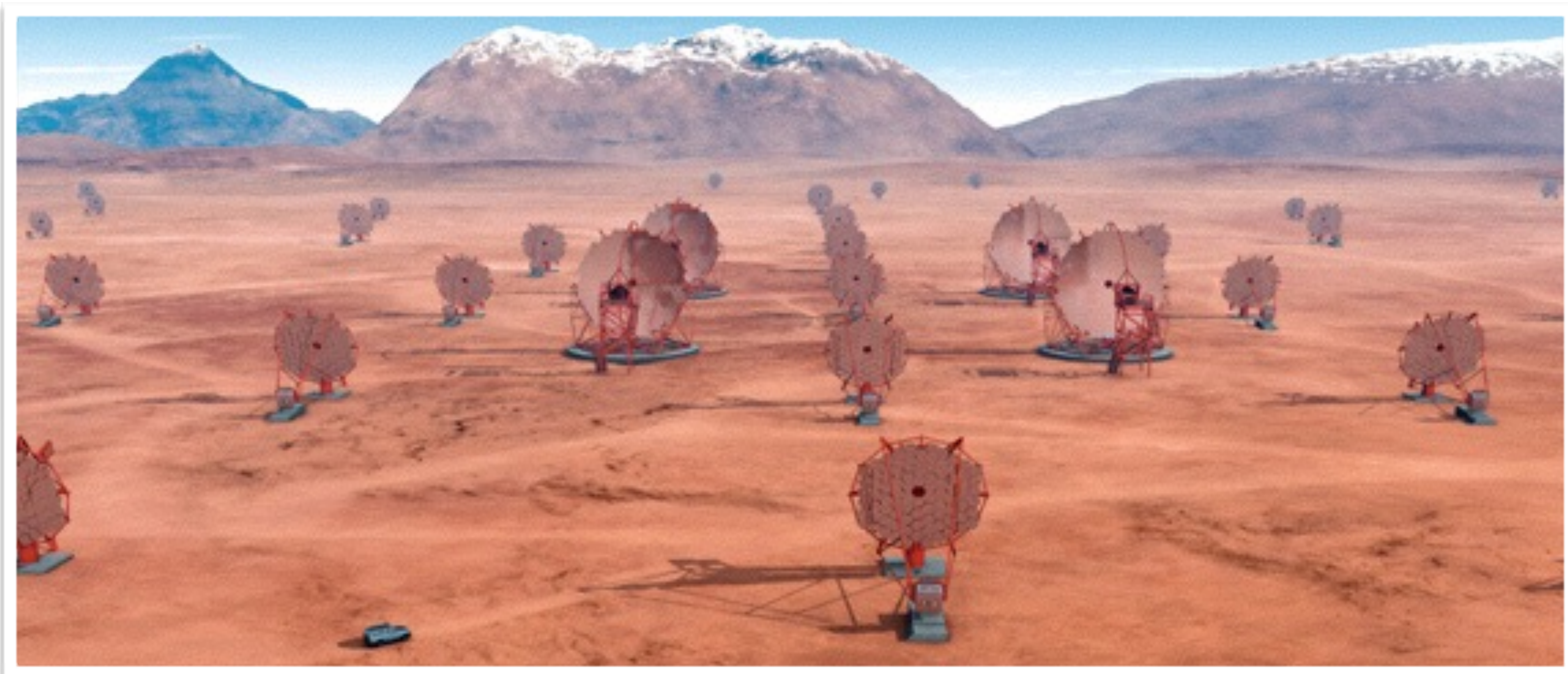
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES



Status of SST-1M camera and of the custom SiPM development

D. della Volpe *on behalf of the CTA consortium*

APPEC Technological Forum - Munich - 23rd April 2915

Why SiPMs

Large scale mass production

No Ageing

Lightweight

High yield

Low Op. Voltage

Higher PDE over larger spectral range

Robust

Insensitive to Magnetic Field

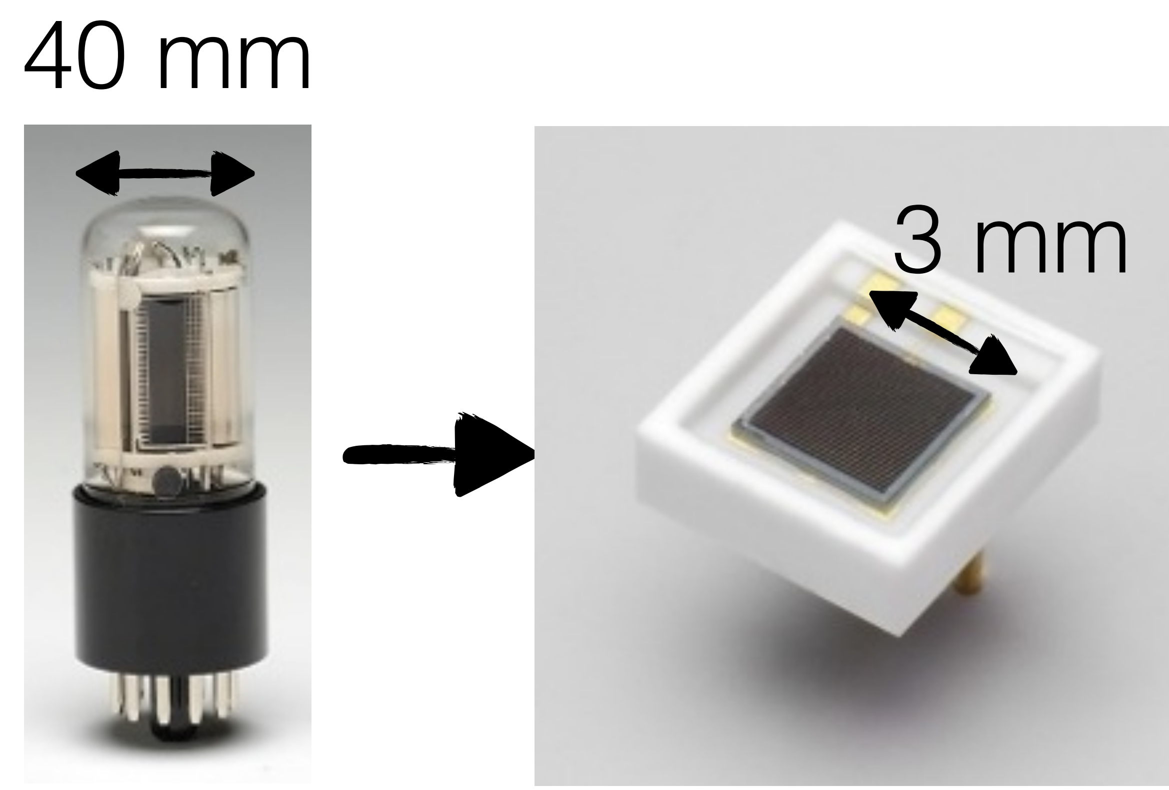
Compact

Very good Single Photon Response

Small variation sample-by sample

Photo detection plane requirements for IACTs Camera

Improve | Worse



- High Quantum Efficiency
- Single Photon sensitivity
- Fast pulses
- Low noise (dark count, after pulses)
- High Fill factor
- Robustness
- Uniformity
- High dynamic range
- Large area to be covered
- Linear response (optical cross talk, pile up)

- Lower voltage and easier cooling
- Lightweight
- High potential for performance improvement and cost decrease
- Characteristics depend on operation temperature

Photo detection plane requirements for IACTs Camera

Improve

Worse

- Fast pulses
- Low noise (dark count, after pulses)

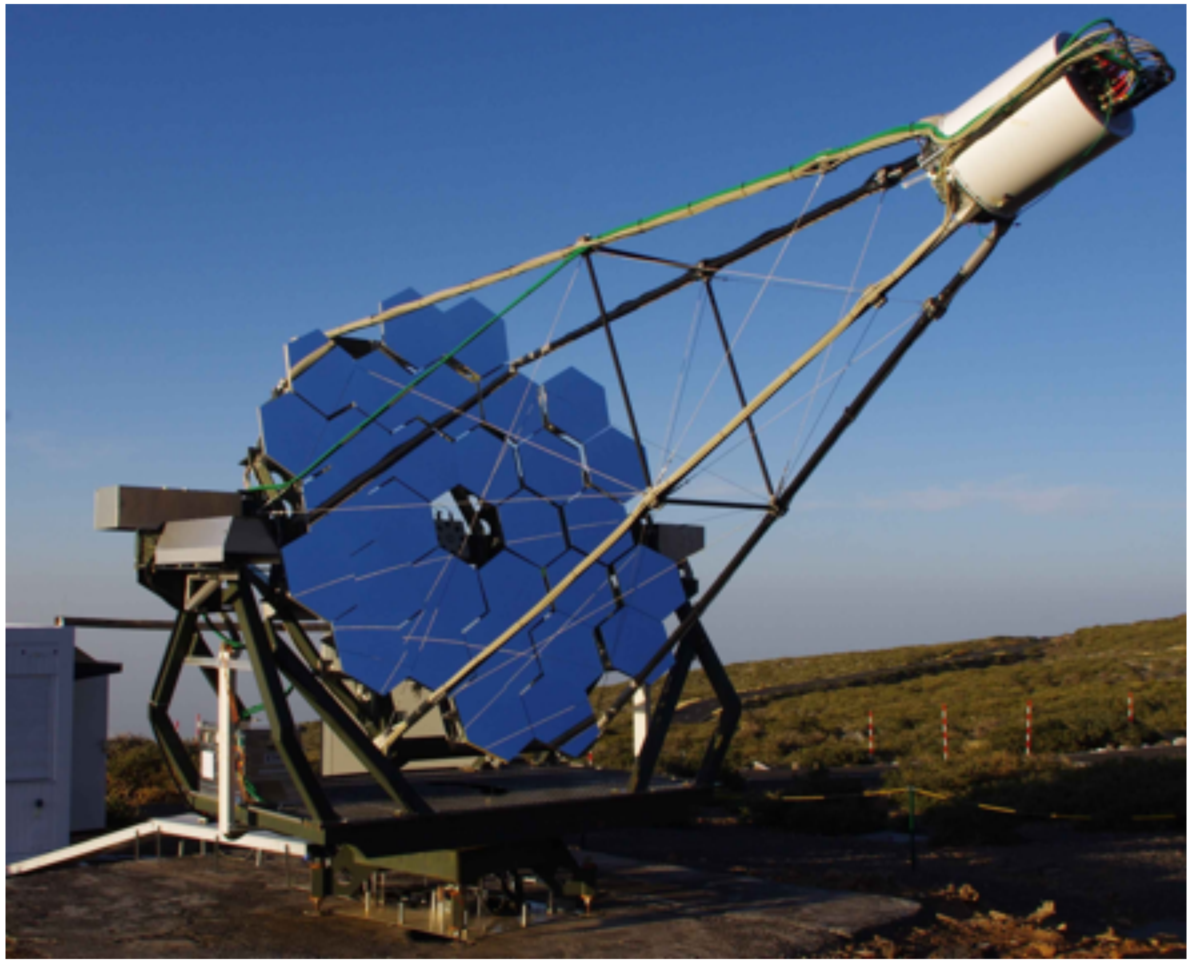
Are these parameters worrisome for gamma ray astronomy ?

- Large area to be covered
- Linear response (optical cross talk, pile up)

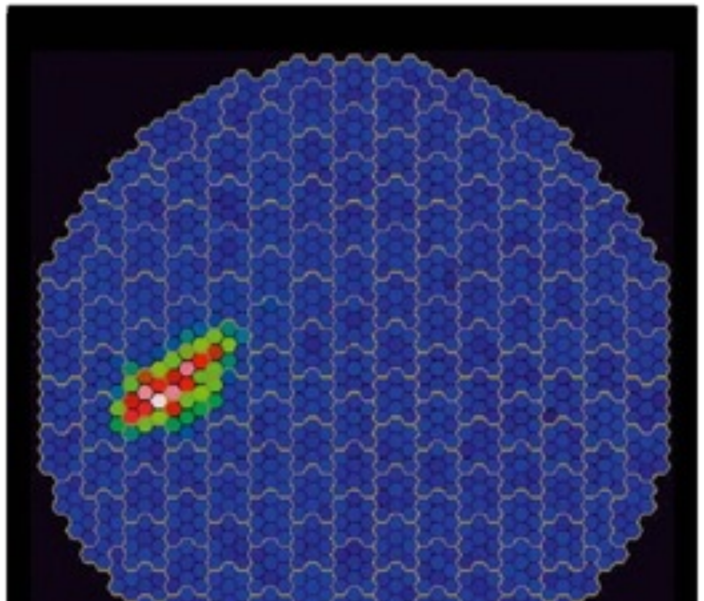
- Characteristics depend on operation temperature

Why SiPM in gamma-ray Astronomy

- Excellent single PE sensitivity
- Lightweight and robust cameras
- No evidence of ageing after 18 months
- Night Sky Background (NSB) rate dominates wrt Dark noise (MHz)
- Current Photo-Detection Efficiency > 40%.
- Operation during Moonlight: ~30% larger duty cycle
- As demonstrated by FACT, SiPM work on the field and with moonlight!)



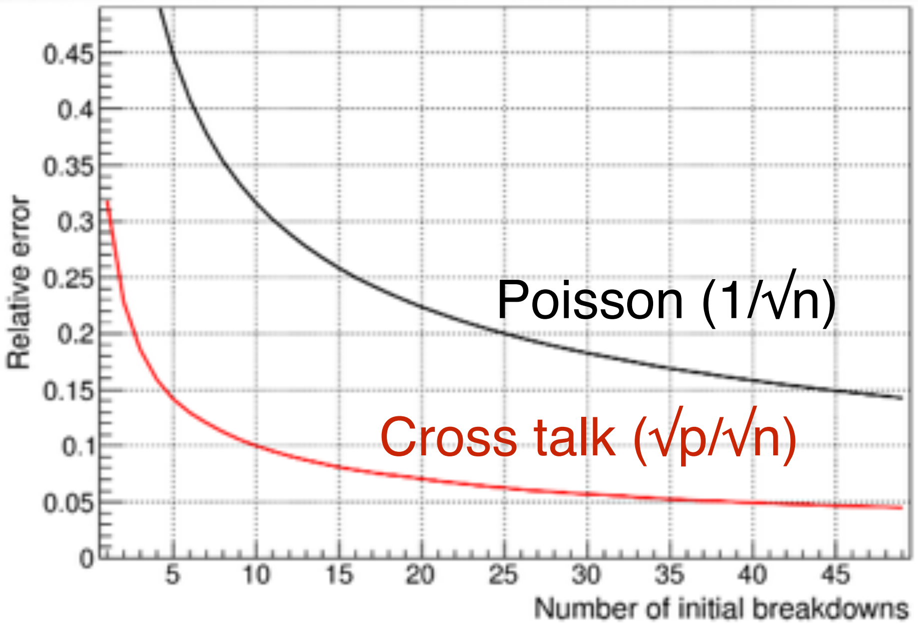
New approach, use fully digital SiPM-based camera on a Davies-Cotton telescope.



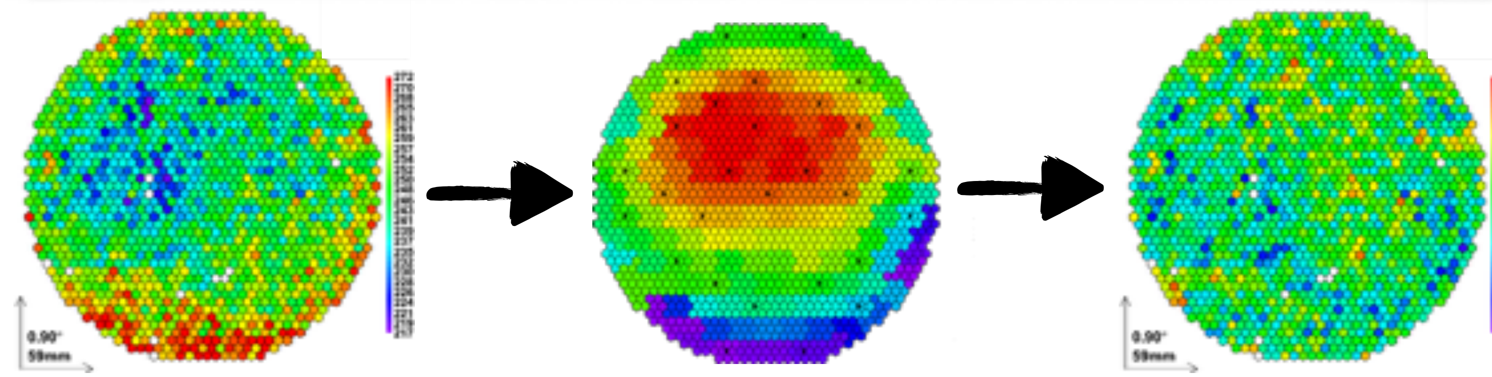
Recorded showers during full moon, CERN Courier Nov 2011:

FACT camera performance

Signal error dominated by Poisson error



Gain uniformity ensured thanks to temperature monitoring
No active cooling needed as V_{break} varies linearly with T
T variations compensated using the HV



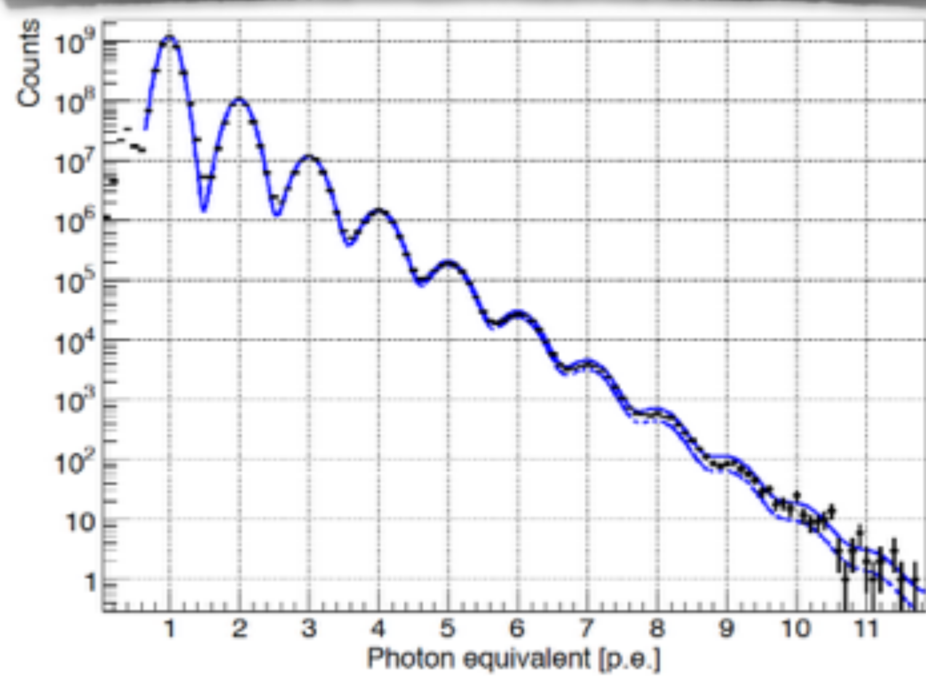
Gain, RMS 4%

Temperature map

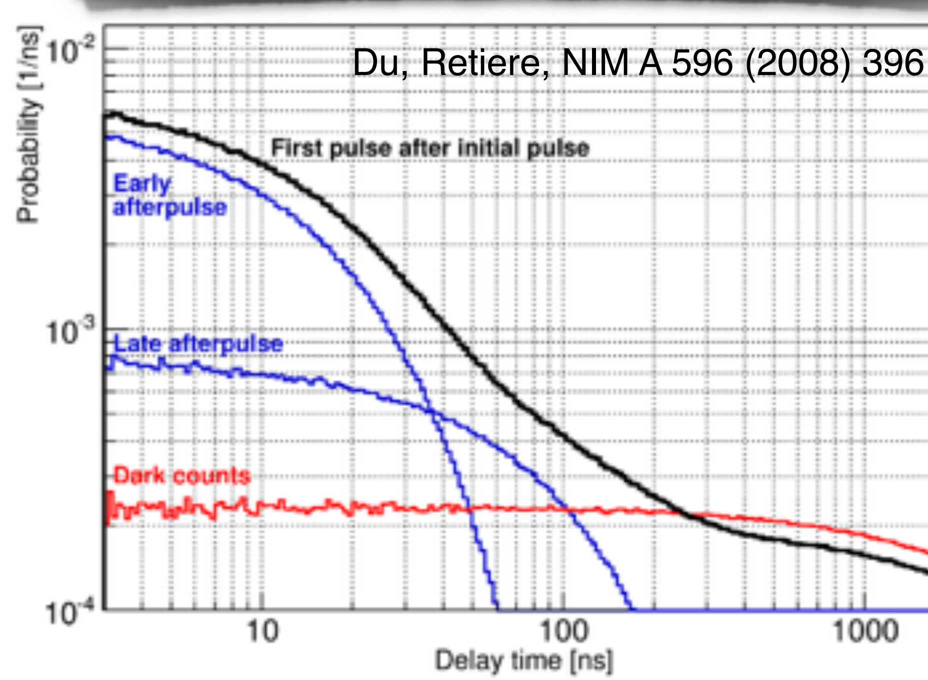
Gain, RMS 2.5%

Dark count rate < Night Sky Background (NSB) rate

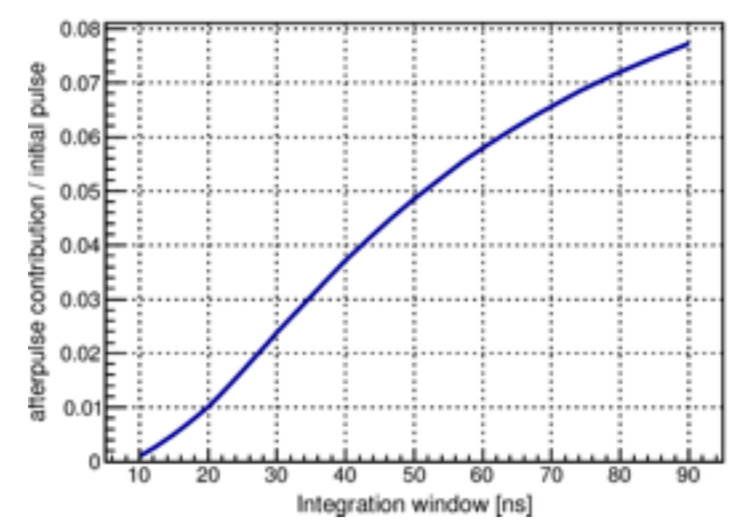
Dark count runs allow to calibrate the photo detection plane



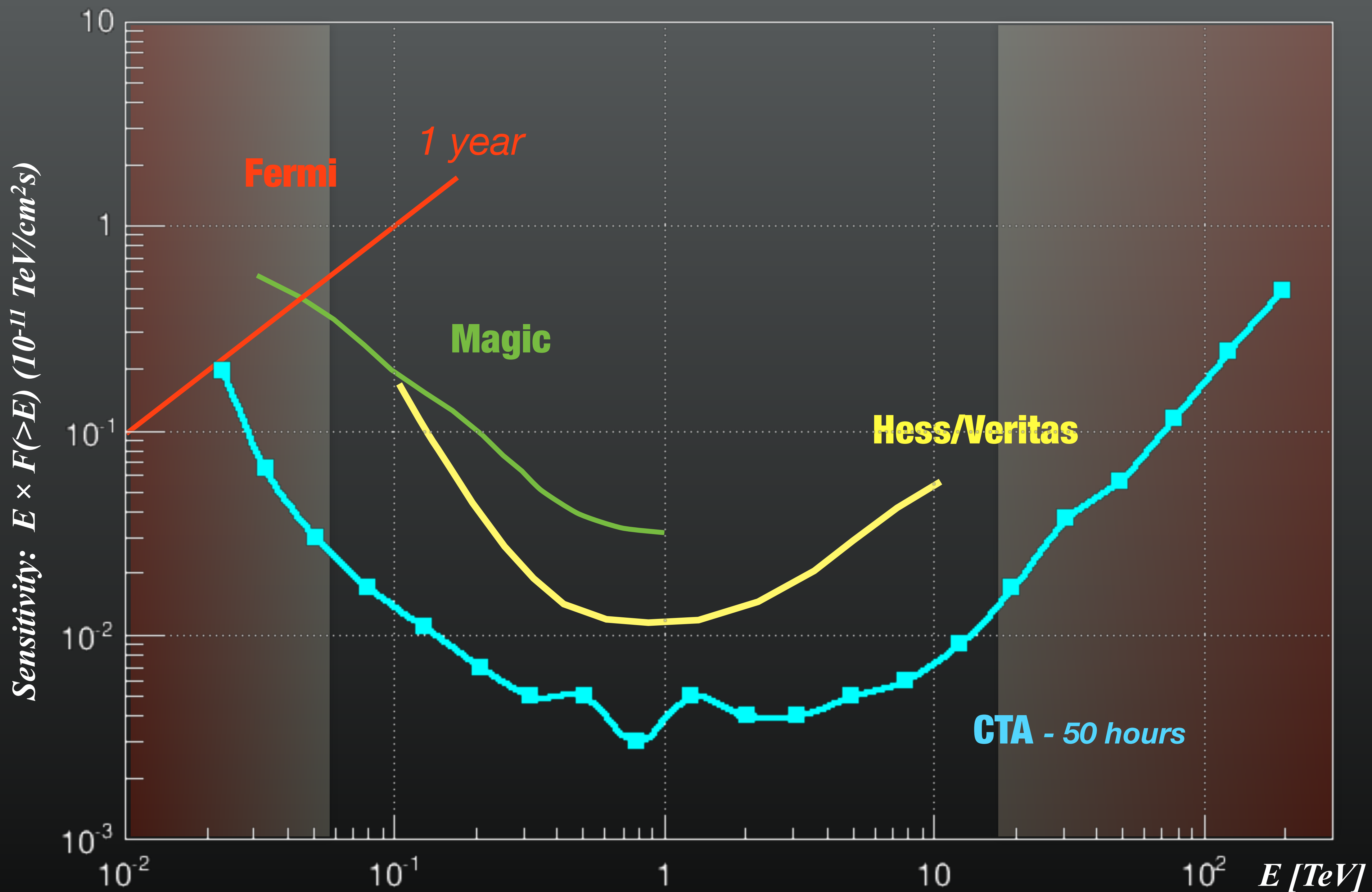
After-pulses cannot fake trigger but can worsen the charge resolution



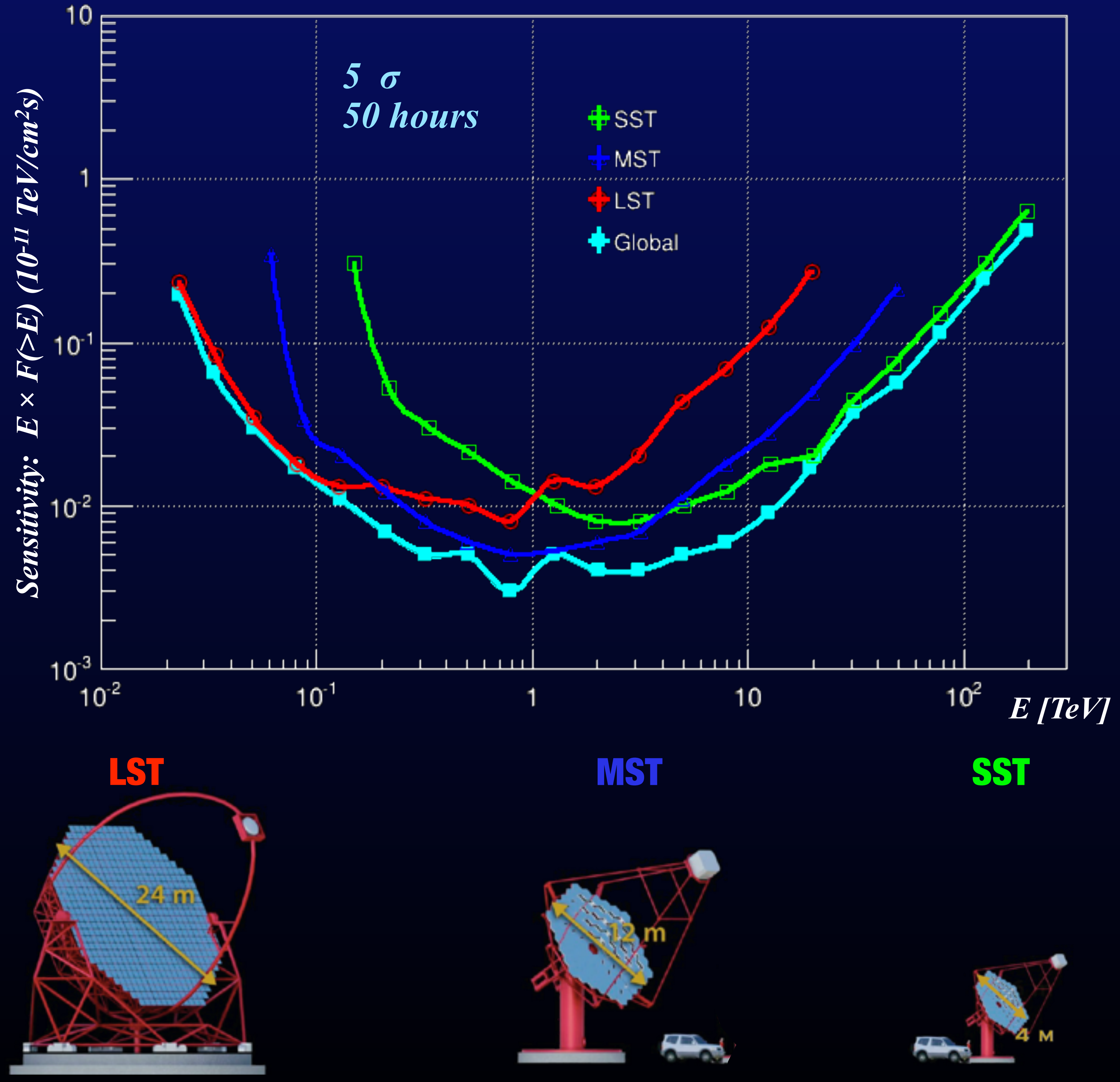
Shorter signal integration window to cure after pulses contribution



improve sensitivity by a factor 10

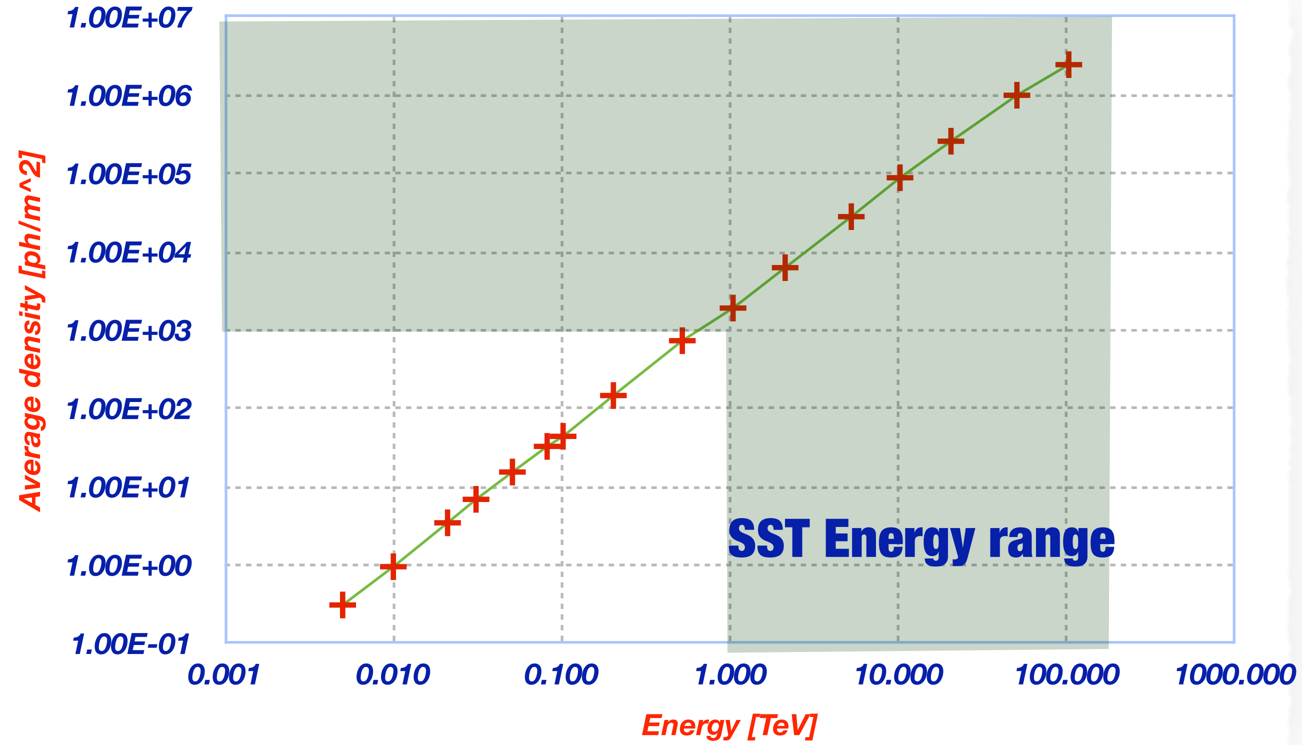


Extend to uncovered energy range for discoveries

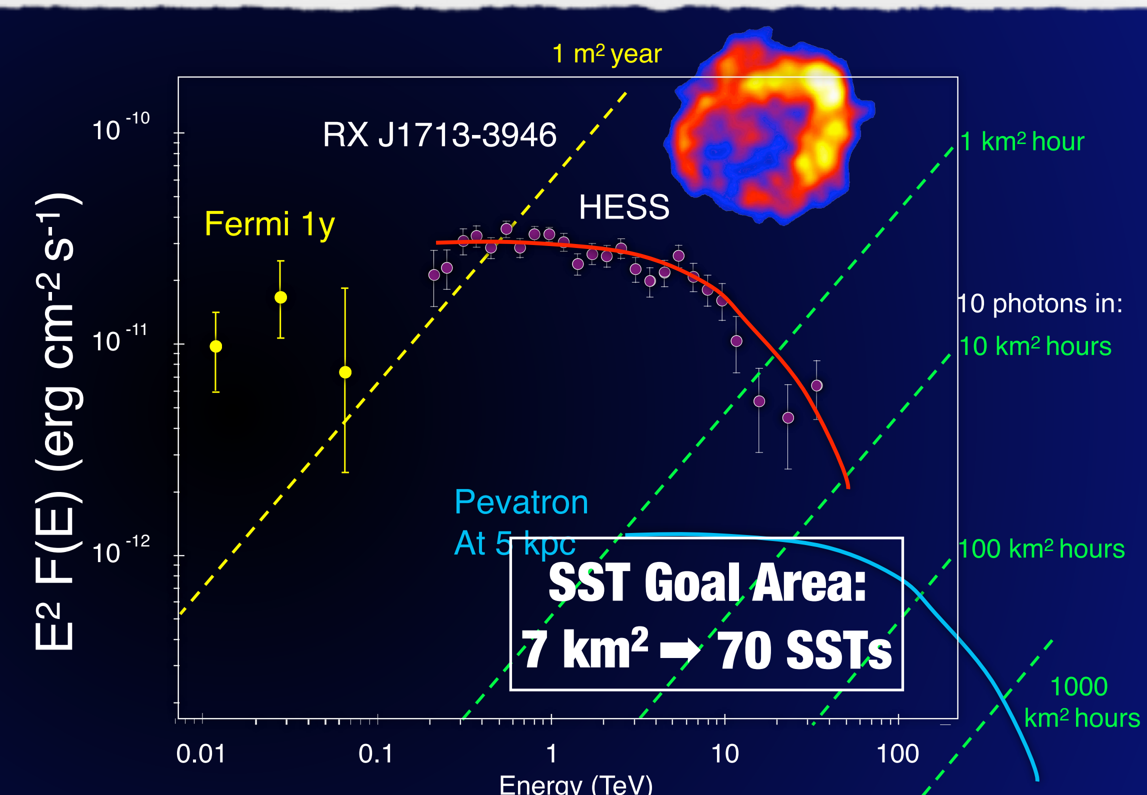

5 σ
50 hours
SST
MST
LST
Global
Sensitivity: E × F(>E) (10^-11 TeV/cm^2s)
E [TeV]
10
1
10^-1
10^-2
10^-3
10^-2
10^-1
1
10
10^2
LST
MST
SST
24 m
12 m
4 M

SST design drivers

High Energy
⬇
High photon density
⬇
Small Dish area ~ 4m



Shower Footprint
⬇
Array Collection Area
⬇
Number of Telescopes



Telescope Design

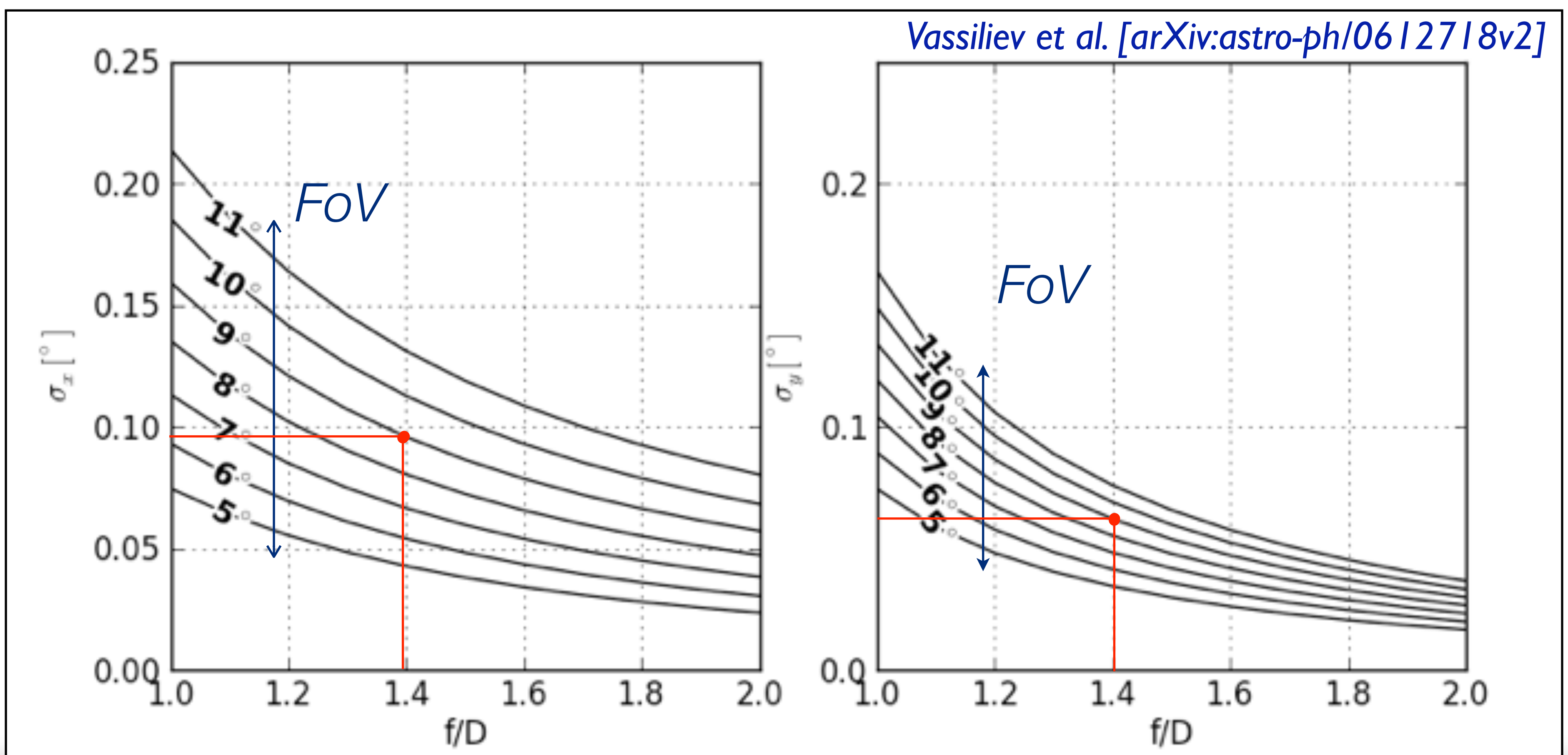
Conditions:

Dish = 4 m → *energy threshold*

FoV = 9° → *explore the galactic center*

f/D = 1.4 → *suitable angular resolution*

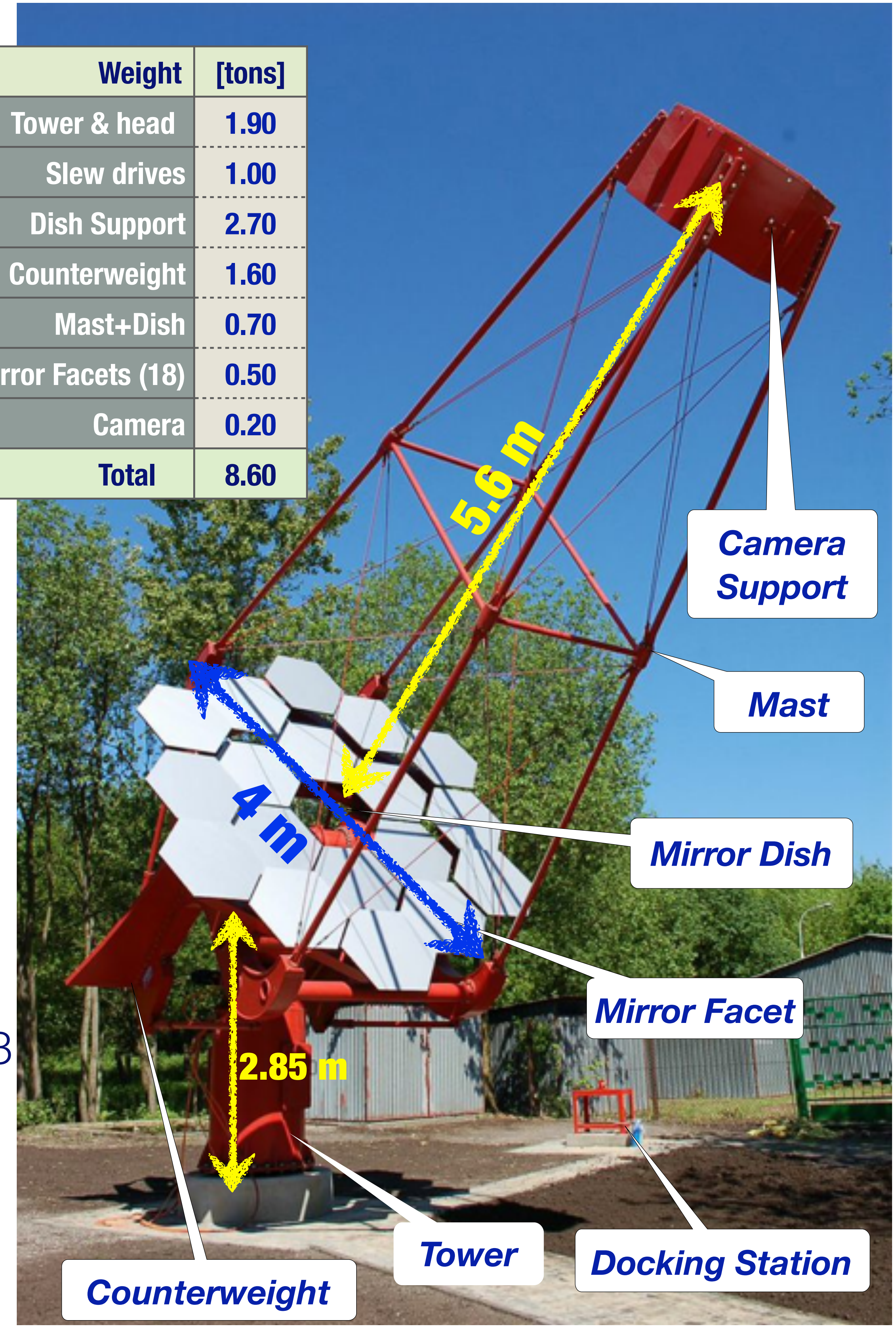
PSF of a 4m Davies Cotton



THE TELESCOPE STRUCTURE PROTOTYPE

Mechanical System	
Dish outer diameter	4000 mm
Focal Length	5600±5 mm
Optical System	
Mirror Facet	780 ± 3 mm
Mirror Area	9.42 m
Effective Mirror Area	6.47 m
FoV (min, max)	(8,7°, 10°)
Tracking / Pointing System	
Driver Encoder Precision	5”
Tracking Precision	0.1°
Pointing Precision	< 7”

Weight	[tons]
Tower & head	1.90
Slew drives	1.00
Dish Support	2.70
Counterweight	1.60
Mast+Dish	0.70
Mirror Facets (18)	0.50
Camera	0.20
Total	8.60



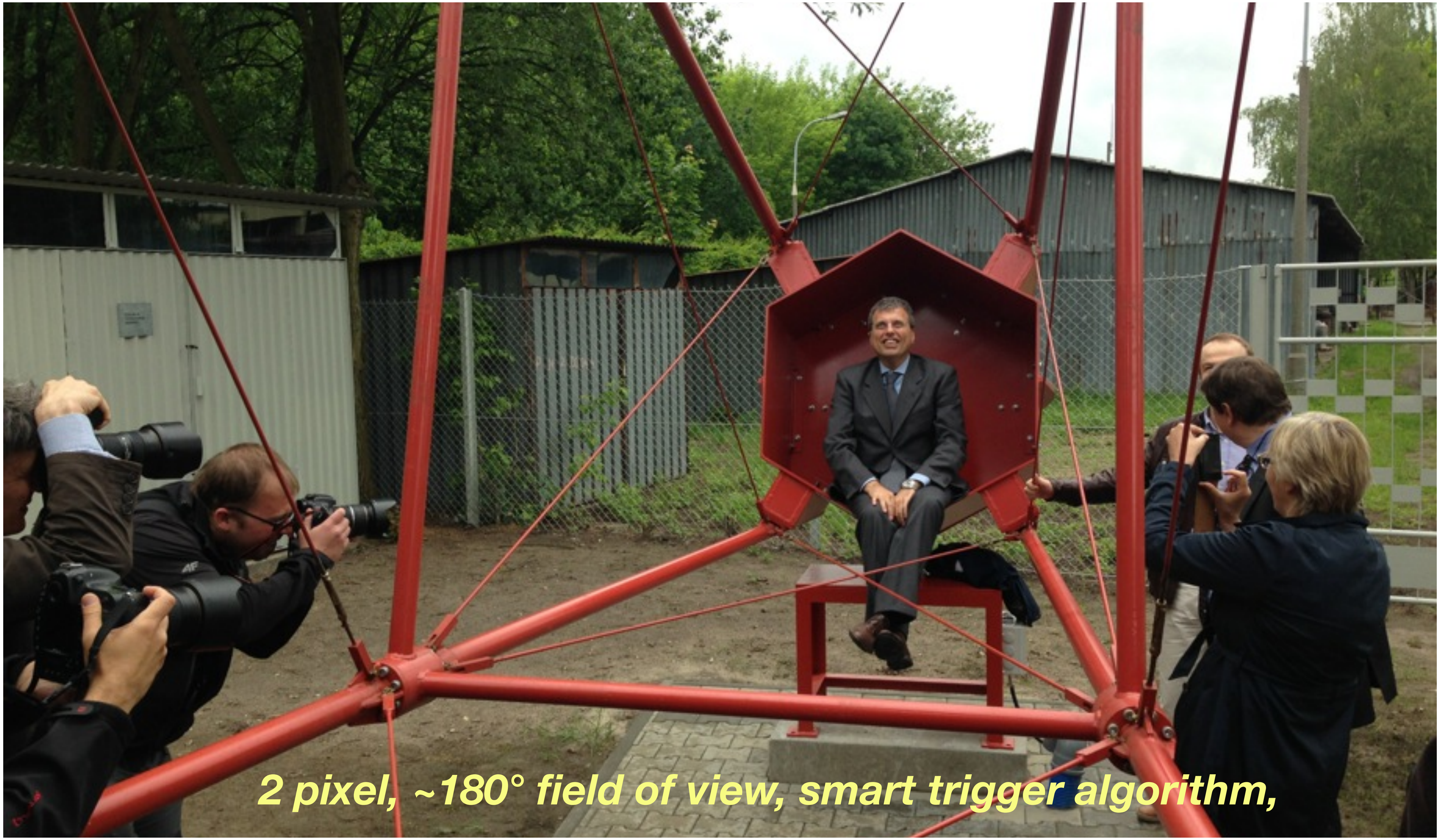
Telescope structure installed in November 2013

Inauguration on 2nd June 2014

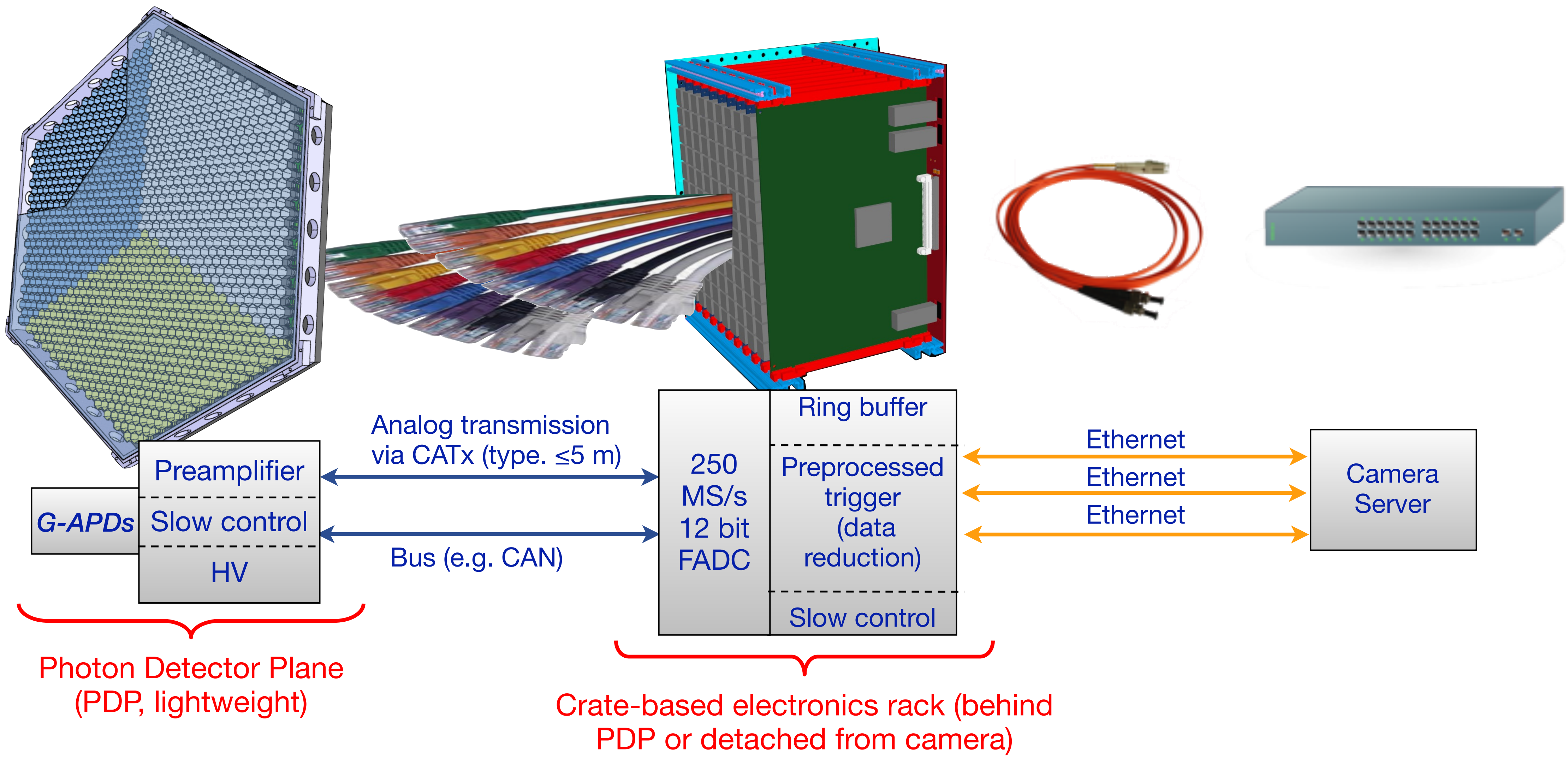
- ✓ Telescope fully operational
- ✗ Mock-up Mirrors,
- ✗ Camera dummy load

KRAKOW 2ND JUNE 2014
OFFICIAL INAUGURATION

First camera prototype



The Camera concepts



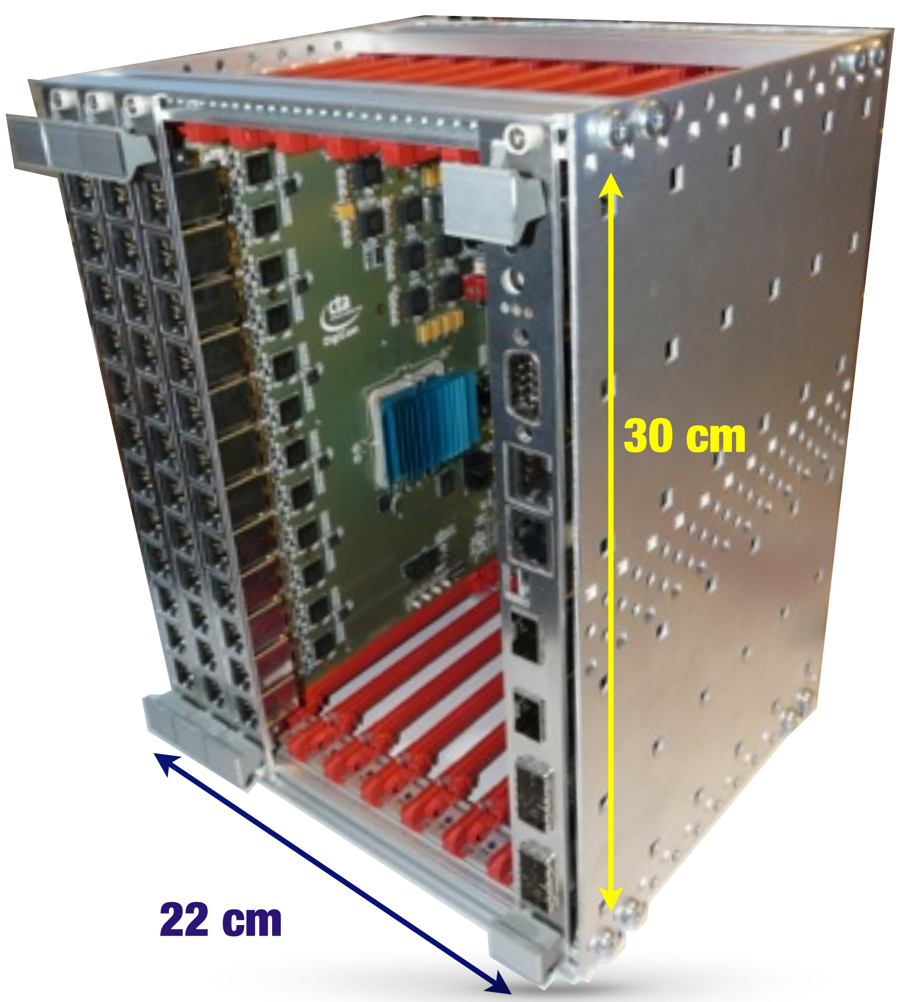
- Separation of PDP and ADC, analogue signal over CAT5/RJ45

  →allows adaption of various photon detectors and pitches
  Fully digital trigger path with reconfigurable algorithms and signal preprocessing

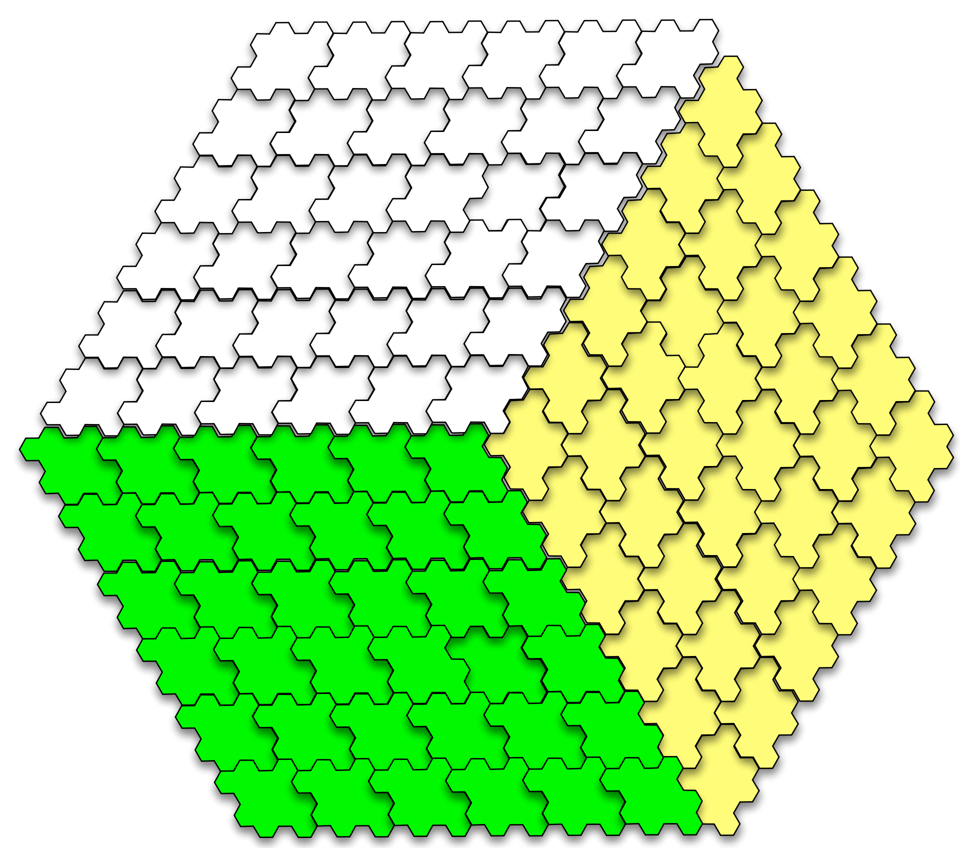
- Fully digital trigger and readout (High-speed/High-throughput)
  - Serial architecture based on multi-Gigabit links (trigger and ADC readout)
  - Reduced numbers of cables and connectors
- Compact, robust, lightweight and self-contained – perfect for SST-1M telescope

DigiCam Electronics

- Fully digital camera for SST-1M telescope
- Highly integrated, lightweight and compact acquisition and readout electronics (based on FlashCam architecture)
- Reduced number of channels of SST allow a more compact approach



μ-Crate -10 Slots



1 Trigger Board

DigiCam Electronics

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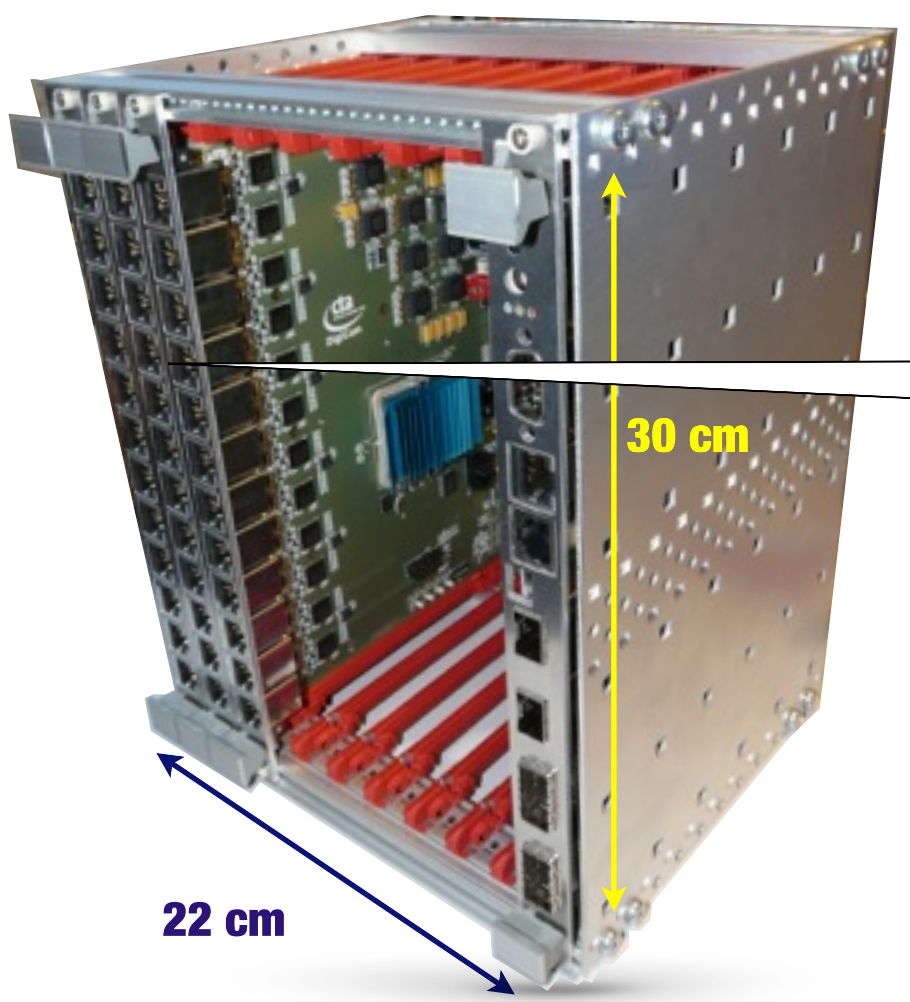
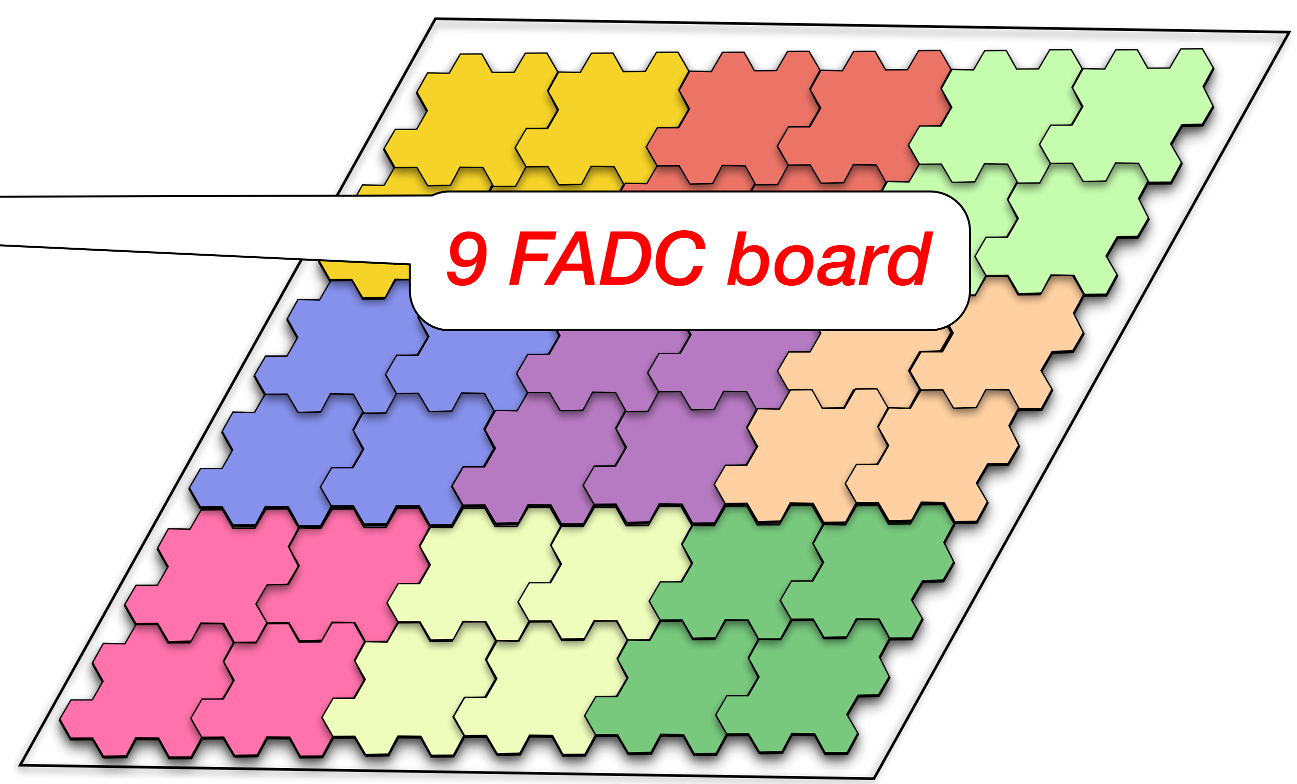
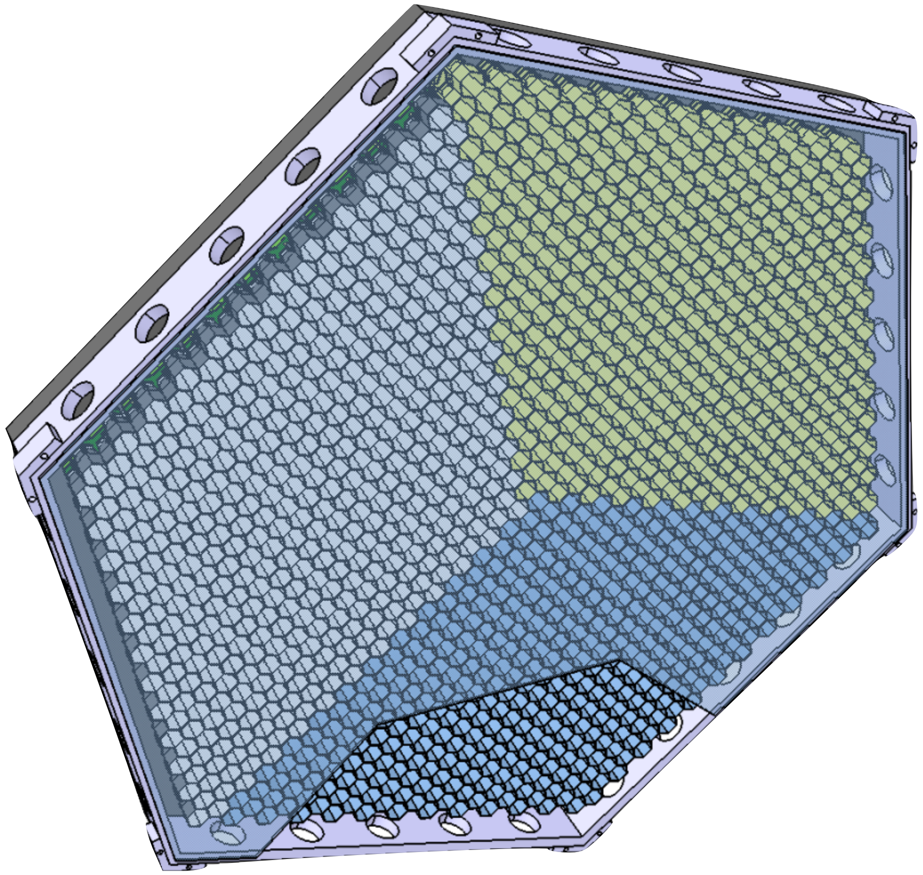
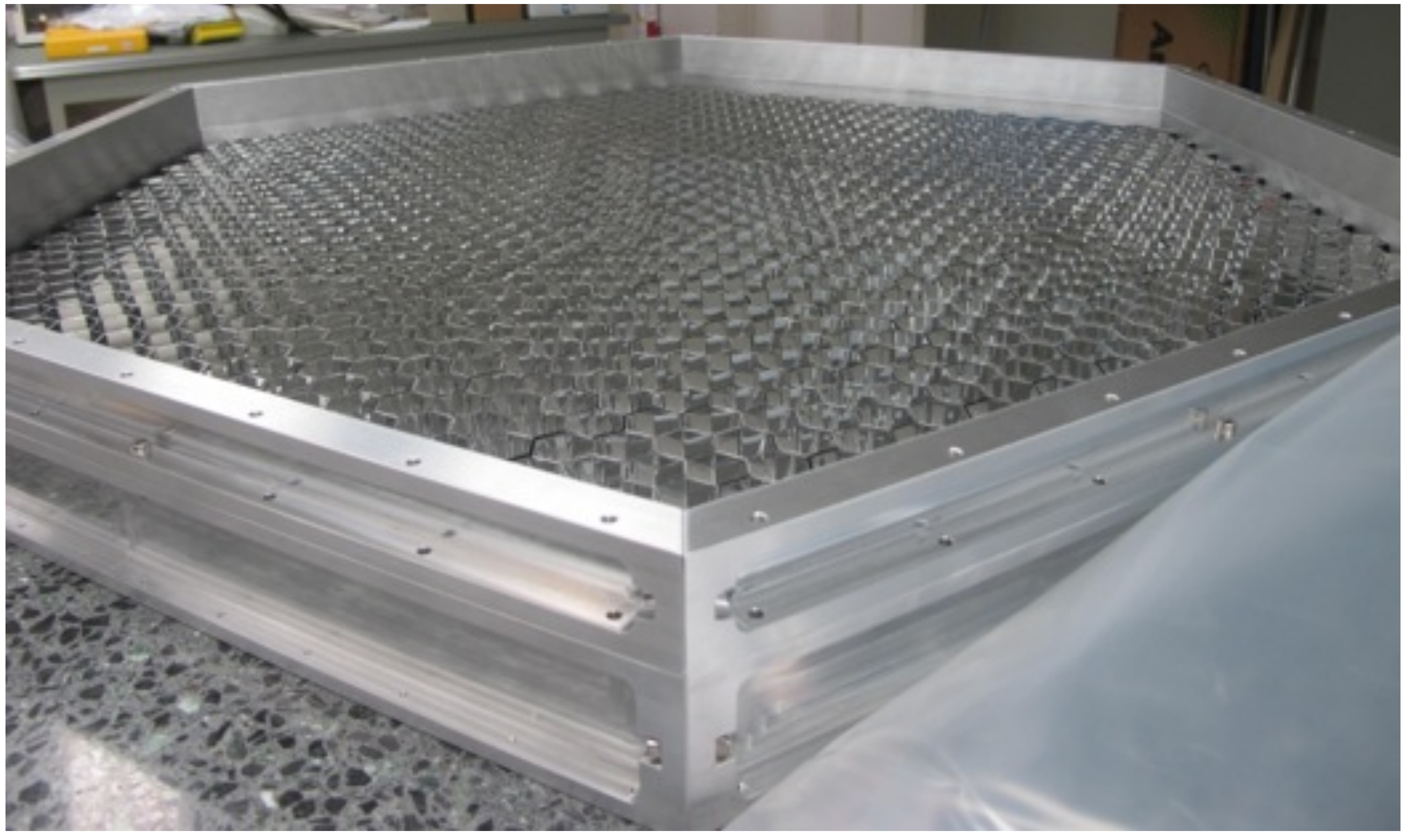


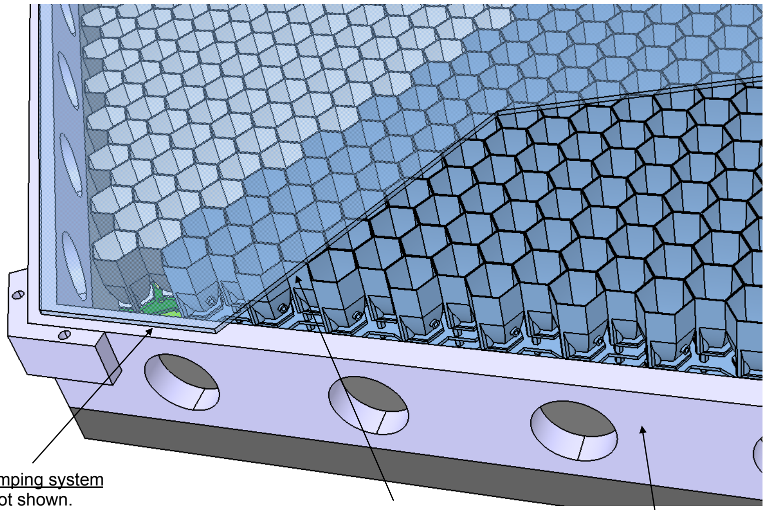


1 Trigger Board

The PDP - PhotoDetection Plane







- 1296 pixels (SiPM+Cones)
- 108 Modules of 12 pixels each
- Entrance window 3 mm Borofloat
- Aluminum Back Plate
- Total PDP weight ~35 kg

Telescope Design Drivers

Too big for a SiPM!!

Conditions:

Dish = 4 m

FoV = 9°

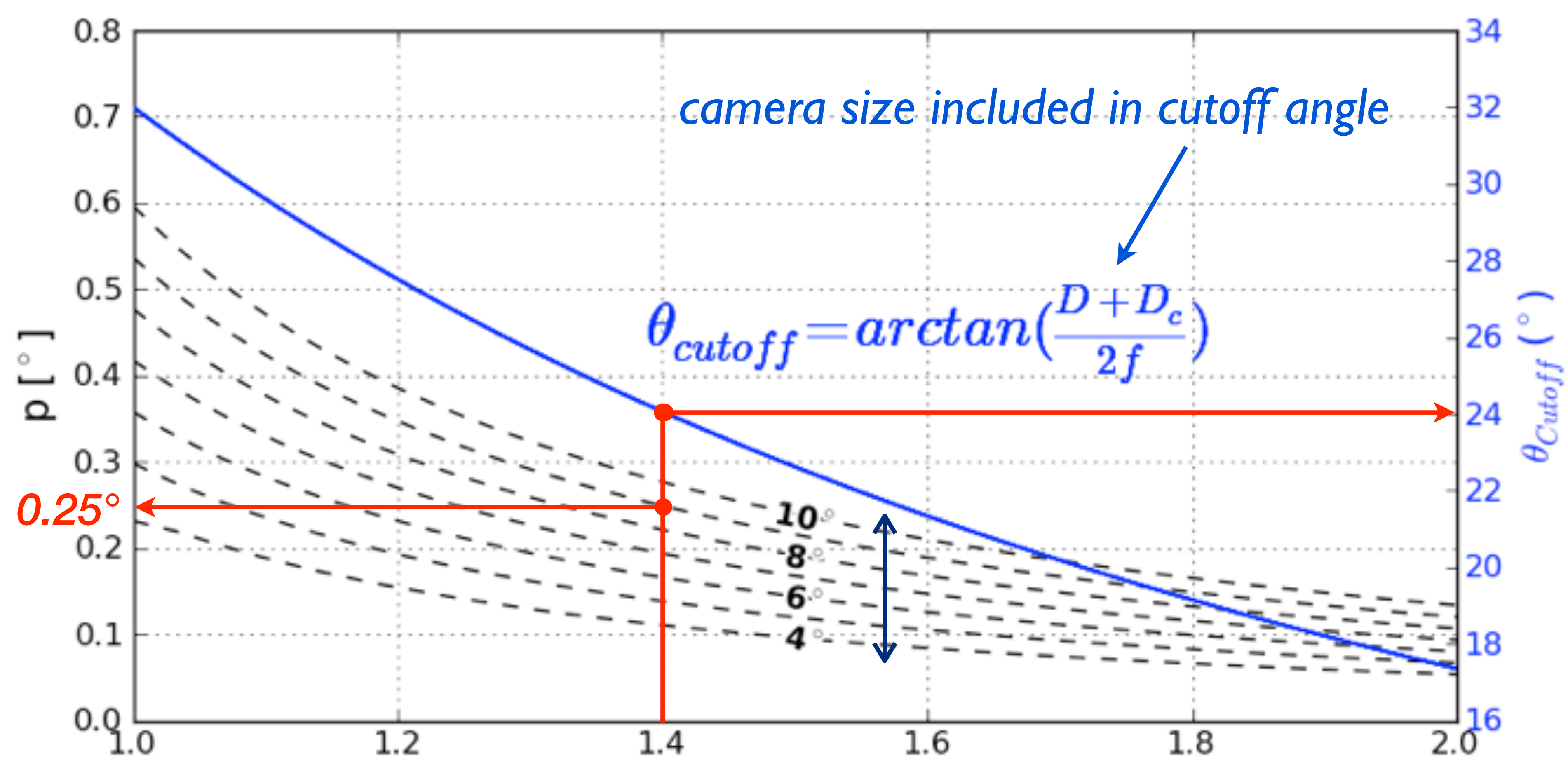
f/D = 1.4

pixel size = 4· min(σ_x, σ_y) = 0.25°

pixel size (linear) = 2.44 cm

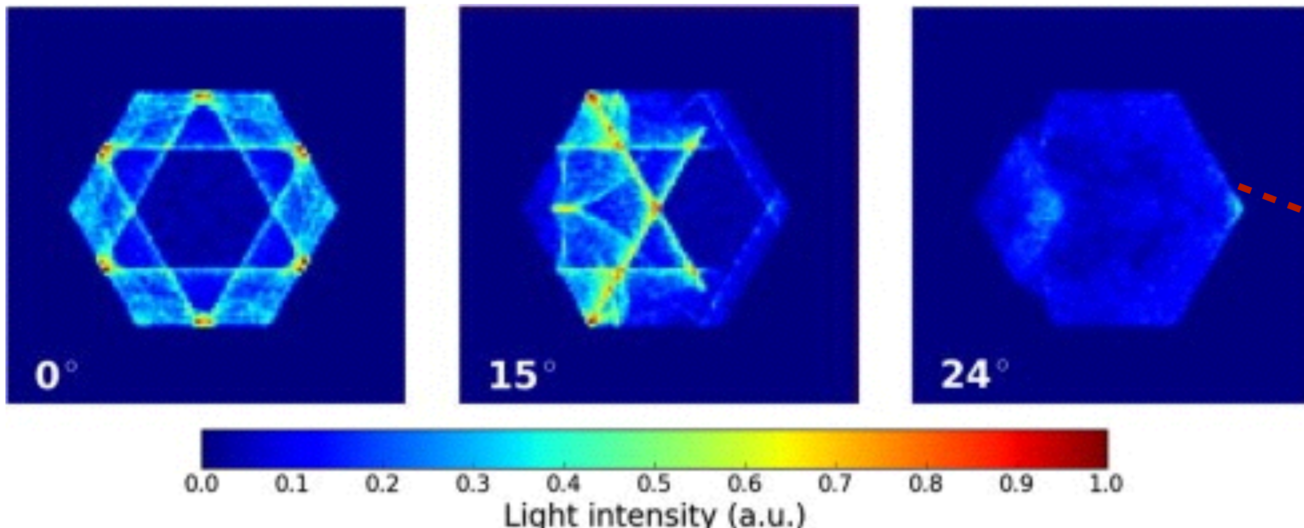
n_p = 1296 pixels

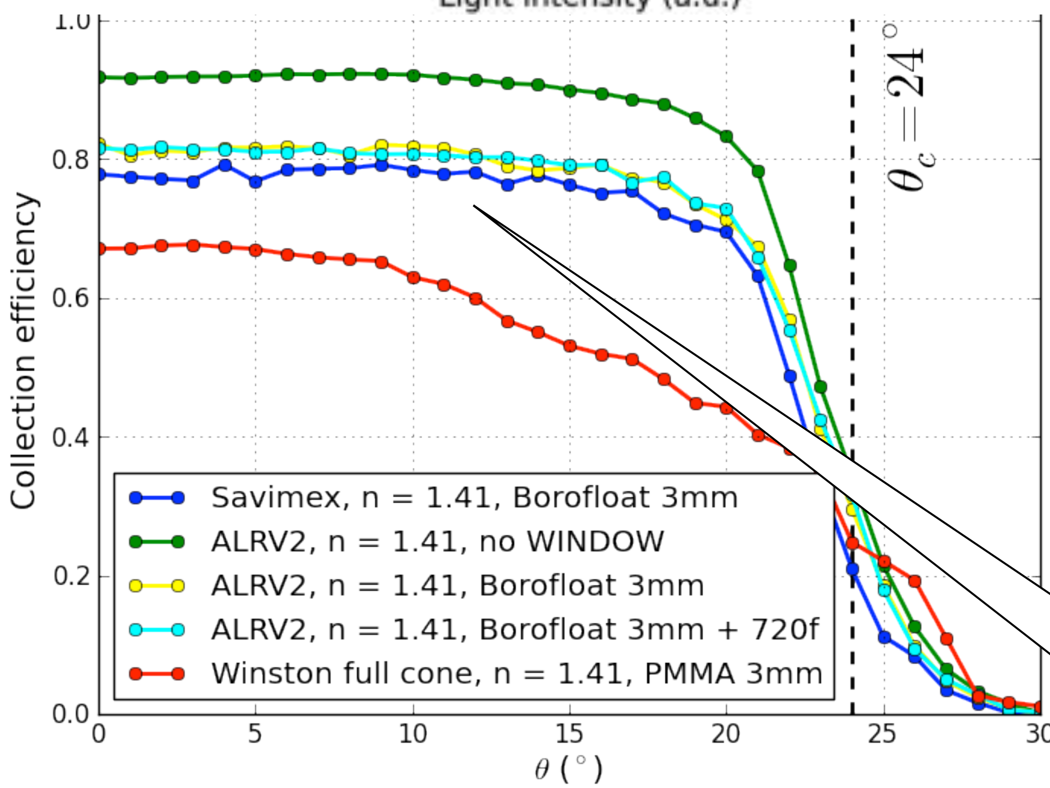
Camera size (D_c) = 88 cm

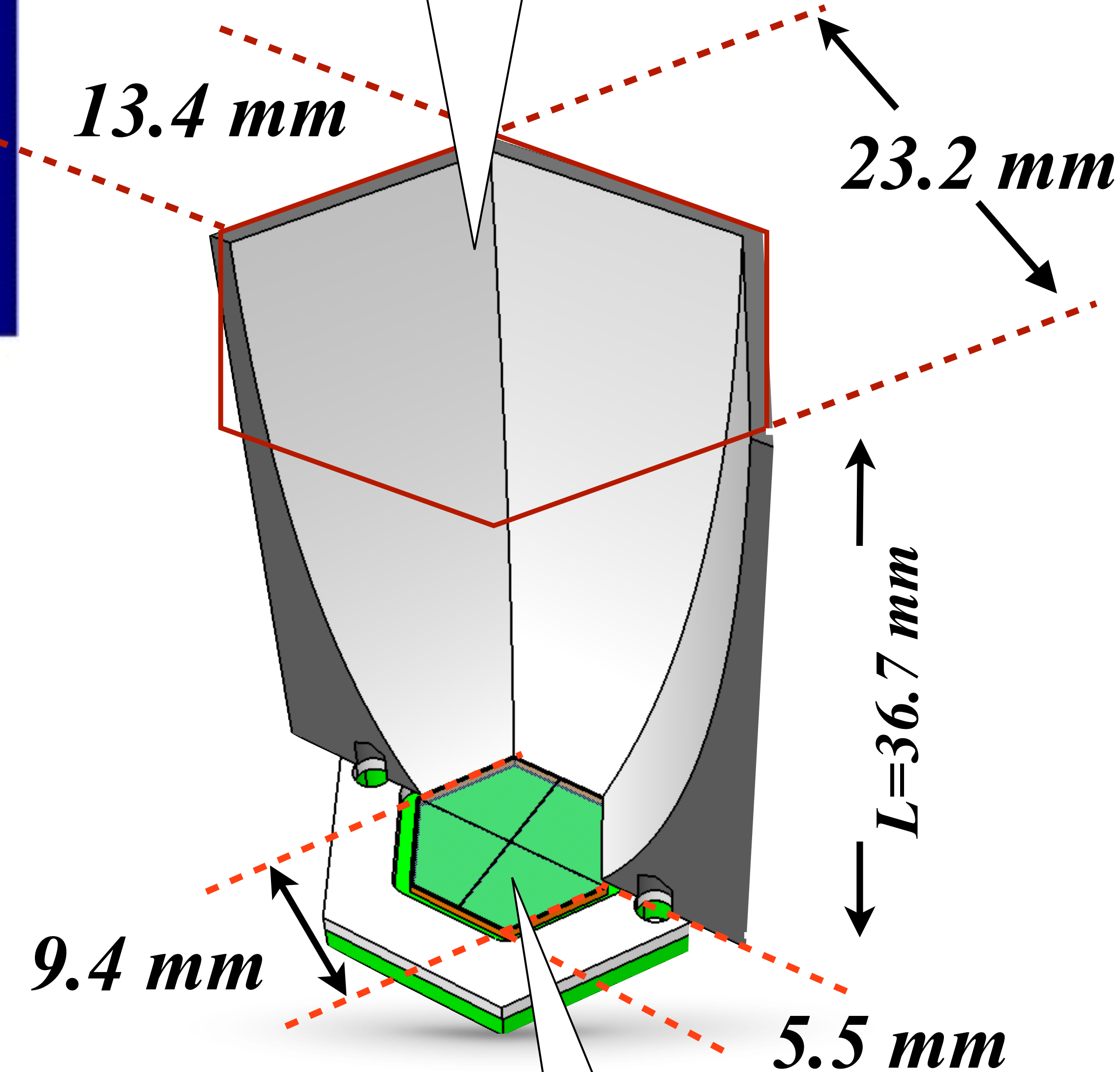


Winston cones

We need an Hollow cone to improve the response in the UV







It's all about coating!

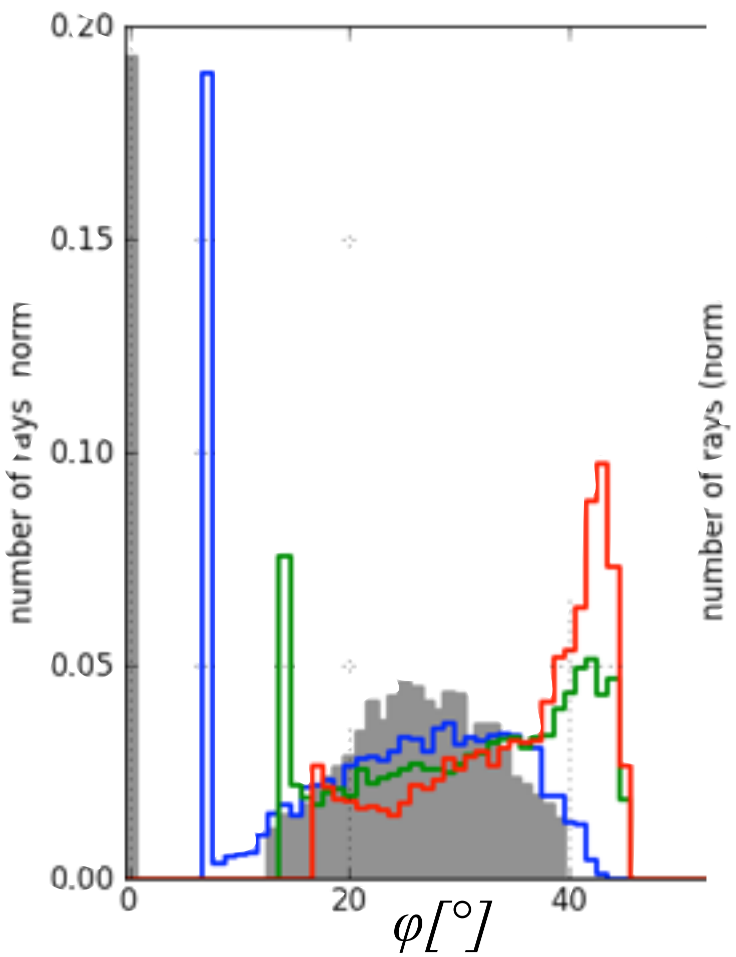
A new type of sensor!

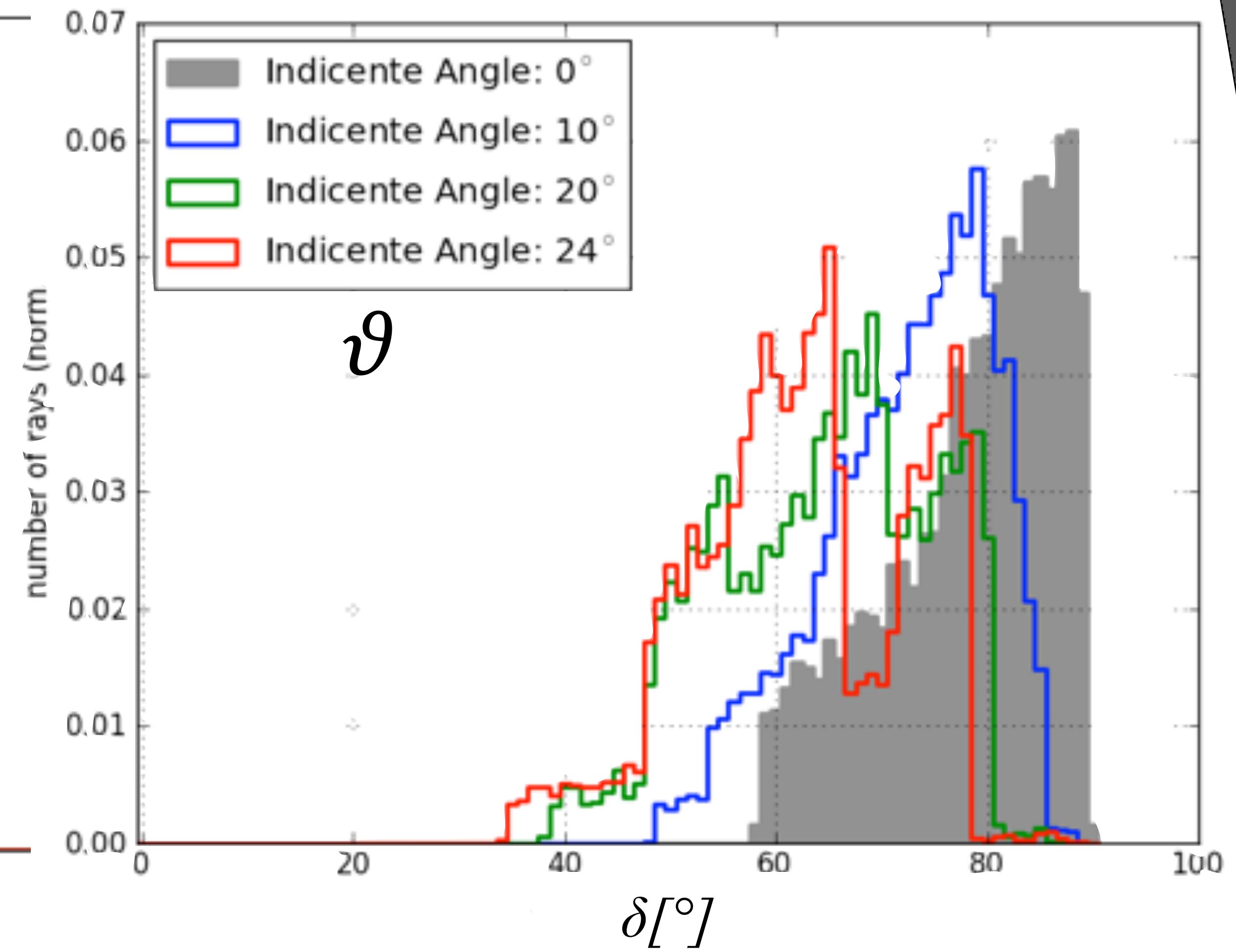
Point Spread Function ➡ angular pixel size: **0.25°** ➡ Top physical size

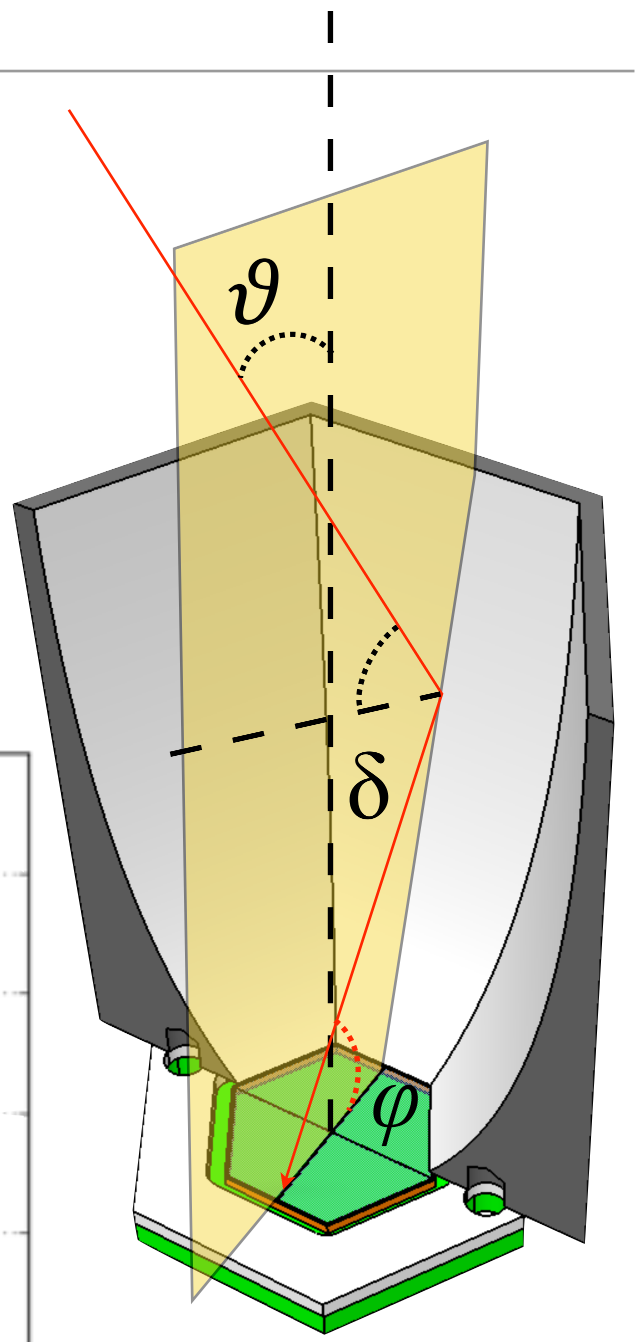
f/D and Camera diameter ➡ Cutoff angle: **24°** ➡ Cone Height

Angular dependency

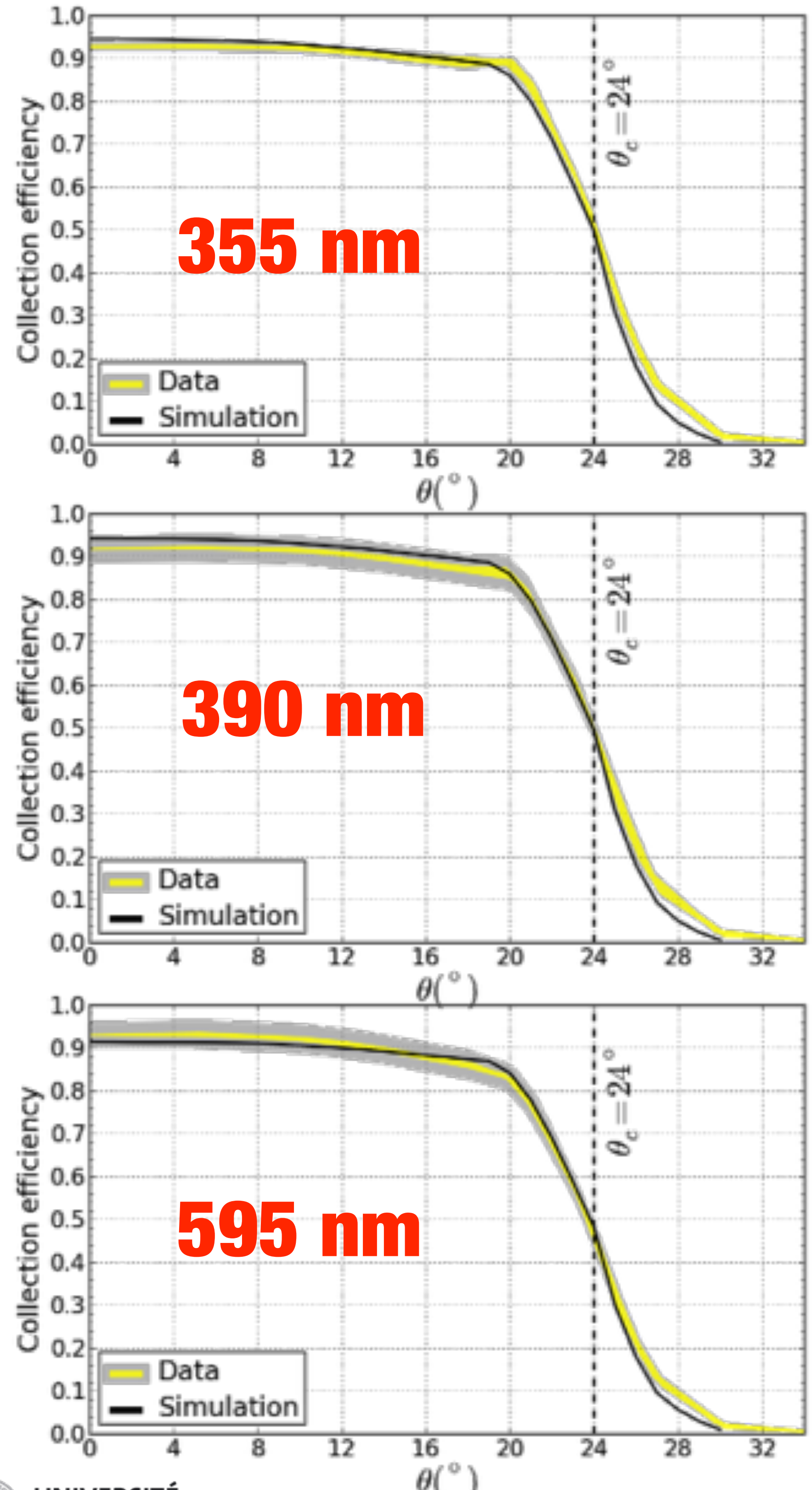
- The angular dependency of the reflectivity is critical
- Most of the light entering at small angles impinges the surface at high angles
- The surface has to have an high efficiency for 40<δ<90







Prototypes and first measurements



- ➡ Measurement done for different wavelengths
- ➡ Simulation of the set-up to validate the coating
- ➡ Very good agreement between simulation and measurement
- ➡ Coating qualified also with 40 thermal cycles (from -15° to +30°) - no measurable effect
- ➡ The collection efficiency shown here does not take into account the effect of the entrance window

Related paper:
J.A. Aguilar et al., *Design, optimization and characterization of the light concentrators of the single mirror small size telescopes of the Cherenkov Telescope Array*, ***Astroparticle Physics, doi:10.1016/j.astropartphys.2014.05.010***

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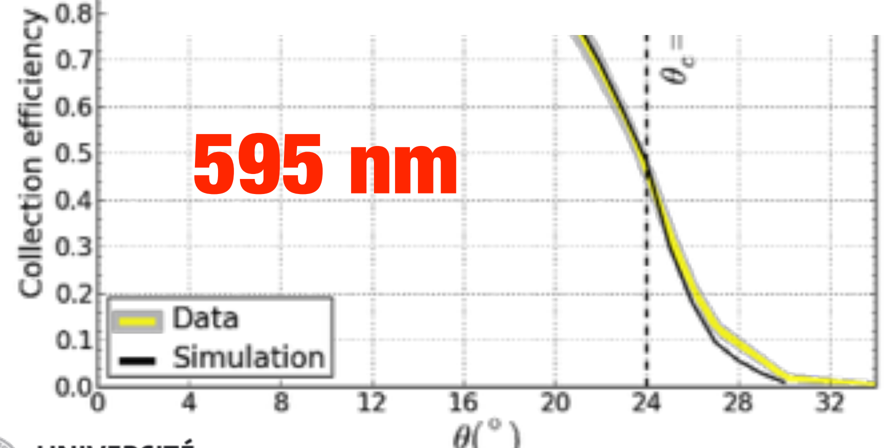

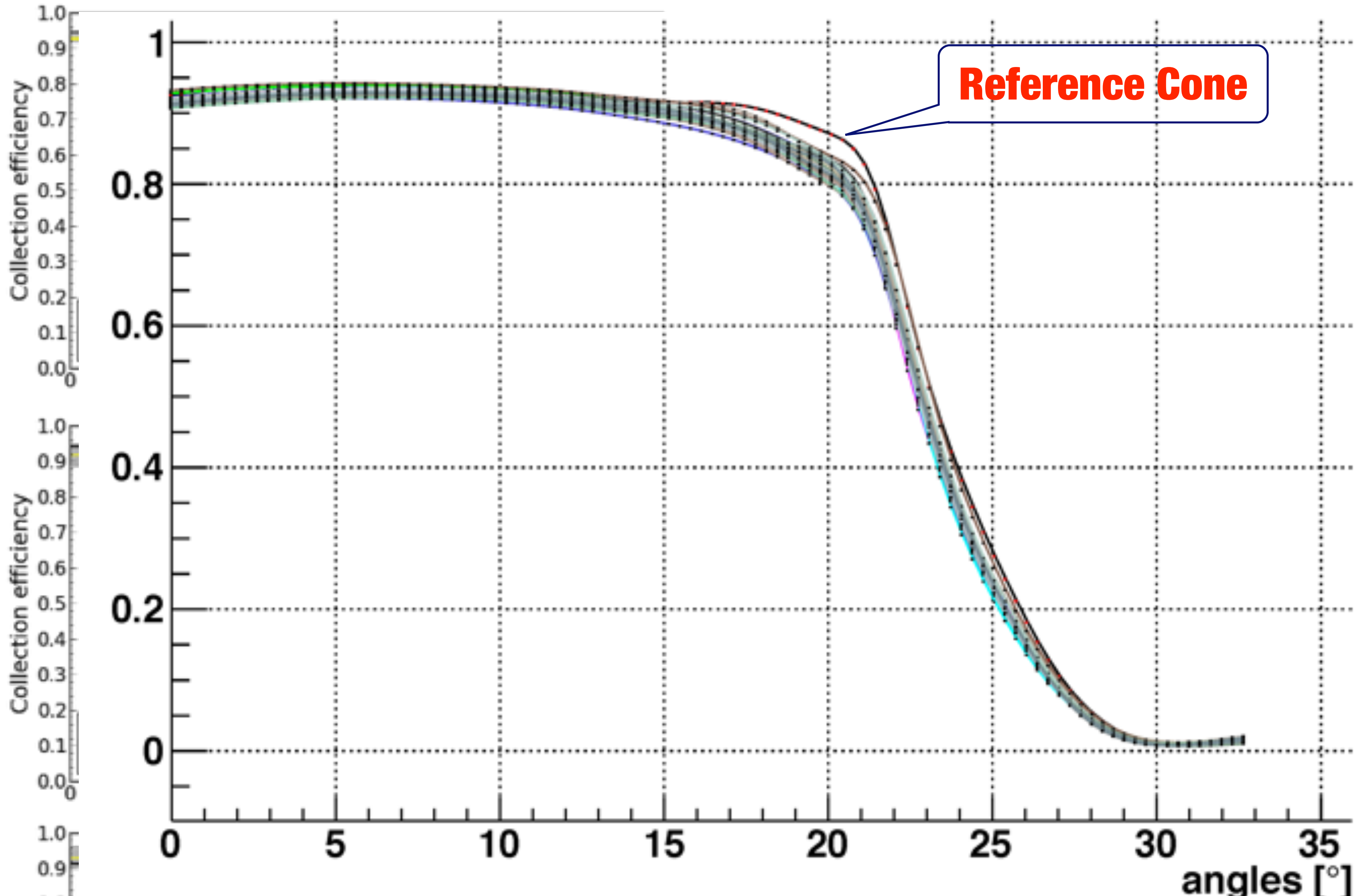

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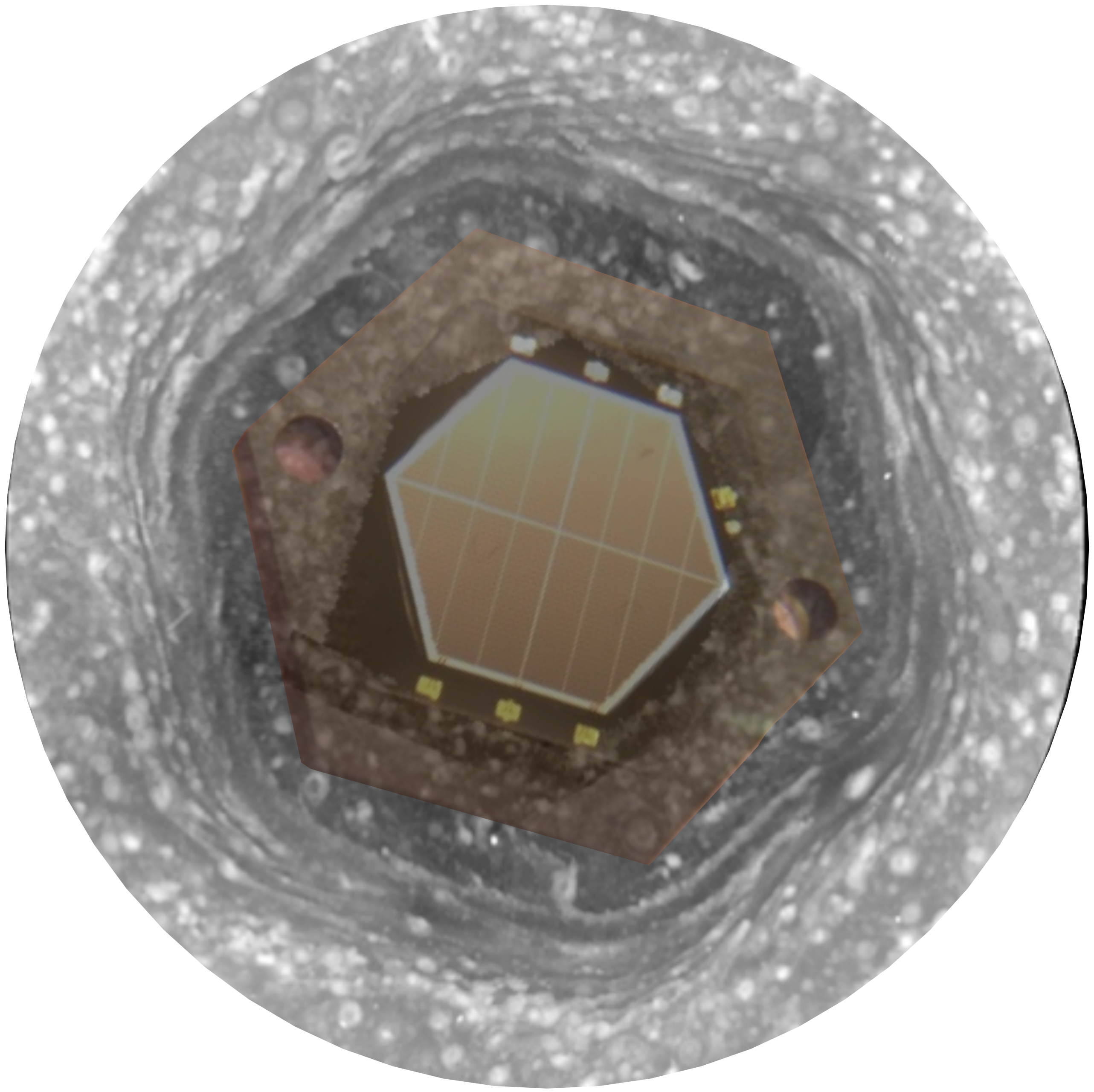
Saturn's hexagonal cloud pattern around its north pole.

The Hexagonal sensor

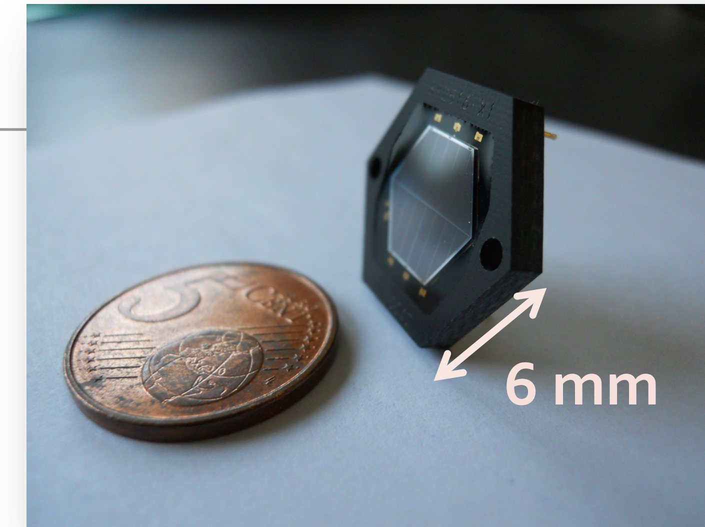


Aguilar, J.A. ; Basili, A. ; Boccone, V. ; Christov, A. ; della Volpe, D. ; Montaruli, T. ; Rameez, M.

Characterization of New Hexagonal Large Area MPPCs

Published in:
Nuclear Science, IEEE Transactions on (Volume:61 , Issue: 3)
DOI: 10.1109/TNS.2014.2321339

The Hexagonal Sensor

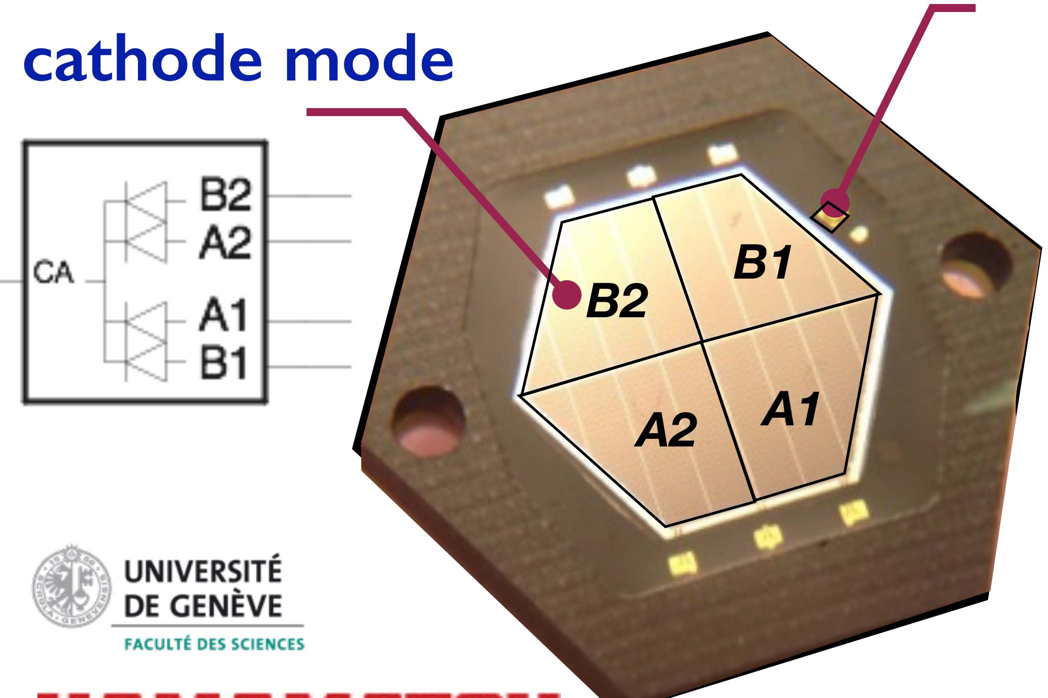


- Despite the use of the light concentrators, the pixel size remains large compared to common devices,
- Result of a collaboration between DPNC University of Geneva and Hamamatsu, the sensors are large hexagonal arrays of G-APD.

SENSOR PARAMETERS (T 25°C)	
Channels	*4*
Effective active area/channel	23.38 mm
Pixels per channel	*9210*
Pixel size	50x50 μm
Fill factor	*61.5%*
Spectral response range	*320 to 900 nm*
Peak sensitivity wavelength	*440 nm*
Rec. Operating V range	*60 – 80 V*
Vop variations between channels	*0.15 (max 0.3)*
Dark count/channel at Vop	*2.8 (max 5.6) Mcps*
Terminal C/channel at Vop	*> 800 pF*
PDE at peak sensitivity λ	*50 (min 40) %*
Crosstalk probability	*10 (max 15) %*
T coefficient of reverse voltage	*56 mV/°C*
Gain at Vop	*7.5 x 10*

4 channels in common cathode mode

Thermistor



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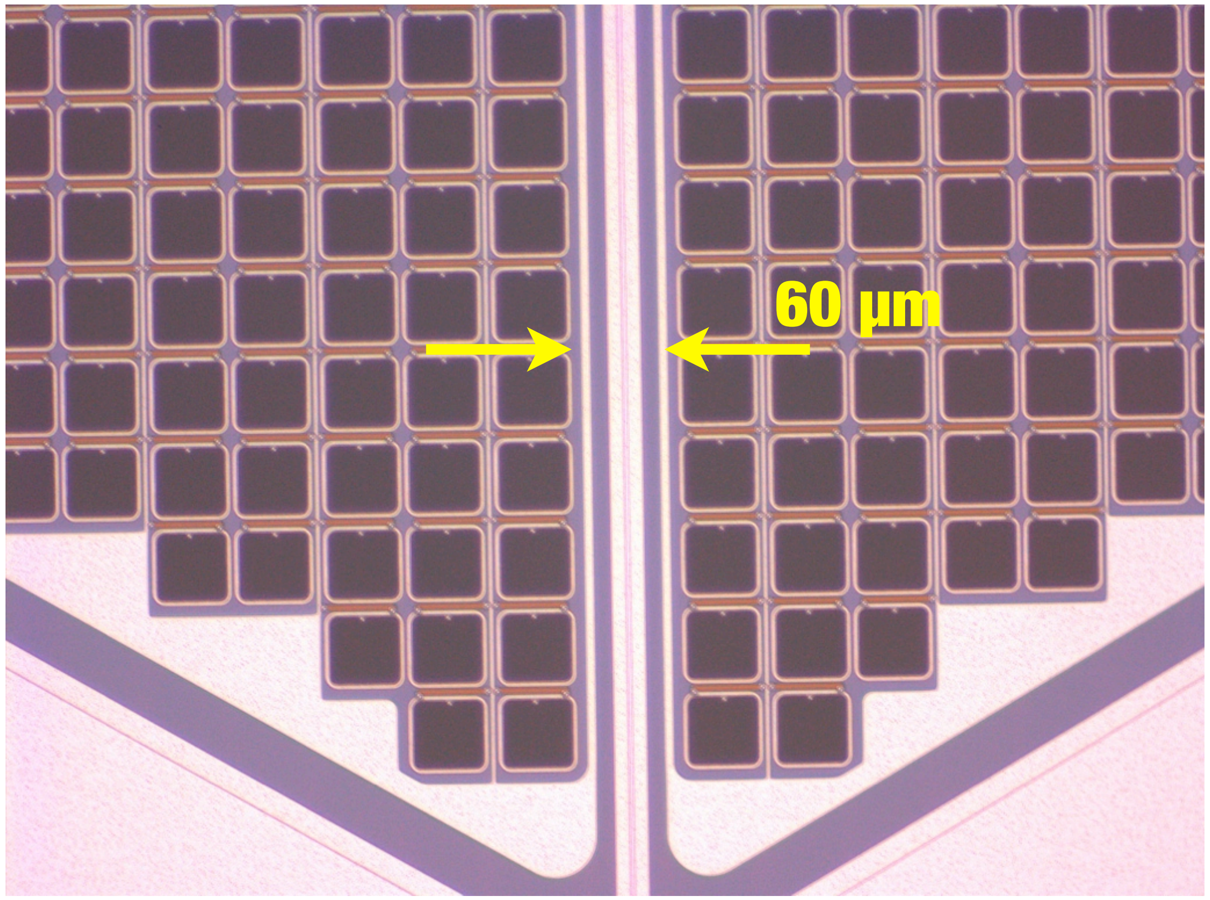
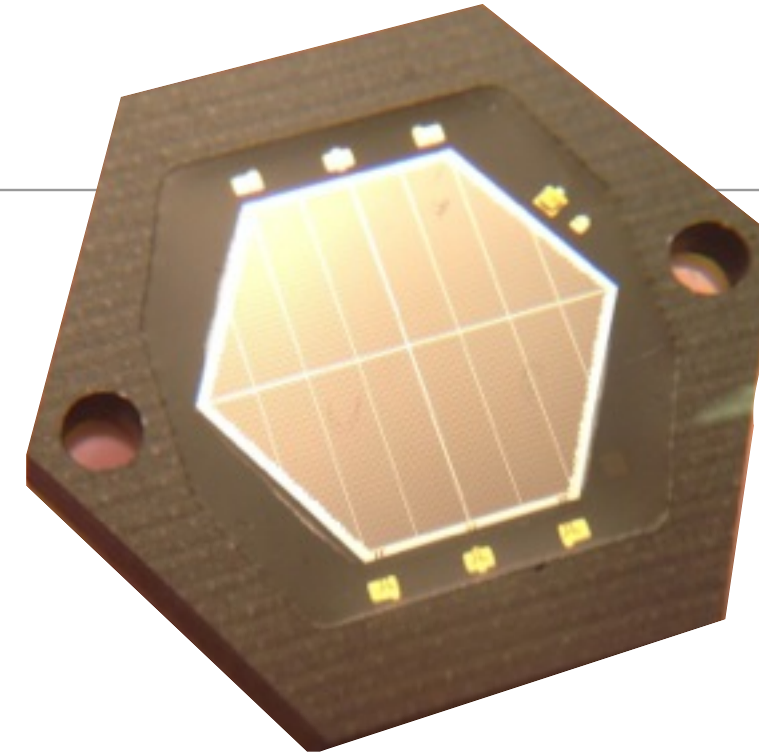
HAMAMATSU
PHOTON IS OUR BUSINESS

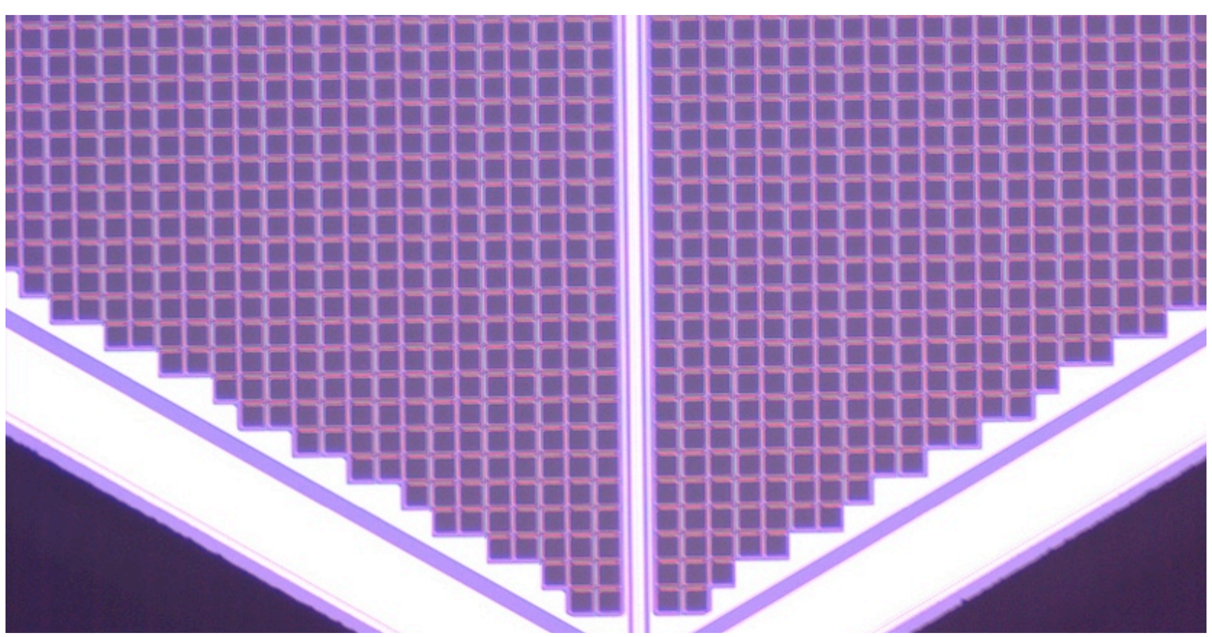
➡ 93.6 mm^2 surface

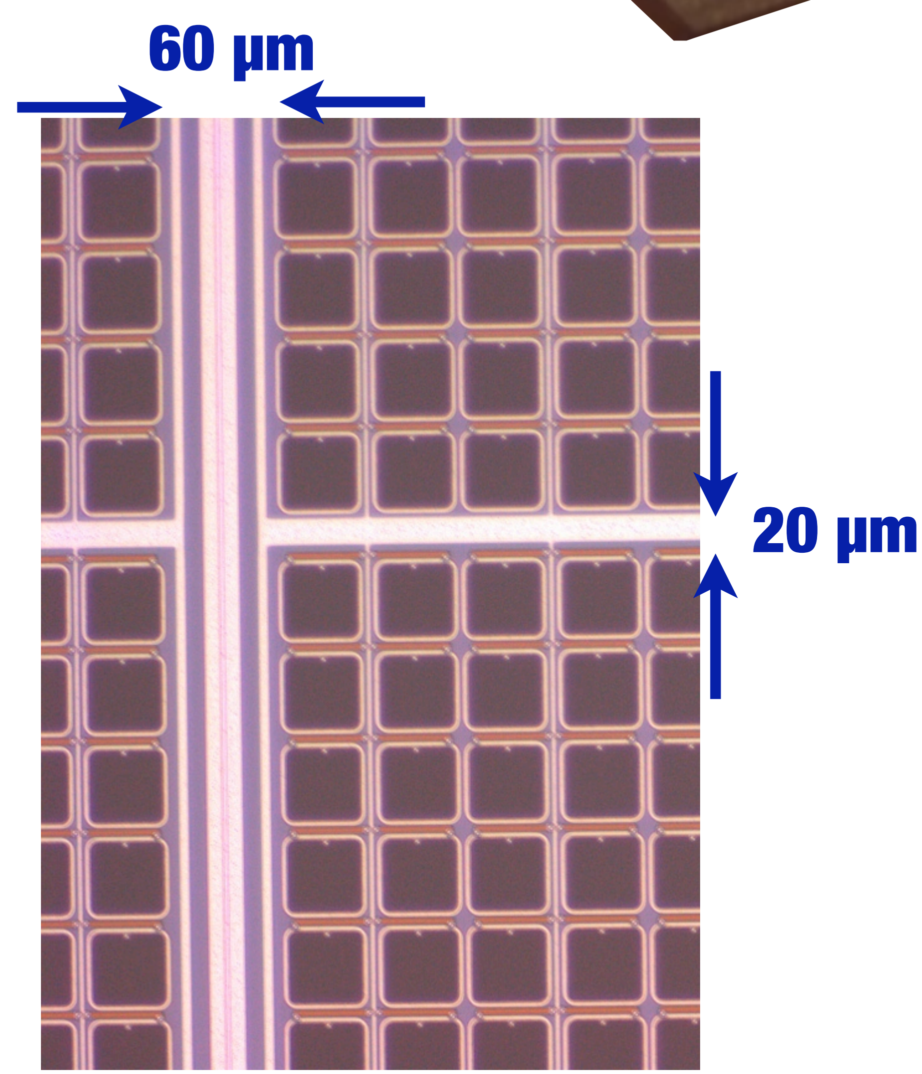
➡ 10.4 mm flat-to-flat

The S12516-050 sensor



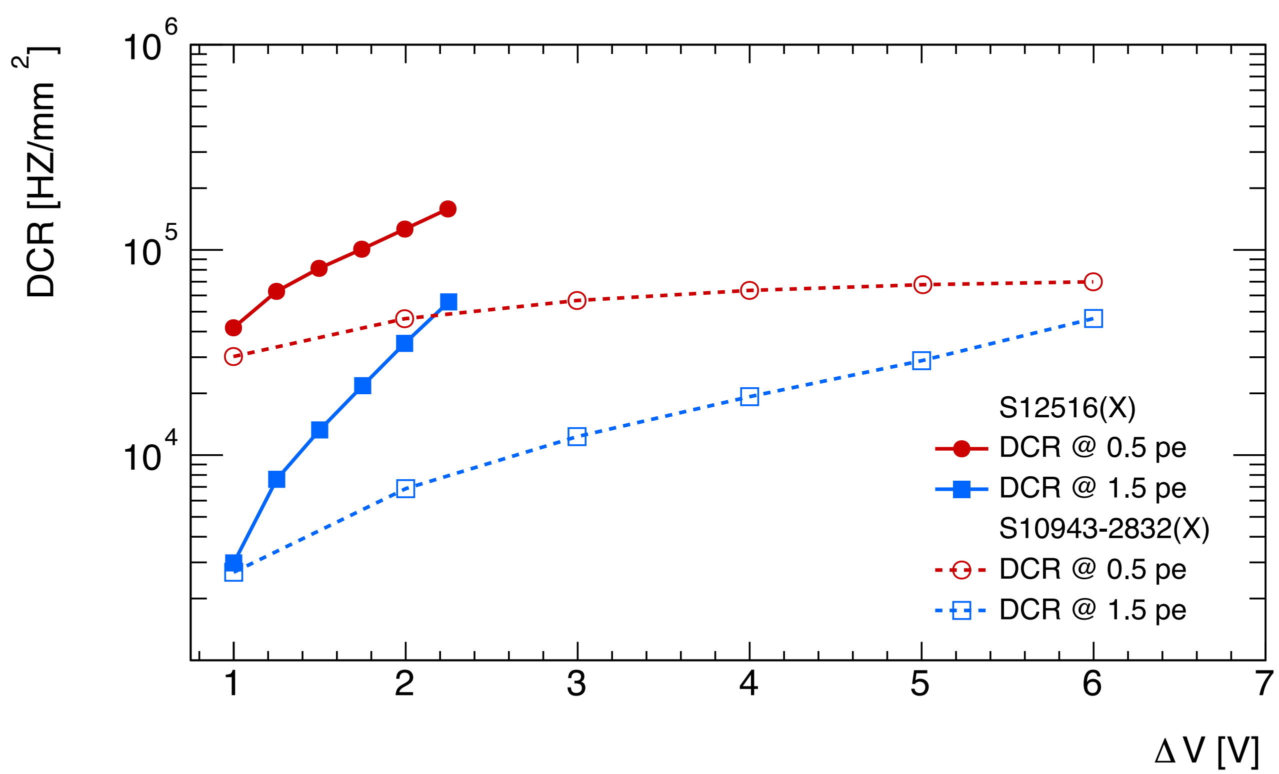


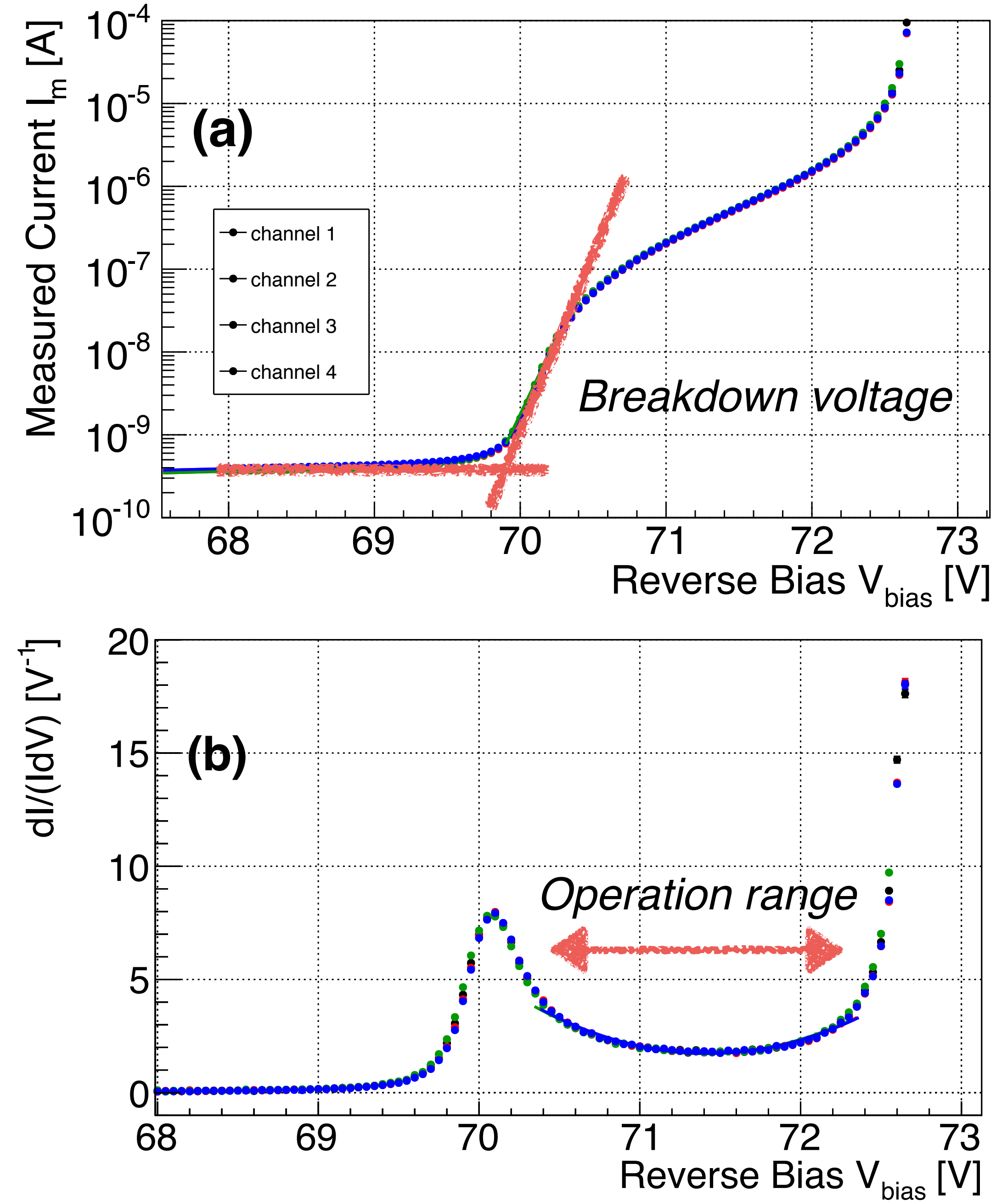




Characterizations of the hexagonal sensors

- IV / CV characteristics to extract the breakdown voltage and the operation range
- Photo Detection Efficiency as a function of over-voltage and wavelength
- Cross talk as a function of over-voltage
- Dark count rate as function of over-voltage
- Gain linearity and charge resolution





Plotting the Optical cross talk vs. the PDE allows to select the proper operational voltage and to easily discriminate between different sensors

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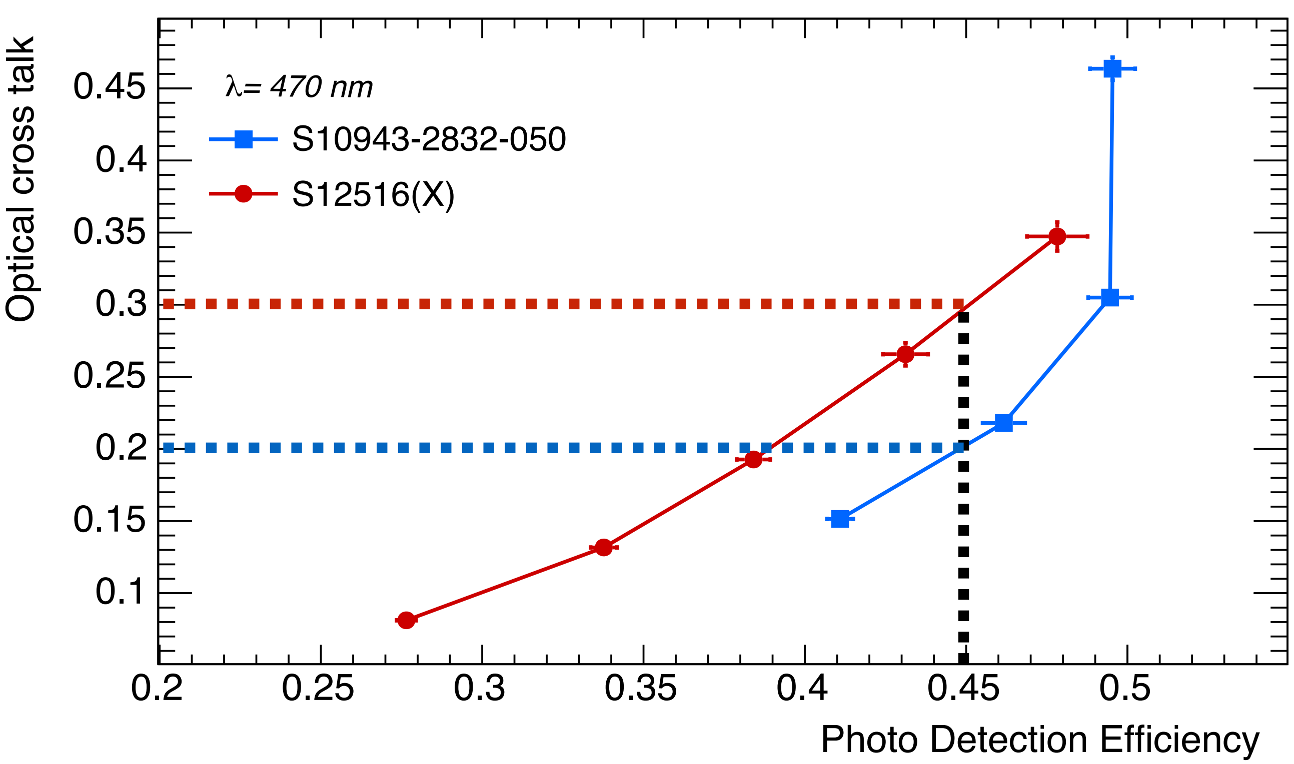
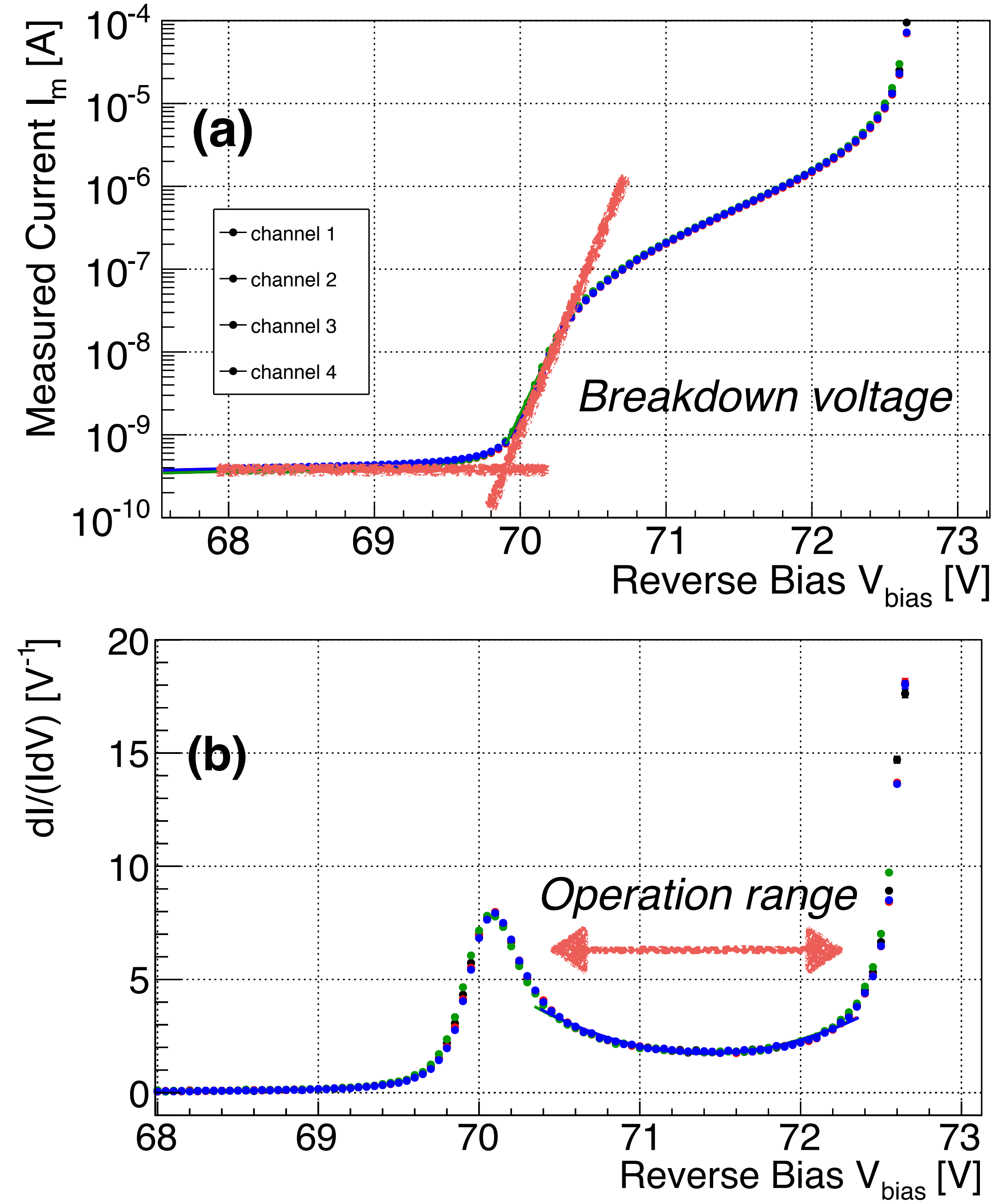
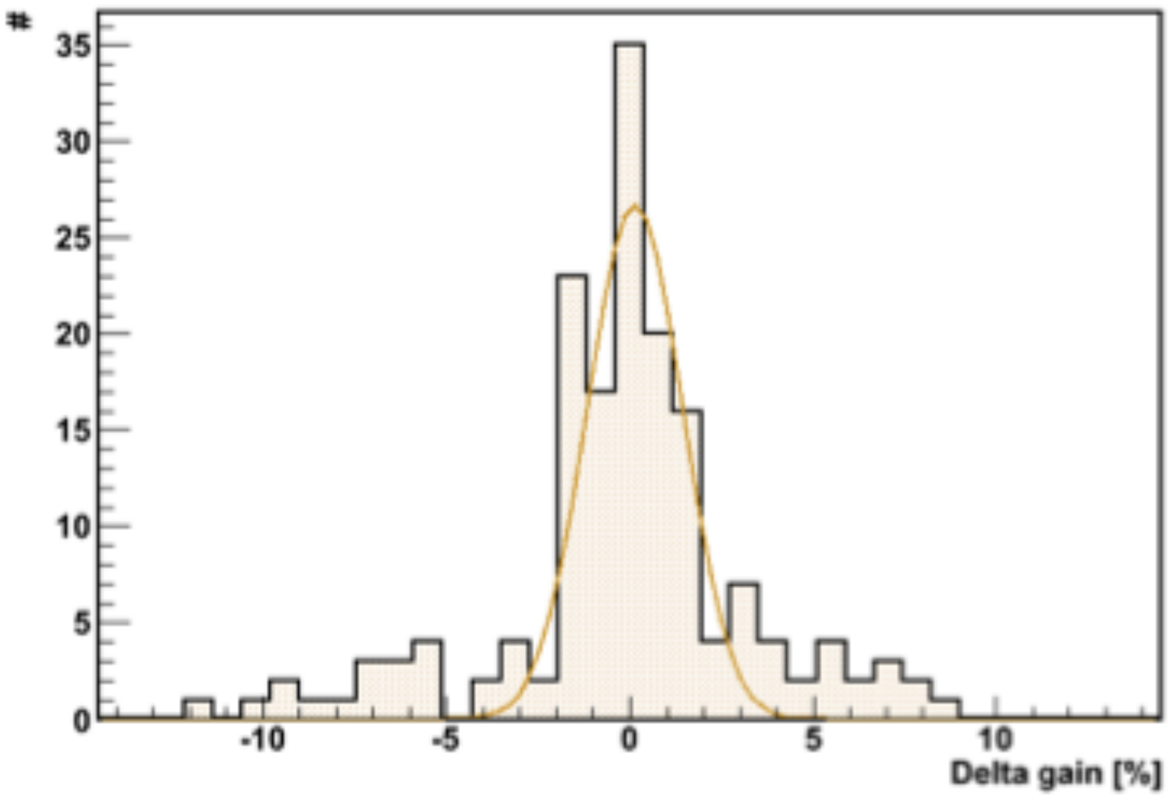
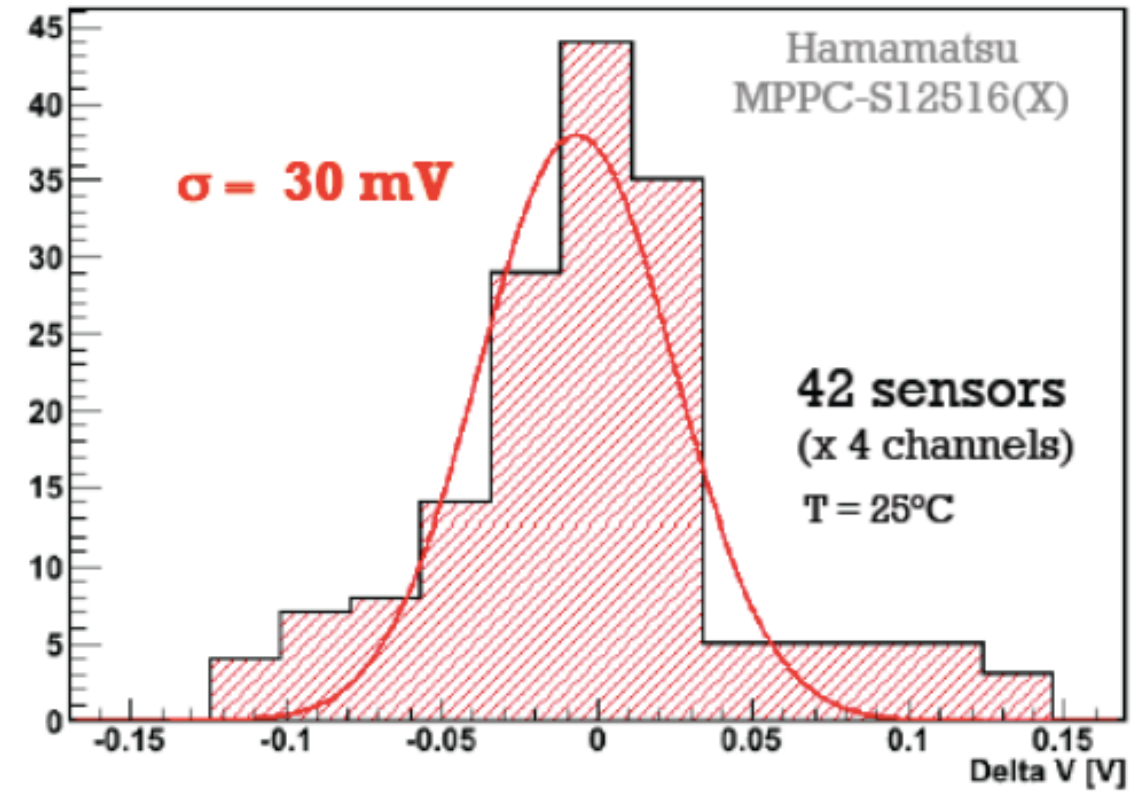




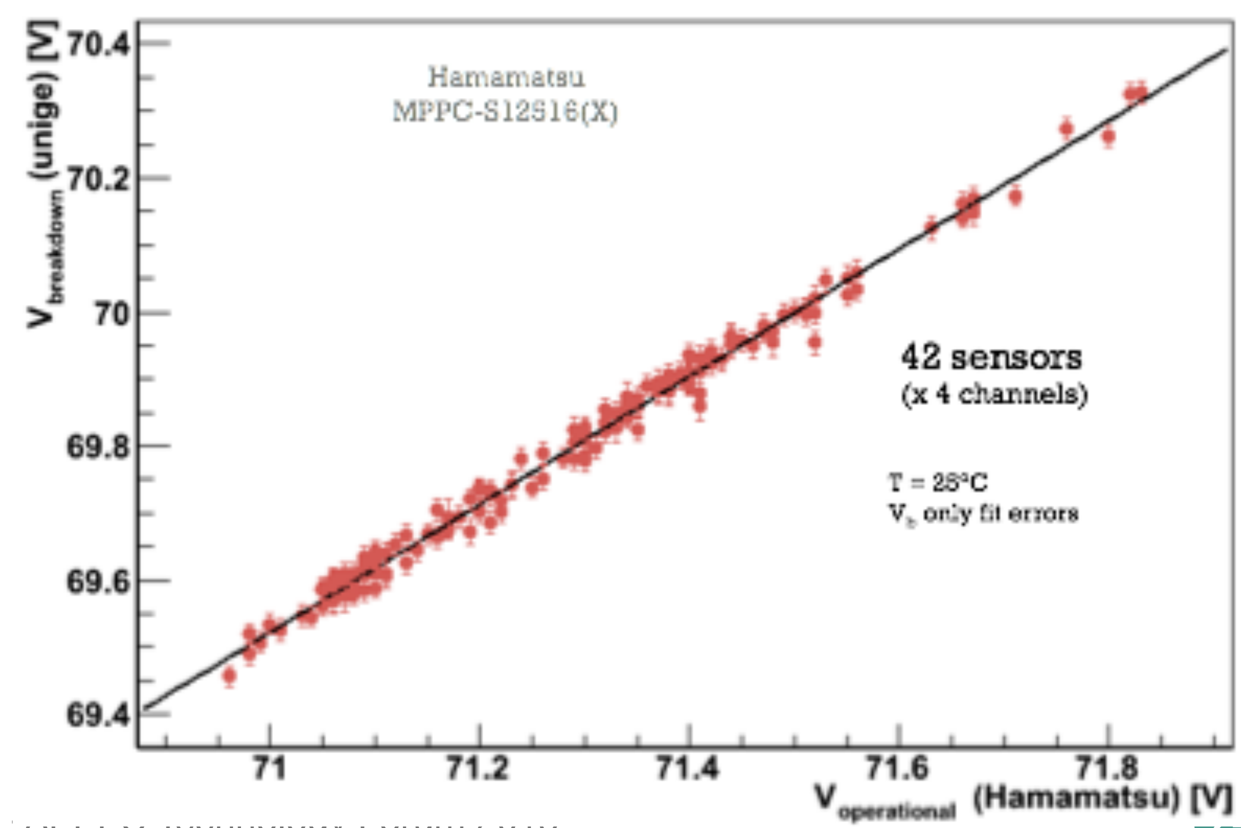
Plotting the Optical cross talk vs. the PDE allows to select the proper operational voltage and to easily discriminate between different sensors

Small variation sample-by sample. Is it True?



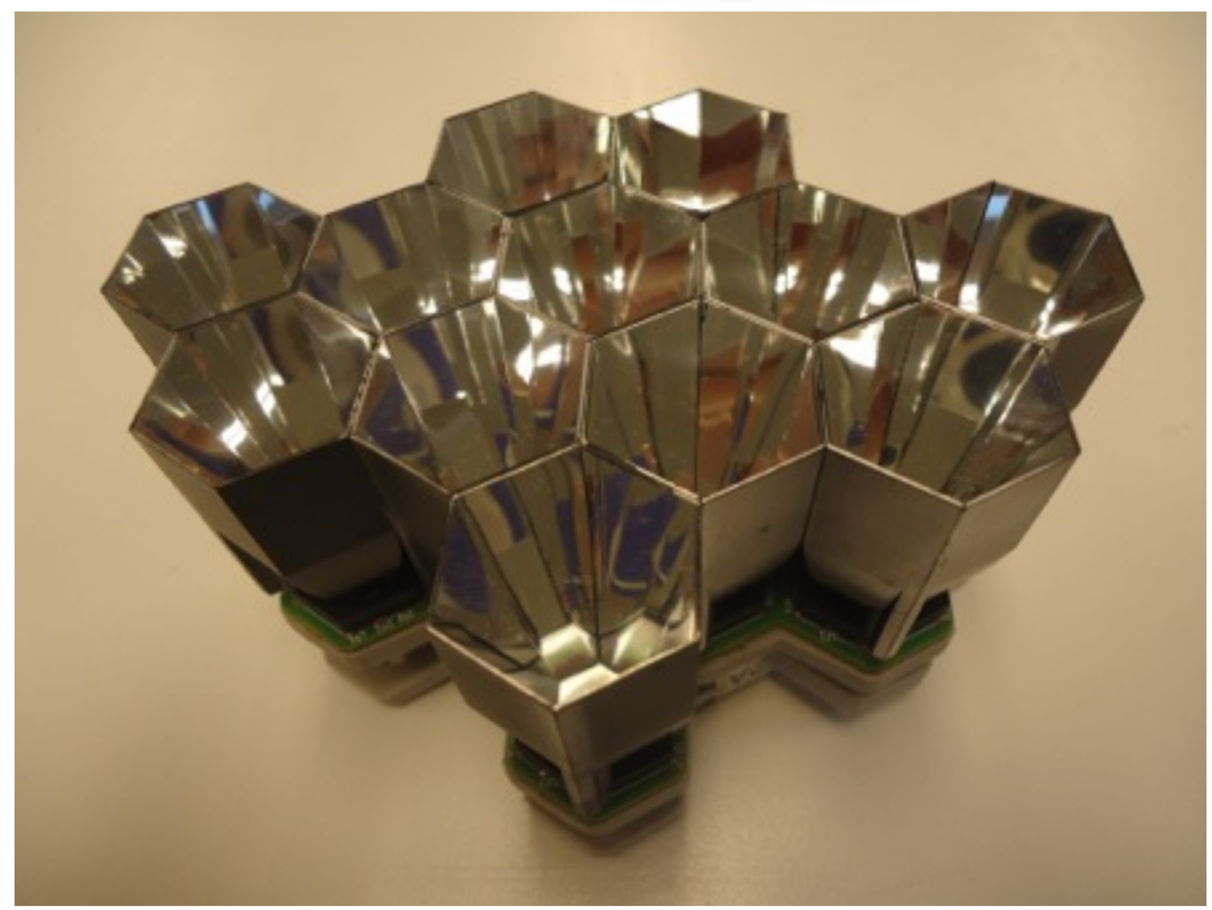


- Yes it is !
- Homogenous parameters
- Reasonable spread
- Perfect correlation of V_{break} with V_{op} as provided by Hamamatsu



The Front-end electronics

- The pre-amp boards
  - read and pre-amplify the analog signals
  - routes out signals, the HV and the output of the NTC probe, present on the sensor package.
- SlowControl Board
  - route pixels signals to Digicam via the RJ45 connector
  - distributes the power and the HV
  - regulate HV to compensate temperature variations to stabilize the sensor performances.
  - Board accessed via CAN-bus



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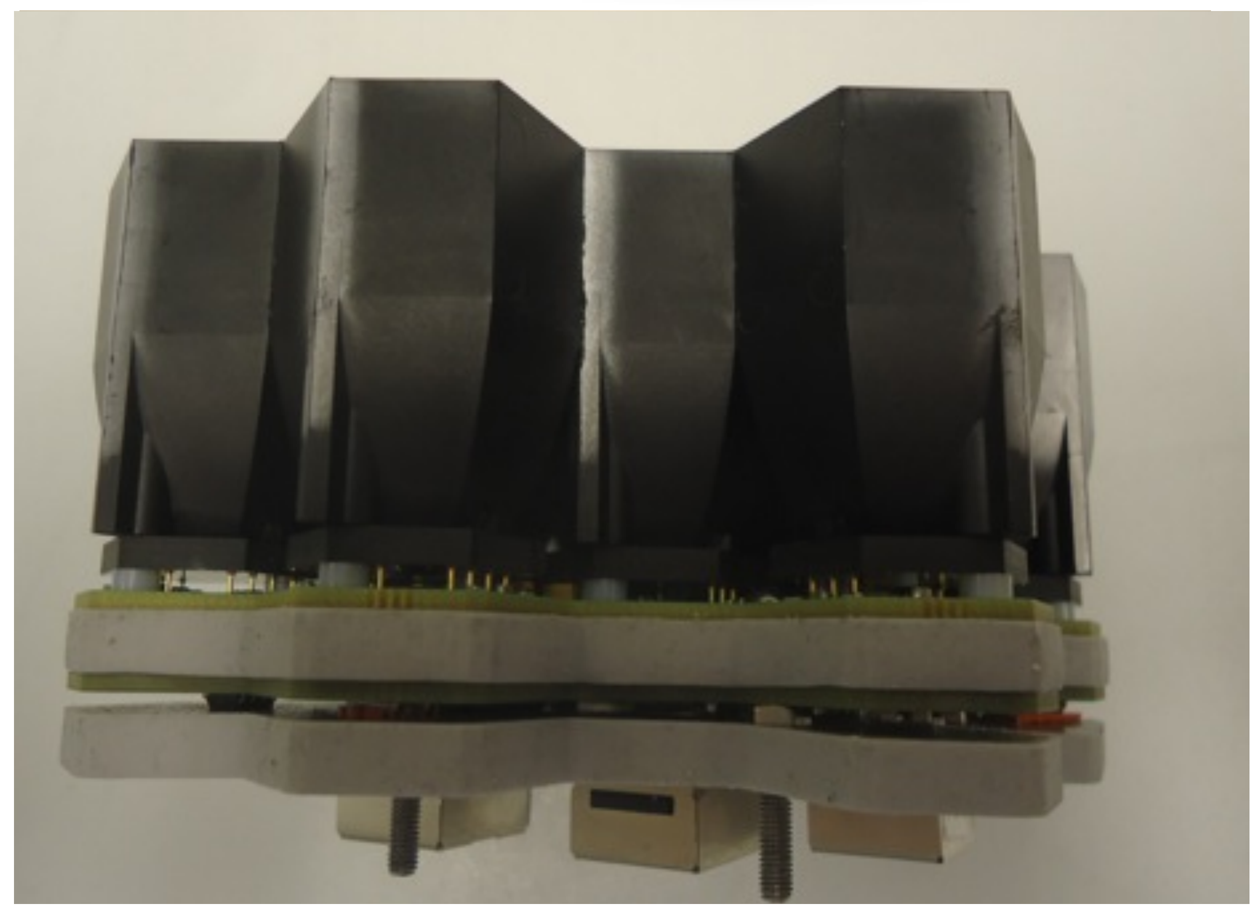
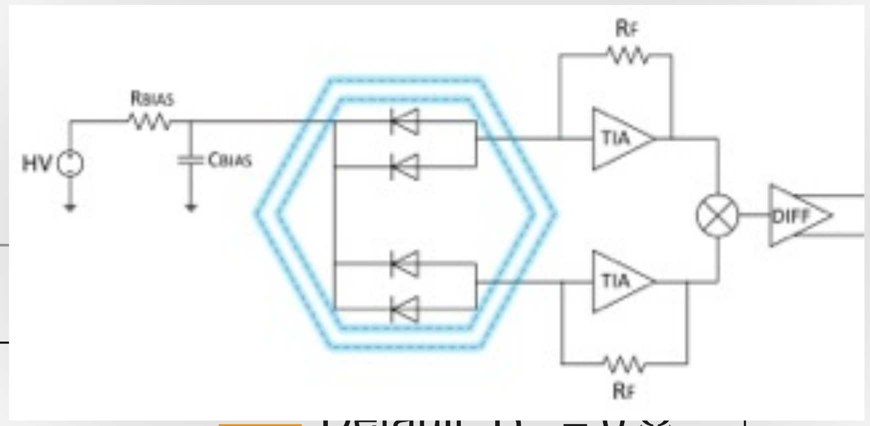
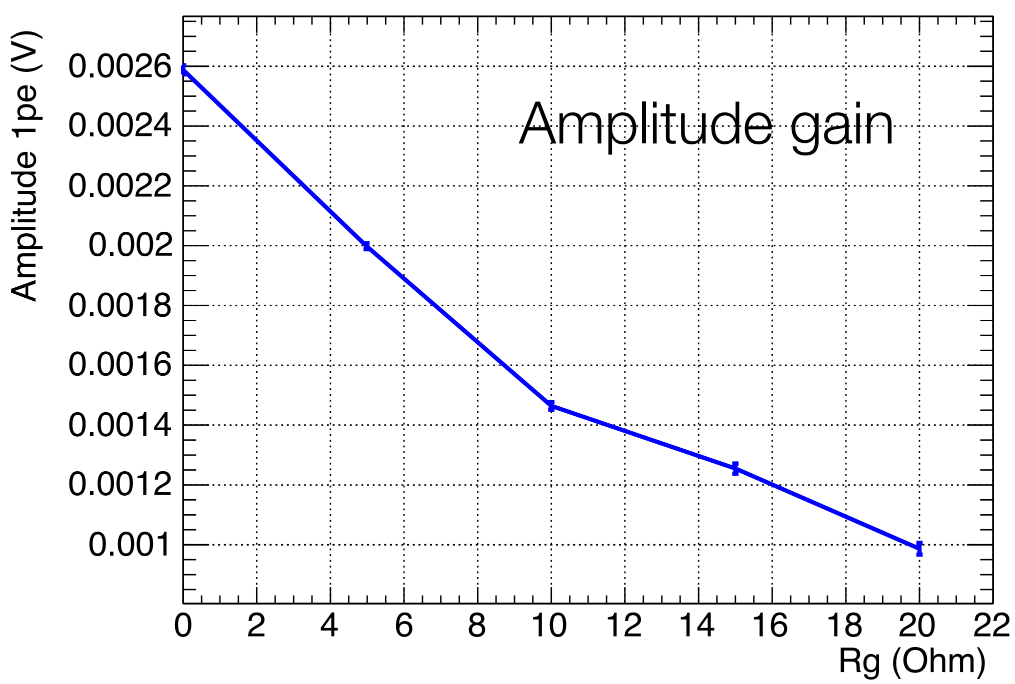
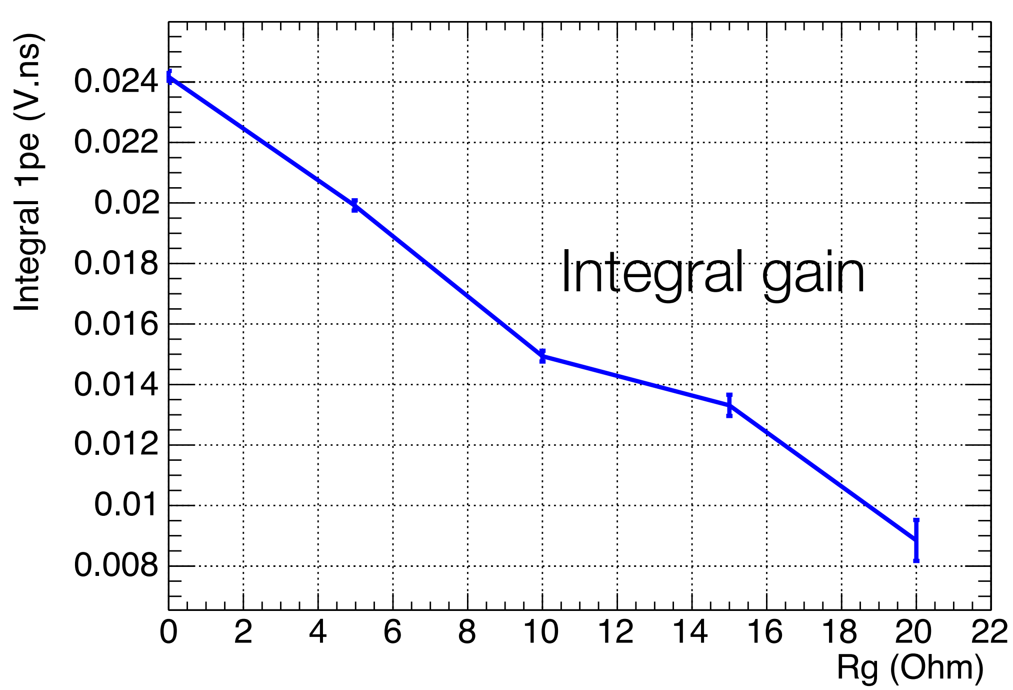
  - regulate HV to compensate temperature variations to stabilize the sensor performances.
  - Board accessed via CAN-bus

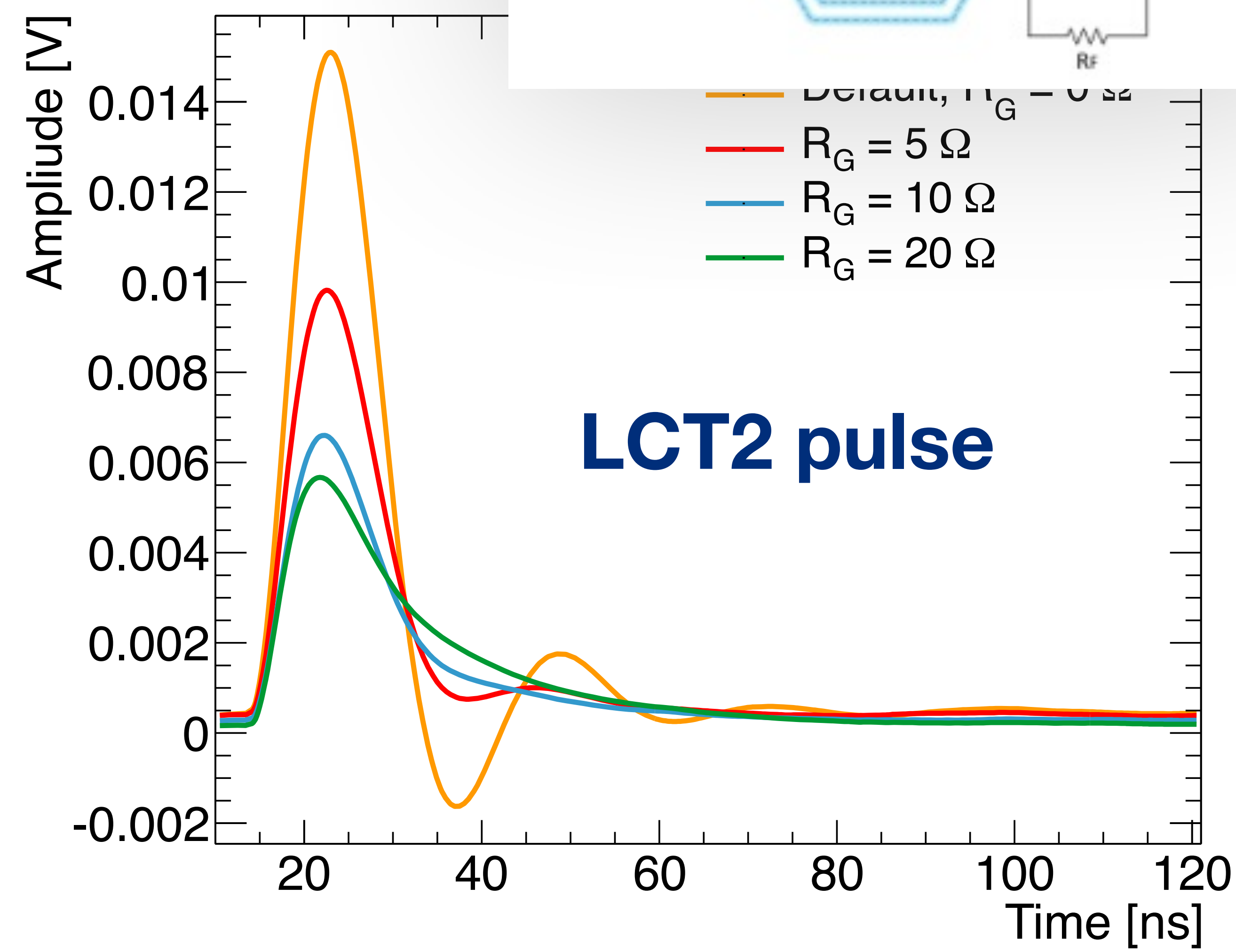


but Electronics Needs Tuning!





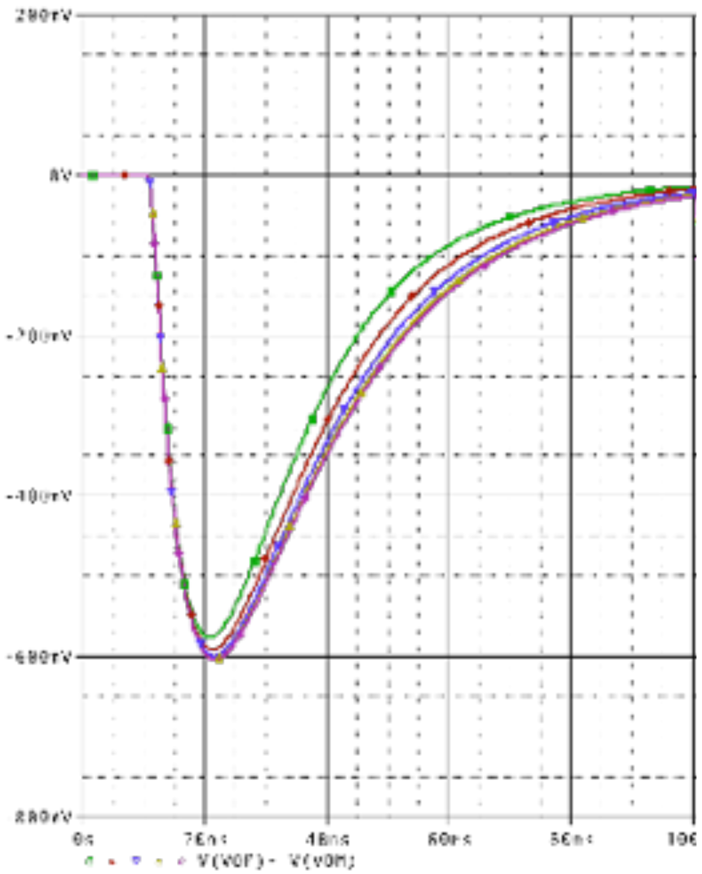




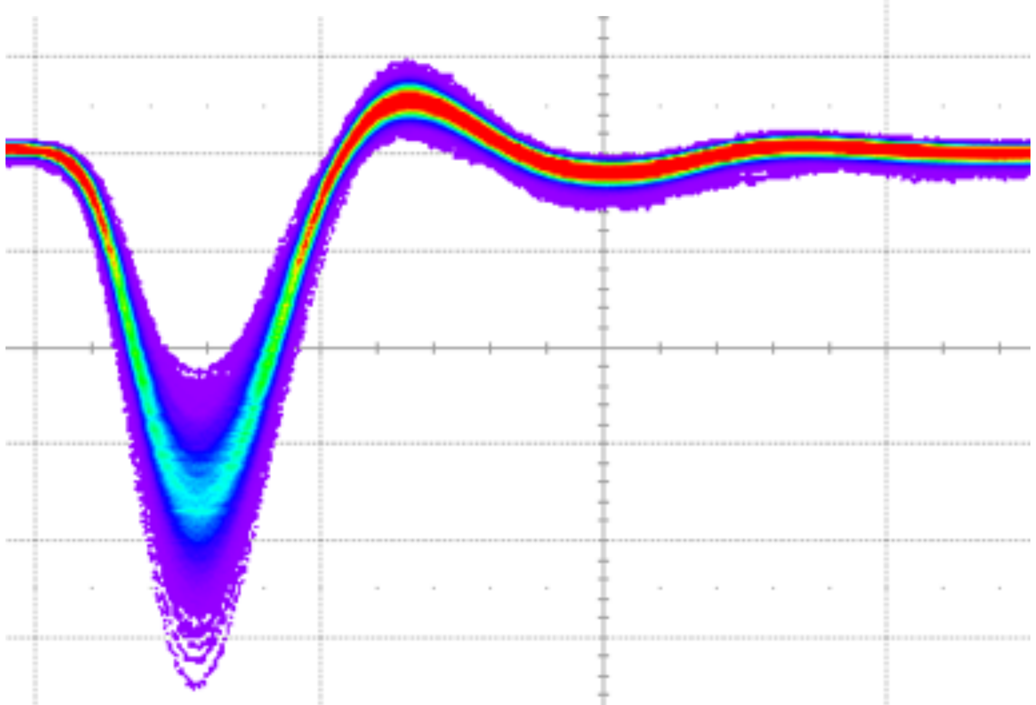
As expected the gain is decreasing when R_G increases

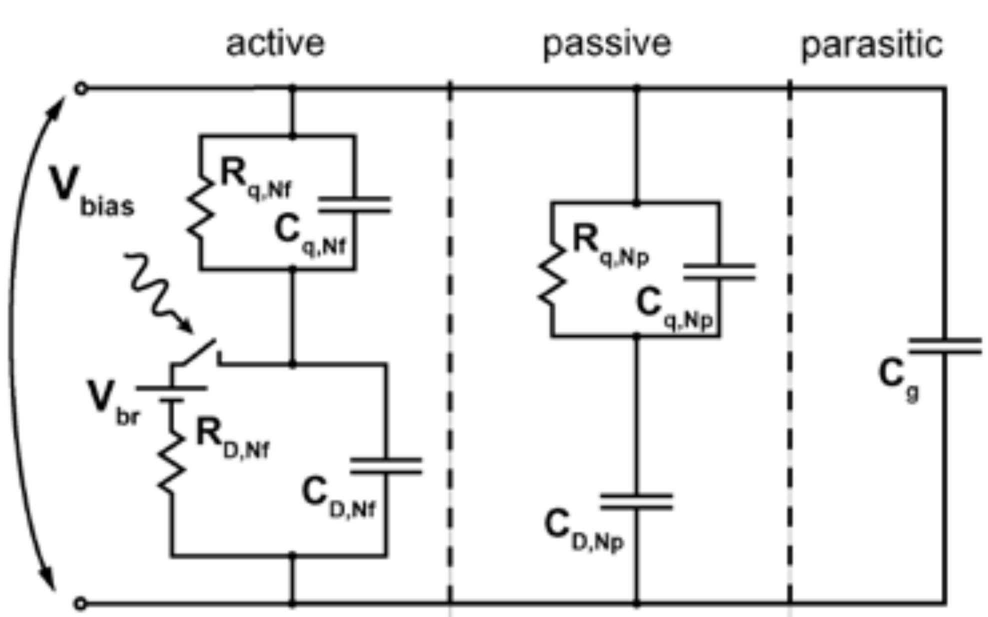
One can possibly tune the gain to equalize the response of both types of sensors, but the trigger scheme can be configured to work with different thresholds

Simulation of the sensor



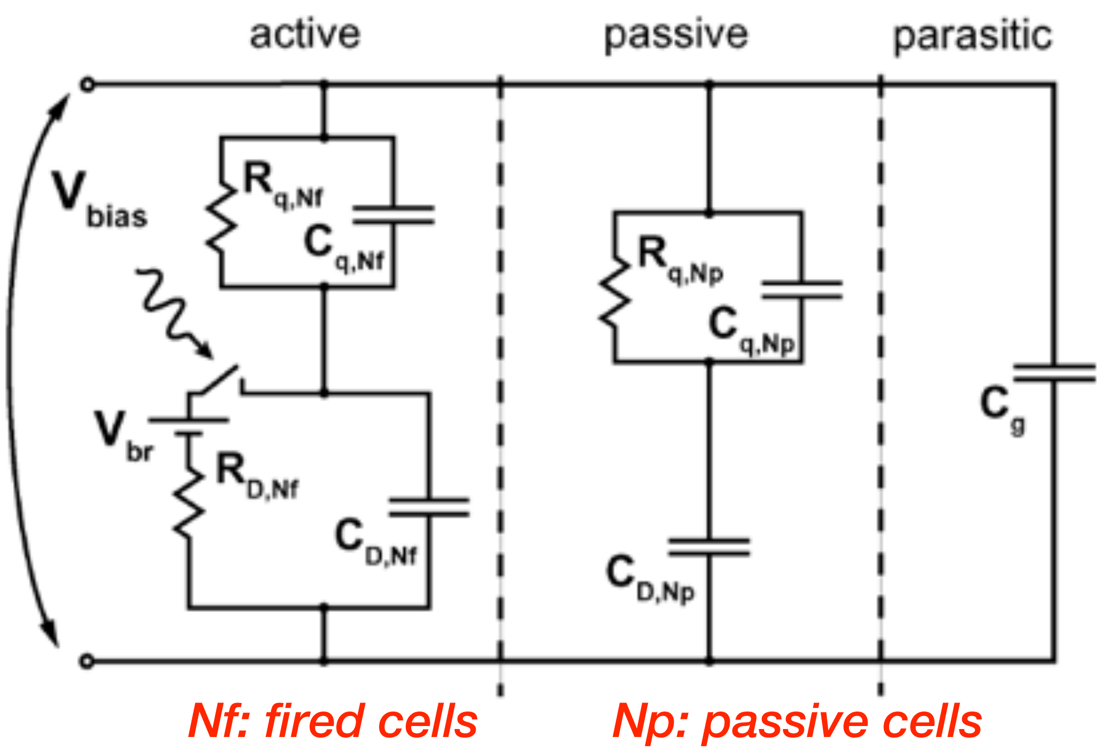
- The Pre-amp design was optimized with simulation but the pulse measured differs in many way from the simulated one.
- In order to tune the preamp for an optimal response, we need to understand the sensor model and to simulate it properly
- Changing the sensor type should not imply systematically empirical tuning, simulation should be able to provide the proper parameters





Corsi Model

The Corsi Model



Nf: fired cells *Np: passive cells*

Parameters:

- V_{br}: breakdown voltage ➡ determined from IV curve
- V_{bias}: bias voltage ➡ User defined
- Rq: quenching resistor ➡ IV forward fit
- R_D: diode resistor ➡ Rising time, preamp bandwidth limited

- C_q: quenching capa
- C_D: diode capa ➡ Use LCR meter
- C_g: parasitic capa

$$Q_C = \frac{R_q}{R_q + R_D}(V_{bias} - V_{BR})(C_D + C_q)$$
$$\approx (V_{bias} - V_{BR})(C_D + C_q).$$

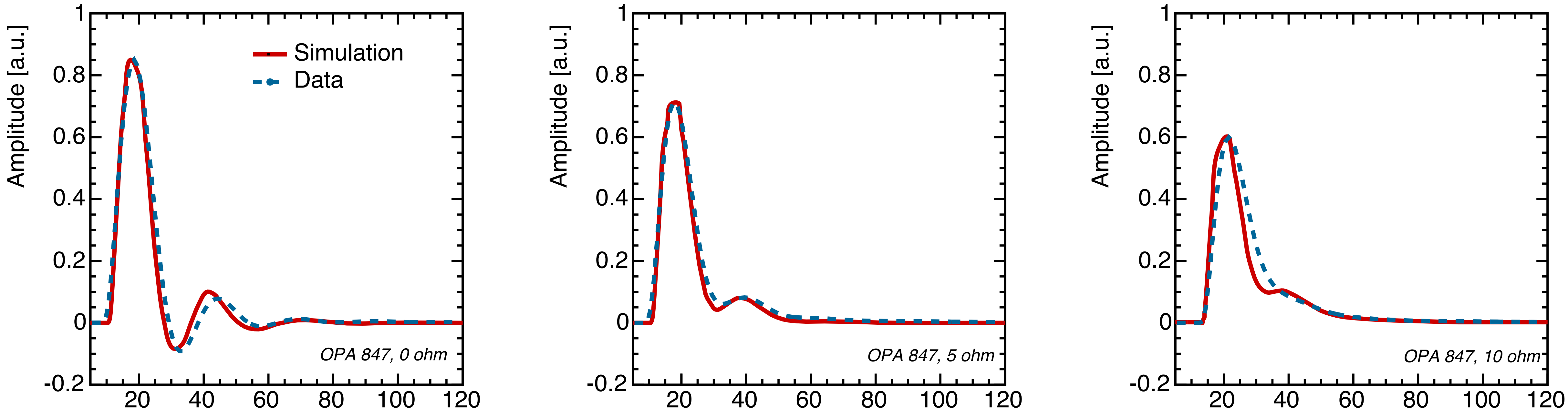
Require accurate preamp characterisation.

$$C_D = \sqrt{\frac{1 + \omega^2 (C_D + C_q)^2 R_q^2}{\omega^2 N_{tot} R_q} \cdot G_\omega}$$
$$C_g = C_\omega - N_{tot} C_D + \frac{\omega^2 {C_D}^2 R_q^2 N_{tot}(C_D + C_q)}{1 + \omega^2 R_q^2 (C_D + C_q)^2}$$

LCR measurement @ 1MHz

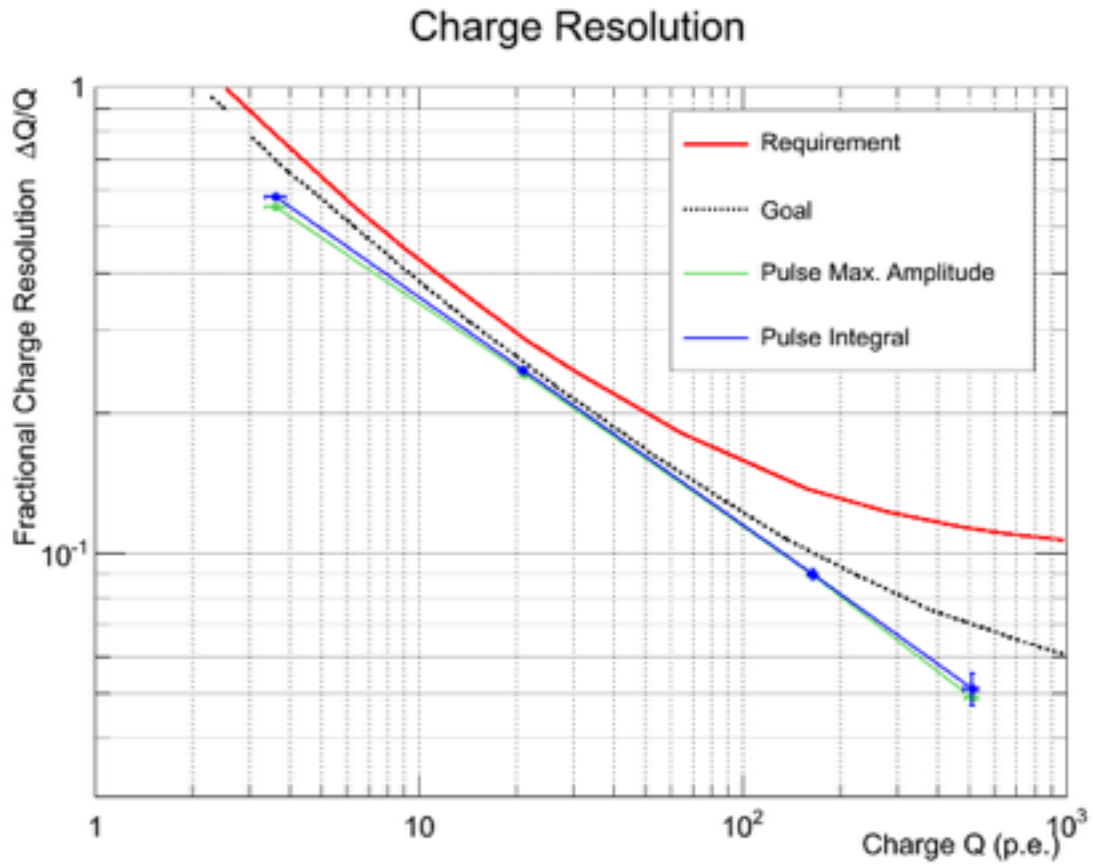
S. Seifert et al., "Simulation of Silicon Photomultiplier Signals"
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 6, DECEMBER 2009

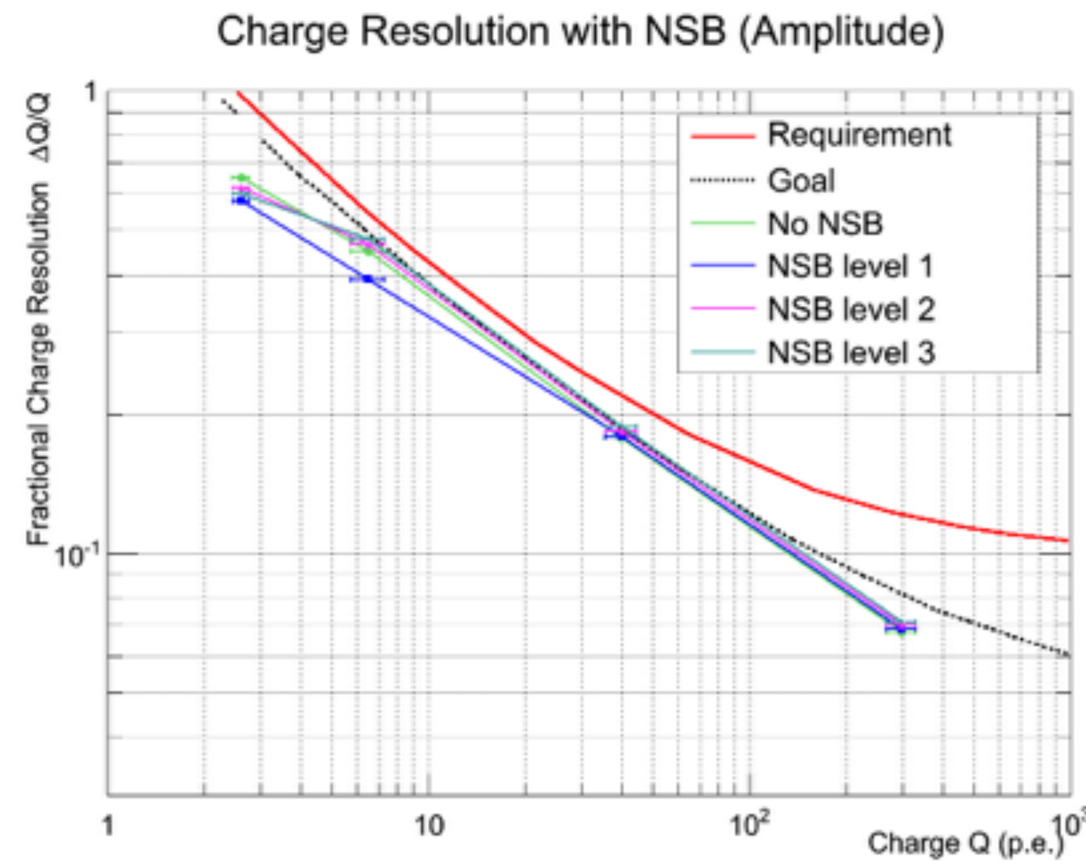
Improving the simulation

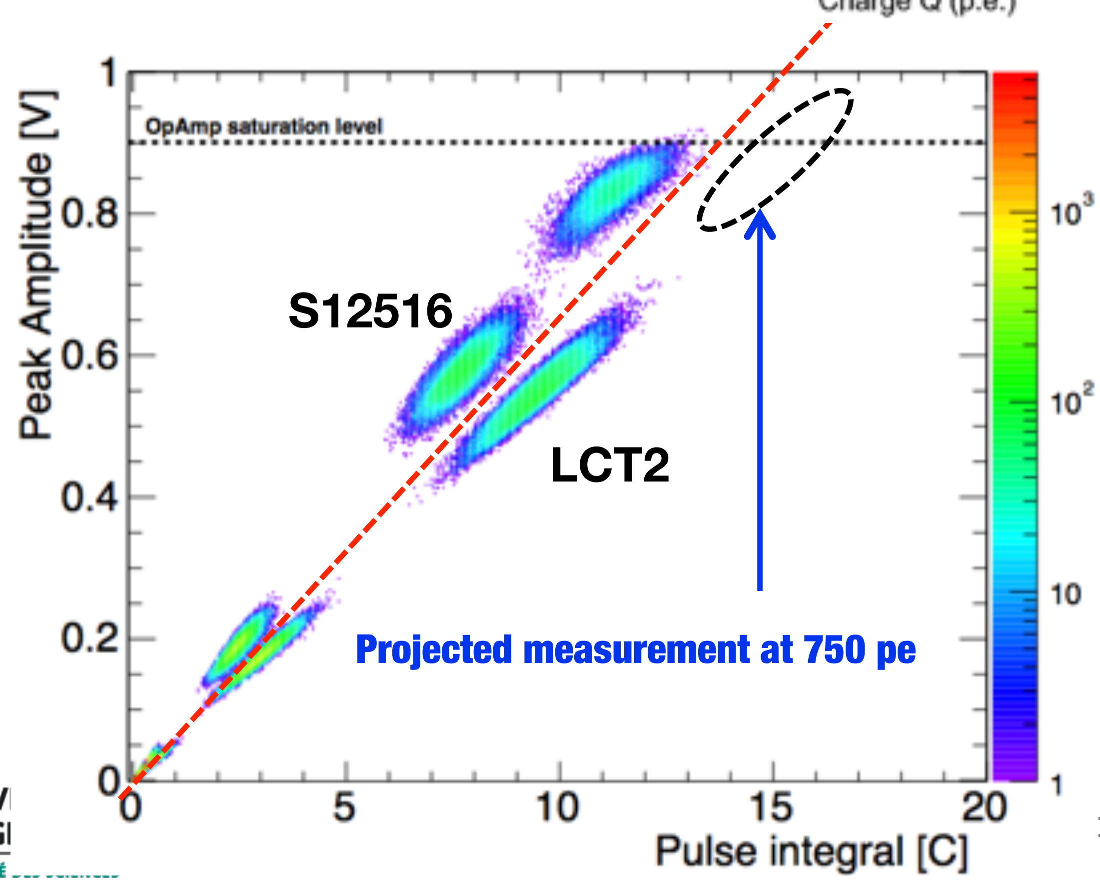


- Hamamatsu collaboration was fundamental to improve the results (THANK!!)
- Using the measurement of the parameter by Hamamatsu there was a substantial improvement
- Very good agreement but still room for improvement
- The good news is that now we can in principle rely on the simulation of the electronics.
- Still some disagreement on the gain (normalized plots)

The Preamp Performance







- Requirements are meet even with such large area and with common electronics
- Peak Amplitude as good as Charge - extremely good correlation

Camera Prototype status

- Photo-Detection Plane
  - All components are ready in Geneva
  - Full testing of the complete assembled module on going
  - Assembly of PDP would be over in few weeks
- Digicam
  - Prototype boards are under validation
  - In 2 weeks the validation should be over an the final production will start

- By end of June the complete camera integration will be complete
- In July the camera will be installed on the prototype and operated
- By fall 2015 we should have the first real data even if a real observation is very difficult in Poland.
- The plan is to move the prototype to the final CTA southern site in 2016 to do first observations

Conclusions

- SiPM use is spreading in many fields given their advantages.
- SiPM are particularly fit for gamma-ray astronomy,
  - Operation during Moonlight ~ 30% larger duty cycle
  - No evidence of ageing
  - Lightweight and robust cameras
  - Excellent single PE sensitivity
  - High Photo-Detection Efficiency at ~ 40%
- This is even more true for the SST of CTA
- SST-1M camera goes in this direction but tried to open a new road towards large area devices.
  - Custom designed hexagonal device in collaboration with Hamamatsu
  - Large Area devices are complicated to handle but can be done!
- Many Lessons learned
  - SiPM parameter spread verified and validated
  - The Simulation of the sensor is a fundamental tool, Corsi Model works but ….
  - …. it is difficult to measure correctly all parameters.
  - Large capacitance can be mastered (next step specific ASIC?)
- In summer the camera will be operated in real condition and a validation on field is possible …. stay tuned!

We gratefully acknowledge support from the agencies and organizations listed under Funding Agencies at this website: http://www.cta-observatory.org/."