Silicon Photomultipliers for the SST Camera of Cherenkov Telescope Array (CTA)

Davide Depaoli for the SST Camera Team

Max-Planck-Institut für Kernphysik

PSD13, Oxford, UK

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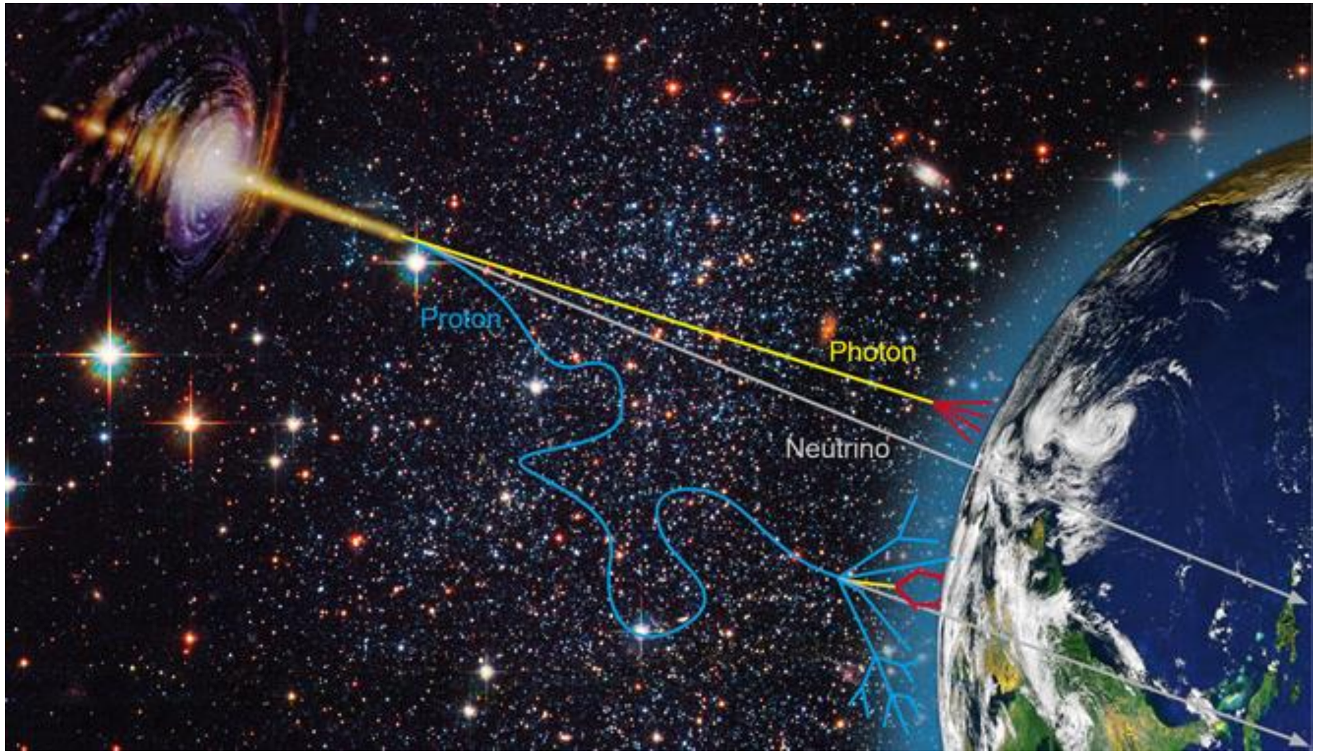
Gamma-ray astronomy

High-energy gamma rays

- Massless
- Neutral
  → not deflected by magnetic fields
  → point back to their sources



Physics with high energy gamma rays

- Origin and Role of Relativistic Cosmic Particles
- Extreme Environments (Neutron Stars, Black Holes, ...)
- New Physics (Dark Matter, Lorentz Invariance Violation, ...)

High Energy γ-ray Detection

SPACE - SATELLITES
(e.g. FERMI)

- Low shower containment in calorimeter
- Low collection area

GROUND (e.g. IACTs)
(e.g. CTA, MAGIC, H.E.S.S., VERITAS)

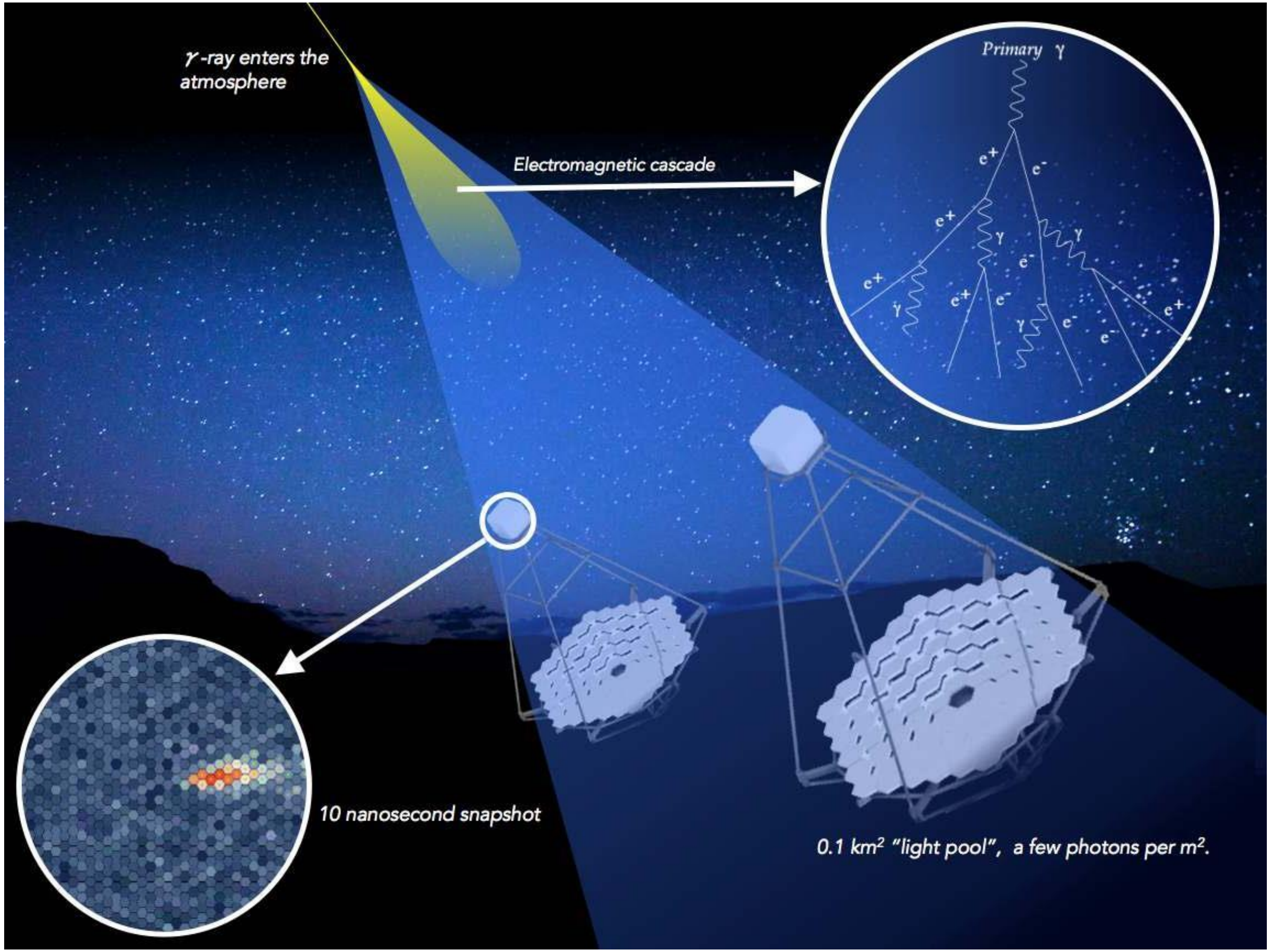
- Atmosphere as calorimeter
- Imaging Atmospheric Cherenkov Telescope (Technique)

γ-ray Energy

γ-ray Flux

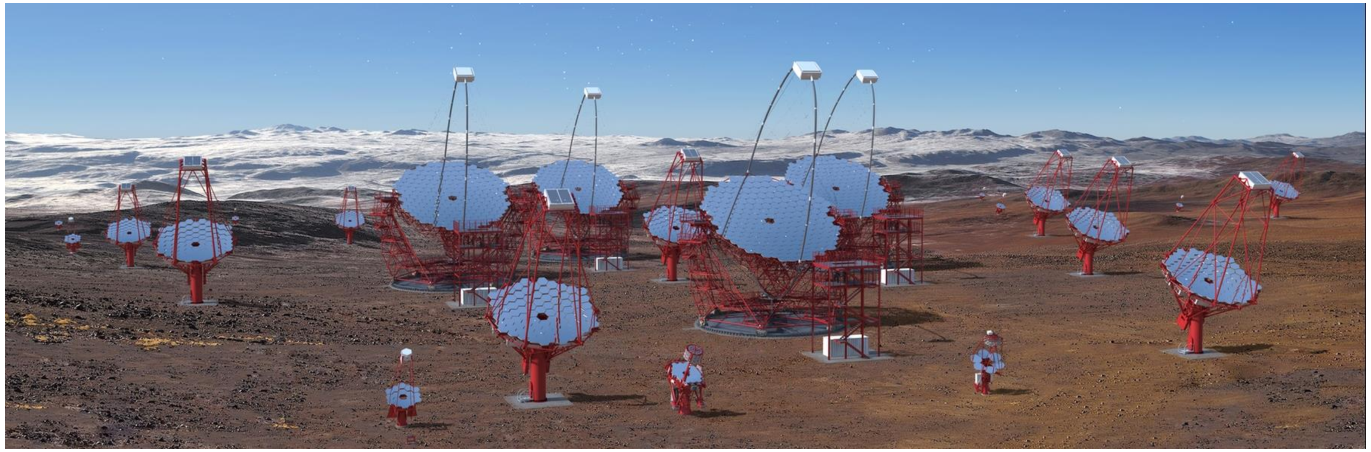
Imaging Atmospheric Cherenkov Telescope

- γ-ray enters the atmosphere
- Electromagnetic shower
- Charged particles (e^+, e^-) emit Cherenkov light
- Sampled by the telescopes (trigger on event)
- Reconstruct
  - Direction
  - Energy
- Excellent γ-hadron separation
- High angular resolution
- Low duty cycle
- Limited field of view



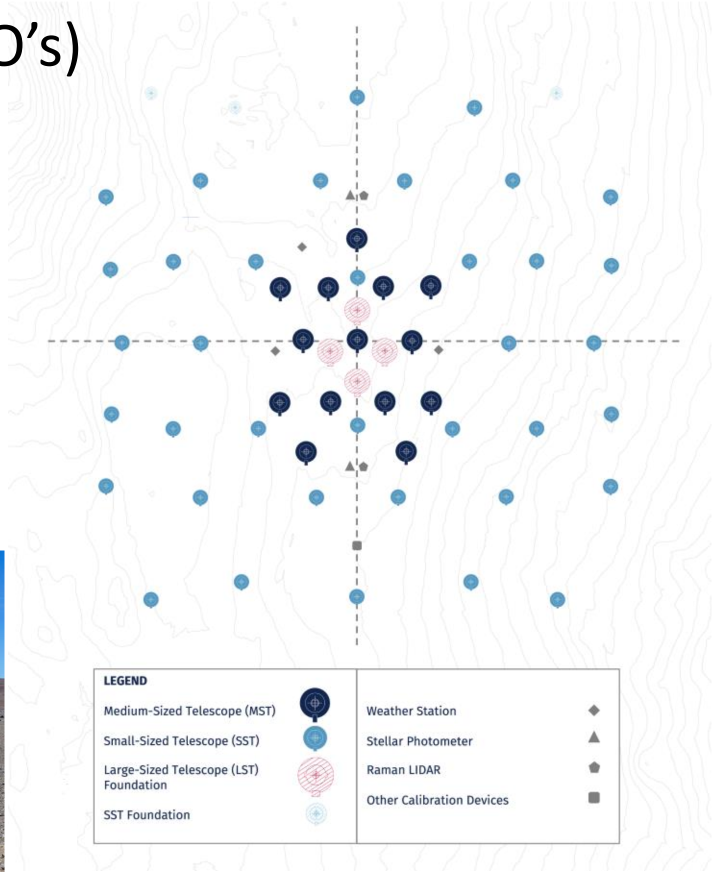
Cherenkov Telescope Array (CTA)

- Next generation IACT observatory
- Sensible to γ-rays in energy range:
  $$E_\gamma = 20\ \mathrm{GeV} - 300\ \mathrm{TeV}$$
- Three types of telescopes, which cover increasing energies:
  - Large (LSTs)
  - Medium (MSTs)
  - Small (SSTs)
- Two sites → full sky coverage
  - Roque de los Muchachos, la Palma, Canary Islands, Spain
  - Paranal, Chile



Small-Sized Telescopes (SSTs)

- Build only for the Southern Site
- 10 km southeast of the European Southern Observatory's (ESO's) Paranal Observatory, Atacama Desert, Chile
- 2200 m above sea level
- How many?
    - Alpha (approved): 37 SSTs
    - Omega: 70 SSTs

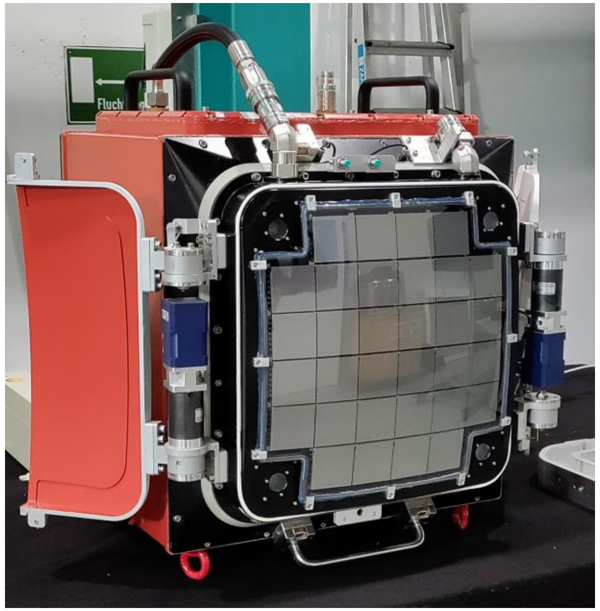


Small-Sized Telescopes (SSTs)

- Will focus on the higher-energy range

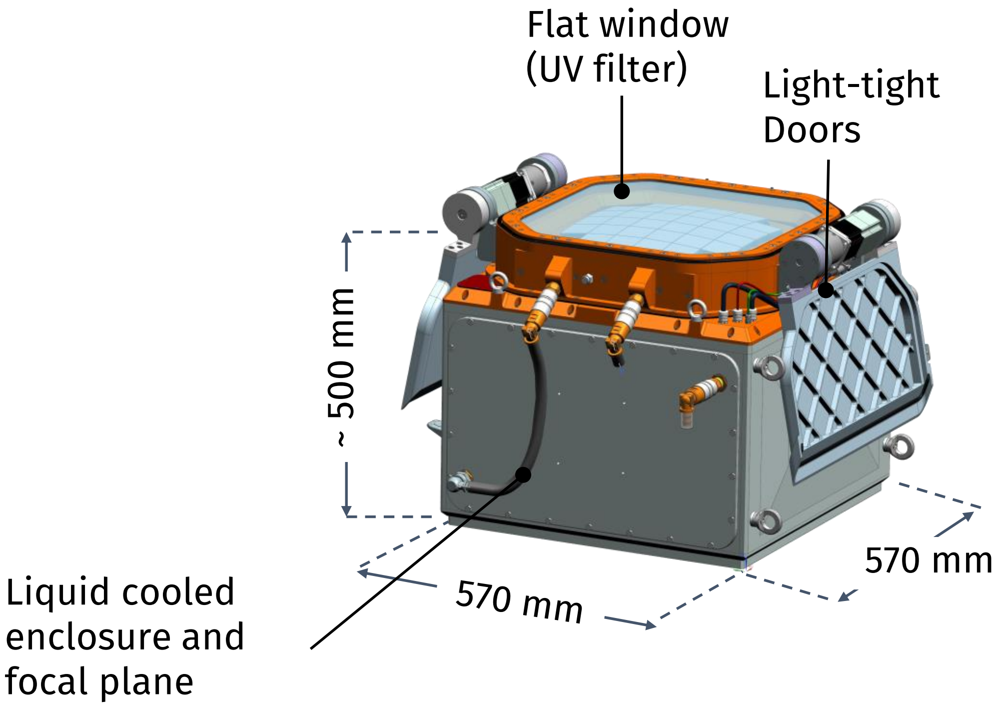
$$E_\gamma = 5\ \mathrm{TeV}\ - 300\ \mathrm{TeV}$$

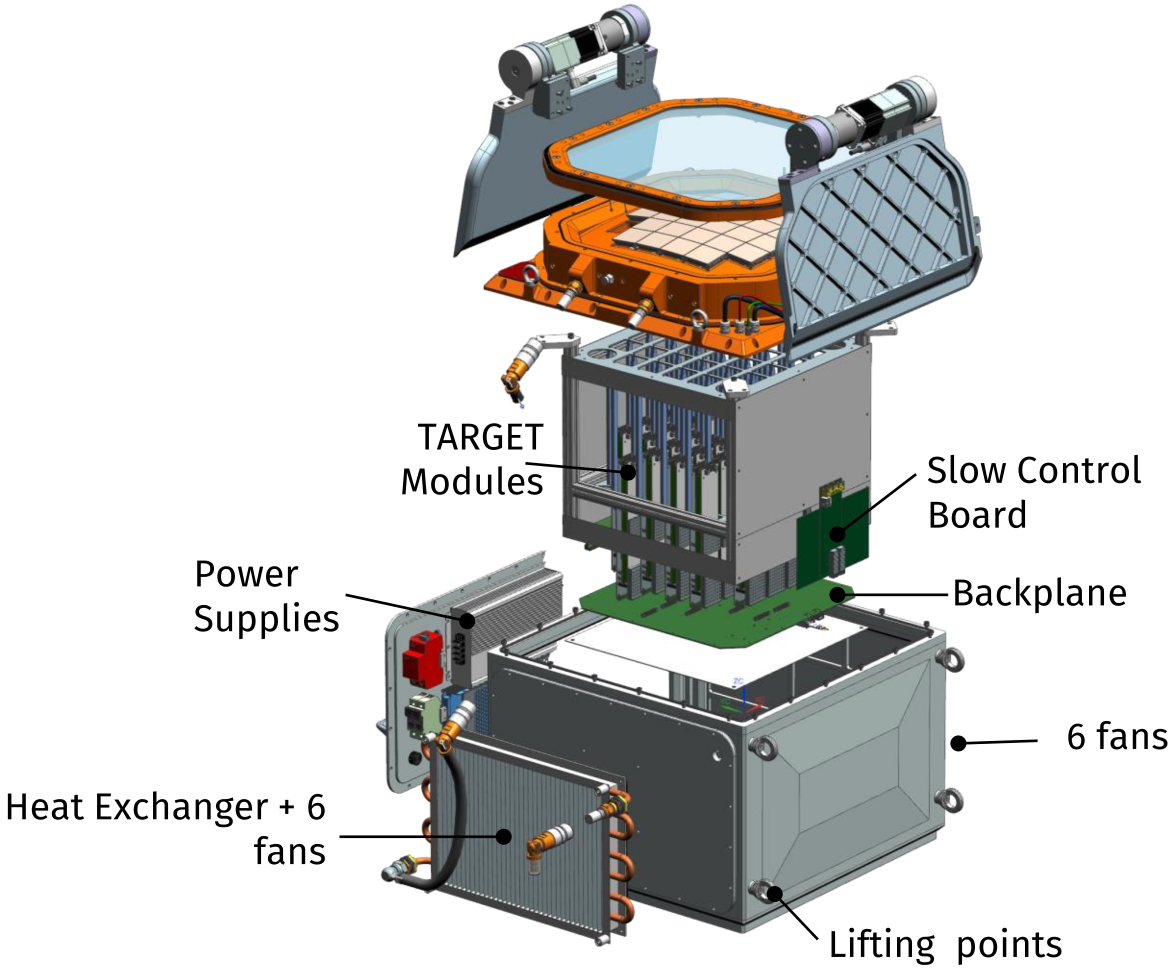
- Three different SST structures were proposed (SST1-M, ASTRI-Horn, CHEC)
- Harmonization process: SST will be based on the **ASTRI** structure and **CHEC** camera
- Telescope structure
  - Dual mirror
  - Schwarzschild-Couder
  - Primary mirror 4.3 m
  - Secondary mirror 1.8 m
  - Focal length 2.15 m
  - Field of view 8.8°



SST Camera

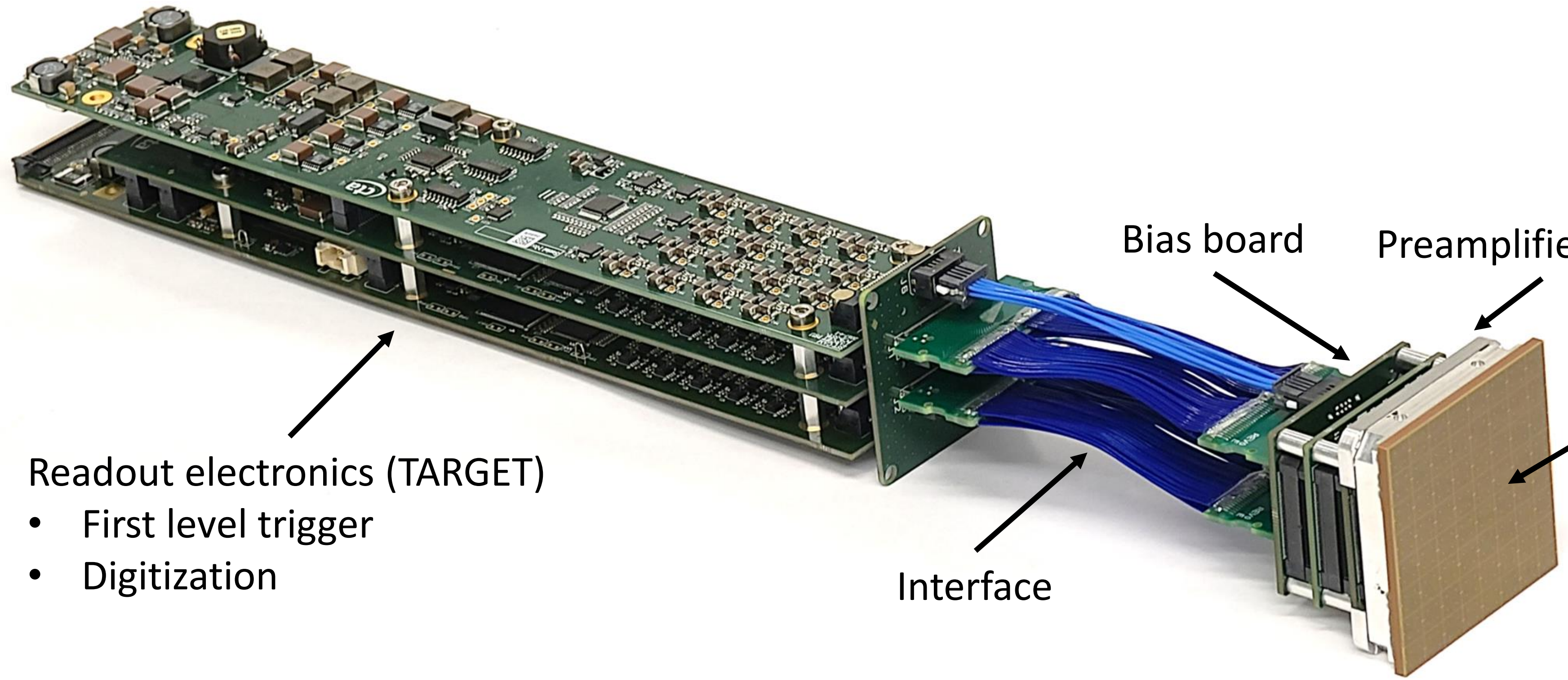
- Dual mirror design results in a small and compact camera
- Diameter 50 cm
- Weight < 100 kg





SST Camera Module

- Modular design
- 32 module, 64 SiPMs each module
  → 2048 SiPMs



Connection to the Backplane

Readout electronics (TARGET)
- First level trigger
- Digitization

Interface

Bias board

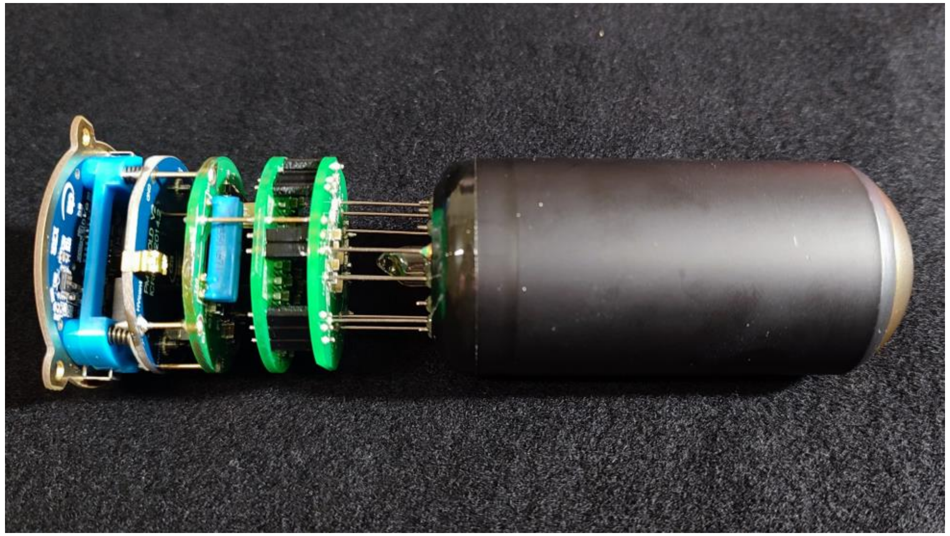
Preamplifier board

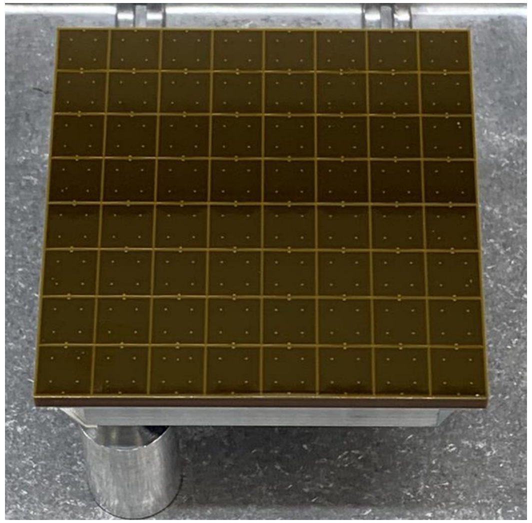
SiPM array (8x8)
HPK S14521-1720
(custom made)

Jon Lapington

Why SiPMs?

- We need to detect Cherenkov light from showers
  - Signal $\sim \mathrm{ns}$
  - Intensity $1 - 10\mathrm{k}$ photons
  - Number of pixels in the camera: few thousands
- Two possible alternatives:
  - PMTs
  - SiPMs
- Advantages of SiPMs
  - Robust under high illumination conditions
    - Can increase duty cycle of the telescope
  - Low operating voltage
    - About $30\ \mathrm{V} - 50\ \mathrm{V}$ (instead of $\sim \mathrm{kV}$)
  - Cost effective for small pixels
    - SST pixel $6 \text{ x } 6\ \mathrm{mm}^2$

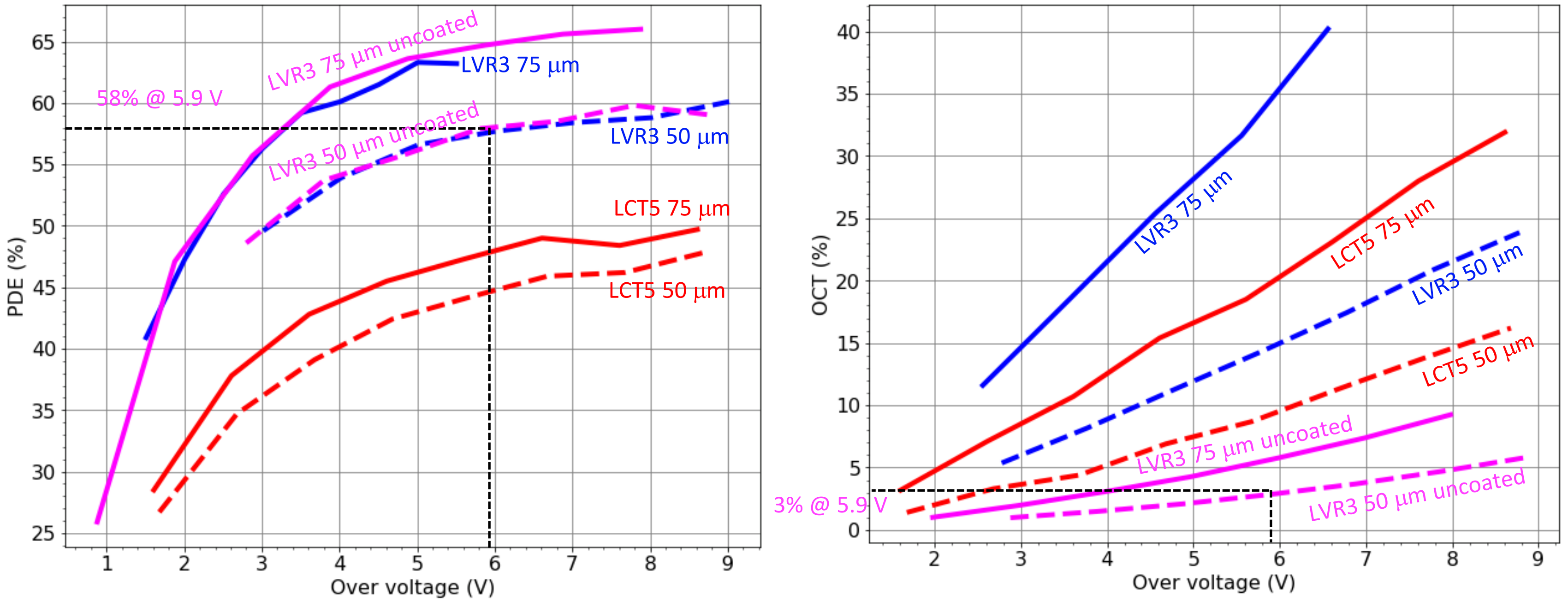




SiPM selection

- Several SiPM candidates and pixel sizes were considered and tested
- Chosen SiPM: Hamamatsu S14521-1720
  - Low Reverse Voltage (LVR3) technology
  - No protective coating

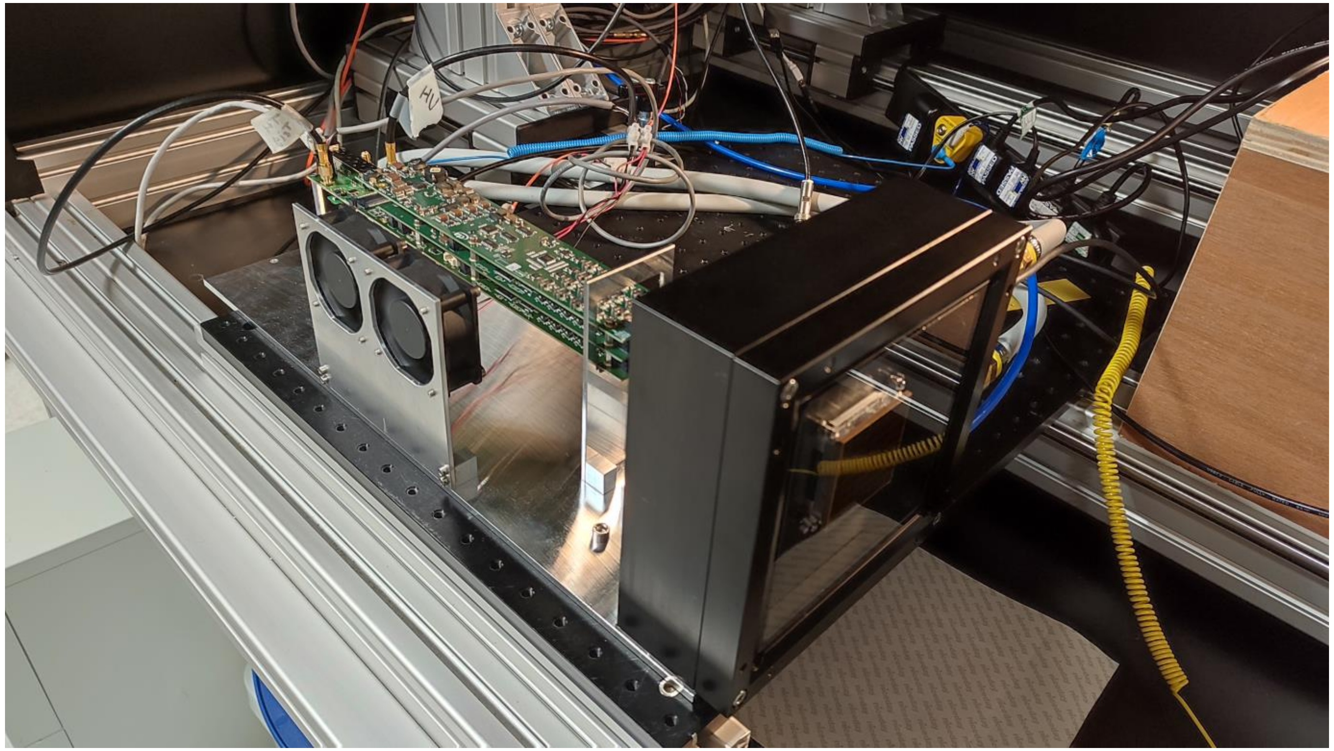
Hamamatsu S14521-1720	
Pixel area	6.0 x 6.0 mm^2
Microcell size	50 μm
Spectral response range	220 *to* 900 nm
Peak PDE	58 %
Breakdown voltage (V_{bd})	38 ± 3 V
Operating Overvoltage	5.9 V
Prompt OCT probability	~ 3 %
Pixel Fill factor	74 %
V_{bd} Temperature Dependence	34 mV/°C



Tajima et al.

First measurements on SST modules + SiPMs

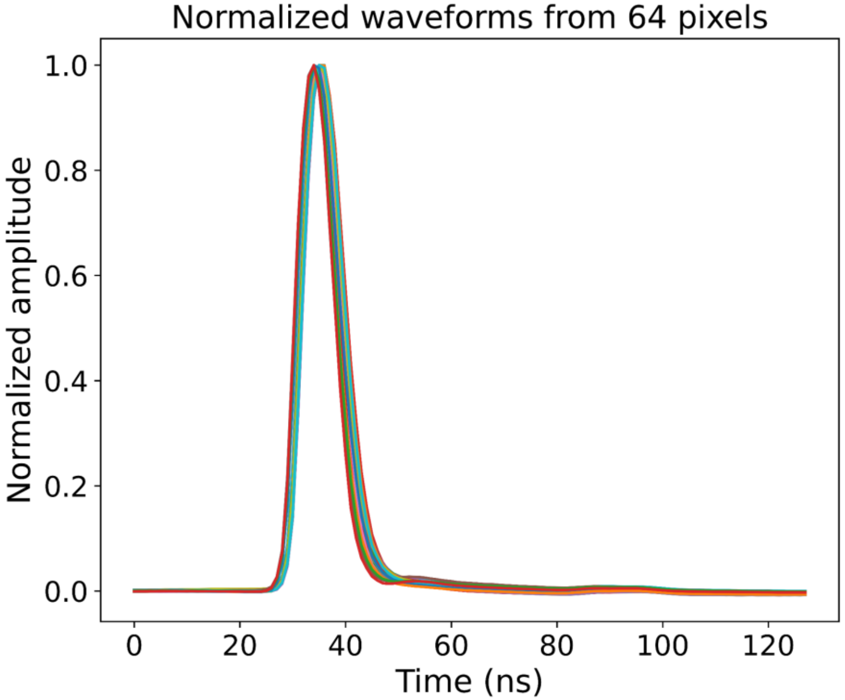
- The first SST modules are currently under test
  - Leicester University, UK
  - ECAP, Erlangen, Germany
  - MPIK, Heidelberg, Germany
- Here report on first tests carried out at Leicester University
  - SST module with SiPM tile
  - Laser source
    - To simulate the Cherenkov signal
  - DC LED
    - To simulate the Night Sky Background
  - XY stage to align the laser spot (focused) to a single SiPM pixel

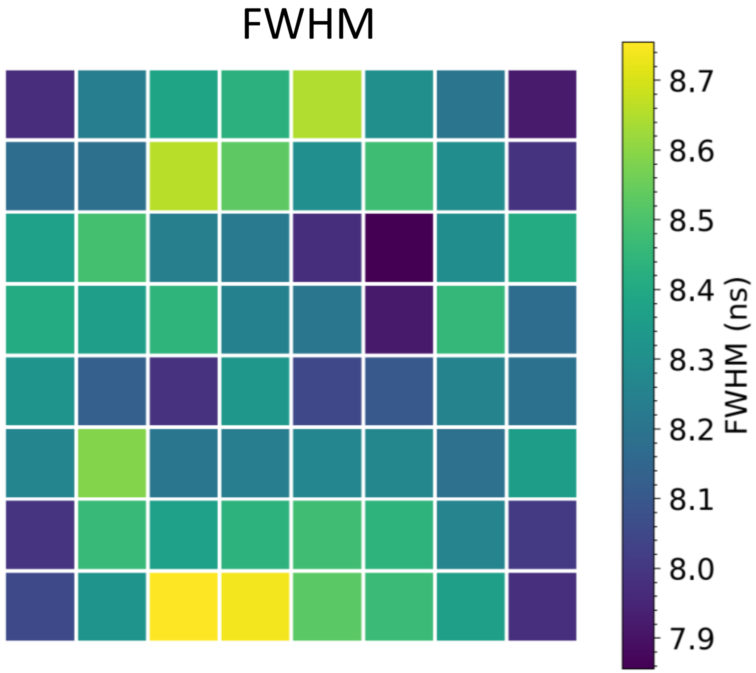


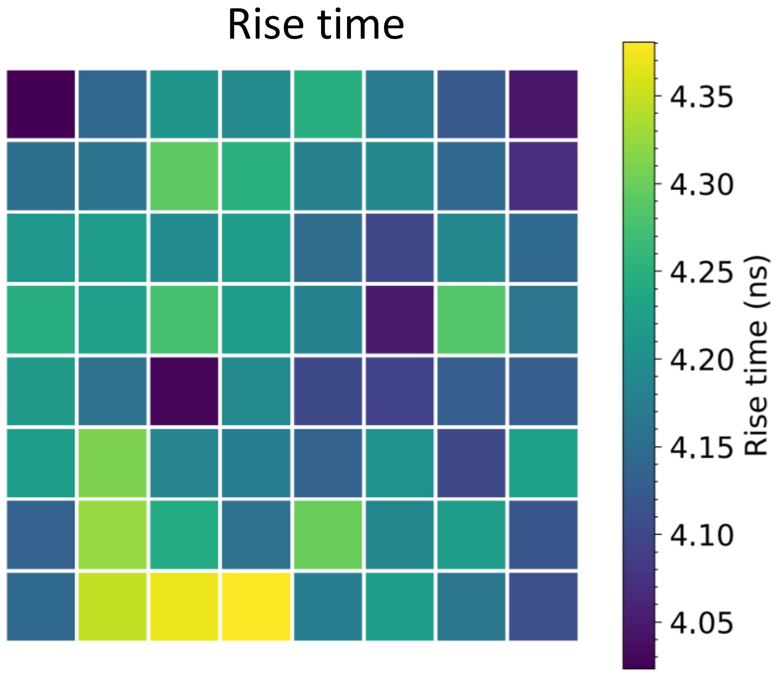
SiPM signals

- SiPM signals are long
- From SST simulations: $5 - 10$ ns
  - $<$ 5 ns: no pile-up for trigger
  - $>$ 10 ns: too much integrated background noise

- Analysis of the SiPM signals
  - $FWHM = (8.3 \pm 0.2)$ ns
  - $t_{rise} = (4.2 \pm 0.1)$ ns



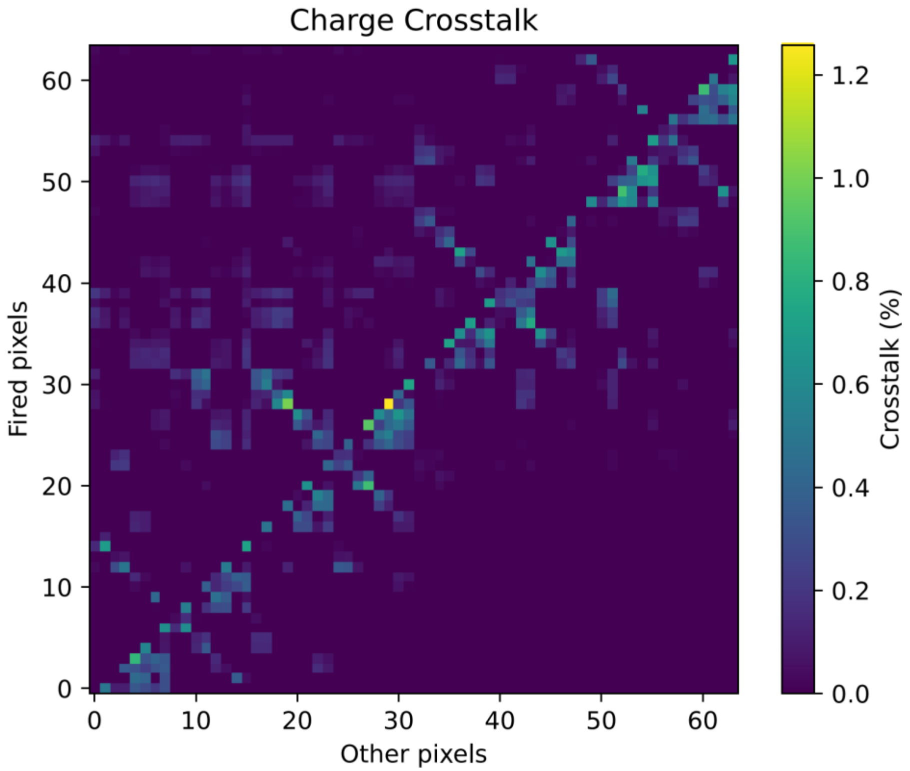


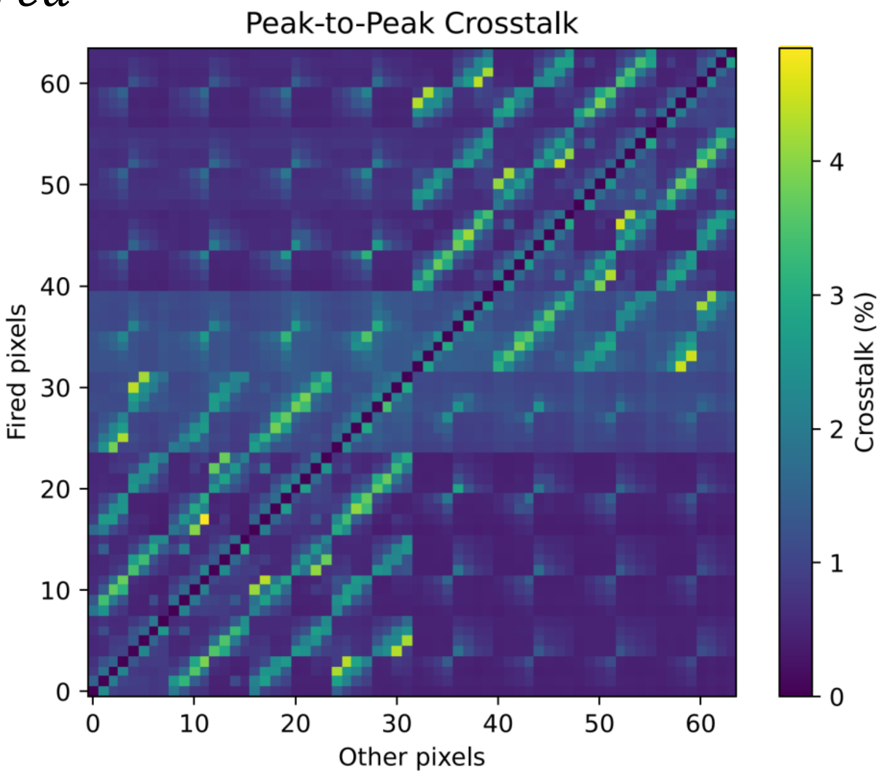


Cross Talk

- Firing only one pixel using focused laser light
- Crosstalk measured as the peak-to-peak (or charge) signal in any other pixel compared to that in the fired pixel

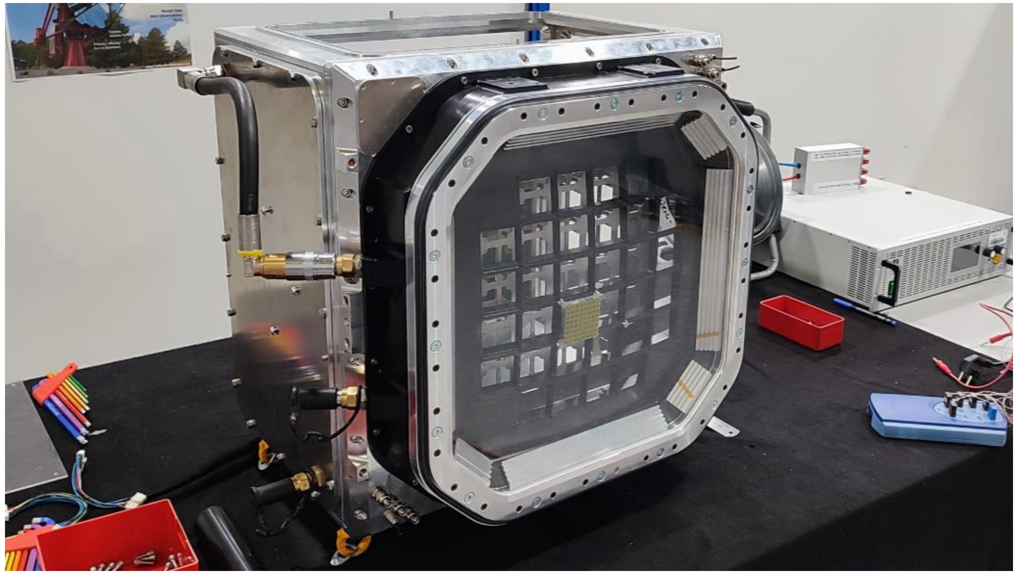
$$CT_A = \frac{A_{notfired}}{A_{fired}}$$



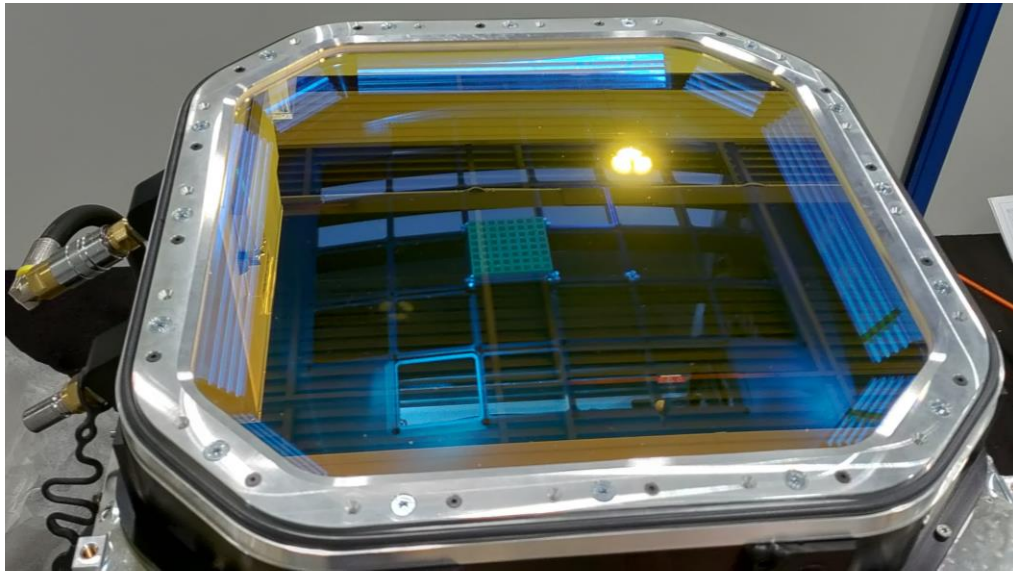


Next steps

- Additional SST modules will undergo detailed testing in the coming weeks.
- Late 2023: QCAM (1/4 camera) ready for testing
- 2024: ECAM (full camera) ready for testing



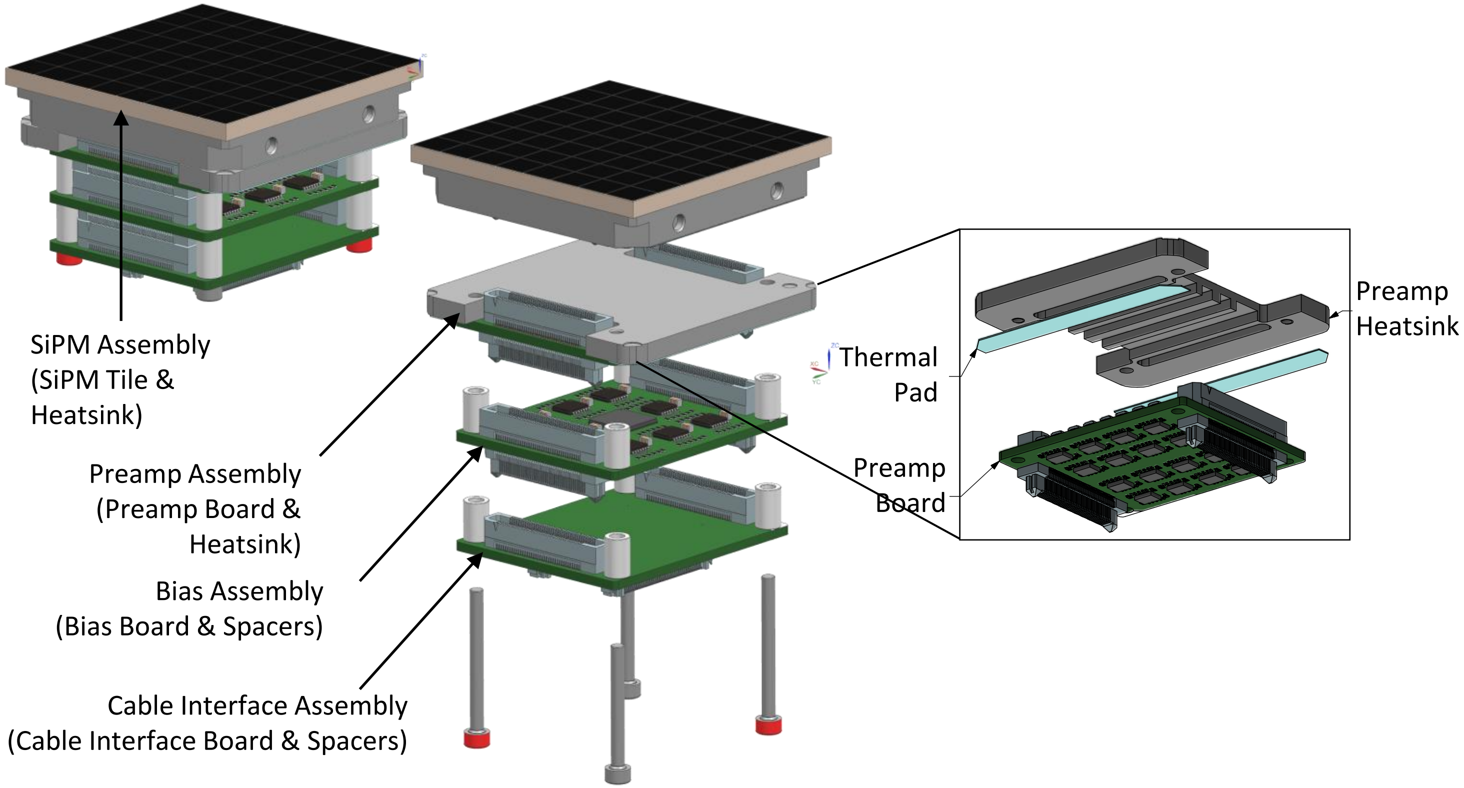
- The mechanics of the camera are almost complete
- Mechanical interface with camera will be tested in Tenerife at end of October



Backup

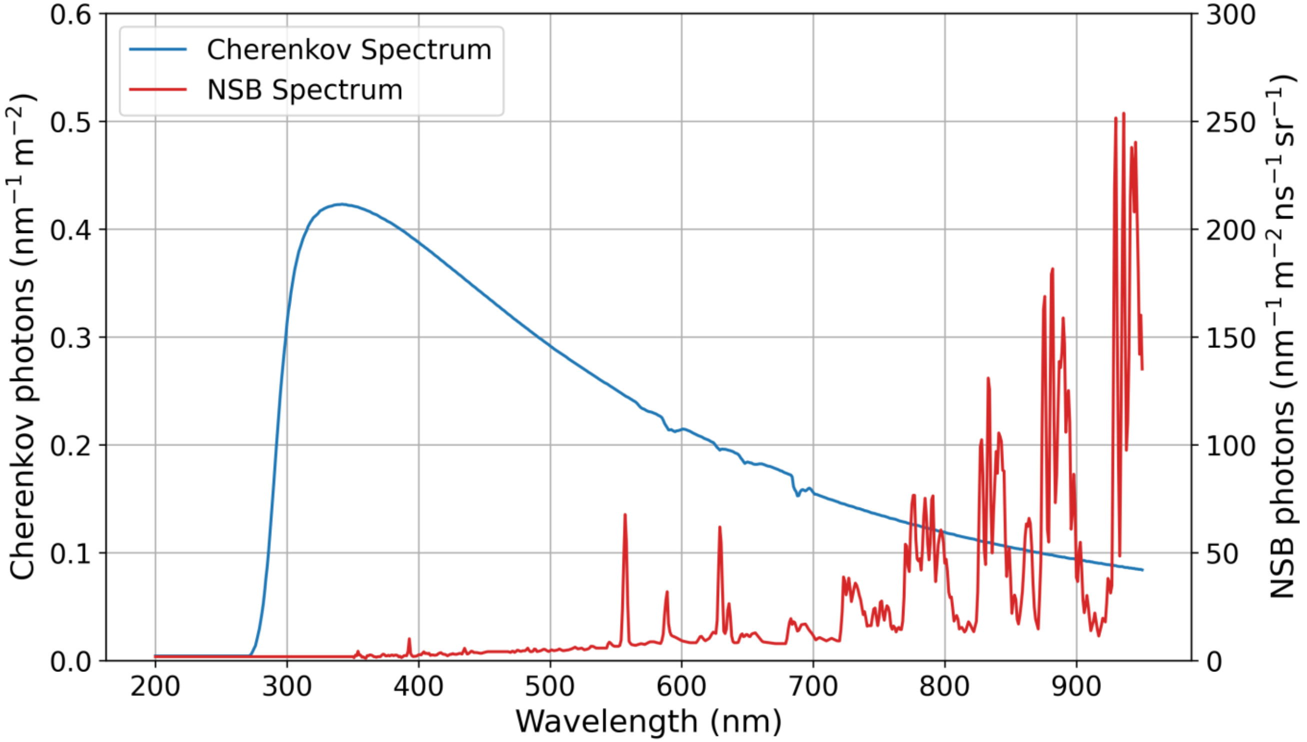
SiPM Power dissipation

- SiPMs
  - More power demanding than PMTs
  - Their gain depends on temperature (at fixed bias voltage)
- We need to remove excessive heat from the focal plane
  - Normal operation 120 W
  - Maximum 200 W
- Liquid-cooled Focal Plate + heatsink



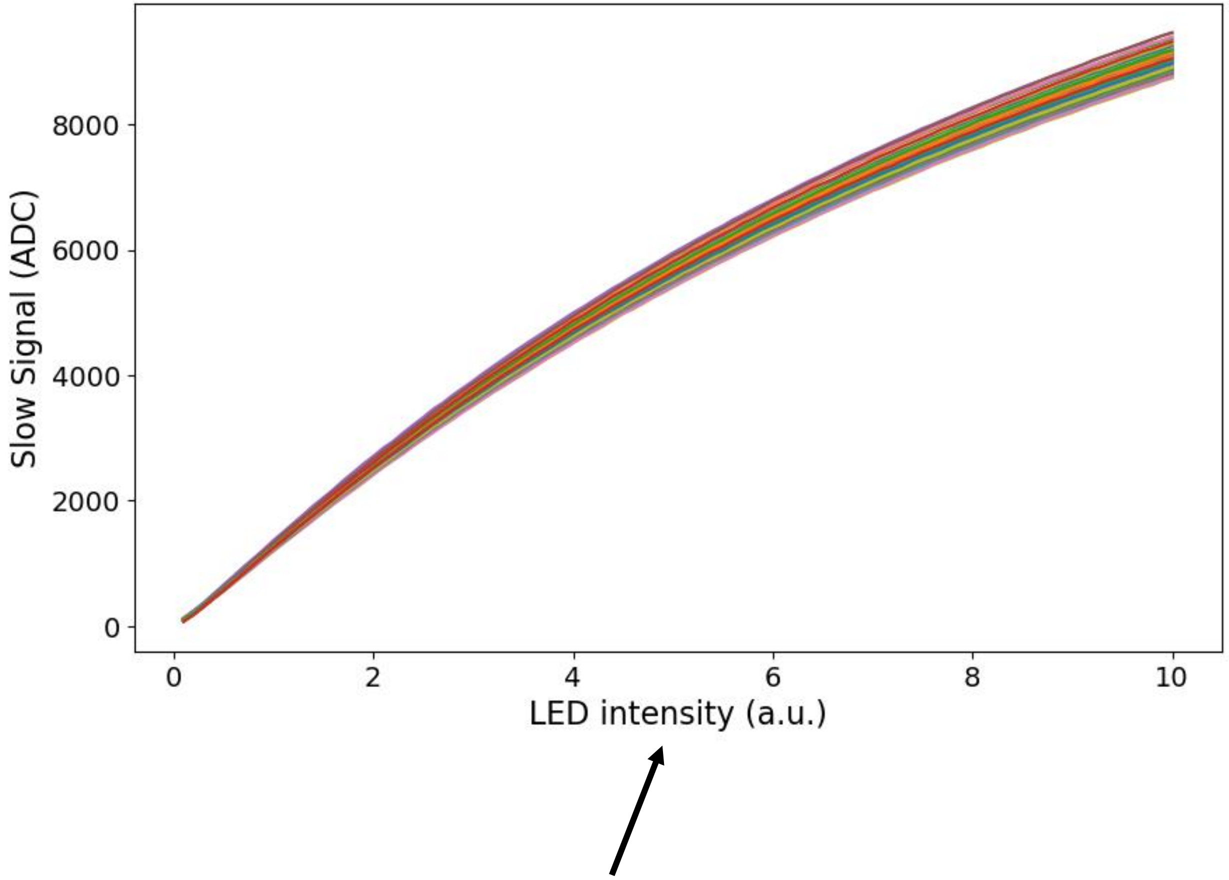
Cherenkov signal and NSB

- Cherenkov light
  - Peaks in the UV band
- Night Sky Background
  - *airglow*: emission of atoms and molecules in the atmosphere
  - *zodiacal light*: sunlight scattered by interplanetary dust
  - Stars



Slow Signal

- Each channel has also a Slow Signal
  - 100 μs integrator
  - Used as current monitor
    - SiPM protected by bias resistor
    - $V_{SiPM} = V_{bias} - R * I$
    - SiPM gain depends on current
  - Currently under calibration
- The SiPM gain is also monitored by a illumination system made by pulsed LED sources



We are currently converting this axis to photons rate

Slow Signal

- We can use this channels also for some checks on the SiPMs in the tile:
  - Breakdown voltage from I-V curve
  - SiPM self-heating
    - SiPM current would increase its internal temperature
    - SiPM gain drops as temperature increases (at same V_{bias})
    - This effect is negligible with in our SiPMs