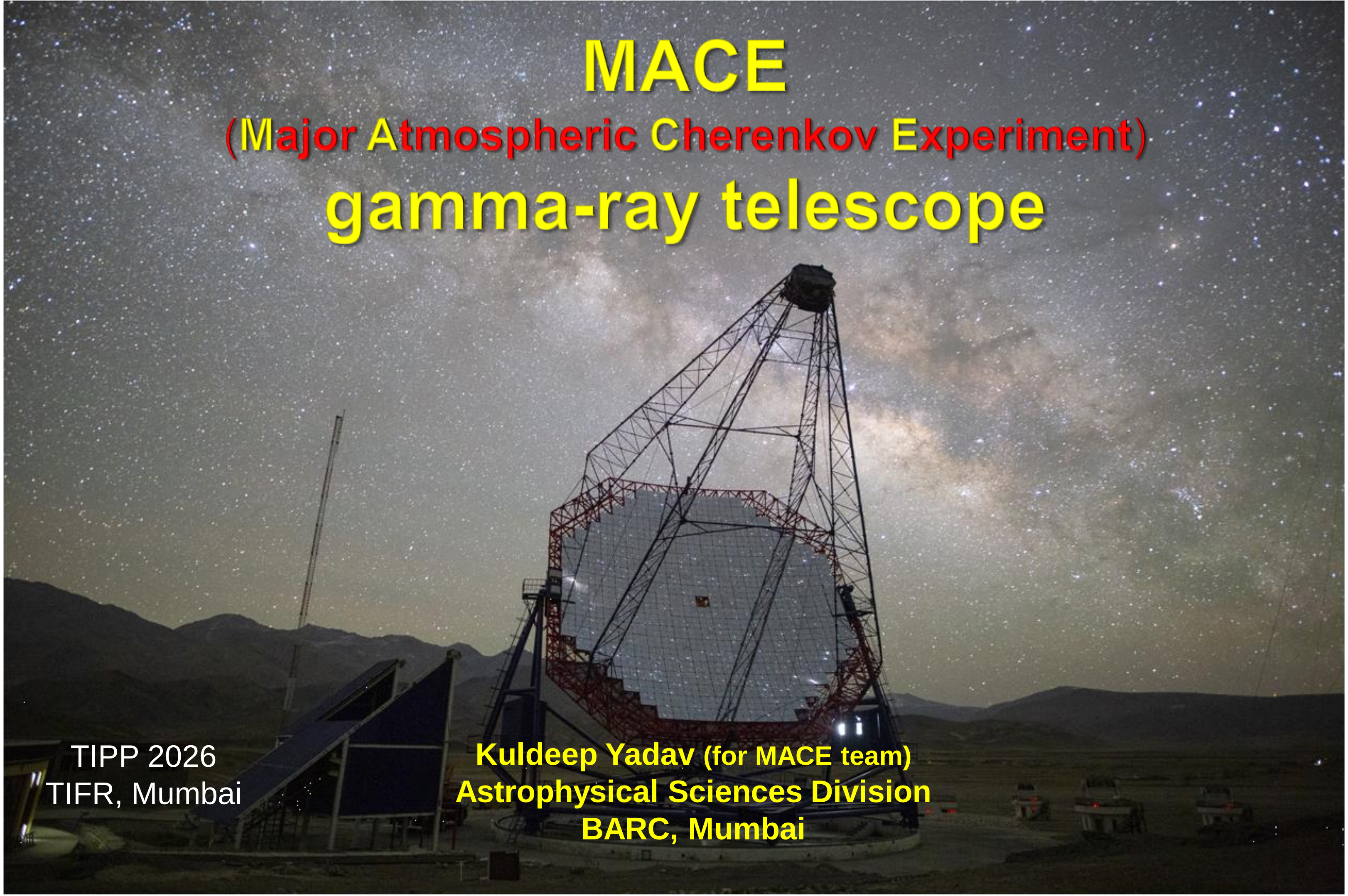


MACE
(Major Atmospheric Cherenkov Experiment)
gamma-ray telescope

TIPP 2026
TIFR, Mumbai

Kuldeep Yadav (for MACE team)
Astrophysical Sciences Division
BARC, Mumbai

MACE Telescope @ Hanle

MACE: Imaging Atmospheric Cherenkov Telescope

Extremely Large Telescopes: Diameter: 21m

Third largest Imaging Cherenkov telescope globally

Location: Hanle ($32^0 46' 46''$N, $78^0 58' 35''$E, 4270m asl) in Ladakh (India)- Fully indigenous efforts

Unique advantages of Longitude, altitude and clear nights

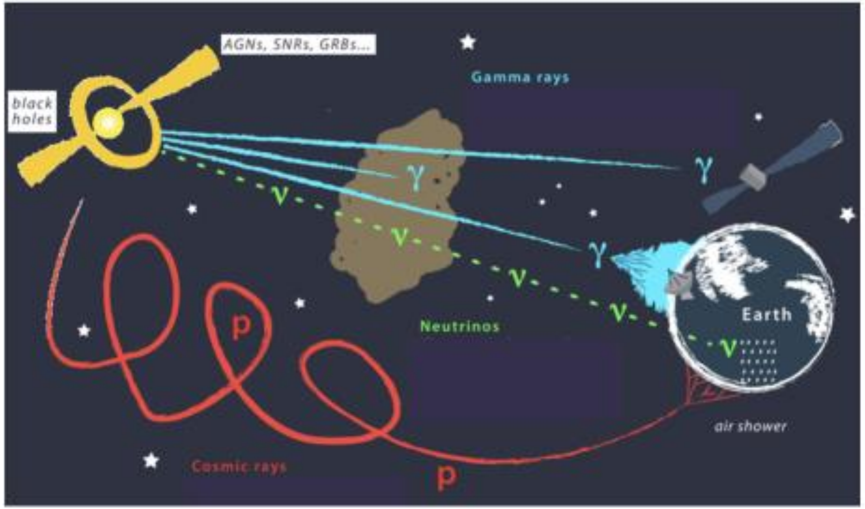
Highest altitude Imaging Cherenkov telescope in the world

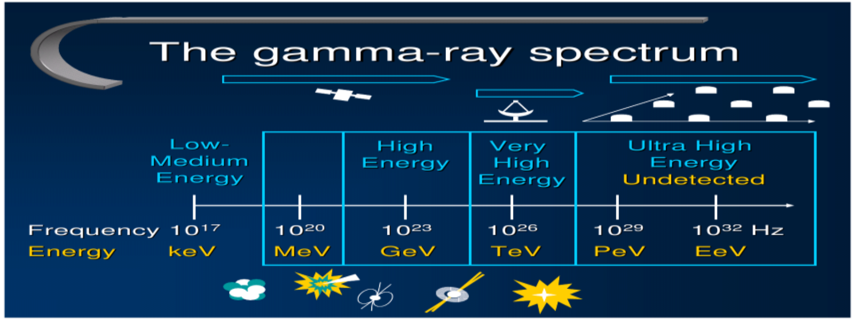
Limited time for outdoor work

Low temperature and power shortage

MACE @ Hanle : Explores gamma-ray sky E > 20 GeV

Gamma ray Astronomy





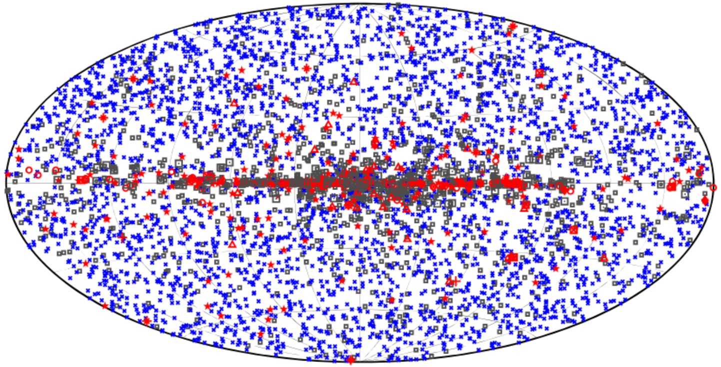
- **Gamma rays of non-thermal origin**
- **Accelerated charged particles (Cosmic Rays)**
- **Gamma Ray Astronomy – Origin of Cosmic Rays**

Detection of high energy photons

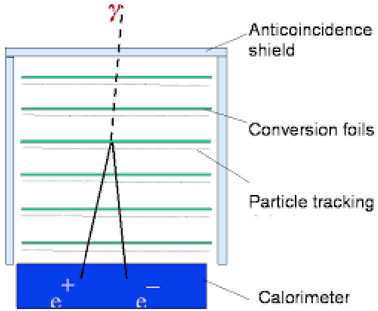
Detection Techniques

Nomenclature	Energy range	Detection Technique
High (HE)	10 *MeV* - 30 *GeV*	satellite based detectors
Very High (VHE)	30 *GeV* - 30 *TeV*	atmospheric Cherenkov detectors
Ultra high (UHE) and Extremely high (EHE)	30 *TeV* and above	air shower arrays and nitrogen fluorescence detector

Fermi-LAT
Sky-map from 4FGL catalogue



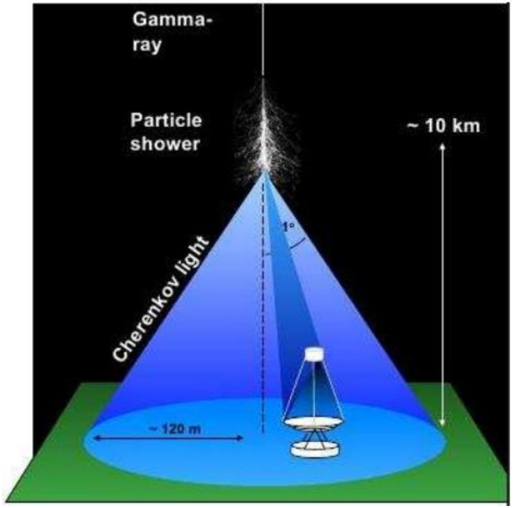
Satellite based gamma ray telescope
Fermi LAT

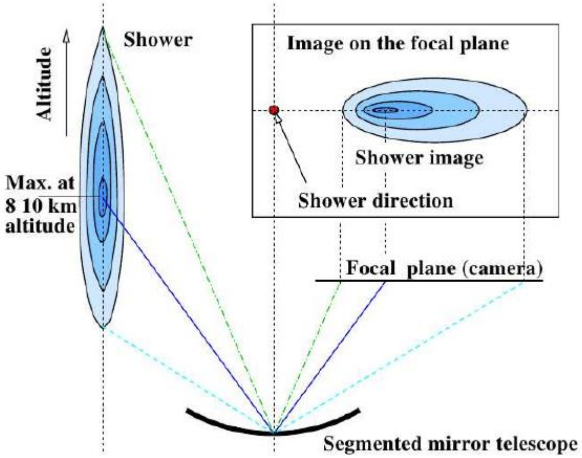


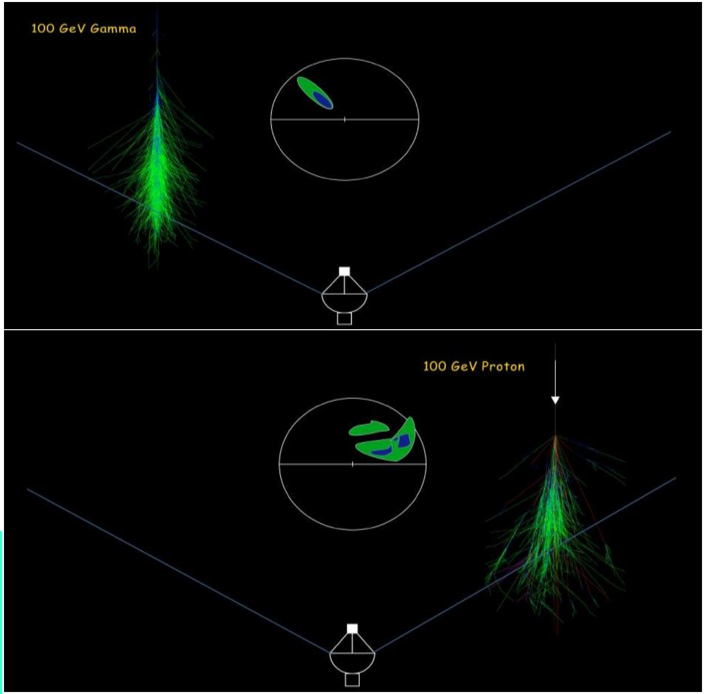
Launched in 2008 Energy: MeV-GeV
More than 7000 sources detected
Small Effective Area (~1m^2)
Power law spectra of sources
VHE showers will leak out

•**Huge detection area is necessary!**

Imaging Atmospheric Cherenkov technique







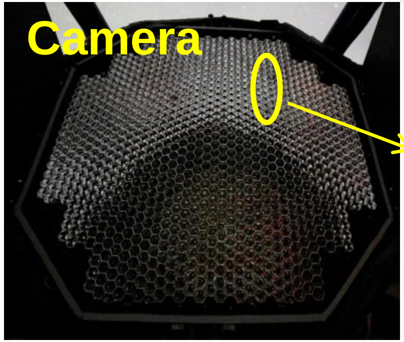
EAS-relativistic particles beamed to ground – directionality
Cherenkov radiation strongly beamed – tight time structure
Cherenkov pulse width ~5 ns & Large collection area ~10^5 m^2

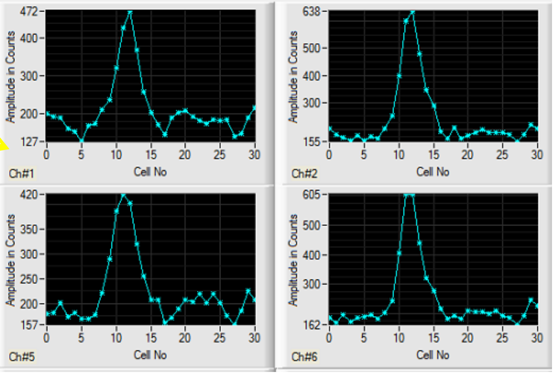
- Energy
- Arrival direction
- Nature of primary particle

Challenges !
1.Night Sky Background
2. Cosmic Rays Background

MAGIC, HESS, VERITAS, FACT, TACTIC, MACE, Cherenkov Telescope array (CTA) …

Data recording and signal estimation





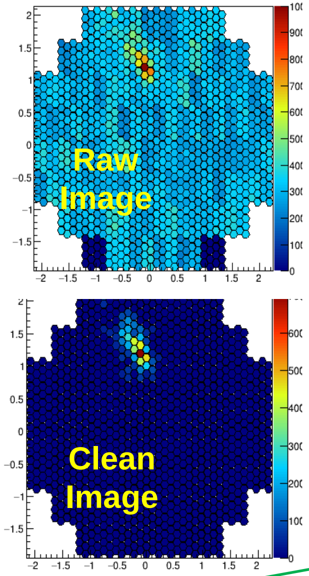
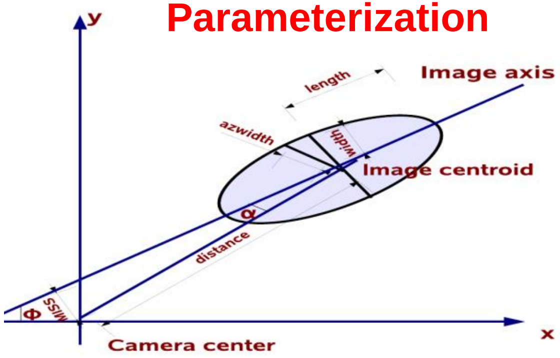
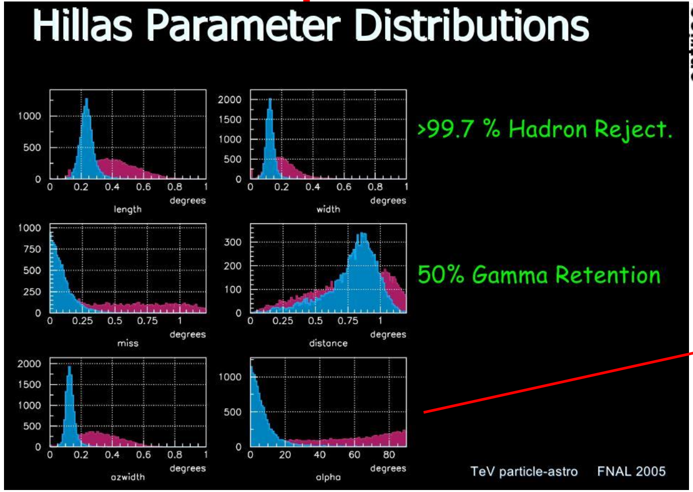
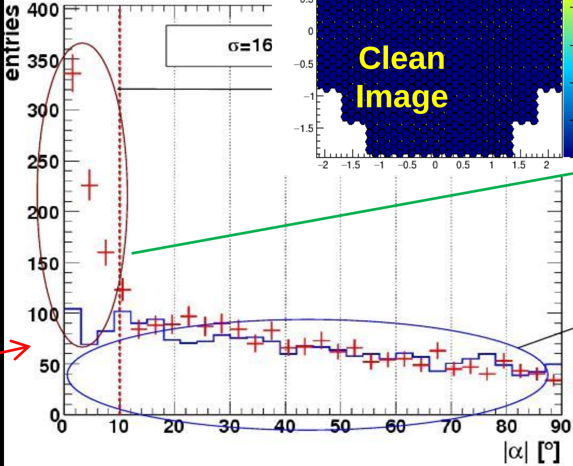


Image Parameterization



Simulation Inputs





Excess events (gamma events characterised by small alpha values)

Background events (hadronic events have a "random" Alpha distribution)

$$S_{Detection} = \frac{N_{excess}}{\sqrt{N_{bgd}}}$$

Key design parameters of an Imaging telescope

Design parameters of the telescope are dictated by the physics objective of the experiment

- ✓ Threshold Energy
- ✓ Sensitivity (Background rejection capabilities)
- ✓ Budget

✓ Budget

- Size of the telescope
- Field-of-View
- Pixel resolution
- --

Threshold Energy of the telescope

Night Sky Background

Cherenkov radiation characteristics facilitating its detection:

1. **Narrow pulse width**
2. **Limited angular extent**
3. **Nature of the spectrum**

Cosmic Ray Background

Number of γ detected from a given source in observation time T for some threshold energy E

$S = \phi_\gamma(E)\,A_\gamma(E)\,T$ where A_γ is the collection area for γ-ray detection

The background CRs recorded during the same time is given by

$B = \phi_{cr}(E)\,A_{cr}\,\Omega\,T$ where A_{cr} is the collection area for the detection of CRs of energy E.

Threshold energy

$$E_{th} \propto (1/y_\gamma)\sqrt{\frac{\phi_{LONS}\,\Omega\,\tau}{A\,R\,\eta_{pmt}}}$$

Cherenkov Photon density **Light collection area**

Flux Sensitivity: $N_\sigma \propto \frac{S}{\sqrt{B}} = \frac{C_\gamma}{\sqrt{C_{cr}}} E^{(0.85-\alpha_\gamma)} \frac{A_\gamma(E)}{\sqrt{A_{cr}(E)\Omega}} T^{1/2}$

Site: Dark sky & high Cherenkov Photon Density
Fast electronics & Better photo-detectors
Large Reflector

Typical sources are observed at minimum possible energy

Why lowest energy threshold ?

- Power law nature of sources: (F=k $E^{-\alpha}$)
  Higher photon flux at lower energies
  (Cosmic ray rejection becomes poor at these lower energies)

- Inputs from Fermi-LAT detections:
  Spectral steepening / cutoff 1GeV < E < 300 GeV

- 20-100 GeV is largely unexplored energy range

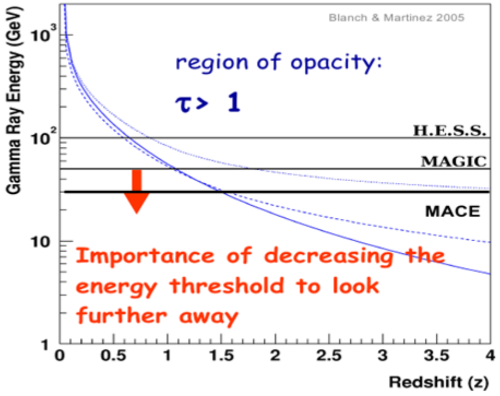
TeV γ+EBL photon -> $e^+ + e^-$

Extension of Gamma Ray Horizon

(**Objects at large cosmological distances becomes visible at lower energies)**

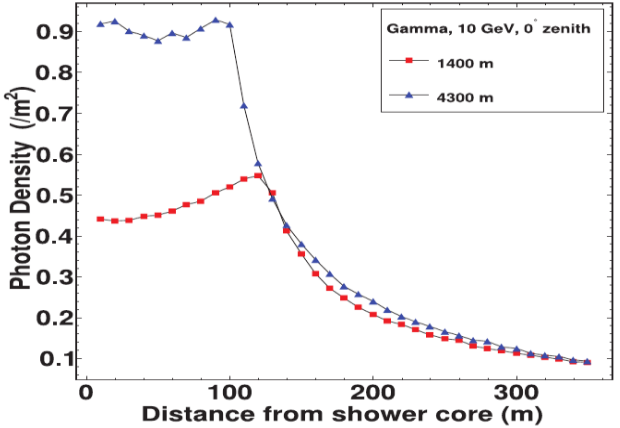
Z=0.1 (~460 Mpc) @ E_γ=1 TeV

Z=1.0 (~6600 Mpc) @ E_γ=50 GeV



MACE: Design goals

- Lower the energy threshold to **~ 20 GeV** (using all possible parameters)
  1. Observatory altitude 2. light collector area 3. appropriate pixel size 4.Fast coincidence gate width 5. Intelligent trigger generation scheme 6.CPCs ----
- Use a f# 1.2 instead of the f# 1.0 design for better PSF
- Employ GHz signal processing for better discrimination particularly at E<100 GeV (Distant AGN, Pulsars, EBL measurements..)



\+ 21m Light Collector

- Fast re-positioning of the telescope for observing high energy tails of GRBs
- Sensitivity improvement by Multi-telescope system in a phased manner

MACE-Sub-systems

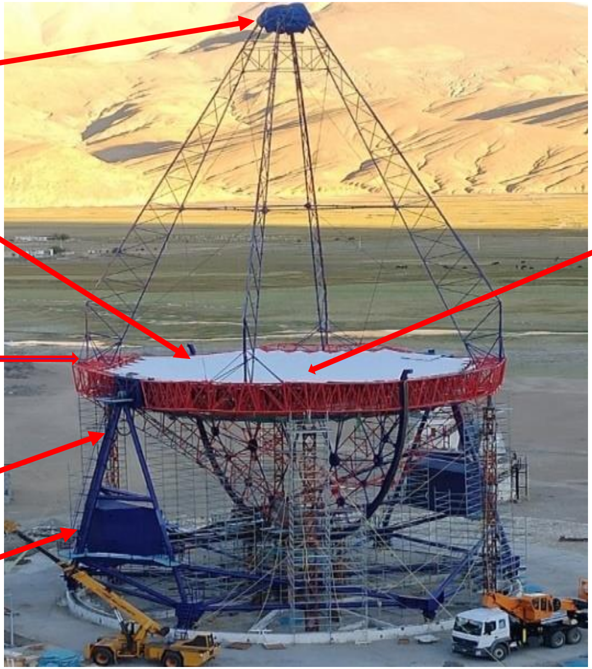
Camera Electronics

Mirror Alignment System

Sky Monitoring System

Mechanical Assembly

Telescope Control Unit



Weather Station

LED Calibration System

Control Room

Time Server

Operator Workstation

Data Archive System

DB

PS

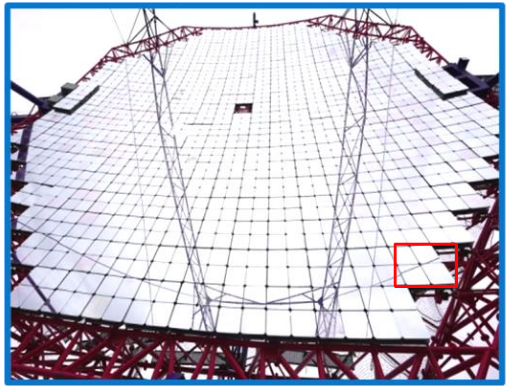
Salient features

Optics and mirror alignment system	356 panels each with **active mirror control**
Camera and signal processing system	1088 pixels, HV, GHz digitization, all signal processing electronics **within the camera**
Drive control system	Track and wheel type for azm. movement **(tracking accuracy < 1 arc-min)**
Relative and absolute gain calibration system	LEDs, SPE, calibrated PIN diodes
Timing system	GPS based
Data Acquisition and control system	LINUX based, capable of handling event rates up to 1 KHz . (data volume ~ 40 GB/ hour)
Tracking accuracy and sky condition monitoring	**CCD cameras**
Mounting	**Alt-Azimuth**

MACE- Light Collector

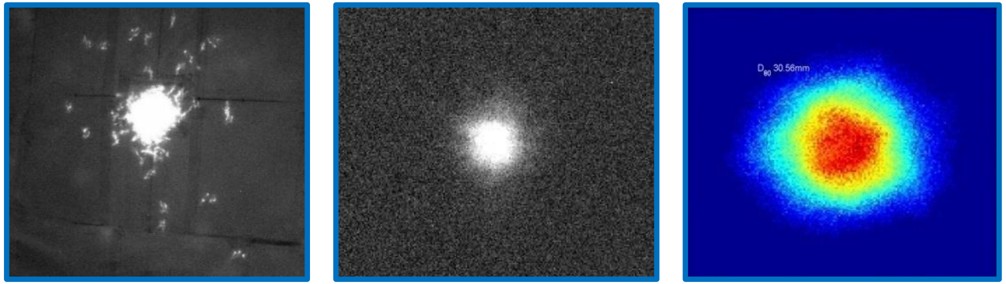
Parameter	Specification
Reflector Geometry	Parabolic Segmented
Mirror Profile	Spherical
Facet Shape	Square with chamfered corners
Facet Size	488mm x 488mm x 32mm
Number	1424
Facet Material	Al MgSi0.5 Al alloy
Radius of curvature	50.1m to 52.3m
Surface Accuracy	Diamond turned reflecting surface of λ/4 quality
Integrated Spot size at focal plane	< 50 mm diameter for an on-axis parallel beam for the full set of 356 panels.
Reflectivity	> 80%
Protection layer	Silicon dioxide layer on diamond turned surface 100 -150nm
Facet Mounting	3 point mounting

356 Mirror Panels

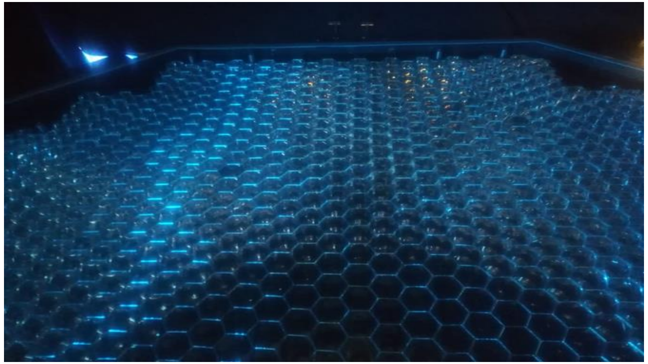


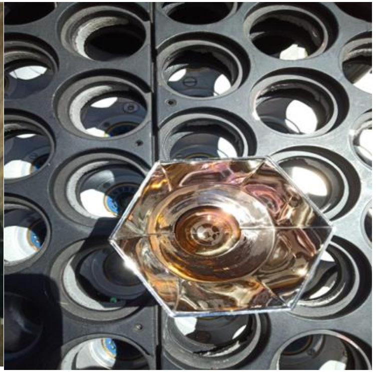
Active Mirror Control with 712 Actuators

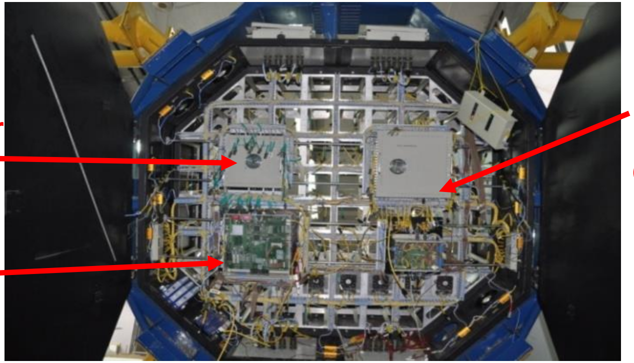
Image of pole star



MACE Camera





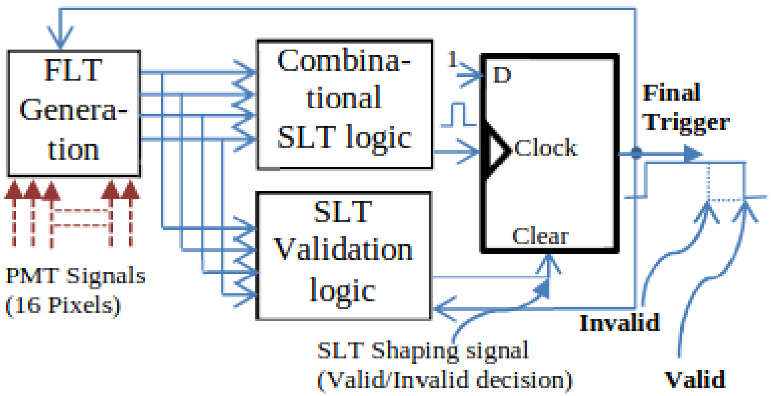


Camera : 1088-pixel PMT (CIM: 68)
Pixel resolution: 0.125º
Field of View: 4.3º x 4.0º
Dual gain channel
1 GSPS Domino Ring Sampler (DRS)
Pulse profile – 31 ns
High event rates – 1 kHz
Data Collection 50 GB/h
Camera : temperature controlled

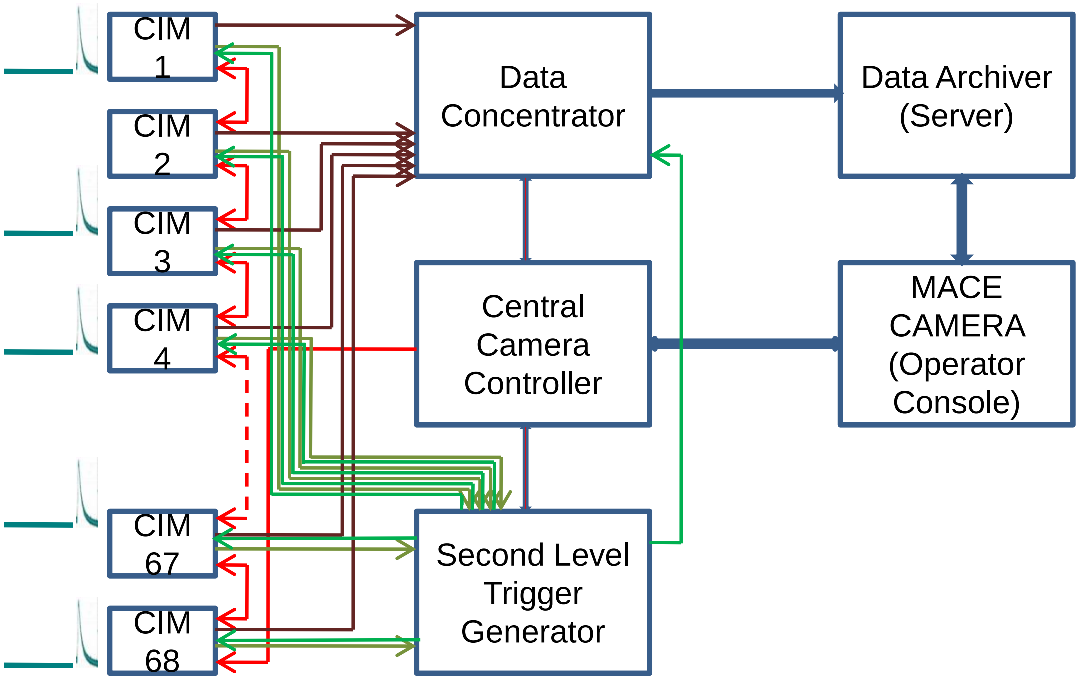
MACE- Event Data Flow

Trigger Generation

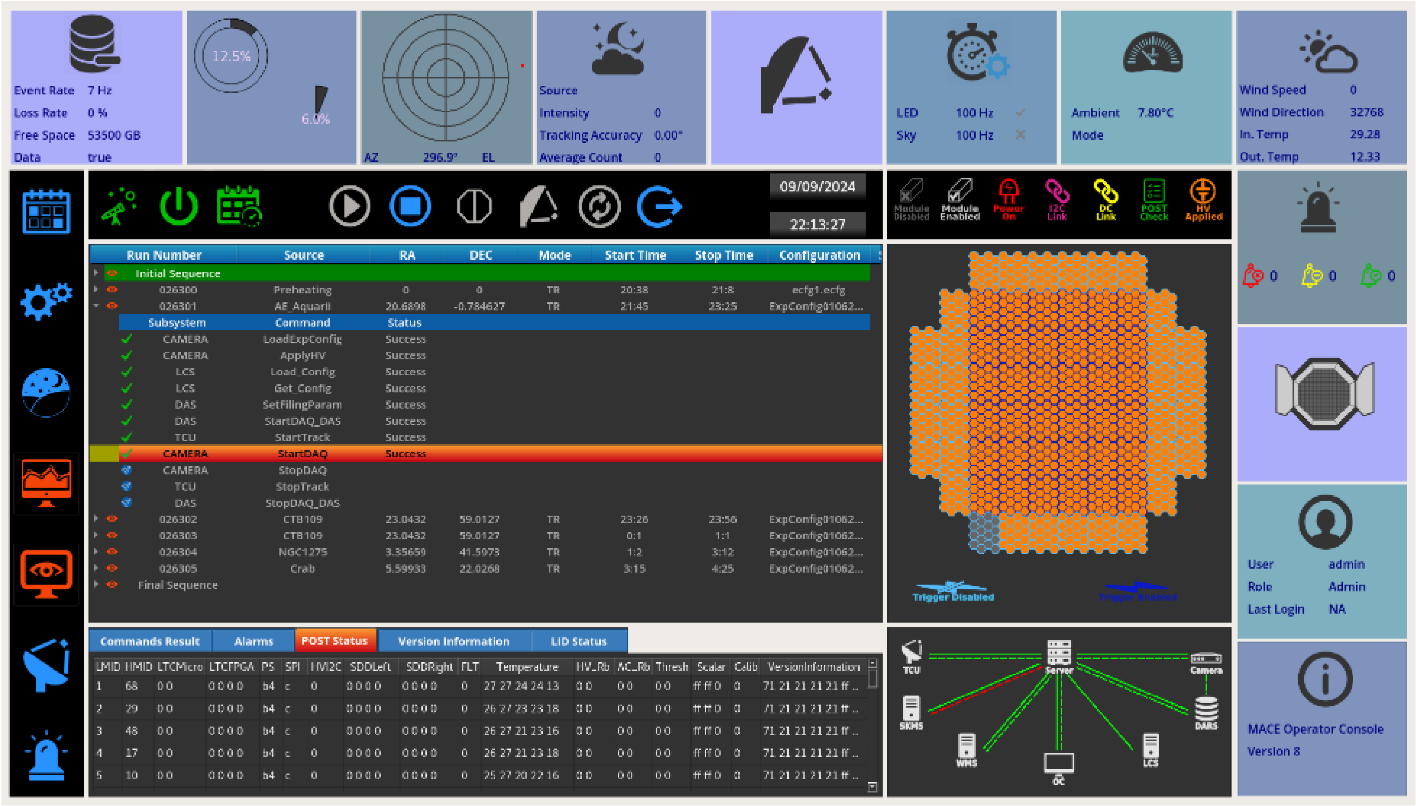
- First Level Trigger (FLT) for 16-pixel segments and a Second Level Trigger (SLT) for full camera-level validation
- Optimized timing windows (FLT~4.5 ns) and (SLT~8 ns)
- Supports programmable trigger selection for 3, 4 or 5-pixel 'next-neighbour logic'



Event Data Flow



MACE Operator Console



- Centralized control software
- Controls & monitors telescope operation
- Local and remote operation
- Parameters related to the subsystems at the top
- Monitoring widgets on the left

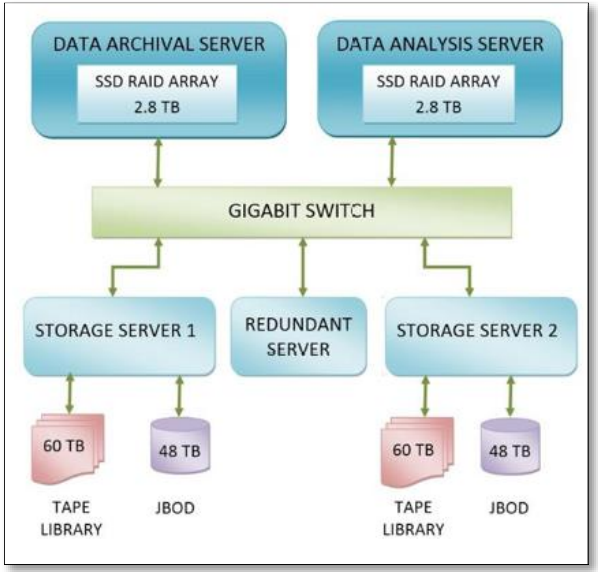
Select mode, load schedule, start, stop, abort observations runs

Data Archival System

Data Archival Hardware

- SSD at critical stage for cost optimization, hard disk & tape drive for backup, redundancy and fault tolerance
- Data Archival, Data Backup, Data Analysis
- 100TB Storage, recently upgraded to ~130 TB

Detailed Architecture



- **Data backed up at Primary storage & synced to Storage Server, BARC, Mumbai**
- **Hanle - Mumbai data transfer over dedicated leased line – 200 Mbps**

Solar Power Station

Only observatory in the world fully operating on green energy (solar) at the high altitude Himalayan desert : Operational since 2014

1343 solar Solar Voltaic panels (80W)

240 kW

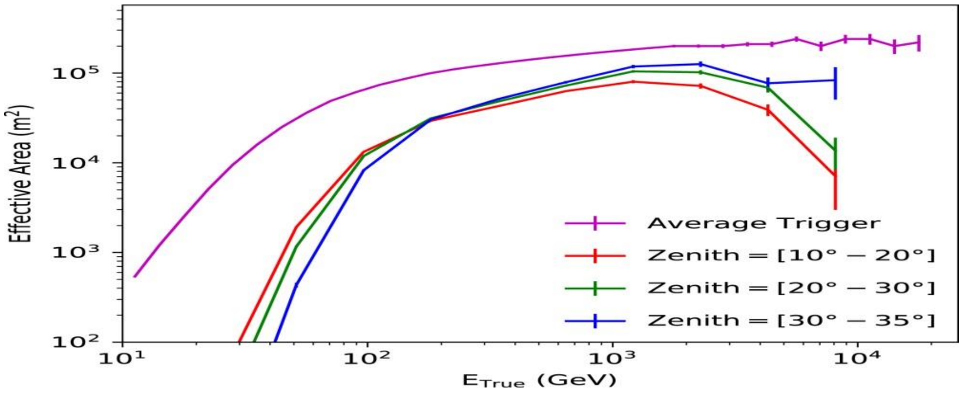
480 batteries

72hrs backup

2 DG sets

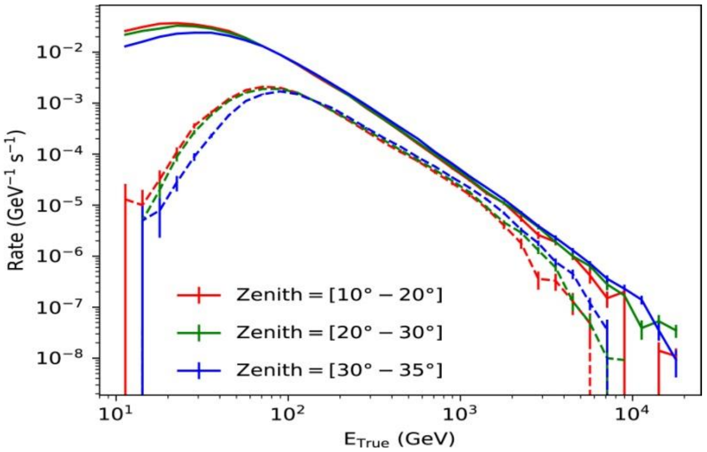
MACE: Effective area & Energy threshold

Effective Area
1. Trigger level
2. After analysis cuts



Average Area ~ 5 x 10^4 m^2

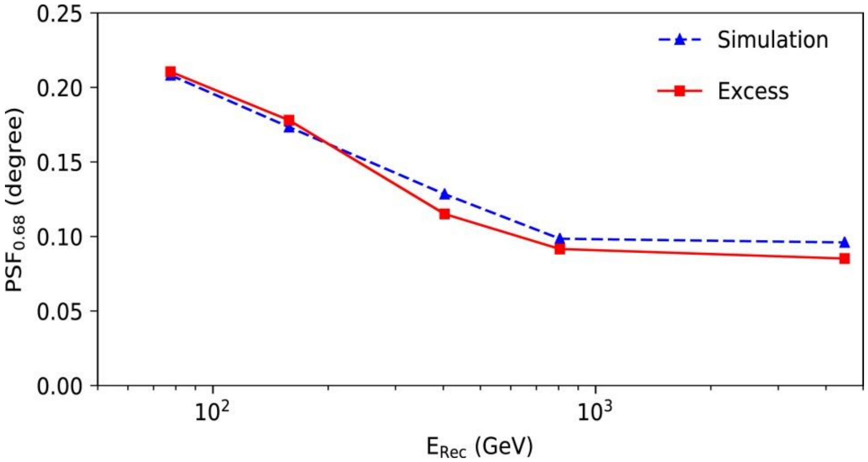
Differential gamma ray rate
1. Trigger level
2. After analysis cuts



Energy threshold ~ 80 GeV

MACE: Angular & Energy resolution

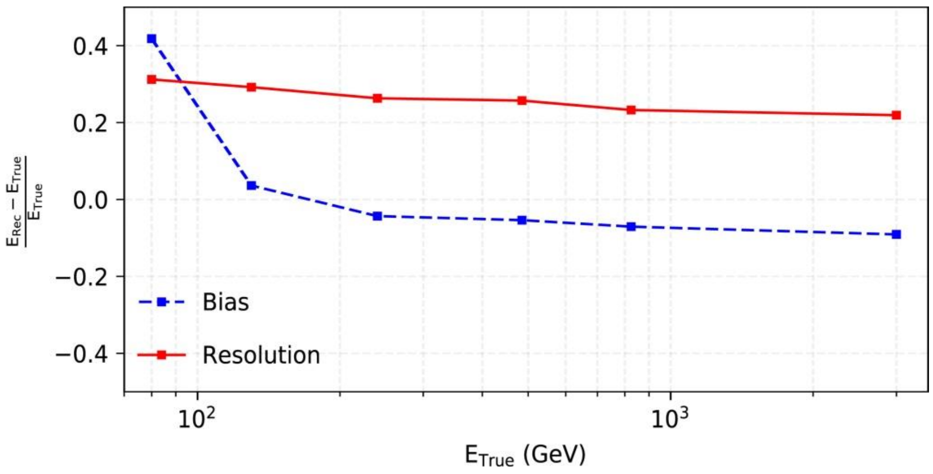
Angular Resolution



~ 0.21° near threshold energy

~ 0.10° at energies > 1 TeV

Energy Resolution

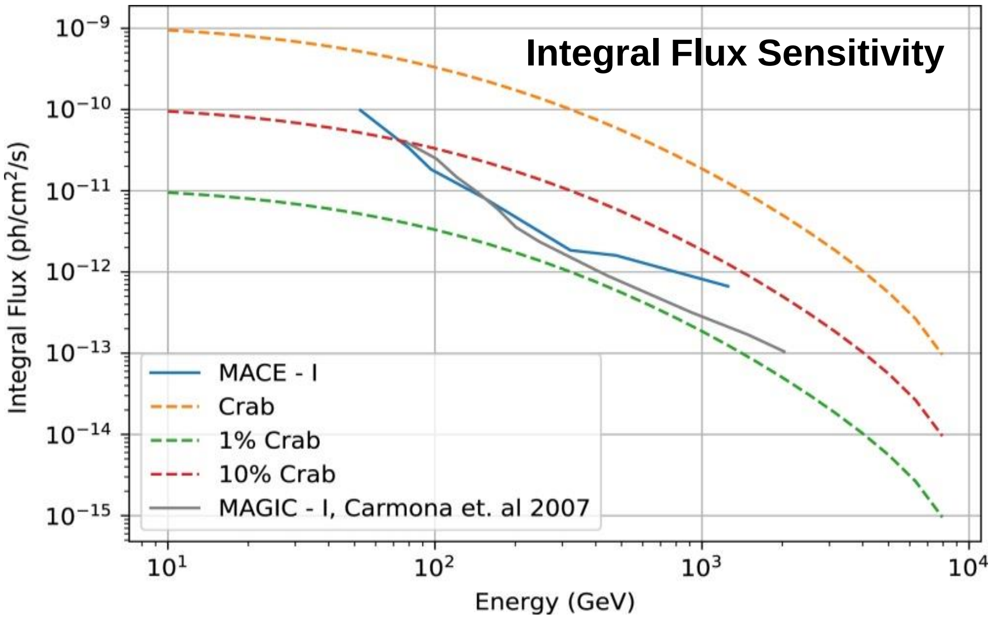


~ 34 % near threshold energy

~ 22 % at energies > 1 TeV

MACE: Flux Sensitivity

Determined by the minimum significant signal (5σ) distinguishable from CR background, in 50-h observation times



For power law spectral shape of Crab Nebula

~ 3.6%C near threshold energy

~ 1.7%C at energies ~320 GeV (best sensitivity)

For log parabola spectral shape Sensitivity ~ 10% C

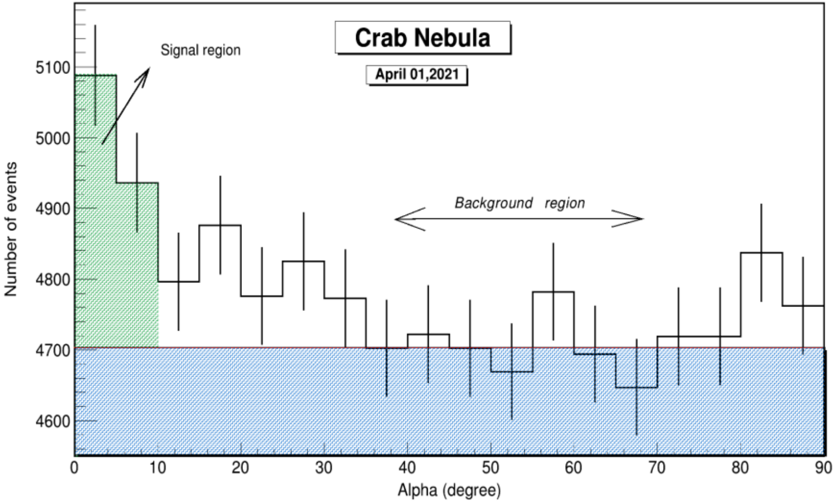
Results from first light

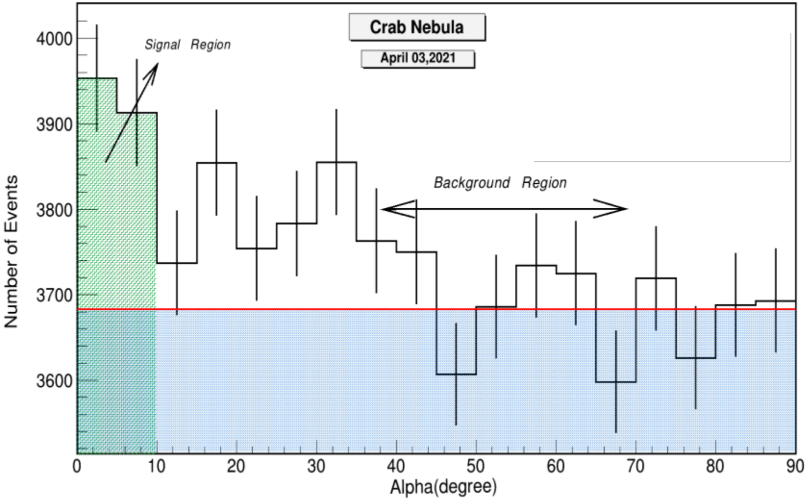
April 1, 2021

Observation time: 1 hour
Live time: 47 minutes
Events : 619±115 Significance 5.4 σ

April 3, 2021

Observation time: 1 hour
Live Time: 31 minutes
Events : 499±101 Significance 4.9 σ



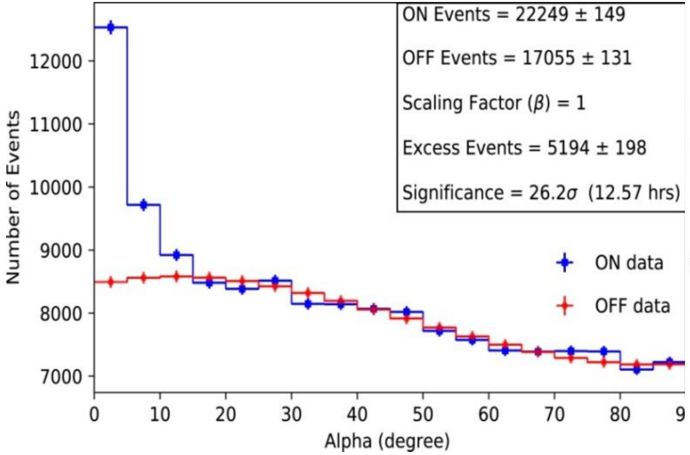


MACE detected statistically significant gamma-ray events from the Crab Nebula on individual nights

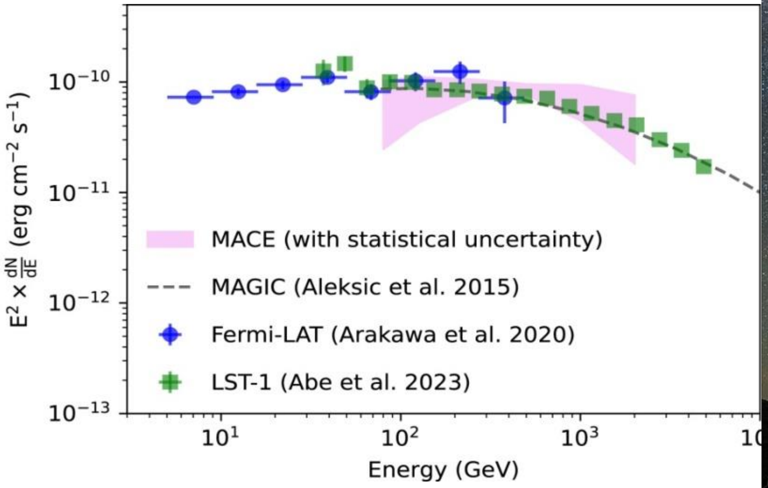
MACE was commissioned in September 2021

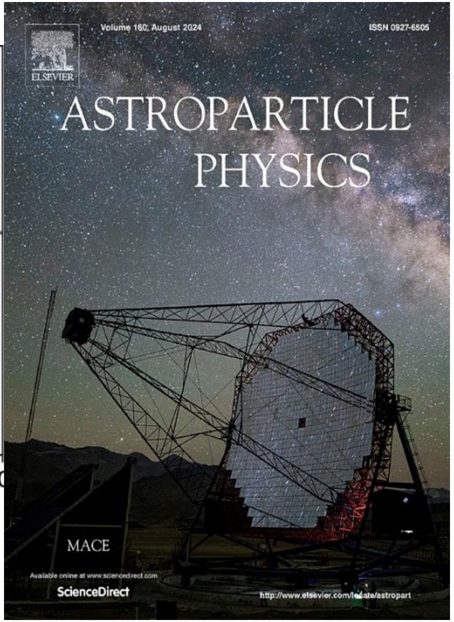
Experimental results - MACE calibration

Crab detection



Spectral Energy Distribution of Crab Nebula





Observations during Nov 2022-Feb 2023

Consistent flux through out the observation

Translate to an integral sensitivity of ~9.6%C consistent with simulated performance

SED measured with MACE is in reasonable agreement with other measurements

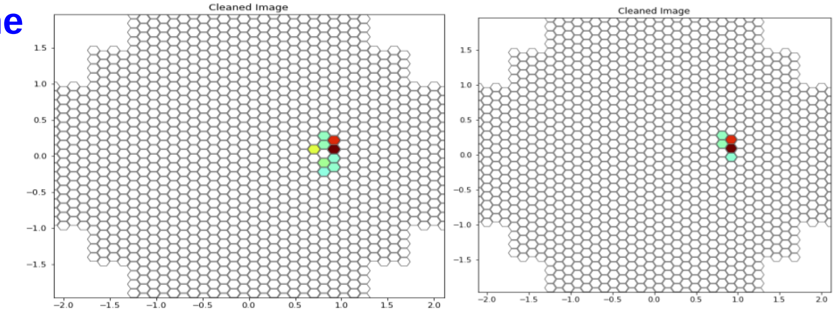
Astroparticle Physics 159 (2024) 102960

MACE Sensitivity improvement : DIOS

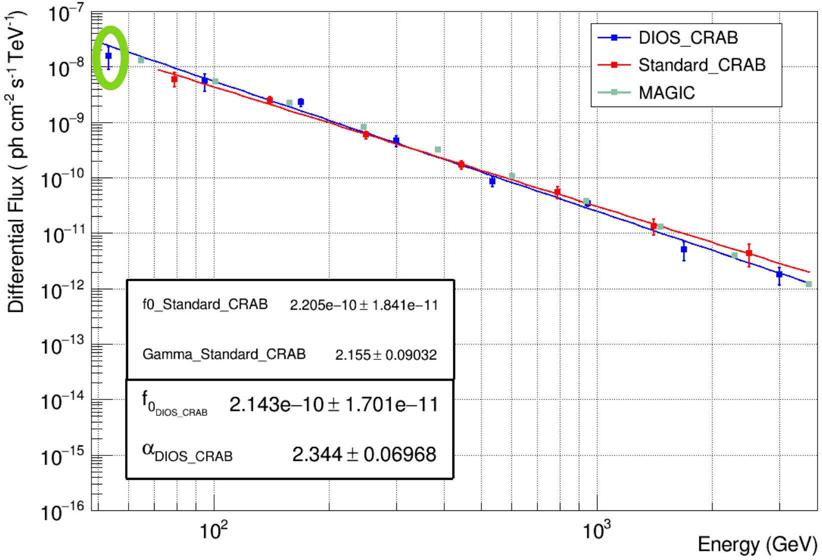
A novel method developed to achieve the lower energy threshold:

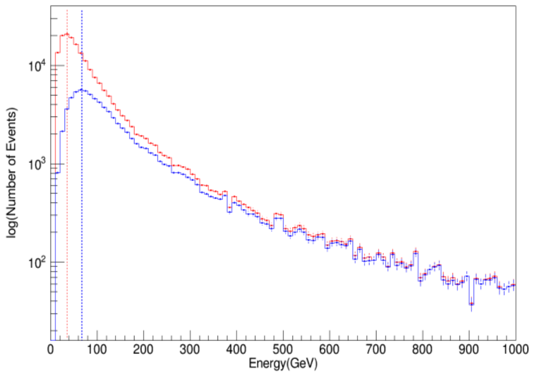
DIOS – Denoising Image Of Shower

Total Events	Standard	DIOS
423006	321275	392563
% of events Retained	76 %	93%



Sensitivity improvement ~10%C to ~7%C





Ref:

PyMAP: Python-Based Data Analysis Package with a New Image Cleaning Method to Enhance the Sensitivity of MACE Telescope

Galaxies 2025, 13, 14

P.A. Volchugov, et al. (2025) cite the DIOS method and implement this image-cleaning technique on their TAIGA-IACT telescope (located in the Republic of Buryatia, Russia) data. (Energy range > 2 TeV)

MACE Sensitivity improvement : Bayesian inference

- Conventional signal detection algorithm measures probability of getting signal given Null hypothesis is true i.e. $P(data|H_0)$ → which is not the probability of detecting the source !

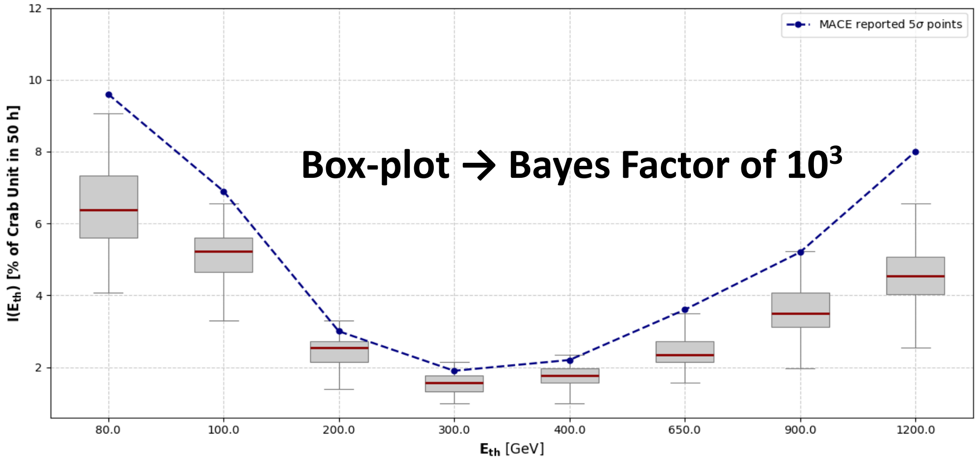
- According the Bayes theorem, in order to validate any hypothesis (Null or alternate) we must calculate $P(H|data)$, written as:

$$P(H|data) = \frac{P(data|H)P(H)}{P(data)}$$

•Integral sensitivity improves to 6.5% of Crab unit (if we use the BF=10^3, instead Li-Ma threshold significance of 5σ)

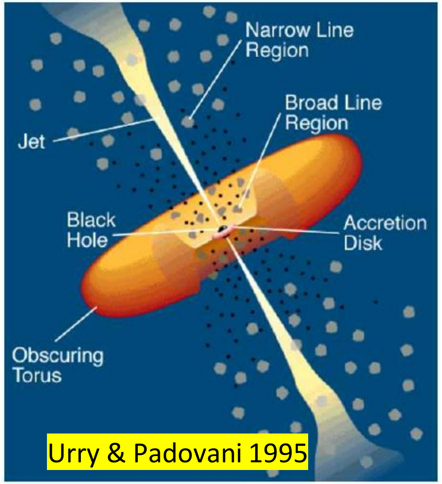
• Validated with Crab Nebula observation data 2022-23

(Manuscript prepared)



Science with MACE

- **Extragalactic**
  - **AGN:** Study of emission mechanism in different classes
  - **VHE Propagation:** EBL, IGMF, ALPs, red-shift determination
  - **Dark Matter:** Gamma-ray signals from dark matter annihilation
  - **GRBs:** From collapsing massive stars and neutron star mergers



- **Galactic**
  - **PeVatrons:** Study of extreme particle accelerators in milkyway
  - **Transients:** Emission from microquasars, magnetars, novae..
  - **SNRs/PWNe:** Particle acceleration at SN shells and pulsar winds
  - **Pulsars:** Pulsed radiation from Neutron star magnetospheres

MACE- General observation strategy

System Calibration

- Dark patch/ off source, pointing observations
- Crab Nebula observations

Extragalactic observations

- Nearby AGNs (TACTIC and MACE)
- IBLs, Radio-galaxies
- High/un-known red-shift sources
- Dark Matter candidates

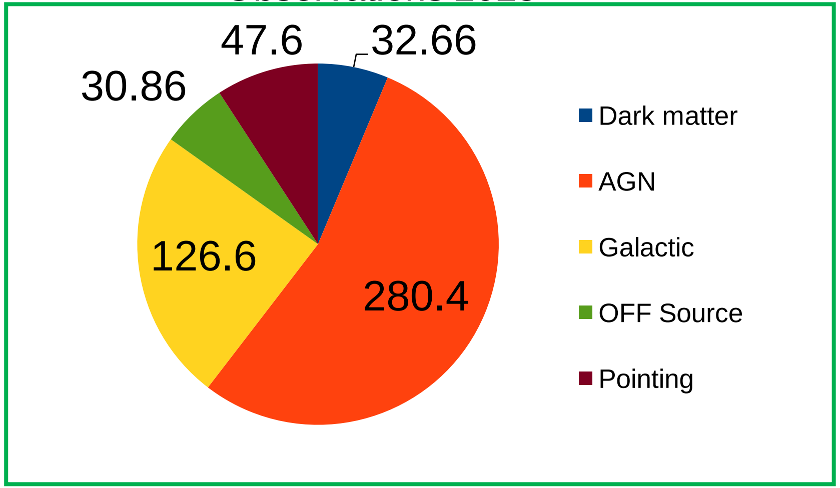
Galactic observations

- SNR (CTB 109, W 51), Pulsars
- LHAASO sources

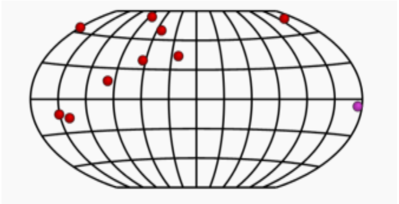
Alerts

- ATel – a short notice publication service to alert fellow-astronomers, based on radio-VHE observations and Multi-messenger instruments
- Gamma-ray (Fermi-LAT) and VHE alerts are more relevant to us

Observations 2025



MACE: Science Achievements



- Continuous Science data collection for more than 1500 hours so far.
- Successful first light in 2021 with the detection of signal from standard candle Crab Nebula. [Astroparticle Physics 159 (2024) 102960]
- Constraints on the jet viewing angle below 30^o from the detection of episodic flaring activity of the radio galaxy NGC 1275 in 2022 and 2023.
  [Astrophysical Journal Letters 974 (2024) L31]
- Maiden upper limits on the very high energy emission from two blazars among the six high redshift blazars.
  [Journal of High Energy Astrophysics 45 (2025) 241-249]
- Capturing the very high energy signal from the most ancient blazar OP 313 on Jan 26, 2025.
  [Astronomer's Telegram # 17003]
- Broadband emission study of a nearby blazar Mrk 501 observed with MACE during June-July 2022.
  [Astroparticle Physics 175 (2026) 103188]
- Search for gamma-ray signal from dark matter interactions.
  [Galaxies 13 (2025) 53]

MACE: A National Facility

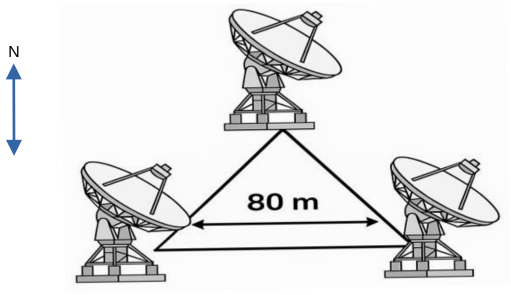
Unique experimental facility for High Energy Astrophysics Research in India

- **Formal inauguration on 4th October 2024.**
- **Proposals from Indian Institutes being invited.**
- **Already part of WEBT international collaboration for multi-wavelength observation of astrophysical sources.**
- **Participating instrument in the proposal for a multi-messenger campaign of gravitational events from binary-neutron star merger.**

Proceedings of the Indian National Science Academy (2025)

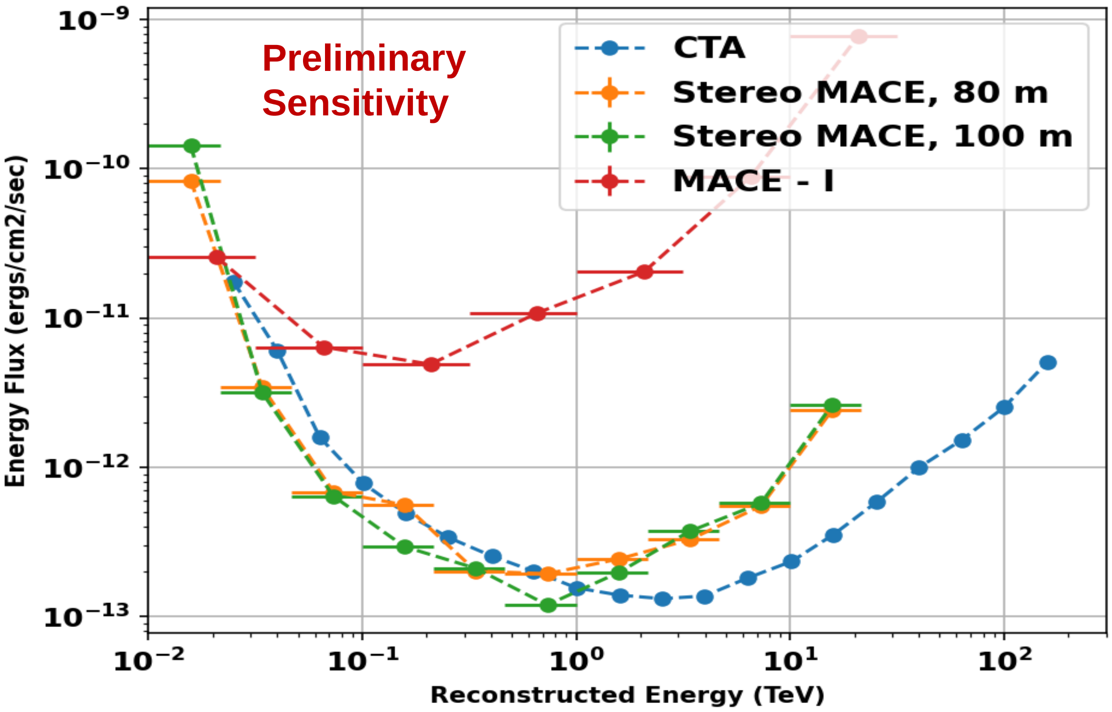
Future plan- Stereo MACE System

Creating a state-of-the-art world class VHE gamma-ray observatory @ Hanle, Ladakh

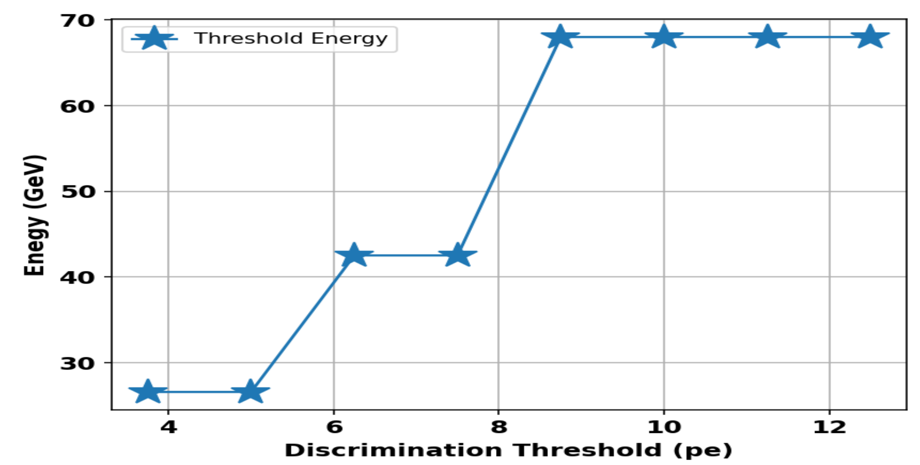


- **Two layout with separation 100 m and 80 m considered.**
- **Trigger combination of at least two telescopes.**
- **Threshold of 6.25 photo-electron.**
- **Energy Threshold of ~ 40 GeV**
- **Integral flux sensitivity of 0.6 % Crab (Improvement of factor 6)**

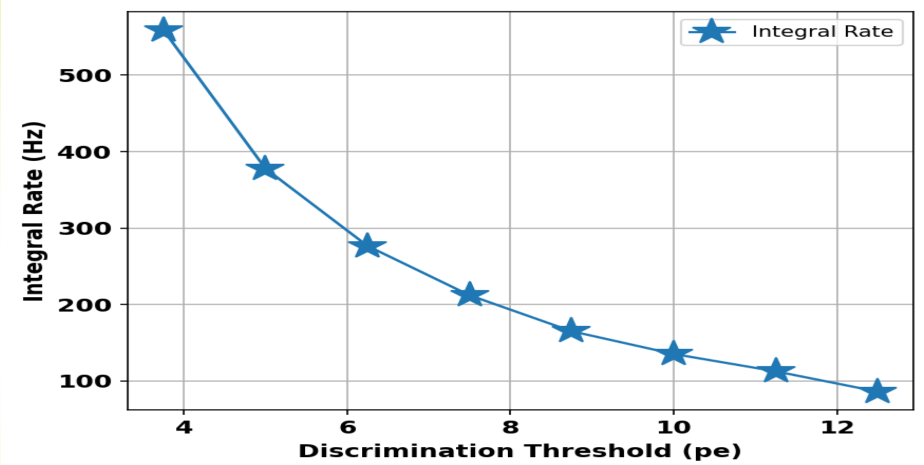
- ✓ **Improved flux sensitivity**
- ✓ **Better energy & angular resolutions**



Stereo MACE- Preliminary Estimates



Energy Threshold v/s Discrimination Threshold with trigger multiplicity of at least 2 telescopes.



Integral Trigger Rate vs Discrimination Threshold with trigger multiplicity of at least 2 telescopes.

Detailed simulations are underway…..

Thank you