Technology overview for the IACT telescopes

FRANCESCO DAZZI

University of Udine & INFN Padova

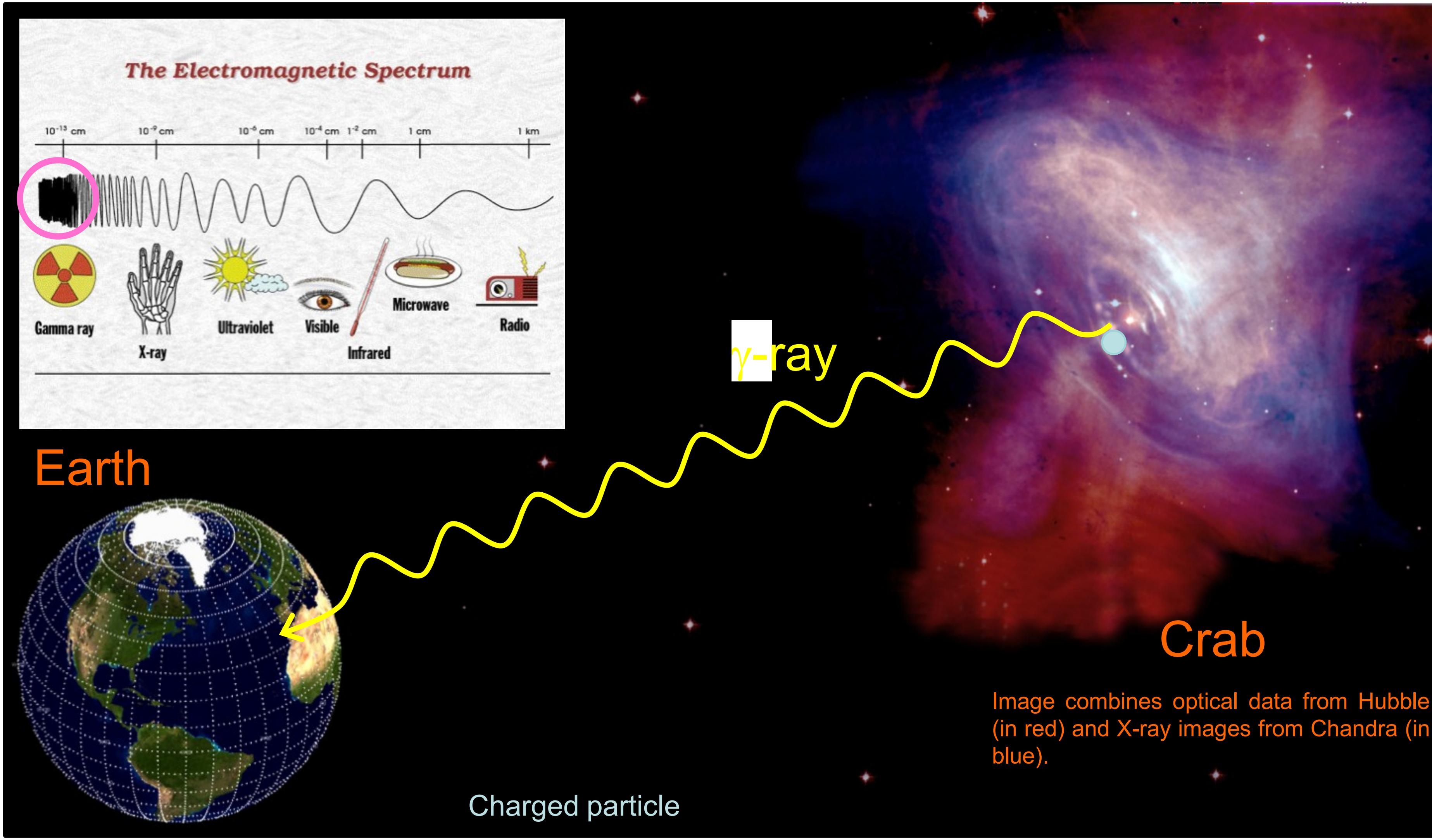
(Mera-TeV meeting)

Merate, 5 October 2011

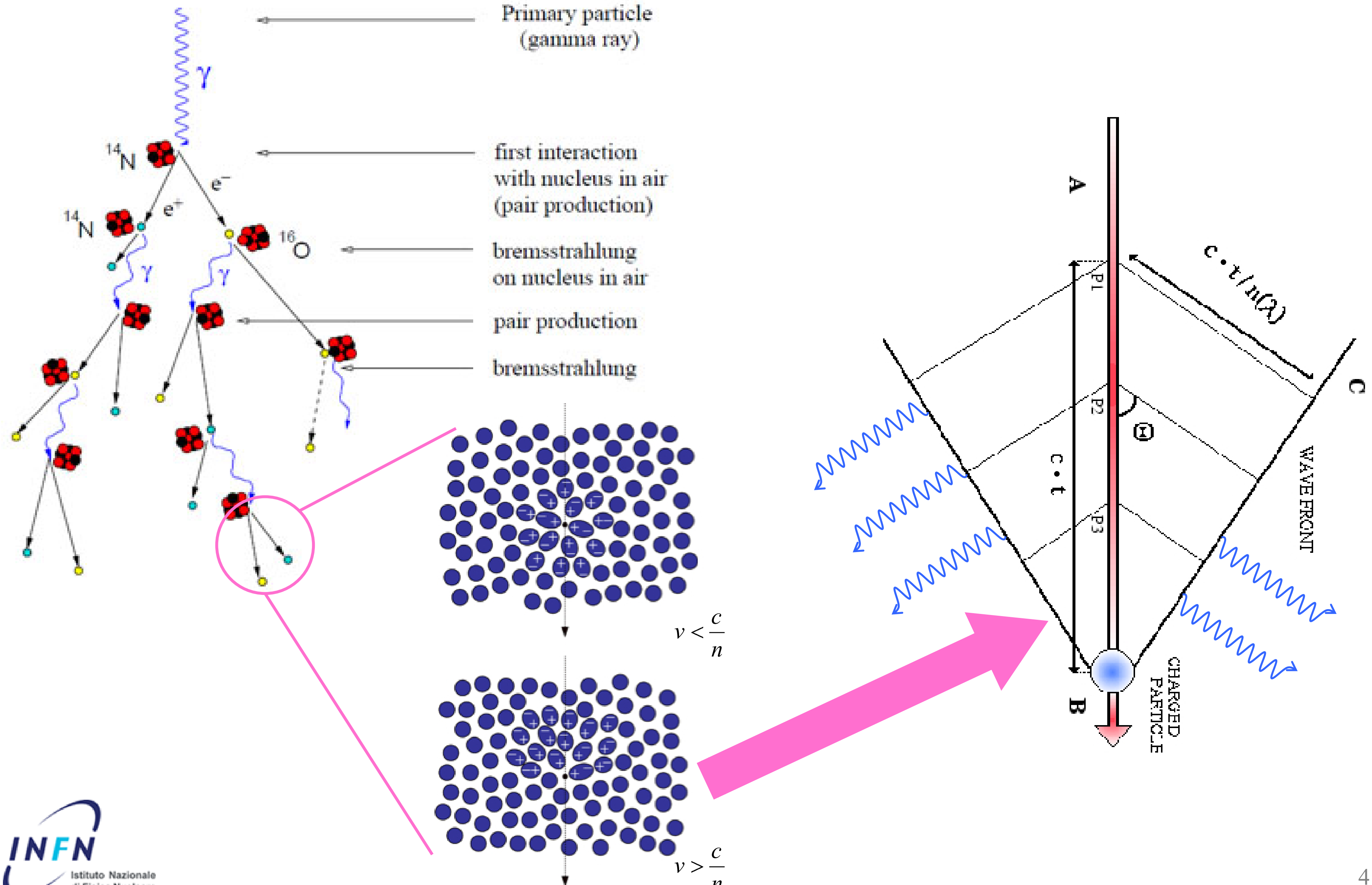
Summary

- Radiation observed
  - Primary gamma ray
  - Extended air shower
  - Cherenkov light & NSB
  - Detector features
- IACT telescopes
- Reflective surface
- Light sensors
- Electronic chain
  - Amplification
  - Trigger
  - Readout & DAQ
- Calibration system
- Conclusions

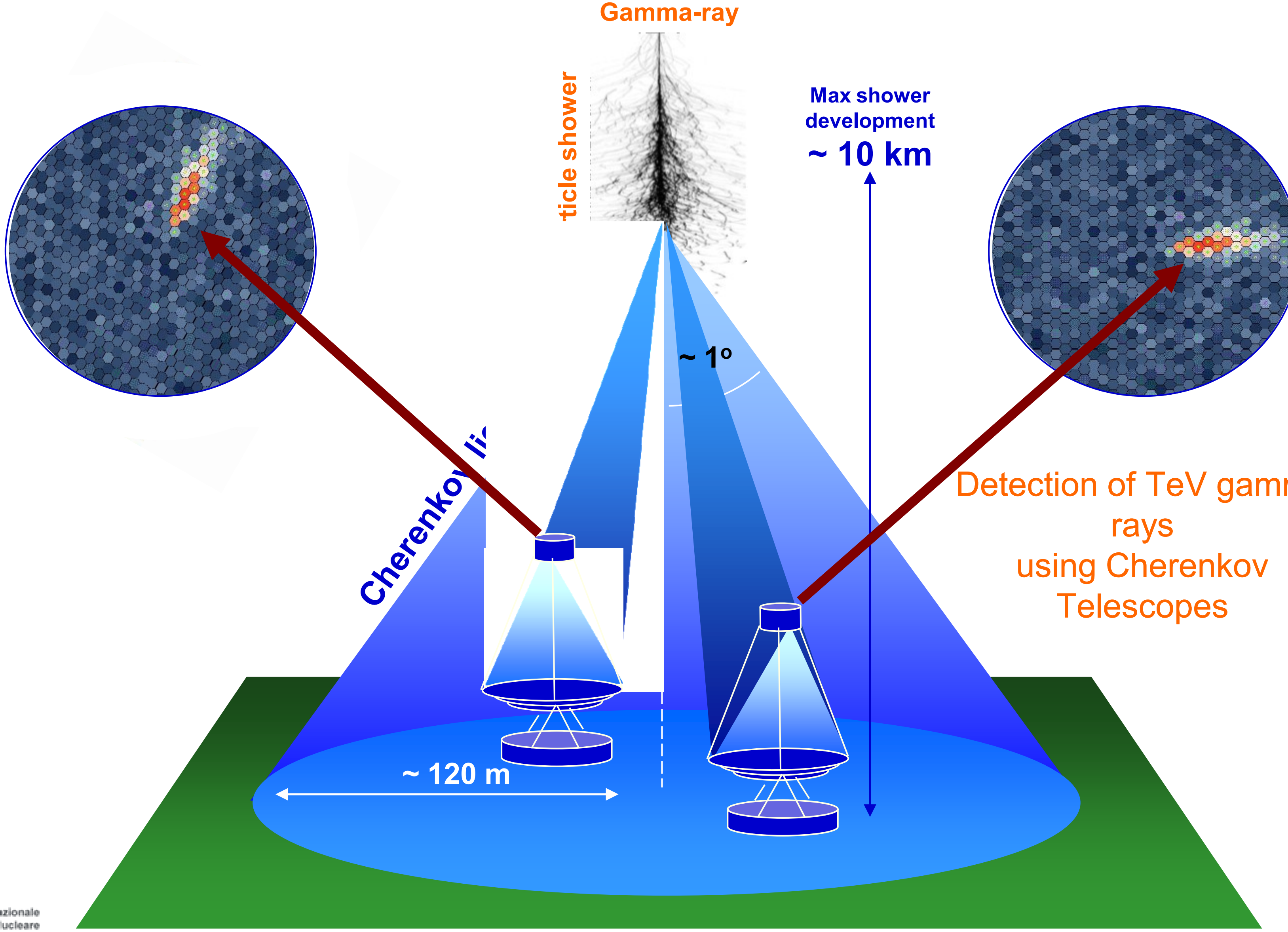
Radiation observed: primary γ-ray



Radiation observed: EAS



Radiation observed: EAS



Detection of TeV gamma rays
using Cherenkov Telescopes

Radiation observed: Cherenkov light & NSB

- Cherenkov light + NSB:
  - Cherenkov light from air showers: spectral range from 300 nm to 700 nm.
    - Below 300 nm absorbed by ozone
    - Above 600÷700 nm dominated by LONS
  - NSB is the Night Sky light Background composed by 2 groups:
    - LONS: diffuse light due to integrated starlight, air-glow & diffuse galactic light
    - NSB due to bright stars

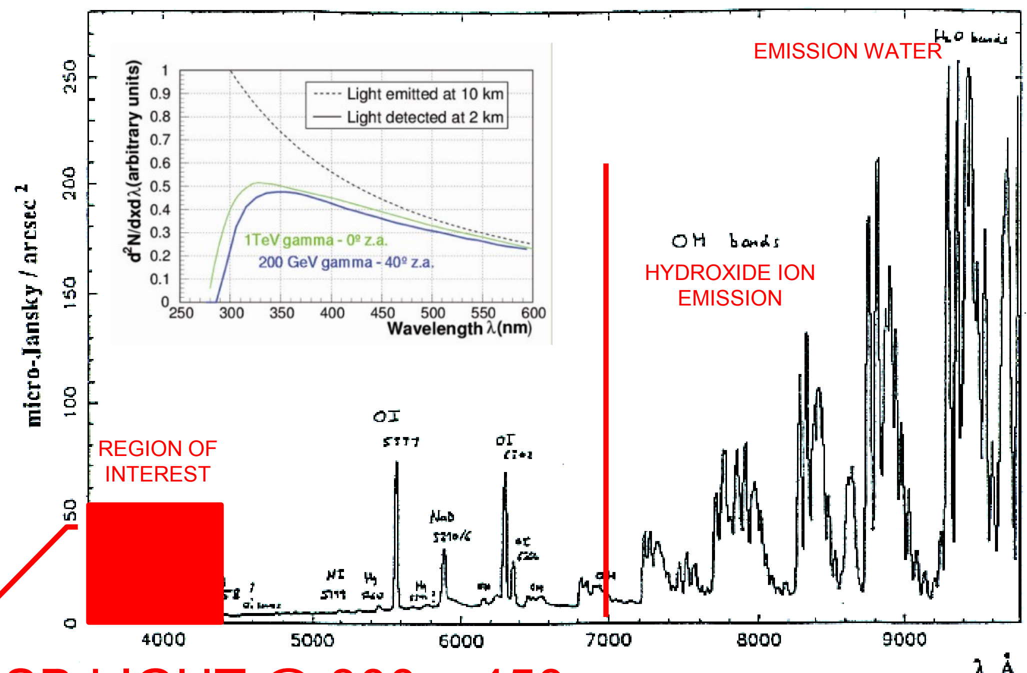
IN THE CHERENKOV RANGE: 300-600nm

Bialkali PMT

$\Phi(LONS) = (1.75 \pm 0.4) \cdot 10^{12}$ ph/m$^2 \cdot$sr•s

R. Mirzoyan & E. Lorenz - MPI-PhE94-35

EMISSION SPECTRUM OF LONS @ LA PALMA



CHERENKOV + NSB LIGHT @ 300 – 450 nm

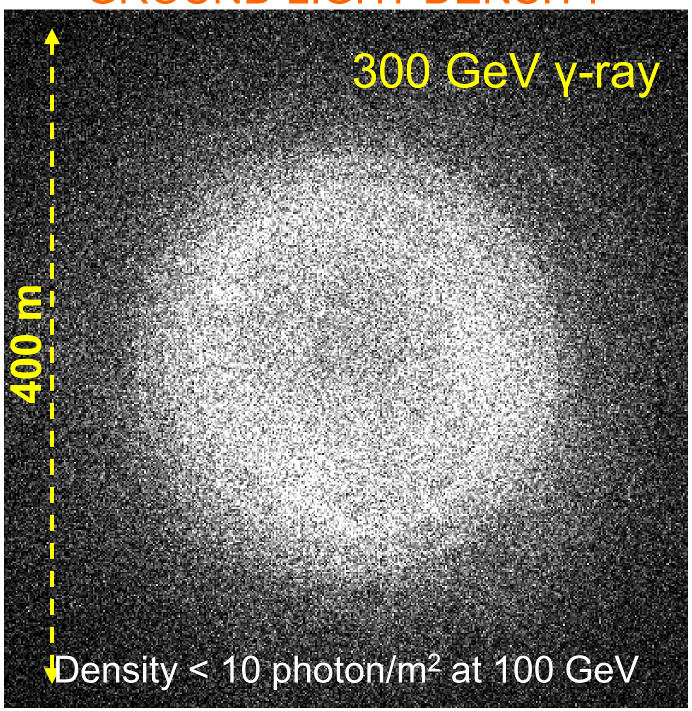
SIGNAL

NOISE

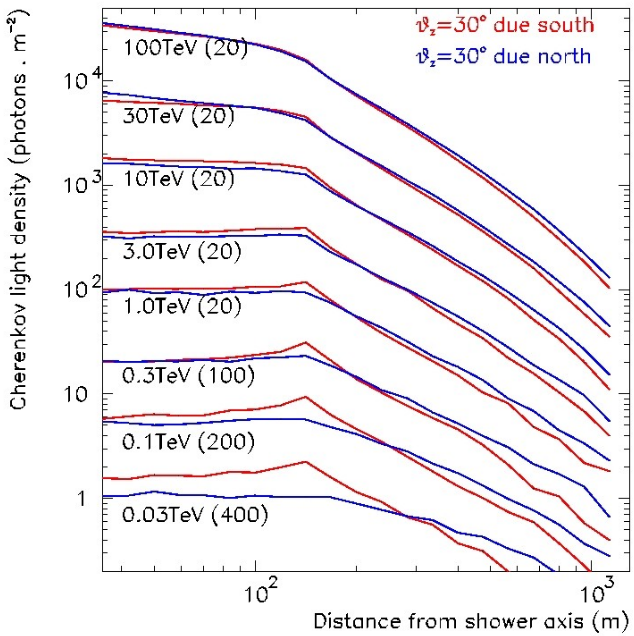
Radiation observed: Cherenkov light

- Signal to noise ratio:
  - It is mainly a function of the trigger threshold & the sky region pointed (events @ trigger input).
    - Trigger hardware input ~ 1 MHz
    - Trigger hardware output ~ 200 Hz (only accidental events and muons rejected)
    - γ rate after software analysis ~ 3 γ/min => 0,05 Hz (hadrons rejection)
    - S/N ~ $5 \cdot 10^{-8}$ (1 good event every 20 millions)

GROUND LIGHT DENSITY



CHERENKOV DENSITY



Radiation observed: detector features

- Very low photons flux (e.g. $\Phi(E_{CRAB} > 1\text{TeV}) = \sim 2 \bullet 10^{-11}\ \text{cm}^{-2}\text{s}^{-1}$) =>
  - Large effective collection area (> $3 \bullet 10^4\ \text{m}^2$, dependency with altitude)
- Small wavelength range detectable for Cherenkov light (300 ÷ 400 nm) =>
  - Optimization of the reflective surface and light sensors efficiency in that range
- Very brief Cherenkov flash (few ns) =>
  - Fast electronics (GHz domain)
- Very high background =>
  - Implementation of nice algorithms in the trigger and in the software cleaning to guarantee high rejection rate of noise and bad events

Reduce the energy threshold
as much as possible
Try to get some overlap
region with space
observations

Istituto Nazionale di Fisica Nucleare

Radiation observed: detector features

- Mathematical formula of the energy threshold:

$$E_{TH} \propto \frac{1}{\mathrm{A}_{\mathrm{dish}} \cdot \mathrm{R}_{\mathrm{mirror}} \cdot \mathrm{LC}_{\mathrm{eff.}} \cdot \mathrm{QE}} = \frac{1}{\mathrm{A}_{\mathrm{dish}} \cdot \varepsilon}$$

- The E_{th} of an IACT is inversely proportional to the number of collected photoelectrons
  - Large telescope dish
  - High reflectivity of mirrors and light collectors
  - High light sensors quantum efficiency

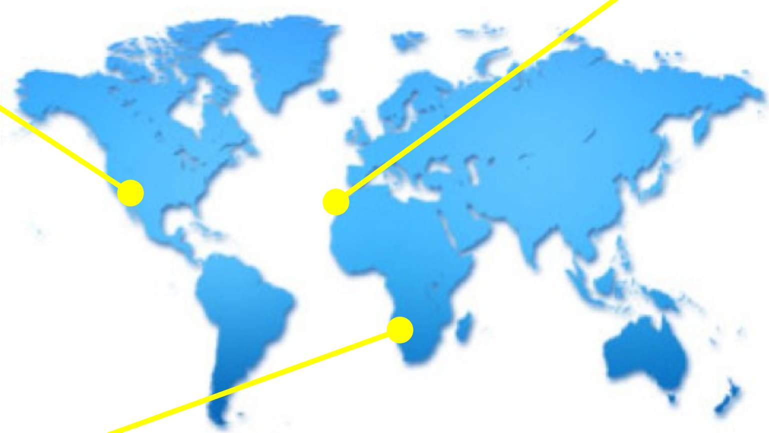
- Mathematical formula of the significance of a detection:

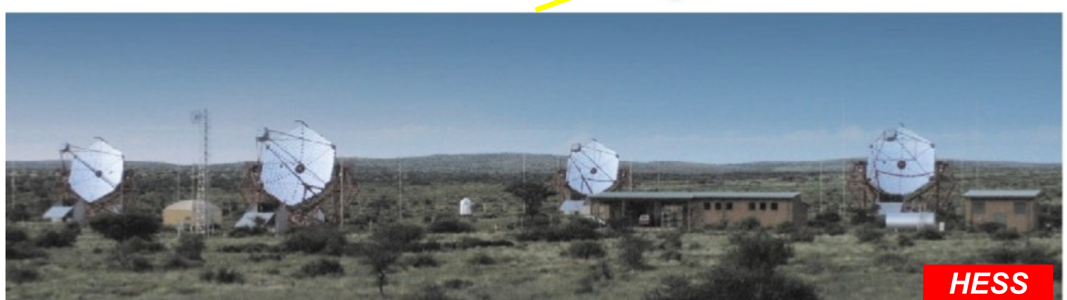
$$S_{Detection} = \frac{N_{excess}}{\sqrt{N_{bgd}}} \propto \frac{A_{dish} \cdot \tau_{gamma} \cdot \Omega_{shower} \cdot \varepsilon}{\sqrt{A_{dish} \cdot G_{trigger} \cdot \Delta\Omega_{NSB} \cdot \varepsilon}} \propto \sqrt{\frac{A_{dish} \cdot \varepsilon}{G_{trigger} \cdot \Delta\Omega_{NSB}}} = \sqrt{\frac{1}{E_{TH} \cdot G_{trigger} \cdot \Delta\Omega_{NSB}}}$$

- The SNR of an IACT is inversely proportional to the energy threshold, the trigger gate and the collected NSB photons.
  - The trigger gate ($G_{trigger}$) should be similar to the spread time of Cherenkov photons (τ_{gamma}) => isochronous mirrors and electronics and fast trigger.
  - Solid angle on which photons fall in a single pixel ($\Delta\Omega_{NSB}$) should not be much greater than the angular size of the shower (Ω_{shower}) => small pixels.

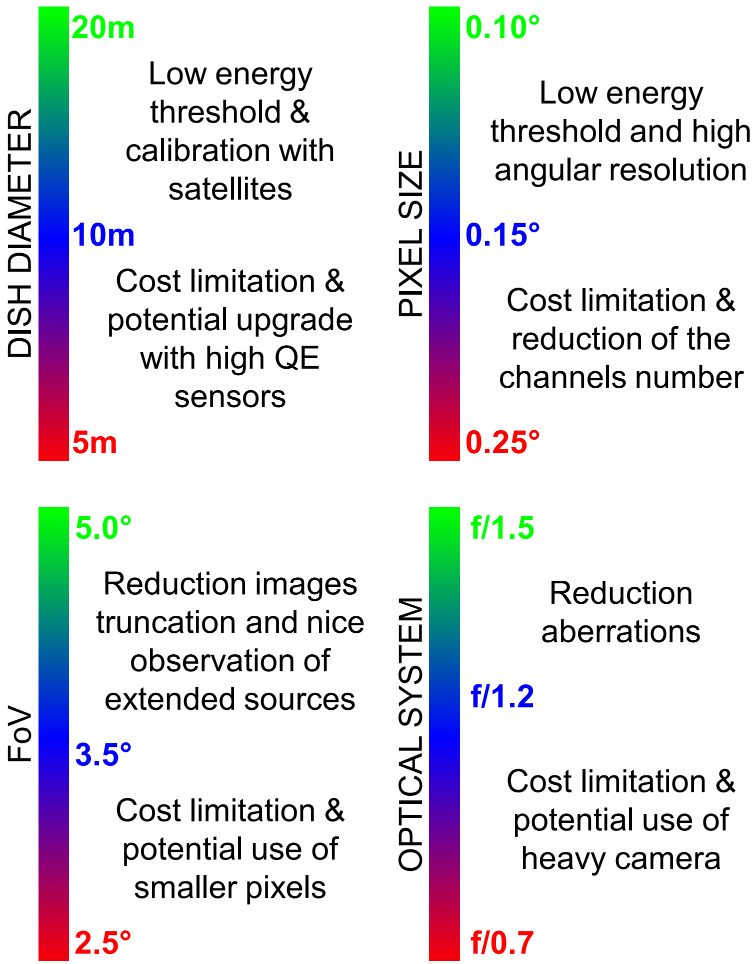
IACT telescopes

- There are three important IACT telescope:
  - H.E.S.S. (Namibia)
  - MAGIC (Canary island of La Palma)
  - VERITAS (Southern Arizona)





IACT telescopes



Technical features	H.E.S.S.	MAGIC	VERITAS
Altitude	1800 m	2225 m	1275 m
Telescope number	4	2	2
Reflector diameter	12 m	17 m	10 m
Reflector genre	Davies-Cotton	Parabolic	Davies-Cotton
Focal distance	15 m	17 m	12 m
Reflective area	107 m^2	236 m^2	106 m^2
Mirrors technology	Glass	Al & glass	Glass
Number pixels	960	576 - 1039	499
Camera FoV	5°	3.5°	3.5°
Light sensors kind	PMT	PMT	PMT
Light sensors QE	15%	20-30%	15-20%
Complete rotation	3 min	40 s	3-4 min
Readout	1 GS/s	2 GS/s	0.5 GS/s

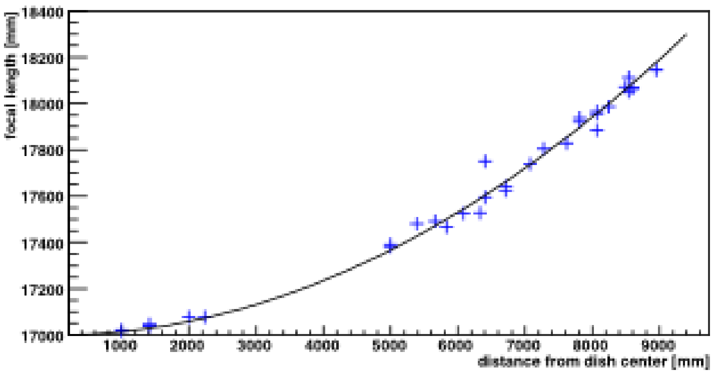
Performances	H.E.S.S.	MAGIC	VERITAS
Sensitivity	0.7% 50h	0.9% 50h	0.7% 50h
Trigger threshold	100 GeV	25 GeV	75 GeV
Energy resolution	15%	15%	10-15%
Angular resolution	0.06°	0.09°	0.03°

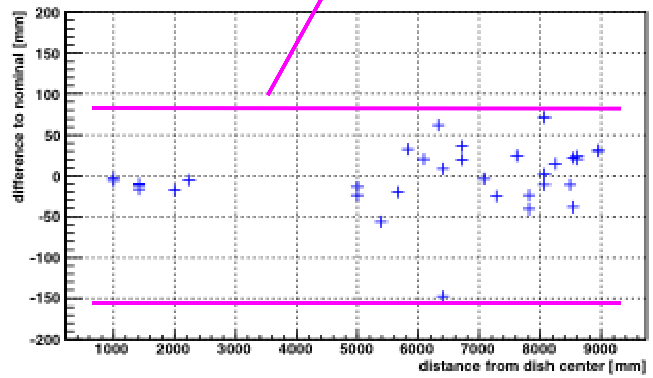
INFN Istituto Nazionale di Fisica Nucleare

Reflective surface

- Mirrors focusing:
  - **FOCAL LENGTH**
  - Reflectivity
  - Mirror's orientation

~ 22 cm => 750 ps





Parabolic structure is isochronous, while Davies-Cotton not (spread of few ns, but better off-axis image).

PARABOLIC OR DAVIES-COTTON STRUCTURE

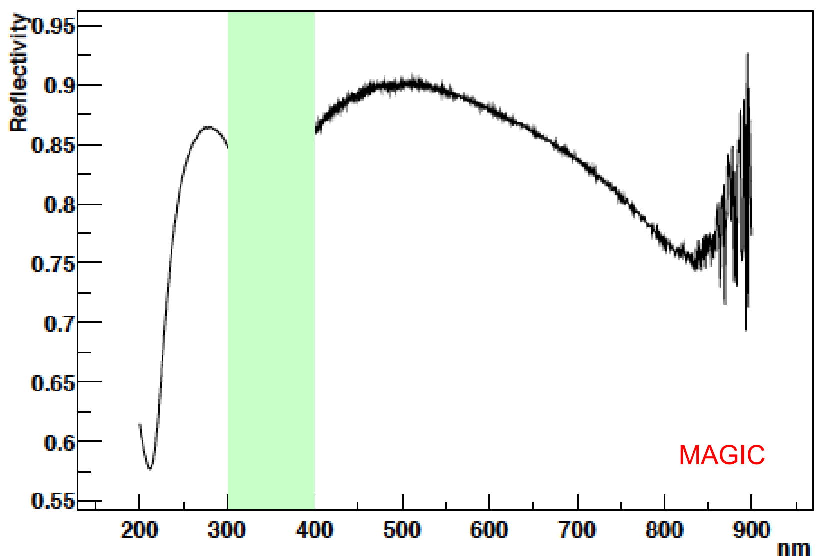
MIRROR SUPPORT

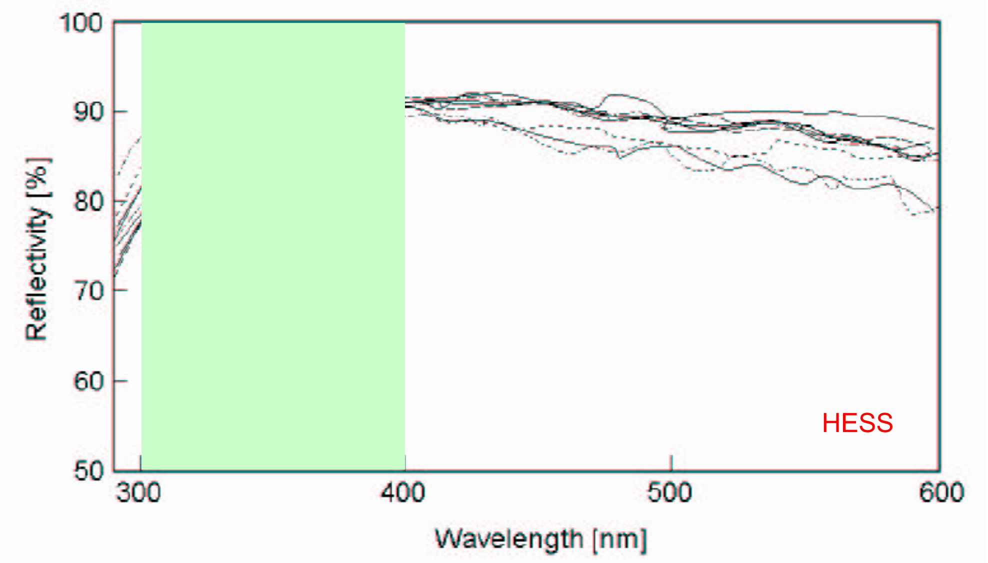
CAMERA POSITION

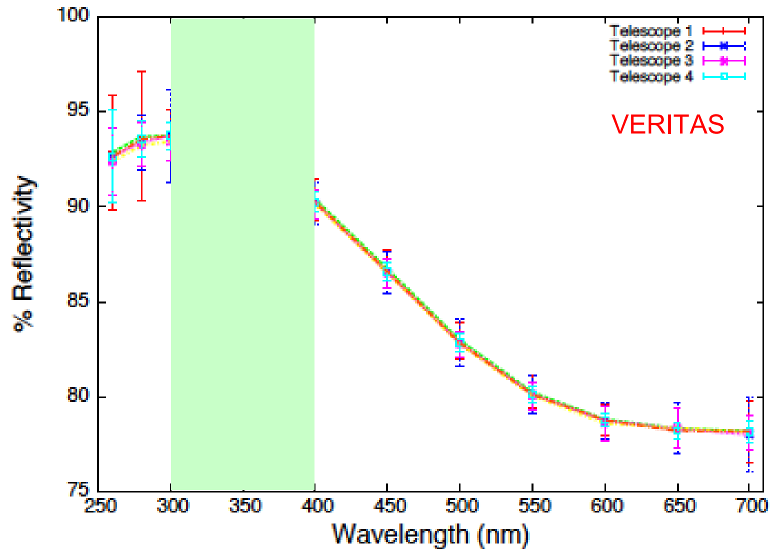
Istituto Nazionale di Fisica Nucleare

Reflective surface

- Mirrors focusing:
  - Focal length
  - **REFLECTIVITY**
  - Mirror's orientation

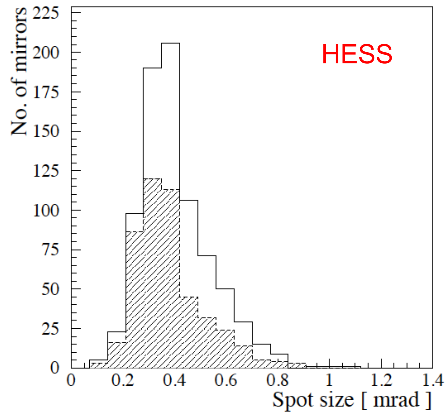


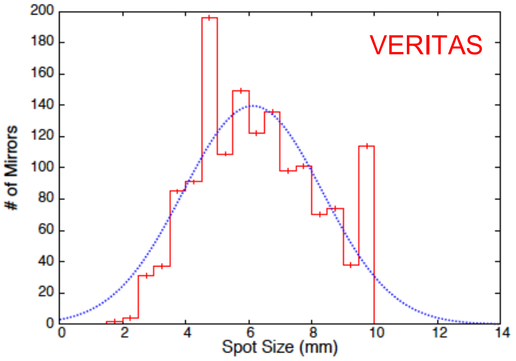


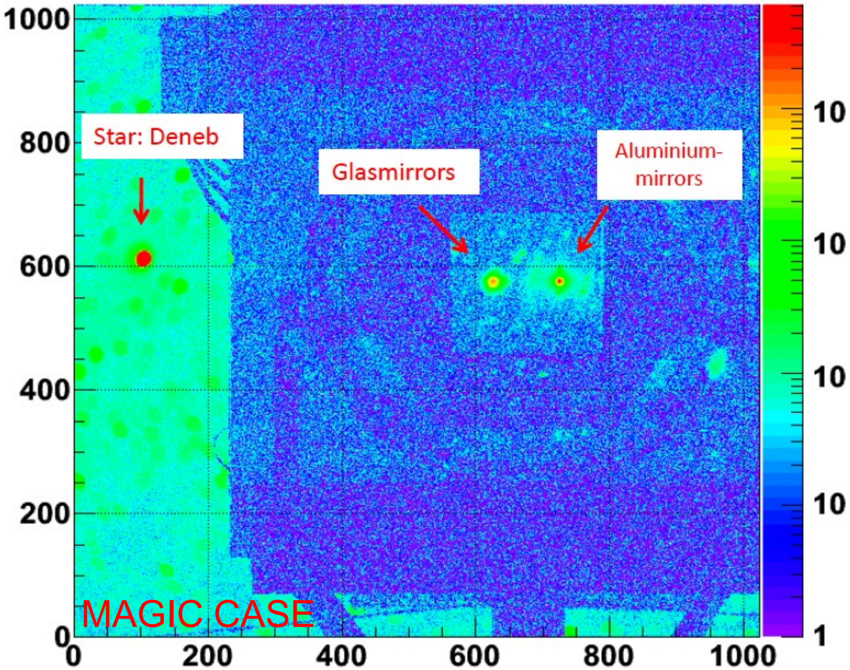


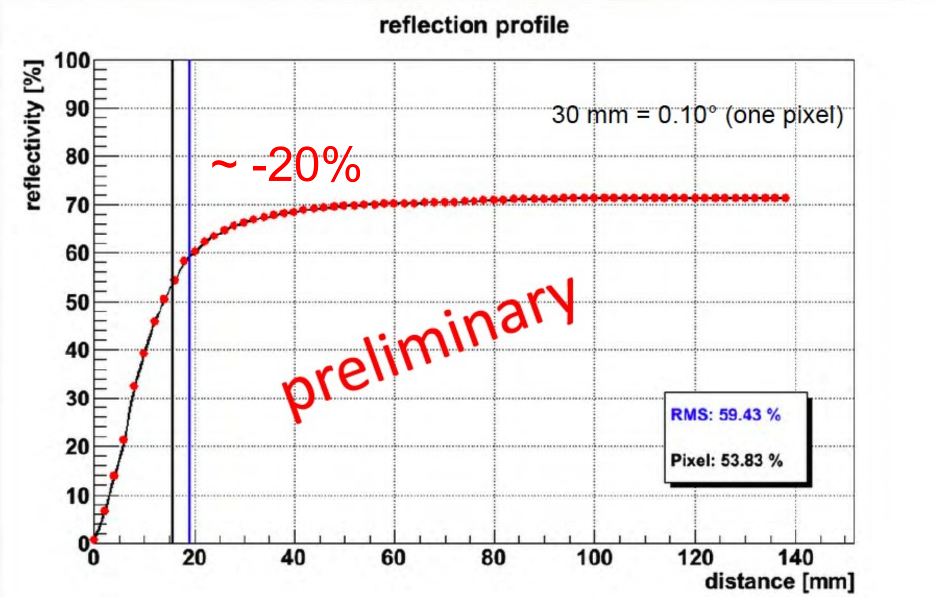
Reflective surface

- Mirrors focusing:
  - Focal length
  - **REFLECTIVITY**
  - **MIRROR'S ORIENTATION**



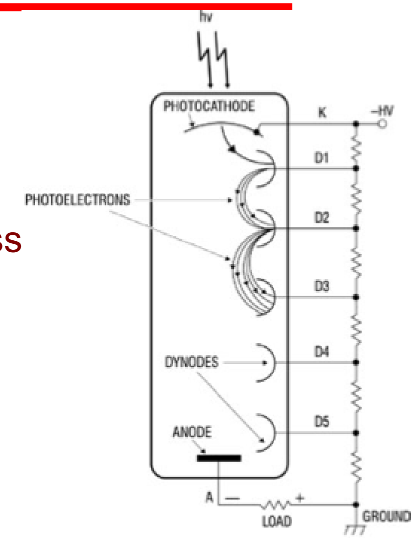


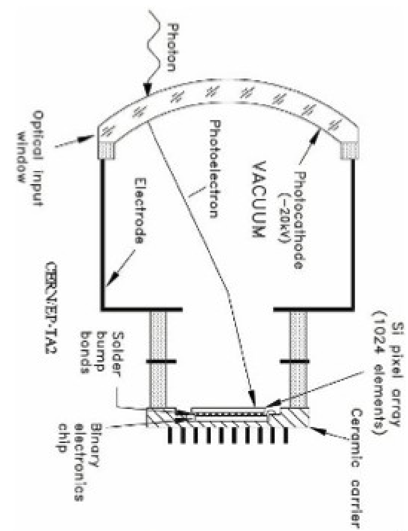


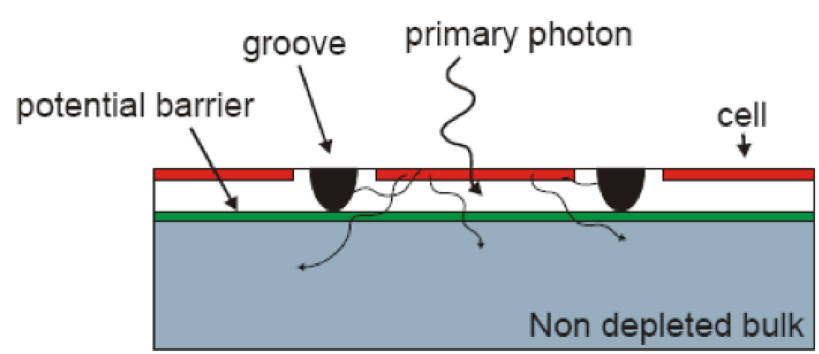


Light sensors

- Light sensors type:
  - Traditional PMTs selected by the three main IACT collaborations.
    - It's a well-known technology at relative low cost.
    - Unfortunately it is mature and so only small improvements are poss
    - Low PDE between 20÷30%.
  - New photo sensors are progressing: HPD
    - High PDE ~ 45% (QE: 50÷55%).
    - Better photon resolution than PMT.
    - Very expensive.
    - Low gain and high voltage.
  - And SiPM
    - Extremely high PDE between 60÷90%.
    - The best photon resolution.
    - Innovative and promising product.
    - Low voltage.
    - High dark current.
    - Not negligible crosstalk.
    - Small active area.
    - Low dynamic range

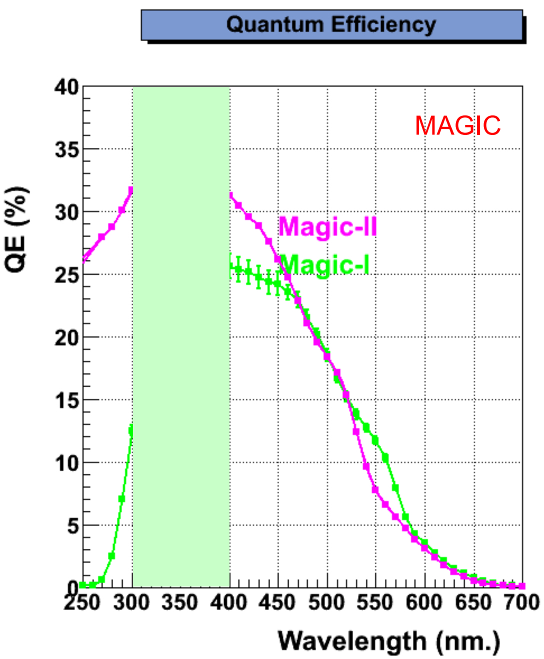


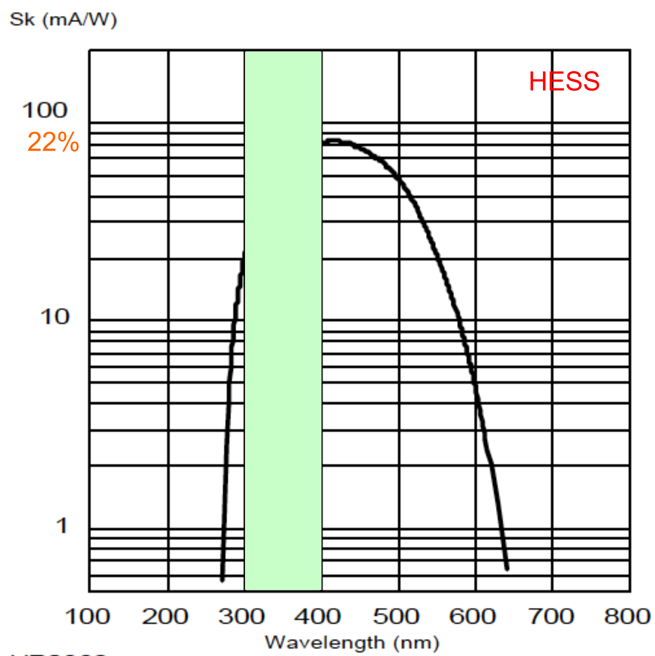




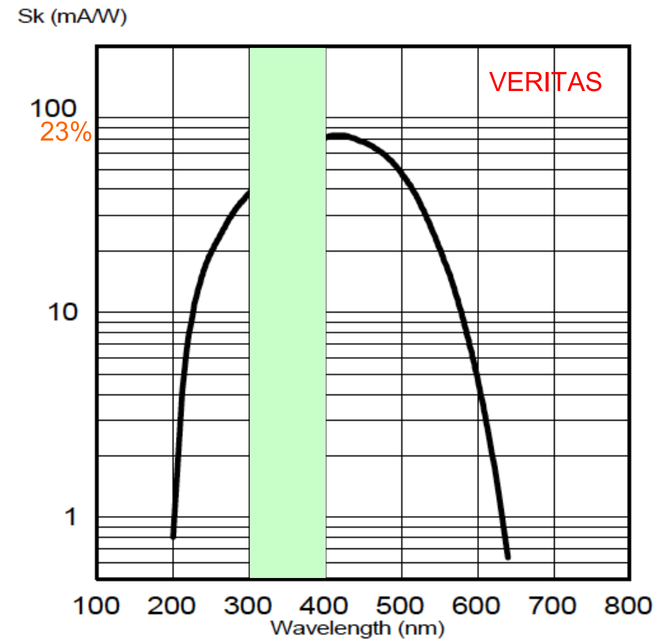
Light sensors

- PMTs kind:
  - HESS: Photonis XP2960
  - MAGIC: Hamamatsu R10408
  - VERITAS: Photonis XP2970





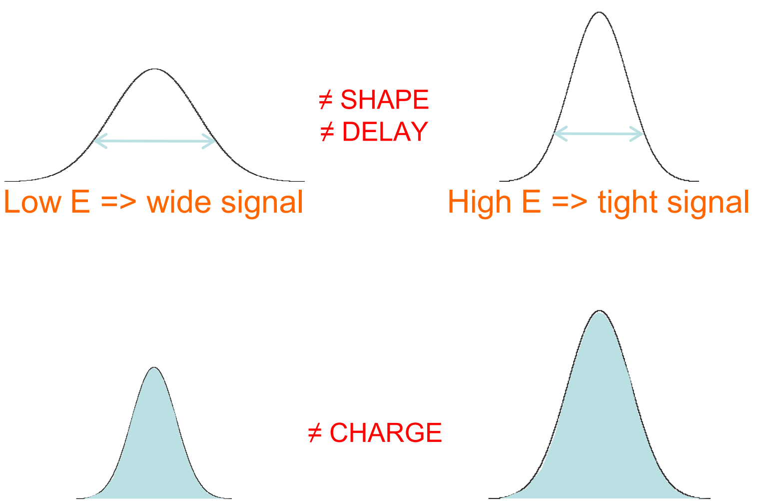
XP2960

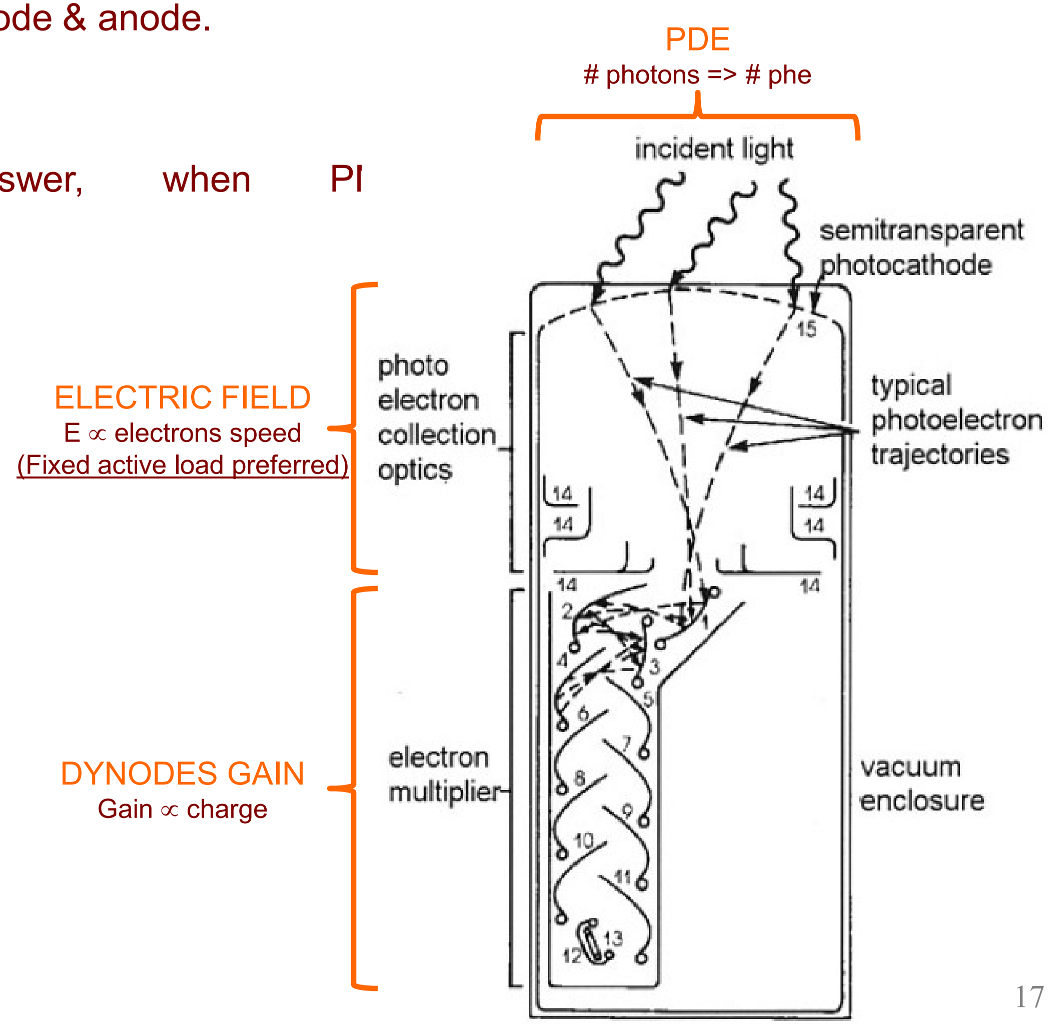


XP2970

Light sensors

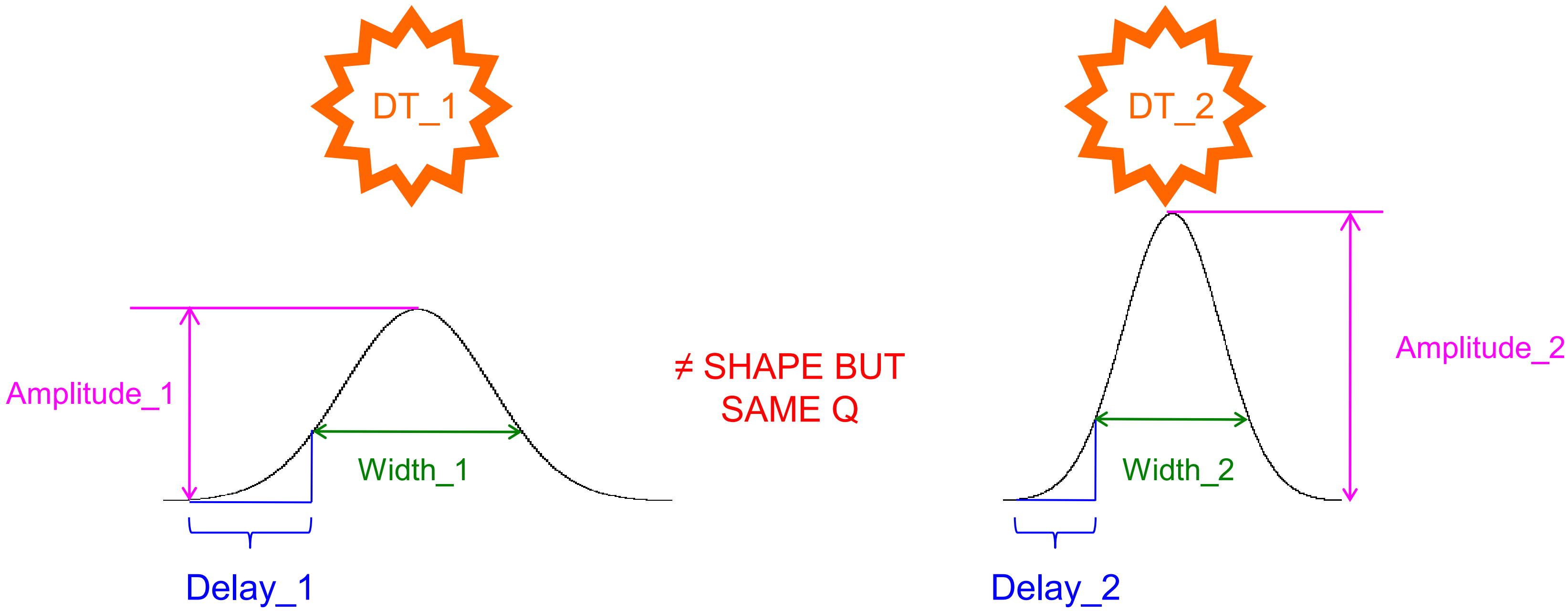
- The main difficulty is to equalize the PMTs answer.
  - The variables that change PMTs electrical output are:
    - PDE (Photo Detection Efficiency).
    - Electric field between cathode & anode.
    - Dynodes gain.
  - Goal:
    - Equal electrical answer, when PI same light.





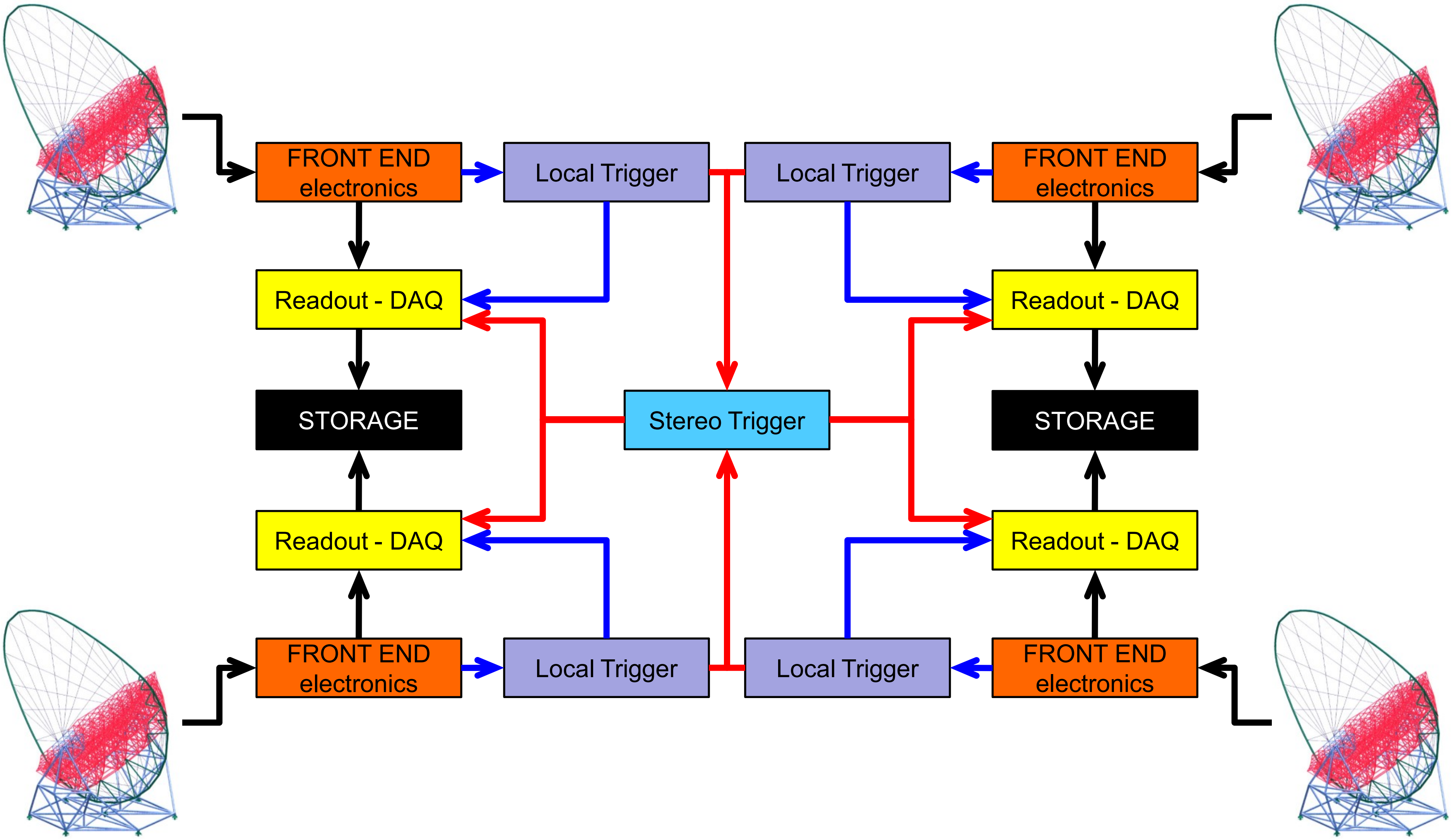
Light sensors

- It's impossible to obtain a completely equal electrical response (same charge, shape, amplitude & width).
  - Typical approach:
    - Get the same charge.
    - Fix the threshold in terms of photoelectrons and not in volts.
    - Minimize the skew between channels.



SAME NUMBER OF PHEs, BUT DIFFERENT ELECTRICAL SIGNAL: EQUALIZATION MANDATORY!!!

Electronic chain



Istituto Nazionale di Fisica Nucleare

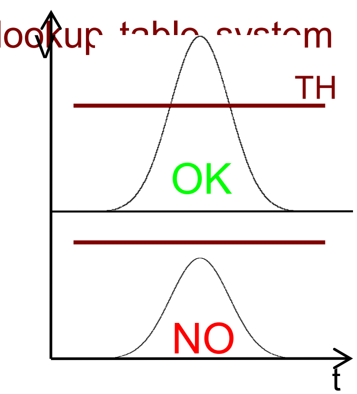
Electronic chain: amplification

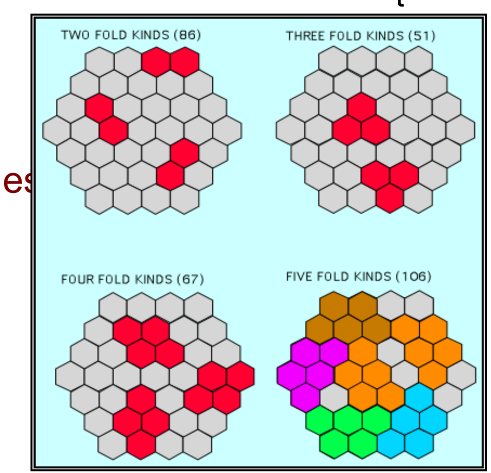
- Average gain calculation MAGIC-II:
  - PMTs gain => $3.2 \cdot 10^4$ (when 1 phe is produced)
  - Preamplifier => x 19.5 (25.8 db) with bandwidth of 800 MHz
  - Optical transmission => x 0.1 (-20 db) with bandwidth modulation of 2.5 Gb/s
  - Optical fibers => x 0.95 (-0.4 db) [2.7db/Km]
  - Receiver boards => x 8.4 (18.5 db) with bandwidth of 530 MHz
- VERITAS:
  - PMTs gain => $2 \cdot 10^5$
  - Preamplifier => 2mV/phe with bandwidth 1GHz
  - Cable transmission => 50m with RG-59 cable to the CDF trigger
  - Analog amplification => 8÷16mV/phe with bandwidth of 500 MHz
- HESS:
  - PMTs gain => $2 \cdot 10^5$
  - Front-end high gain => x -54 (~97mV for 1phe)
  - Front-end high gain noise => ~20mV, namely 0.2phe
  - Front-end low gain => x -4
  - Front-end low gain noise => ~7mV, namely 1phe

Istituto Nazionale di Fisica Nucleare

Electronic chain: Trigger

- General trigger concept for IACT Telescopes:
  - Detect close compact images produced by few photons and reject noise (NSB & PMT afterpulses), preventing DAQ saturation.
  - Based on different levels. For instance MAGIC standard trigger:
    - L0: accept signals higher then an adjustable thresholds.
    - L1: fast coincidence (some nanoseconds) between neighbour PMTs (2-3-4-5 NN logic).
    - L2: enhanced topologic selection made with tree structured lookup table system and apply a prescaler factor.
    - L3: stereoscopic coincidence (100ns) between telescopes.
  - VERITAS trigger:
    - L1: CDF discriminator for each pixel at 4.2phe.
    - L2: 3 adjacent pixels exceed the threshold in 10ns.
    - L3: stereoscopic coincidence between telescopes.
  - HESS trigger:
    - L1: single pixel threshold at 4phe for 1.5ns.
    - L2: coincidence of 3 pixels in a sector of 64 pixels.
    - L3: stereoscopic coincidence (80ns) between at least 2 teles

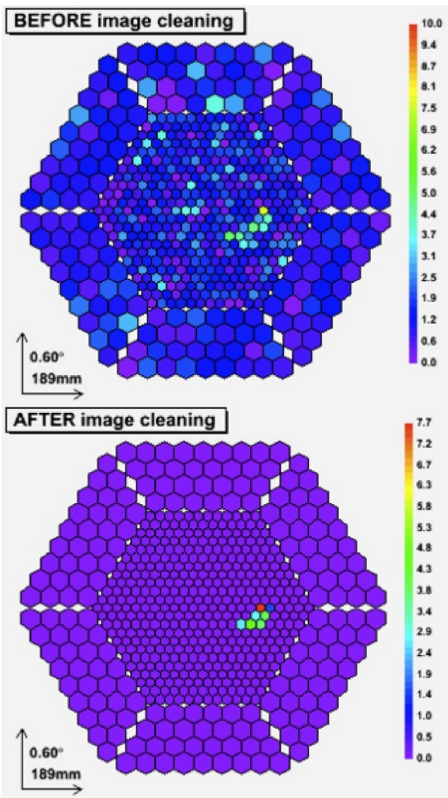


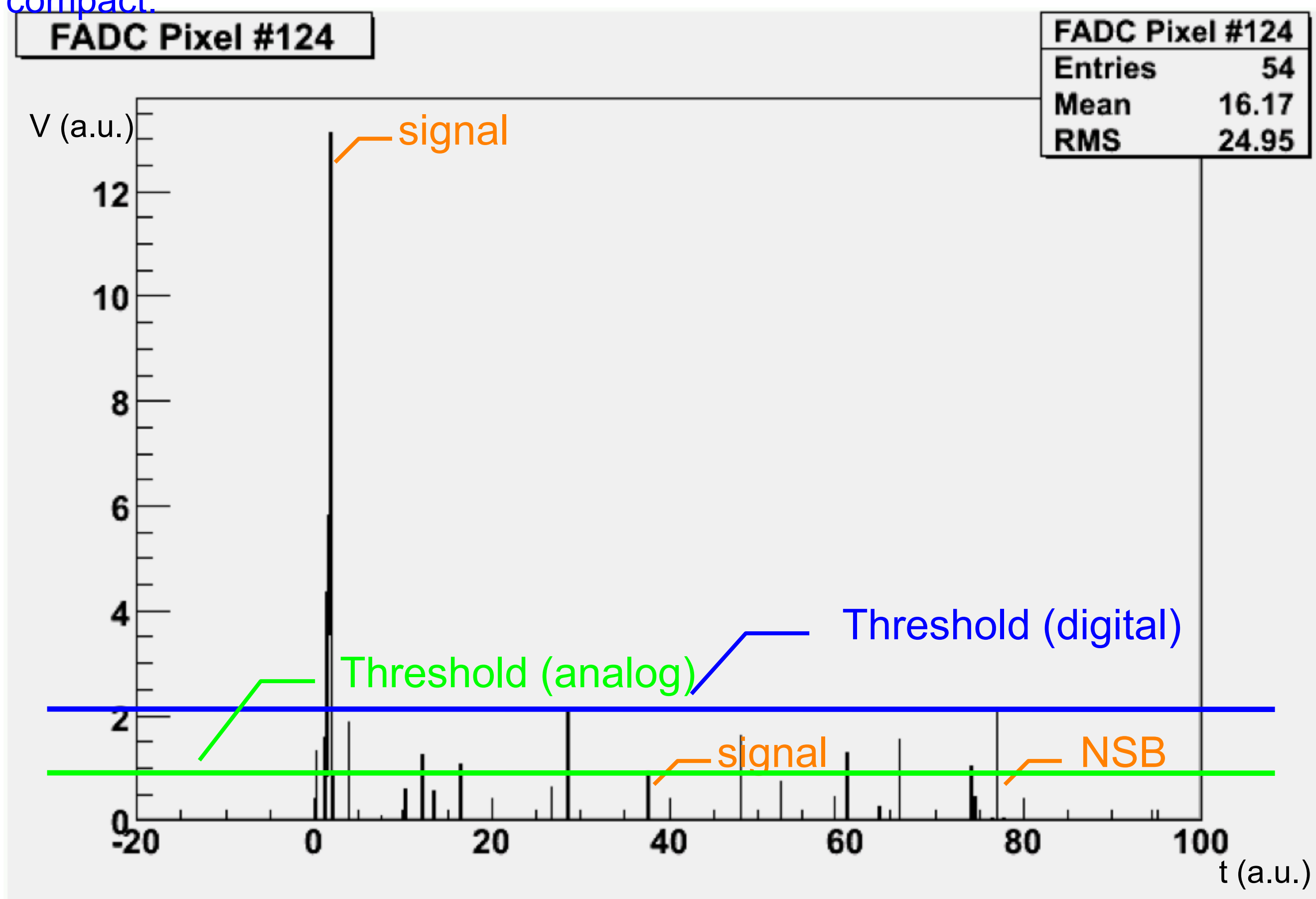


An on fly hardware trigger is mandatory, because the maximum DAQ rate is ~ 1KHz!

Electronic chain: Trigger

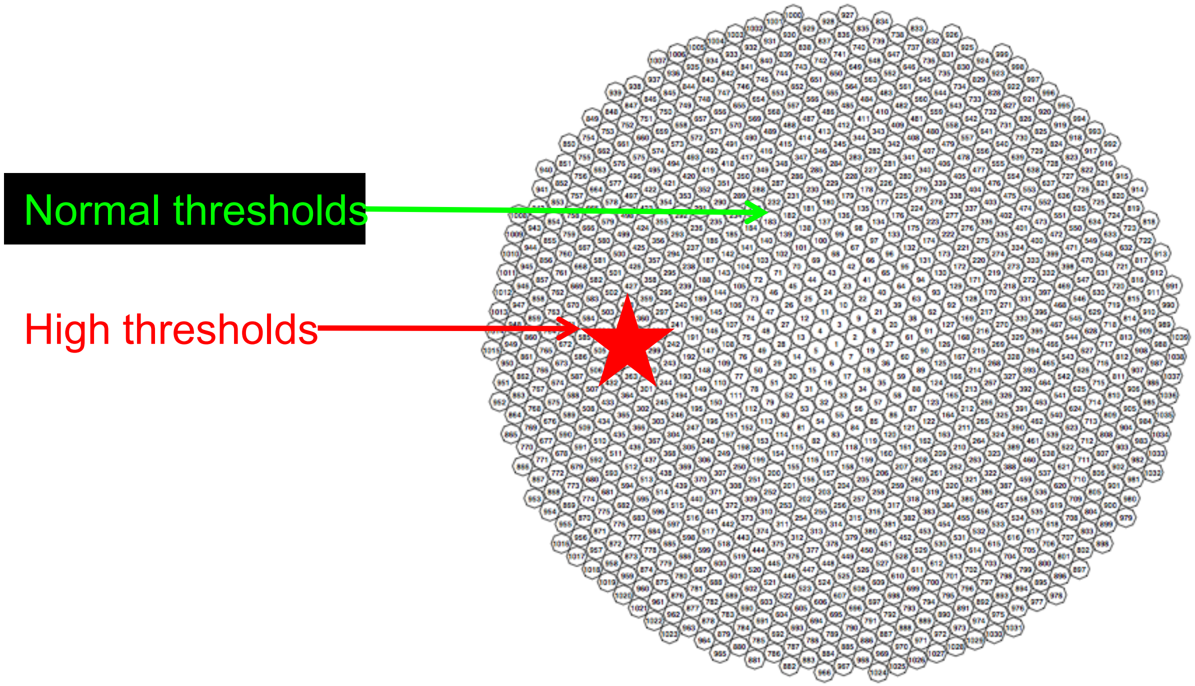
- Basic idea (innovative):
  - Summing up all single photons increases signal to noise ratio.
  - Sum up a large region increases the signal to noise ratio than requiring individual pixels to trigger, because images of low energy showers extend over many pixels. 19 pixels versus 4 close compact.





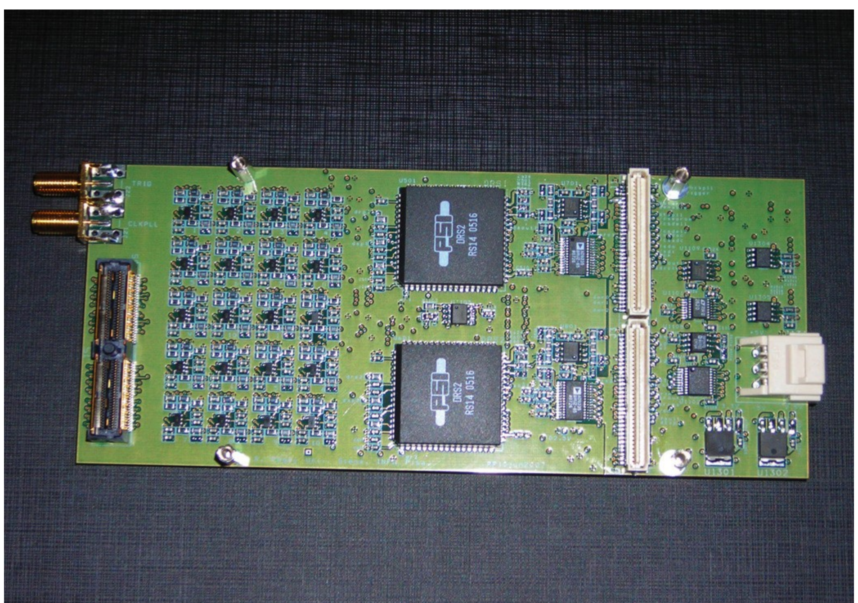
Electronic chain: Trigger

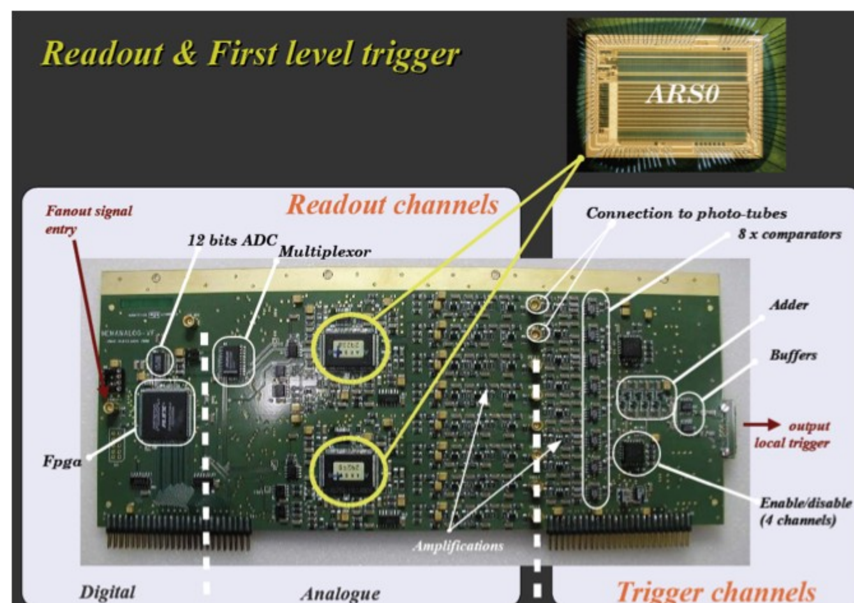
- Stars in the trigger FoV:
  - Stars light is very strong and can activate the trigger.
  - Stars move around the camera.
- On-line solution:
  - Control the LT0 rate. In case there is a star, it explodes.
  - MIR increases the LT0 thresholds for the affected pixels.
  - When the star moves a little bit away, the old affected pixels are restored with the proper thresholds and new pixels are changed.



Electronic chain: Readout & DAQ

- General DAQ features for IACT Telescopes:
  - Fast sampling to reconstruct the brief Cherenkov flash (> 0.5GS/s).
  - High bandwidth to conserve the analogue signal shape of few ns (> 300MHz).
  - High stability for a stable long data taking (many hours).
  - MAGIC DAQ
    - Based on the analogue ring DRS chip (2GS/s), with a memory depth of 512ns
  - VERITAS DAQ:
    - Commercial 8 bits FADC (0.5GS/s) with a memory depth of 64μs
  - HESS DAQ:
    - Based on analogue ring sampler ARS0 circuit (1GS/s).



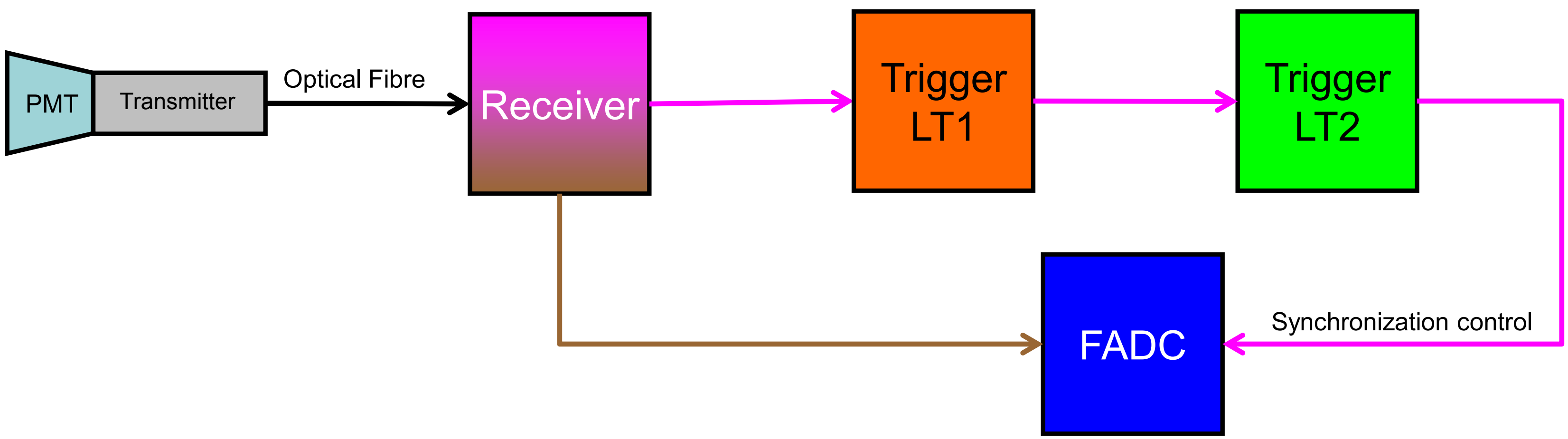


Calibration system

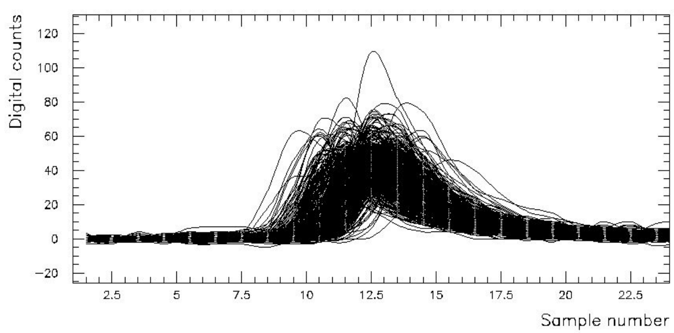
- Calibration concept:
  - It is the operation to settle a device under test (DUT), using standard and well known test instruments (TI), in order to improve its precision.
- Calibration procedure for MAGIC:
  - Reflective surface:
    - Mirror's focusing
    - Mirror's reflectivity
  - Flat-fielding PMTs:
    - Dead pixels
    - Flat-fielding charge
  - Flat-fielding receiver boards (LT0):
    - Thresholds using IPRscan (Individual Pixel Rate scan) NSB (Night Sky Background)
    - Thresholds using IPRscan calibration laser
  - Flat-fielding trigger level one (LT1):
    - Delays synchronization
    - Effective gate equalization
  - DAQ linearity:
    - Domino calibration run
  - Data taking:
    - Calibration & pedestal run

Calibration system

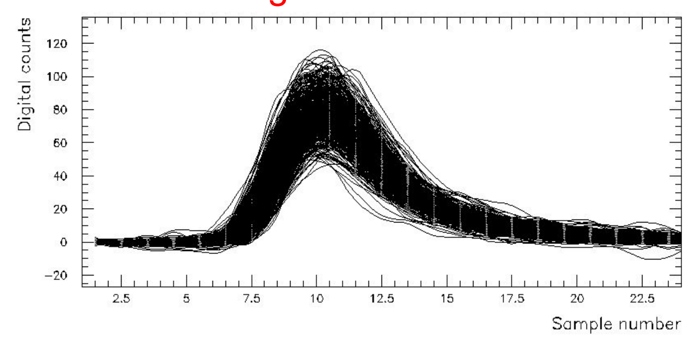
- Trigger point of view (catch the event) [magenta line]:
  - Equalized gain means equalized amplitude => Flat-fielding thresholds
- FADC point of view (reconstruction of the event) [brown line]:
  - Equalized gain means equalized charge => Calibration runs + software calibration



Raw data



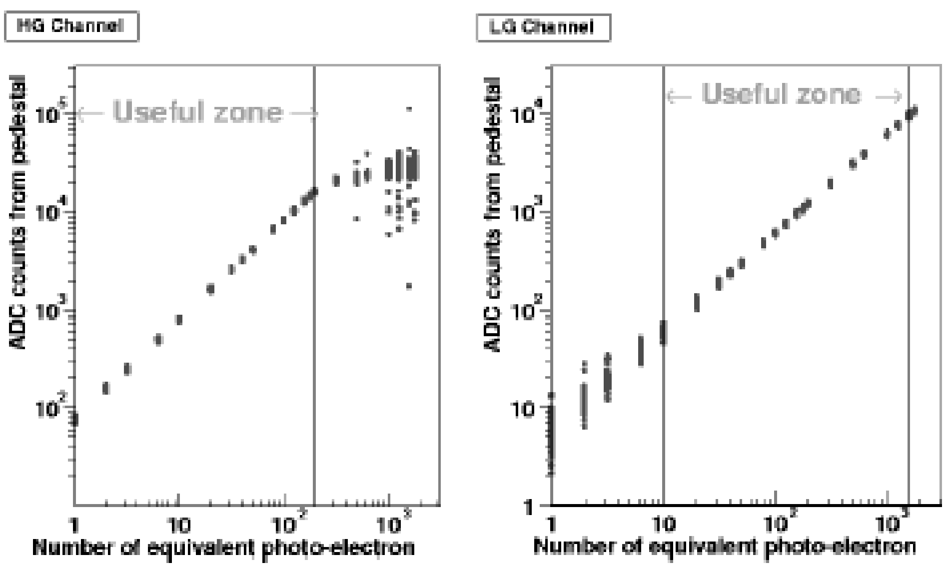
Time and gain corrected data



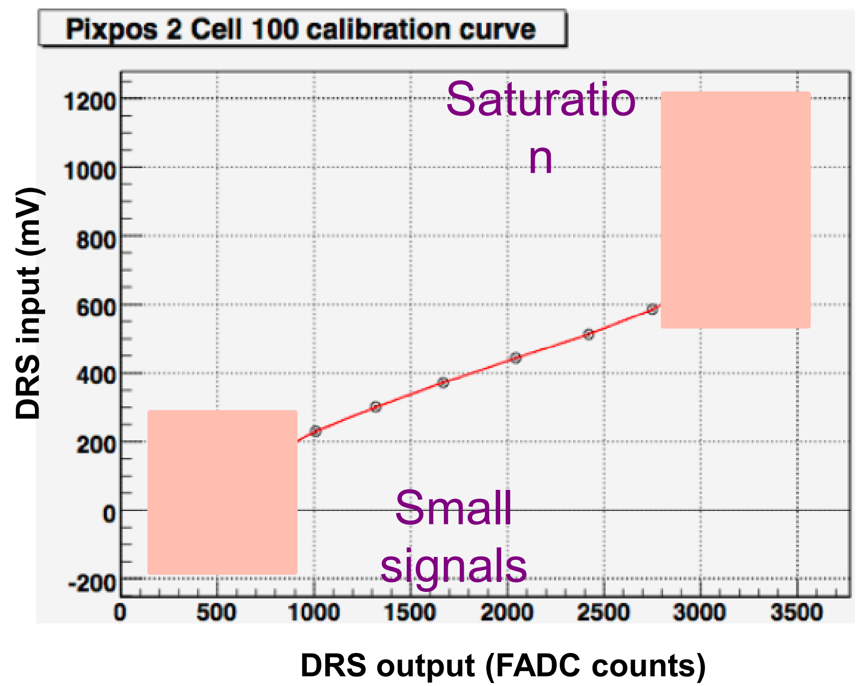
Istituto Nazionale di Fisica Nucleare

Calibration system

- Very wide dynamic range:
  - HESS up to 1600 phe
  - MAGIC to 900 phe
  - VERITAS up to 1800 phe
- DAQ linearity control:
  - Characterization of the FADC.
  - Dedicated linearity runs.



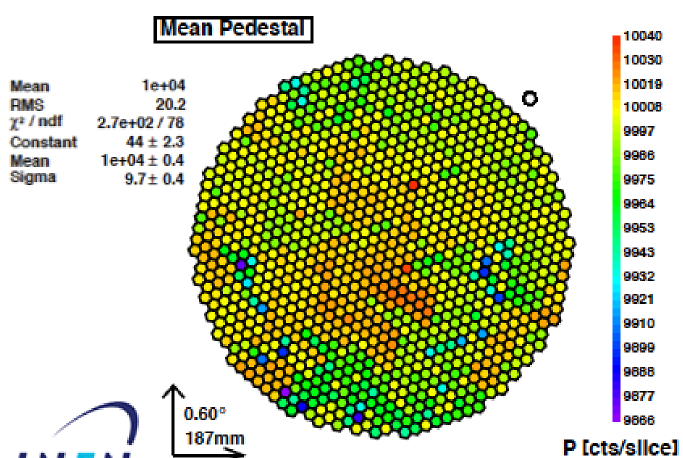
HESS

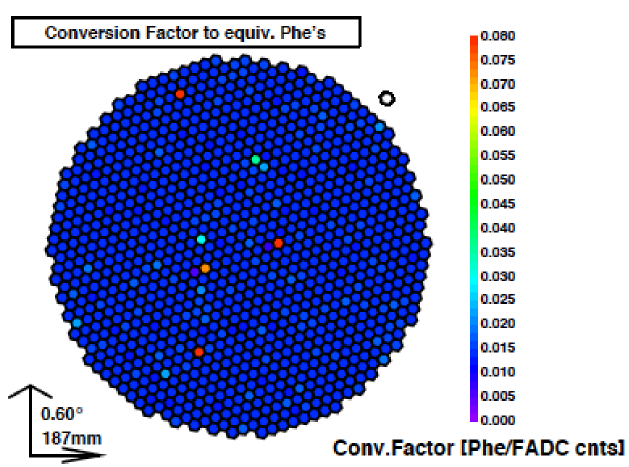


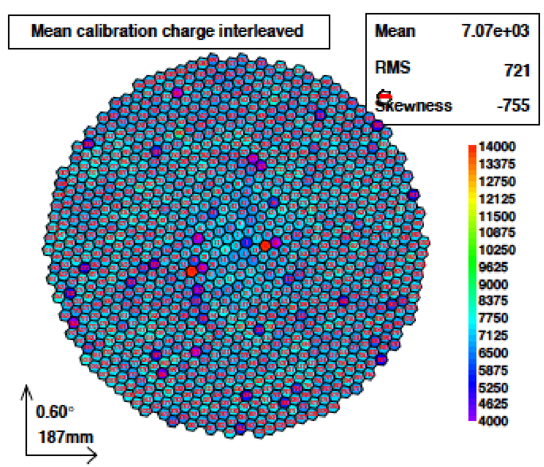
MAGIC

Calibration system

- Online calibration:
  - There are many short terms variations:
    - Temperature
    - Stars in the FoV [$\Delta Q \sim \sqrt{phe}$]
    - Moon
    - Atmospherical conditions: clouds, humidity, calima, etc…
    - Electronic noise
    - Electronic fluctuations: FADC baseline, VCSEL stability
  - Continuous monitoring:
    - Interleaved calibration runs => conversion factors
    - Interleaved pedestal runs (It is the FADC output when the input is zero)

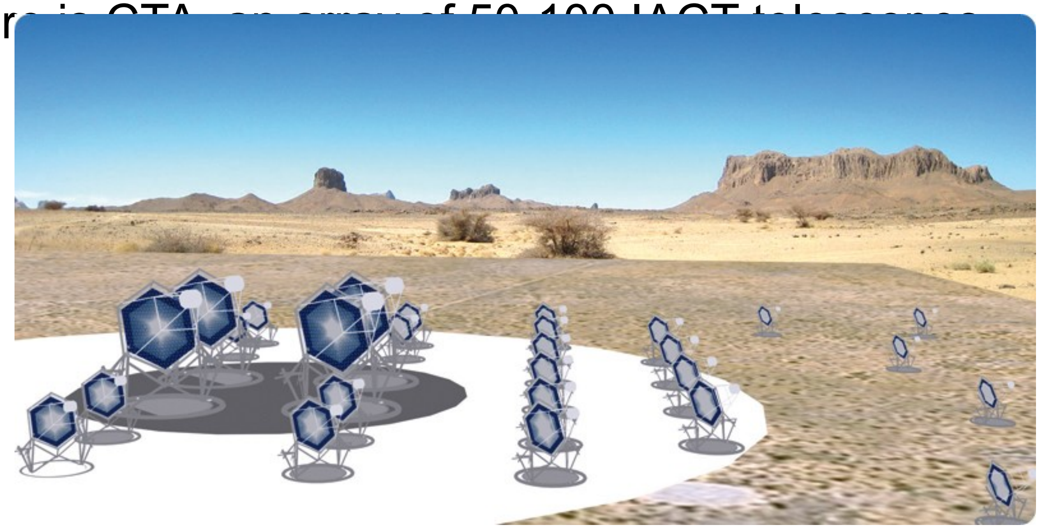






Conclusions

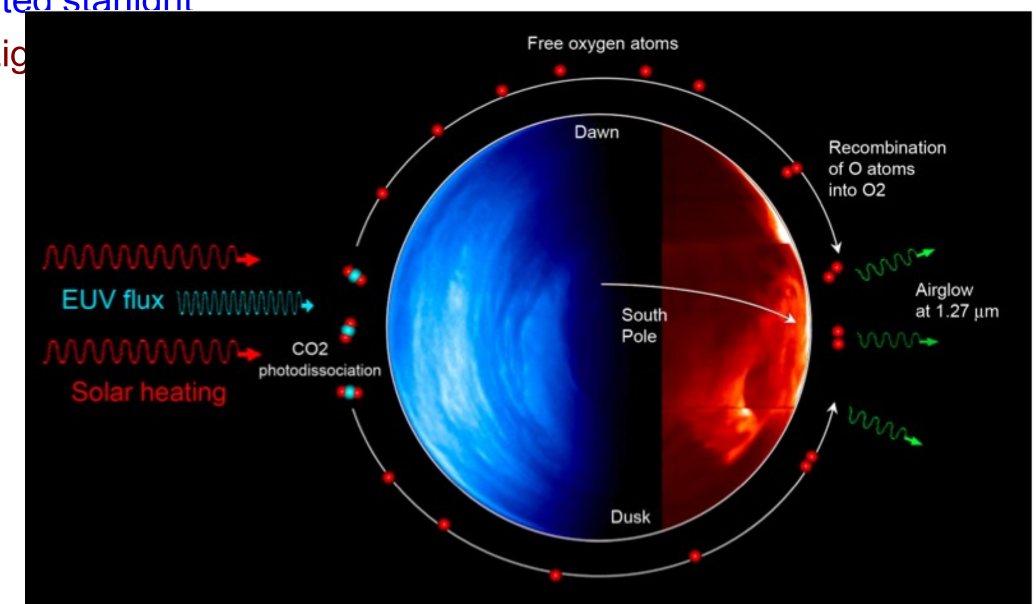
- The main IACT telescopes are: HESS, MAGIC & VERITAS.
- Successful experiments with many important publications.
- The total cost compared to the accelerator factories is negligible.
  - The total cost of MAGIC telescopes is around 12 million euro.
  - The Italian annual contribution for LHC is around 80 million euro (total cost ~ 7.5 billion euro).
- Less time for the construction.
  - The construction of HESS & MAGIC has been done in 3-4 years.
  - LHC was approved in away back in 1995.
- Good physics, studying extreme astronomical environments, where the released energy is even higher then in the colliders.
- The futur



Backup slides

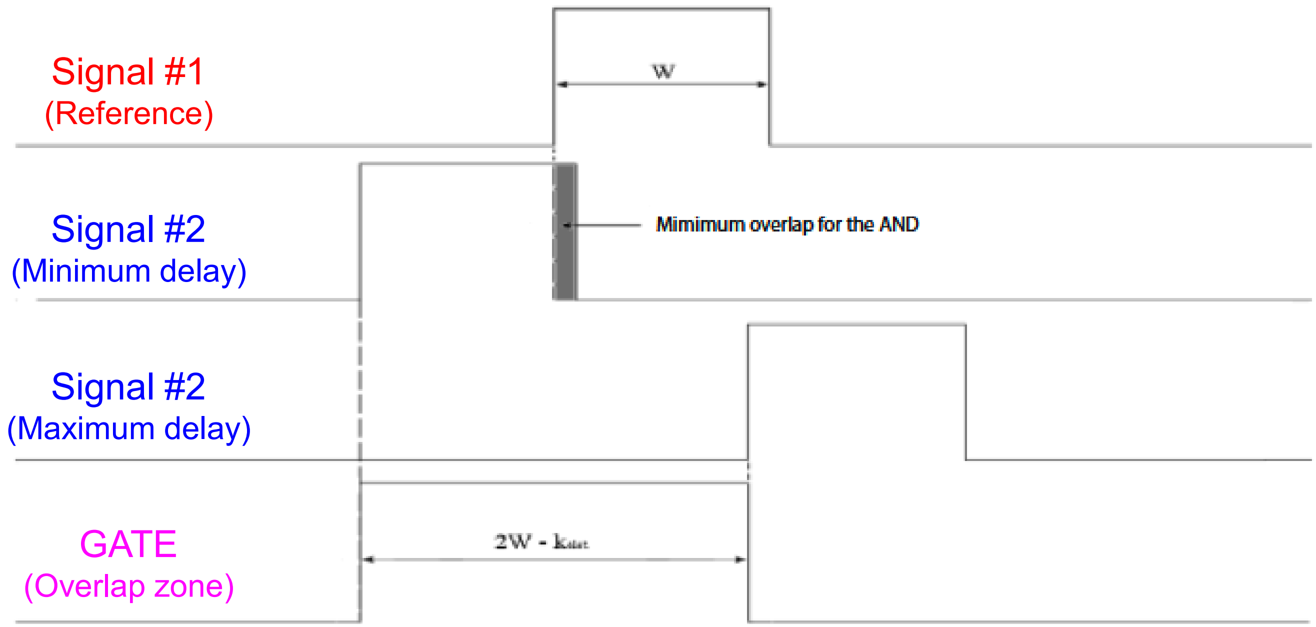
Background

- LONS components:
  - Air-glow
    - Weak light emitted by atoms in the upper atmosphere, due to UV radiation excitation.
  - Zodiacal light
    - Very faint light caused by sunlight scattered by space dust in the zodiacal cloud.
  - Diffuse galactic light
    - Light due to starlight reflected and scattered by interstellar dust near the galactic plane.
  - Integrated starlight
    - Lig



Trigger gate

- Trigger gate concept:
  - Mathematics: the space where the intersection between signal sets is not void.
  - Electronics: the time where the AND between signals is at the logic state ‘1’.



$$GATE_{2NN} = (W_1 + W_2) - k = 2W - k$$

$$GATE_{3NN} = \frac{3}{4} \bullet (GATE_{2NN})^2$$

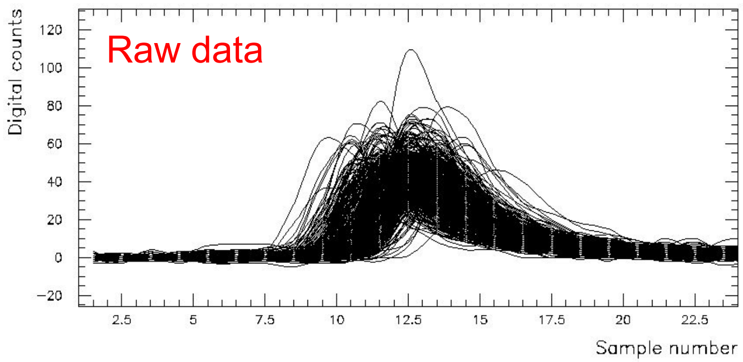
$$GATE_{4NN} = \frac{1}{2} \bullet (GATE_{2NN})^3$$

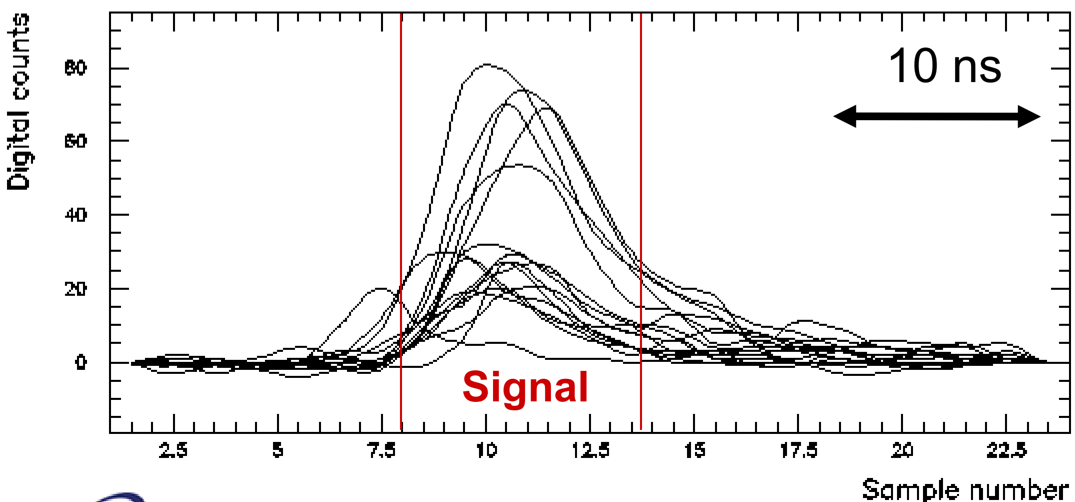
$$GATE_{nNN} = C_n \bullet (GATE_{2NN})^{n-1}$$

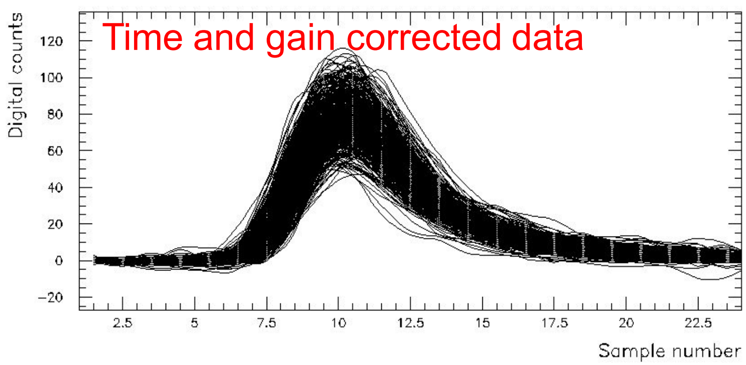
Istituto Nazionale di Fisica Nucleare

Calibration

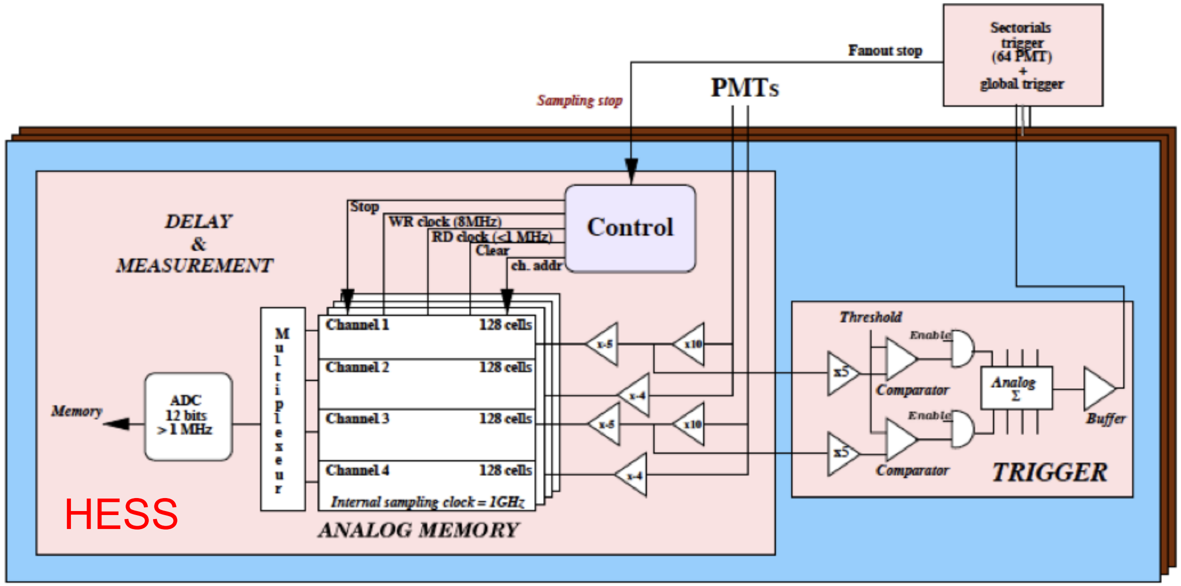
- Calibration ingredients:
  - Photo Detection Efficiency of each pixel
  - Gain of each pixel (relative and absolute)
  - Relative Time delay between pixel and telescope
- Calibration method:
  - Uniform light flash injection (Flat fielding)
  - PMTs PDE (Single-photoelectron, F-factor)
  - Muons signal
  - Pedestal subtraction (Trigger without shower)

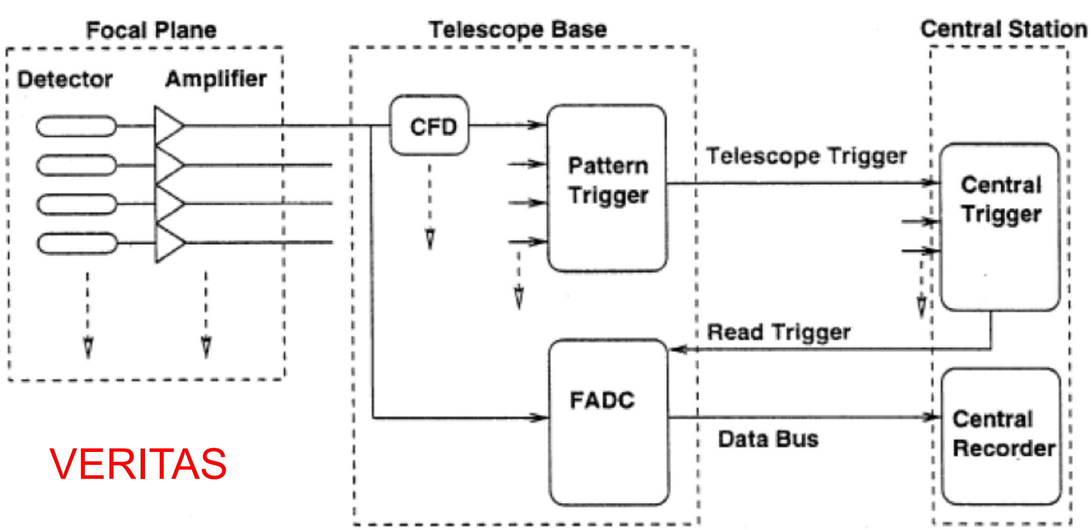






Electronic chain





VERITAS