Introduction to Very High Energy Gamma-Ray Astronomy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea
NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
INSTITUTO DE ASTROFISICA DE CANARIAS · IAC
AGENCIA ESTATAL DE INVESTIGACIÓN
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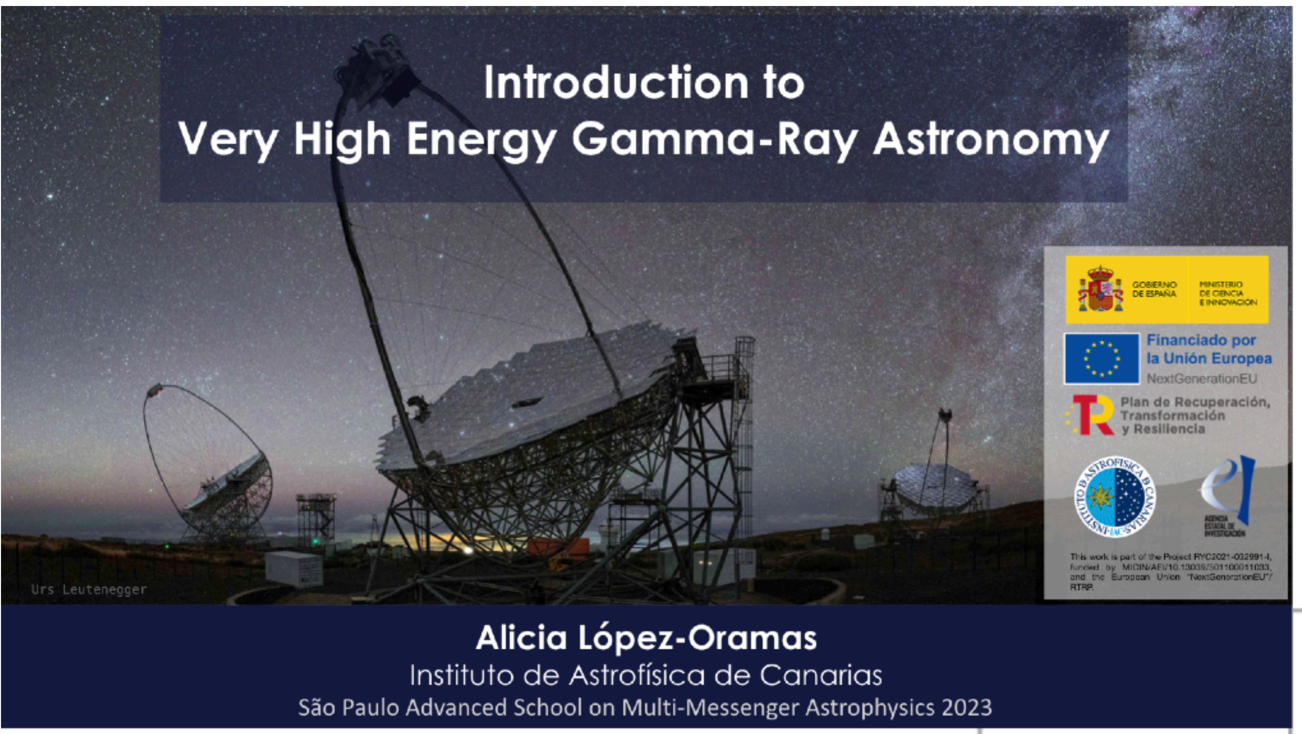
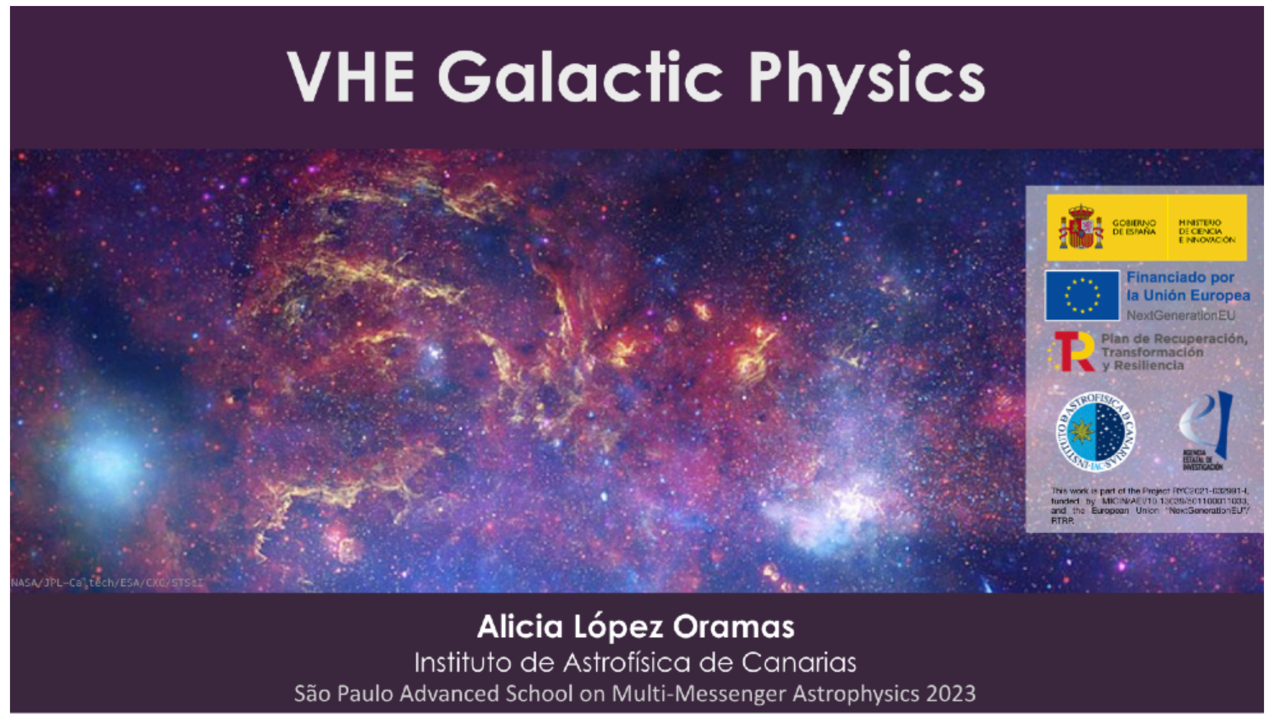
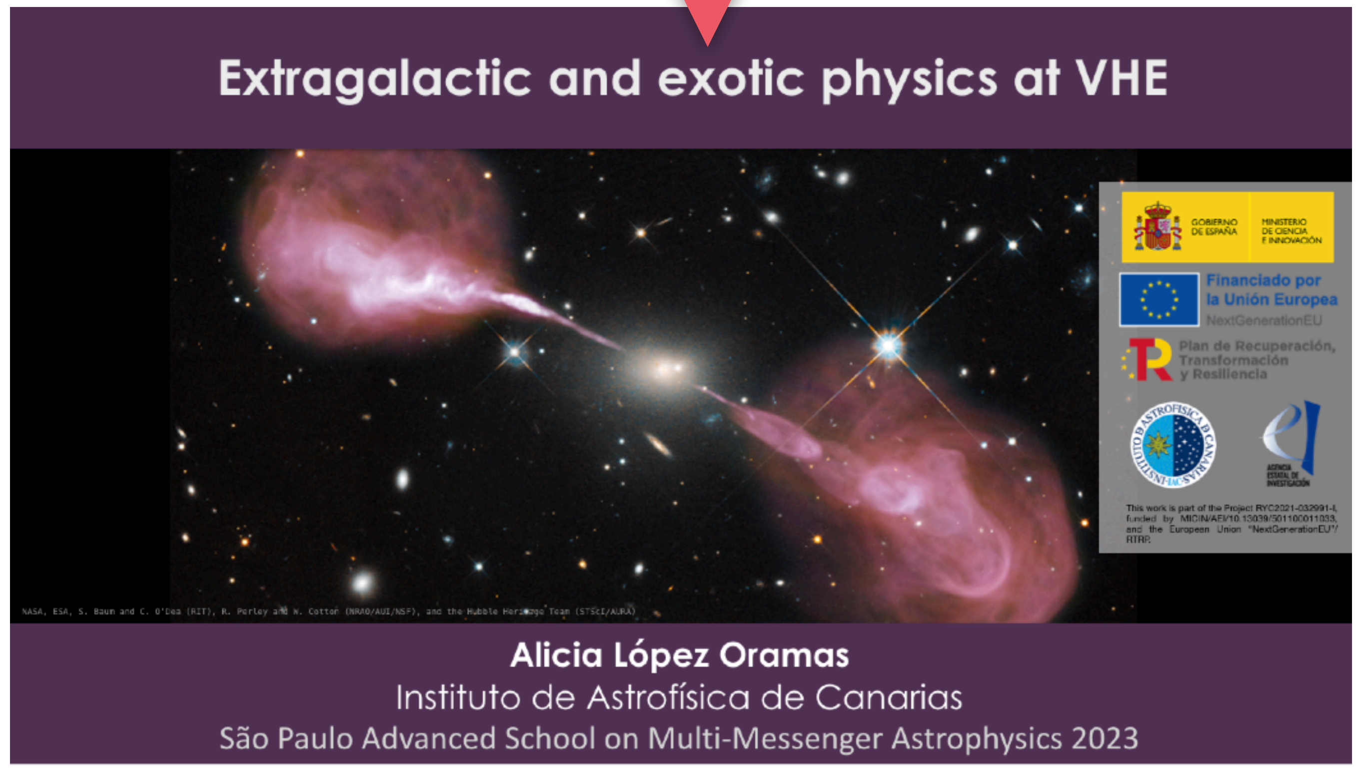
Alicia López-Oramas
Instituto de Astrofísica de Canarias
São Paulo Advanced School on Multi-Messenger Astrophysics 2023

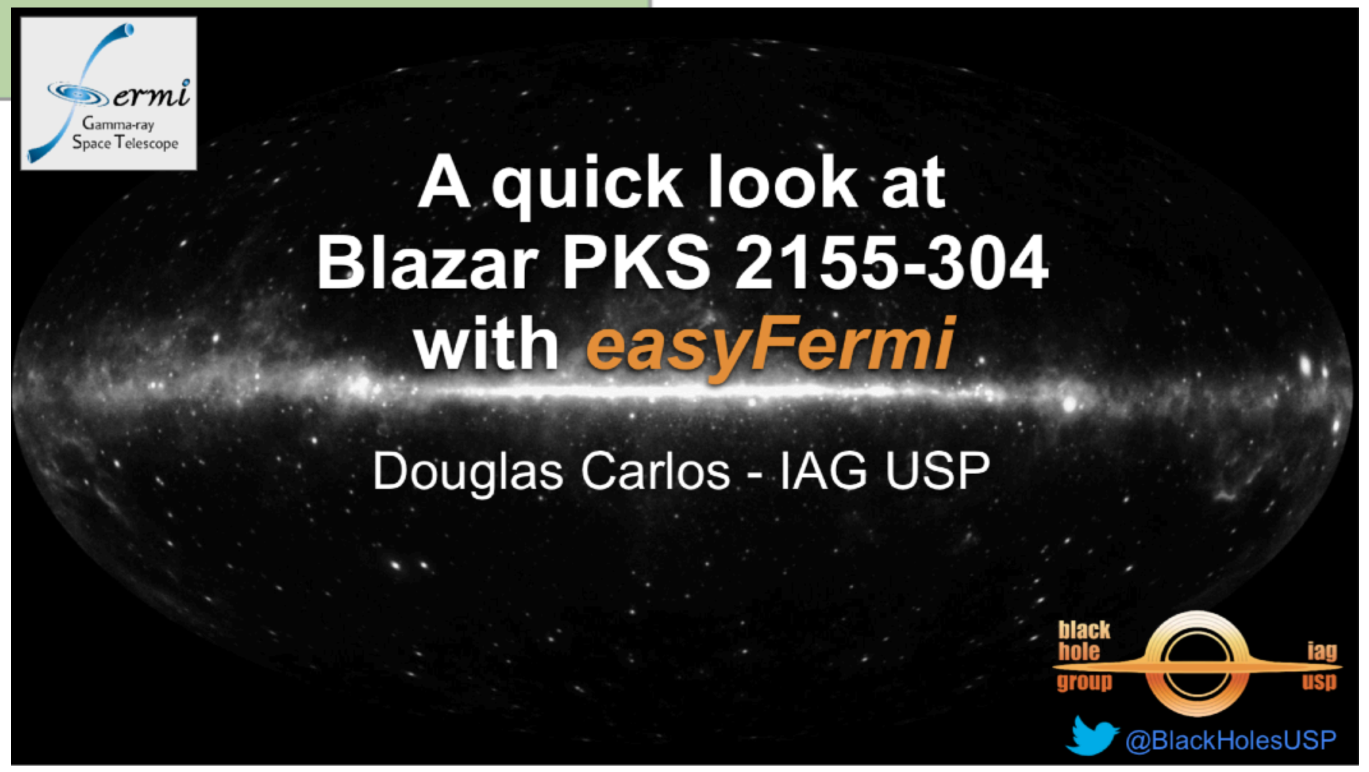
Gamma-ray Astrophysics Sessions



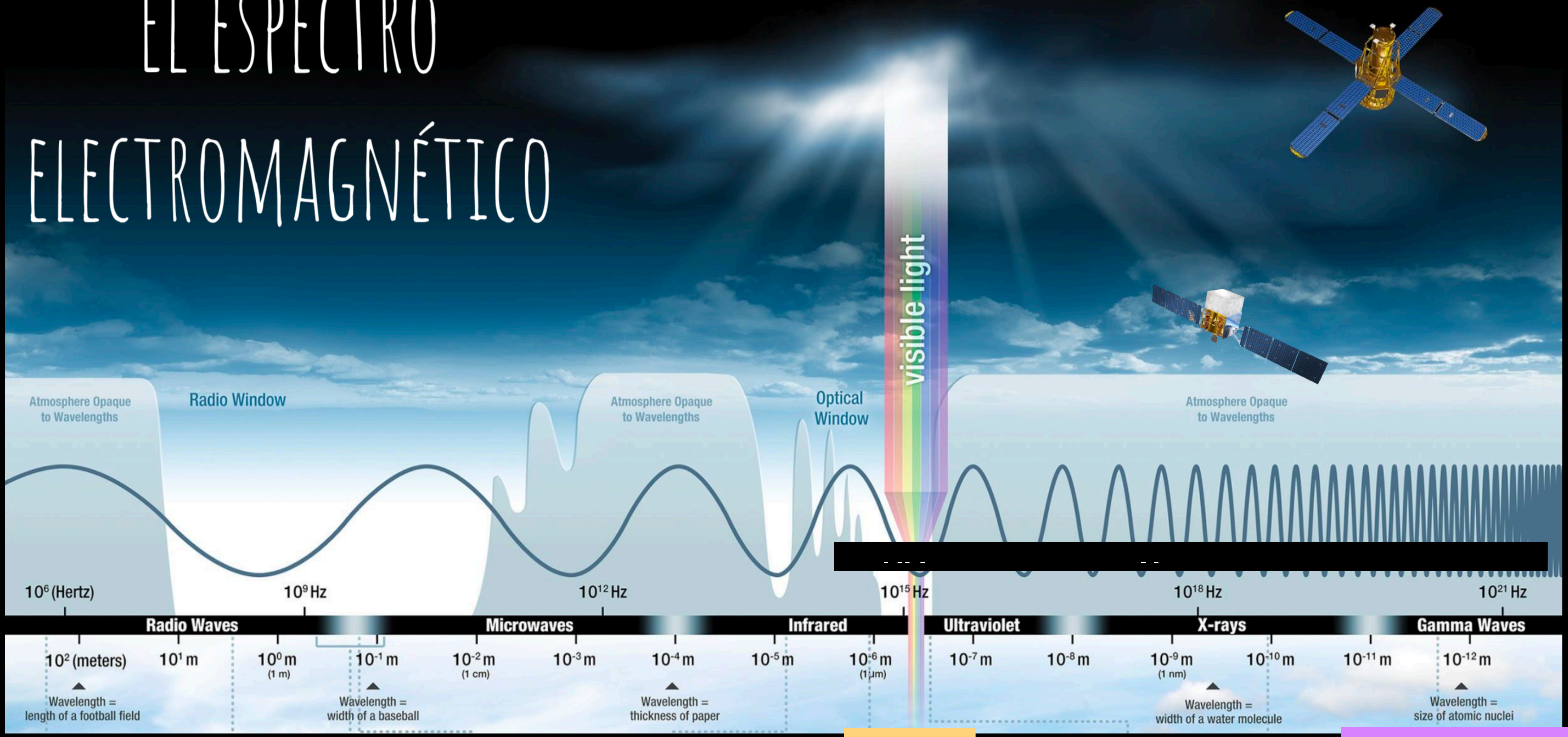
	Mon (29/5)	Tue (30/5)	Wed (31/5)	Thu (1/6)	Fri (2/6)
9:30-10:00 10:00-11:00	Registration Welcome, Local Information, School Organization	**Brian Reville** *Particle Acceleration and Radiation Processes* **Lecture 1**	**Brian Reville** *Particle Acceleration and Radiation Processes* **Lecture 2**	**Irene di Palma** *Gravitational Waves* **Lecture 4**	**Visit to Sirius (LNLS, CNPEM)**
11:00-11:30	**Coffee**	**Coffee**	**Coffee**	**Coffee**	**Bus leaves Flat Universe at 11 am, arrives at LNLS at 12:30.**
11:30-13:00	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 1**	**Irene di Palma** *Gravitational Waves* **Lecture 2**	**Irene di Palma** *Gravitational Waves* **Lecture 3**	**Emille Ishida** *Using machine learning to find astronomical transients*	**Visit to Sirius (LNLS, CNPEM)**
13:00-14:30	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Visit to Sirius (LNLS, CNPEM)**
14:30-16:00	**Irene di Palma** *Gravitational Waves* **Lecture 1**	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 2**	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 3**	**Hands-on sessions**	**Visit to Sirius (LNLS, CNPEM)**
16:00-16:30	**Coffee**	**Coffee**	**Coffee**	**Coffee**	**Visit to Sirius (LNLS, CNPEM)**
16:30-17:30	**Martin Makler** *Strong gravitational lensing of supernovas, gravitational waves and other sources*	**Mario Diaz** *A Brief History of Gravitational Waves: From Denial to Multimessenger Astrophysics*	**Aion Viana** *Dark Matter searches in the multi-messenger era*	**Student seminars - Session 1: posters & short talks (5 mins)** **Social gathering at end of the day in the rooftop lounge**	**Visit to Sirius (LNLS, CNPEM): bus leaves lab at 5pm, arrives on Flat Universe at 6:30pm**







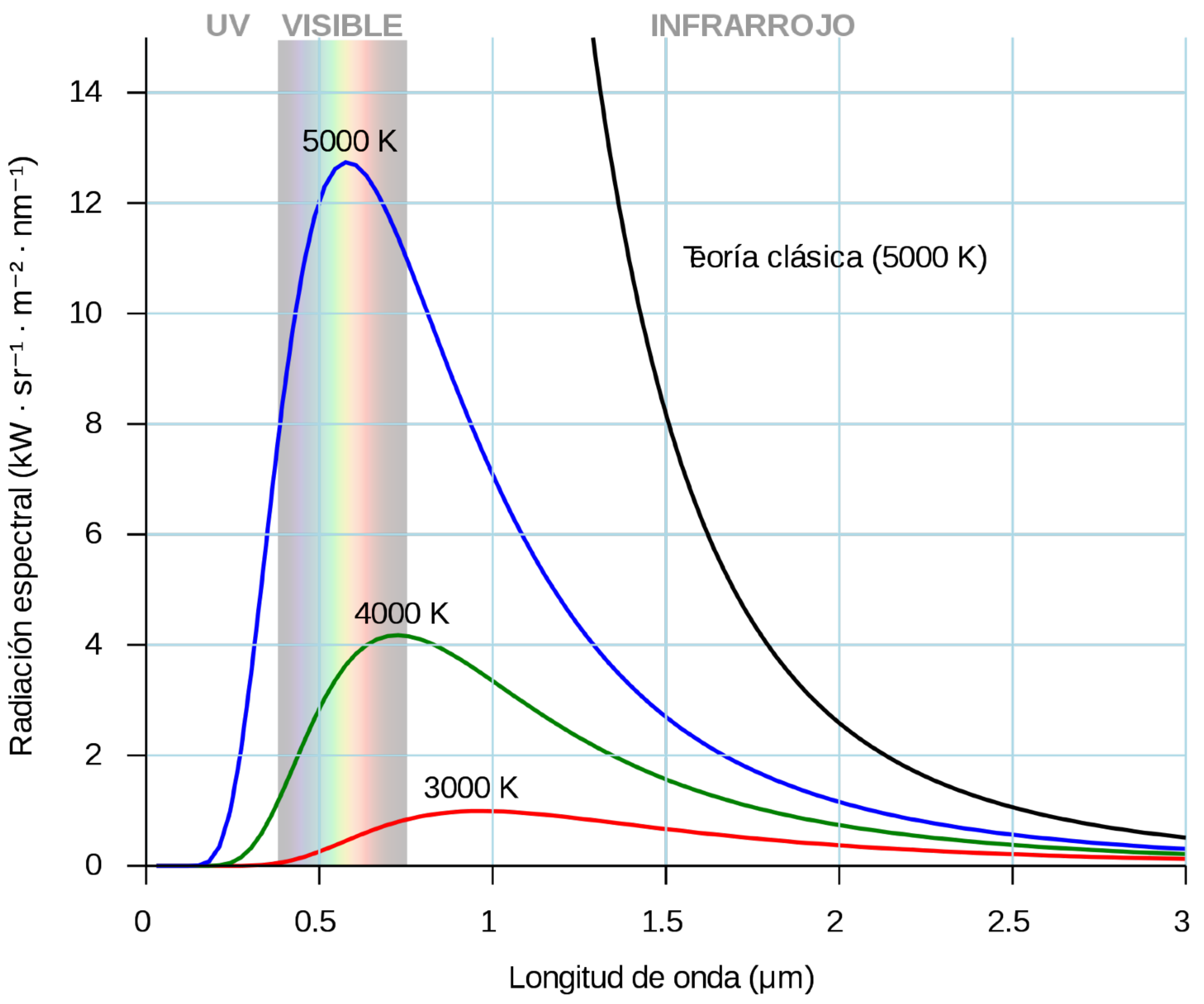
El espectro electromagnético



eV

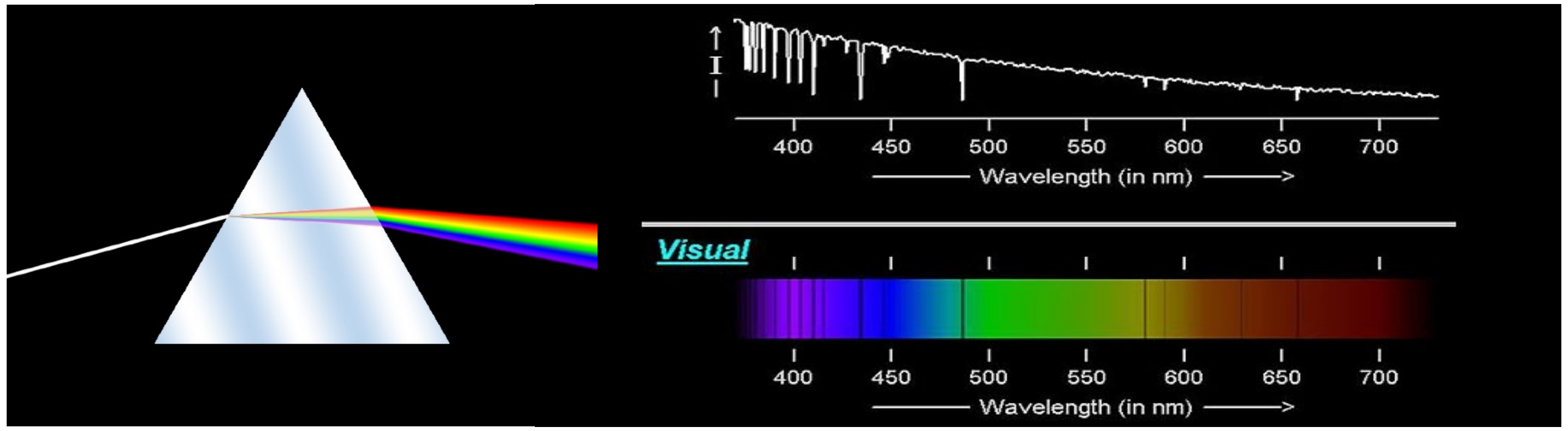
MeV - TeV

Black body radiation

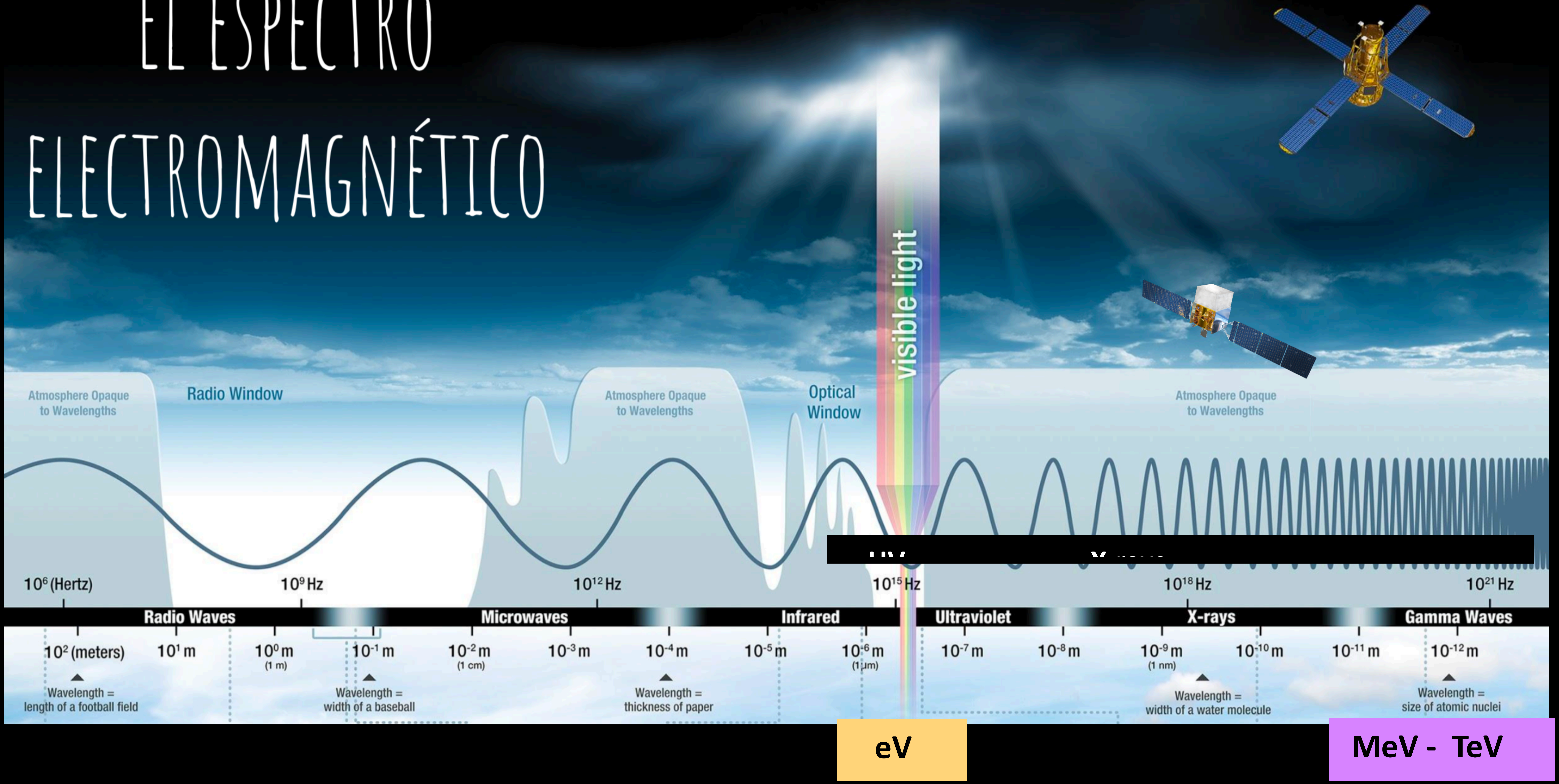


- Electromagnetic radiation
- Continuum spectrum
- **Thermal radiation**
- Spectroscopy

Is gamma-ray emission of thermal origin?
NO



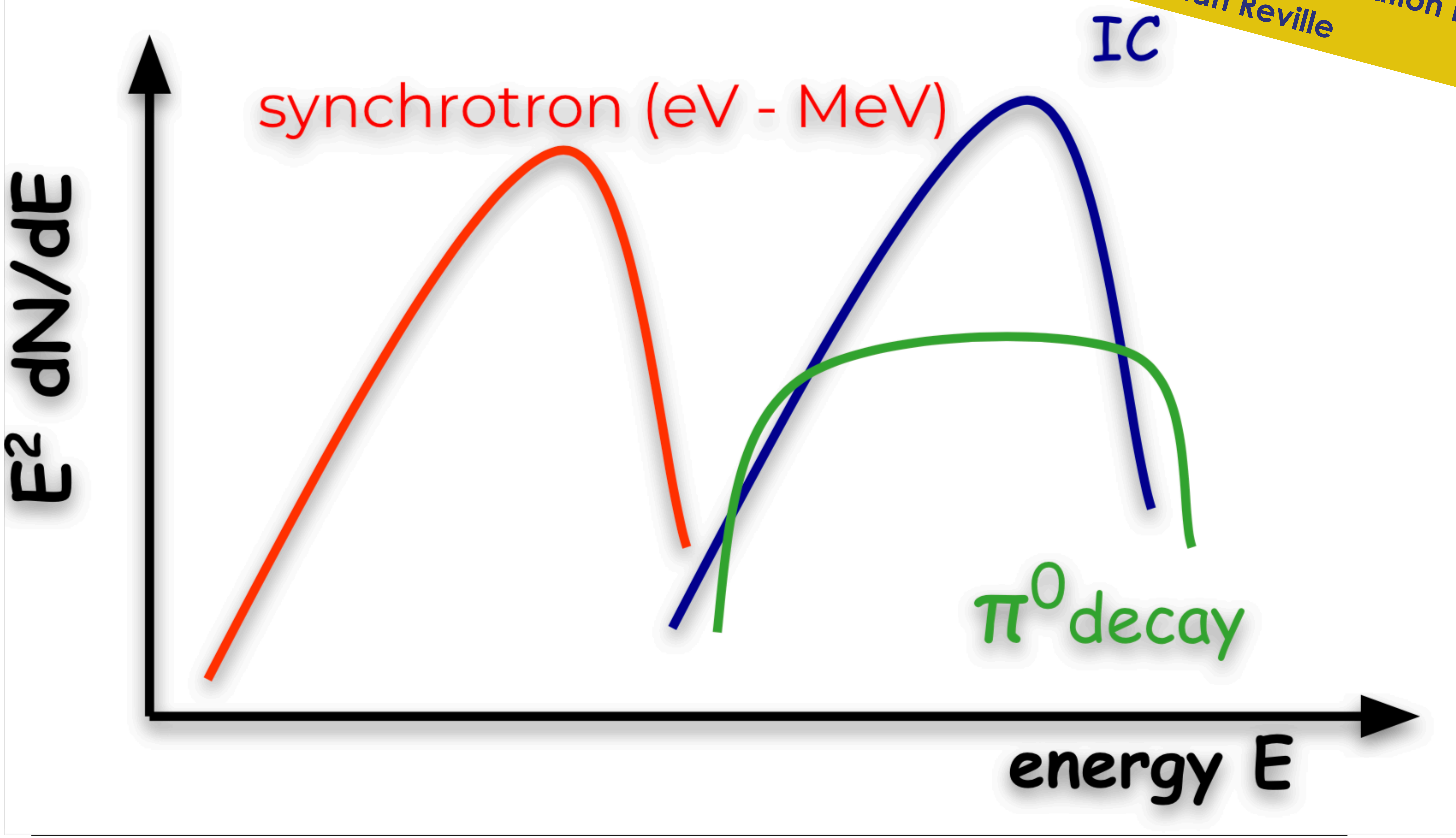
El espectro electromagnético



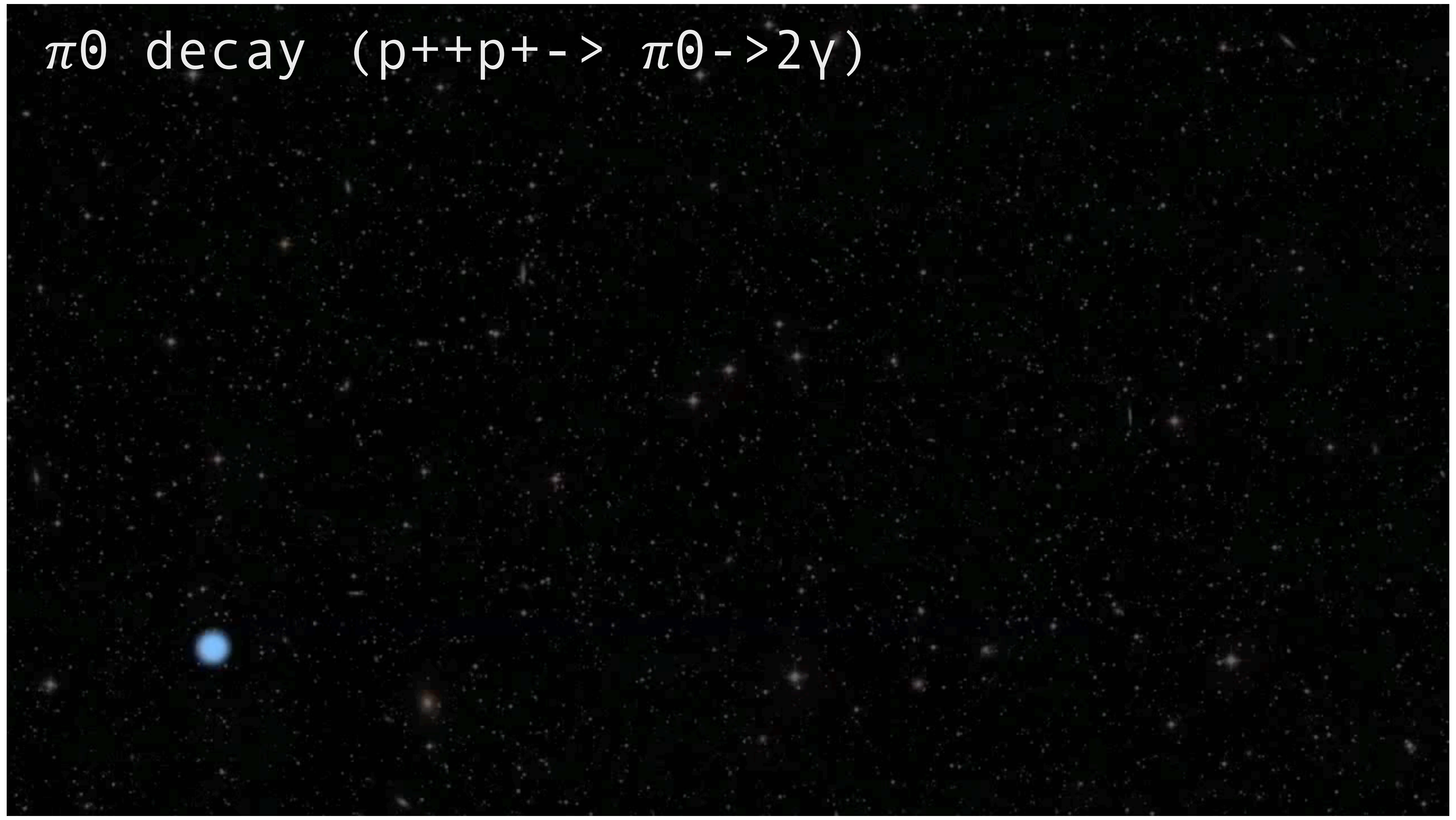
Gamma rays are produced by **non-thermal** processes

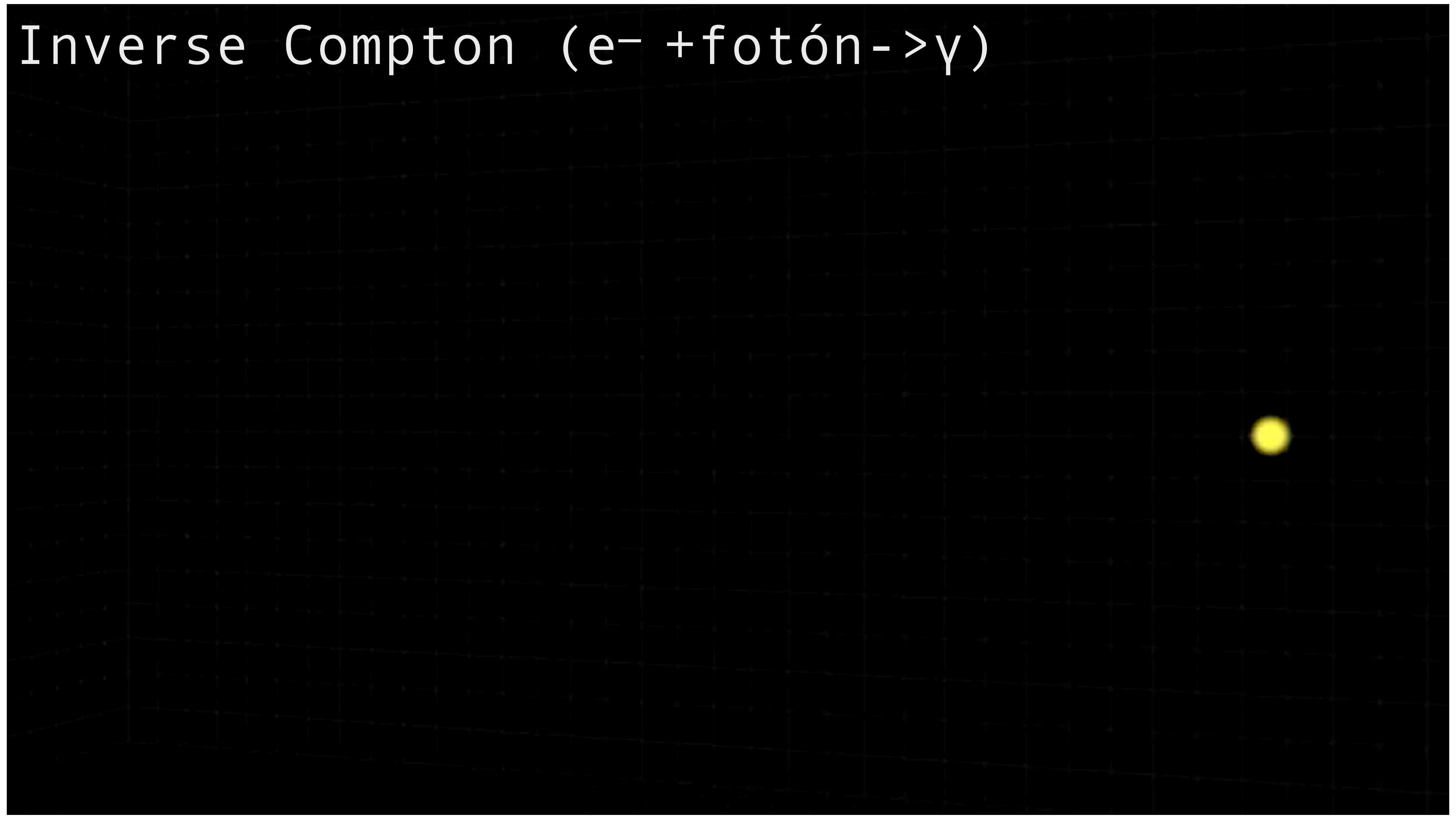
Non-thermal processes

Lectures
Particle Acceleration and Radiation Processes
Brian Reville

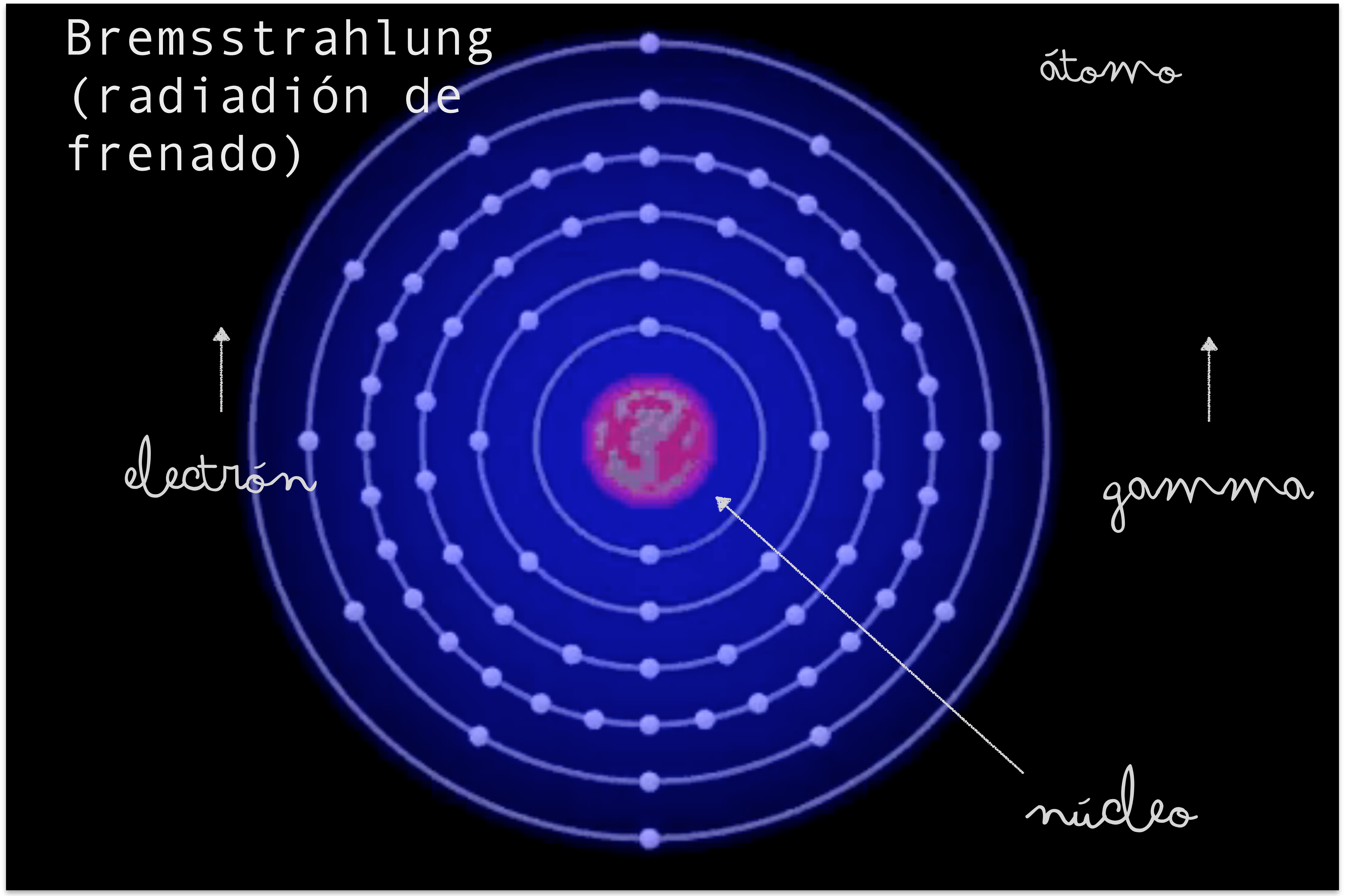


Non-thermal processes





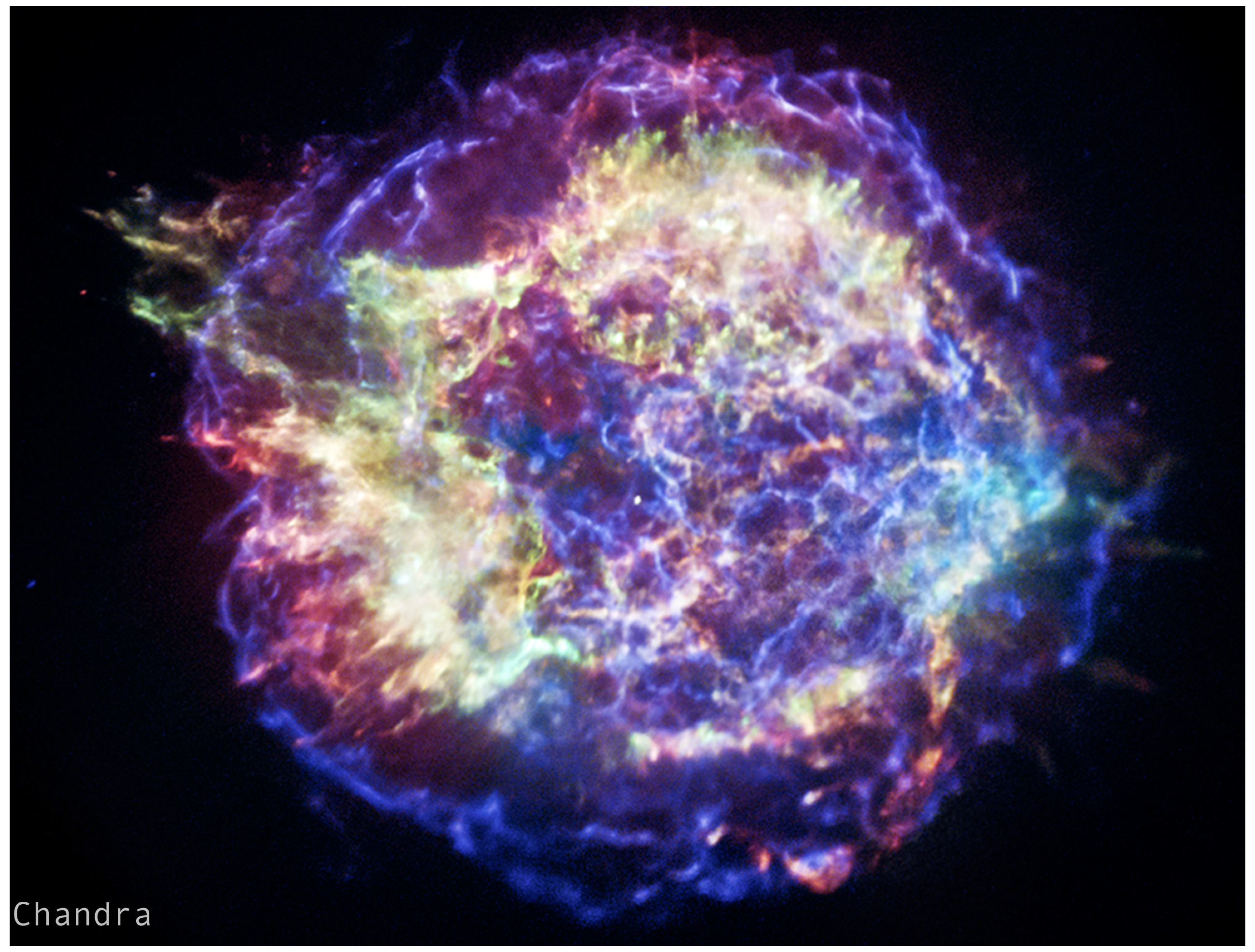
- **Interaction of/with particles/photons**
- Can lead to **gamma-ray production**
  - **Temperature independent**
- **Electromagnetic radiation**

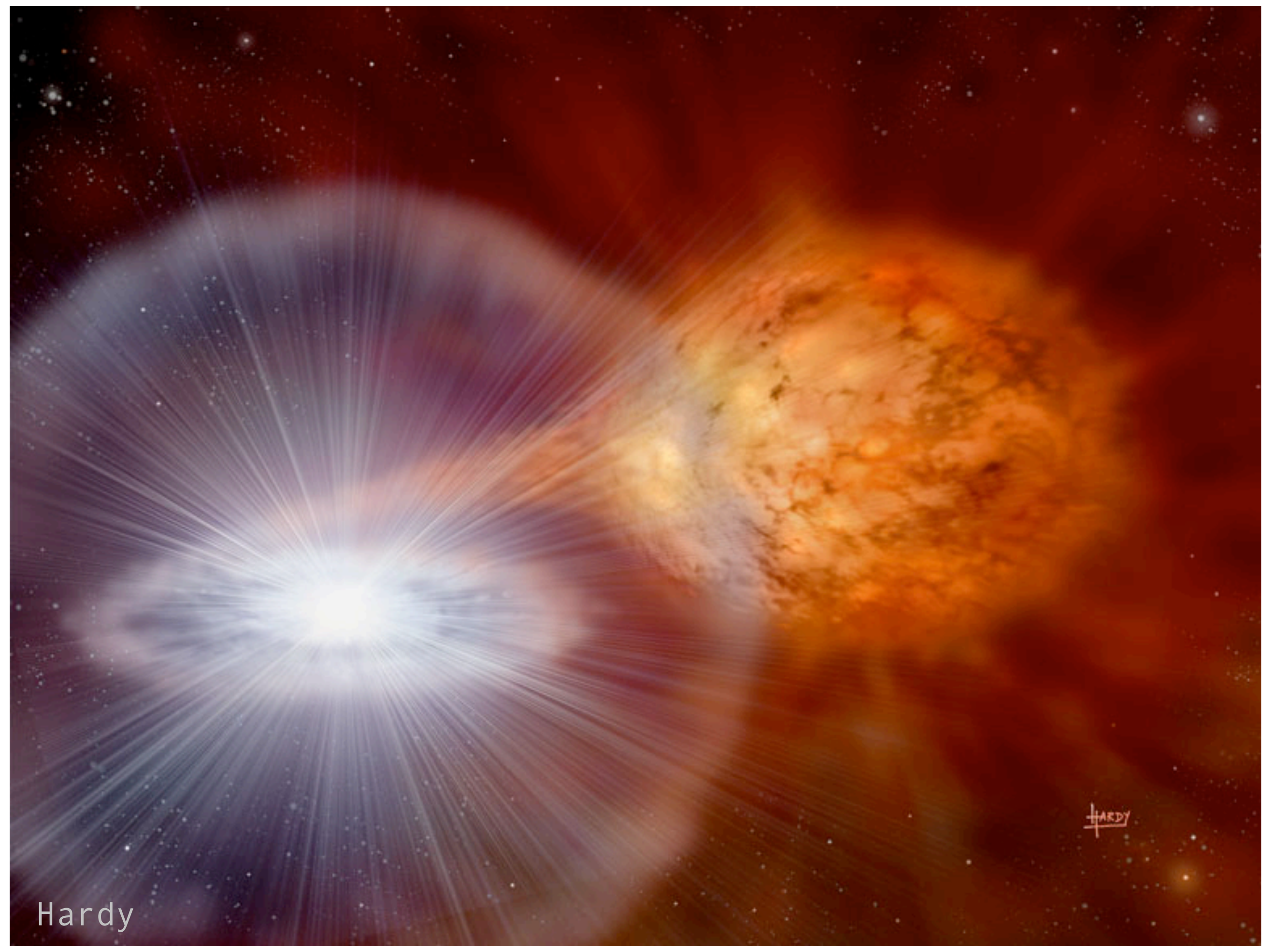


Gamma rays: why are they interesting?

- They are the product of the **interaction of relativistic particles in extreme phenomena**
  - accretion/ejection processes
  - jets, outflows and/or strong winds
  - magnetic reconnetion…
- Carry **information**:
  - **Particle acceleration and interaction mechanisms**
  - **Characteristics of the intergalactic/interstellar medium**
  - **Origin of cosmic rays** (PeVatrons?)
- Since gammas are photons, not deflected by magnetic fields

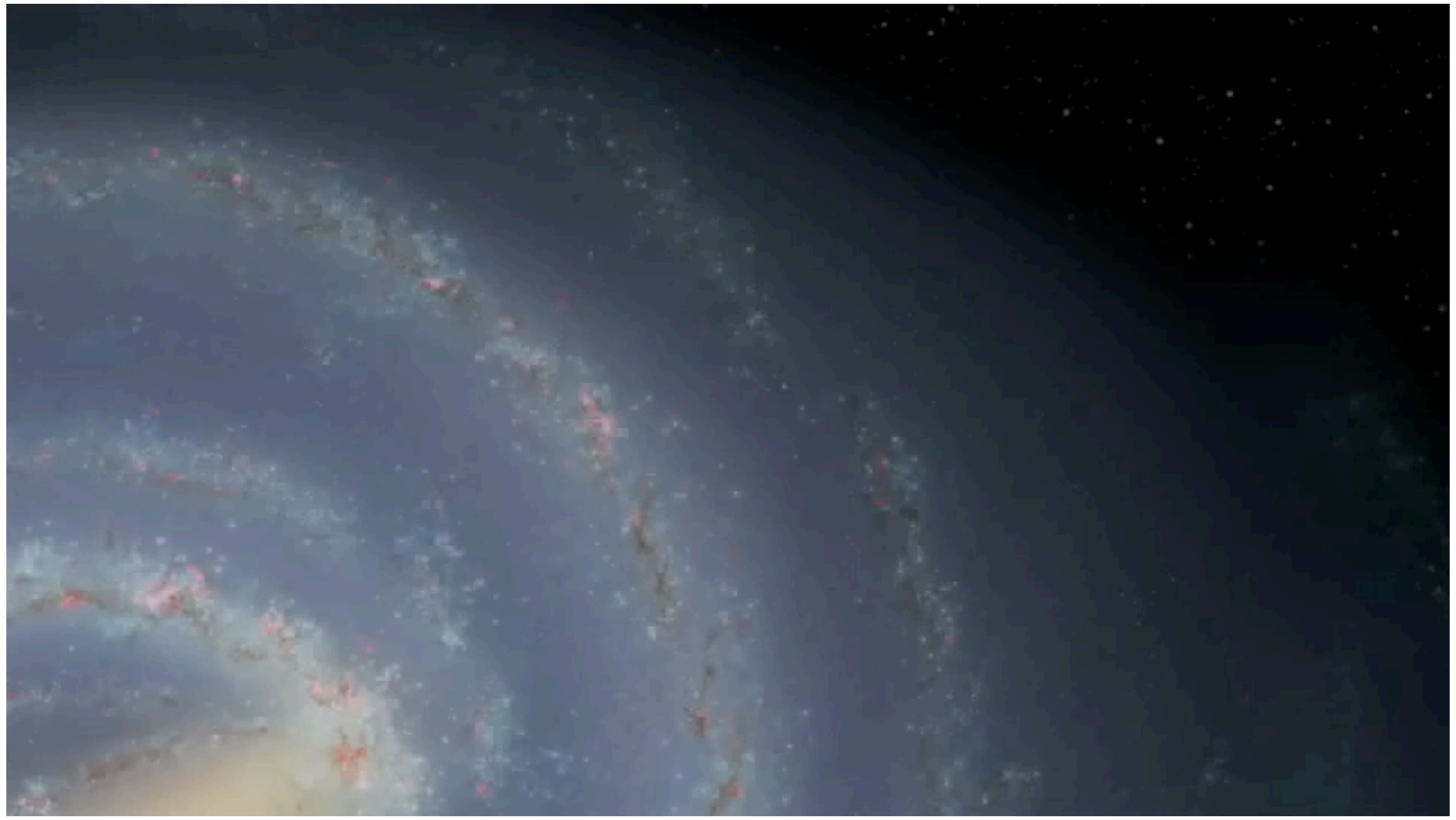
Gamma rays give us **information** about the
most violent processes in the Universe and cosmic accelerators

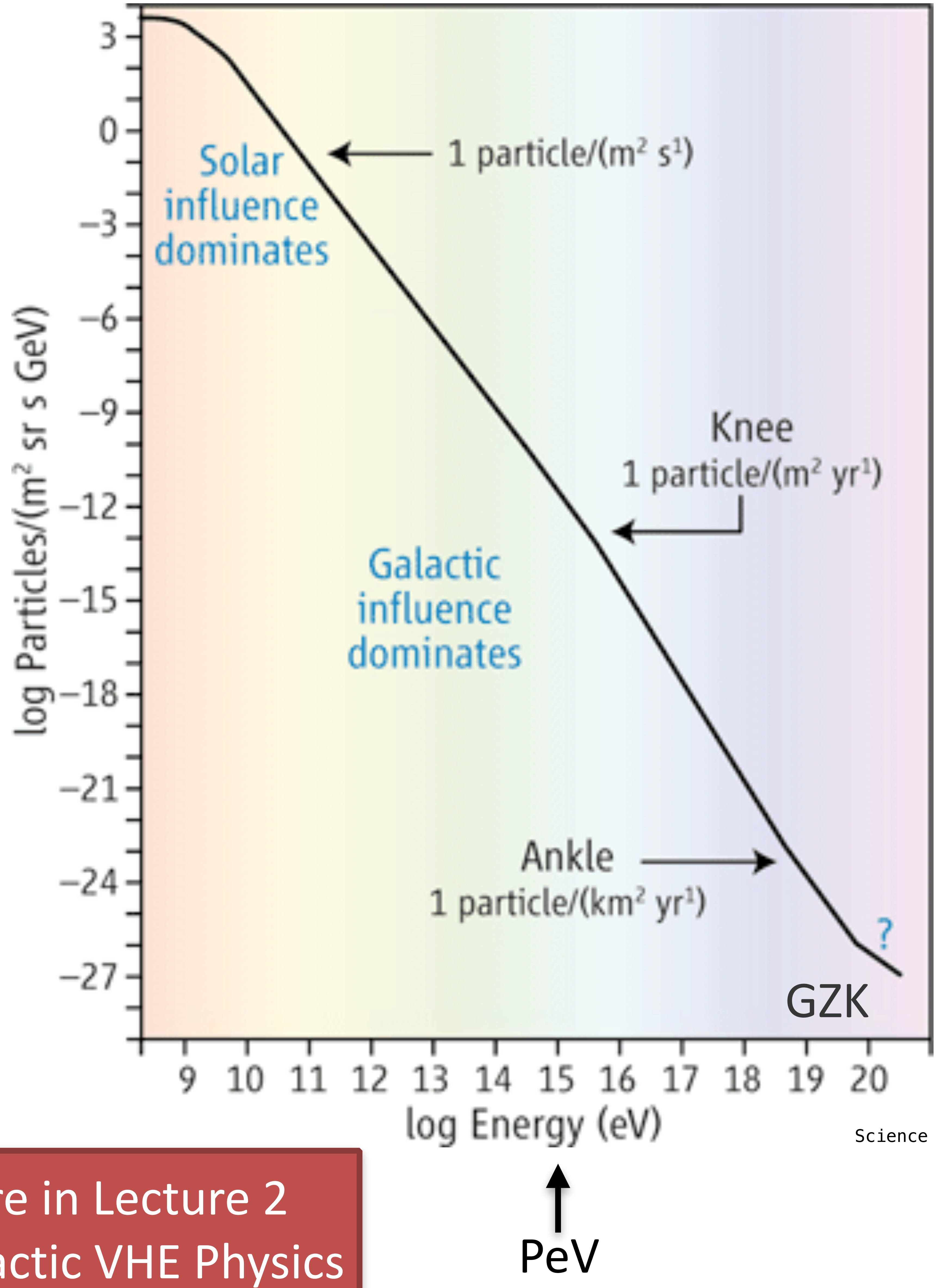




Gamma rays: why are they interesting?

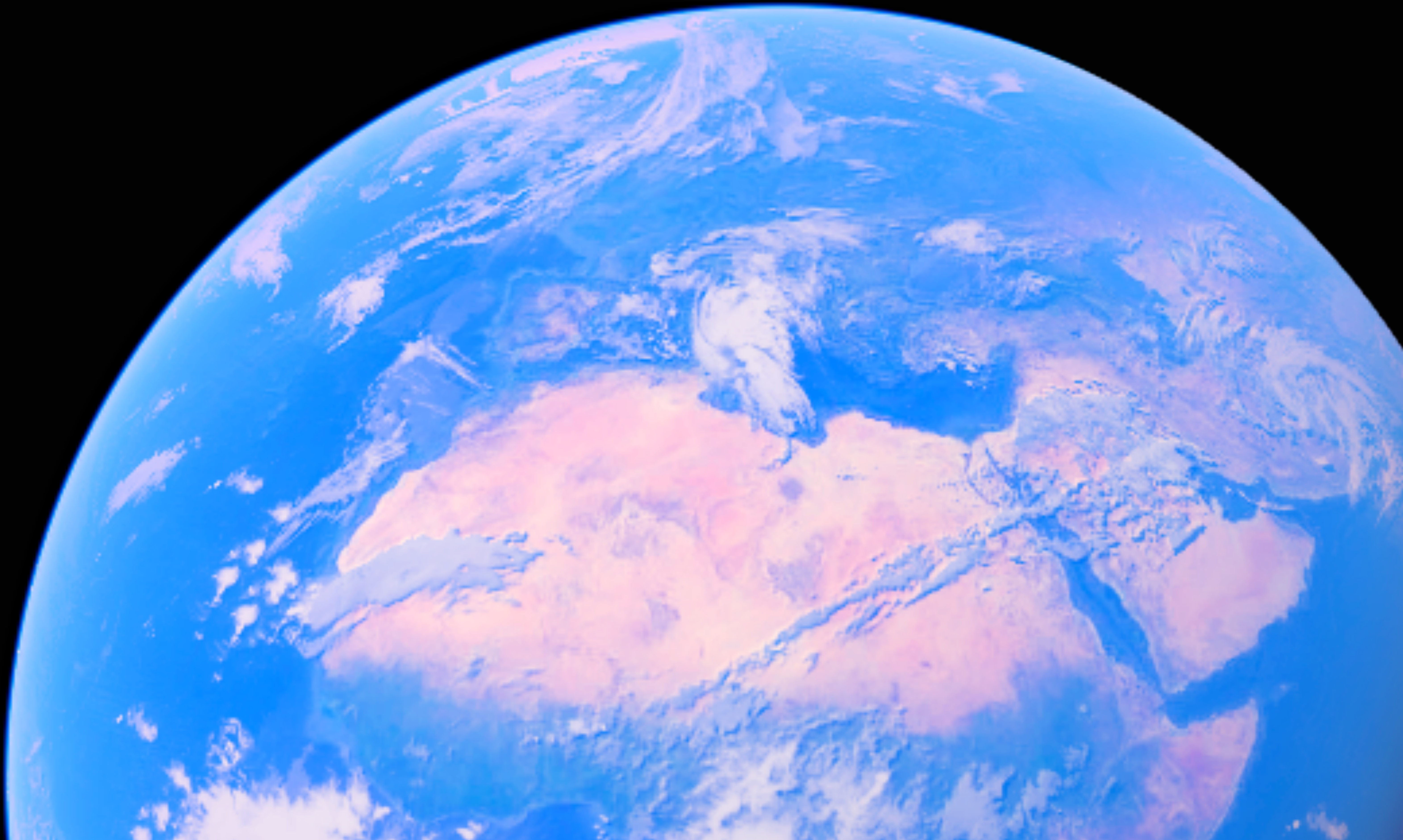
- **Origin of cosmic rays**
  - **~98% p^+**, He^{++}, nuclei…
  - $F \sim E^{-\Gamma}$
    - **Below** the knee (~ 10^{15} eV): **Galactic** origin (?)
    - **Above** the ankle (~ 10^{18} eV): **Extragalactic** origin
    - GZK limit ~ 10^{20} eV
  - **Deflected by magnetic fields**
- **Gamma rays to track the origin of cosmic rays**
  - Where are the PeVatrons?



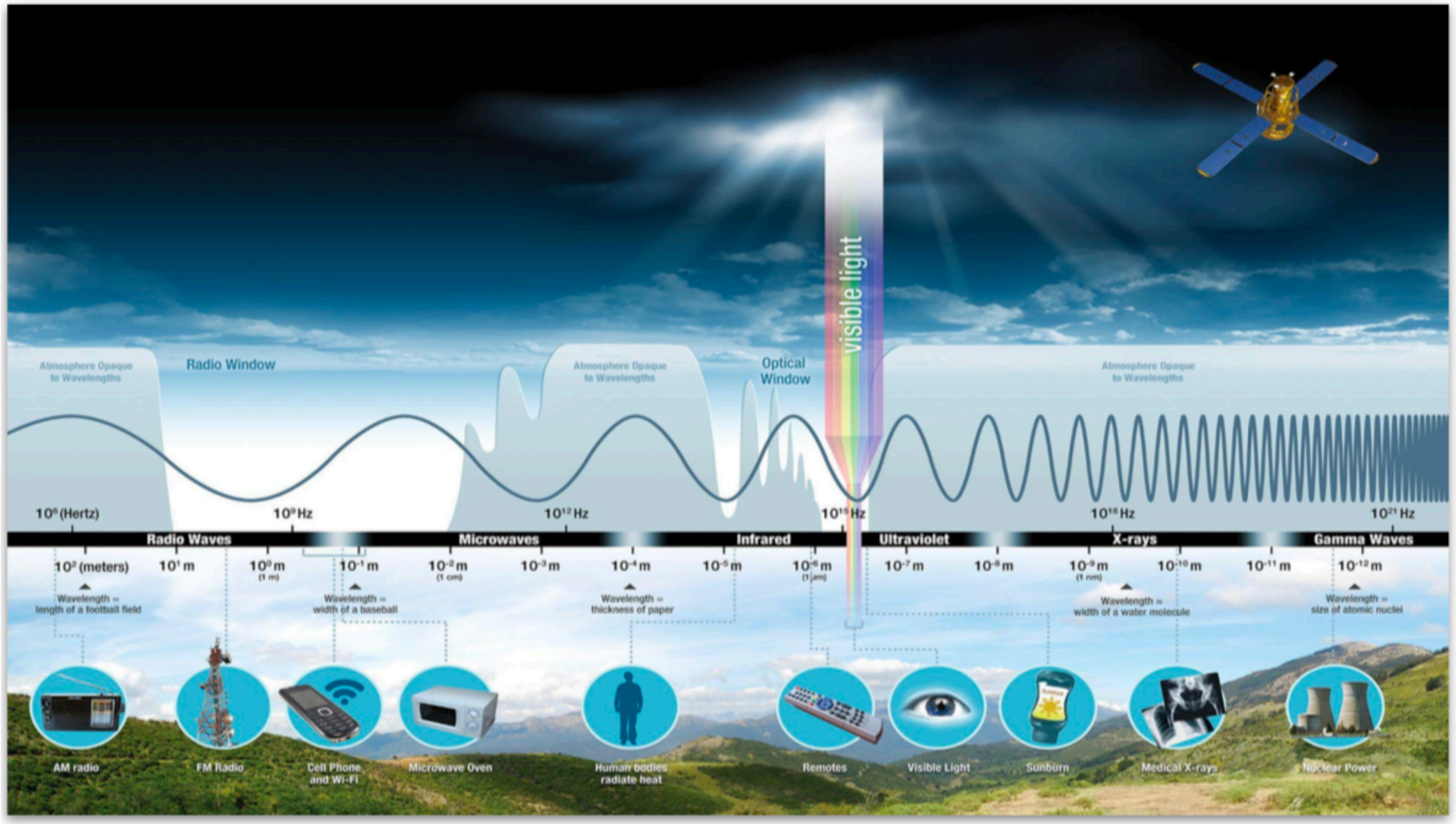


More in Lecture 2
Galactic VHE Physics

How do we detect gamma rays?



Classification and detection of gamma rays



Definitions are somehow arbitrary however:

- **X** 0.1 keV-300 keV
- **X/soft gamma** 300 keV-10 MeV
- **HE** 10 MeV-30 GeV
- **VHE** 30 GeV-30 TeV
- **UHE** 30 TeV-30 PeV
- **EHE** above 30 PeV

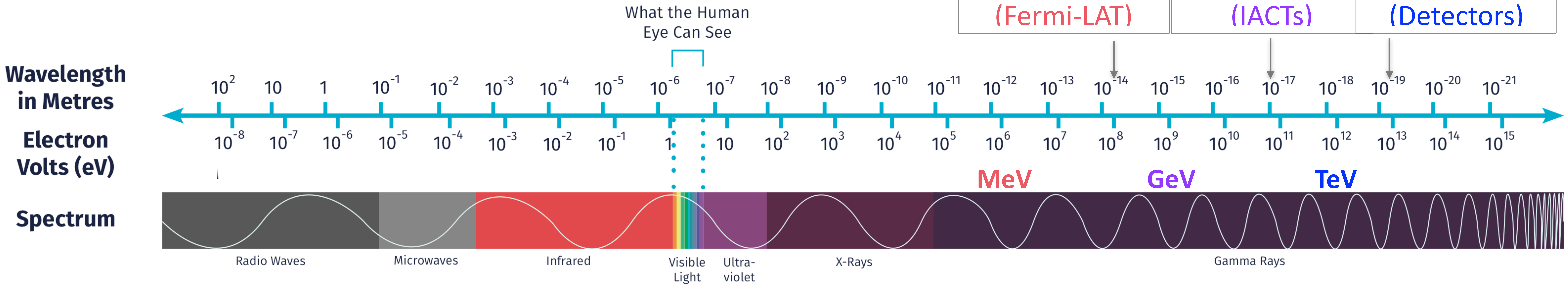
No upper limit, apart from low flux (at 30 PeV, we expect ~ 1/km^2 /day)

Classification and detection of gamma rays

- High energy **(HE) > 100 MeV**
  -> Satellites (*Fermi*-LAT)
- Very high energy **(VHE) > 100 GeV**
  -> (IACTs) Cherenkov telescopes (MAGIC, VERITAS, H.E.S.S., CTA)
- Ultra high energy **(UHE) > 10 TeV**
  -> Particle (EAS) detectors (LHAASO, HAWC)



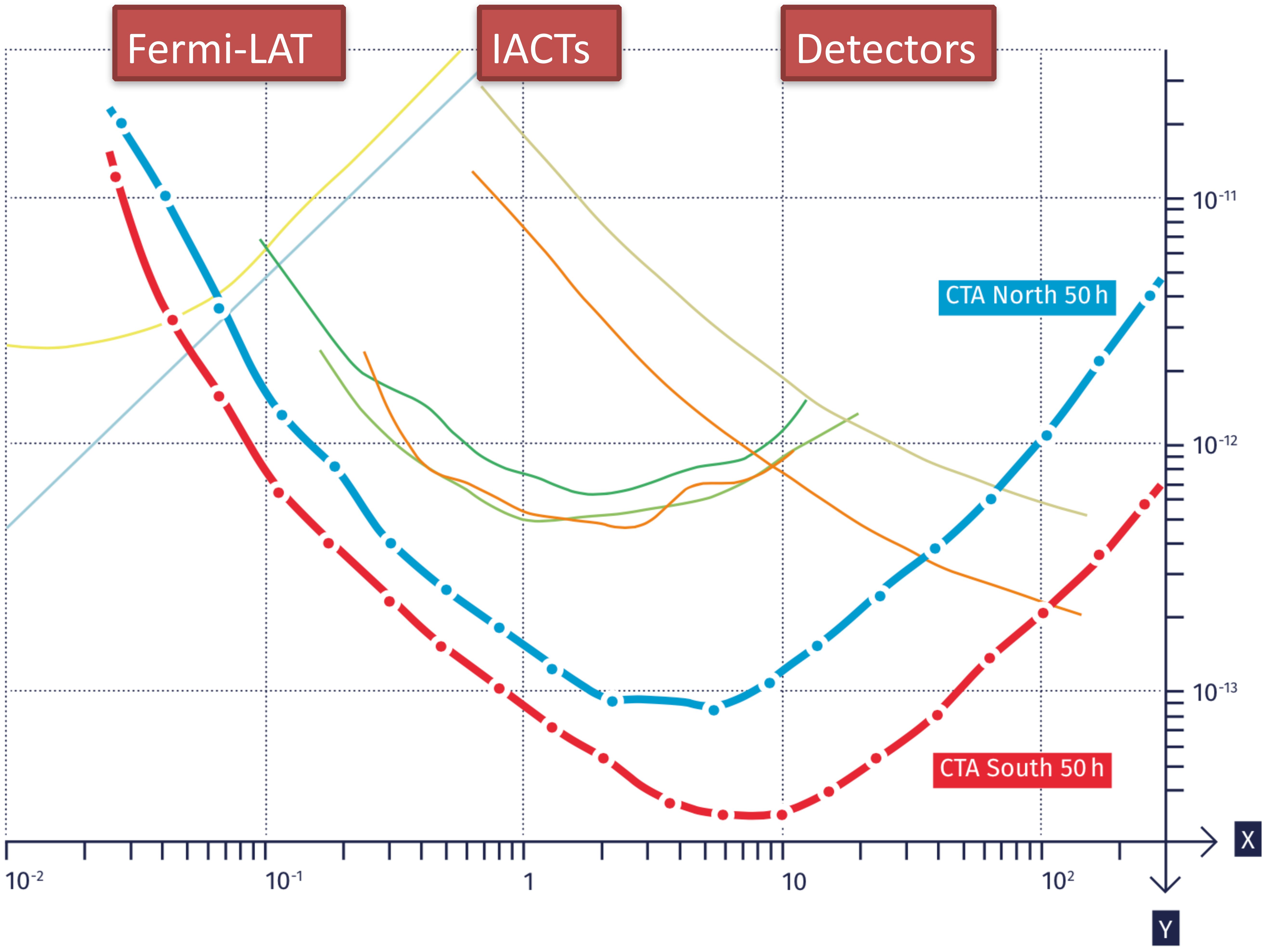
HE	VHE	UHE
E > 100 MeV	E > 100 GeV	E > 10 TeV
(Fermi-LAT)	(IACTs)	(Detectors)



Quantity	*Fermi*	IACTs	EAS
Energy range	20 MeV–200 GeV	100 GeV–50 TeV	400 GeV–100 TeV
Energy res.	5–10%	15–20%	~50%
Duty cycle	80%	15%	>90%
FoV	$4\pi/5$	5° × 5°	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1% Crab (1 GeV)	1% Crab (0.5 TeV)	0.5 Crab (5 TeV)

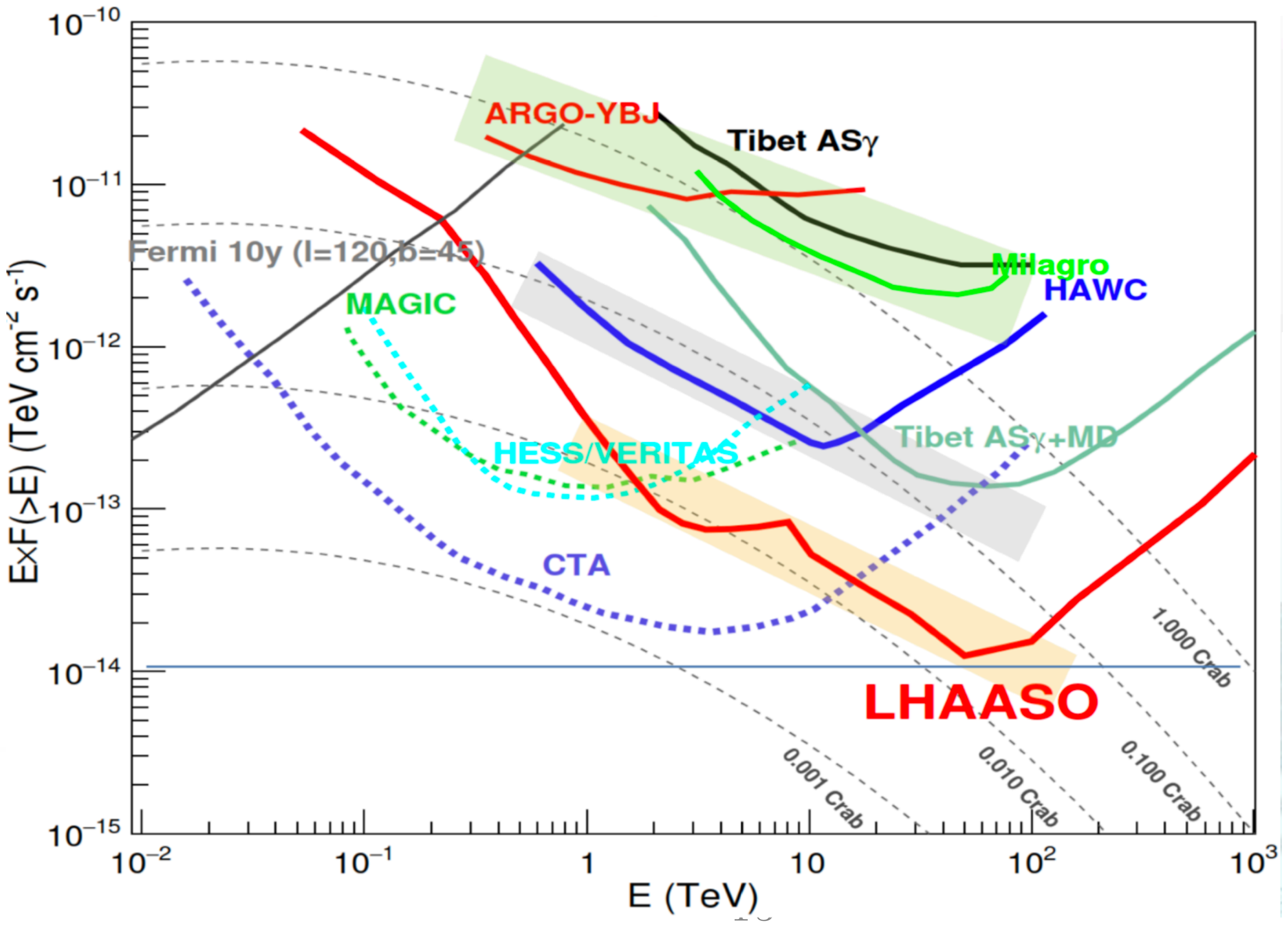
A. De Angelis & M. Pimienta

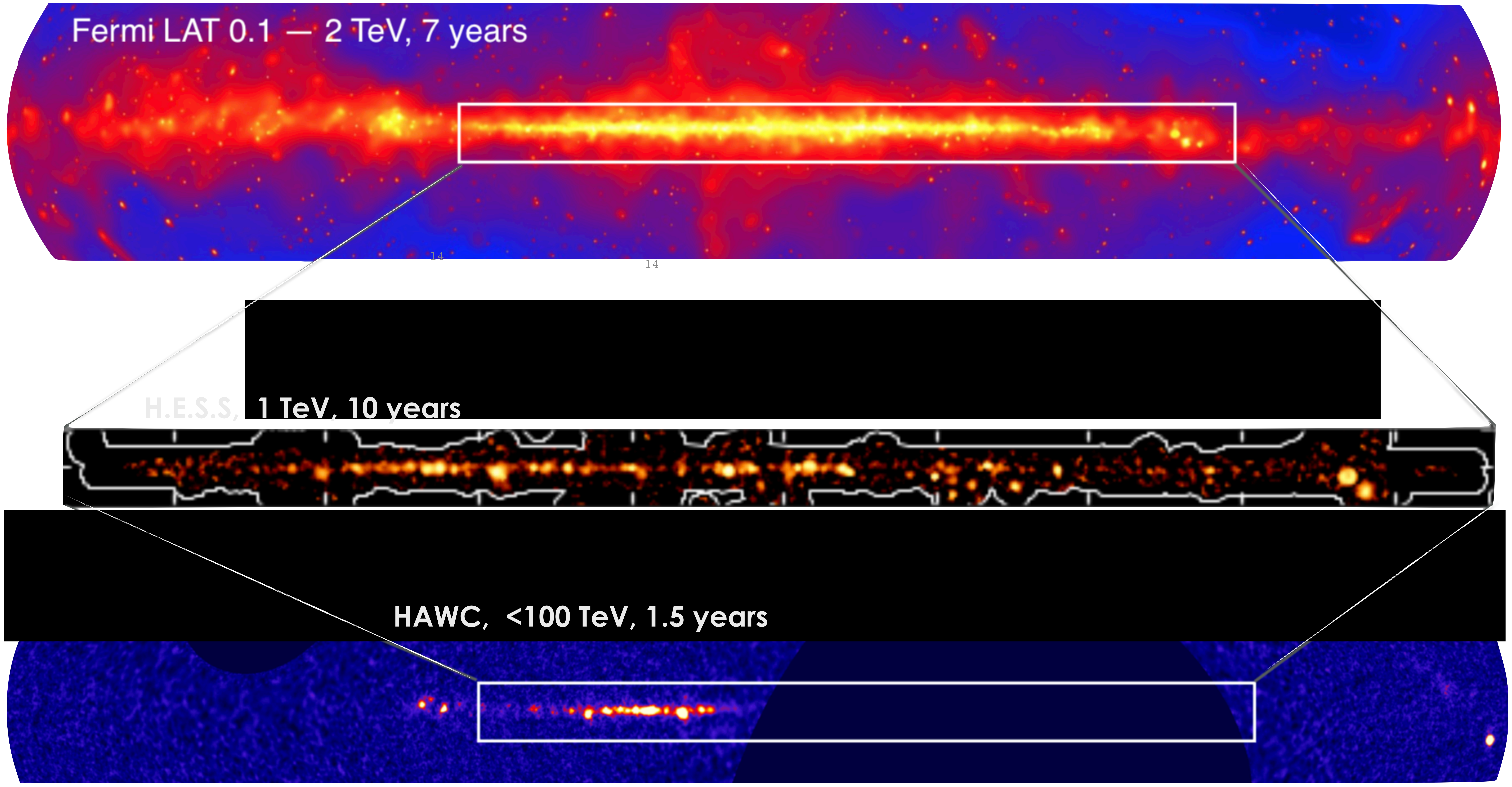
Detecting gamma rays



X = Energy E_R (TeV) Y = E^2 x Flux Sensitivity (erg cm^{-2} s^{-1}) (Differential Flux Sensitivity)

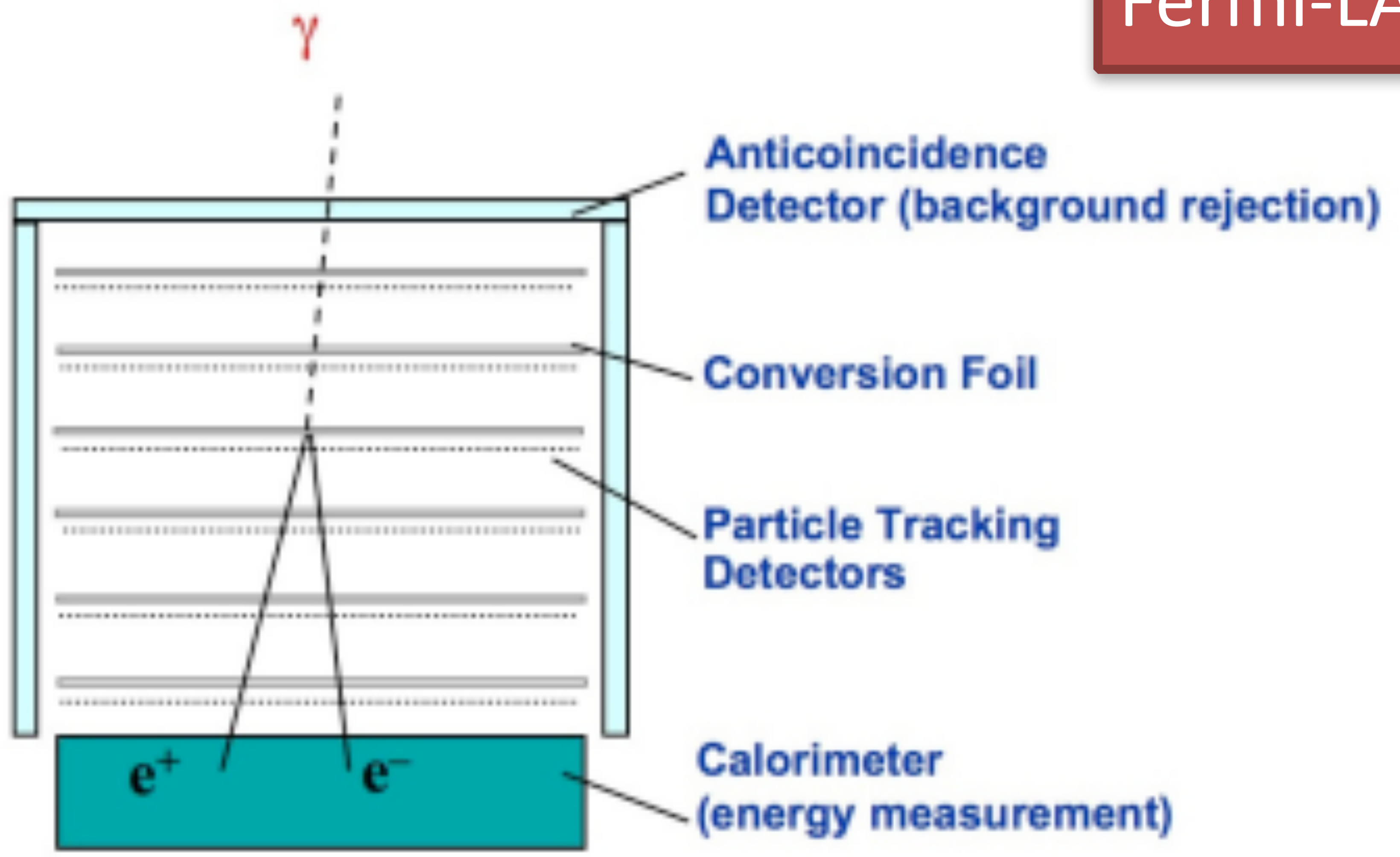
- Fermi-LAT 10 years (Galactic Centre)
- Fermi-LAT 10 years (Extragalactic)
- MAGIC 50 h
- VERITAS 50 h
- H.E.S.S. 50 h
- HAWC 1 year
- HAWC 5 years



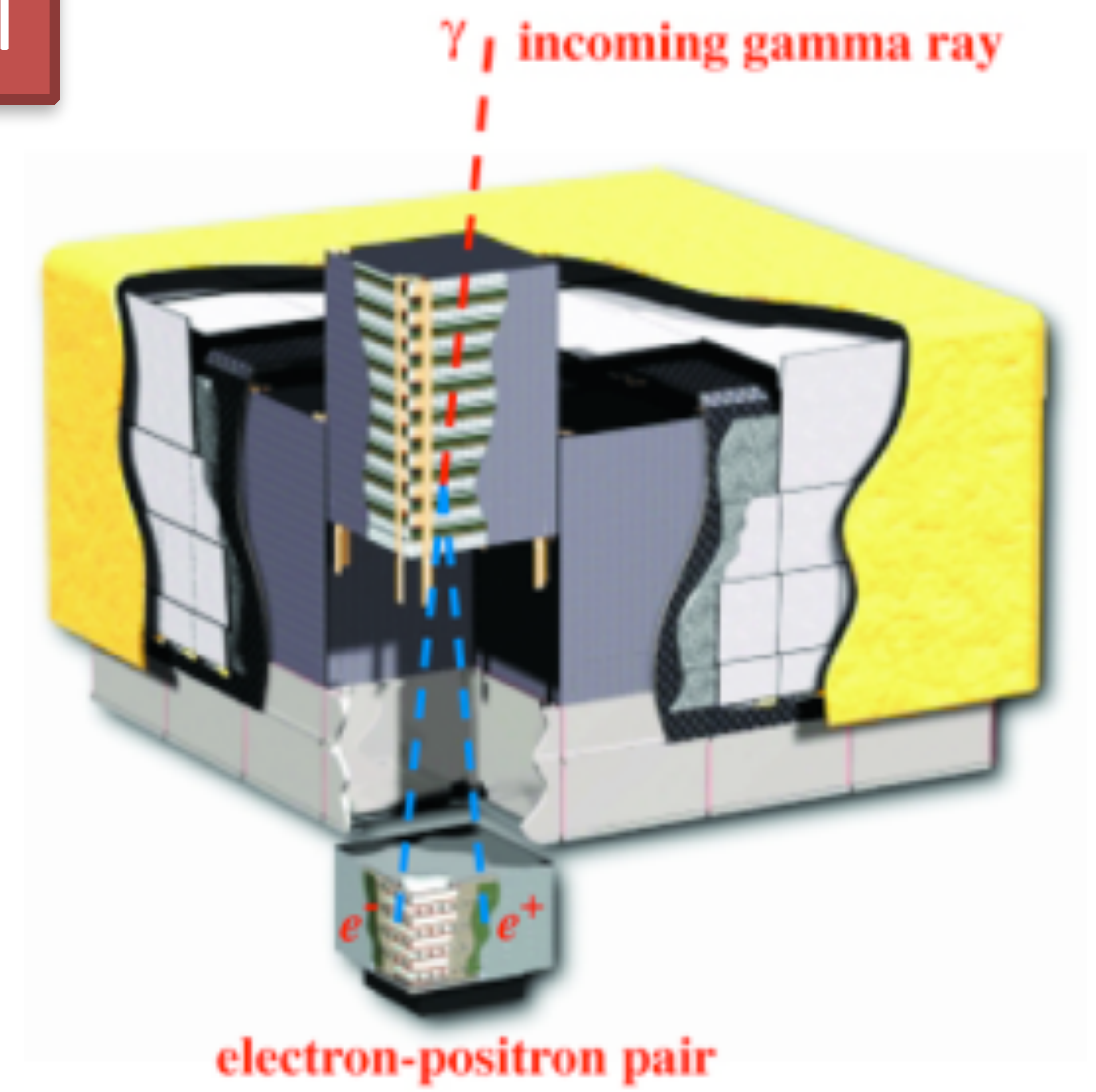

Fermi LAT 0.1 — 2 TeV, 7 years
H.E.S.S., 1 TeV, 10 years
HAWC, <100 TeV, 1.5 years

HE gamma rays: Fermi satellite

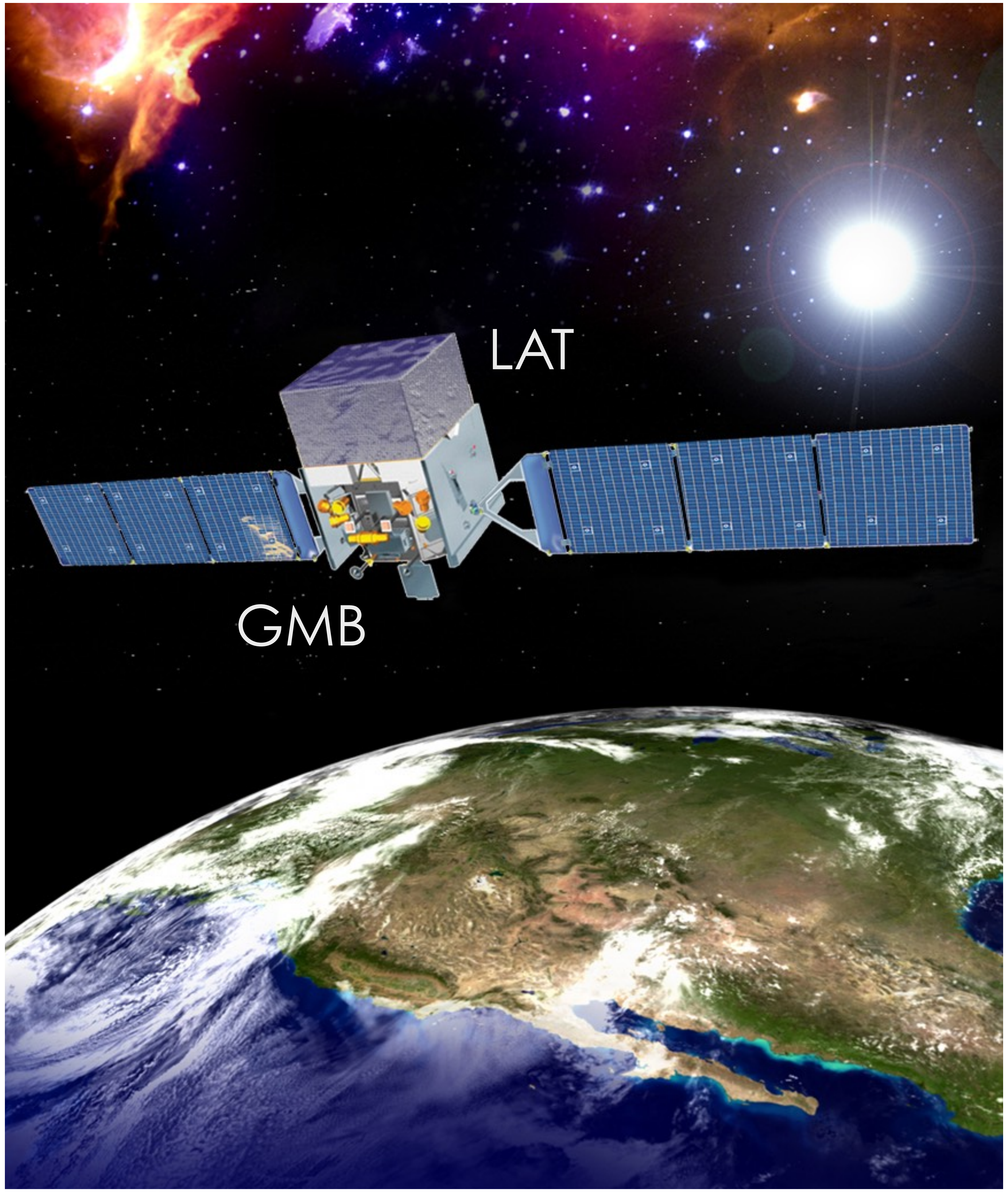
- NASA satellite, launched in 2008
  - FoV: 1/5 of the sky
  - Survey mode: full sky every 3h
- Two instruments onboard:
  - Gamma-ray Burst Monitor (GBM): 10 keV-25 MeV
  - **Large Area Telescope (LAT) : ≳ 50 MeV** -> HE gamma rays
    - **Good angular resolution** -> source localization
    - **High sensitivity in a broad FoV** -> transients and variability



Fermi-LAT



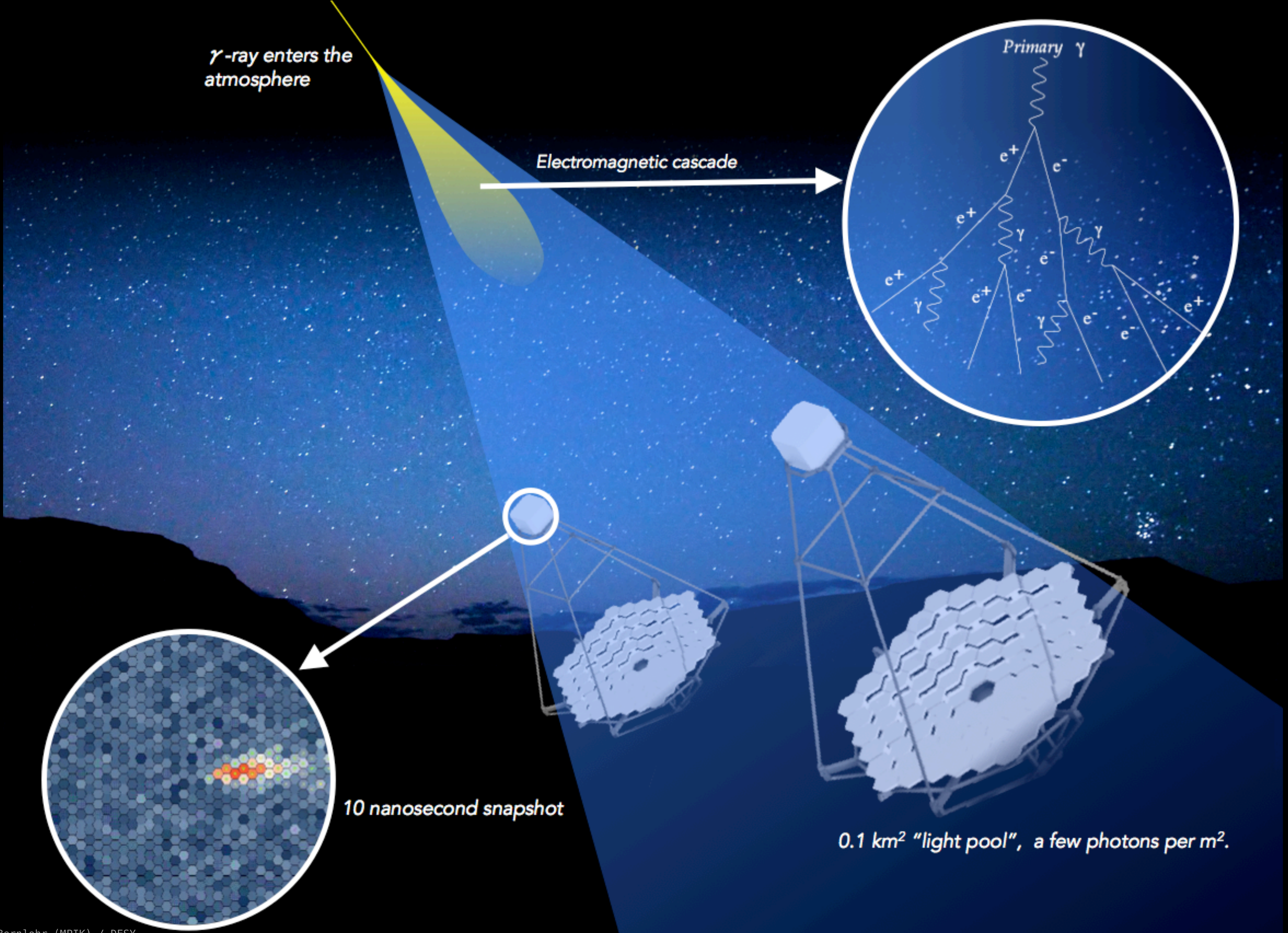
Credits: NASA's Goddard Space Flight Center



IACTs: Imaging Air (Atmospheric) Cherenkov Telescopes (Technique)

VHE gamma rays > 100 GeV

Atmosphere as calorimeter



Credit R. White (MPIK) / K. Bernlohr (MPIK) / DESY

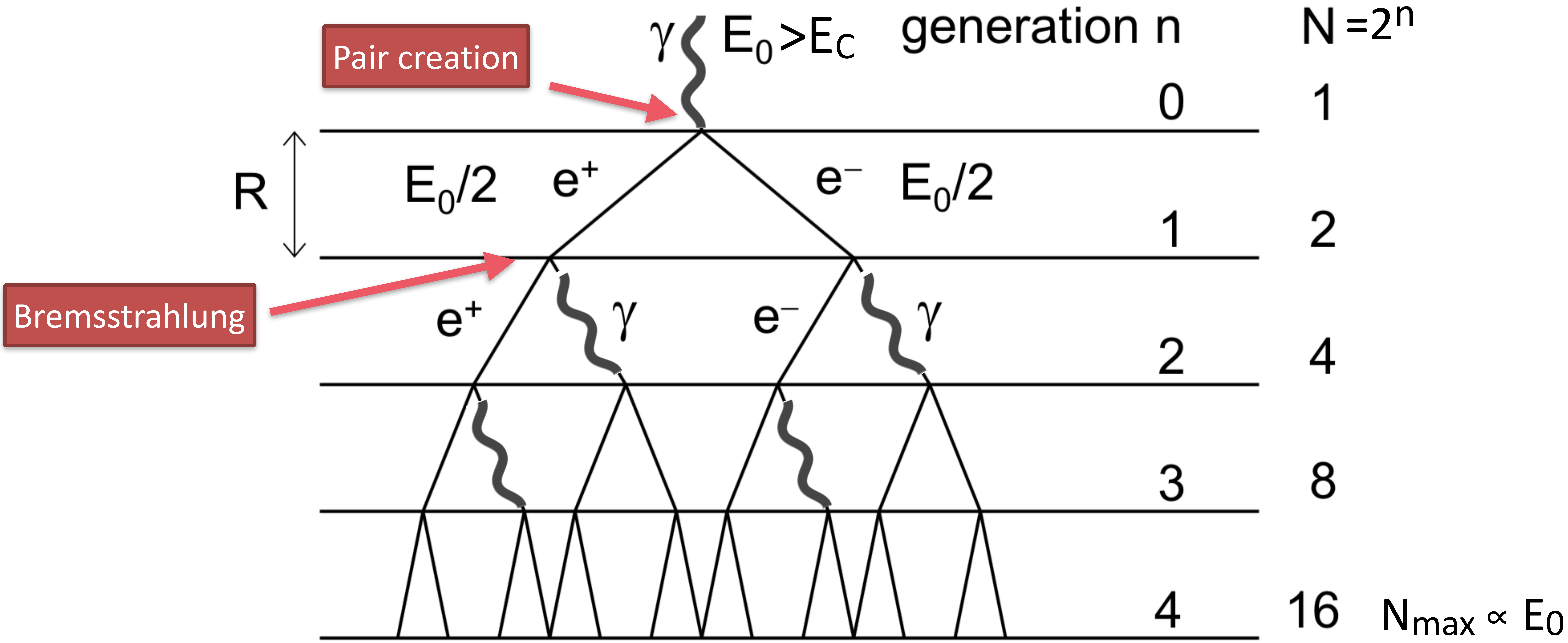
Cherenkov (**355nm**) flashes (~**ns**) emited in air showers

Cherenkov (**355nm**) flashes (~**ns**) emited in air showers

atmosphere as calorimeter

Indirect observation of gamma rays by detecting the **Cherenkov light** that emited by the **air showers** produced by the incident **gamma rays** that interact with the **atmosphere**

Electromagnetic shower: Heitler model



E_C(air)≃85 MeV -> shower stops at $E<E_C$ (ionization loss>bremsstrahlung)

Electromagnetic shower: Heitler model

A simple model for em shower (Heitler 1944):

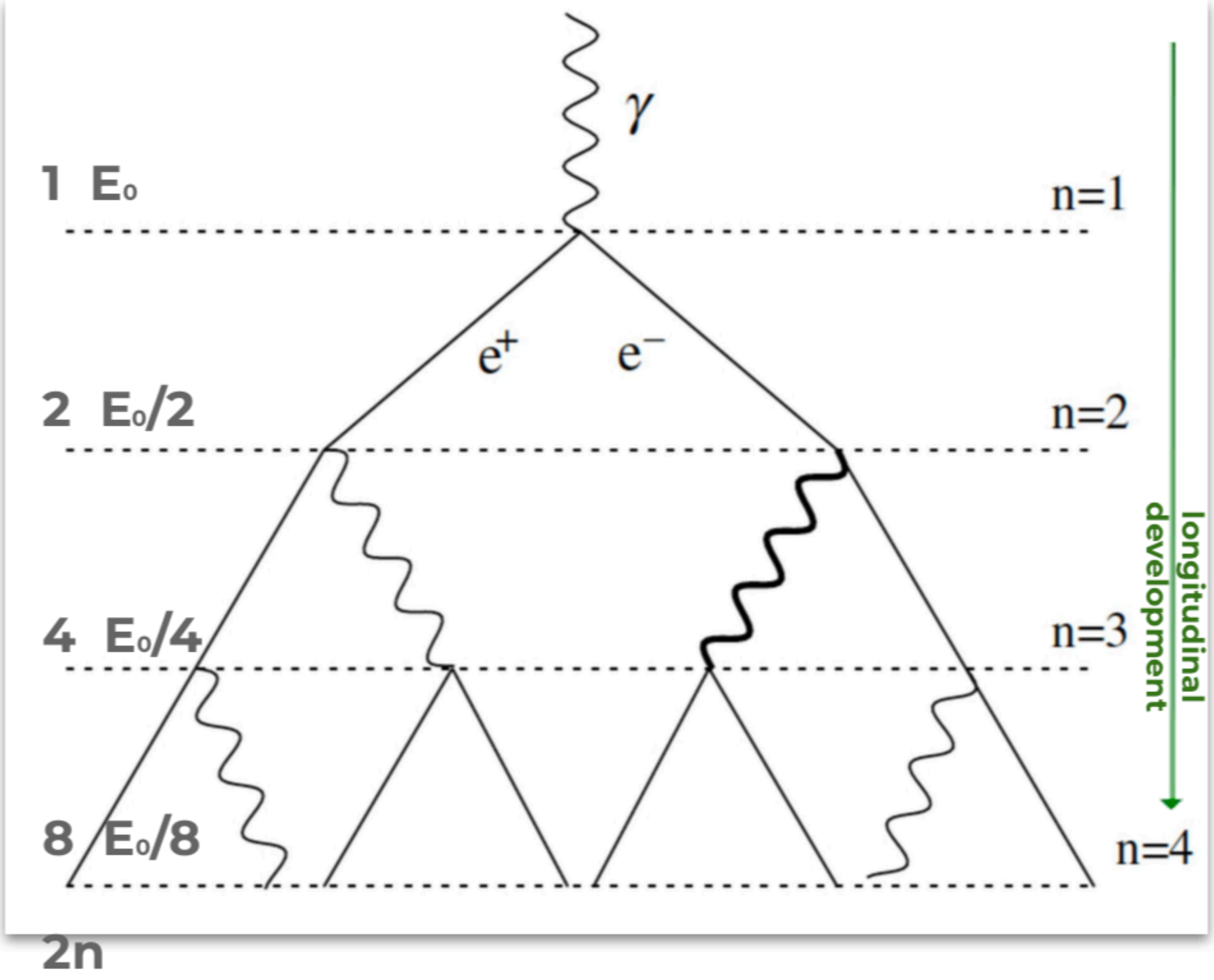
e.m. shower

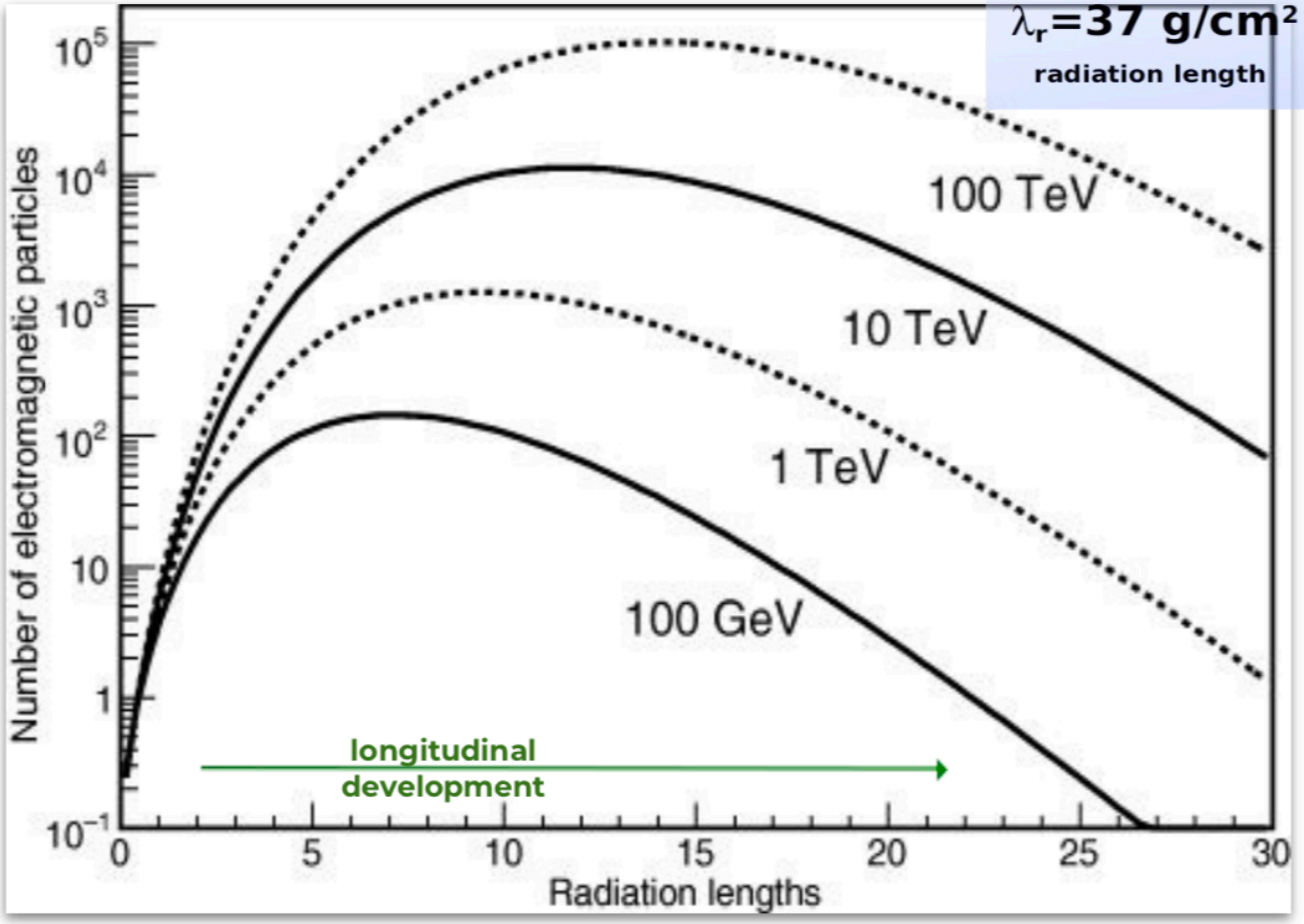
$N_{max} \sim E_0/E_c$

$X_{max} \sim \lambda_r \cdot \ln(E_0/E_c)$

λ_r**=37 g/cm²**

radiation length





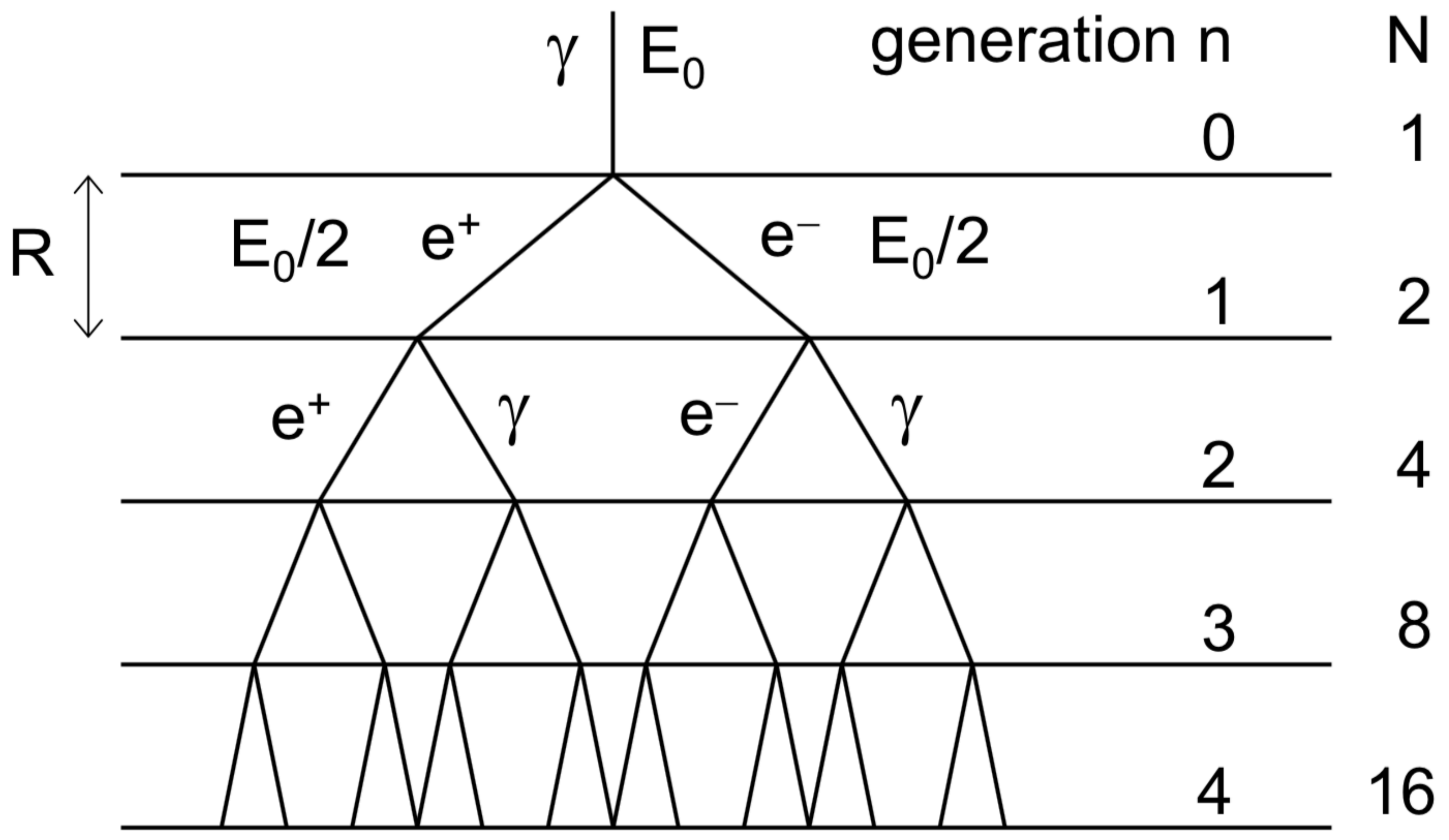
Electromagnetic shower: Heitler model

- The incoming particle has an **initial energy E_0 >> E_c (critical energy)**
    - E_c = 85 MeV -> below which ionization losses >> over bremsstrahlung

- **Energy is equally shared between the products** of each interaction
    - Each electron travels one radiation length and then gives **half of its energy** to a bremsstrahlung photon
    - Each photon travels one radiation length and then creates an electron–positron pair; the electron and the positron **each carry half of the energy** of the original photon

- After traveling a distance $R = X_0 \ln(2)$
- Radiation length X_0 : average distance traversed by an electron in a medium in the time in which its energy drops by a factor e: $E = E_0 e^{-X/X_0}$
    - For air, X_0 = 36.7 g/cm2

- The **number of particles** in the cascade (N) goes on until $E < E_c$, with $N_{max} = E_0/E_c$

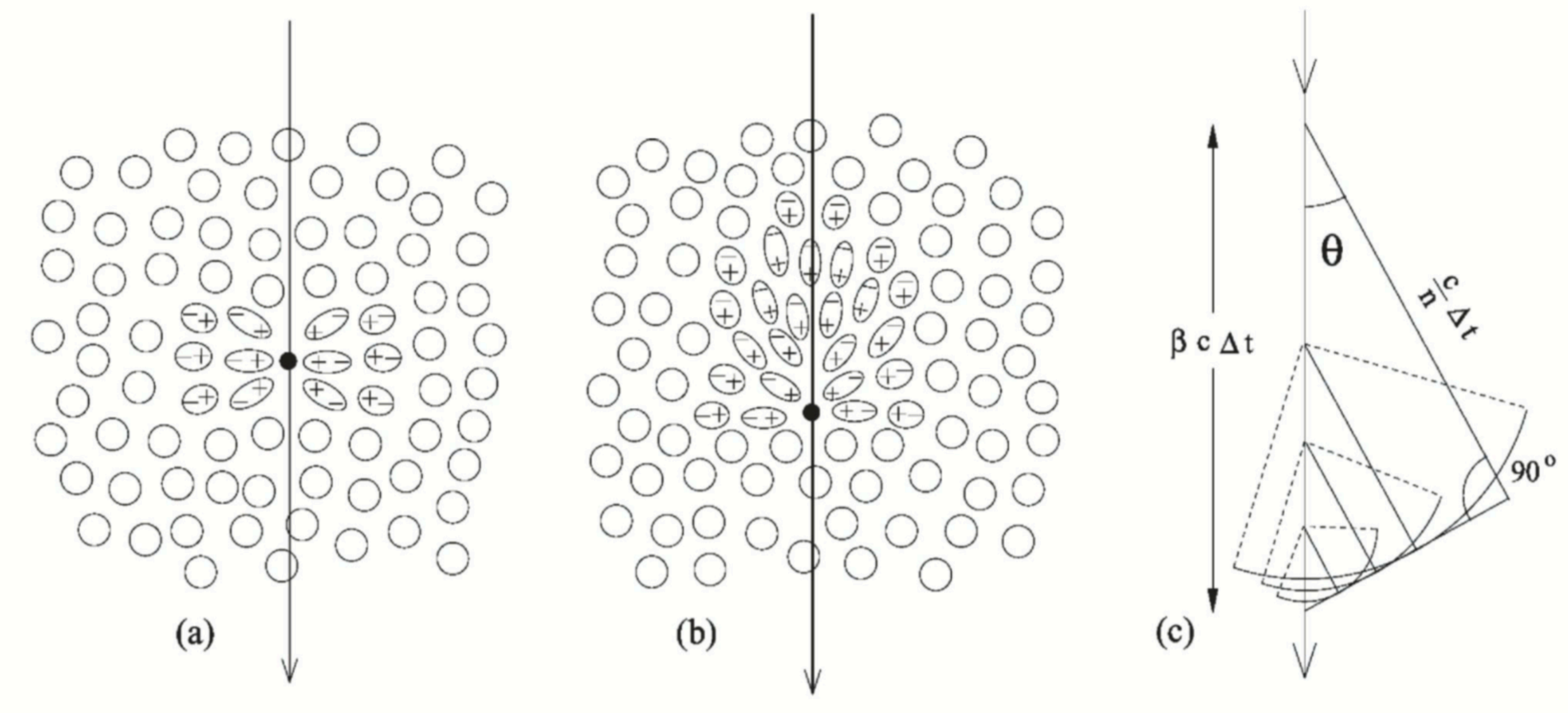


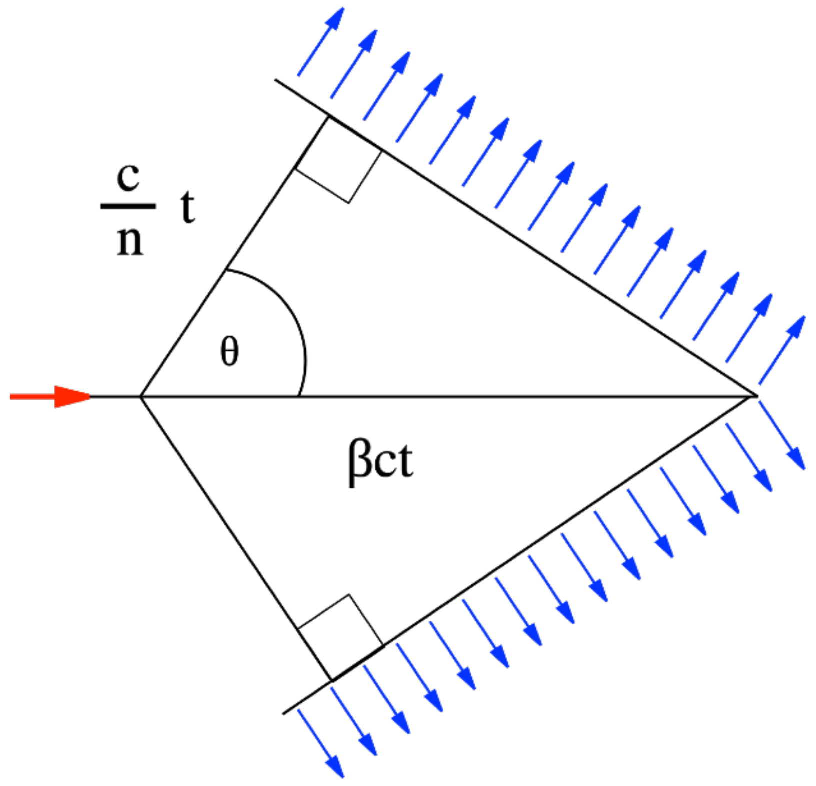
(Vavilov-)Cherenkov radiation

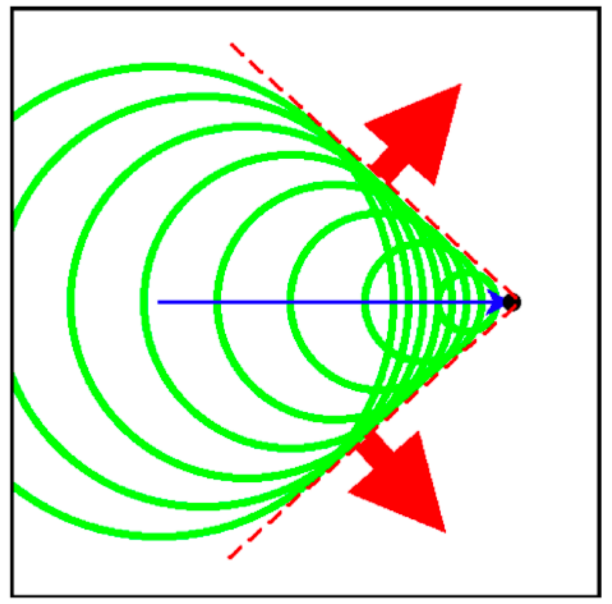

Igor Tamm, Pavel Cherenkov,Ilya Frank

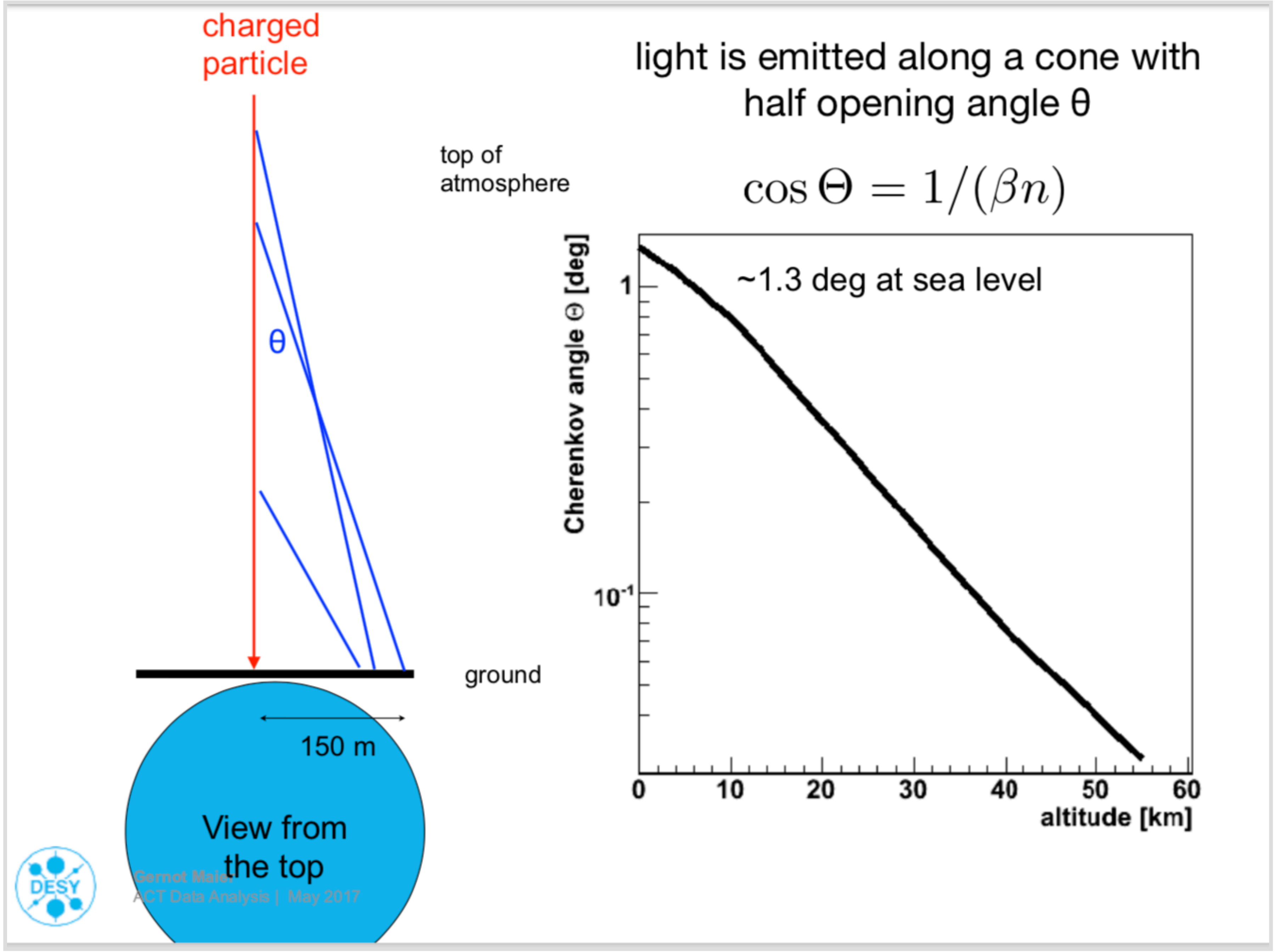

Sergey Vavilov

- Experimentally discovered by Pavel Cherenkov in 1934 (Nobel prize 1958)
- **Particle moving faster than light in a medium**
  - **Peak at 350 nm**
  - **Flashes of ~ns duration**
- Originated by the **re-orientation of electric dipoles** which have been previously polarized by the charge passage
  - wavefronts emitted along the charged particle's trajectory sum coherently
- The light pool of the Cherenkov emission at 2000 m a.s.l is about 120 m radius for 100 GeV EM showers









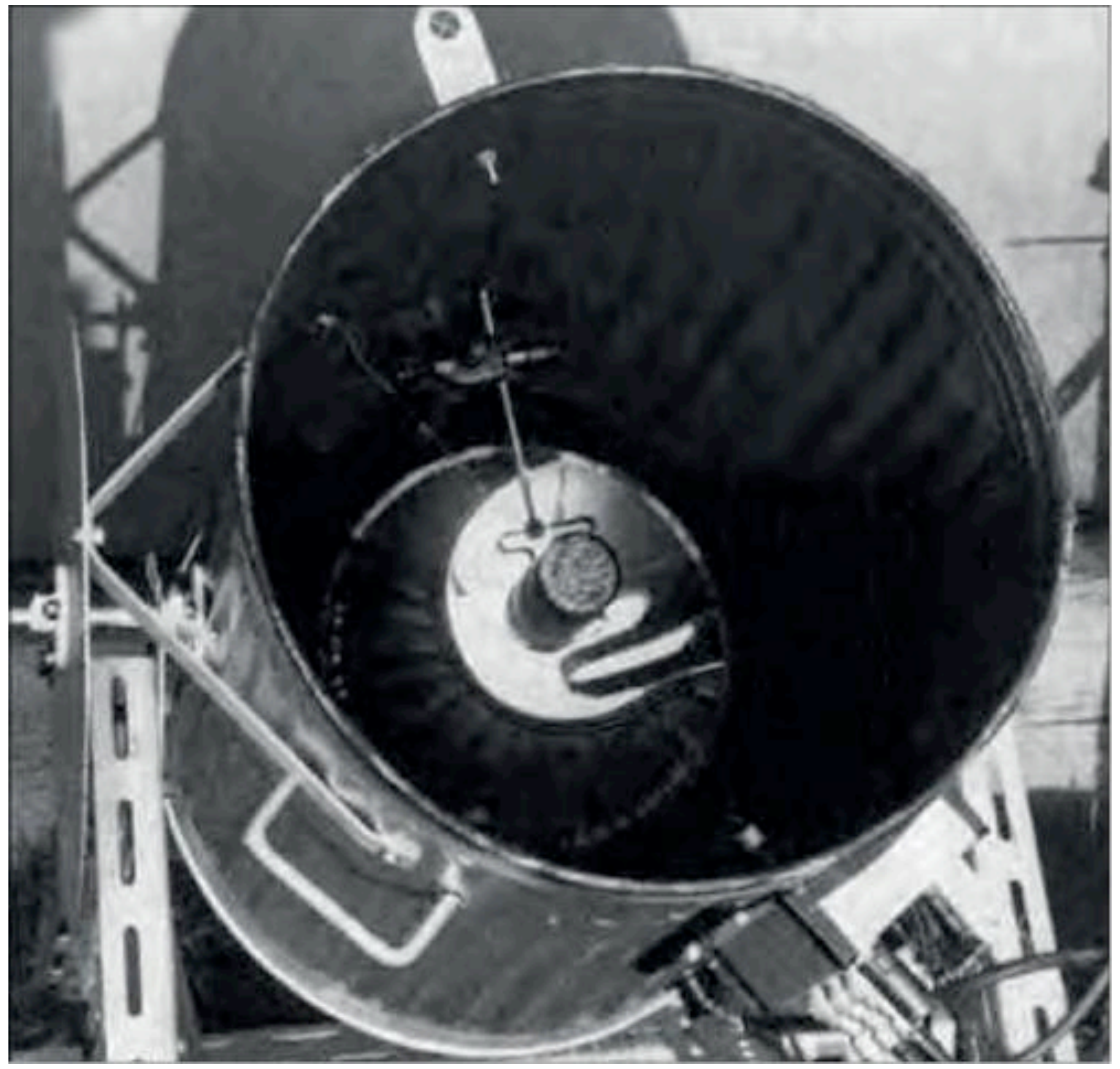
How do we detect them?

IACTs: Imaging Air (Atmospheric) Cherenkov Telescopes (Technique)

Discovery of Cherenkov emission in the atmosphere

Patrick Blackett

- Nobel prize in 1948: for his investigation of cosmic rays using his invention of the counter-controlled cloud chamber
- First person to propose that Cherenkov light should be emitted from particles in the atmosphere



- Bill Galbraith and John Jelley first measure flashes of Cherenkov light in the night sky (Galbraith & Jelley, Nature 1953)
- Confirmed Blackett's assertion that Cherenkov light from charged cosmic rays traversing the atmosphere should contribute to the overall night sky intensity

- Experiments for Cherenkov detection in atmosphere
- First Air Cherenkov observatory for gamma-ray sources (no detection)

Il Nuovo Cimento

Volume 7, Issue 6, March 1958, Pages 858-865

On gamma-ray astronomy(Article)

Morrison, P.

1960ICRC....6b.309C

AN AIR SHOWER TELESCOPE
AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

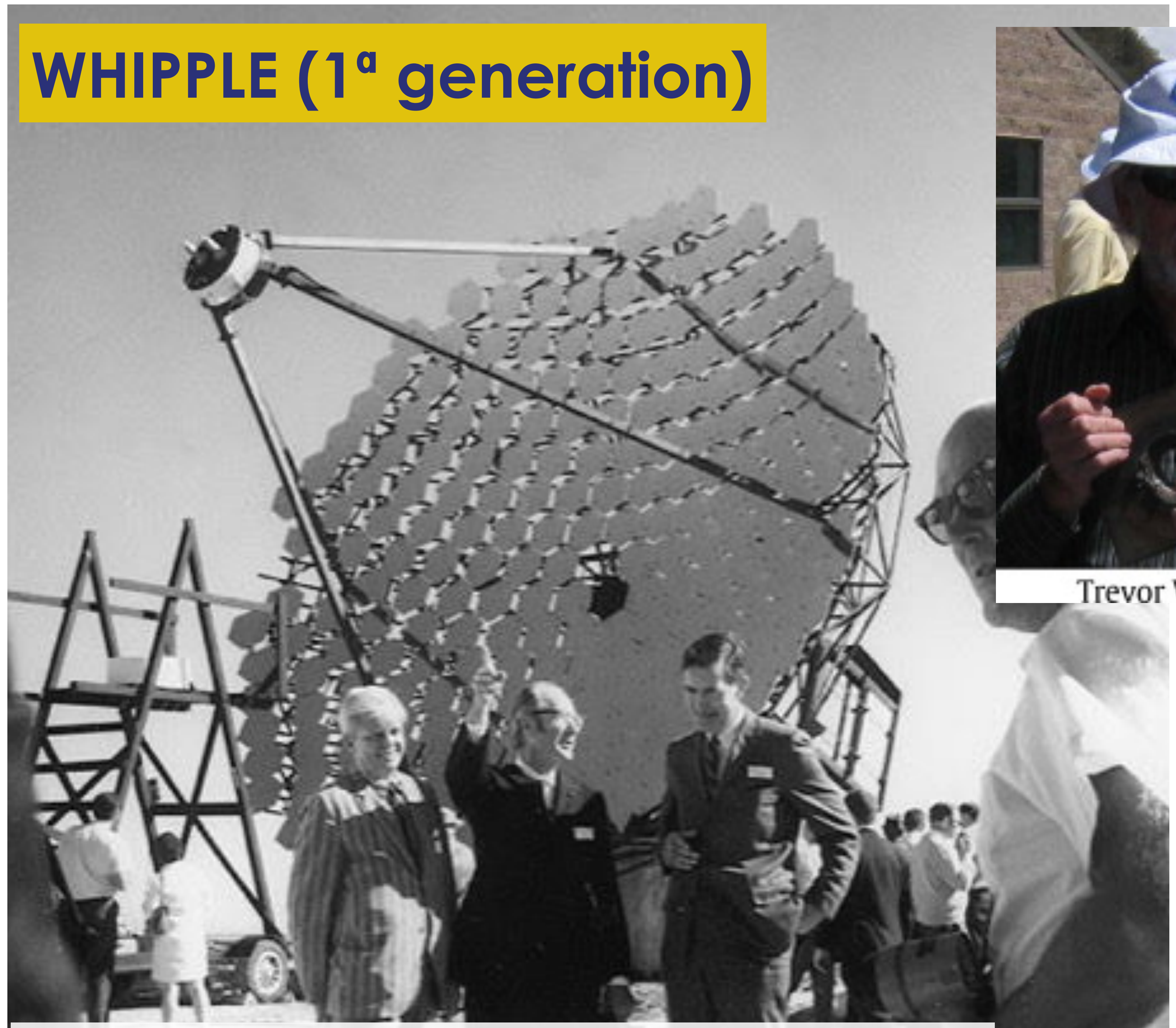
It is proposed that the direction of arrival of the photons, i.e. the direction of their source relative to the earth, be determined by timing on a horizontal plane the arrival of the front of the Air Shower (AS) generated by the photon in the atmosphere.

As shown later, one has to consider photon energies around 10^{12}eV, that initiate showers whose maximum development is reached at high altitudes. If the measurements are performed at about 1/2 atmosphere (5.5 km above sea level), the electromagnetic cascade is there still in full development and contains $\sim 10^3$ ionizing particles.

see Mirzoyan 2014

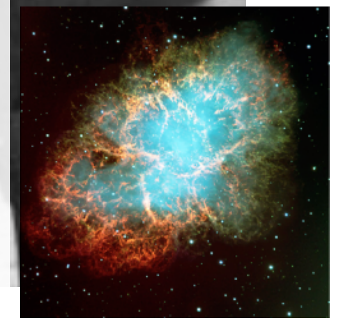
The Imaging Air Cherenkov Technique

WHIPPLE (1ª generation)



Trevor Weekes

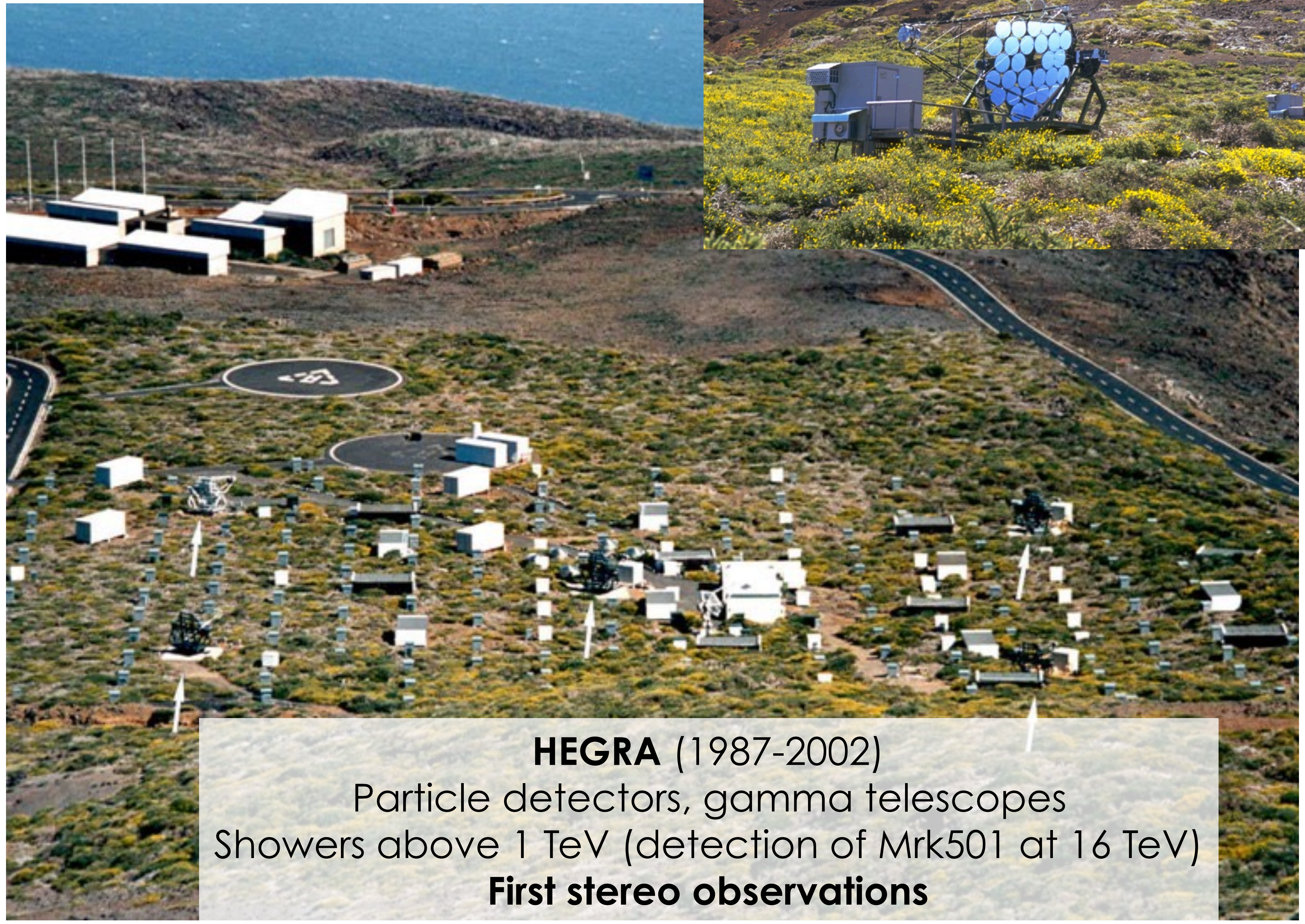
Inaugurated in 1968
1989: 1st source ever detected: Crab Nebula
1996: 2ª detection "Mrk501"
Imaging technique is born



Hillas parameters, 1984
Gamma/hadron discrimination
Milestone for IACT

Michael Hillas

2º generation



HEGRA (1987-2002)
Particle detectors, gamma telescopes
Showers above 1 TeV (detection of Mrk501 at 16 TeV)
First stereo observations

The Imaging Air Cherenkov Technique

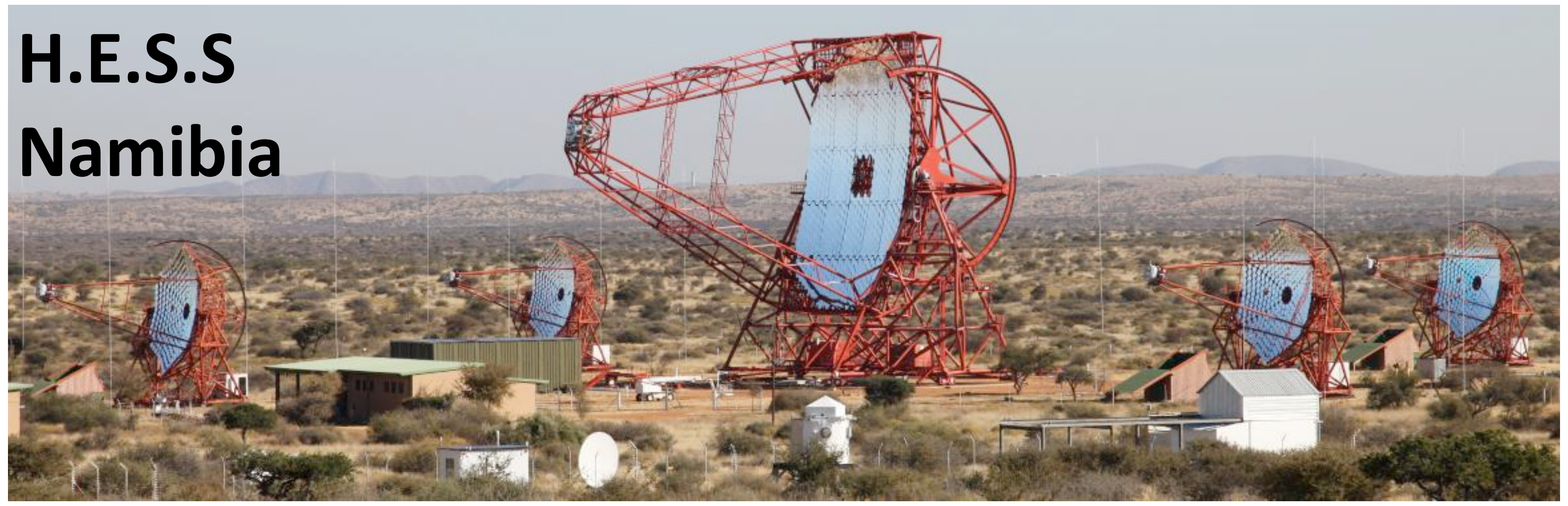
The Imaging Air Cherenkov Technique

3 generation

- **Indirect detection** of VHE gamma rays
- **Cherenkov** (**355nm**) flashes (**ns**)
- Characteristics:
  - **Large collection areas** (12-24m)
  - Highly sensitive pixelized camera (**PMTs**)
  - **Fast trigger system and readout** electronics
- Constructed and operated by collaborations of scientists

$$E_{th} = \frac{\sqrt{\phi\ \Omega\ \tau}}{\epsilon\ A}$$

Born as experiments, they proved VHE astrophysics as a fully-developed discipline



IACTs: H.E.S.S.

- High Energy Stereoscopic System
- 4 telescopes 10m (H.E.S.S. I) + 1 telescope 24 m (H.E.S.S. II)
- 2002: first H.E.S.S. telescope
- 2012: H.E.S.S. II telescope

IACTs: VERITAS

- Very Energetic Radiation Imaging Telescope Array System
- four 12m telescopes
- 2004: first light of VERITAS prototype
- 2007: Completion of 4 telescope array

IACTs: the MAGIC *Florian Goebel* telescopes

Major
Atmospheric
Gamma-ray
Imaging
Cherenkov

- 2 telecopes, Φ=17 m
- E: ~30 GeV-100 TeV (VLZA technique)
- MAGIC-I: 2003
- MAGIC-II: 2008

Extensive Air Showers (EAS)

A. Chantelauze, S. Staffi, L. Bret

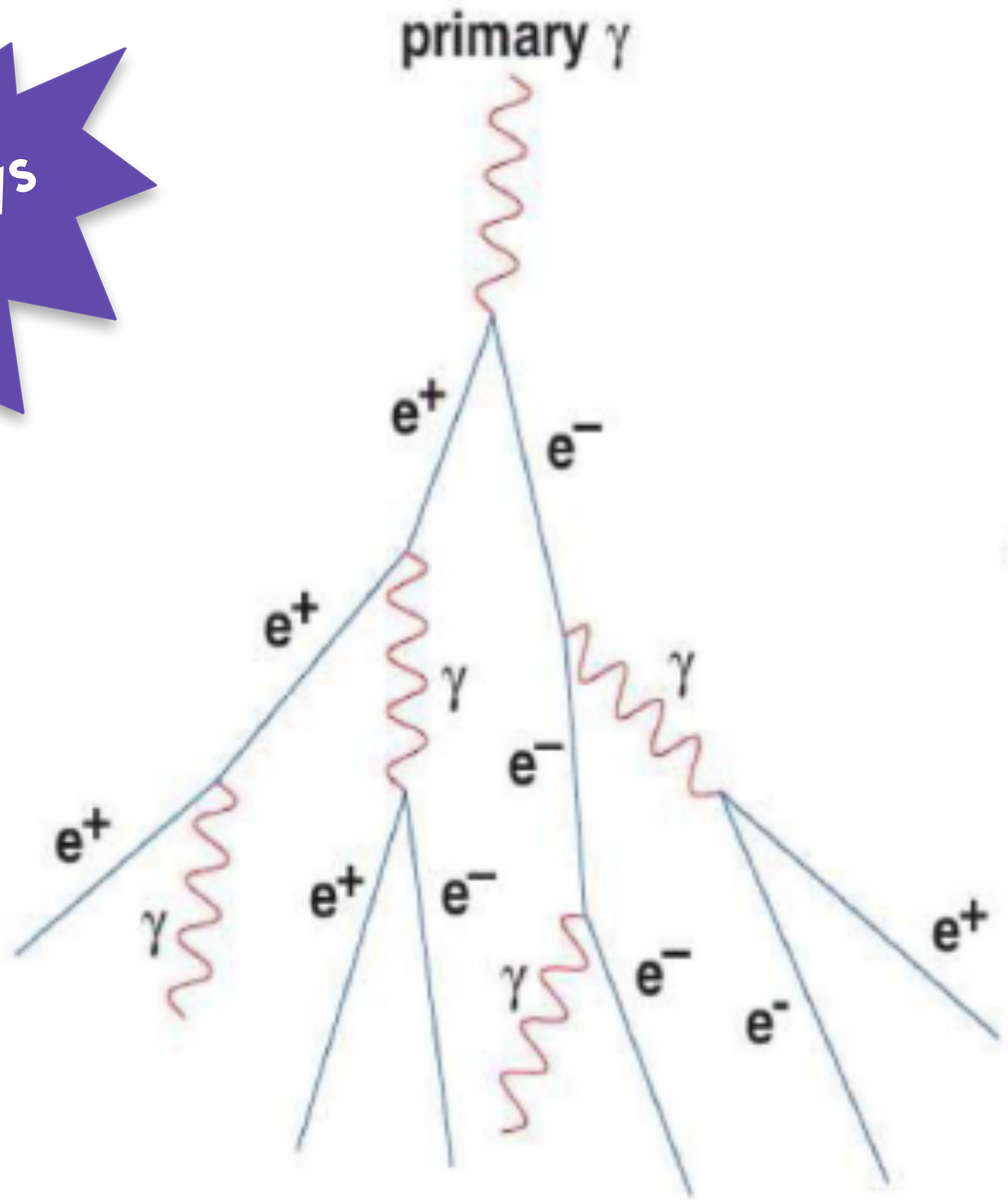
Extensive Air Showers (EAS)


EAS discovered by Pierre Auger in 1938

GAMMA RAYS

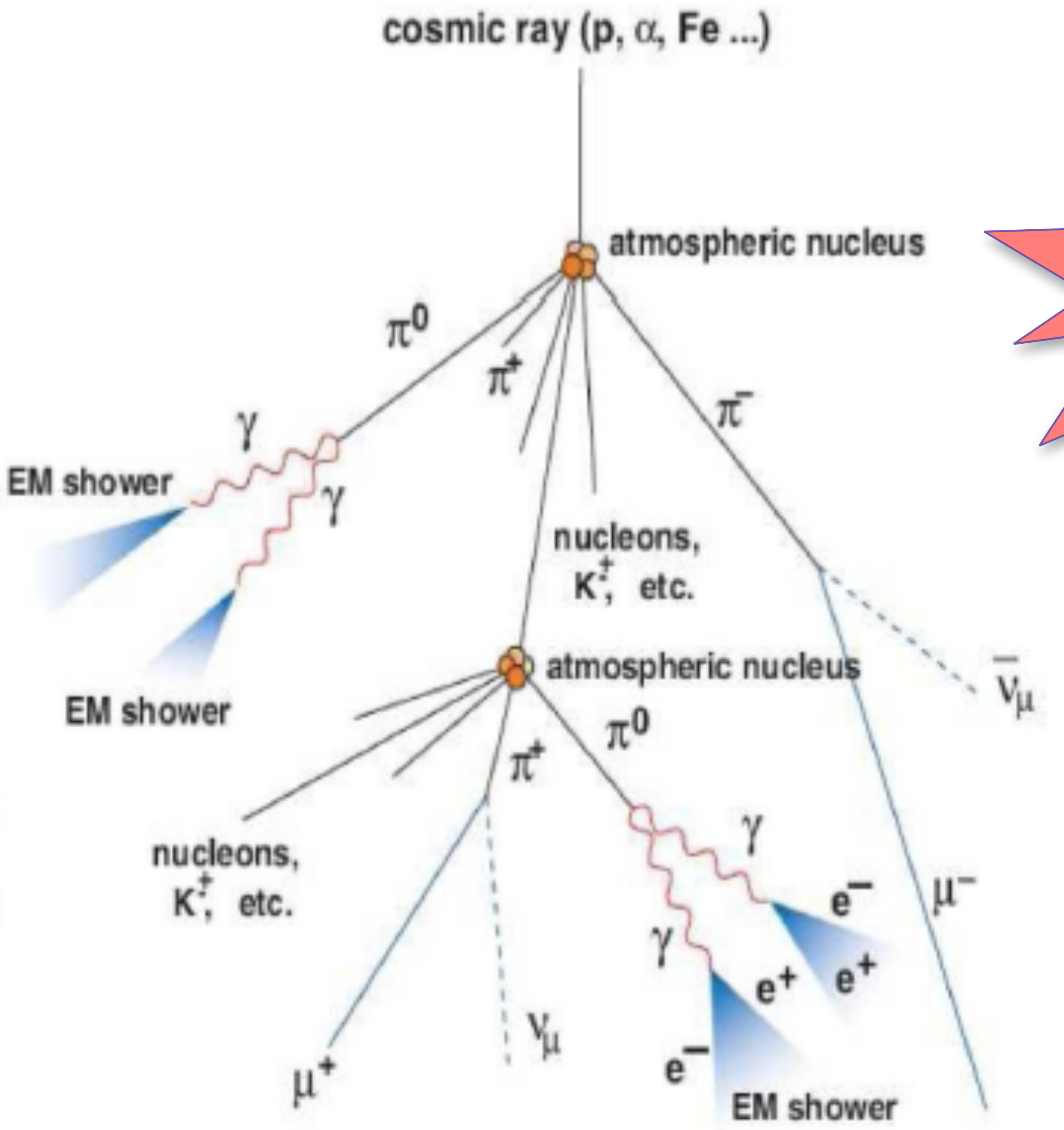
Electromagnetic Shower

Gamma rays



Cosmic rays

Hadronic Shower



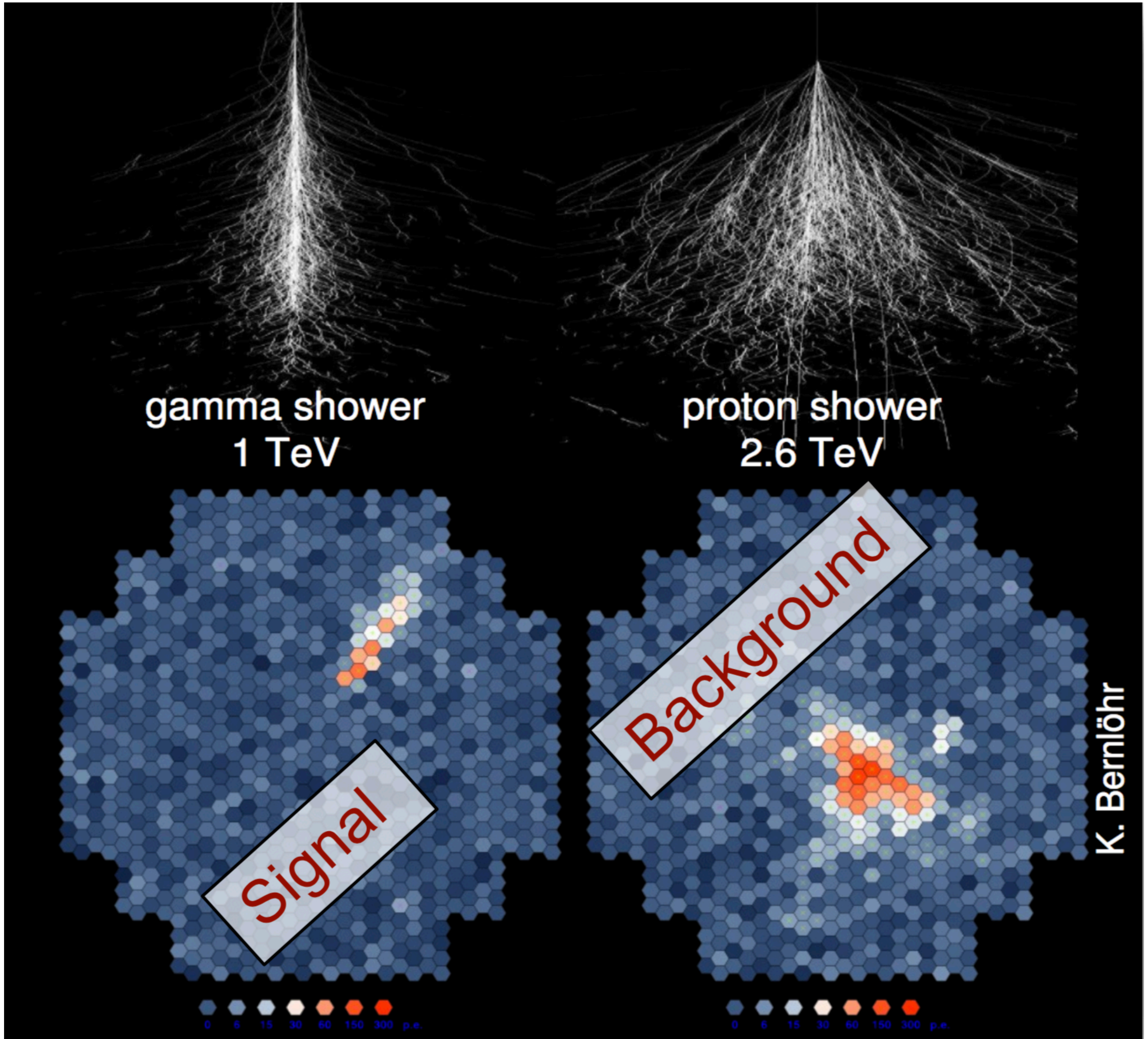
Background

Pair production + bremsstrahlung

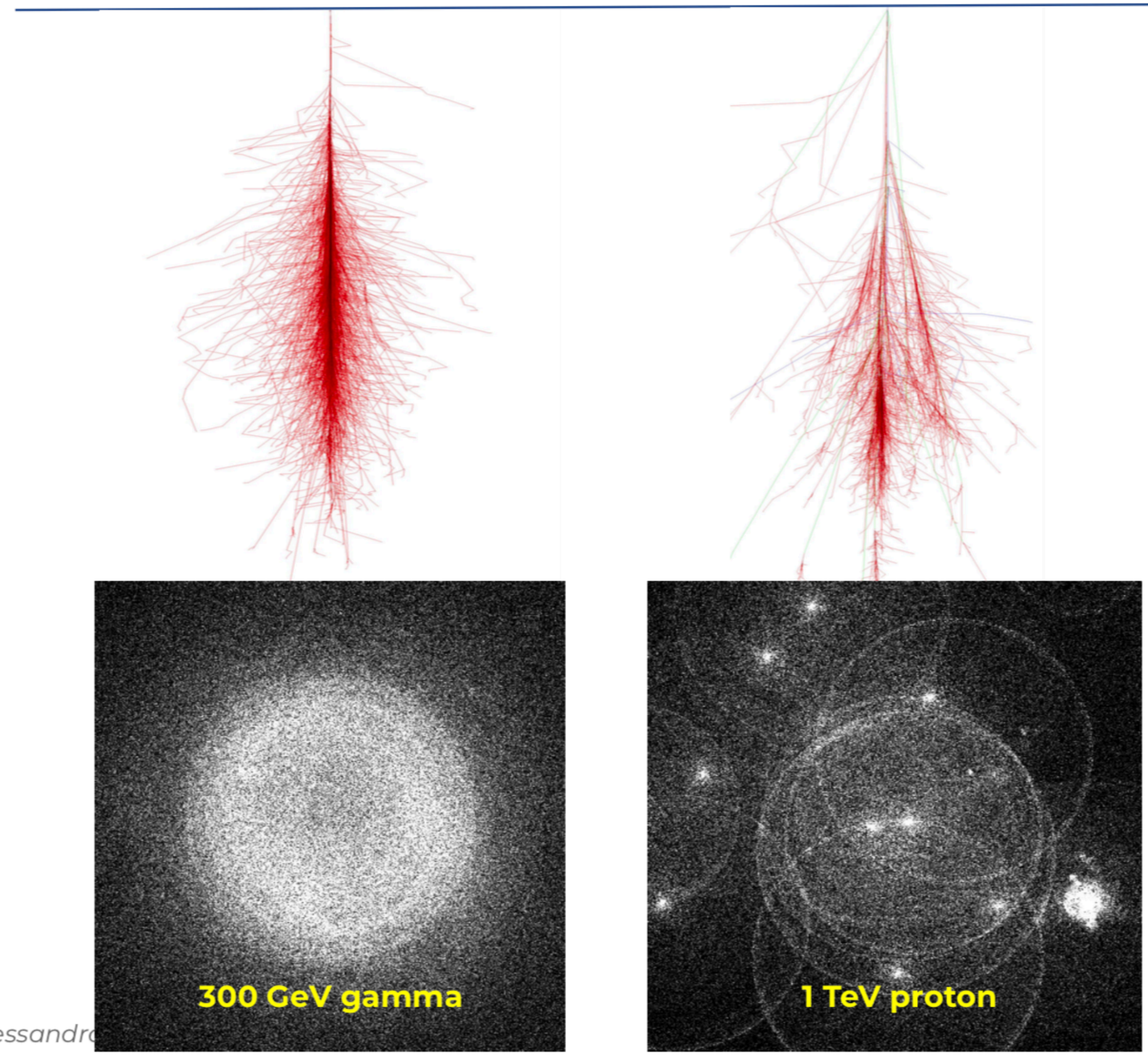
Hadronic interaction + sub-showers from π0 decay

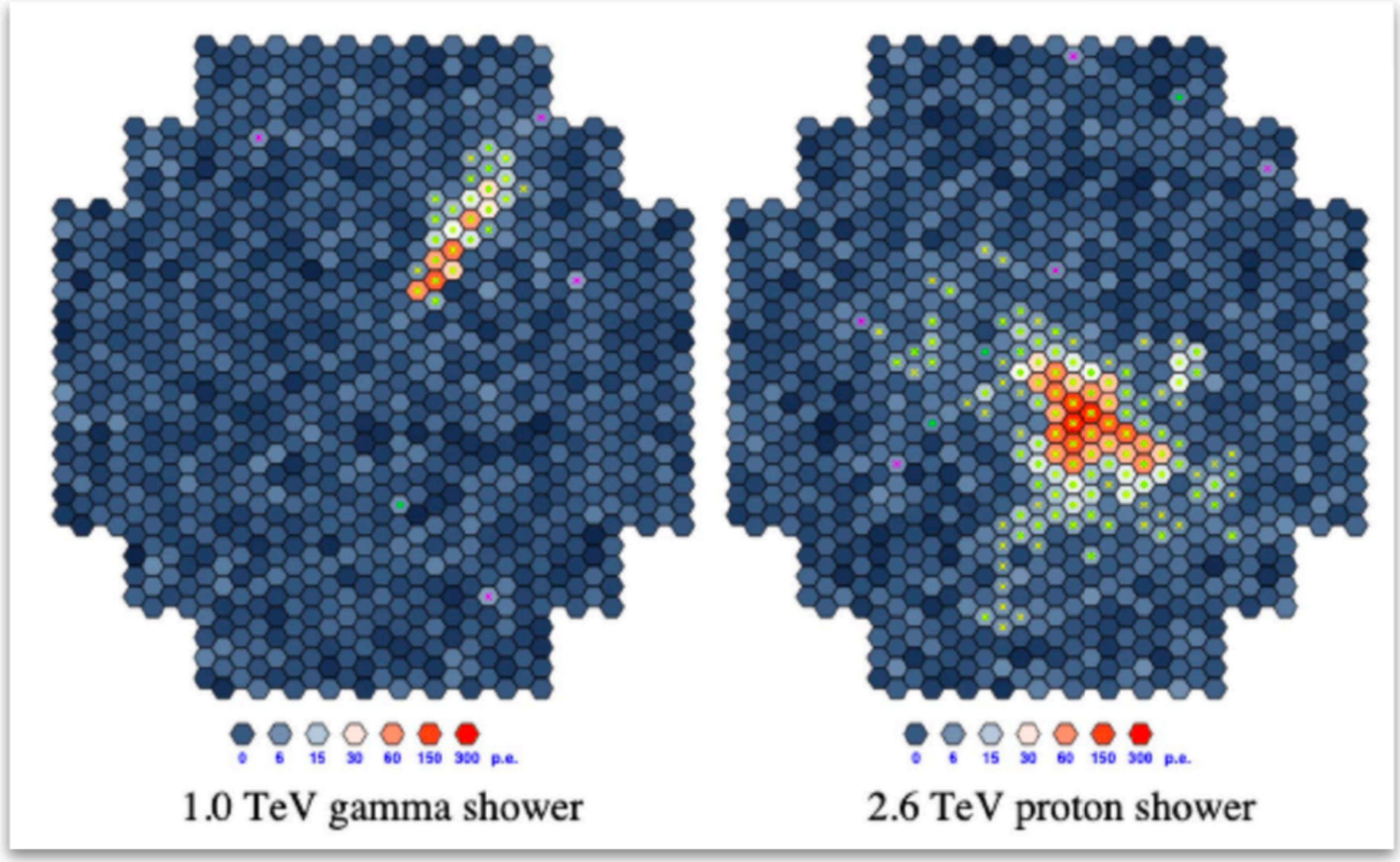
1 gamma - 1000 cosmics

Extensive Air Showers (EAS)



Extensive Air Showers (EAS)

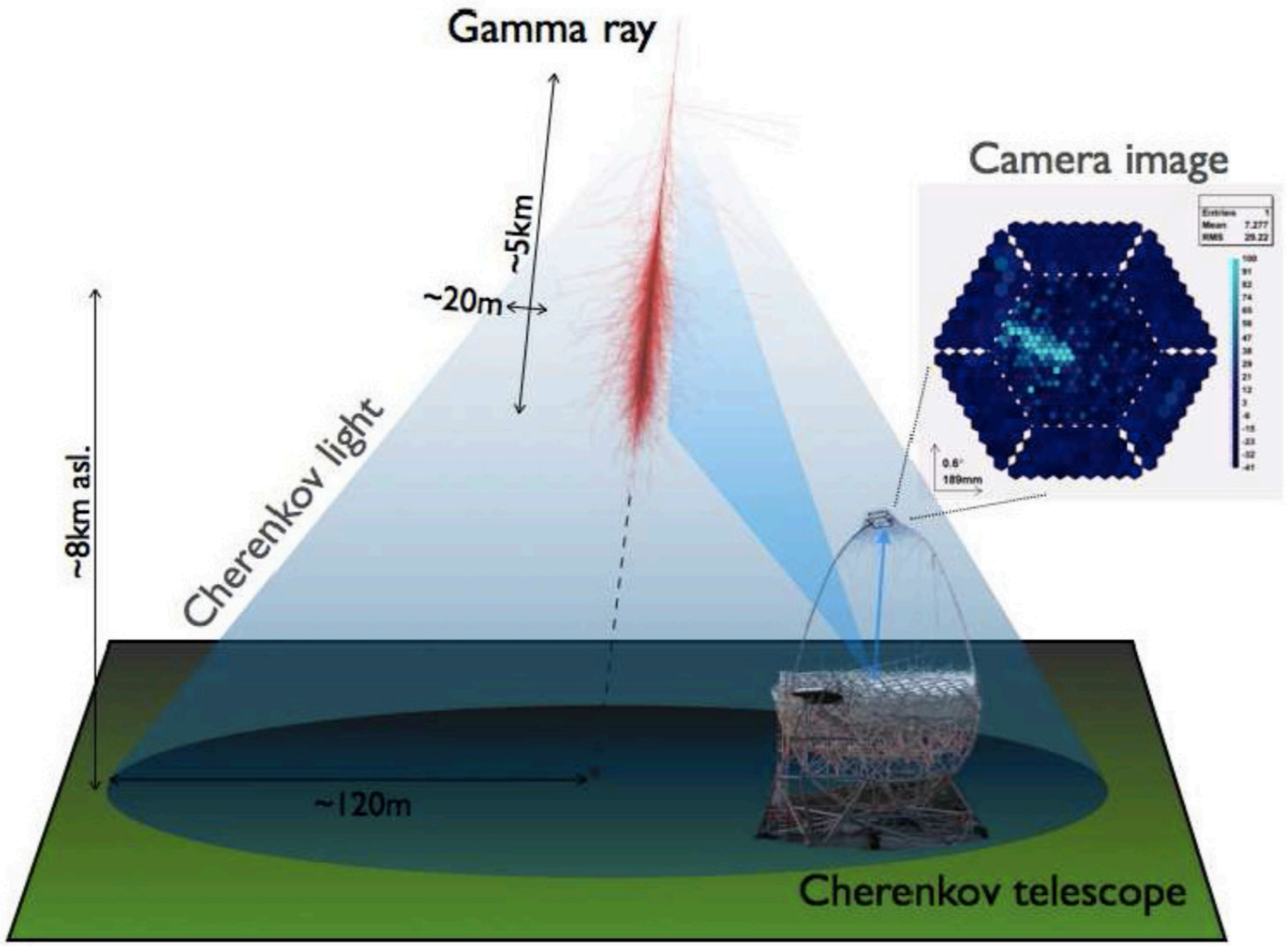


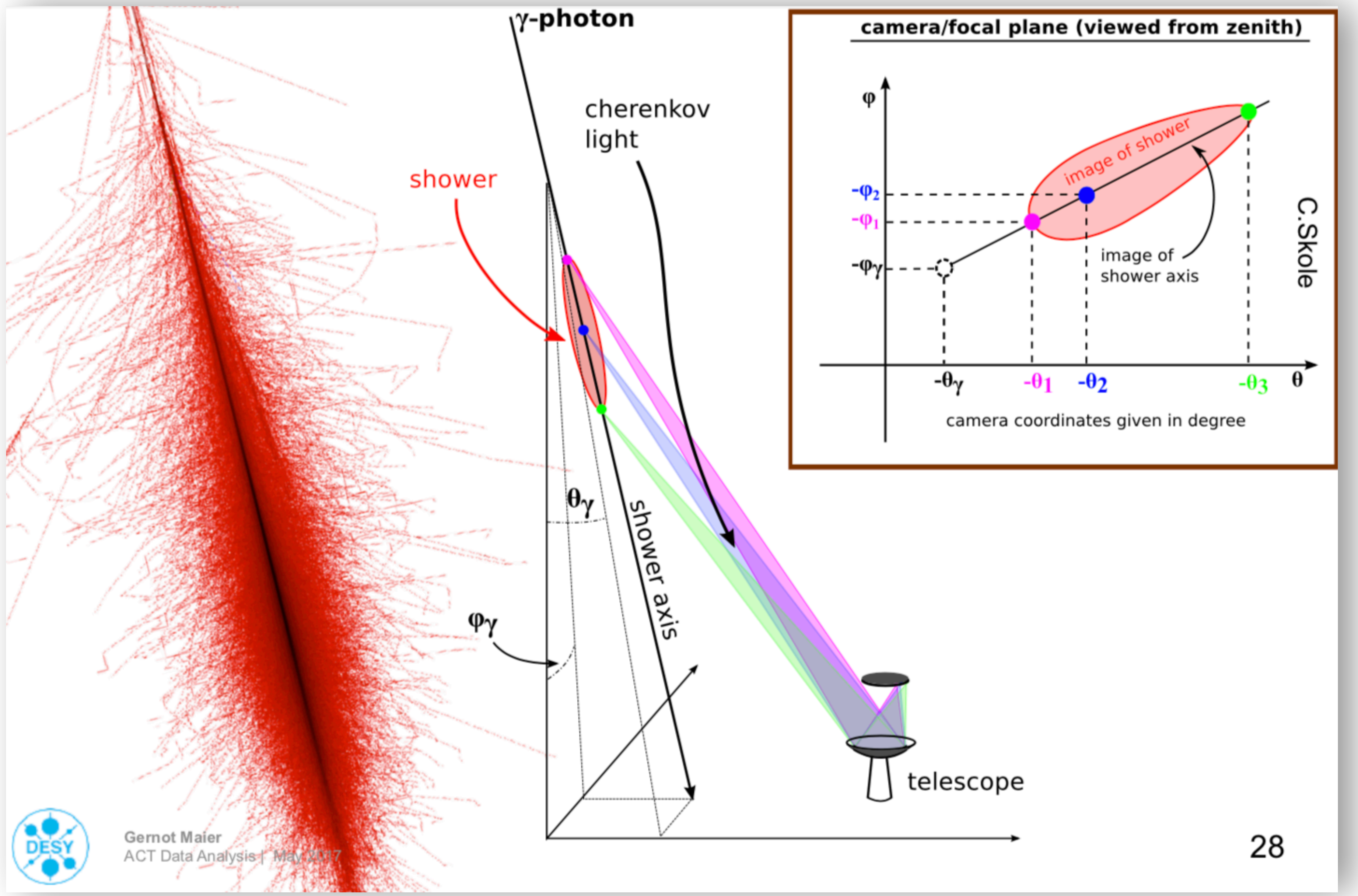


gamma hadrons showers → different physical processes → different shape of the image

Slide from A. Carosi

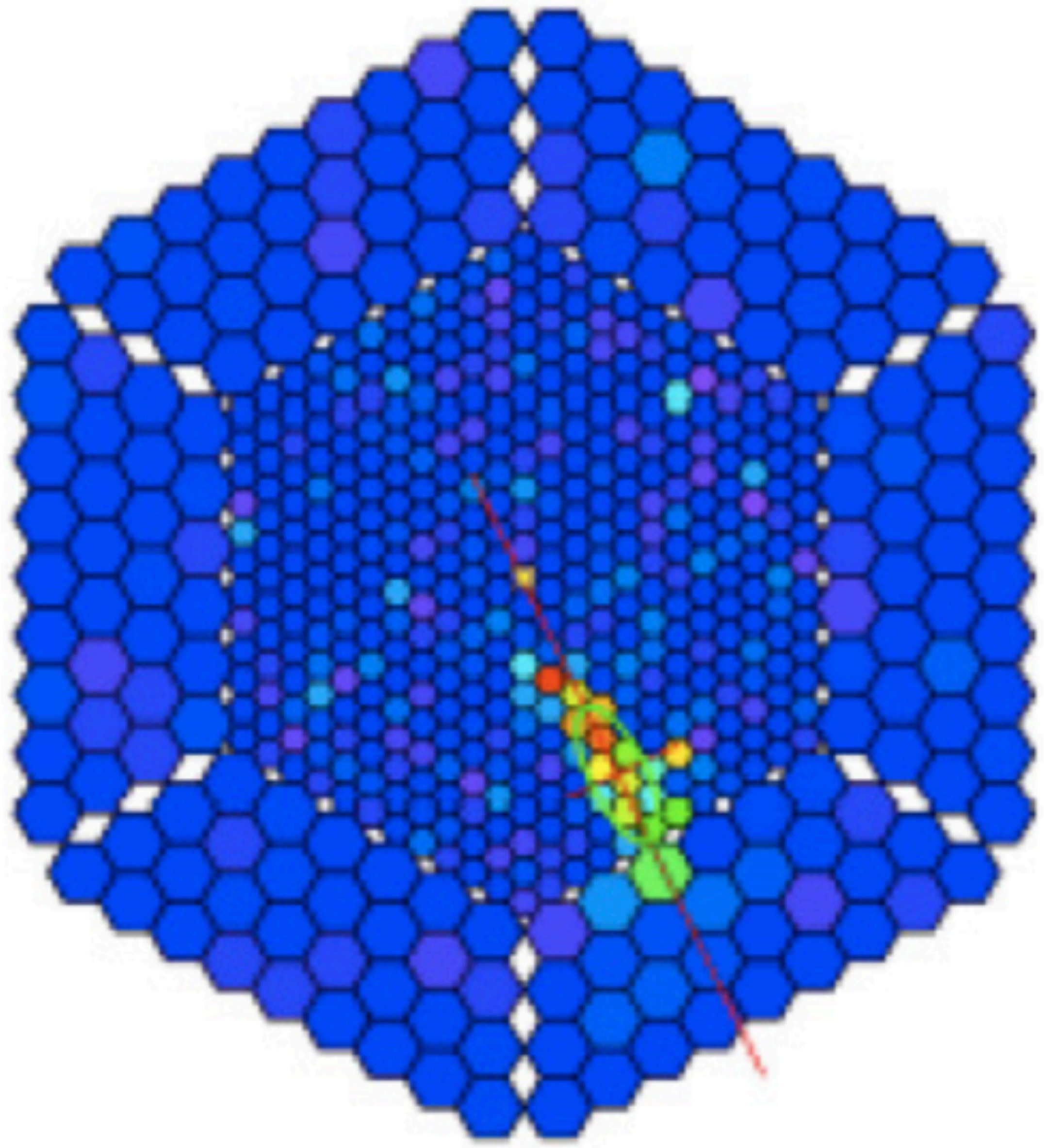
Extensive Air Showers (EAS)



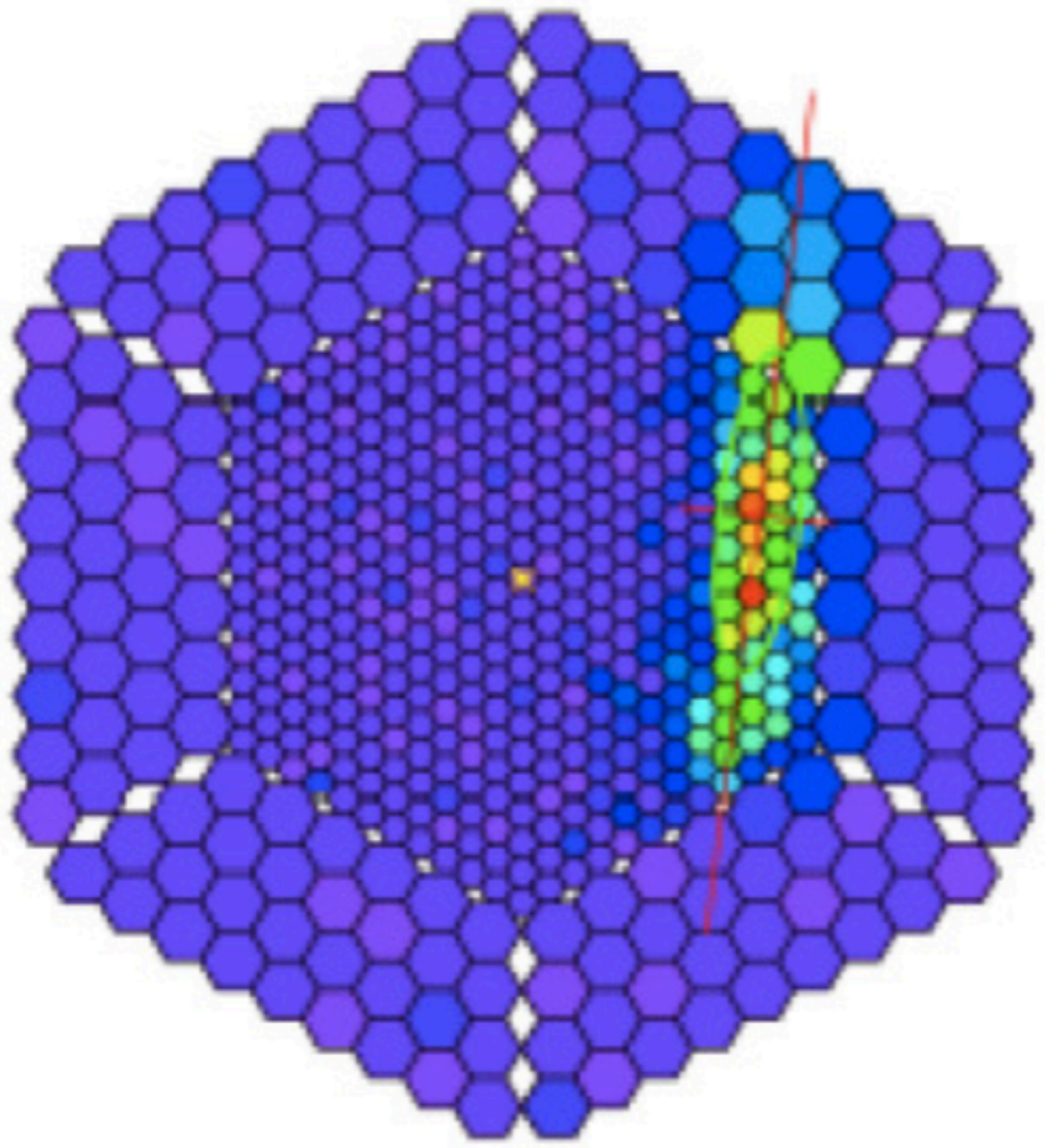


Extensive Air Showers (EAS)

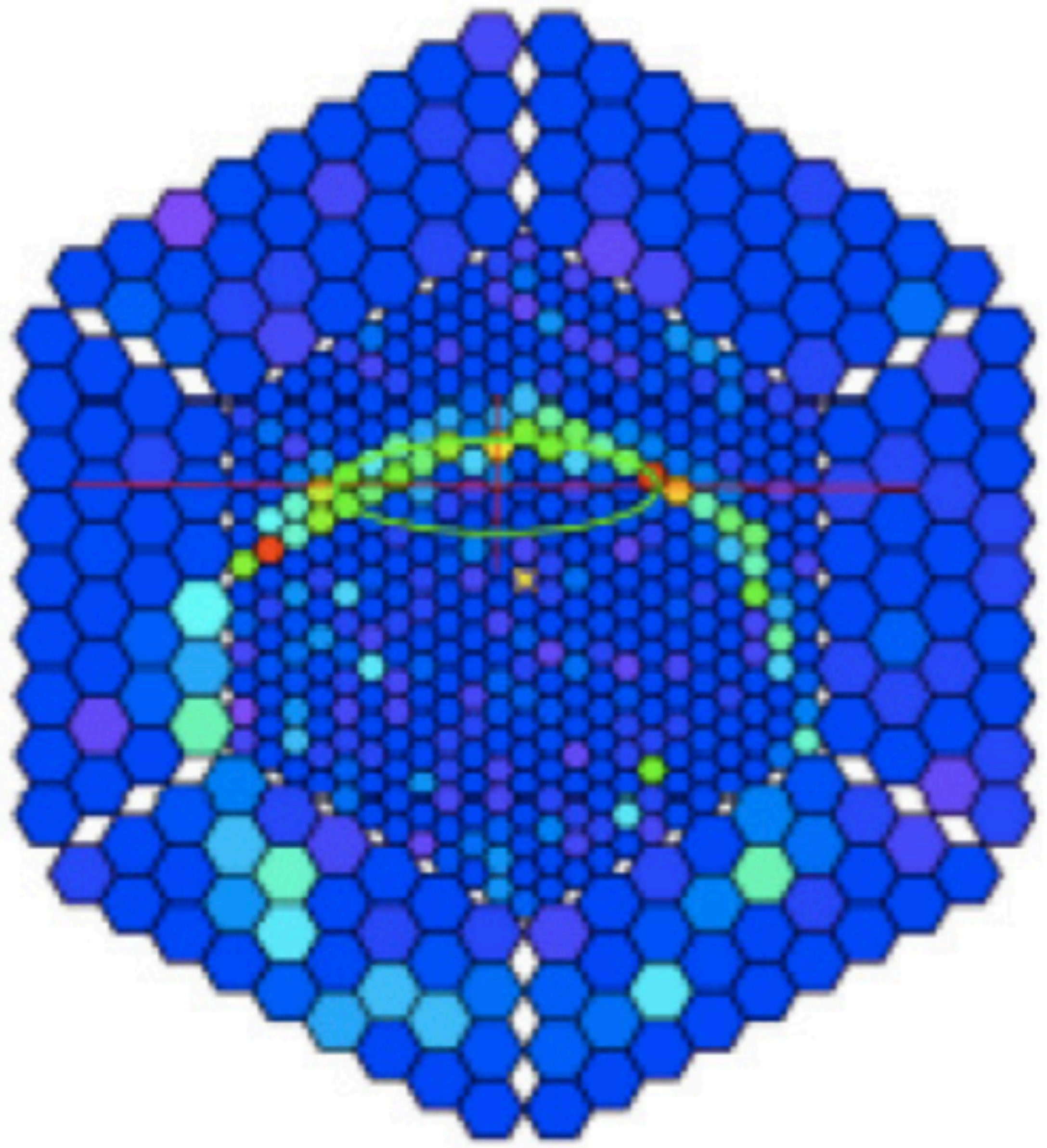
Gamma



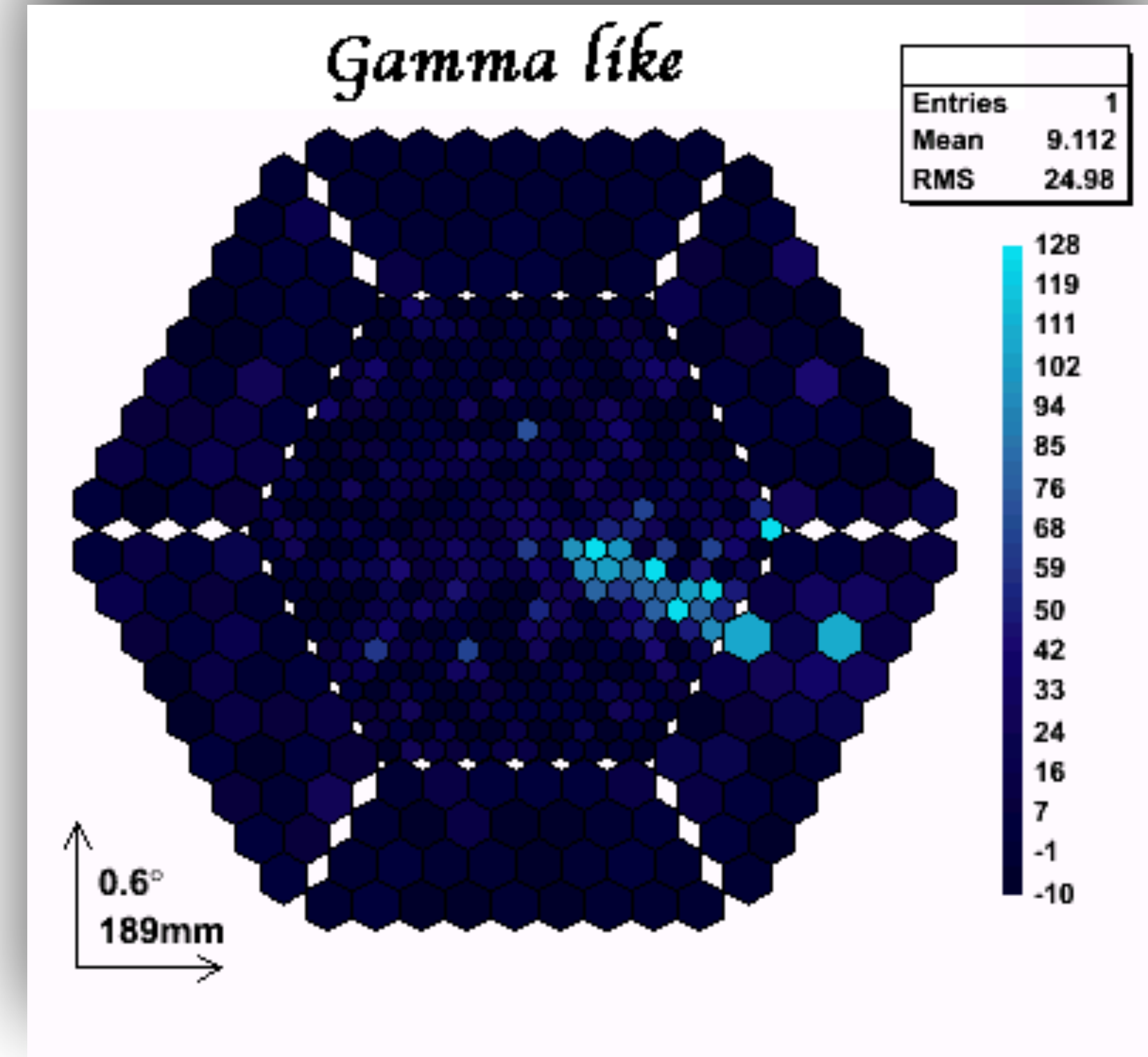
Hadron



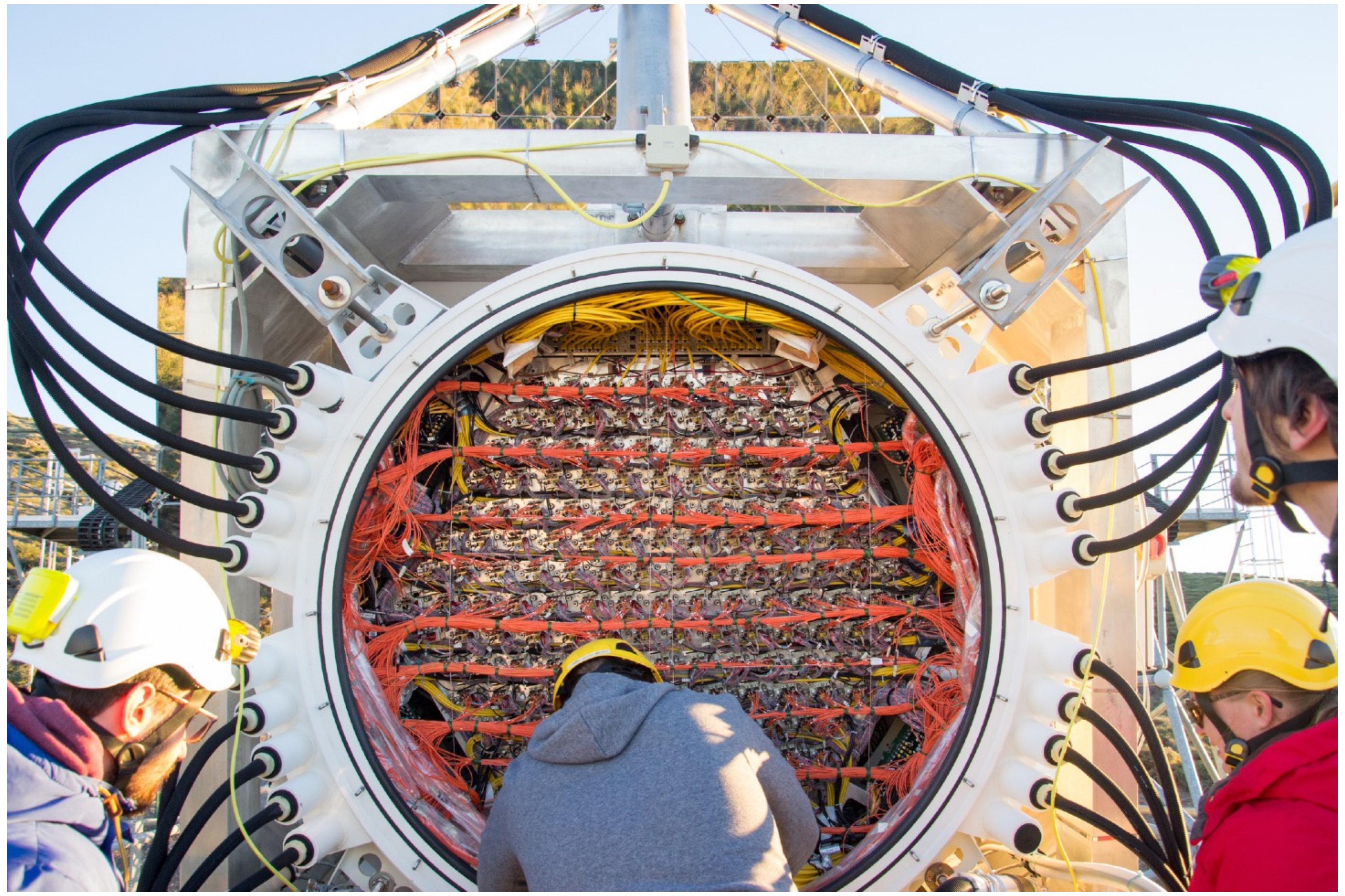
Muon



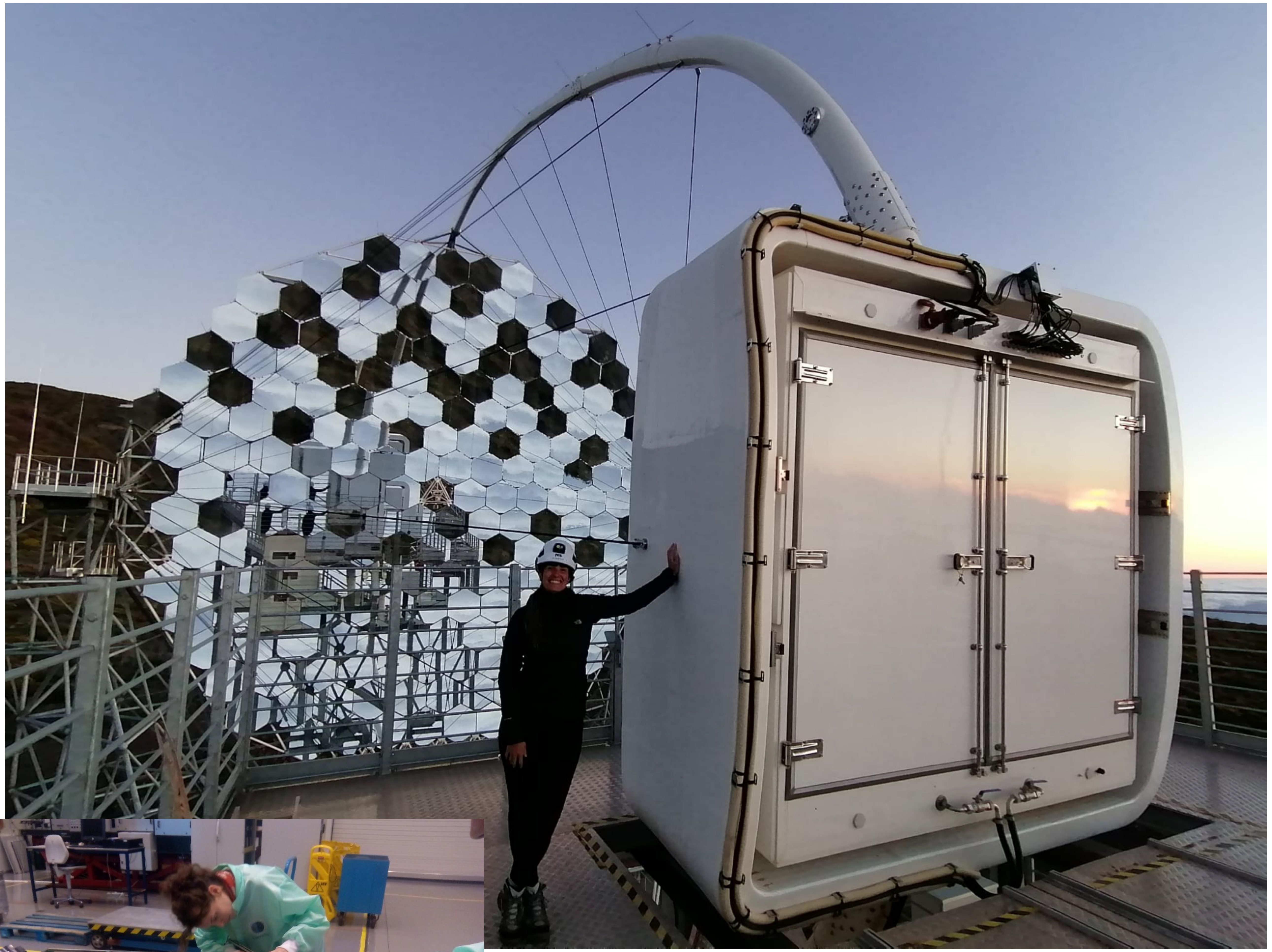
Camera events



MAGIC-II camera

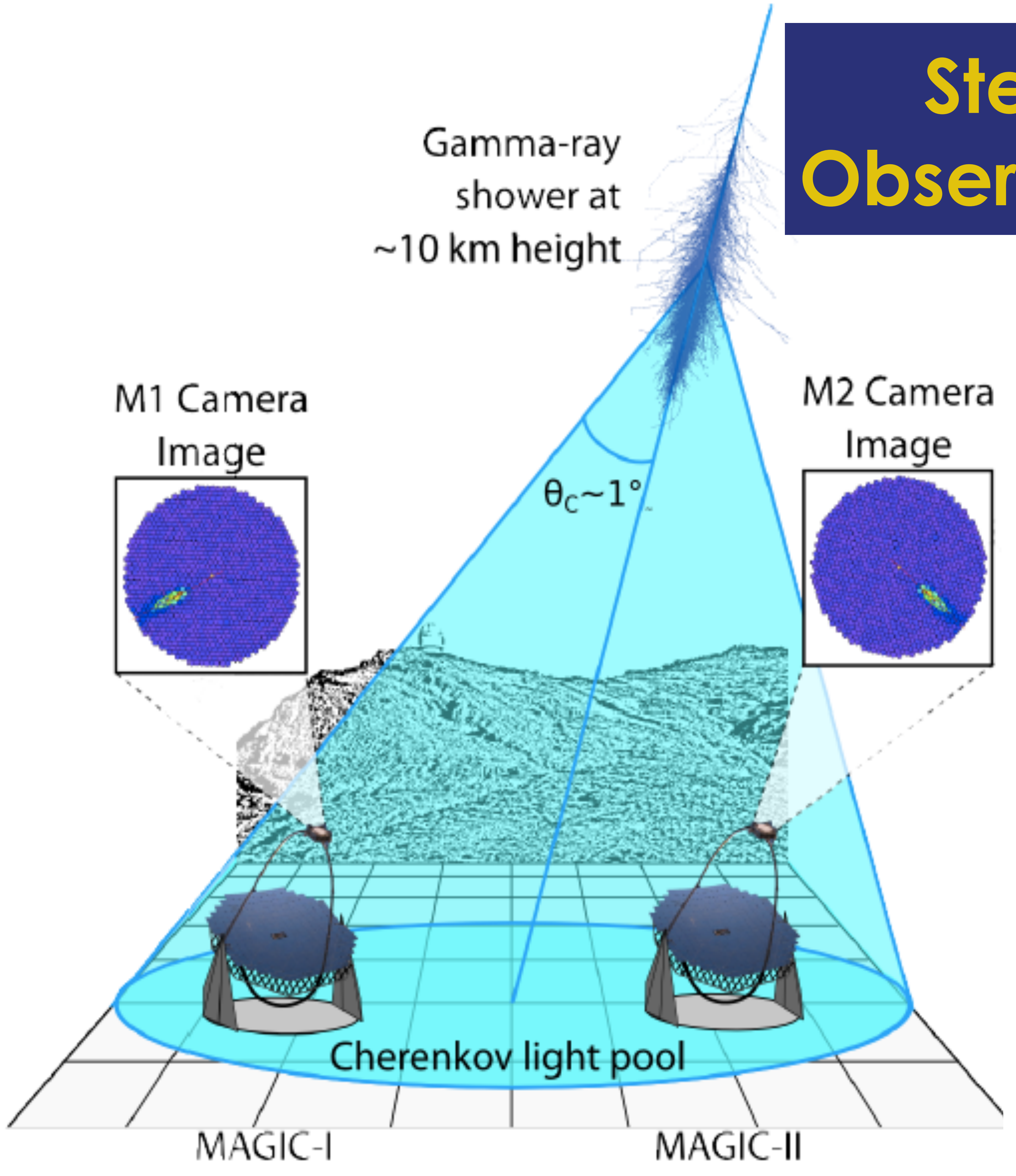


LST1 camera

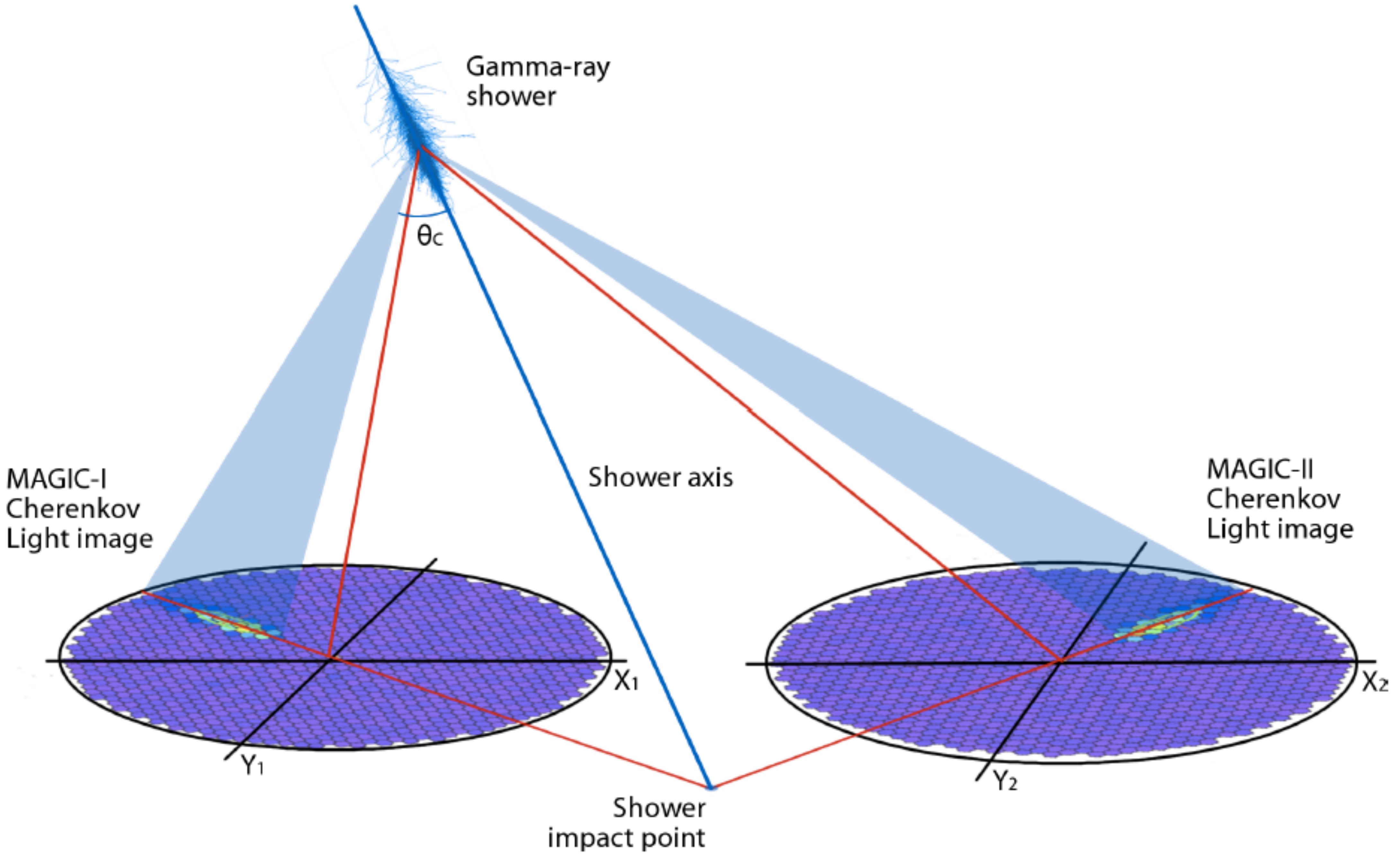


The Imaging Air Cherenkov Technique

Stereo Observations

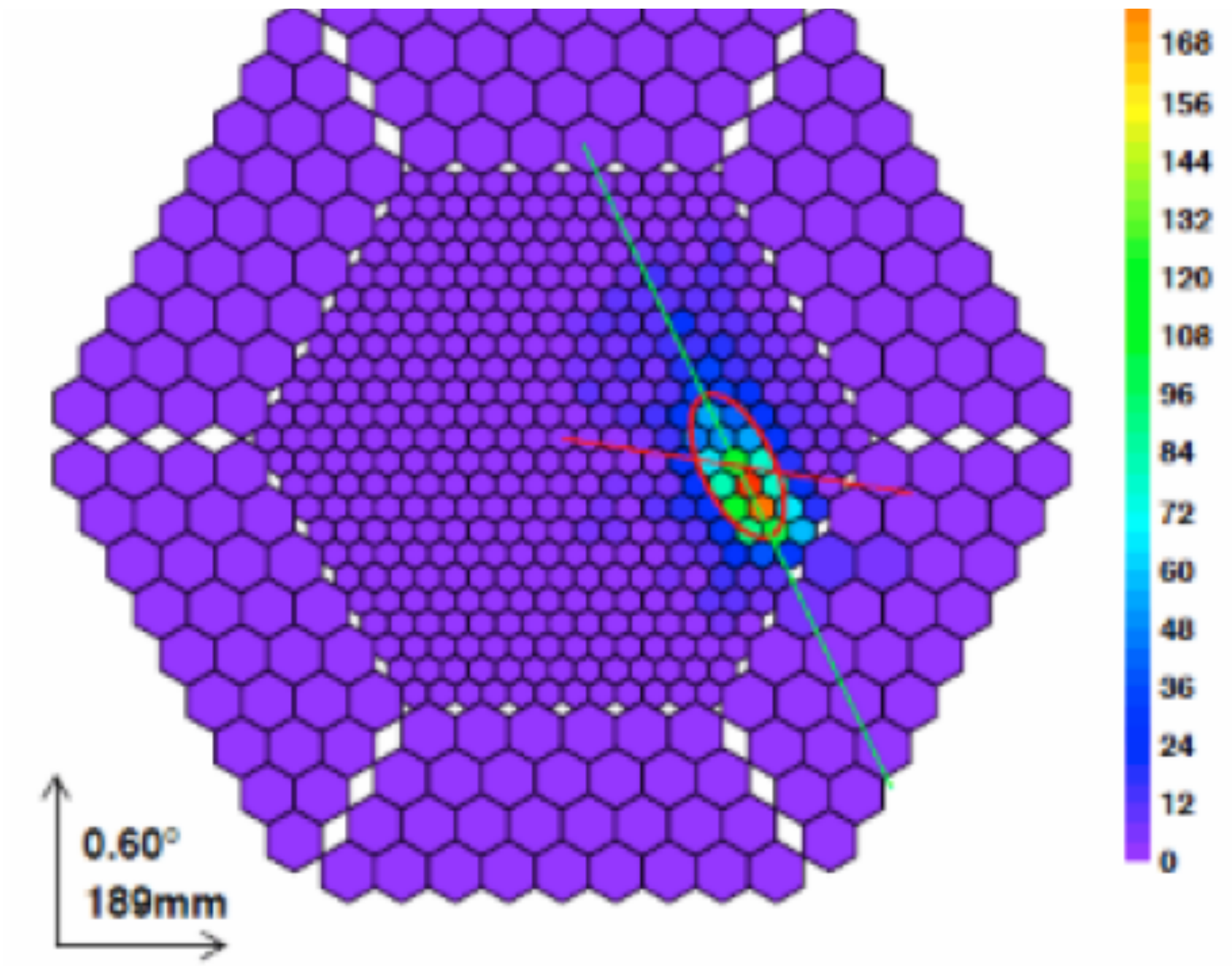


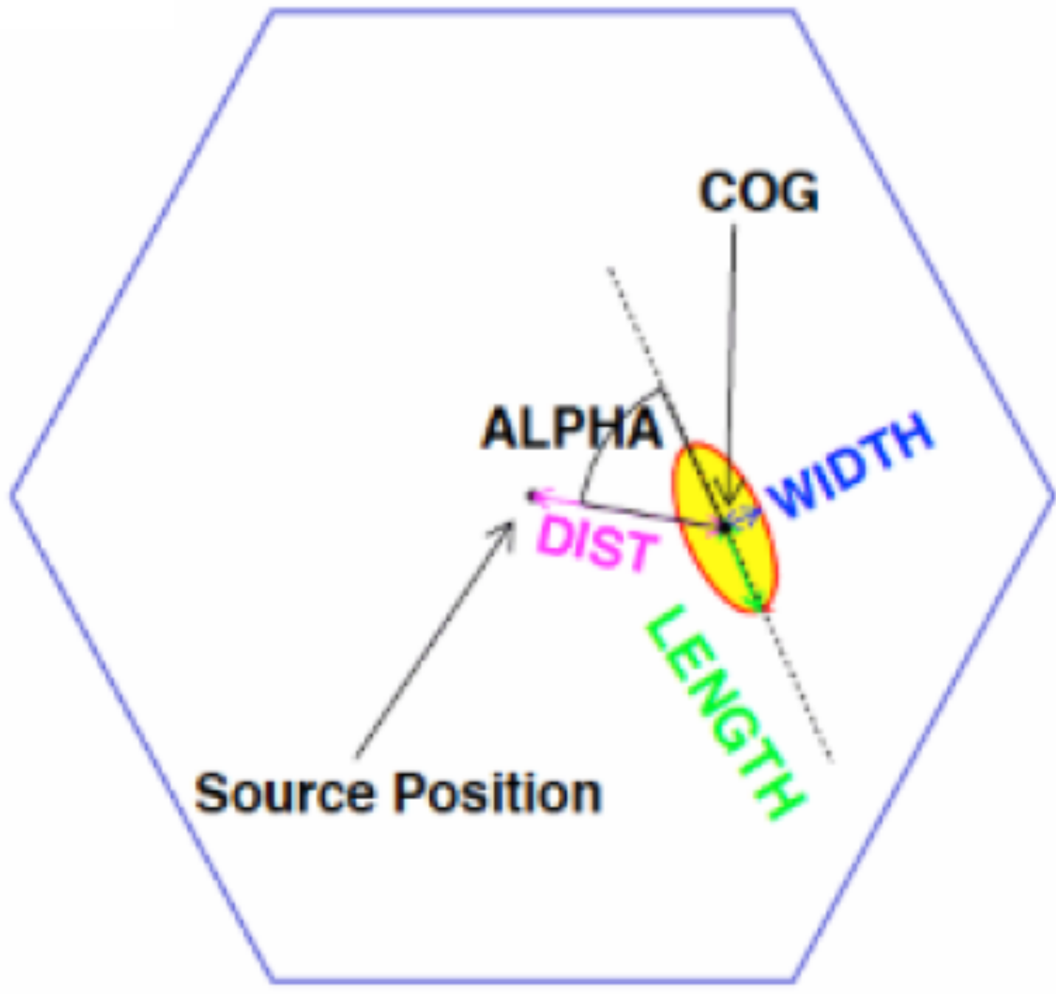
Giavitto, 2012



Shower Image Parametrization

Hillas parameters (Hillas 1984)





Analysis steps

The **final goal** of the data analysis is to extract the information of the **incoming photons** and measure the **gamma -ray flux**

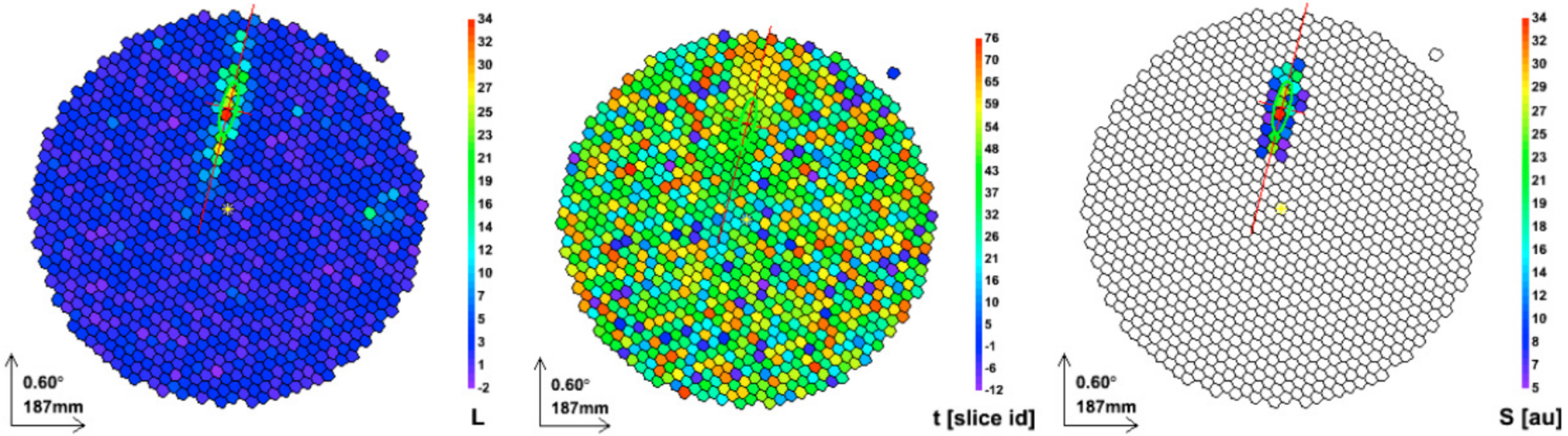
- **Signal extraction and calibration**: intensity+arrival times
- **Event reconstruction**: image cleaning and parametrization
- **Signal and background discrimination & energy estimation**: gamma/hadron separation, RF…
- **Signal evaluation**: physics

Programming language: **ROOT/C++ (+MARS**: MAGIC Analysis Reconstruction Software)
Recently: **python**, **gammapy**, **ctools**

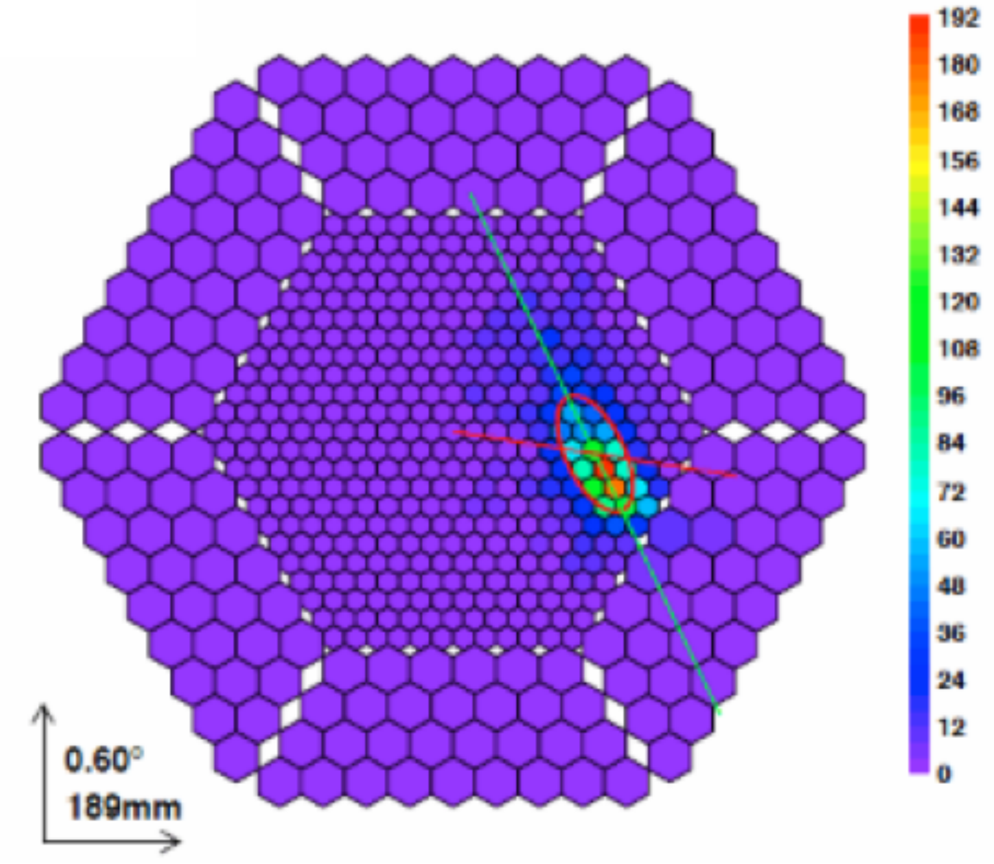
Analysis steps: low level

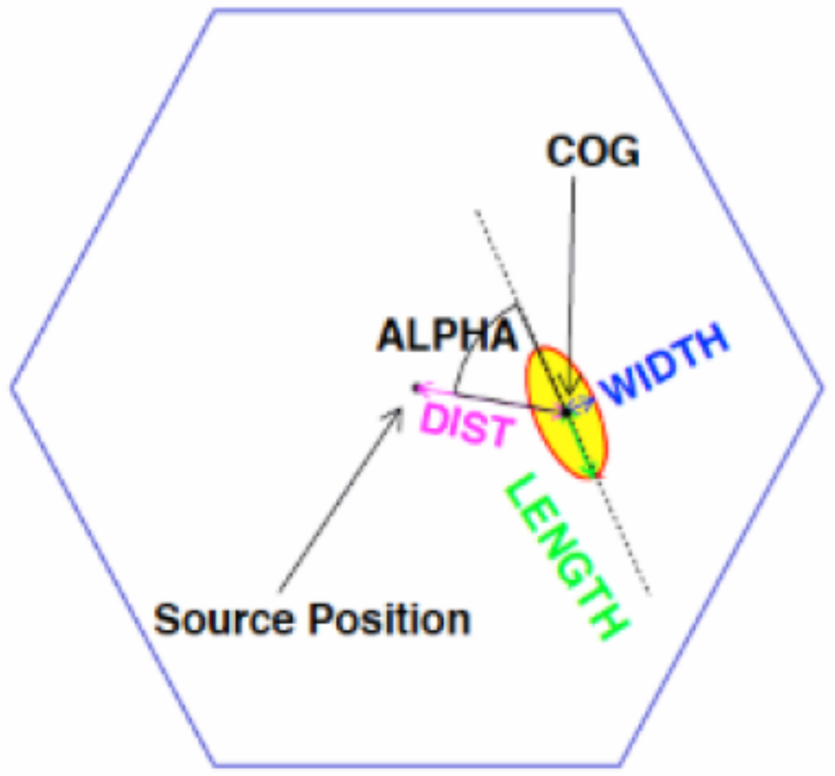
- **Signal extraction and calibration & event reconstruction**: intensity+arrival times
  - **Identify** which pixels belong to signal/background (apply cleaning)
  - **Arrival time** assigned -> timing coincidence window

each telescope separately



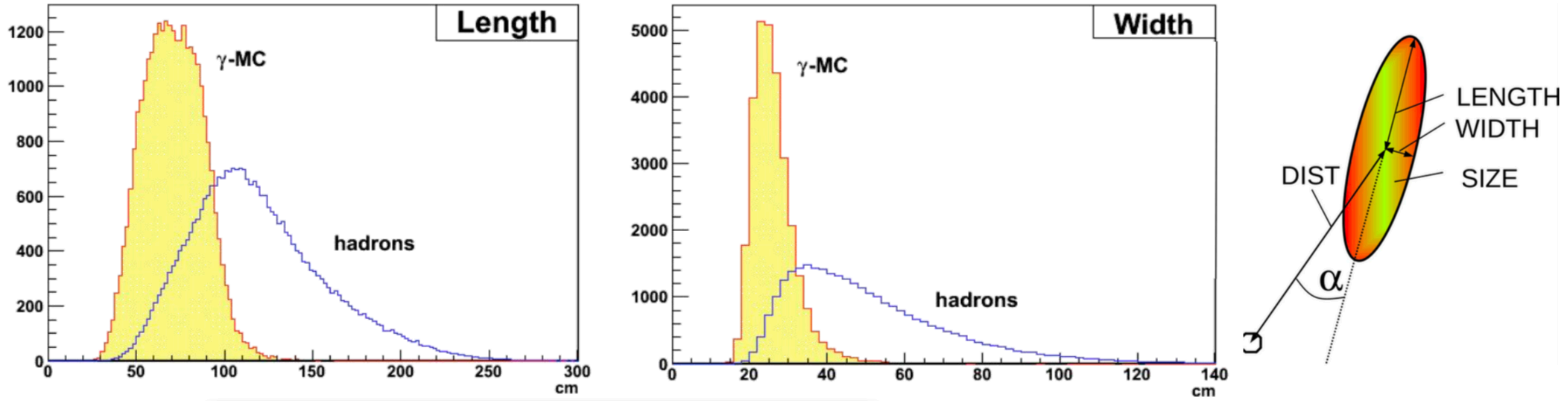
- **Parametrization via Hillas parameters**:
  - Gamma rays: compact ellipse
  - Different order momenta of the spatial distribution in the camera plane
  - Size, length, width, theta (stereo)…





Parametrizarion

How to discriminate gamma showers from hadrons from the image?



Simplest way:
- Static cuts on image parameters
- Dynamical cuts
  g-efficiency ~50%
  h-rejection ~95%

method used by the past generation of IACT

Alessandro Carosi

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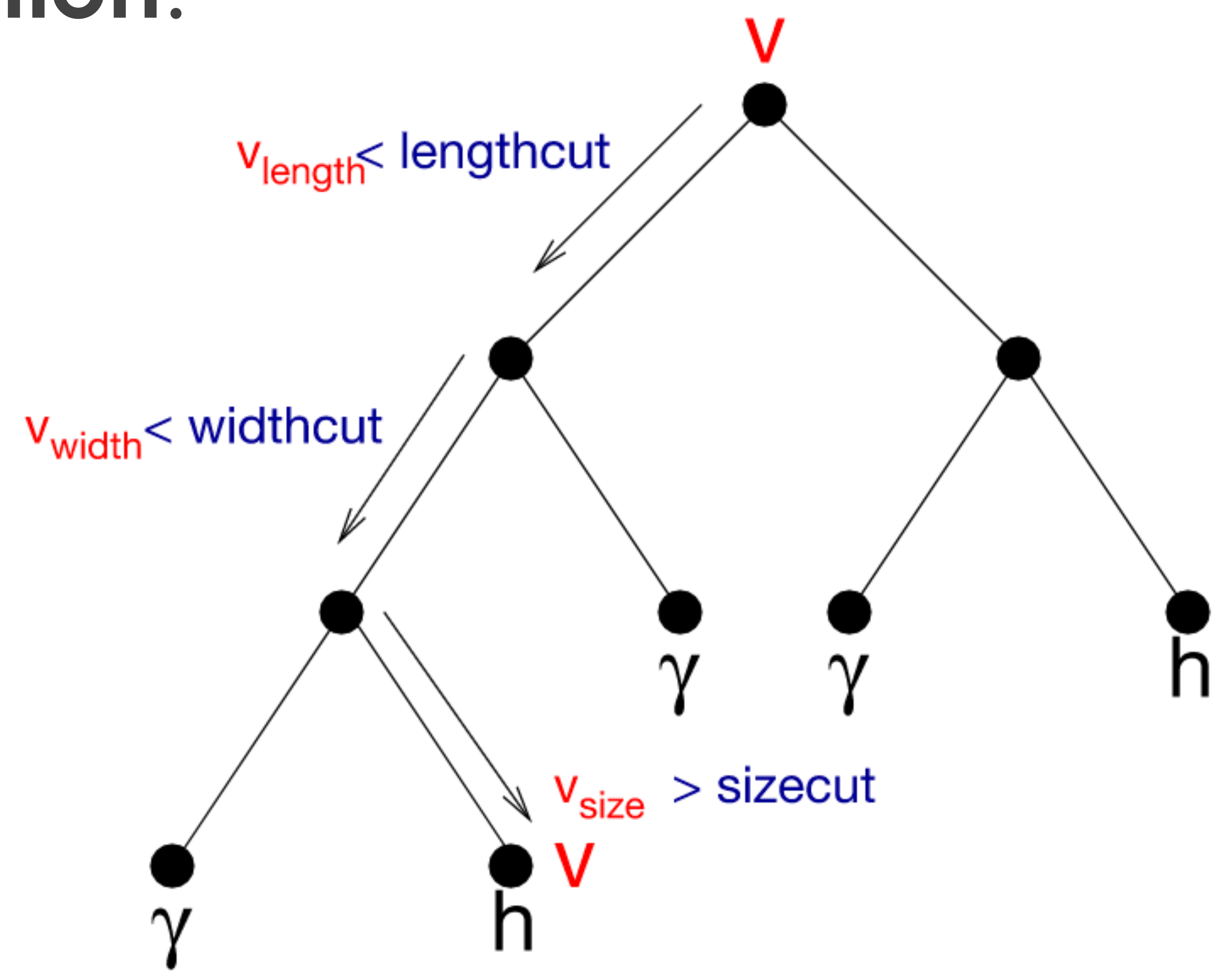
Slide from A. Carosi

Analysis steps: intermediate level

- **Signal and background discrimination & energy estimation**:
  - Merge of each telescope data
  - Hadronic or gamma origin? : **gamma/hadron separation**
    - Randon Forest algorithm-> hadronness of an event
    - Train of the MC with OFF data (hadrons)
  - Energy estimation and position reconstruction
  - Convertion of Hillas parameters into **fully analyzed events, assigning hadronness and energy to each event**

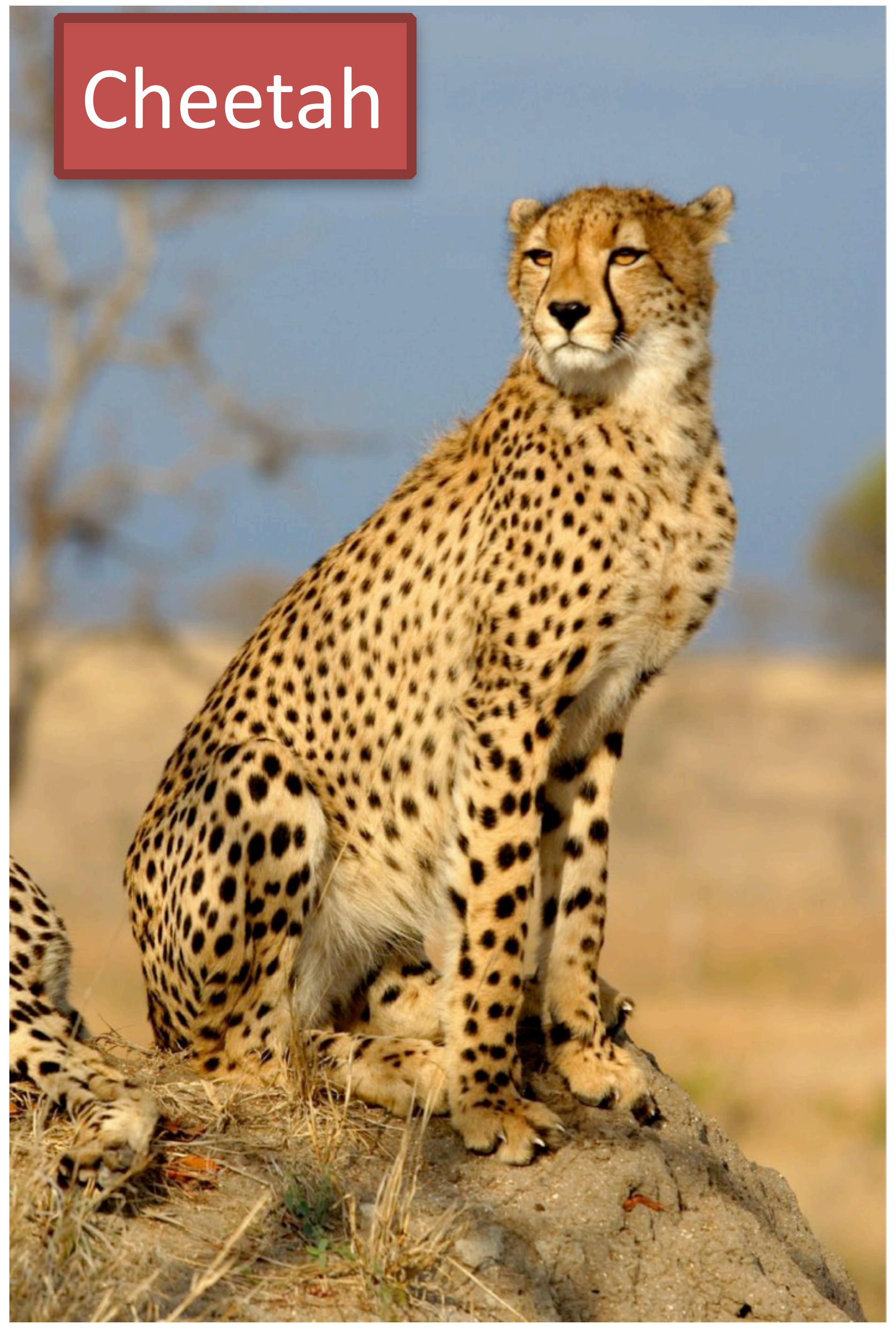


Random forest algorithm = a machine learning algorithm that is used for classification

Machine learning!!!!

Types of wild cats

Gamma or hadron?



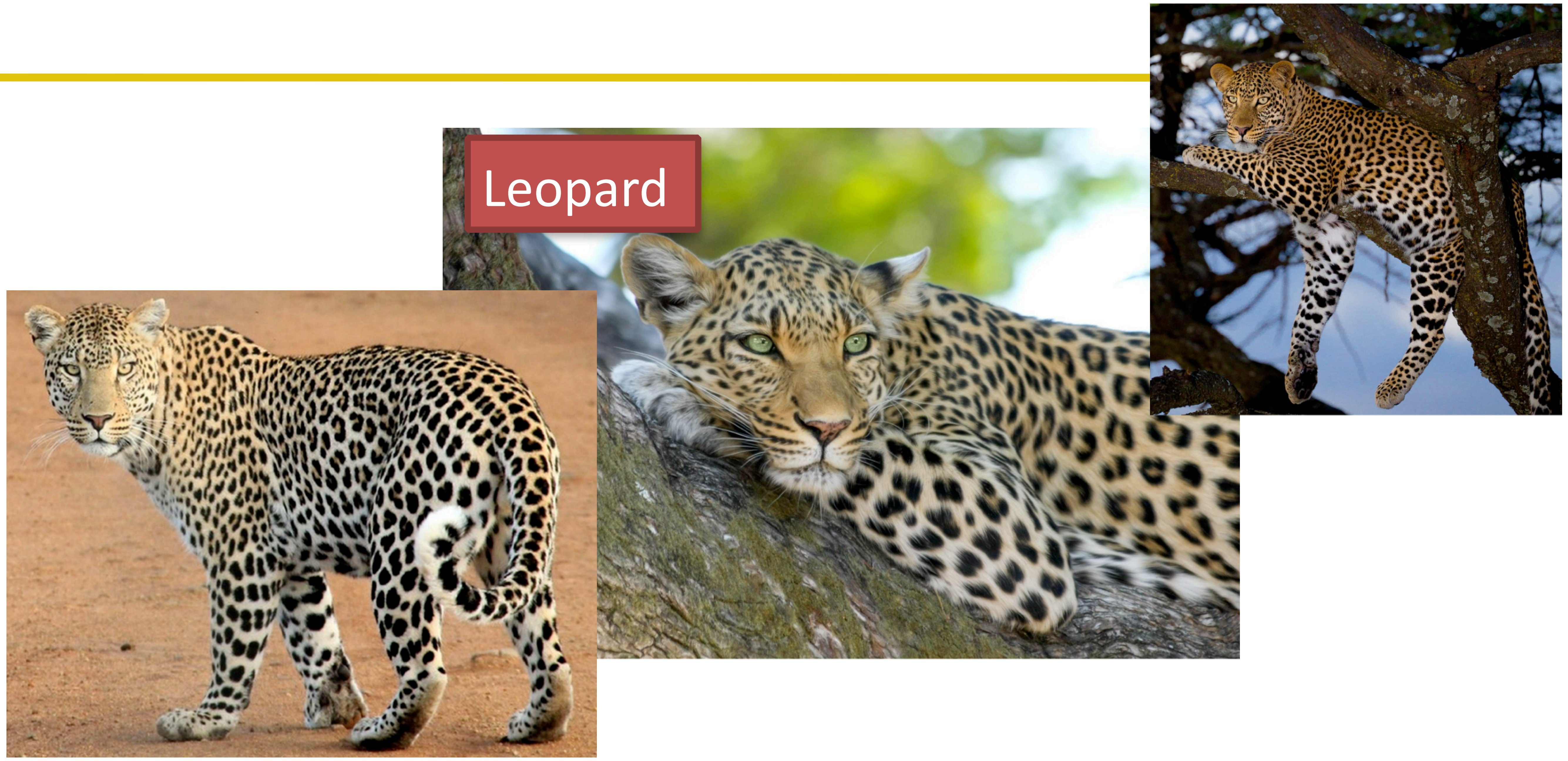
Leopard

Cheetah

Lions

Machine learning!!!!

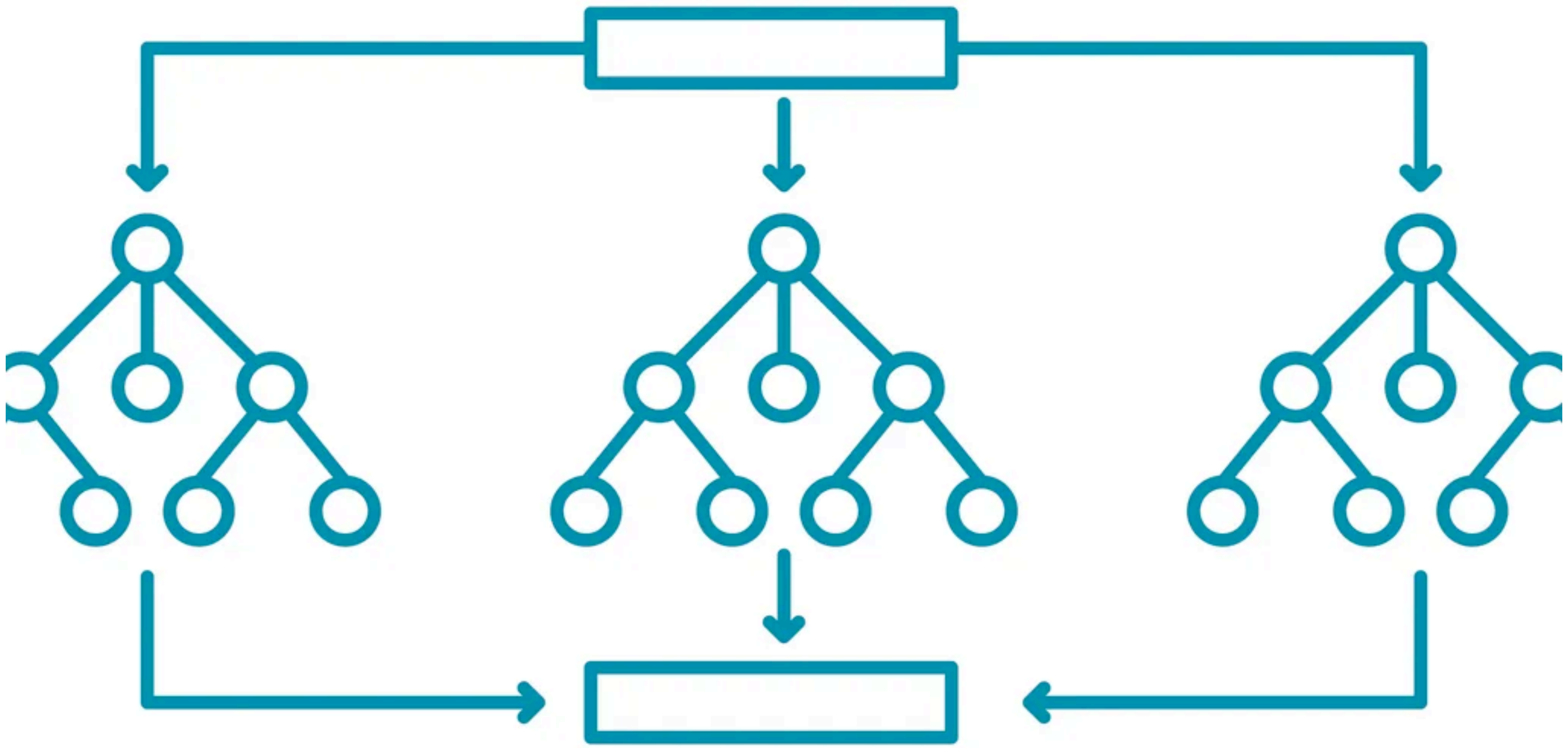
Train



Input: hadron samples

Machine learning!!!!

Select your algorithm

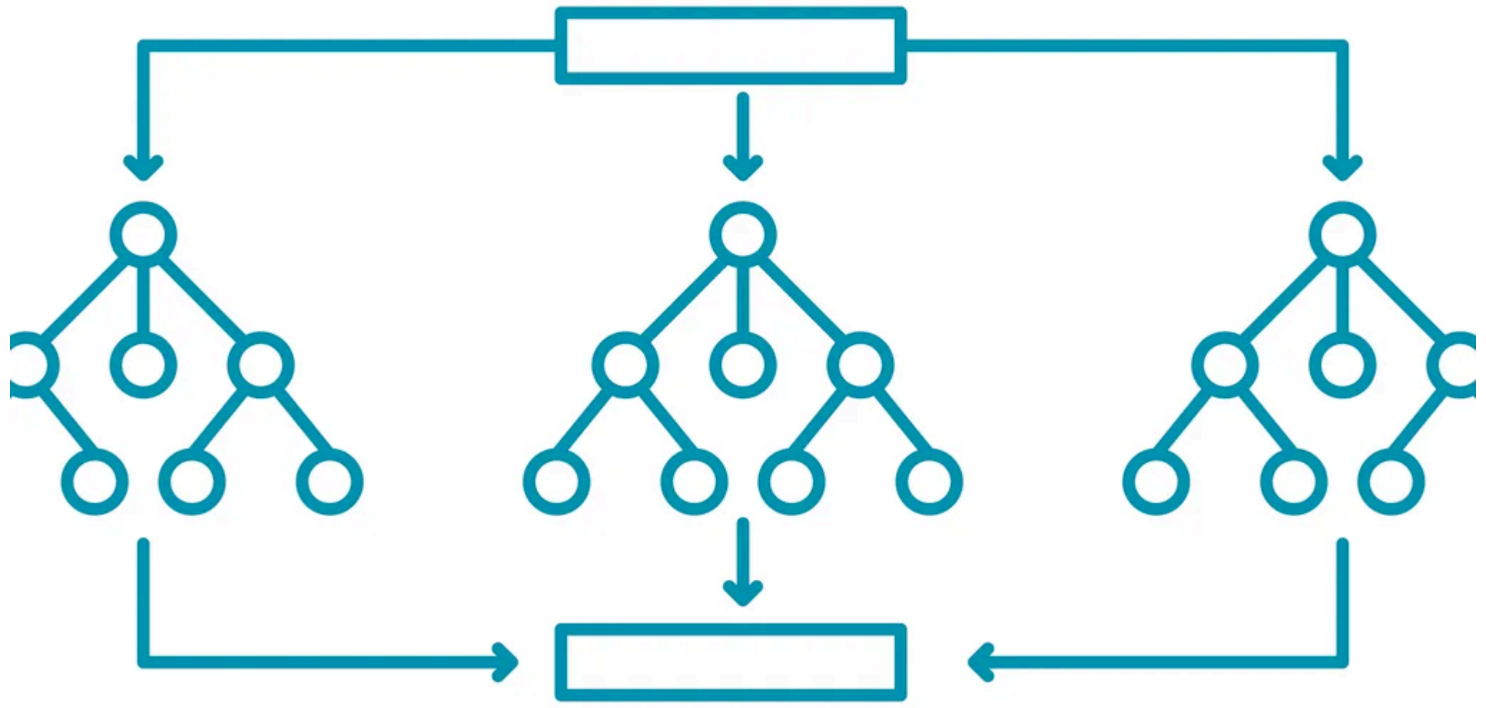


Random Forest

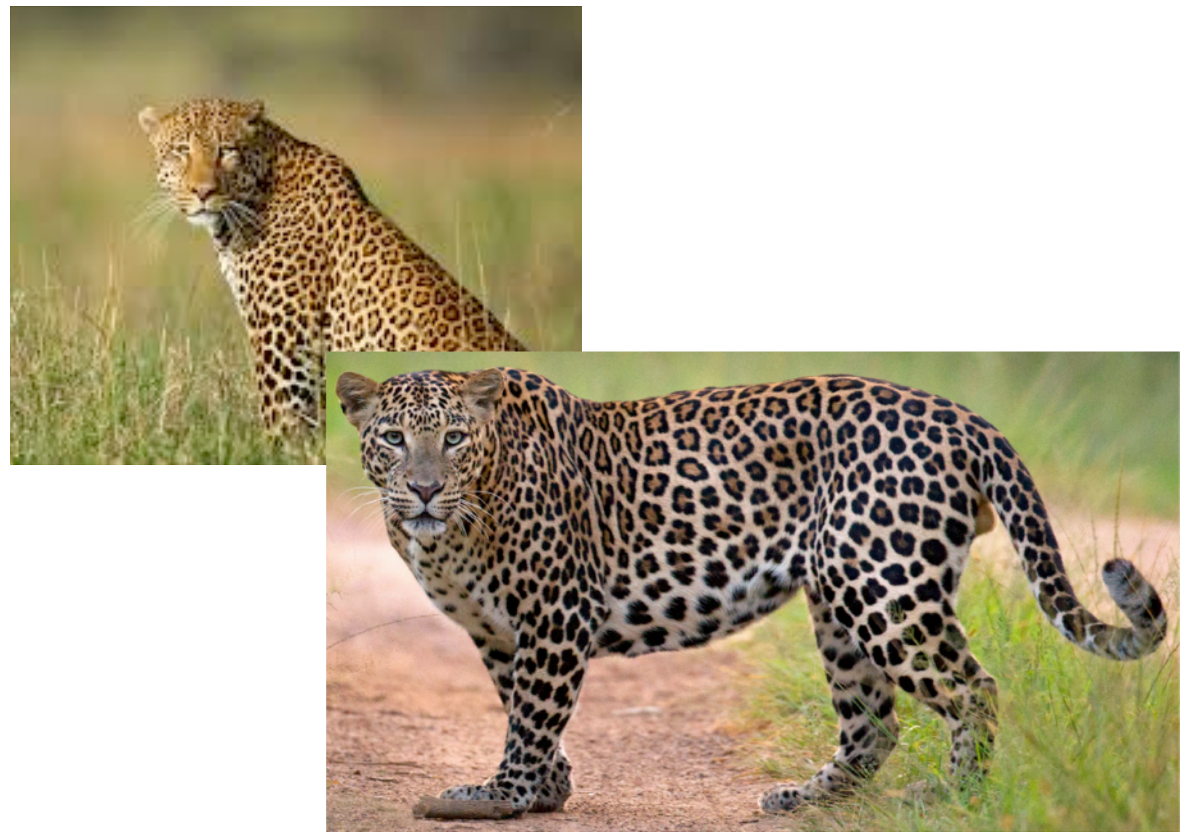
Machine learning!!!!

Classification

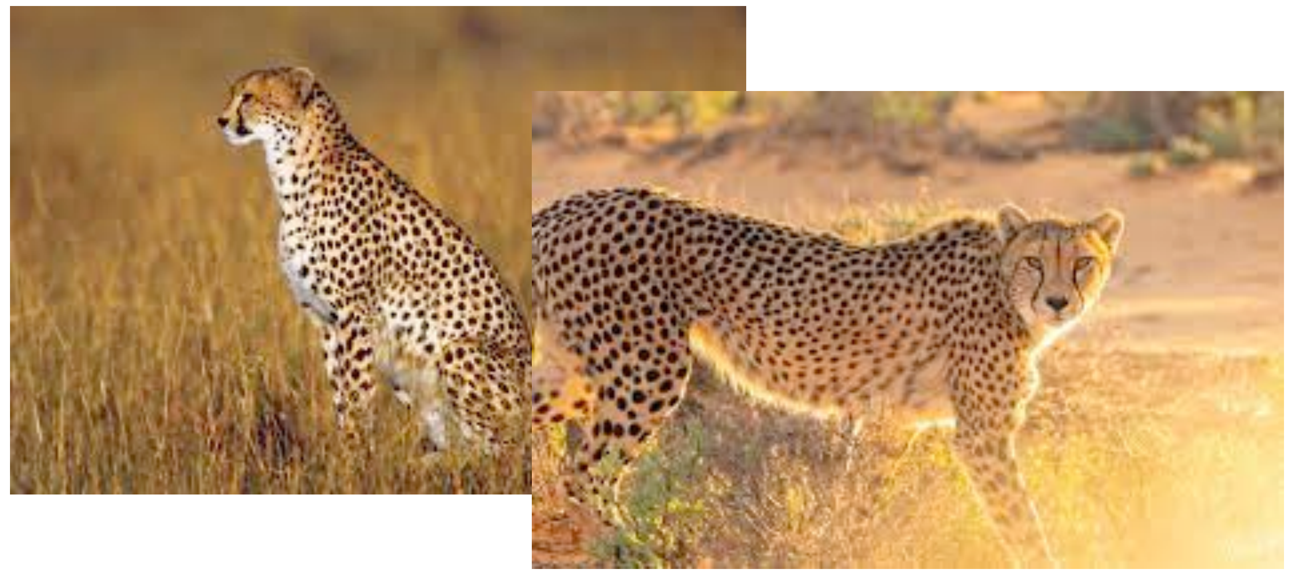
Test



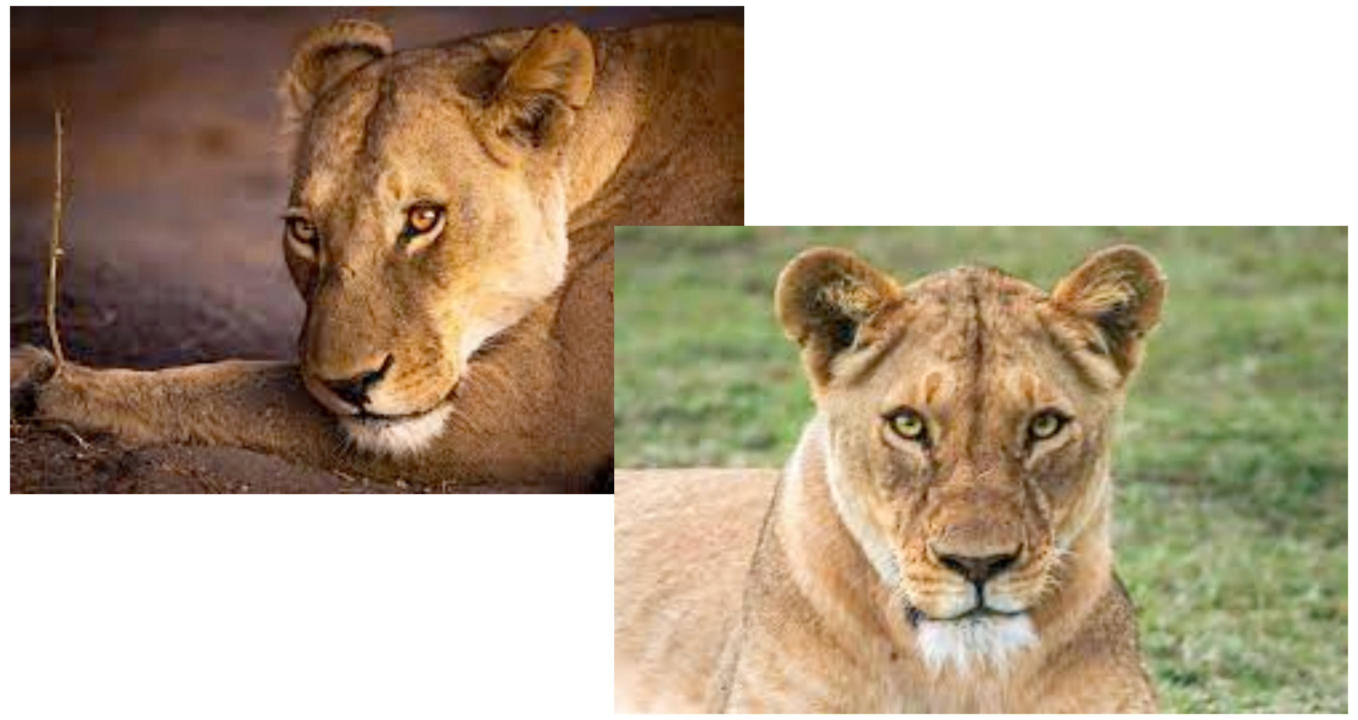
Leopard



Cheetah



Lions



Machine learning!!!!

Confusion matrix

Pedricted values	Real values: Leopard	Real values: Cheetah	Real values: Lion
Leopard	98%		
Cheetah		99 %	
Lion			98 %

True Energy vs Estimated energy

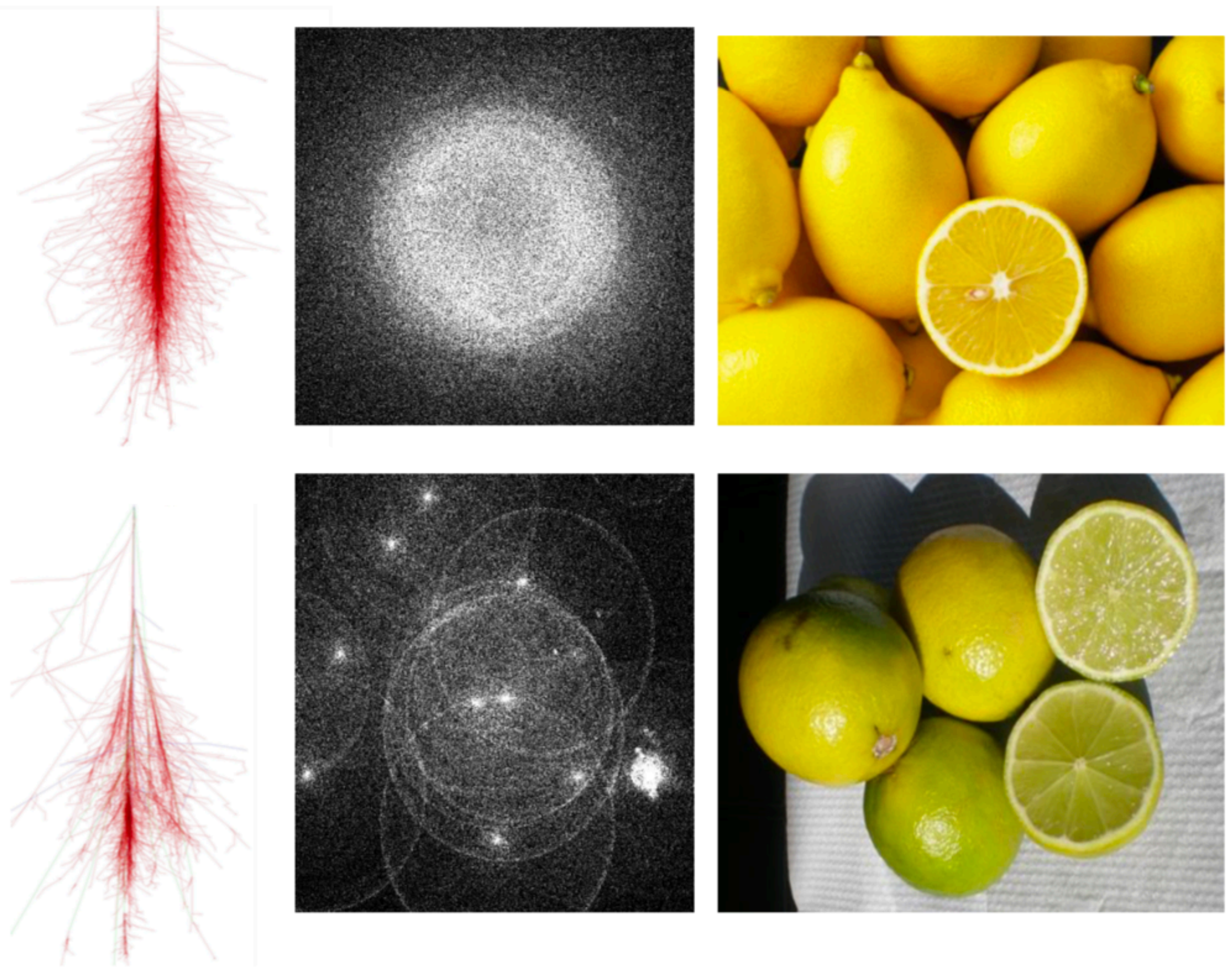
Machine learning!!!!

Confusion matrix

Pedricted values	Real values: Leopard	Real values: Cheetah	Real values: Lion
Lion	98%		
Cheetah		99 %	
Leopard			98 %

True Energy vs Estimated energy

Random Forest



HOW TO CLASSIFY
MILLIONS OF EVENTS??

(how to pick up few lemons over thousands of lime)

More complex methods include statistical classification method (ie, random forest)

What does RF need to work?

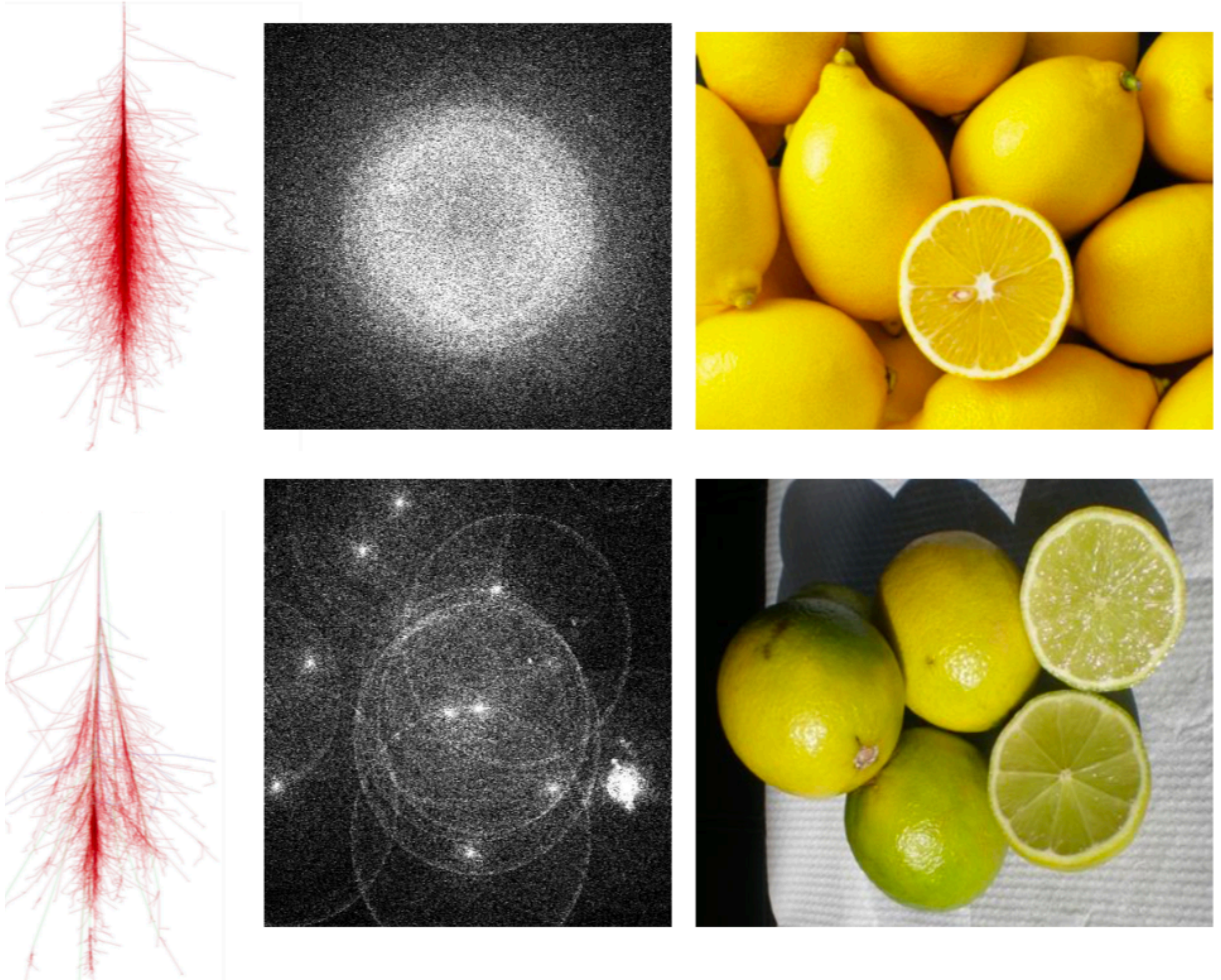
Train samples of both species
(gamma/hadrons, lemons/limes...)

&

a list of parameters to be used
(length, width, size etc or colour, weight etc. for our example)

Slide from A. Carosi

Random Forest



More complex methods include statistical classification method (ie, random forest)

RF choose randomly three parameters out of the selected ones and for each one find the value c that minimizes the *Gini index* Q(c)

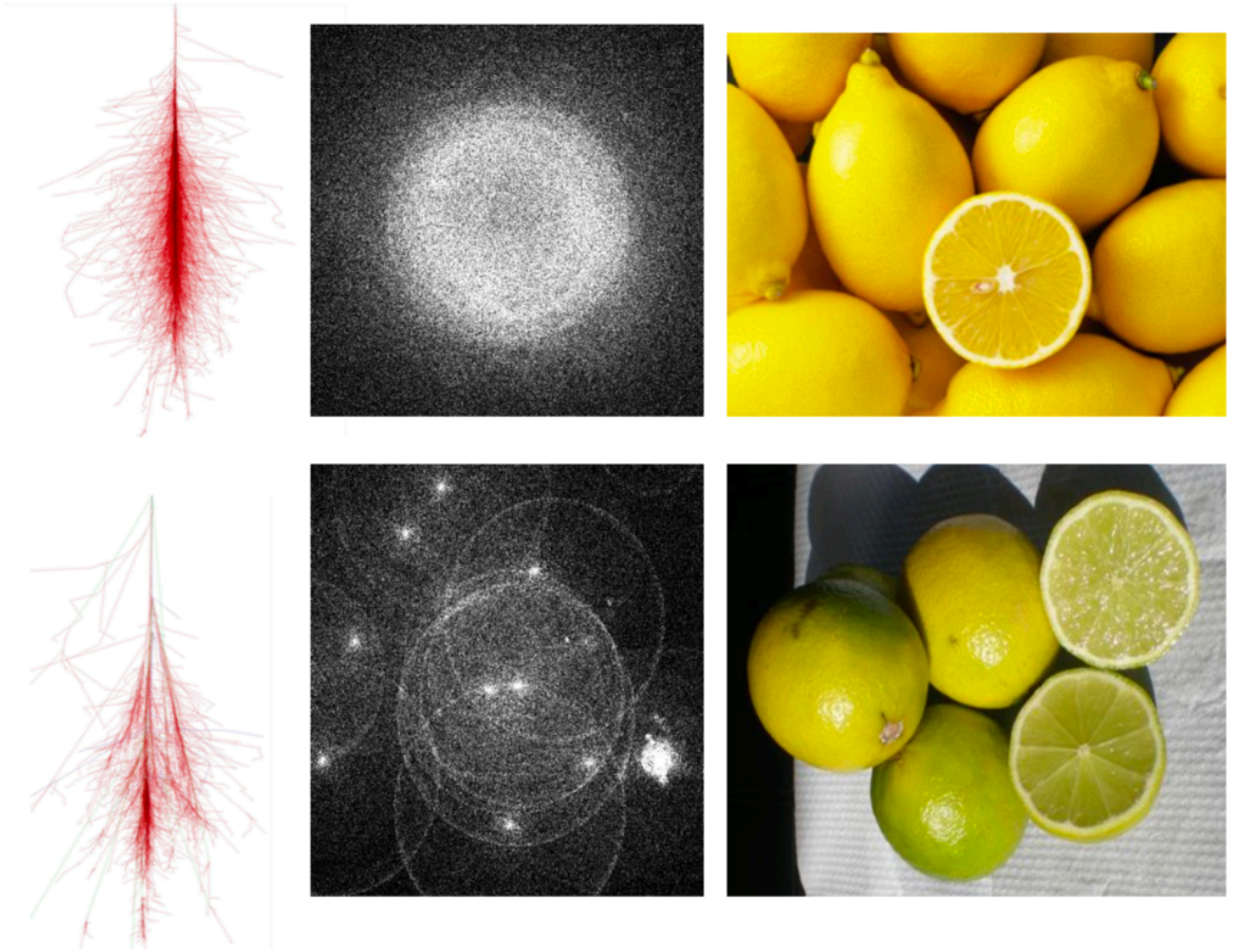
HOW TO CLASSIFY
MILLIONS OF EVENTS??

(how to pick up few lemons over thousands of lime)

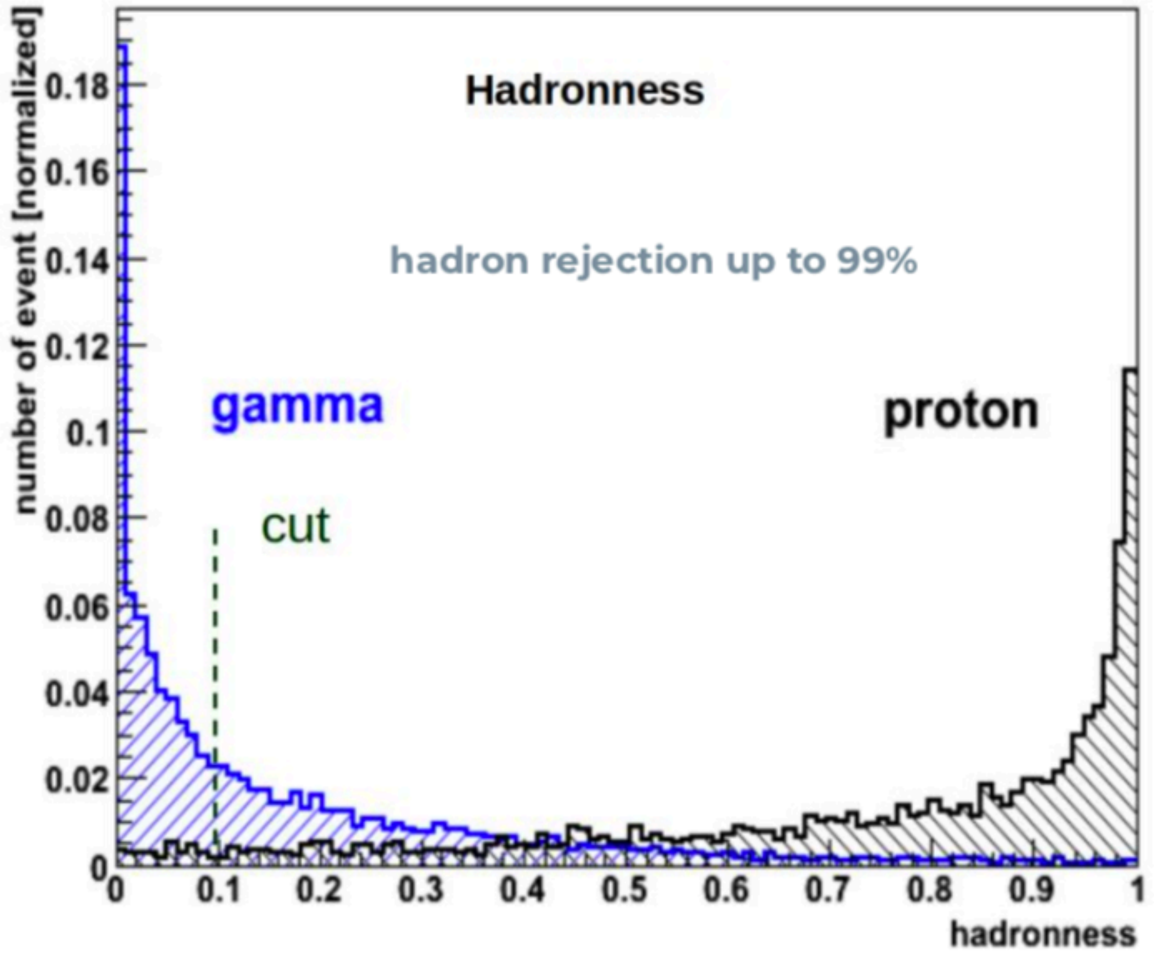
$$\frac{Q(c)}{2} = \frac{N_p^{\mathrm{left}} \cdot N_h^{\mathrm{left}}}{N_p^{\mathrm{left}} + N_h^{\mathrm{left}}} + \frac{N_p^{\mathrm{right}} \cdot N_h^{\mathrm{right}}}{N_p^{\mathrm{right}} + N_h^{\mathrm{right}}}$$

Slide from A. Carosi

Random Forest



Parameters space are divided in two subset: one rich of hadrons, one of photons. The procedure is then repeated for the randomly chosen parameters until the remaining subset (leaves) are smaller than a fixed size and then the whole procedure is repeated with a different set of parameters and another “tree” is built.



HOW TO CLASSIFY
MILLIONS OF EVENTS??

(how to pick up few lemons over thousands of lime)

Hadronnes can be computed counting how many times an event has been put in an hadron rich subsample

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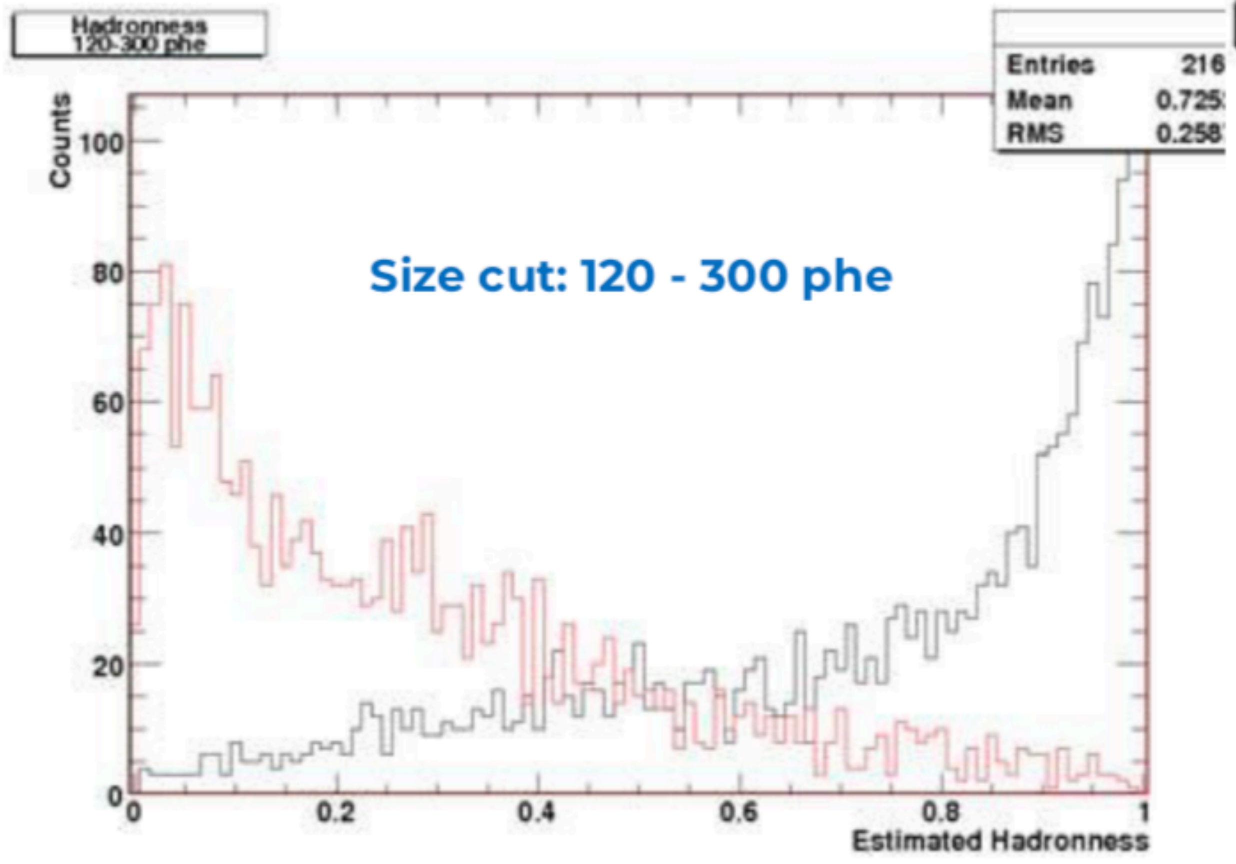
Slide from A. Carosi

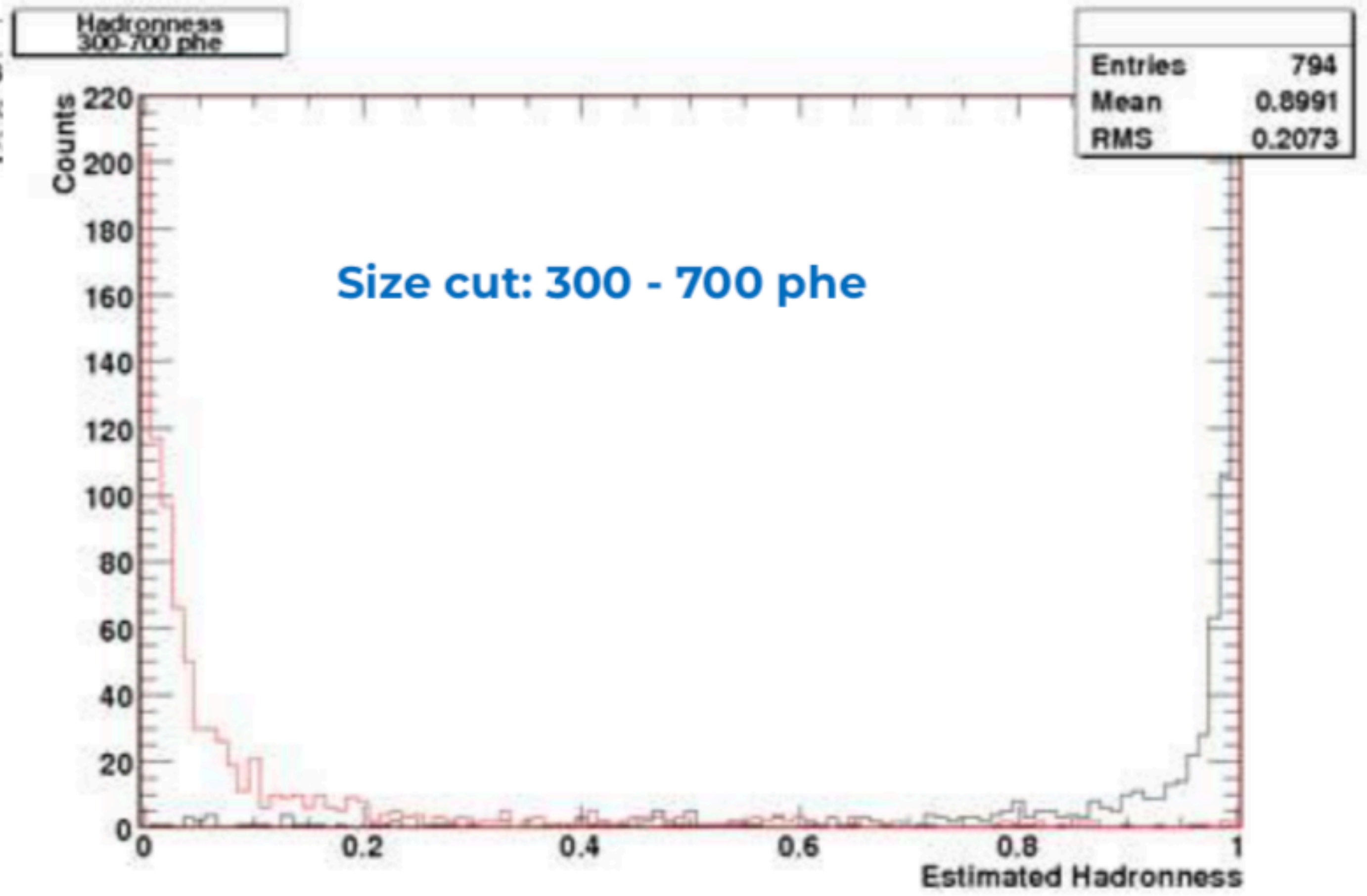
Random Forest

However, classification is never perfect

What is important is:

- MC have to match real data
- Hadron sample should be pure
- Same zd
- High quality data
- Huge samples





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Moreover:
very difficult to have /hadron separation at low energy.
(Trigger Threshold != analysis threshold)

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Slide from A. Carosi

Random Forest

Other more modern technique include image recognition algorithms and/or **deep learning**

Still under development for new generation IACT but promising results

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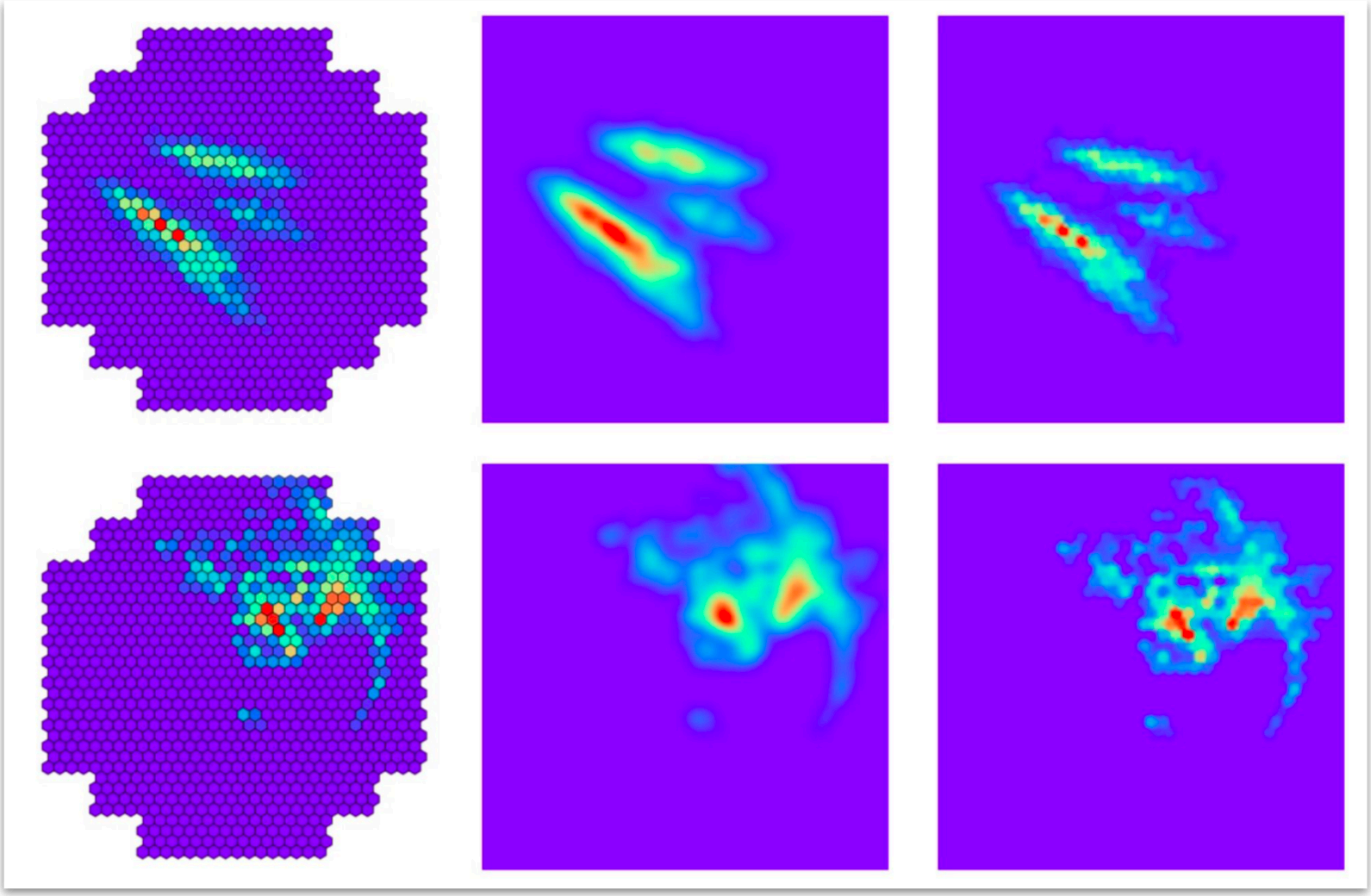
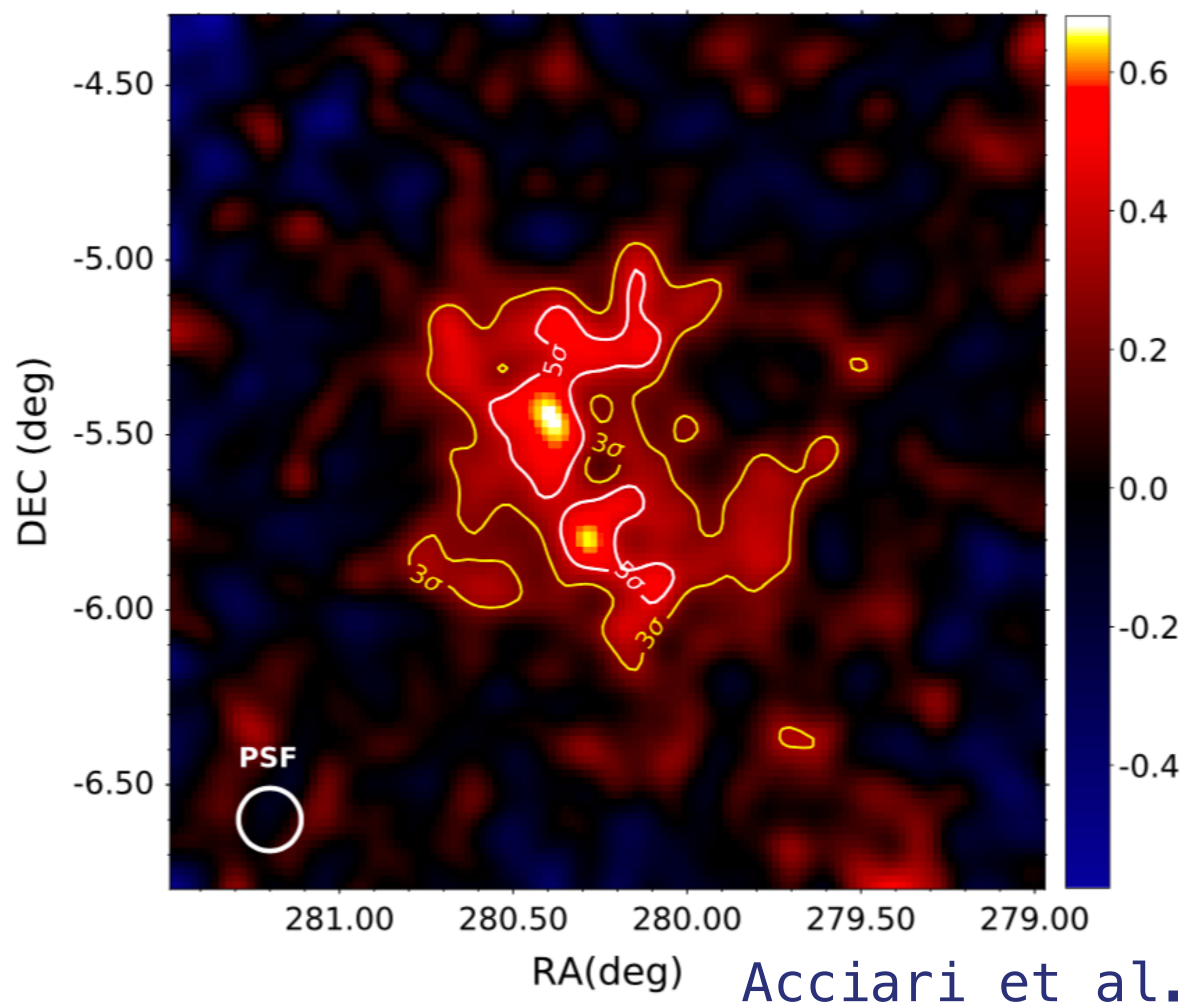


Slide from A. Carosi

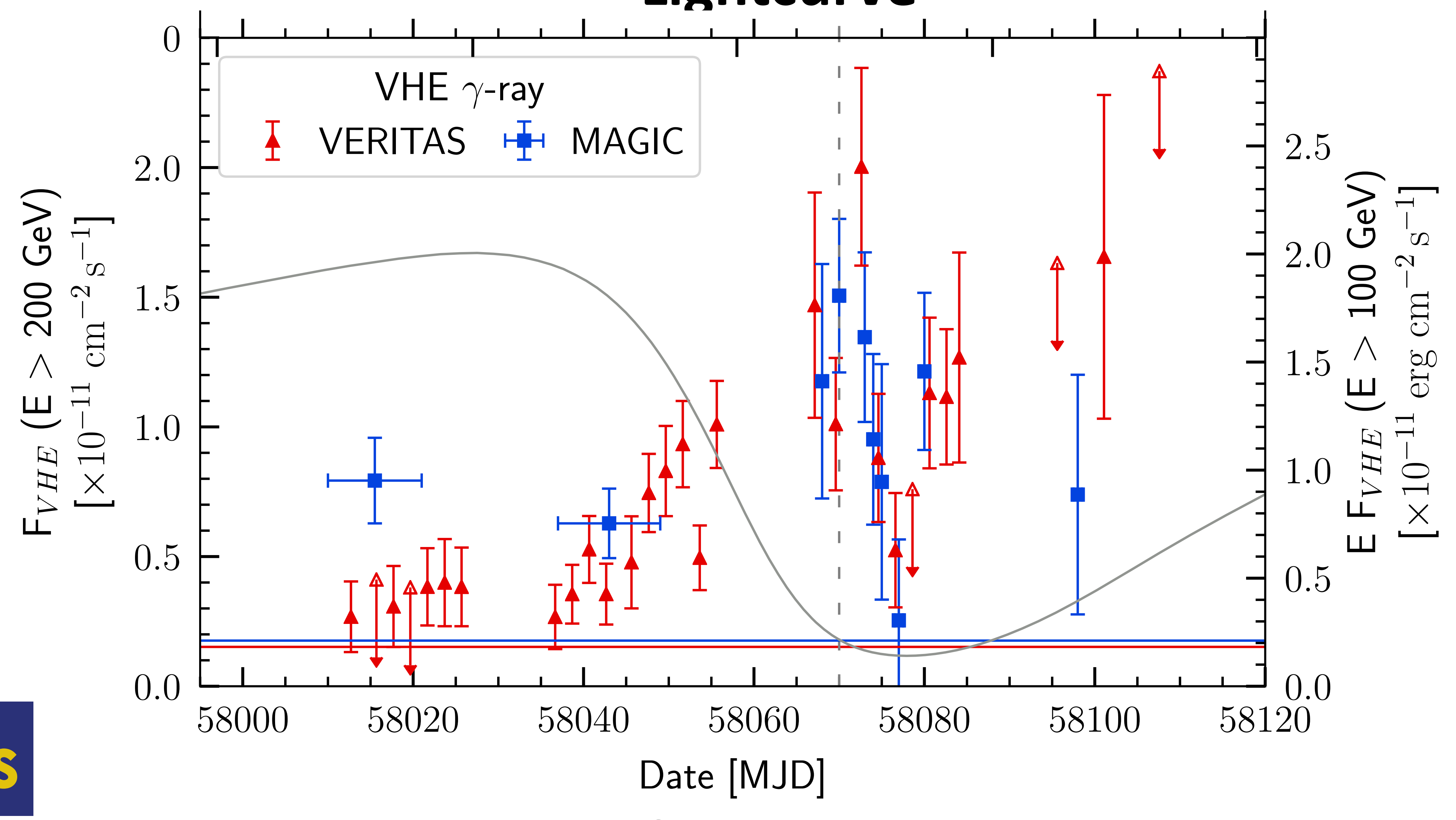
Analysis steps: signal evaluation level

Skymap



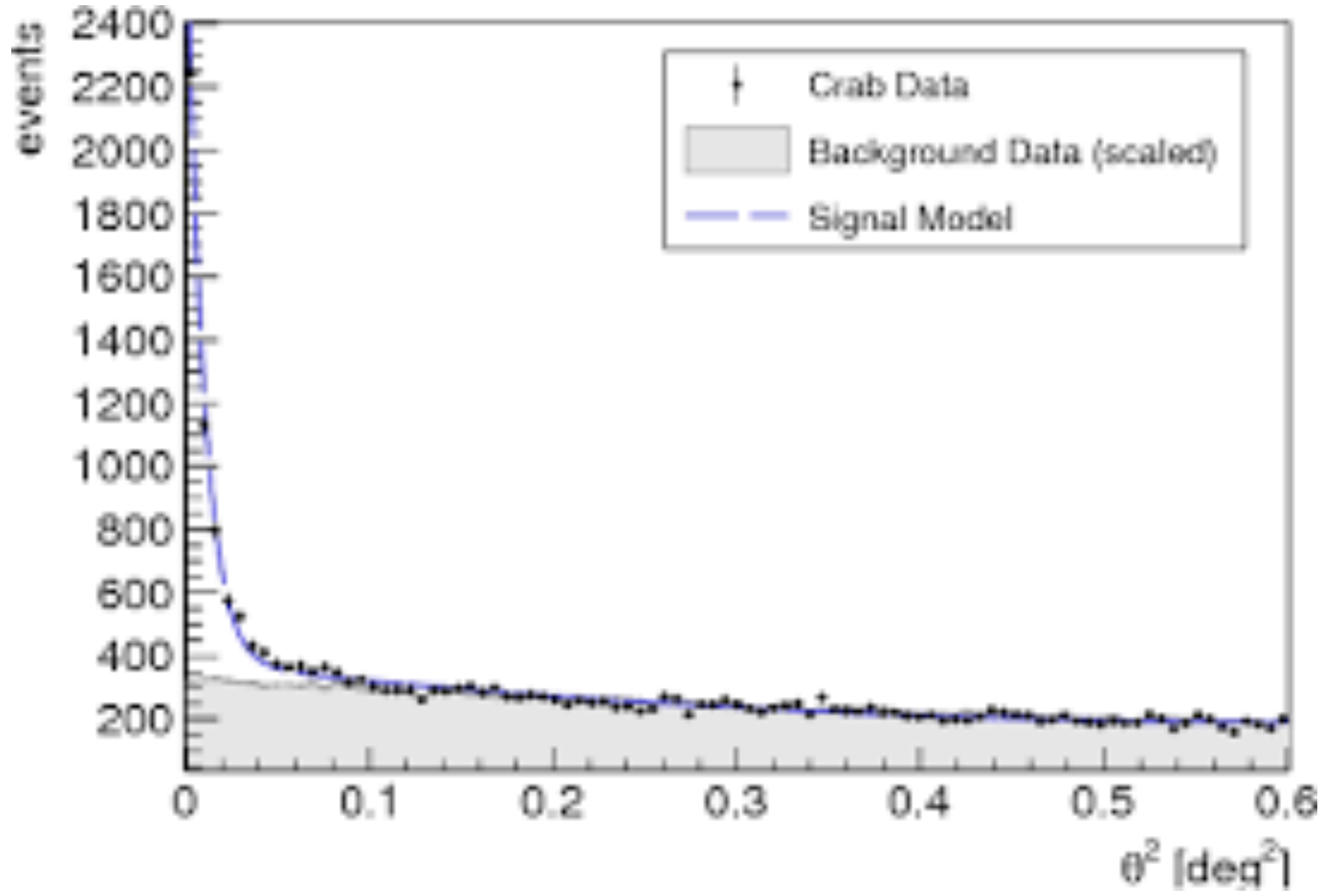
Acciari et al. 2020

Lightcurve

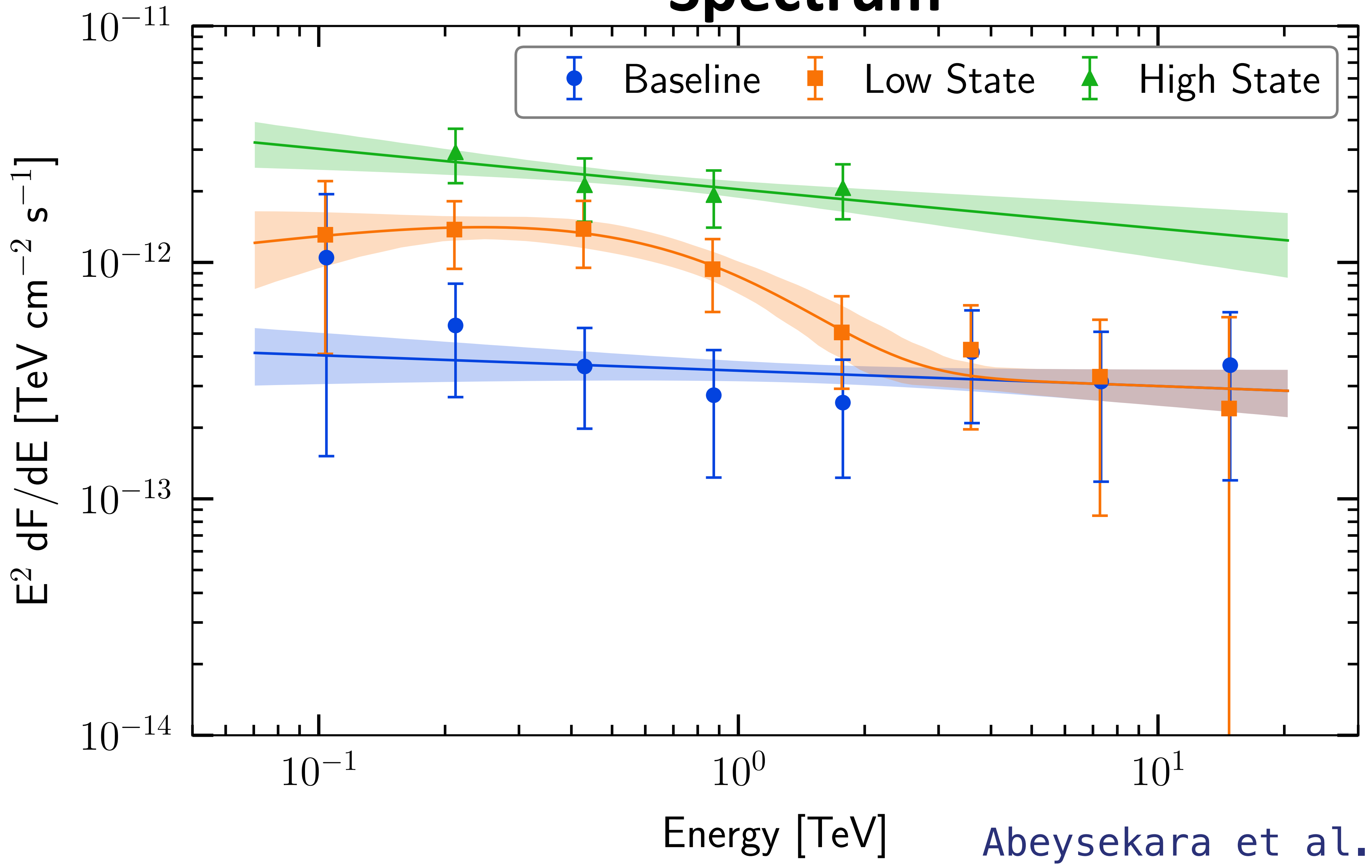


Final products

theta2 plots (significance)



Spectrum

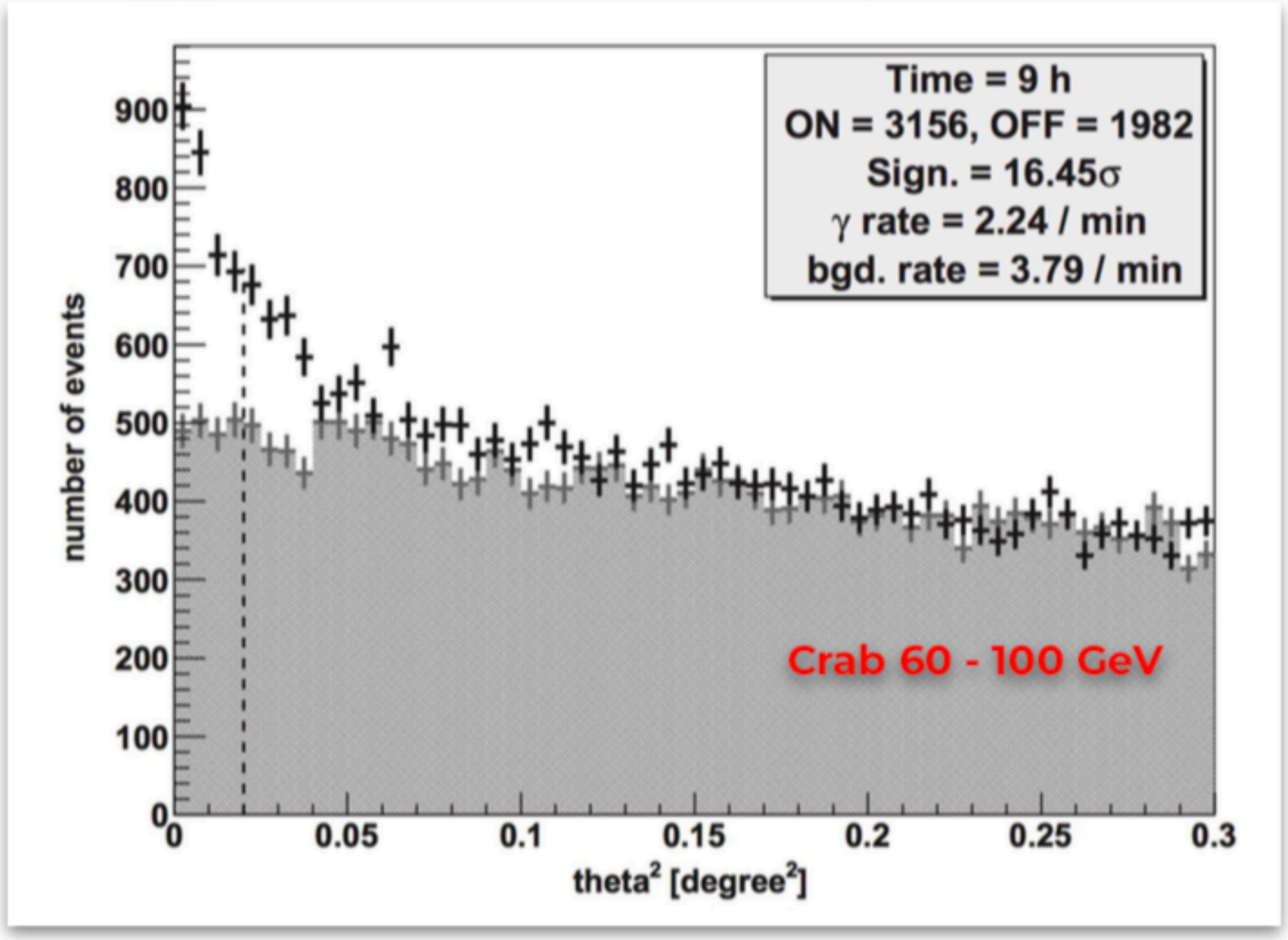


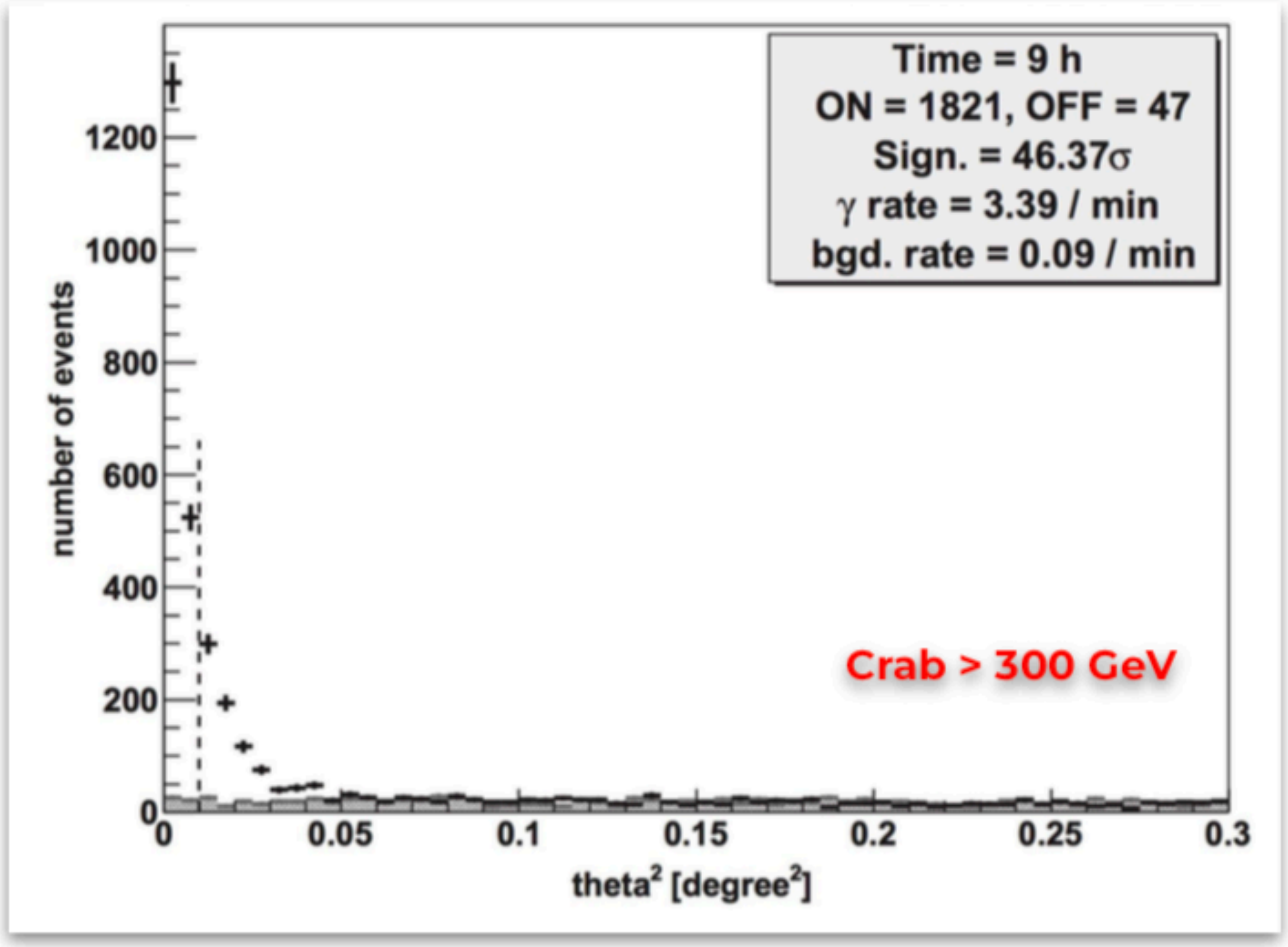
Abeysekara et al. 2018

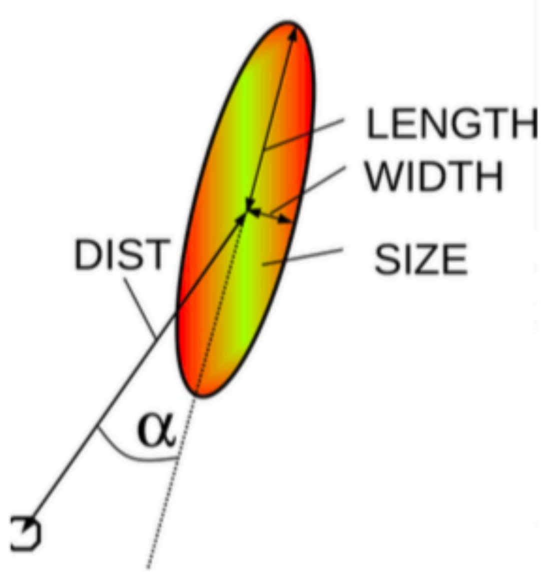
Analysis steps: signal evaluation level

Cut in hadronness is used to discriminate gamma events from hadrons ones

- 2 kinds of events are left: real gamma & hadrons that are gamma-like! alpha (or th2) parameters to separate them
- Signal is evaluated statistically; the signal region contains gamma and background event







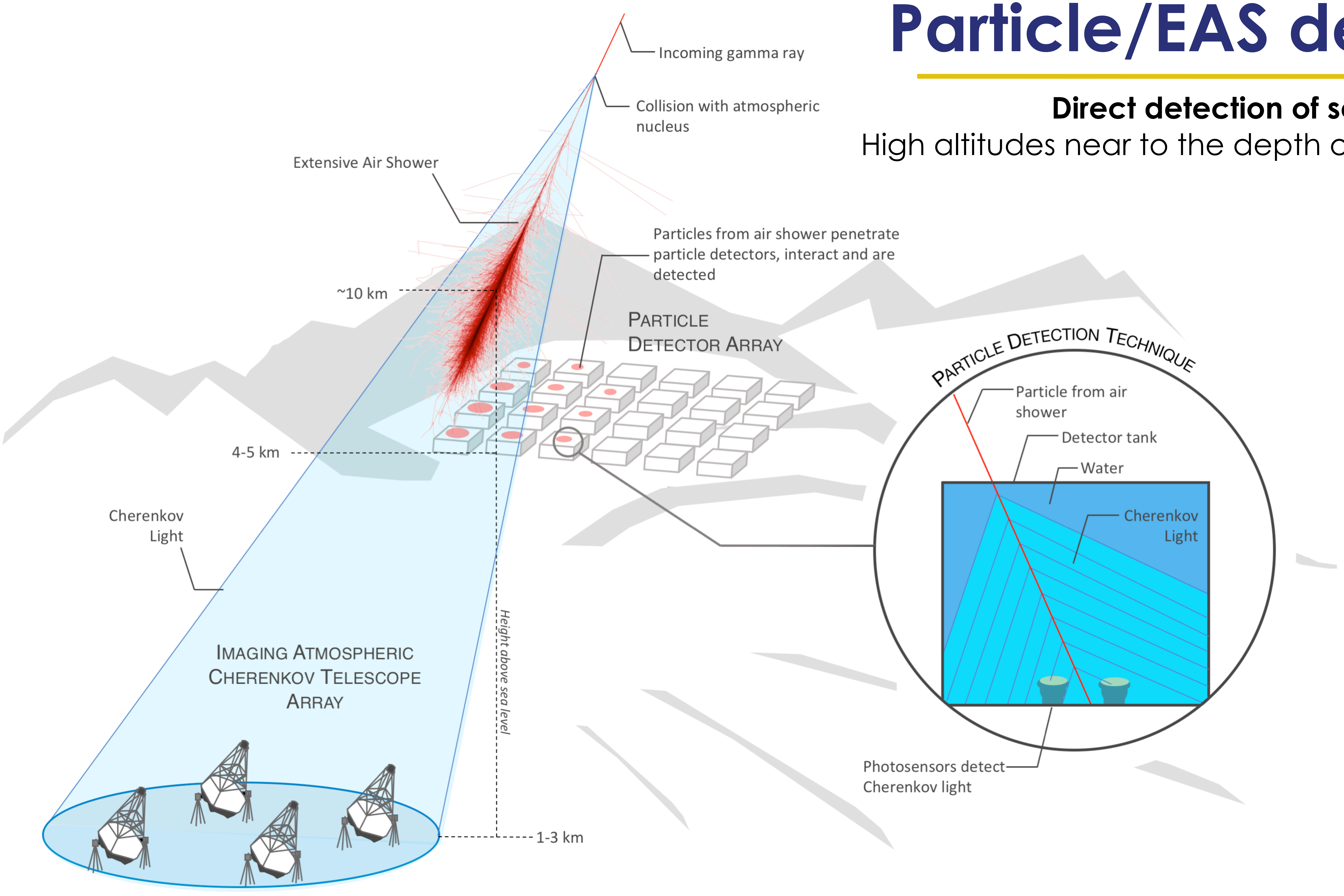
Li&Ma Significance

$$S = \sqrt{-2\ln\lambda} = \sqrt{2}\left\{N_{\text{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right] + N_{\text{off}} \ln\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]\right\}^{1/2}$$

Particle/EAS detectors: UHE

Direct detection of secondary particles of the EAS

High altitudes near to the depth of the shower maximum Xmax



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

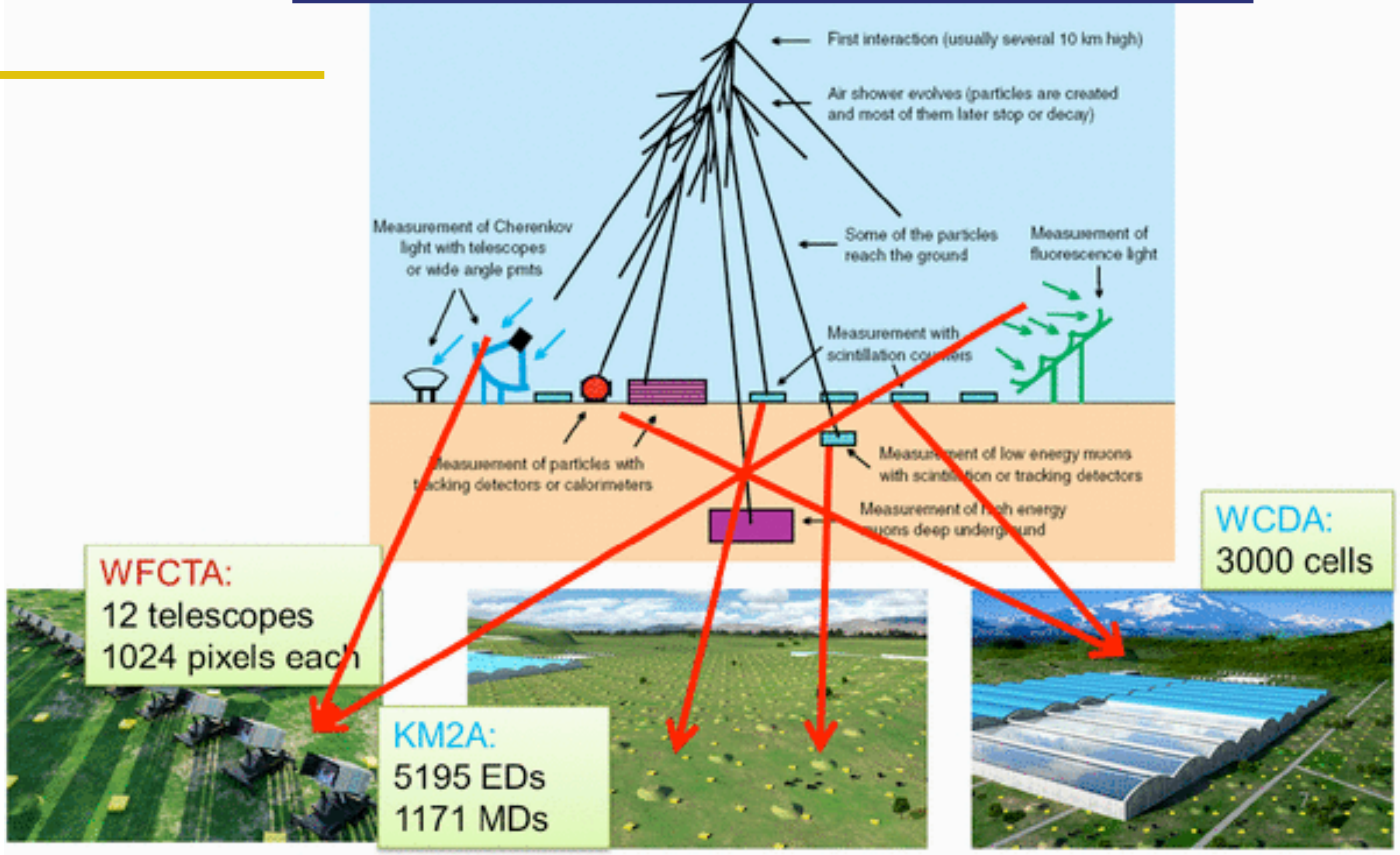
Schoorlemmer et al. 2019

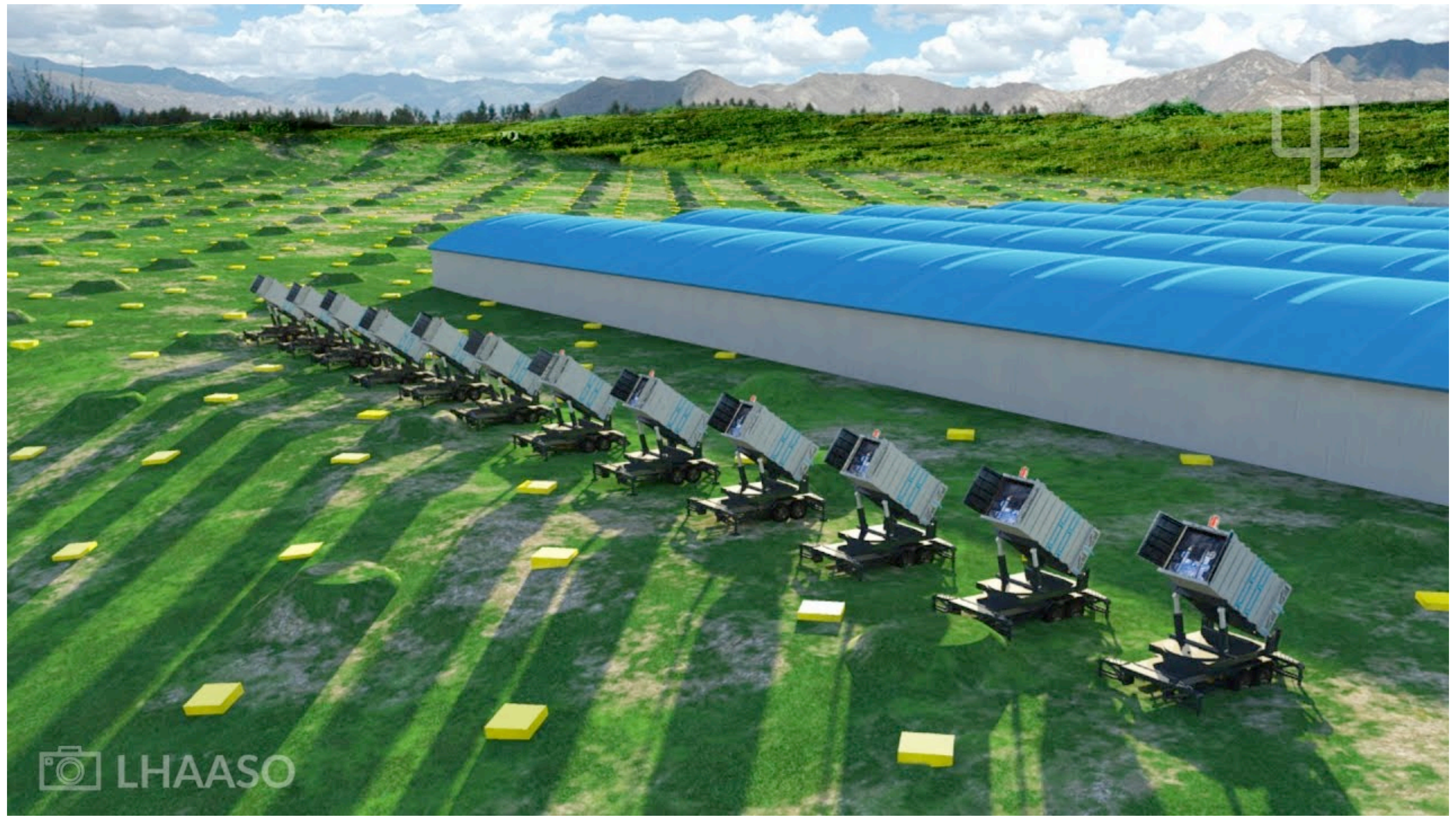
Particle/EAS detectors: UHE

HAWC (México): 4100 m

Water Cherenkov Detector (WCD)

LHAASO (China): 4410m



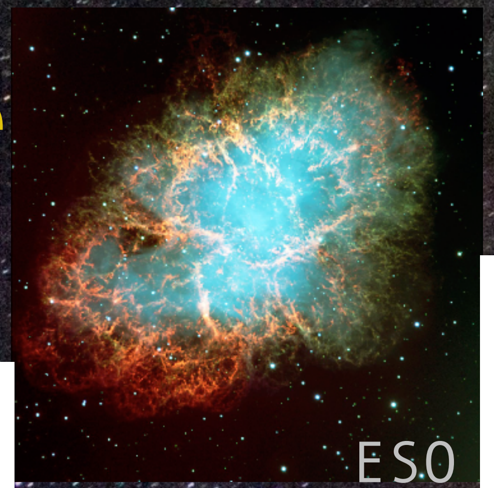


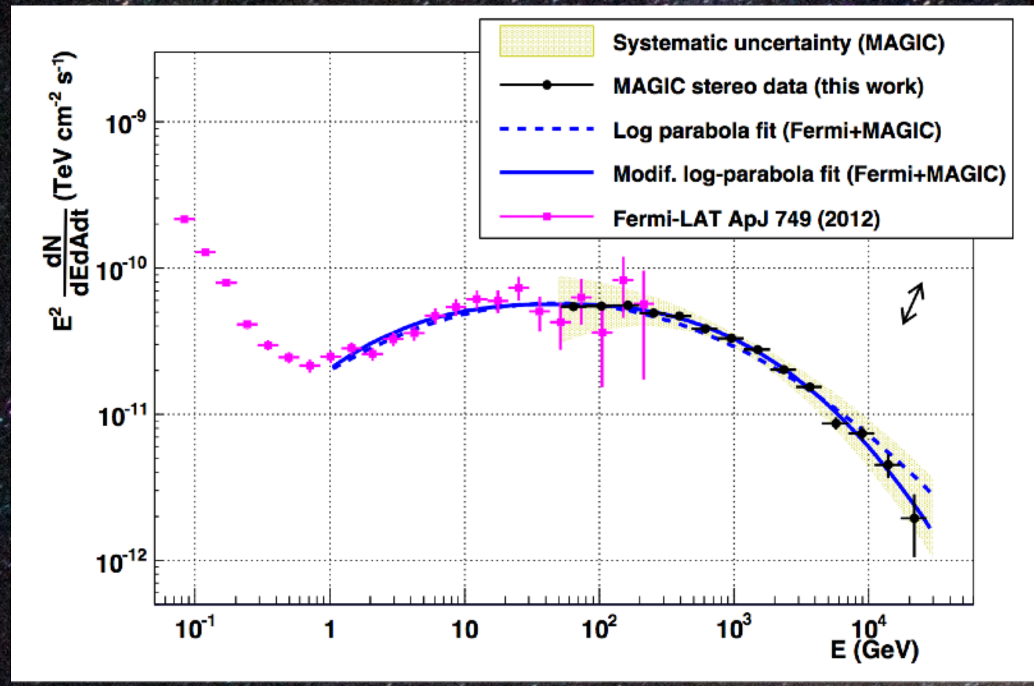
 

	IACTS	Particle detectors	
Energy range	tens GeV - tens TeV	> tens TeV	
Background rejection	Excelent	Moderate	
Angular and energy resolution	Better than particle detectors	Worse than IACTs	
Duty cycle	Dark time - moderate moonlight	>99%	
FoV	Small	Big	

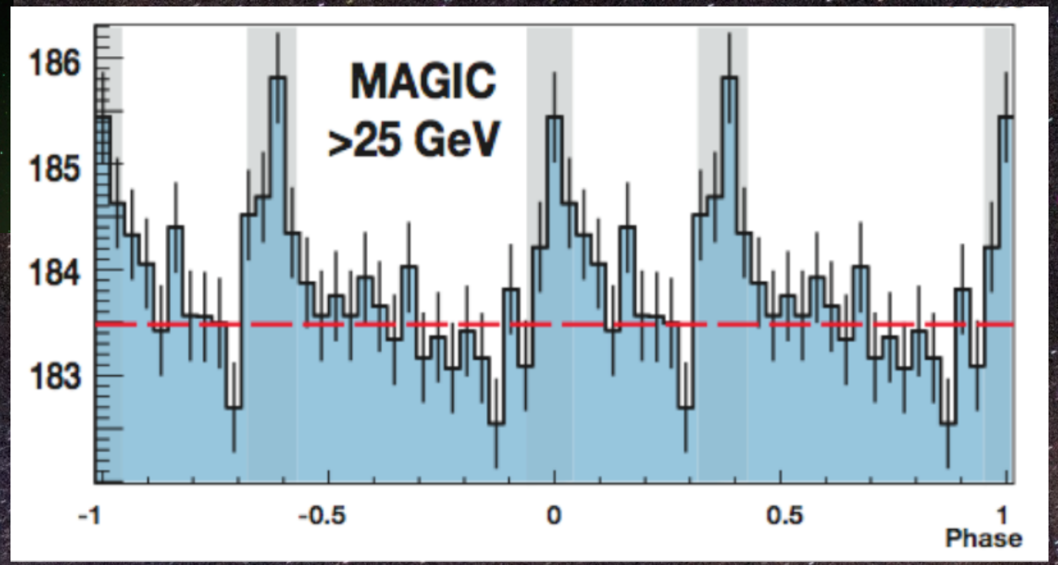
VHE Galactic Sources

Pulsar-wind nebulae & Crab Nebula

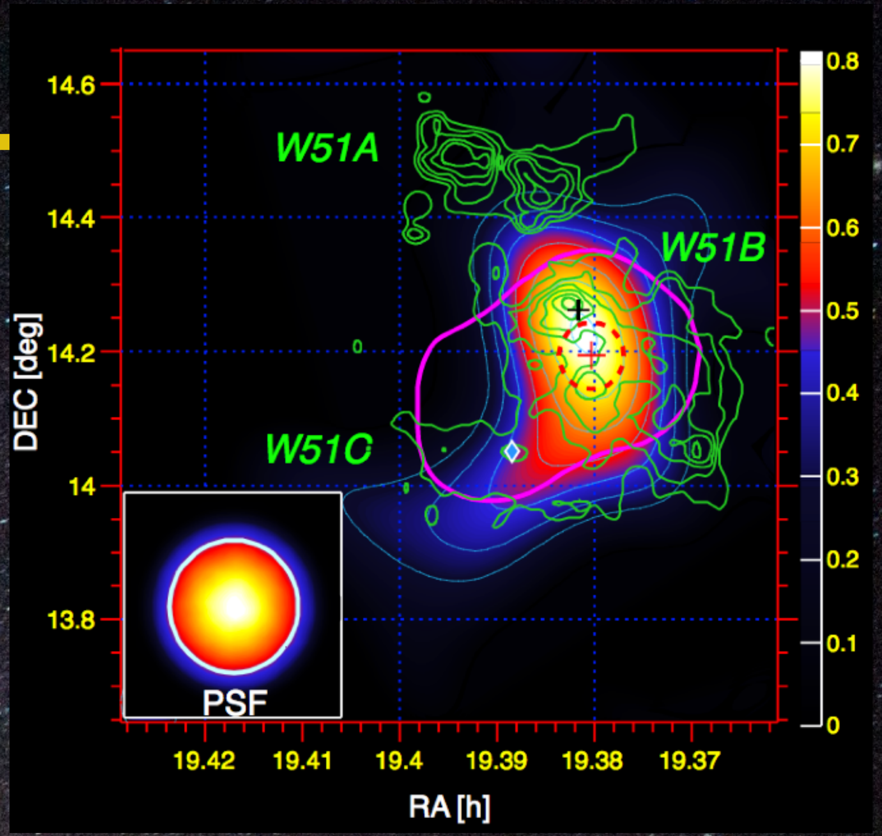




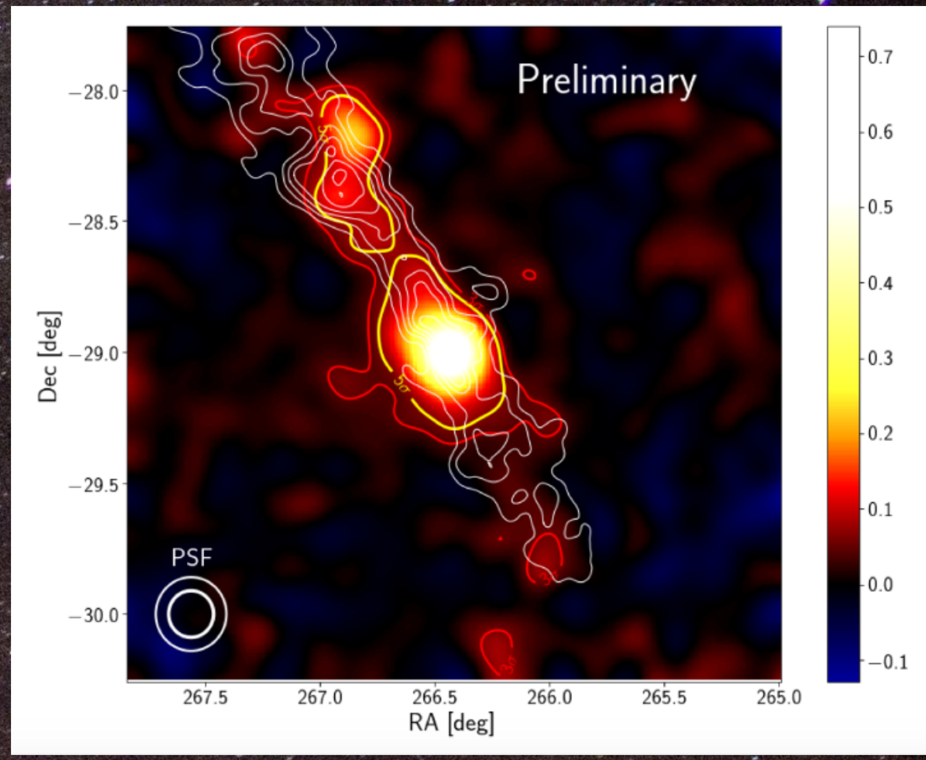
Pulsars



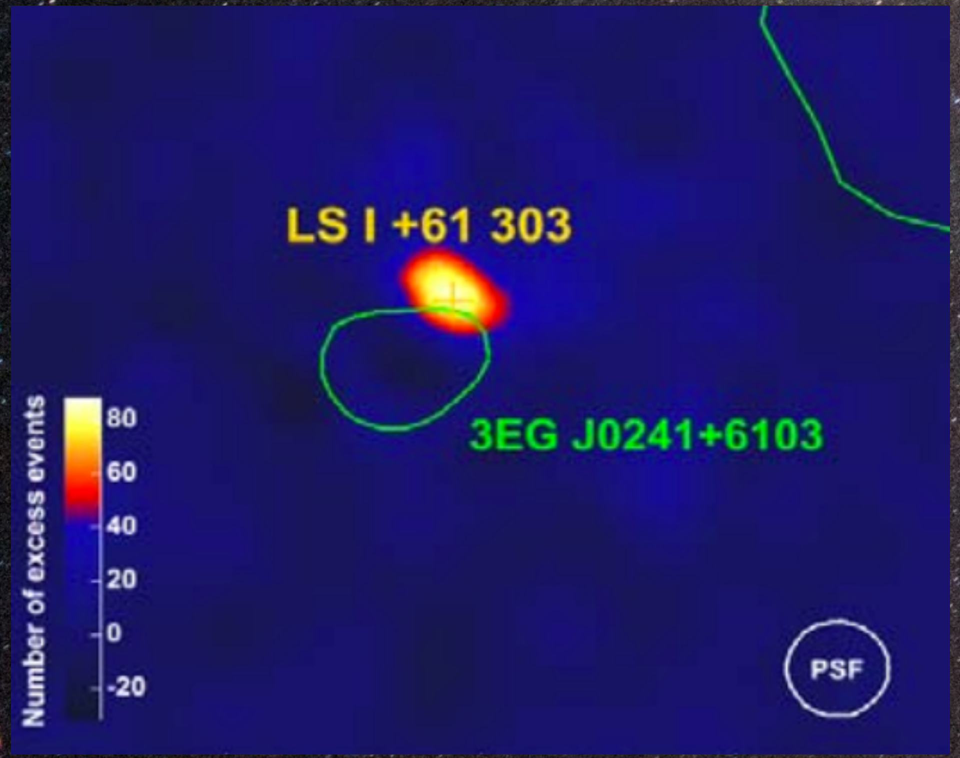
SNRs



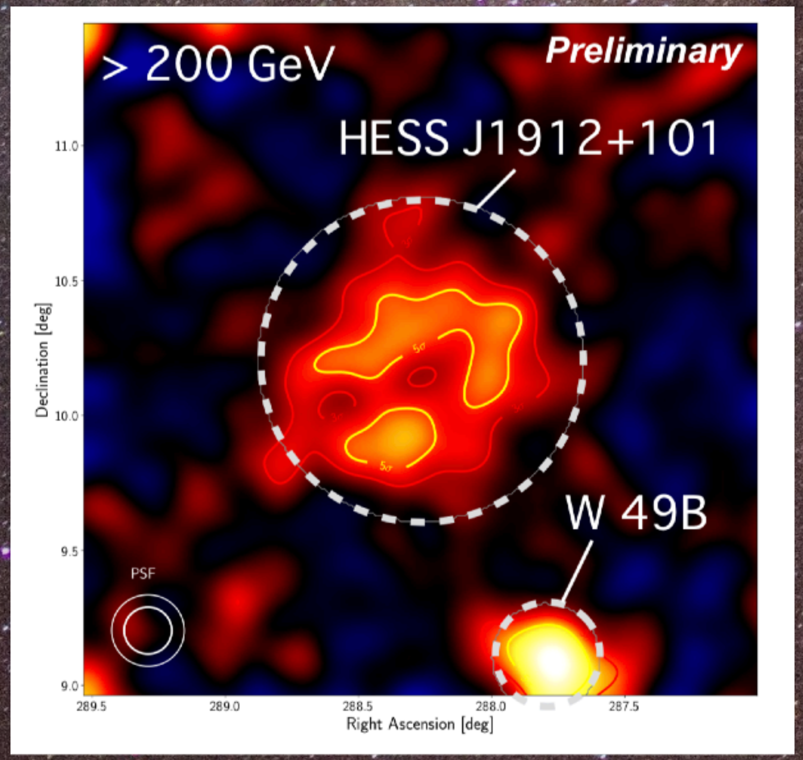
Galactic Center



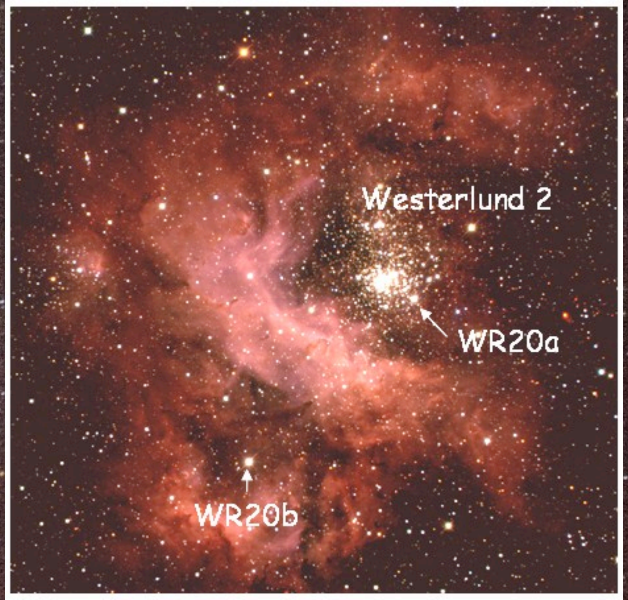
Binaries



Extended/unidentified sources



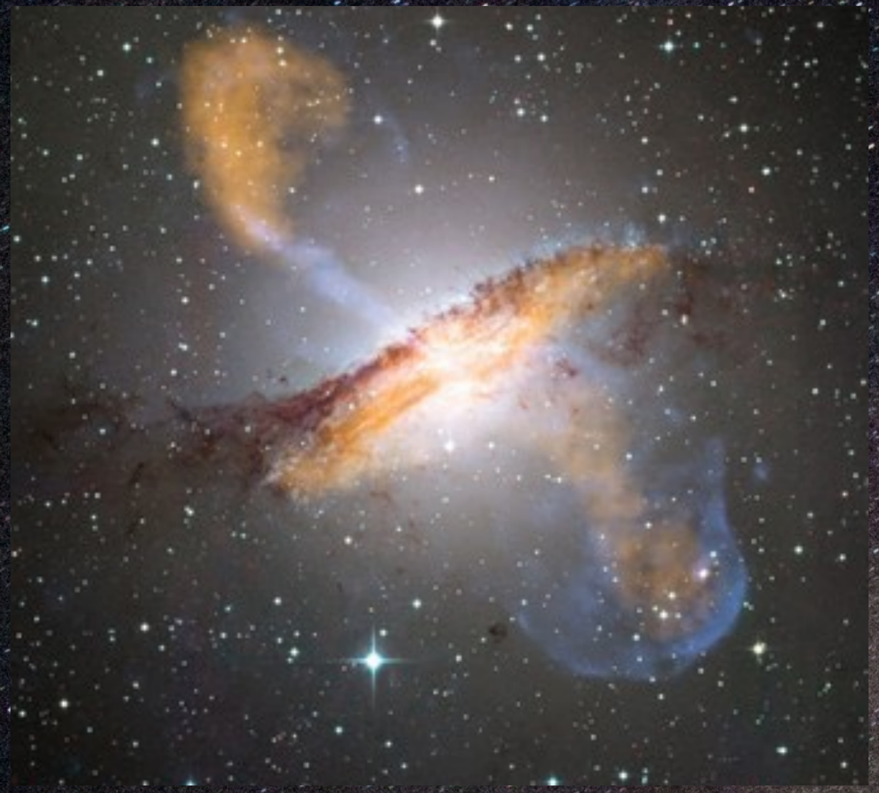
Star-forming regions



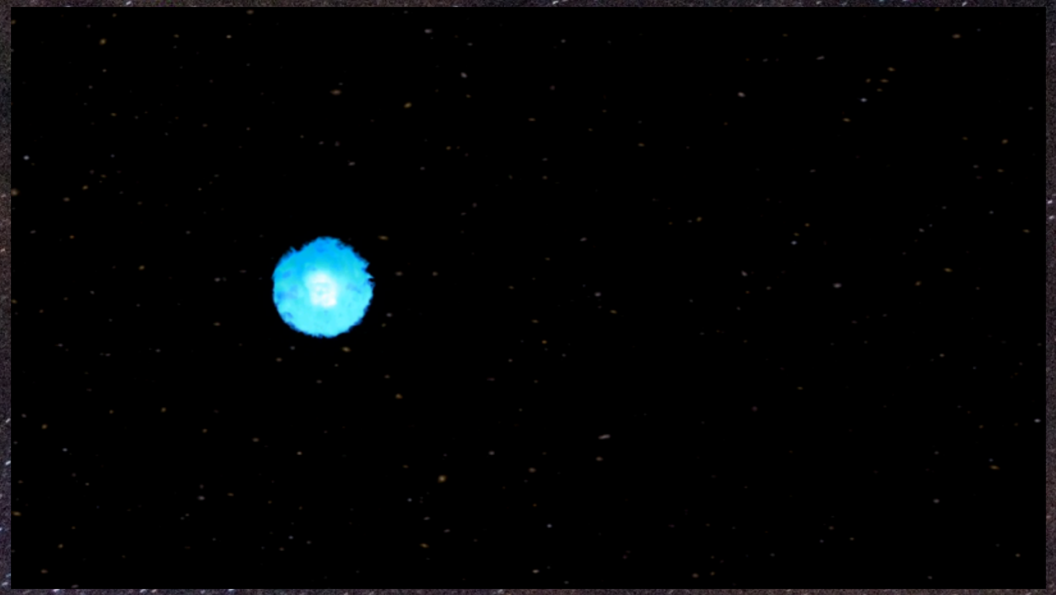
Transient phenomena

VHE extragalactic sources

AGNs



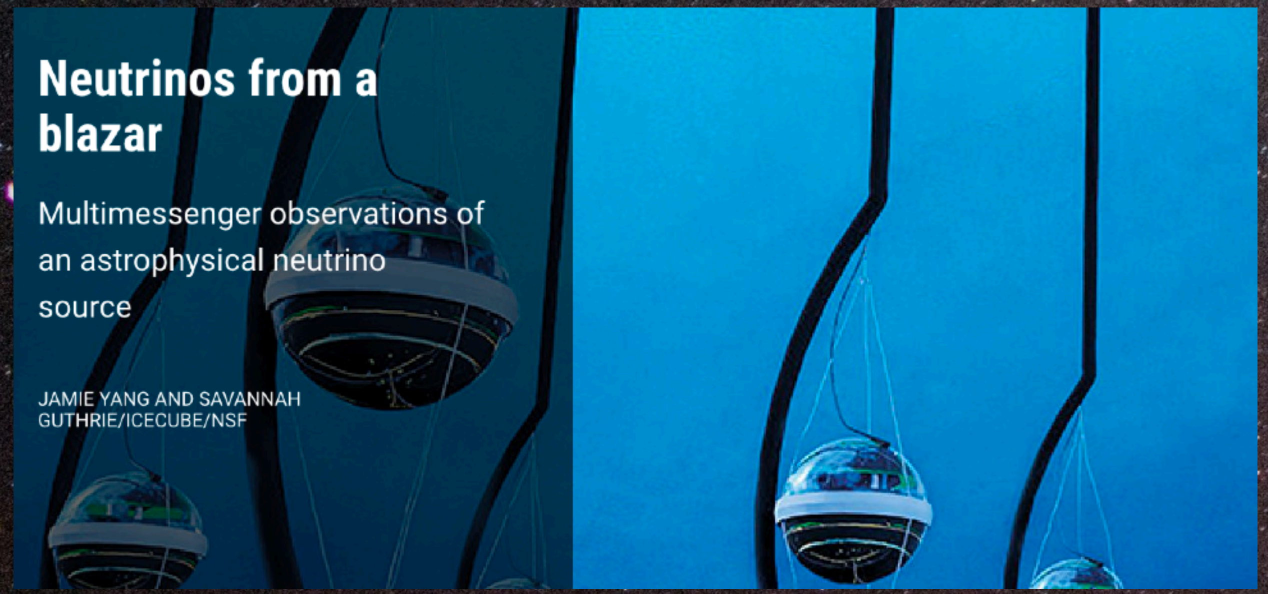
GRBs



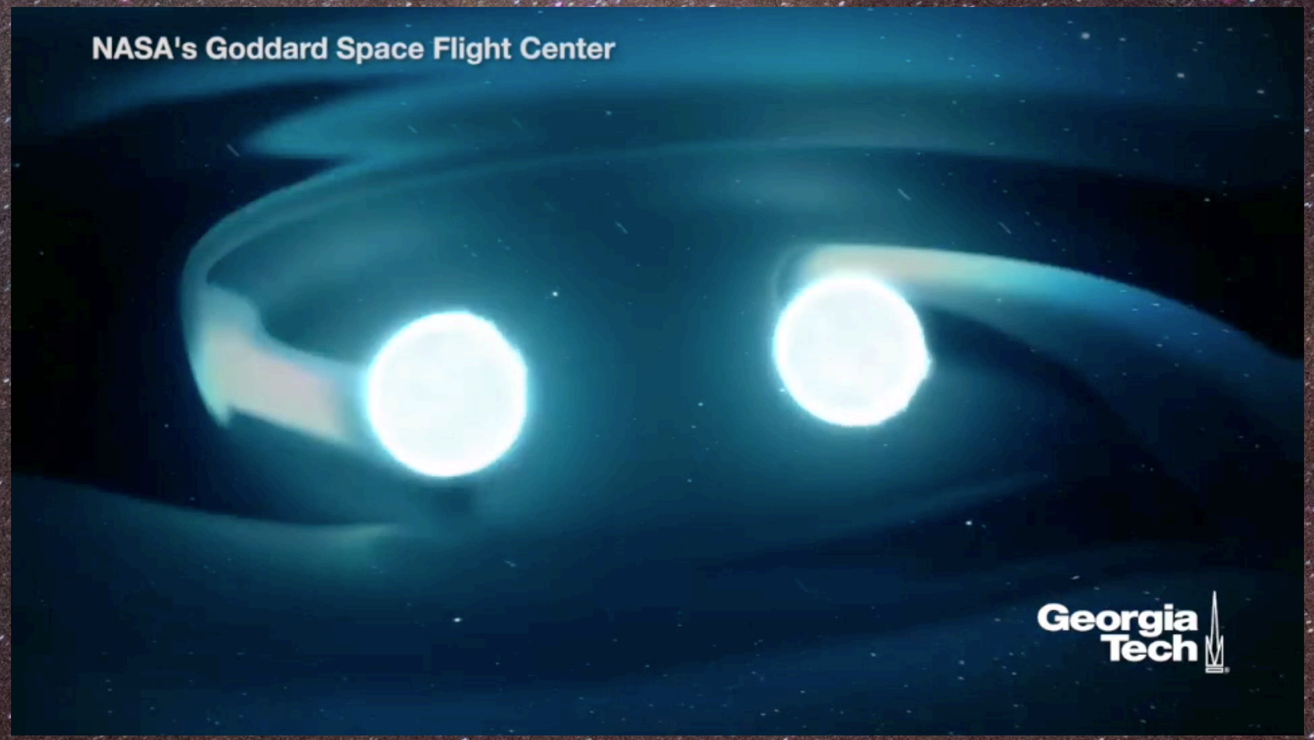
Fundamental Physics

Dark Matter
Lorentz Invariance

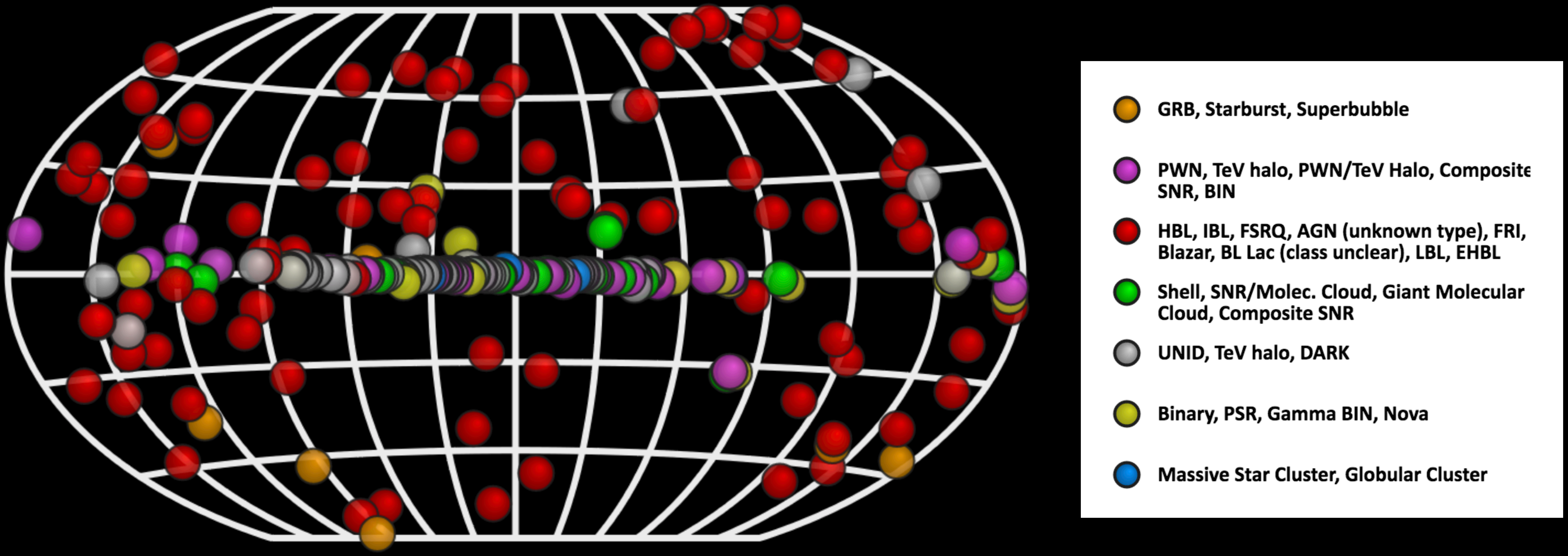
Neutrino counterparts



GW counterparts



VHE Galactic Sources



- **252* sources of VHE gamma rays** (http://tevcat2.uchicago.edu/)
  - Blazars are the largest population (~80)
  - Followed by SNRs and PWNe (63)

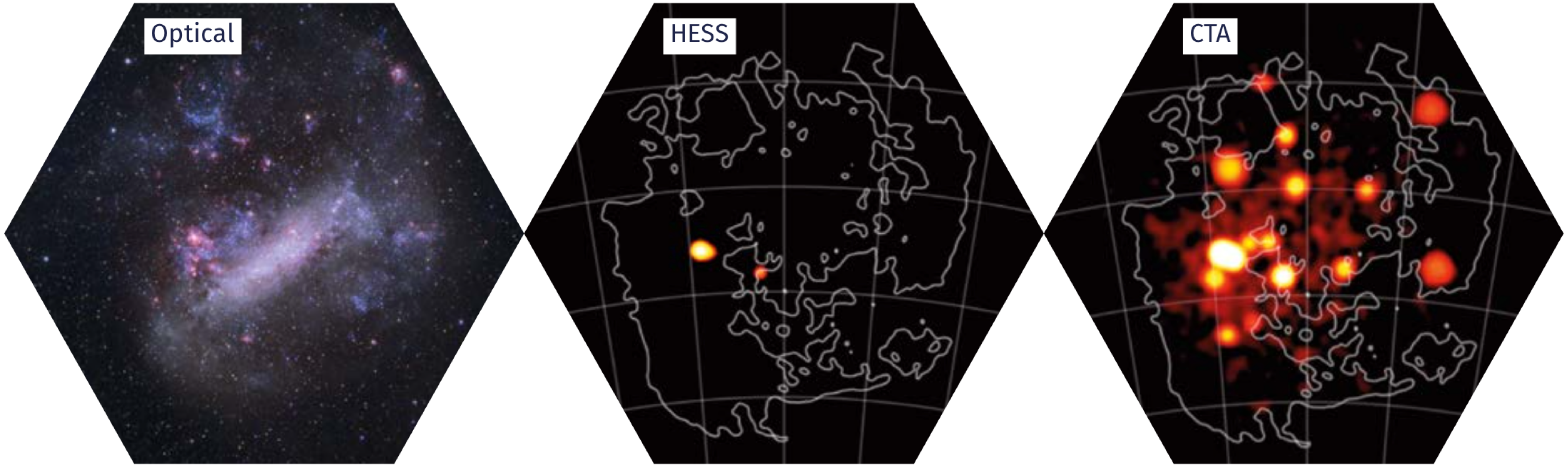
* March 30, 2023

Note: 1st LHAASO catalog released today: https://arxiv.org/pdf/2305.17030.pdf

Building the future:
the Cherenkov Telescope Array Observatory

Cherenkov Telescope Array (CTA)

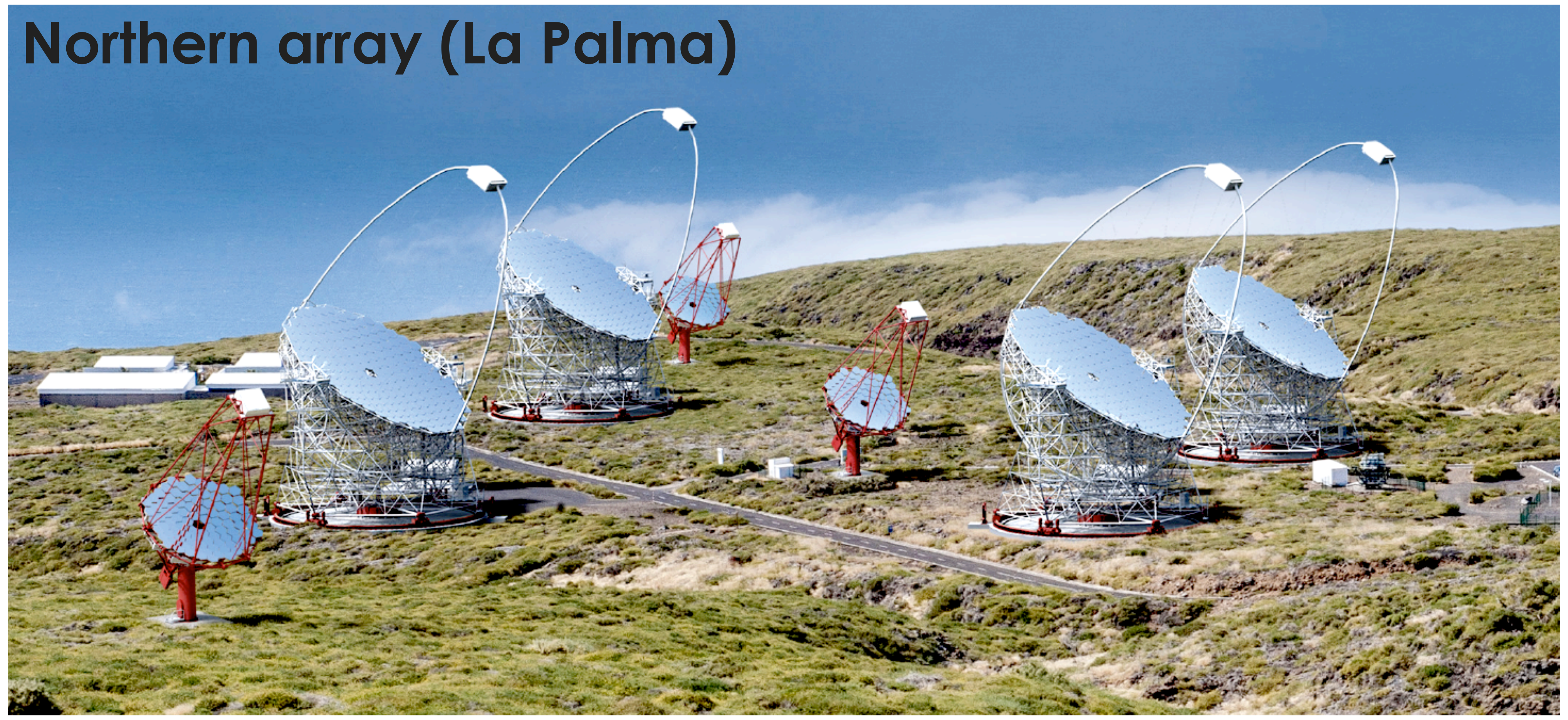
- Next generation ground-based VHE gamma-ray observatory
- Goals
  - **Improve current sensitivity**
  - **Enlarge the energy range**
  - **Improve energy and angular resolution**

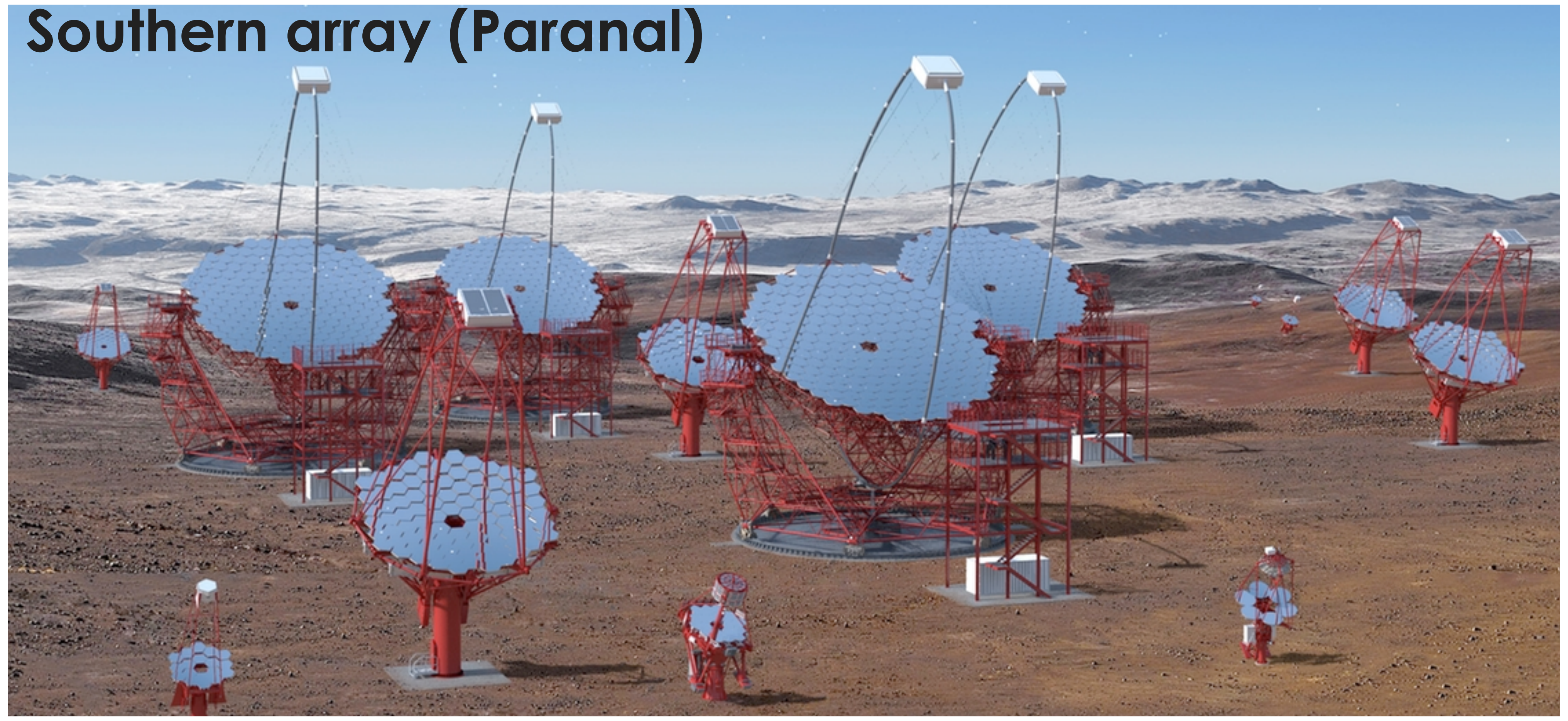


A simulated comparison of CTA's survey of the LMC with current optical and H.E.S.S. images.

CTA consortium: aboutt **1400 members** from **32 countries** and 210 institutes

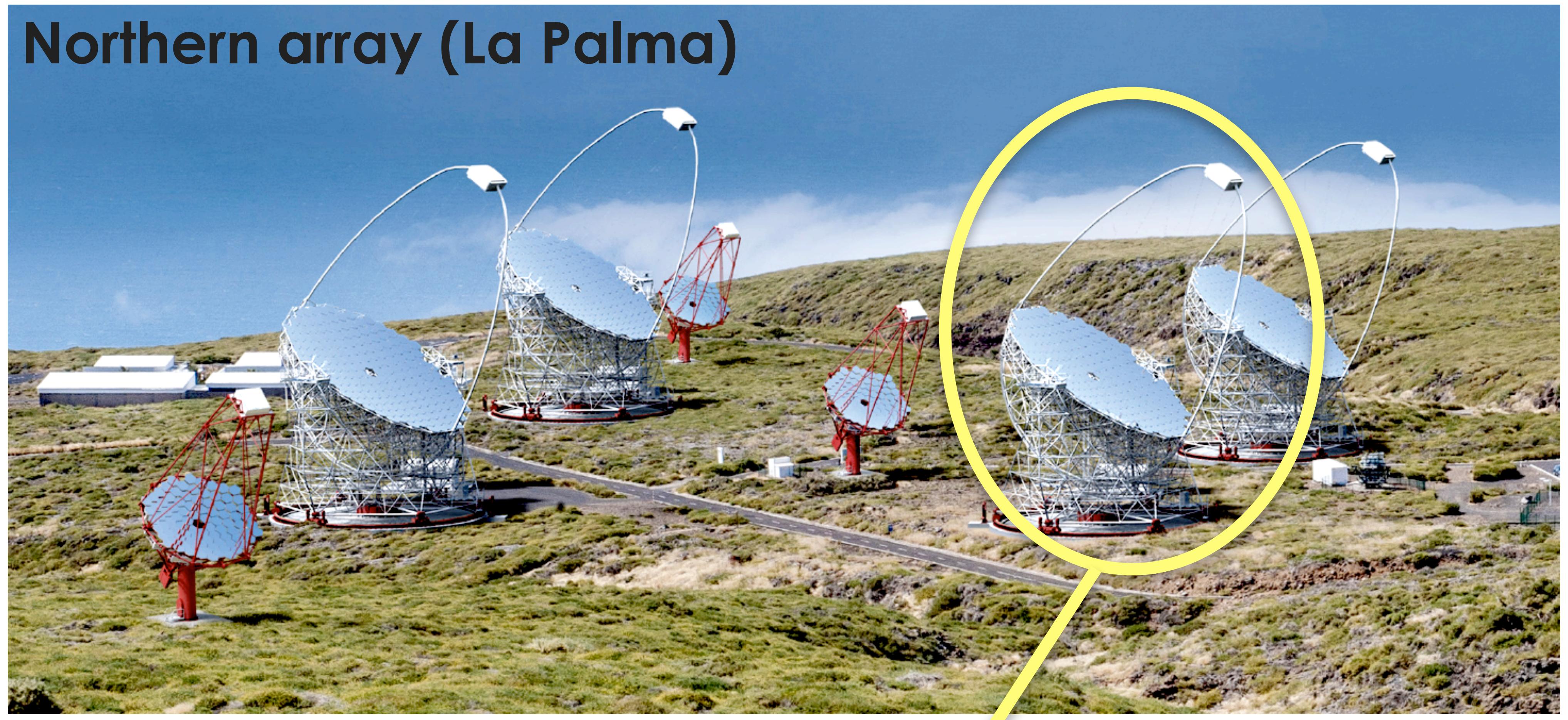
Cherenkov Telescope Array (CTA)

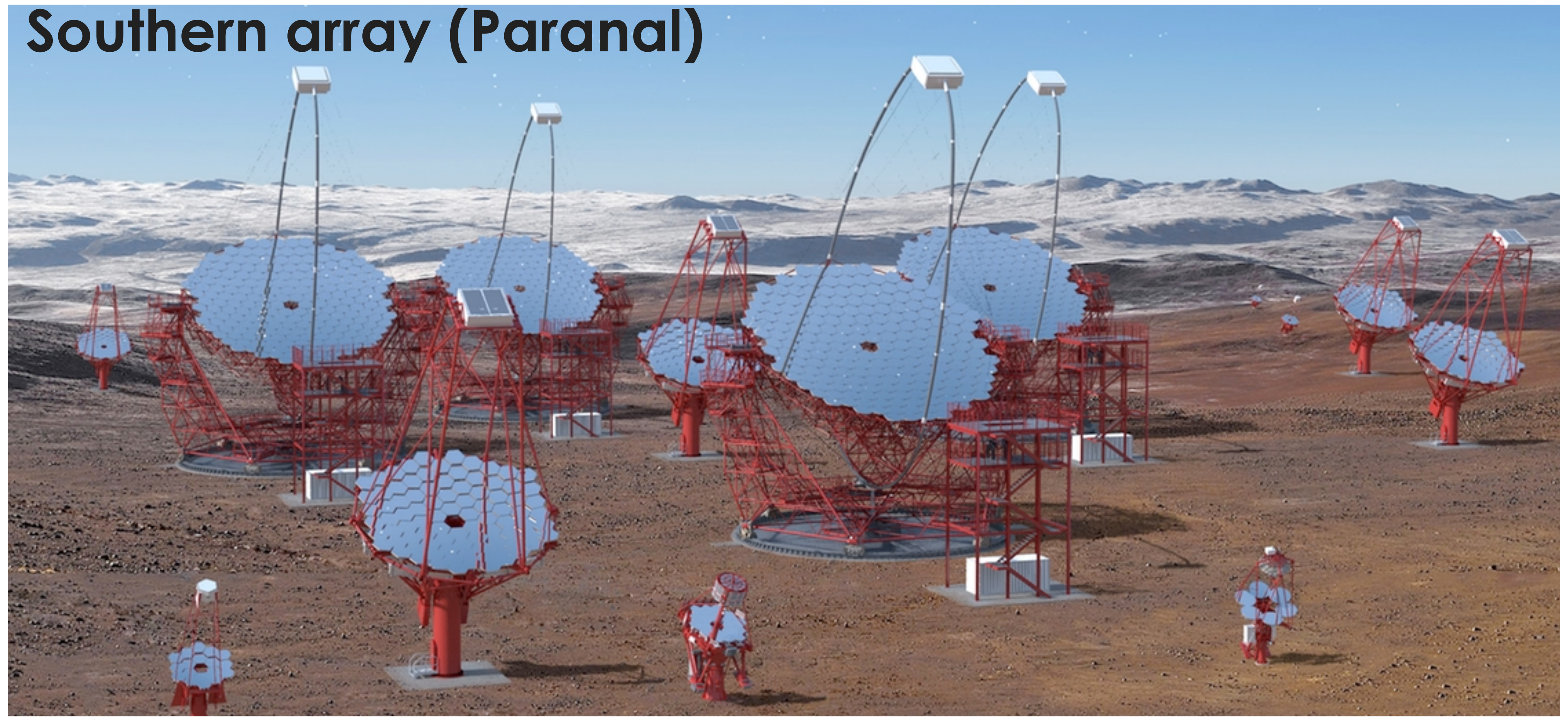


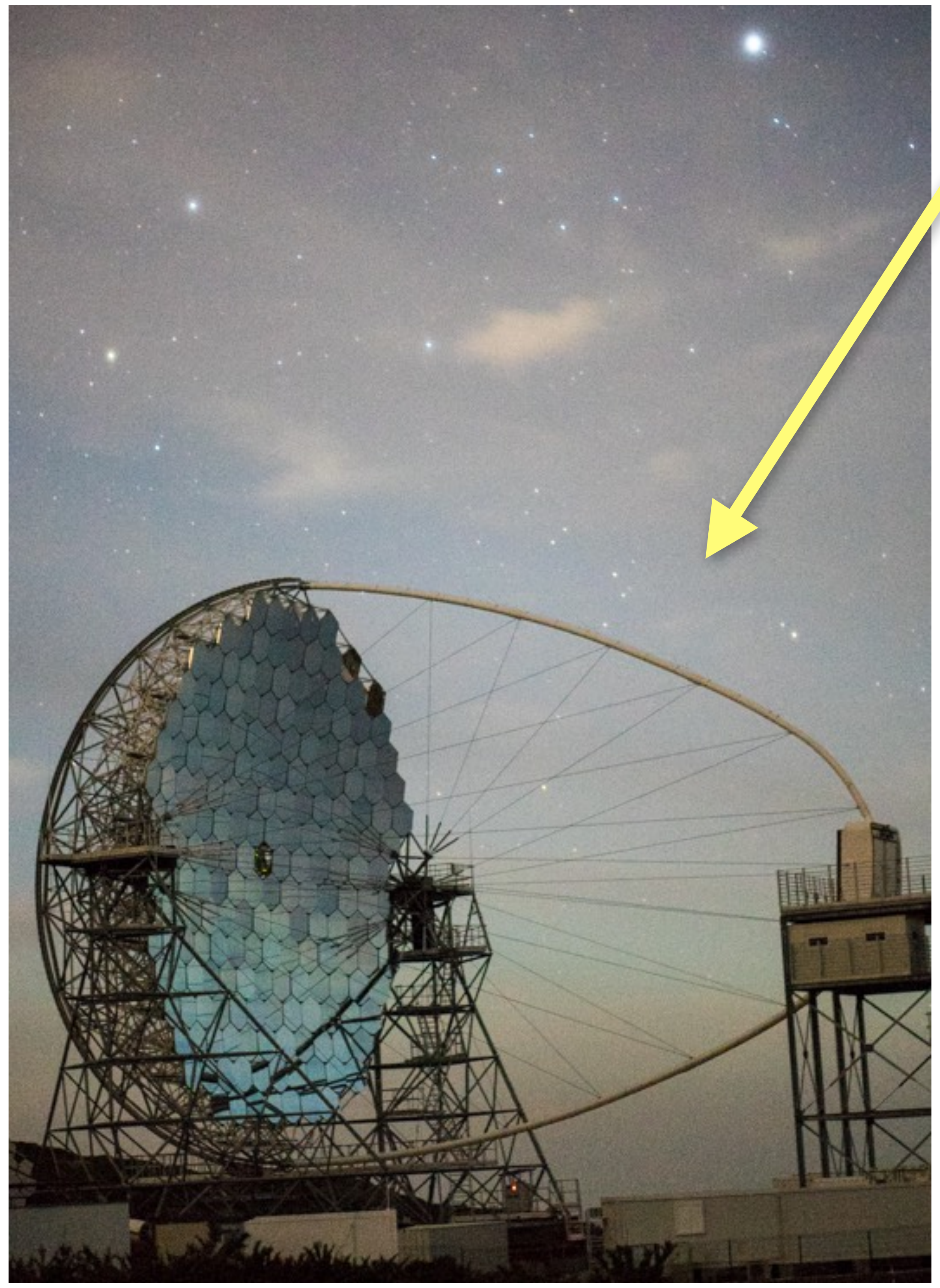


- Future **ground-based gamma-ray observatory** (www.cta-observatory.org)
- Science with CTA: (https://doi.org/10.1142/10986)
- Two sites:
  - **Northern array: La Palma** (Canary Islands, Spain)
  - **Sourthern array: Paranal** (Chile)

Cherenkov Telescope Array (CTA)

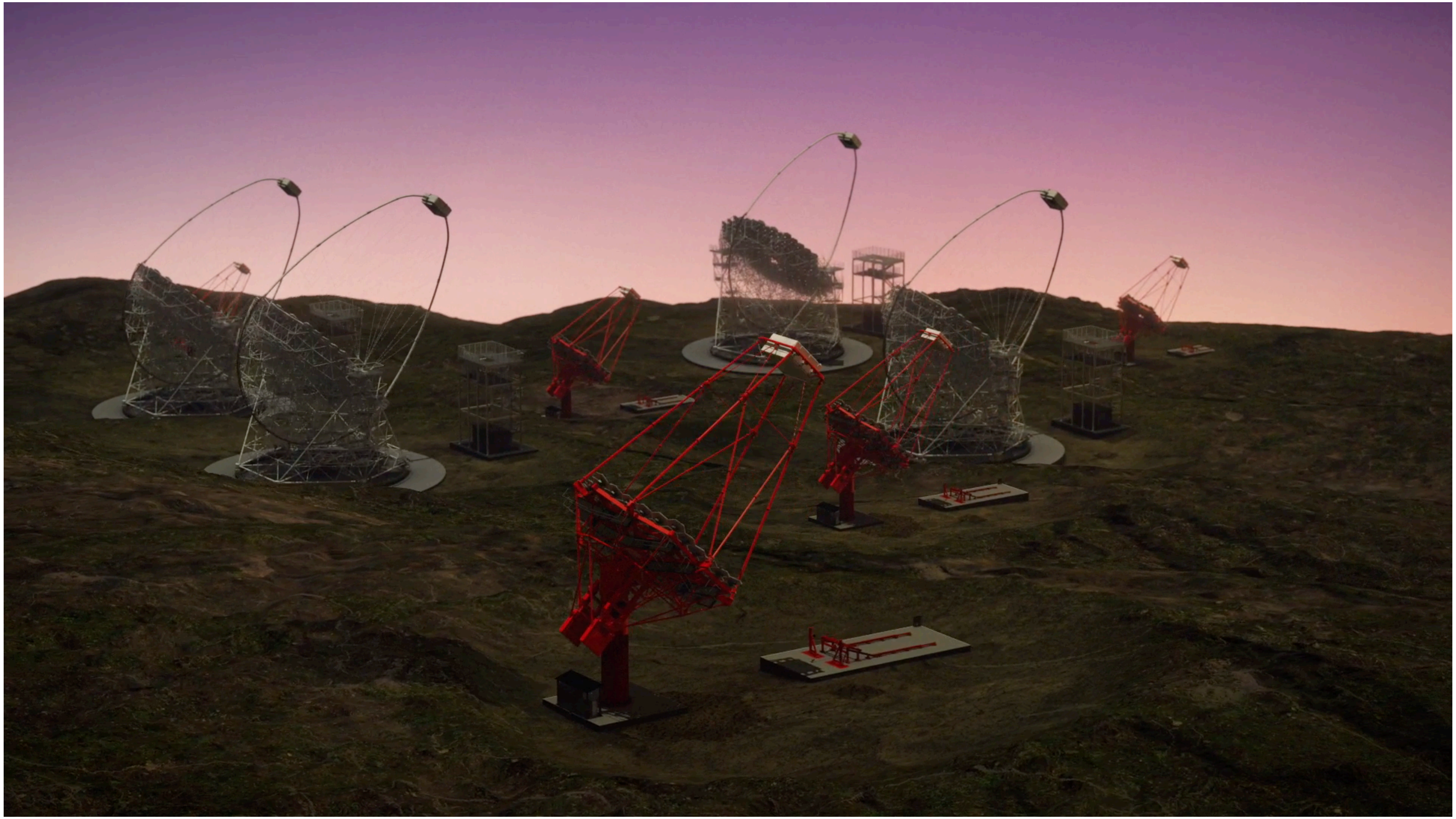




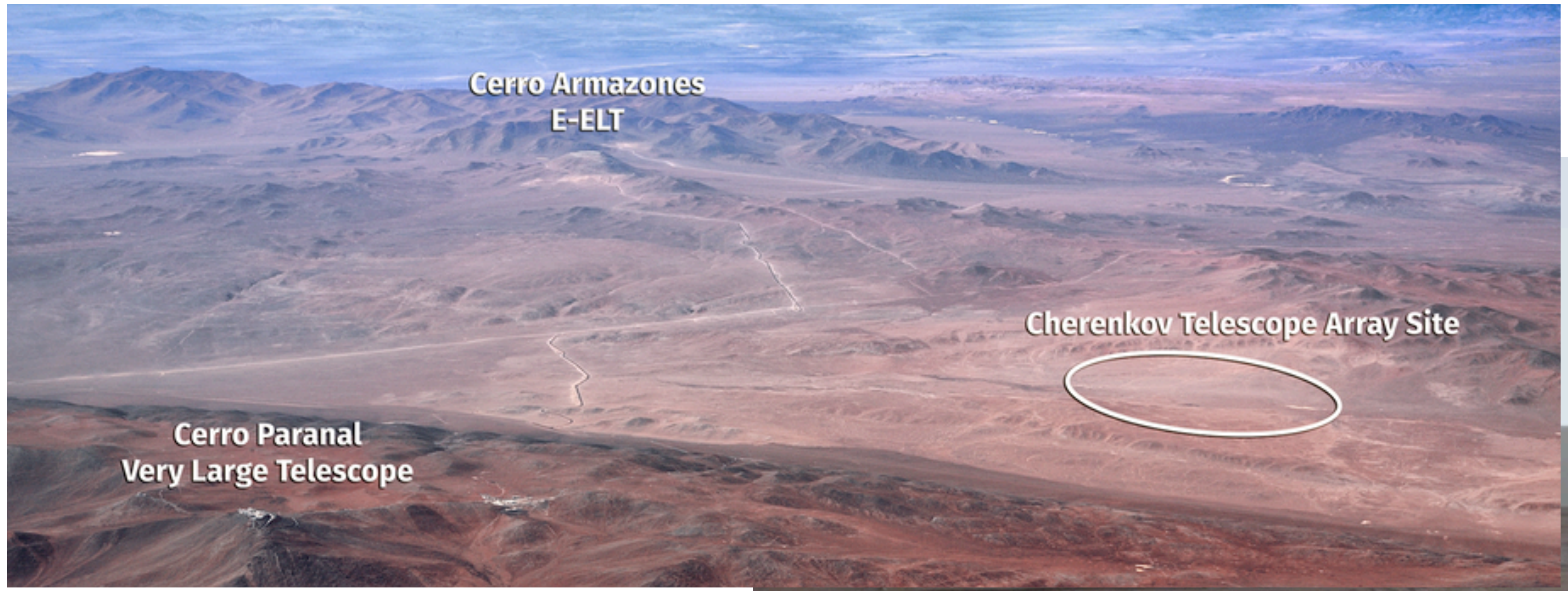


- Future **ground-based gamma-ray observatory** (www.cta-observatory.org)
- Science with CTA: (https://doi.org/10.1142/10986)
- Two sites:
  - **Northern array: La Palma** (Canary Islands, Spain)
    - First Large Size Telescope (**LST1**) under **commissioning**
  - **Sourthern array: Paranal** (Chile)
- **Three sizes of telescopes**:
  - Cover a large energy range: **20 GeV- 300 TeV**

CTA-North



CTA-South



Cerro Armazones
E-ELT
Cherenkov Telescope Array Site
Cerro Paranal
Very Large Telescope

CTA energy range: 20 GeV- 300 TeV

MST (Medium Size Telescope)
Optimized for mid-energies
Rapid surveys of the sky
Diameter: 12 m
Energy range: 100 GeV-10 TeV
otype but 2 cameras (Flashcam, NectarCAM)
o SCT prototype @Whipple observatory site
~100 Tons (i.e. H.E.S.S. II is 580 Tons)

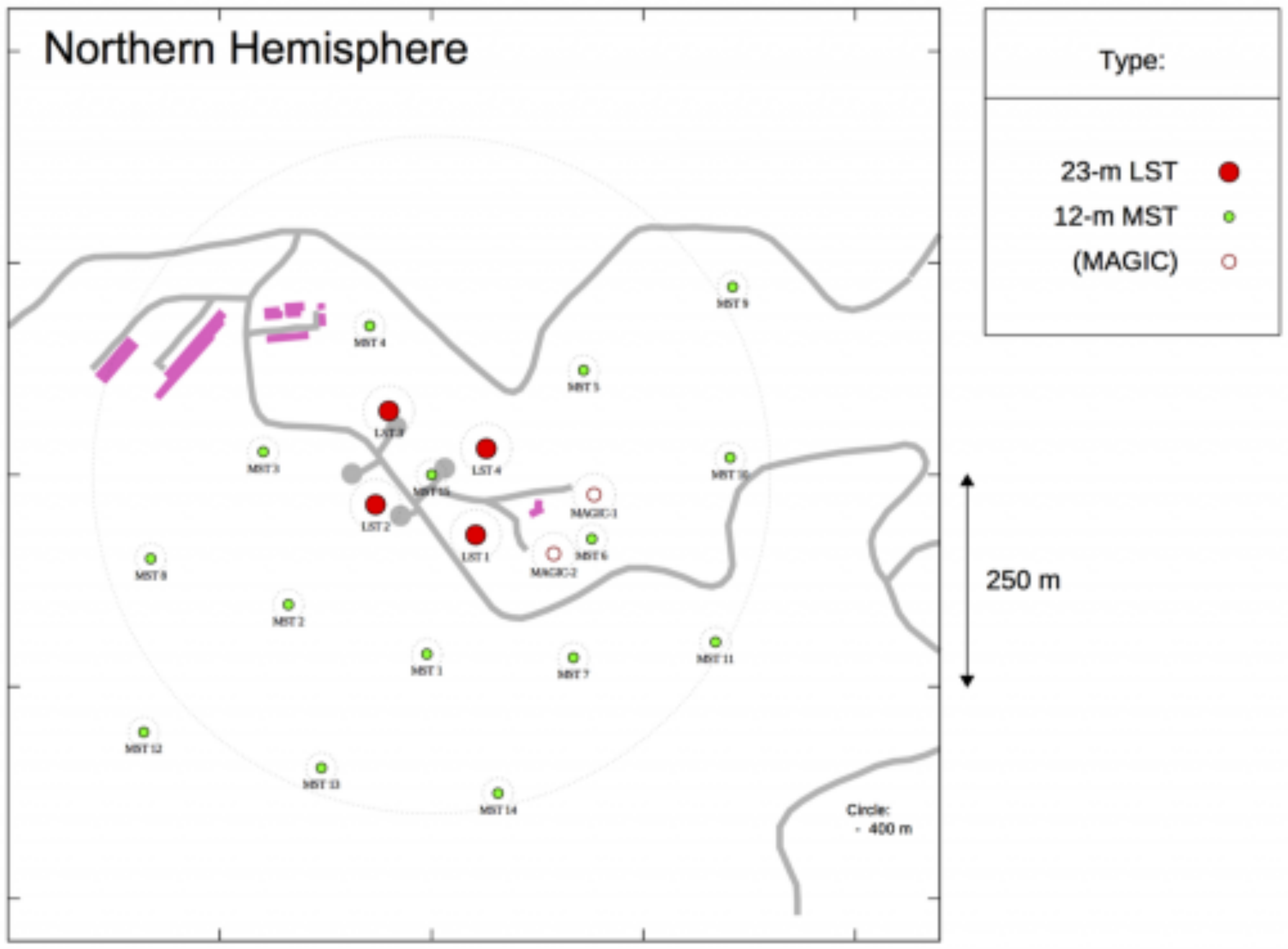
LST (Large Size Telescop

SST (Small Size Telescope)
Sensitive to highest energies
Diameter: 4 m
Energy range: 1-300 TeV
ASTRI: dual mirror
ASTRI Mini Array: 9 telescopes
@Teide Observatory, Tenerife, Spain

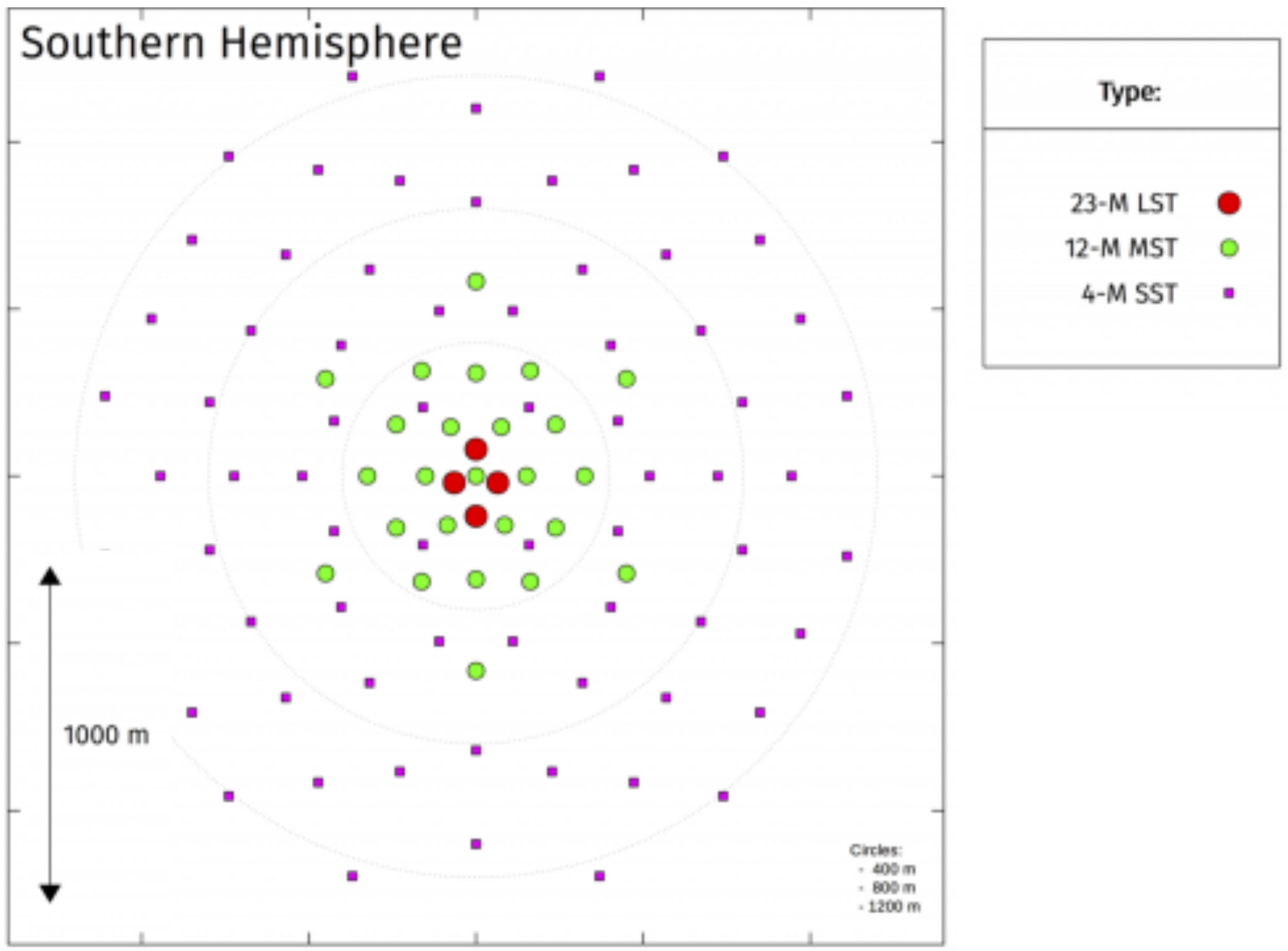
Rendering Credit: Gabriel Pérez Diaz, IAC, SMM

Array configurations

- **Omega configuration** (**ultimate goal**):
  - Northern Array: 4 LSTs, 15 MSTs
    total of 19 telescopes
  - Southern Array: 4 LSTs, 25 MSTs, 70 SSTs
    total of 99 telescopes



4 LS4 LSTs, 15 MSTs

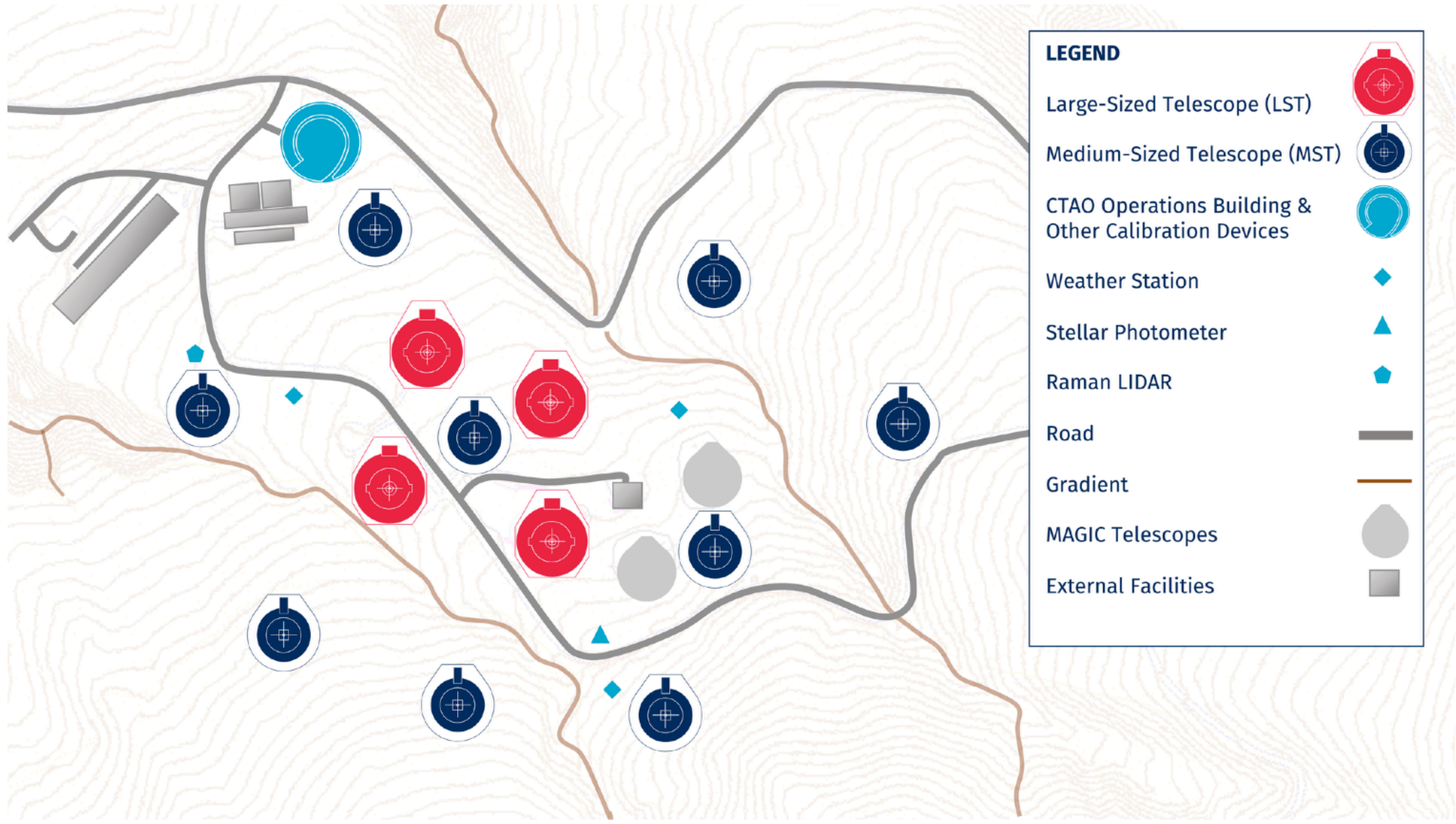


4 LSTs, 25 MSTs, 70 SSTs

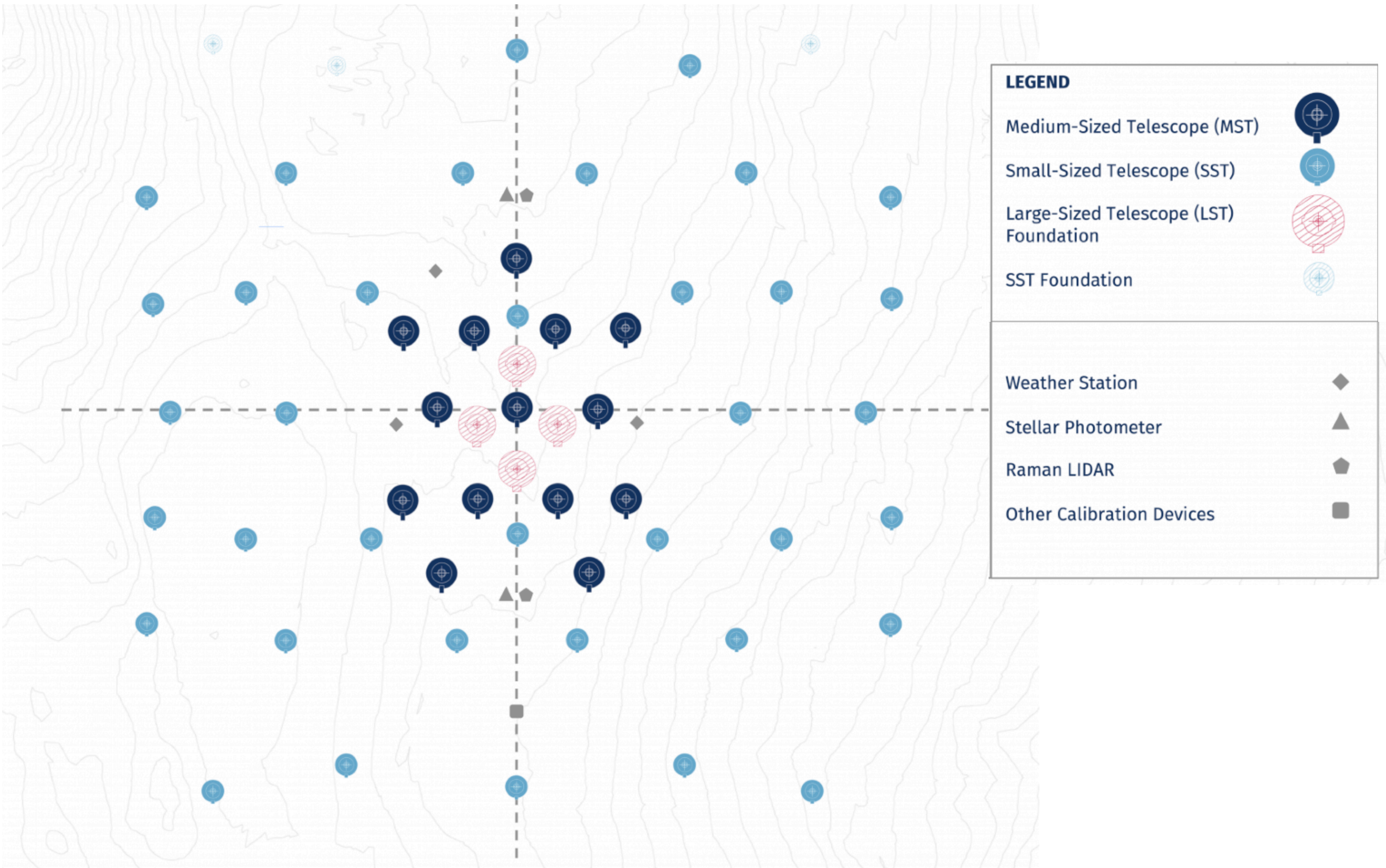
Array configurations

- **Alpha configuration (first construction phase):**

  - Northern Array: 4 LSTs + 9 MSTs

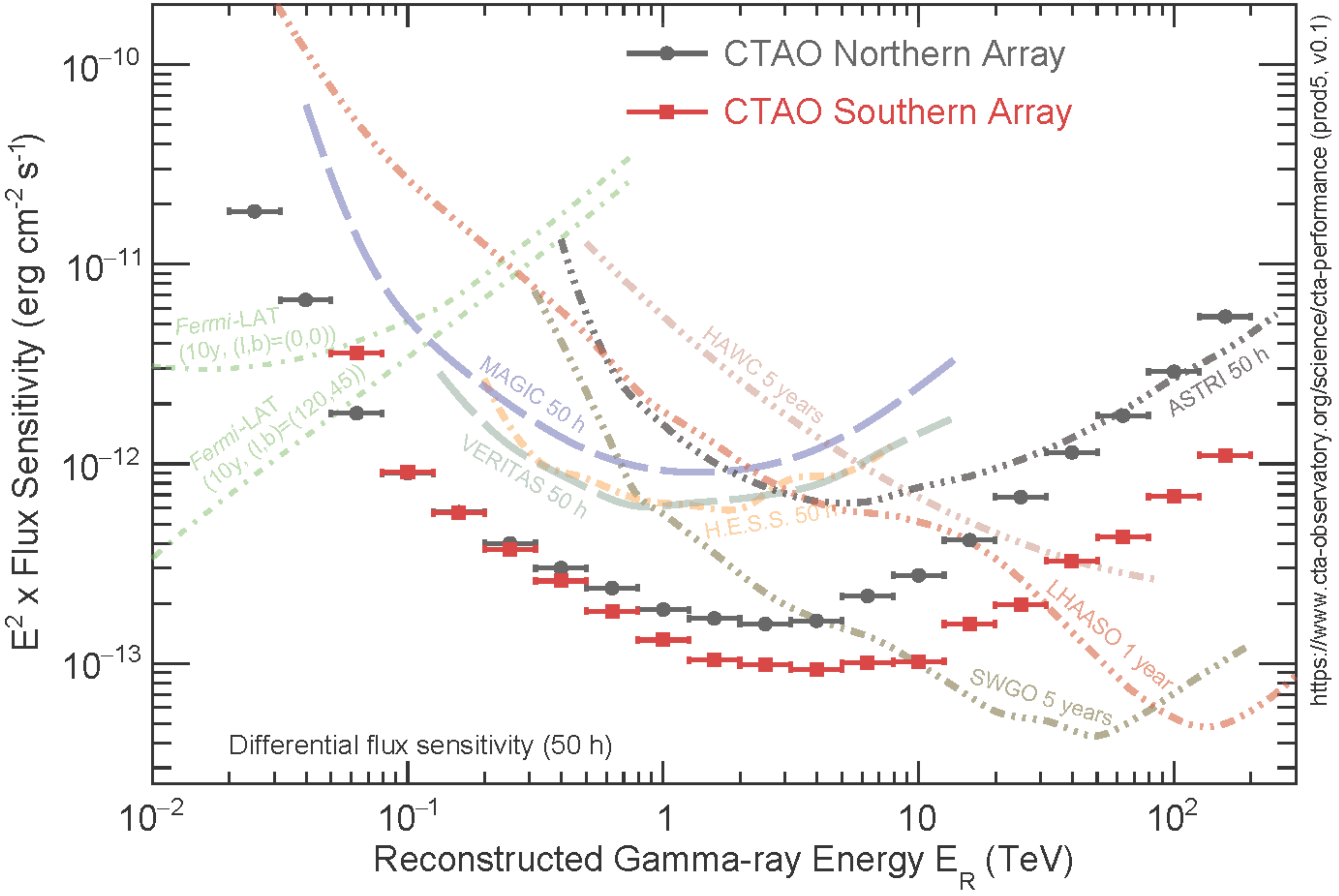


  - Southern Array: 0 LSTs* + 14 MSTs + 37 SST
    *2 LSTs to be installed



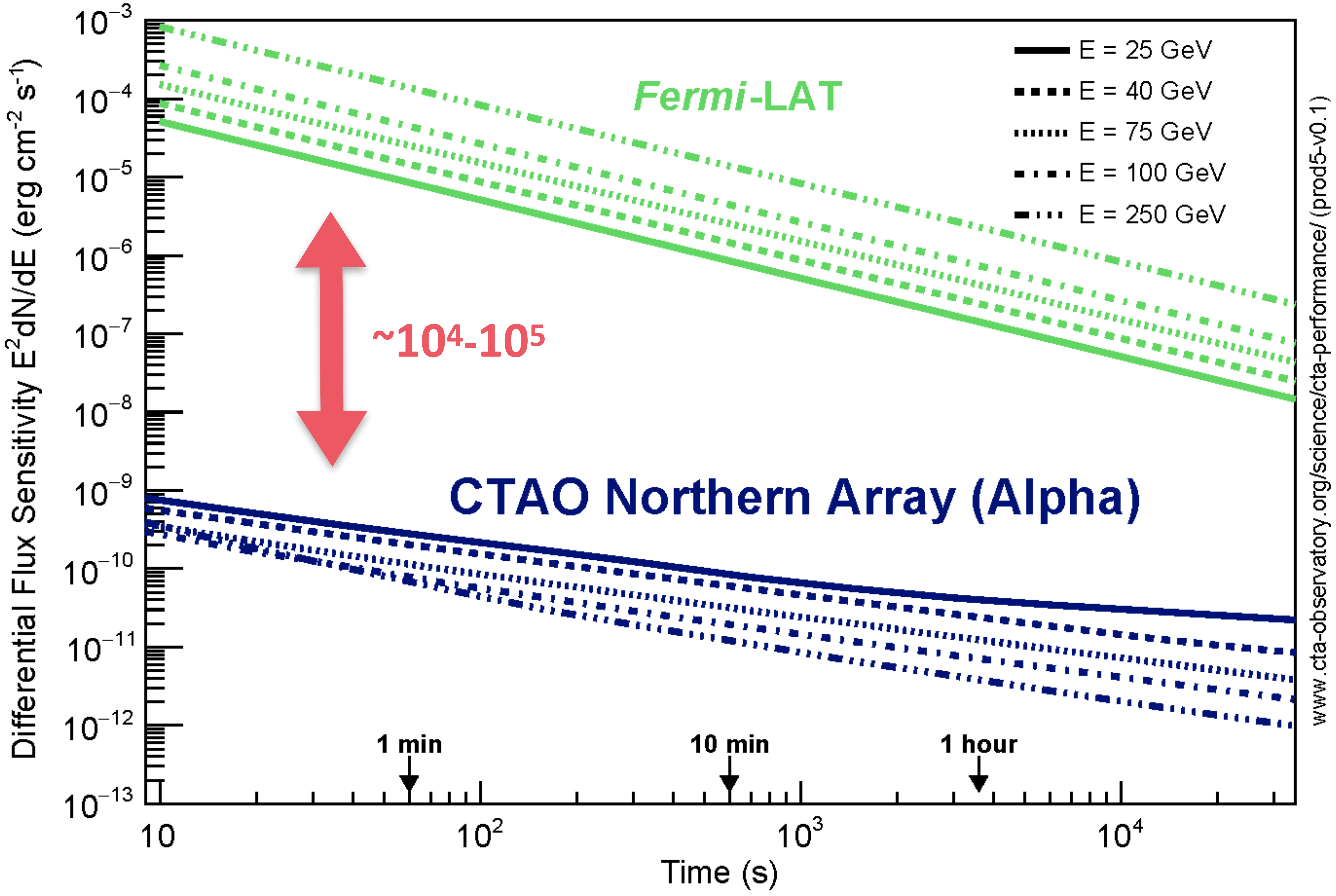
Sensitivity

Alpha configuration



- **Improved sensitivity** compared to current IACTs**:** **5 to 10 times** better
- **Enlarge the energy range** : almost **four decades** in energy
- **Improve energy and angular resolution**: by a **factor ~2**

Short-time sensitivity



- Unprecedent **sensitivity at short timescales** -> **transient detection**
  - **Fast slewing** (LST: 20 sec)
  - **Low energy threshold** (20 GeV)

How many sources will CTA detect?*

*according to our simulations

Galactic Plane Survey

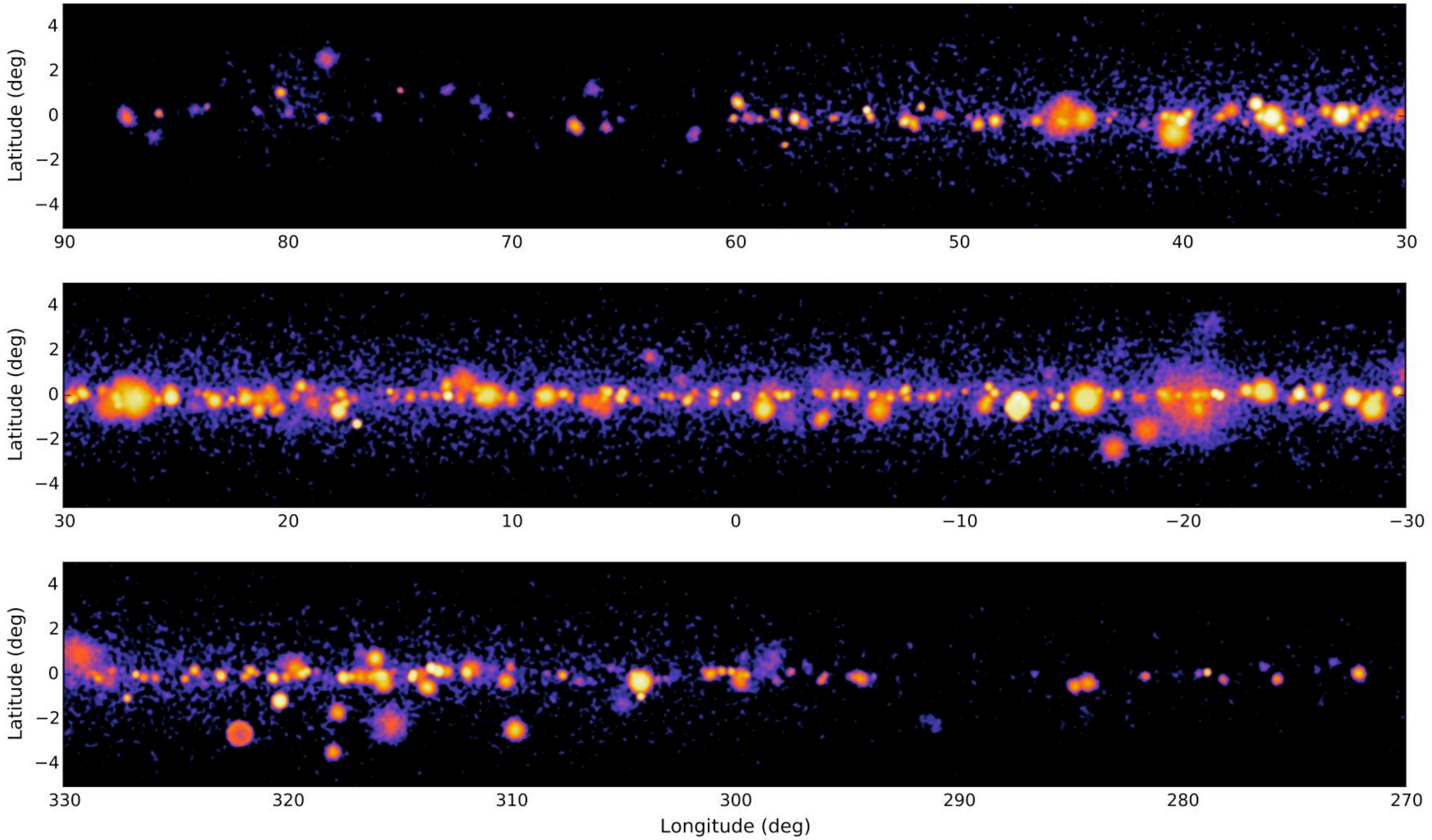
H.E.S.S. GPS

Abdalla et al. 2018

- 78 VHE sources
- 2700 h

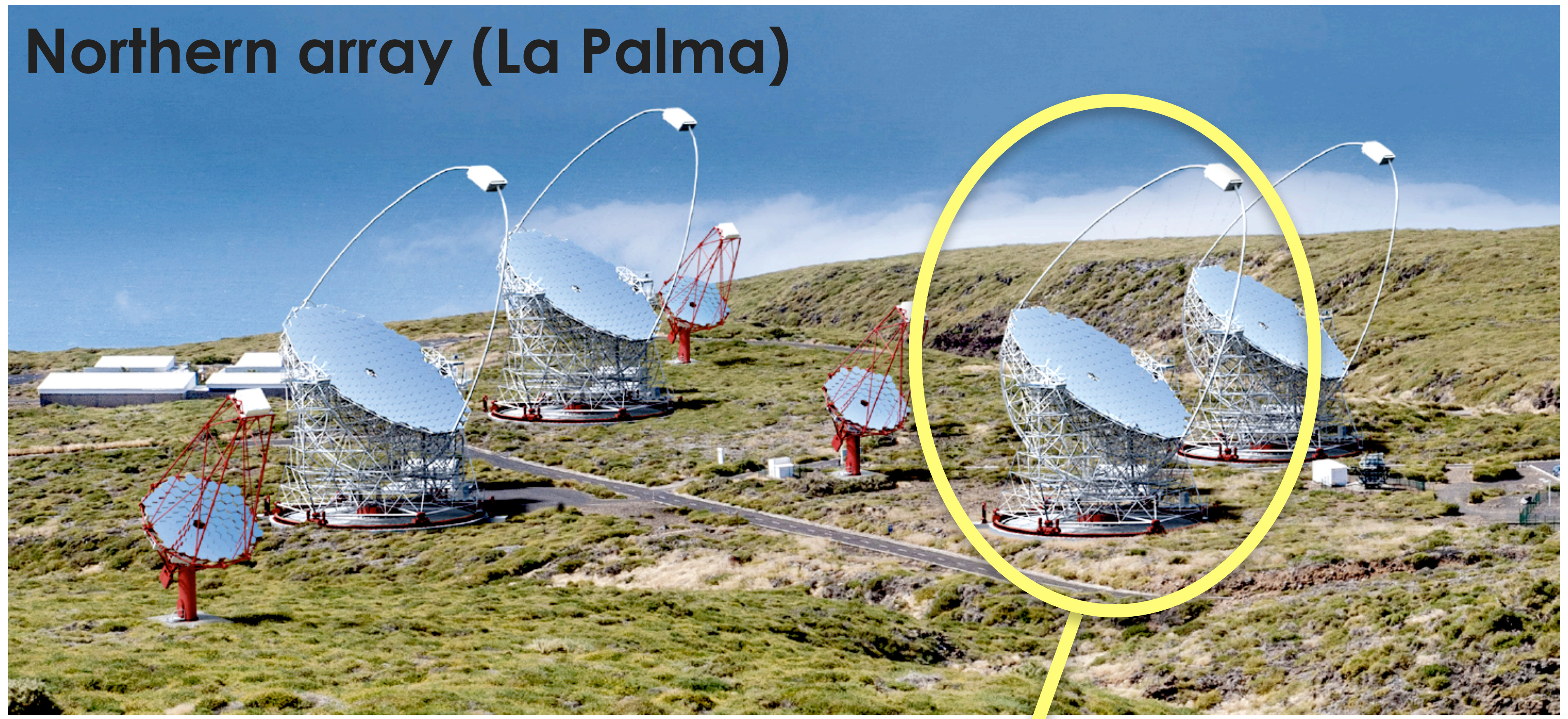
CTA GPS

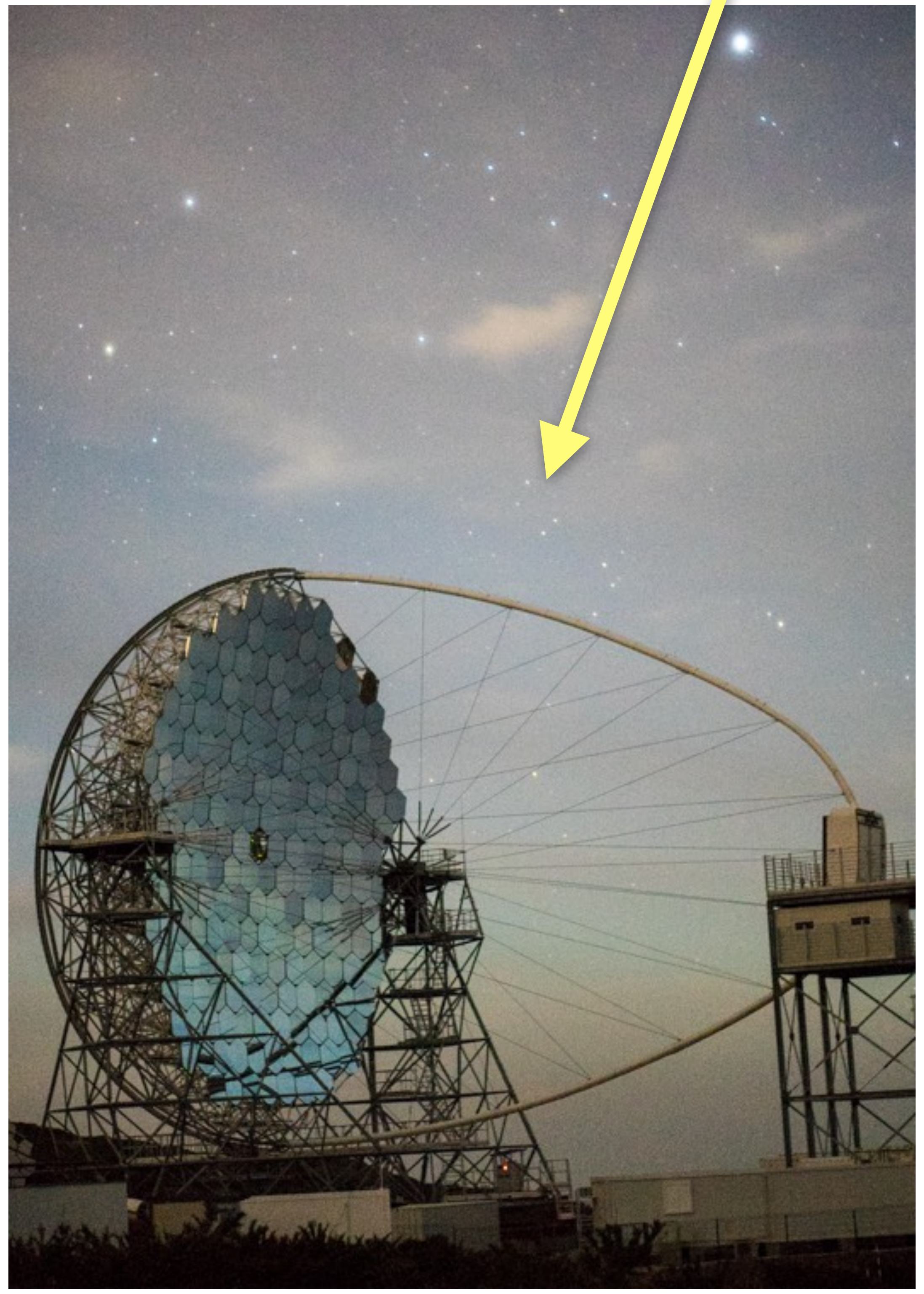
CTA Consortium, 2018



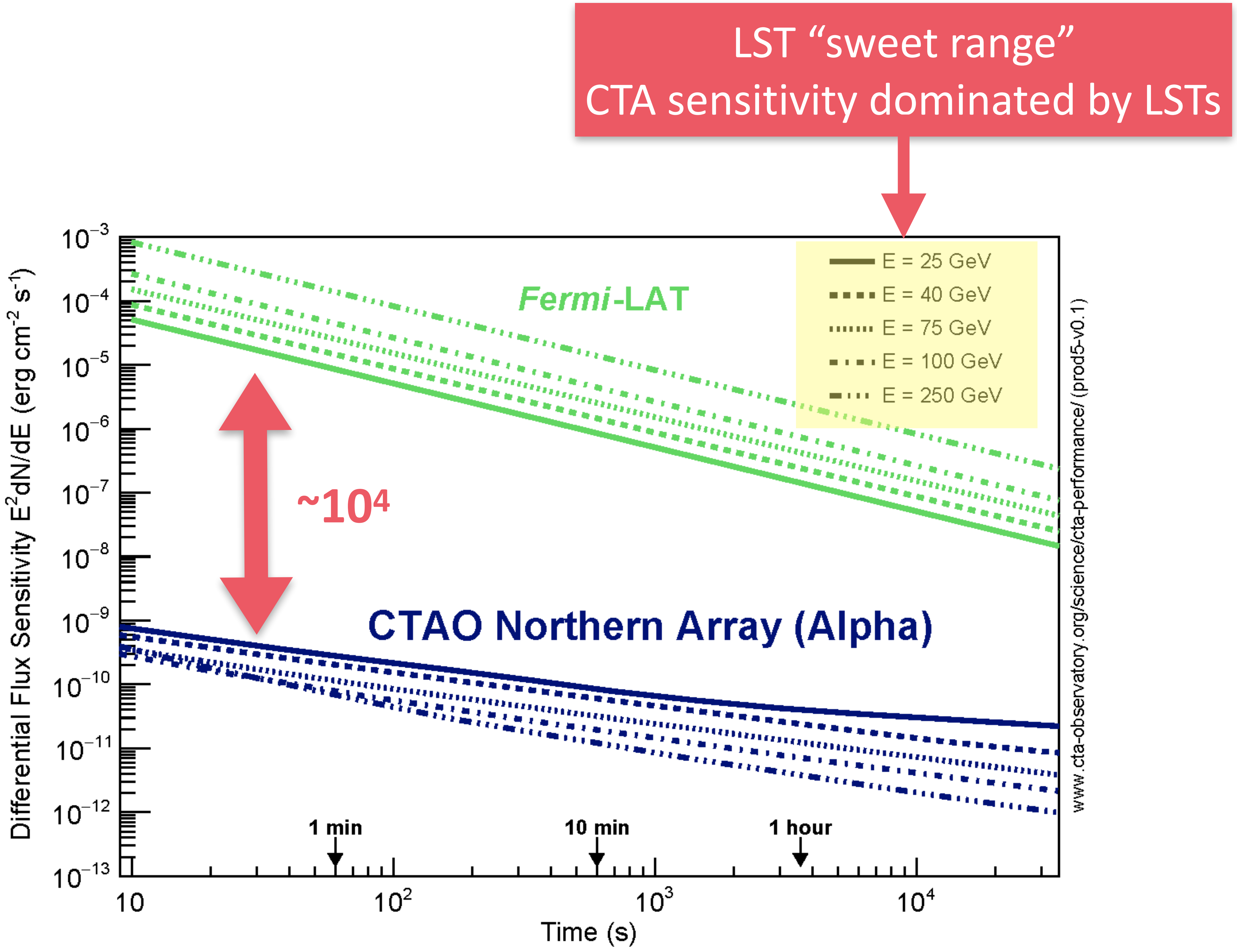
- Prediction: 300 – 500 sources
- 1600 h

Towards CTA



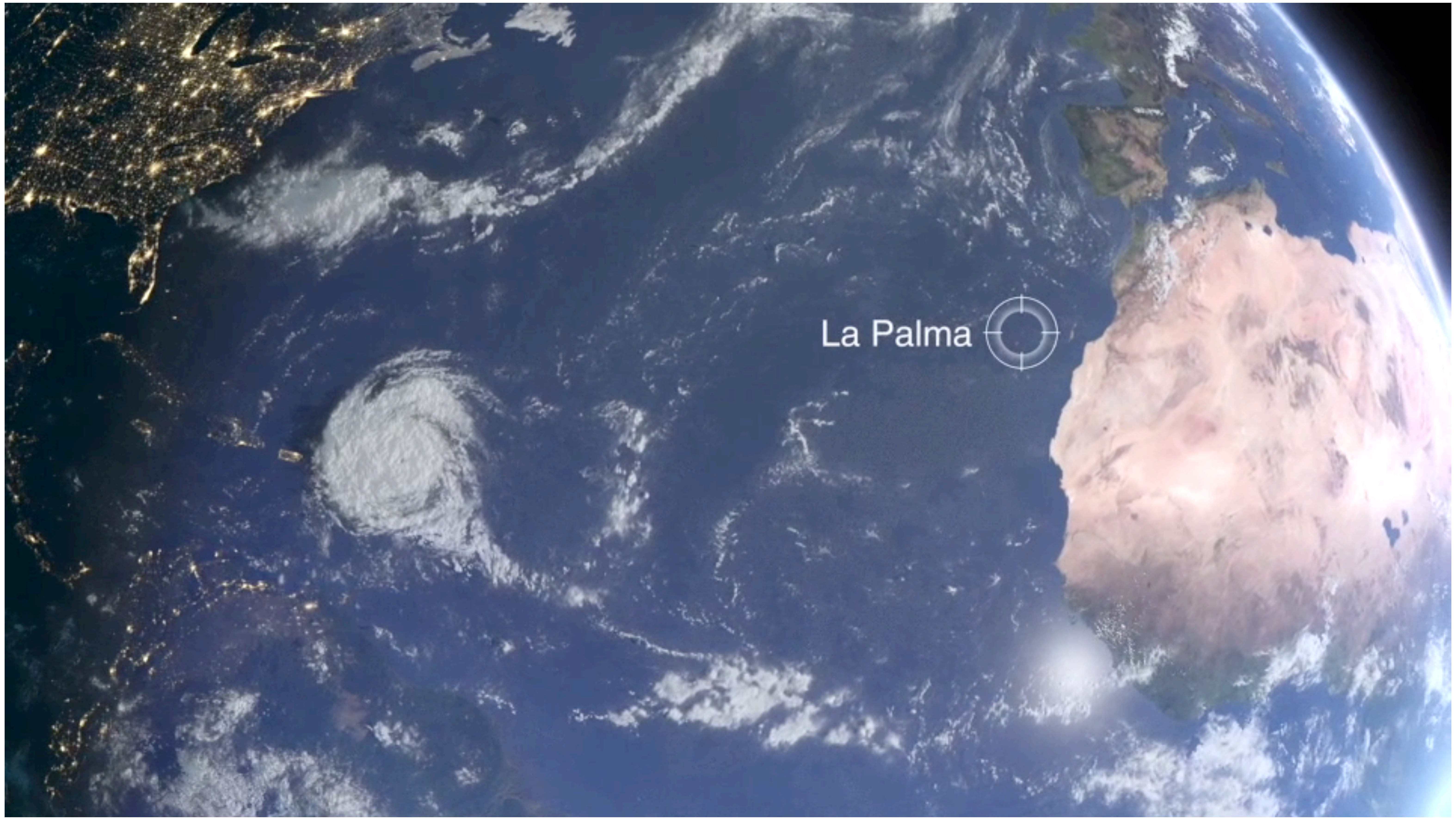


- LST1 inaugurated in 2018
- It is finalizing its commissioning phase and **producing scientific data**
- LST2-LST4 construction finalization planned for 2024

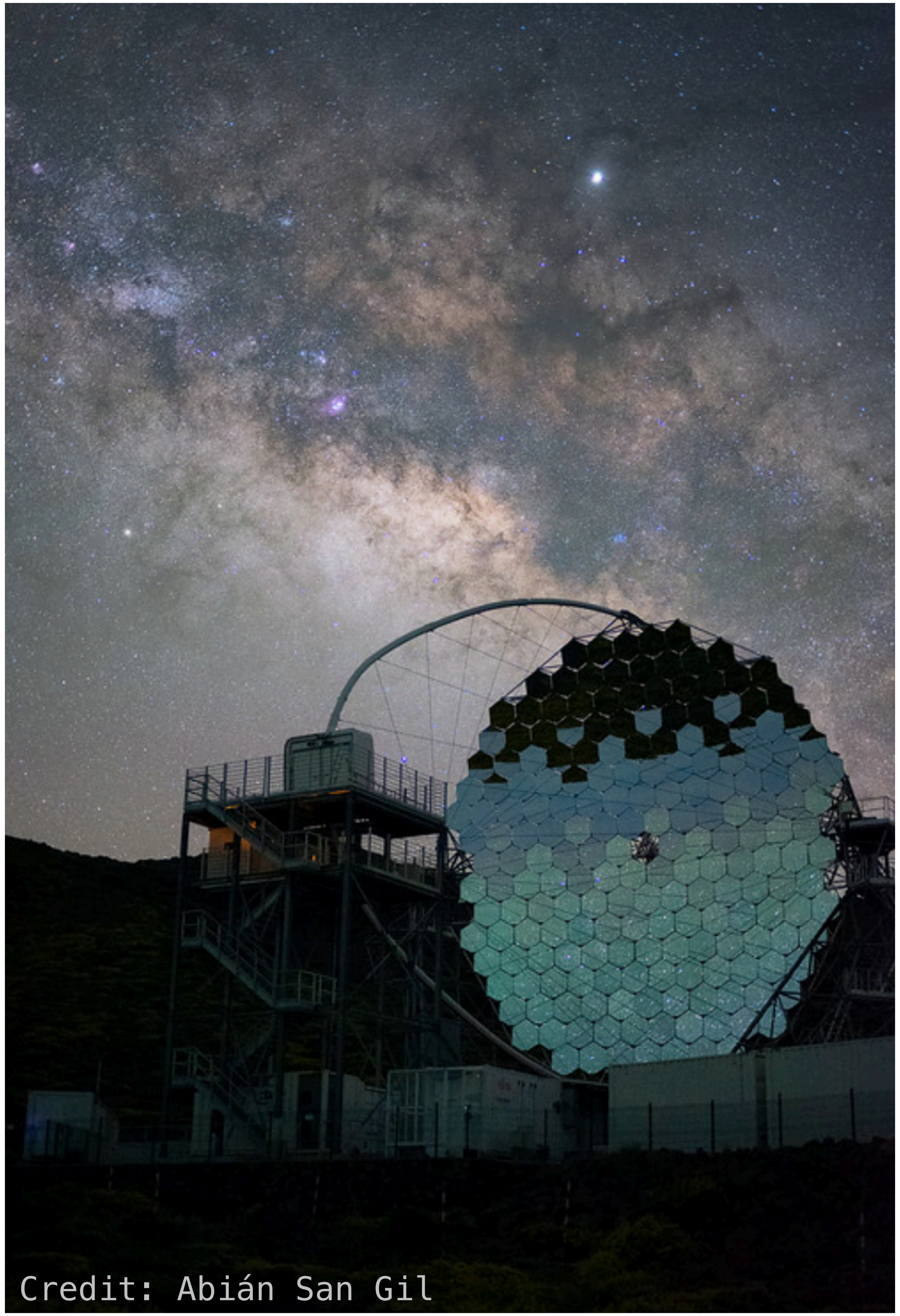



MAGIC
LST1
FACT

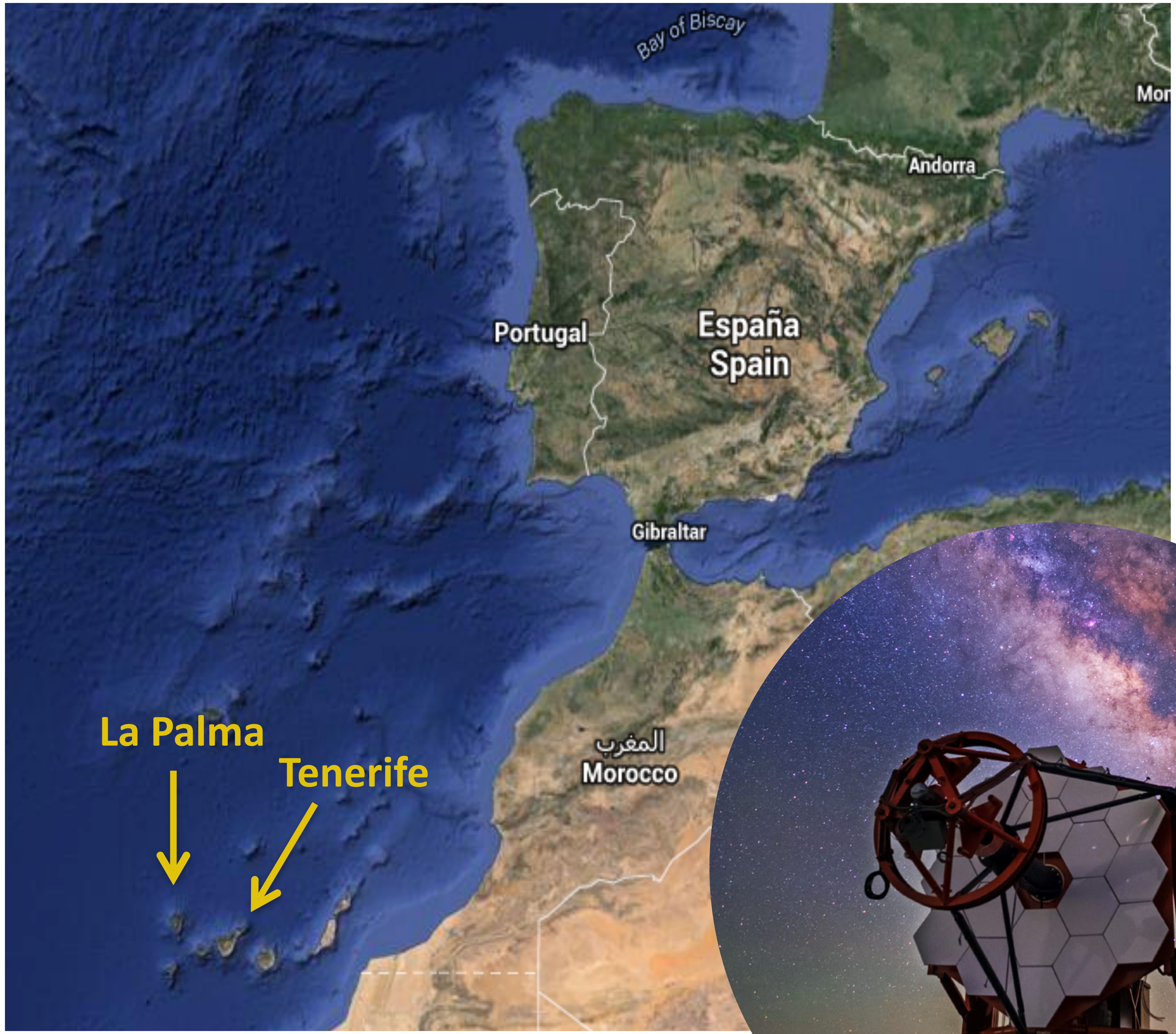
Large Size Telescope 1 (LST 1) @ORM



Under commissioning but
already producing scientific results



ASTRI Mini-Array @Teide Observatory



- ASTRI: *Astrofisica con Specchi a Tecnologia Replicante Italiana*
- 150 researchers (mainly Italian Institutions)
- Construct, deploy and operate an **array of 9 Cherenkov telescopes**
  - **1 – 300 TeV energy band**
  - ASTRI-I already at Teide observatory
    - camera will arrive soon!
  - **Full ASTRI Mini-Array ready for commissioning mid 2025**

Summary

Gamma rays: the most energetic electromagnetic radiation

- **Non-thermal** origin
- Information about **particle population and acceleration/interaction mechanisms**
- **Extreme phenomena**
  - Accretion/ejection, jets, outflows, shocks…
- 252 sources of VHE gamma rays up to now

Detection techniques: novel methods

- **HE -> satellites**
- **VHE -> IACTs**
  - current generation of IACTs only 20 years old
  - born as experiments, they proved **VHE astrophysics as a fully-developed discipline**
  - CTA: future open observatory

UHE -> particle/EAS detectors

Introduction to Very High Energy Gamma-Ray Astronomy

Thanks

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GOBIERNO DE ESPAÑA
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INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·
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Instituto de Astrofísica de Canarias

São Paulo Advanced School on Multi-Messenger Astrophysics 2023