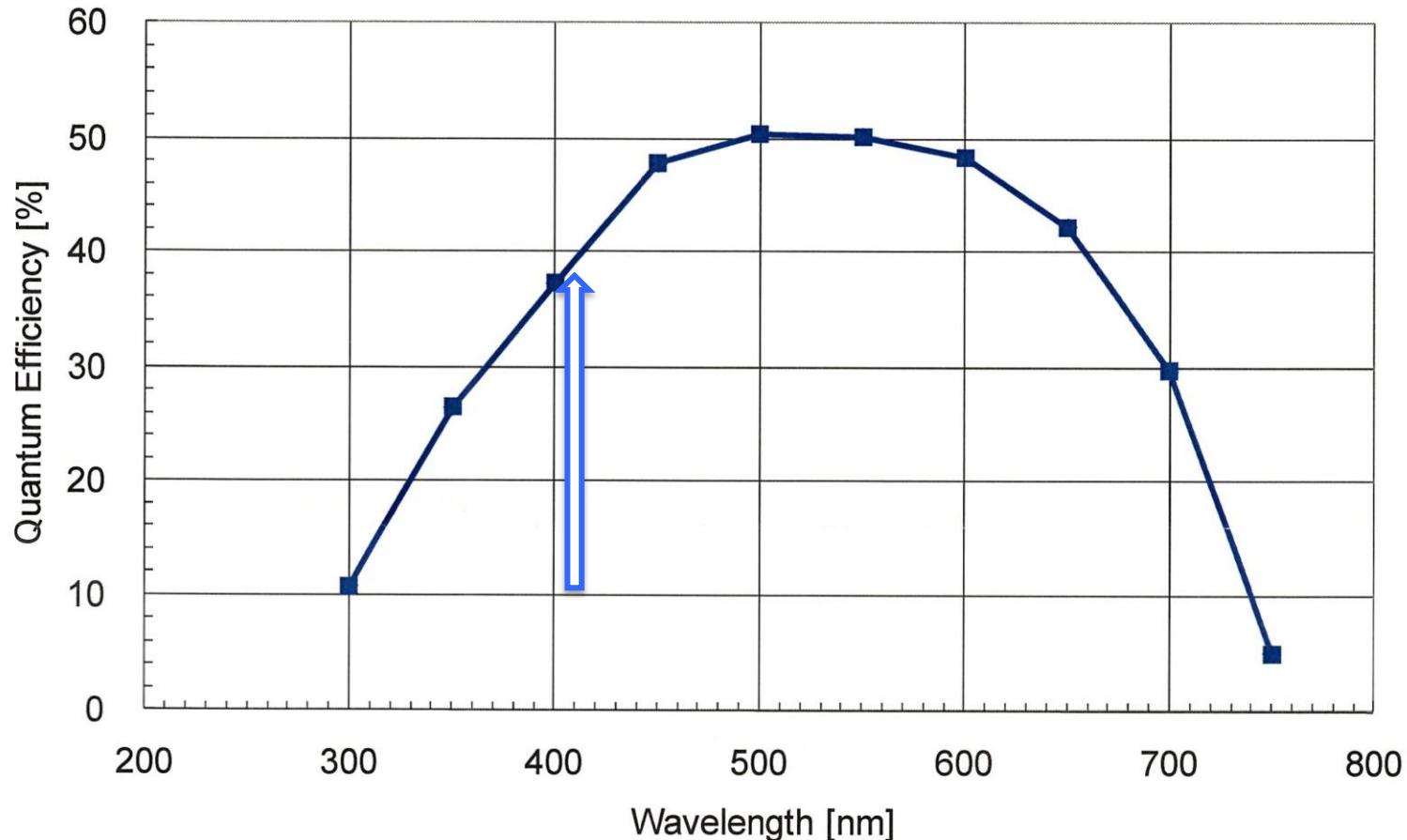
New generation Hamamatsu MPPCs



Efficiency

Photocathode Spectral Response

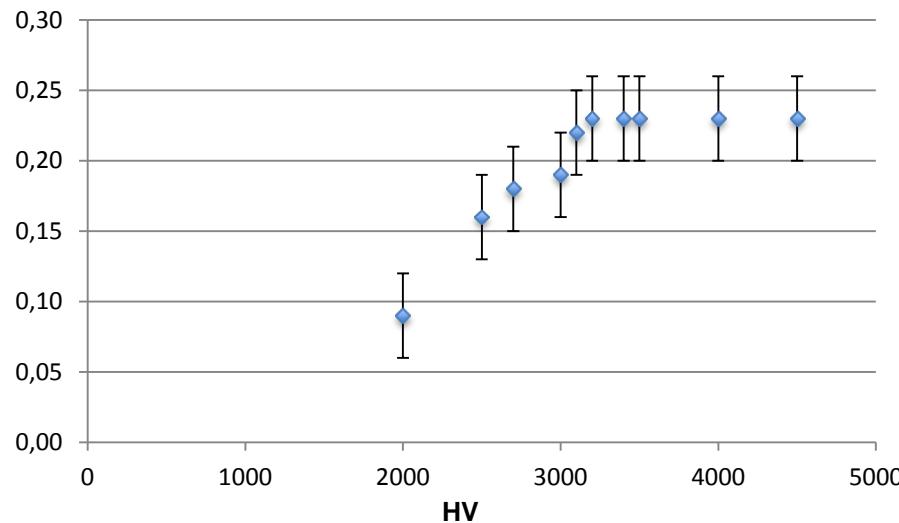
(Photocathode applied voltage: 90V)



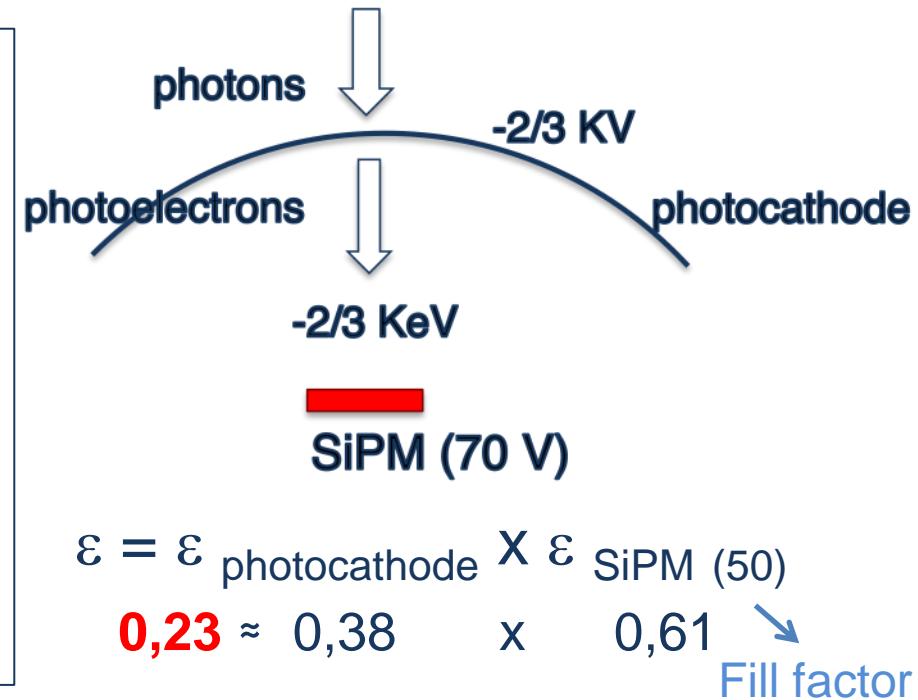
Efficiency

VSiPMT (ZJ5025) Operating point

Efficiency



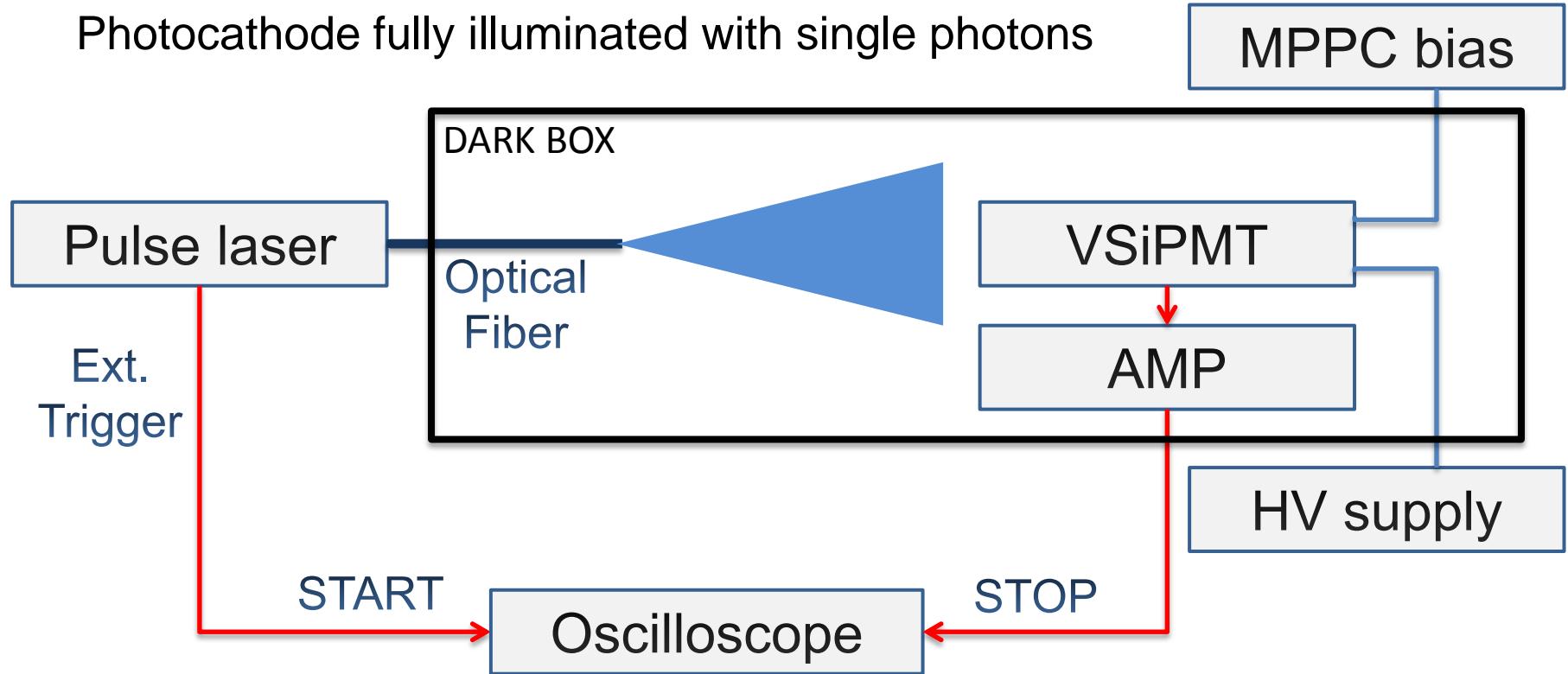
VSiPMT (ZJ5025)
measured efficiency
 $\varepsilon = 0.23$
in agreement with
expectations



Efficiency is highly stable over 3200 V.
No need for high voltage stabilization.

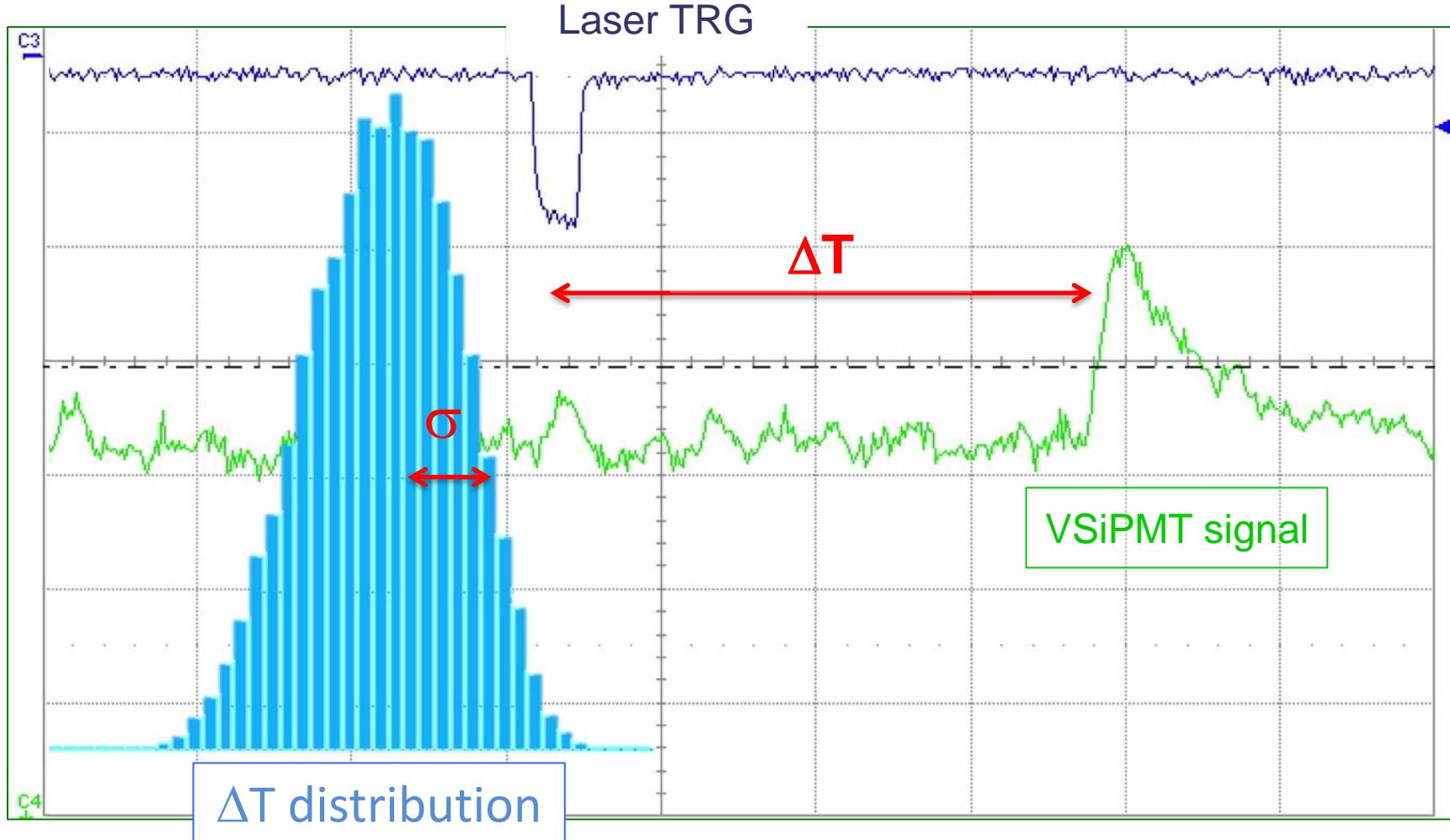
- Reducing the SiO_2 coating layer it will be possible to reach the plateau region at even lower voltages.
- The HV implies NO power consumption (NULL current) unlike PMTs. Moreover, for PMTs the power consumption increases with the rate!

Photocathode fully illuminated with single photons



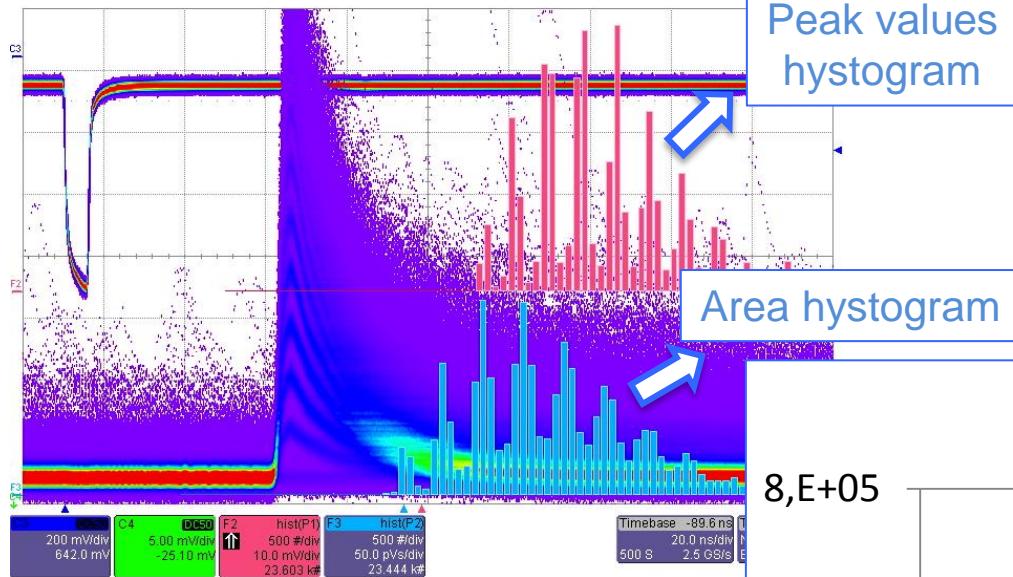
- The output from the VSiPMT is fed as the stop signal via a discriminator;
- We measure the time interval between the "start" and "stop" signals.

Transit Time Spread



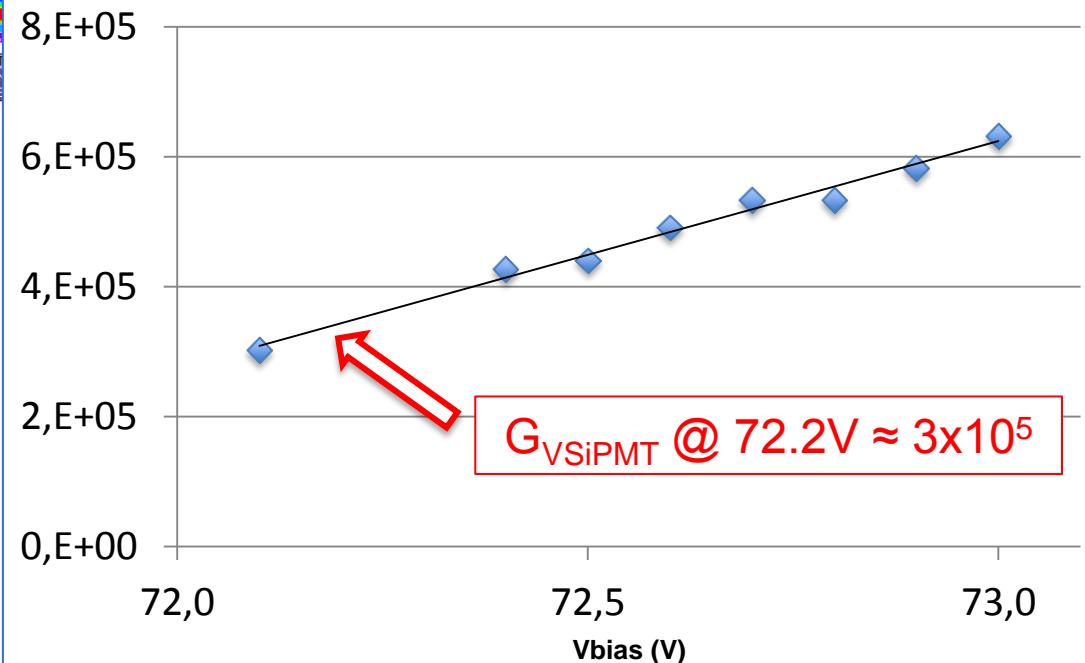
VSiPMT
TTS (sigma) < 0.5 ns

Gain



Measure of the charge corresponding to 1 pe
(peaks in area histogram)

VSiPMT (ZJ5025) Gain

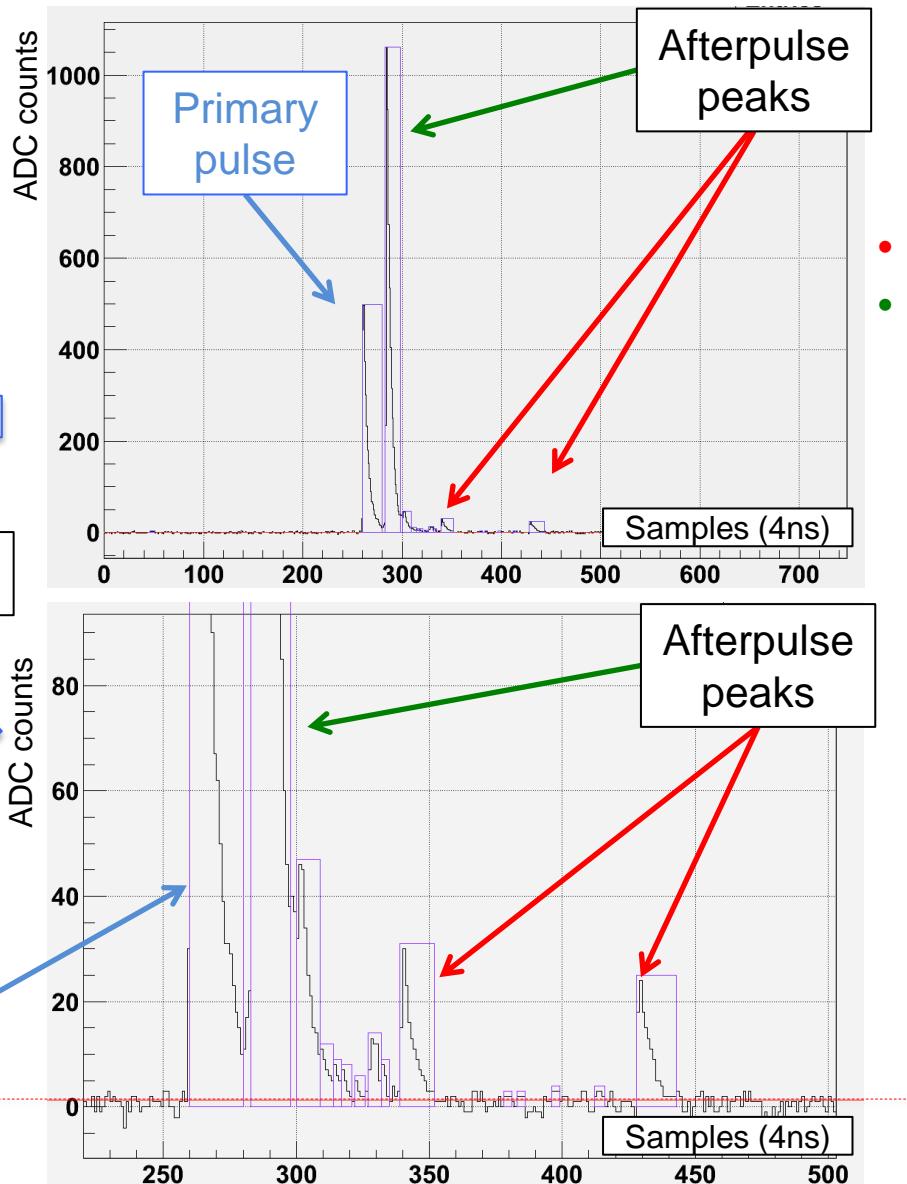


$$\text{Total Gain} = G_{VSiPMT} \times G_{AMP}$$

Ideal Working Point: 72.2V

- $G \approx 6 \times 10^6$ ($G_{AMP} = 20$);
- Dark Count ≈ 60 kcps;
- TTS < 0.5ns.

Afterpulses



2 Afterpulse classes:

- SiPM afterpulses (1-3 pe, $\approx 10\%$)
- “Vacuum” afterpulses (gas residuals contribution, high intensity, $\approx 0.02\%$)

Peak finder:

Searches for peaks above 3 RMS of the noise level distribution

For each peak we reconstruct:

Arrival time
Integral
Pulse height

Afterpulse rate

$$R_{AP} = \frac{\text{å} I_{AP}}{\text{å} I_{MP}}$$

R_{AP} : afterpulse rate;

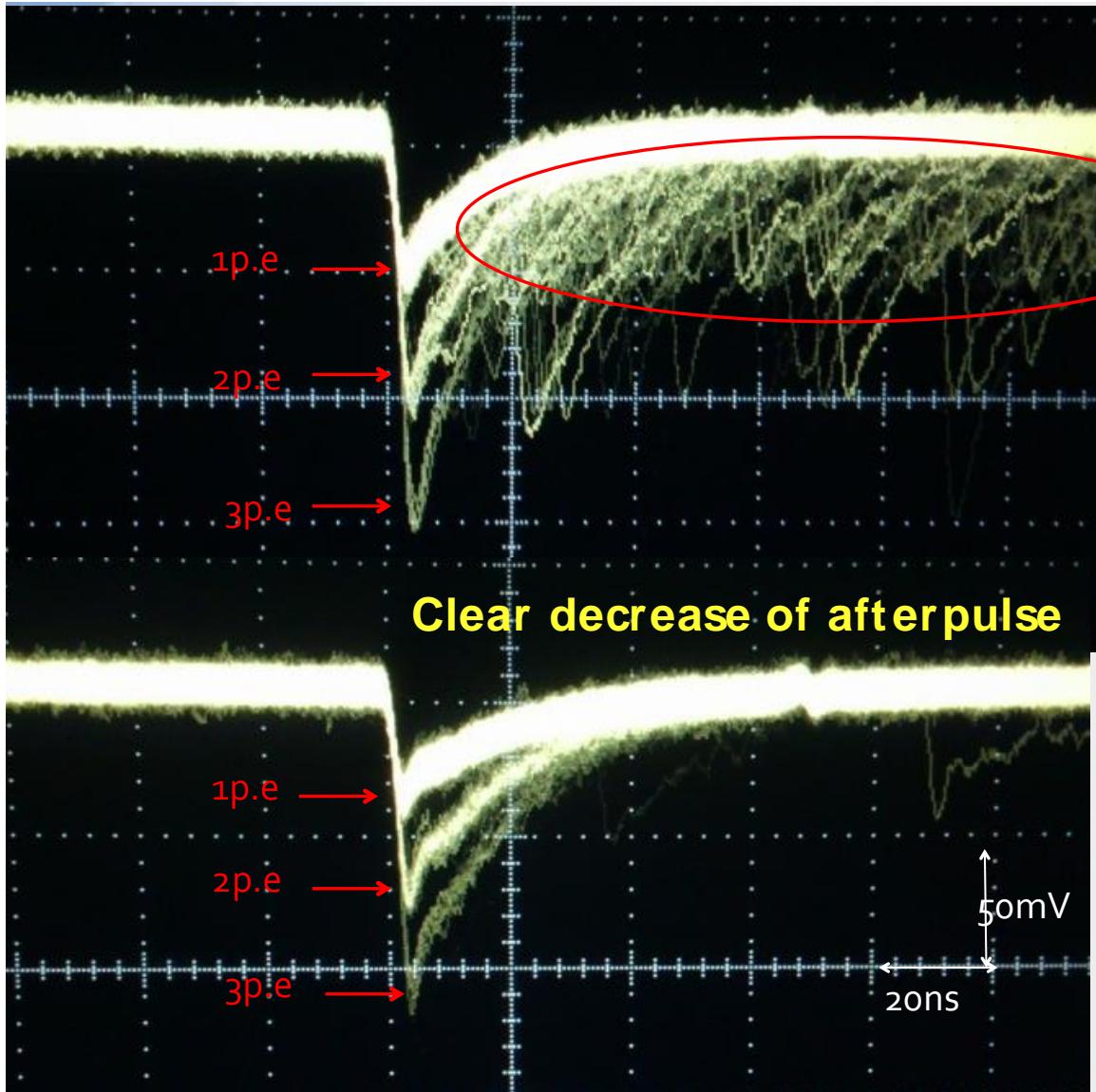
I_{AP} : sum of the intensities of each afterpulse peak found in 100.000 waveforms;

I_{MP} : sum of the intensities of the primary pulses of 100.000 waveforms;

Afterpulse rate Table summary

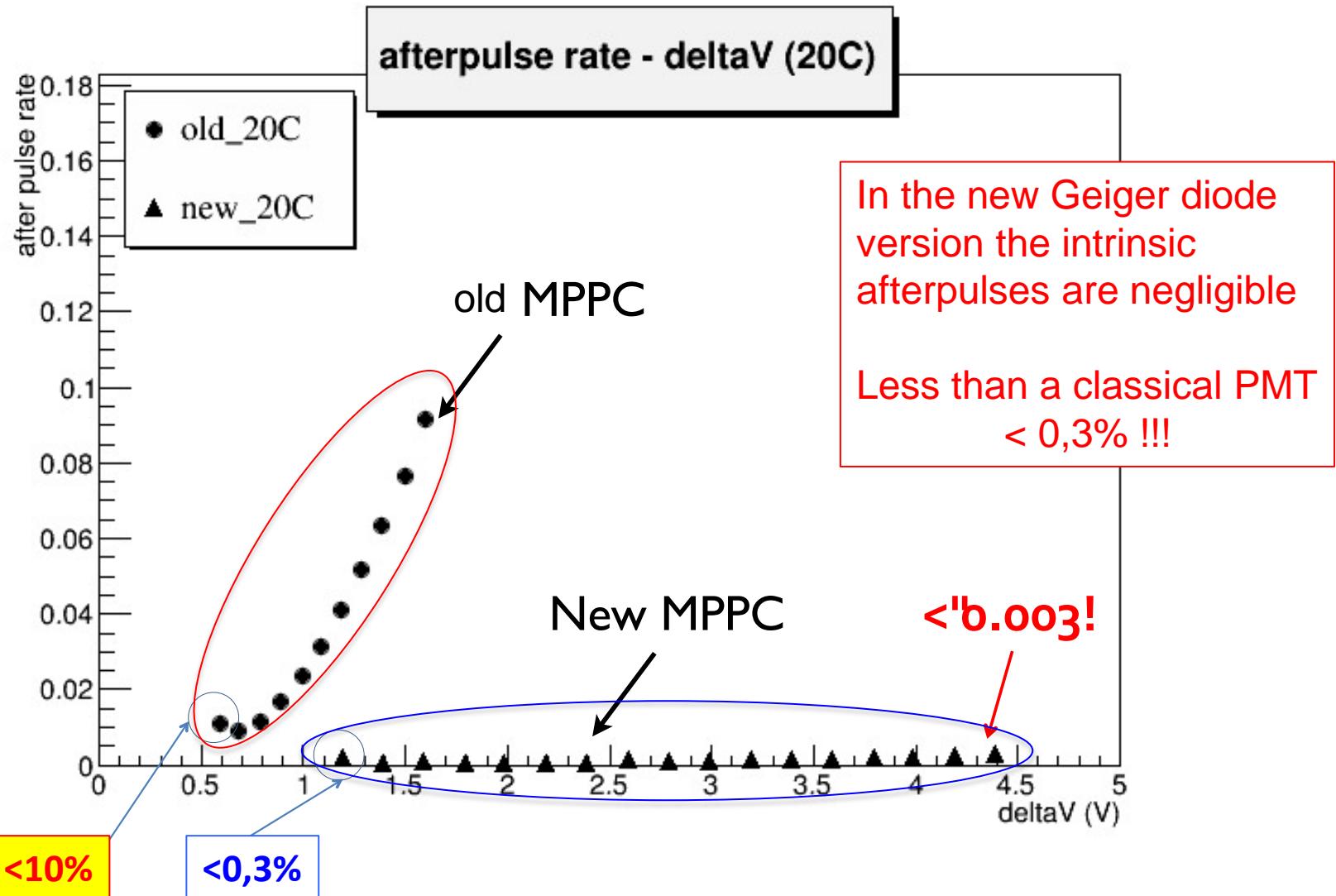
Threshold (pe)	Afterpulse rate
>0.50	10.41%
>0.75	9.40%
>1.00	7.34%
>2.00	2.38%
>5.00	0.23%
>10.00	0.02%

Afterpulse rate

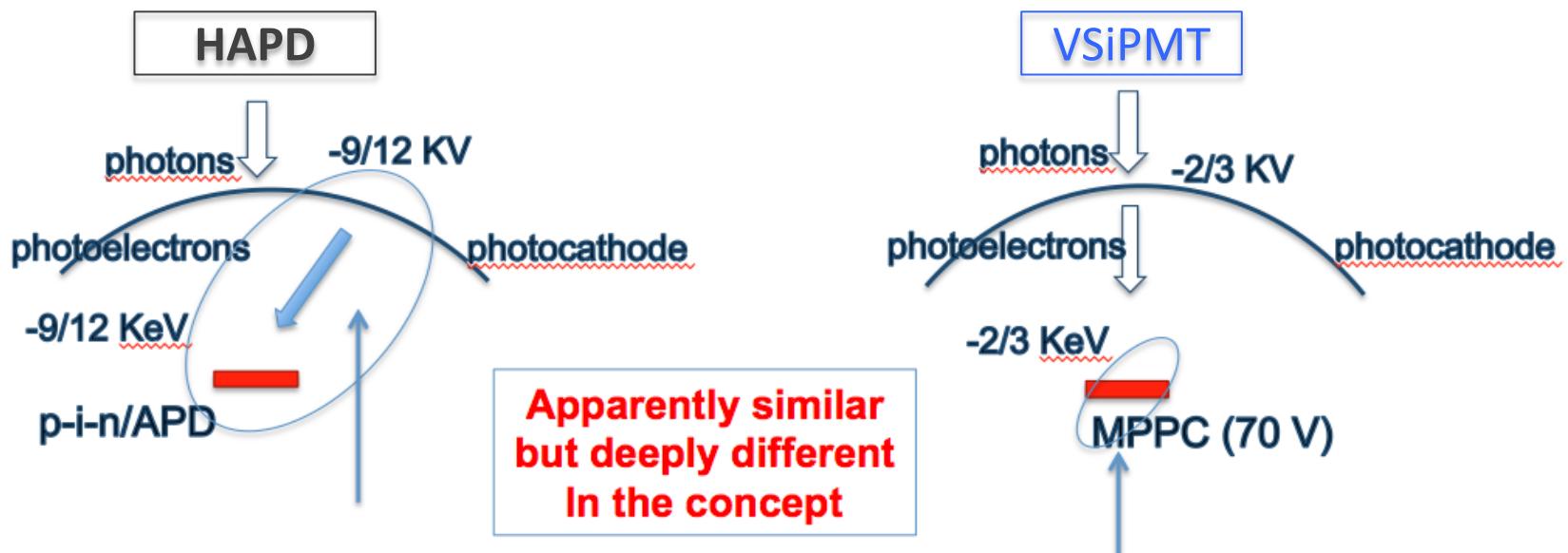


3

Afterpulse rate



VSiPMT vs HAPD



Need of HV to obtain a high gain

High gain obtained with low voltage in the SiPM

Drawbacks of the APD solution

- $G = E_{phe}/E_{e,h} \approx 10^4 - 10^5$
- too low Gain. HV gain required
- G depending on HV
- Need a strong HV critical stabilization.
- Difficult and expensive insulation

Advantages in the VSiPMT solution

- $G > 10^6$: a factor 10 higher.
- Low HV, no need for bombardment gain only energy for photoelectron transfer
- Low voltage Gain: easy to stabilize
- Normal insulation

VSIPMT VS PMT

	PMT	VSiPMT	comparison
Efficiency	Photocathode x 1 st dynode	Photocathode x Fill factor MPPC ($\rightarrow 1$)	\approx comparable (slightly worse)
Gain	$10^5 - 10^6$	$10^5 - 10^6$	\approx equivalent
Timing	nsec	fractions of nsec (no spread dynodes)	+ VSiPMT
Power Consumption	Divider Dissipation	No dissipation: just amp. G=10-20 (<5mW)	+VSiPMT
Stability H.V.	H.V. stabilization for stable gain	No H.V. stability (plateau)	+VSiPMT
Dark counts	\approx kHz @ 0.5pe	VLT $\rightarrow \approx$ 10Hz	+VSiPMT
Photon counting	difficult	excellent	+VSiPMT
Peak-to-valley ratio	≈ 3 (typ.)	> 60	+VSiPMT
Afterpulse (@0.5pe)	$\approx 10\%$	Next gen. MPPC <0.3%	+VSiPMT
SPE resolution	$\approx 30\%$ (typ.)	$\approx 17.8\%$	+VSiPMT

Conclusions and Perspectives

VSiPMT is an innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope

It has many **UNPRECEDENTED** features, such as:

- Photon counting capability;
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

making it a very attractive solution in many Cherenkov experiments

STILL IMPROVABLE!!

New generation of Hamamatsu MPPCs:

- sensibly lower afterpulse rates;
- lower noise: much reduced dark counts;
- higher gain → no amplification required (persp.)

An attractive solution for Cherenkov experiments

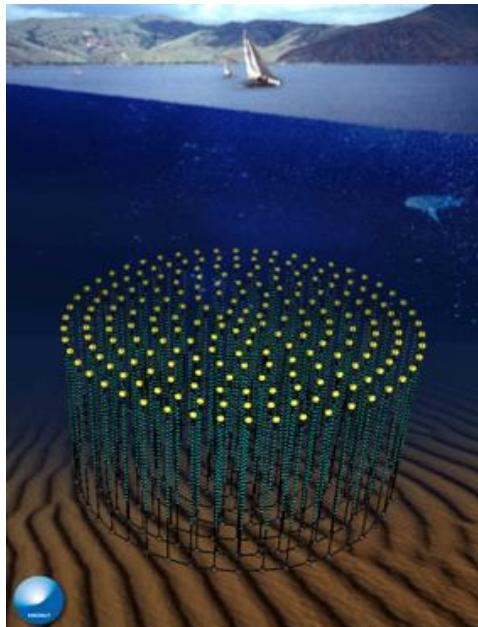
VSIPMT

Unrivalled performances
optimal solution for Cherenkov
experiments

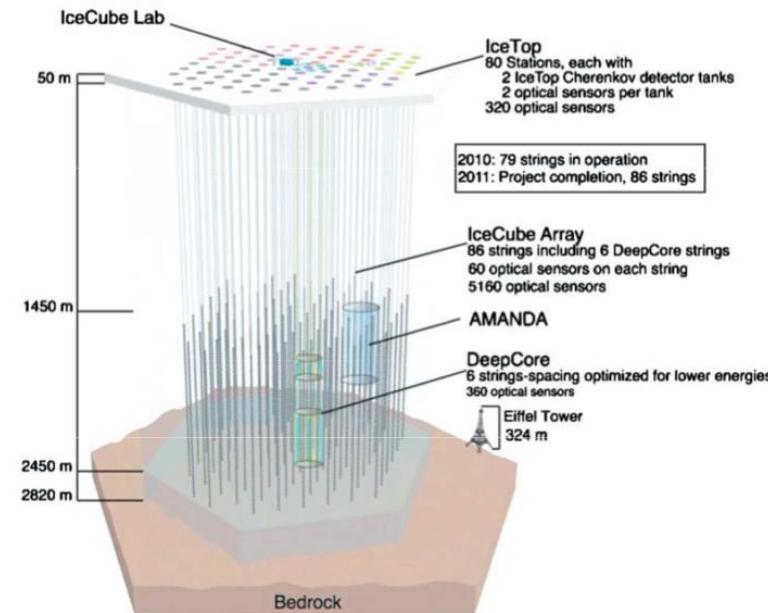
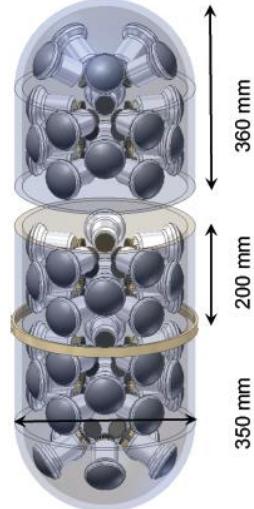
Unprecedented features:

- Photon counting capability;
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

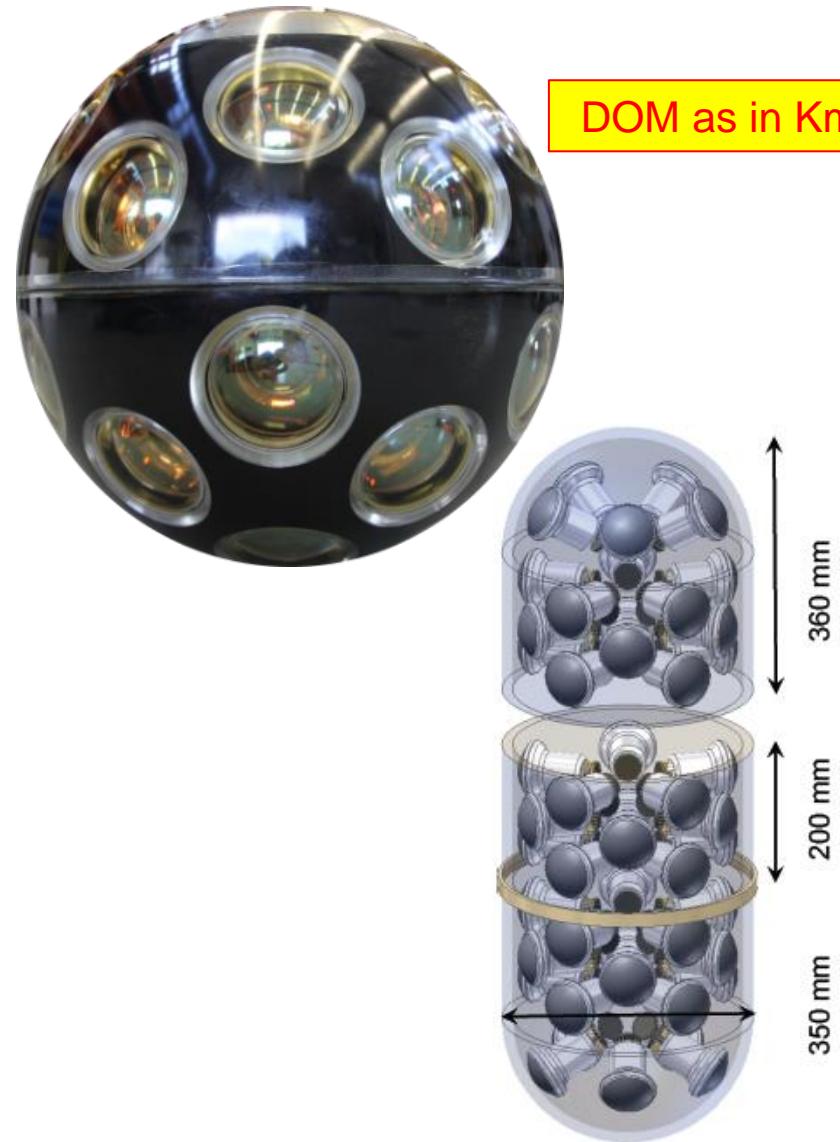
Application to under-water/under-ice neutrino telescopes



KM3NeT/Icecube (m)DOM



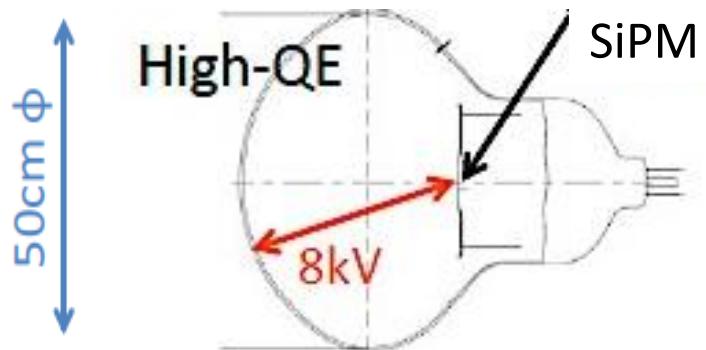
...and for applications in HK



- Use small PMTs
 - High granularity required for background rejection in KM3Net
 - Several manufacturer of small PMTs
- Photon trap could be used in this configuration
 - Cover the inner side of the glass with dichroic mirrors
 - Add wavelength shifter sheets with mirror backing between PMTs

F. Retièr @ NNN13: International Workshop
on Next generation Nucleon Decay and
Neutrino Detectors
11-13 November 2013 Kavli IPMU

...and for applications in HK

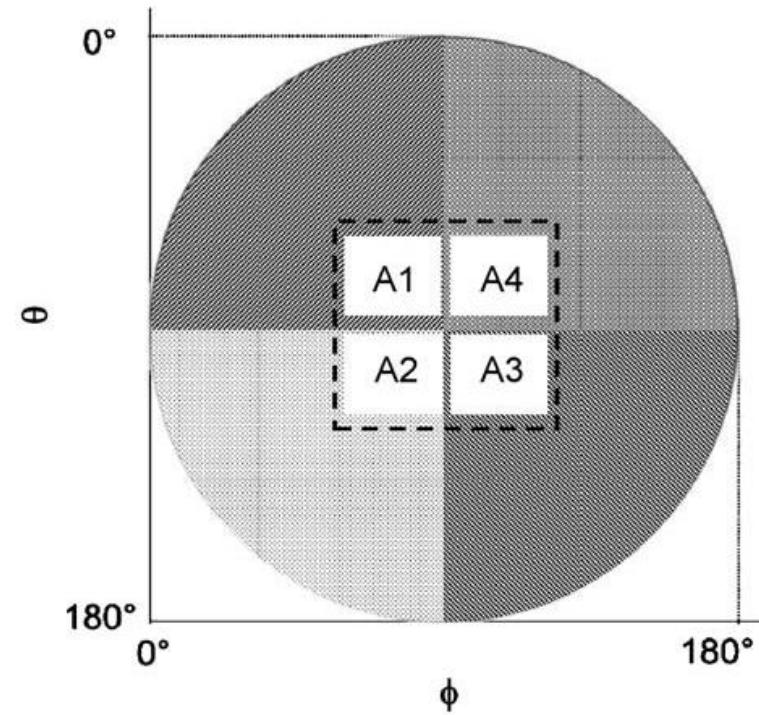


Very Large
Photocathode for
the VSiPMT

Advantages with respect to the
HPD solution: higher gain

Segmented
Photocathode
VSiPMT

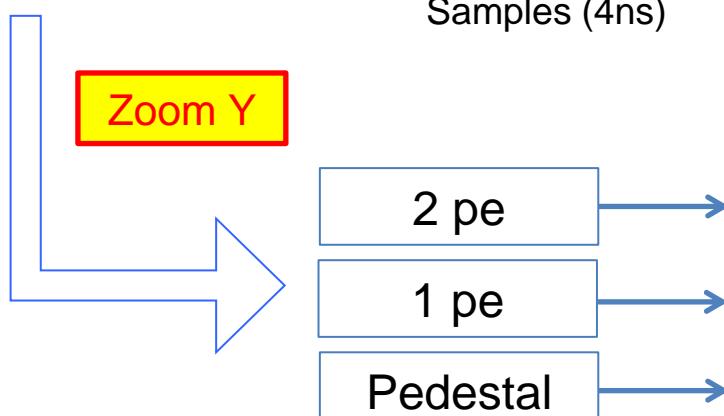
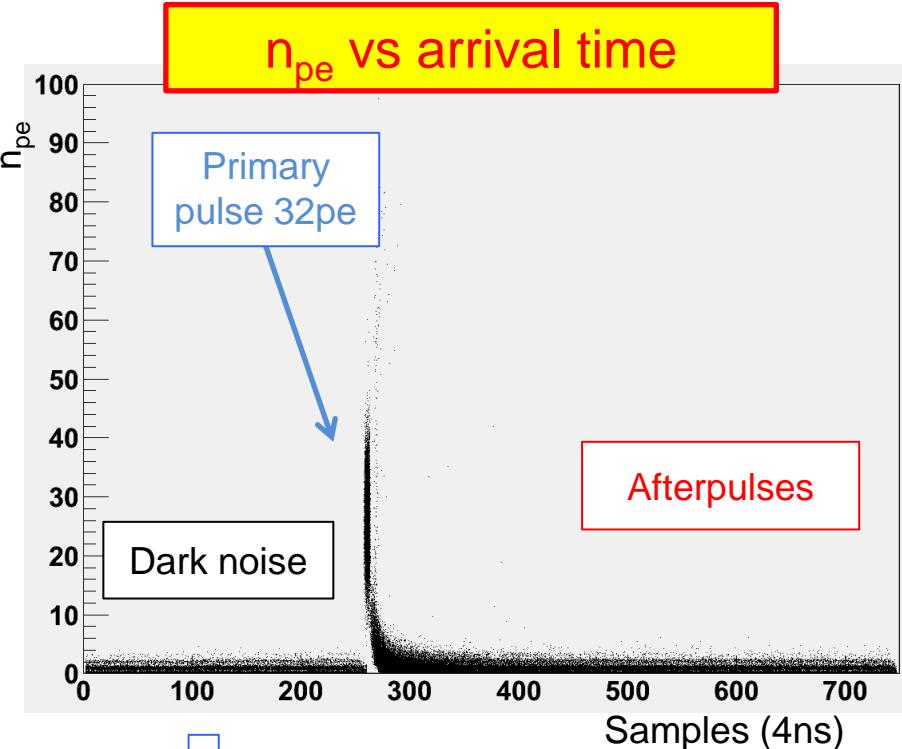
Each segmented part
focusing on a SiPM



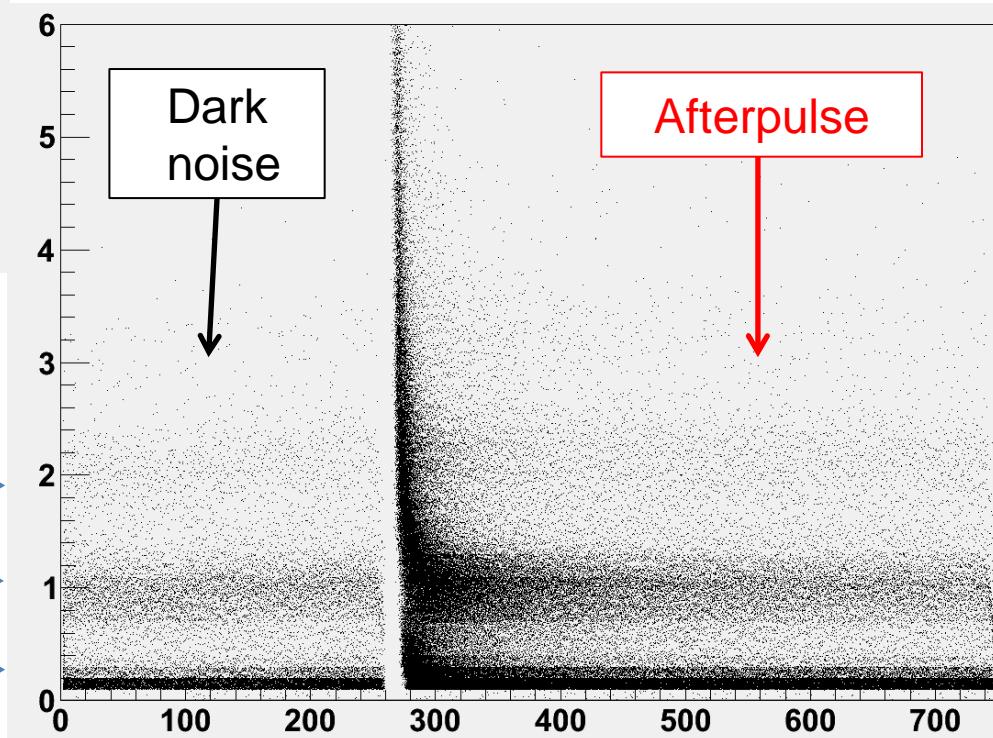
Thank you

Backup slides

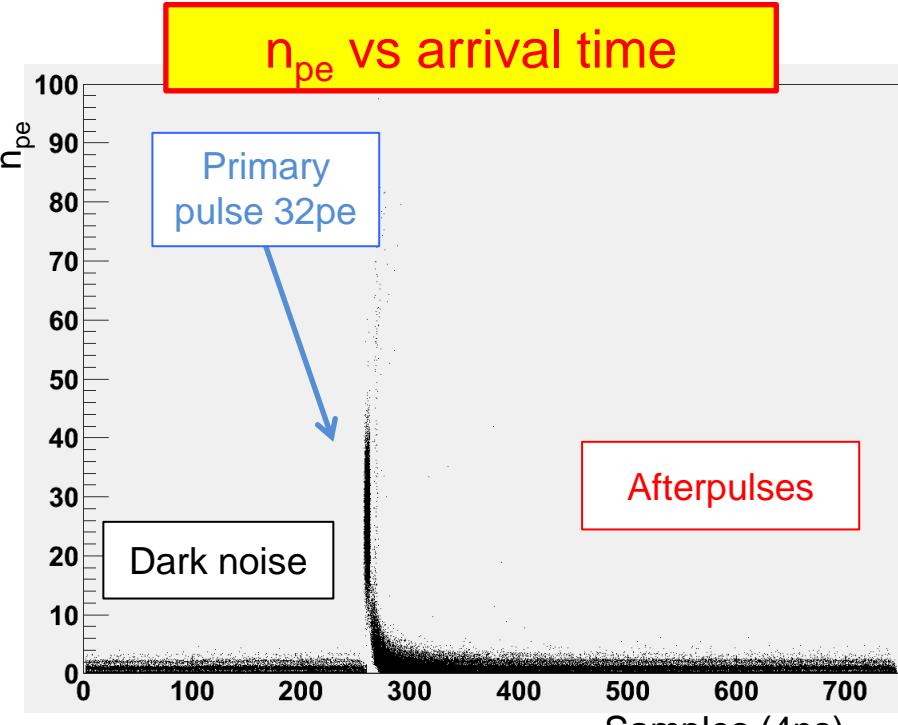
AP typical amplitude/1



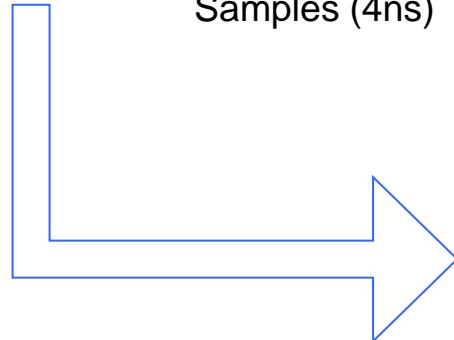
Low intensity AP 1-3 pe
Dark noise 1-2 pe



AP typical amplitude/2

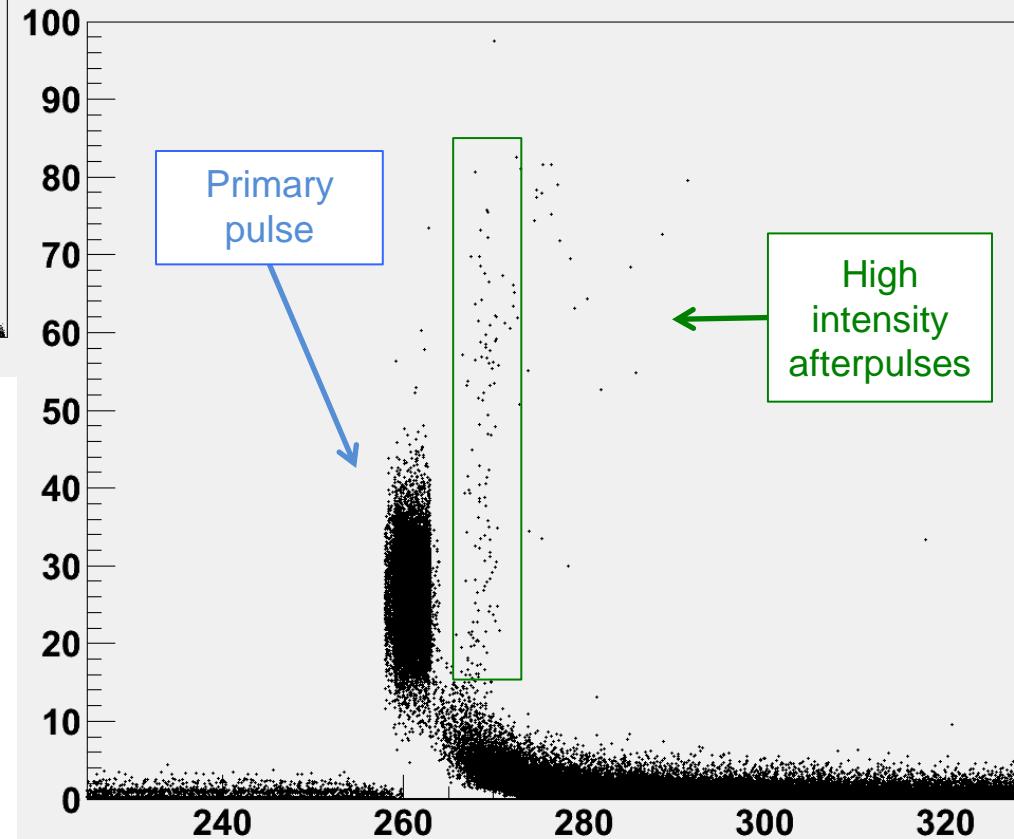


Zoom X

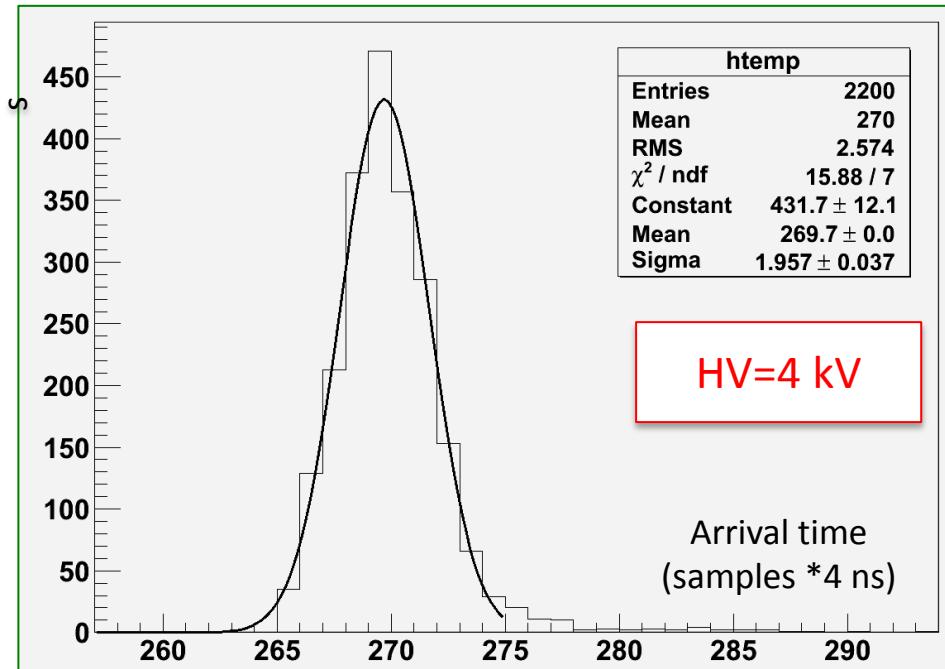


High intensity AP band
20-80 pe

Ionization of residual gases??

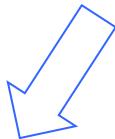


High intensity AP time distribution



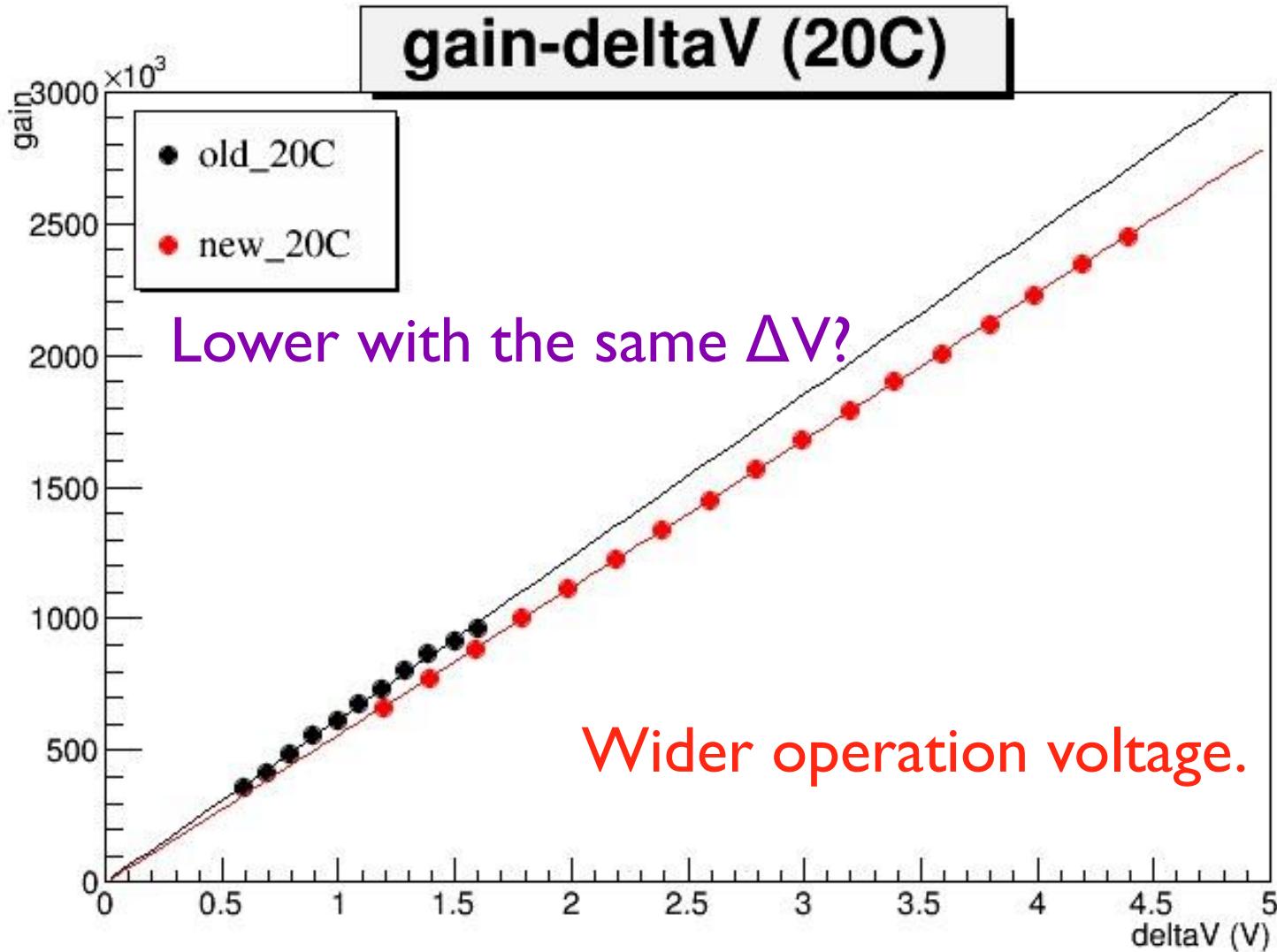
>10 pe, 0.02%

HV (kV)	Delay (ns)	Intensity (pe)
2	52.8	10-25
3	43.6	18-70
4	38.4	22-80



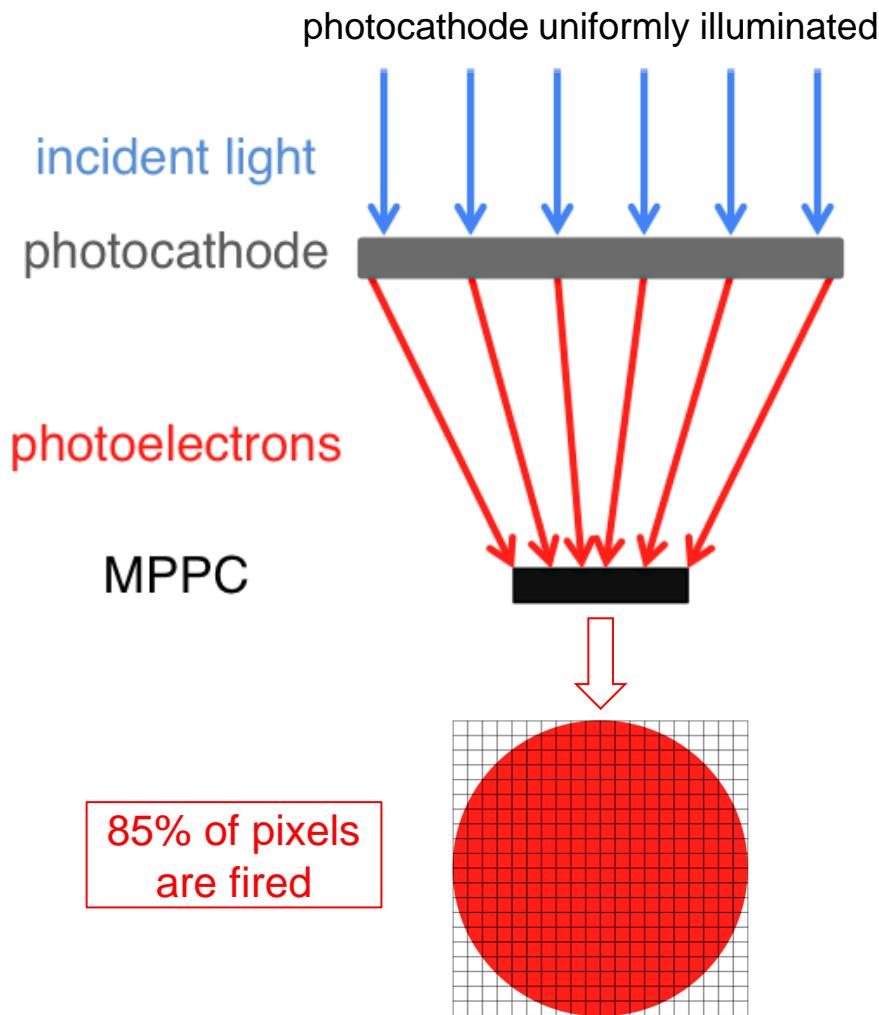
Strong hint for ionization
of residual gases

New generation MPPC gain

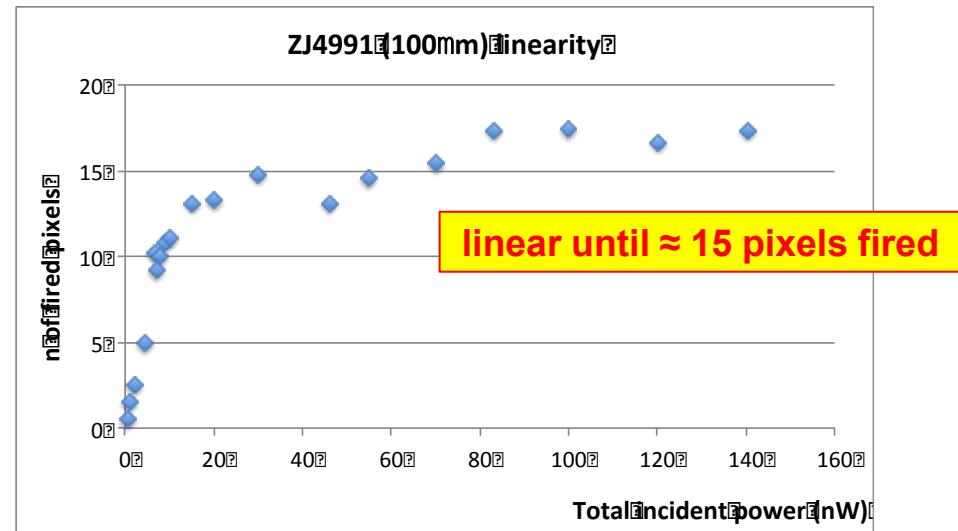


Linearity

The ideal case

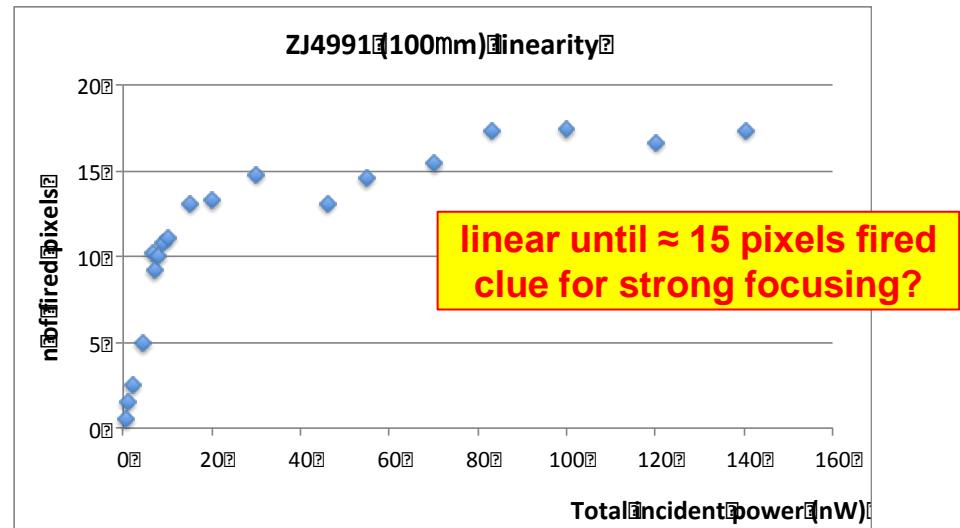
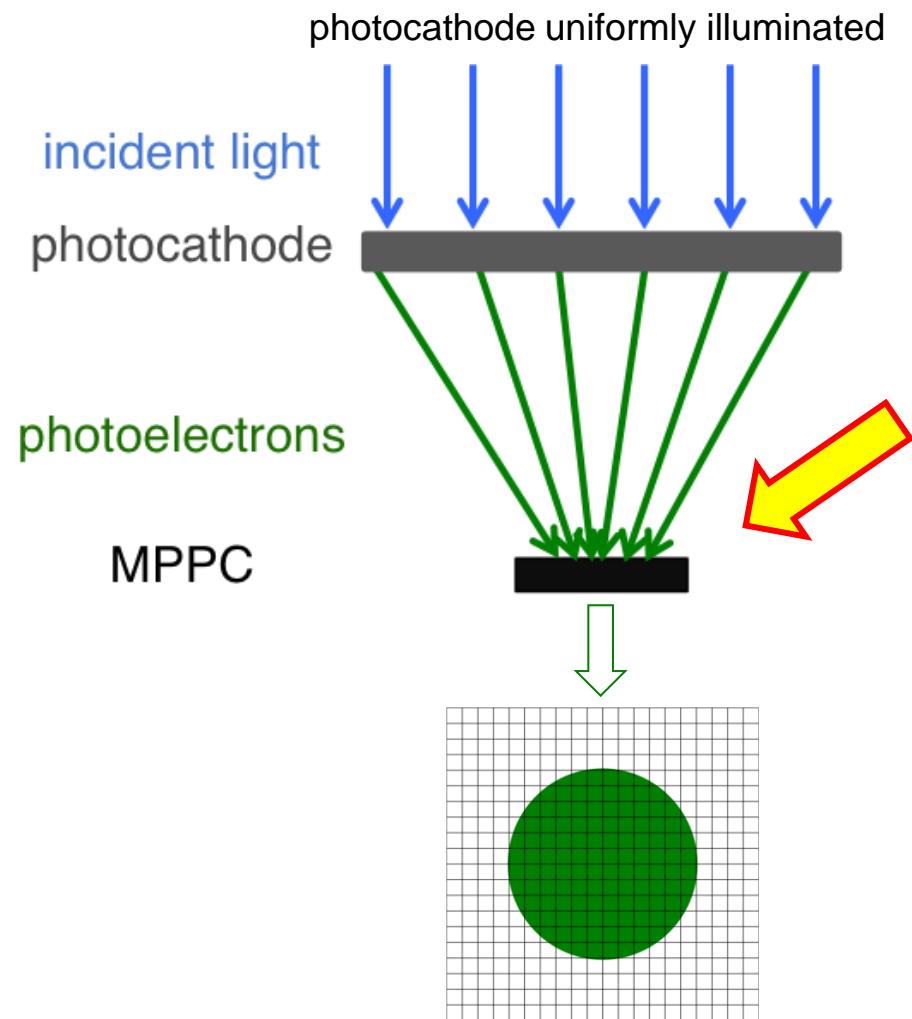


What we measured

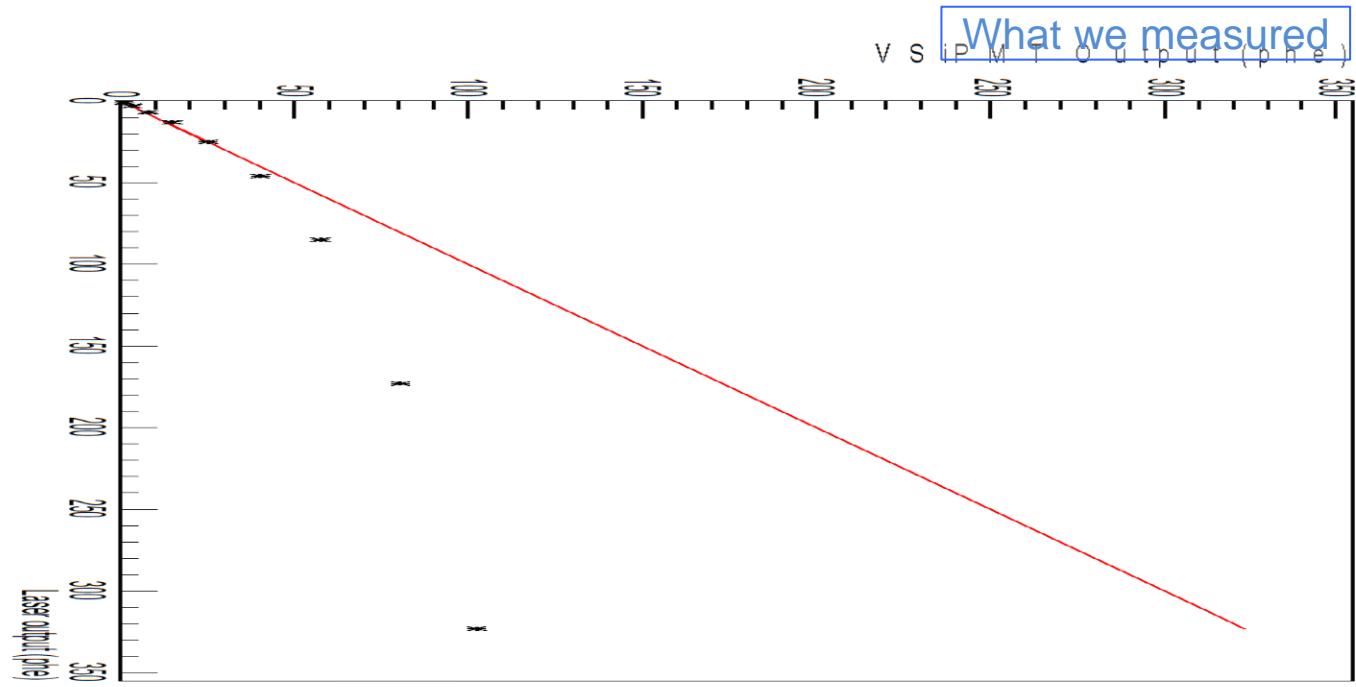
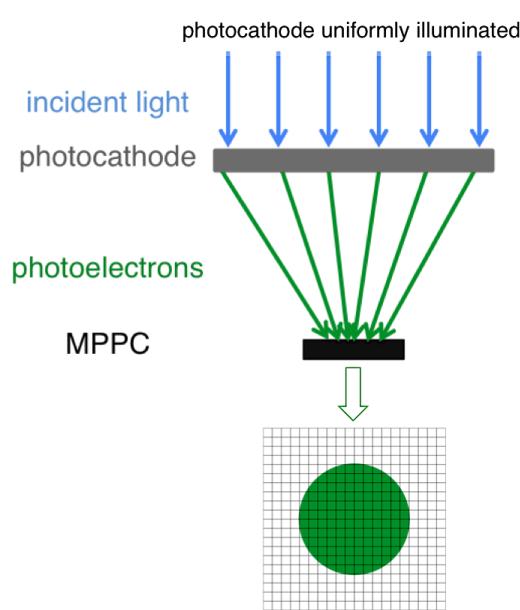


Linearity

What we measured



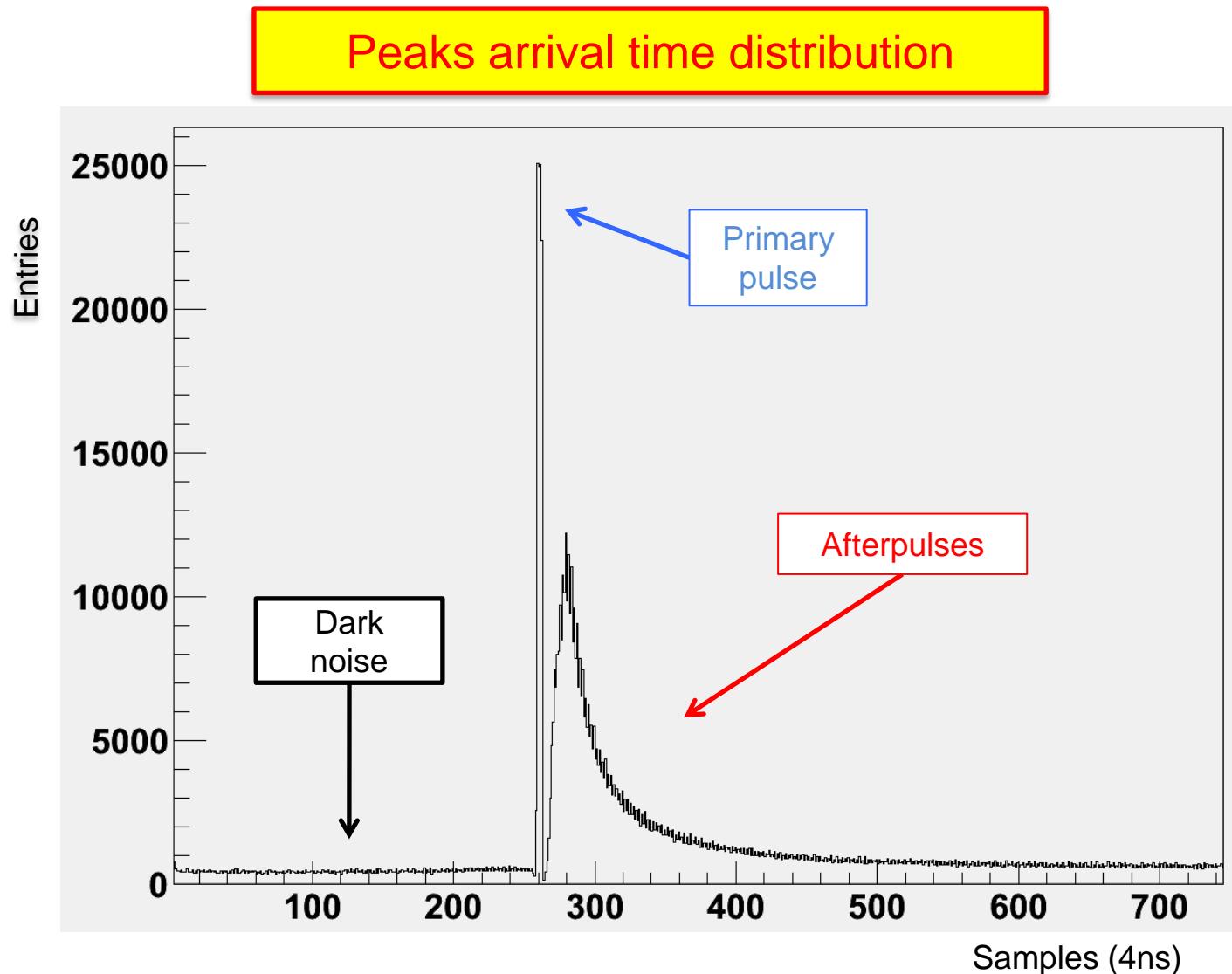
Linearity



ZJ4991 (100 μ m) has a too limited linearity

Optimal solution: 25 μ m – 50 μ m pixel size MPPC with improved Fill Factor for QE maximization

Time structure of afterpulses



An attractive solution for cryogenic applications

Requirements for next generation DM experiments

- Good bg discrimination → High S/N ratio and high SPE resolution;
- Low radioactive bg → PMTs < 1mBq/(3" PMT);
- Low power consumption;
- Stable operation at LAr/LXe temperature.

Uranium, Thorium and Potassium from ceramics/metal parts in a standard PMT are the main source of background in DM noble liquids experiments

VSIPMT

Unrivalled performances
optimal solution for next
generation DM experiments

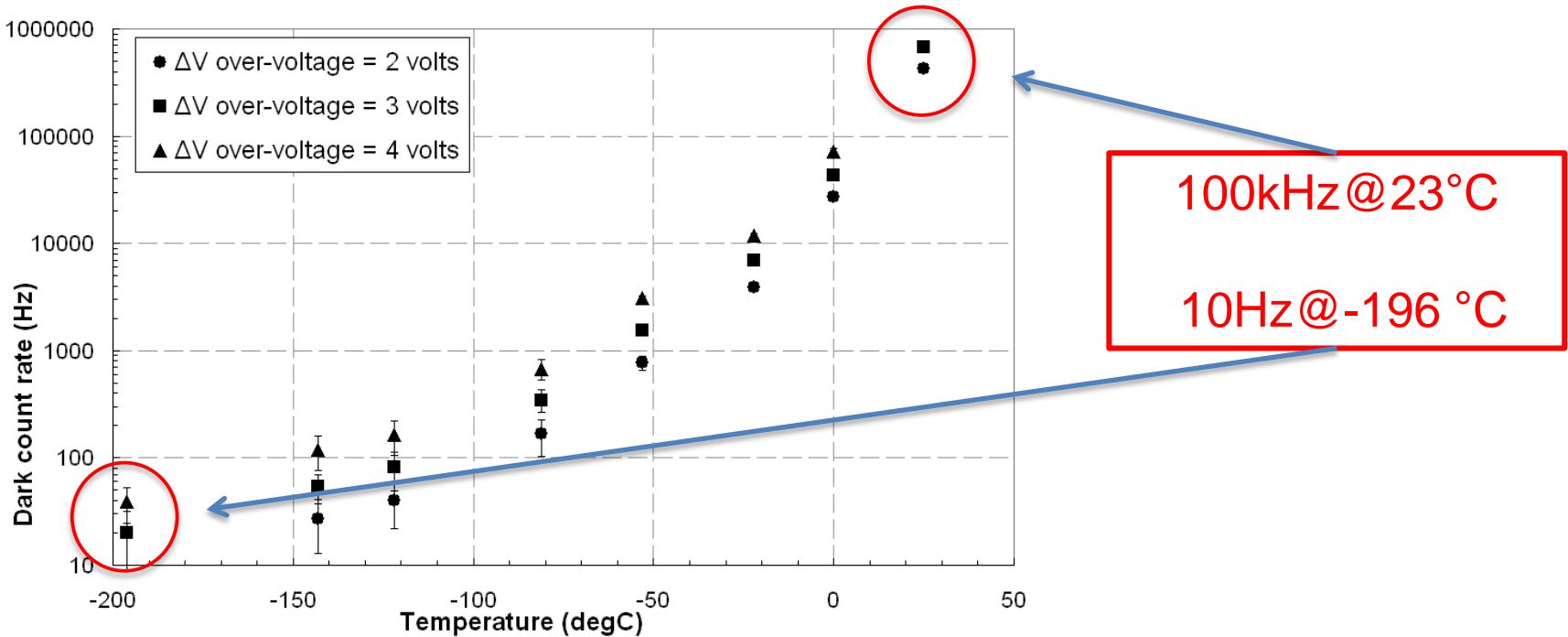
Unprecedented features wrt cryogenic PMTs:

- Photon counting capability;
- Low power consumption;
- Silicon virtually **free of radioactivity** (in addition reduced mass);
- Excellent timing performances (low TTS);
- **High stability (not depending on HV);**
- Excellent SPE resolution.

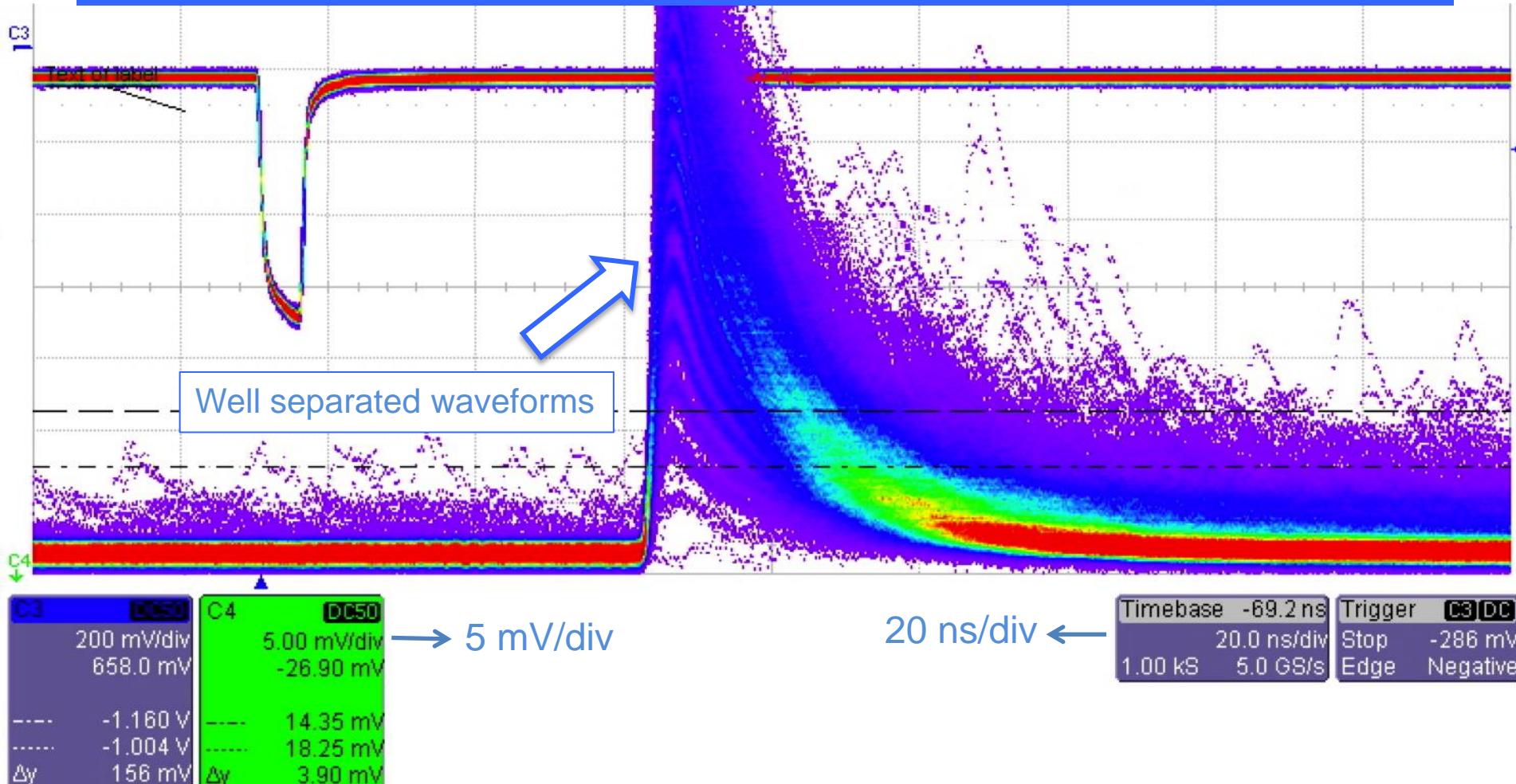
Advantages at low temperature

Cryogenic application would reduce drastically the dark rate

P.K. Lightfoot, Characterization of a silicon photomultiplier device for applications in liquid argon based neutrino physics and dark matter searches, JINST 3 P10001, 2008.

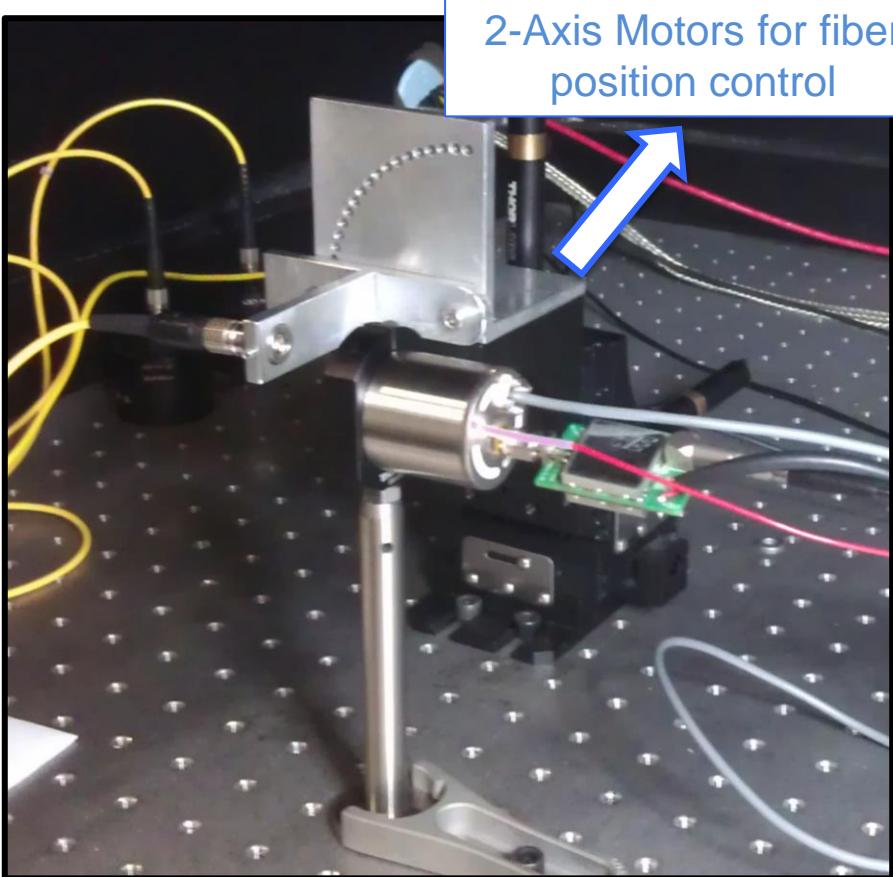


Waveforms

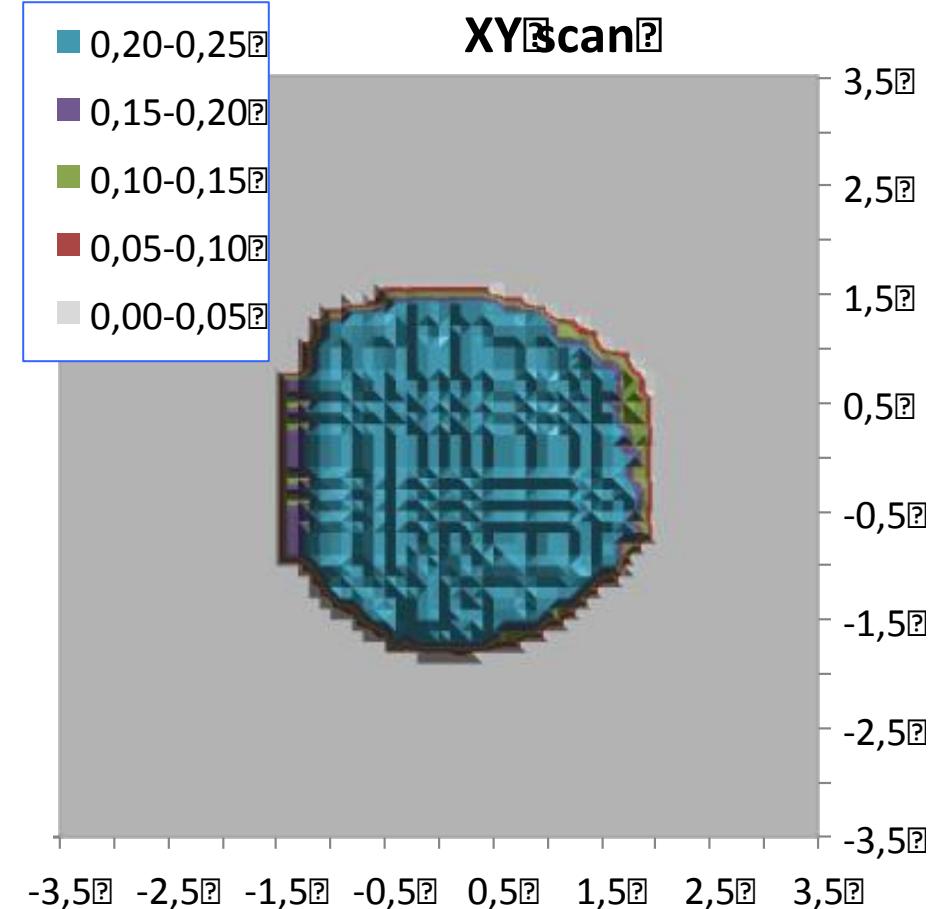


Excellent photon counting capabilities

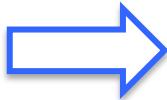
XY scan



2-Axis Motors for fiber position control



Homogeneous efficiency
 ≈ 0.2 over a 7mm^2 surface



Surface increase factor ≈ 7

SPE spectra

100.000 waveforms for each acquisition run with low laser intensity.

Integral of the waveform in a window of 100 ns after subtracting the baseline.

DAQ ADC CAEN V1720E
12 bit – 4 ns sampling
Laser TRG 10kHz

VSiPMT working point
 $V_{bias} = 72.5 \text{ V} - HV = 4 \text{ kV}$
Amplification x20

