The Silicon Photomultiplier Telescope FAMOUS for the Fluorescence Detection of UHECRs

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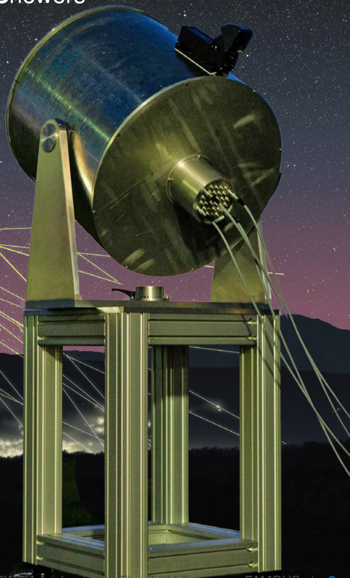
Schule für Astroteilchenphysik, Obertrubach-Bärnfels

Outline

First **A**uger **M**ulti-pixel-photon-counter-camera for the **O**bservation of **U**ltra-high-energy-cosmic-ray air **S**howers



1. Introduction
2. Baseline design of FAMOUS
3. Silicon photomultipliers
4. Fresnel lens characterization
5. Readout electronics & data acquisition
6. Summary & outlook

The World's largest cosmic ray observatory

The Pierre Auger Observatory

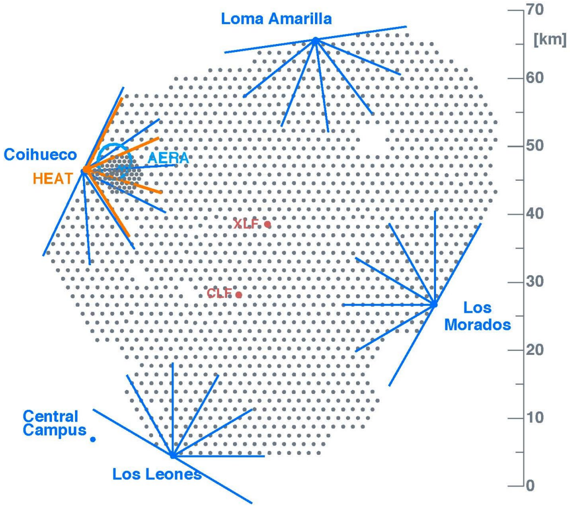
- Hybrid cosmic ray detector for energies above 10^{17} eV
- $3000\,\text{km}^2$ array in the Argentinian Pampa near Malargue

Fluorescence Detector

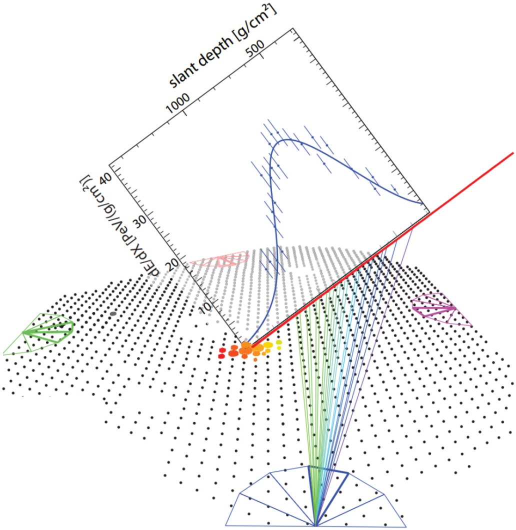
- 27 telescopes at four sites
- Duty cycle $\approx 13\,\%$
- **Samples longitudinal shower profile**

Surface Detector

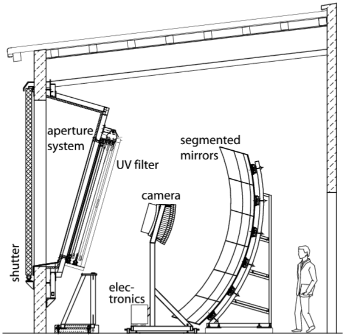
- Over 1600 water Cherenkov tanks
- Duty cycle near $100\,\%$
- **Samples lateral shower profile**



Fluorescence detection at the Pierre Auger Observatory

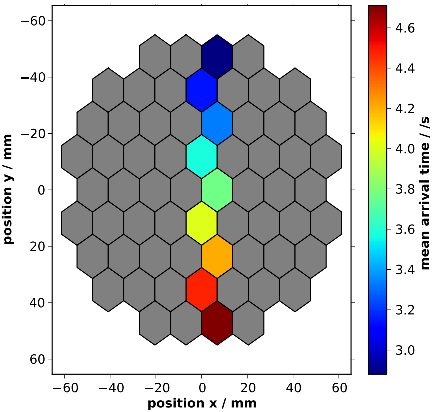


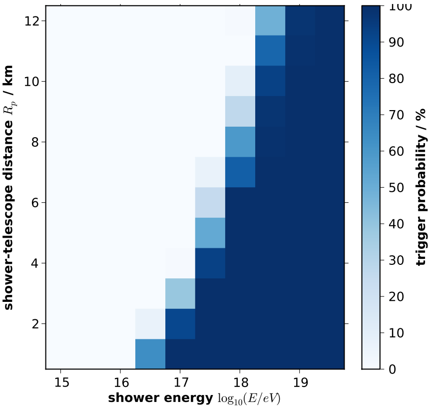
- Schmidt telescope design
- Field of view (FOV) per telescope $30\,° \times 30\,°$
- Camera with 440 PMTs ($27\,\%$ efficiency)
- $1.5\,°$ FOV per pixel
- UV-pass filter for fluorescence light ($280\,$nm- $420\,$nm)



Goal of the FAMOUS R&D

- Improve the fluorescence detection technique with silicon photomultipliers





Simulation of a vertical $E = 10^{18}$ eV shower, 4 km distance

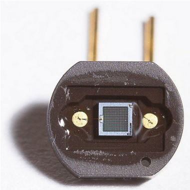
Simulated. Full efficiency for vertical 10^{18} eV showers up to 6 km distance

$\rightarrow$ increase duty cycle of up to 40 %

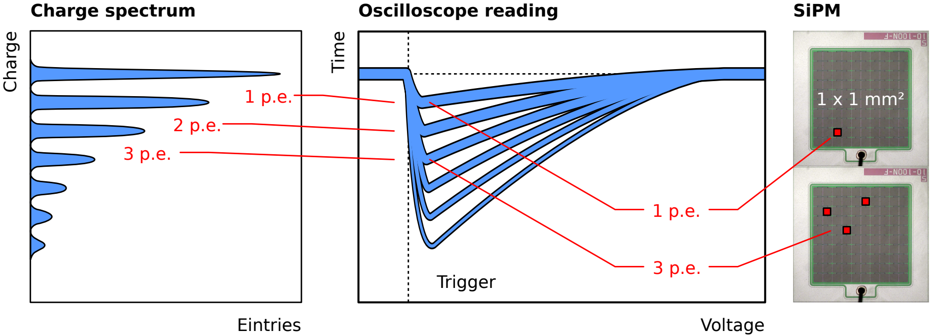
$\rightarrow$ increase shower profile resolution to enable shower-to-shower comparison

Silicon photomultipliers

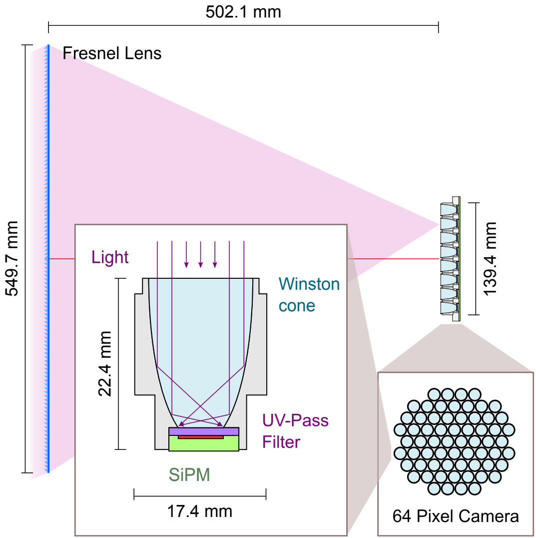
- Light detectors with single photon detection capability
- Made up of cells $(100, 3600, 14400, ...)$
- Small form factor ($1 \times 1\,\text{mm}^2$, $3 \times 3\,\text{mm}^2$, $6 \times 6\,\text{mm}^2$, ...)
- Promise high photon detection efficiency $> 40\,\%$
- Dark noise rate $\approx 2\,\text{kHz/cell}$



Hamamatsu



Baseline design of FAMOUS



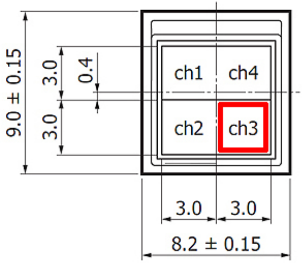
- Large Fresnel lens as refractor
- Pixel = Light funnel (Winston cone) + four $3 \times 3\,\mathrm{mm}^2$ SiPMs (Hamamatsu S10985-100C)
- 1.5 ° field of view per pixel
- 12 ° field of view in total

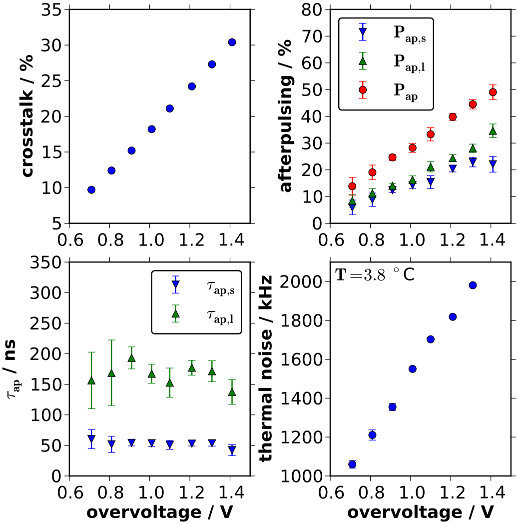
- Transmission efficiency of the Fresnel lens $\approx 70\,\%$
- Transmission efficiency of the system w/o SiPMs $\approx 55\,\%$ (= Auger FD w/o PMTs)

→ Famous pixel single channel characteristics

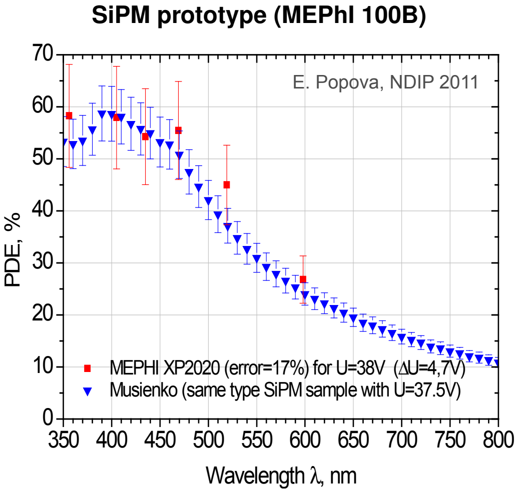
Hamamatsu S10985-100C

- PDE up to 36% for UV light
- Extensively studied and characterized
- Correlated noise effects well understood





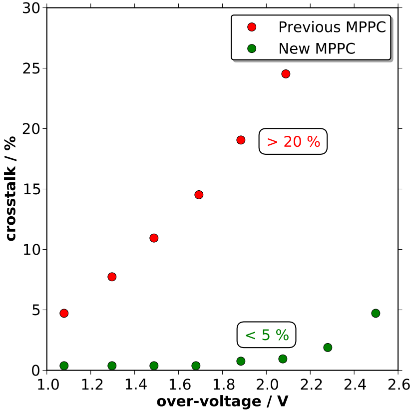
Photon detection efficiency of future SiPMs

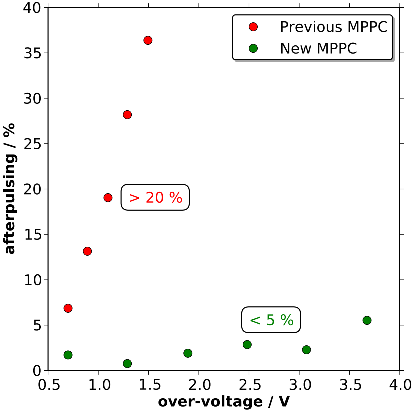


- Very high PDE in UV regime up to $60\,\%$ but not yet commercially available!
- Typical PDE of photomultiplier tubes used in fluorescence detection telescopes $\approx 27\,\%$, $\approx 35\,\%$ (optimized in Wuppertal)

Next generation of Hamamatsu SiPMs

- Hamamatsu at the VCI 2013 (Id 180):
  "Physics experiments are also an important application of the MPPC"
- SiPMs can be modified to meet requirements of our applications



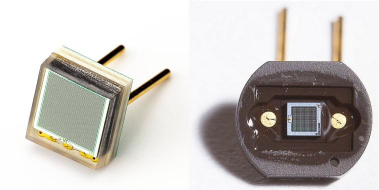


Data for a $50\,\mu$m cell pitch SiPM

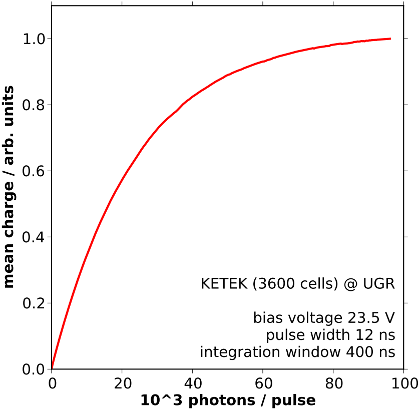
- Tremendous improvements in UV sensitivity and correlated noise suppression!

SiPM dynamic range

- Dynamic range measurements of Hamamatsu and Ketek SiPMs in Aachen and Granada
- Journal paper in preparation



Ketek Hamamatsu



- First results reveal satisfying dynamic range (up to 10^5 photons) for fluorescence measurements!

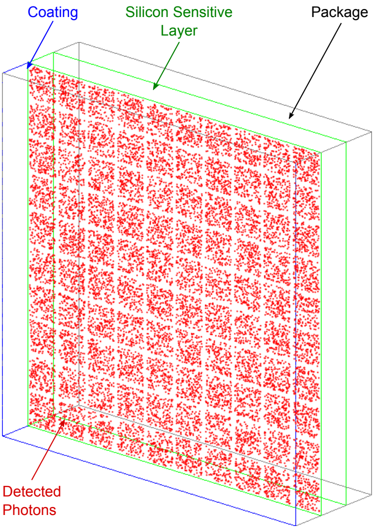
- Setup for the characterization of the pixels of FAMOUS!

G4Sipm

- C++ Monte-Carlo code
- Based on Geant4
- Phenomenological model based on quantities accessible in the lab
- Validated against laboratory measurements (with CMS working group)
- Publicly available: forge.physik.rwth-aachen.de/projects/g4sipm

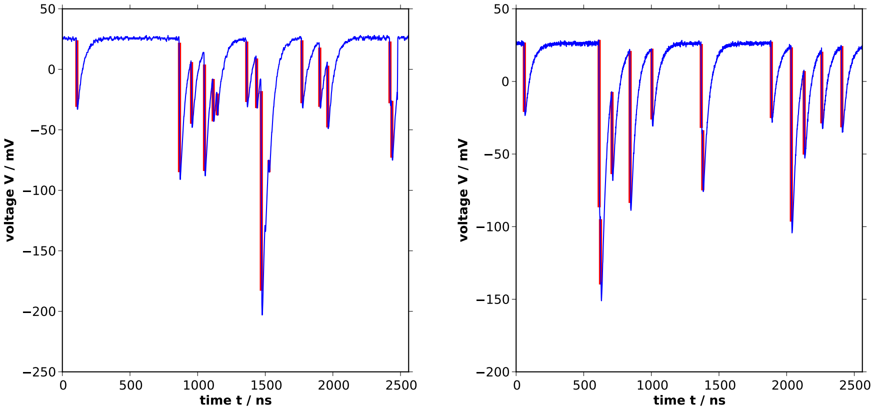
Modeled effects

- Dead space between cells
- Photon detection efficiency (including angular dependence)
- Thermal noise
- Correlated noise
- Recovery- & dead-time



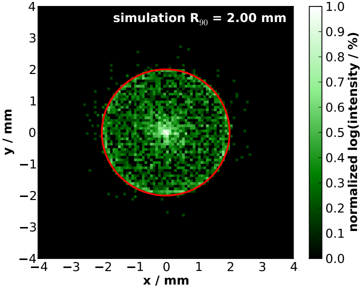
Screenshot of Geant4 visualization

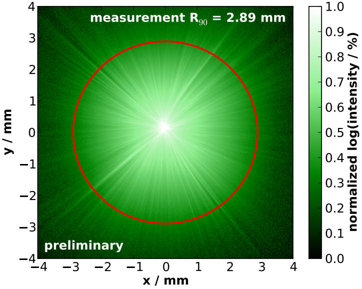
Which is real, which is fake?



Fresnel lens characterization

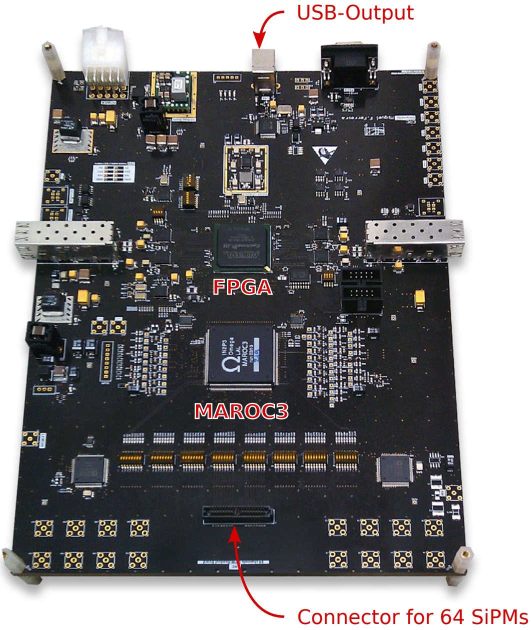
- Picture Fresnel lens image of a parallel light source
  - Vary sensor position to seek focus
  - R_{90}: circle containing $90\,\%$ of the light in the image plane
- **Sensor**: commercial system camera :
  Sony Nex5, sensor $22.2 \times 14.8\,\text{mm}^2$
- **Light source**: LED behind circular aperture (Ø < 1 mm) in $d \approx 25$ m distance





- Measurements match reasonably well the simulations

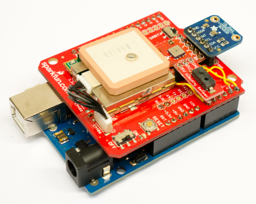
FAMOUS readout electronics

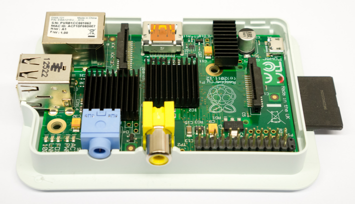


- Based on MAROC3 chip
- 64 channels (2 discriminators each)
- ADC for digital readout
- Individual control of bias voltage for each pixel
- FPGA handles all digital functions including trigger
- USB output

FAMOUS data acquisition

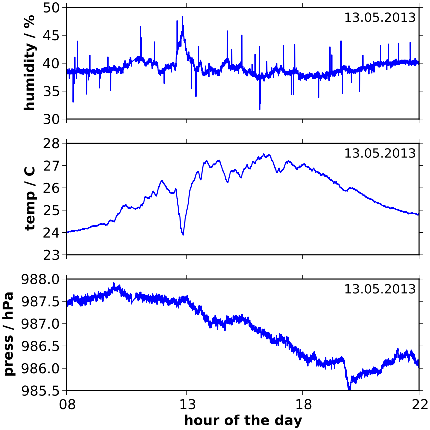
- **Raspberry Pi** mini-PC with 1GHz, 512Mb Ram
- **Arduino** microcontroller board with sensors
- Battery-pack (mobile phone charger) as contingency power supply
- **Database** data storage (mirrored via LAN / WLAN)
- **Web-frontend** for easy control and access of data

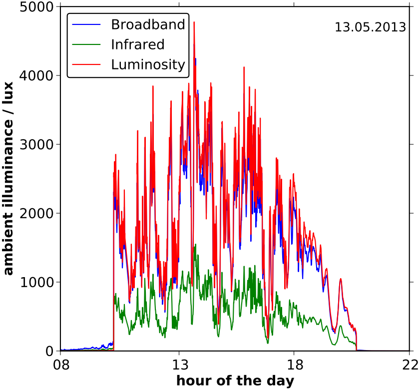




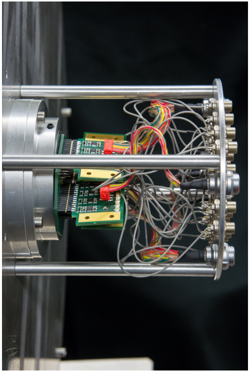
FAMOUS data acquisition

- GPS for timing
- Records environmental data
  temperature, pressure, humidity, ambient light flux, ...
- Data taken in one of our laboratories





Assembly of FAMOUS^{SEVEN}

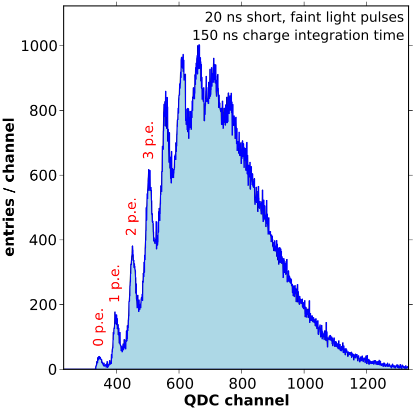


- Final baseline design of FAMOUS but with 7 pixels to test construction
- Modular design easily extendable to 64 pixels
- Made in Aachen's mechanical facility
- 7 pixel version of FAMOUS fully assembled!

First light with FAMOUS^{SEVEN}

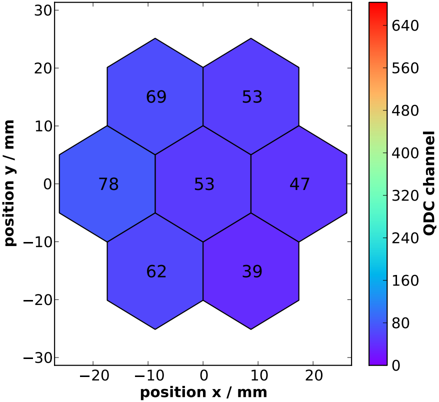
First light with FAMOUS^{SEVEN}

First light with pulsed LED



- Enables calibration of the bias-voltage and the gain of the pixels

First dark noise measurements



- Operating voltage not calibrated yet!
- Telescope is ready for calibration $\rightarrow$ perform flat-fielding

Summary

- **FAMOUS** = compact fluorescence telescope prototype with **64 SiPM pixels**
- Test feasibility of SiPMs for fluorescence detection with higher accuracy
- Dedicated SiPM simulation **G4Sipm** publicly available
- FAMOUS$^{\text{SEVEN}}$ fully assembled
- Firmware for dedicated 64 channel readout currently being tested
- DAQ interface for FAMOUS ready

Outlook

- Flat-fielding of FAMOUS$^{\text{SEVEN}}$
- Star / Moon tracking with FAMOUS$^{\text{SEVEN}}$
- **Upgrade to 64 pixels**

Thank you for your attention!

Further information available here:

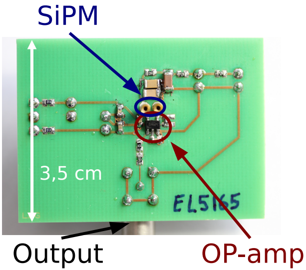
http://www.physik.rwth-aachen.de/institute/institut-iiia/forschung/auger/famous

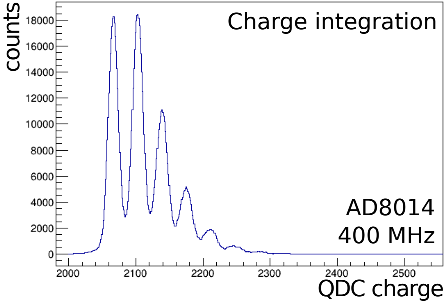
http://forge.physik.rwth-aachen.de/projects/g4sipm

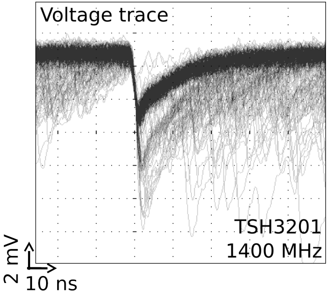
Backup

Front-end electronics for characterization studies of SiPMs

- Trans-impedance amplifier design
- Very fast low noise op-amp
- Optimized for SiPM timing and low noise signal integration
- Low bandwidth option for charge spectrum, high bandwidth for voltage traces





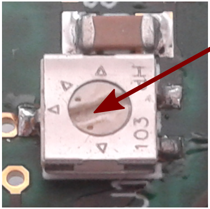


Front-end electronics for characterization studies of SiPMs

- Includes fully analogue temperature compensation circuit
- Compensates linear temperature dependence of SiPM's breakdown voltage V_{bd}
- Slope β manually adjustable* from $0\,\text{mV K}^{-1}$ to $80\,\text{mV K}^{-1}$

$$V_{\text{bd}}(T) = V_{\text{bd}}(0\,℃) + \beta\,T$$

- For Hamamatsu SiPMs: $\beta \approx 56\,\text{mV K}^{-1}$



* Adjustable by trim potentiometer

Prototype of FAMOUS is simulated by Raytracing in GEANT4

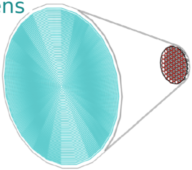
“Think out of the box”
Small, mobile detectors ?

Monte-Carlo studies to evaluate an array layout

Conservative application
FAMOUS as large scale FD

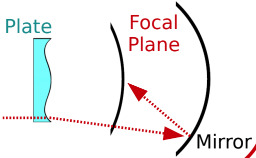
A

Refractive Design with Fresnel Lens



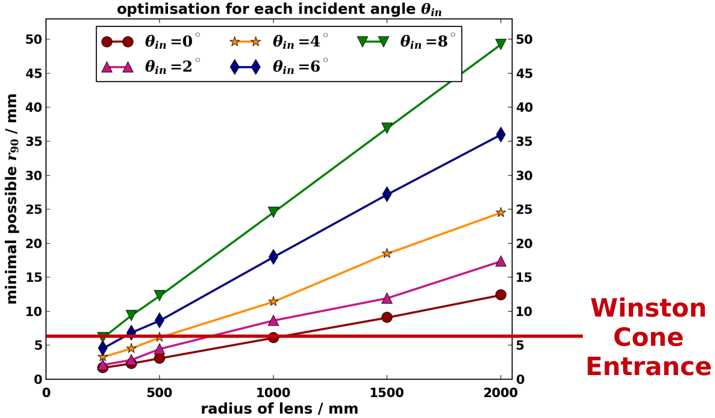
B

Schmidt Telescope using the FAMOUS Detector Technology



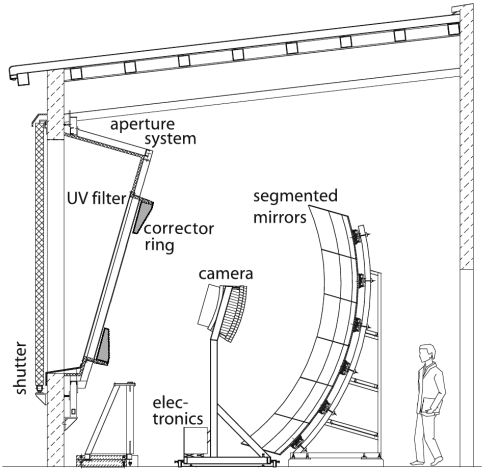
A) Refractive design with Fresnel lens

- Optimization of refractive design corrected for curvature of field for different incident angles θ_{in} with respect to normal



- For lens radii above 500 mm: r90 radius is not sufficiently small

B) Reflective design: Schmidt camera optics



spherical mirror introduces spherical aberration

↓ correction

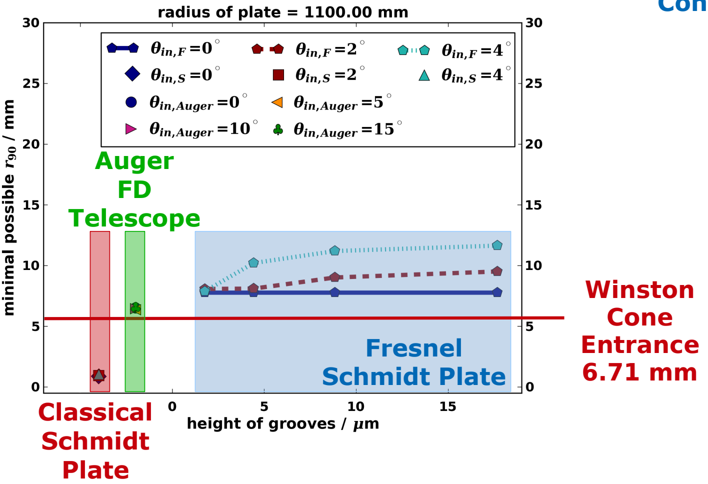
Schmidt corrector plate

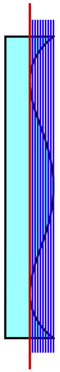
less absorption

Auger FD telescope	**FAMOUS successor**
corrector ring	Fresnel corrector plate

B) Reflective design with different corrector plate types

- Transmission Fresnel plate $> 90\,\%$, Schmidt Plate only $\approx 82\,\%$





- Fresnel Schmidt Plate performs reasonably good