INAF ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS
IASFPa Istituto di Astrofisica Spaziale e Fisica cosmica di Palermo

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Catania

Using reference stars to verify the end-to-end absolute calibration and for the long term monitoring of the Fluorescence Detector telescopes at the Pierre Auger Observatory

A. Segreto

for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

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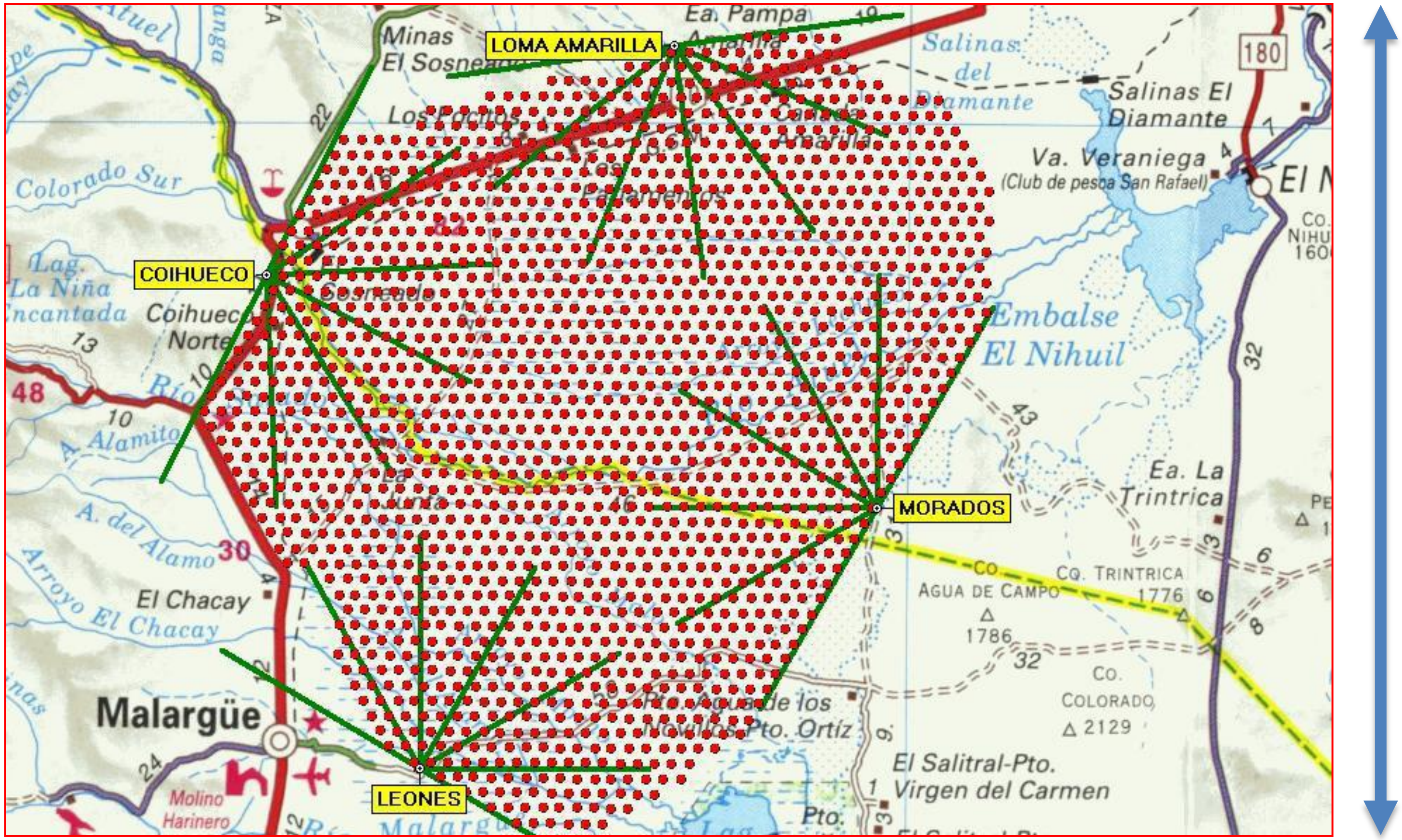
The Pierre Auger Observatory



~65 km

- The Pierre Auger Observatory, covering an area of ~3000 km^2, is the largest cosmic-ray observatory in the world
- Its main goal is to study Ultra-High Energy Cosmic Rays
- It is located in Malargue, Argentina at 1400 m above sea level

Main Detector types

Surface Detectors (SD)

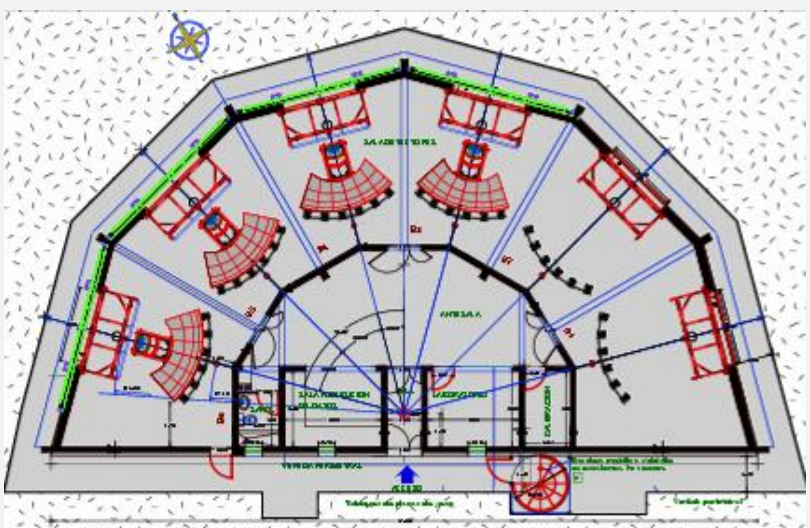
- 1660 water Cherenkov stations
- operated night and day, independently on weather conditions
- 100 % duty cycle

Fluorescence Detectors (FD)

- 27 telescopes @ 4 sites
- operated only during moonless and clear nights
- ≈ 15 % duty cycle

- Hybrid detector: two complementary measurement techniques
- FD has lower duty cycle, but its energy scale (with lower systematic uncertainties) is used to calibrate the data from the SD array

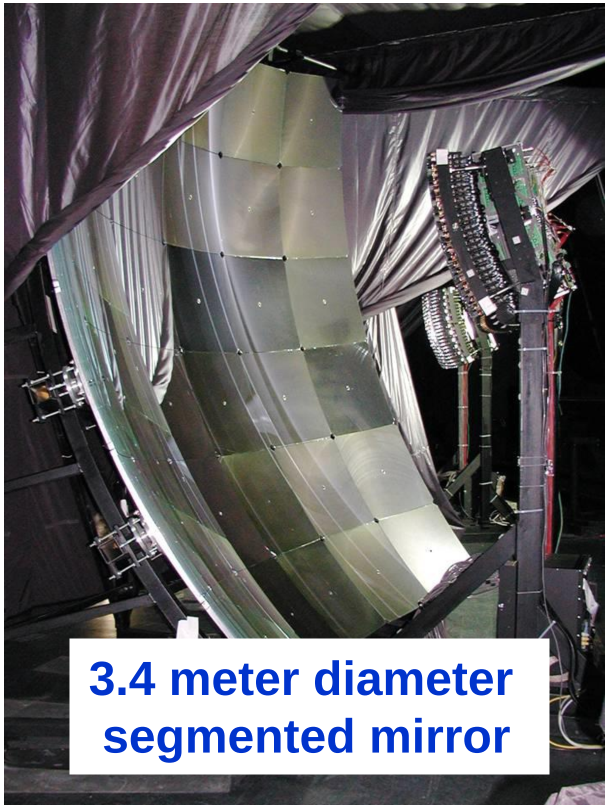
The Fluorescence Detector

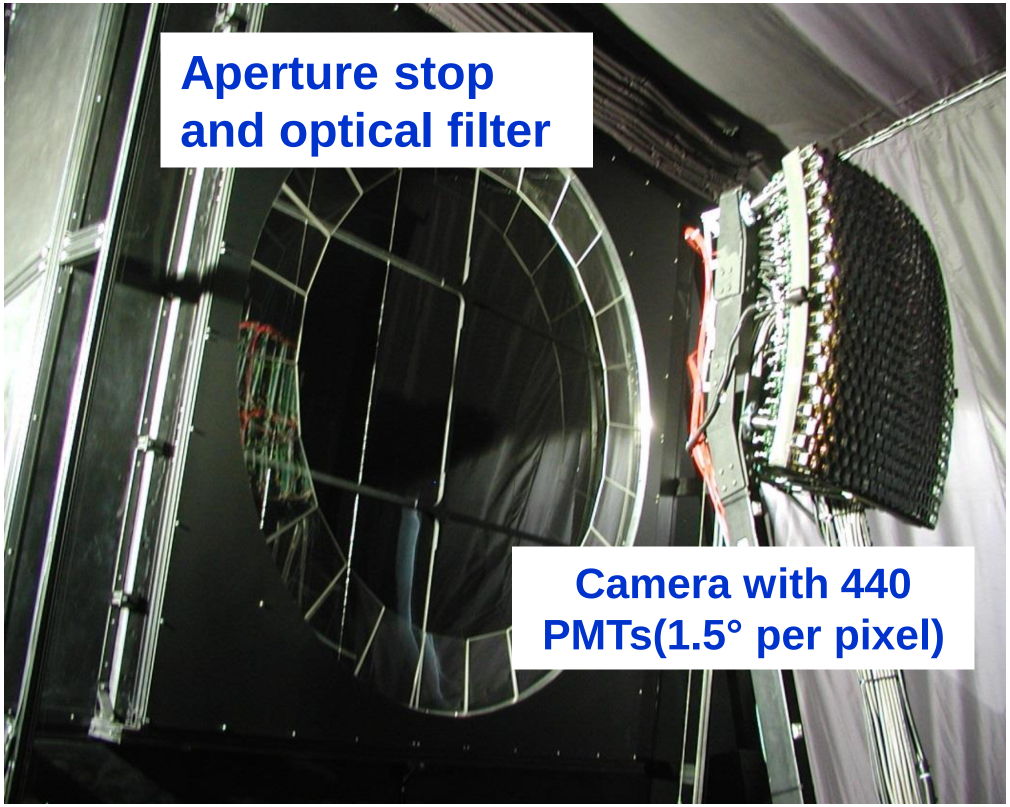


- 27 FD telescopes with a 30° x 30° field of view
- 24 FD telescopes are grouped in 4 buildings (in widely separated locations) and point the sky at an elevation angle centered at ≈ 15°
- 3 additional telescopes (HEAT) point to the sky at an elevation angle centered at ≈ 45°

HEAT (High Elevation Auger Telescopes)

The Fluorescence Detector optical system





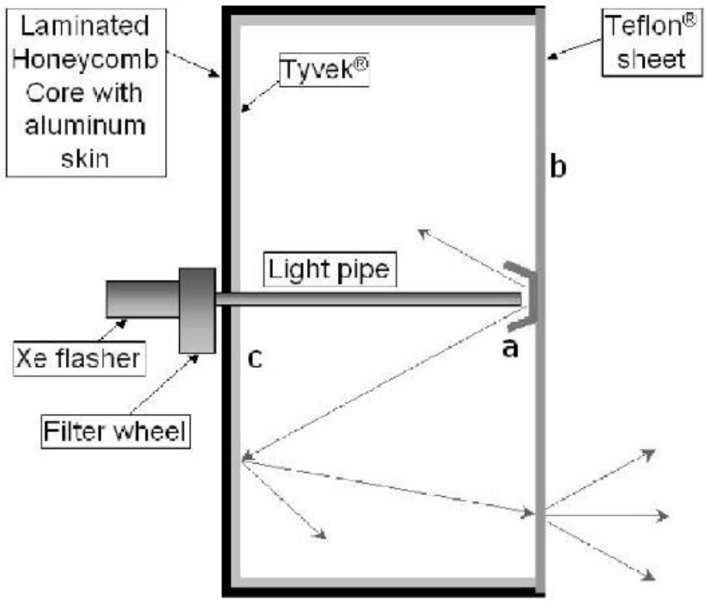
To obtain the overall telescope response there are two alternative methods:

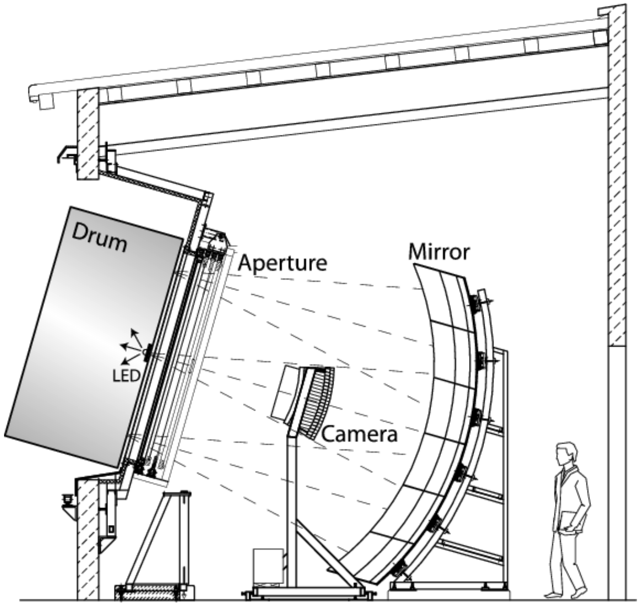
- calibration (in lab.) of its individual components (i.e. mirror reflectivity, efficiency of camera PMTs, filter transmission) and then taking into account the optical system geometry by performing a Monte Carlo simulation
- "end to end" calibration: illuminate the detector with a reference light source and record its response. Advantage: no need to know the contribute of individual elements, and lower systematic uncertainty

The Drum

- The FD end-to-end calibration technique involves a portable light source that mounted at the aperture of each telescope to uniformly illuminate its camera
- The “portable” light source, referred to as the Drum because of its appearance, is a cylinder 1.4 m deep with a 2.5 m diameter
- The ratio between the known flux from the light source and the response of the camera PMTs gives the required “end to end” calibration factor
- However, due to its complexity, only a few campaigns have been performed to calibrate the whole array of FD telescopes

… but the Drum needs to be calibrated





- **The Drum is a complex device and needs itself to be accurately calibrated every time it is used.**
- **A ray-tracing program is used to calculate corrections for small non-uniformities that are measured in lab. Another small correction for internal reflections has also to be taken into account.**
- **The Drum operation is rather complex and can't be done too often. A relative calibration system is used to track the calibrations between Drum campaigns.**

It is desirable to have a totally independent method to verify and monitor frequently the FD absolute calibration

Calibration with flying light sources

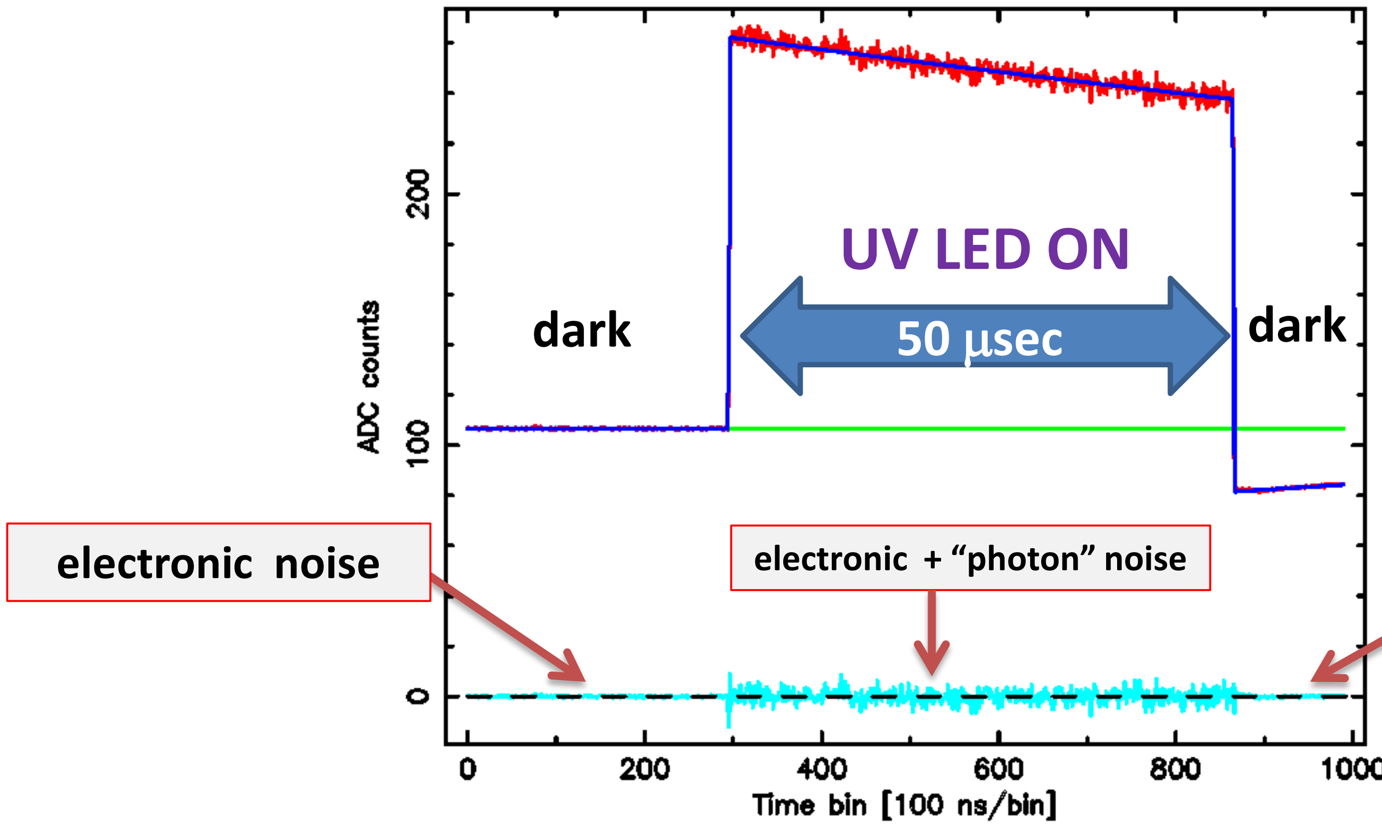
- Several calibration campaigns using calibrated source on a flying platform, the octocopter, have been performed to study, in particular the point spread function of the FD telescopes
- Main limitation of the method is the reduced flying time that allows to calibrate only a few pixels/night

What about using reference stars?

- The calibration of astronomical optical telescopes is frequently verified by observing stable reference stars
- Why not use a similar method to verify the absolute calibration of the FD telescopes?

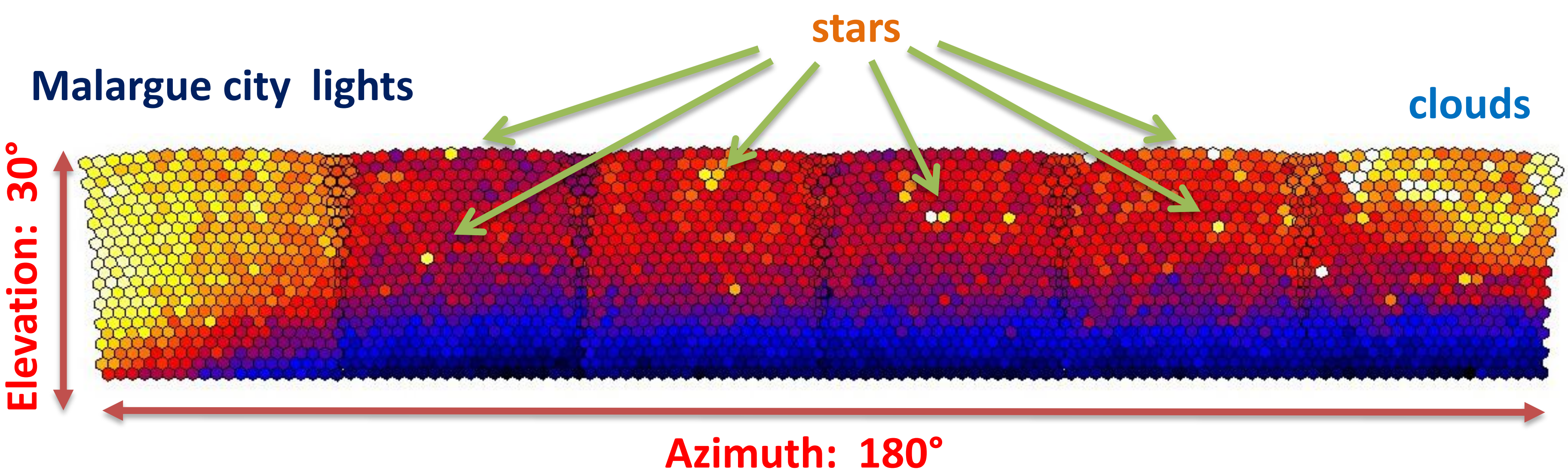
… not that easy because FD electronics is optimized to detect the very fast (few μsec) signals produced by cosmic rays initiated showers but it is (almost) blind to the (slowly varying) night sky background flux!

FD response to calibration pulses



- a square pulse illumination (from the internal calibration system) generates in the FD electronics a signal whose amplitude, notwithstanding the constant photon flux, decreases rapidly in time
- due to its quantum nature, the light pulse induces also an increment of the signal noise proportional to the number of detected photons
- In case of long lasting (> 1 msec) illumination, the amplitude of the electronic signal vanishes, but the fluctuations due to the “photon noise” remain stable!

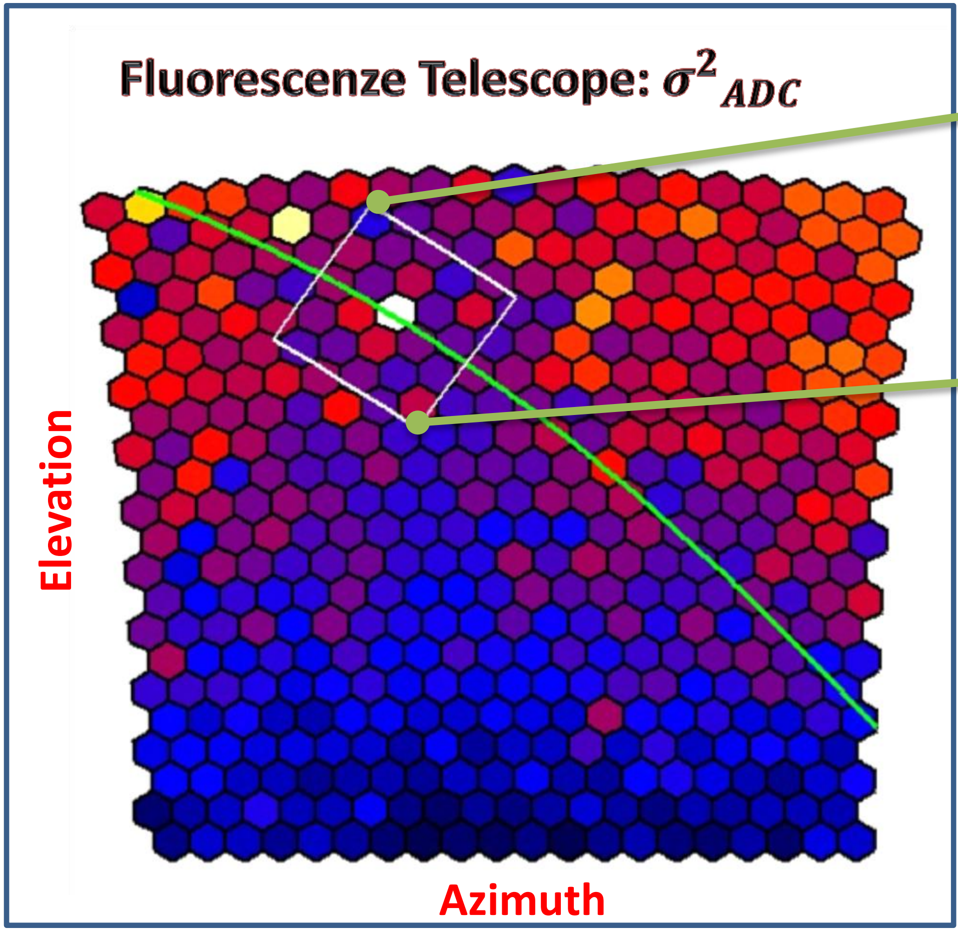
Night sky reconstructed from “variance”

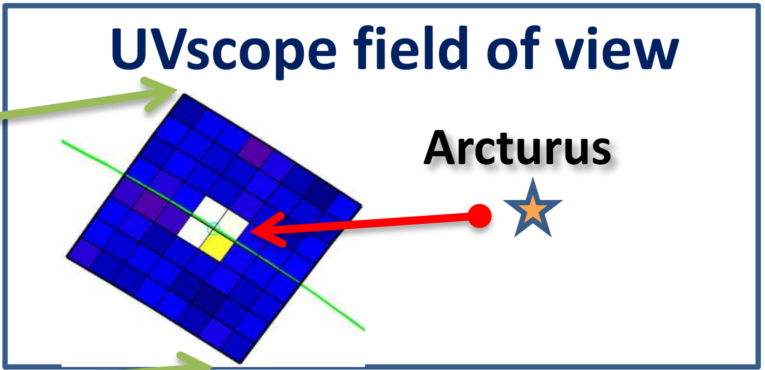


- The statistical analysis of the noise in each PMT signal has been implemented in the FPGA logic on the FD electronic boards (no additional hardware resources used!)
- For each FD telescope a “variance” (square of the standard deviation) image of its field of view is periodically recorded (usually every 30 sec, but can be reduced to 5)
- The wide-field NSB image shows the excellent inter calibration status of the six telescopes in a same building

… how much accurate can be the absolute photon flux indirectly obtained from measurements of a detector noise?

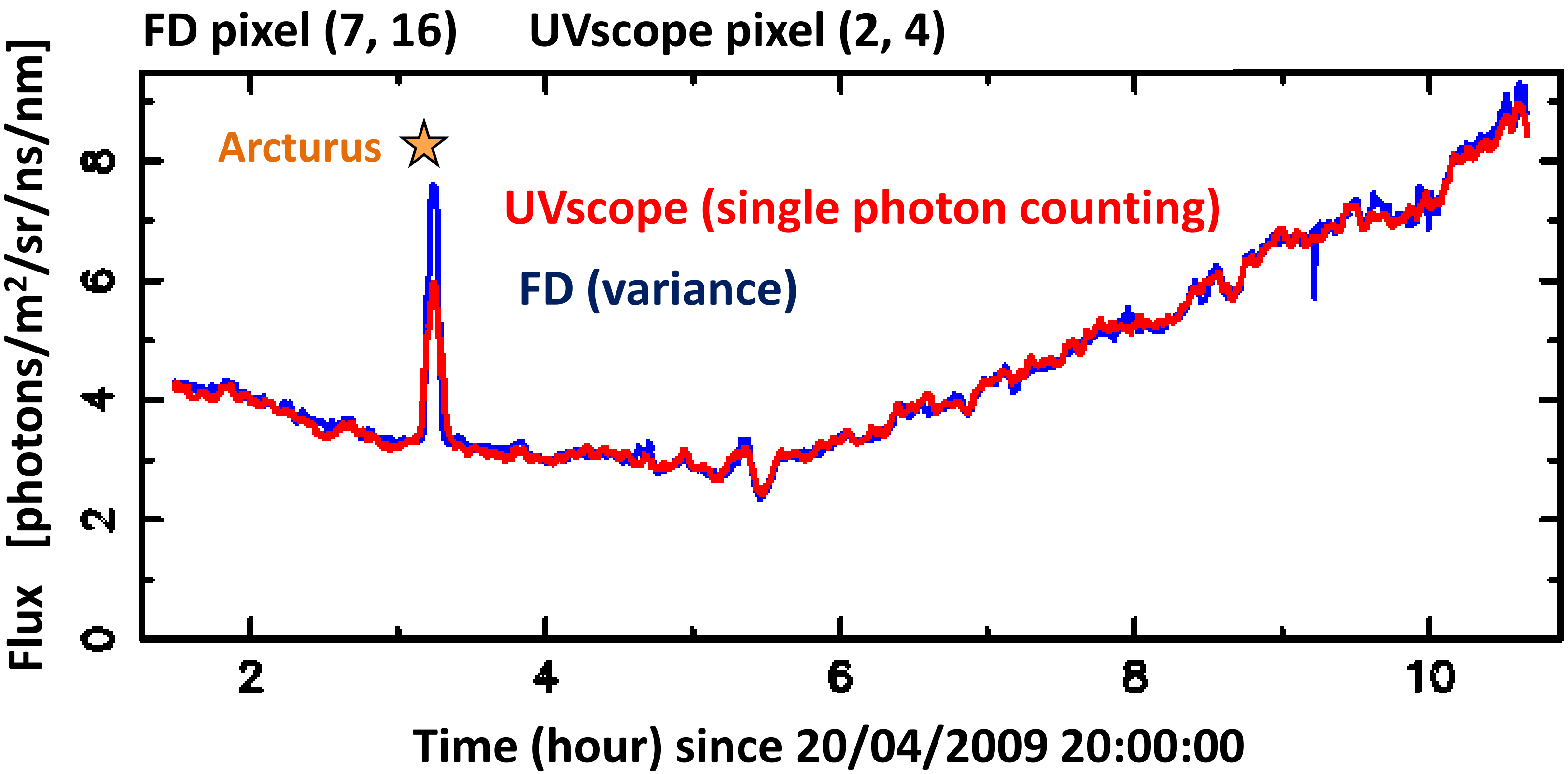
Fluorescence Detector vs. UVscope





- On April 2009 the 1st measurement campaign was performed to compare the NSB fluxes measured by a "single-photon" counting instrument (UVscope) to the values obtained, in the same direction, by the "statistical method" (FD variance)

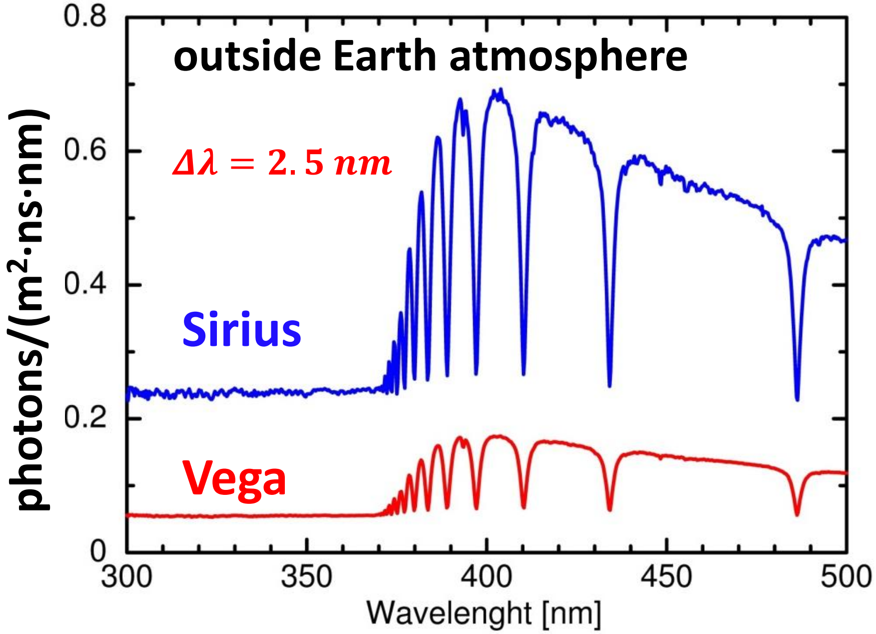
single photon counting" vs. "variance



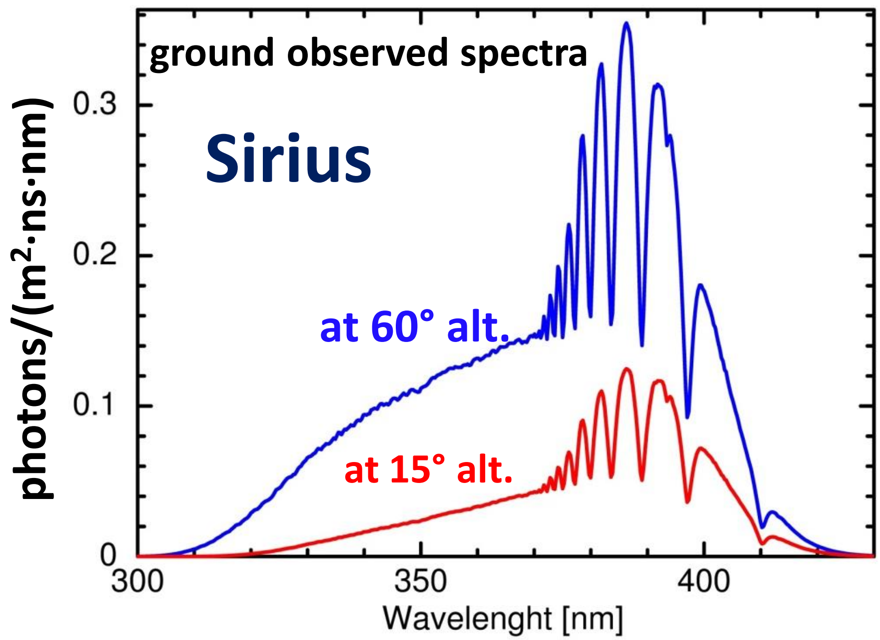
- ... excellent (quite surprising) result: "Variance" (i.e. noise) is as good as "photon counting" to measure the night sky background flux!
- Minor differences are due to different geometrical pixels shape (square vs. hexagonal)

... now we need to compare the star fluxes obtained from the FD "variance" to the values that are expected from a well known reference star

How to analyse signals from stars?



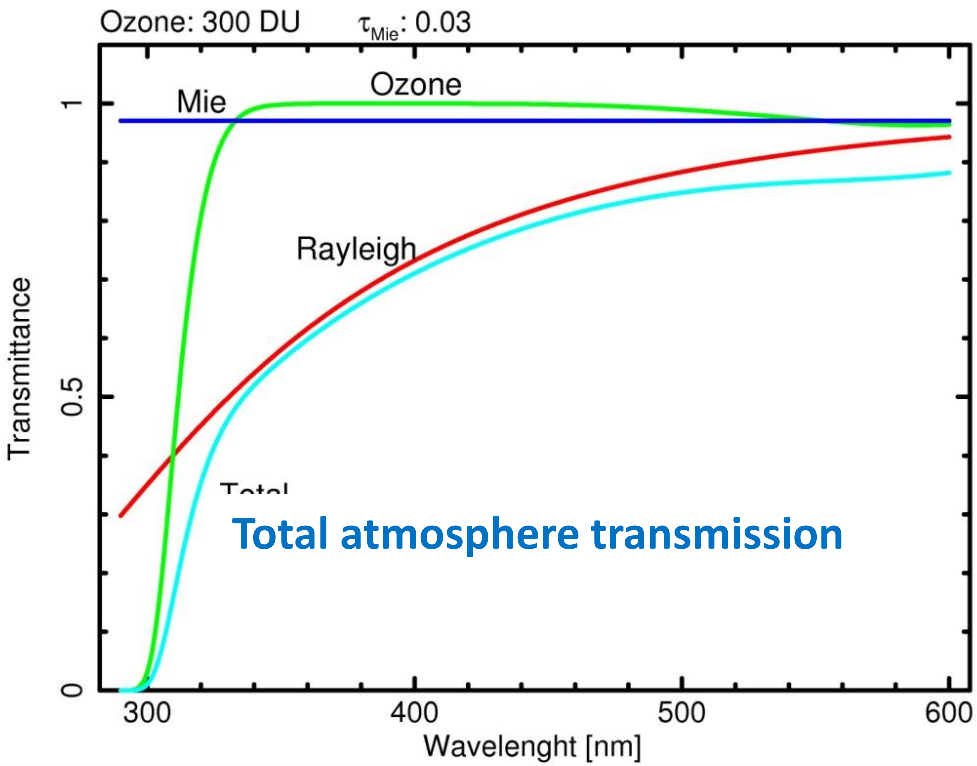
intrinsic star spectral distribution



spectral distribution of detected photons (including typical atmosphere attenuation and FD spectral response)

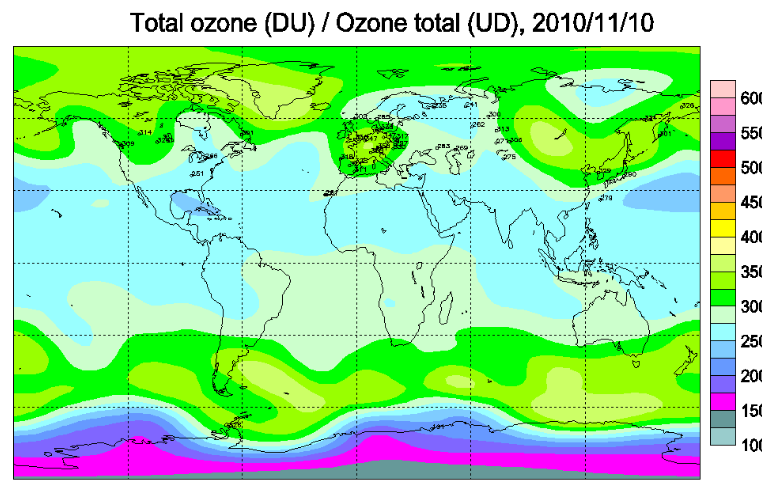
- To use a star as a "reference source", its absolute calibrated spectrum "on top of the Earth atmosphere" must be retrieved from astronomical data bases
- The primary reference star for absolute astronomical photometry is Vega, however, in the Southern Hemisphere, Sirius is preferred as it can be observed at higher elevation angles
- The ground observed spectra are altered by the detector spectral response and atmospheric attenuation (dependent on star elevation)

Atmospheric attenuation



Total atmosphere transmission

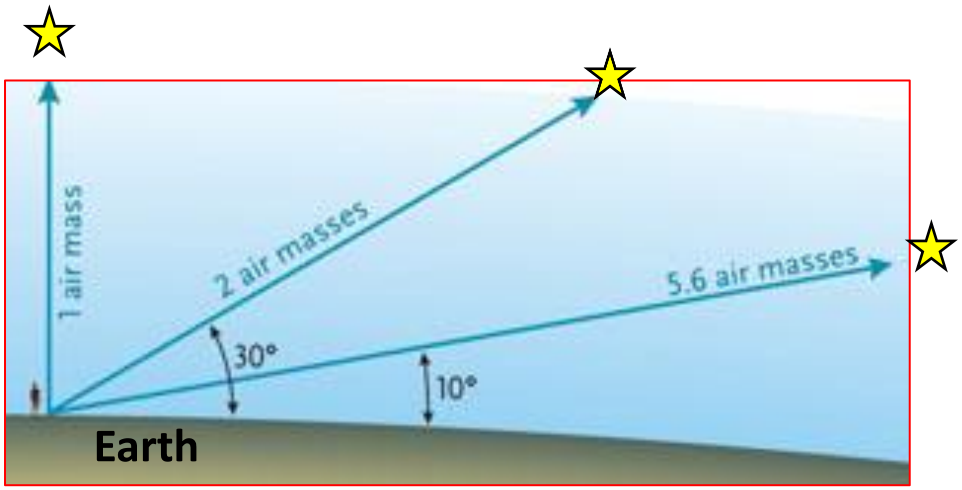
overhead ozone maps



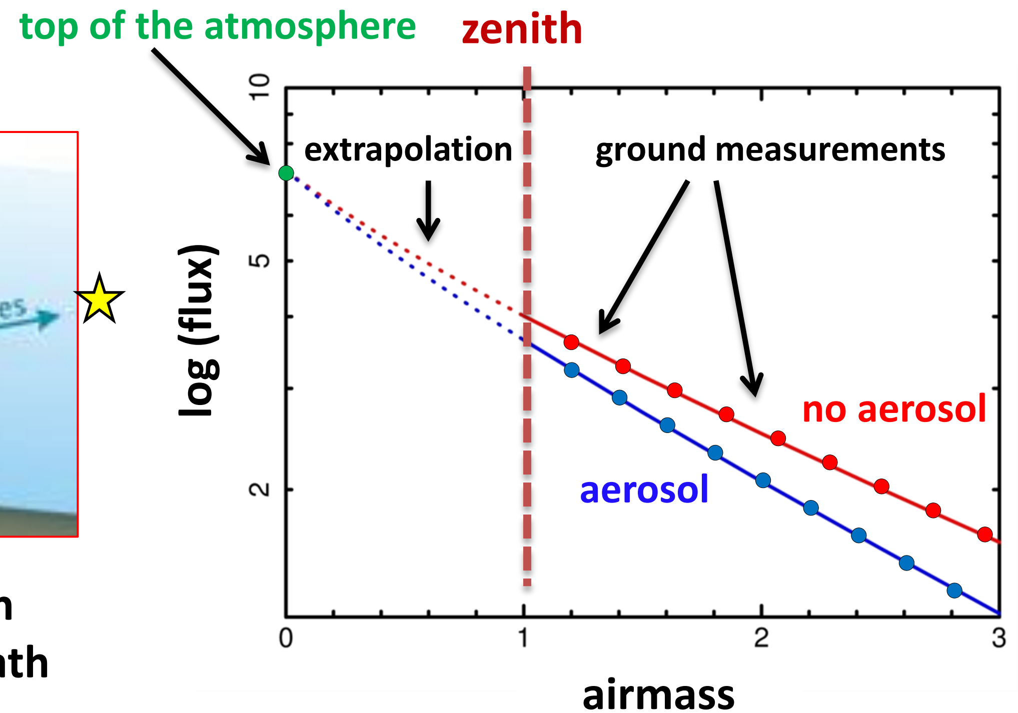
Groud measured star fluxes must always be corrected for the attenuation of light during its propagation in the atmosphere:

- **Ozone absorption**: < 320 nm; daily ozone thickness maps are on the web
- **Molecular (Rayleigh) scattering**: can be matematically computed from the local barometric pressure
- **Aerosol scattering**: highly variable from night to night, depends on local, unpredictable, aerosol density and composition therefore must be accurately measured!

The Langley plot method



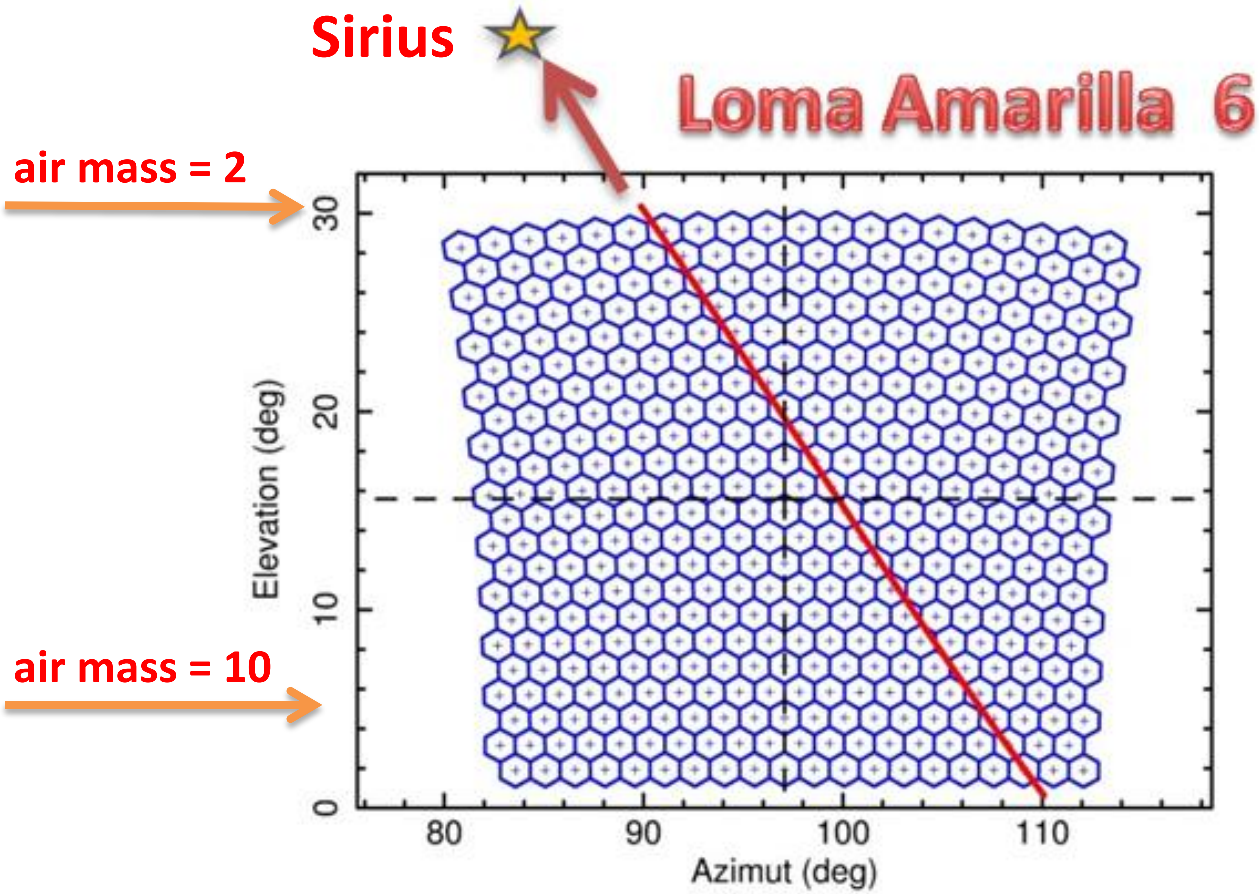
The "*air mass*" is the path length through the Earth's atmosphere relative to the path length at zenith

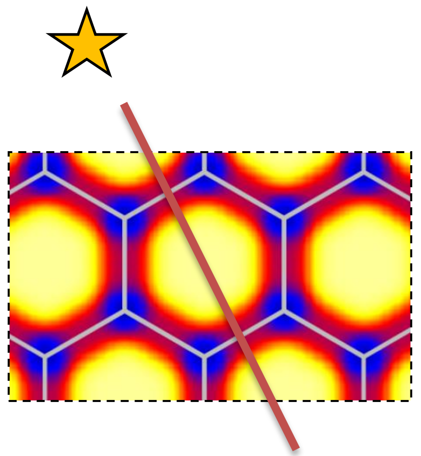


- A standard method used in astronomy to correct ground based measured star fluxes for the atmospheric attenuation, is to plot the logarithm of the star signal as a function of the amount of "*air mass*" traversed by the light

- A fit to the measured data provides both the total atmosphere attenuation (the slope), and (its extrapolation to zero air mass) the star flux as it would be measured if the instrument were placed on top of the atmosphere

Star tracks in the FD telescopes

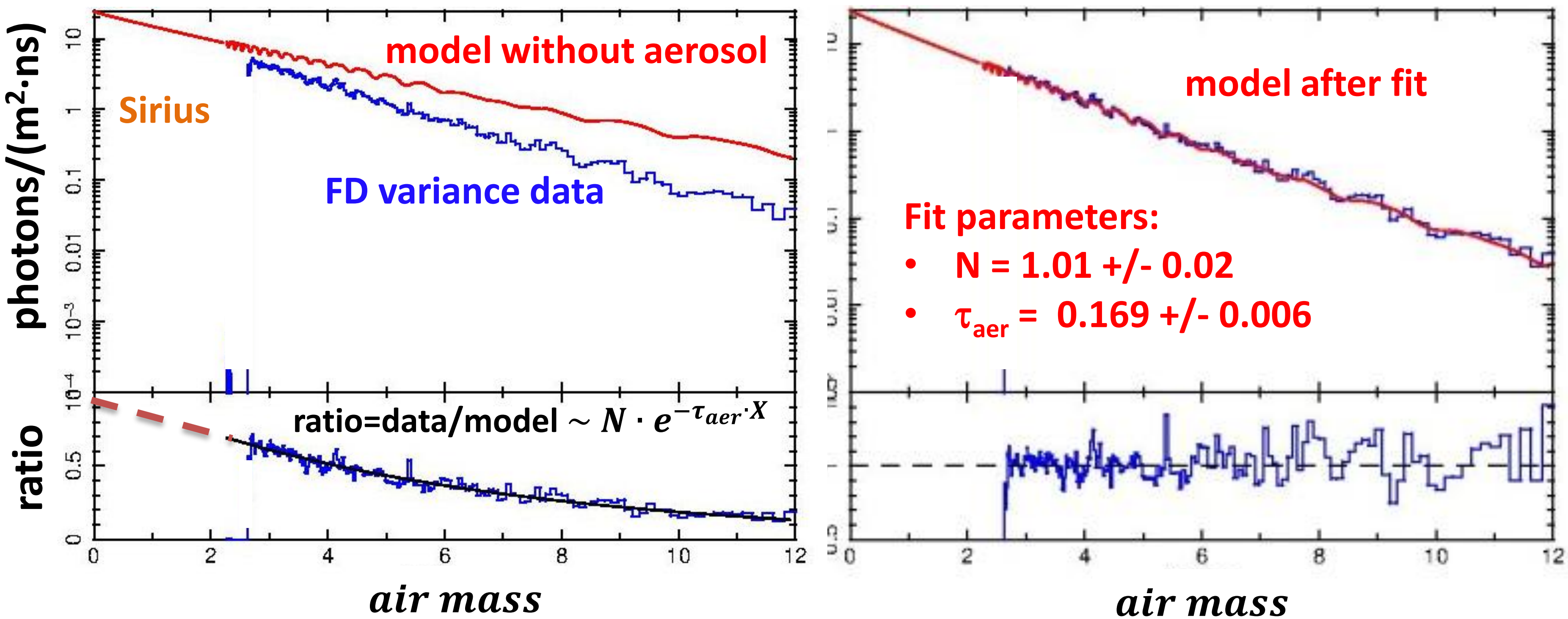




The detection efficiency map reproducing the reduced photon collection efficiency observed when a star crosses the pixel boundaries

- Stars crossing the FD field of view are observed for an air-mass interval large enough to apply the Langley plot method
- The non uniform spatial response of the PMTs, introduces an additional modulation along the star track that has been included in data analysis

Check of absolute calibration with Sirius



- The aereosol optical depth and a corrective normalization factor are obtained by fitting the simulated star flux to the values obtained from the FD variance data
- A normalization factor consistent, within statistical uncertainty, with a unitary value, is an independent verification of the absolute calibration of the FD telescope obtained from the Drum measurements

Summary

- The Fluorescence Detectors of the Pierre Auger Observatory are the first telescopes of this kind that, thanks to measurements of detector noise (variance), are able to monitor continuously the night sky background flux

- Results obtained by analyzing the signals induced by reference stars traversing the FD field of view provide an independent proof of the telescopes absolute calibration

- The features of this method makes it a perfect tool for the long term monitoring of the FD absolute calibration