Medium-Sized Telescopes for the Cherenkov Telescope Array

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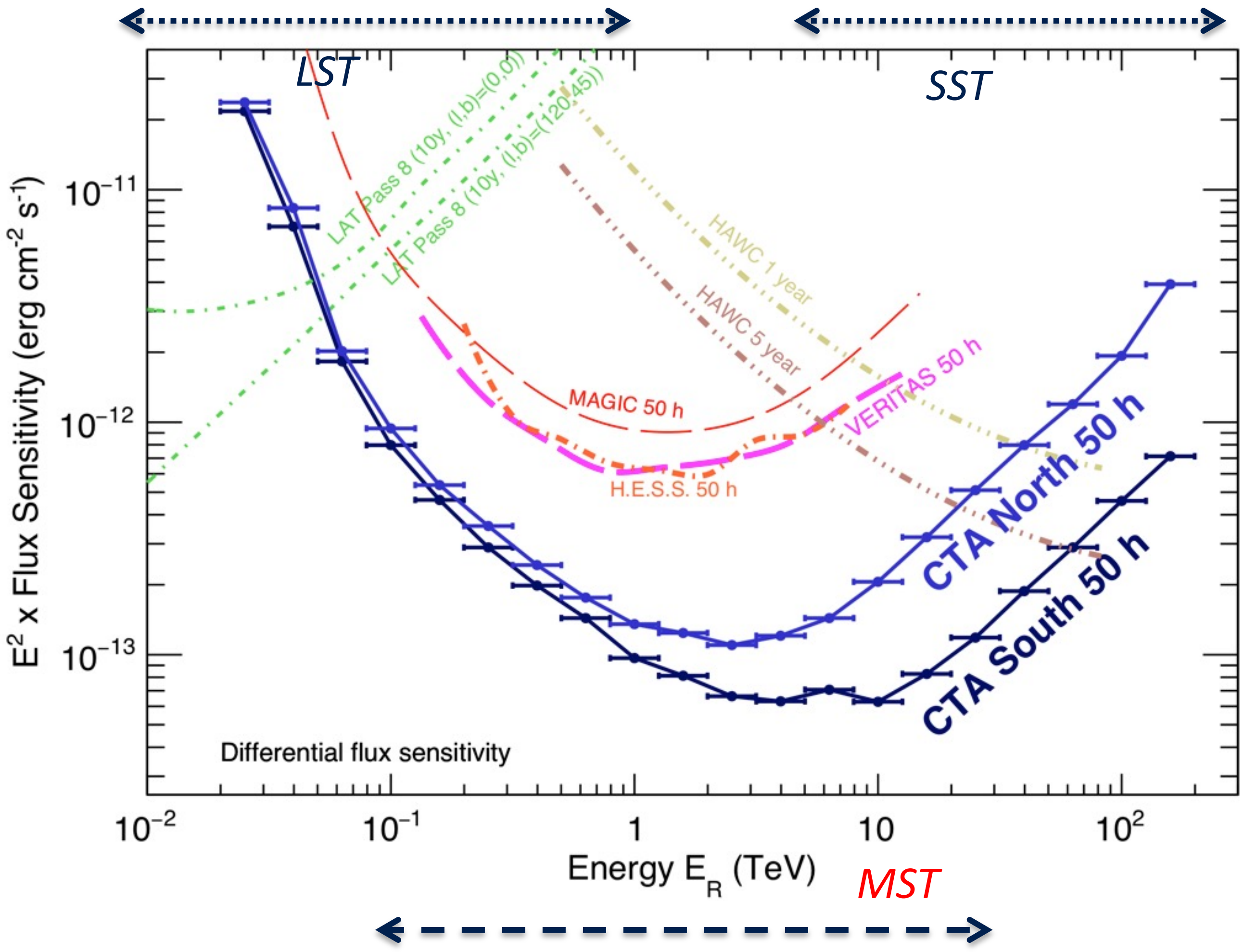
The CTA Medium-Sized telescopes



www.cta-observatory.org/science/cta-performance/ (prod3b-v2)

energy range covered: (100 GeV -> 30 TeV)

The sensitivity improvement over previous generations of IACT comes from

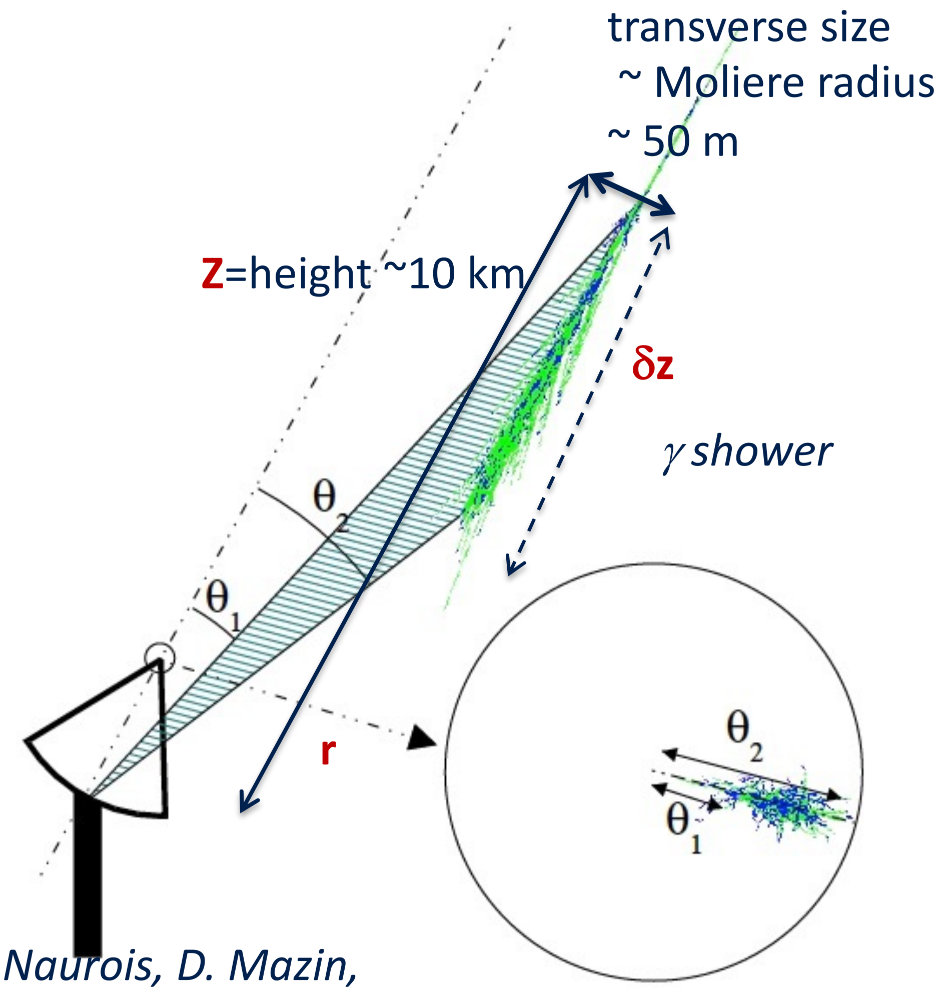
- number of telescopes
- better instruments

In this talk, only the second aspect is addressed.

Outline

- From physics requirements to instrumental requirements
- Design and performances
  - Telescope structure
    - Mirror technology
  - Cameras
    - FlashCam
    - NectarCAM
    - Performances
- Field tests
- Installation plans

Input from shower physics



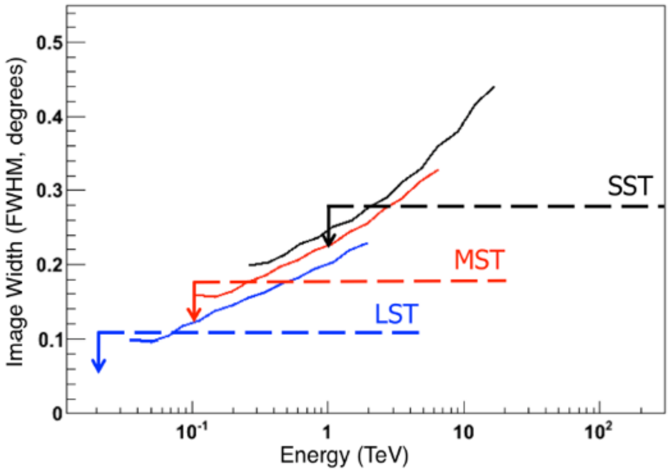
M. de Naurois, D. Mazin, 2015

Imaging of shower in the focal plane of telescope

- Shower maximum located at $h_{max} \sim 11.7 - 2 \log_{10}(E\gamma/100\ \mathrm{GeV})$ km

-Typical angular length of image:
$\delta\theta \sim r\,\delta z/Z \sim$ **0.6^{o}** $(r/1\mathrm{km})(\delta z/1\mathrm{km})$

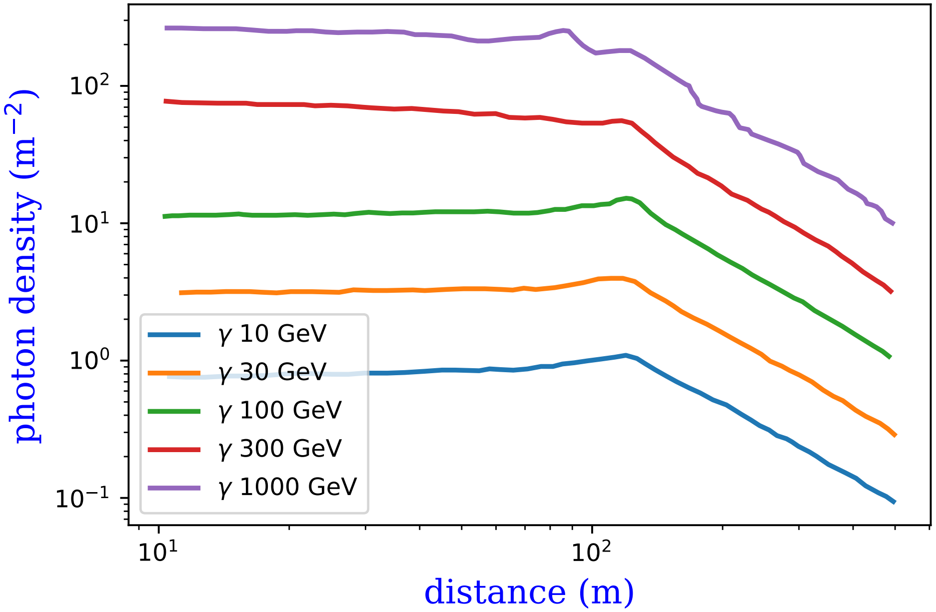
-Typical angular width
~ 50m/10km ~ **0.3^{o}**

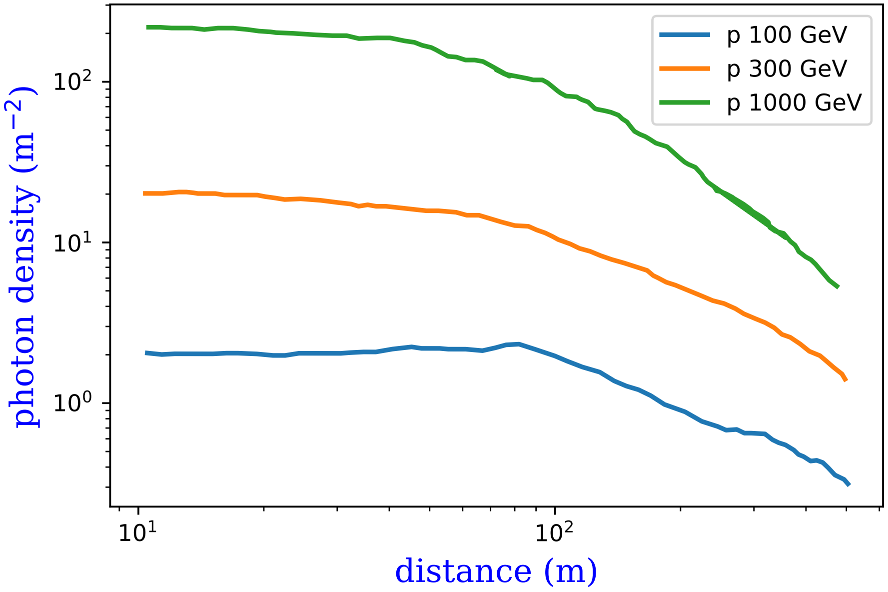


Pixel size for MST: **0.18^{o}**
#hit pixels ~ **10-100**

Input from shower physics (2)

Shower simulations at 2200 m (Aharonian et al 1997)





- Photon density on the ground almost linear with photon energy:

  $N_\gamma/m^2 \sim 0.26\ E_\gamma$
- For a « dish » area of $90m^2$, N_γ (100 GeV) ~ 1800

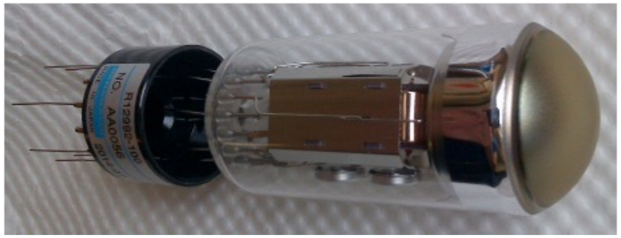
  N_γ (30 TeV) ~ 780000
- A 1 TeV (10 TeV) γ at 500 m (1 km) gives the same photon density than a 100 GeV γ in the « Cherenkov pool » (r < 150 m)
- A 440 GeV (200 GeV) proton gives the same photon density as a 100 GeV (80 GeV) γ.

From photons to photoelectrons

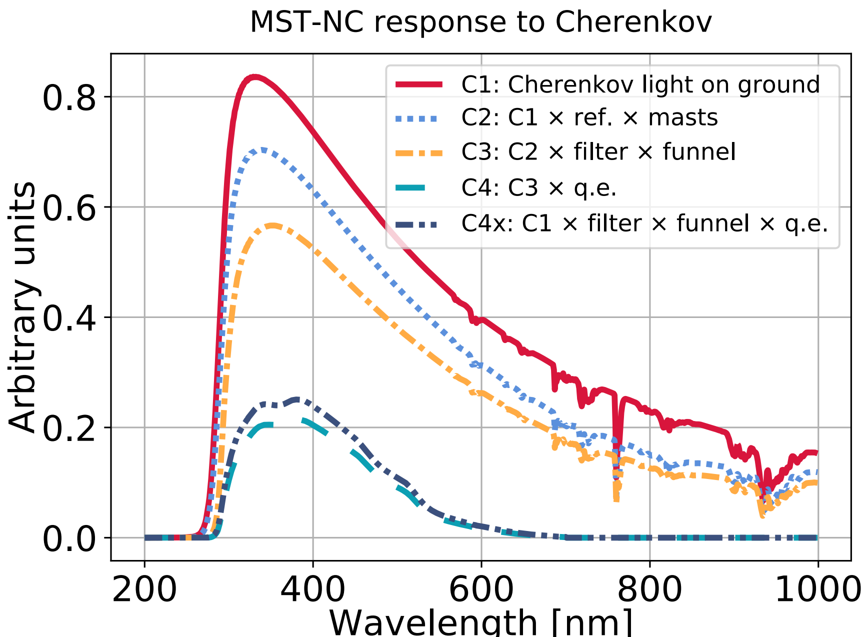
mirrors

Entrance window

Light guides

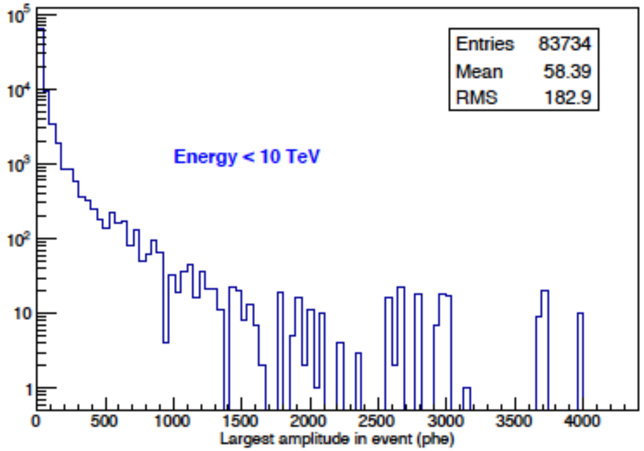


Hamamatsu vacuum photomultiplier



Reflectance of mirrors ~85%

Efficiency of γ -> photoelectrons (phe) conversion ~25%



Dynamic range: 1-> 3000 phe/pixel

Cosmic trigger rates

- Trigger rates dominated by charged cosmic rates once the statistical background from night sky background is eliminated.

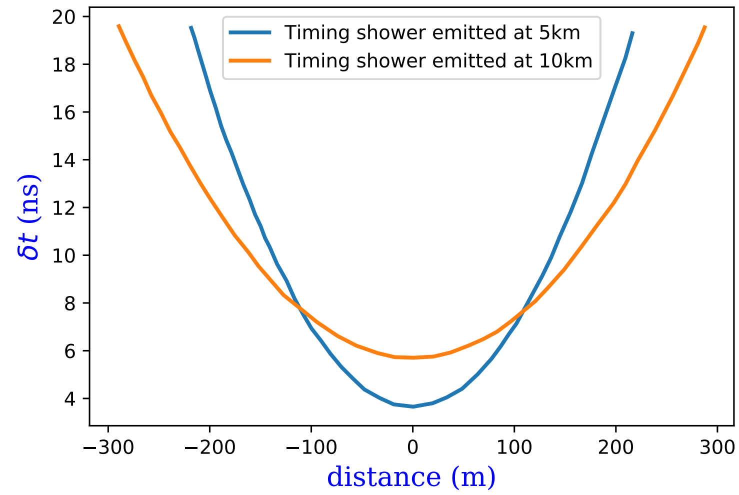
- Proton rate is approximatively

$$\frac{dN}{dE} = 1.8\ 10^{4} \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-2.7} \quad /\mathrm{m}^{2}/\mathrm{s}/\mathrm{sr}/\mathrm{GeV}$$

- Using a maximum distance of r_{max}=200 m and a field of view of 8° gives cosmic trigger rates of 2.5 kHz (100 GeV threshold)
  9.5 kHz (80 GeV threshold).

- In addition, there are isolated muon triggers from distant hadron showers (contributing a factor ~ 2 to trigger rate).

Shower timing



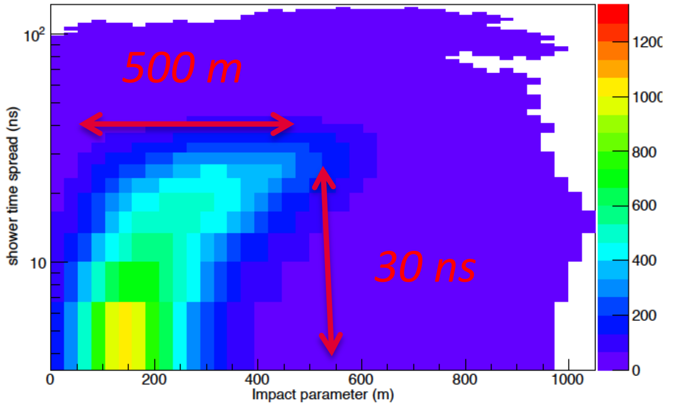
Rules of thumb for durations in camera

100 GeV showers: $\delta t \sim 1.7\ (\text{distance}/100\ \text{m})^2$ ns

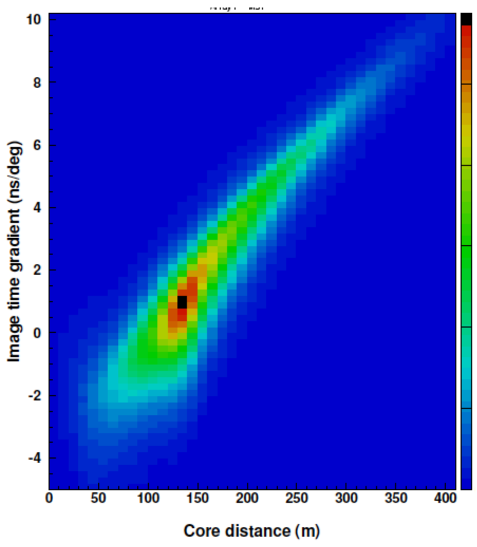
200 TeV showers: $\delta t \sim 82\ (\text{distance}/500\ \text{m})^2$ ns

Duration of signal in 1 pixel

$\Delta t \sim 0.18^\circ$ x timing gradient < 2 ns



signal duration (simulated MST telescope)

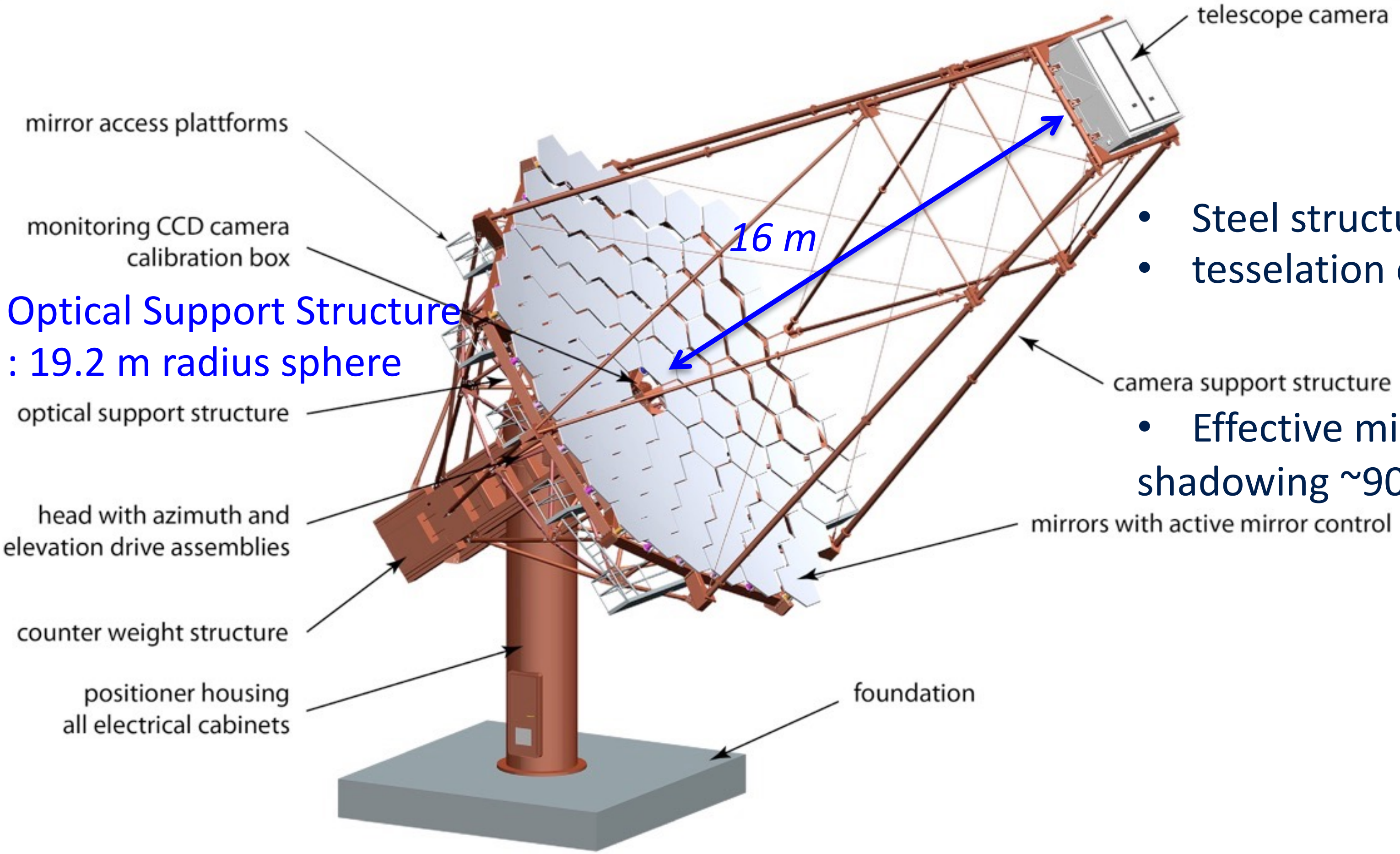


CTA scientific requirements for Medium-Sized Telescopes

- Astrometric accuracy < 20 ’’ (standard) <7’’ (precision)
- Angular resolution above 10 TeV < 0.04 deg. (CTAN)
  < 0.03 deg. (CTAS)
- Repositioning time < 30 seconds (zenith angle < 30 deg)
- Optical PSF < 0.18 degrees
- Telescope/Camera Deadtime < 6% of observing time
- Inter-telescope pixel timing information < 3 ns rms

- Gamma-ray field of view > 7 degrees (0.1-30 TeV)
- Event information: 60 ns readout time, integration time 15-20 ns
- Energy resolution <10% (>1 TeV)
- Absolute event time precision < 100 ns (<2ns single telescope)
- Event rate > 7kHz

Davies –Cotton structure for MST



Optical Support Structure
: 19.2 m radius sphere

- Steel structure 86 t
- tesselation of 86 mirrors

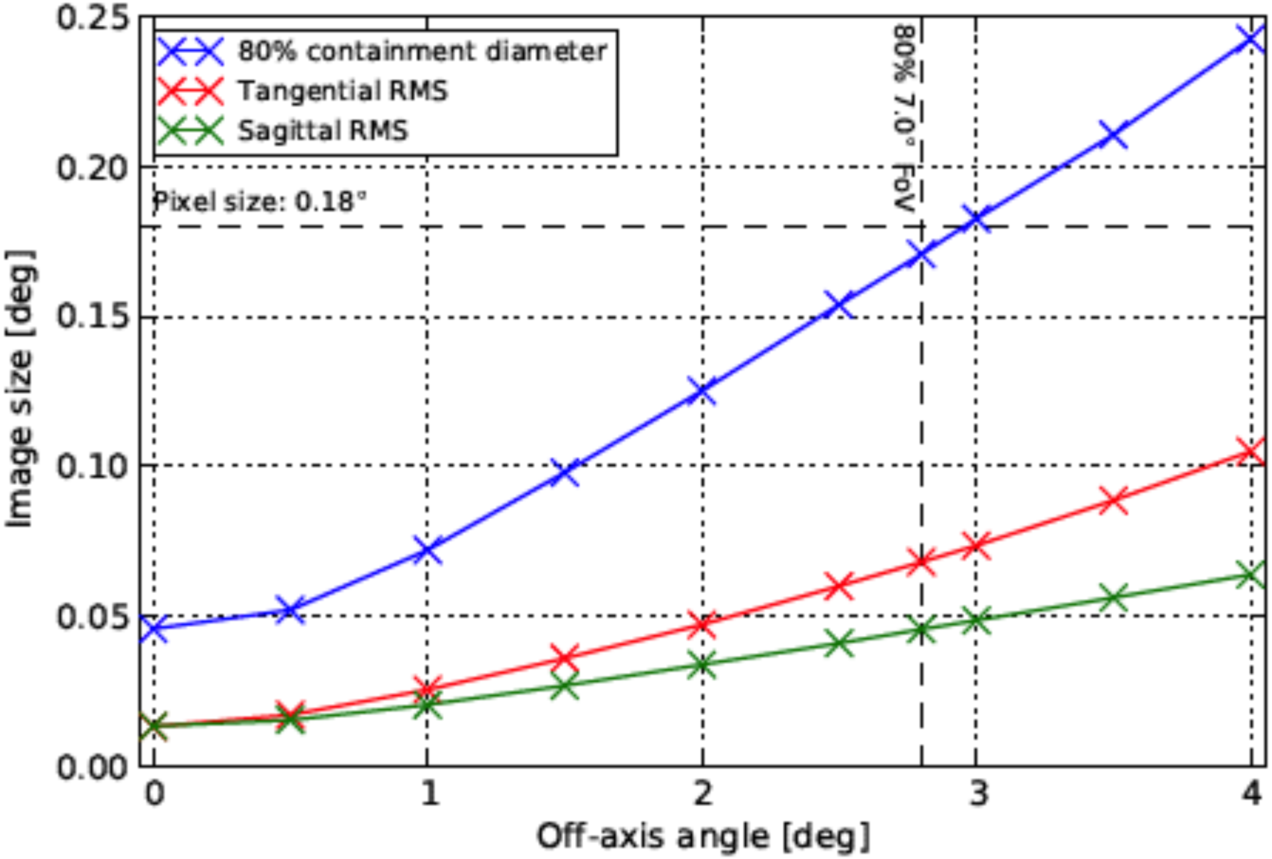
- Effective mirror area (inc. shadowing ~90 m^2

The Davies-Cotton structure has been slightly modified (sphere radius = 1.2x focal length) to reduce the dish-induced signal dispersion.

Davies –Cotton structure prototype

- Installed at Adlershof (Berlin) between 2012 and 2019
- Several components upgraded: dish, camera support structure..
- Tests: mirror alignment software, pointing model
- Long term tests of mirror aging
- Campaigns with the FlashCam (2017) and NectarCAM (2019) cameras -> mechanical + water, electricity, data networks tested sucessfully.

Mirrors for the MST: requirements



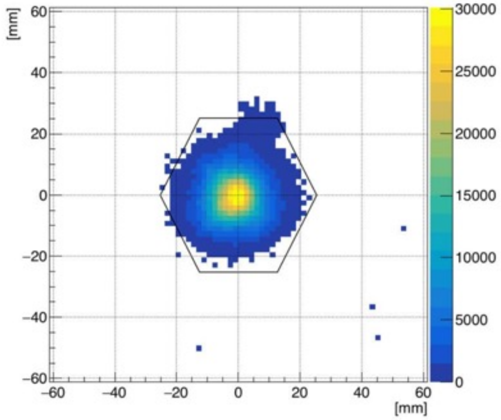
courtesy S.Fegan

- In a Davies-Cotton design, the facet radius should be R=2f ~ 32 m for MST
- To account for off-centered mirrors, the single facet containment radius should be ~0.06°
- The mirrors should be light (18kg), with a low rate of reflectance loss.

Mirrors performance

INAF mirrors

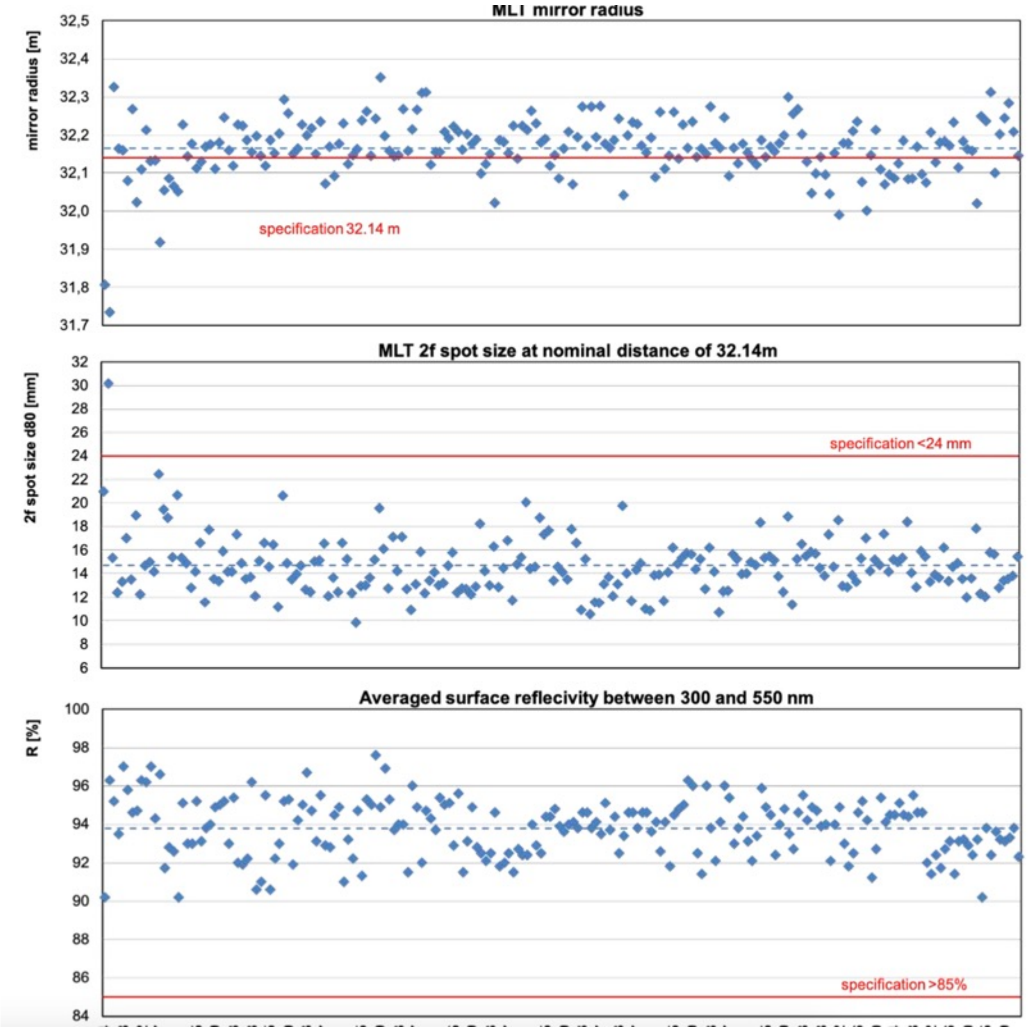
- 2 mirror designs, INAF (CTAN) and IRFU-JPAN (CTAS)
- both designs based on **cold slumping**



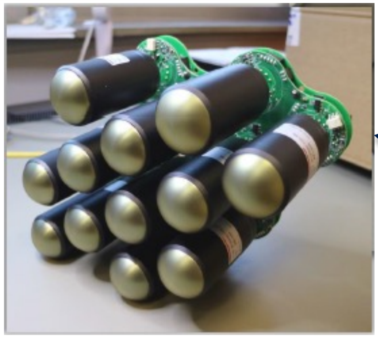
Expected optical PSF from ray tracing

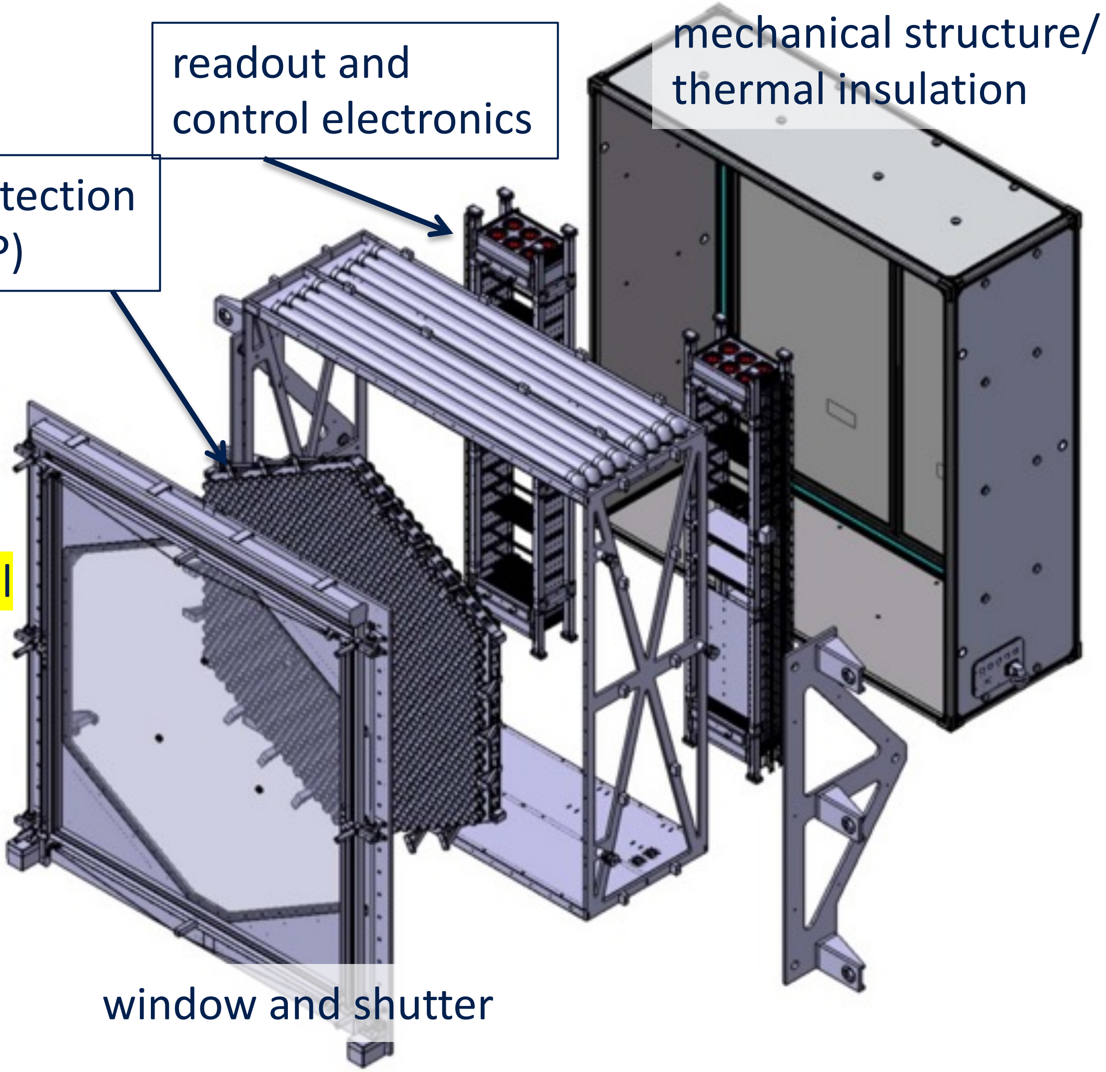
d80 = 21.4 mm

< pixel « radius » = 2.5 mm



FlashCam





photon detection plane (PDP)

readout and control electronics

mechanical structure/ thermal insulation

window and shutter

- 1764 pixels (vacuum PMT)
- 7.7° field of view
- Shaping+non-linear amplification

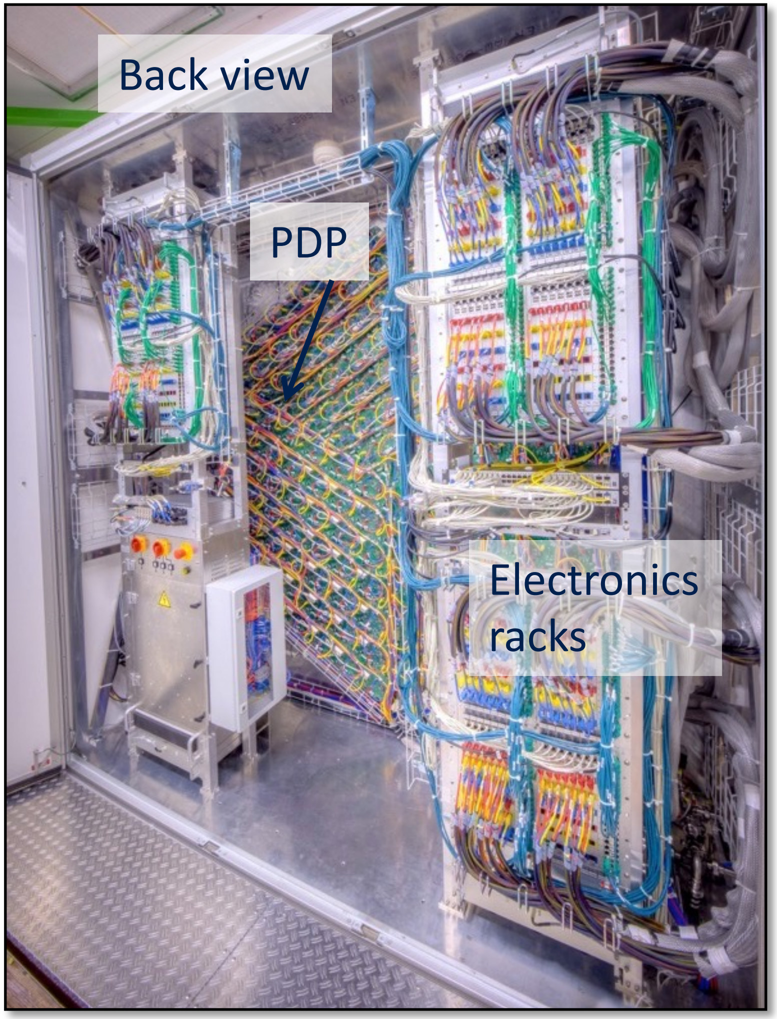
-> 0.2->3000 p.e dynamic range/channel

- 12-bit continous digitization at 250 MHz
- Fully digital, trigger formation directly on data
- Waveforms: up to 15.6µs
- 30 kHz deadtime-free

Ethernet-based DAQ

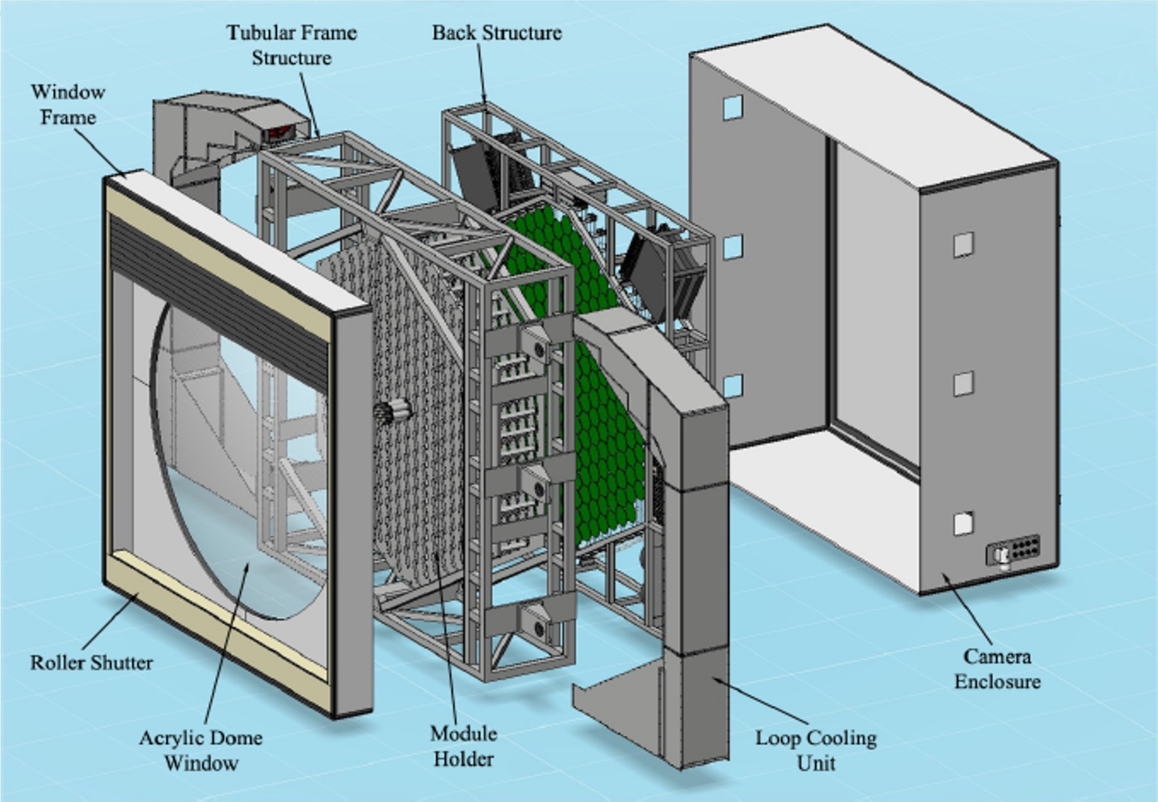
- <4.5 kW power consumption

FlashCam prototype

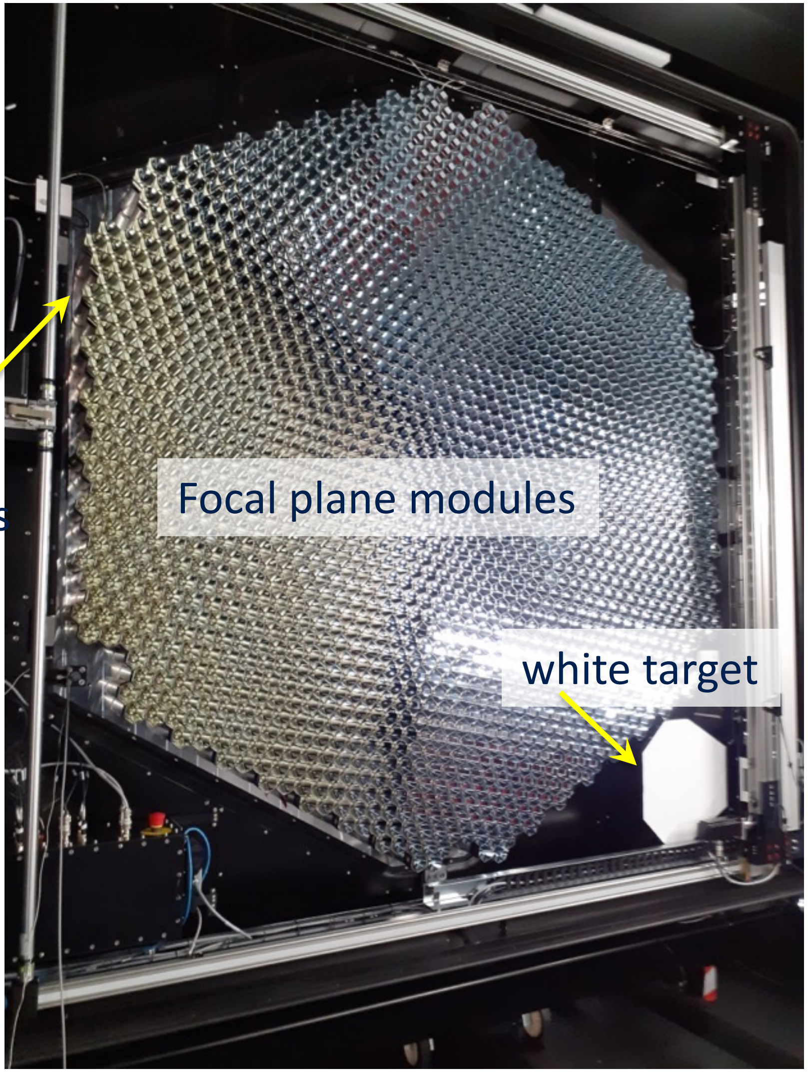


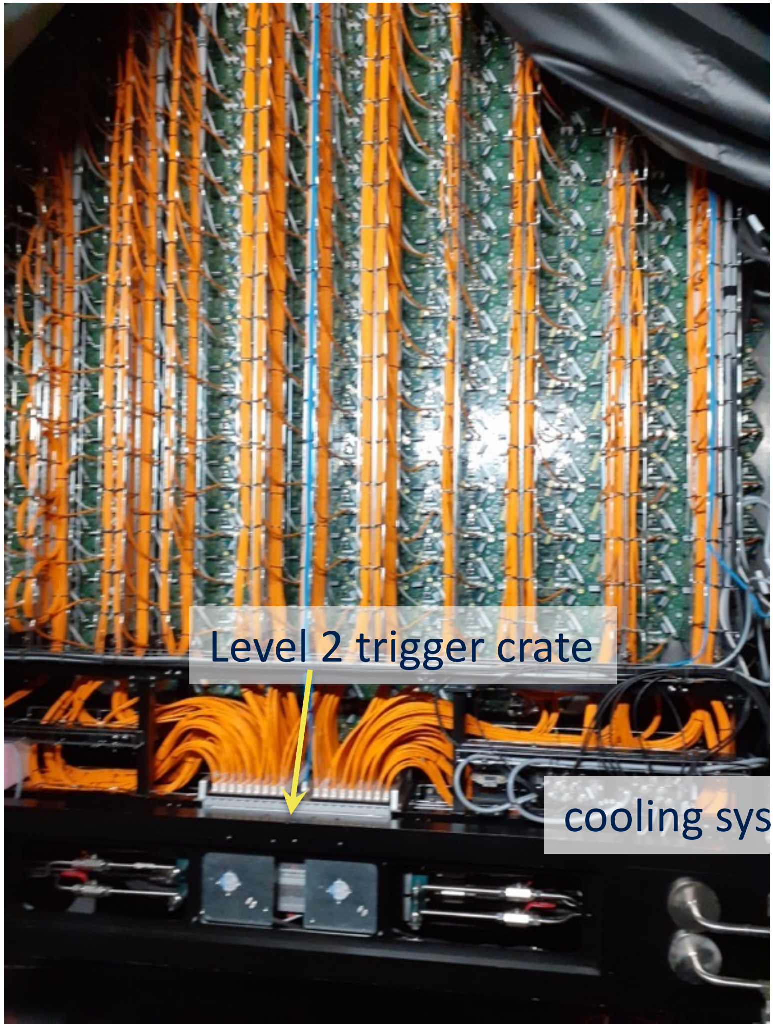
NectarCAM

- Modular structure with 265 7-pixel modules
- Field of view: 8°
- 1 module = 1 focal plane module (PMs, HV, preamplification) + 1 front-end board (amplifiers, Nectar ASICs, level 0 trigger electronics)
- Nectar chip combines a switched capacitor array (1 μs long) (sampling rate 1 GHz) and a 12-bit ADC
- Readout window: 60 ns
- 2 gain channels (combined dynamic range 0.5-> 2000 p.e)
- 1 independent trigger channel
- deadtime <1 % at 7kHz trigger rate.



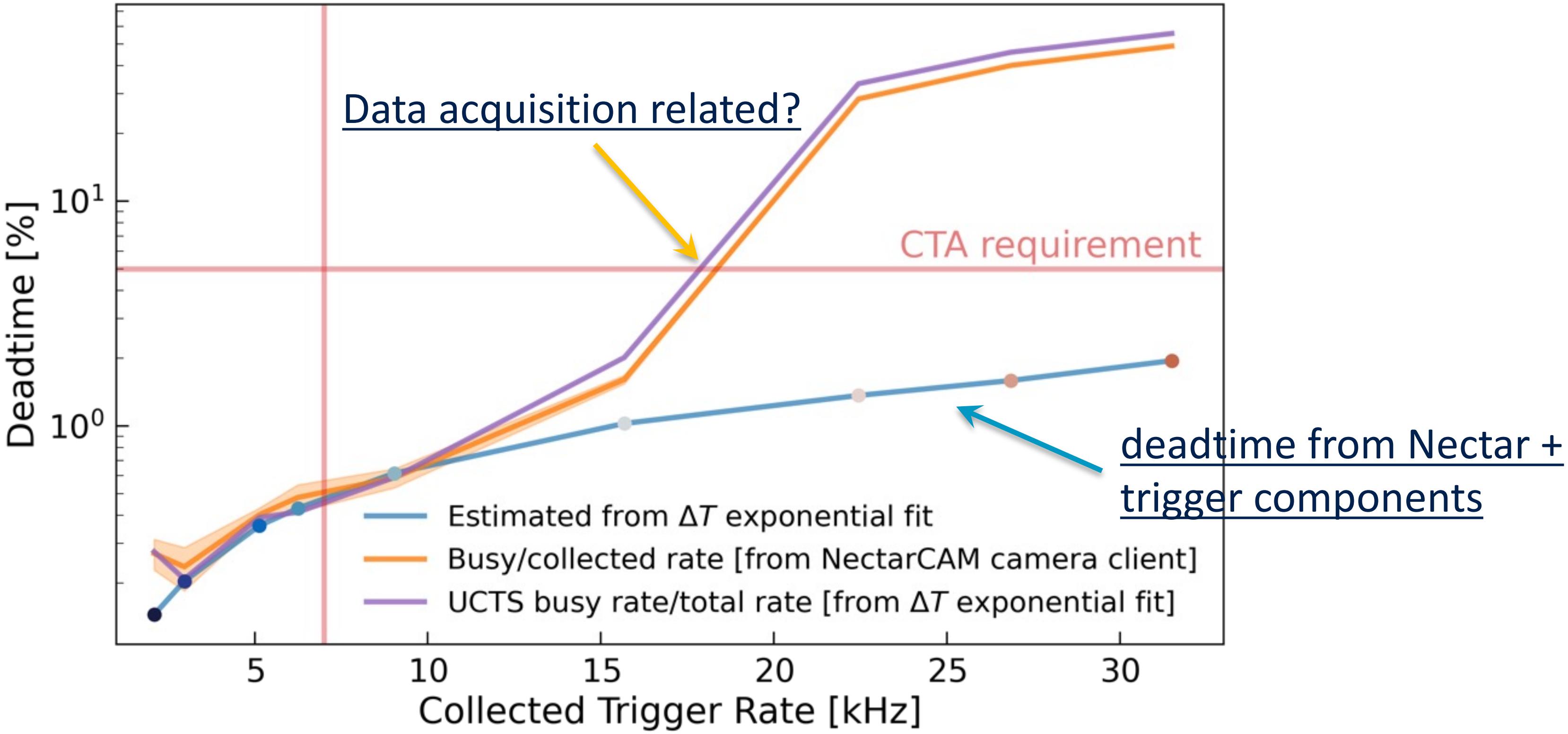
NectarCAM qualification model





NectarCAM deadtime

- NectarCAM deadtime was (until 2021) dominated by the readout of the NECTAr chip.
- The deadtime of NECTAr was ~7 µs for a 60ns readout => 5% deadtime at 7 kHz trig. rate.
- The NECTAr chip was upgraded to operate in « ping-pong » mode achieving a readout deadtime <500 ns.



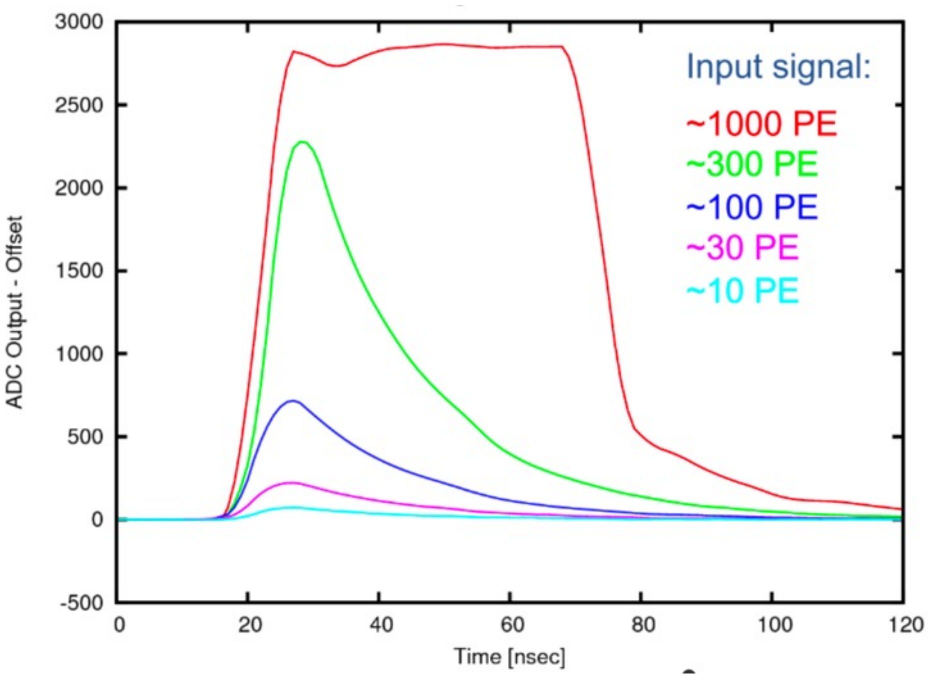
FlashCam/NectarCAM comparison

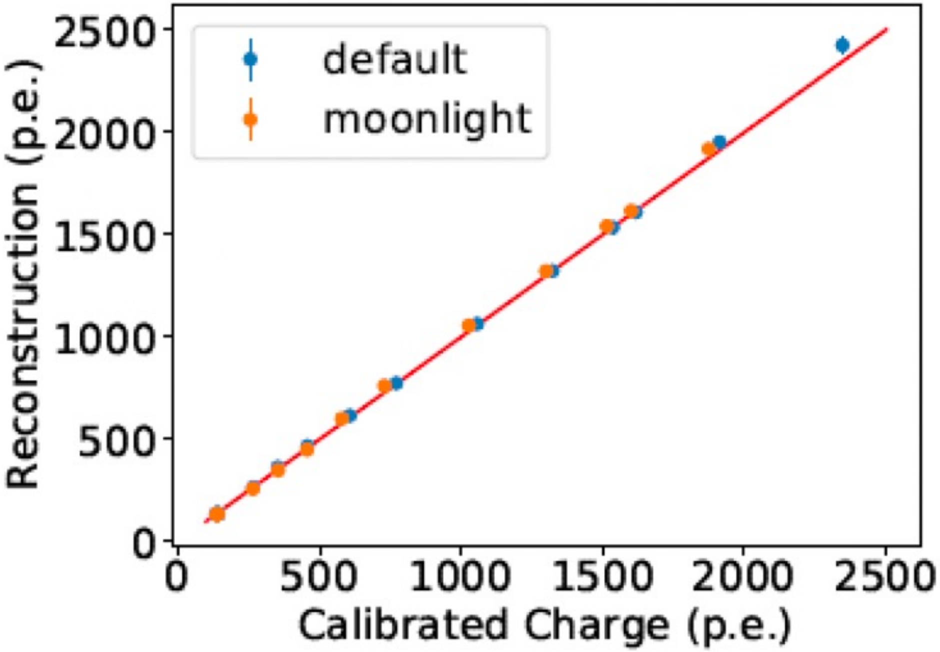
The main differences between FlashCam and NectarCAM are the electronics and trigger designs.

FlashCam	NectarCam
rack based electronics	integrated modules
separation between γ detection and electronics/processing	electronics mounted on phototubes
« off the shelf » components	**A**pplication **S**pecific **I**ntegrated **C**ircuits
non-linear amplification of pe current	linear amplification
1 gain channel	2 gain channels
250 MHz FADC	1GHz sampler+digitizer (NECTAr)
trigger from data	independent trigger channel

Camera linearity: FlashCam

Dynamic range obtained with one channel per pixel and non-linear amplification

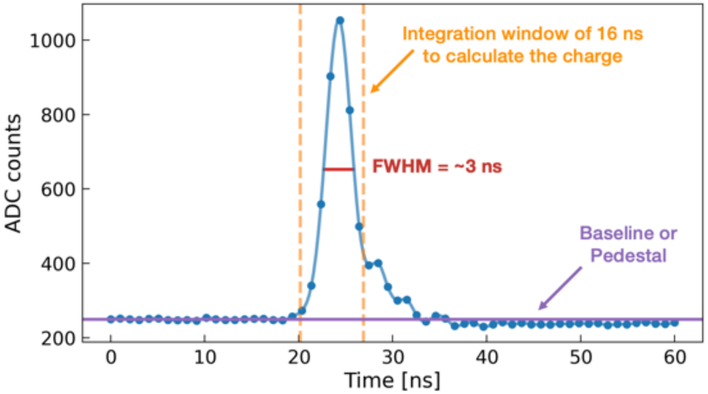


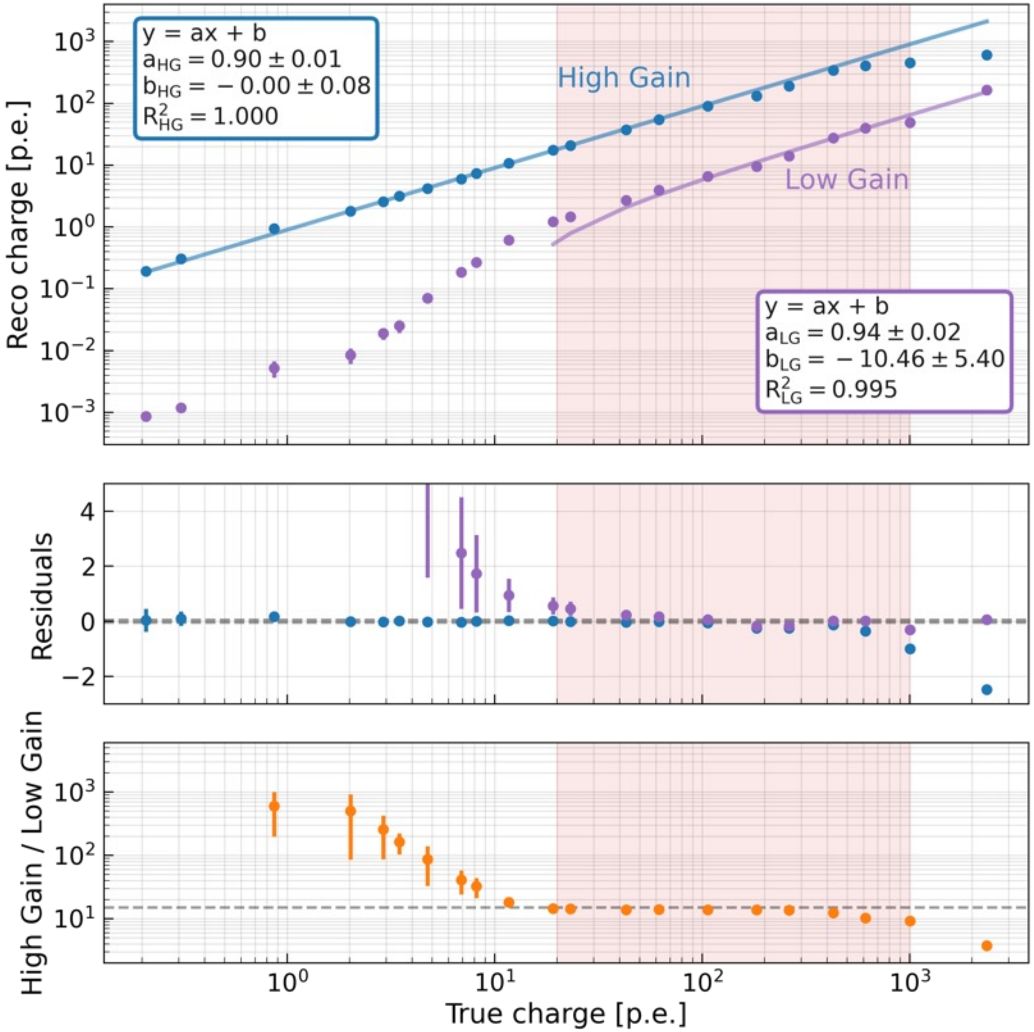


Linearity check with flat-fielding units on HESS telescopes (2020)

Camera linearity: NectarCAM

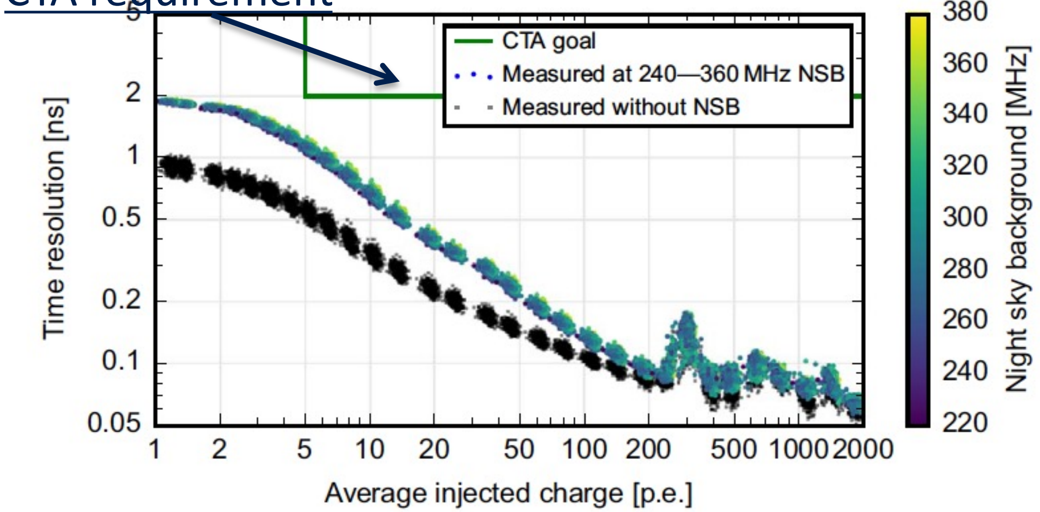
Dynamic range obtained obtained with 2 gain channels per pixel and linear amplifiers





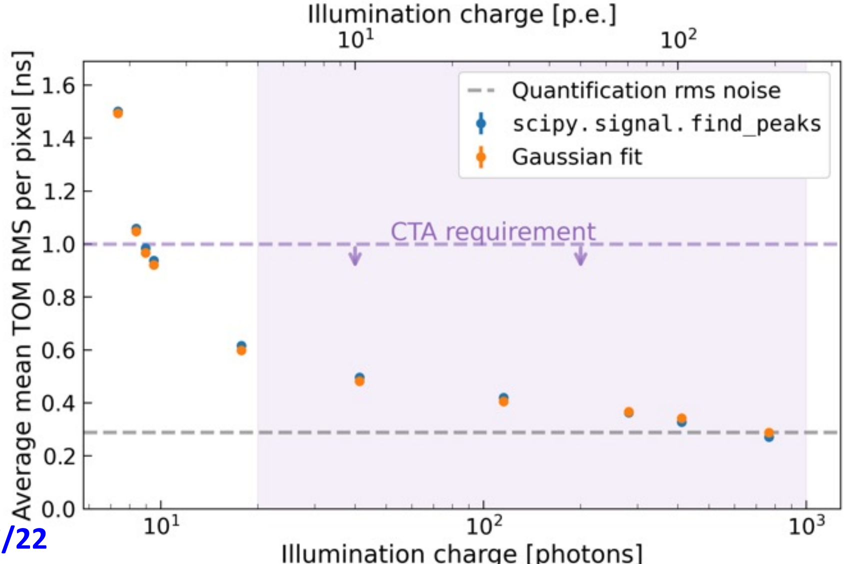
Single pixel time resolution

CTA requirement



FlashCam (from test bench)

CTA requirement: Δt < 2ns
(> 20 photons = 5 pe)

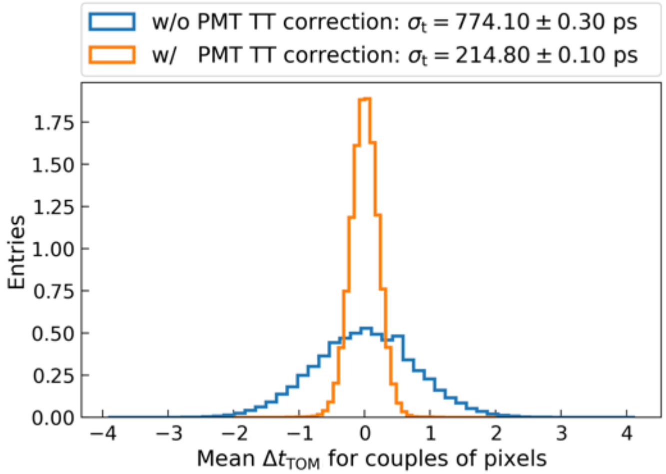


NectarCAM (from test bench)

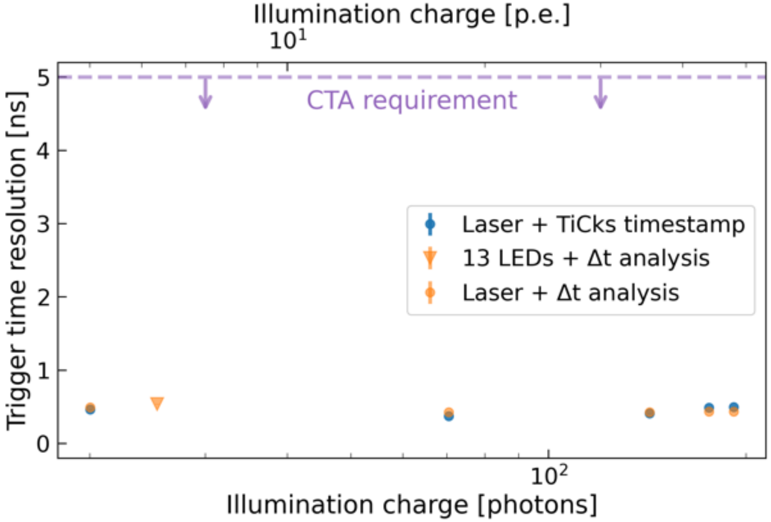
limited by Nectar readout to $^1/_{\sqrt{12}}$ns = 290 ps

Overall camera timing

NectarCAM qualification model

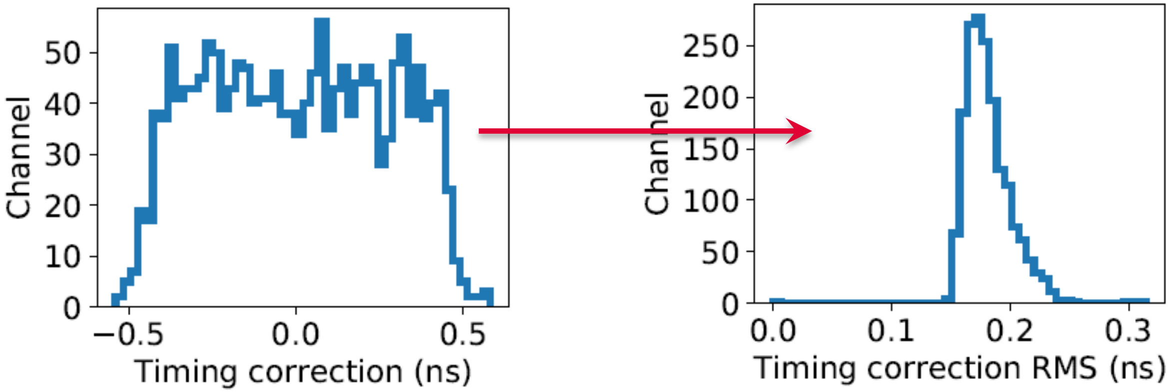


Relative pixel timing



Timestamping accuracy < 1ns

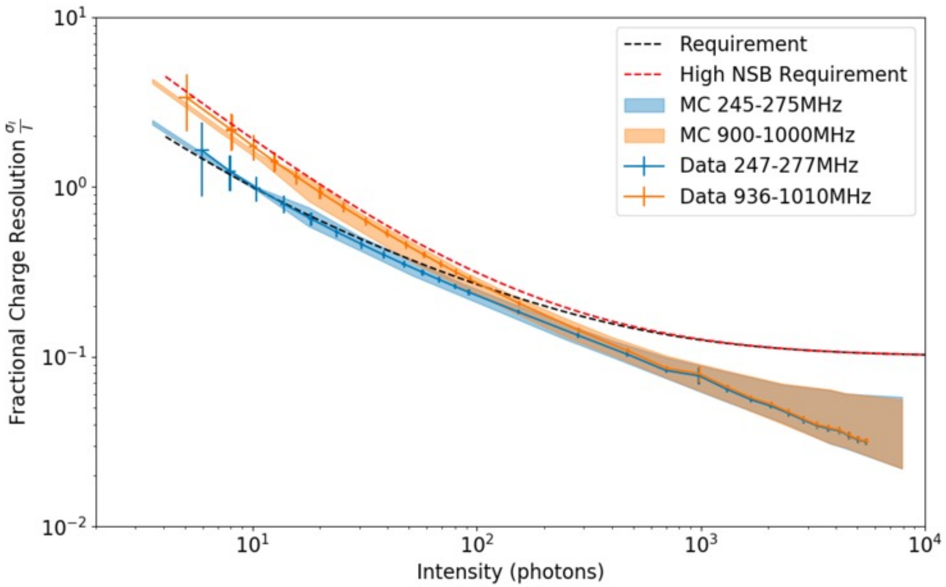
FlashCam on HESS CT5



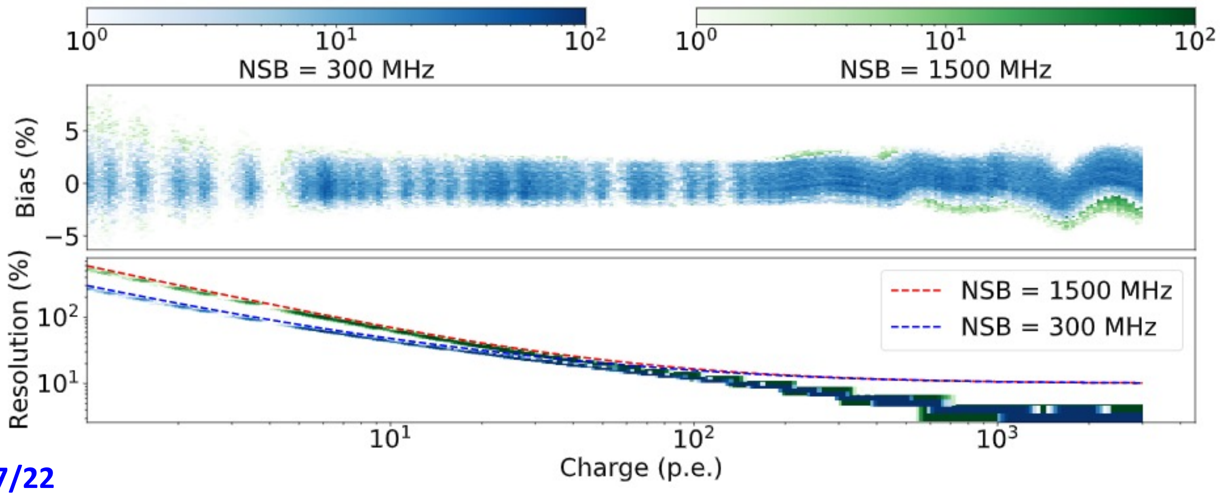
Timing flat-fielding

Charge resolution

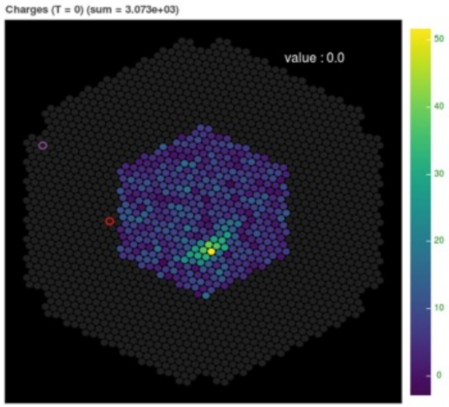
NectarCAM



FlashCam

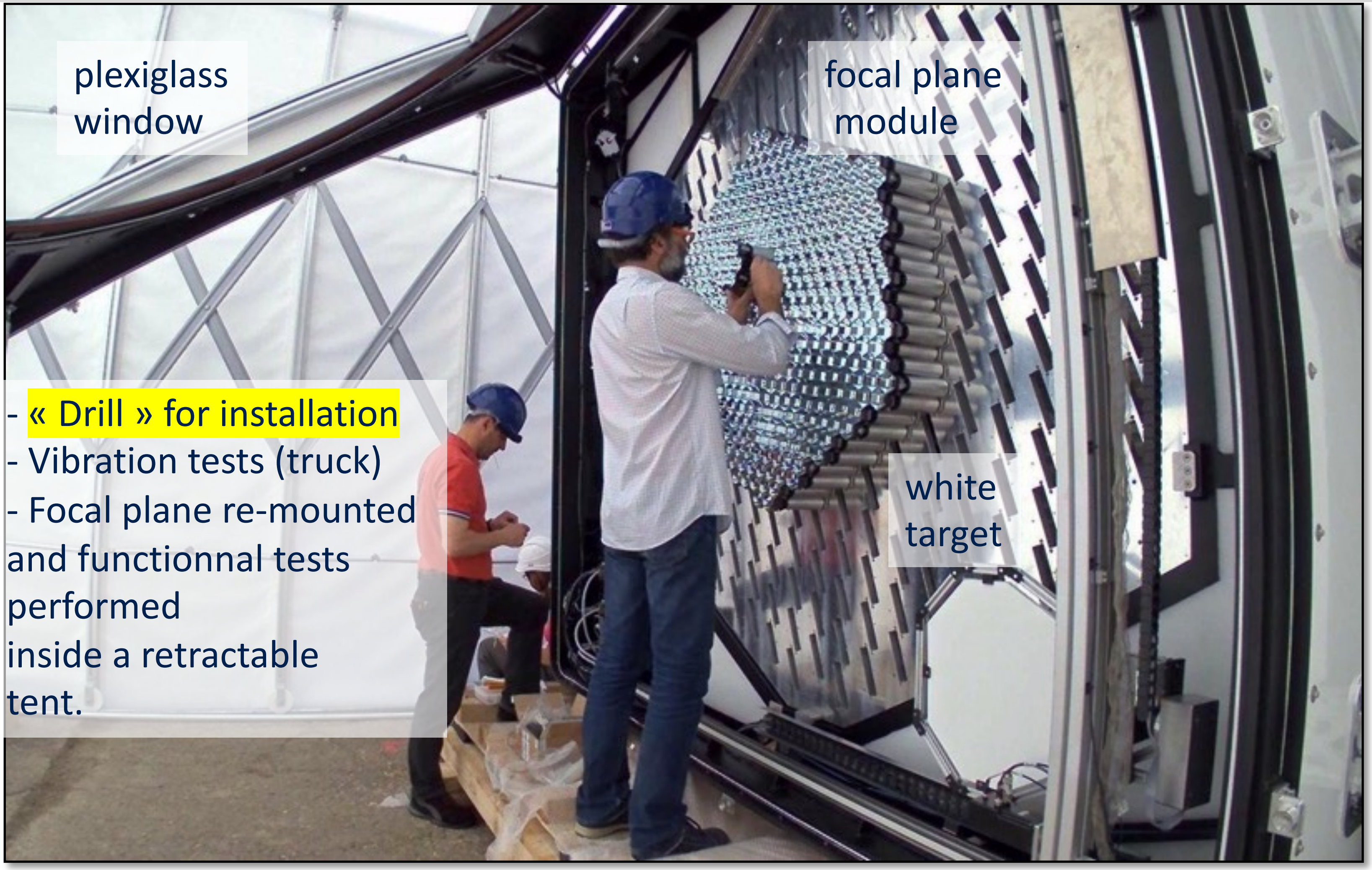


NectarCAM campaign at Adlershof



First light in 2019

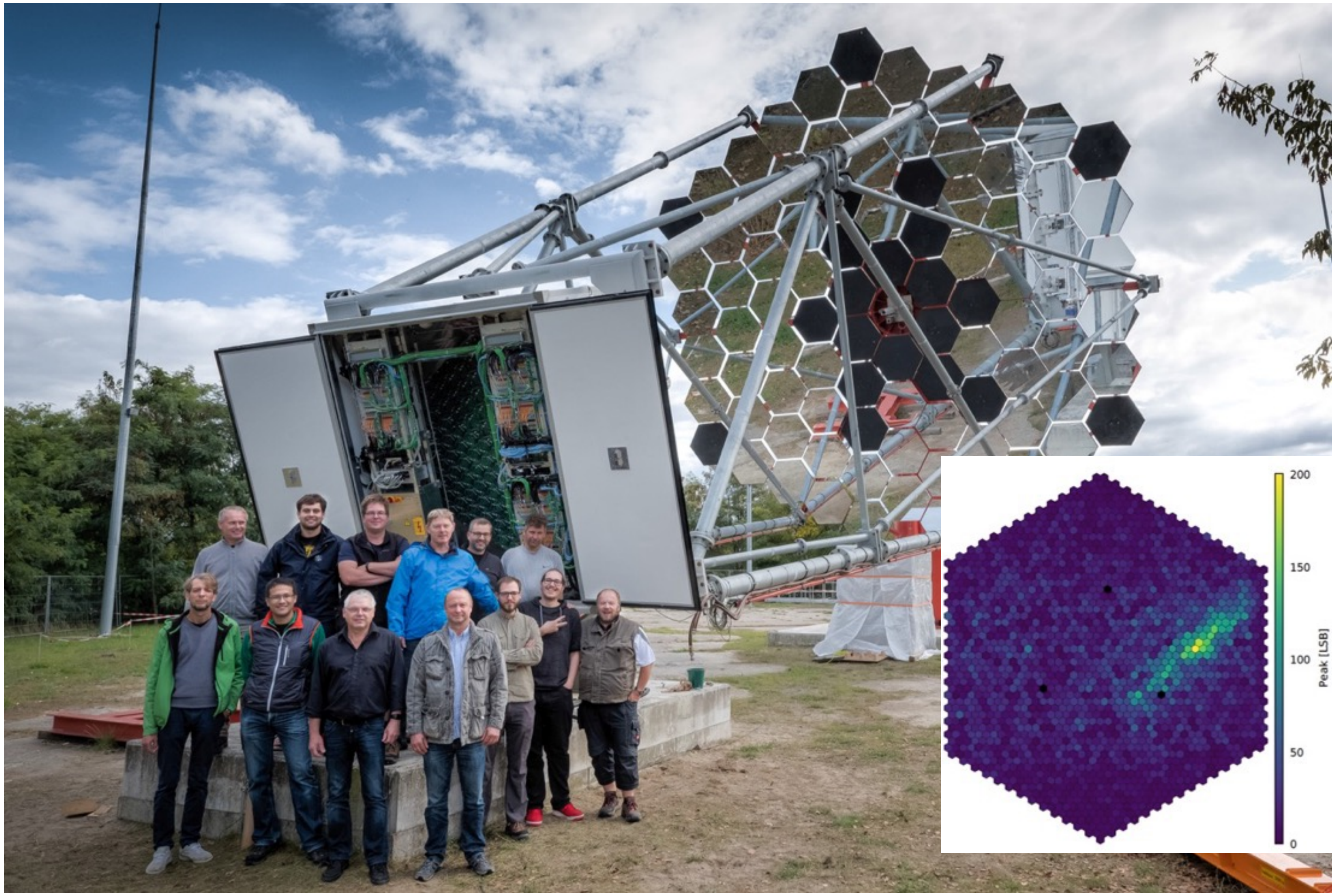
NectarCAM Adlershof prototype



- « Drill » for installation
- Vibration tests (truck)
- Focal plane re-mounted and functionnal tests performed inside a retractable tent.

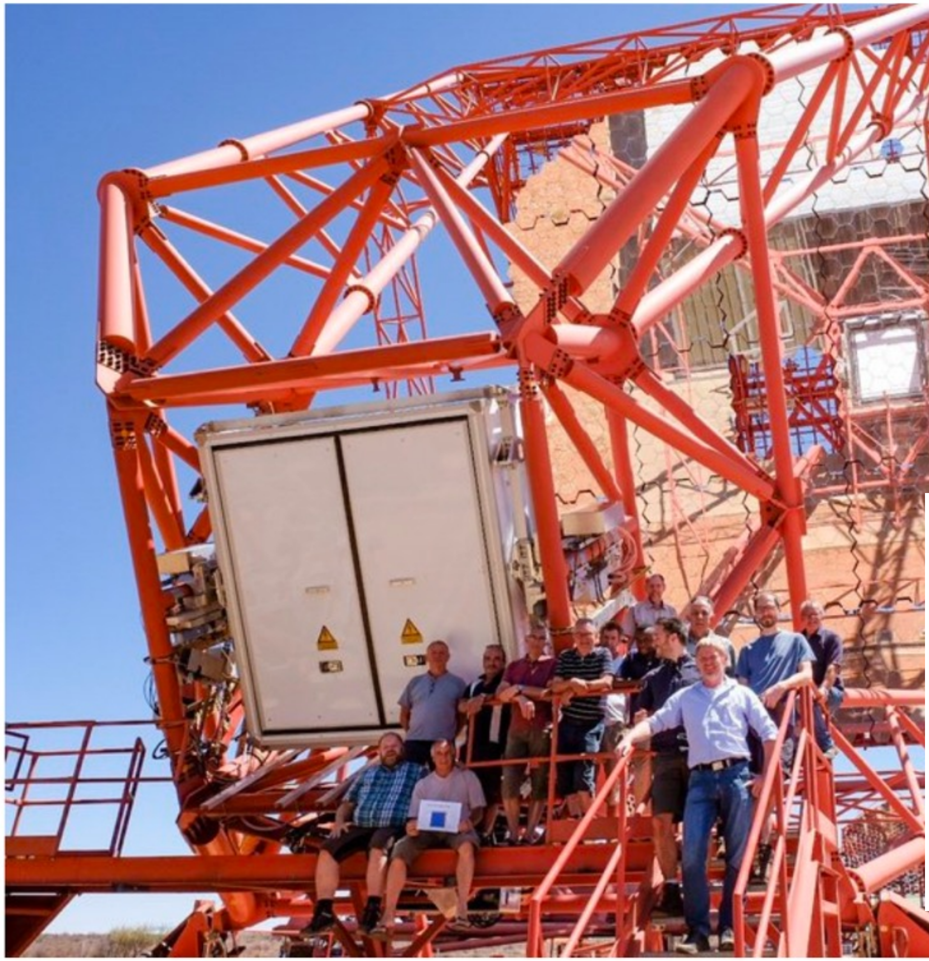
Partially equipped, NectarCAM, front view

FlashCam campaign at Adlershof

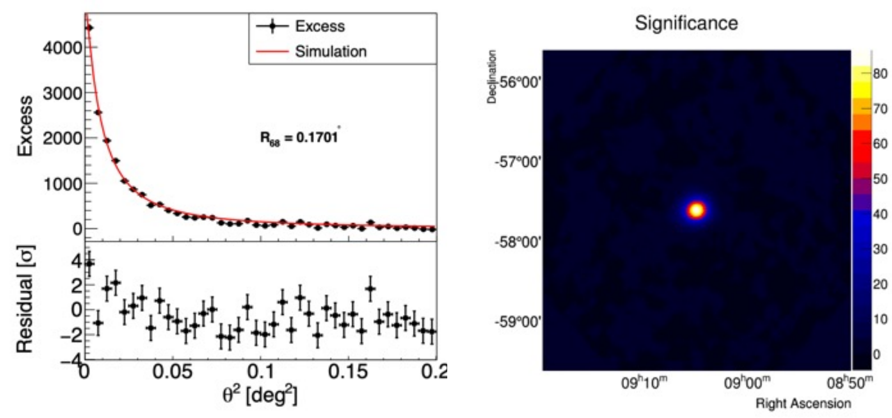


First light in 2017

FlashCam on HESS site



- Installed on HESS CT5 (28 m diameter) since 10/2019
- Smooth operations with >98% availability
- Allows doing « low level »
- verification (trigger, timing) as well
- as science verification.



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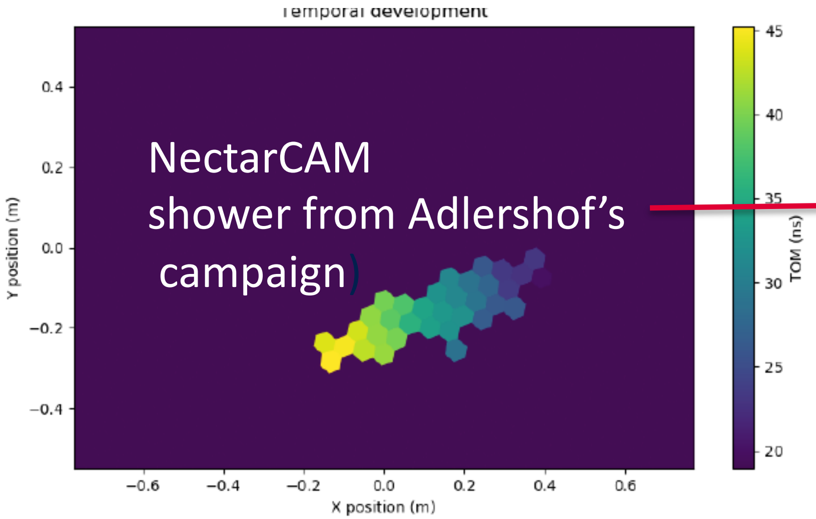
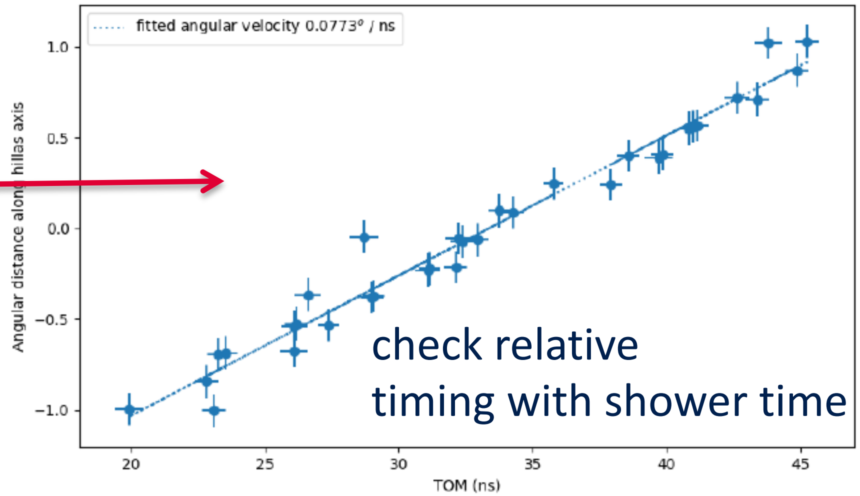
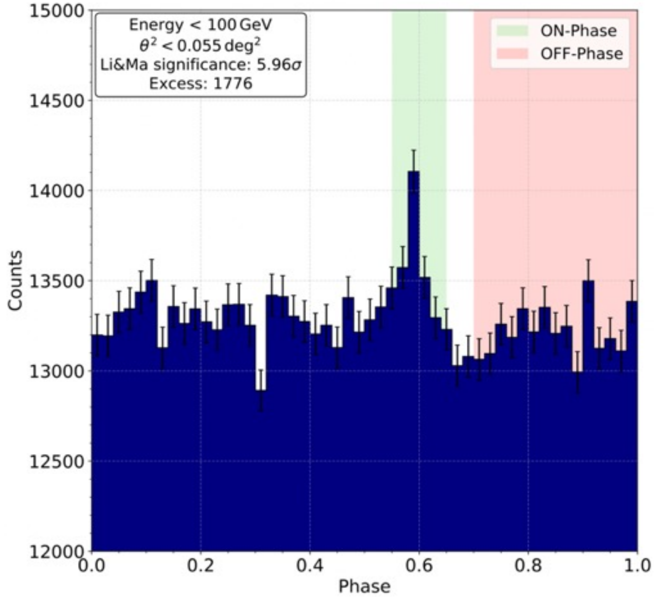
Fun with timing



NectarCAM
shower from Adlershof's
campaign



check relative
timing with shower time devlpt.



FlashCam:
test of trigger time-stamping with the Vela Pulsar.
P_{vela} = 89 ms => only low precision ~1ms needed

Installation plans

- Installation in the North and South will go in 2 steps:
  - 1. installation of « **pathfinders** »
  - 2. full array when telescopes are accepted by CTA Observatory

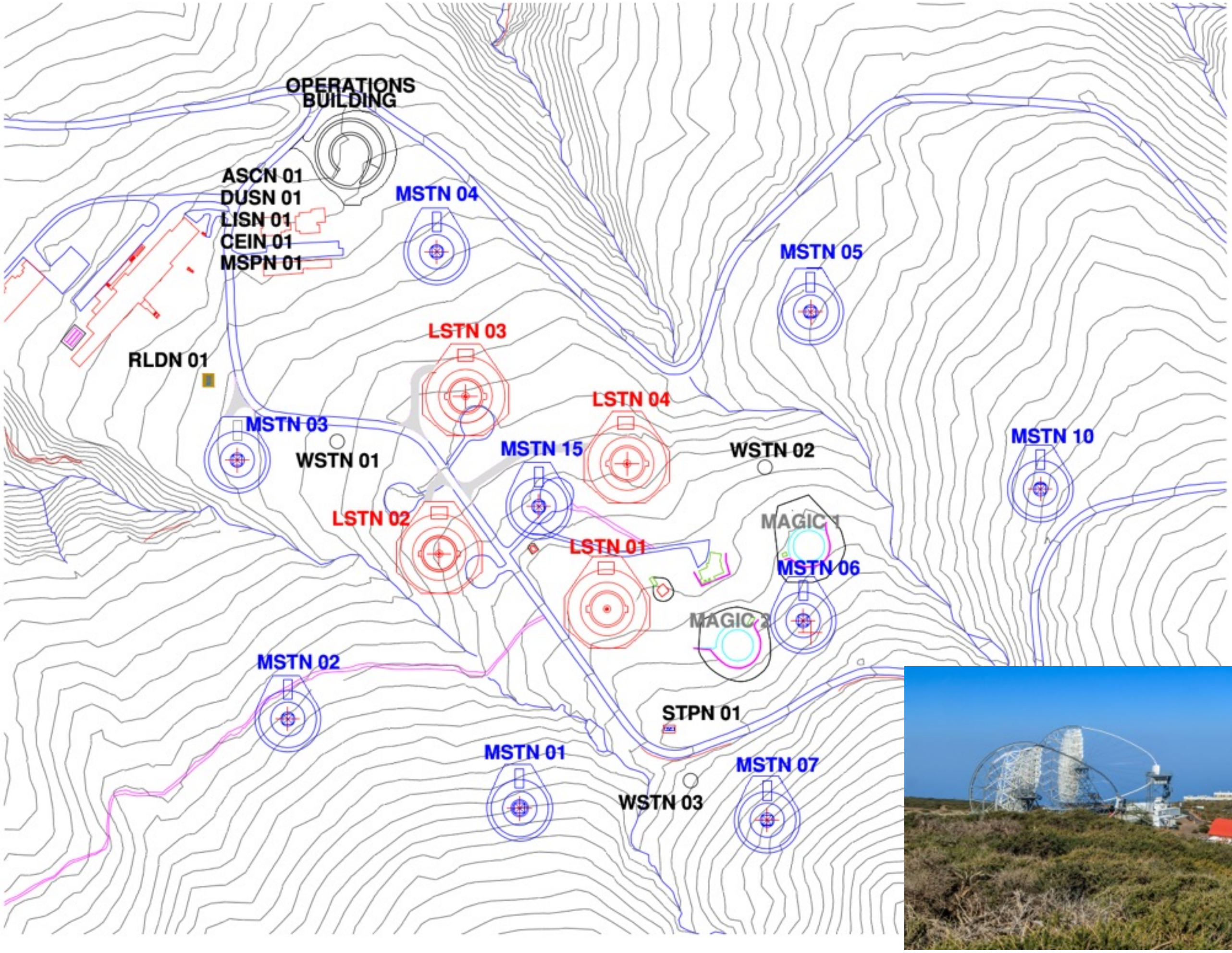
- CTAN: installation of 1 telescope in 2023-2024, in parallel to LST2-4 installation
  - First NectarCAM camera already available and in test
  - Production of first structure and shipment to site: mid 2023
  - Commissioning and science verification: 2024-2025
  - Expected acceptance by CTA Observatory in 2025.

- 2023-2027: production of remaining 8 cameras
- 2024-2027: production of remaining 8 structures

- CTAS: installation of 1 telescope in 2023-2024, near Paranal
  - FlashCam camera already available
  - Commissioning and science verification: 2024-2026
  - Expected acceptance by CTA Observatory 2026

- Installation remaining 14 cameras on CTAS site starting 2026

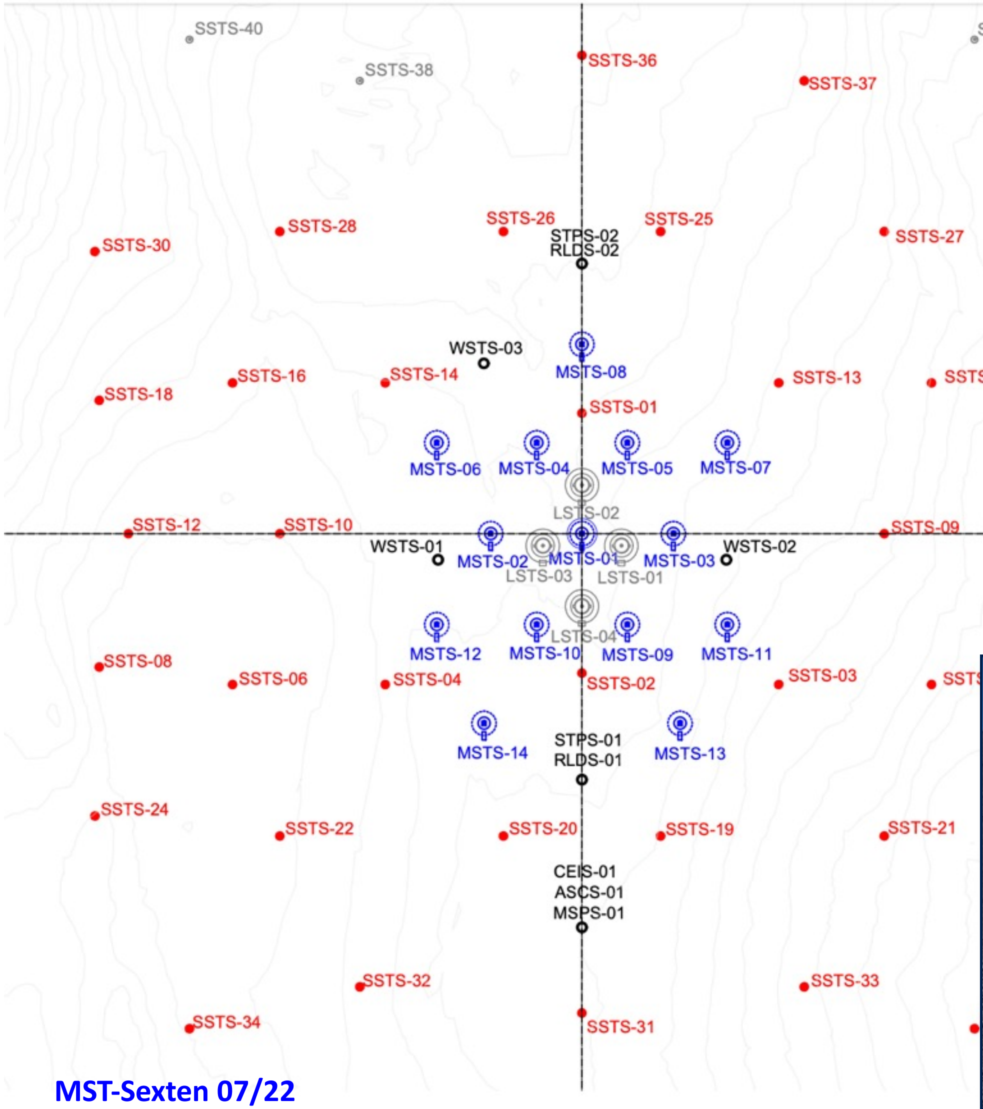
Array Layout at CTAN



4 LST telescopes
(1 already installed)

9 MST telescopes equipped with *NectarCAM cameras*

Array Layout at CTAS



2-3 LSTs

14 MST telescopes equipped with FlashCam cameras

37 SSTs


View of proposed site

Conclusion and « take home messages »

- The instrumental requirements on MST structures and cameras follow from the
- physics requirements of CTA.

- The MST telescopes use a common mechanical Davies-Cotton and 2 cameras designs: NectarCAM (CTAN) and FlashCam (CTAS).

- A prototype of Davies-Cotton structure has been implemented near Berlin in 2012 and extensively tested.
- NectarCAM and FlashCam fulfill all CTA requirements and have comparable performances.
- The FlashCam camera uses off-the-shelf component with a photon detection plane and electronics racks. It had its first light in 2017. A FlashCam is succesfully operated since October 2019 on the CT5 telescope of H.E.S.S.
- The NectarCAM camera has a modular structure based on the Nectar ASIC. It has its first light in 2019.

- The installation will follow the « pathfinder » strategy before acceptance of telescopes by CTA.
- The first telescopes should be installed on CTAN and CTAS in 2023-2024.

Selected references

Cosmic shower physics and Cherenkov Telescopes:

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MST telescope structure:

- M.Garczarcyk, S.Schlenstedt, L.Oakes, U.Schwanke, Proc. of ICRC 2015, arXiv:1509.01361

Mirror technology for MST:

- N.LaPalombara et al, JATIS, 8, 014005 (2022), arXiv:2201.08103

FlashCam:

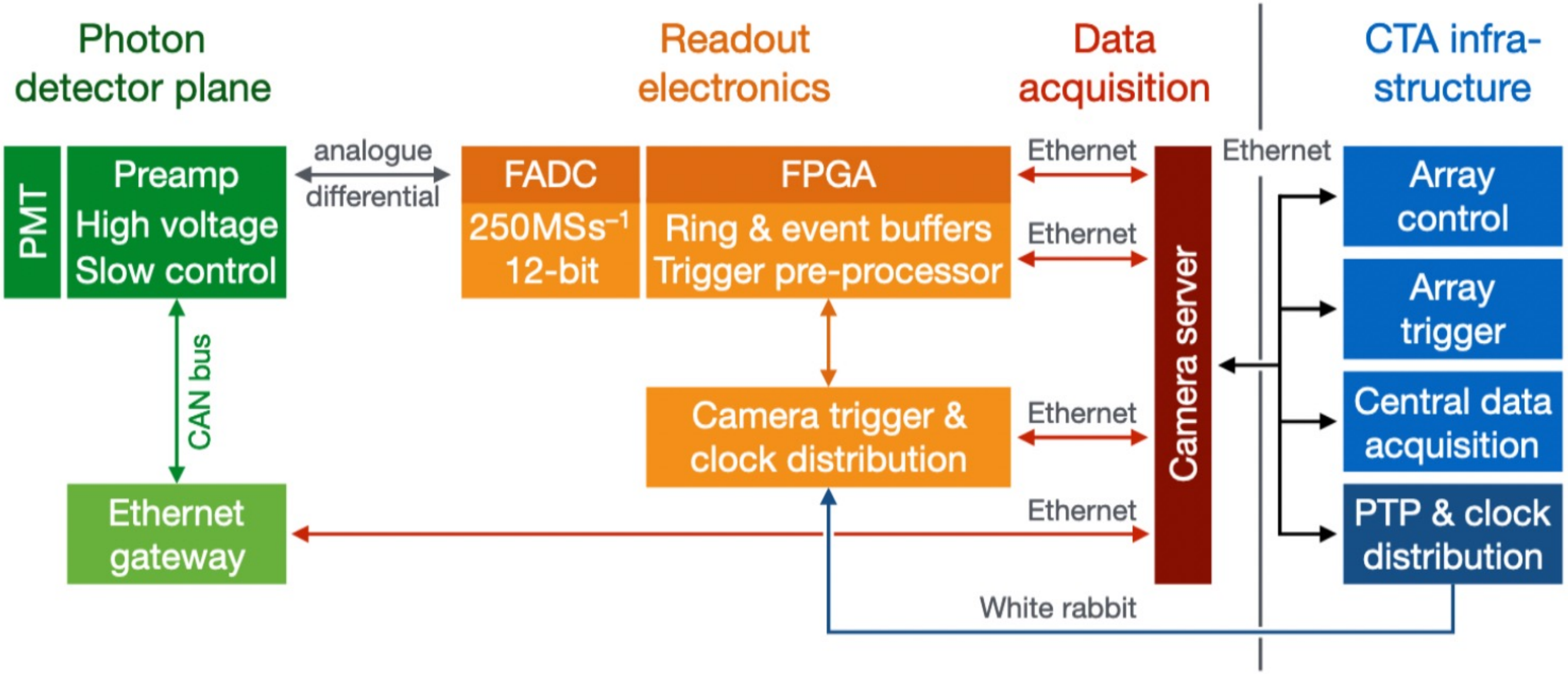
- F.Werner et al, NIM A, 876, 31 (2017), arXiv:1612.09528
- G.Puehhofer at al, Proc. of ICRC 2021, arXiv:2108.02596

NectarCAM:

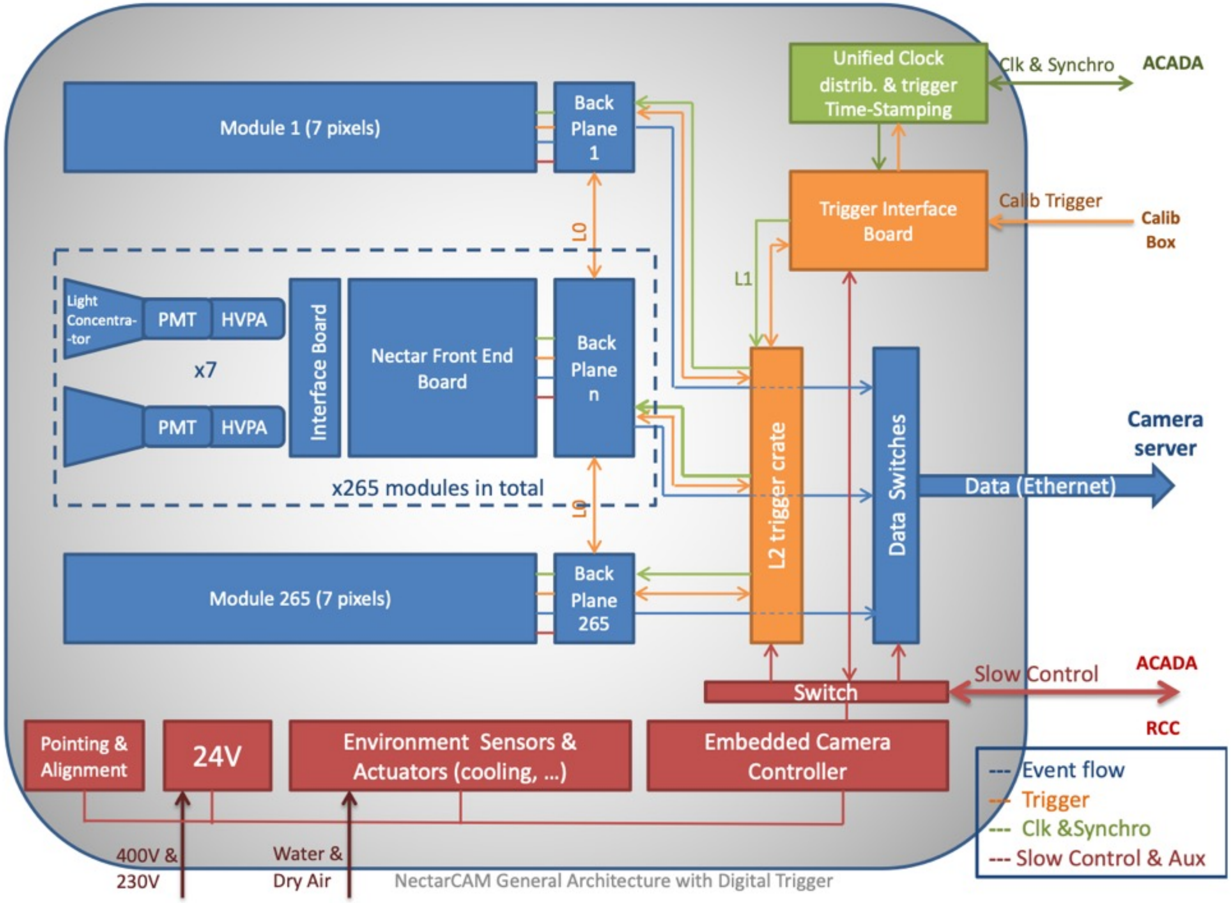
- J-F. Glicenstein, M.Shayduk et al, AIP Conference Proceedings, 1792, 080009 (2015), arXiv:1610.04173
- T.Armstrong, H.Costantini, J-F. Glicenstein, J-P. Lenain, U.Schwanke, T.Tavernier, Proc. of ICRC 2021, arXiv:2108.00426

Backup slides

Principle of FlashCam operations

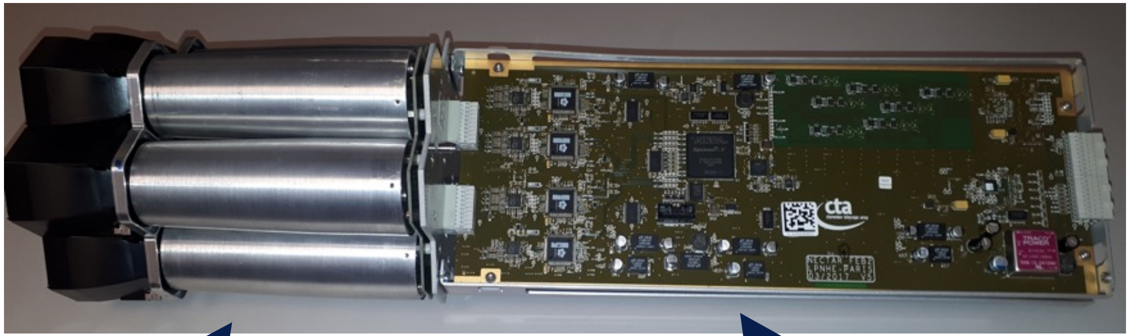


Principle of NectarCAM operations



NectarCAM General Architecture with Digital Trigger

NECTAr module structure



Focal Plane
(PMs, HV, preampfification)

1. Light deposited in the camera is first detected in the focal plane, converted into electric signal by the PMTs and preamplified towards 2 gain channels.

Front End Board (FEB)
(Amplifiers, Nectar ASICs, level 0 trigger electronic)

2. Signal is amplified again and splitted into 3 channels: low and high gain channels (sampled at 1 GHz and memorised in the NECTAr chip), and trigger channel.
3. When a trigger occurs, sampling is stopped, data are readout, digitized and sent to the camera server by Ethernet.

The NectarCAM Trigger scheme

From the single pixels to a camera trigger

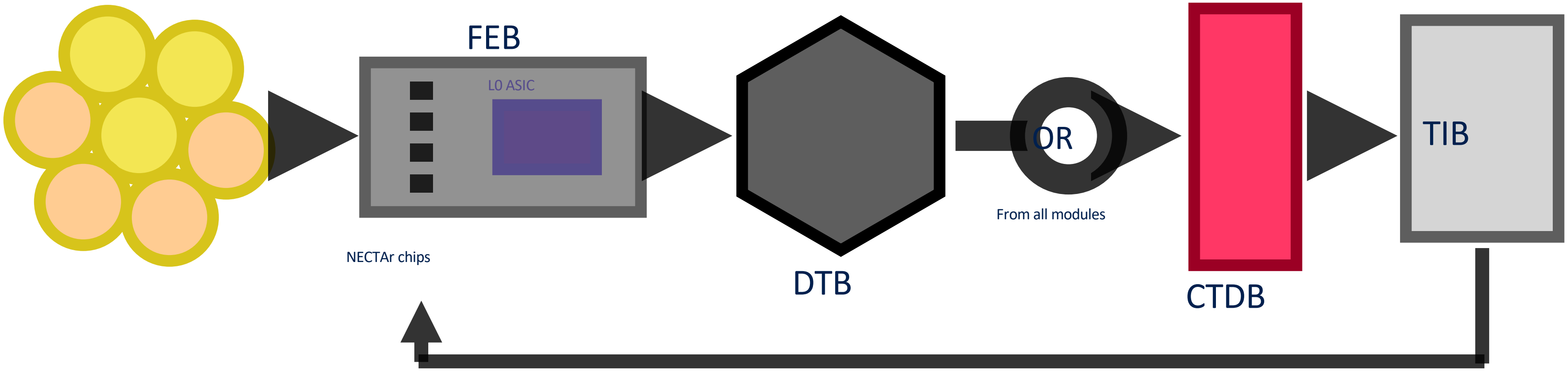
1. Significant amount of light in minimum 3 pixels

2. Level 0 trigger signal in each FEB

3. Level 1 trigger signal in the Digital Trigger Board

4. L2 = camera trigger

5. Trigger decision is formed

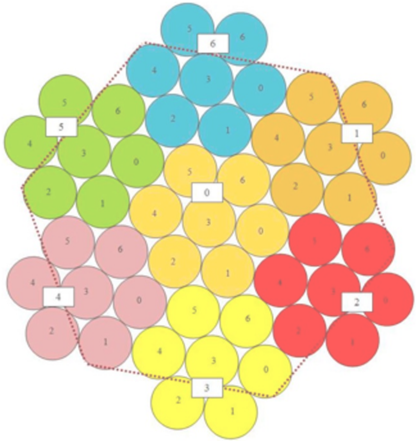


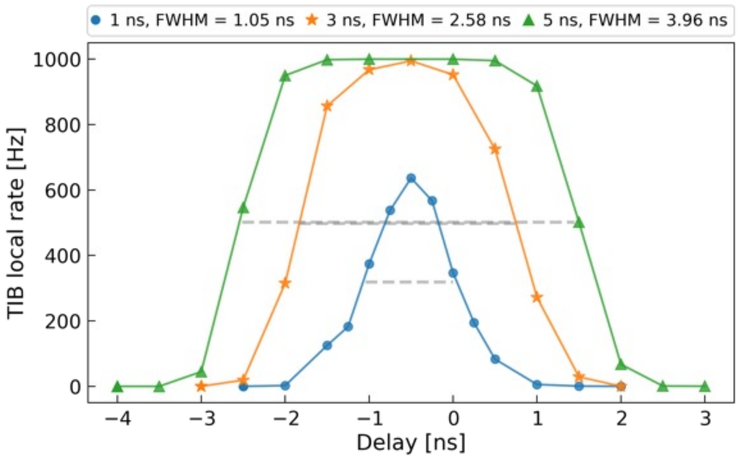
Sampling in the NECTAr chips is stoped and data readout

The 3 Nearest Neighbours (3NN) algorithm (NectarCAM)

When is an event recorded?

Significant amount of light is received in a compact region of the focal plane (~0.2 deg^2)





L1 signal is formed if 3 neighbour pixels or if 3 pixels within a 3ns time window are above a discrimination threshold within a 37-pixel region