Pevatrons with CTAO Study of the Boomerang SNR in the LST-1 era

Dr Gabriel Emery, Post-doc at CPPM

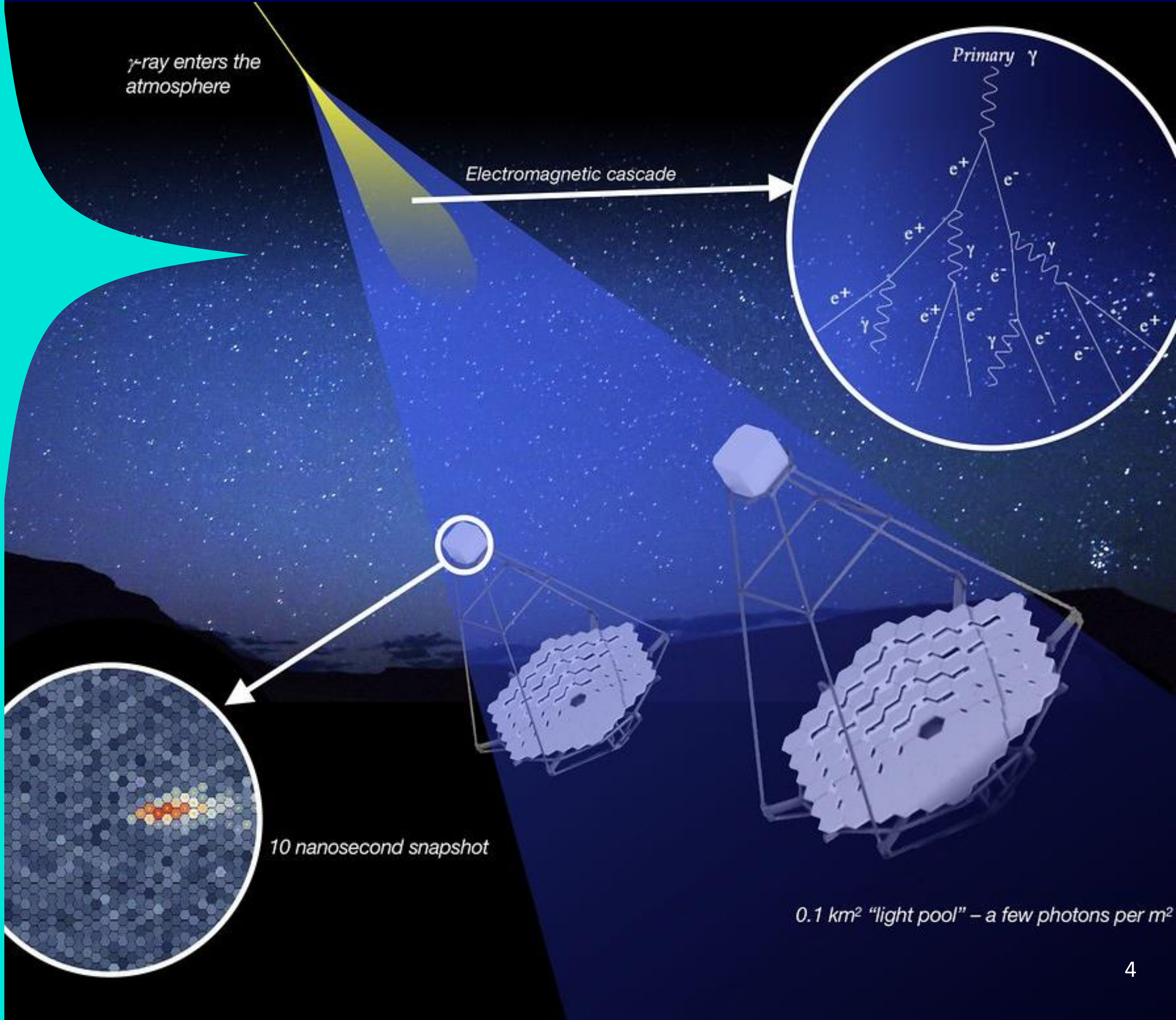
CTAO

1
CTAO

IACTs

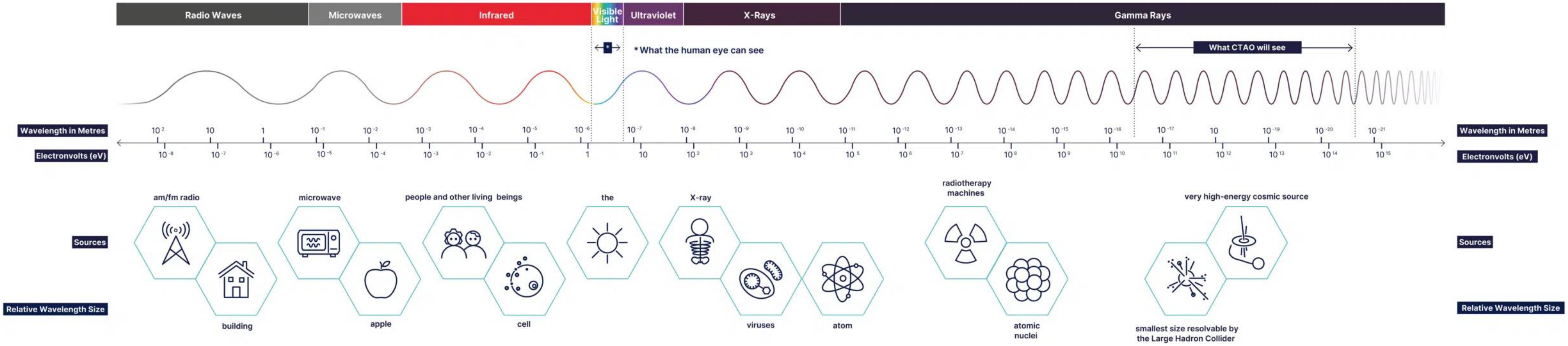
Imaging Atmospheric Cherenkov Telescopes

- VHE Gamma-ray telescopes
  - Very High Energy : O(TeV)
  - Indirect detection
    - Large effective detection area O($10^{5-6}m^2$)
- Extensive air shower
  - Primary photon or cosmic ray interacts
  - Particle cascades
  - Superluminal > Cherenkov light
- Intensity and extension of the light pool increase with the primary energy
- Better in arrays



Very High Energies?

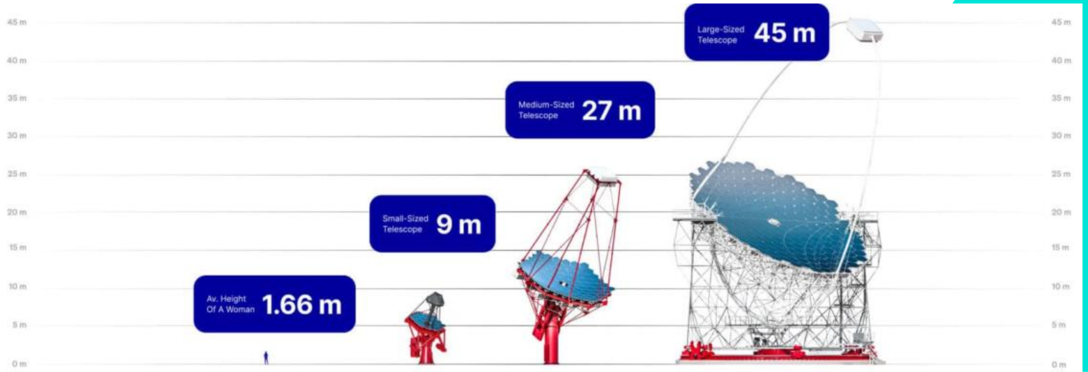
1 TeV = 2 millions electrons mass = 1000 protons mass



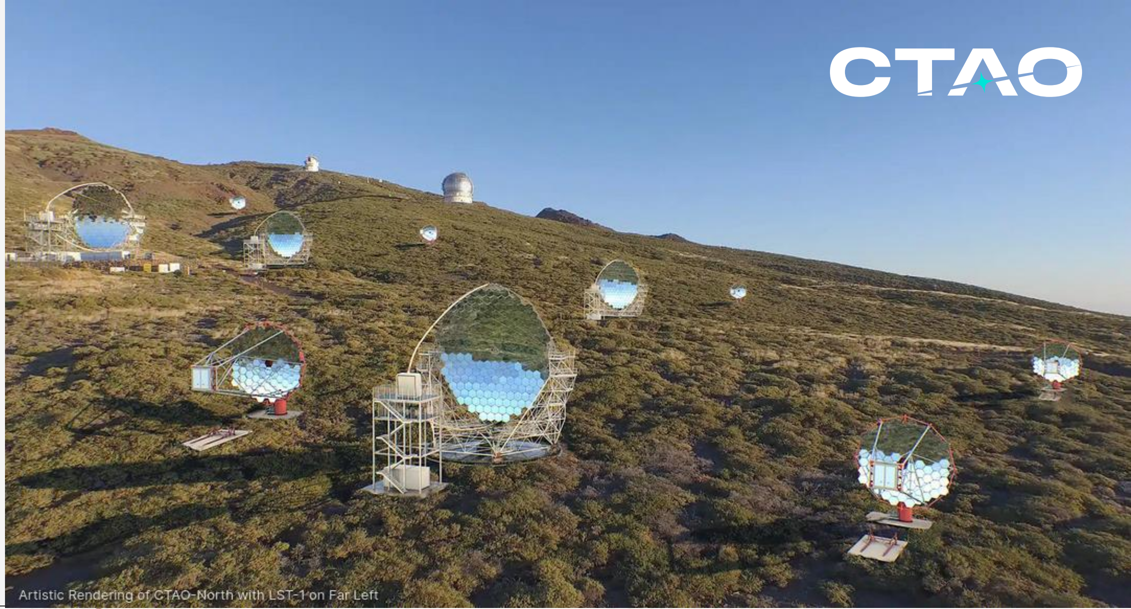
What is CTAO?

The Cherenkov Telescope Array Observatory

- The CTAO is the next generation of very high energy photon observatories
- Two hybrid IACT arrays : 3 types of telescopes
    - LSTs : Large Size Telescopes sensitive down to ~20 GeV
    - MSTs: Medium Size Telescopes, most sensitive in the multi-TeV
    - SSTs: Small Size Telescopes sensitive up to 300 TeV
- Observatory > Observation time is open



Northern Site



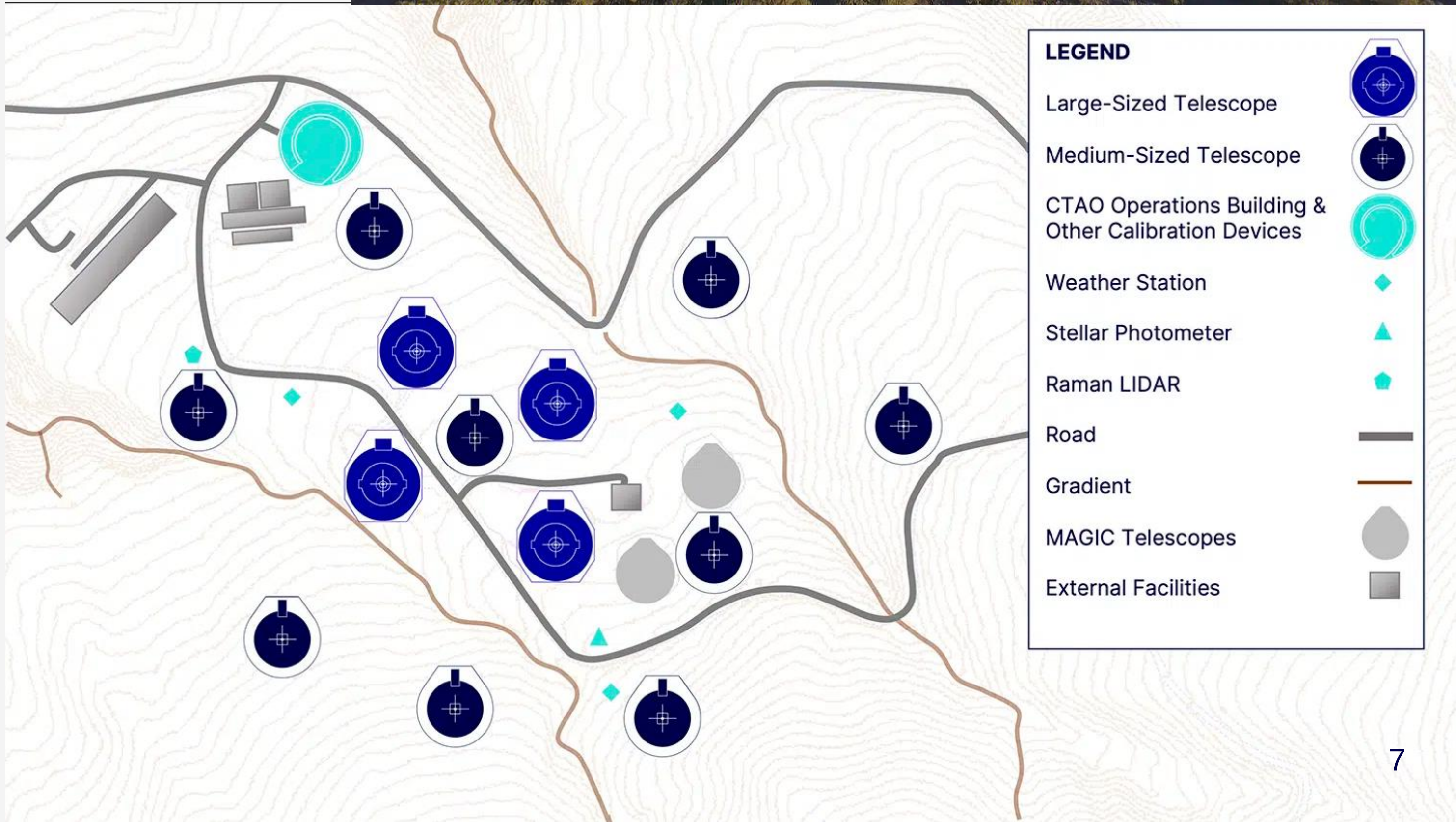
La palma Island

Located in the observatory de la Roque de los Muchacos (ORM)

Plan : 4 LSTs, 9 MSTs

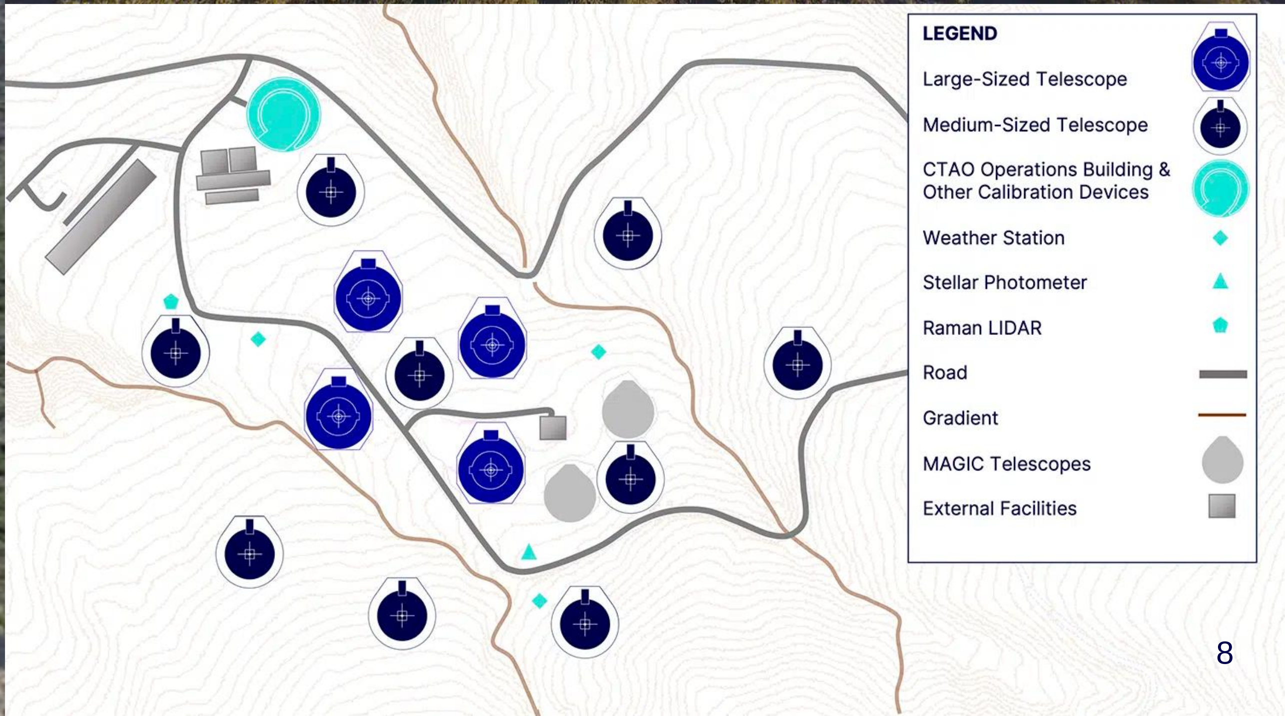
Currently : LST-1 + 3 LSTs ongoing

E range : 20 GeV to 5 TeV



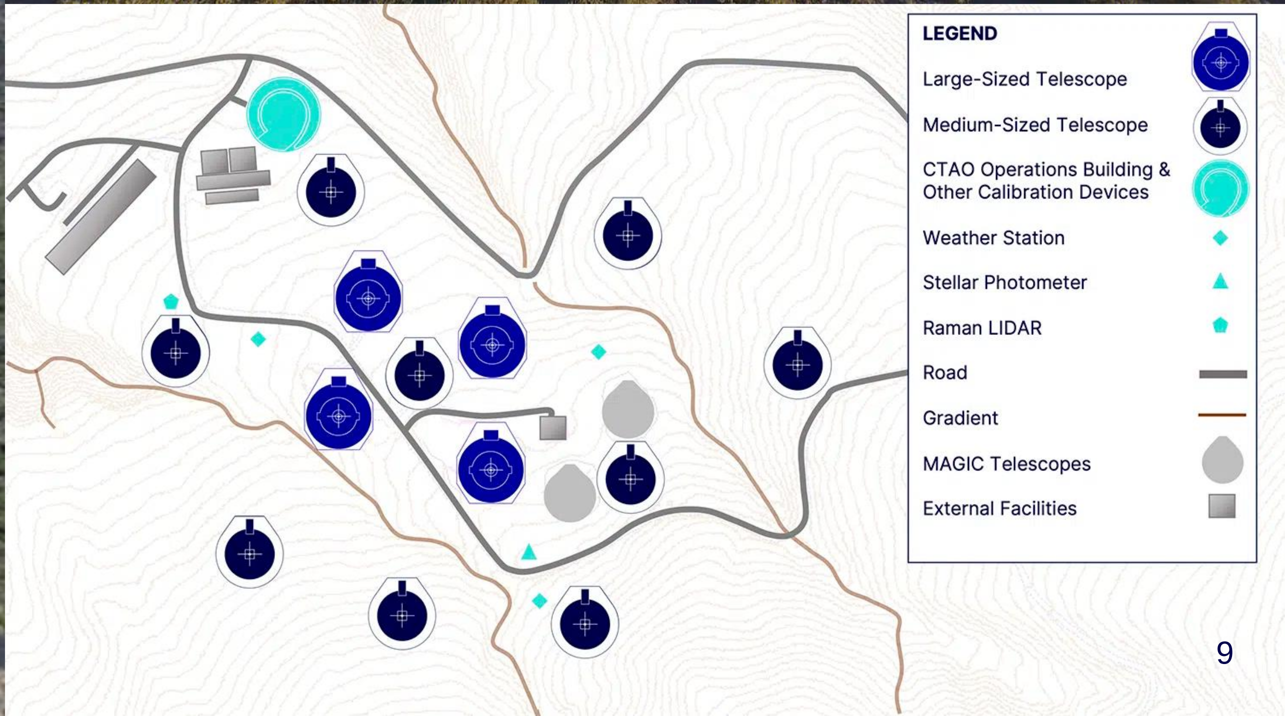
Northern Site

La palma Island – current



Northern Site

La palma Island – current



Southern Site

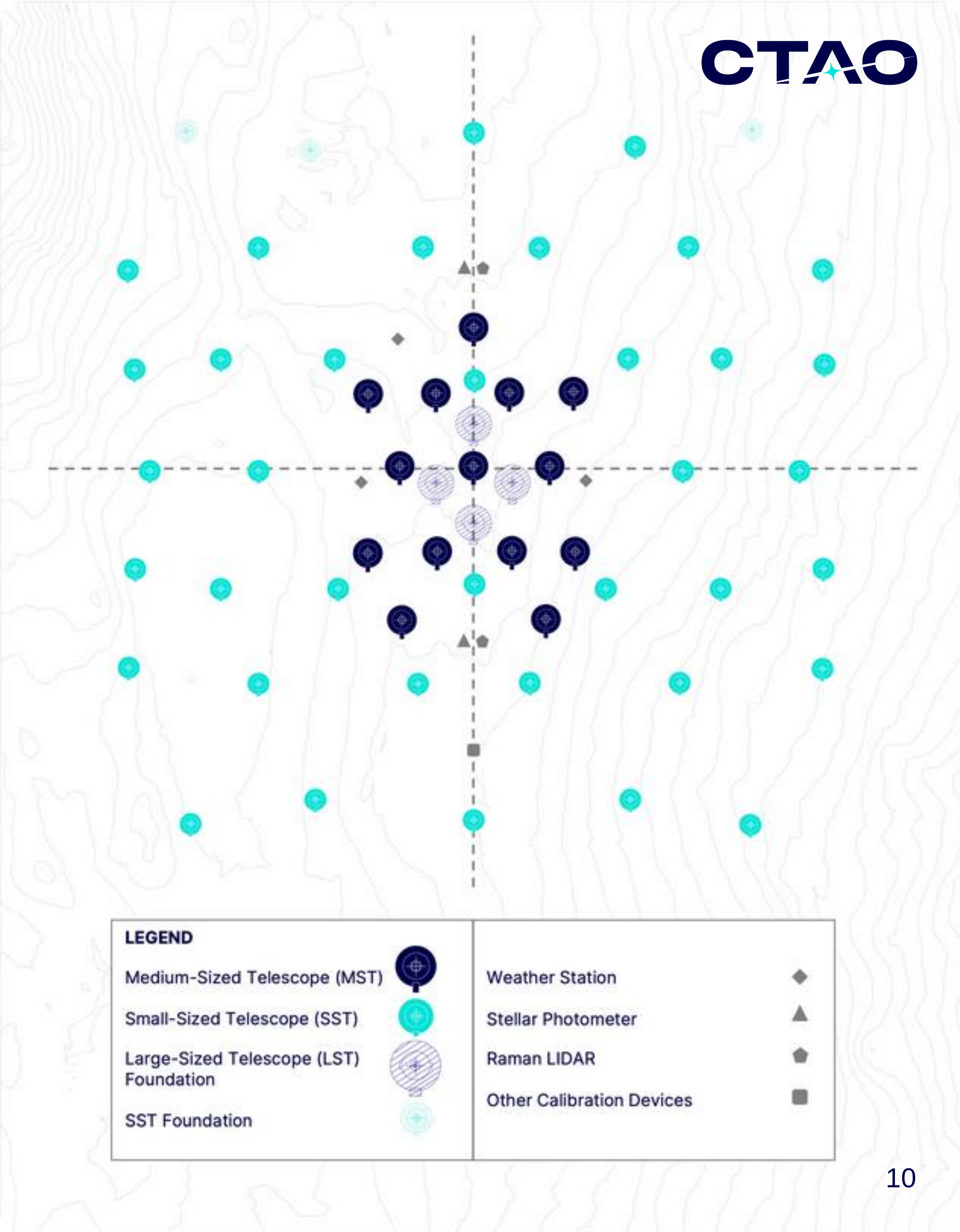
Paranal, Chile

Location : Chile’s Atacama Desert

Plan : 14 MSTs, 37 SSTs
(+2 LSTs, 5 SSTs)

Currently : Access road + infrastructure plans

E range : 150 GeV to 300 TeV



Status of CTAO

The light at the end of the tunnel

- A new visual identity

cta cherenkov telescope array → CTAO

- North site, LST construction ongoing

20 May : "Northern Hemisphere Array Begins to Take Shape with Installation of LST-4 Dish Structure"

Science with CTA

CTAO Consortium and open time

Once the observatory officially starts taking data, observation time will be divided between:

- Time dedicated to "key science projects" defined by the scientific consortium
  - Long term projects requiring long data taking such as galactic and extra-galactic source catalogues, dark matter searches, PeVatron searches, …
- Time open to proposals (public or limited to specific groups) evaluated regularly for the next observation periods

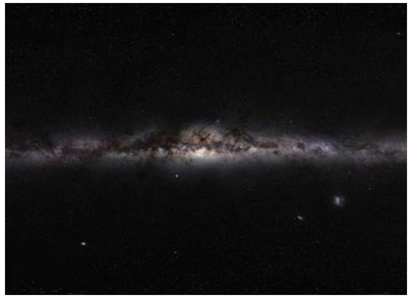
Science with CTA

Some sources

Gamma Ray Bursts

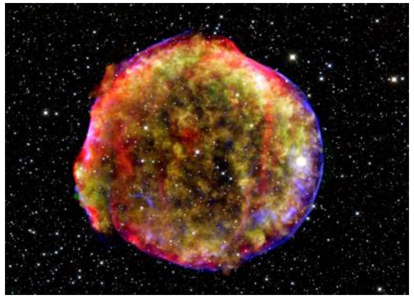
Active Galactic Nuclei

Star Forming regions



Galactic Center

Supernova remnants



Pulsars

2
LST-1

CTAO

LST

Fast, precise, sensitive

LSTs are designed to be sensitive to very faint signals from multi-GeV photons

- 400 m^2 mirrors
- 1855 PMTs camera

LST designed for fast transient follow-up

- 100 tonnes
- Fast repointing ~ 30 seconds

credit: Tomohiro Inada

LST

Data acquisition

Event rates : 5-10 kHz

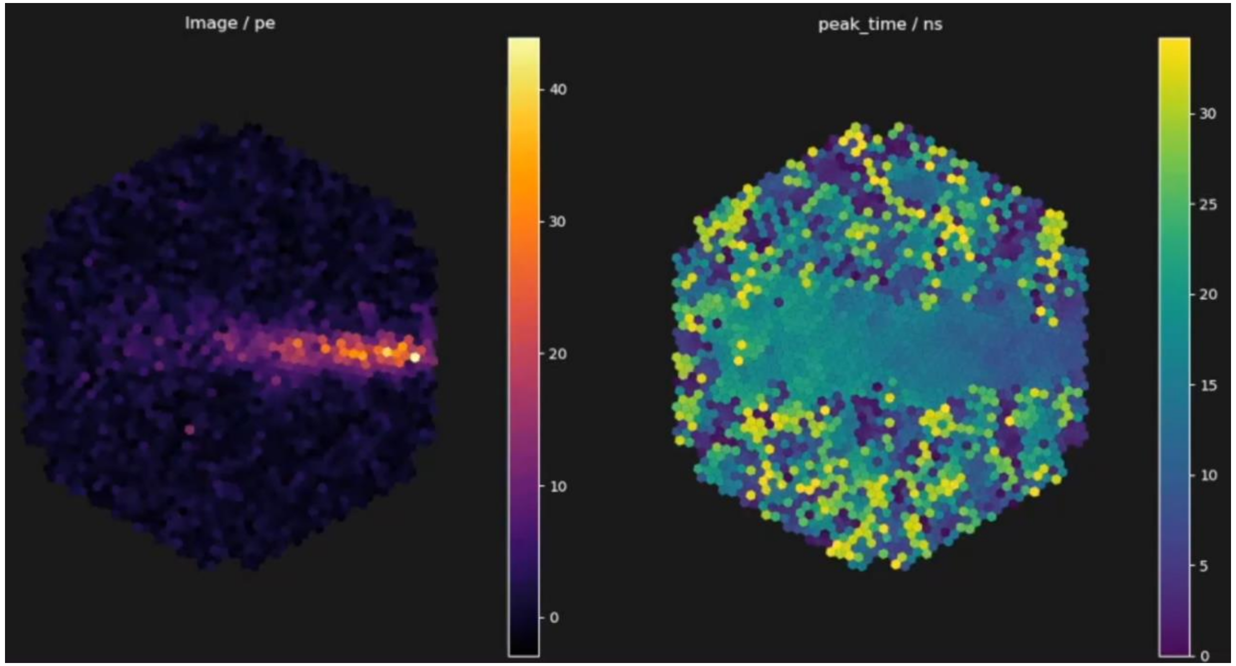
Event raw data : waveforms with 40 samples/pixel

Event builder developped at CPPM
(also for the MST NectarCam)

PMTs sensitive to single photons

Sub-nanosecond timing

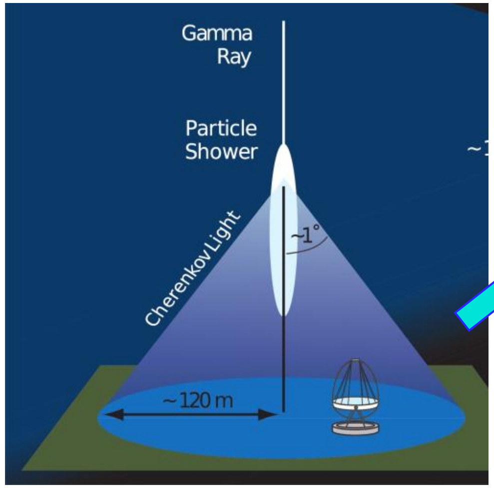
Calibration developped at CPPM



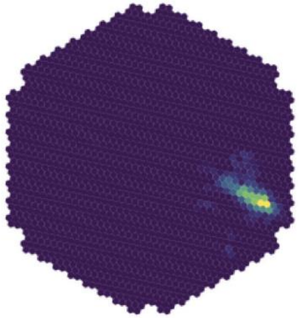
Charge and timing used in the subsequent event reconstruction

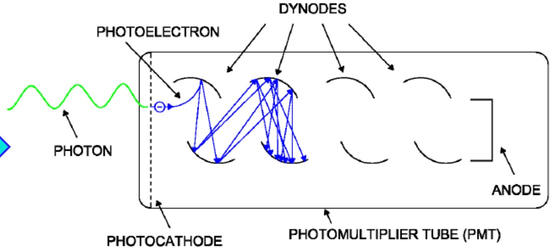
Camera calibration

Gamma-ray event

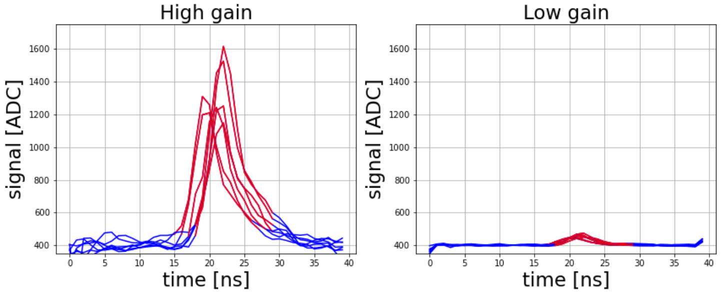


LST-1 Camera = 1855 PMTs

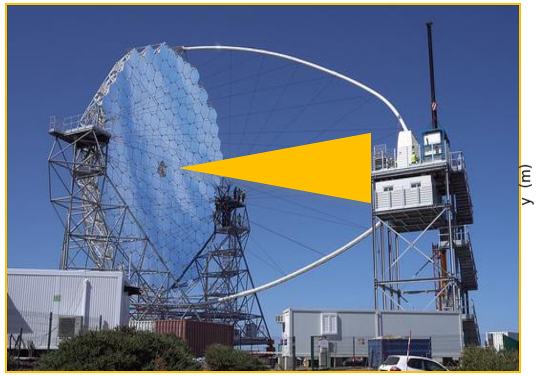


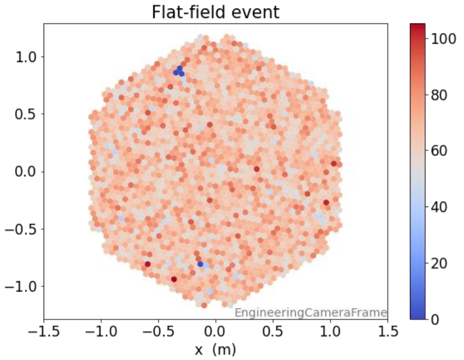


PMT signals are in ADC and two gains

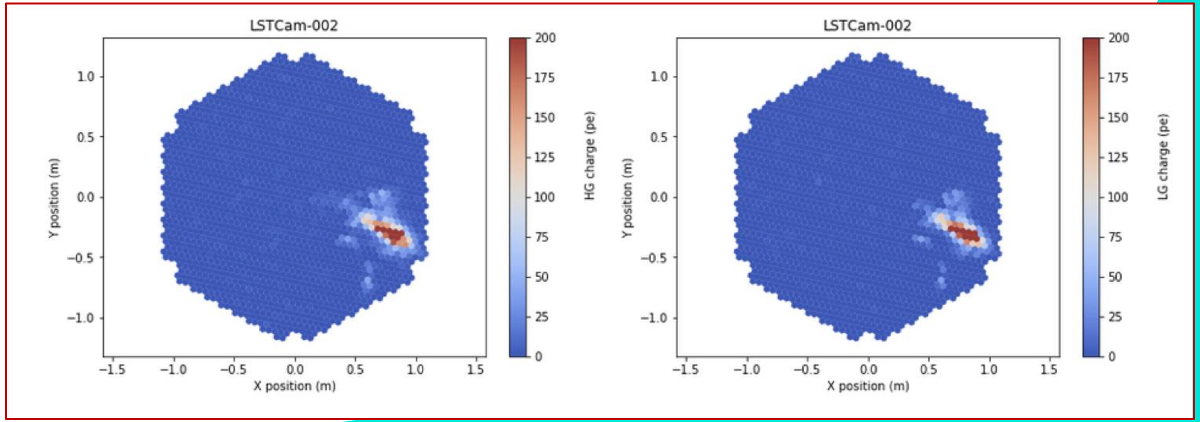


Calibration converts signals from ADC to photoelectrons units (pe). It is based on the analysis of laser events that illuminate uniformly the camera. Machine learning algorithms permit then to estimate the energy of the gamma-ray events from the shower image in pe.





High and low gain calibrated images in pe units



CTA-North Event Builder

How to adapt 265 Gb/s into 40 Gb/s using off the shelves material

Camera : 1855 pixels > 265 modules > 265Gb/s

Data : 5 kHz with 1855 pixels and 40 ~1ns samples

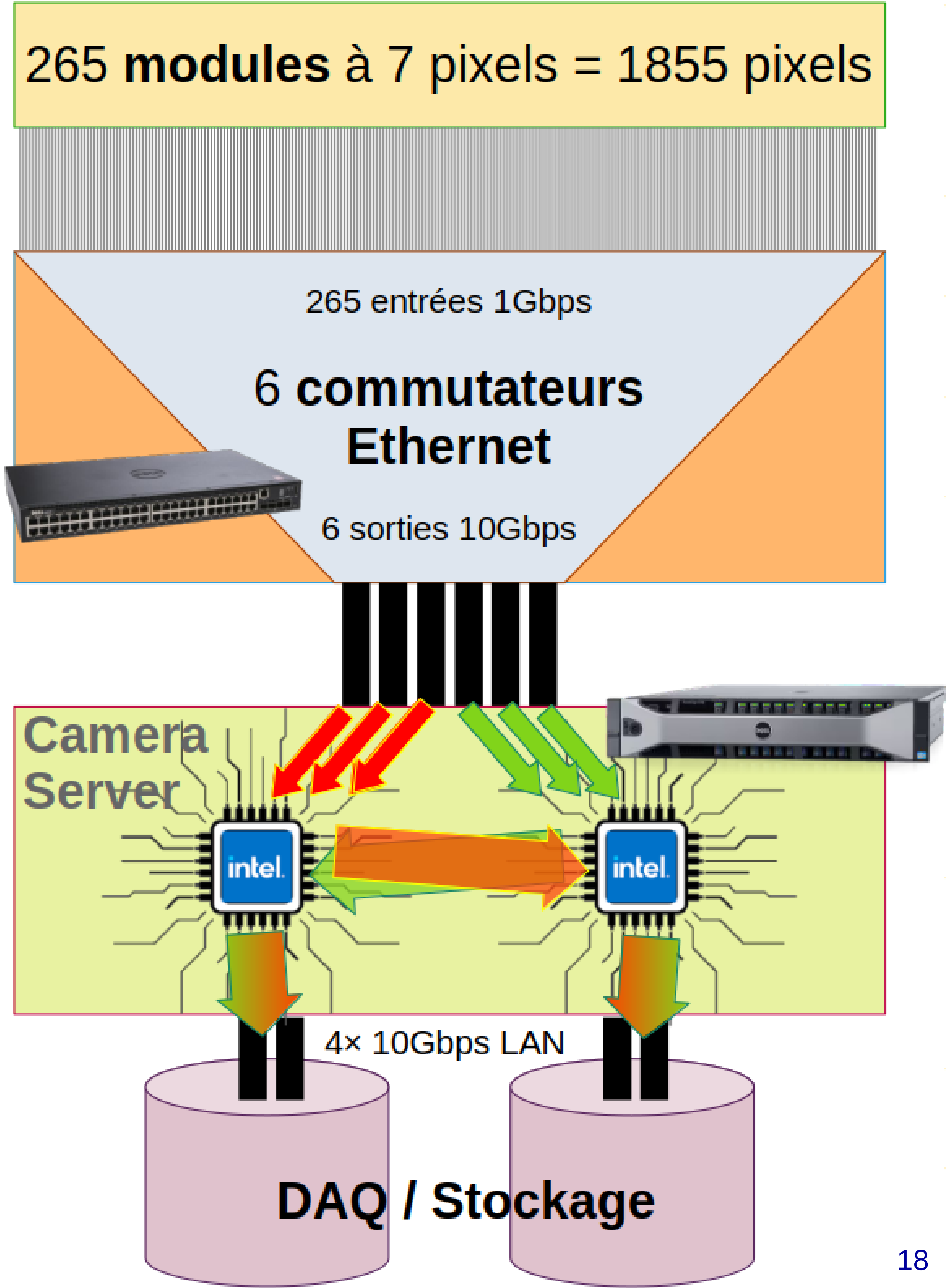
Cost and maintenance : use standard hardware and protocols

Goals : reliable handling of 8h/night of data on a bi-processor, 40 cores computer.

Pre-processing and online calibration

Timeline :

2015 : 1er EVB MST-NectarCam
2016 : 10 modules MST-N
2017 : 19 Modules LST-CAM
2018 : LST-1, ORM (La Palma)
2019 : 1/4-NectarCam, Adlershof (Berlin)
2023 : NectarCam integration, IRFU (Saclay)
2024 : LST 2-4 integration, IACTEC (Ténerife)
2025 : LST 2-4, ORM
2026+ MST 1-9, ORM



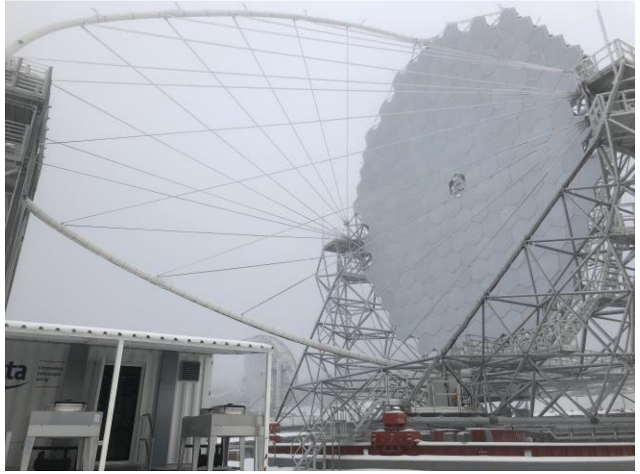
The first LST

Testbench and first science

- Inaugurated on October 10th, 2018
- Commissioning and first science by the LST collaboration
- Extensive work on improving hardware and software

  Valuable experience and groundwork for future LSTs + CTAO
- Now mature for high impact science > competitive with other IACTs
  and lower energy threshold

e.g. circulated in the CPPM/CNRS news :
Une première observation prometteuse pour le grand télescope de l'observatoire CTA



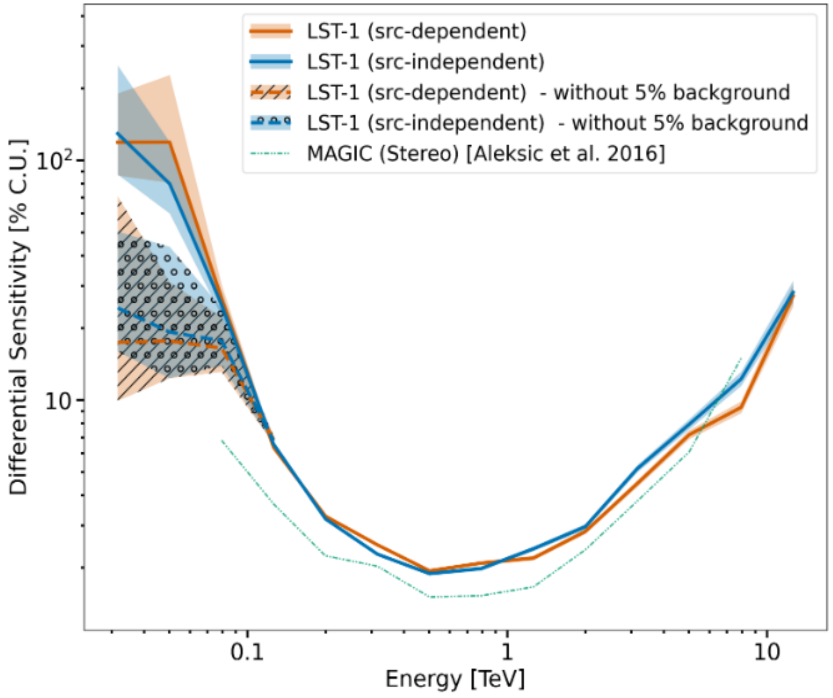
credit: Tomohiro Inada

Early science

An accelerating project

We now are at a time with :

- Mostly stable systems
- Fully working analysis pipeline
- Performant calibration
- Less time required for tests



LST-1 sensitivity from H. Abe et al 2023 ApJ 956 80

It allows for significant science focused activities:

- Hundreds of hours of data taking per year
- Galactic, extra-galactic, transients, fundamental physics projects

Performance papers, for both LST-1 standalone and combined with the neighbors MAGIC published.

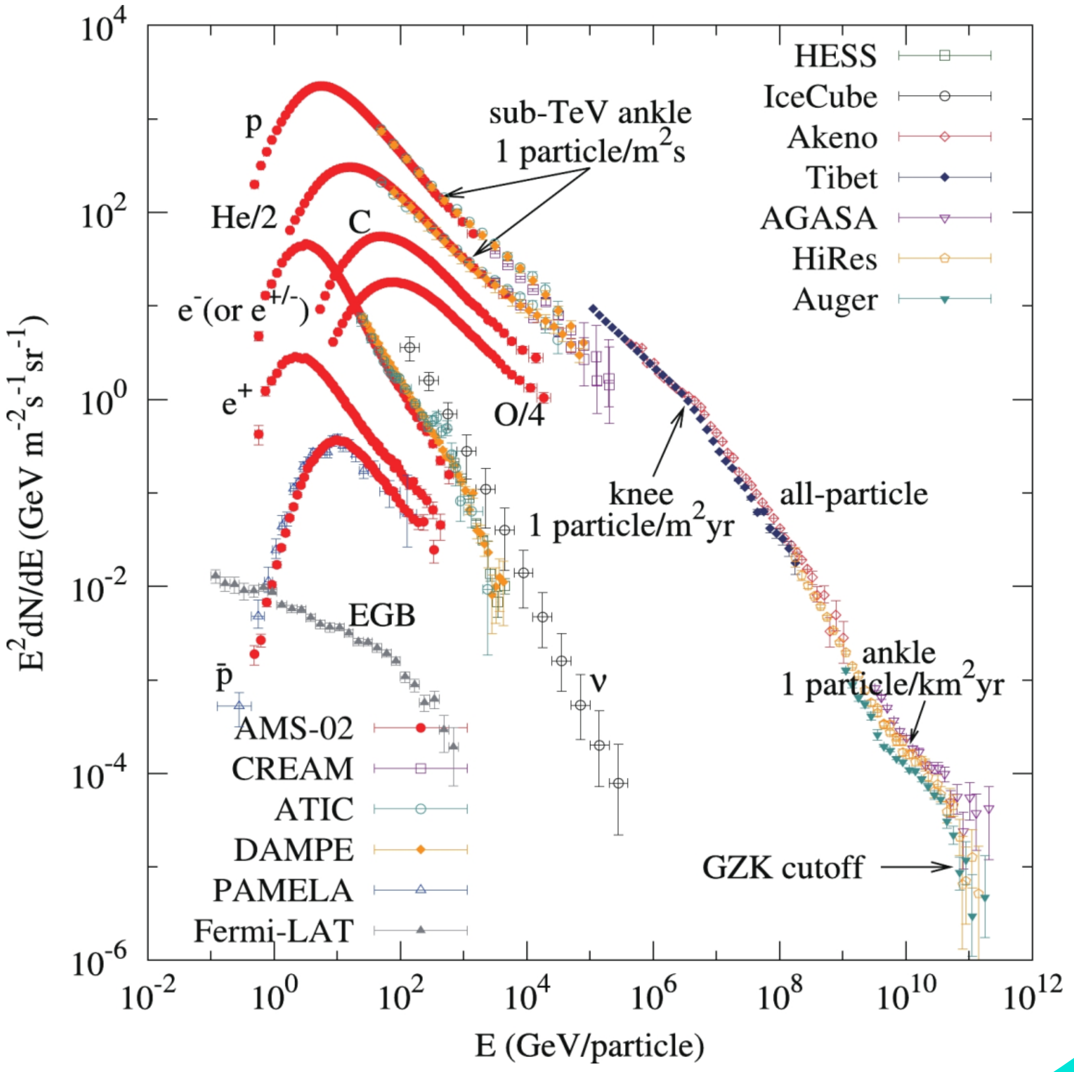
Multiple contributions to conferences and publications in preparation.

3
PeVatrons

Cosmic rays

An enigmatic simplicity

- Charged particles in space
- Isotropic
- Proton dominated
- Spectrum:
  - Covers 12 decades in energy
  - Has few features
    - Power law with some "breaks"
- Possibly galactic up to the "Ankle"



Chinese Physics C, 2022, Vol. 46, Chapter 4

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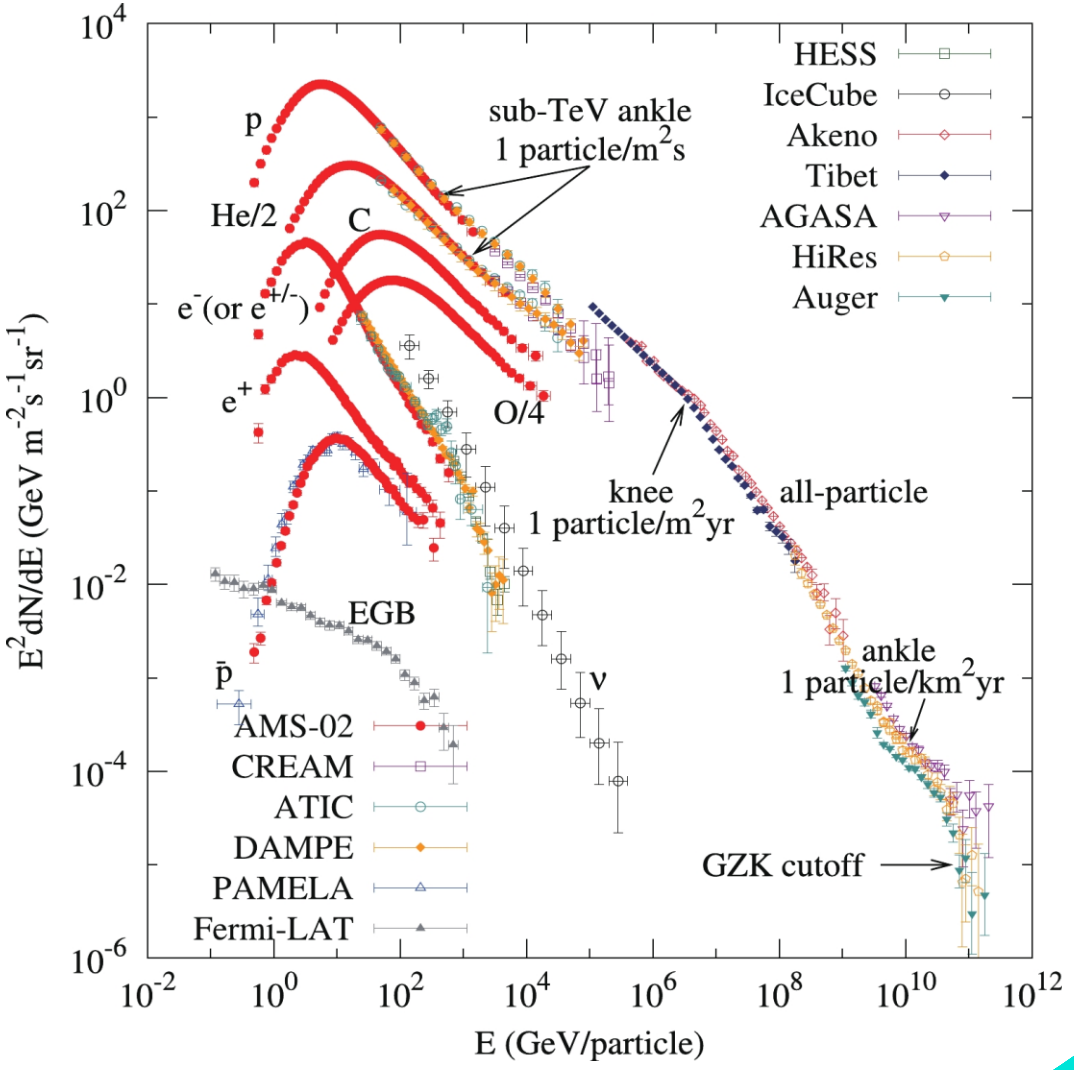


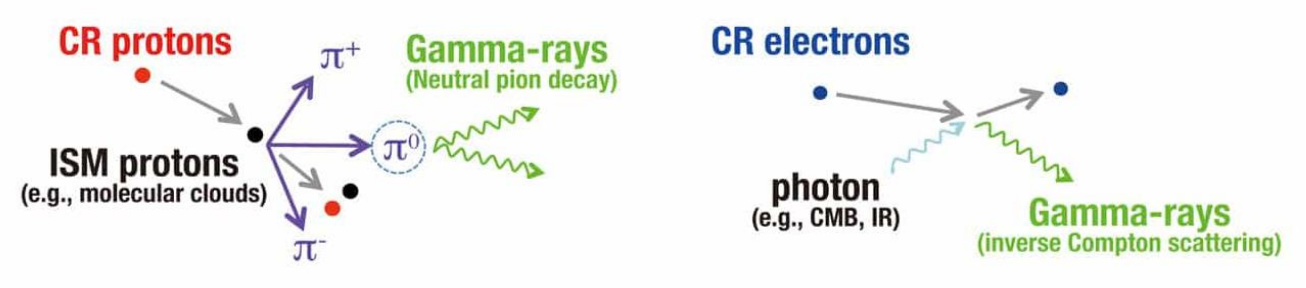
Chinese Physics C, 2022, Vol. 46, Chapter 4

How and where in the galaxy are cosmic rays accelerated above PeV energies?

PeVatrons

PeV cosmic ray accelerators

- We are searching for **hadronic** PeV particles
- Current models are challenged by such acceleration
- Charged cosmic rays are isotropised by magnetic fields
    - Search for another messenger? Photons, neutrinos
- Photons produced by both leptons and hadrons



Credit: Astrophysics Laboratory, Nagoya University

$E_\gamma \sim E_{CR}/10$

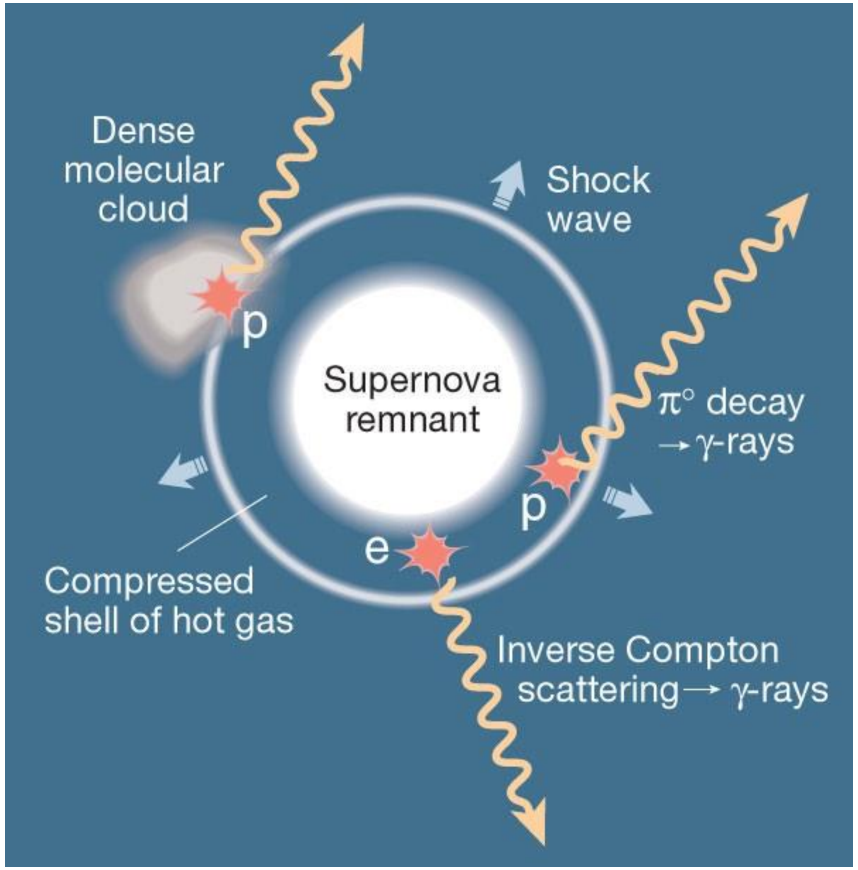
So PeV CR > 100 TeV photons

Klein-Nishina suppression:
Inverse compton scattering
Inefficient above 50 TeV

- Neutrino detector sensitivity limited

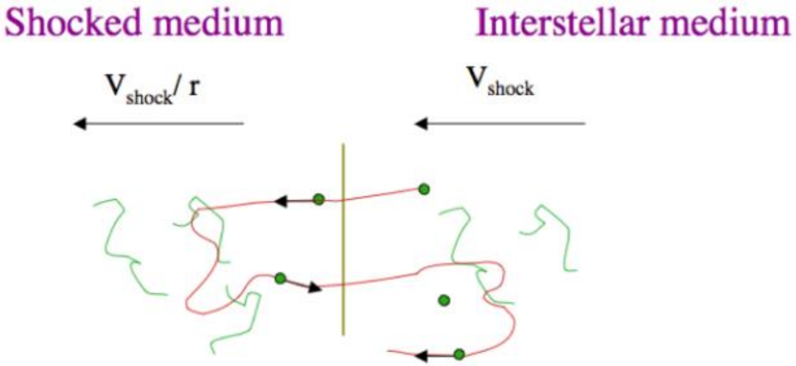
PeVatrons

Main candidates : supernova remnants (SNRs)

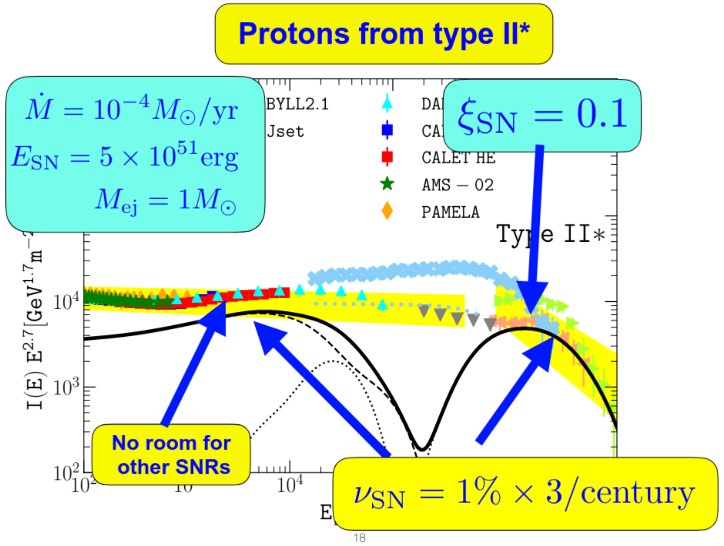


Nature volume 416, pages 797–798 (2002)

Diffusive shock acceleration



Credit : D. Allard, High Energy Astrophysics course at APC



Credit : P. Cristofari, CPPM seminar 2021

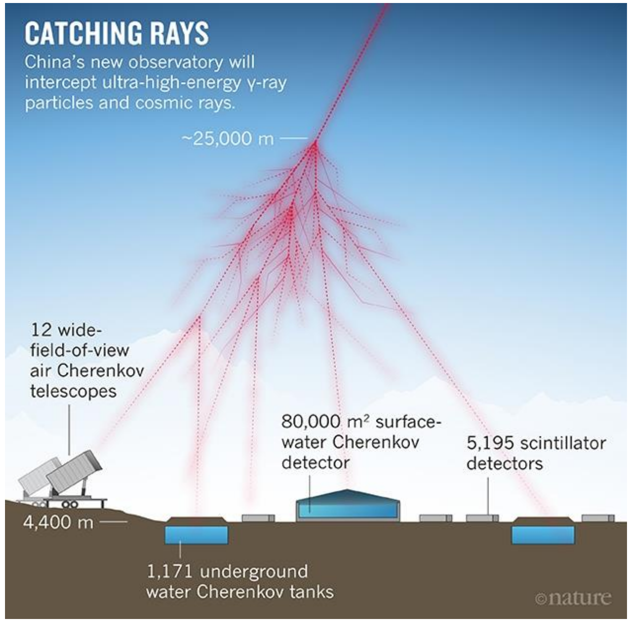
Maximum energy generally considered to be linked to the saturation of non-resonant (Bell) streaming instability in the magnetic field turbulences

P. Cristofari : Rare, extreme supernovae (type II*) could explain the highest CR energies

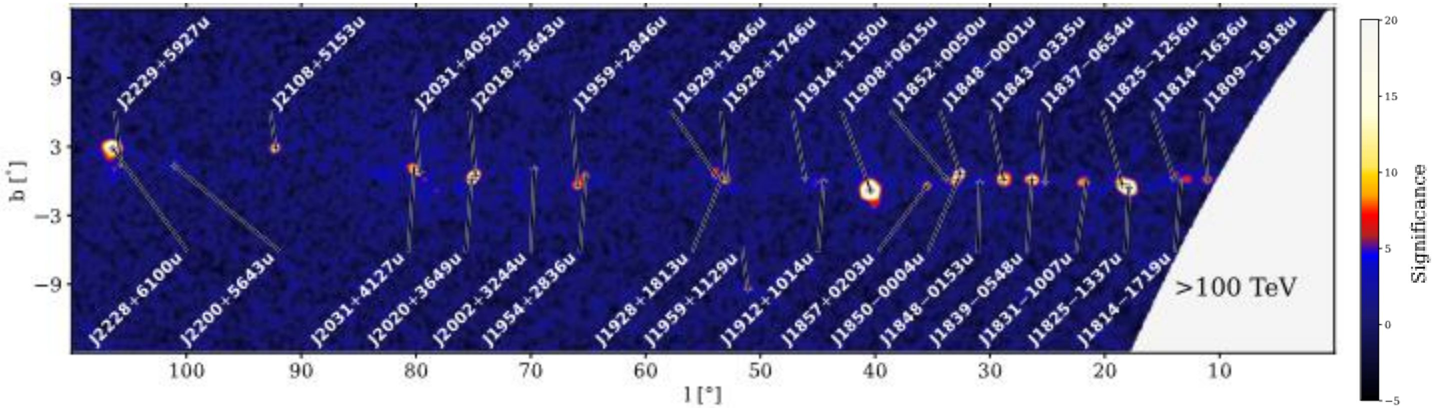
PeVatrons

Recent breakthrough

- LHAASO detected multiple sources of photons > 100 TeV
- 43 sources with significance above 4σ at energy beyond 100 TeV ("The First LHAASO Catalog of Gamma-Ray Sources" The Astrophysical Journal Supplement Series, Volume 271, Issue 1, id.25, 26 pp.)



LHAASO concept, nature | vol 543 | 16 March 2017



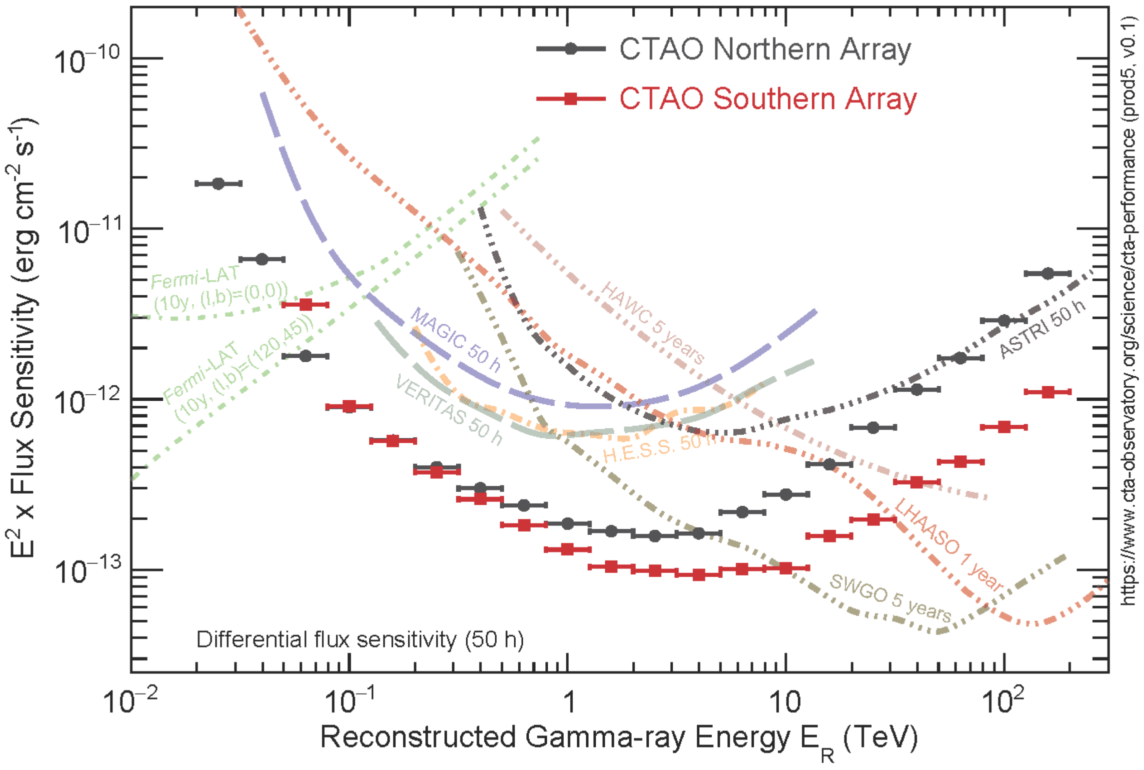
PeVatrons

CTAO outlooks

- South better for ~100TeV
- North still very good
  - Better than 1 year of LHAASO in 50 h with better resolutions
- LHAASO covers the northern sky

  Identify target for CTA observations
- No equivalent in the south

  CTA surveys in Key Science Projets could be used to identify PeVatron candidates using the Southern array higher sensitivity

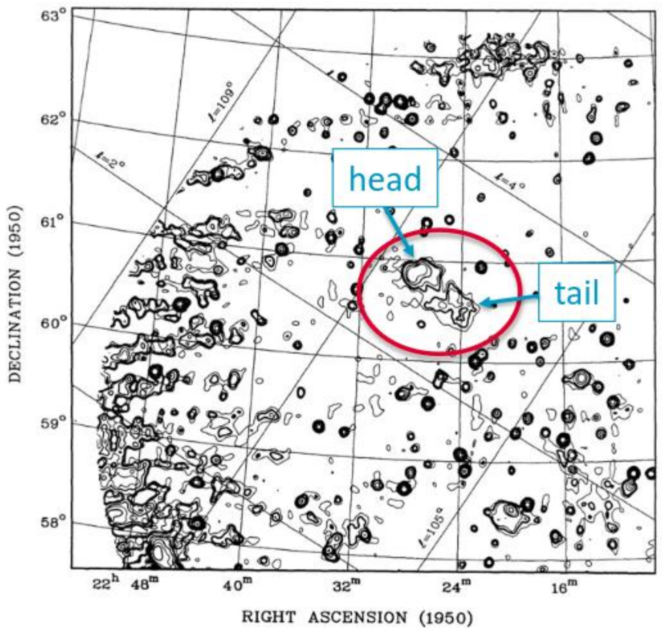


4
Boomerang SNR

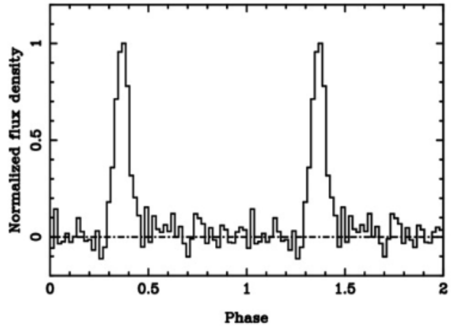
General

SNR, Pulsar and PWN

- SNR G106.3+2.6 first detected in radio
- Pulsar Wind Nebula later identified in the head
    - Pulsar also detected
- Connected to molecular clouds (HI and CO)

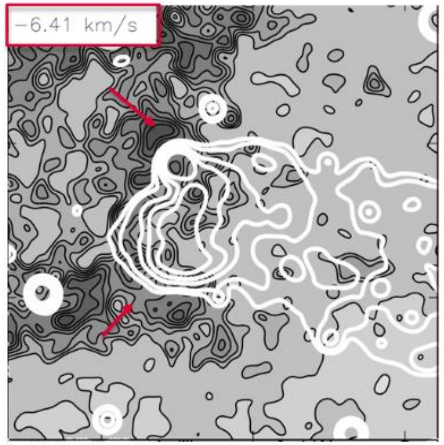


Joncas & Higgs (1990)



Radio pulse profile a 1412 MHz

Halpern et al. (2001b)



Khotes et al. (2001)

HI (grey) and radio continuum 1420 HZ (white)

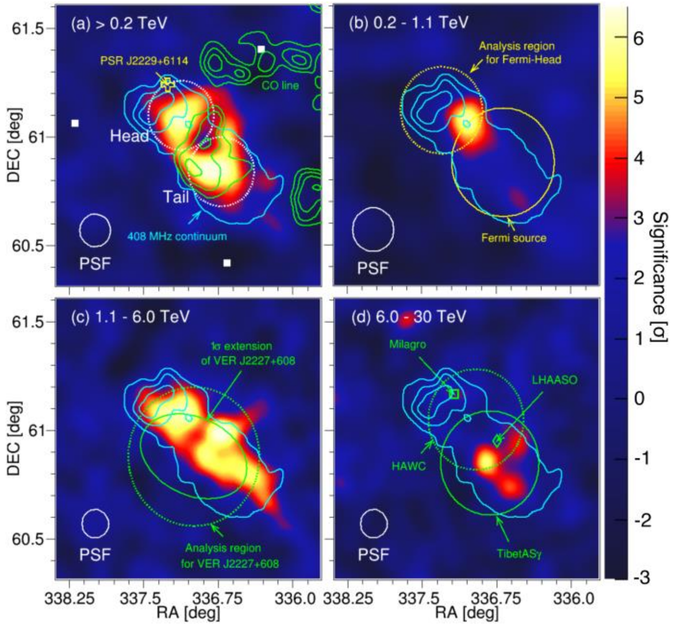
General

Gamma ray observations

Observed by multiple IACTs in the O(TeV)

Veritas, MAGIC

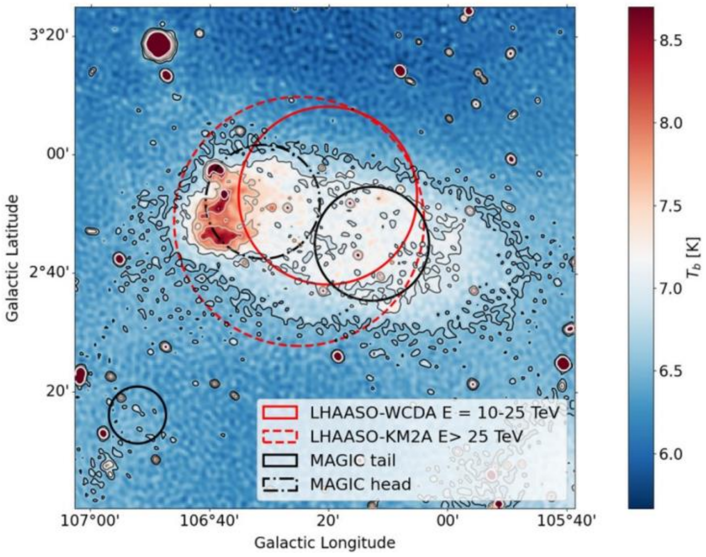
MAGIC clearly detected the source in 120h showing energy dependent morphology

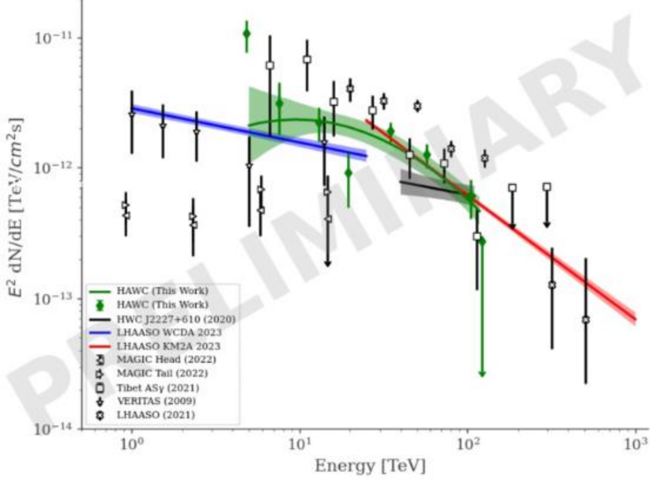


MAGIC collaboration, A&A, 671 (2023) A12

Observed by particle detector in the O(10-100TeV)

HAWC , Tibet ASγ, LHAASO





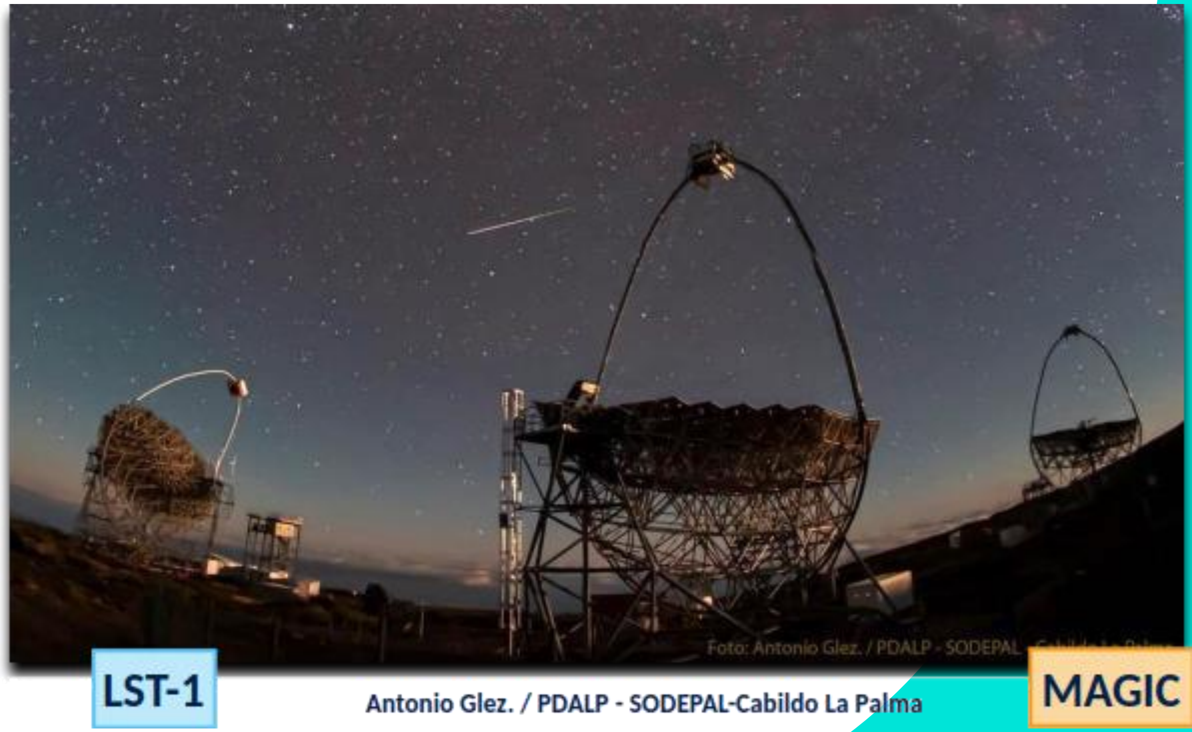
HAWK collaboration, ICRC 2023

LST+MAGIC at Large Zenith Angle

Concept and problematics

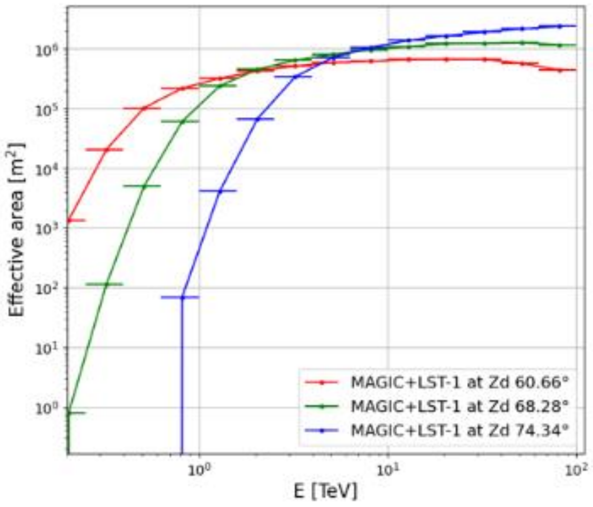
- LST not optimal for PeVatron studies
  How can we increase the sensitivity above 10 TeV?
  - Use multiple telescopes > LST+MAGIC
  - Observations at "large zenith angle" (low altitude) = Showers illuminate a larger ground area

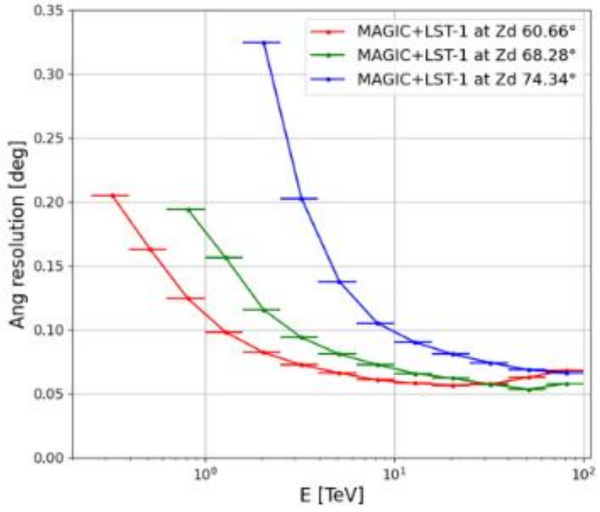
- Challenges :
  - Complex data taking and analysis
  - Large dependence of image properties with pointing

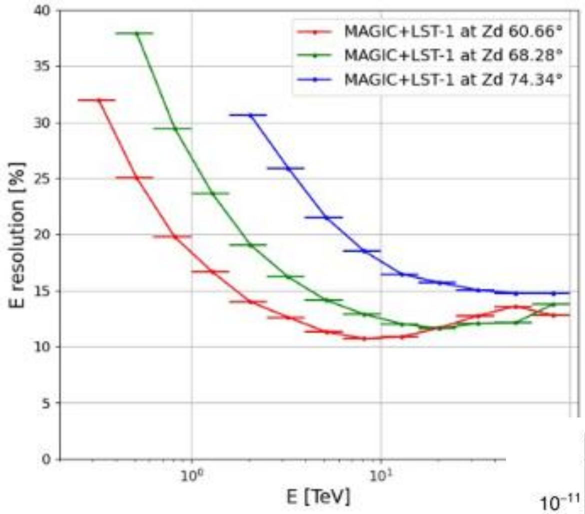


LST+MAGIC at LZA

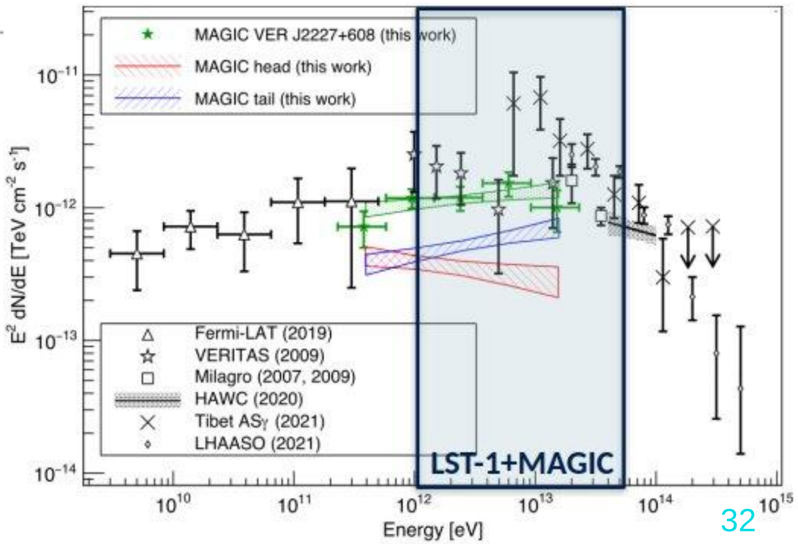
Performance vs zenith

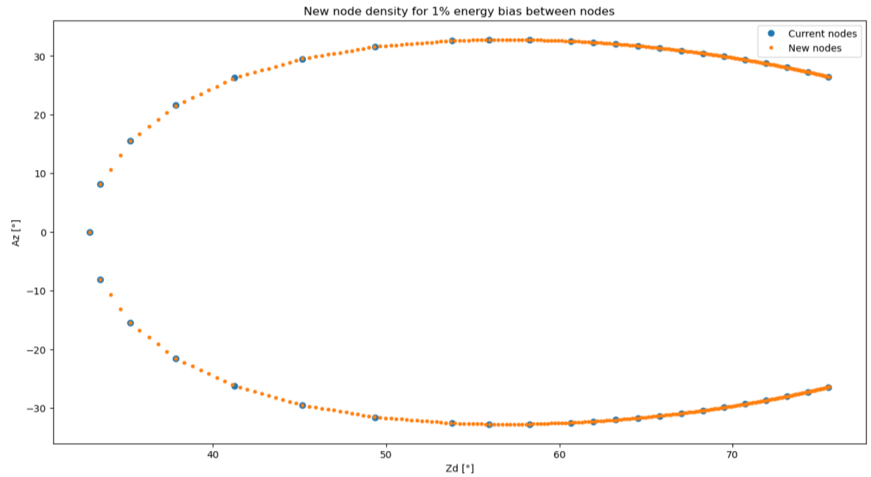






- With both LST and LST + MAGIC effective area at the highest energy increases with zenith declination
- In the LZA region (60-75°):
  - Angular resolution still reaches < 0.1°
  - Energy resolution< 15%



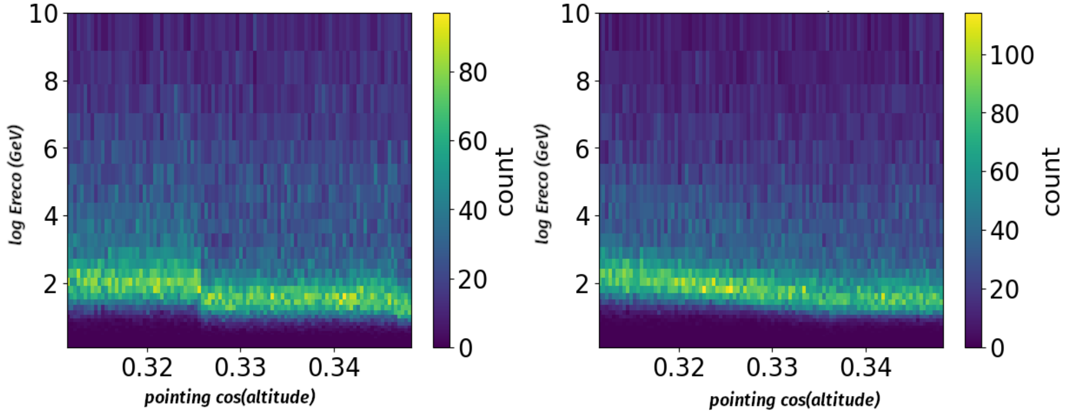


LST+MAGIC at LZA

Reconstruction challenge

- LST+MAGIC analysis pipeline uses Monte Carlo simulation on discrete pointing to train random forest for event reconstruction
  - Old simulation strategy > high bias at LZA
- Solutions we implemented :
  - Single node random forest interpolation
  - High pointing density Monte Carlo : low stat nodes every 0.5% Ebias
  - Both solutions solve biases without degradations

Reconstructed energy before/after fixes



High level analysis

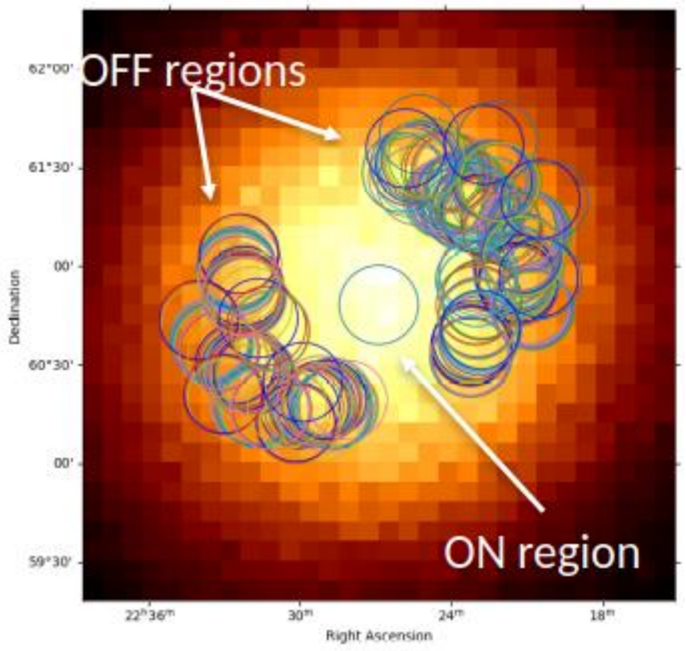
Energy spectrum and extension

- IACT data is contaminated by electrons and hadrons misidentified as gamma-rays
- Need to estimate this background for high level analysis
  - We worked on extracting a model of **acceptance of the background** vs energy and position from data
- Multiple high level analysis:
  - Spectral analysis (1D) : spatially integrated spectrum of the source is obtained using background vs energy estimates.
  - Skymaps (2D) : significance vs position obtained by estimating the energy integrated background vs position
  - 3D analysis : global likelihood fit of spectra and morphology of sources along with a model of background vs position and energy

High level analysis

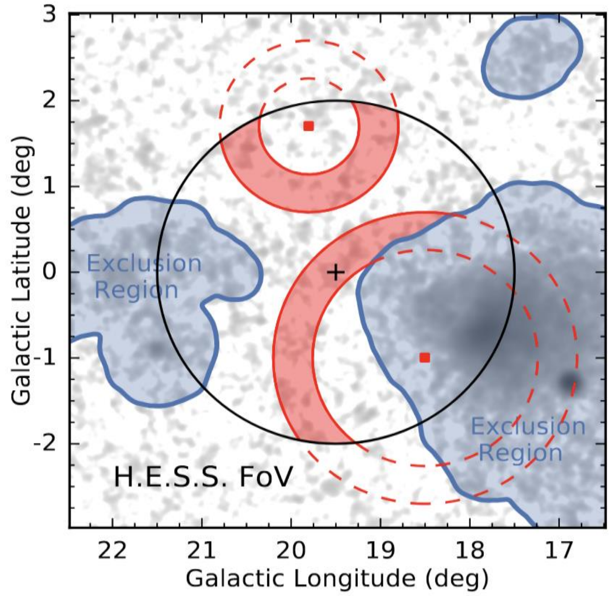
3 ways to estimate the background

- Reflected background : background vs energy estimated in OFF regions



- Direct rescaling of the background acceptance

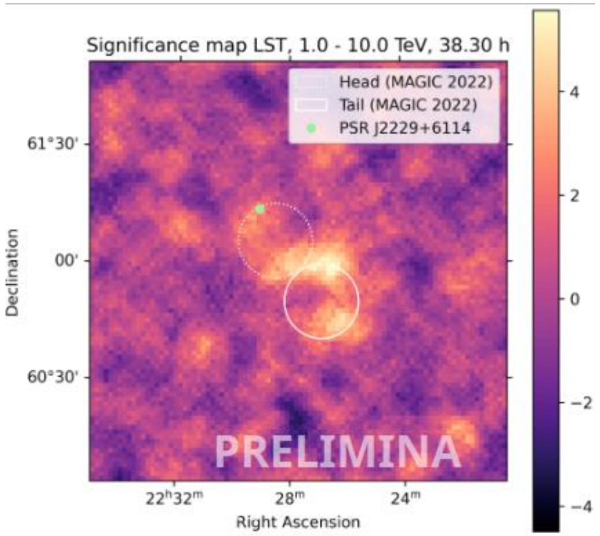
- Ring background : Background re-averaged on data by integrating on a ring around each position (weighted by the background acceptance)

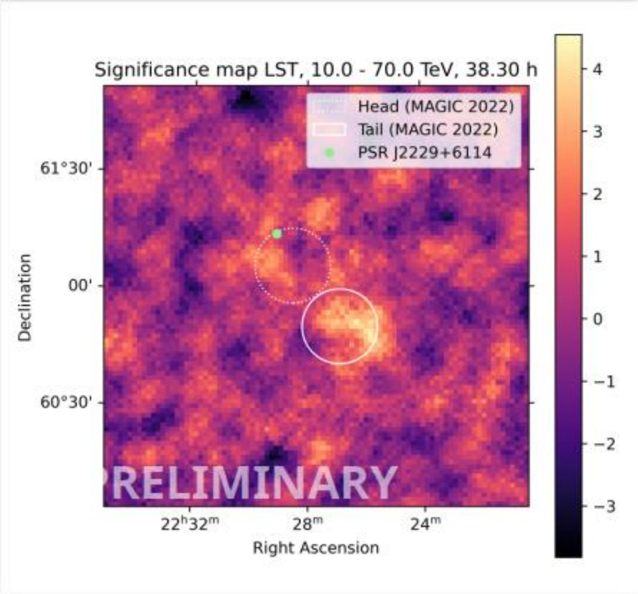


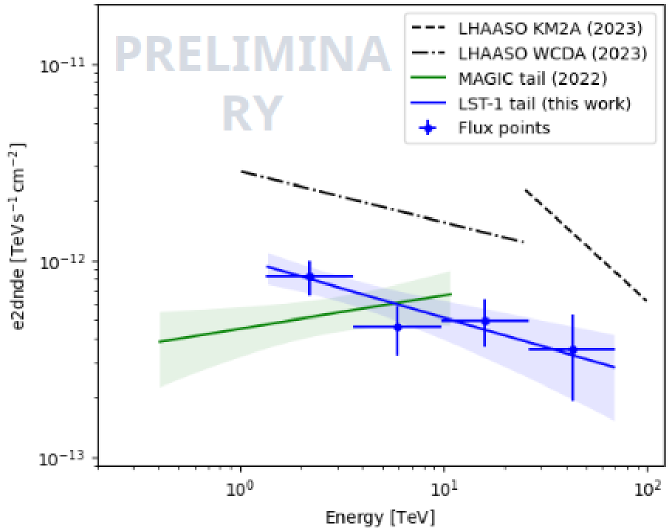
Results

Spatial extension

- First LST mono results shown at the CTAO symposium 2024 :
  Skymaps using the ring background method and Spectrum using reflected background







- Hints of energy dependent morphology

Results

Going further

- We are working on the optimal way to combine data taken in different conditions : LST, LST+MAGIC, MAGIC
- Use of the ring background for spectral analysis investigated
- Use of the ring background model in 3D analysis was tested
- Best strategy for the full 3D analysis of our region is being defined
    - Identify independent sources, extensions, spectra

5
Outlooks

Outlooks

The CTAO construction is advancing and PeVatron studies in both the North and South are promising

LST-1 already has the potential to bring critical information in understanding PeVatron candidates

The Boomerang project is accumulating data (target 120h). We showed novel results already and vastly improved the analysis pipeline

Final outputs of the campaign should thus be very informative on the PeVatron nature of the source

Thank you