Medium Size Telescope

Federica Bradascio (CEA Paris-Saclay)

CTA School - June 2024

MST

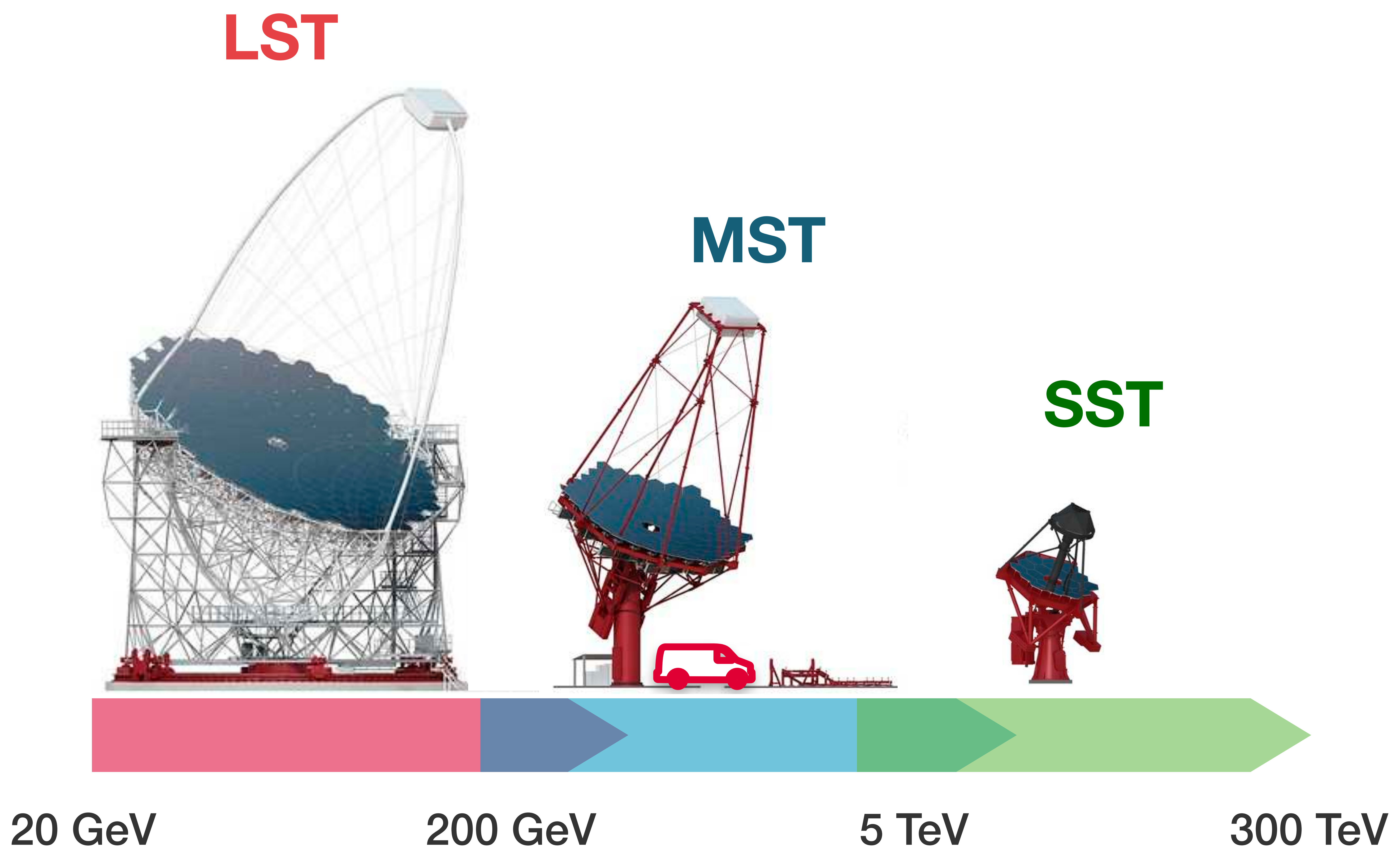
The Workhorse

- Large portion of the Observatory's energy range: 100 GeV - 30TeV
- Large field of view: ~8°
- Pointing precision of 7”
- Positioning to any point in the sky (>30° elevation) in 90 s

Why MST telescopes?

Why a Medium Size Telescope?

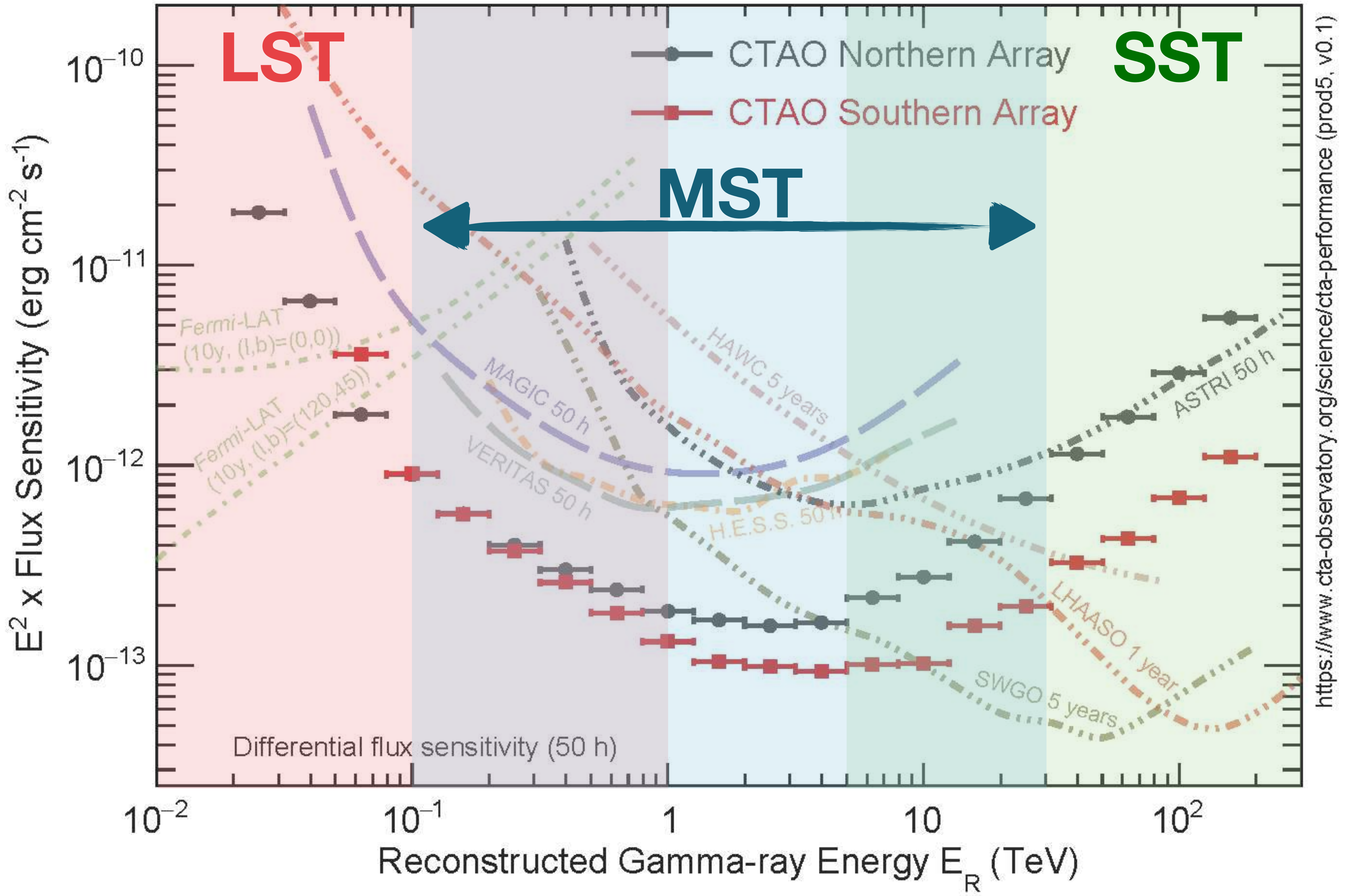
To cover the energy range between 100 GeV and 30 TeV



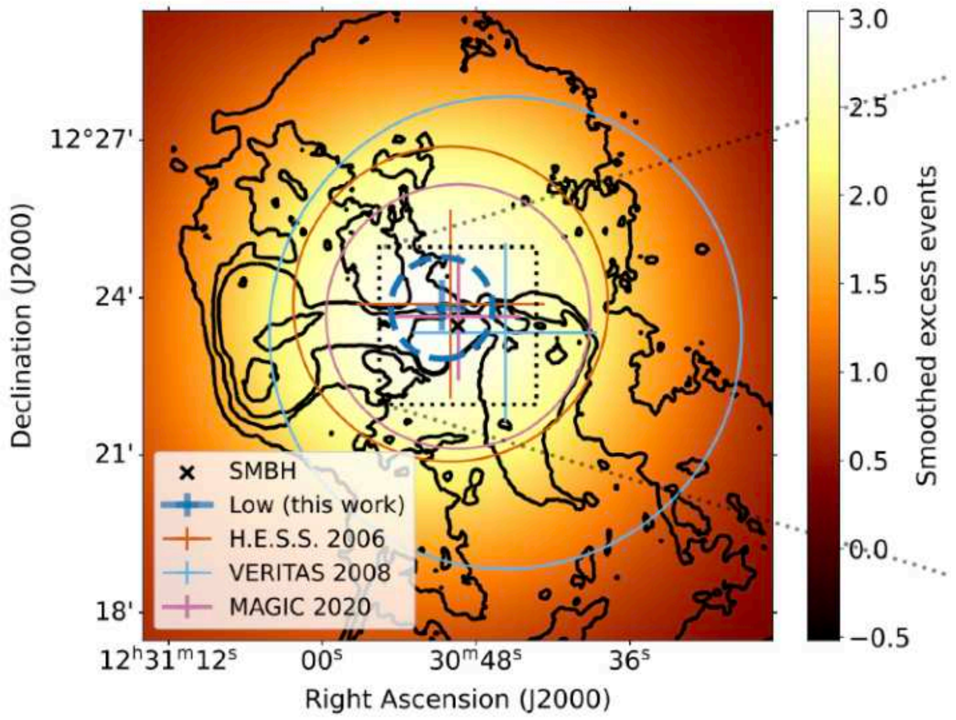
Why a Medium Size Telescope?

To cover the energy range between 100 GeV and 30 TeV

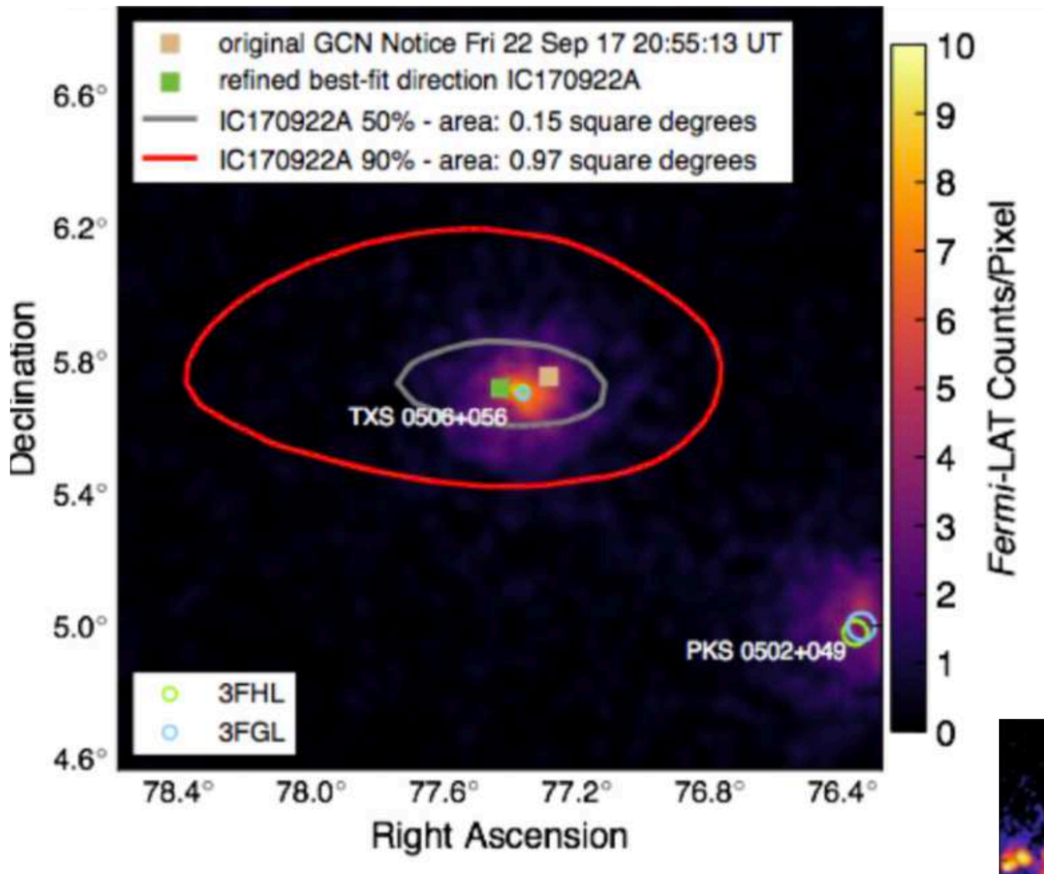
AGN (e.g. M87)



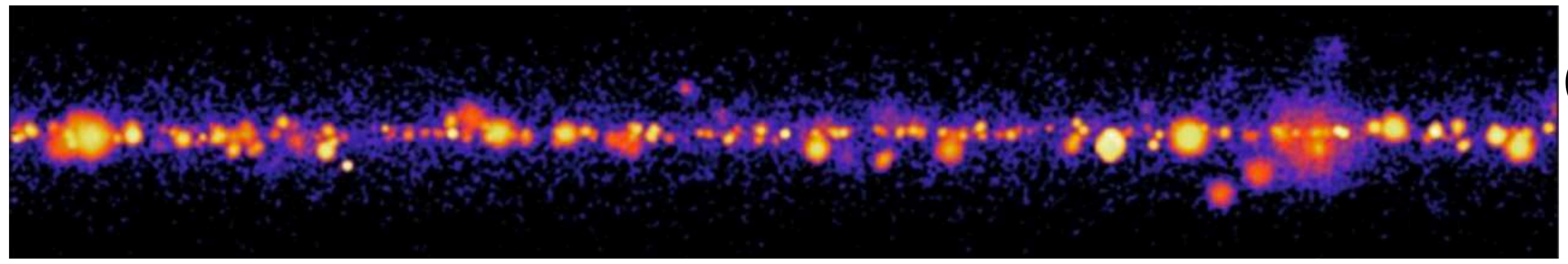
EXTREME BLAZARS



MORPHOLOGICAL STUDIES



UHE NEUTRINOS



GALACTIC/ EXTRAGALACTIC SURVEYS

EBL, DARK MATTER ...

Where?

Where do we install MSTs?

CTAS

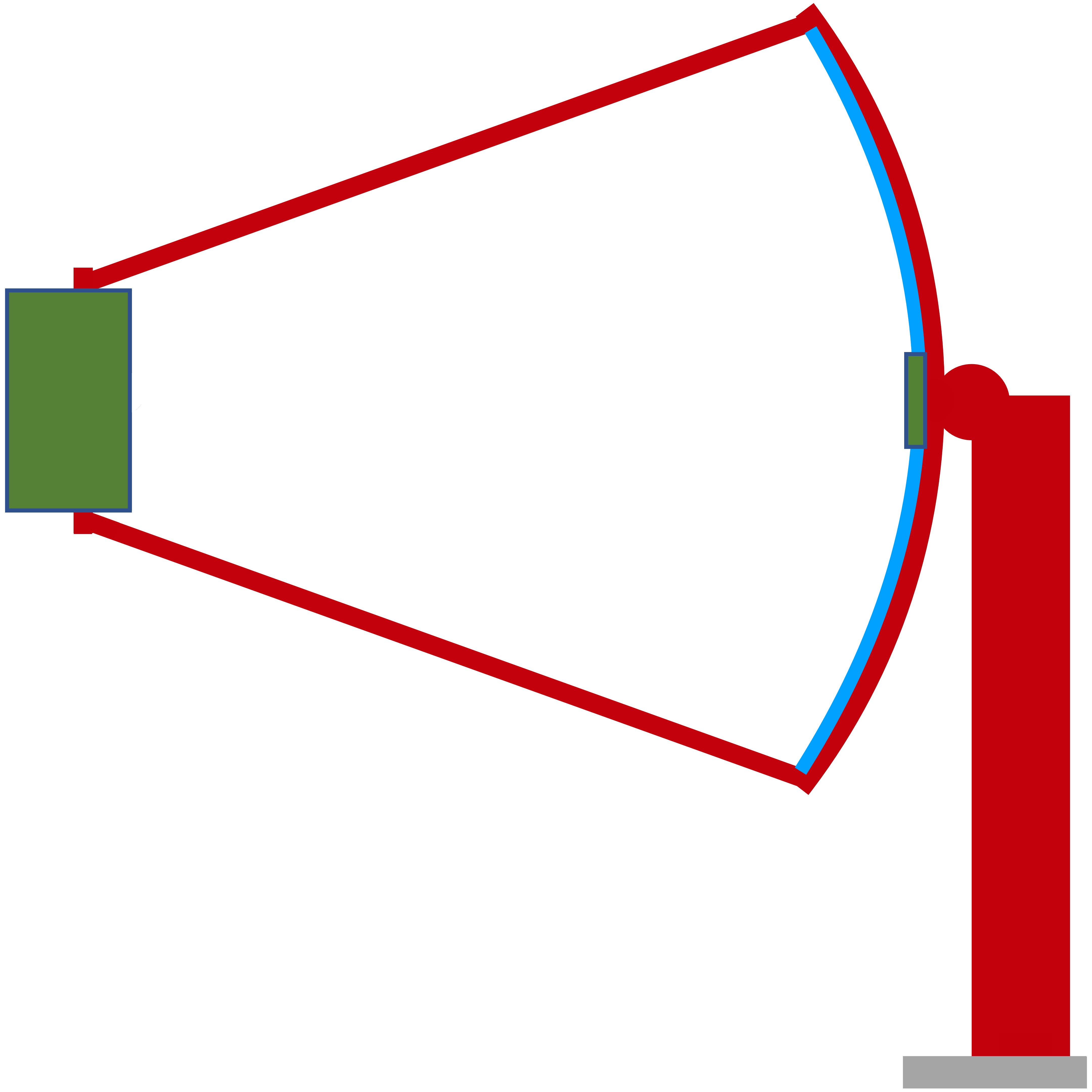
14 MSTs

- FlashCam cameras
- Structures funded by Germany and Poland
- Mirrors from France and Poland

CTAN

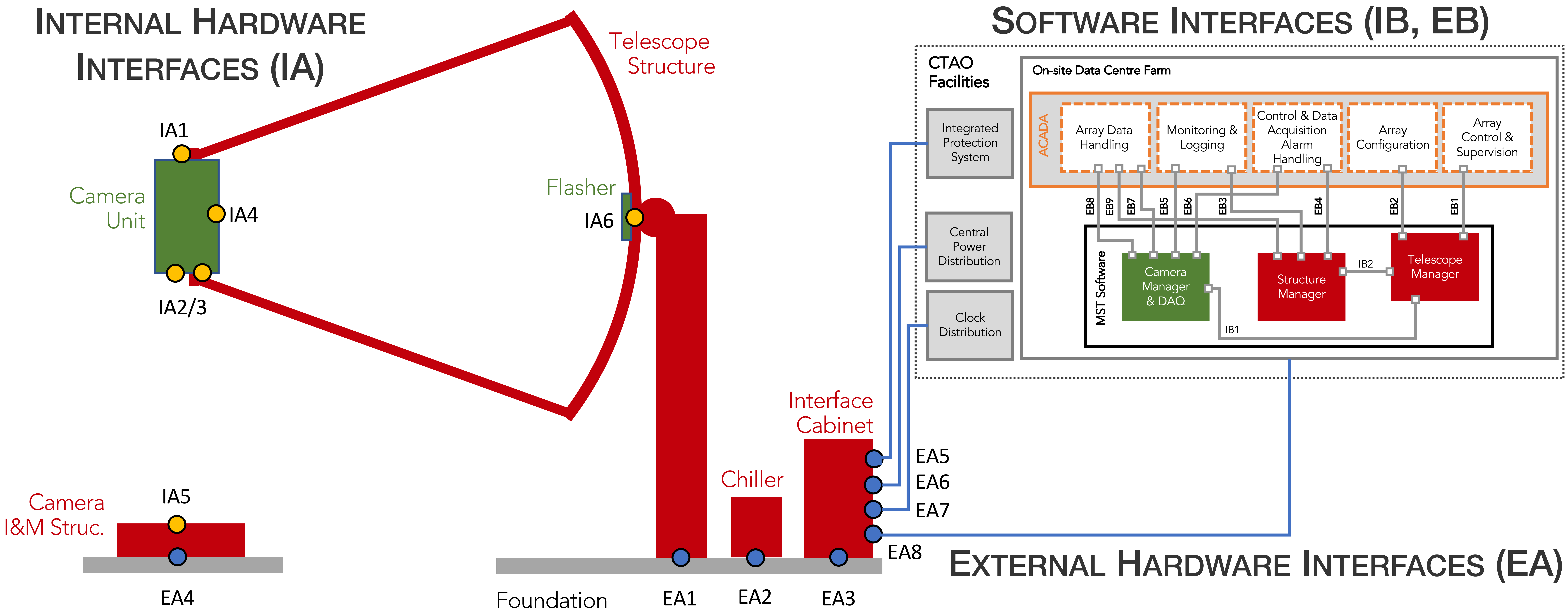
9 MSTs

- NectarCAM cameras
- Structures funded by Spain
- Mirrors from Italy



What is an MST telescope?

MST in a diagram



Element Colour Code: Camera, Structure, CTAO

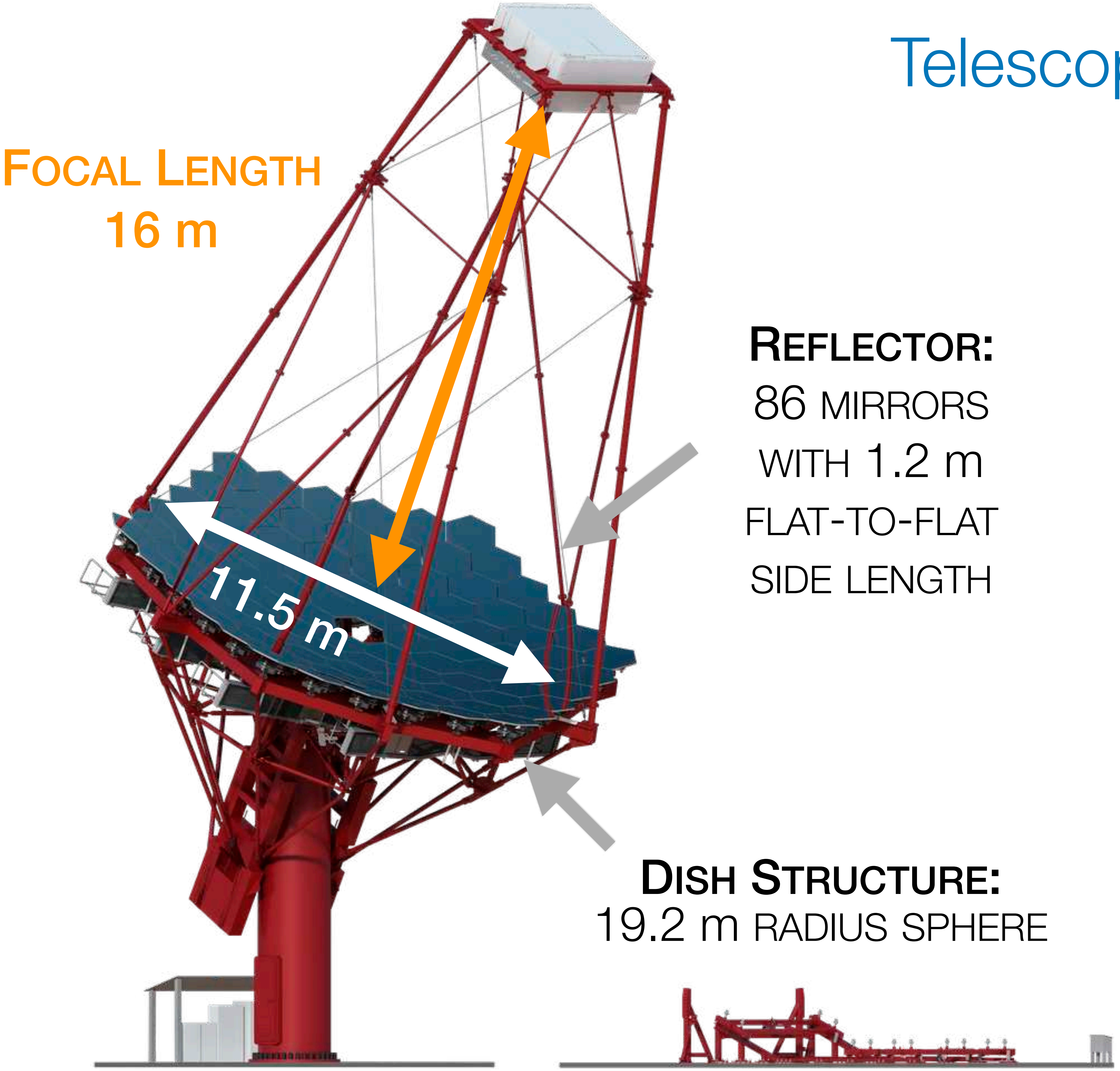
MST Structure

Material

- Made of **steel**
  - ➡To ensure sufficient stiffness
  - ➡No need for mirrors re-alignment for compensation of structure deformations during observations
- Total weight of **89 t**

MST Structure

Telescope optics

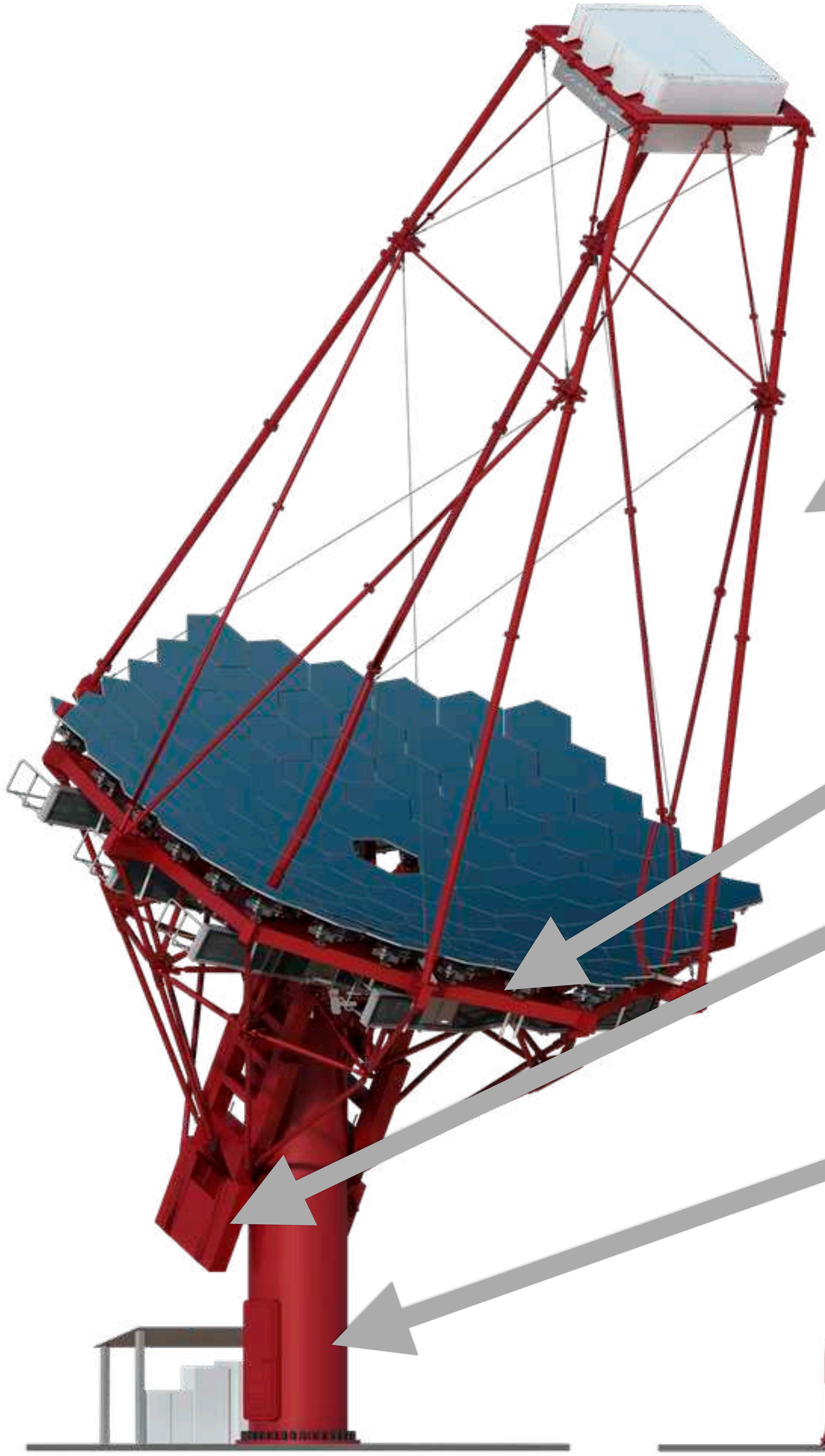


- **Single mirror modified Davis-Cotton design**
  - ➡ Reducing the dish-induced signal dispersion
  - ➡ Improve isochronicity of reflector
  - ➡ Focusing of light over 80% FoV w/ RMS < 0.8 ns

Radius of curvature of each mirror (32.14 m) is x2 focal length

MST Structure

Optical Support Structure

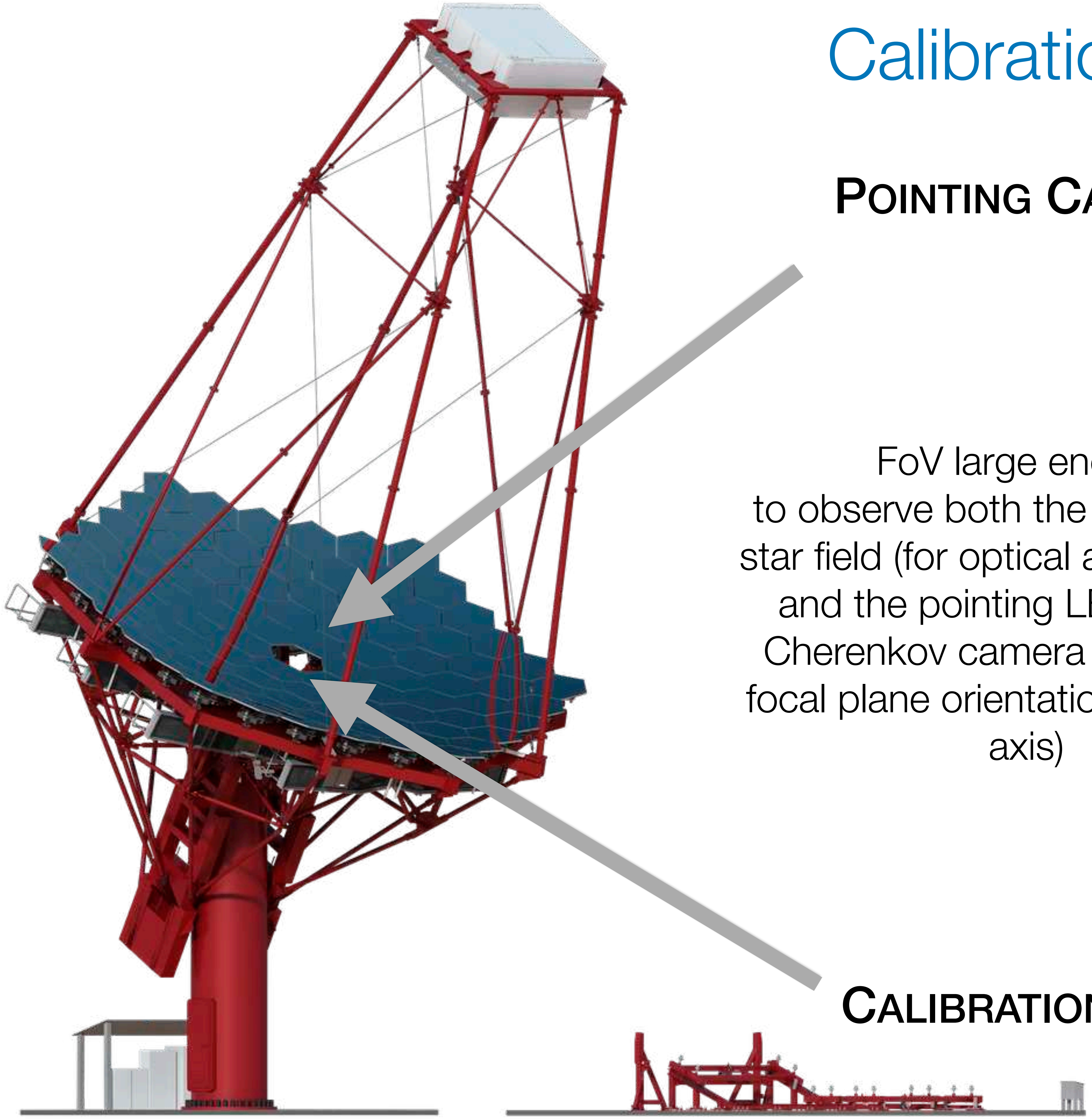


CAMERA SUPPORT STRUCTURE	Holds camera in the reflector's focal plane
DISH STRUCTURE	Maintains the ideal spherical shape of mirror segments
COUNTER WEIGHT STRUCTURE	Reduces load on the telescope's elevation axis, balancing it properly
POSITIONER HOUSING ALL ELECTRICAL CABINETS	Allows pointing and tracking of objects on the sky: azimuthal + elevation movements

$-270° < \text{Azimuth} < +270°$
$0° < \text{Elevation} < 91°$

MST Structure

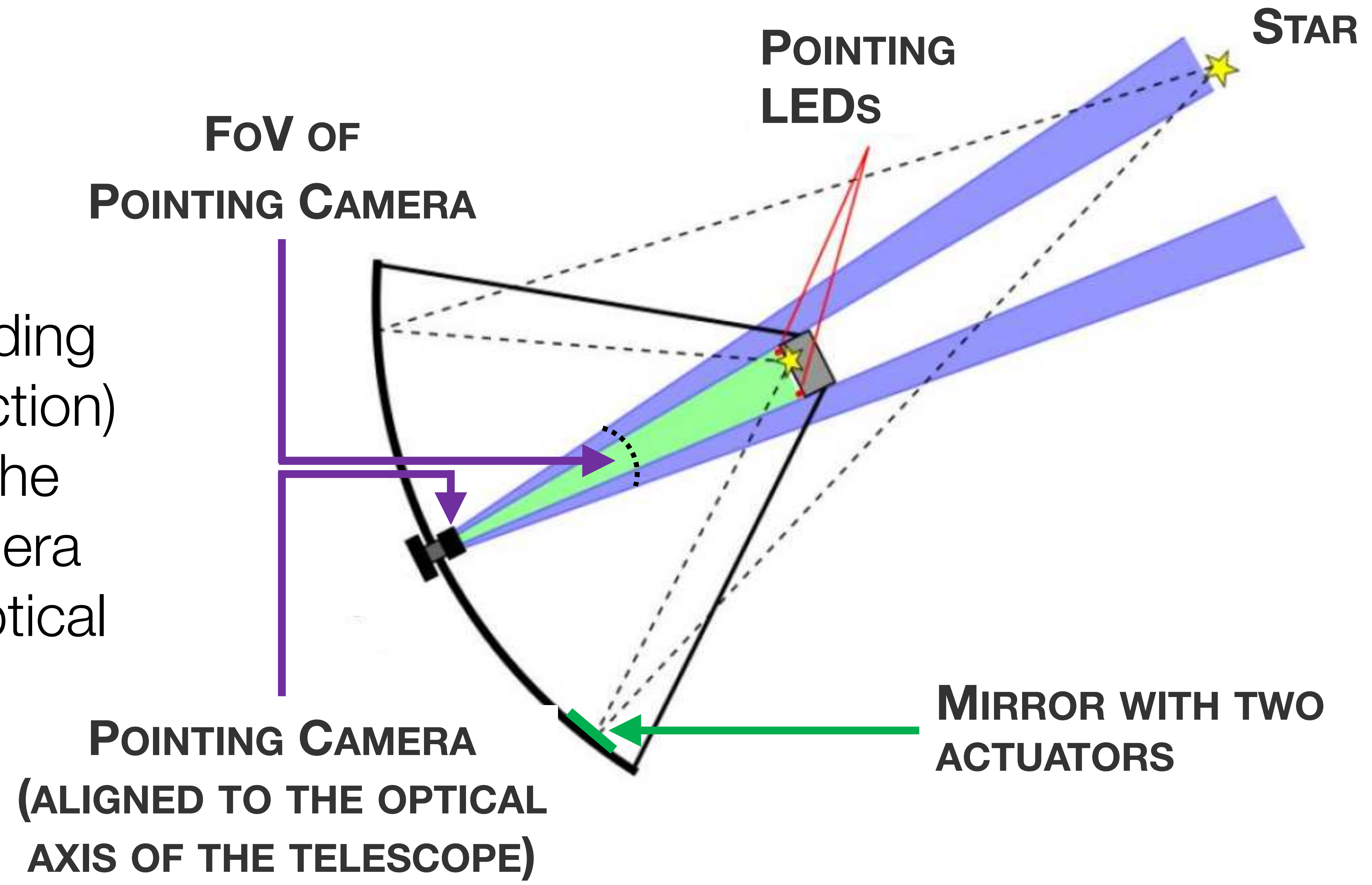
Calibration system



POINTING CAMERA

Wide FoV (26.5° x 17.8°), CMOS-based camera for pointing calibration and mirror alignment

FoV large enough to observe both the surrounding star field (for optical axis direction) and the pointing LEDs on the Cherenkov camera (for camera focal plane orientation wrt optical axis)



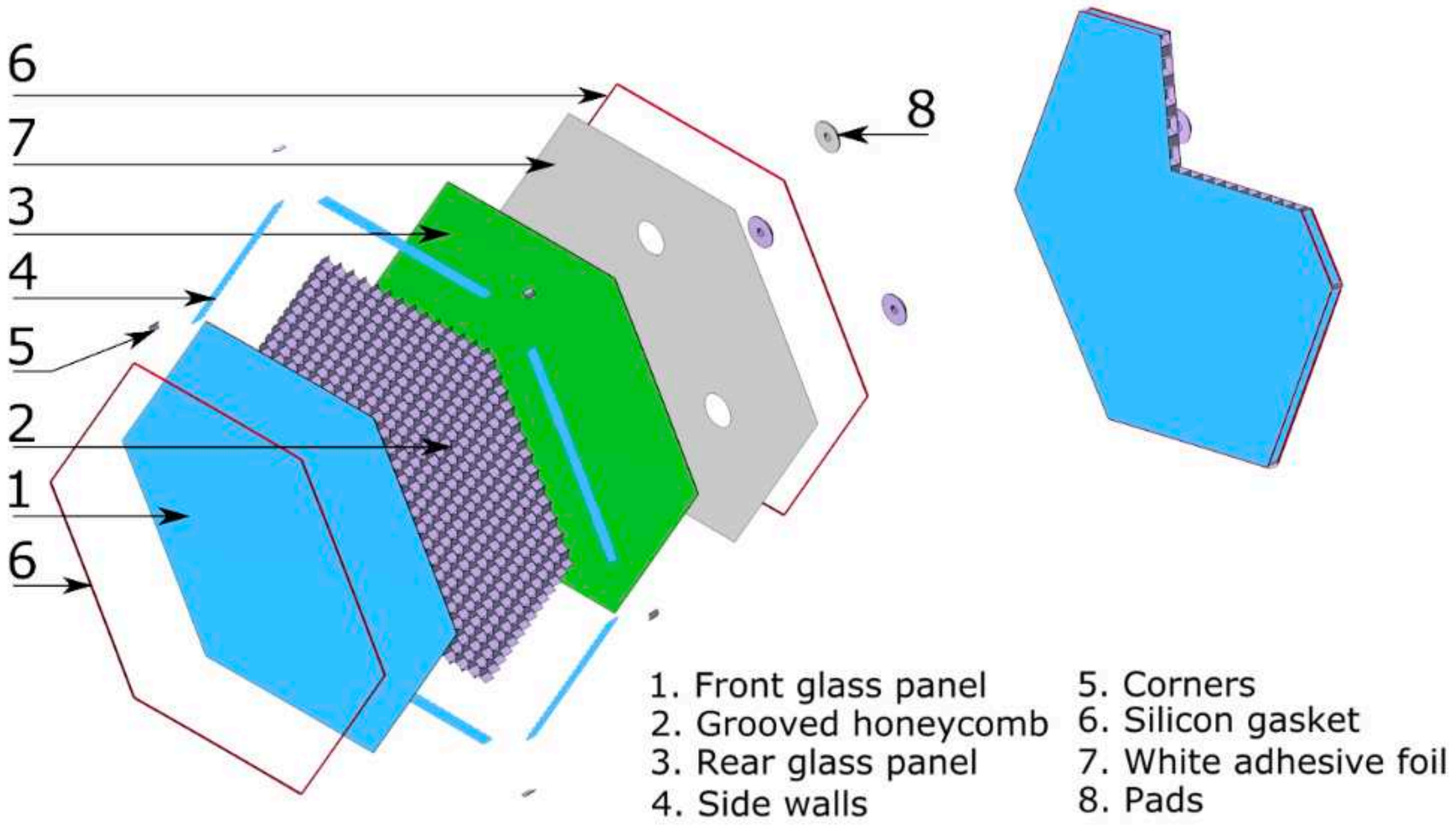
CALIBRATION BOX

LED-based source to illuminate the camera and perform charge and gain calibrations

MST mirrors

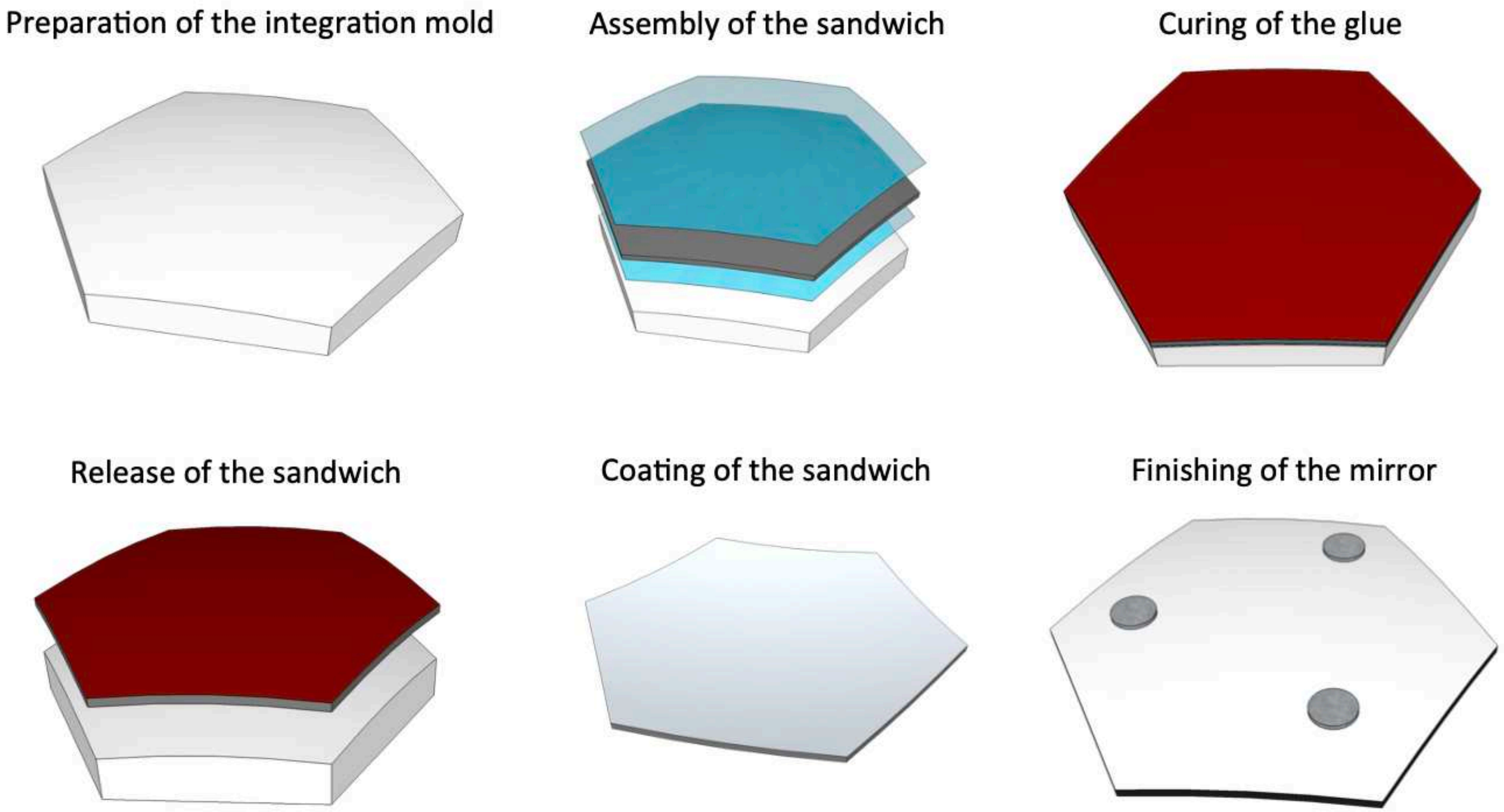
Al plate with honeycomb sandwich structure for enhanced stiffness

- **86** hexagonal-shaped with 1.2 m flat-to-flat side length to have effective mirror area ≥ 88 m^2 to cover energy range [150 GeV, 5 TeV]
- Radius of curvature of each mirror (32.14 m) is x2 focal length (**r = 2f**) to obtained a modified Davis-Cotton design
- Mirrors **aligned to reflect rays parallel to the optical axis** into the focal point
- Single mirror **containment radius of ~0.06°** to accurately reflects light to the focal point
- Lightweight (**~18 kg** each), with a **low rate of reflectance loss**



MST mirrors

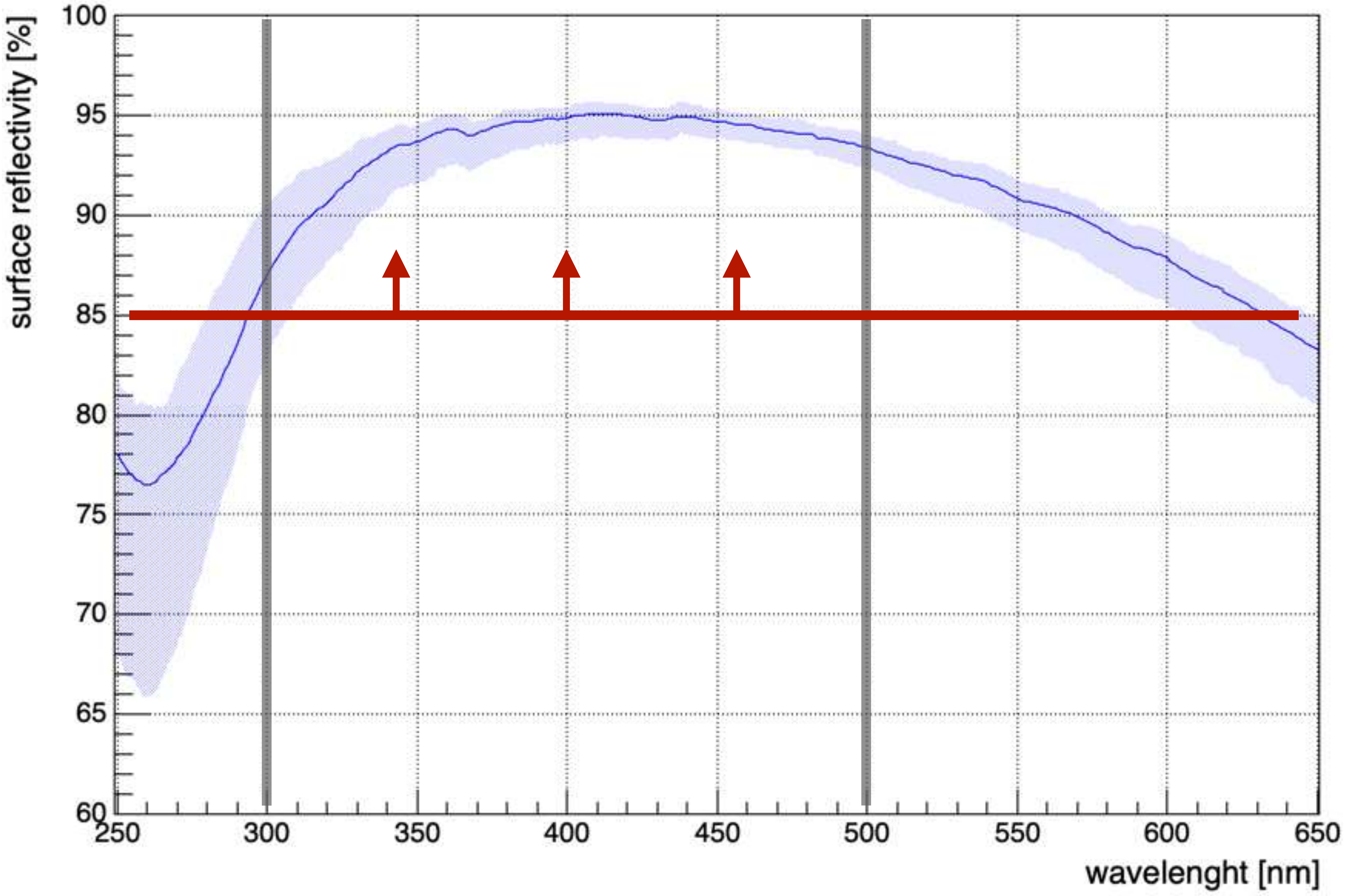
Obtained with “cold-slumping” technique



Mirror shape achieved by bending a thin glass sheet onto a mold with minimal thermal stress

MST mirrors

Reflectivity > 85% in [300, 500] nm

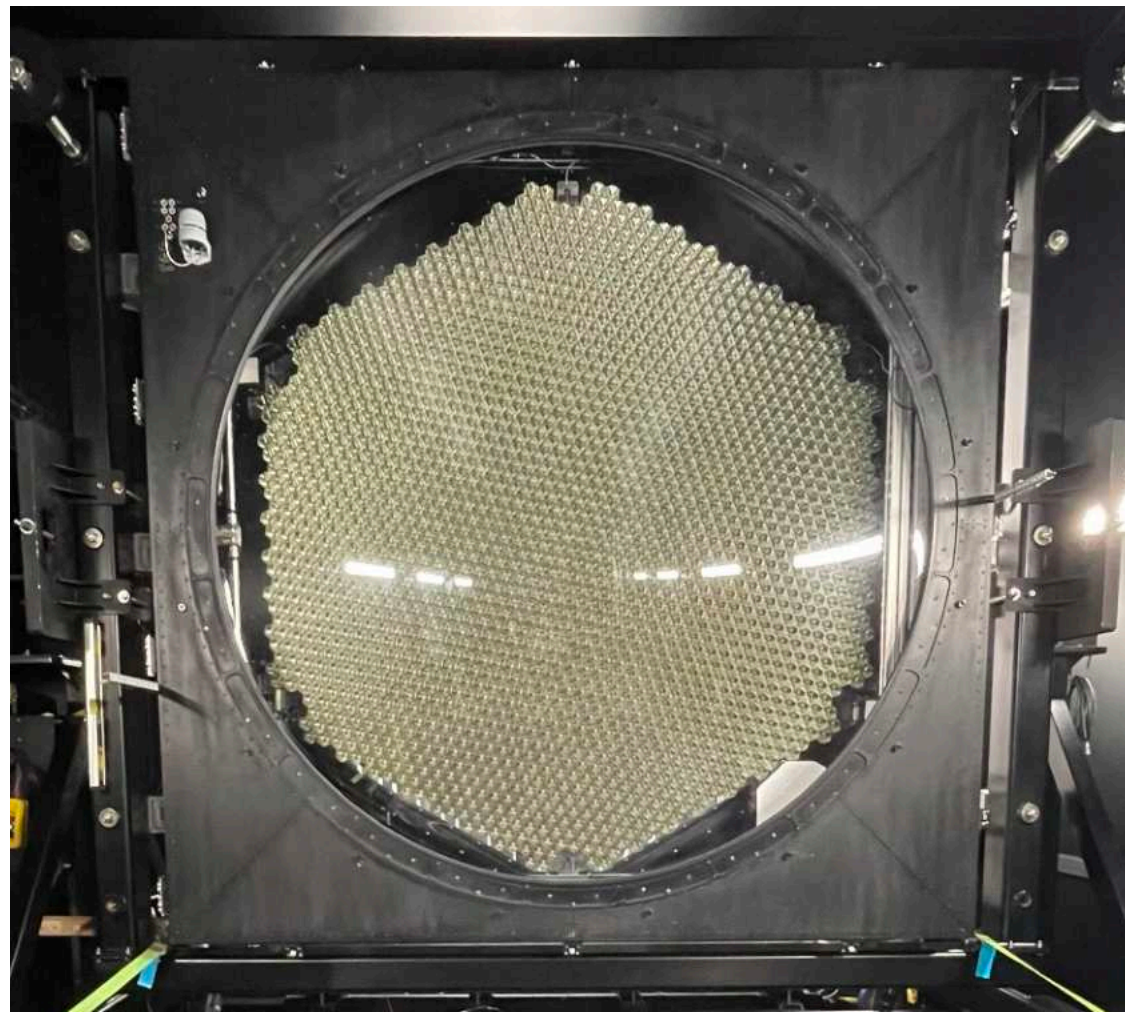


Mirror facets coated with protective multilayer (SiO_2, HfO_2/ZrO_2)

FlashCam vs NectarCAM

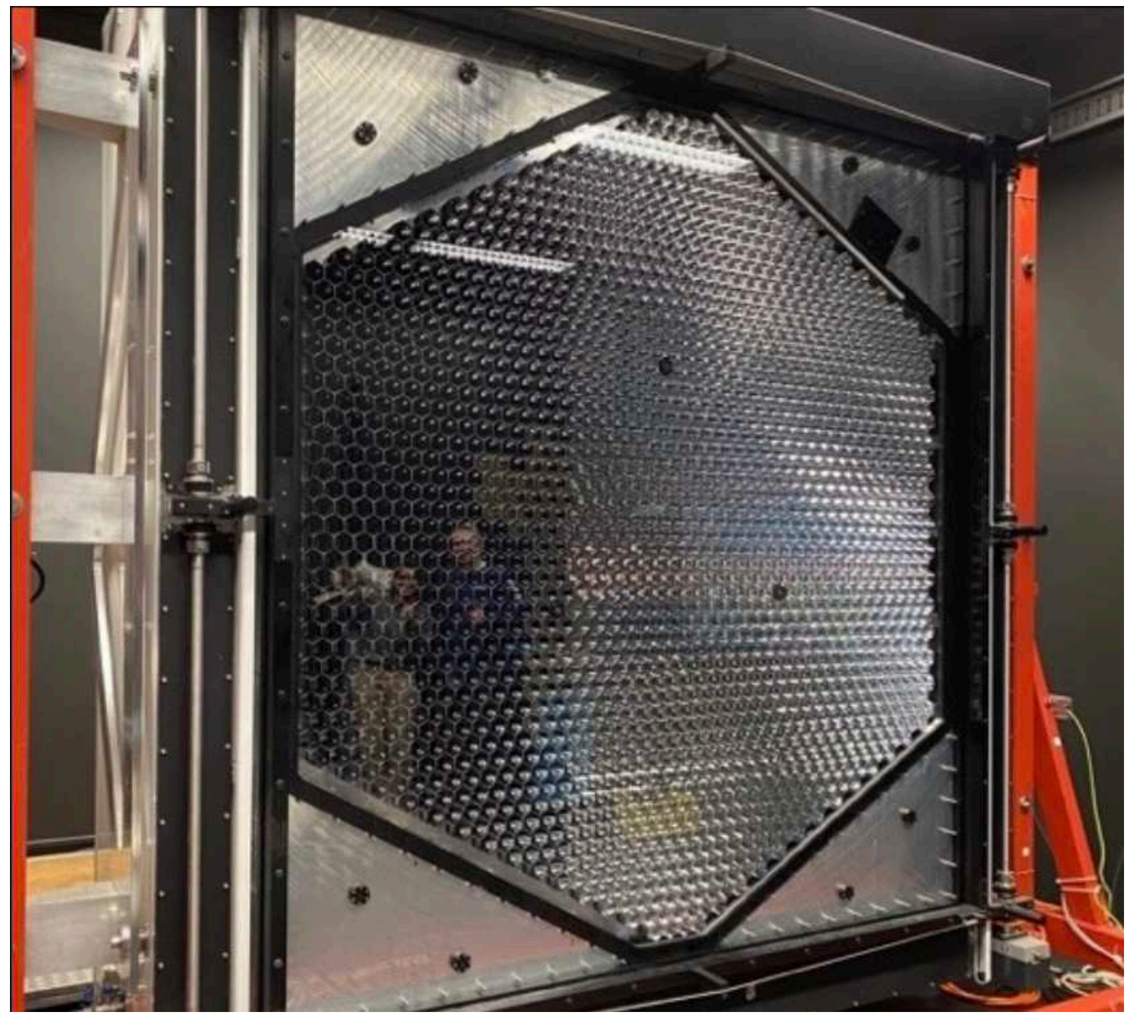
CTAN

9 MSTs with NectarCAM



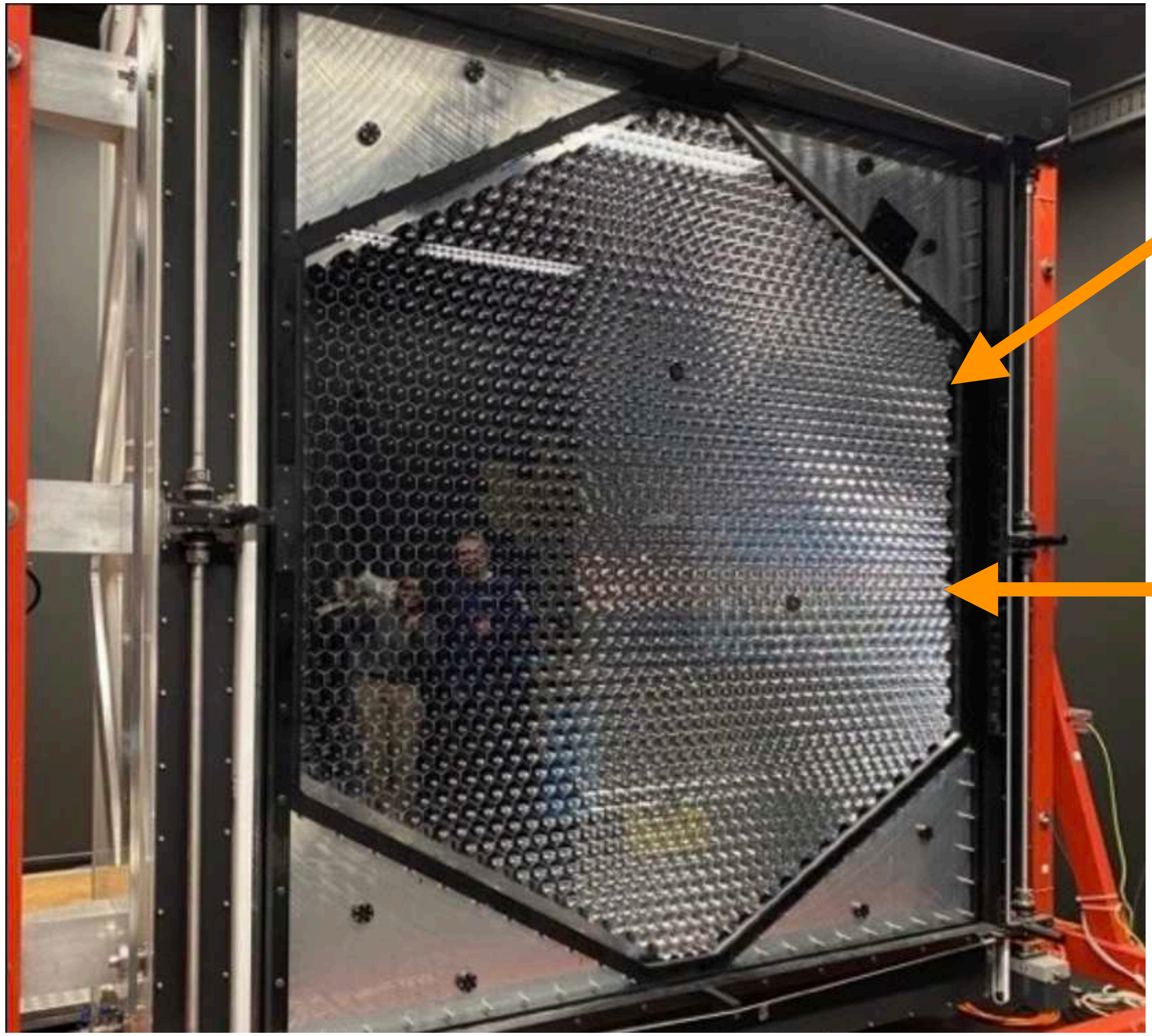
CTAS

14 MSTs with FlashCAM



FlashCam

Based on fully-digital readout and trigger systems



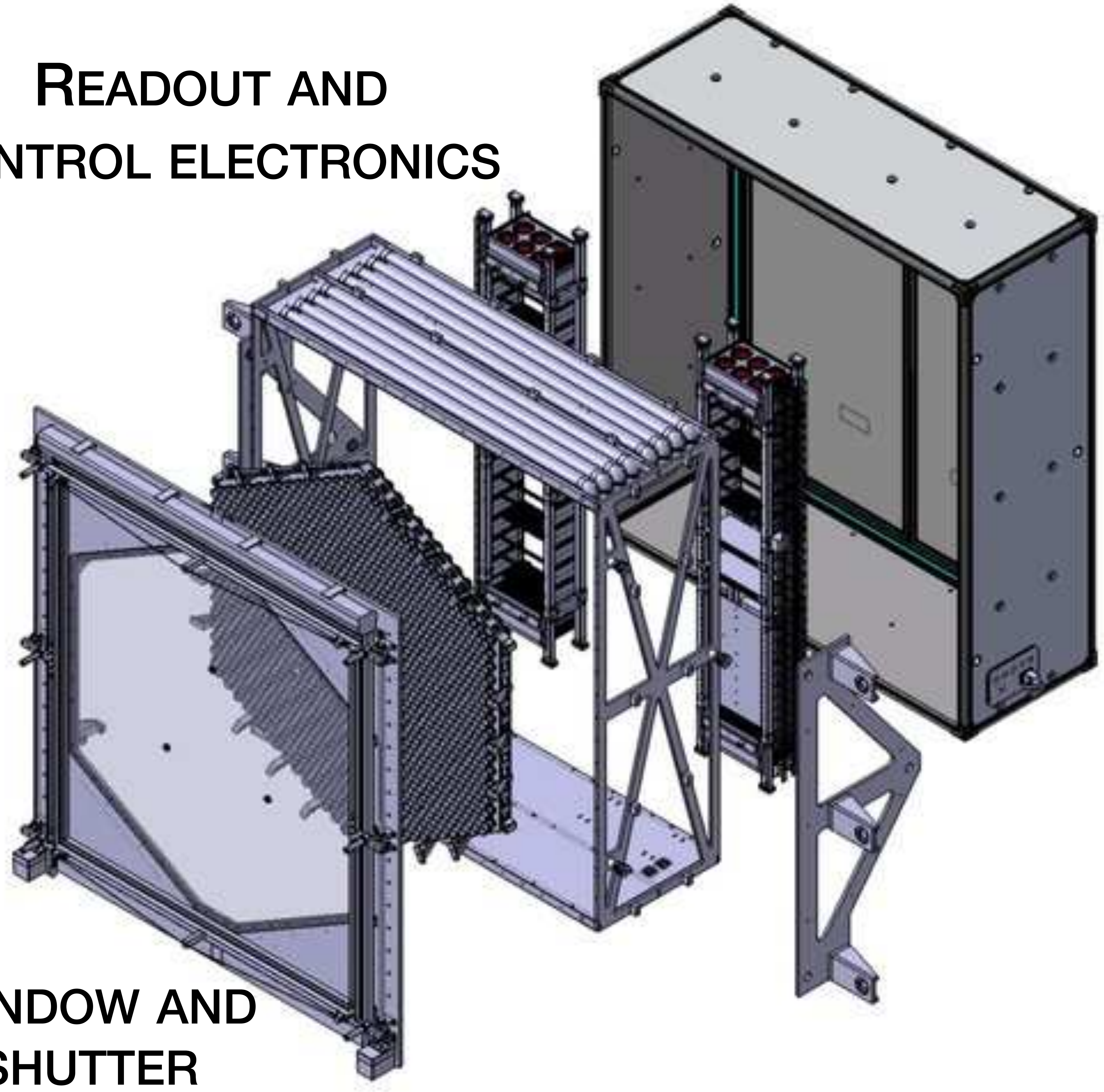
1764 vacuum PMTs + Winston cones

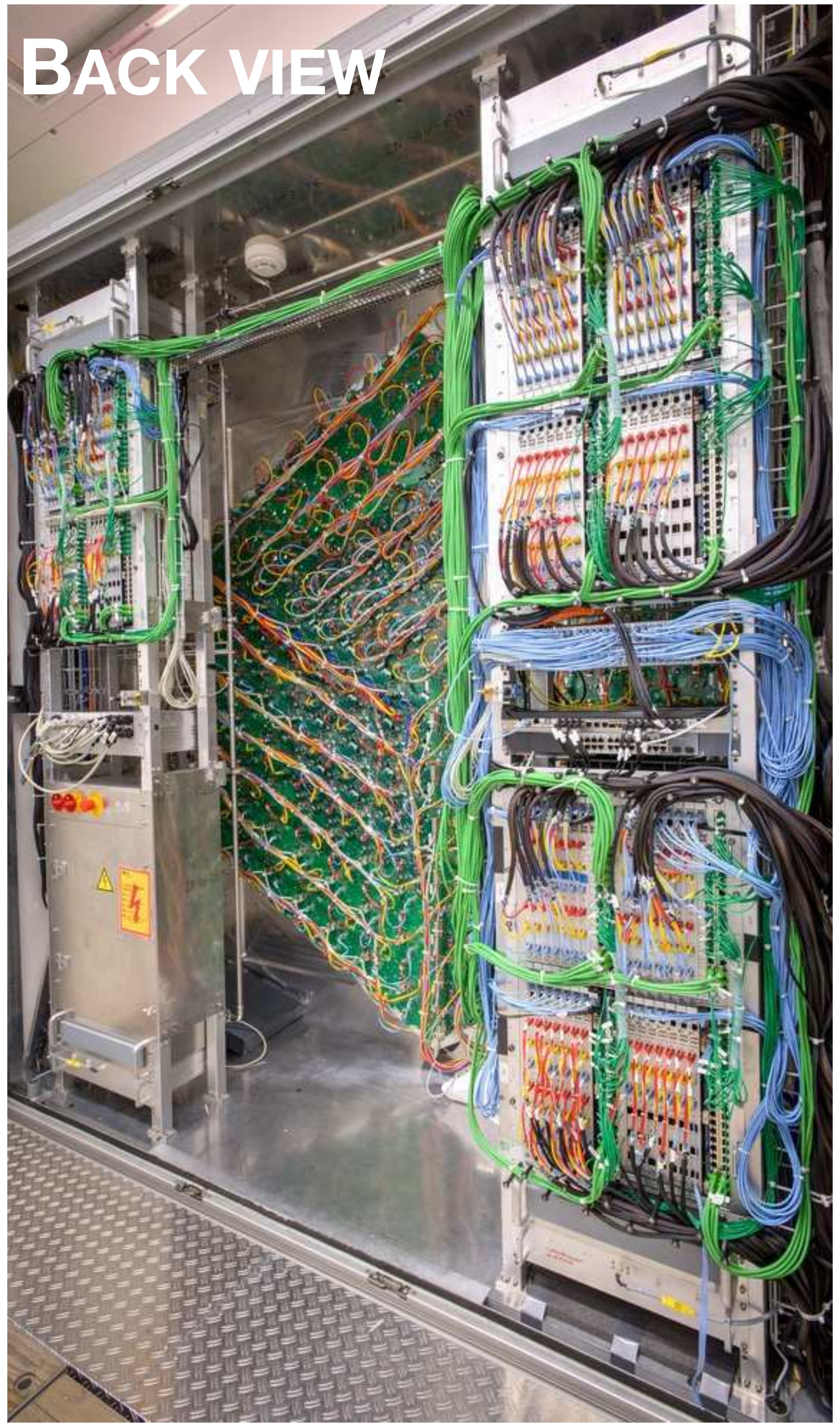
Formation of electrical signal + improved photon collection efficiency

147 Photon Detection Plane (PDP) modules

Provide high voltage to PMTs, pre-amplification and interface for slow control, monitoring, and safety functions

FlashCam

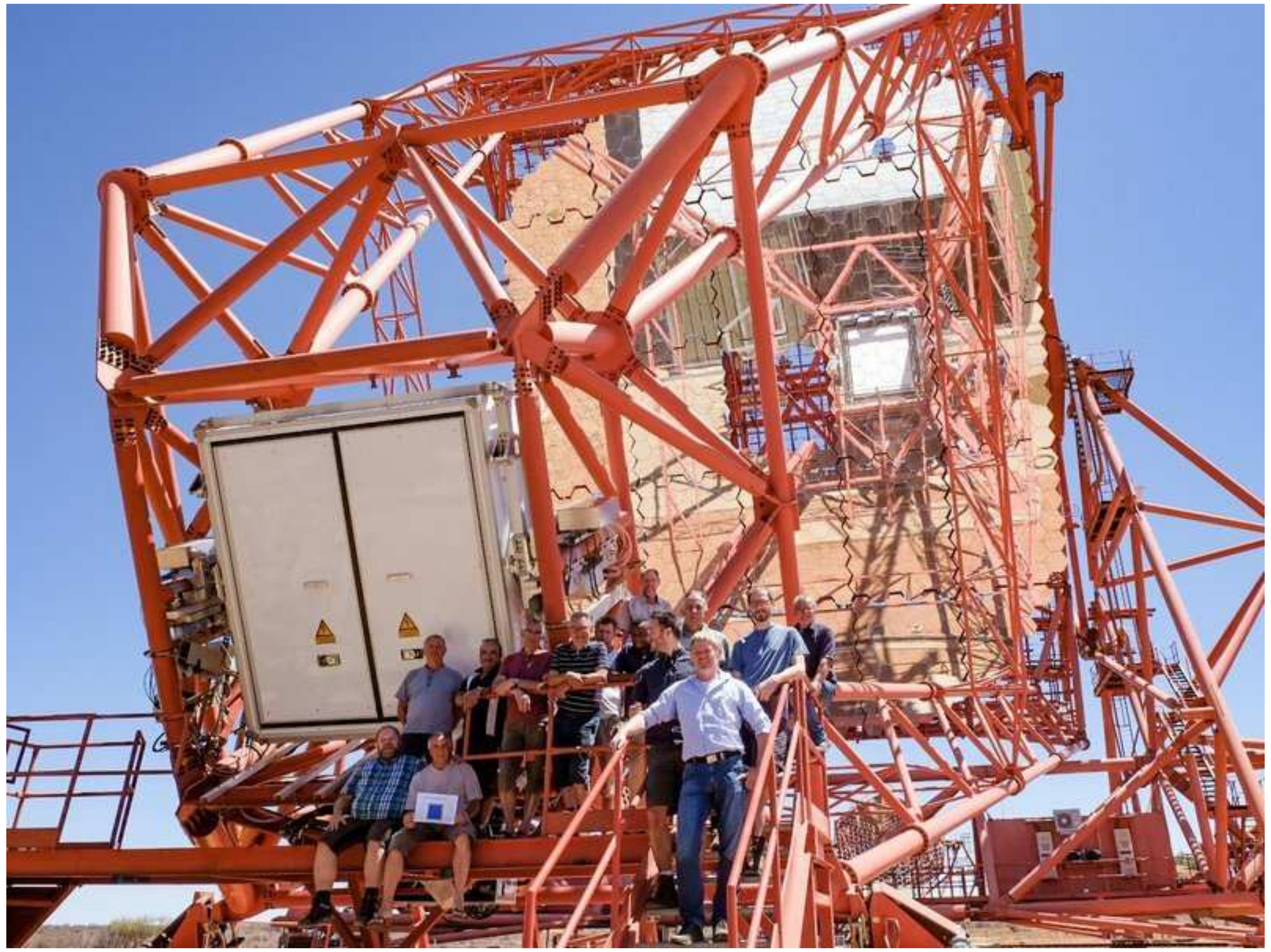




ELECTRONICS RACKS

FlashCam

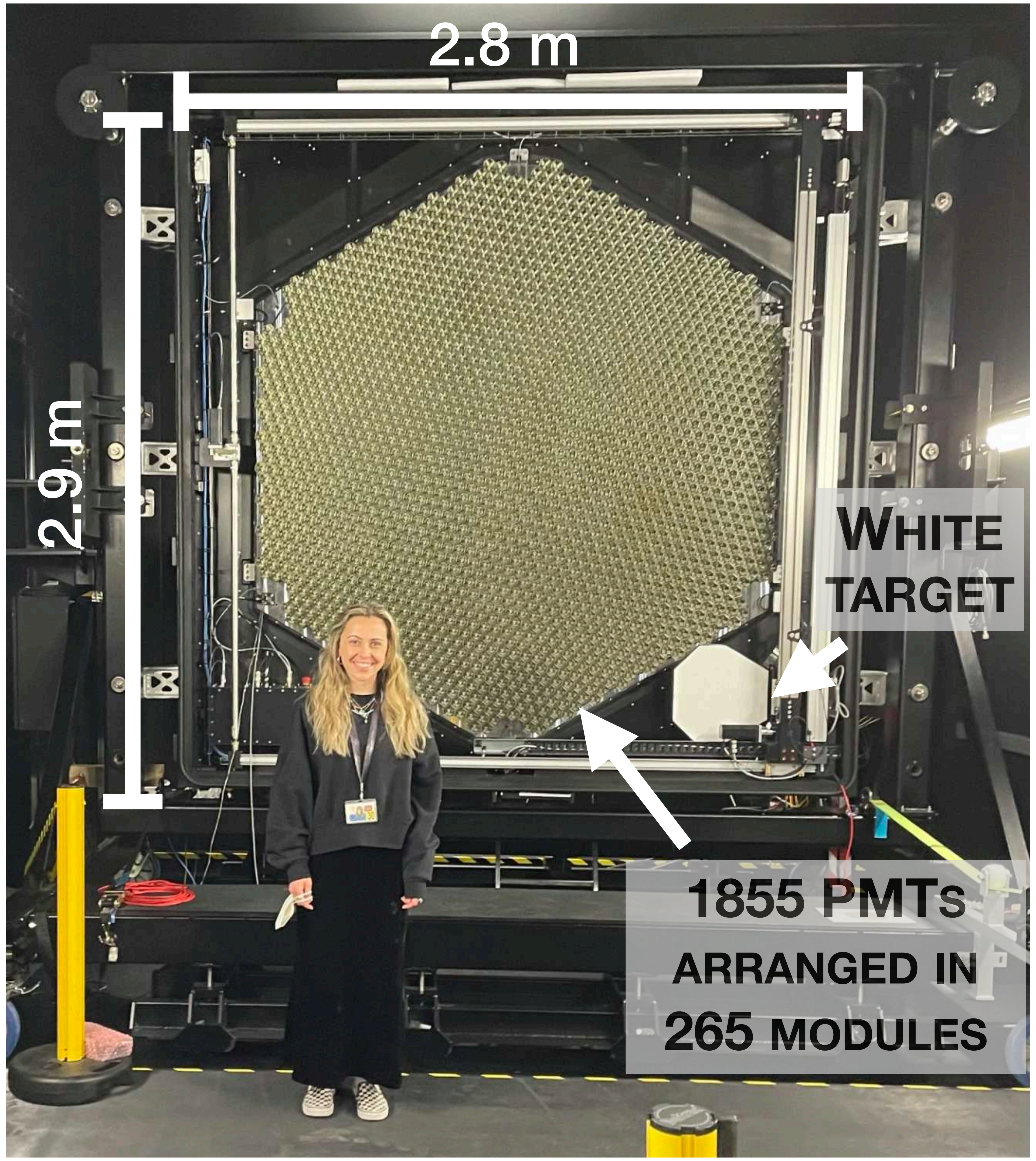
First flight on the MST structure
in Adlershof (Berlin)
in September 2017

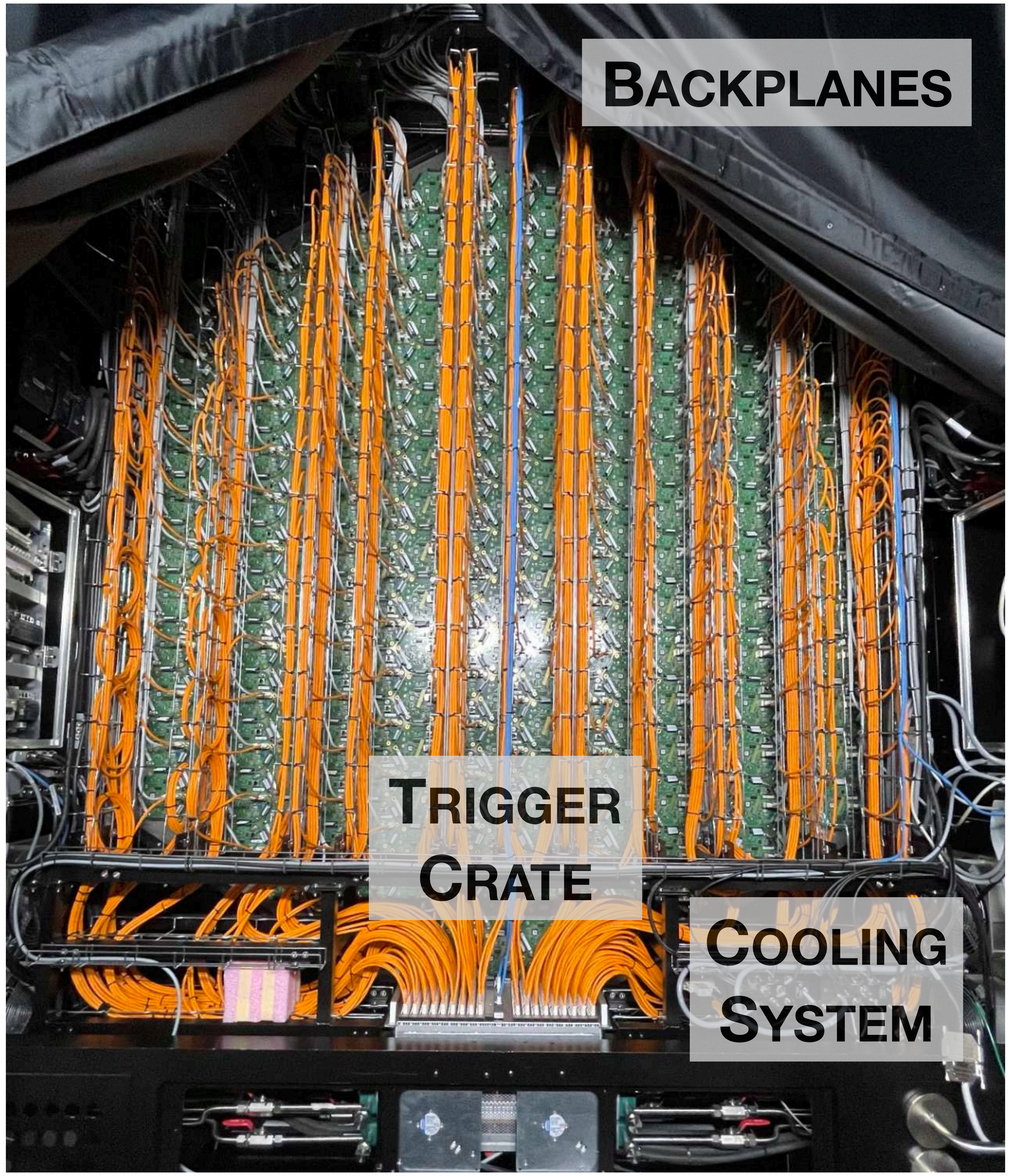


Successfully installed
on H.E.S.S.—CT5 in Oct 2019
Regularly taking data with uptime of ~98%

NectarCAM

Modular structure with 265 7-pixels modules



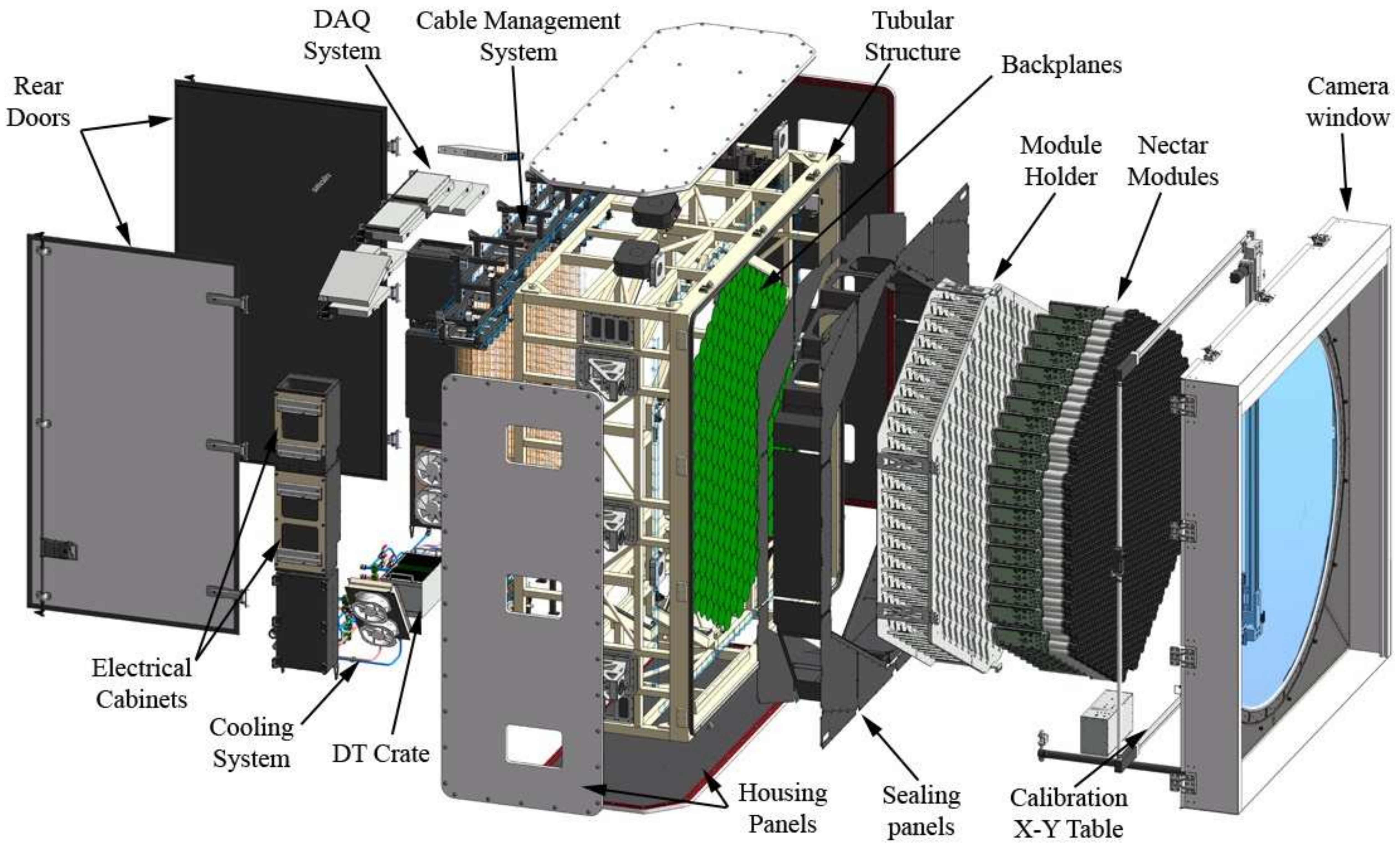


NectarCAM mechanics

Built from independent units for construction and integration flexibility

BACK ASSEMBLY

TRIGGER AND DATA ACQUISITION SUBSYSTEMS



FRONT ASSEMBLY

CAMERA ENTRANCE APERTURE, FOCAL PLANE

CENTRAL ASSEMBLY

PRIMARY LOAD BEARING COMPONENT, COOLING SYSTEM

NectarCAM

First prototype installed on the MST structure in Adlershof (Berlin) in May 2019

FlashCam vs NectarCAM

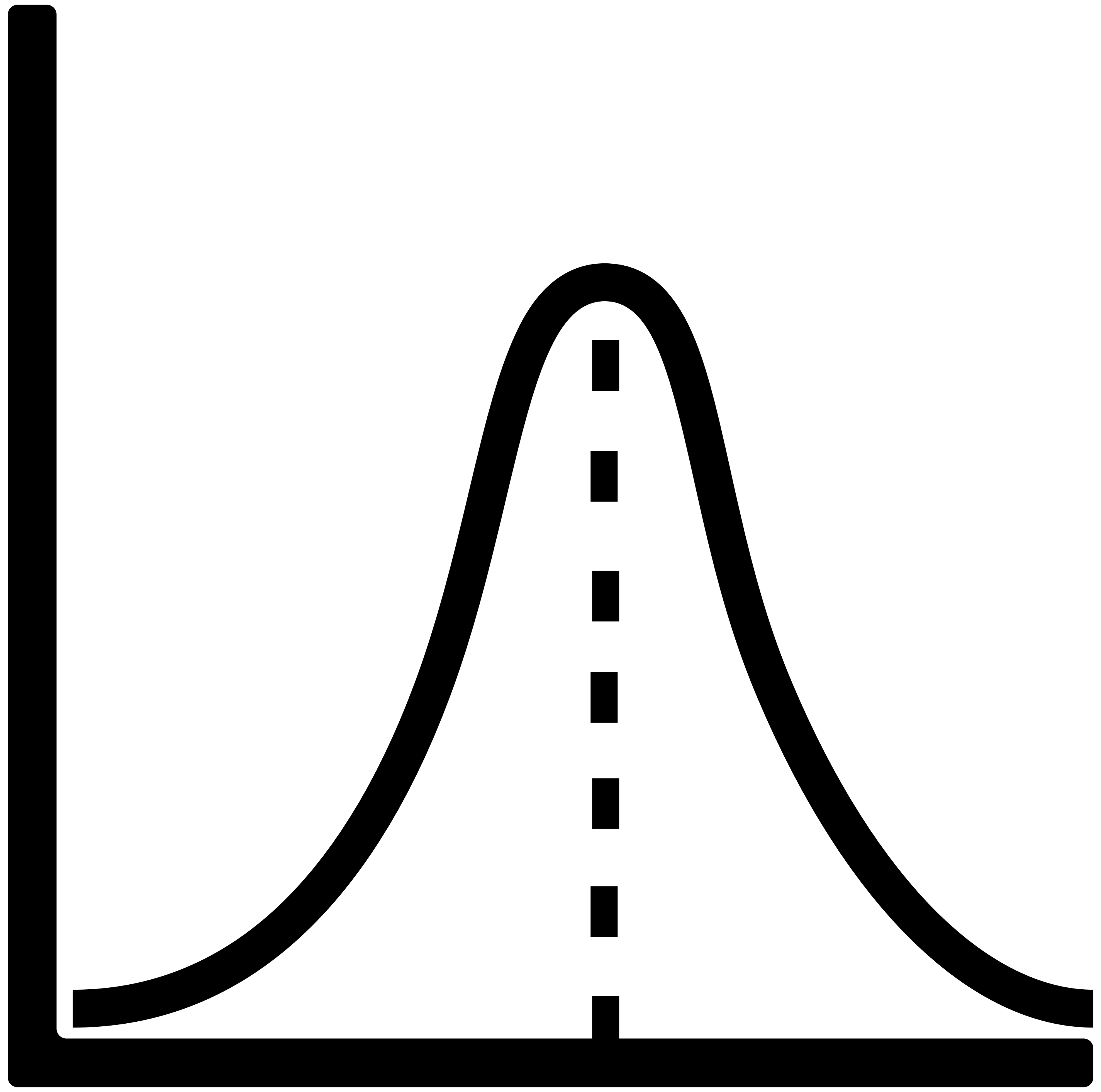
Main differences are the electronics and trigger designs

FlashCam

- Field of view of 7.5°
- Rack based electronics
- Separation between γ detection and electronics/processing
- "Off-the-shelf" components
- Non-linear amplification of P.E. current
  - 1 gain channel
  - Dynamic range of 0.2—3000 p.e.
  - 12-bit continuous digitization at 250 MHz
- Fully digital trigger form directly on data
- 128 ns waveforms to camera server

NectarCAM

- Field of view of 7.7°
- Integrated modules
- Electronics mounted on phototubes
- **A**pplication **S**pecific **I**ntegrated **C**ircuits
- Linear amplification of P.E. current
  - 2 gain channels
  - Dynamic range of 0.5—2000 p.e.
  - 1GHz sampler+digitizer (NECTAr)
- Independent trigger channel
- Waveform integration window of 1—60 ns

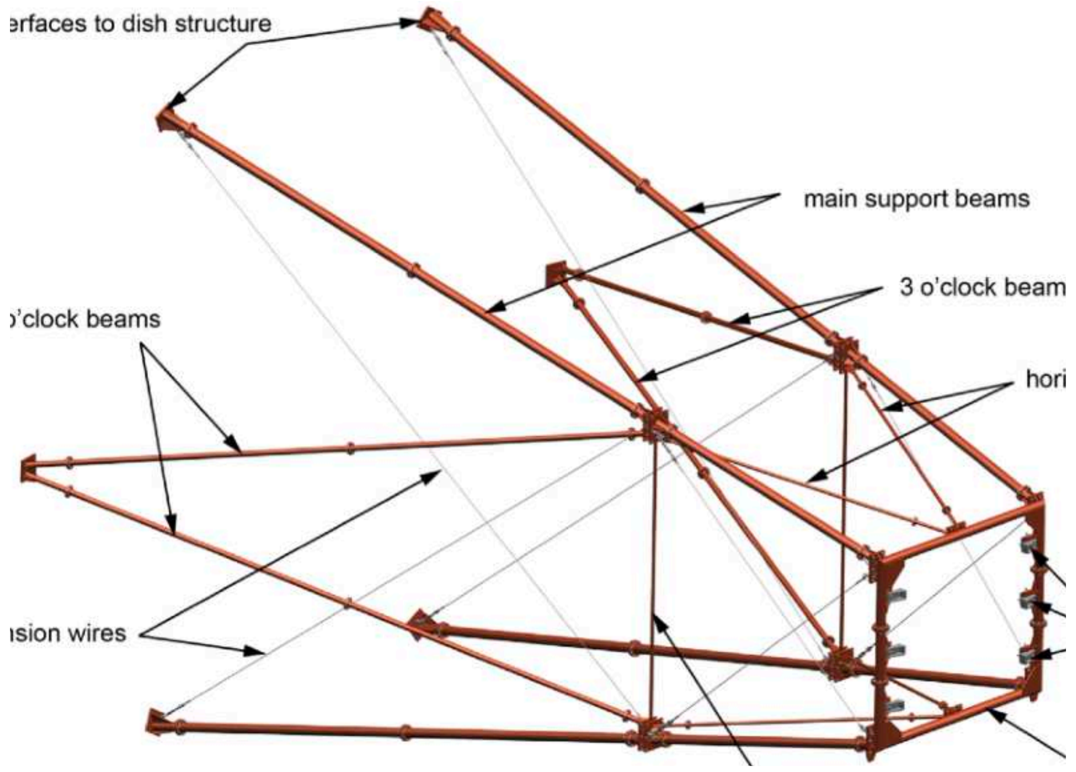


How do we measure Cherenkov photons?

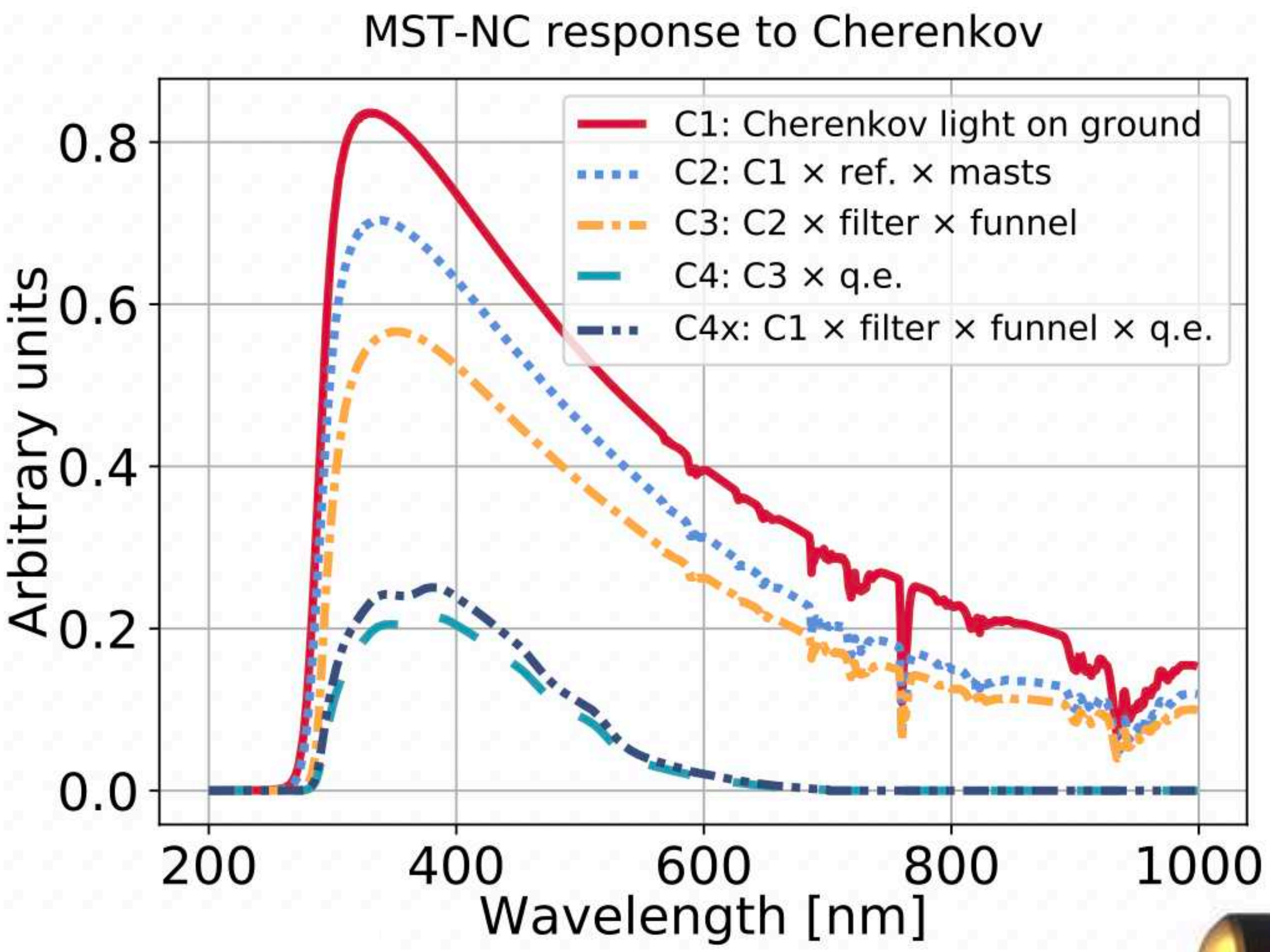
The case of NectarCAM

From photons to photoelectrons

Impact of components on Cherenkov light detection efficiency



TELESCOPE STRUCTURE



ENTRANCE WINDOW

LIGHT GUIDES

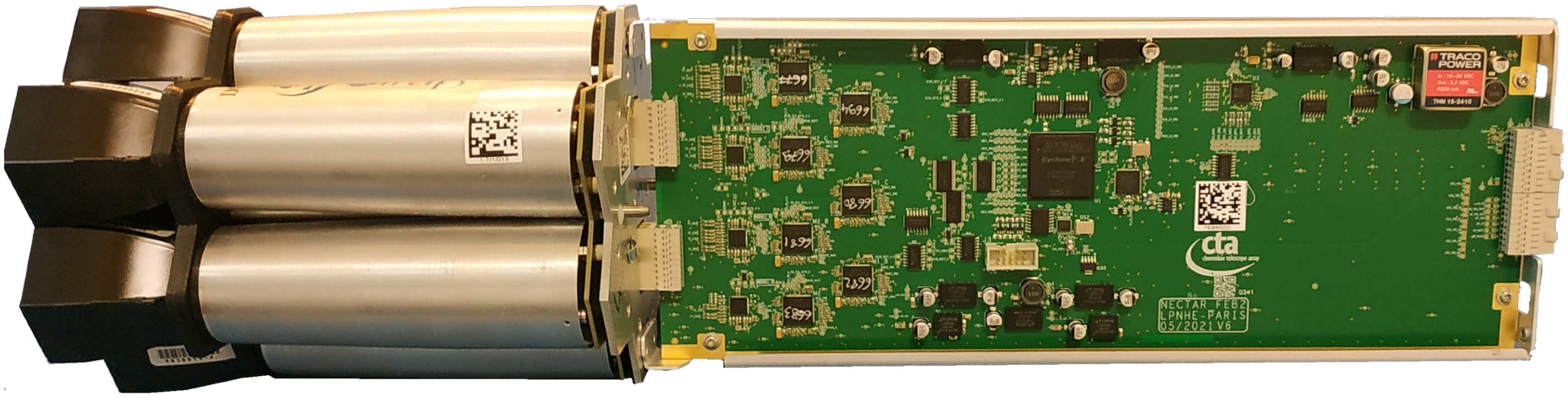
HAMAMATSU PMT

From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

FRONT END BOARD (FEB)

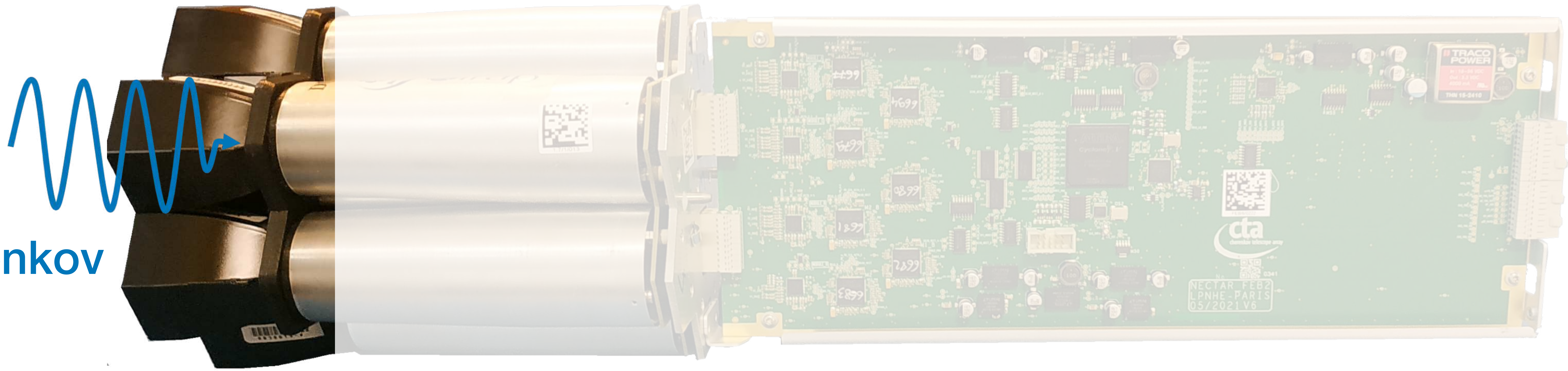


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

FRONT END BOARD (FEB)

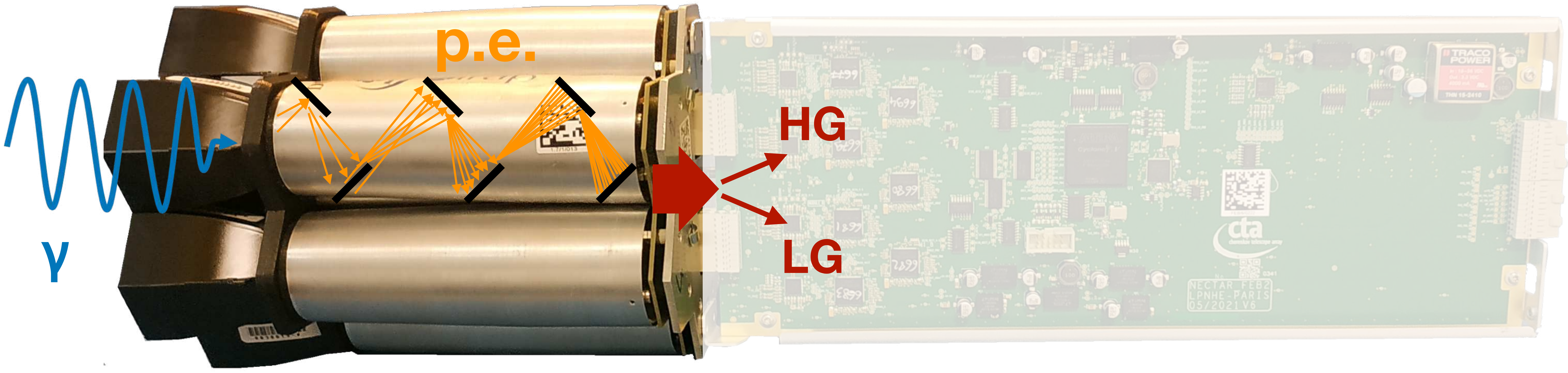


WINSTON CONES

1. Light deposited in the camera is first collected in the **light guides** and detected in the focal plane

From photons to photoelectrons

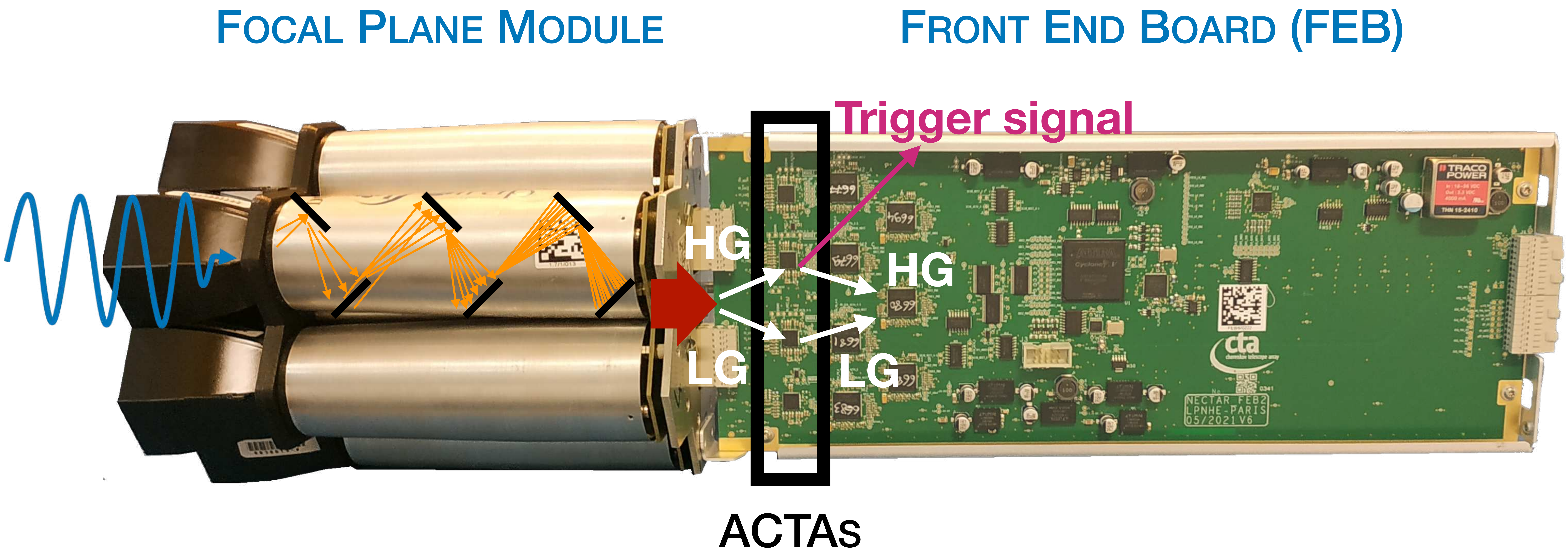
Formation of the electric signal



2. The signal is converted into electric signal by the **PMTs** and pre-amplified towards 2 gain channels: High Gain and Low Gain channels

From photons to photoelectrons

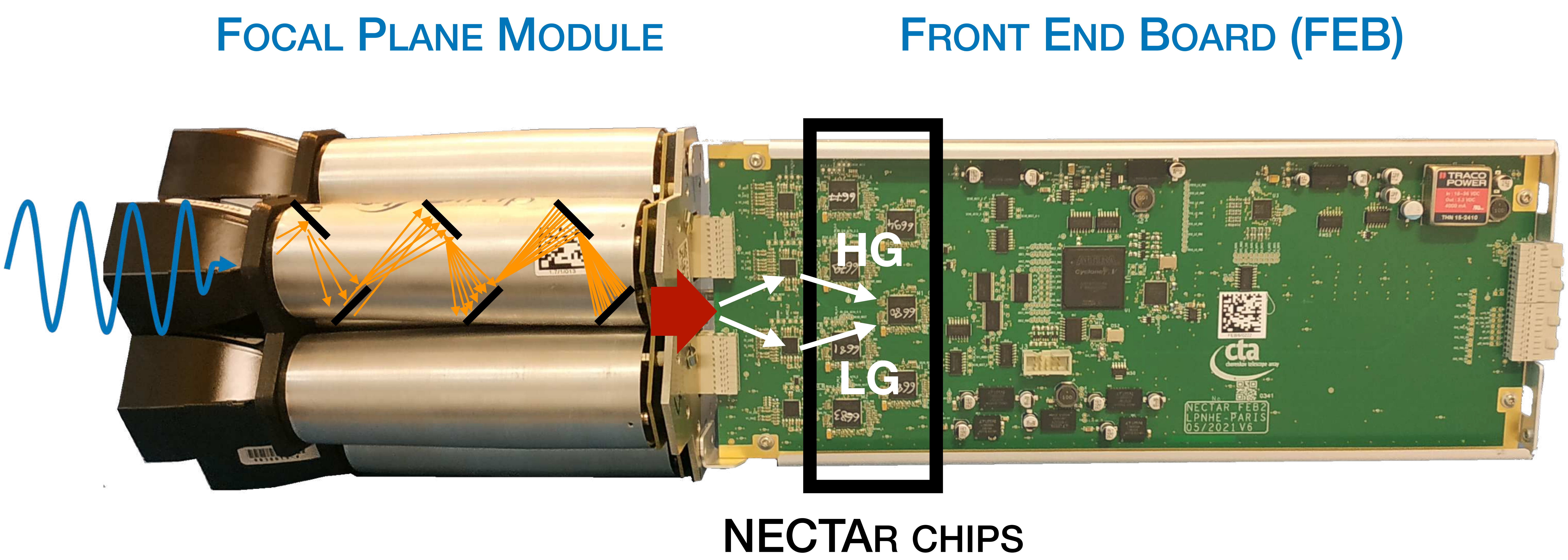
Formation of the electric signal



3. The signal is amplified again in the **ACTA amplifiers** and splitted into 3 channels: low and high gain channels and trigger channel

From photons to photoelectrons

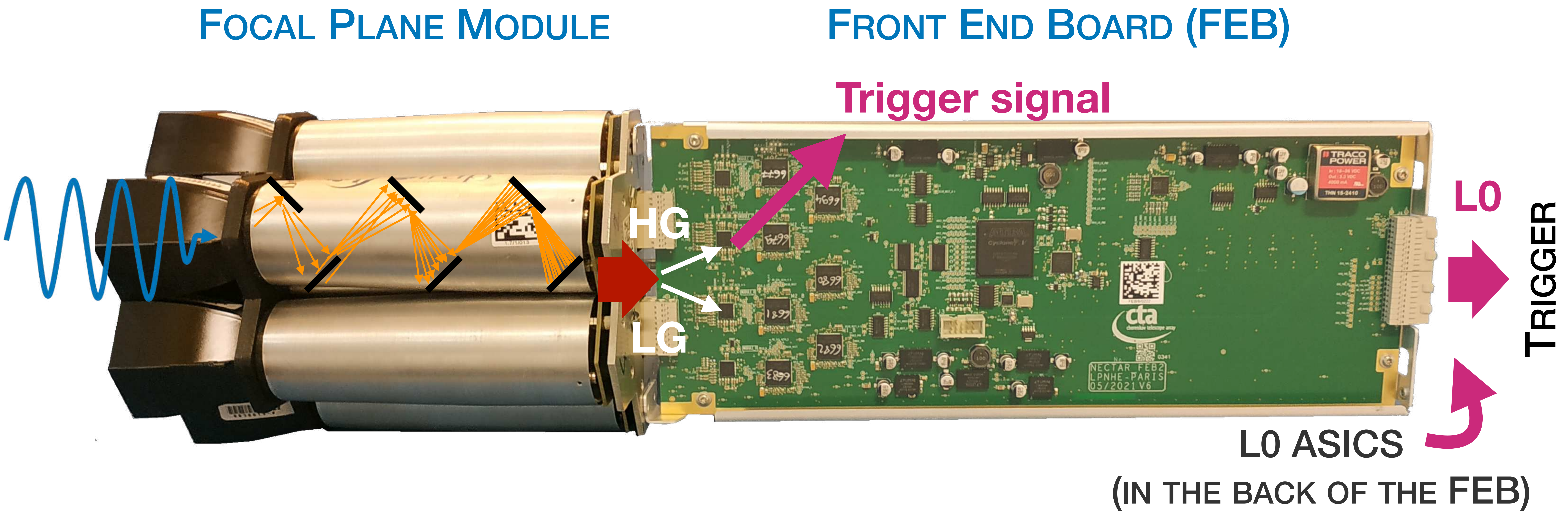
Formation of the electric signal



4. The HG and LG signals are sampled at 1 GHz in the **NECTAr chips** → acts as a circular buffer which holds 500 ns of data until camera trigger occurs

From photons to photoelectrons

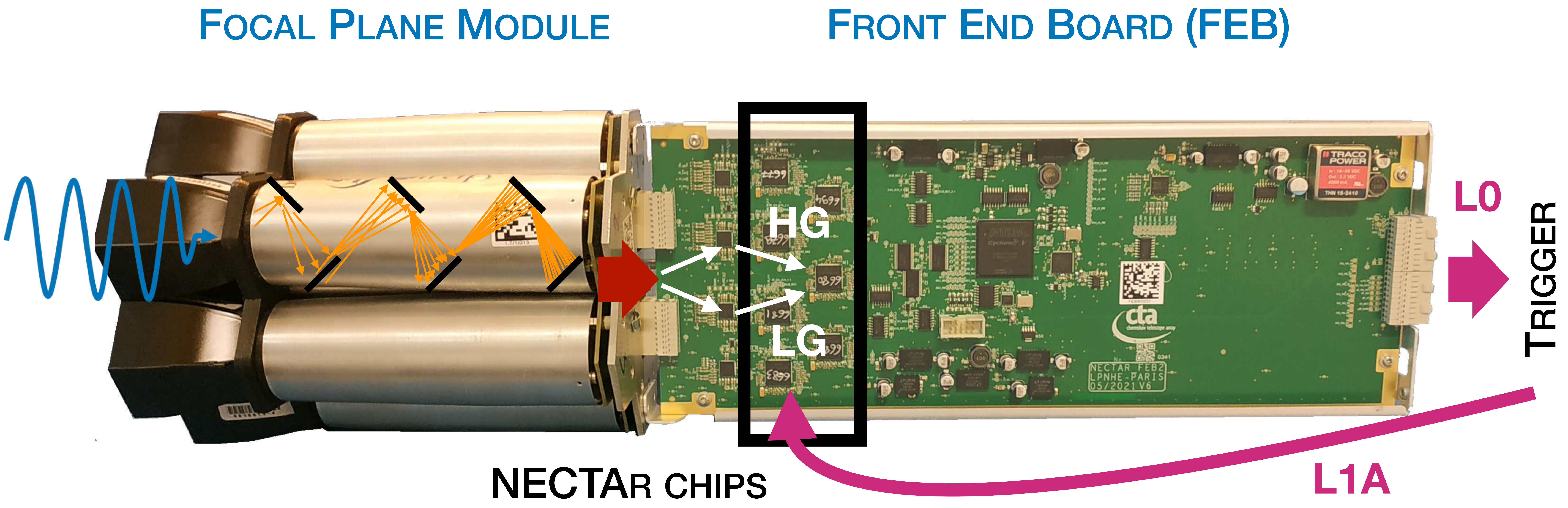
Formation of the electric signal



5. The **L0 ASICS** processes analog signals from each PMT, comparing them to a threshold; if exceeded, it generates a digital L0 signal

From photons to photoelectrons

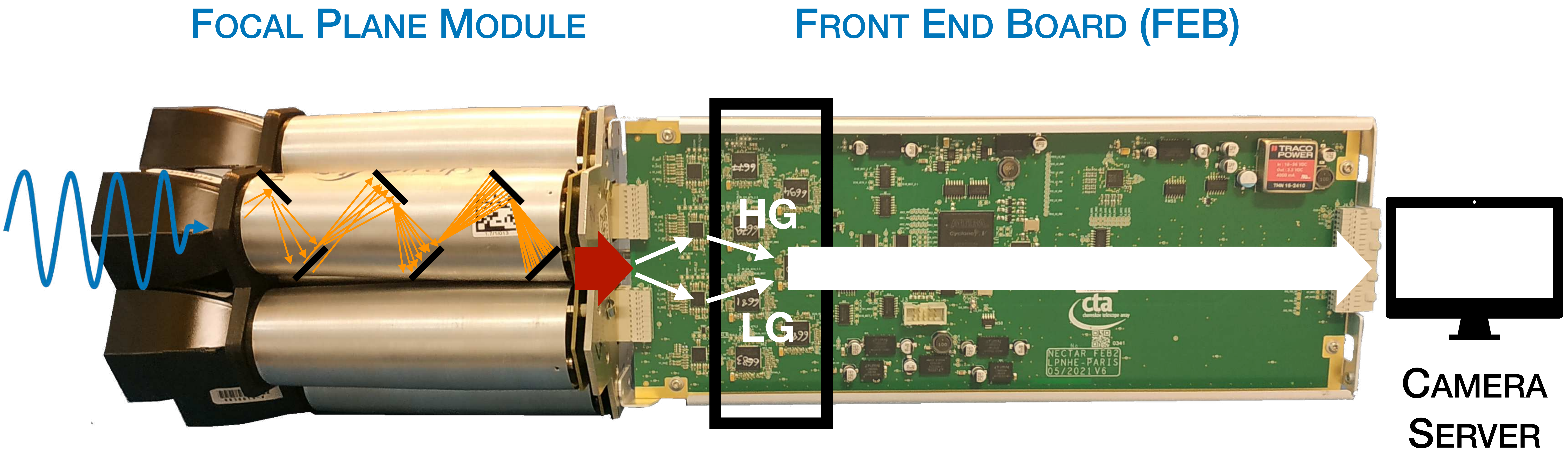
Formation of the electric signal



6. When a trigger is formed, sampling is stopped, data are readout, digitised in a 12-bit ADC and sent to the camera server by Ethernet

From photons to photoelectrons

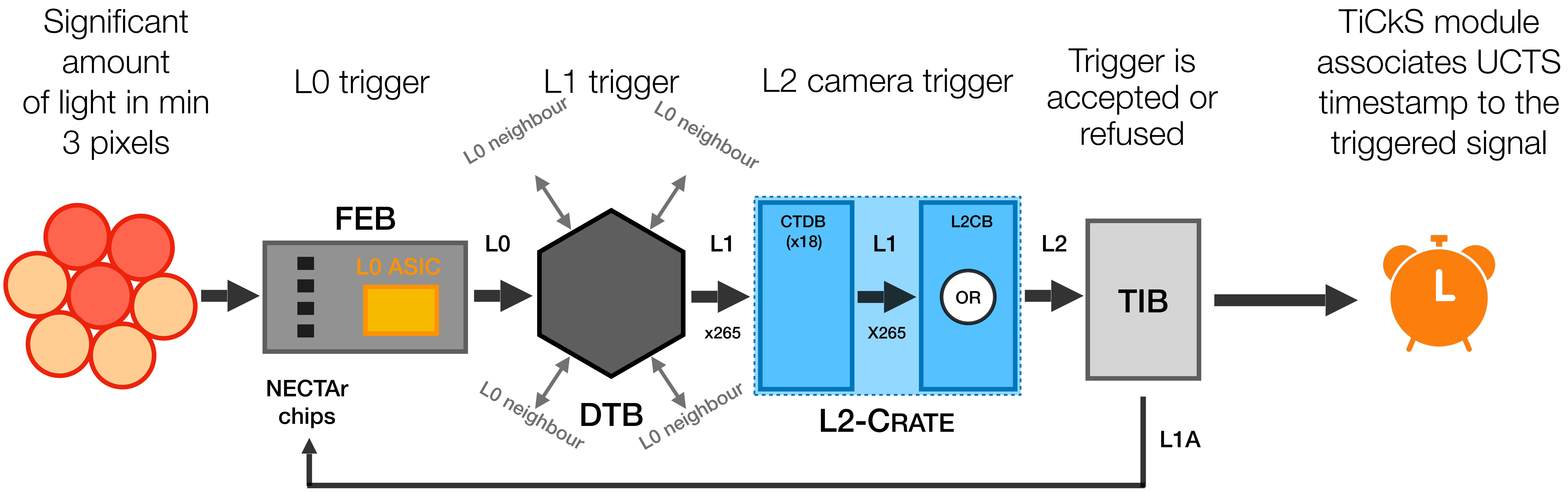
Formation of the electric signal



6. When a trigger is formed, sampling is stopped, data are readout, digitised in a 12-bit ADC and sent to the **camera server** by Ethernet

The NectarCAM Trigger

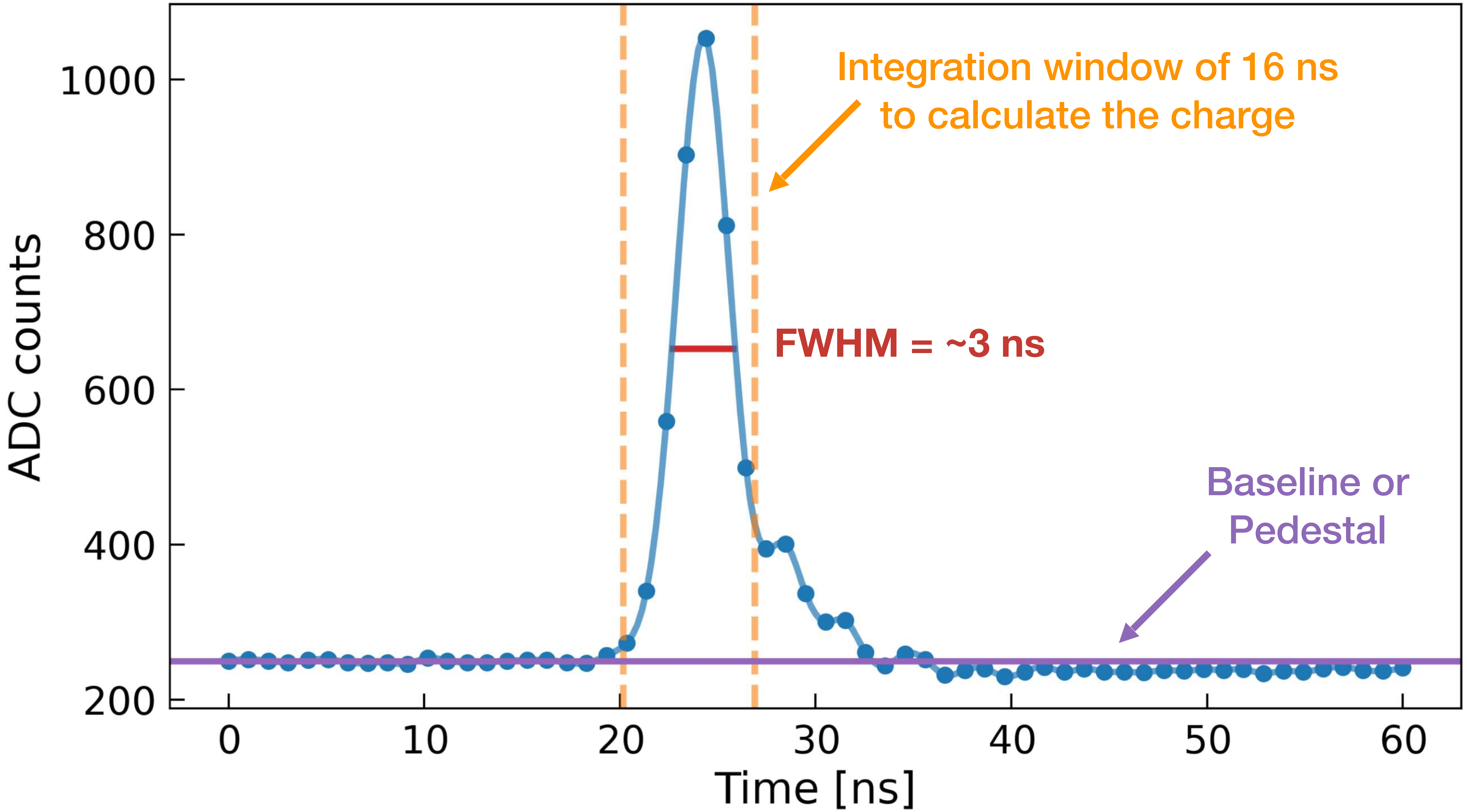
From the single pixels to a camera trigger



Sampling in the NECTAr chips is stopped and data readout

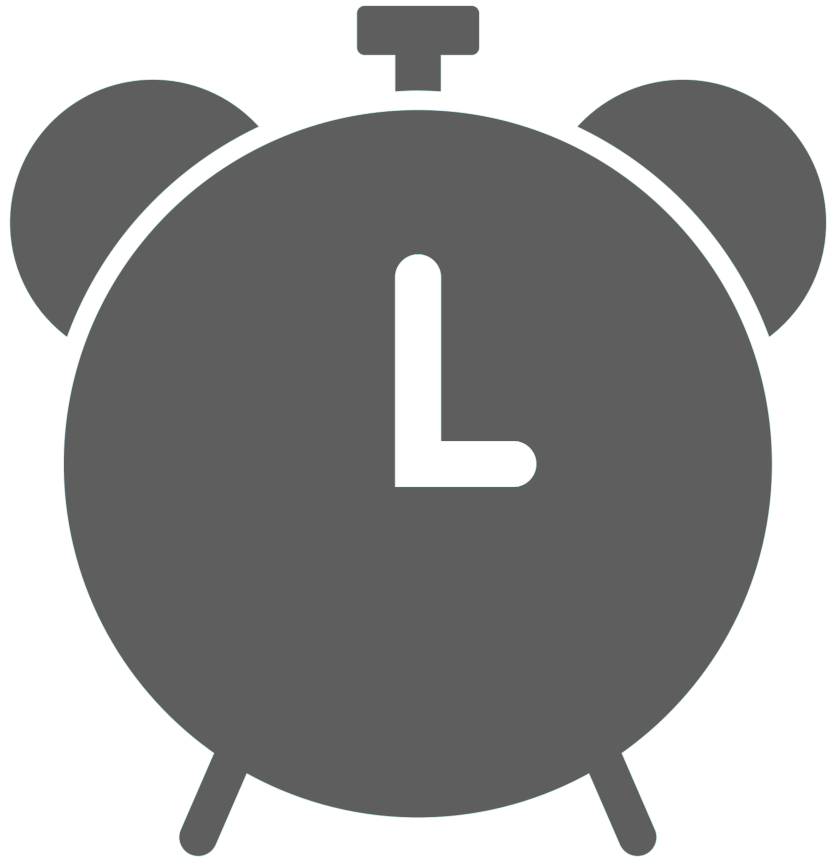
PMT waveform

How a signal looks like in a pixel



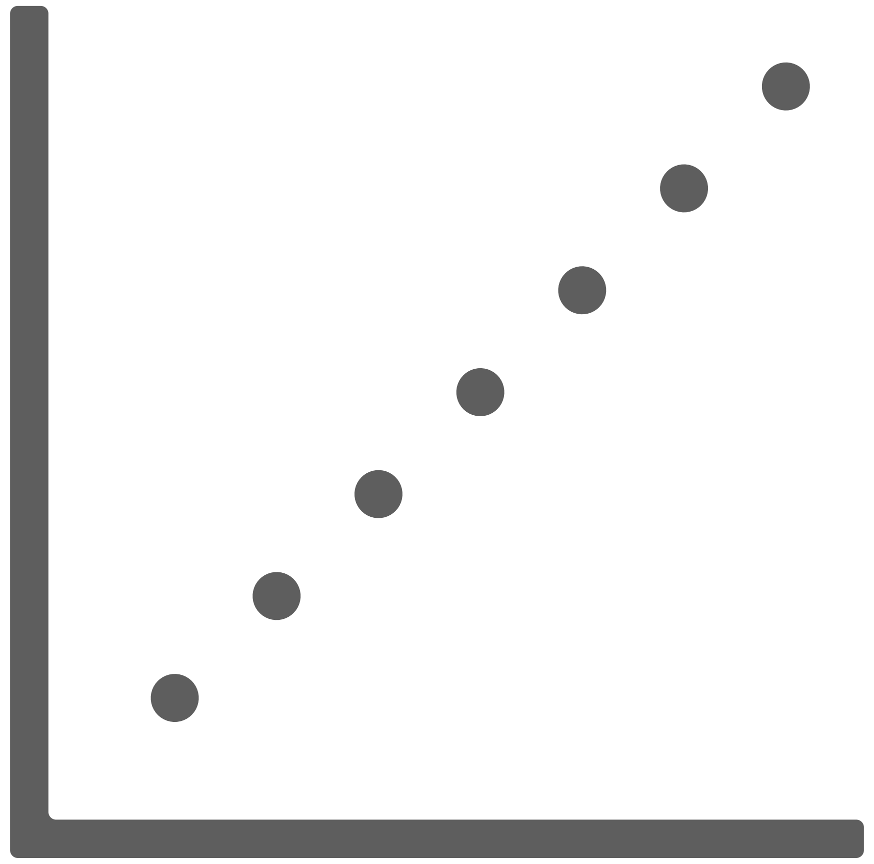
Which parameters we need to calibrate?

Some examples…



TIMING

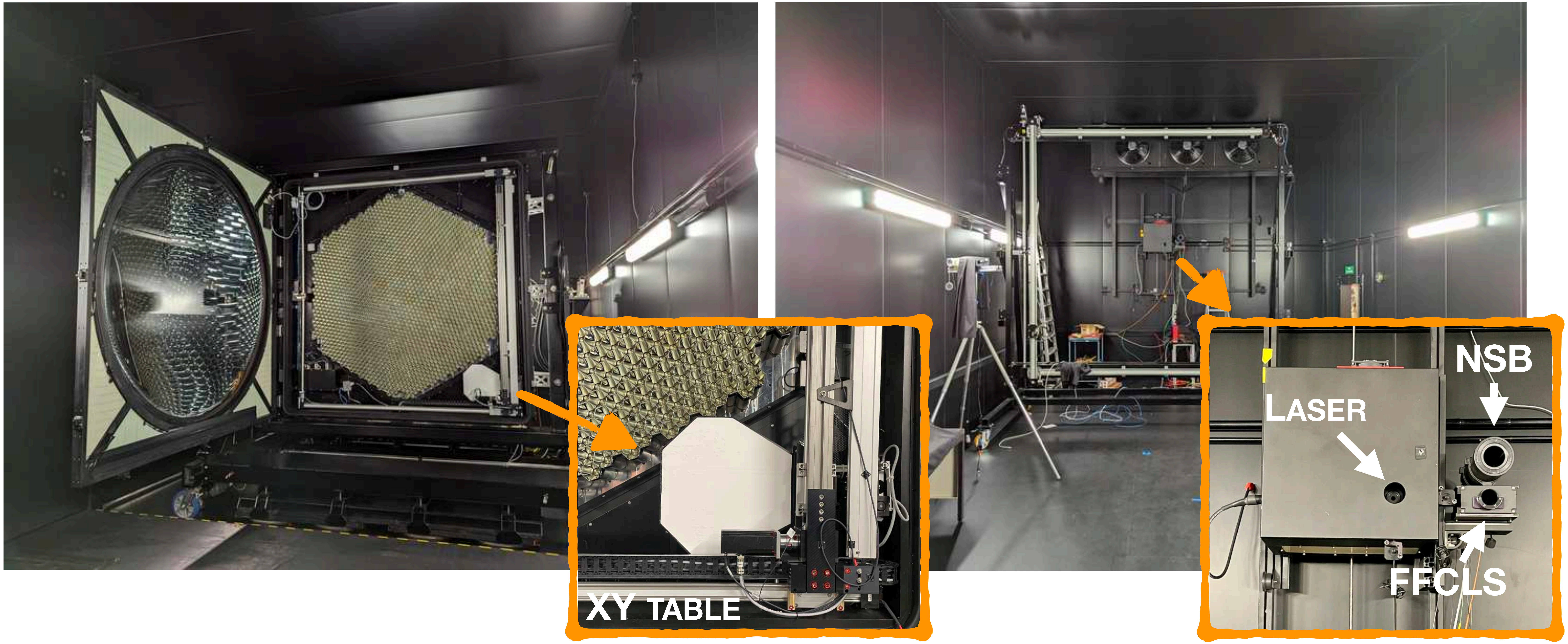
DEADTIME



LINEARITY

Light sources of NectarCAM

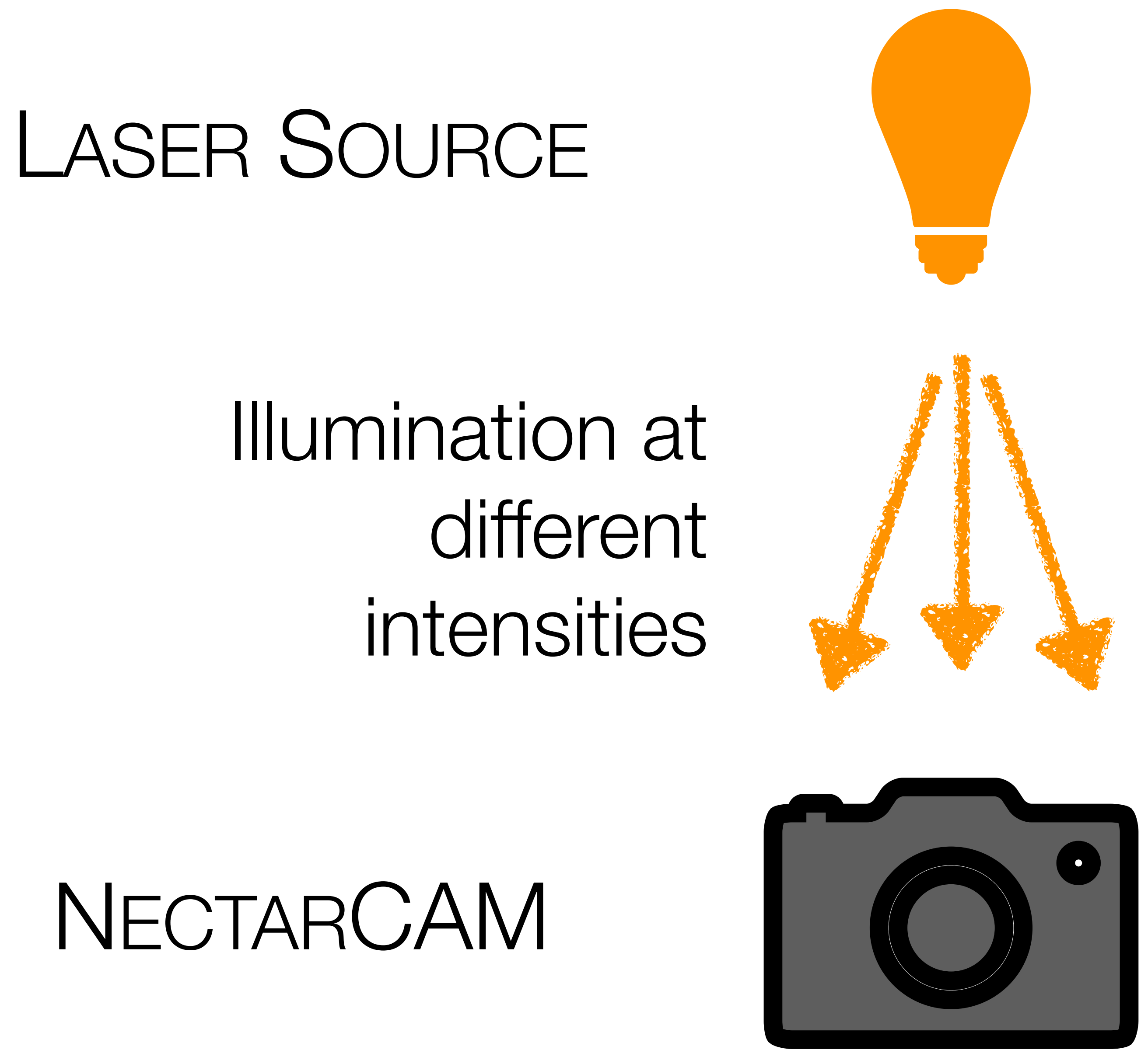
In the testbench at CEA Paris-Saclay



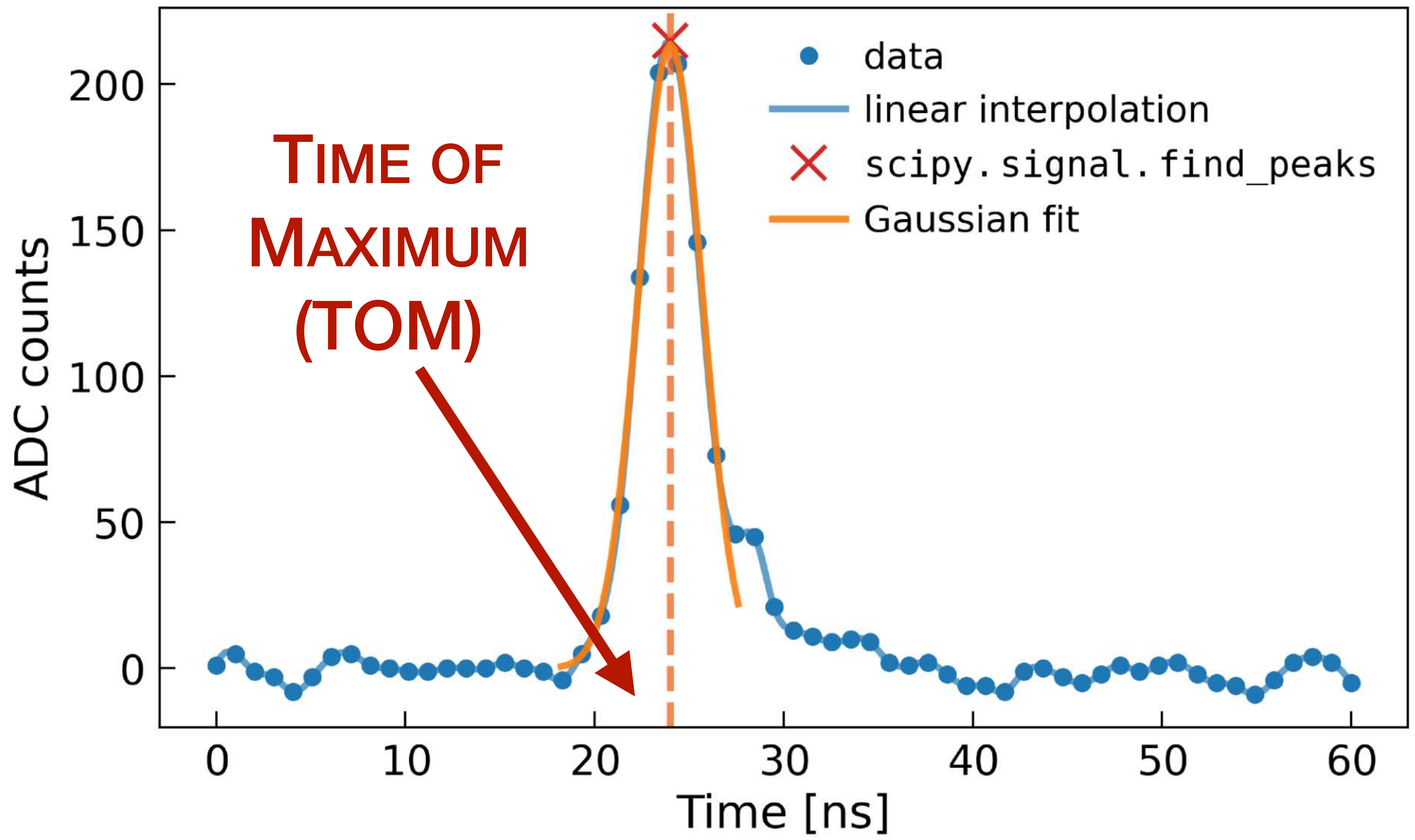
NectarCAM timing performance

Precise timing information to combine Cherenkov light from all telescopes and accurately reconstruct the showers

Test Setup

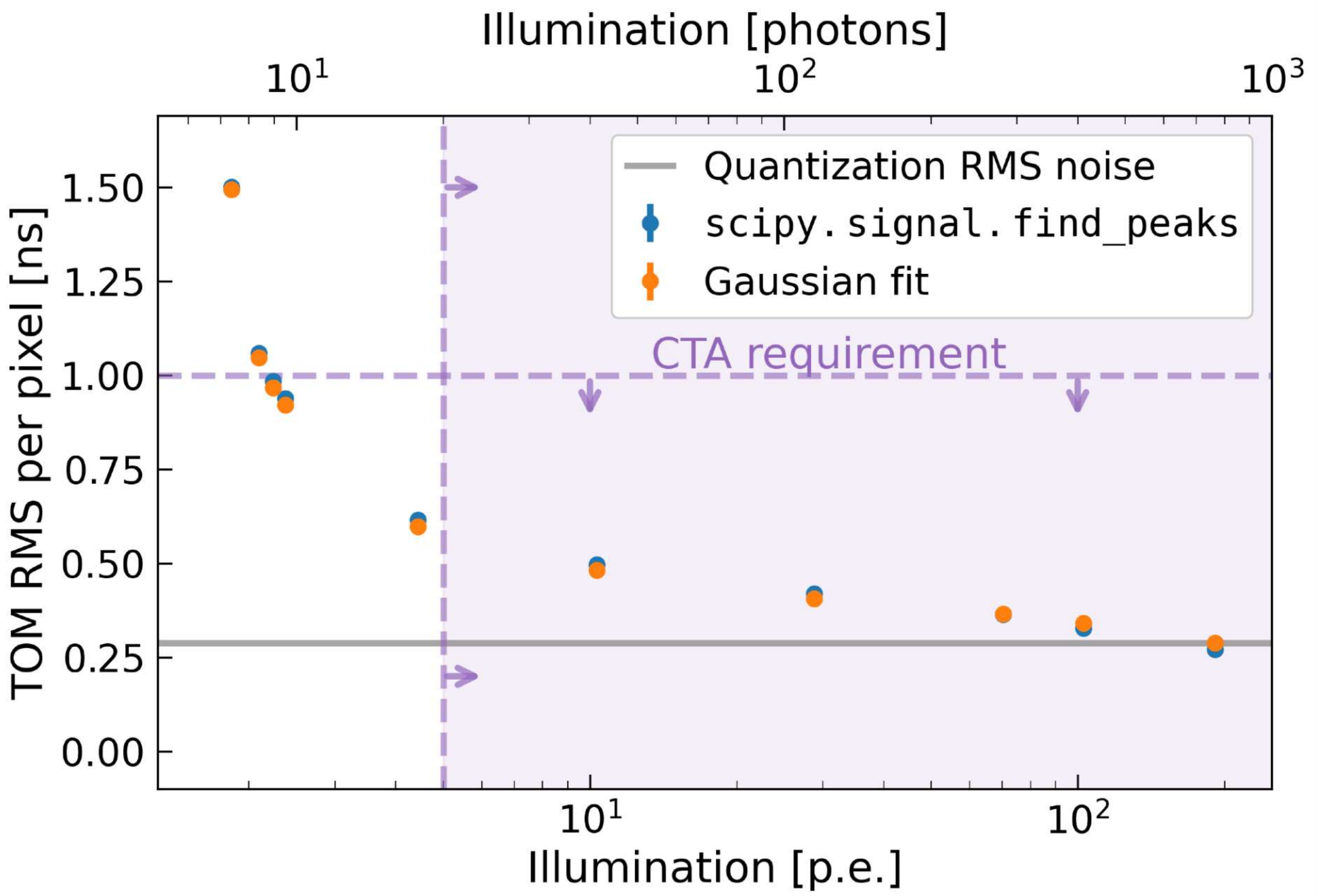


Measurement



NectarCAM timing performance

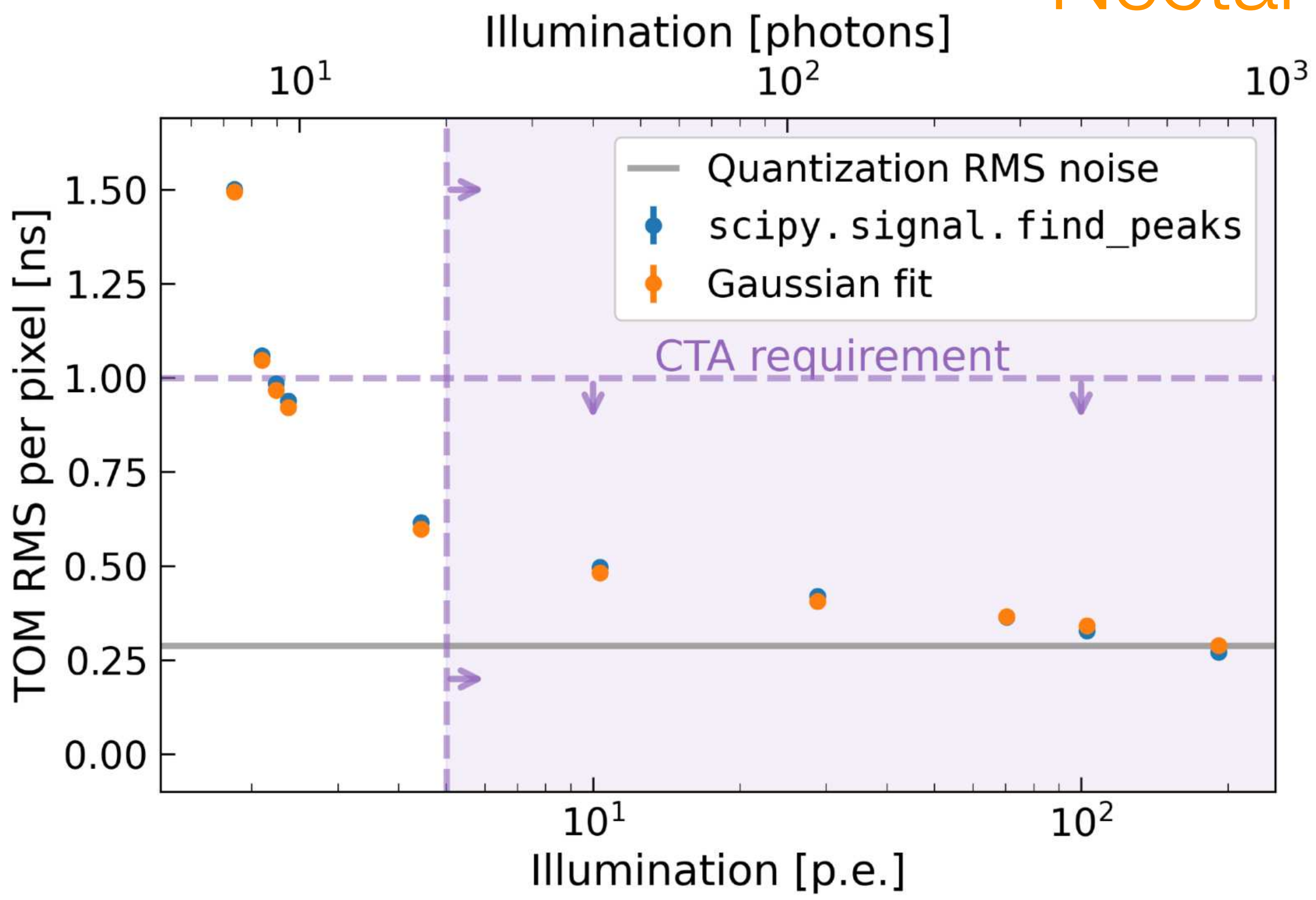
Single pixel timing precision

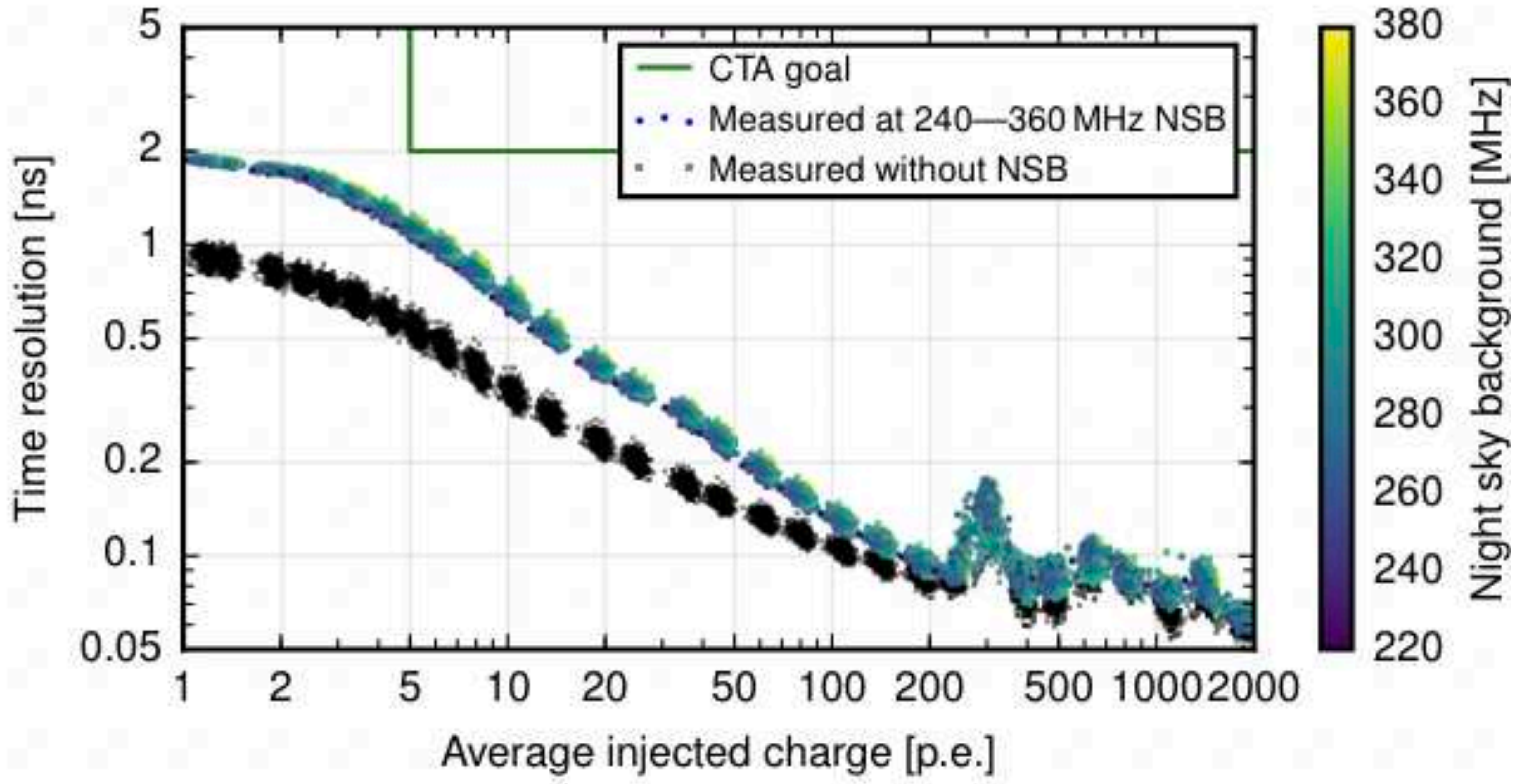


CTA requirement: < 2 ns RMS for an incoming light of intensity > 20 γ (= 5 p.e.)

Timing performance

NectarCAM vs FlashCam





Limited by **NECTAr readout** to

$$1 \text{ ns}/\sqrt{12} = 290 \text{ ps}$$

At **low intensities**, limited by statistical noise + PMT TT
At **~250 p.e.**, limited by transition from linear to non-linear amplification

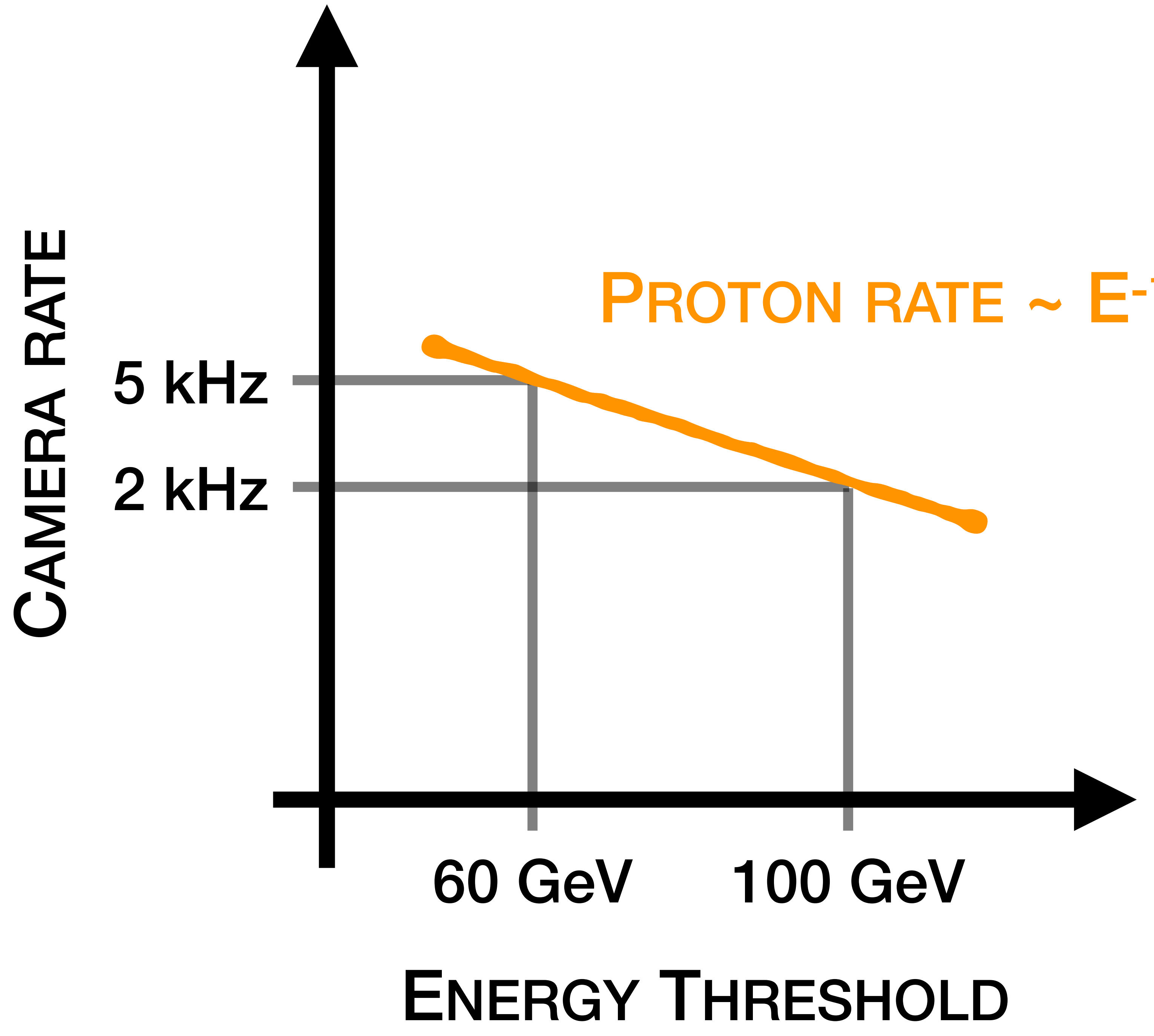
CTA requirement: < 2 ns RMS for an incoming light of intensity > 20 γ (= 5 p.e.)

NectarCAM deadtime

A new NECTAr chip to reduce the deadtime

LOWER DEADTIME → HIGHER TRIGGER RATE → LOWER ENERGY THRESHOLD

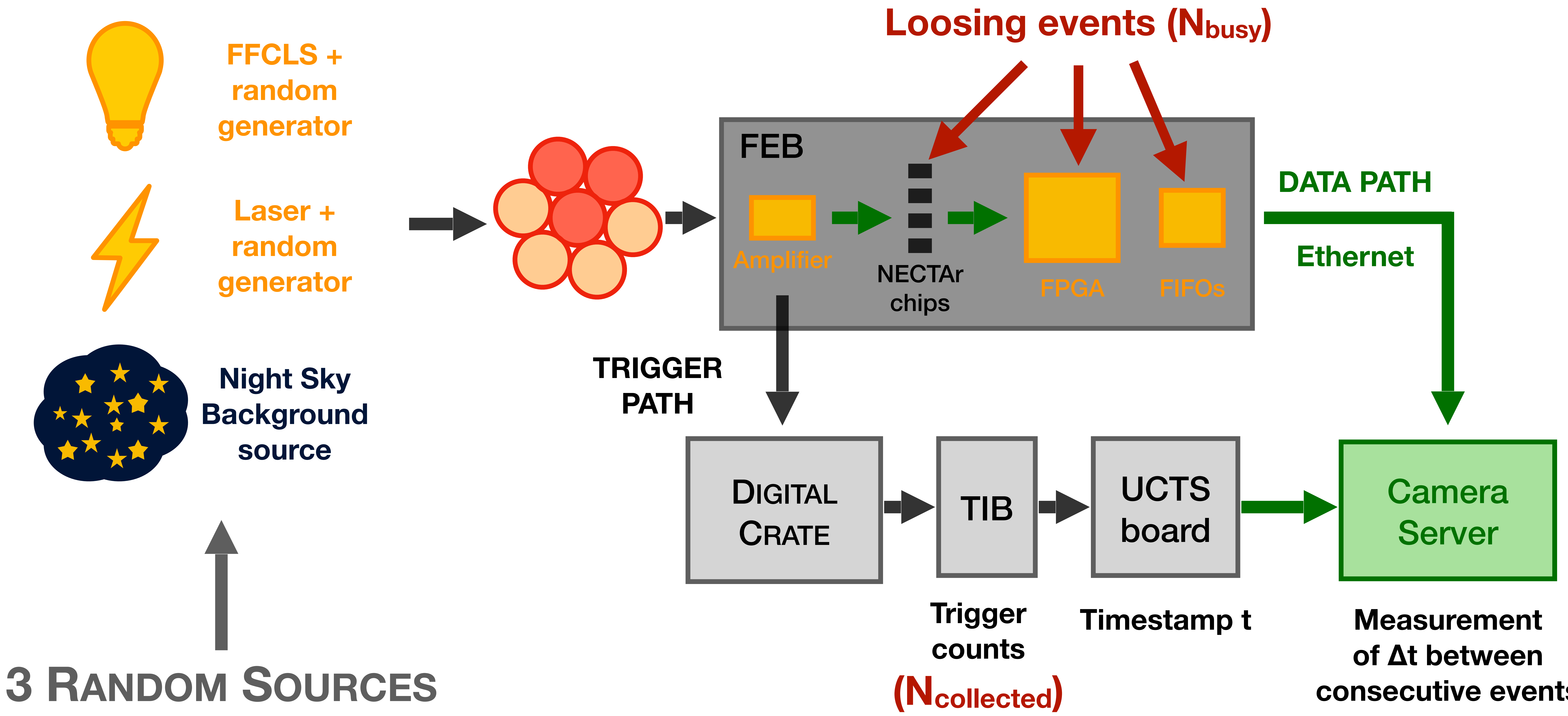
- The current NECTAr chip readout dominates the deadtime ~5% at 7kHz
- The new FEB (version 6) uses a new NECTAr chip which can run in ***ping-pong*** mode
- This reduces the deadtime by an order of magnitude



Deadtime tested at IRFU with ~10 preseries FEBv6

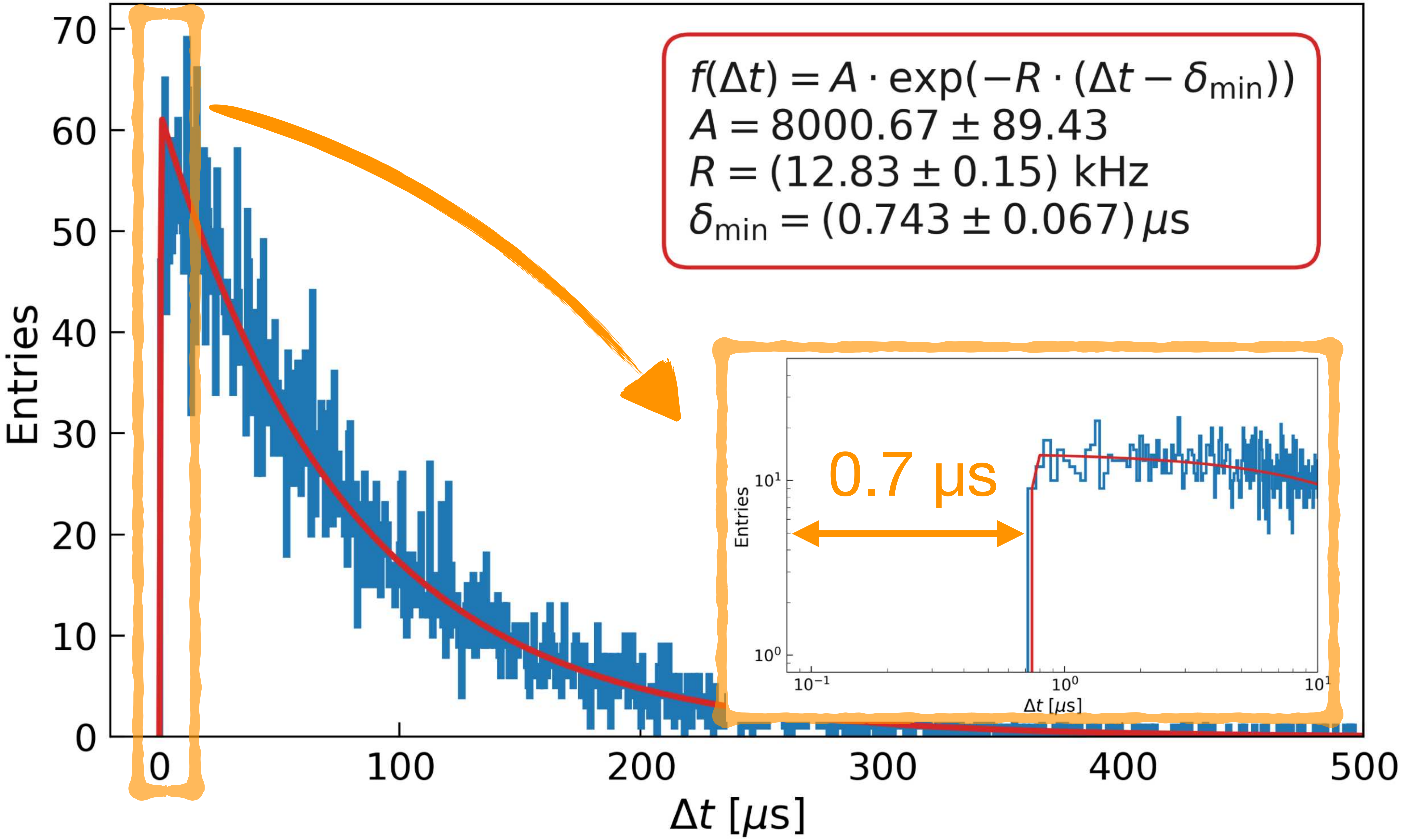
NectarCAM deadtime fraction

Method 1: $N_{busy} / N_{collected}$



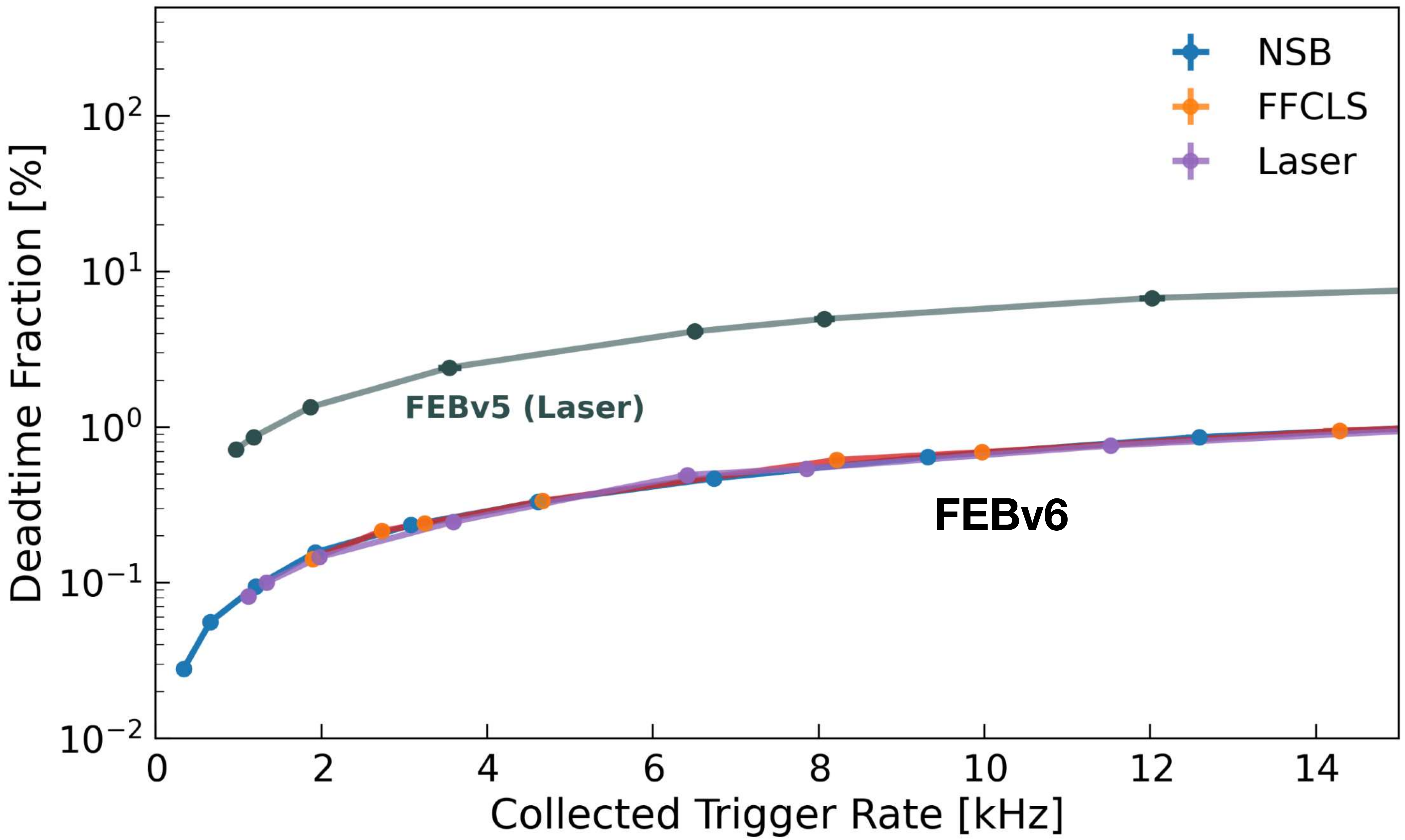
NectarCAM deadtime fraction

Method 2: $\delta_{deadtime} \times R$



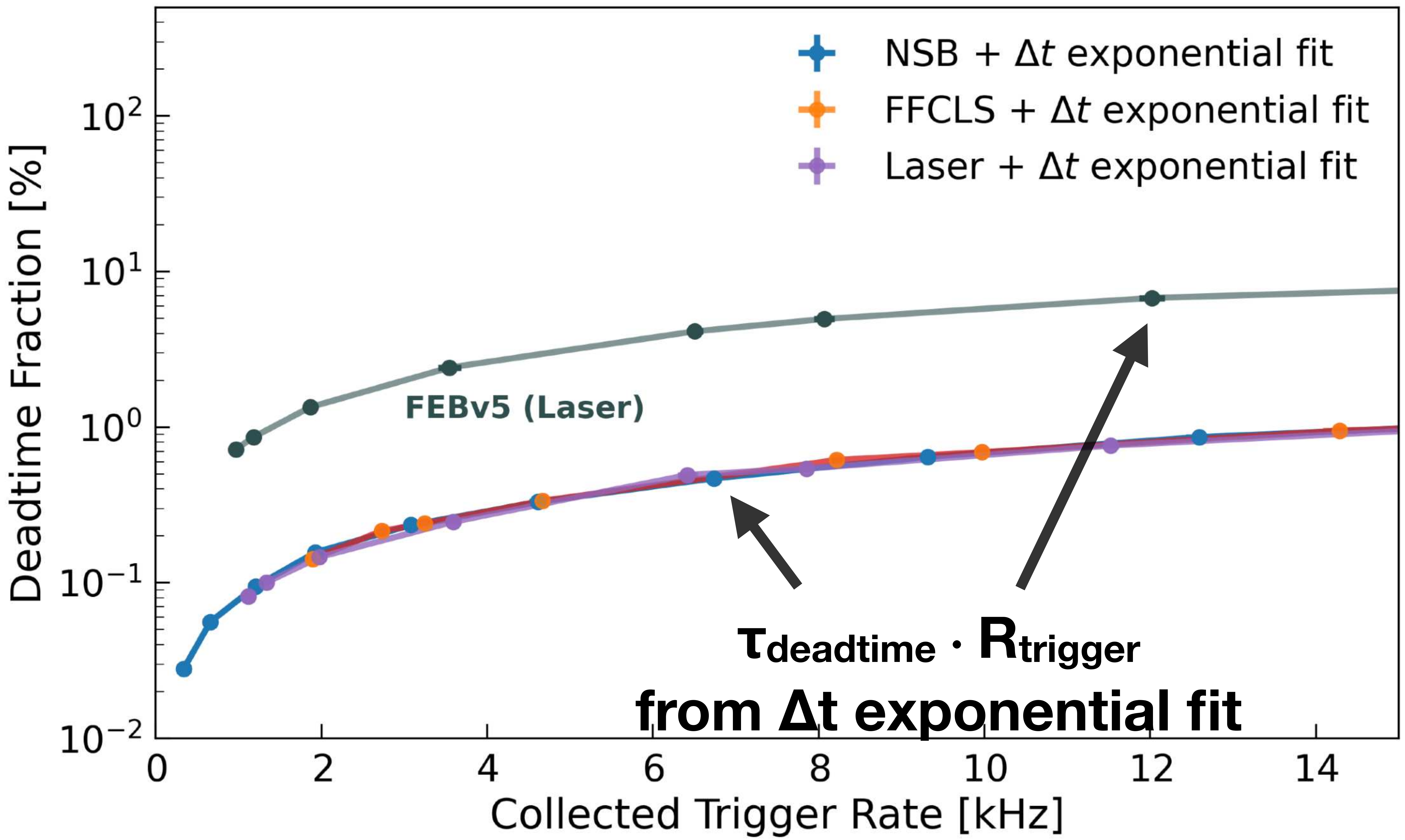
NectarCAM deadtime results

Results for the 3 sources and 2 methods



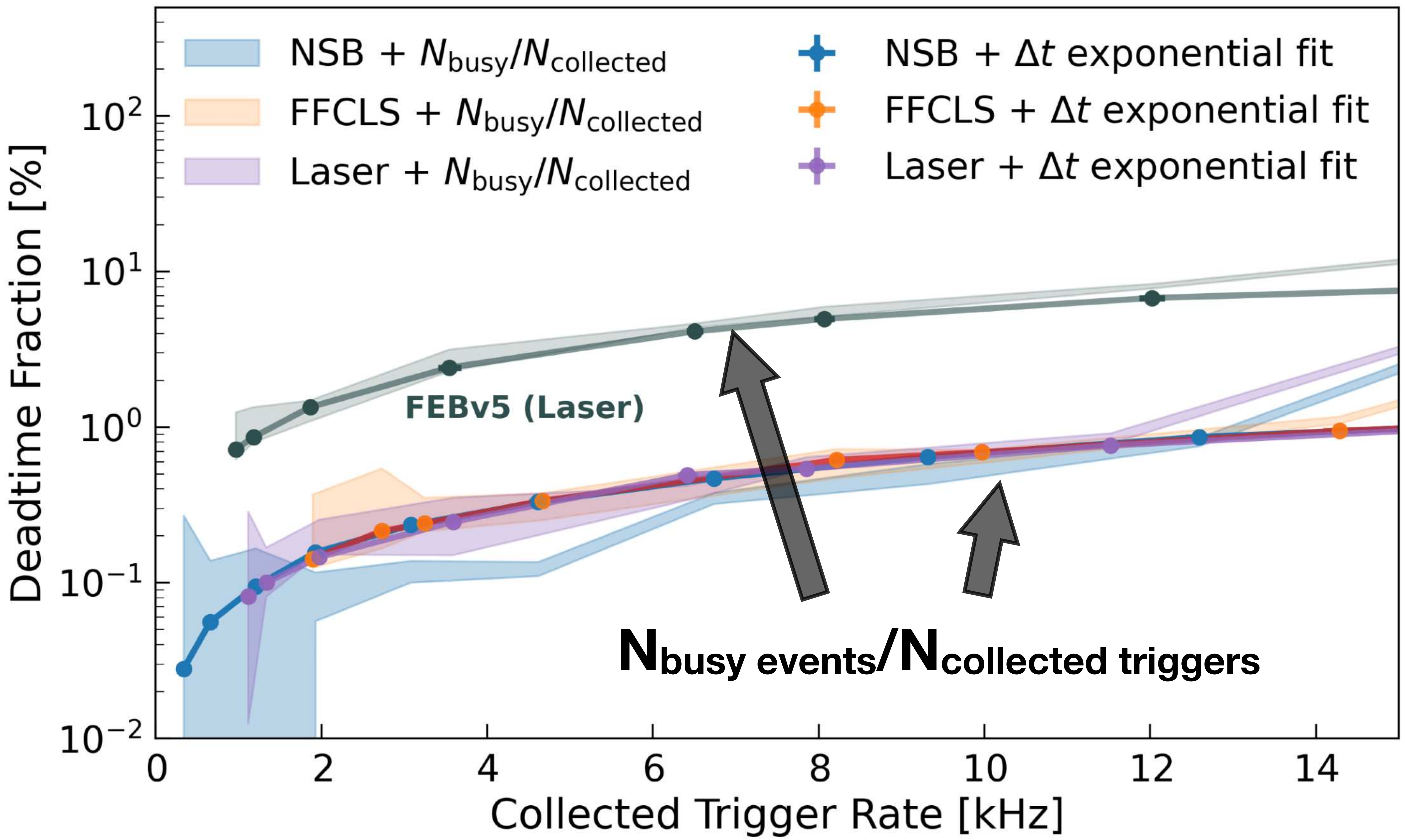
NectarCAM deadtime results

Results for the 3 sources and 2 methods



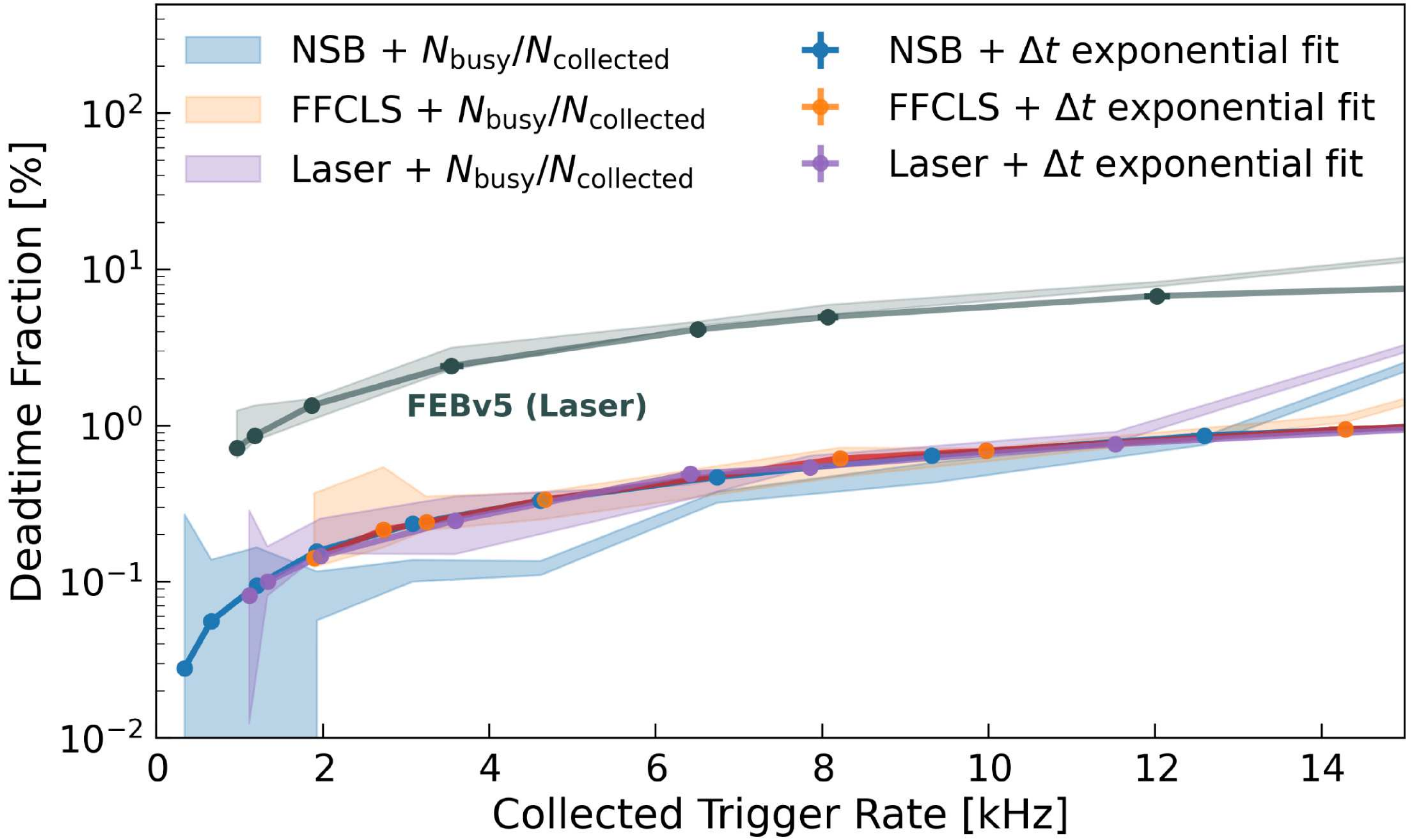
NectarCAM deadtime results

Results for the 3 sources and 2 methods



NectarCAM deadtime results

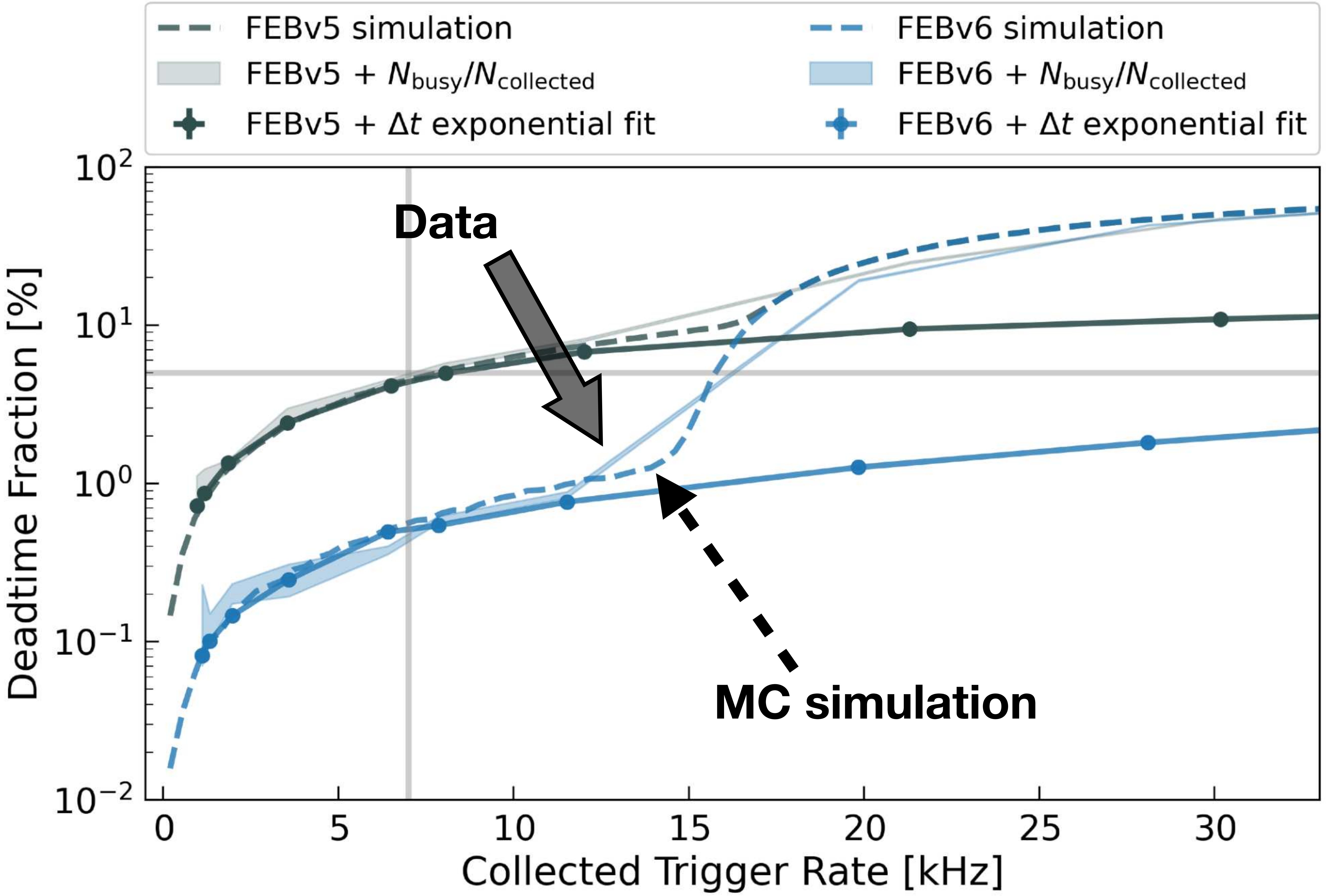
Results for the 3 sources and 2 methods



3 measurements give comparable results: FEBv6 deadtime < 5% at 7 kHz

NectarCAM deadtime results

Measurement vs MC simulations



FIFOs become main contributor of deadtime fraction above 15 kHz

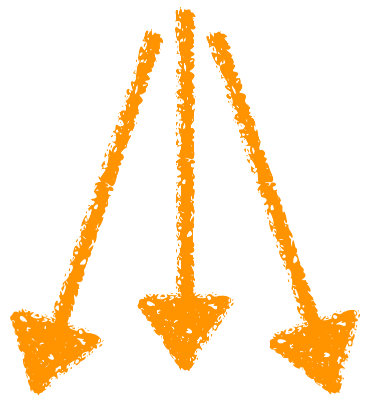
NectarCAM linearity test

Goal: to show that the light measured by the new FEBv6 is linearly proportional to the input light

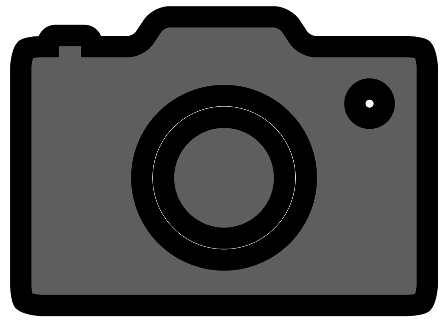
Test Setup

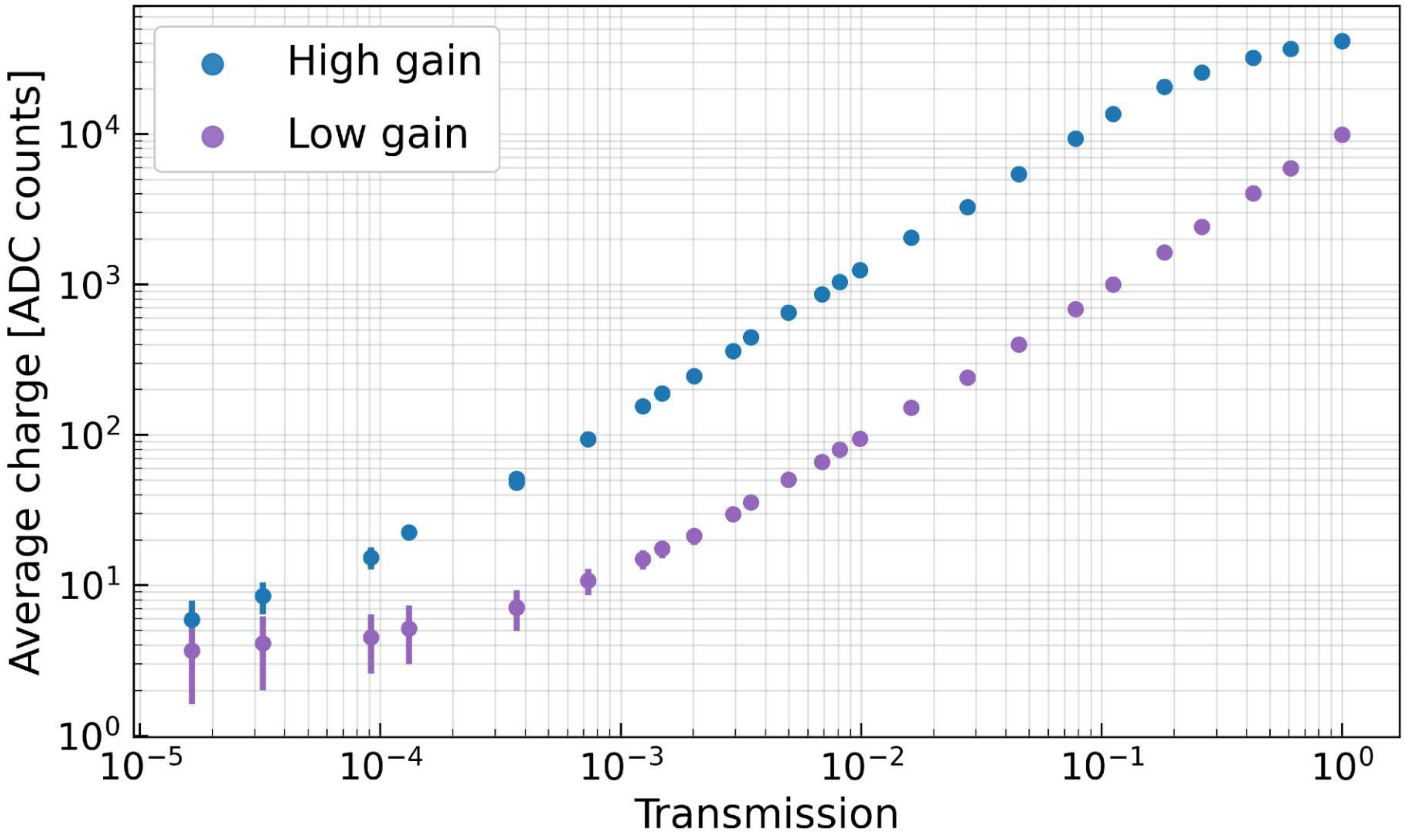
FFCLS + EDMUND FILTERS

Illumination at same intensity with different filters

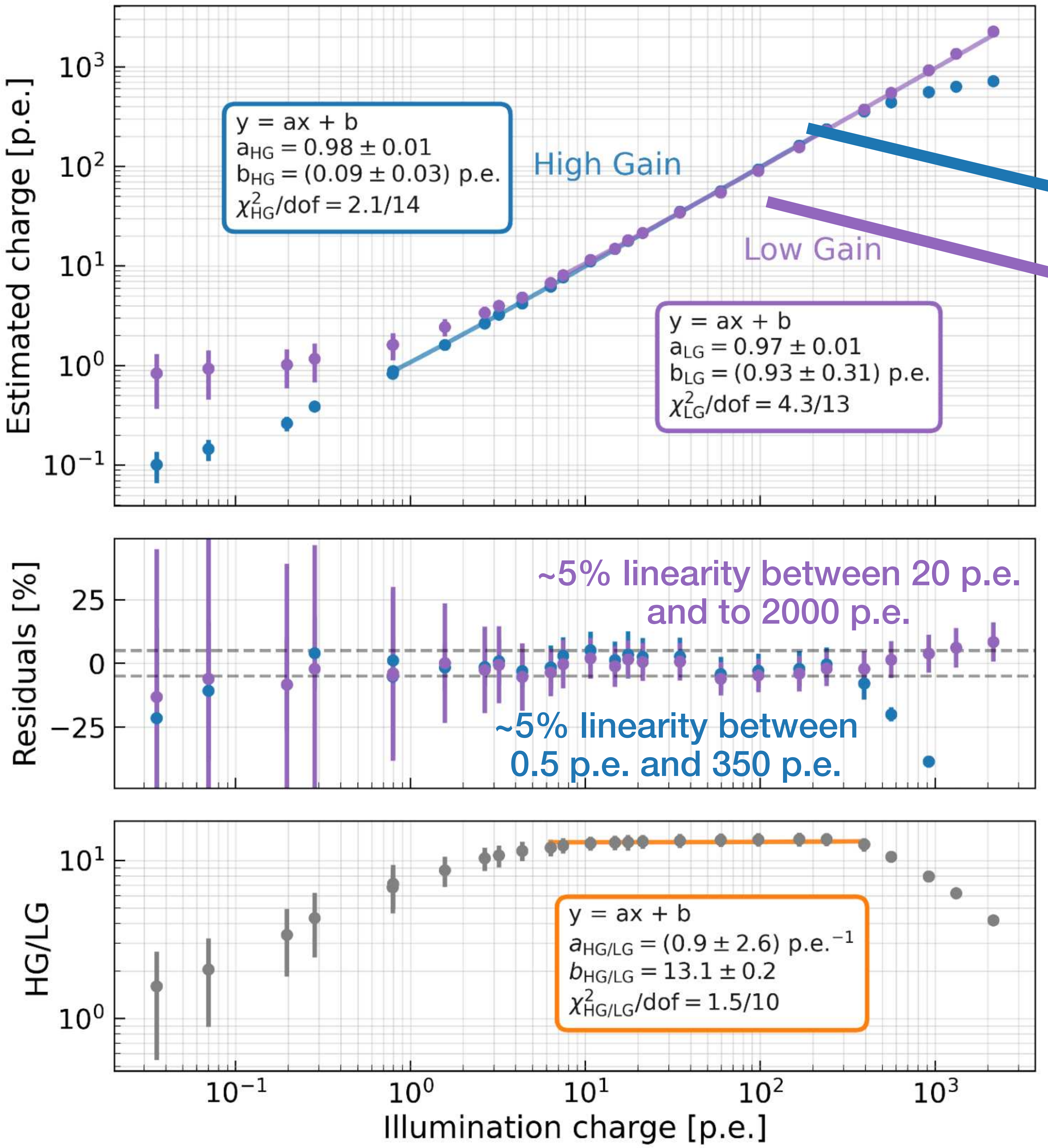


NECTARCAM





NectarCAM linearity results



High gain, expect slope of 1

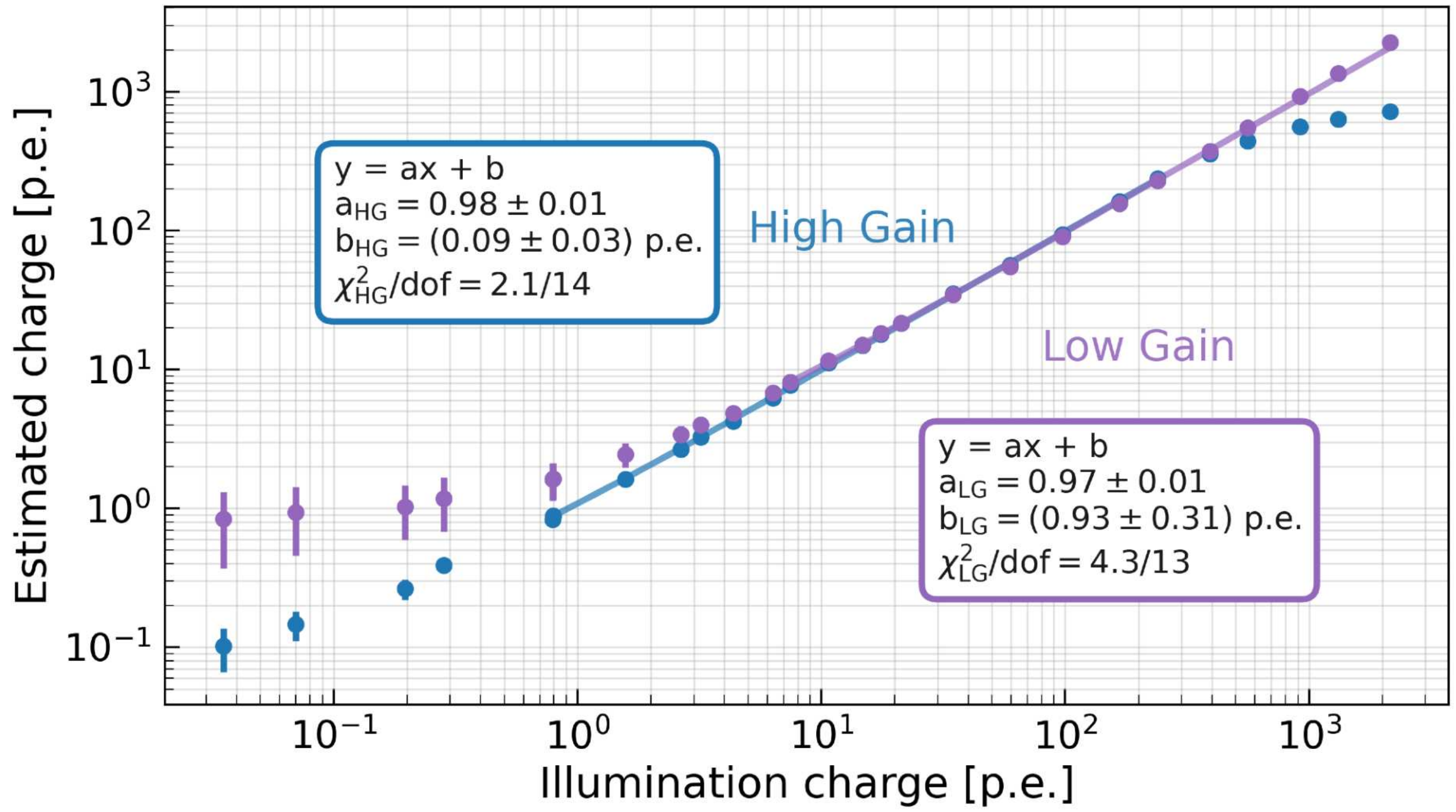
Low gain, expect slope of 1

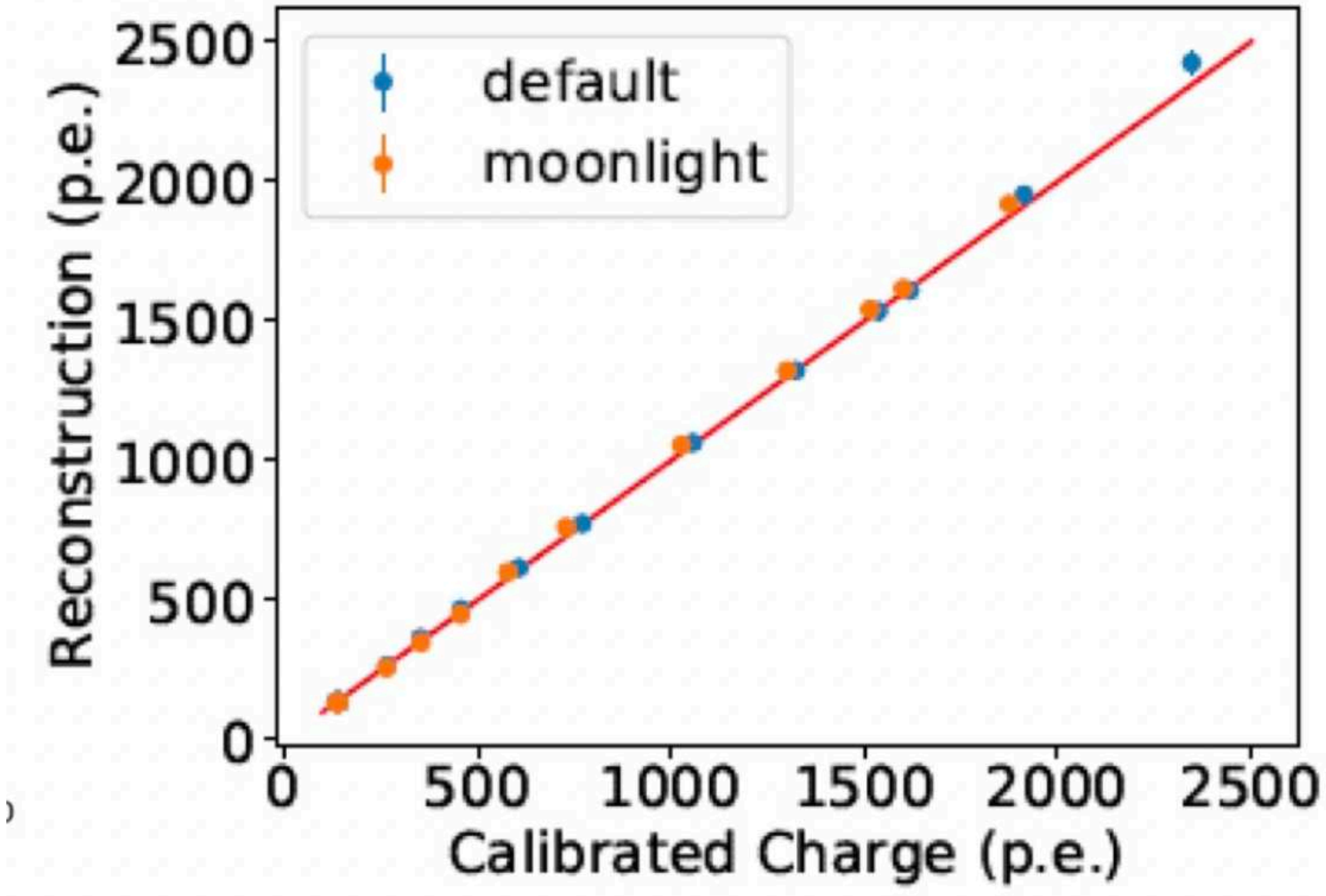
NectarCAM read-out is linear at better than 5% in range [0.5 — 2000] p.e.

Overlap region between low and high gain channels: 20-300 p.e. (useful for cross calibration)

Linearity

NectarCAM vs FlashCam



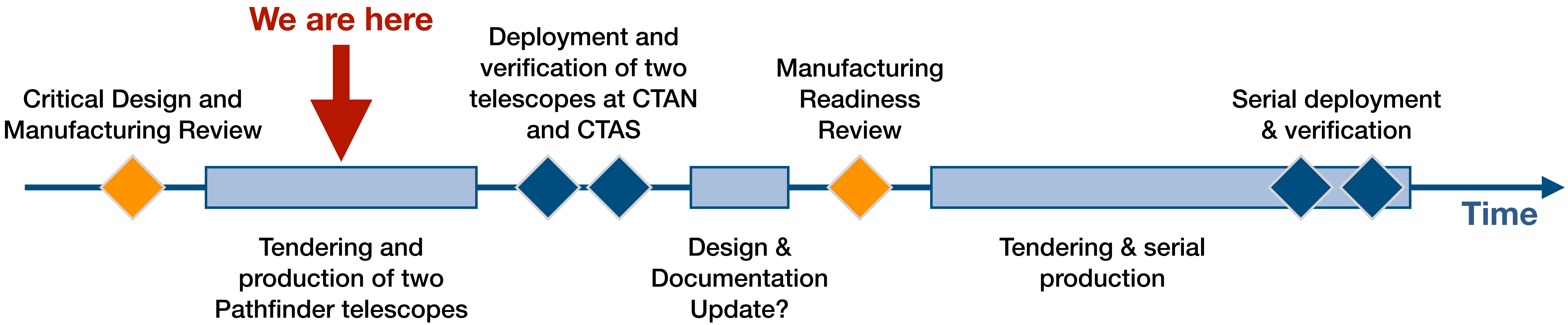


Dynamic range **0.5—2000 p.e.** obtained with **2 gain channels** per pixel and **linear amplifilication**

Dynamic range **0.2—3000 p.e.** obtained with **1 channel** per pixel and **non-linear amplification**

When? The MST Project Timeline

Pathfinders: one MST on each site by summer 2025



1. 2 Pathfinder telescopes for CTAN and CTAS
2. Manufacturing Readiness Review (MRR) of telescopes structure after the deployment of the first pathfinder telescope
3. Tendering of serial production units after MRR

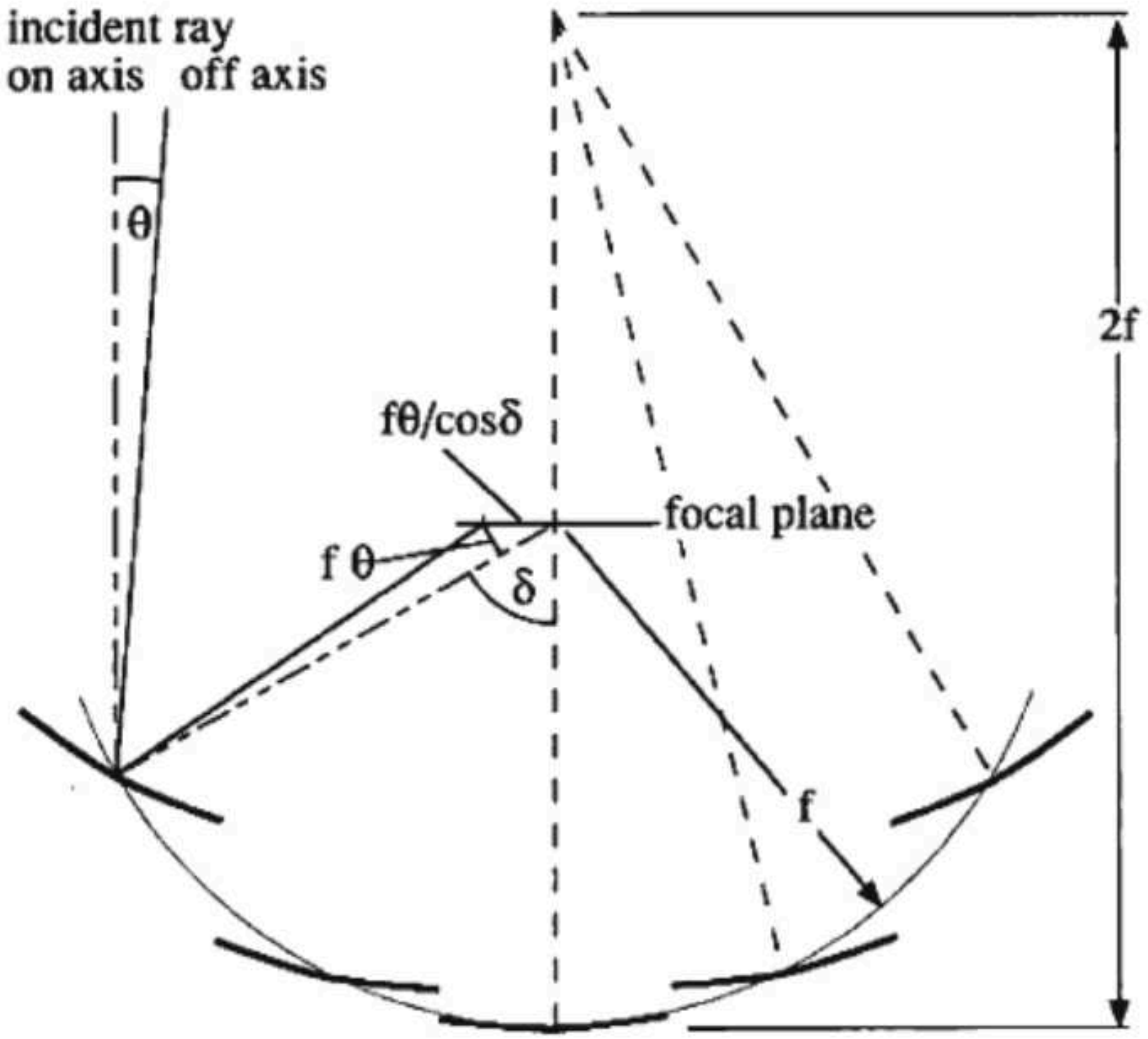
Take home messages

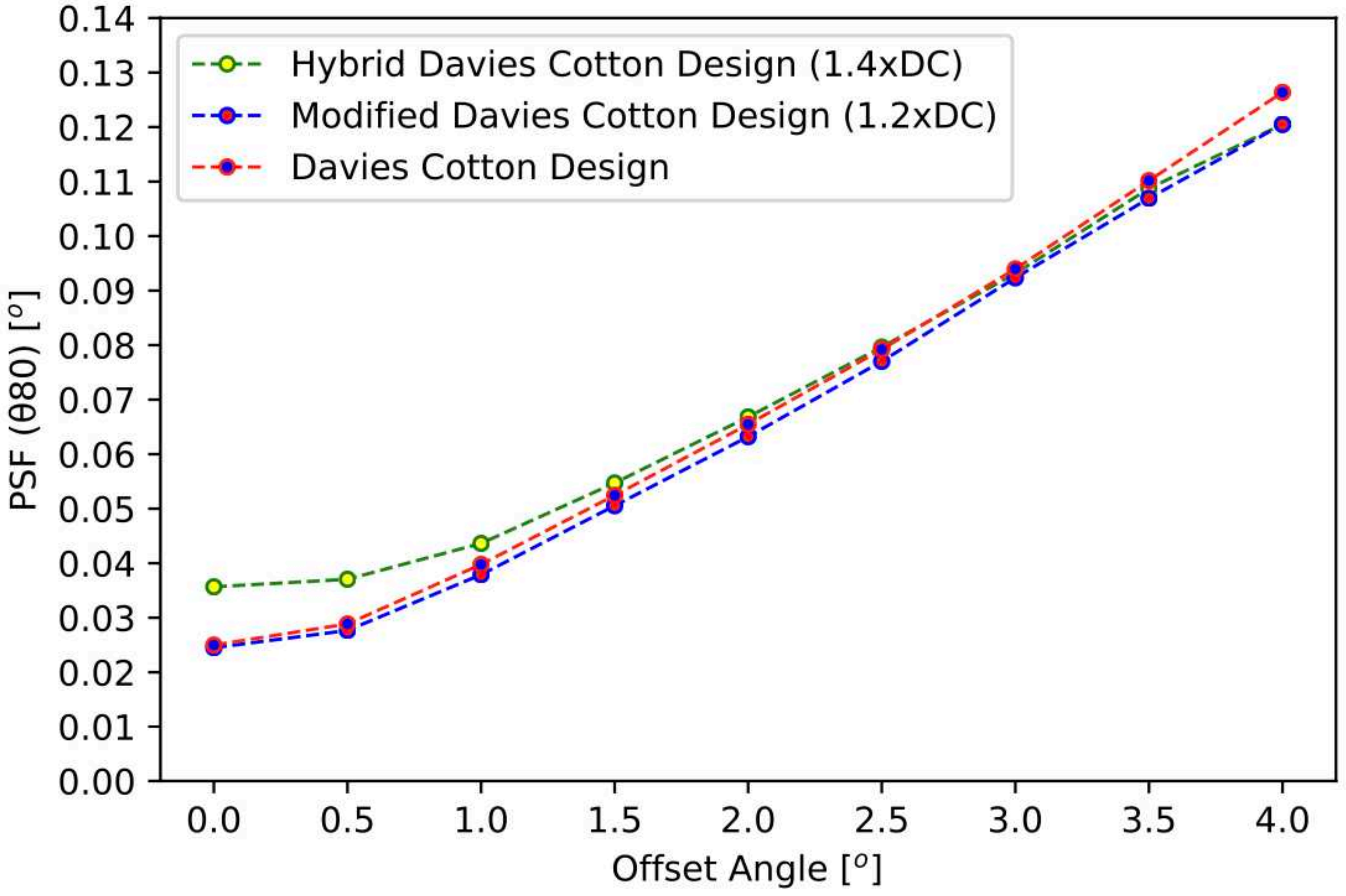
- **Why MSTs?** To detect γ-rays in middle energy range [100 GeV, 30 TeV]
- **Where?** 14 MSTs in CTAS and 9 MSTs in CTAN
- **What is an MST?**
  - Modified version of the Davies-Cotton design
    - Positioning to any point in the sky (>30° elevation) in 90 s
  - Two cameras: FlashCam (CTAS) and NectarCAM (CTAN)
    - Large field of view of about 8°
- **How do they work?**
  - FlashCam: fully-digital readout and trigger systems
  - NectarCAM: modular structure with analog trigger
- **When?** Soon :D —> in the meantime we test the cameras!

Backup

MST Structure

Davies-Cotton Optics

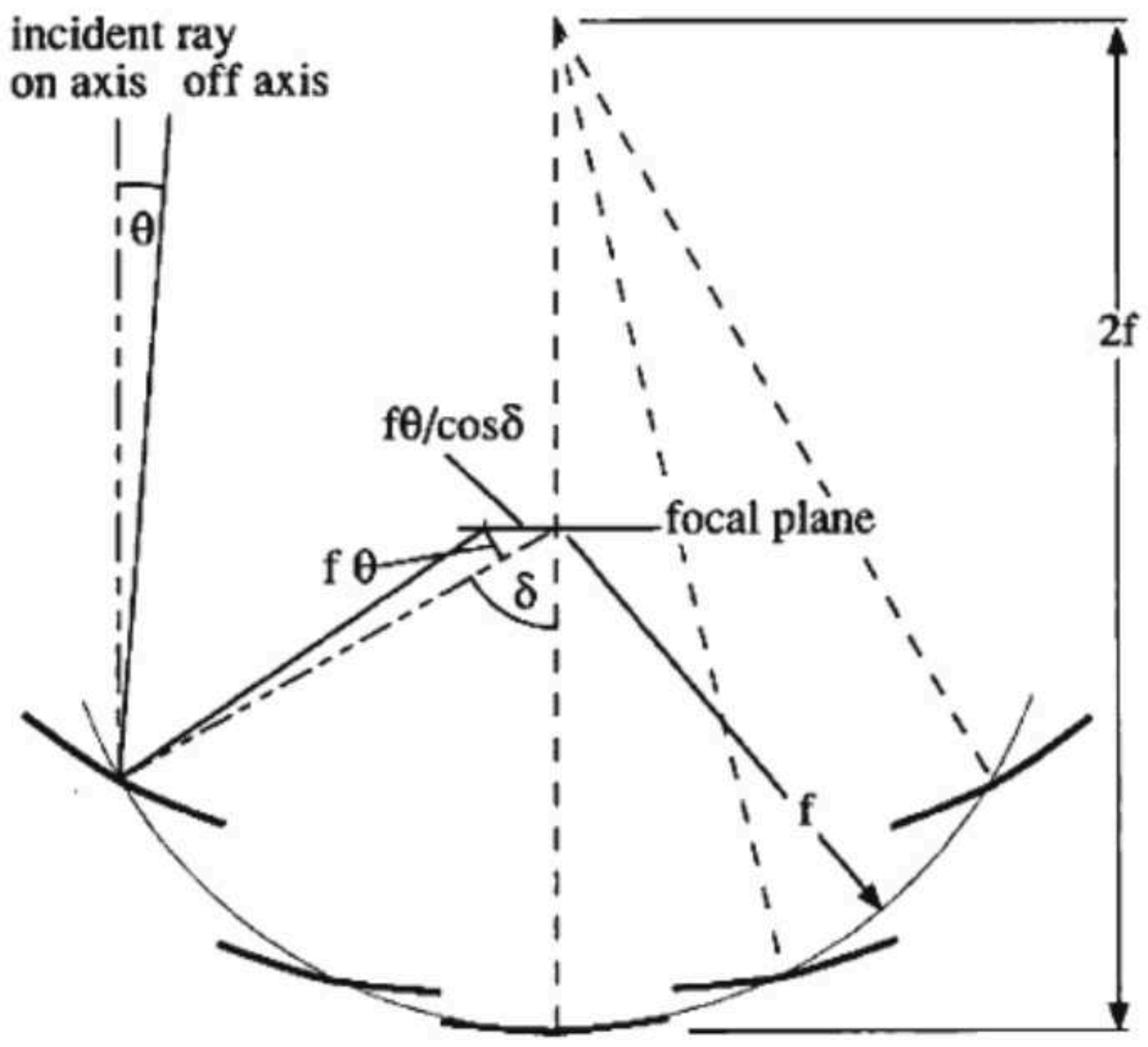


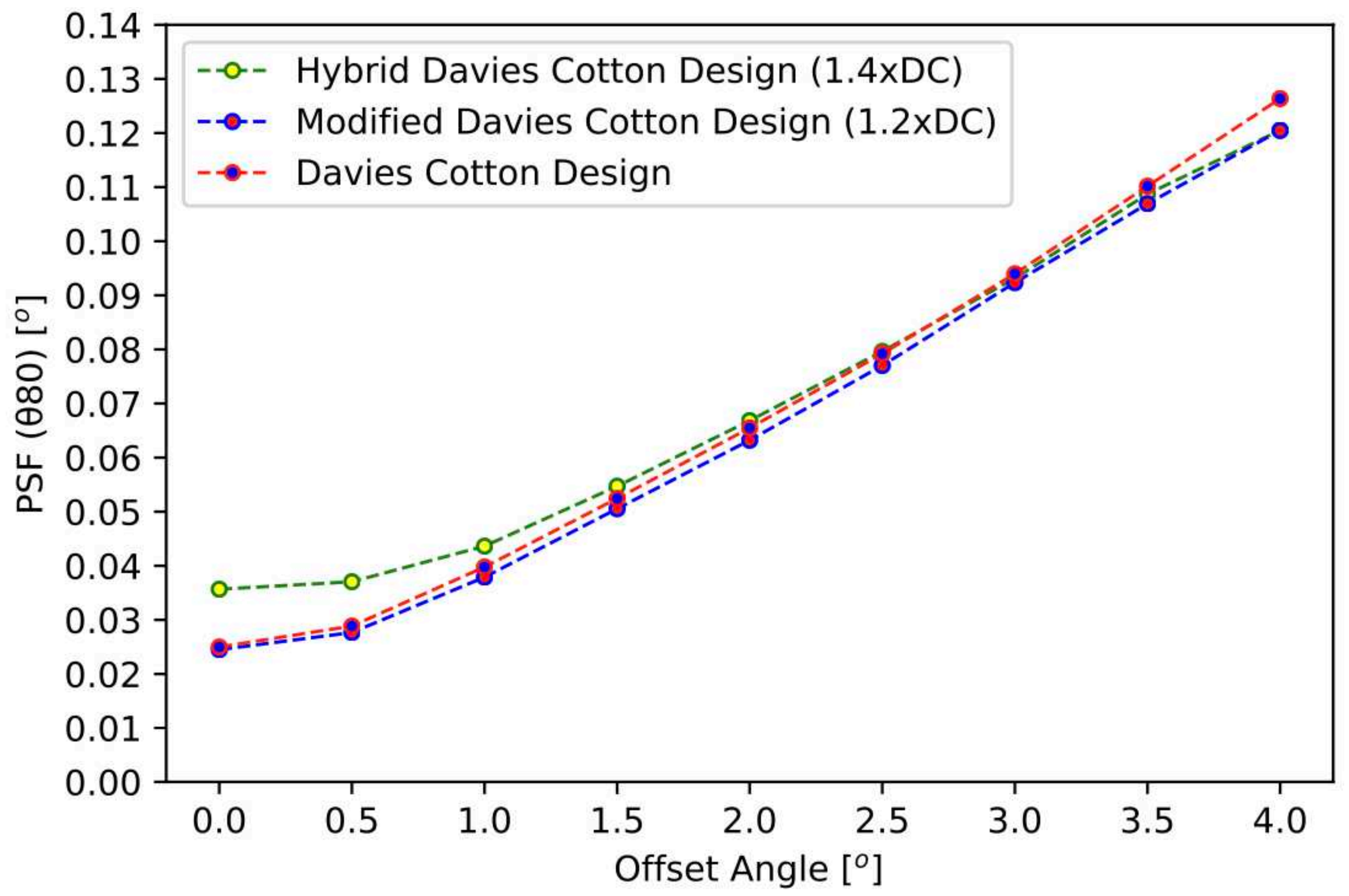


PSF of three different telescope designs on "ideal" conditions and different offset angles. Red line represents the classic Davies-Cotton design, blue line represents the Modified DC and the green line represents the Hybrid DC design.

MST Structure

Davies-Cotton Optics

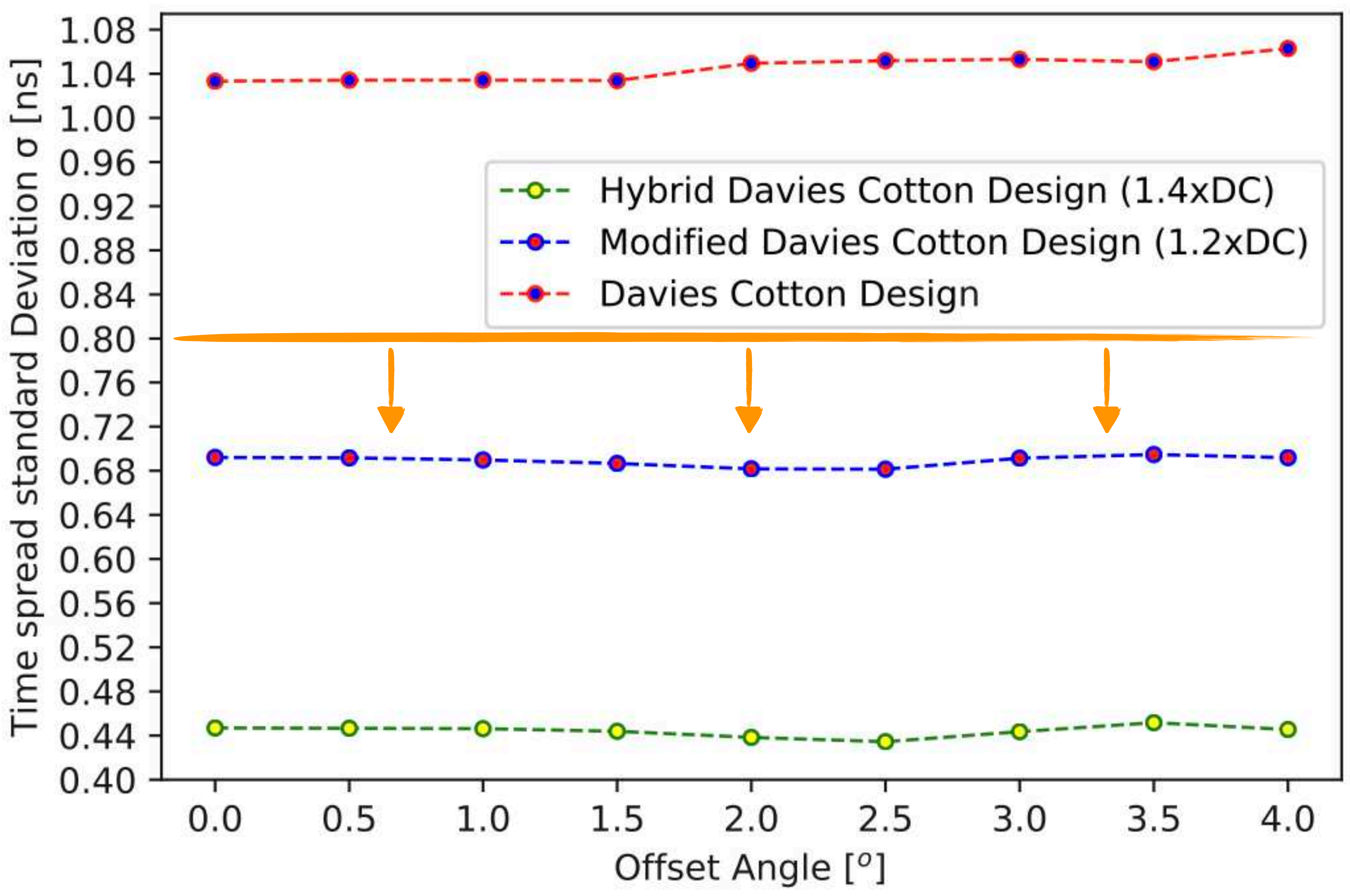




PSF of three different telescope designs on “ideal” conditions and different offset angles. Red line represents the classic Davies-Cotton design, blue line represents the Modified DC and the green line represents the Hybrid DC design.

MST Structure

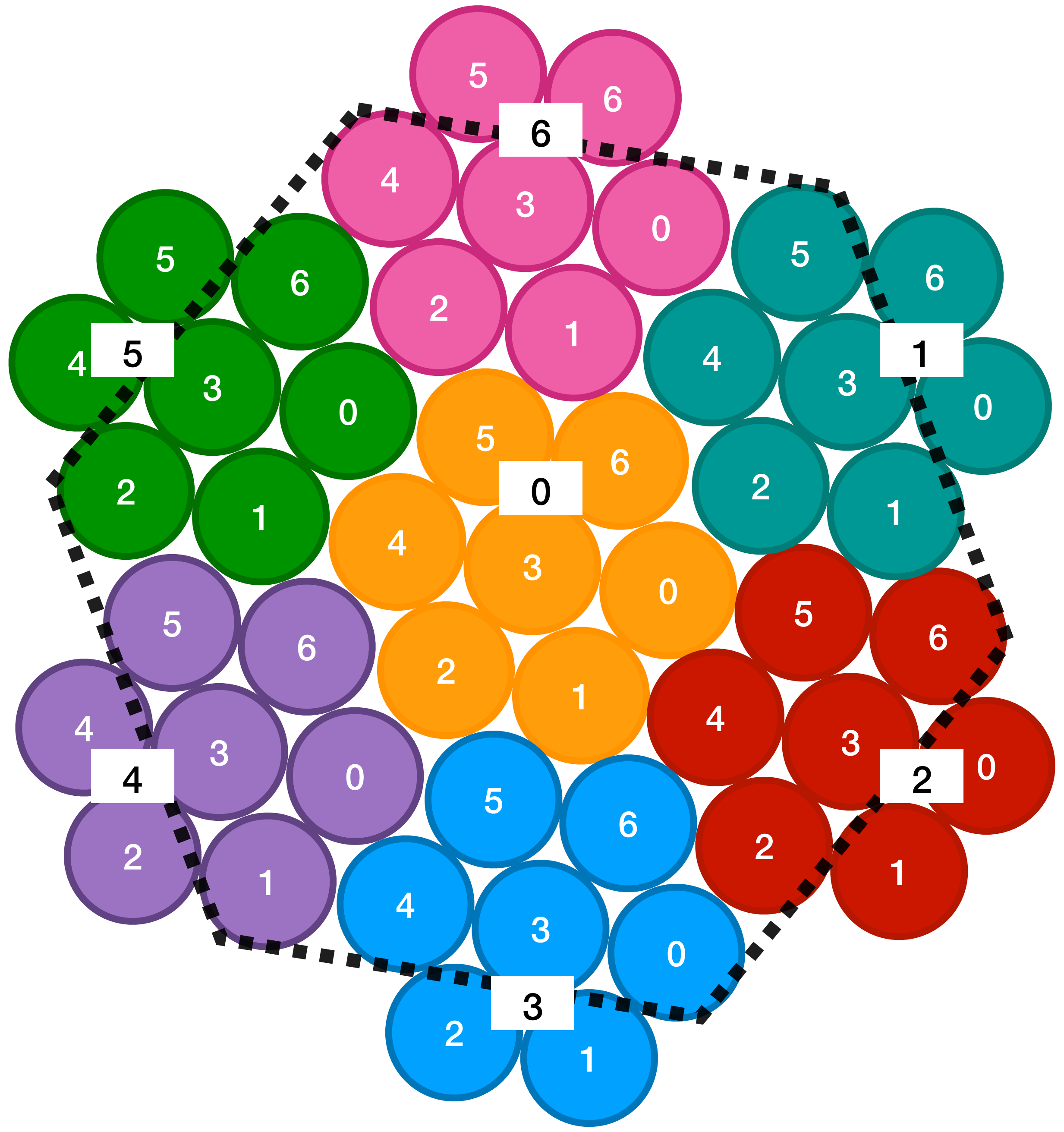
Davies-Cotton Optics

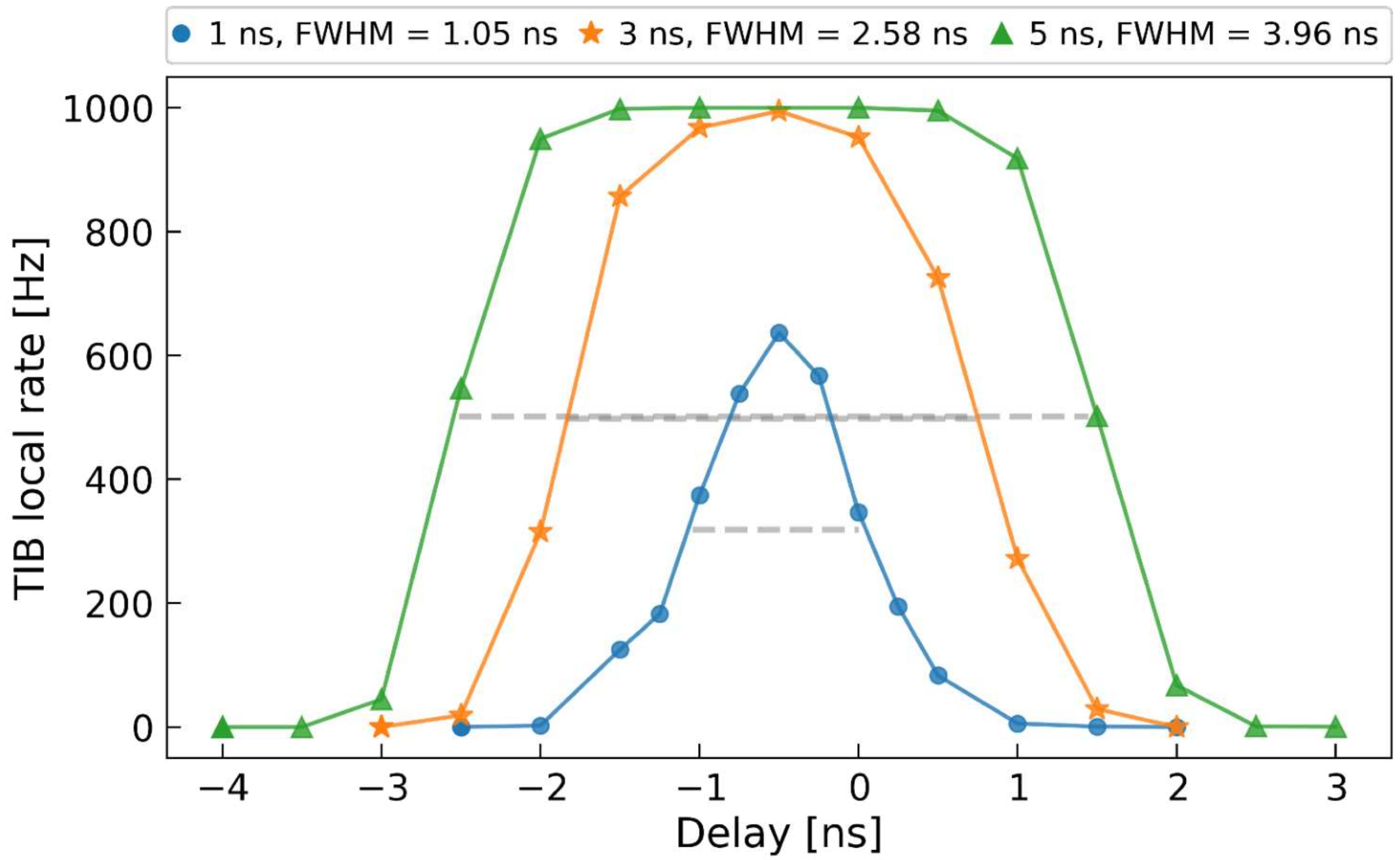


The 3 Nearest Neighbours (3NN) algorithm

When is an event recorded?

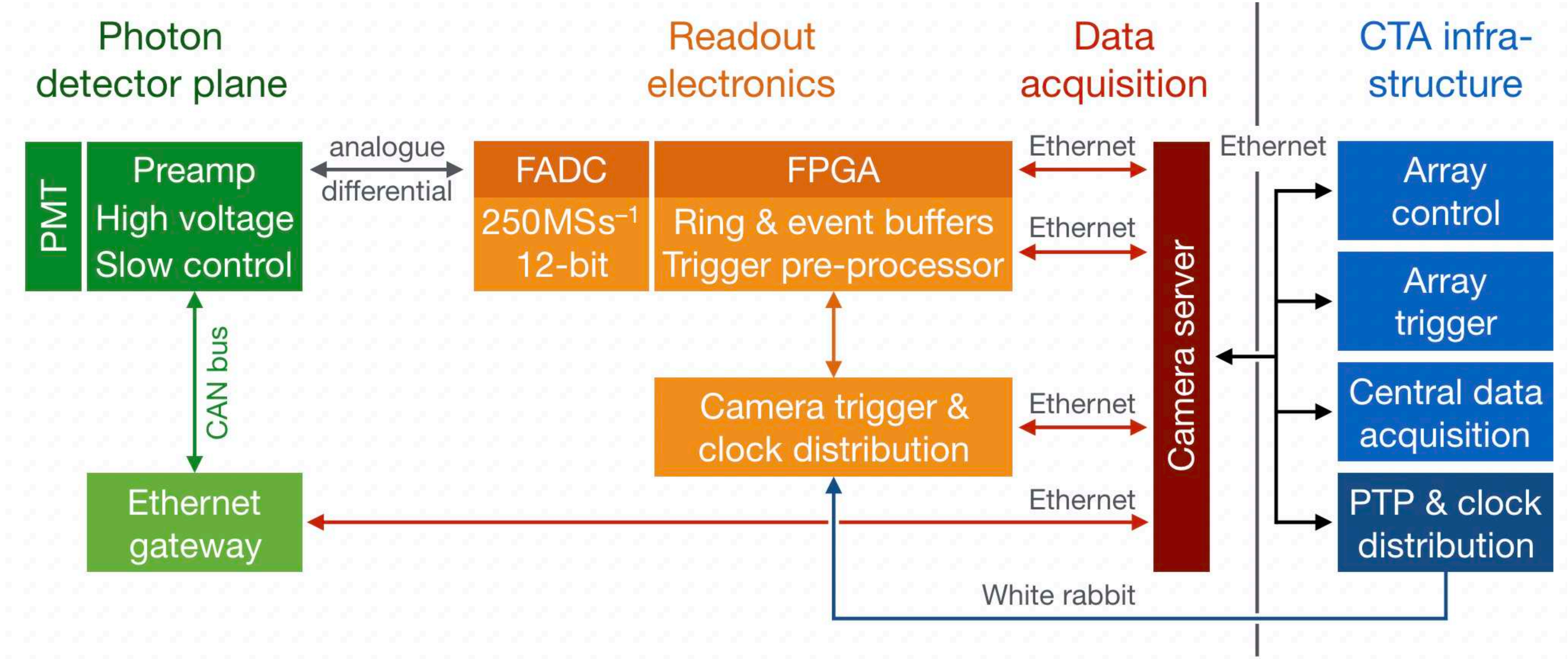
Significant amount of light is received in a compact region of the focal plane (~0.2 deg²)





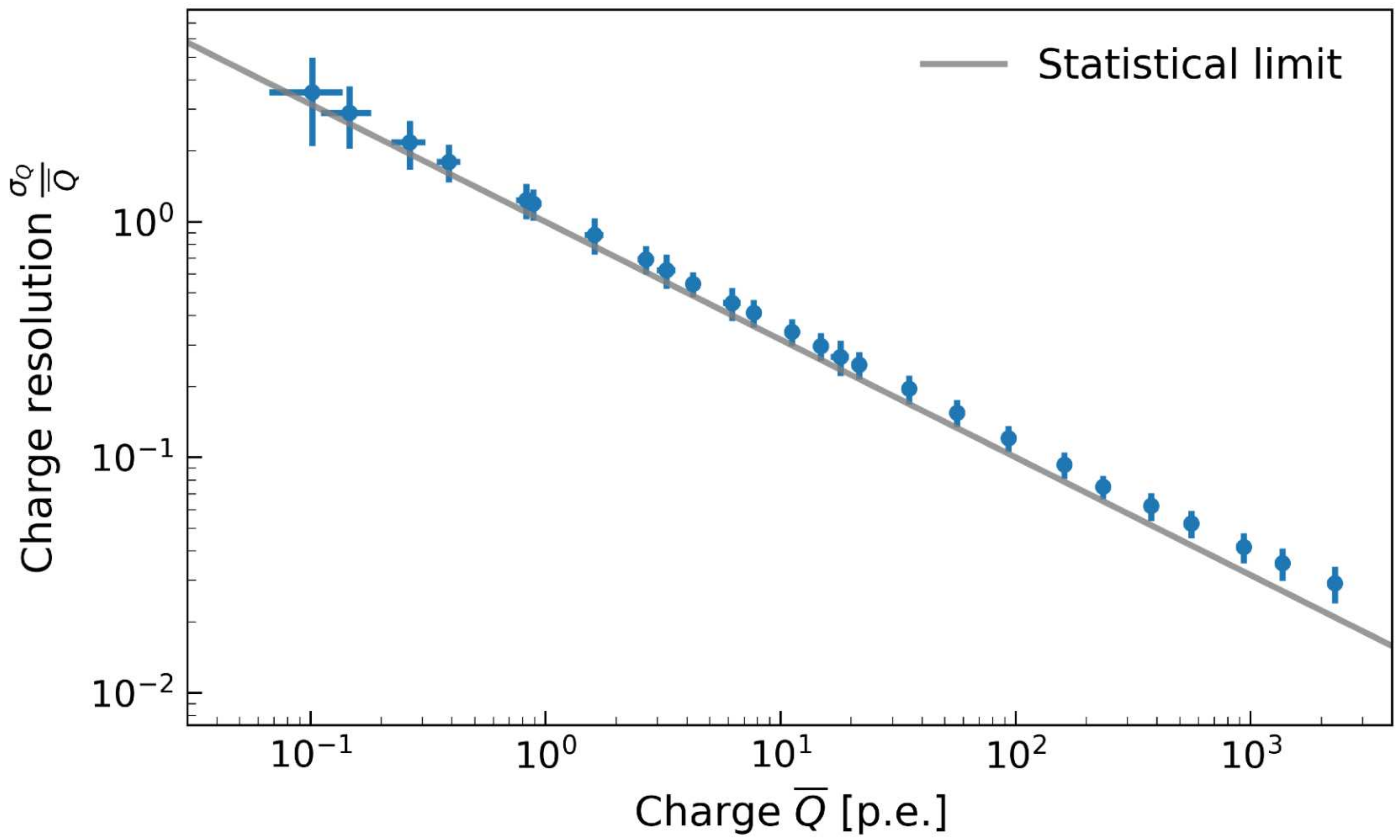
L1 signal is formed if 3 neighbour pixels or if 3 pixels within a 3ns time window are above a discrimination threshold within a 37-pixel region

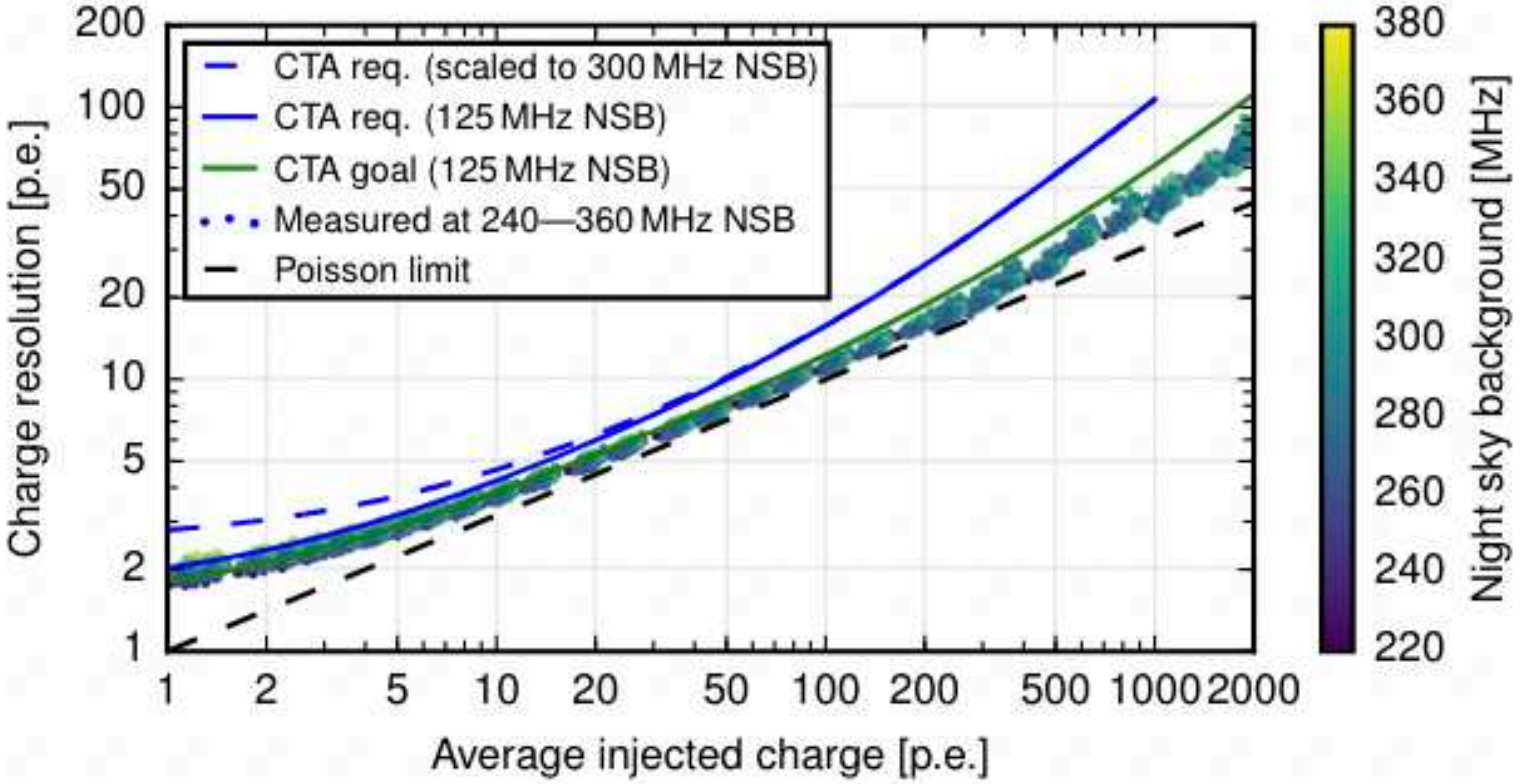
Principle of FlashCam operations



Charge resolution

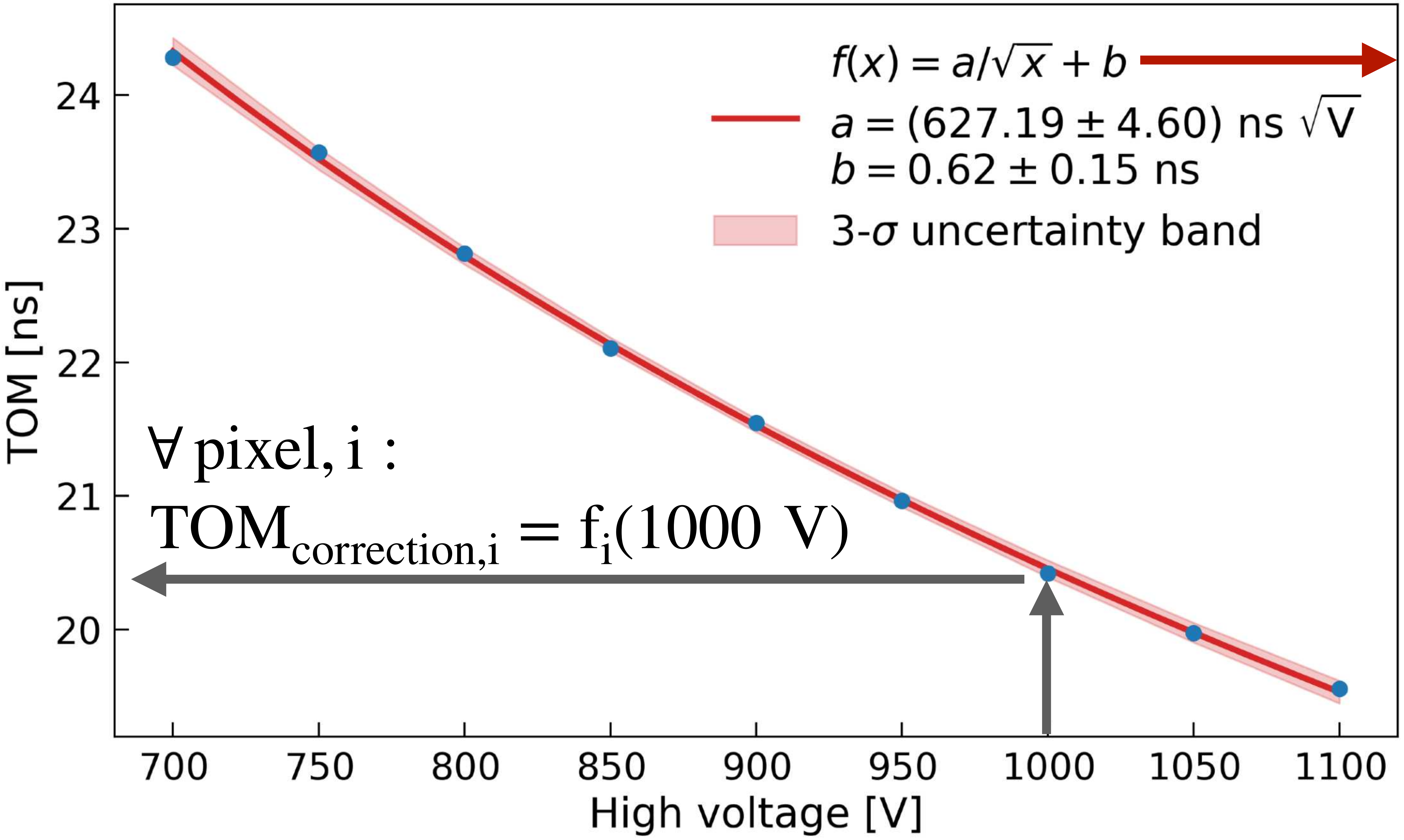
NectarCAM vs FlashCam





NectarCAM PMT transit time

Transfer time of e^- avalanche in the PMT depending on dynodes HV

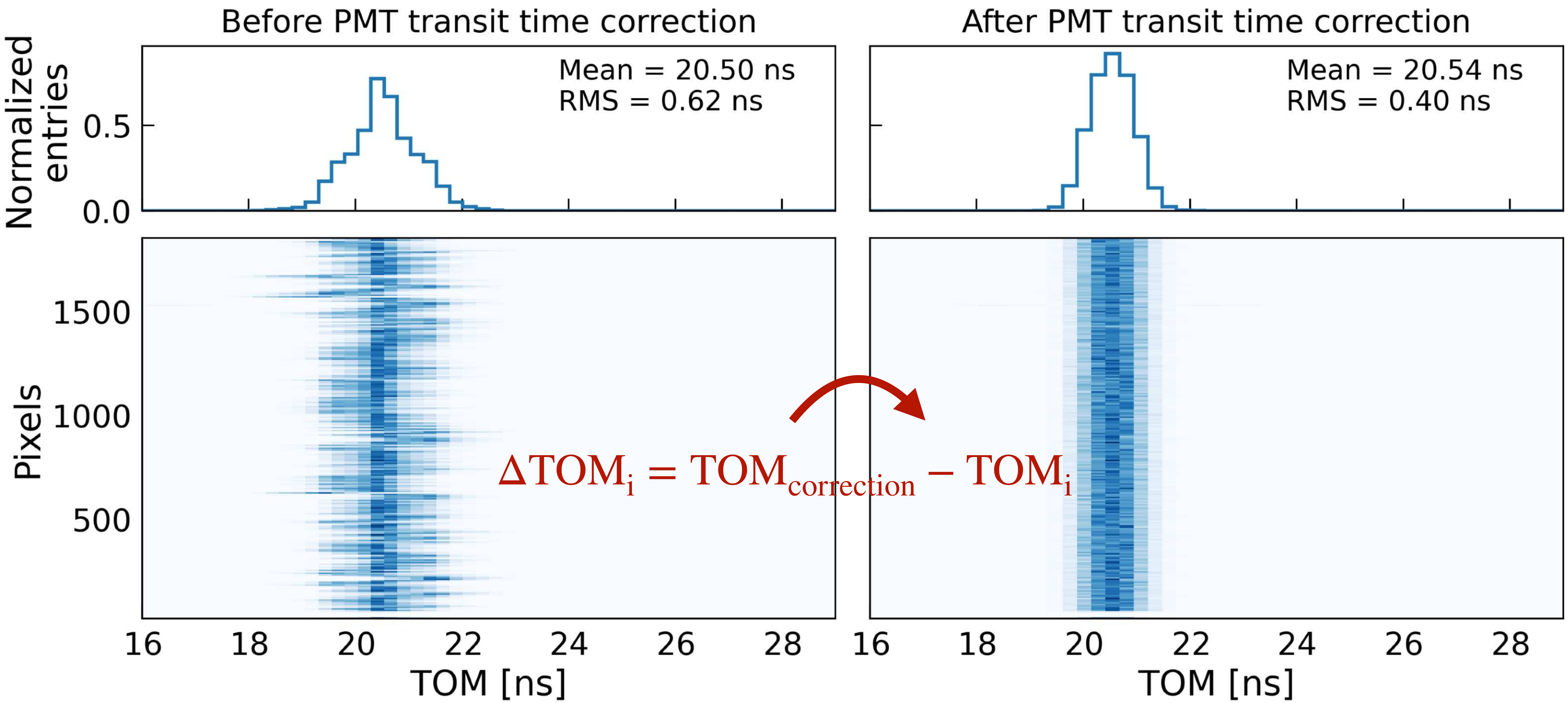


Time required by an e^- to be accelerated by the PMT $\vec{E}$

Each TOM shifted to overall correction factor $\mathrm{TOM_{correction}} = \overline{\mathrm{f(1000\ V)}}_{\mathrm{pixels}}$

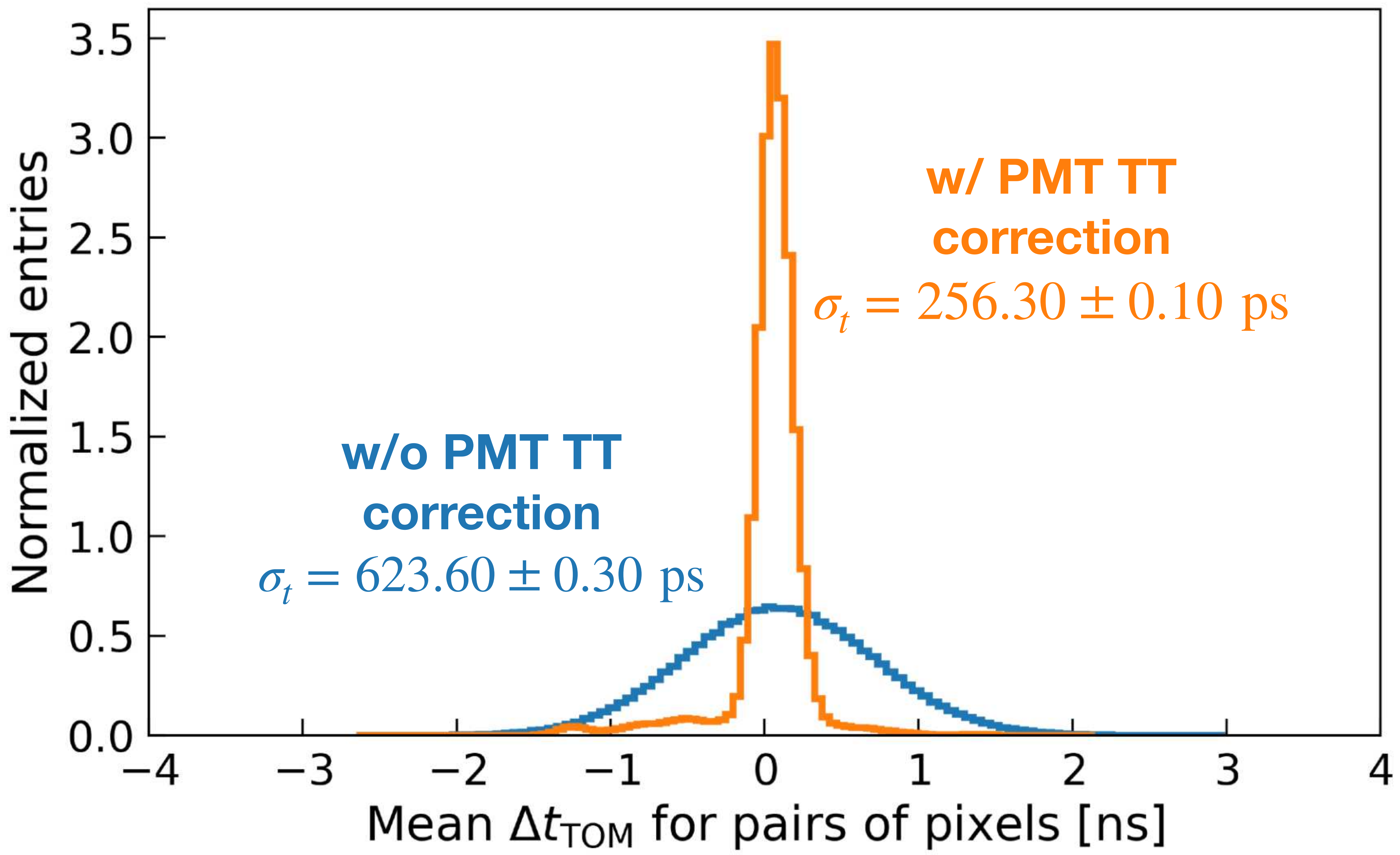
PMT transit time correction

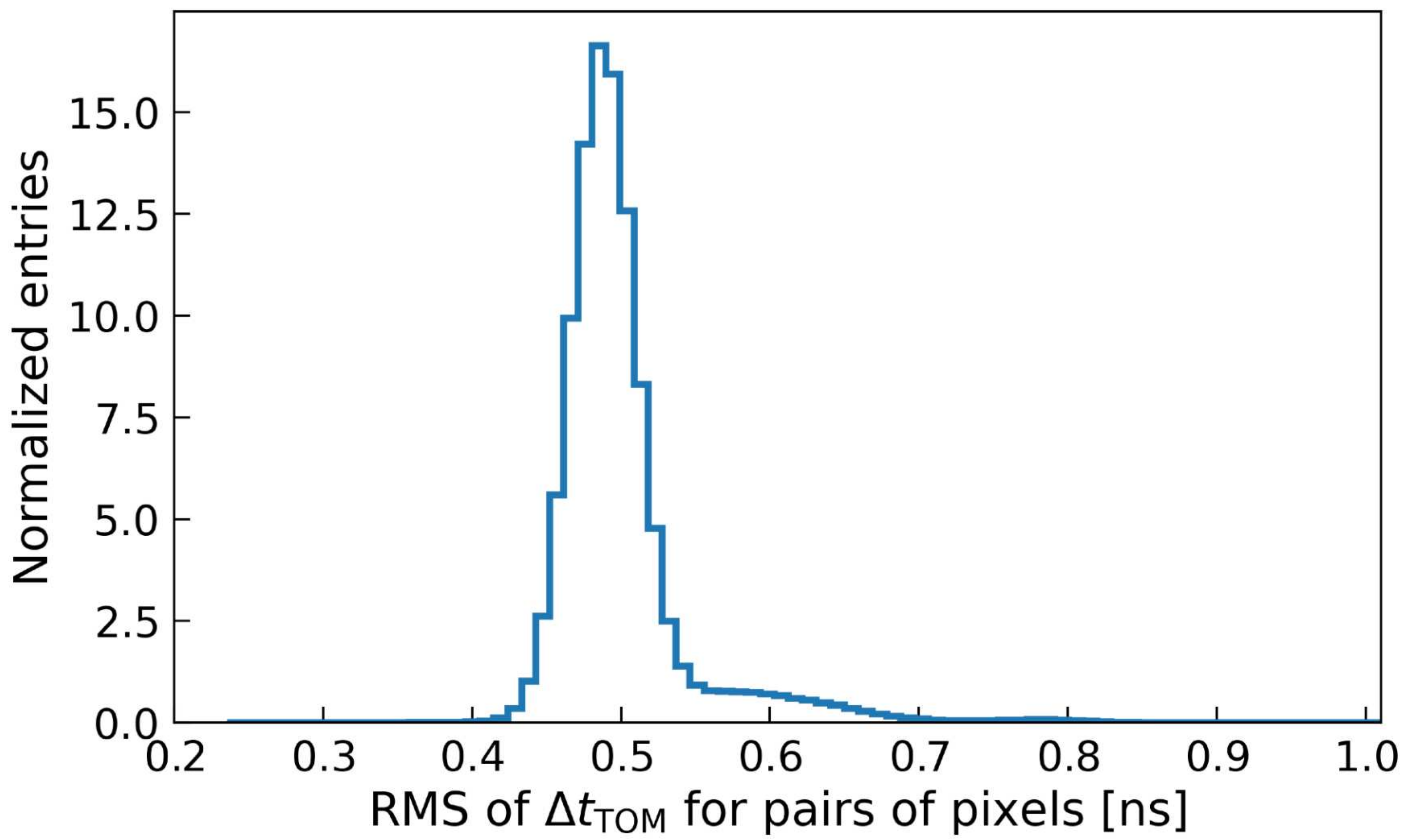
TOMs are synchronised after correction



NectarCAM global camera timing precision

After correcting for PMT transit time



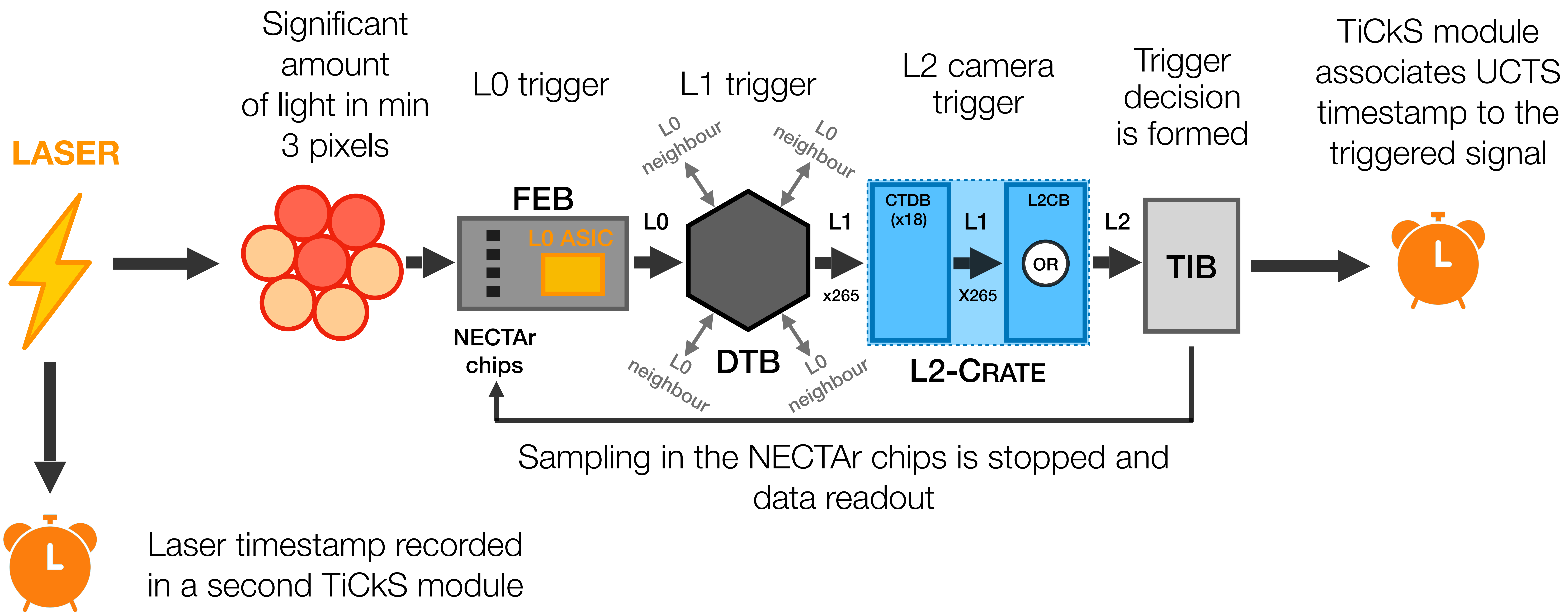


<2 ns RMS between each pair of pixels

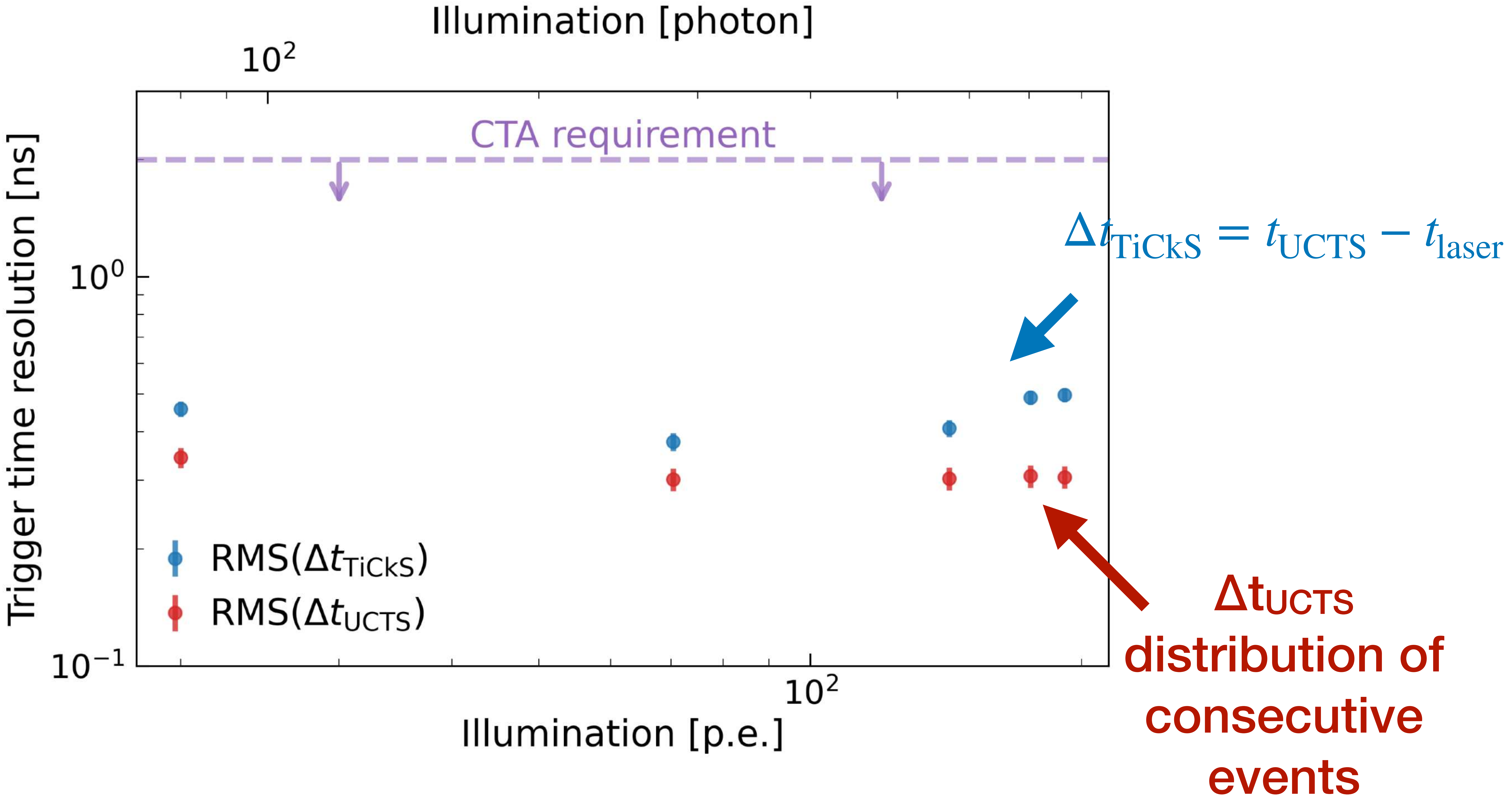
⇒ PMT transit time correction values updated in MC-simulations

Camera trigger timing precision

NectarCAM trigger system



NectarCAM camera trigger timing precision



Timestamping accuracy < 2ns