Calibration of Imaging Atmospheric Cherenkov Telescopes (IACTs)

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Outline

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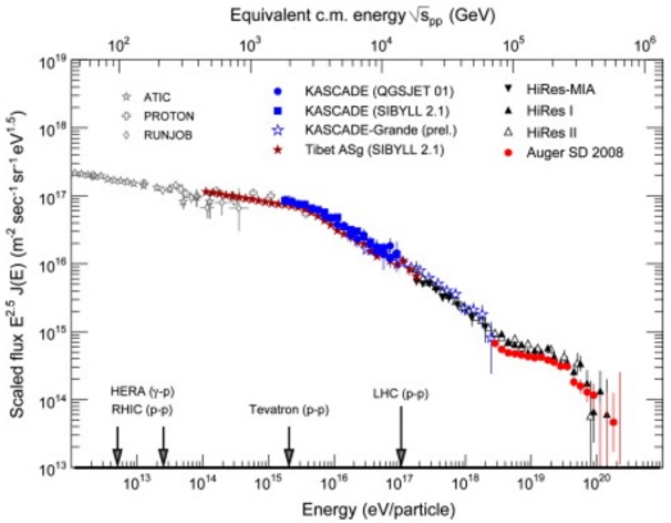
1. TeV astronomy and IACTs

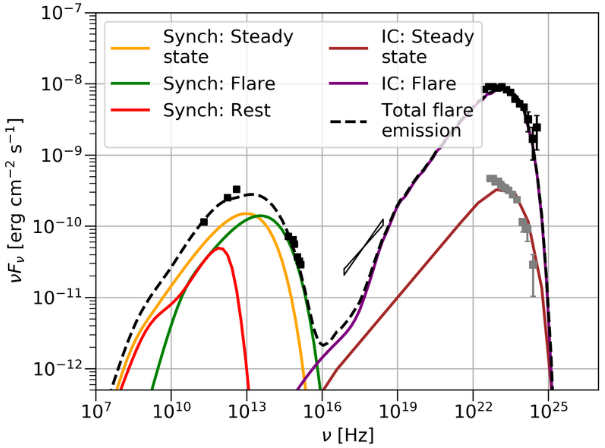
2. Calibration of IACTs (mainly for large dish IACTs)

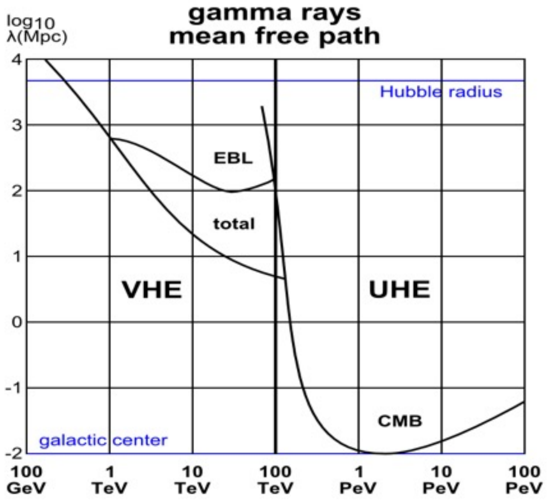
3. Status of CTAO and recent results

TeV astronomy and IACTs

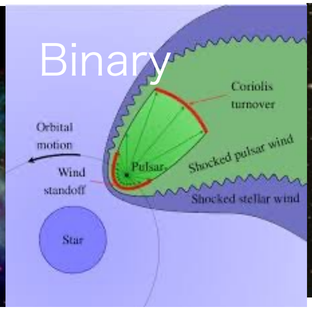
TeV Astronomy

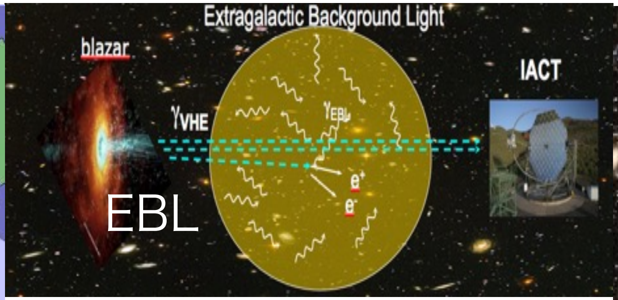


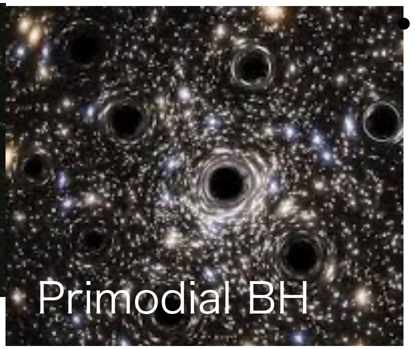


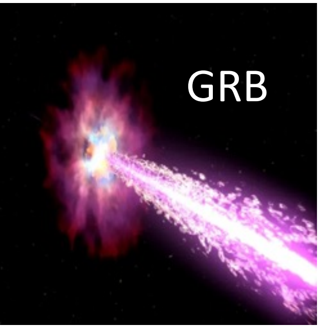


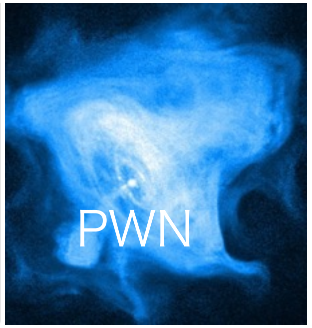
- Origin of Cosmic Rays
  - PeVatron Search
  - Acceleration
  - Emission
- Physics around compact Objects
  - AGN
  - Pulsars
- Cosmology and Fundamental Physics.
  - EBL
  - WIMP
  - PBH
  - ALP
  - Quntum Gravity

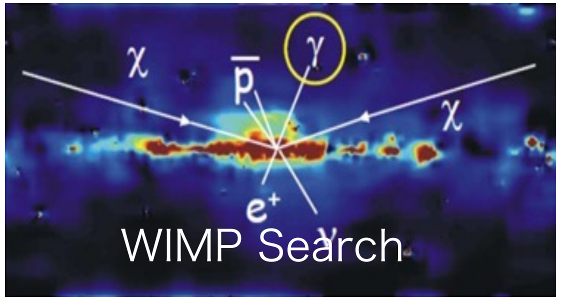




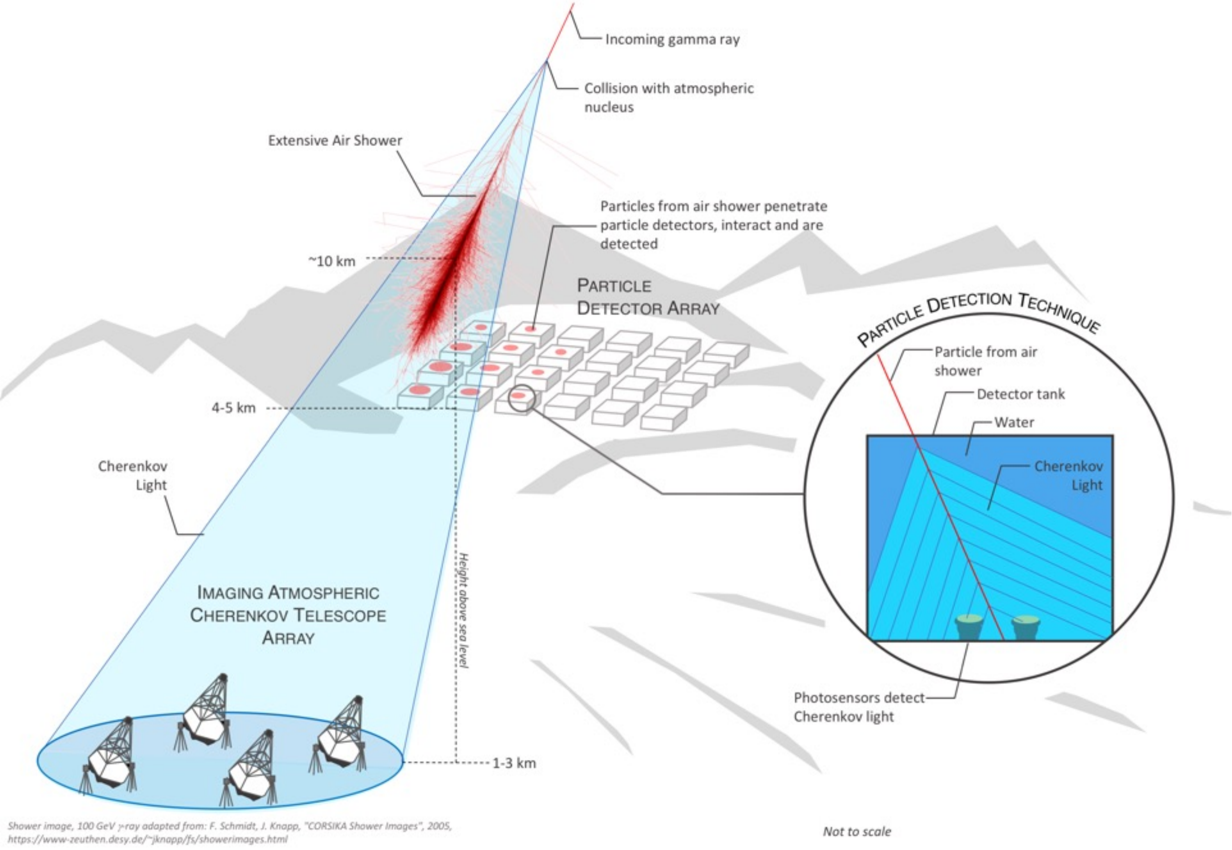








TeV Detectors



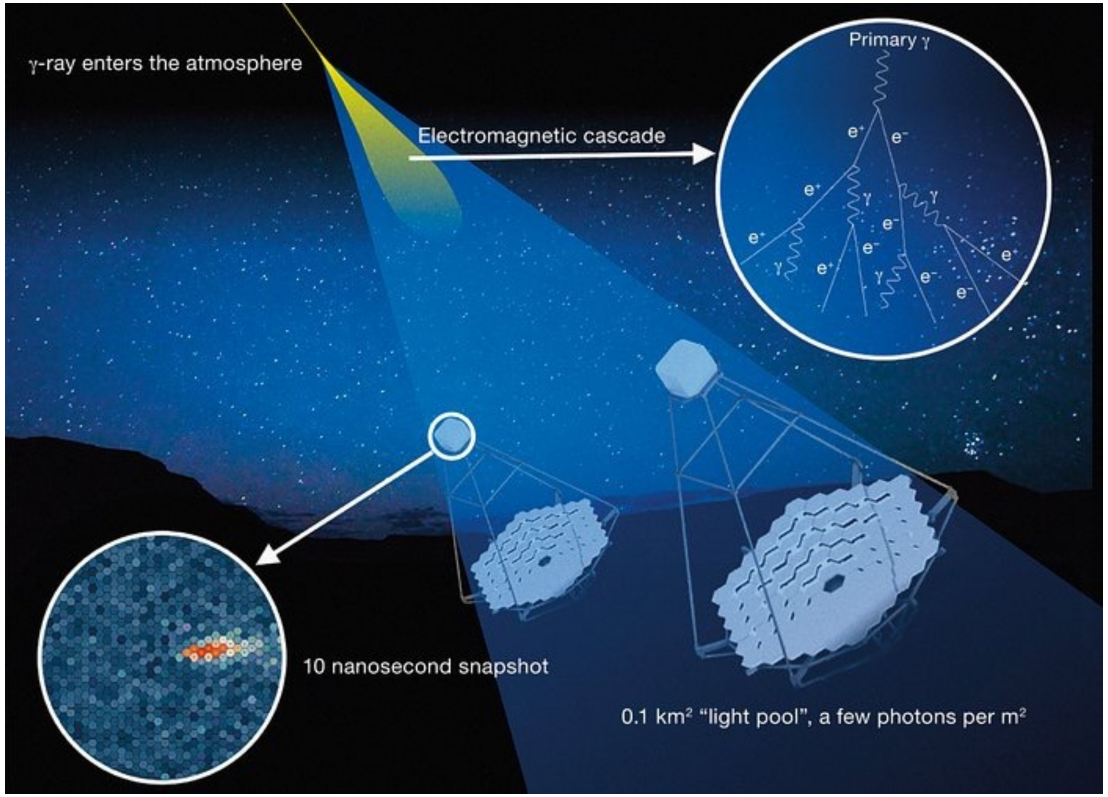
From SWGO wep site : https://www.swgo.org/SWGOWiki/doku.php

	IACT	Air Shower Array
Angular Resolution	~ 0.05 deg	~ 0.3 deg
Energy Resolution	~10%	~20%
BG supression	Good	Good > 30 TeV
Effective Area	10^5 m	10^{5-6}
Duty Cycle	10%	95%
FoV	~5-10 deg	60 deg
Experiments	H.E.S.S. VERITAS MAGIC CTAO	Tibet ASg HAWK LHAASO

In general,

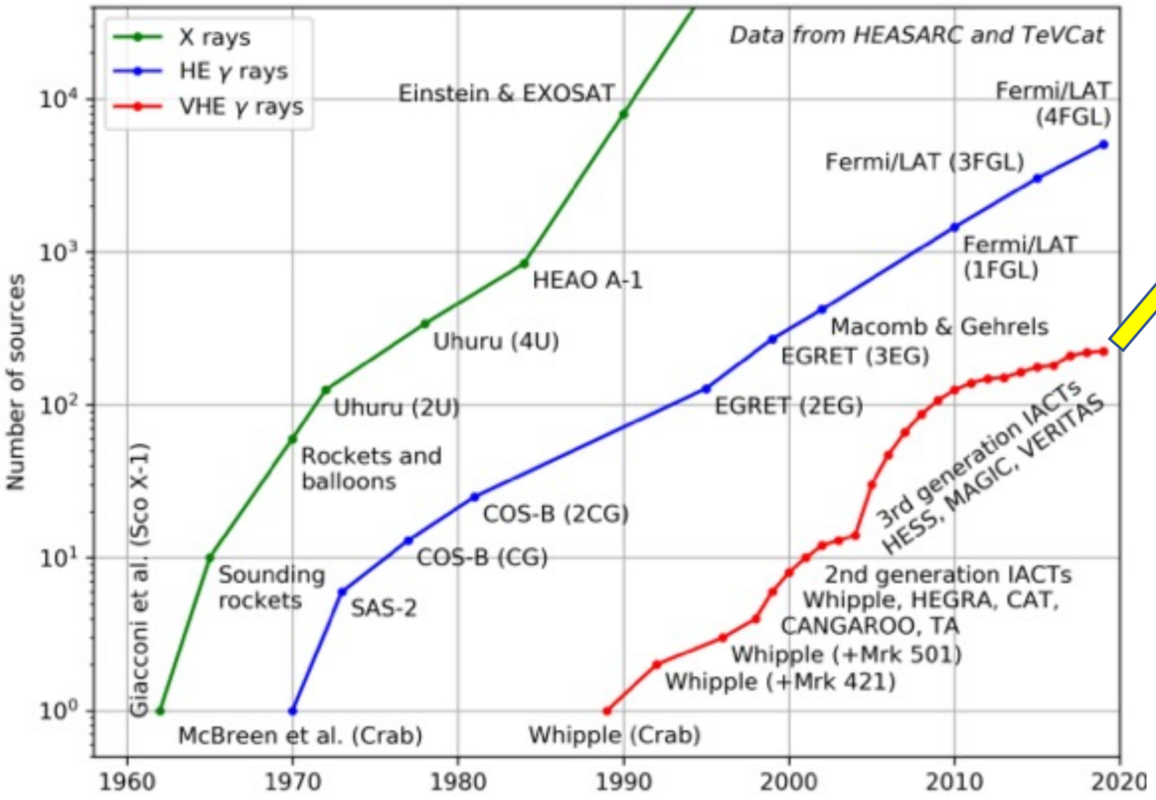
- Air Shower Arrays are better for stready >10 TeV sources
- IACTs are better for transient, 0.1 – 10 TeV sources

Imaging Atmospheric Cherenkov Telescopes



1st-2nd generation

3rd generation



>2000 objects
With CTAO

- The first source was Crab detected in 1989
- Currently ~300 sources are known in TeV.
- With CTAO, it will increase to more than 2000.

IACT working principle: Air Shower

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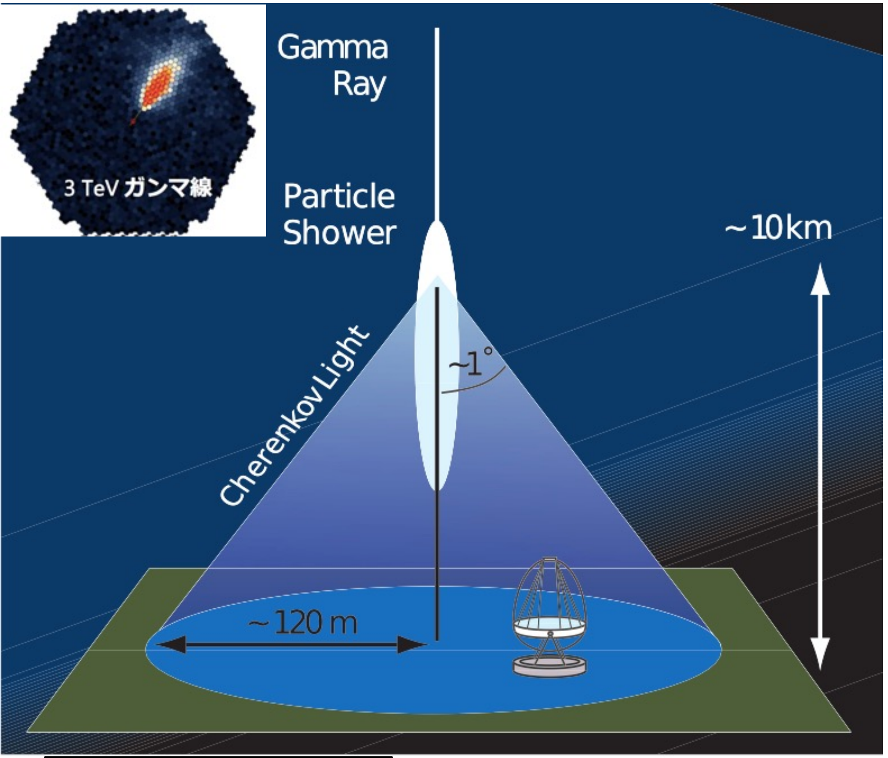
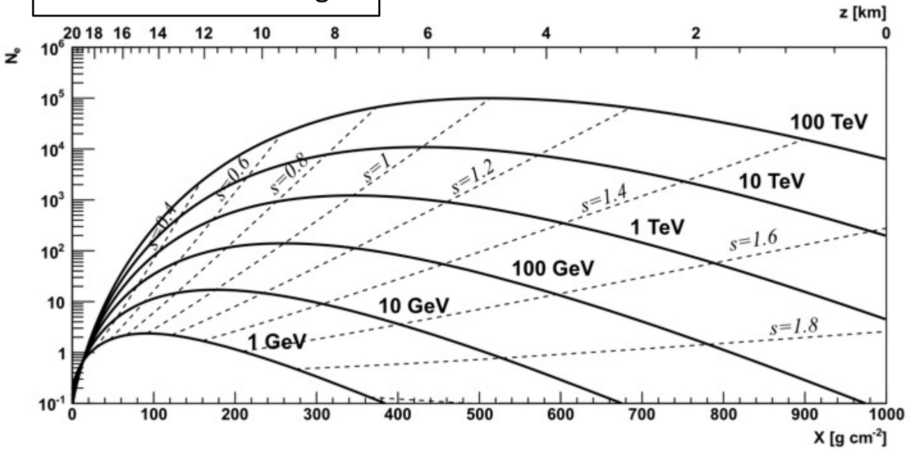


# of electrons vs Height



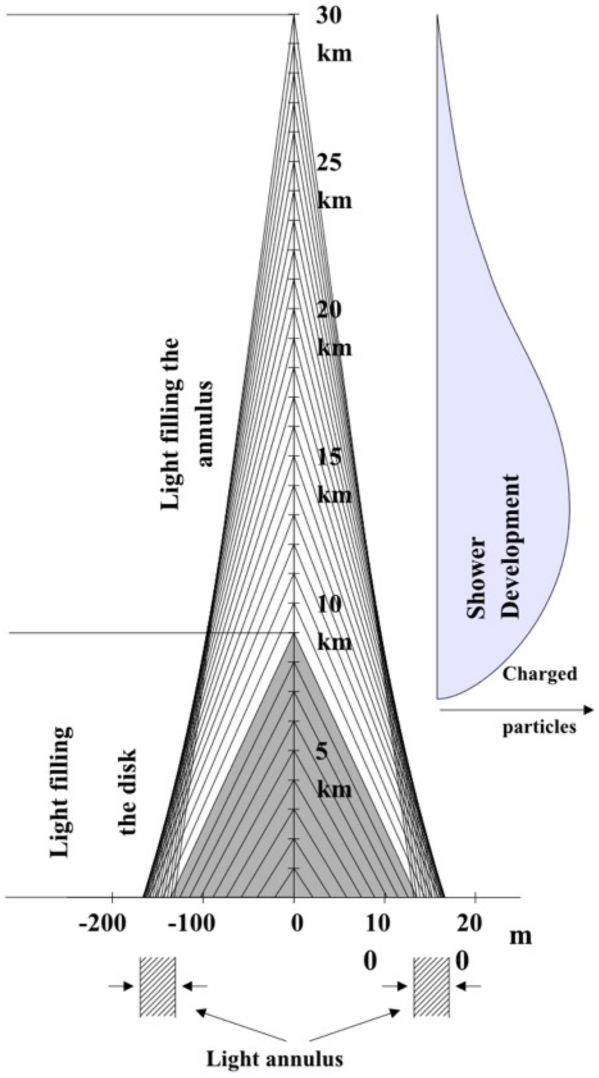


Fig. 4. (Color online.) **Left:** Shower development. **Top Right:** Latera
function of lateral distance for various altitudes of emission.

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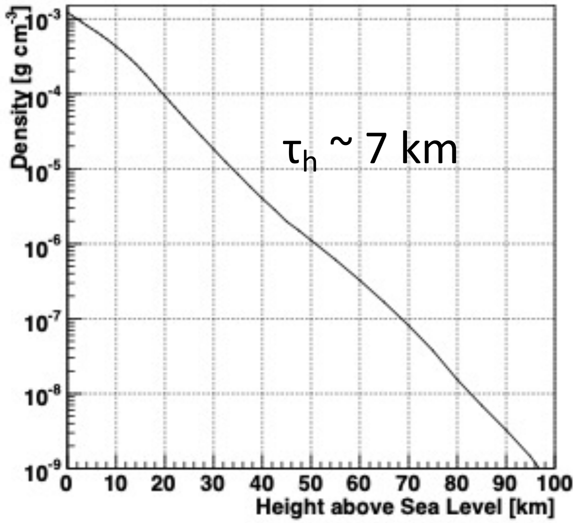
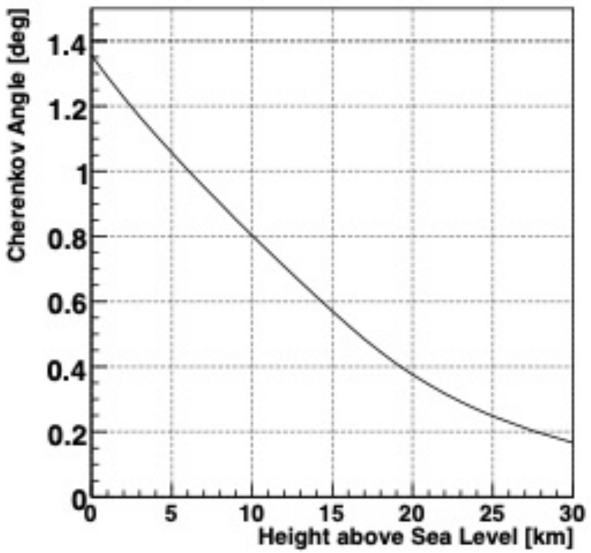
Density vs Height (log scale)

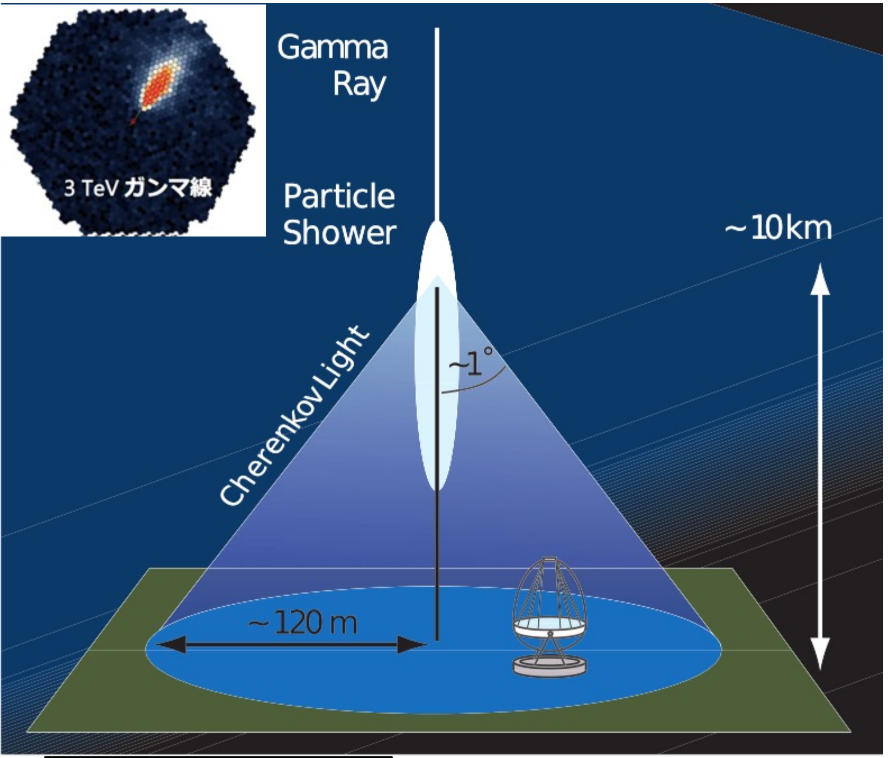


Cherenkov Angle vs Height



$$\cos\theta = \frac{c/n}{\beta c} = \frac{1}{\beta n}$$

IACT working principle: Air Shower



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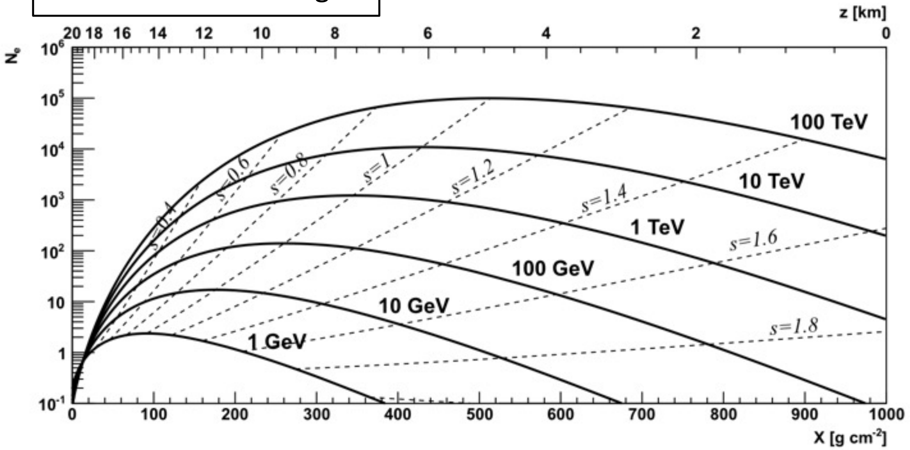

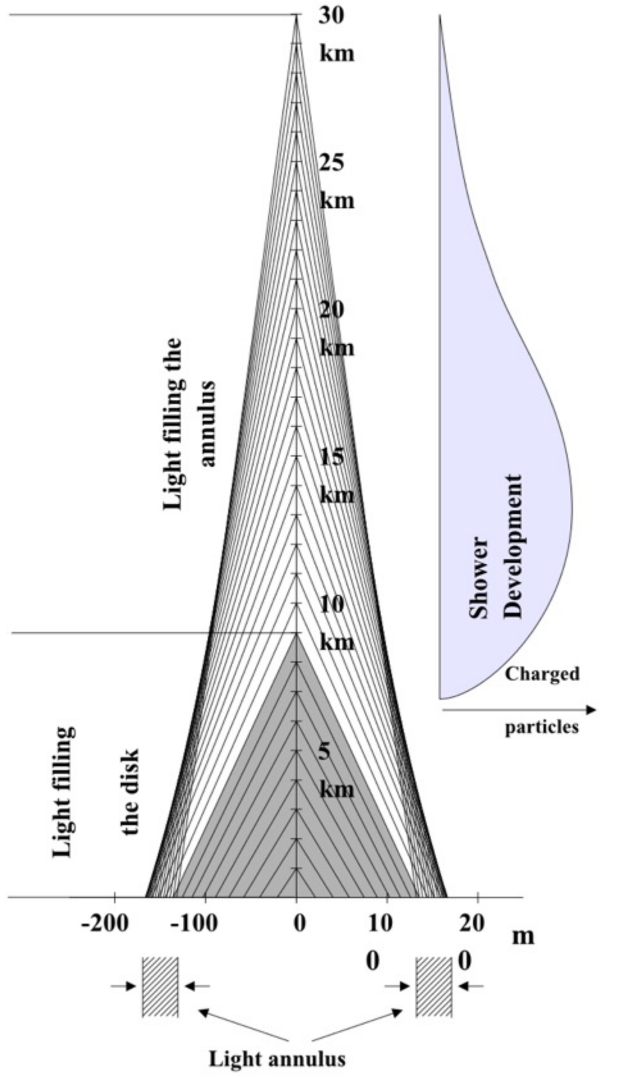

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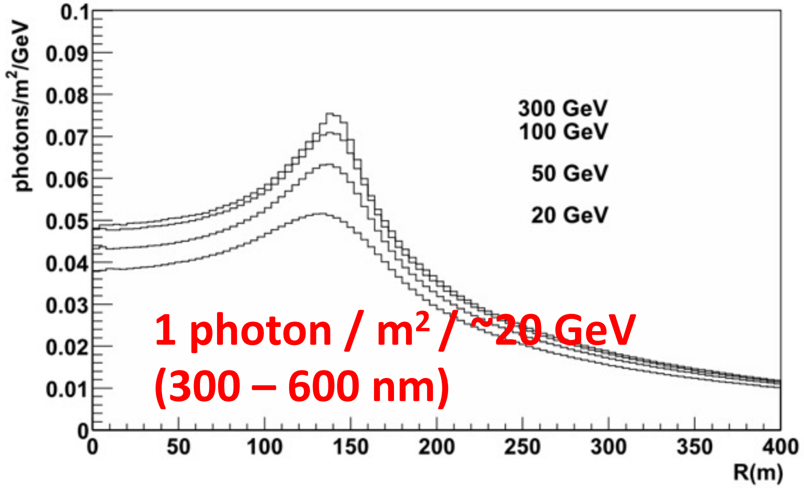
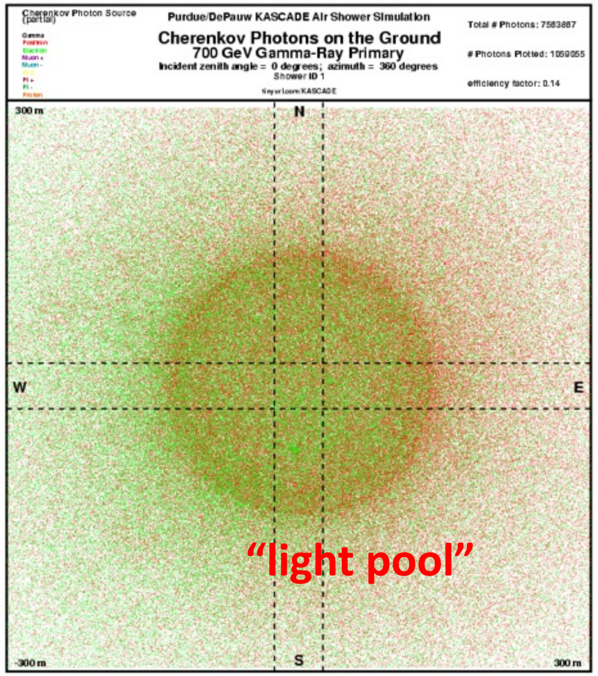
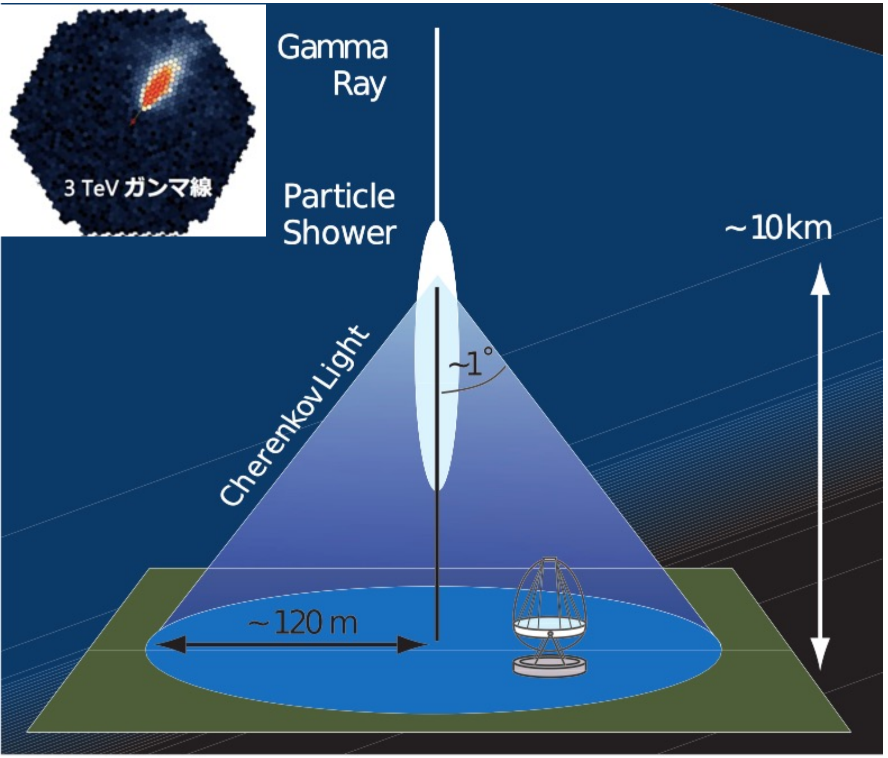
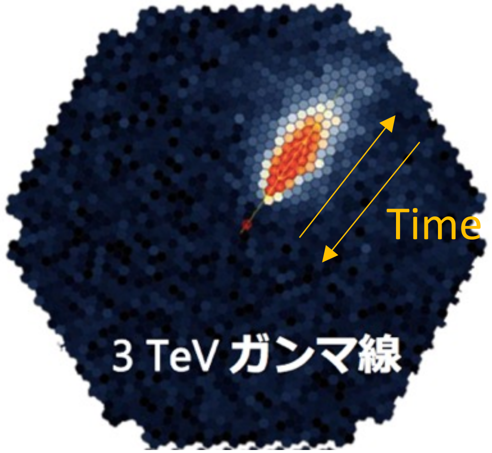




IACT working principle: Air Shower





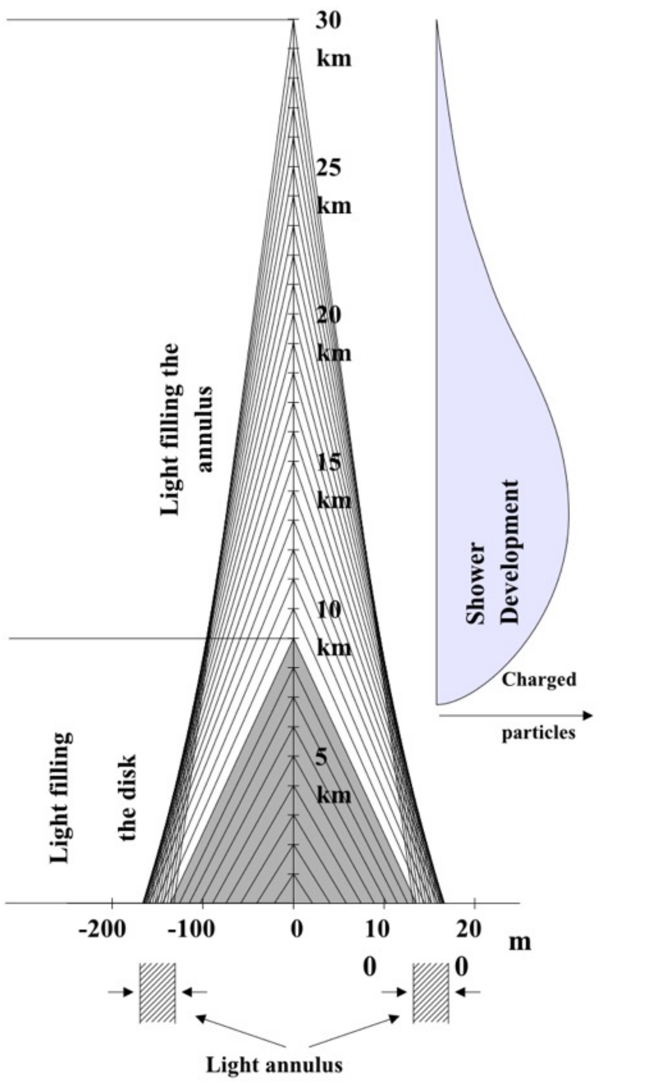


Fig. 4. (Color online.) **Left:** Shower development. **Top Right:** Lateral function of lateral distance for various altitudes of emission.

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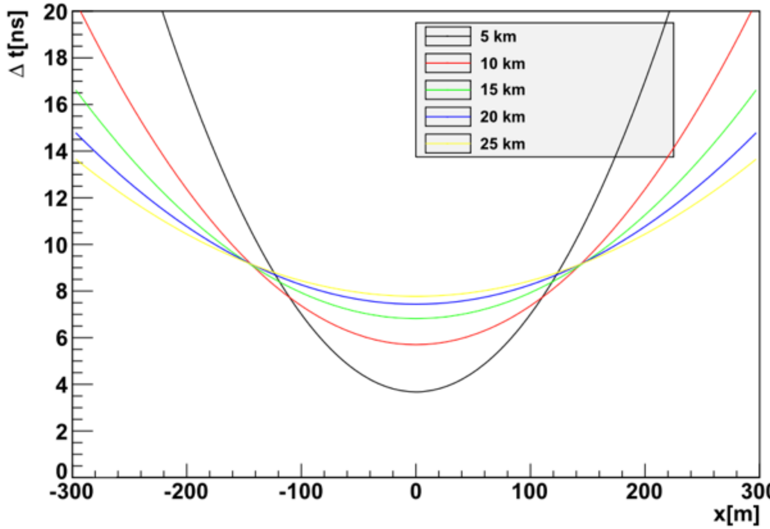
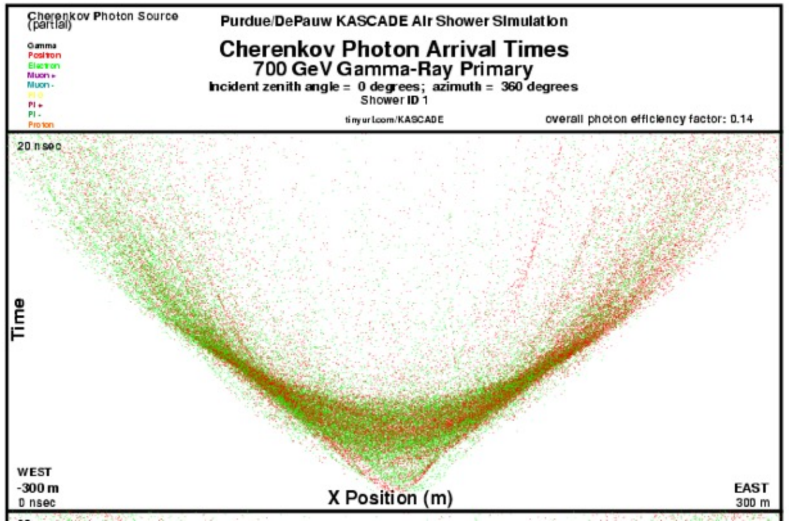
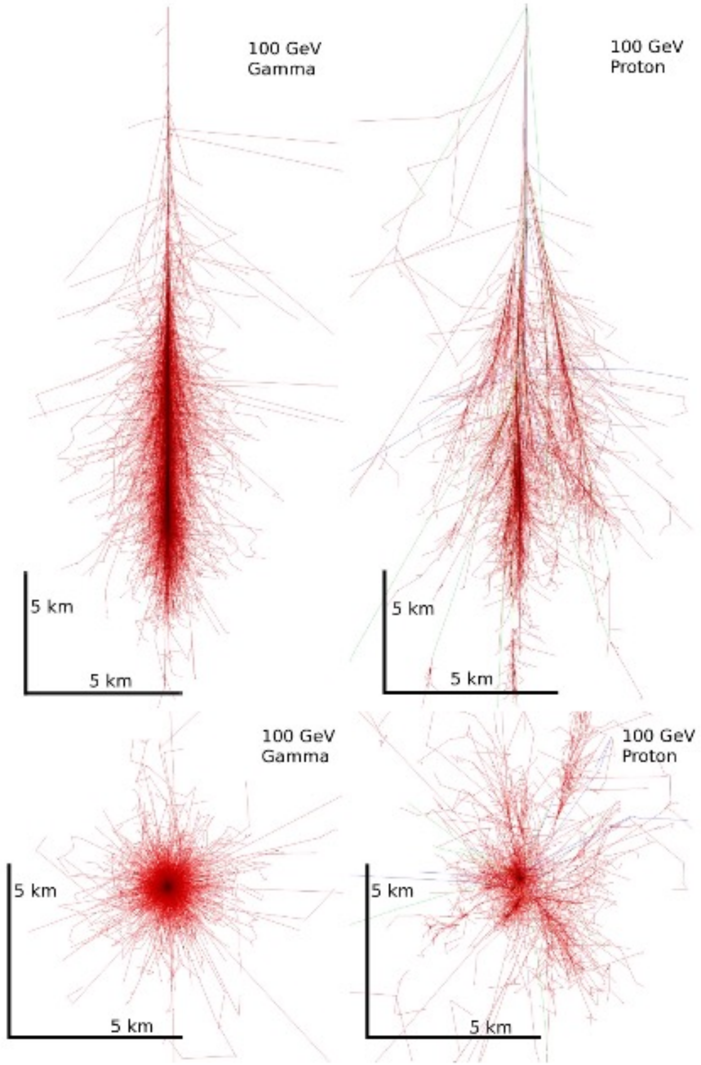


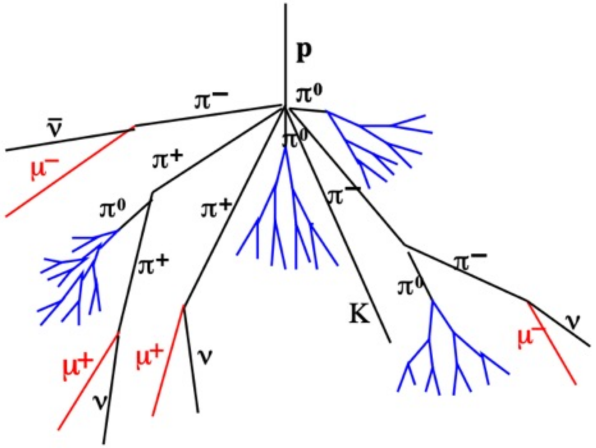


~ a few ns duretion.

time gradient can tell the distance.

Hadron Cosmic Ray Air shower

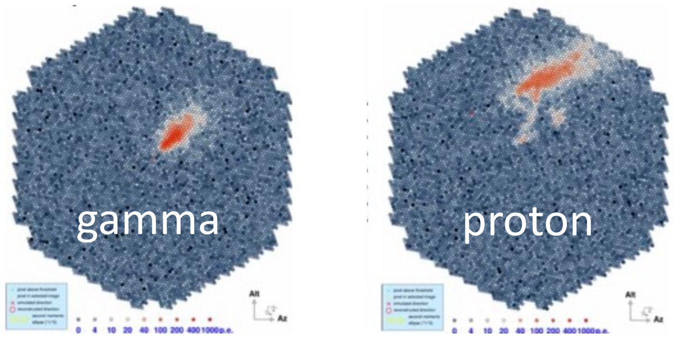




$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

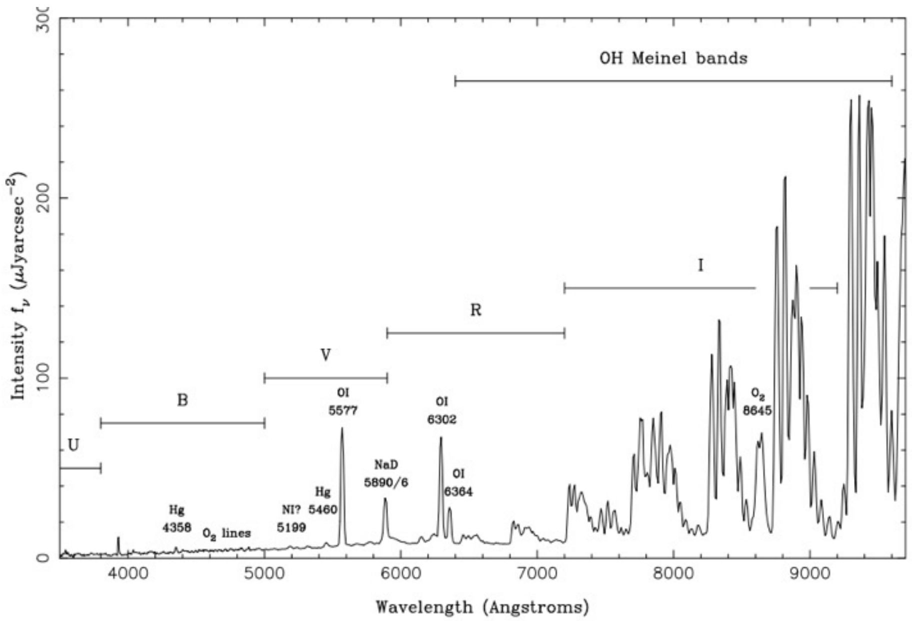
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

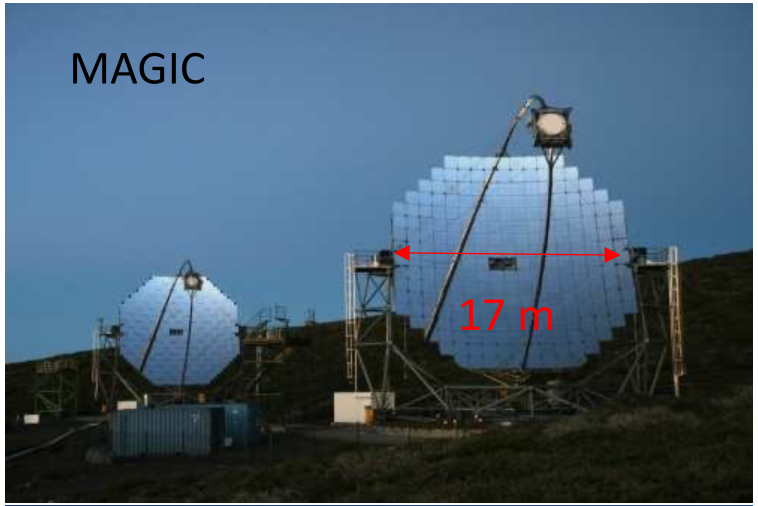
$$\pi^0 \rightarrow 2\,\gamma$$

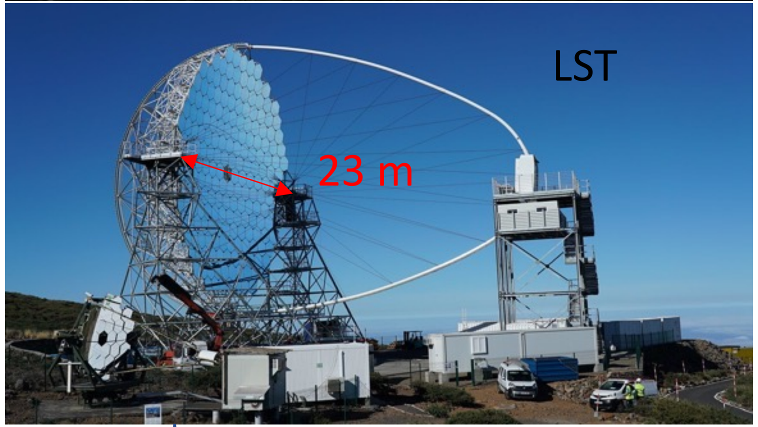


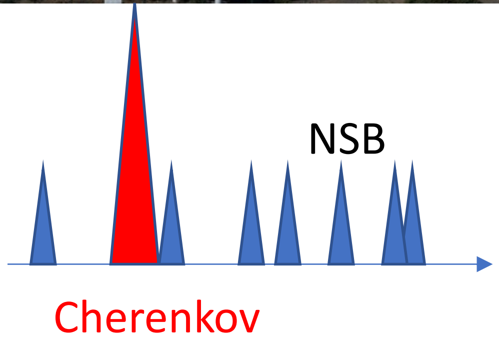
- Hadron Cosmic Rays also produce air showers.
- P + Nuclei -> pions
- Neutral pions -> electromagnetic air shower.
- Charged pions -> pions and muons.
  - Muons reaches ground.
- Image is a composition of multiple EM showers.
- From the irregularity, one can distinguish gamma-rays and hadronic cosmic rays.

Night Sky Background vs Cherenkov Photon









Night sky is not completely dark.

- airglow
- zodiacal light
- Integrated light of faint stars
- Scatterd starlight

Even for "moonless" night,
~2.3x10^{12} photons/m2/sr/s.

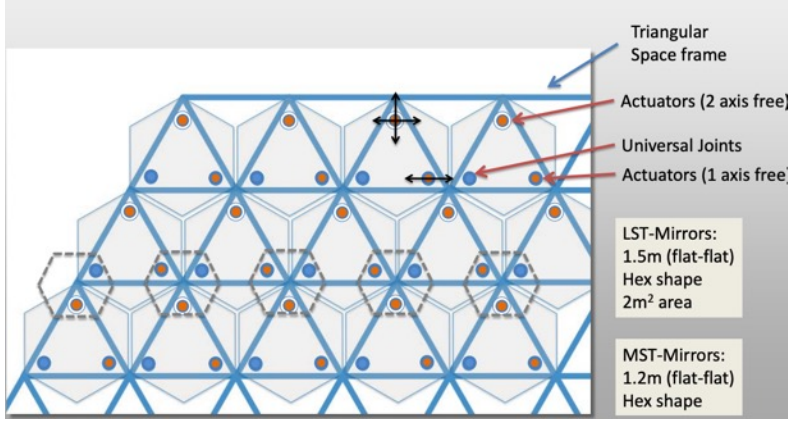
150 MHz/pixel for MAGIC
260 MHz/pixel for CTAO-LST.

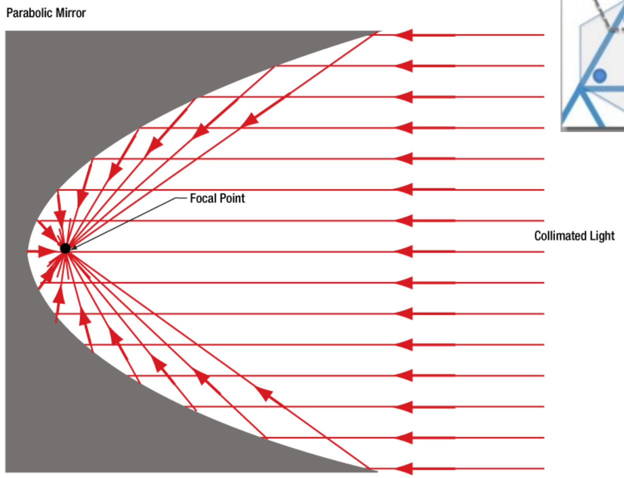
For galaxtic plane, 1.5 times larger.

Requirements:
Optics: Isochronism
Sensor: Fast pulse
Readout: High bandwidth

Calibration of (large dish) IACTs

(Large) Mirrors

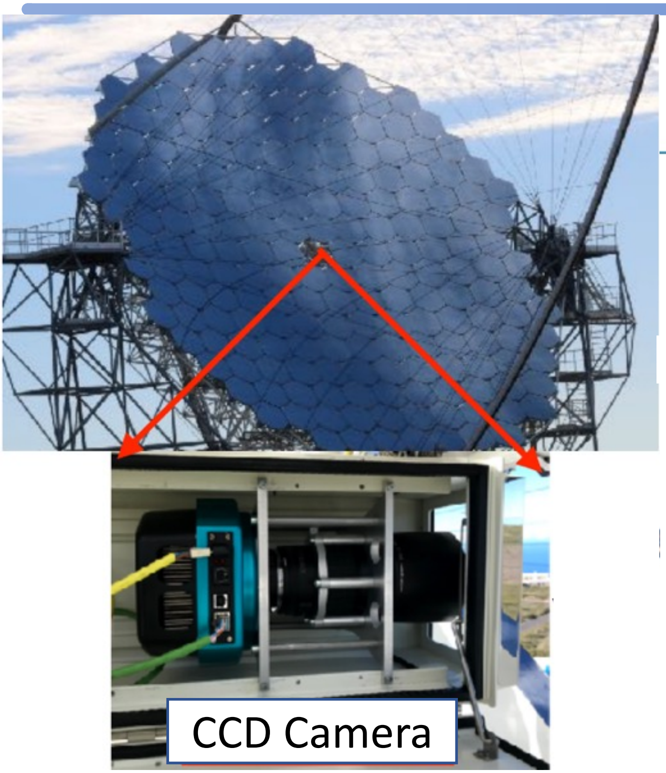


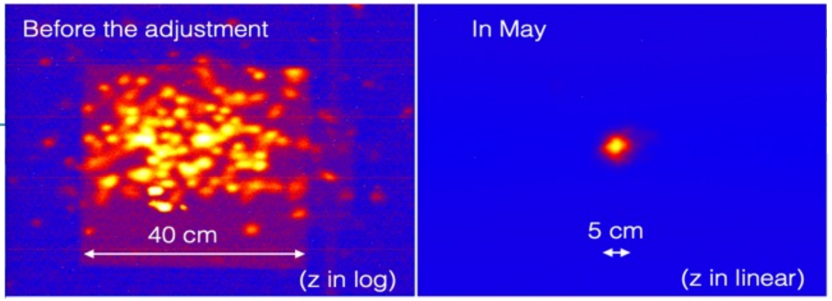


- 1 photon/m^2/20 GeV. (300-600 nm)
  - ➢ Mirror needs to be large
  - ➢ To detect 100 photoelectrons from a 100 GeV gamma-ray shower, 200 m^2 area is needed. (assuming overall photo-detection effciency 10%).
  - ➢ Segmented mirror
- In order to maintain isochronism
  - ➢ Parabolic Shape

- The telescope structure slightly deforms due to its self-weight
  - ➢ Each segments are equipped with actuators.
  - ➢ Needs calibration

Pointing Calibration (CTAO-LST)





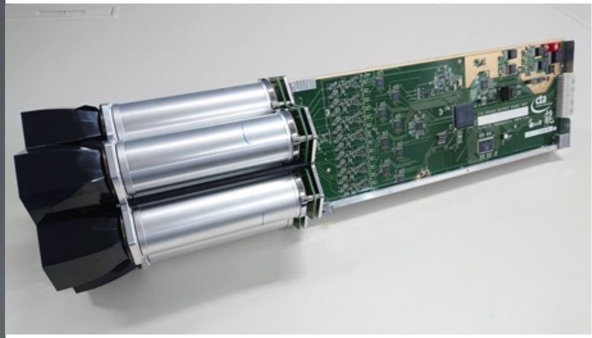
Internal document

Screen On Focal plane

- Prepare a screen on the focal plane (automatic).
- Track a bright star.
- Defocus all mirror segments except for a calibrating one.
- Take a star image photo using the CCD camera on the dish center.
- Move the actuator so that the star image comes to the center.
- Repeat the procedure for all segments.
- Repeat the procedure for several different zenith angles.
- Prepare a Look-up-table for actuator values for all segments and all Zd angles (interpolation).

Camera (CTAO-LST)





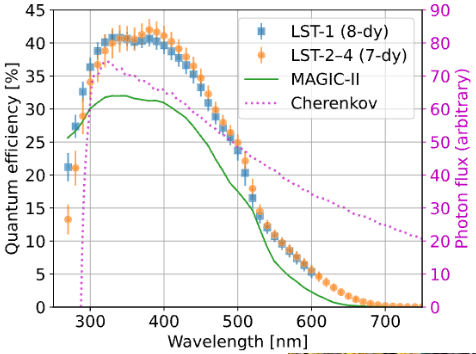
- 7-PMT modules x 265
- 1855 pixels
- 40% QE at 330-400 nm
- < 3 ns pulse width

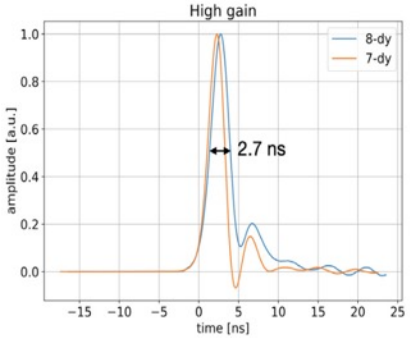
- Trigger is generated on the mezzanine board on the readout board.

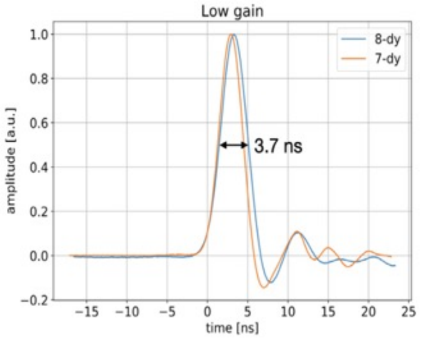
- Trigger is distributed via the backplane network.

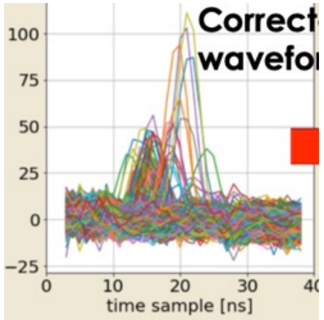
- Waveform for 40 ns is digitized with 1 GHz sampling.

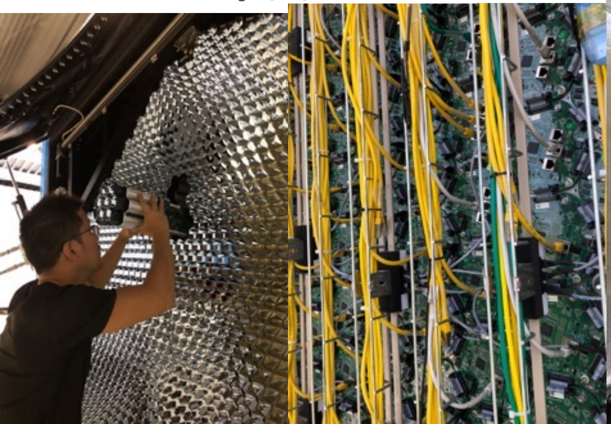
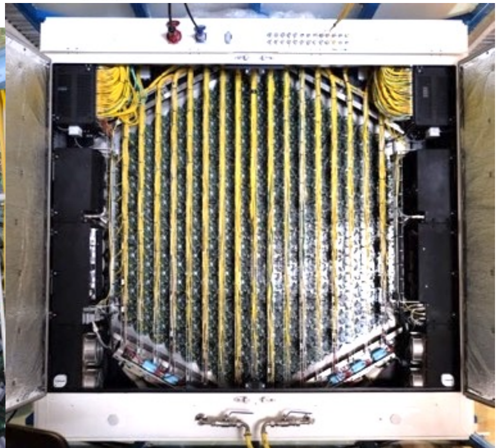
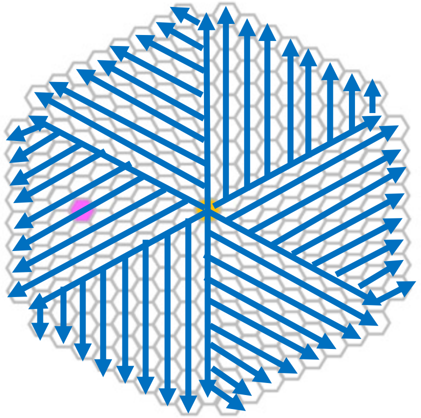
- Digital waveforms are sent to the server through Ethernet.



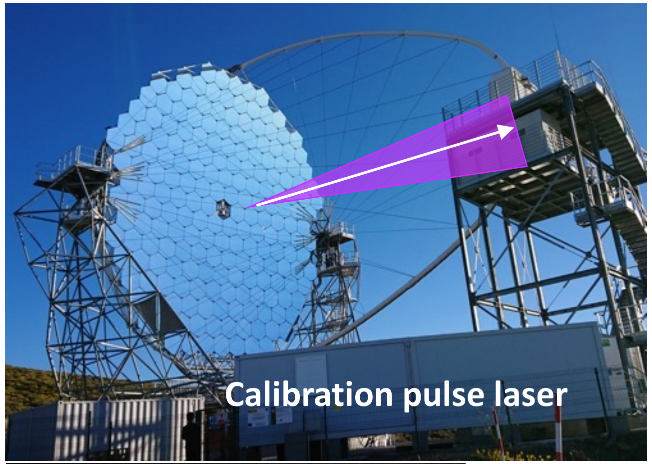


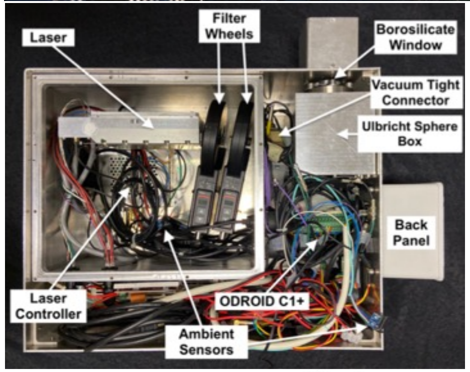


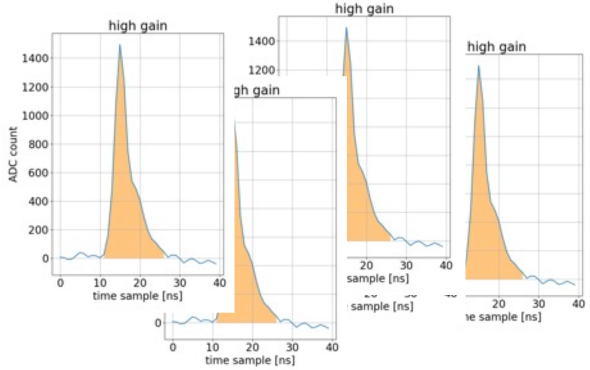


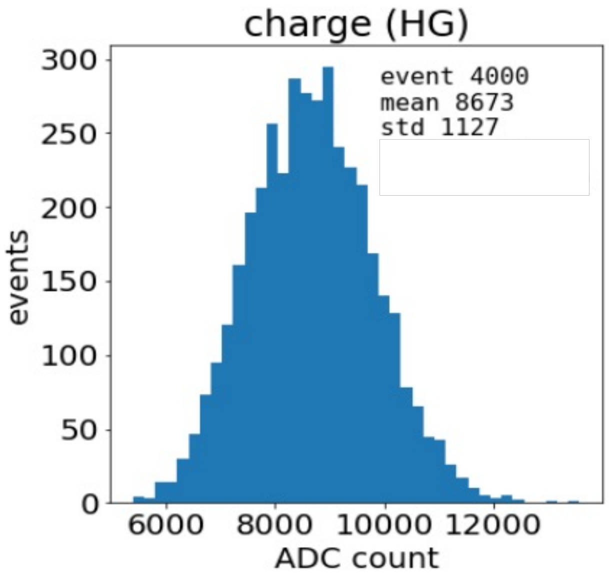




Camera: ADC to #p.e. calibration





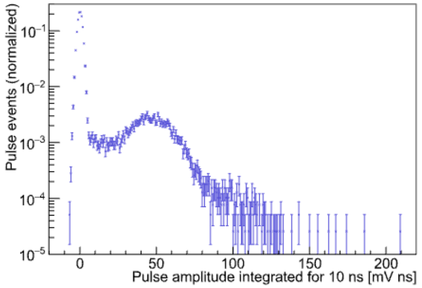




$\mu_{ADC} = 8673$
$\sigma_{ADC} = 1127$

Mean # of p.e.: $N = F \cdot \mu_{ADC}^2 / \sigma_{ADC}^2 = 58.9$ [p.e.]
Conversion factor: $G = \mu_{ADC}/N = 146.9$ [count/p.e.]

The factor "F" is measured in the lab.



$$F = \sqrt{1 + \frac{var\left(\hat{N}_1(q_i)\right)}{\langle \hat{N}_1(q_i)\rangle^2}},$$

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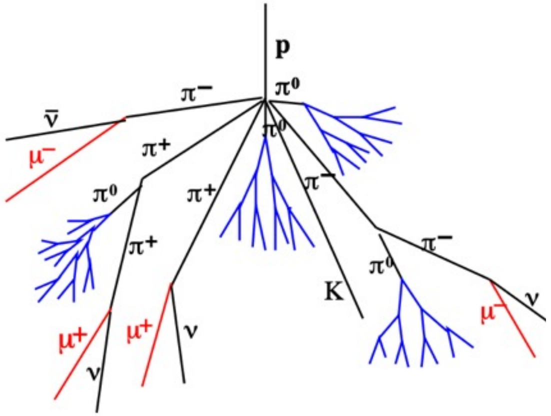
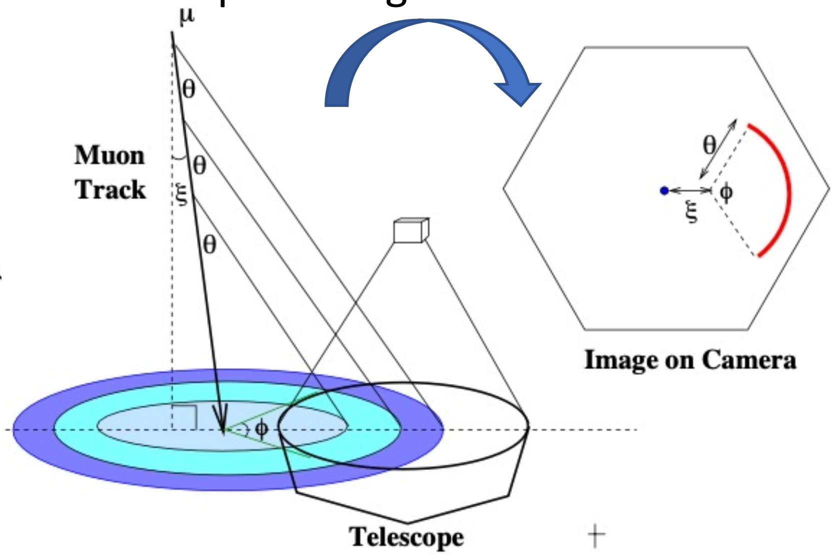
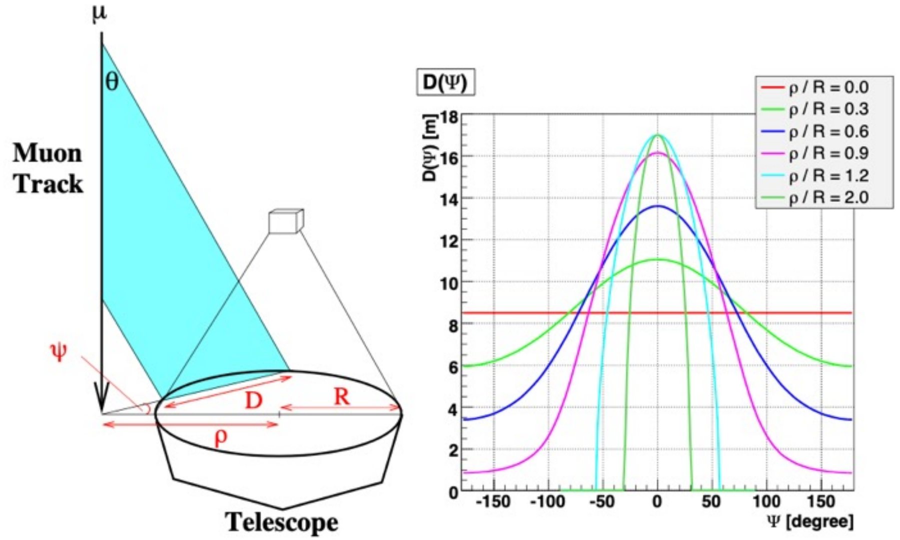
- There is a laser in the dish center.
  - Light pulse width is ~ 1ns.
  - Intensity is not well calibrated.
  - Intensitiy is stable within 1%
  - Uniformity is ~1%
  - *Astropart Phys, 167 (2025), 103079*
- Shoot the laser pulses ~4000 events and measure the charge distribution in ADC counts.
- The ratio of the mean and the variance tells the mean number of detected photoelectron.
- Readout time is calibrated at the same time.
- The calibration is continously done during the observation.

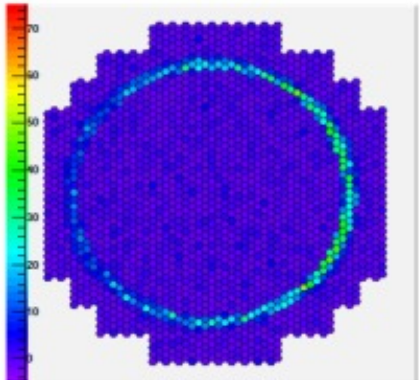
Muon Events in IACTs



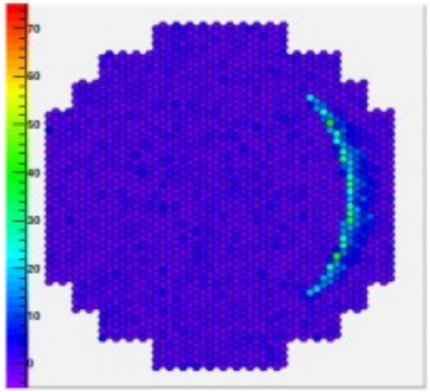
Optics: Angle to Position conversion



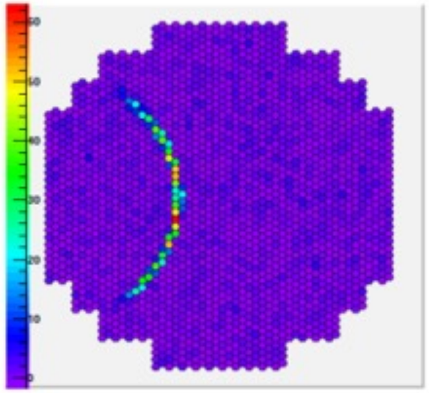




Parallel to the telescope axis.
Hit the telescope



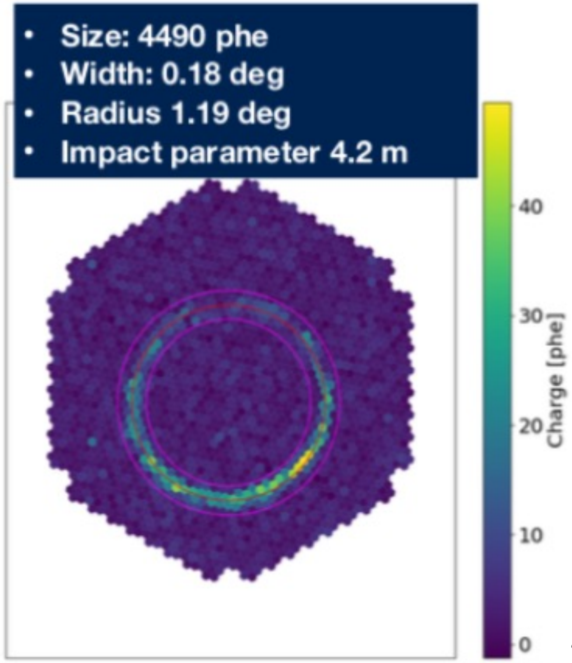
Parallel to the telescope axis.
Did not hit the telescope

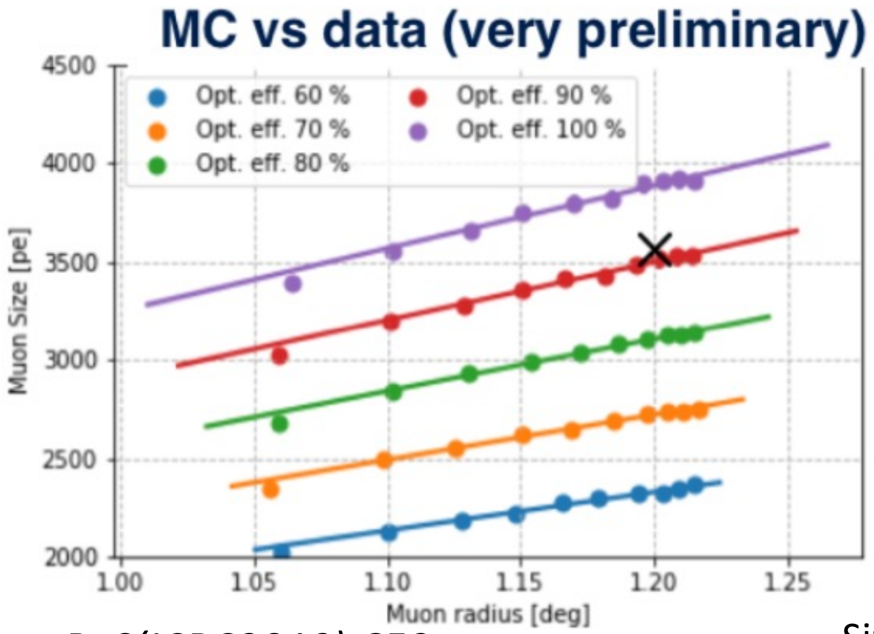


Inclined to the telescope axis.
Did not hit the telescope

- Muon from airshowers reaches on ground without bremsstrahlung.
- Cherenkov radiation in the last 500 m creates a ring/arc-like images on the Cherenkov Camera.
  - Ring center -> Arrival Direction
  - Ring radius -> Emission angle
  - Azimuthal charge distribution -> Impact parameter
- Very useful to calibrate optical and photo-detection perfomance.

Muon Calibration





J. Cortina, PoS(ICRC2019) 653

Ring Radius

$$\cos\theta = \frac{c/n}{\beta c} = \frac{1}{\beta n}$$

$$\frac{dN(\omega)}{dx d\omega} d\omega = \frac{1}{\hbar\omega}\frac{dI(\omega)}{d\omega dx} d\omega = \frac{\alpha}{c}\left[1 - \frac{1}{\beta^2 n^2}\right] d\omega$$

$$= \frac{2\pi\alpha}{\lambda^2}\left[1 - \frac{1}{\beta^2 n^2}\right] d\lambda$$

Emitted # of photons

Known,
1.0003

Size (total Charge) vs Raidus tells

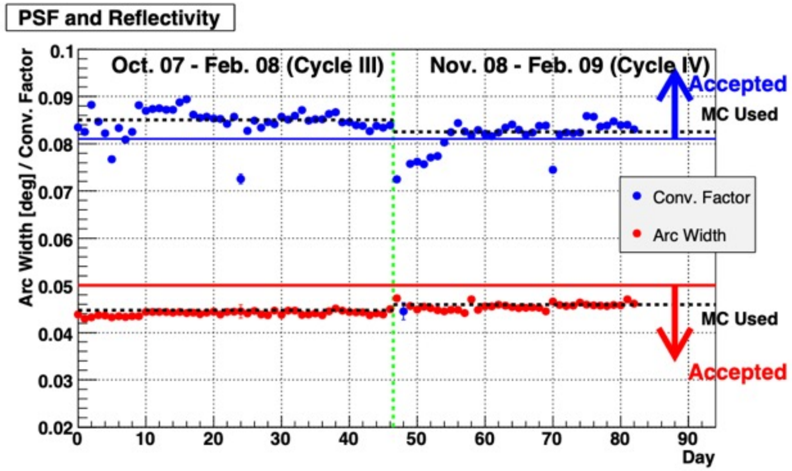
- Mirror reflectivy
- photodetection efficiency

Ring width tells

- Point spread function

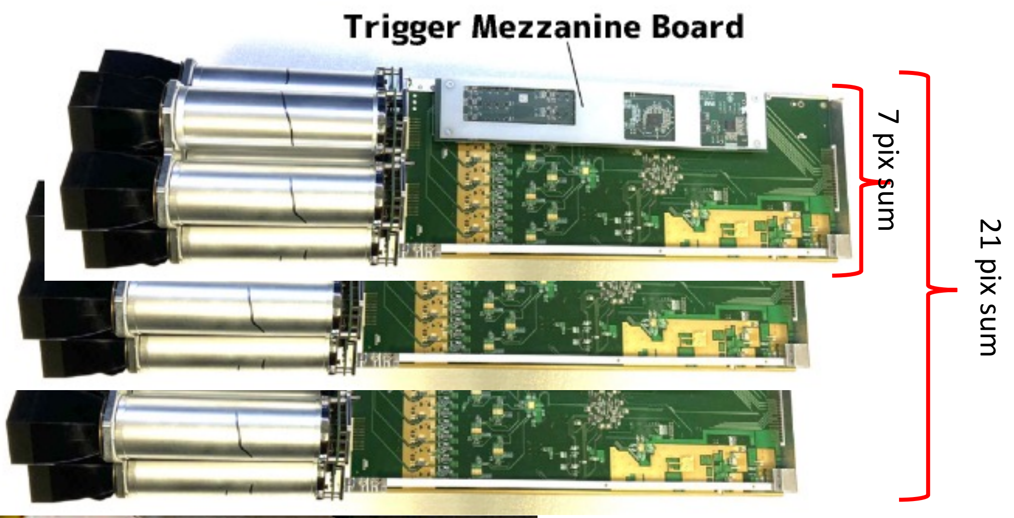
By comparing with MC, one can calibrate the refelctor and camera performance.

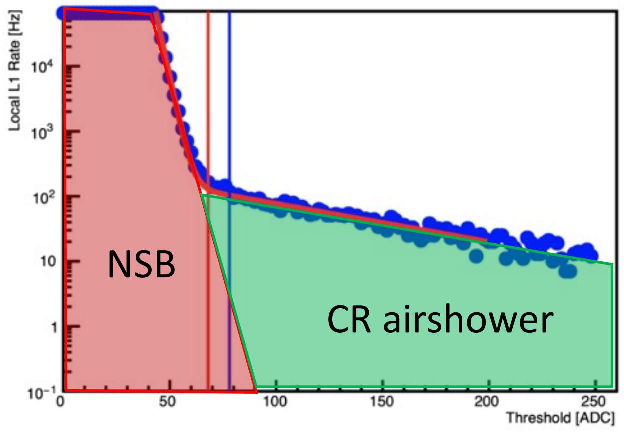
Good muon rate is >200 Hz.
Very useful also for data selection.



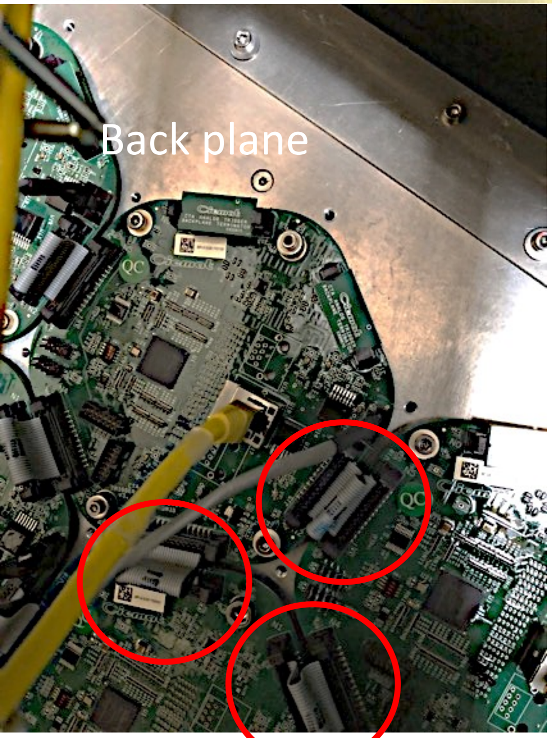
T. Saito PhD thesis

Trigger Threshold Calibration (CTAO-LST)

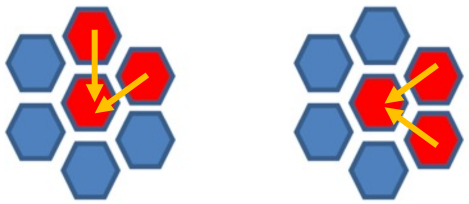




- 21 pixel analog sum trigger
- Analog signals are distributed among PMT modules.
- Trigger mezzanine of each PMT module has 2 discriminators and 2 different types of combinations.



Mode 3:

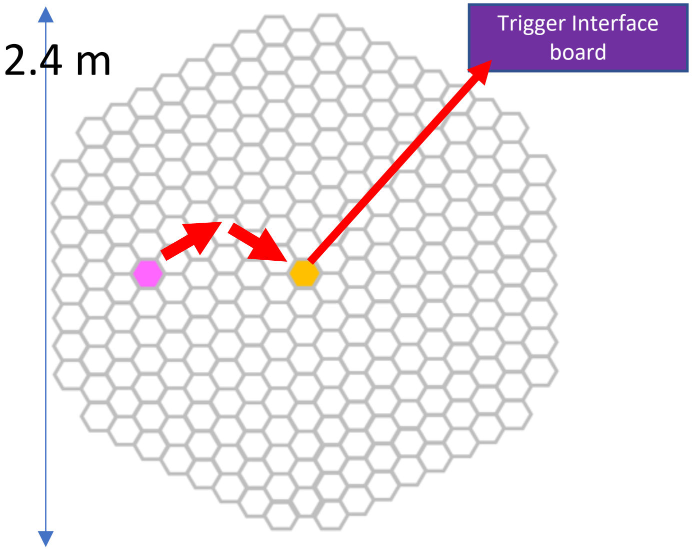


Each module evaluate 2 types of combination

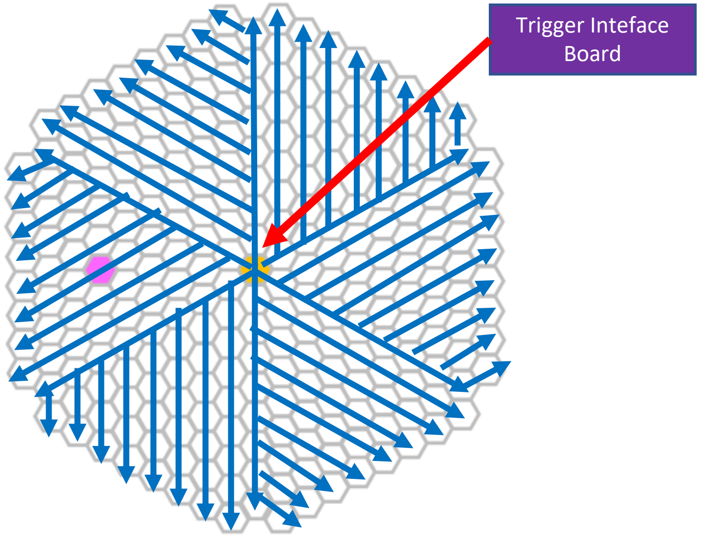
Internal document

- Optimize the threshold
  - as low as possible
  - Uniform
  - stable
- Tracking the dark patch and make a rate scan.
- Choose the value where NSB contamination is less than 10%.
- Should be changed for galactic plane observation, or moon observation.

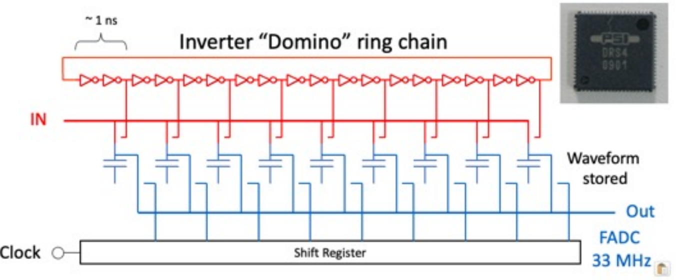
Clock and Trigger timing Calibration

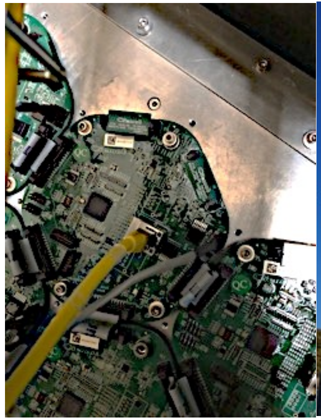


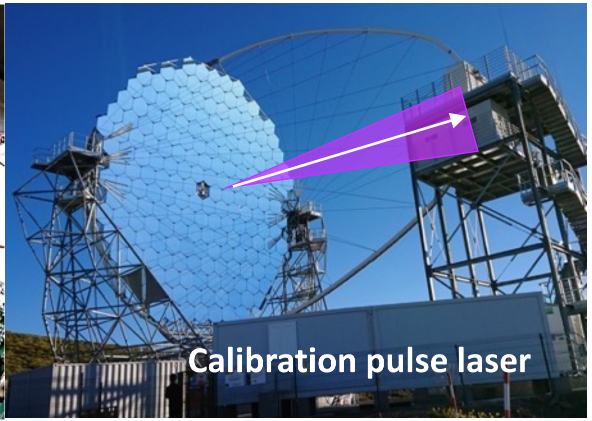
When a trigger is generated in a module, it is propagated to the trigger interface board (TIB), through the BP network.



TIB judges if this event should be taken or not. (BUSY state, stereo coincidence etc.) If yes, the trigger signal is propagated to all PMT modules.

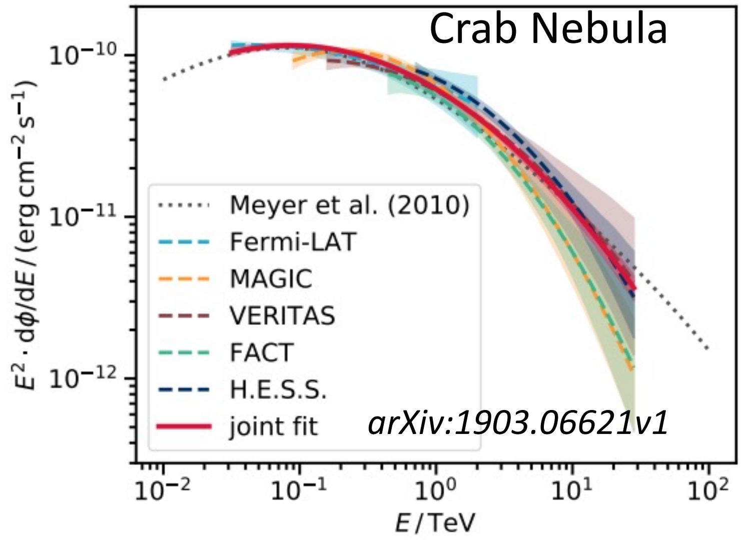


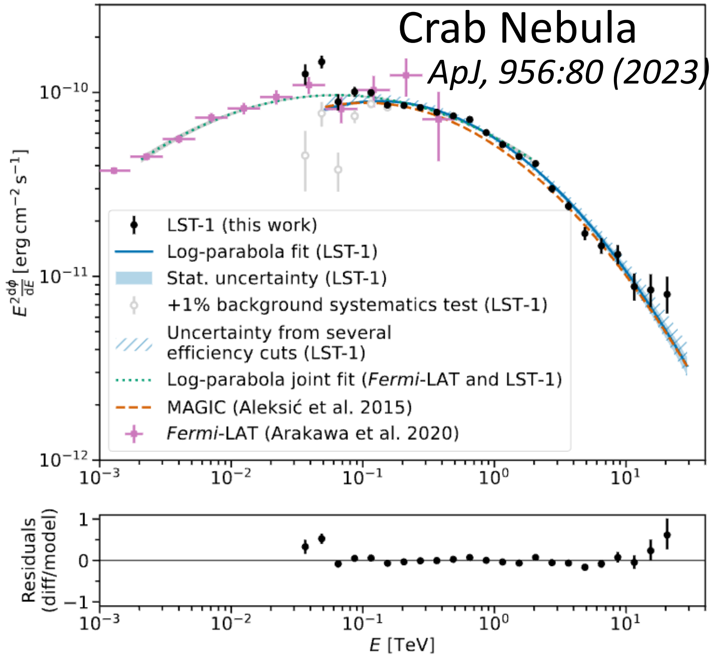


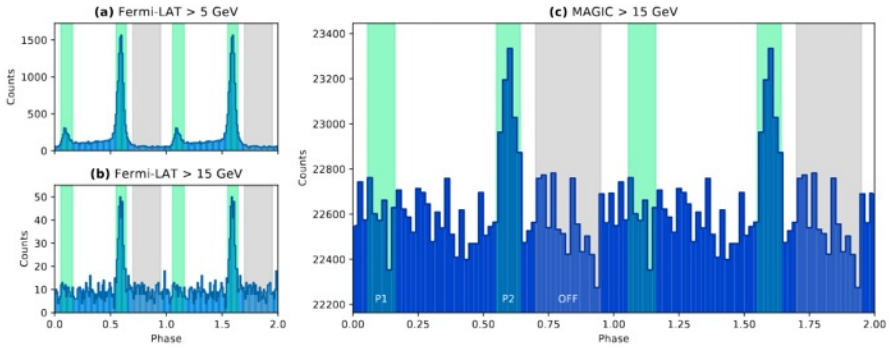


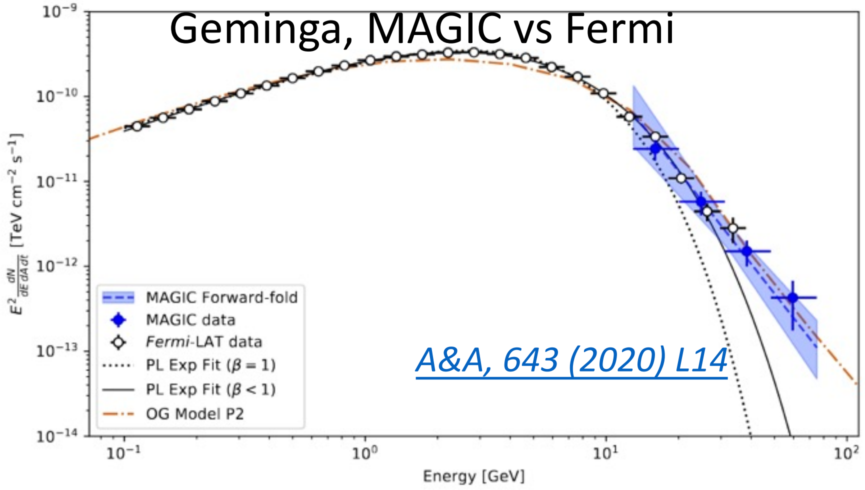
- There is a 4 us buffer (analog capacitor array)in each readout board and waveform is continuously sampled. Readout (40 ns window) happens when trigger signal comes.
- Cherenkov Flash is fast. The trigger signal should be injected to all PMT modules at the same time within a few ns precision.
- But Camara is big, ~ 2.4 m.
- Each back plane has configurable delay lines. By using the laser flash, delay lines are calibrated such that
  - The trigger signal generated by any modules reaches TIB at the same delay.
  - The trigger signal sent by TIB reaches all modules at the same time.
  - 10 MHz clock edge for each module is aligned.

Standard Candle: Crab Nebula, pulsars

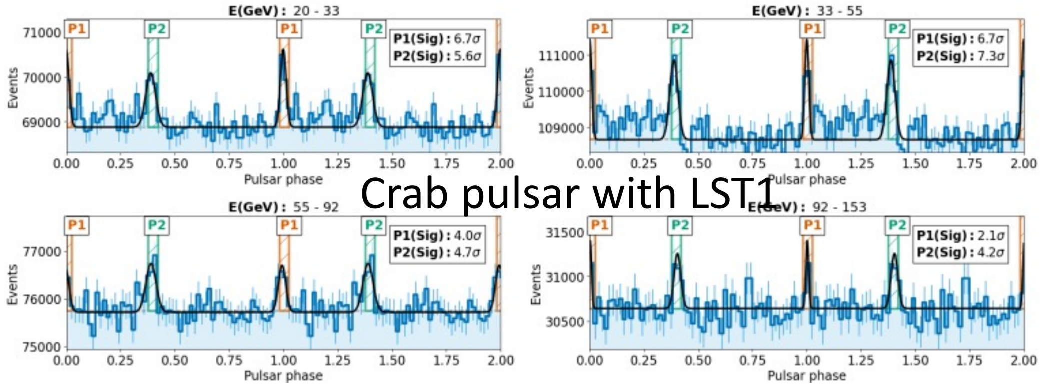








[A&A, 643 (2020) L14](#)

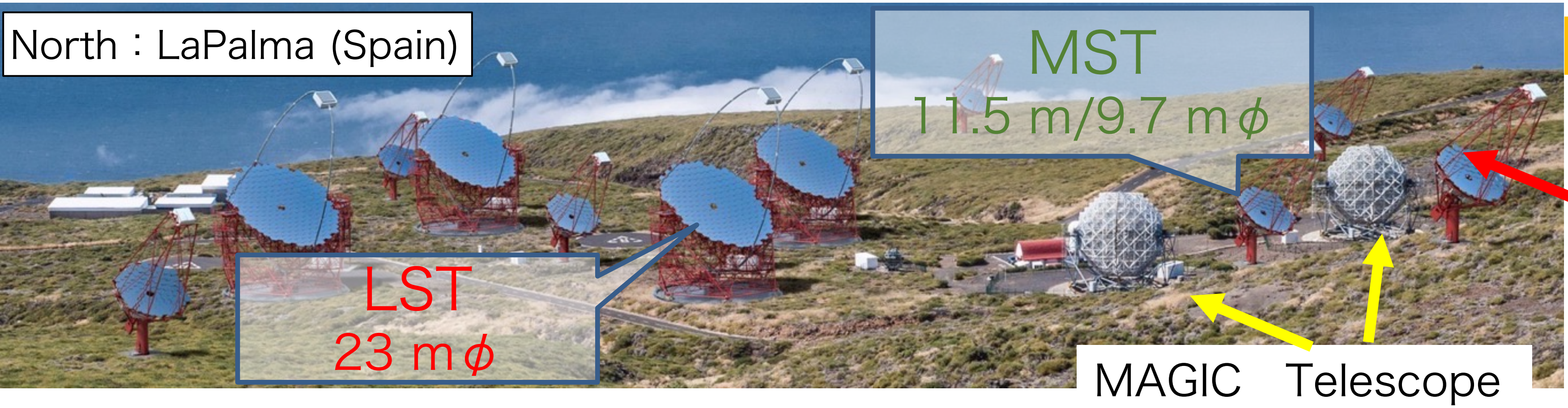


A&A, 690 (2024) A167

- After all calibrations and MC tuning based on measurements, energy spectra are computed.
- Absolute Energy/Flux scale can be tested with Standard Candles.
- Crab Nebula
  - Very bright
  - Stable
  - Curved at around 100 GeV.
  - All IACTs and Fermi-LAT
- Pulsars
  - Spectrum is very soft above 10 GeV.
  - Energy dependent light curves
  - Fermi-LAT

Status of CTAO and recent results

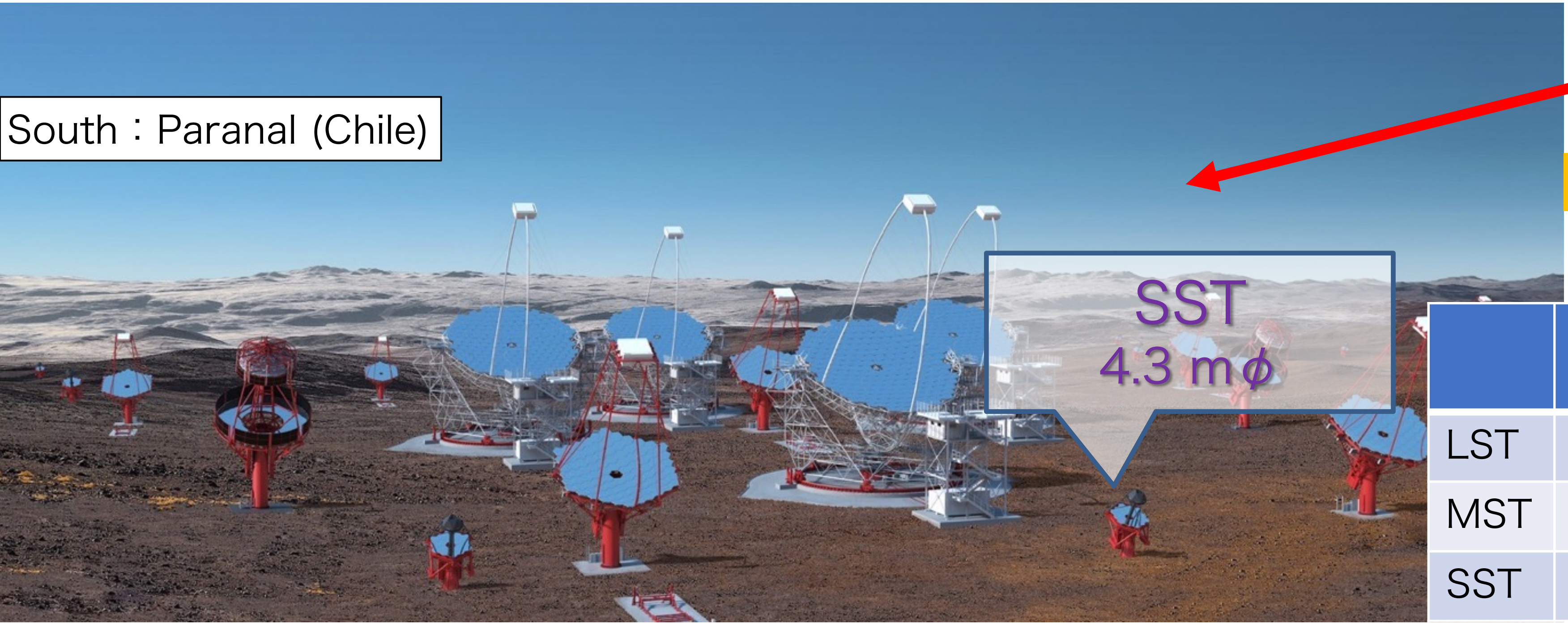
Cherenkov Telescope Array Observatory



North | Array Coordinates | 0.5 km x 0.5 km

Latitude: 28° 45′ 43.7904″ North

Longitude: 17° 53′ 31.218″ West



South | Array Coordinates | 2 km x 2 km

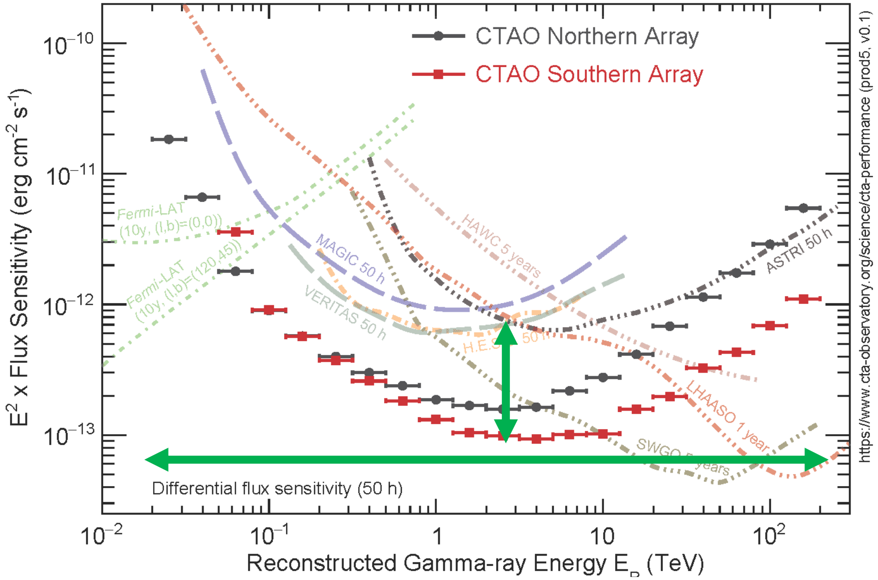
Latitude: 24° 41′ 0.34″ South

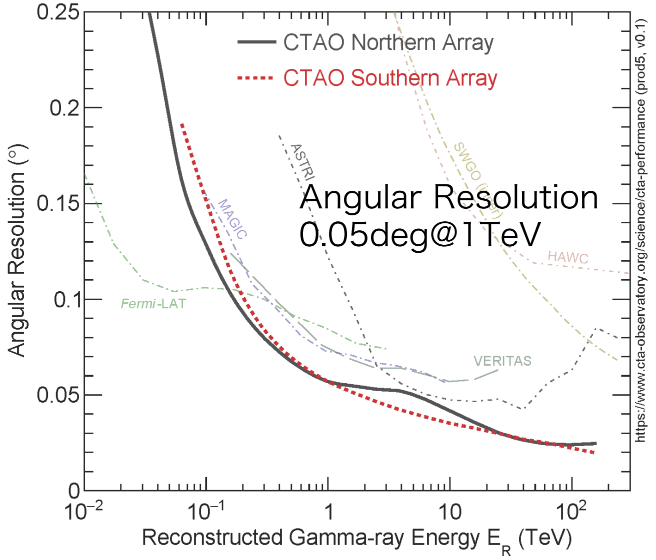
Longitude: 70° 18′ 58.84″ West

	#tel (N)	#tel (S)	Energy [TeV]	FoV [deg]
LST	4	2→4	0.02 - 3	4.5
MST	9→15	14→25	0.08 - 50	7.5
SST	0	42→70	1 - 300	10.5

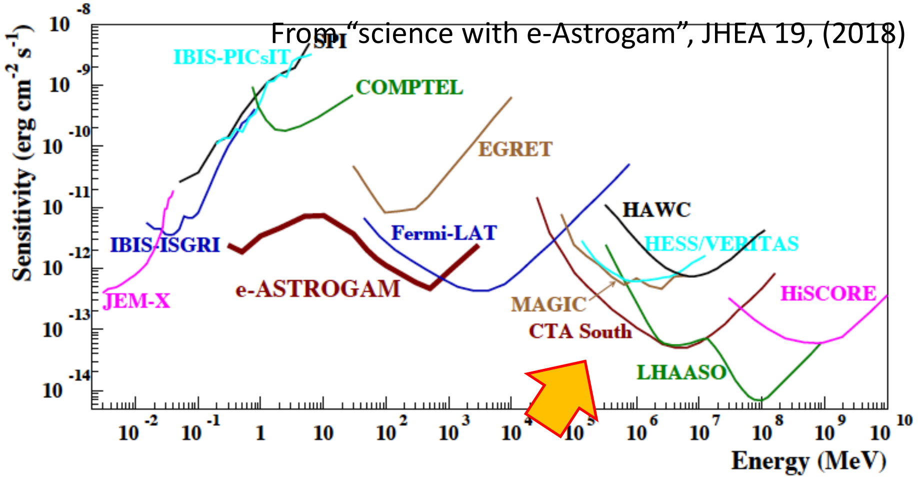
“Alpha” Configuration Operation starts in ~20xx

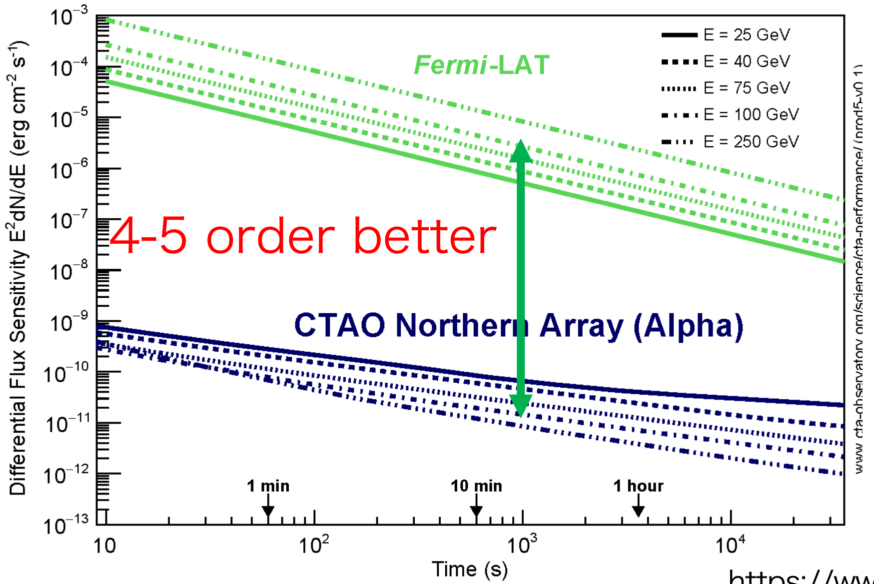
CTAO Performance

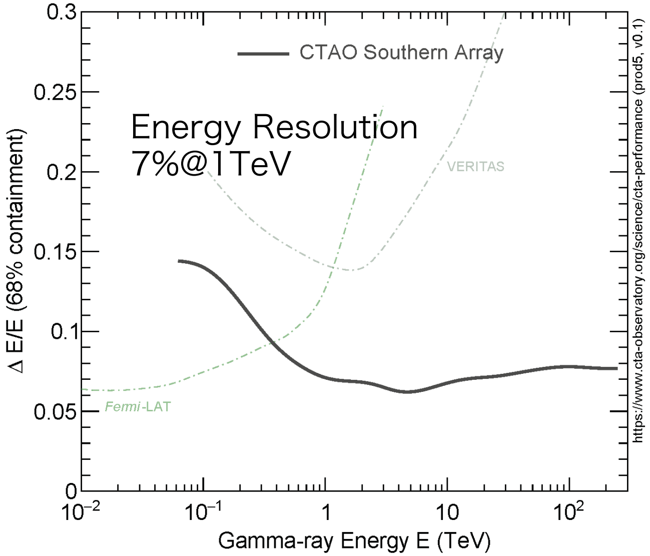




From "science with e-Astrogam", JHEA 19, (2018)



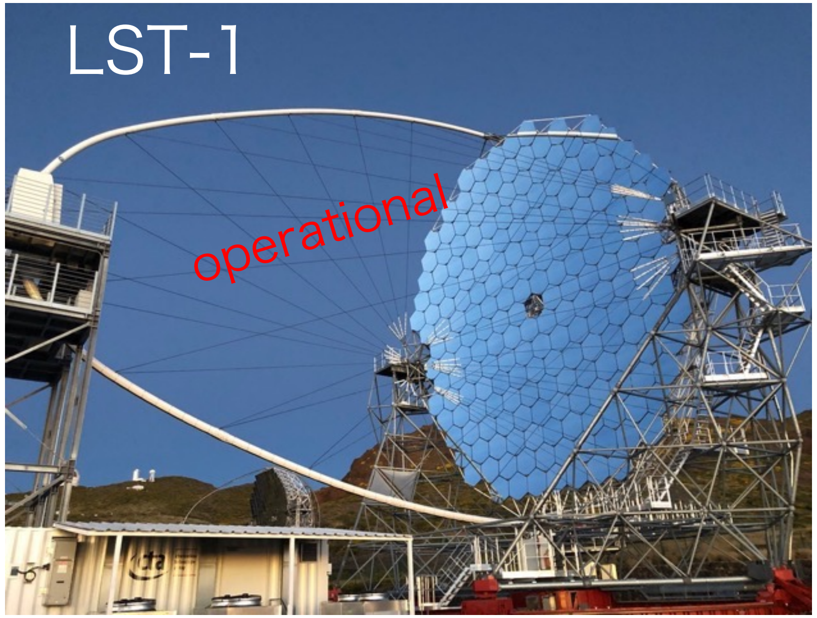


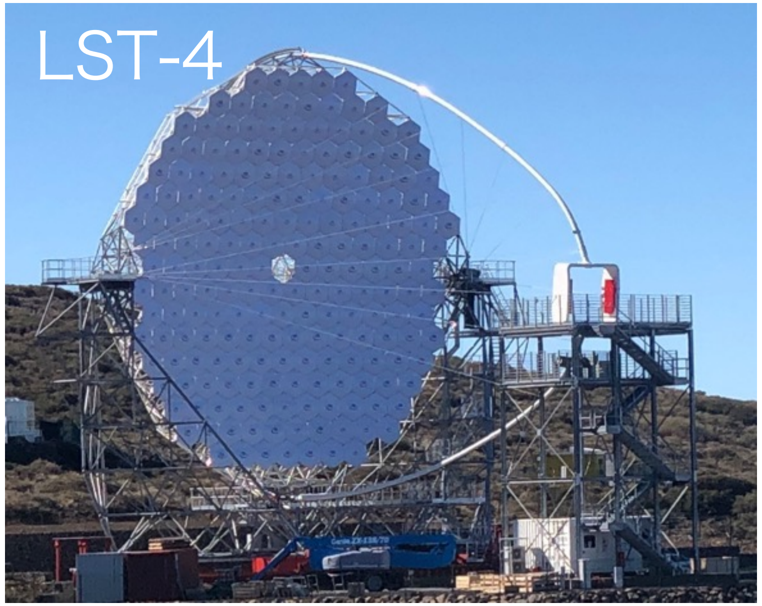


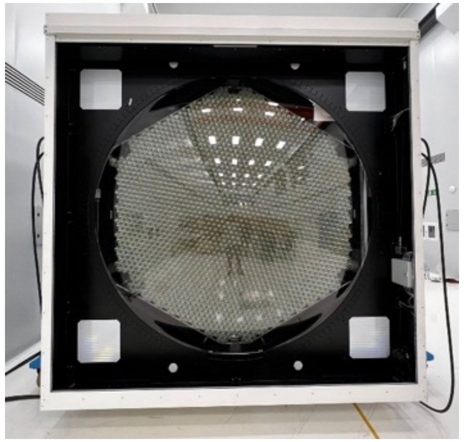
10^{-13}erg/s/cm^2
@1-10 TeV

https://www.ctao.org/for-scientists/performance/

LST North construction status







Camera@Tenerife

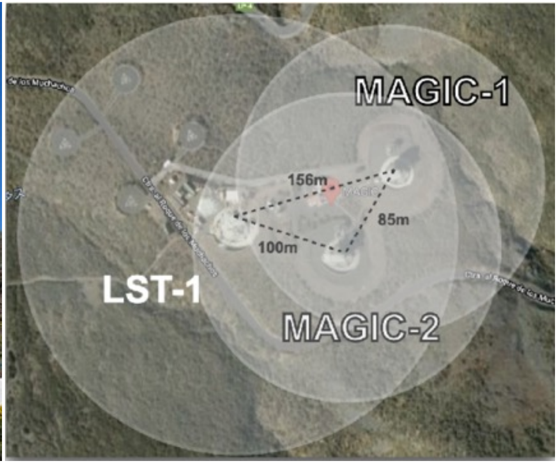
Mirror@LaPalma

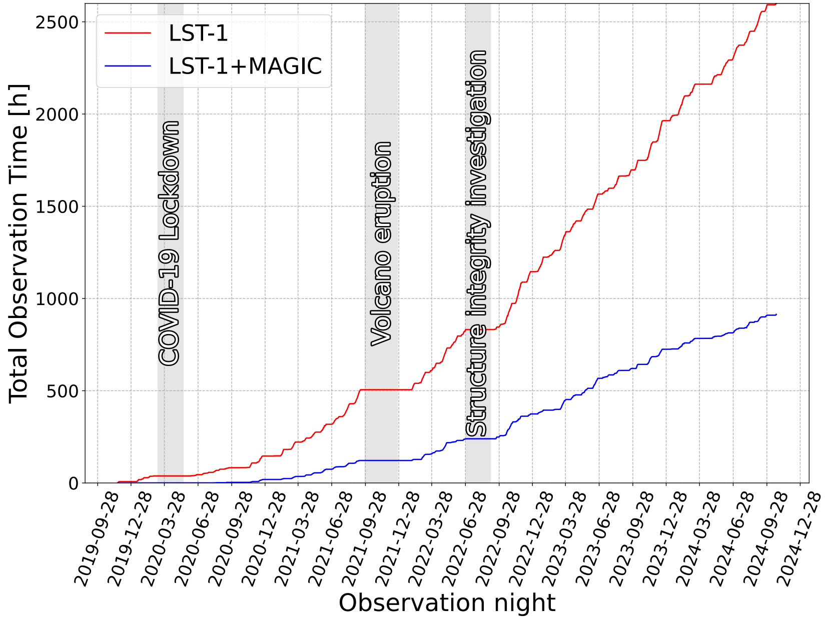
Schedule

	Arch	Mirror	Camera
LST1	operational		
LST2	25/6	25/8	26/03
LST3	24/1 done	25/5	25/9
LST4	24/8 done	24/12 done	25/5

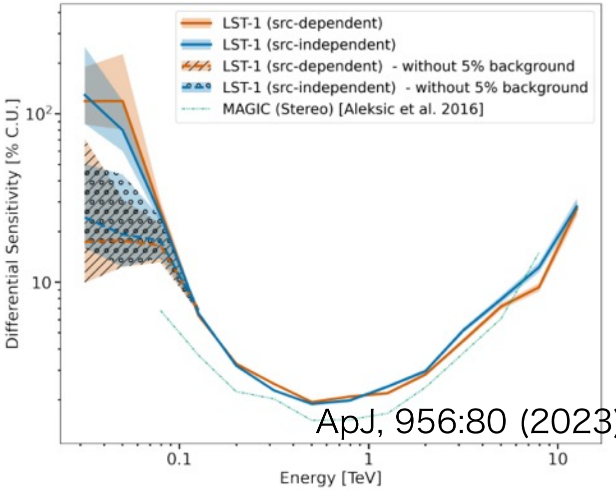
4-LST array obs. starts in 2026

LST-1 Operation Status



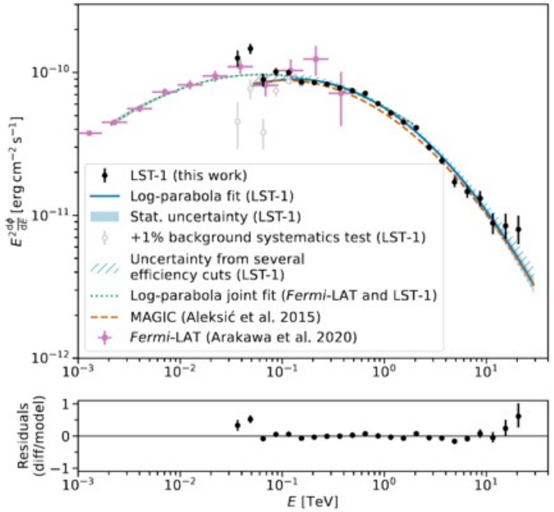


- More than 2700 hours since 2020
  - 30-40% of the time with MAGIC-Joint
  - 90% availability

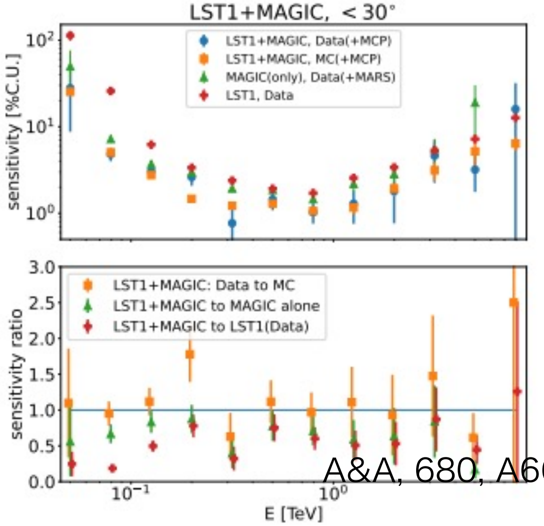


ApJ, 956:80 (2023)

LST-1 Sensitivity



Crab Nebula SED

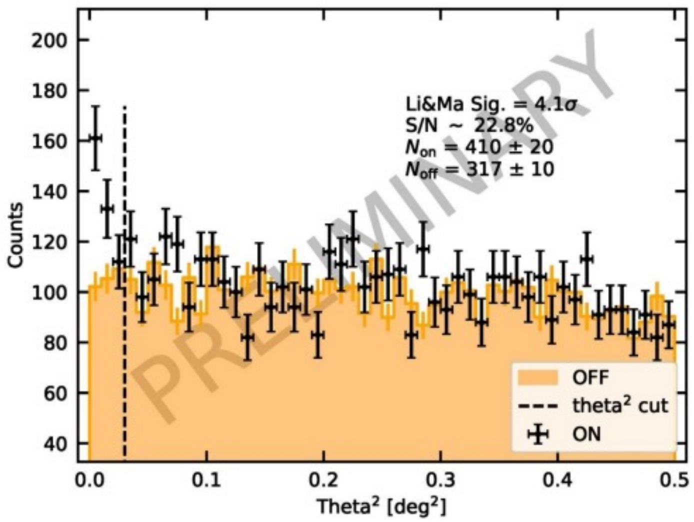


A&A, 680, A66 (2023)

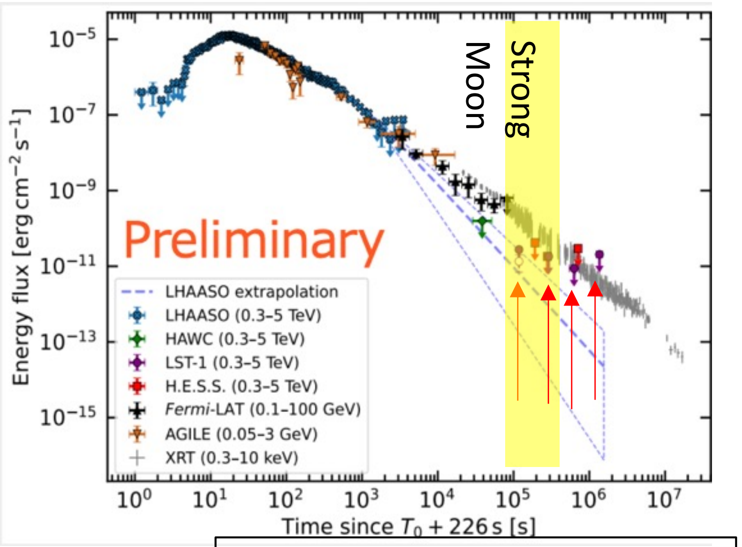
LST + MAGIC Sensitivity

LST-1 : Extragalactic Sources

- **BOAT** GRB. Z = ~0.151, E^{iso} ~ 10^{55} erg



θ²-plot for the moon data (Oct. 10)



K. Terauchi (TeVPa 2024)

- Observation started at T0+1.3d under very strong moon
- To bypass the “Safety Limit”, PMT HVs had to be reduced. Analysis was very difficult.

- 4 sigma excess could be obtained
- Consistent with LHAASO extrapolation after break.

- **FSRQ OP313**

Not public yet

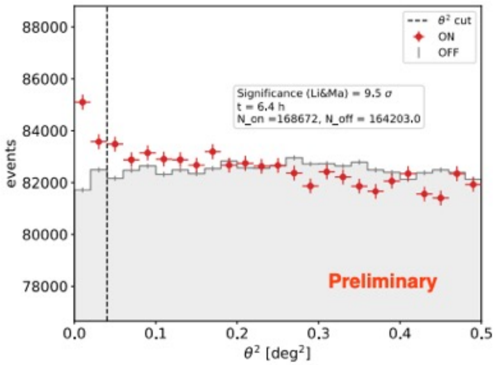
S. Nozaki (Cospar 2024)

- Z = 0.997, the farthest AGN detected with IACT
- Detected only upto 250 GeV.
- Very important for EBL study

- Very active again in 2025

LST-1 : Galactic Sources

- **Reccurent Nova, RS Ophiuchi**



A&A, 695, A152 (2025)

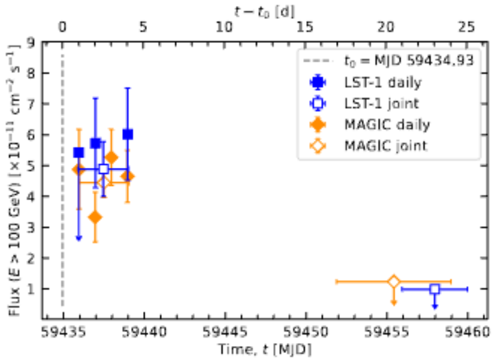
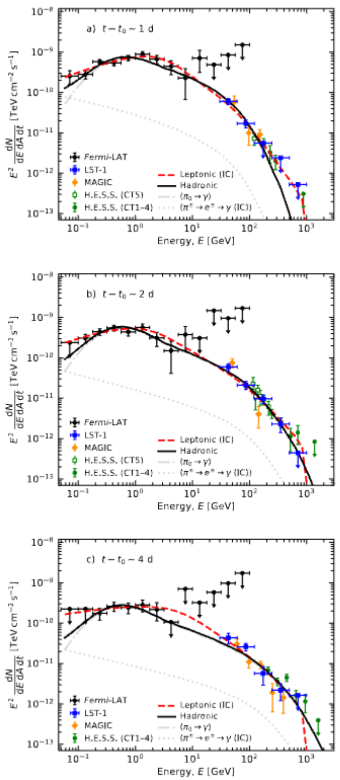


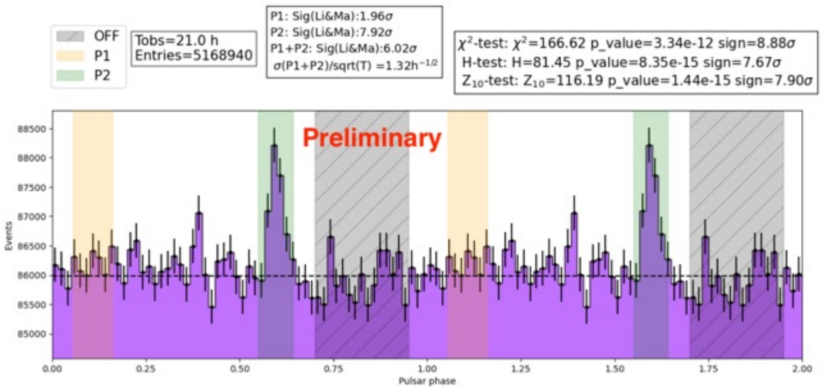
Fig. 2. Daily integral fluxes at $E > 100$ GeV for LST-1 (filled blue squares) and MAGIC (filled orange diamonds; Acciari et al. 2022) as a function of MJD (bottom axis) and time after the eruption onset (top axis), which is represented as the dashed line. We also show the joint LST-1 (empty blue squares) and the joint MAGIC (empty orange diamonds) integral fluxes during observation-day intervals 1 and 4, and more than 21 days after the eruption.



- First Nova detection VHE together with MAGIC and HESS.
- Signal detected in the first 4 days.

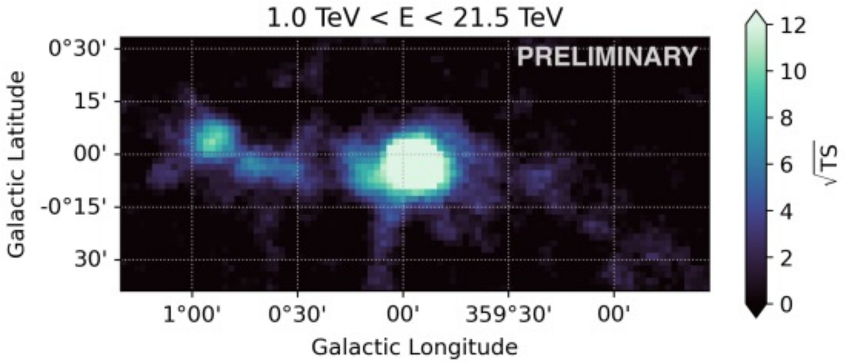
- Hadronic Scenario is preferred.
- The cutoff energy increases in the first 4 days.

- **Geminga pulsar**



PoS(ICRC2023), 569

- **Galactic Center**



PoS(ICRC2023), 574

- Geminga pulsar detection in 20 hours.

- Galactic Center well observed with large zenith angle observations.

Summary

- IACTs detect tens to thousands of Cherenkov Photons within a few ns duration. They suffers from NSBs and Cosmic Ray background. Charge and Time calibration is essential.

- Stars, Calibration laser, Muons are used to calibtrate telescopes.

- CTAO will come in North and South in 20xx.
  - 4 LSTs in North will start operation in 2026.
  - LST1 in north is operational since 2020 and several interesting results have already been reported.