cta
cherenkov telescope array

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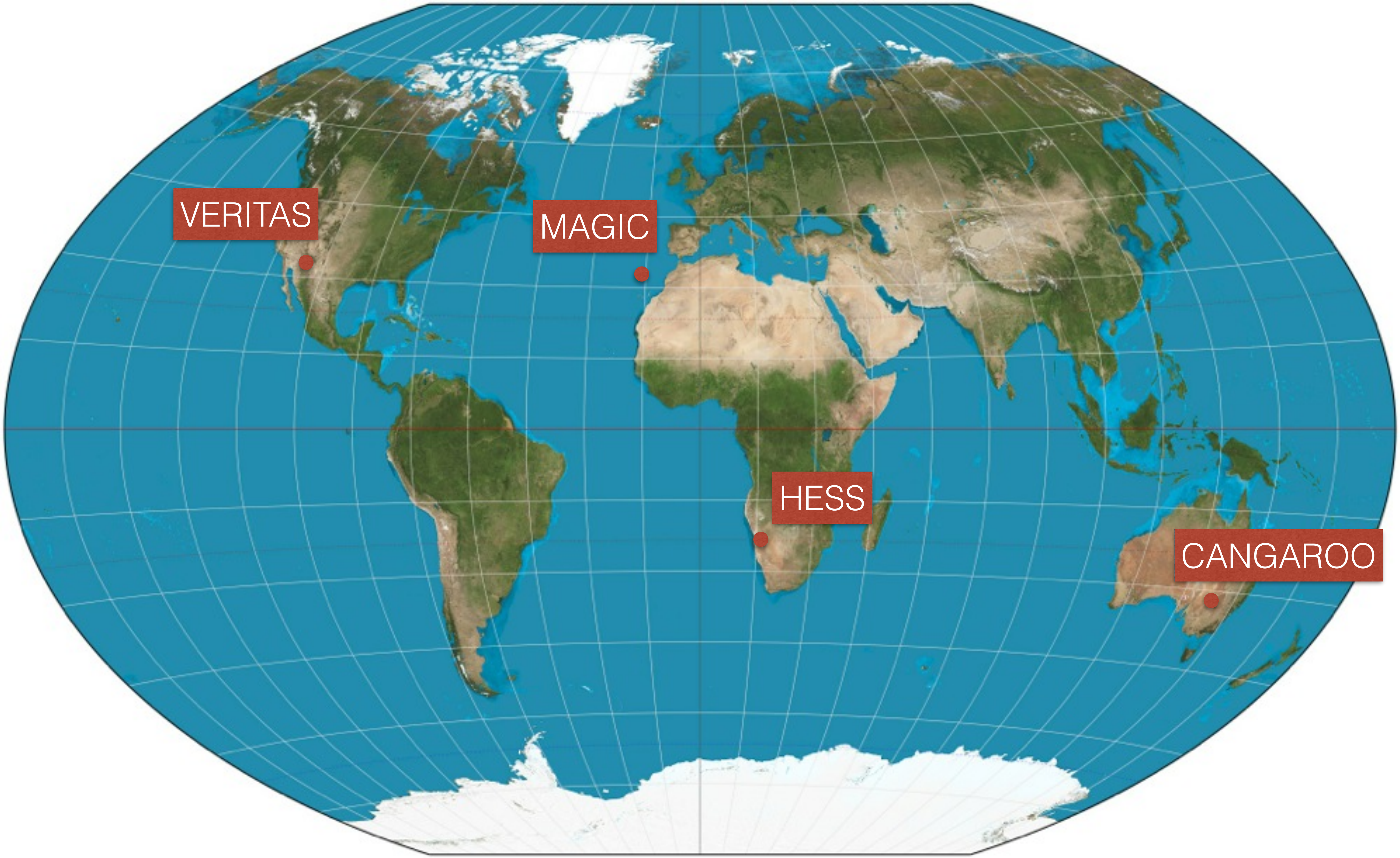
FACULTÉ DES SCIENCES

Future Cherenkov cameras in astroparticle physics

Matthieu Heller
DPNC - Université de Genève

Map of Imaging Atmospheric Cherenkov Telescopes (IACT)



Map of Imaging Atmospheric Cherenkov Telescopes (IACT)

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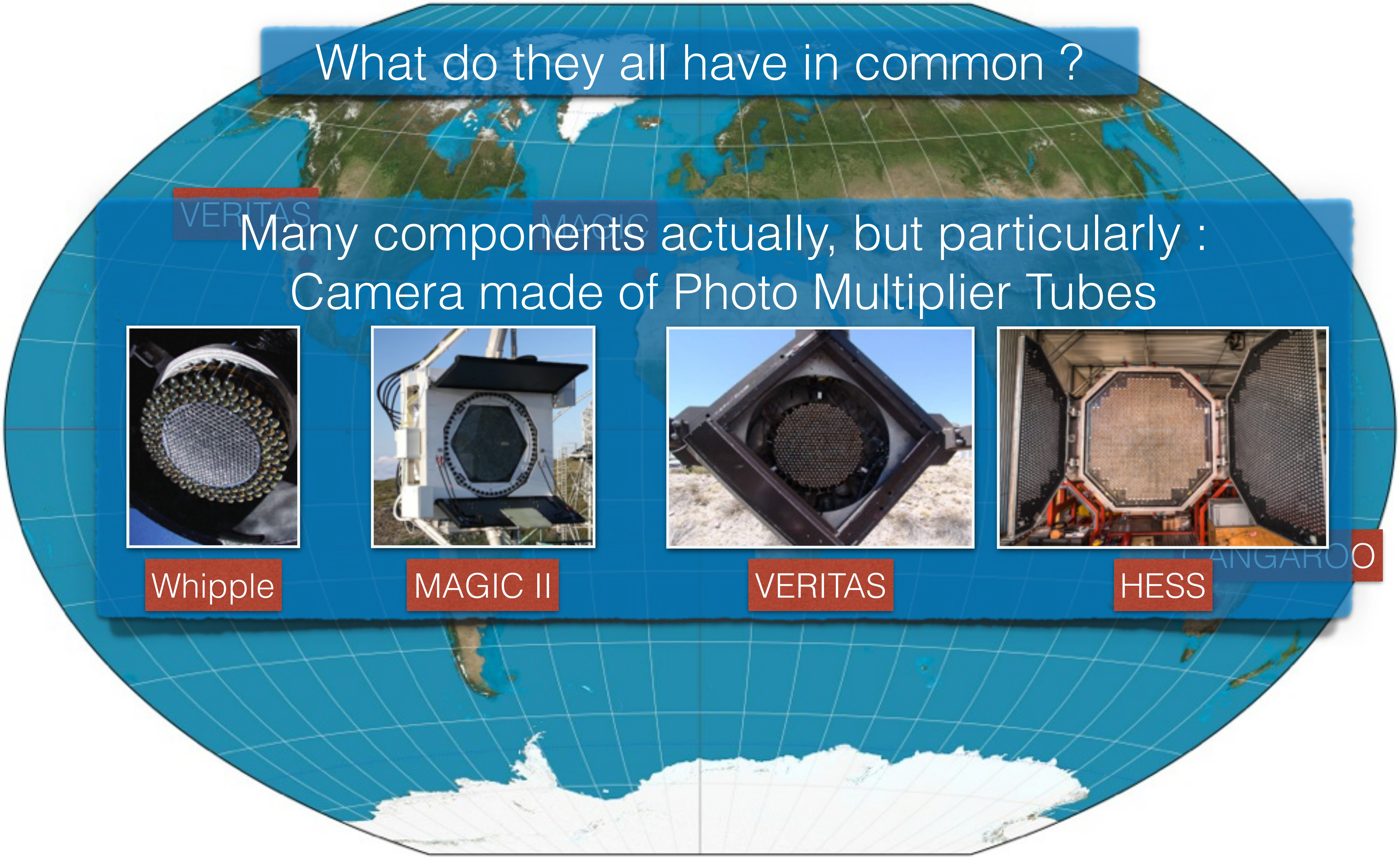
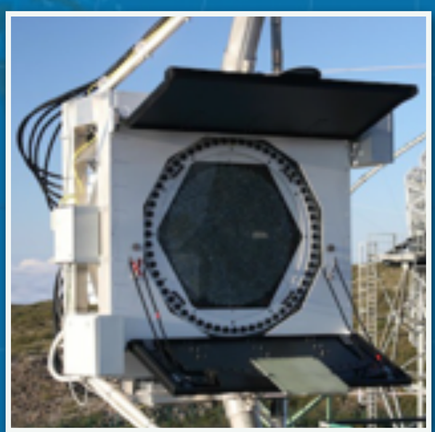


Map of Imaging Atmospheric Cherenkov Telescopes (IACT)

What do they all have in common ?

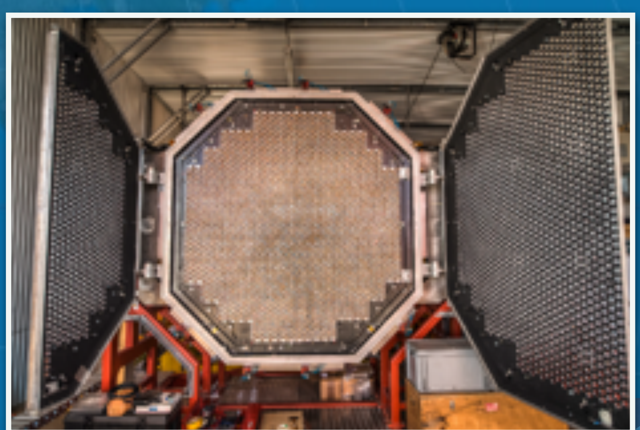
Many components actually, but particularly :
Camera made of Photo Multiplier Tubes

Whipple



MAGIC II

VERITAS



HESS

Are SiPMs, which are widely used in HEP detectors, a possible alternative to standard PMTs and what would we gain from them ?

Photo detection plane requirements for IACTs Camera

- High Quantum Efficiency
- Single Photon sensitivity
- Fast pulses
- Low noise
- High Fill factor
- Robustness
- Uniformity
- High dynamic range
- Large area to be covered
- Linear response

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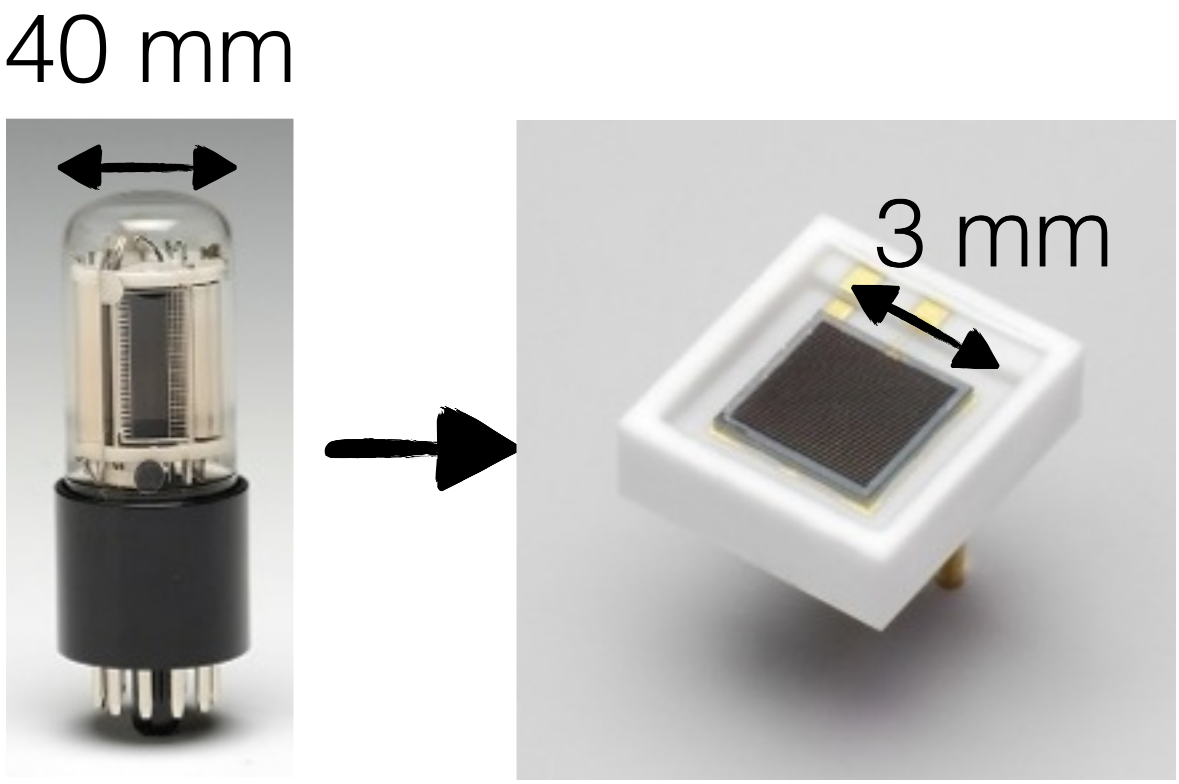
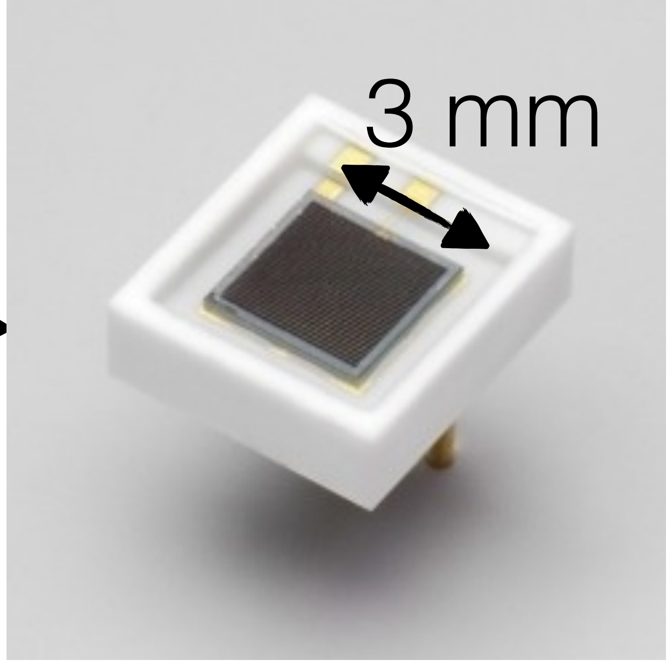


Photo detection plane requirements for IACTs Camera

- 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)

40 mm



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

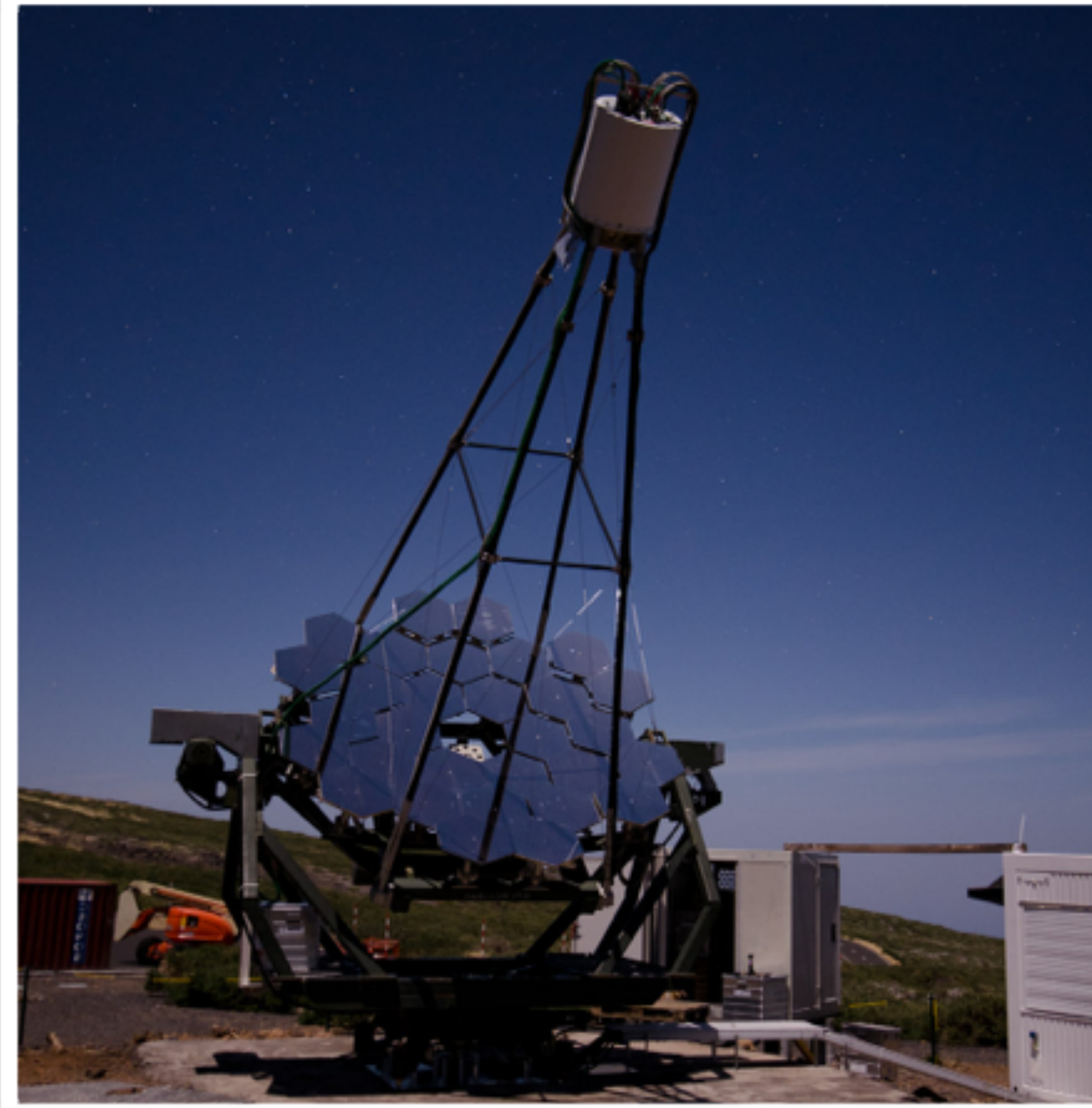
Photo detection plane requirements for IACTs Camera

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

Do these parameters impact gamma ray imaging performance ?

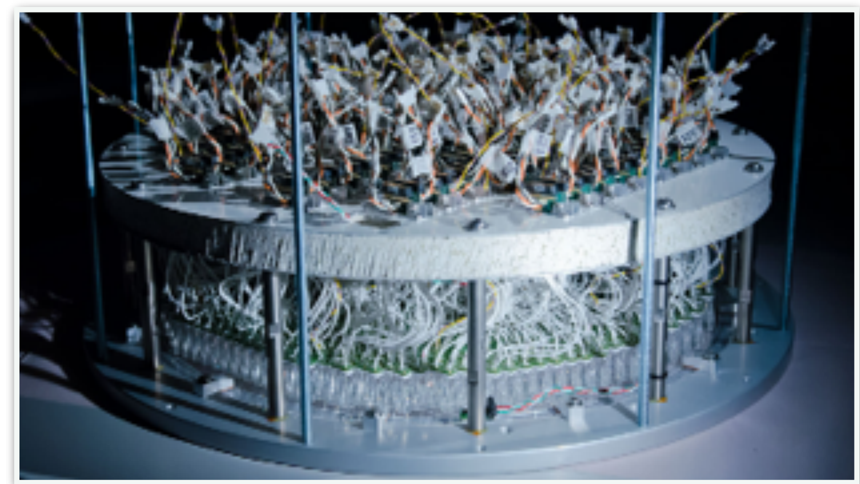
- Large area to be covered
- Linear response (optical cross talk, pile up)

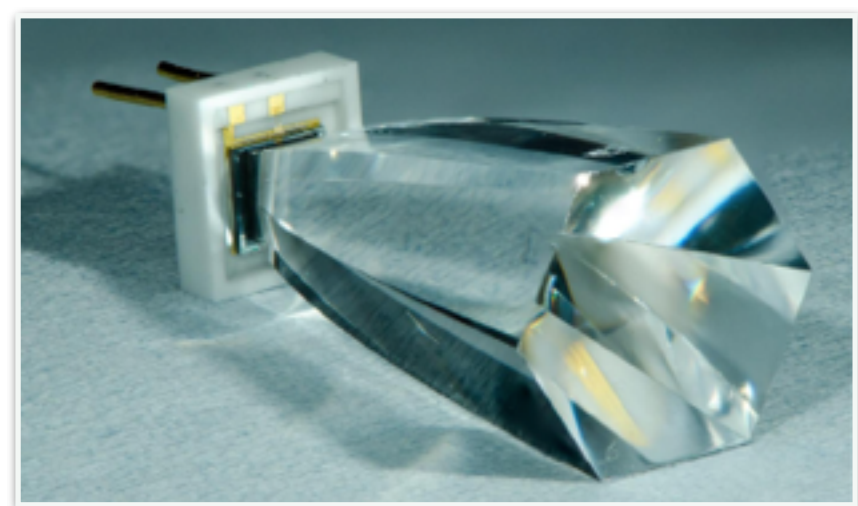
- Characteristics depend on operation temperature



Proof of concept: The FACT telescope

FACT telescope and camera





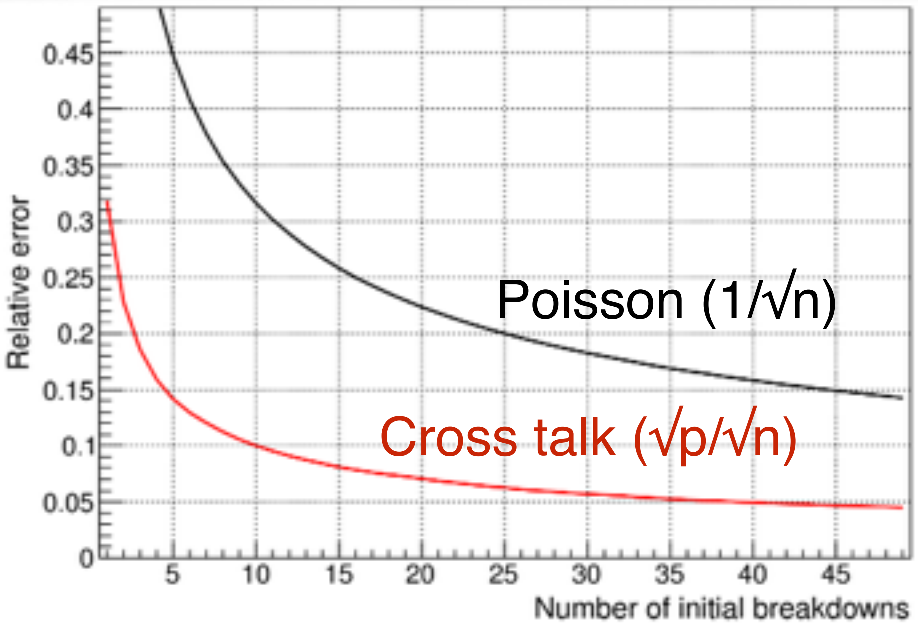
Davies-Cotton design (HEGRA-CT3) with 4.5° FOV
Camera:

- 1440 pixels (MPPCs 3x3 mm^2, Hamamatsu)
- solid UV transparent PMMA light concentrators

FACT camera performance

FACT camera performance

Signal error dominated by Poisson error



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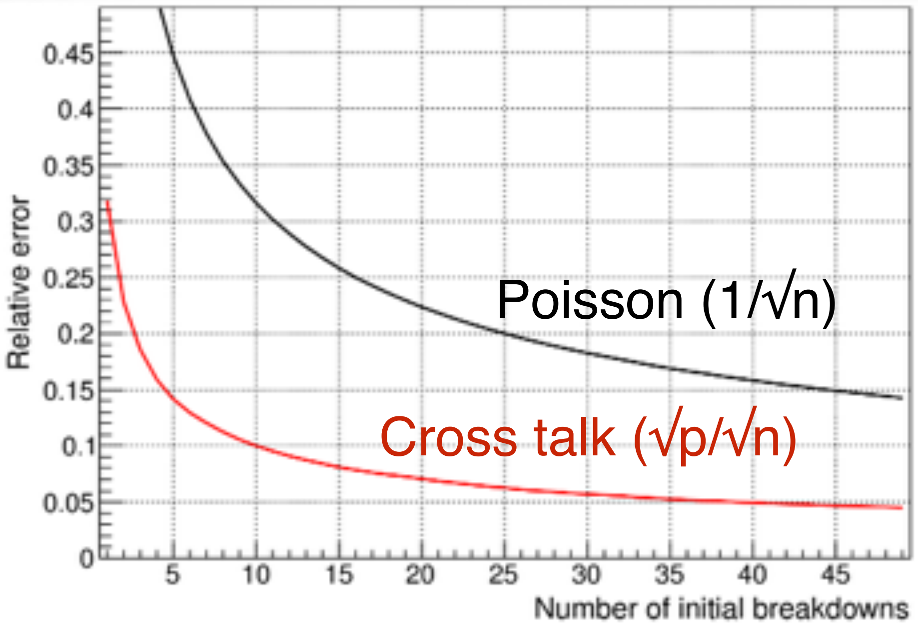
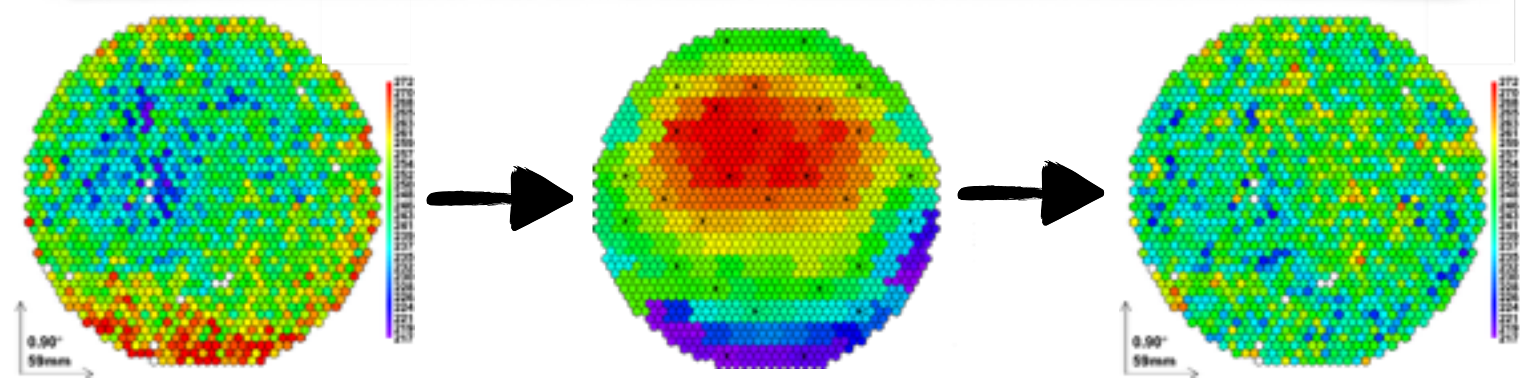


Gain uniformity ensured thanks to temperature monitoring



Gain, RMS 4%

Temperature map

Gain, RMS 2.5%

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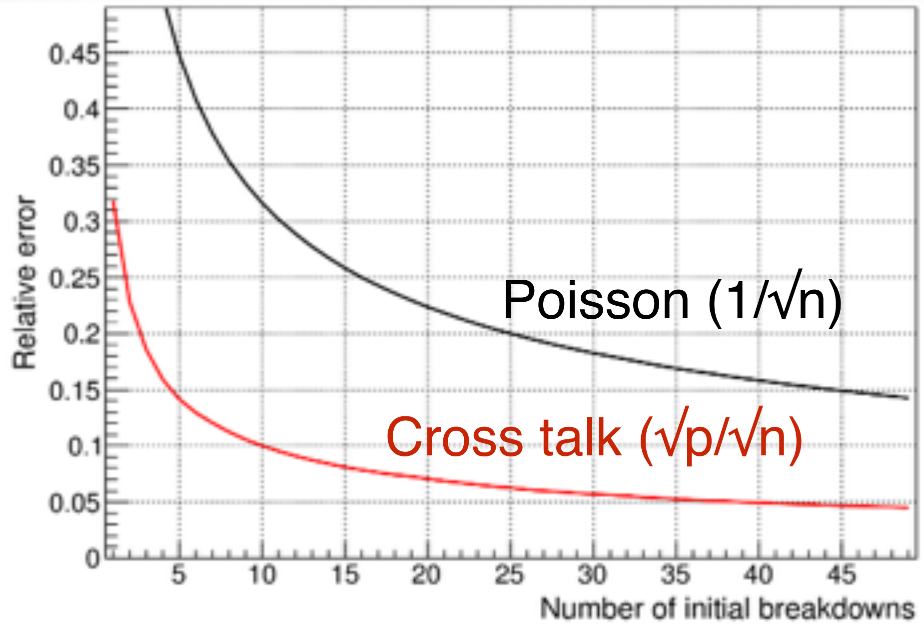

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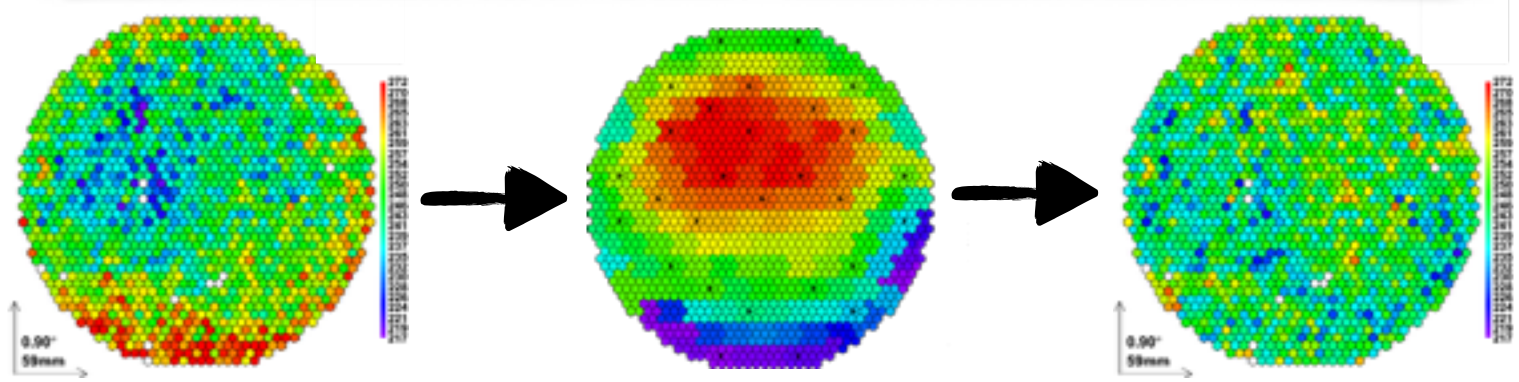

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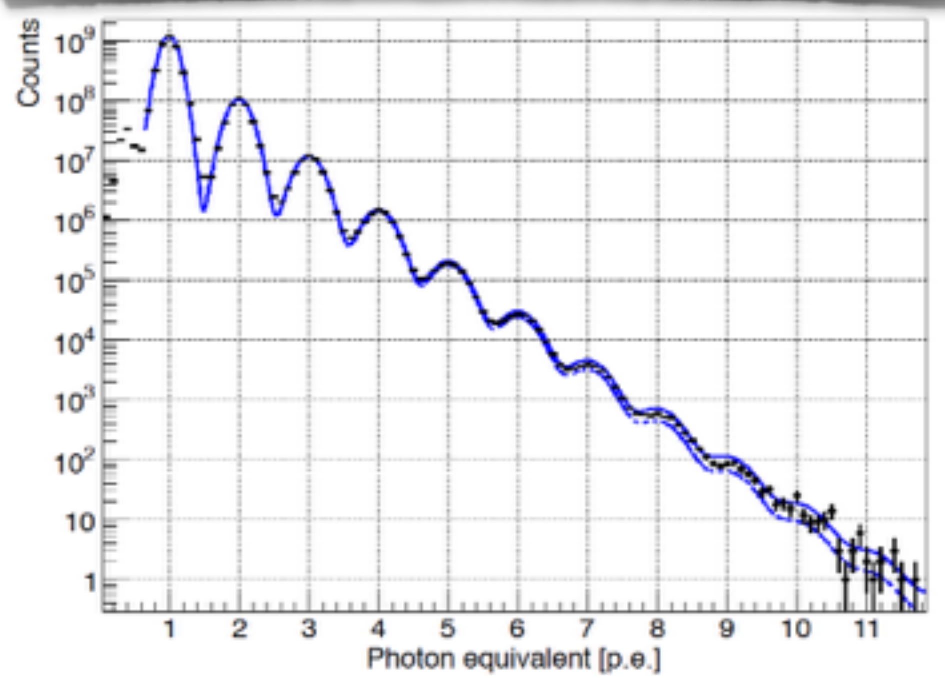

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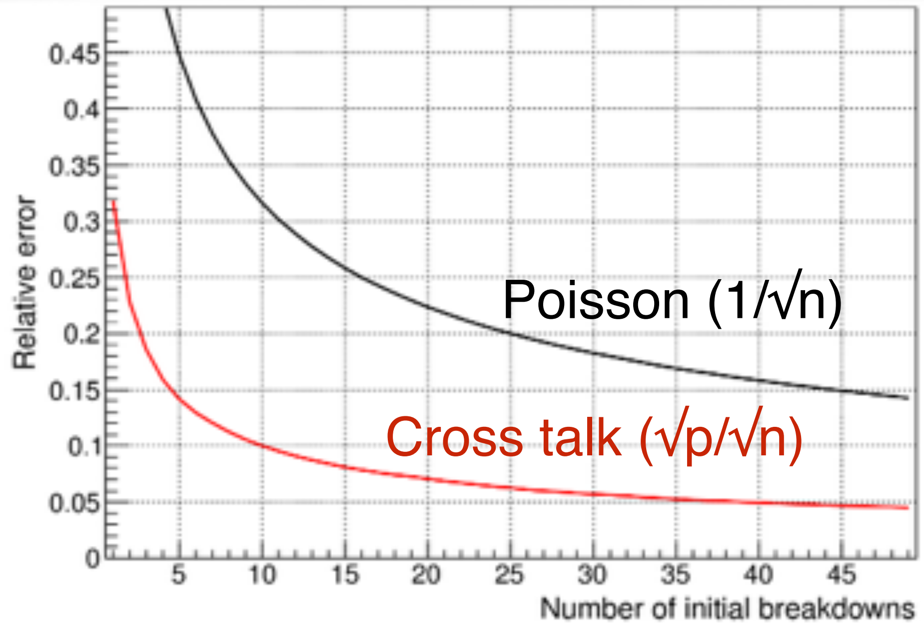

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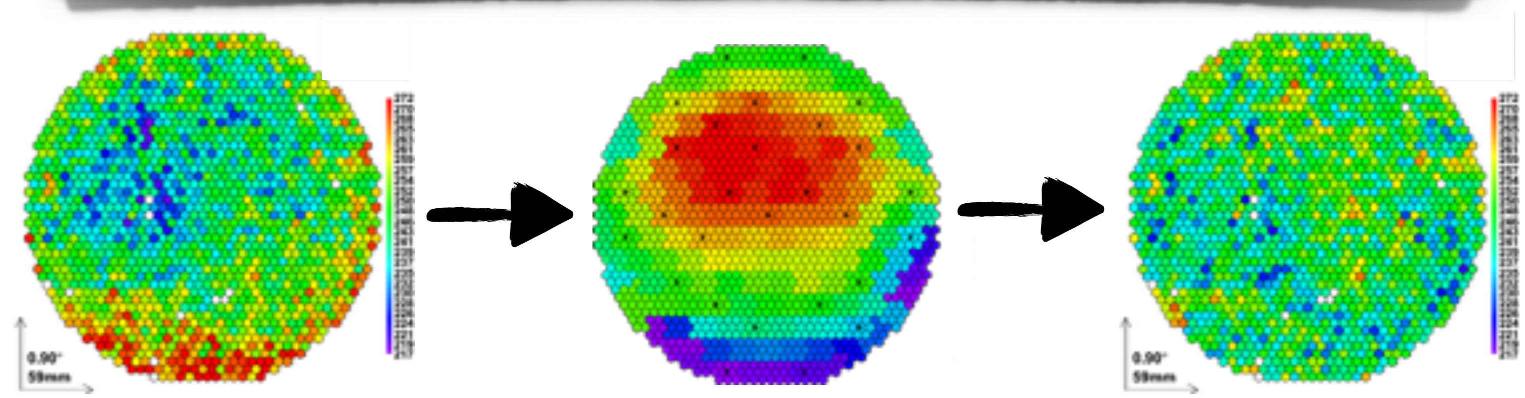

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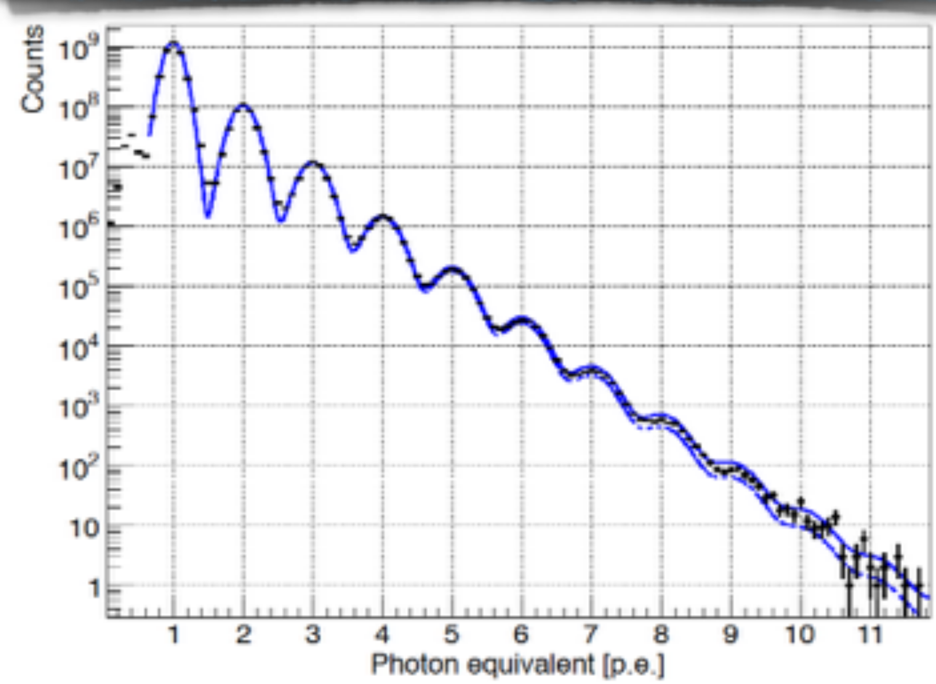
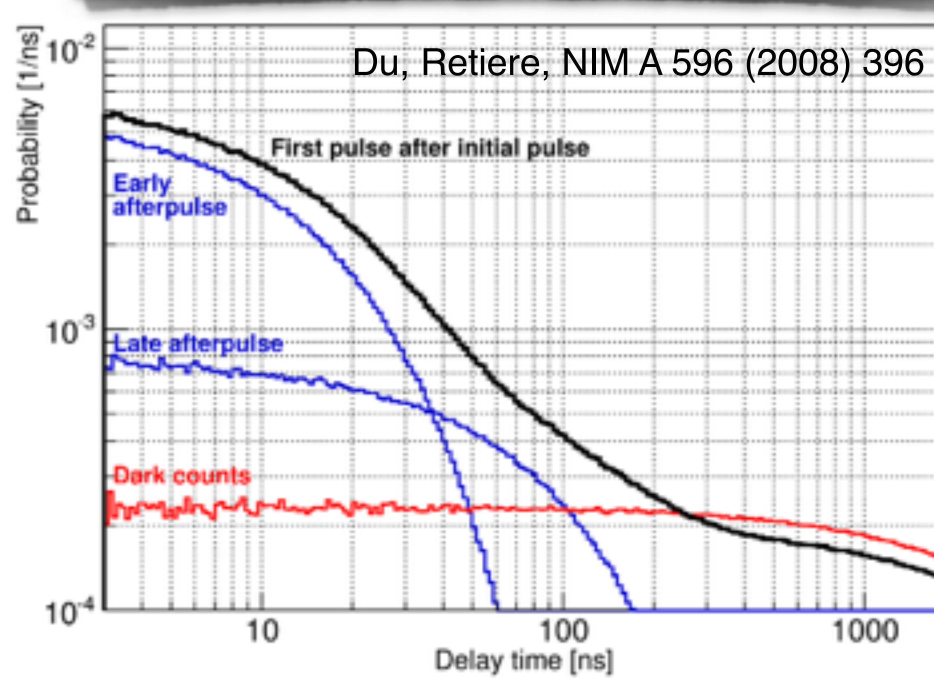


Afterpulses cannot fake trigger but can worsen the charge resolution



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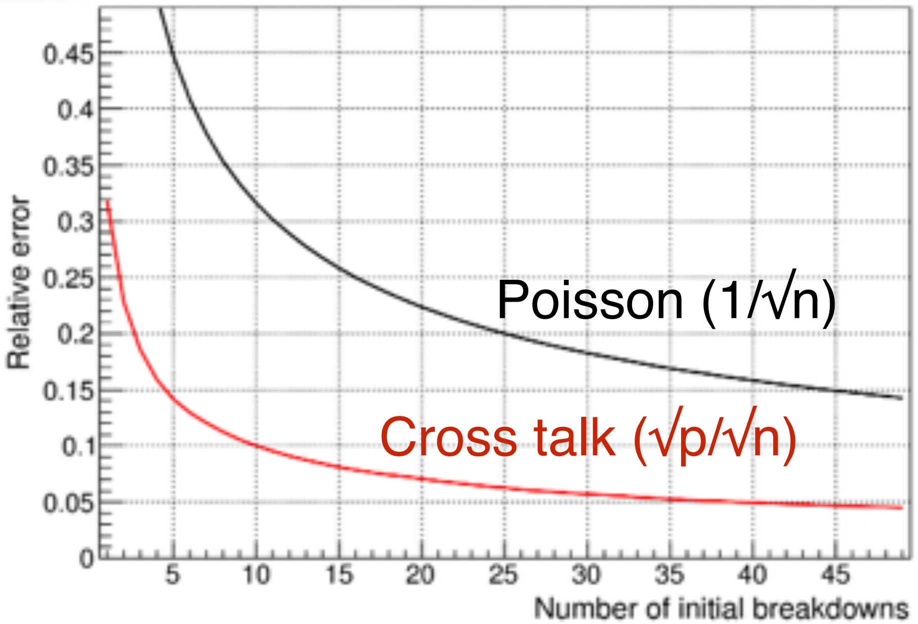

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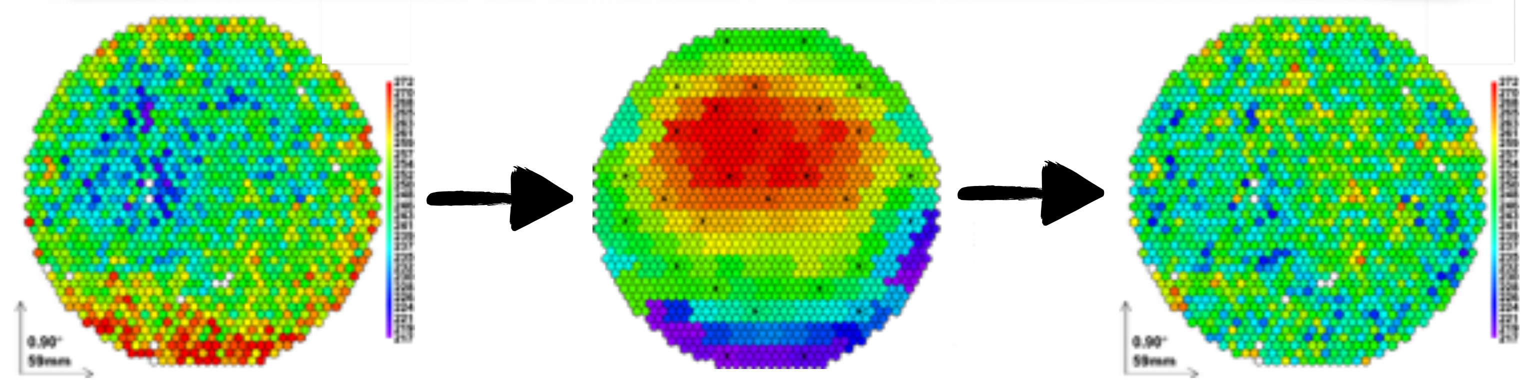

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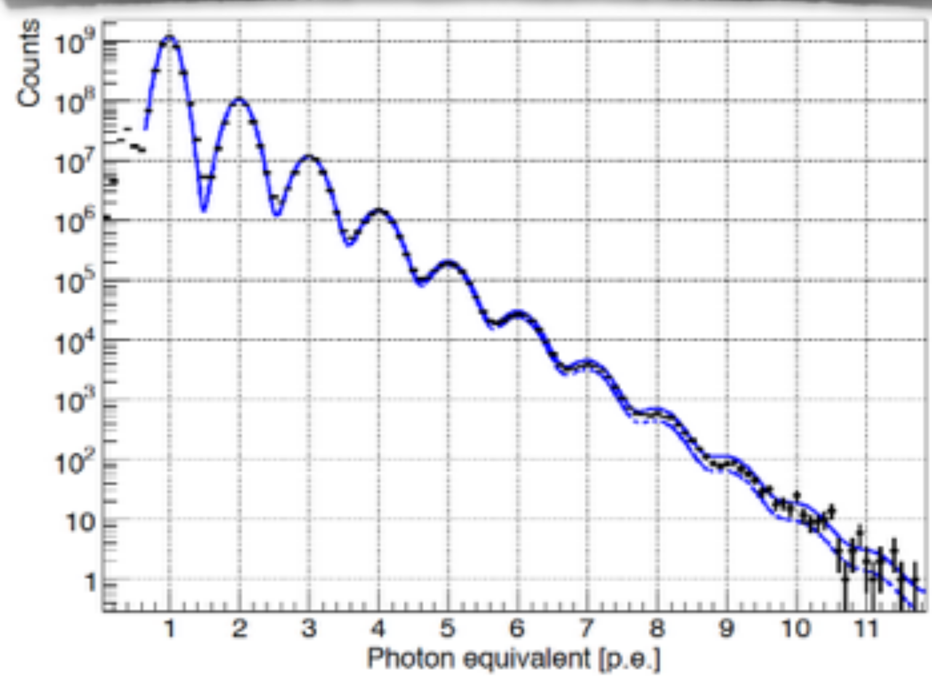

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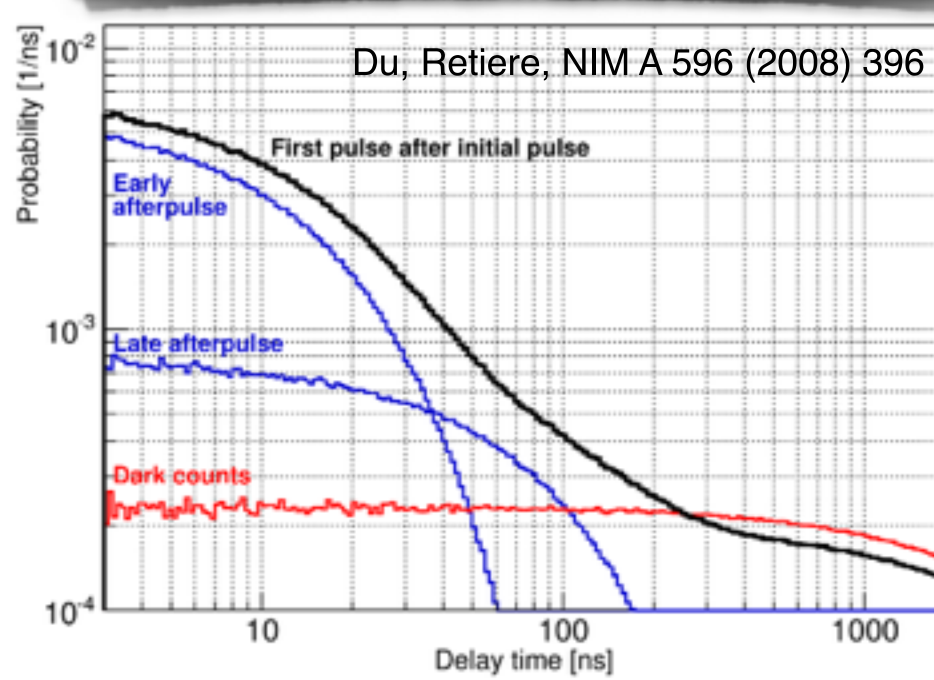
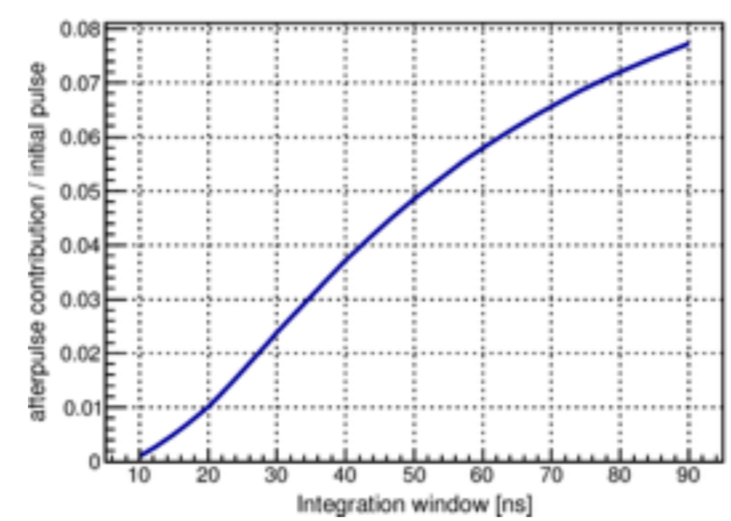


Shorter signal integration window to cure after pulses contribution



FACT camera performance

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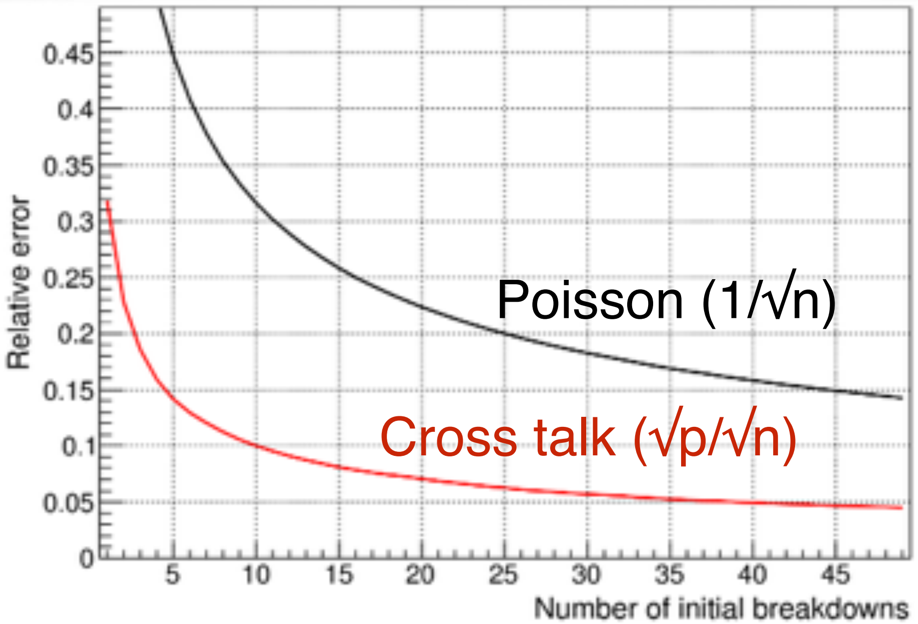

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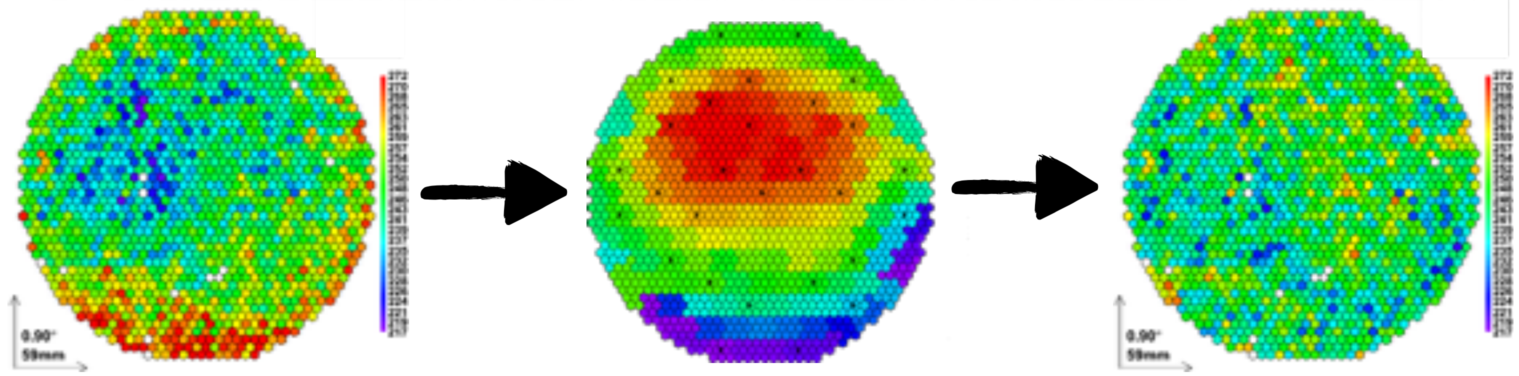


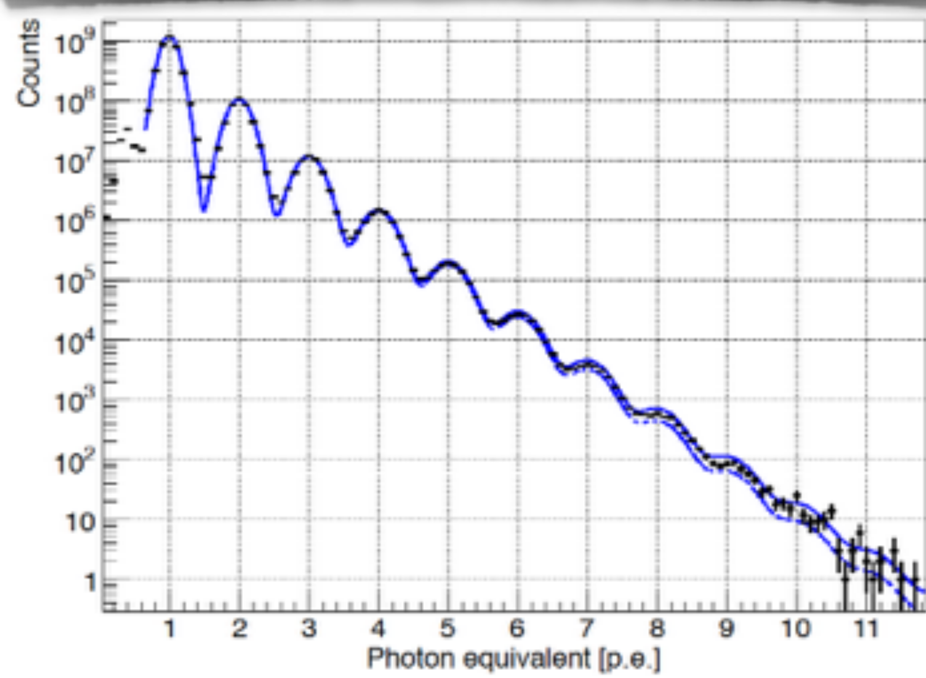
Gain, RMS 4%

Temperature map

Gain, RMS 2.5%

Dark count rate < Night Sky Background (NSB) rate

Dark count runs allow to calibrate the photo detection plane



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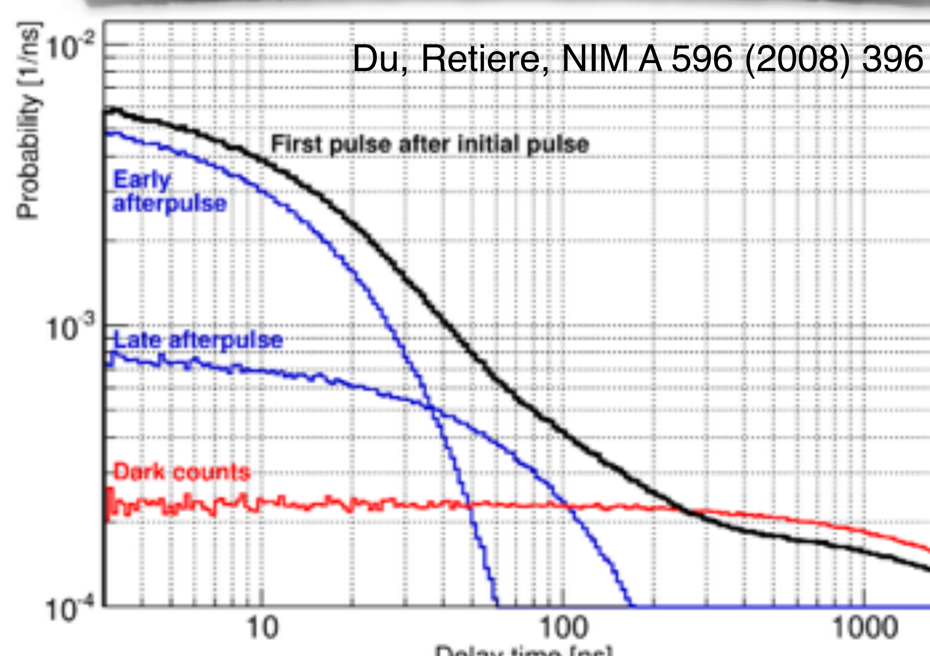

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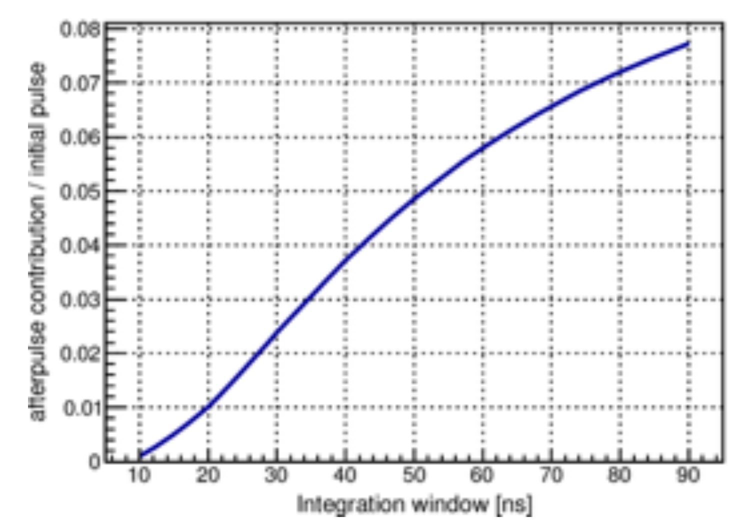
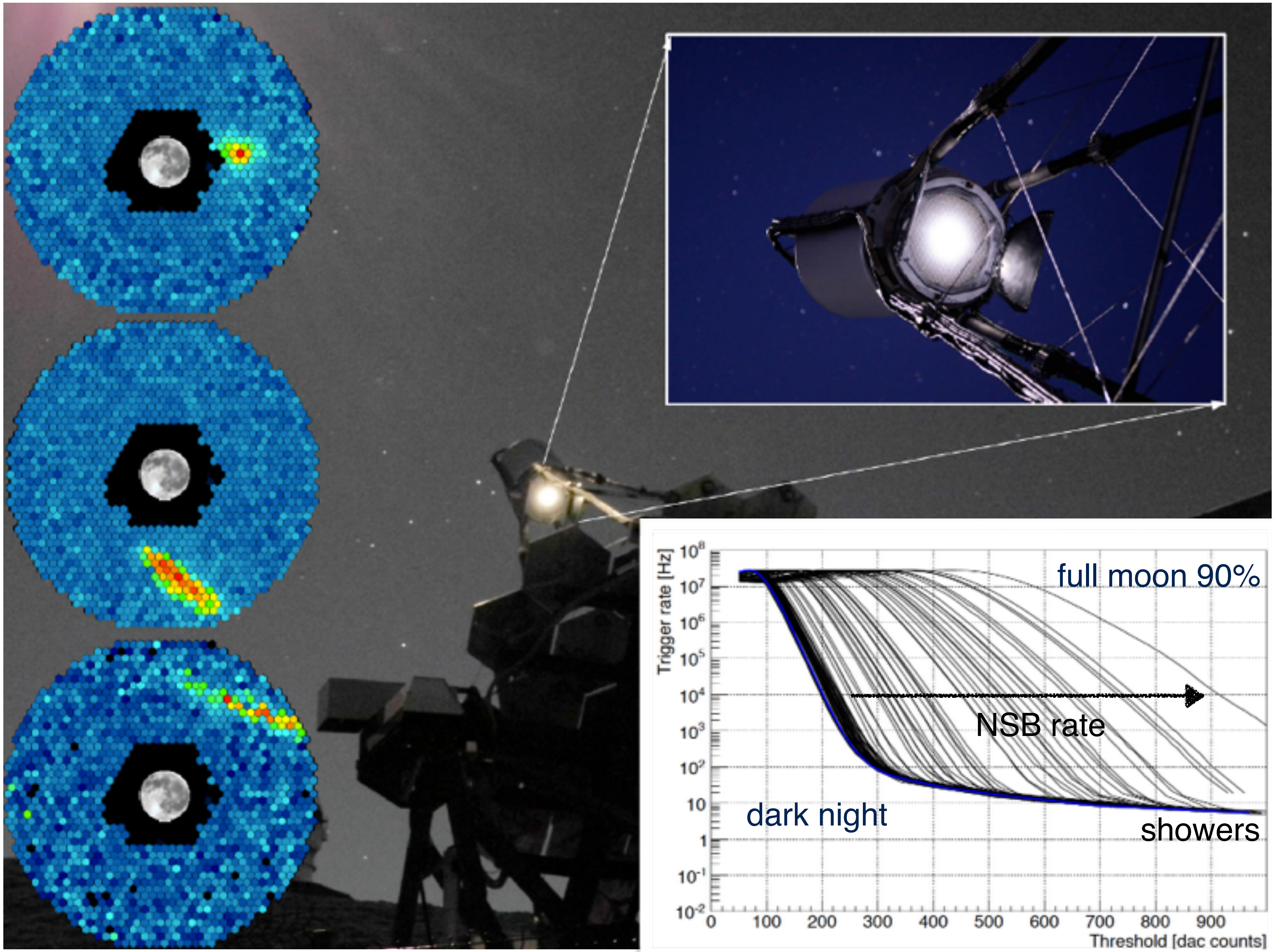


Data taking during full moon



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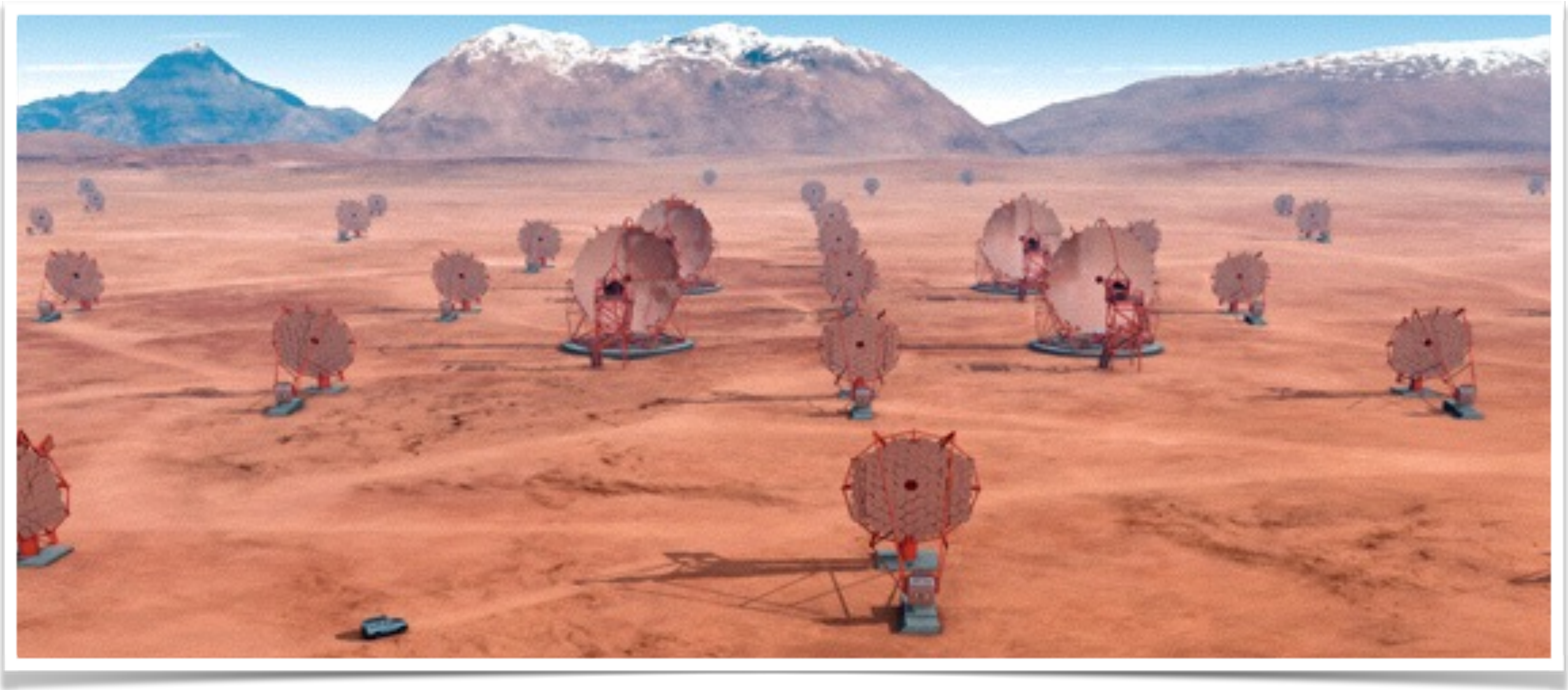
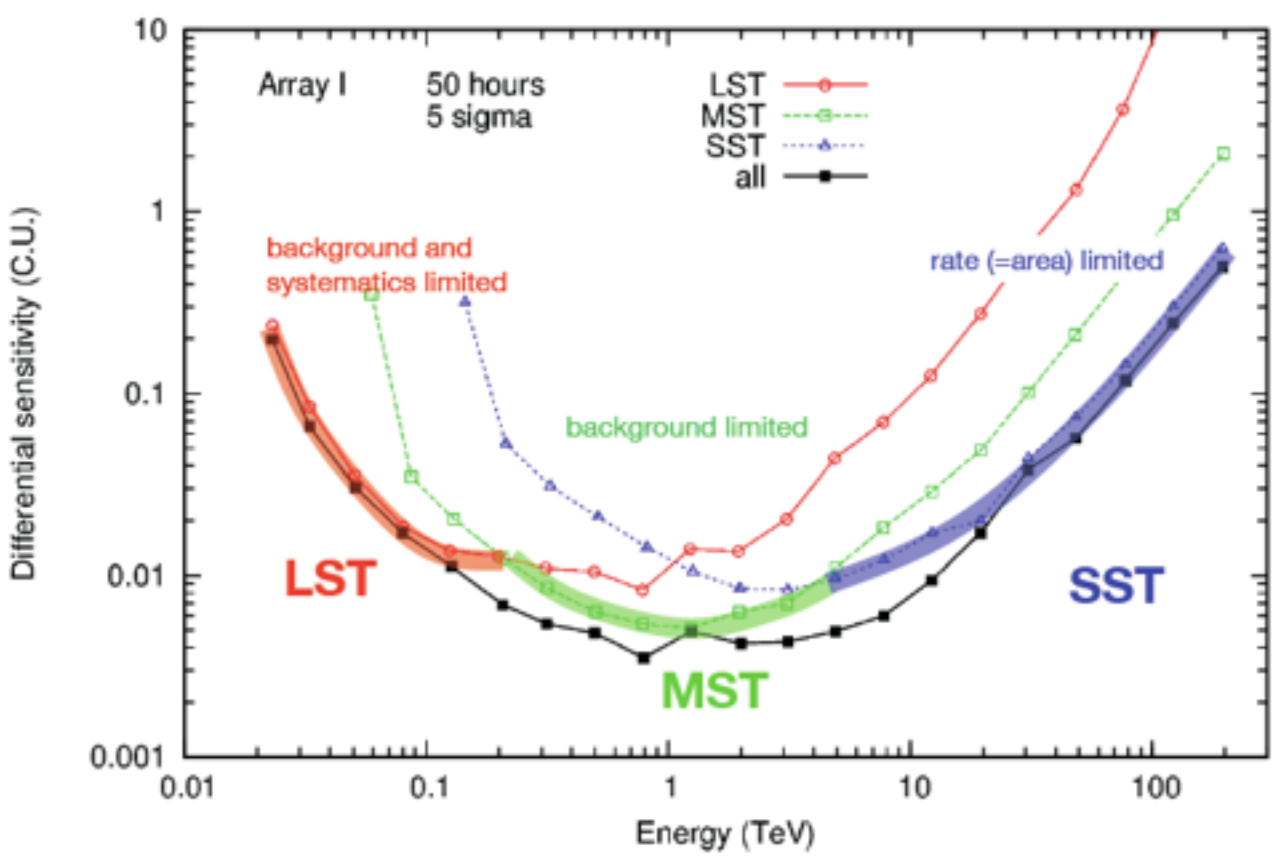
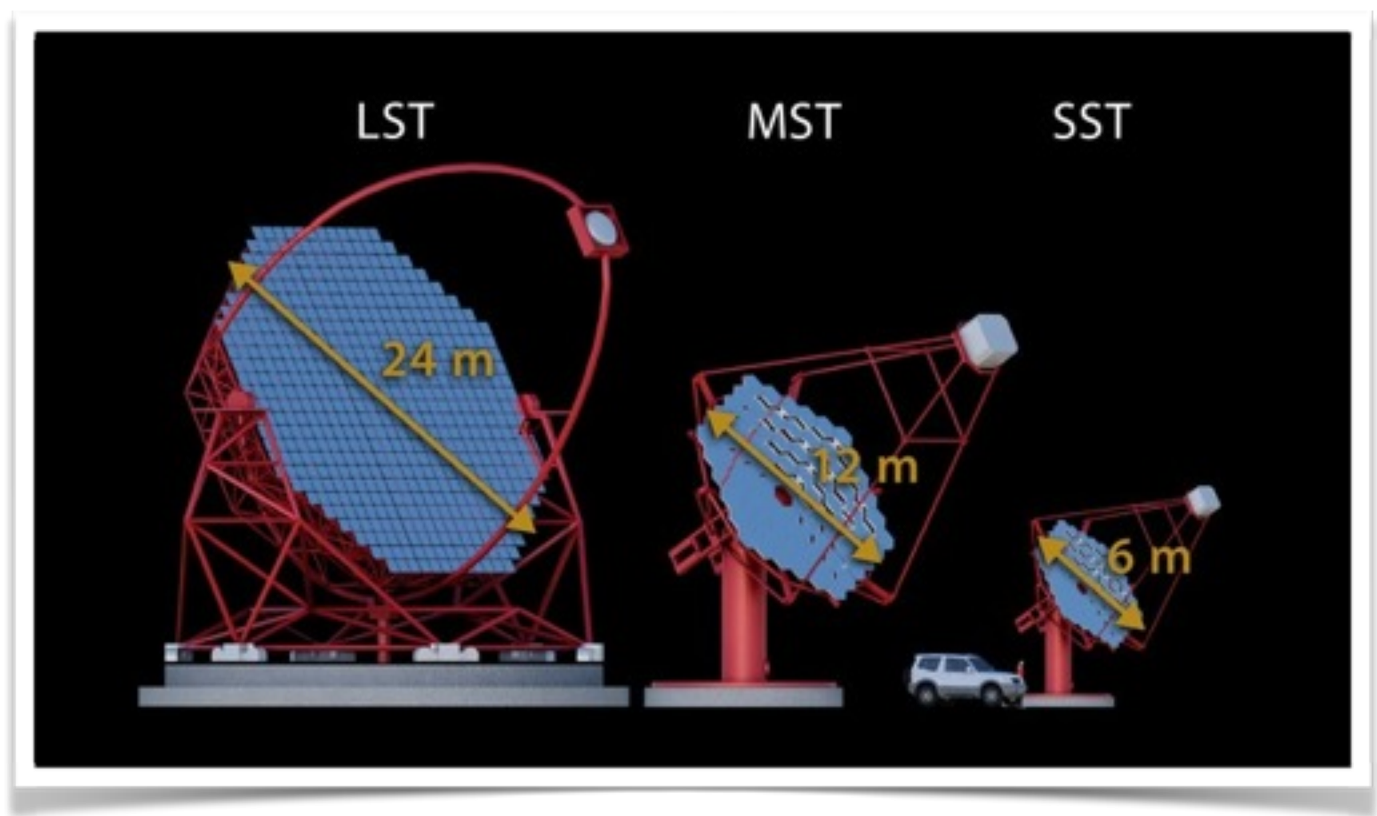


The Cherenkov Telescope Array SiPM cameras

Cherenkov Telescope Array

- 1000 members working in 27 countries
- Array composed of:
  - ~ 4 LST [10 GeV-200 GeV]
  - ~ 24 MST [200 GeV - 500 GeV]
  - ~ 70 SST [500 GeV - 200 TeV]





Small Size Telescope design

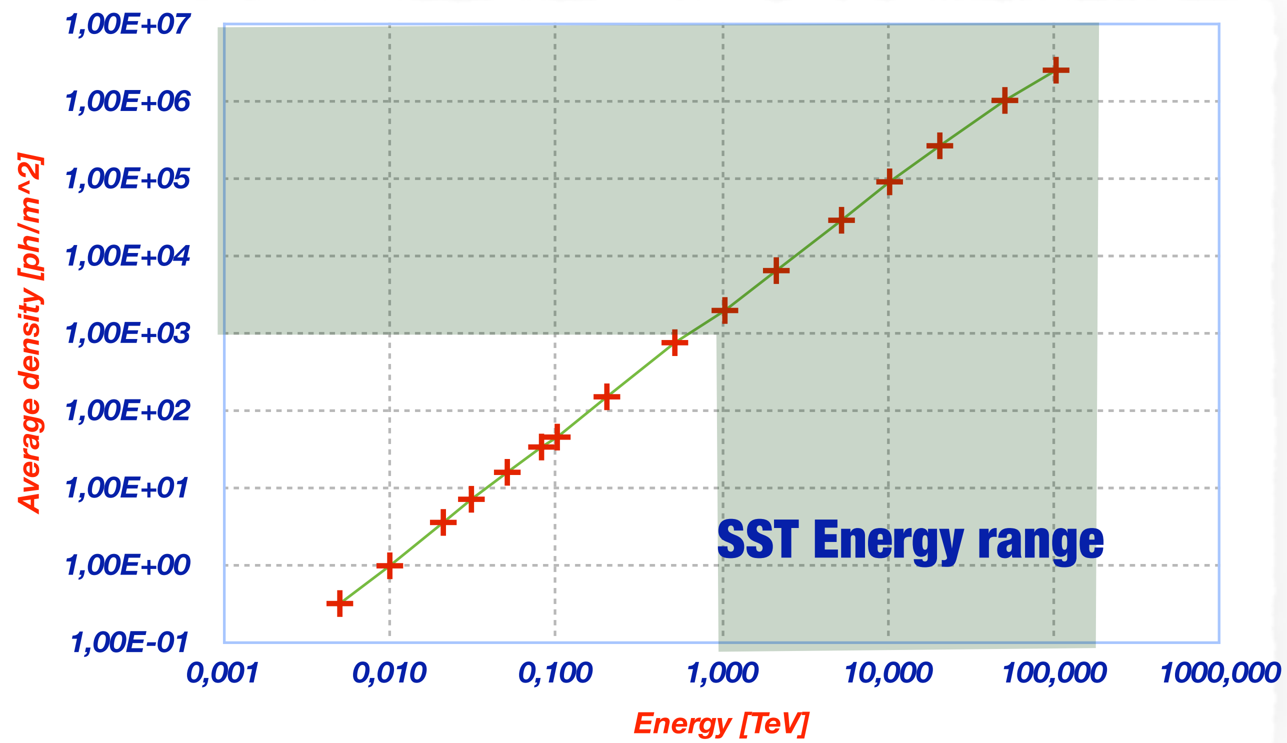
High Energy

⬇

High photon density

⬇

Small Dish area ~ 4m



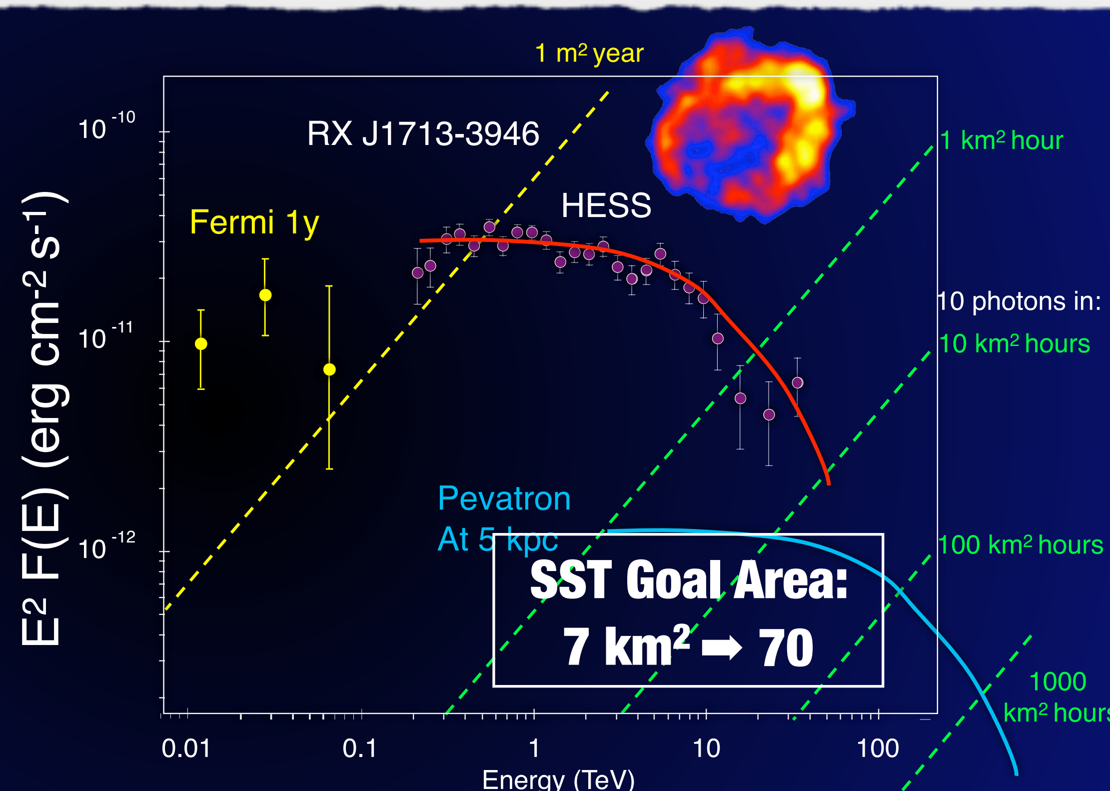
Shower Footprint

⬇

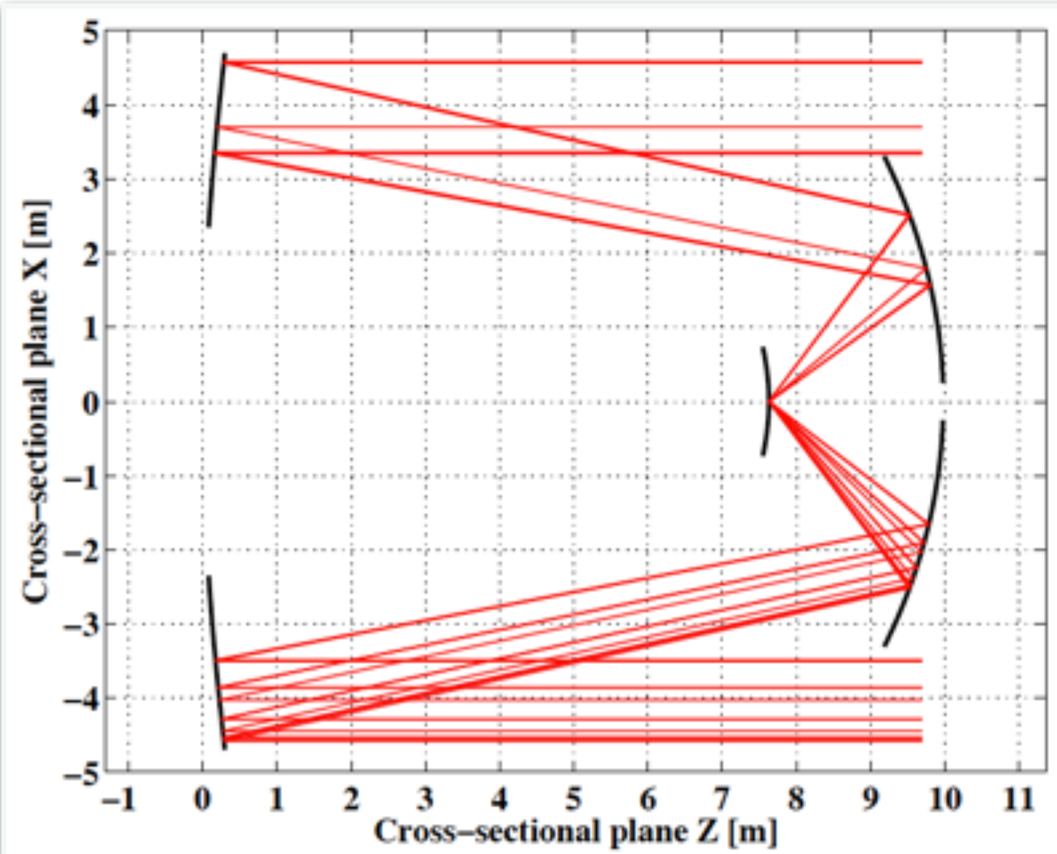
Array Collection Area

⬇

Number of Telescopes



- The new challenge is to build ~ 70 SSTs with high performance
- It implies to design a camera which can be produced at industrial scale



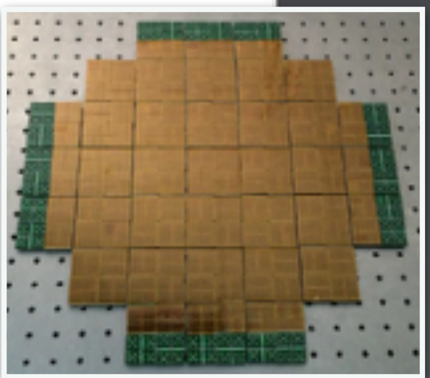
The Dual Mirror Small Size Telescope camera

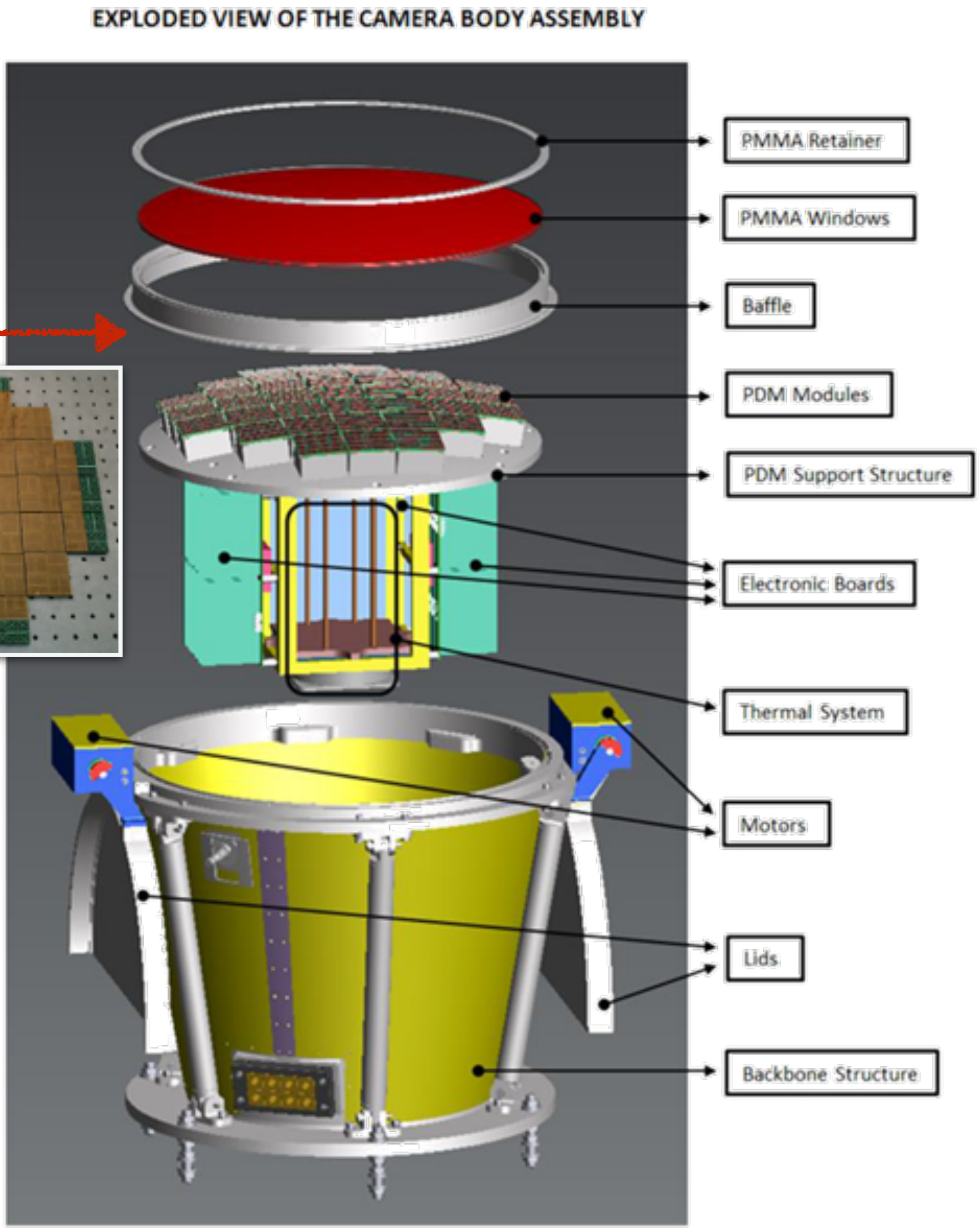
Complex optics, small camera

SST-2M prototypes: The ASTRI concept

Inauguration last week at INAF on Etna site

~40 cm

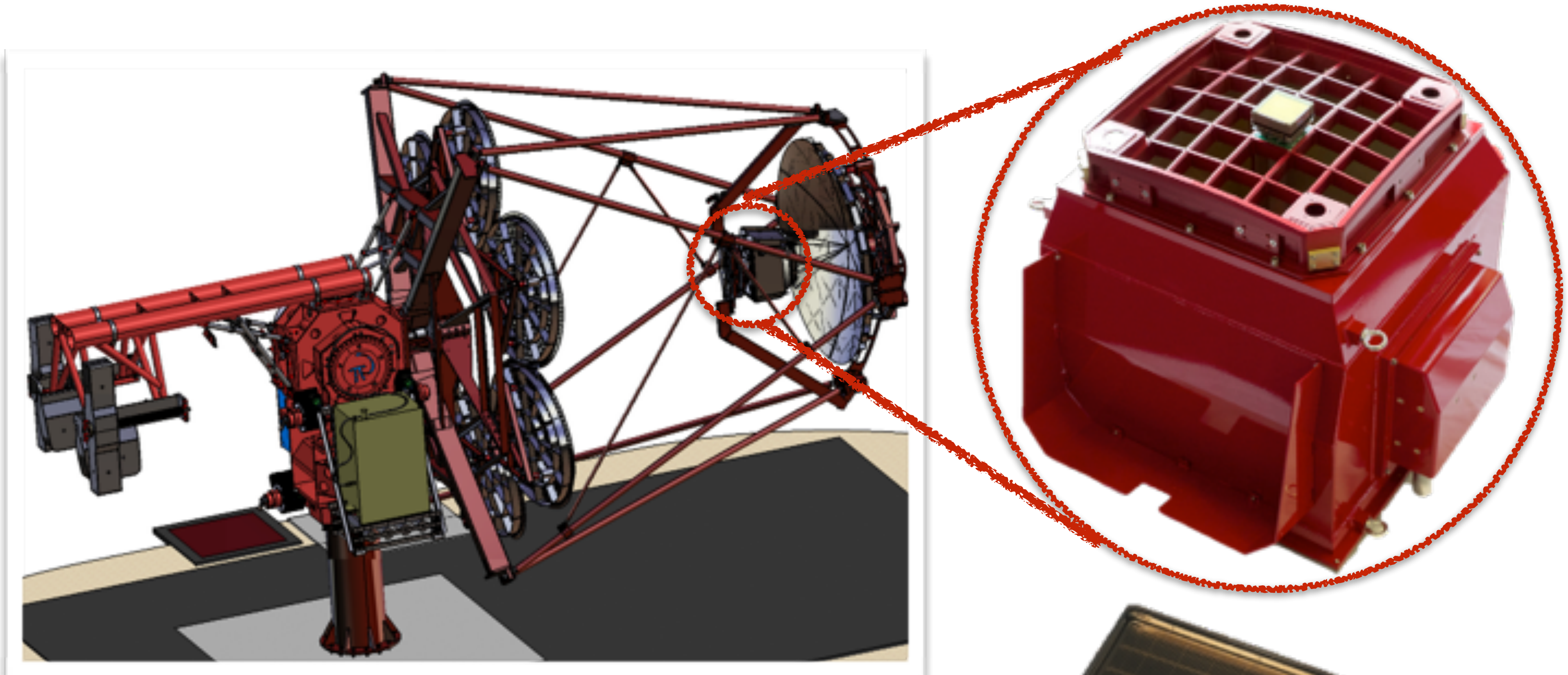


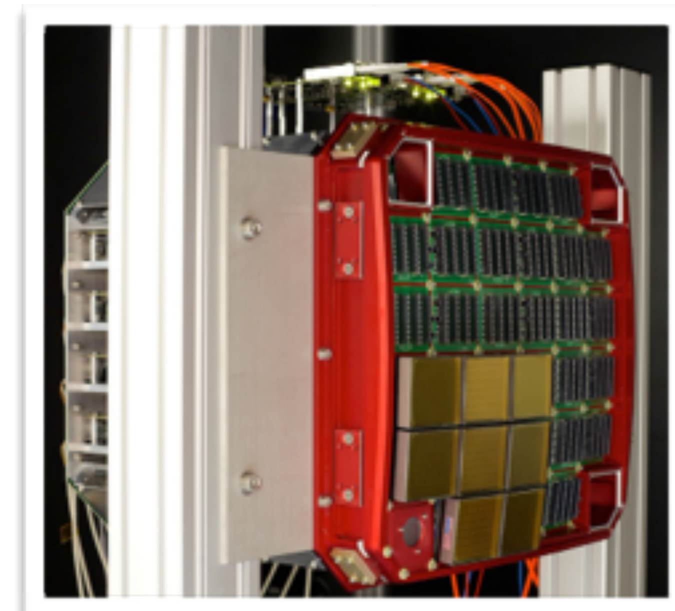


- 25 full SiPM tile, 12 halves
- Front-End electronics ASIC (CITIROC)
- FPGA for trigger and ZYNQ PCB for readout

- Very encouraging results shown in last CTA consortium meeting

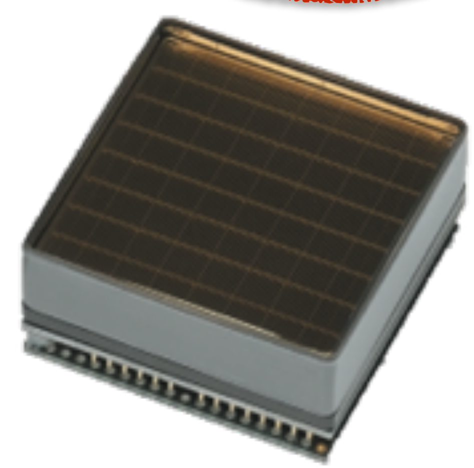
SST-2M prototypes: The GATE- CHEC concept



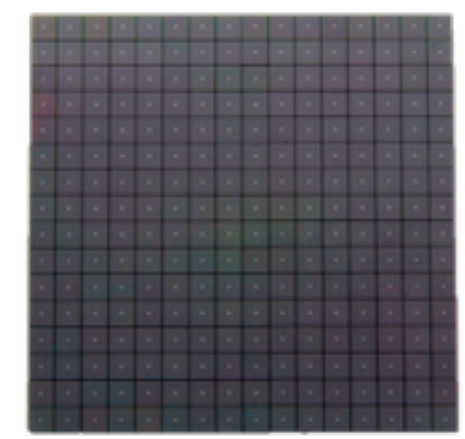


- 32 photosensors modules
- Two alternatives:
  - MAPMT
  - SiPM tile
- 45 kg
- Digital readout (TARGET 7)

- For the time being, the MAPMT camera is the most advanced, SiPM one still under design (electronics)



MAPMT



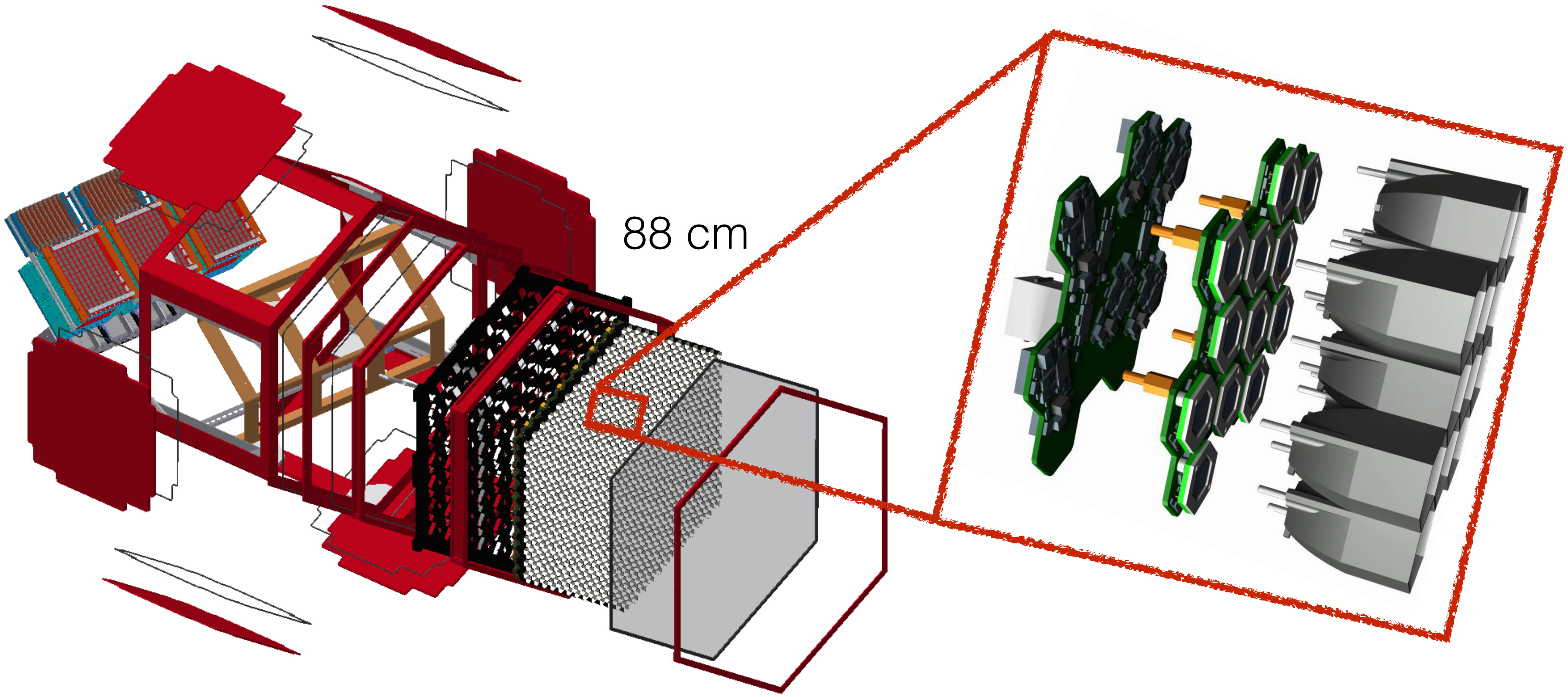
SiPM Tile

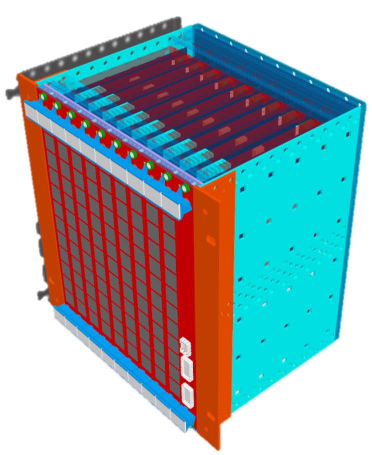
- 32 x 64 pixel modules
- 2048 pixels
- 0.17°
- ~3 mm gaps ➔ < 1 mm
- 9° FoV ➔ ~8.6° FoV

The Single Mirror Small Size Telescope camera

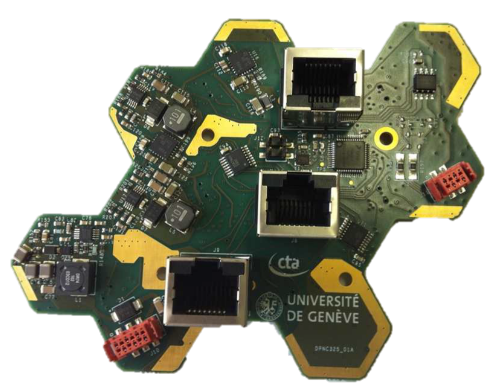
Simple optics, large camera

The Single Mirror SST (SST-1M) camera concepts

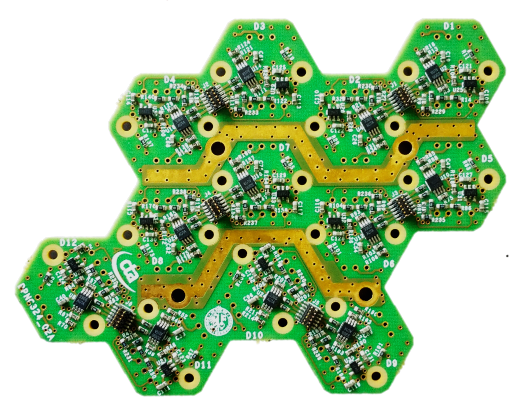




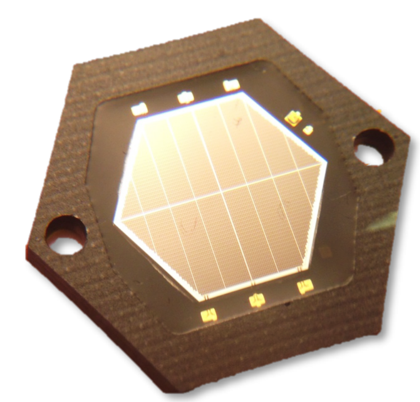
Digital readout DigiCam



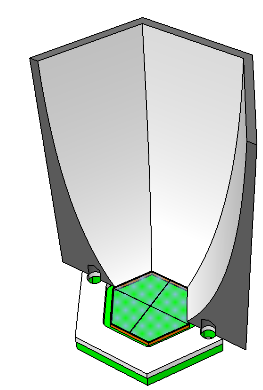
Slow Control Board



Preamplifier board

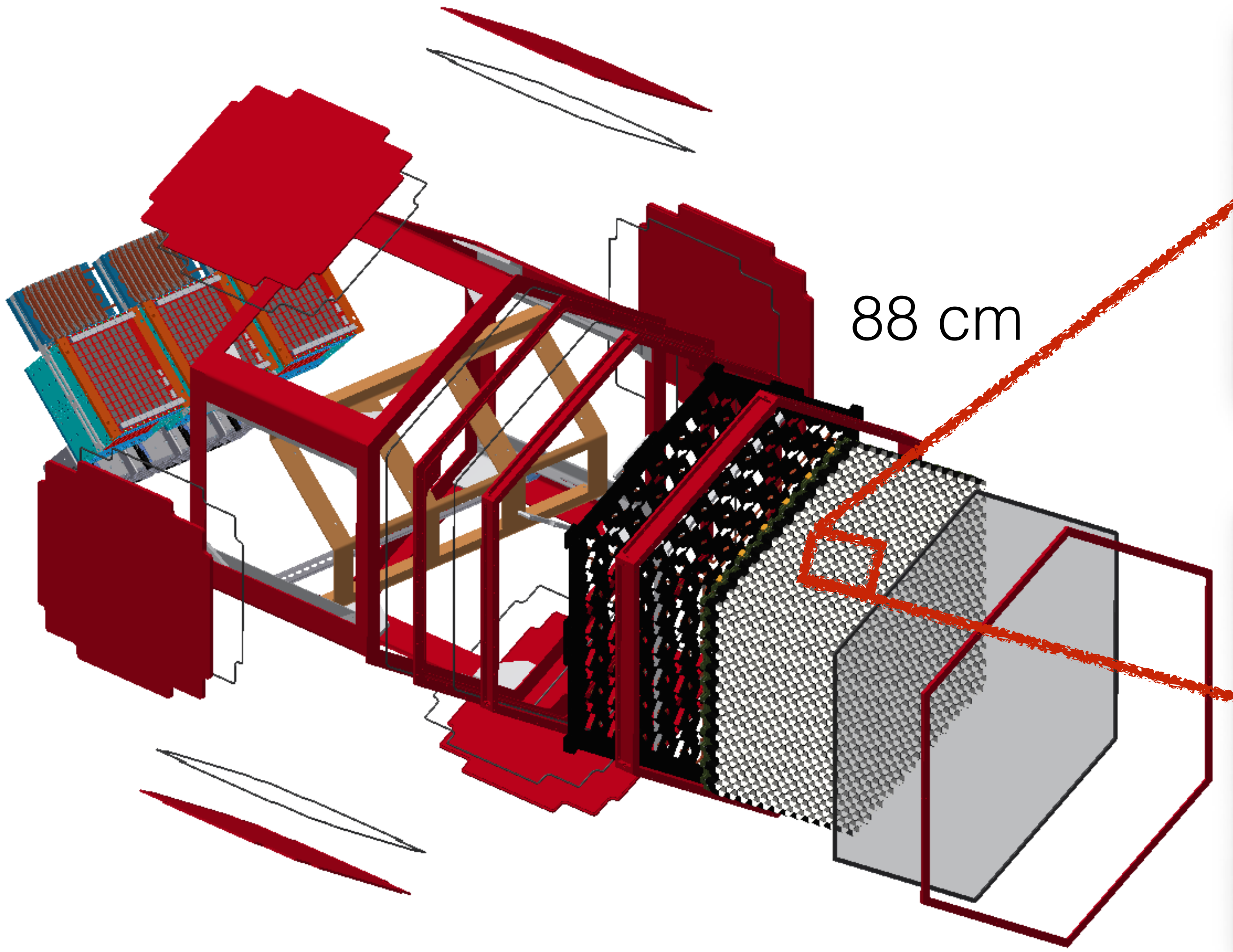


Hexagonal sensors



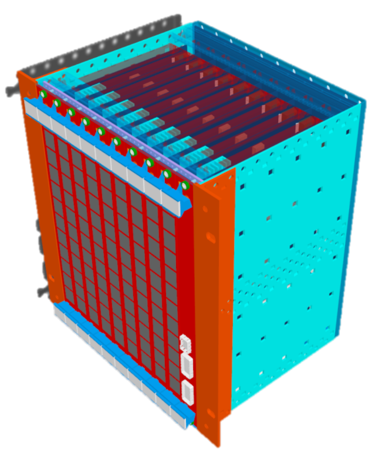
Light guides

The Single Mirror SST (SST-1M) camera concepts



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

- Fully Digital readout electronics
- Fully digital trigger path with reconfigurable algorithms and signal preprocessing
- Compact, robust, lightweight and self-contained



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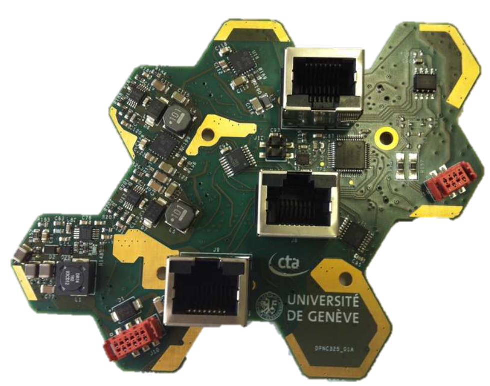

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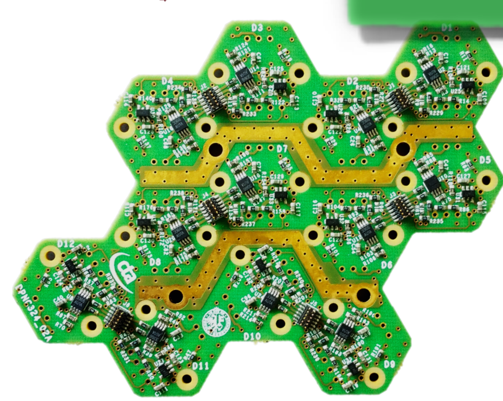

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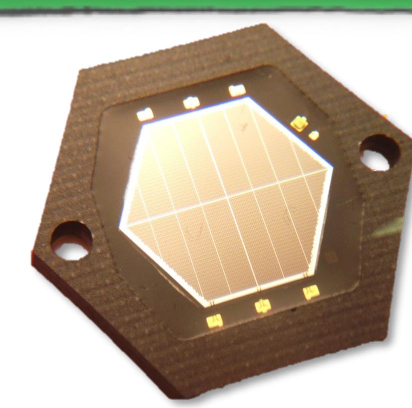

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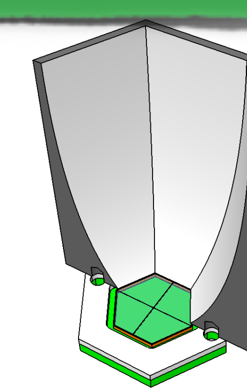


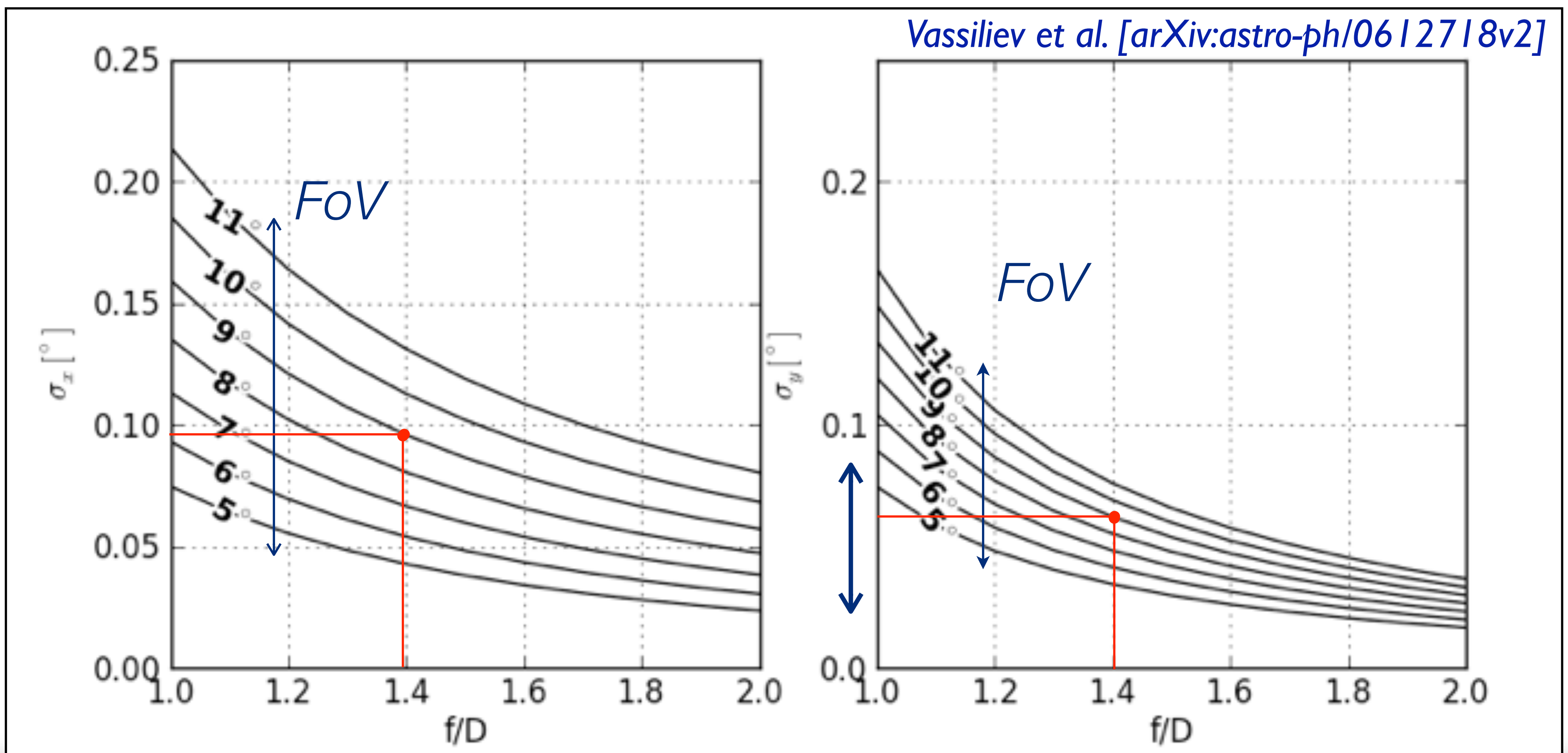
Light guides

Camera design for SST-1M

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

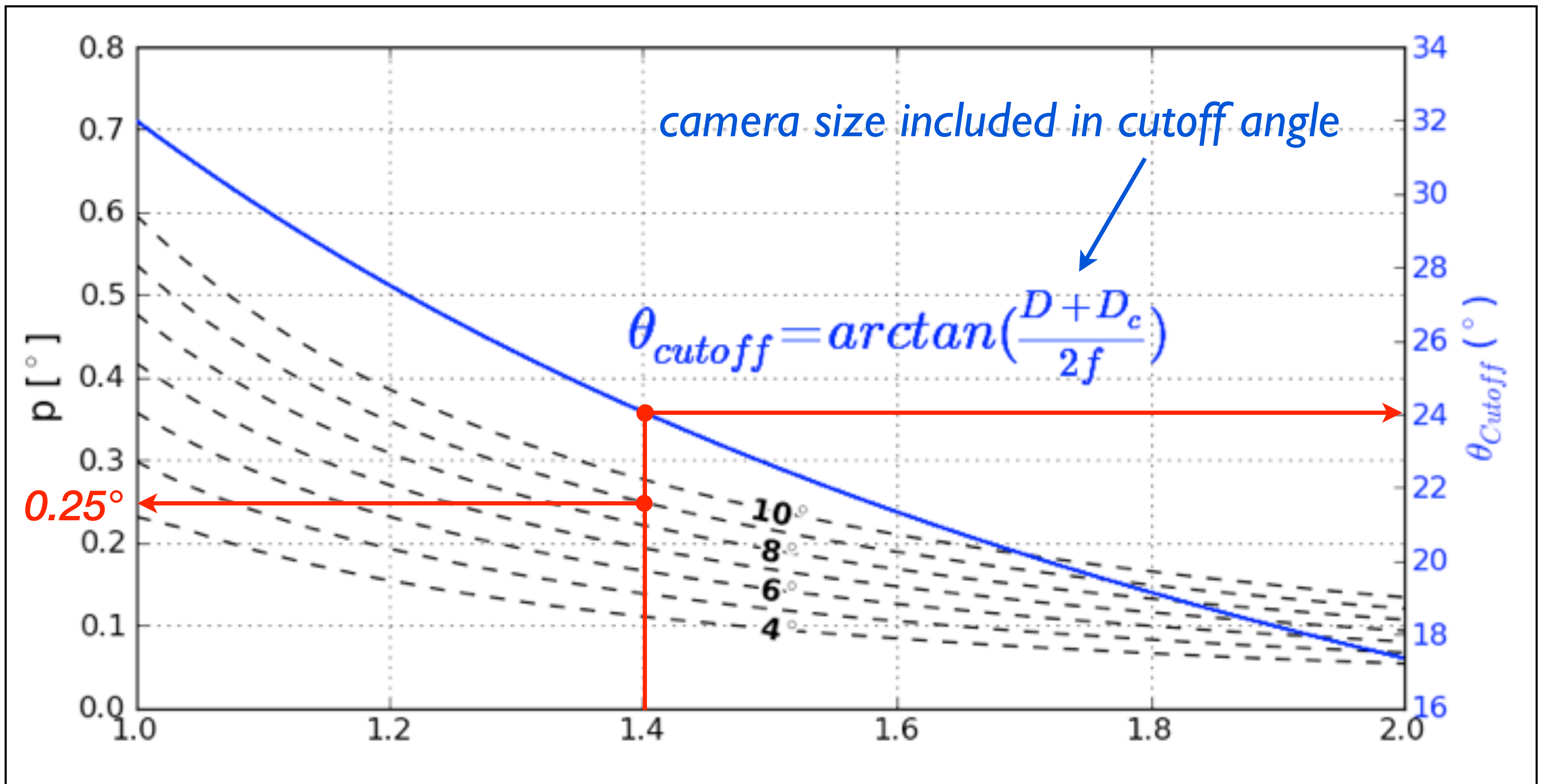


Camera design for SST-1M

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**



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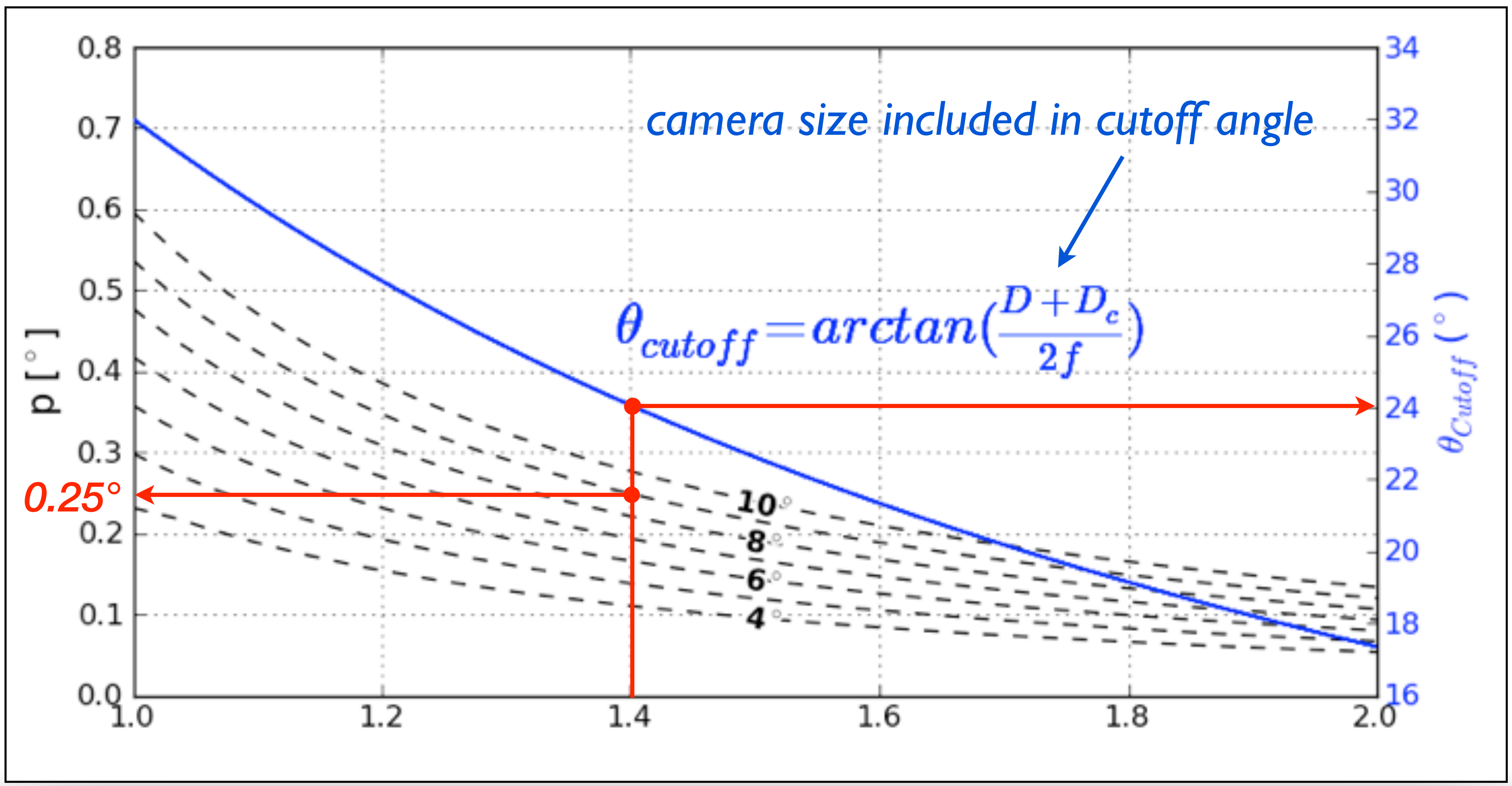
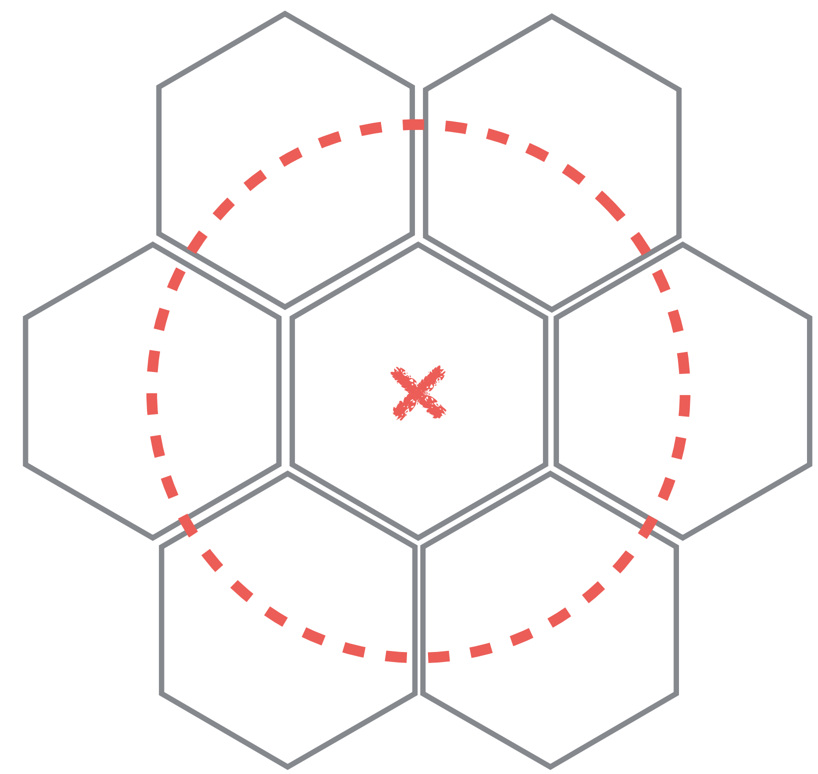


Pixel shape : why hexagonal ?

Light concentrator entrance:

- No dead space between pixels
- The mutual distance between pixels is kept constant along the camera, their response for different orientations of the shower images is geometrically unbiased



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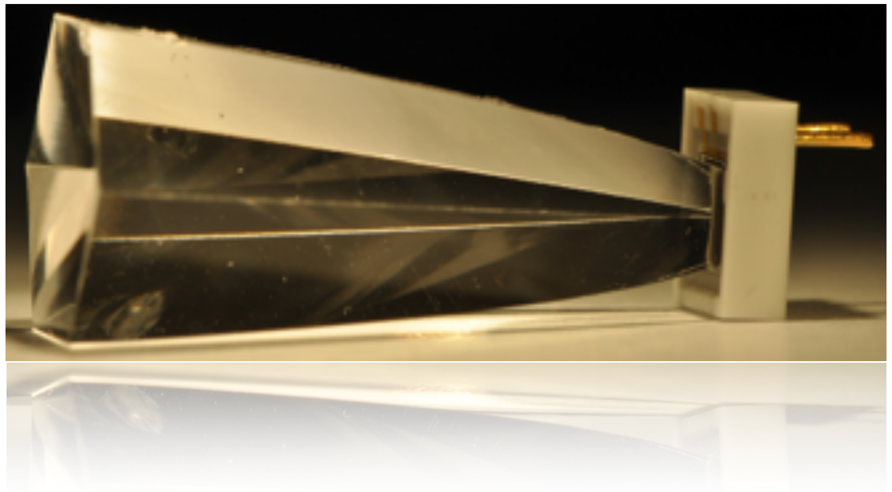
Light concentrator output:

- If solid, little constraint on the output shape but absorb UV light
- If hollow, for symmetry reason hexagonal



Pixel shape : why hexagonal ?

Light concentrator entrance:

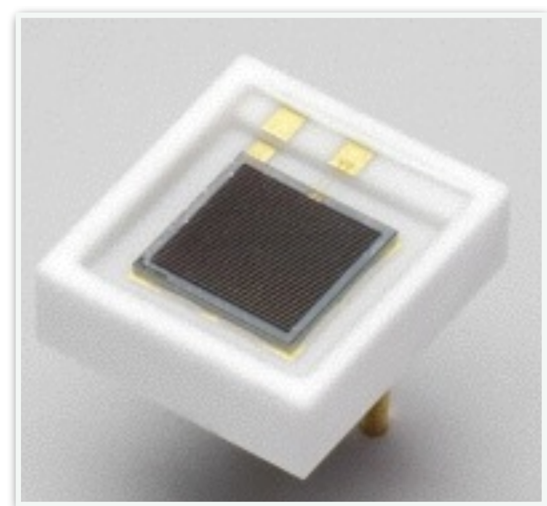
- No dead space between pixels
- The mutual distance between pixels is kept constant along the camera, their response for different orientations of the shower images is geometrically unbiased

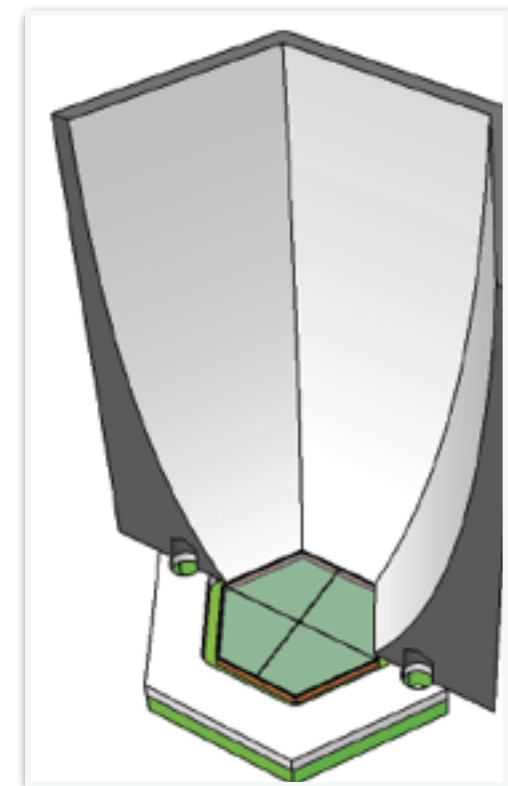
Light concentrator output:

- If solid, little constraint on the output shape but absorb UV light
- If hollow, for symmetry reason hexagonal

Sensor type:

- If solid light concentrators, standard square devices would work (FACT design) ➔ small pixels
- If hollow light concentrators, need custom design of hexagonal shape ➔ large pixels

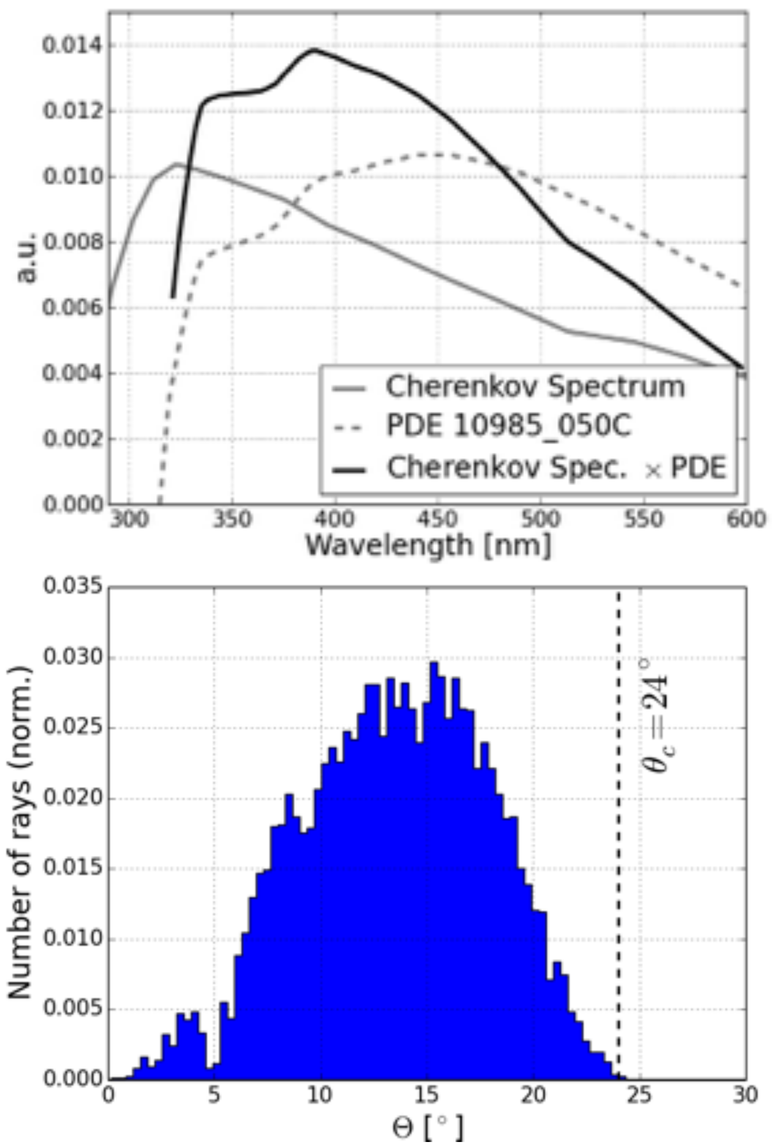




Light Concentrator optimization for SST-1M

Optimization using ray tracing simulation (Zemax)

- Light source: Cherenkov spectrum convoluted with sensor response
- Simulated incident angular distribution



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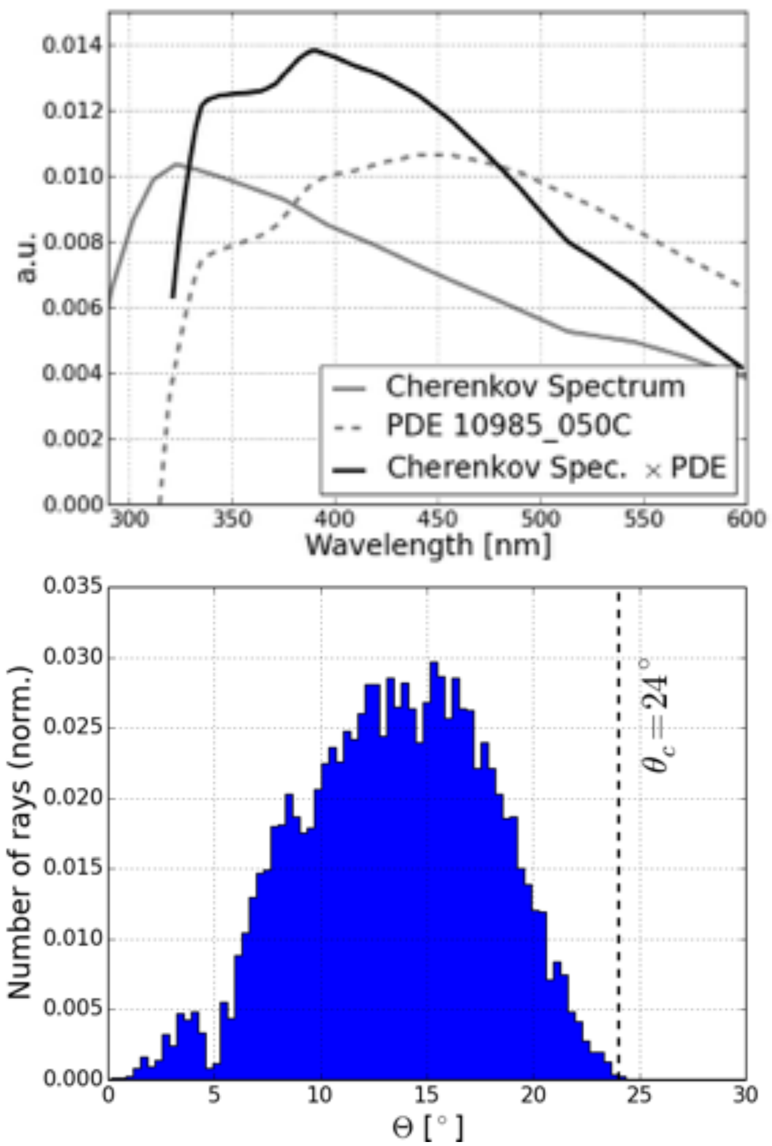

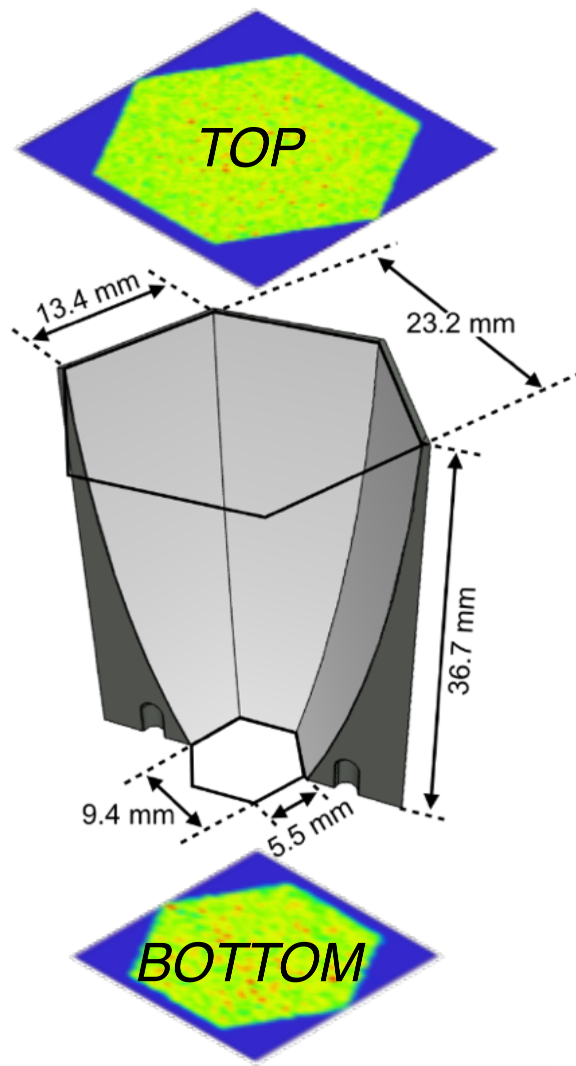

Collection Efficiency = BOTTOM / TOP

Light Concentrator optimization for SST-1M

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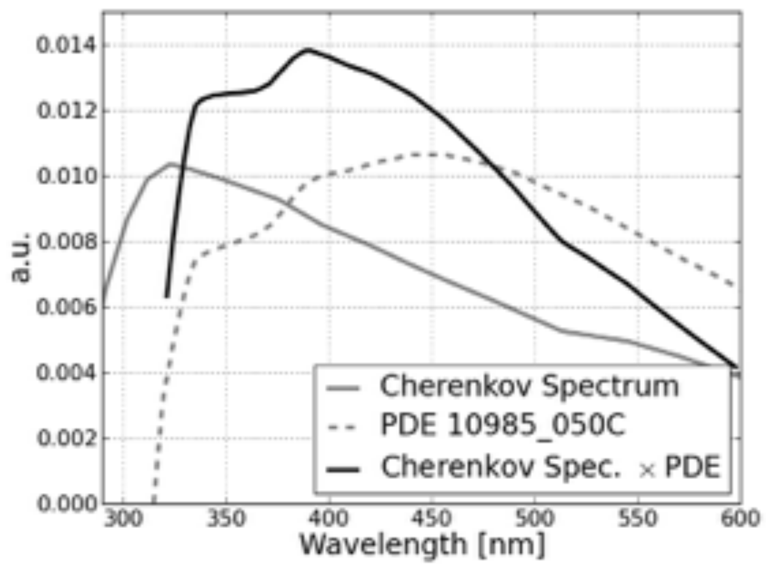
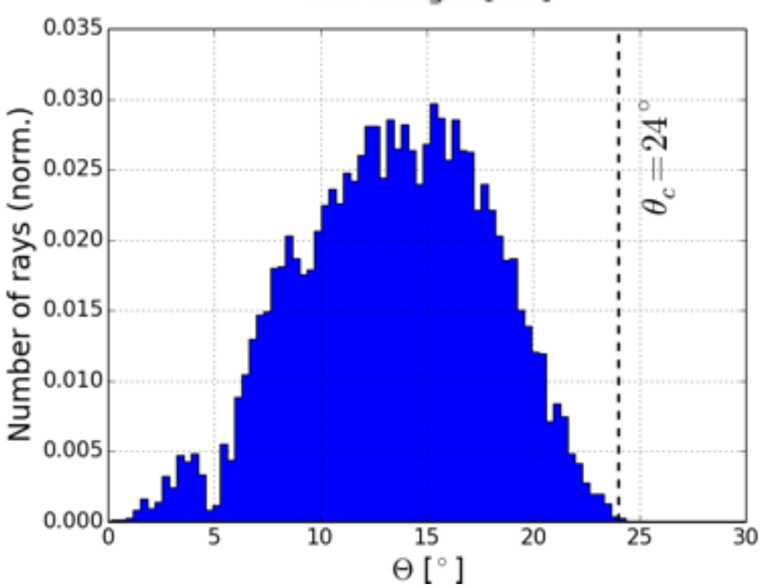
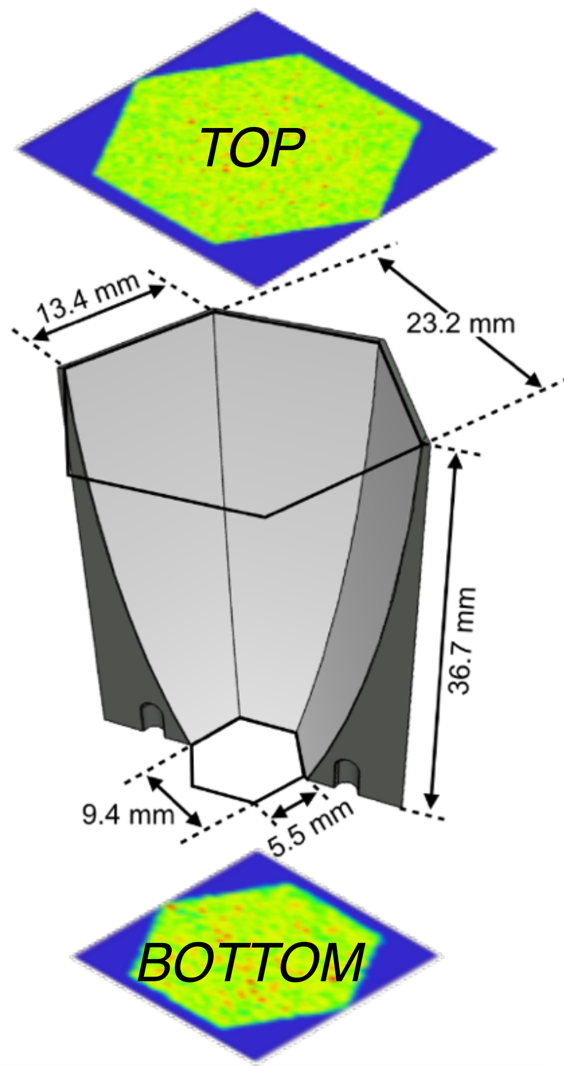
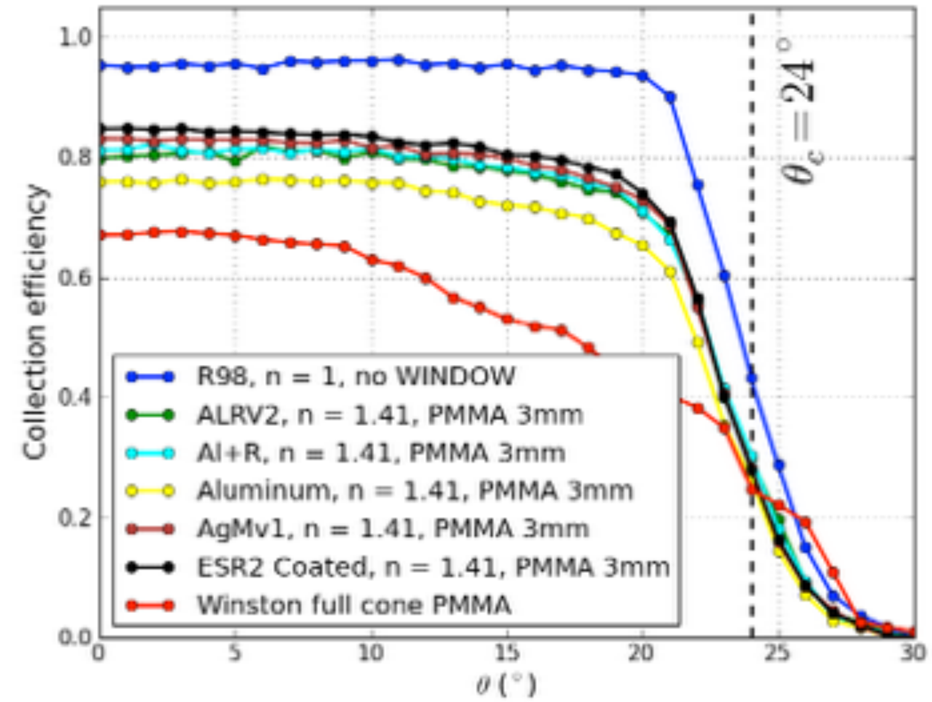
Shape, coating and window optimization









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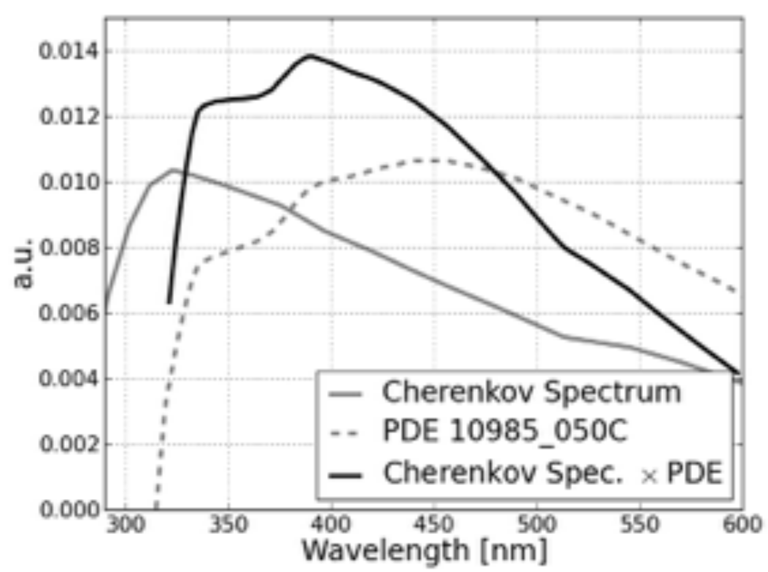

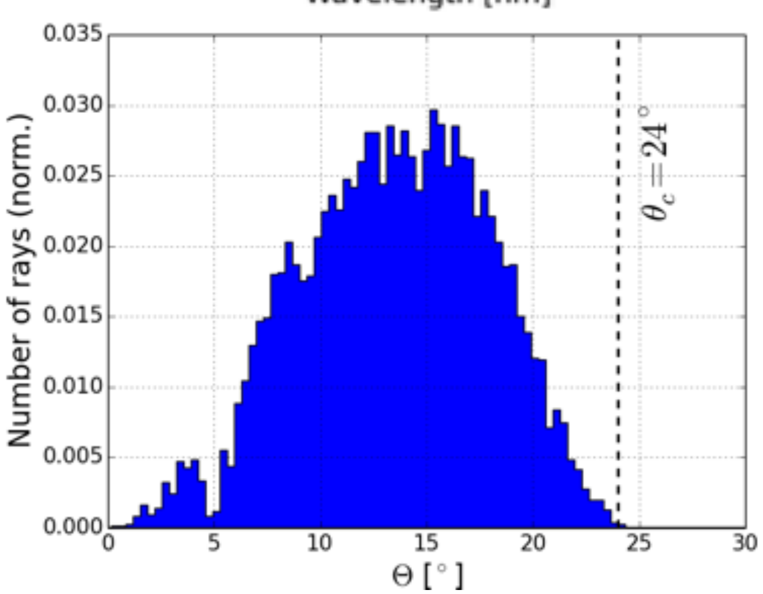

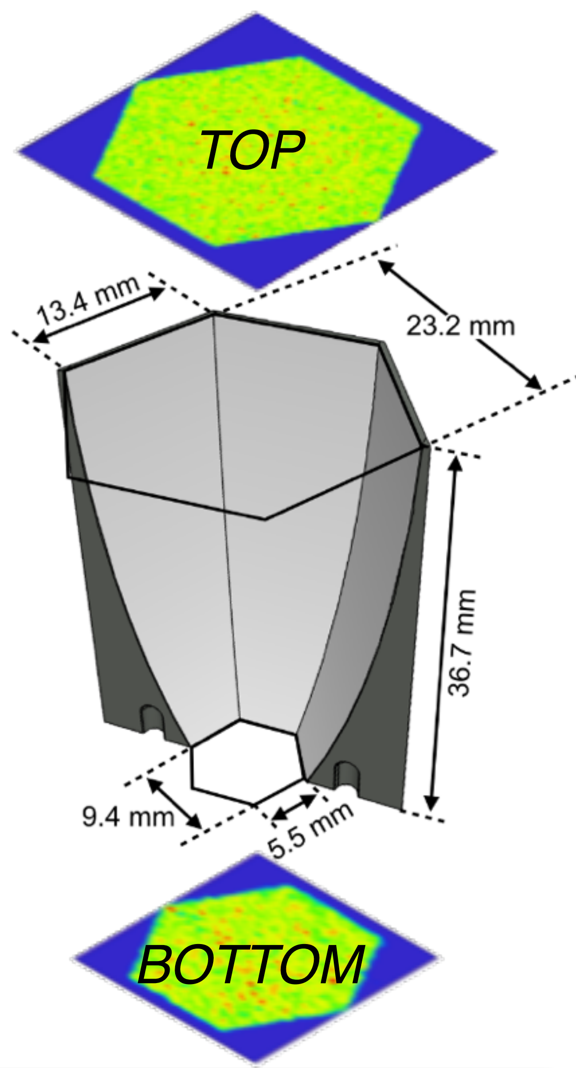

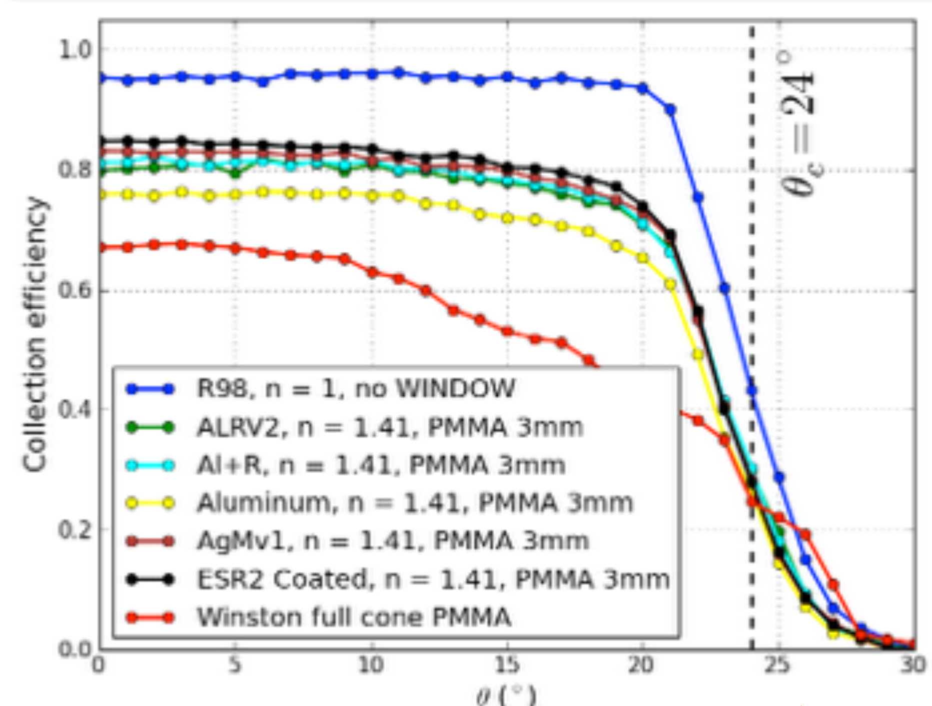

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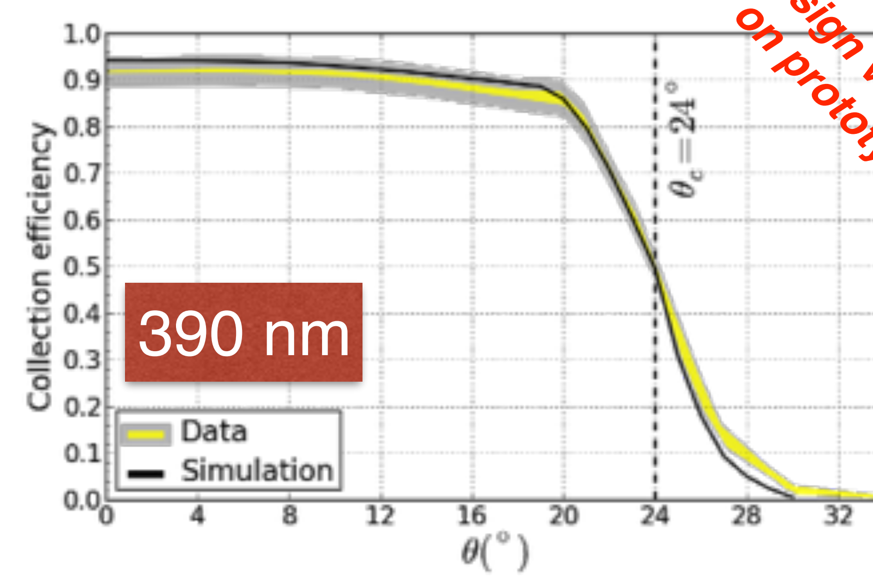
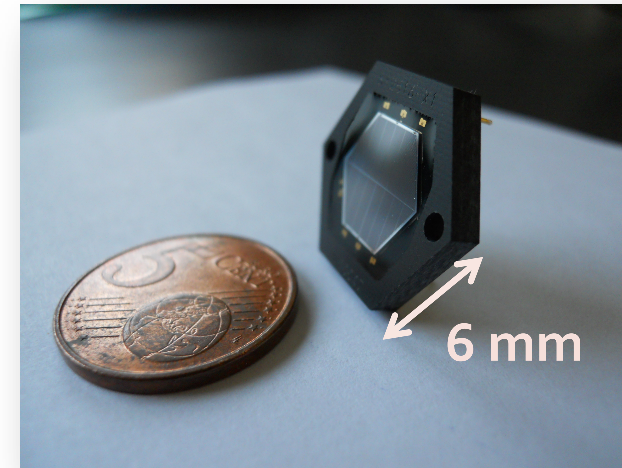
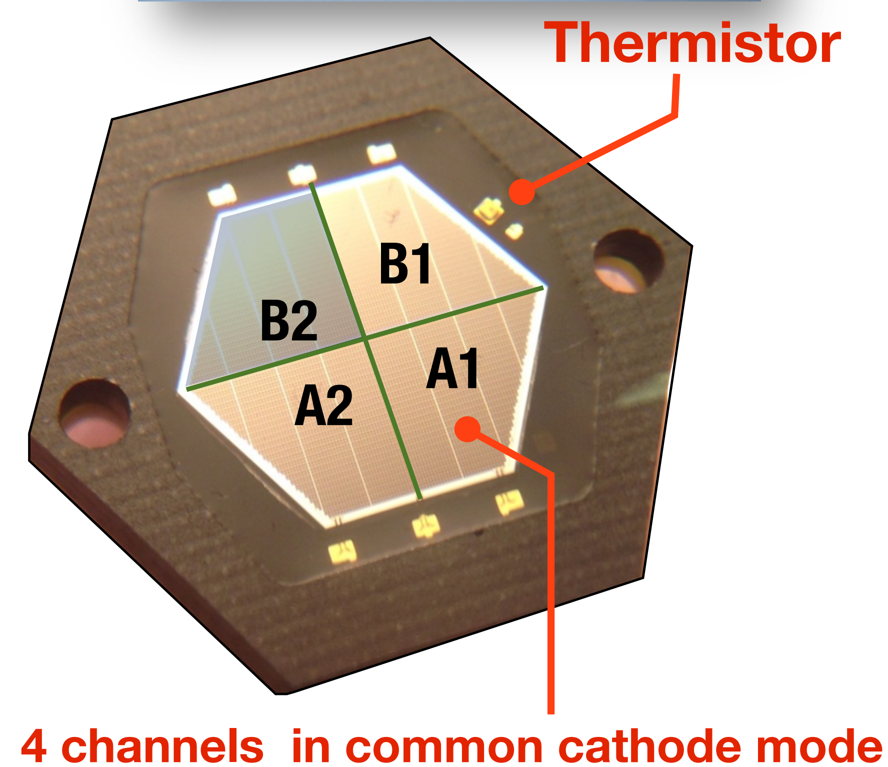


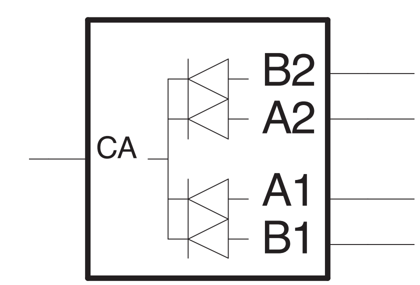
Design validated on prototypes

The hexagonal sensor

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





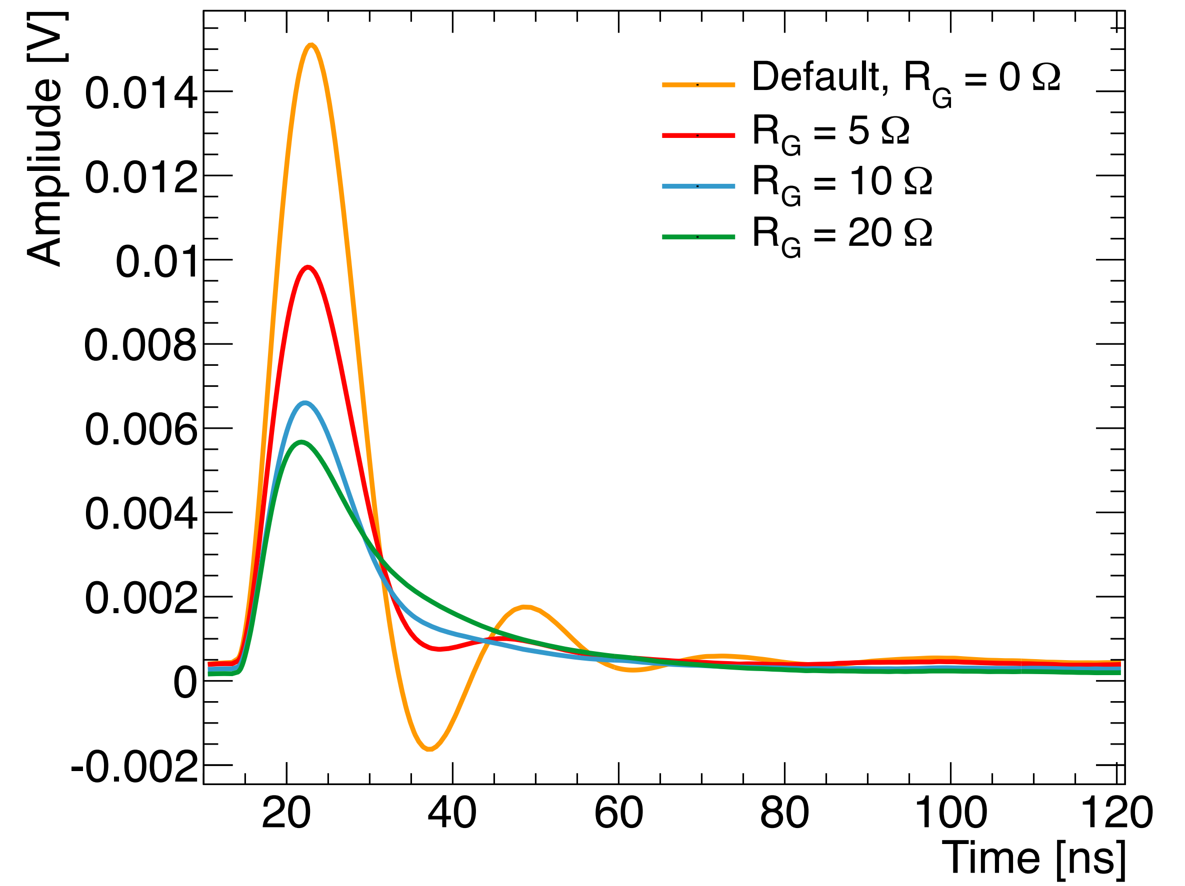


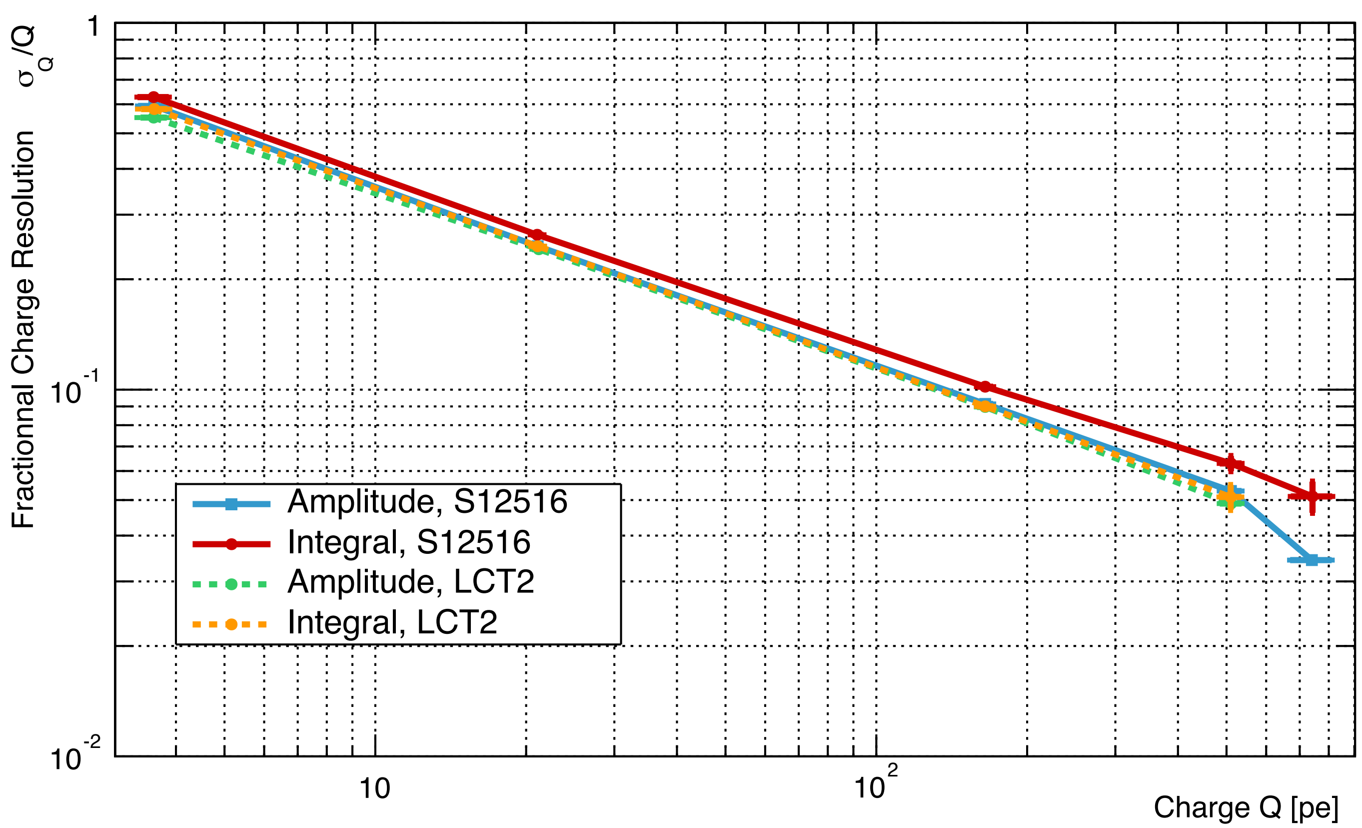
Channels:	**4**
Area:	**23.8 mm²/ch**

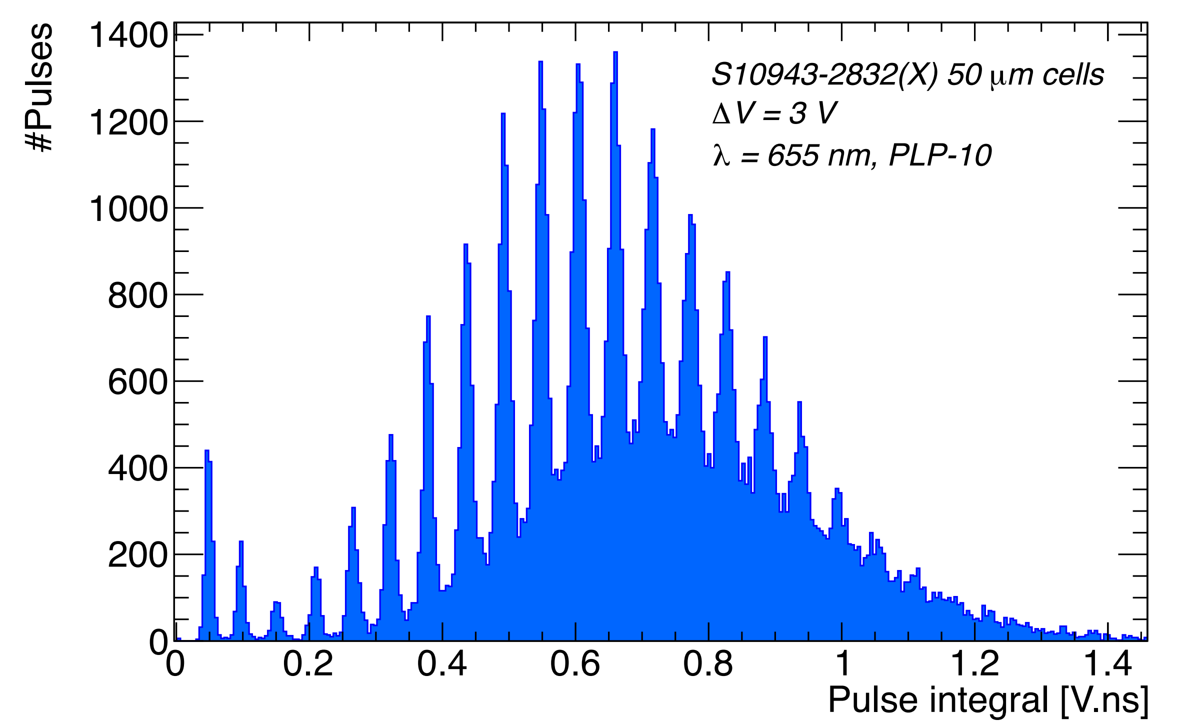
SENSOR PARAMETERS (T 25°C)	
Channels	*4*
Effective active area/channel	23.38 mm
Pixels per channel	*9210*
Pixel size	50x50 µm
Fill factor	*61.5%*
Spectral response range	*320 to 900 nm*
Peak sensitivity wavelength	*440 nm*
Rec. Operating V range	*60 – 80 V*
Vop variations betw channels	*0.15 (max 0.3)*
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*

Performance of the hexagonal sensors

- The signal shape is related to the sensor capacitance (area) and the preamplifier chain design.
- The pulse shape is very sensitive, tuning needed for every sensor type (simulations +measurements)
- Even with our device (~ nF capacitance), high performance are achievable







Conclusions

FACT has paved the way for the use of SiPM in IACT cameras and has already proven that G-APDs are suitable for gamma ray astronomy:

- Stable operation
- No evidence of aging after 18 months
- Observation with moonlight: larger duty cycle (30%)

The 3 ongoing SST projects (SST-1M, ASTRI, GCT) using SiPM cameras for CTA have:

- proven that present sensors allow to achieve high performance satisfying the CTA requirements
- characterized a large amount of sensors in the scope of gamma ray astronomy. These studies were fundamentals for manufacturers to improve their devices and start dedicated development for gamma ray cameras;
- developed new light concentrators and dedicated coating, highly efficient in the UV region, cost effective and mass producible;

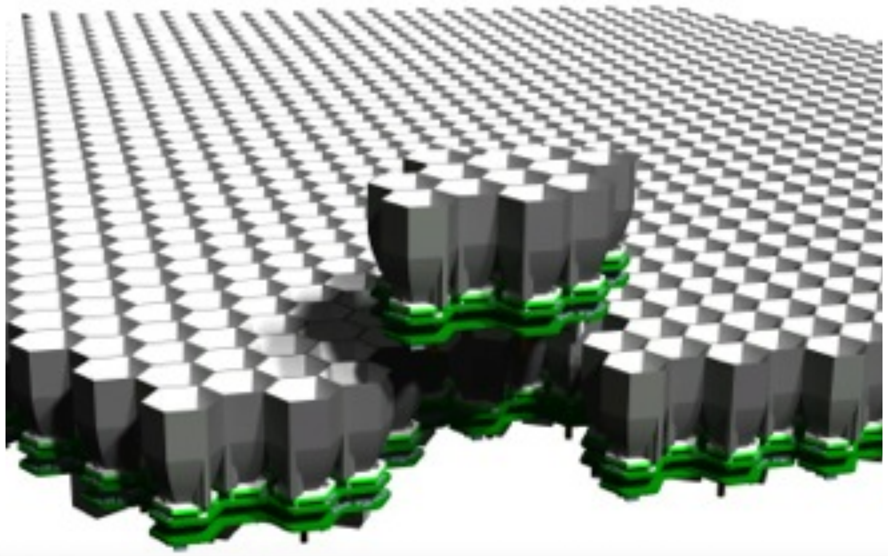
Stay tuned, the three camera prototypes will be ready by early 2015

Backup slides

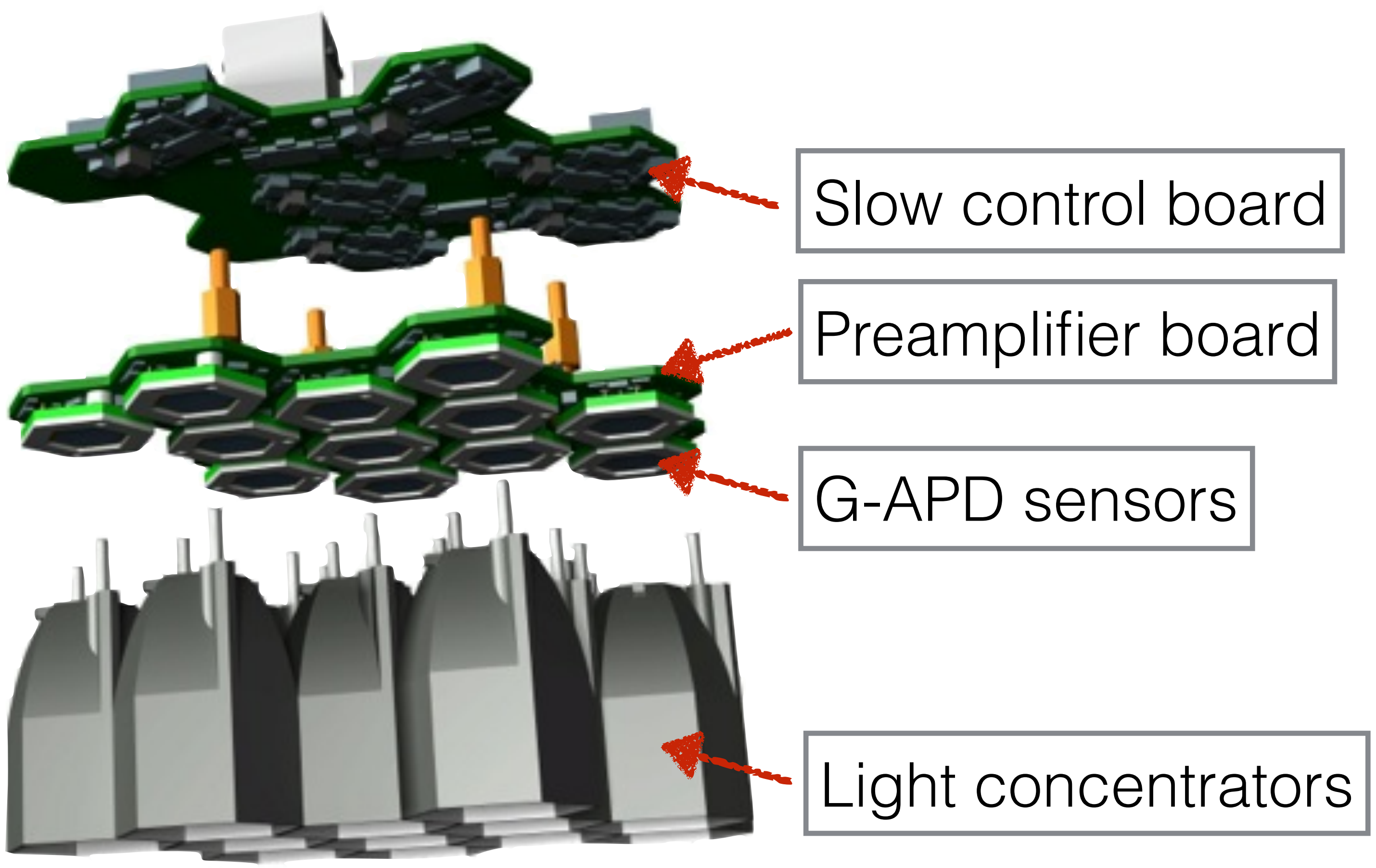
The Single Mirror SST (SST-1M) camera concepts

- Use GAPD-based camera on a Davies-Cotton telescope
- All components should be cost-effective and fabrication process easily scalable

- Fully Digital readout electronics
- Fully digital trigger path with reconfigurable algorithms and signal preprocessing
- Compact, robust, lightweight and self-contained



- 1296 pixels (SiPM+Cones)
- 108 Modules of 12 pixels each
- Entrance window 3 mm Borofloat
- Aluminium Back Plate
- Total PDP weight ~35 kg
- Power Consumption ~ 600 W



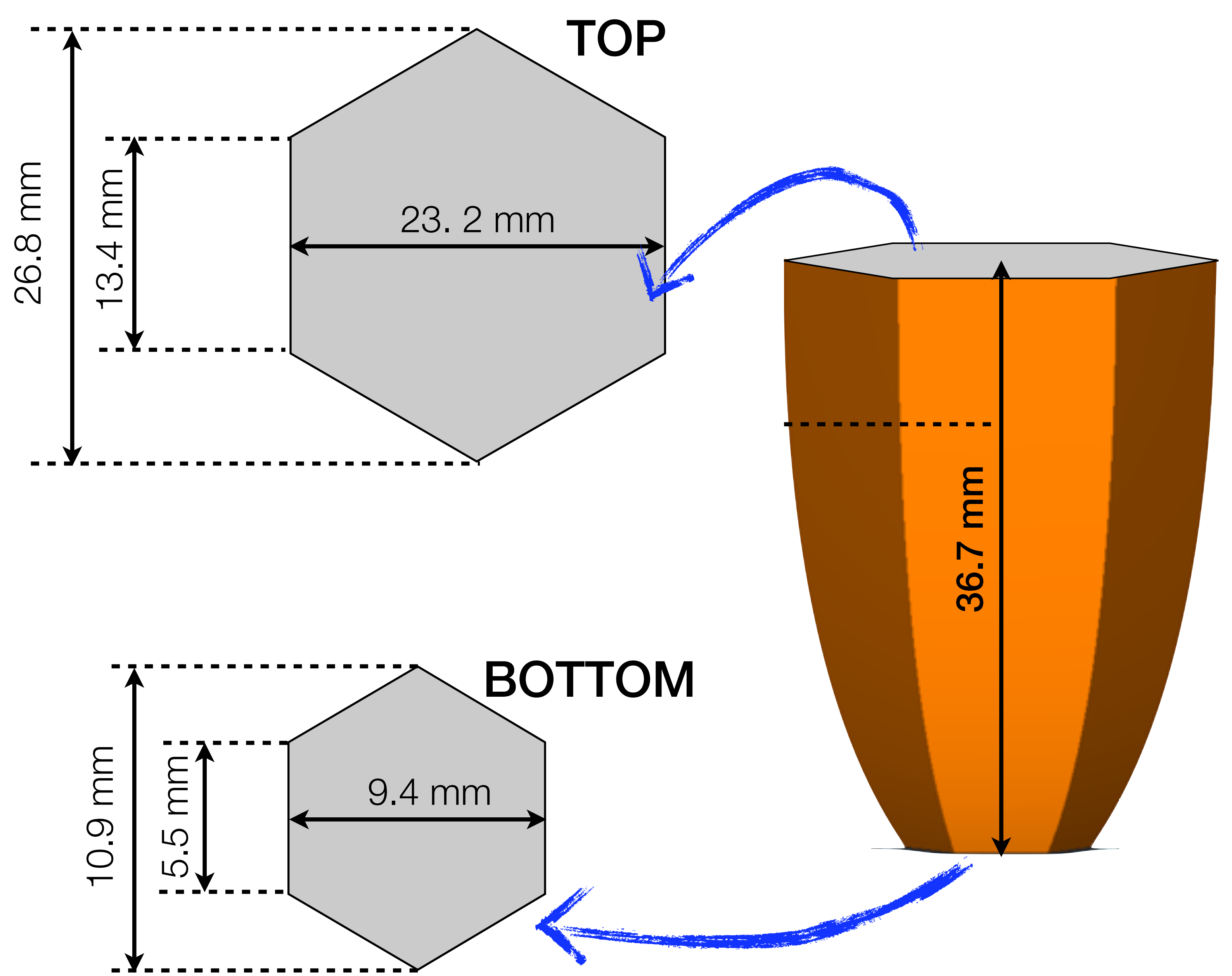
Light Concentrator design for SST-1M

Design guidelines:

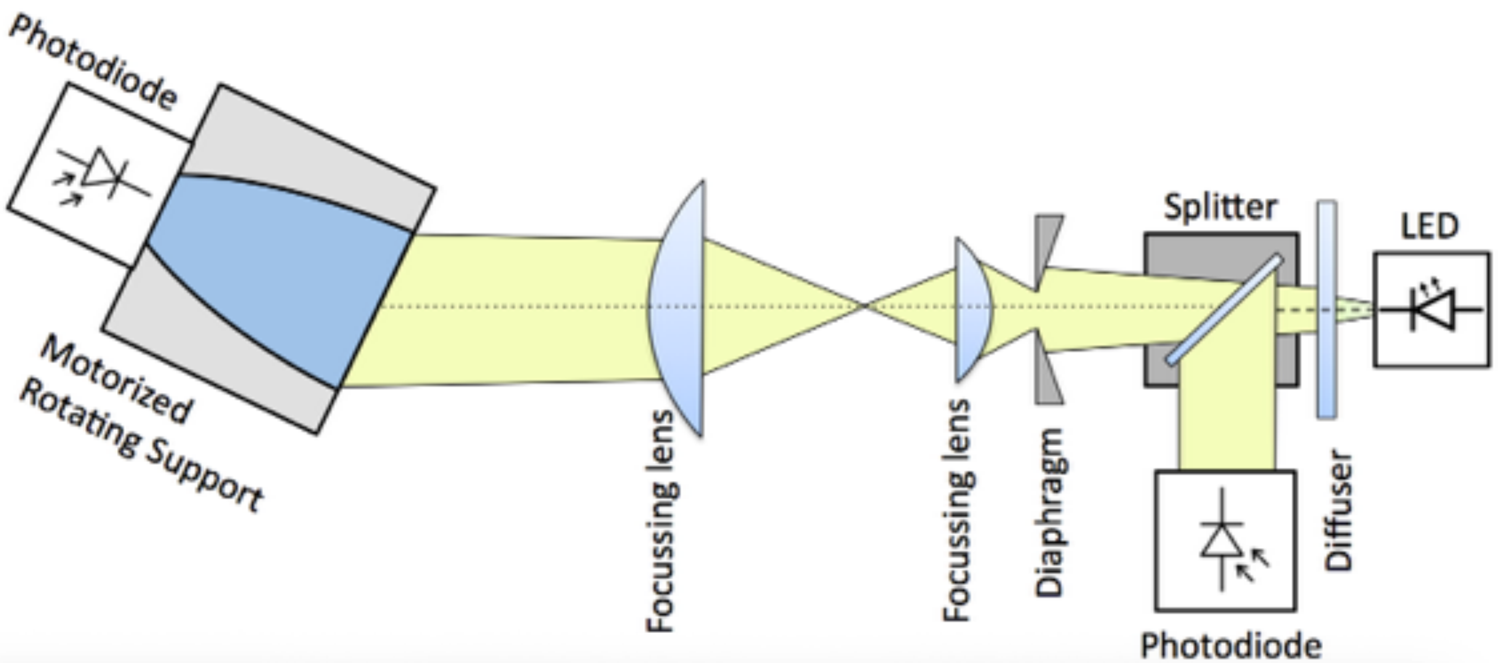
- PSF → angular pixel size → top physical size
- f/D and Camera diameter → Cutoff angle → Cone height

Dimensions:

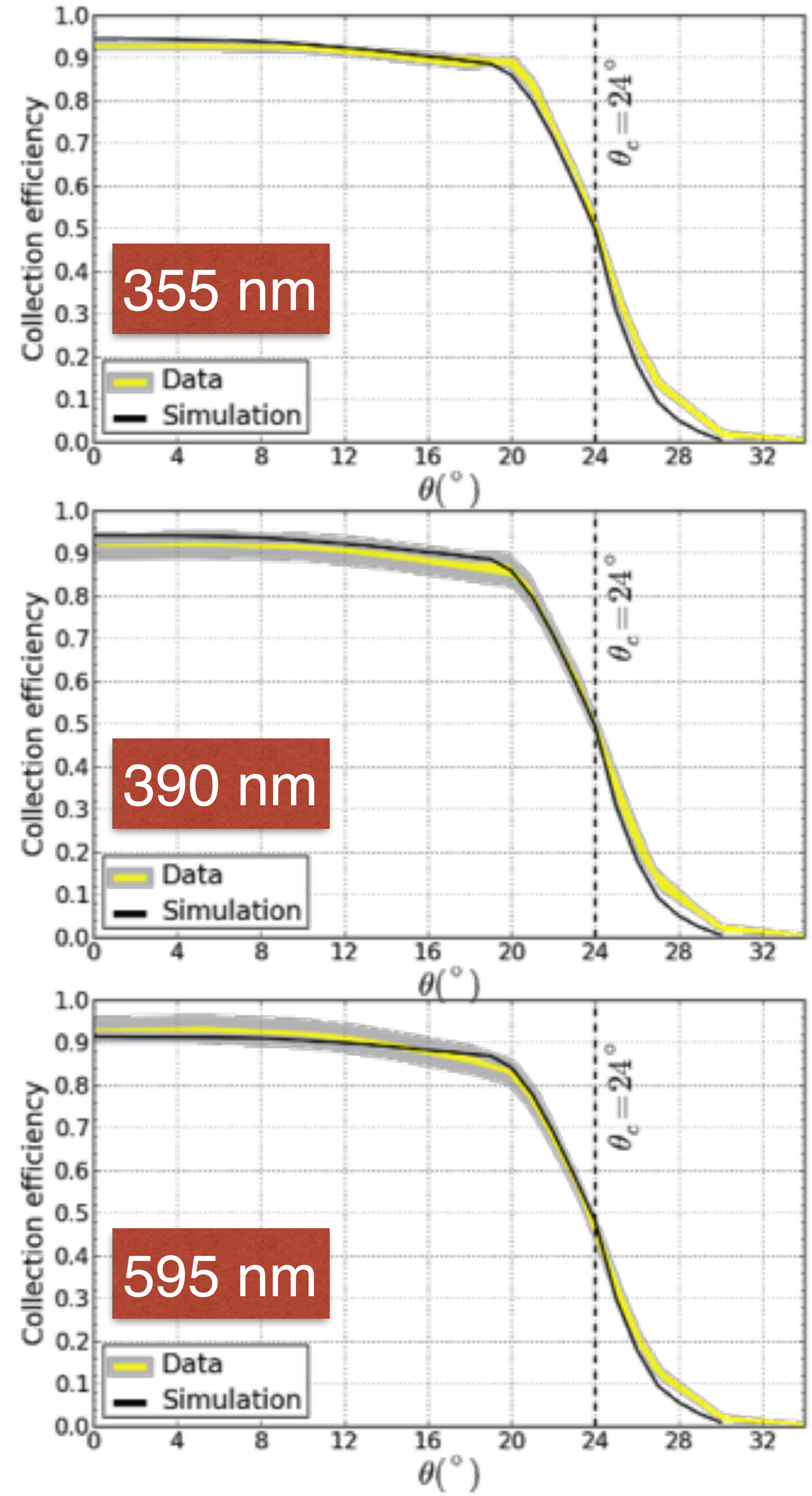
- Angular pixel size: **0.25°**
- Cutoff angle: **24°**
- Length: **36.7 mm**
- Comp. Factor: **~6**



Light guides tests and validation for SST-1M



- Measurement done for different wavelength
- Simulation of the set-up to validate the coating
- Very good agreement between simulation and measurement
- The collection efficiency shown here does not take into account the effect of the entrance window



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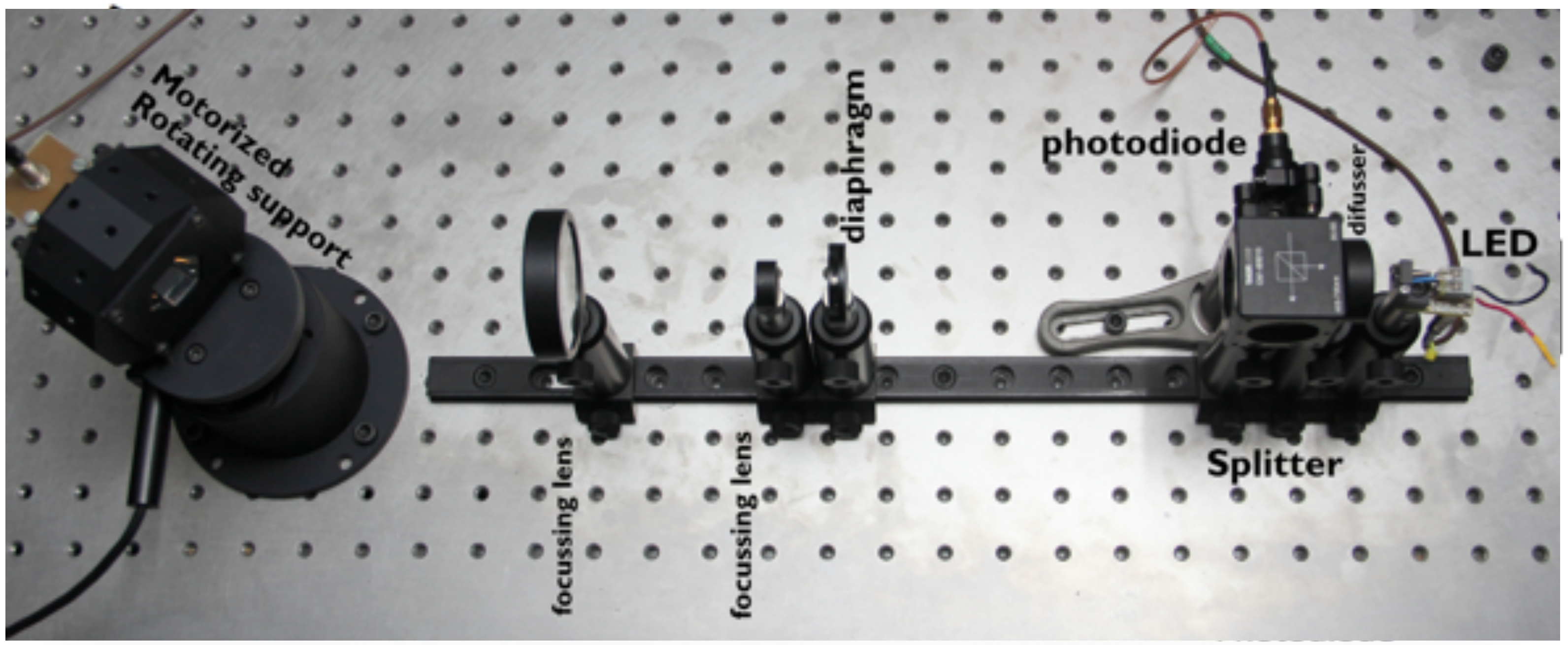

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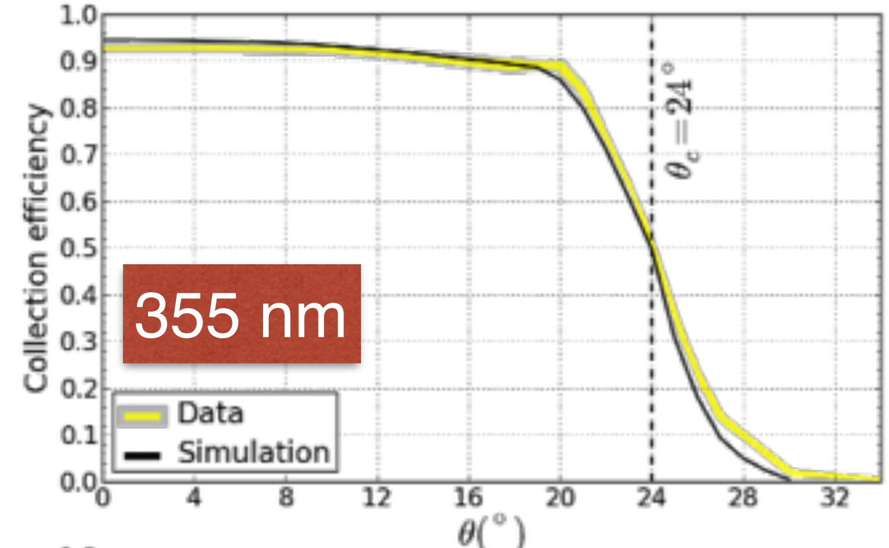

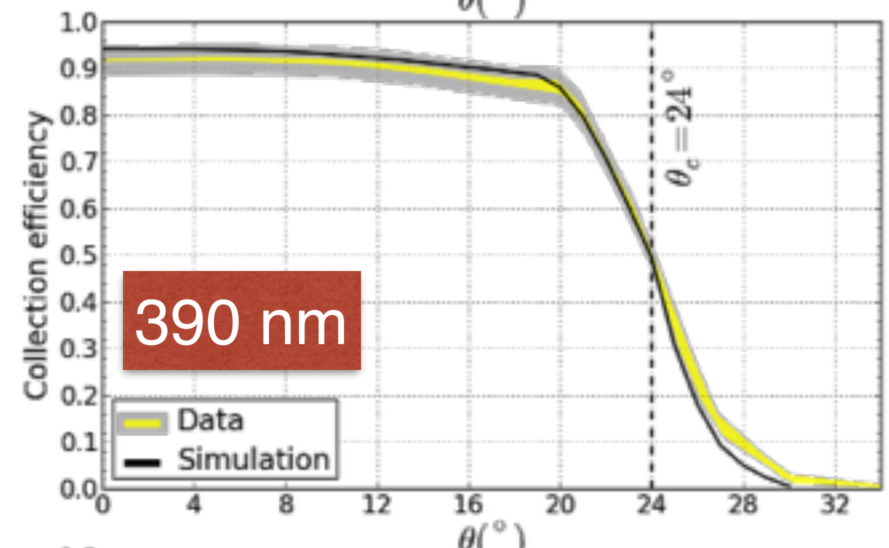

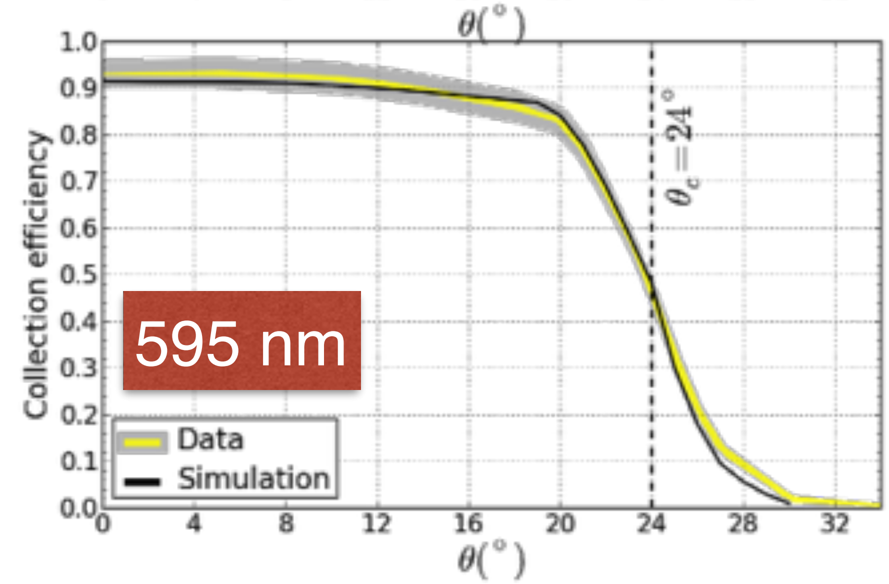

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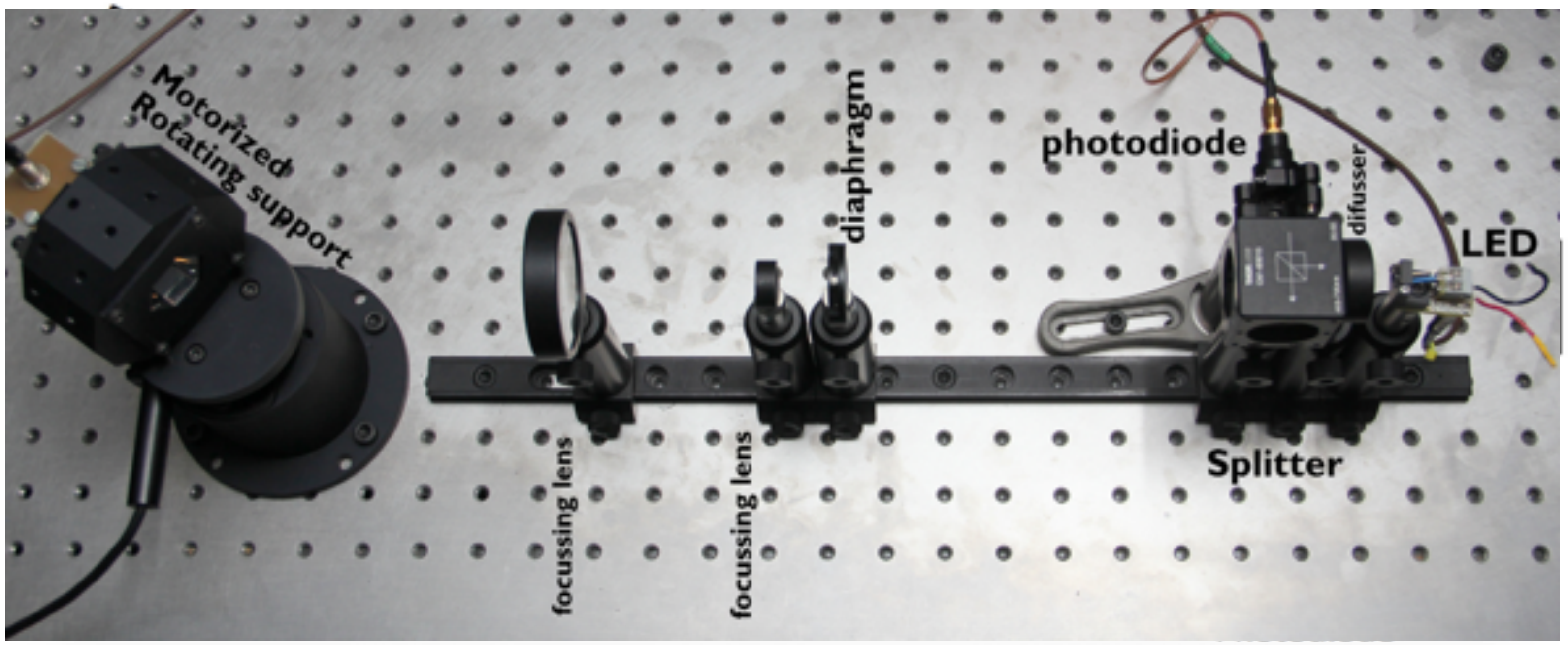

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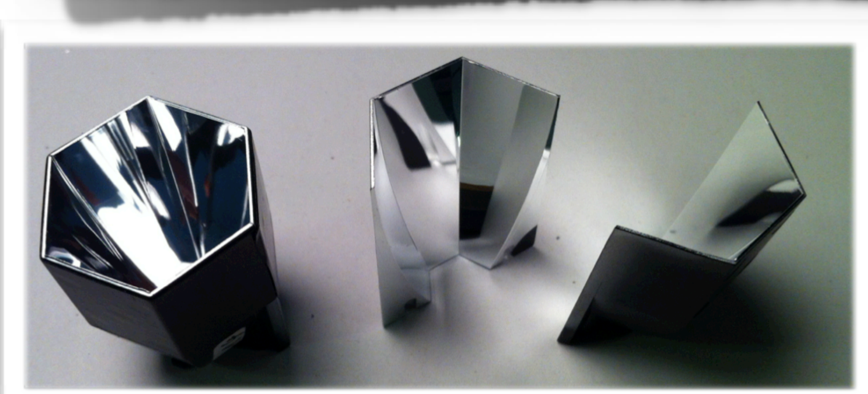
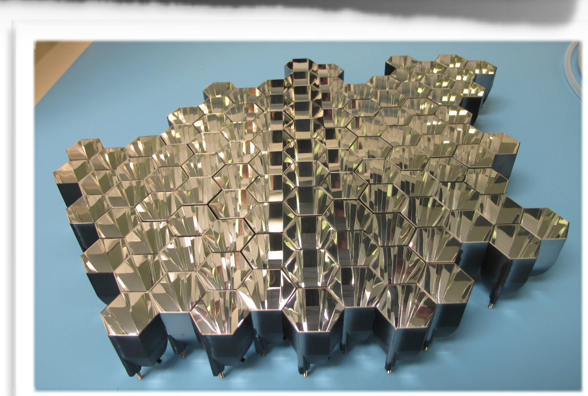
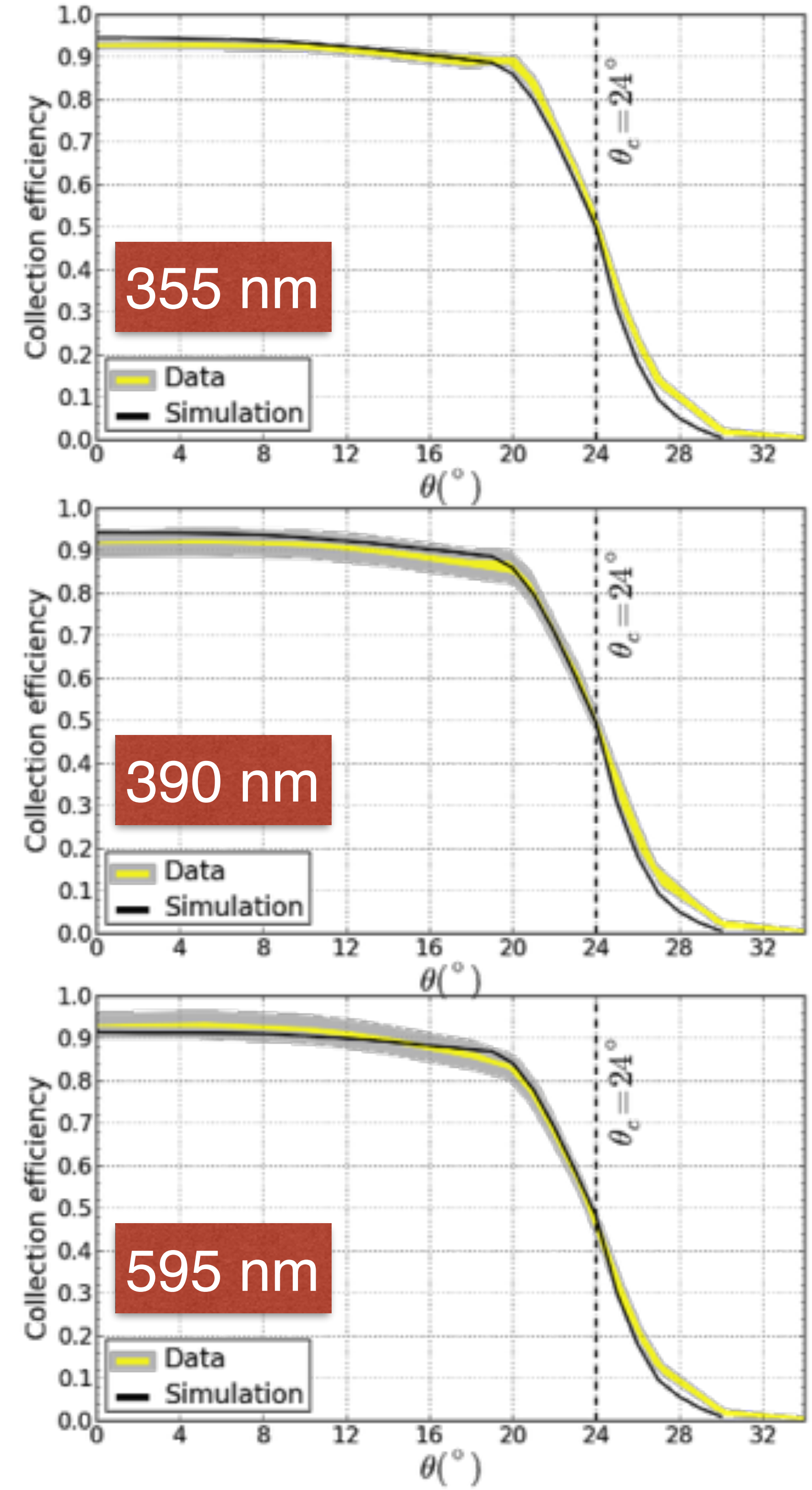
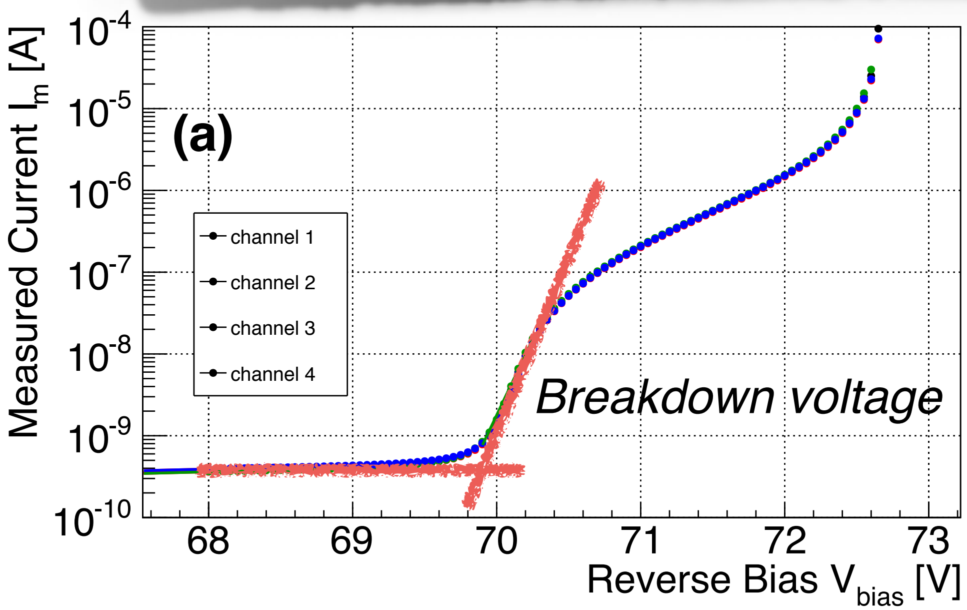


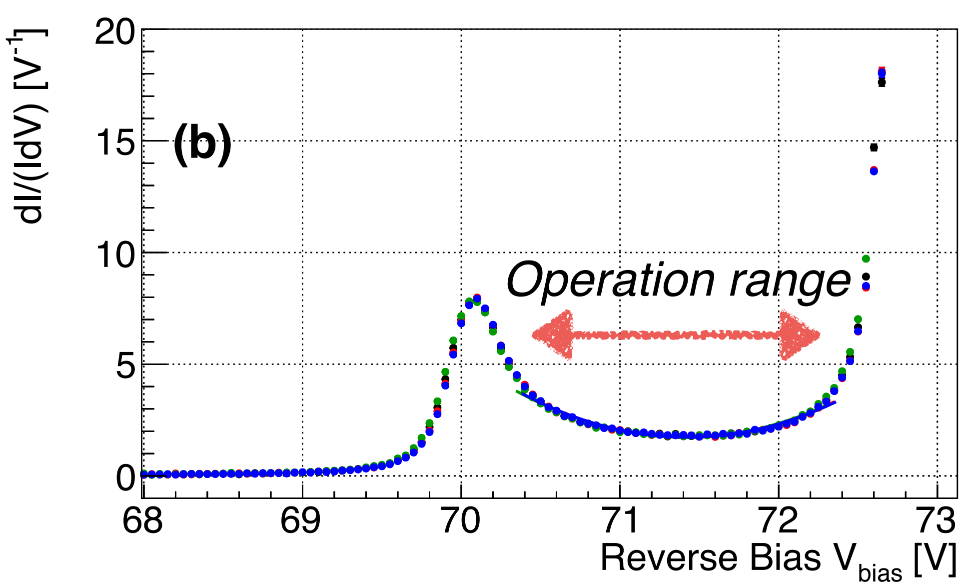




Characterization of the hexagonal sensors

- 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