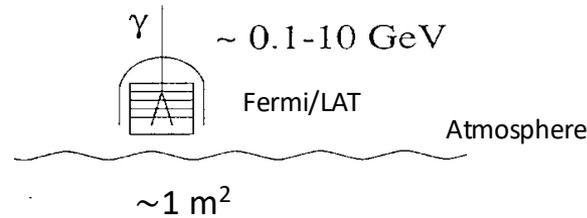# Lesson 4.2:

**Detection from the ground:**
**- Introduction to atmospheric showers**
**- Cherenkov telescopes**

# Detection from space is limited to <10 GeV



As we shall see tomorrow, at energies >10 GeV:

▪ $\gamma$-rays have so much energy that they sometimes "fly through the detector", i.e. they are not contained in the calorimeter and is impossible to determine their energy. We would need **impossibly large volumes** in space.

▪ Typical sources have power law spectra: flux gets so low at >10 GeV that 1m$^2$ is not enough. For instance, we get $\sim$ 1 $\gamma$-ray/3 hours for one the brightest sources, Crab Nebula, in a 1m$^2$ detector at 30 GeV. We would need **impossibly large detection areas** in space.

# Alternative: from the ground
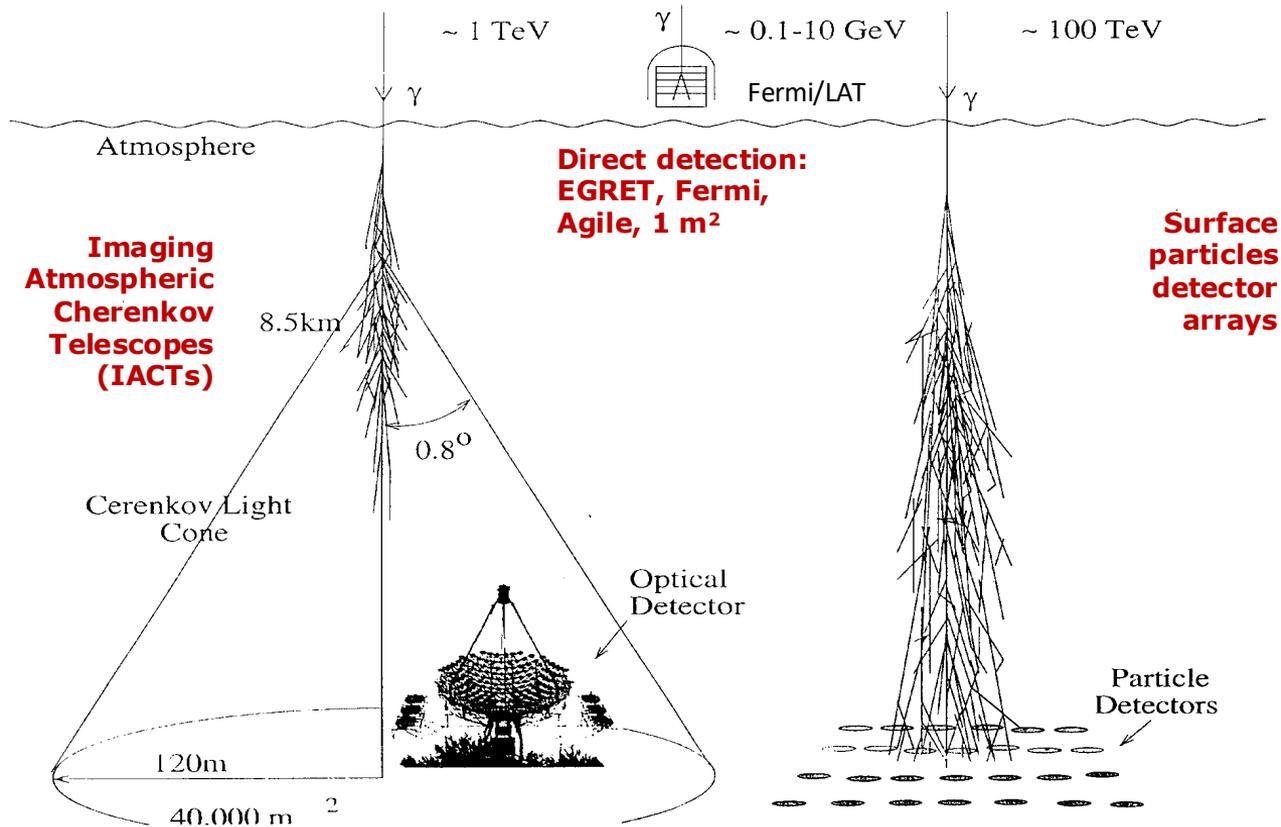
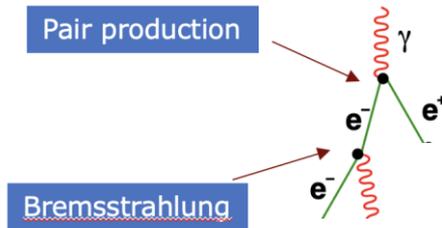# Introduction to atmospheric showers

# Atmospheric showers
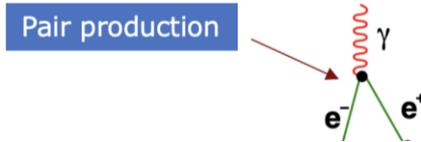


Pair production:

▪ After one "**radiation length**", a fraction 1/e (~33%) of the gammas have produced a pair.

▪The γ-ray energy is shared between the e⁺ and e⁻.

▪ The actual value of a radiation length depends on the material and its density.

▪ The air changes density with height (roughly exponentially) so it's more practical to express the radiation length in mass, rather than length.

▪ Actually one measures the length is **g/cm²**. There is 1024 g of air on top of every cm² at sea level. So a particle passes through 1024 g/cm² when it travels all the way down to sea level.

▪ A pair-production radiation length is ~40 g/cm².

# Atmospheric showers



Bremsstrahlung

▪ After another "**radiation length**", a fraction $1/e$ ($\sim 33\%$) of the $e^+/e^-$ have produced a $\gamma$-ray again via Bremsstrahlung.

▪ The $\gamma$-ray takes 50% of the $e^+/e^-$ energy.

▪ A Bremsstrahlung radiation length is essentially the same as that of pair-production: ~40 $g/cm^2$.

# Atmospheric showers

**Electromagnetic Shower**

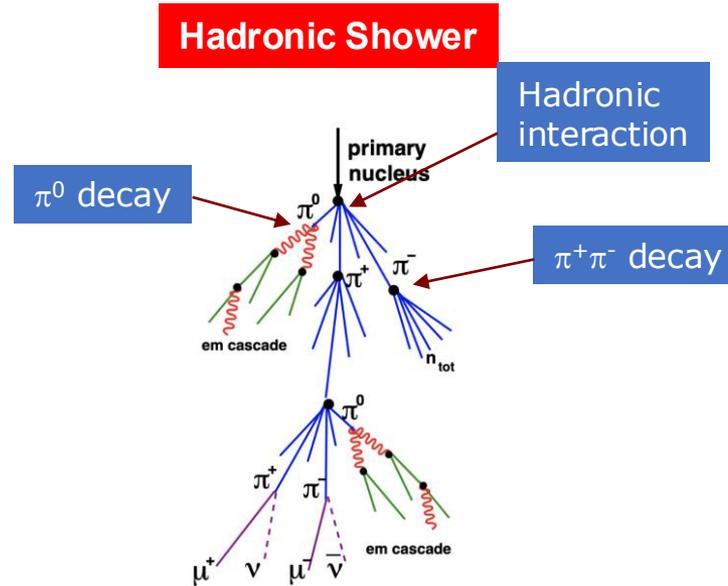Pair production
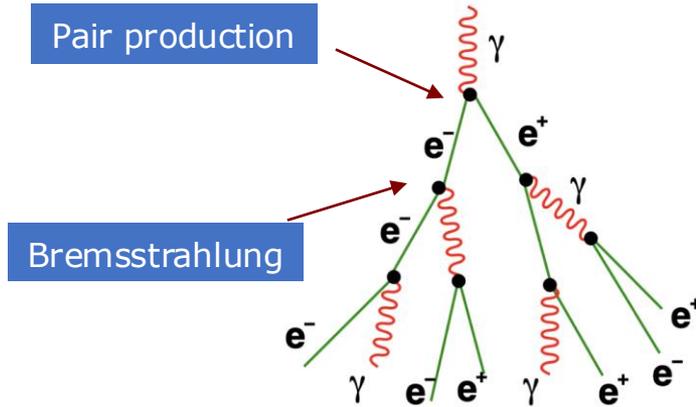
Bremsstrahlung
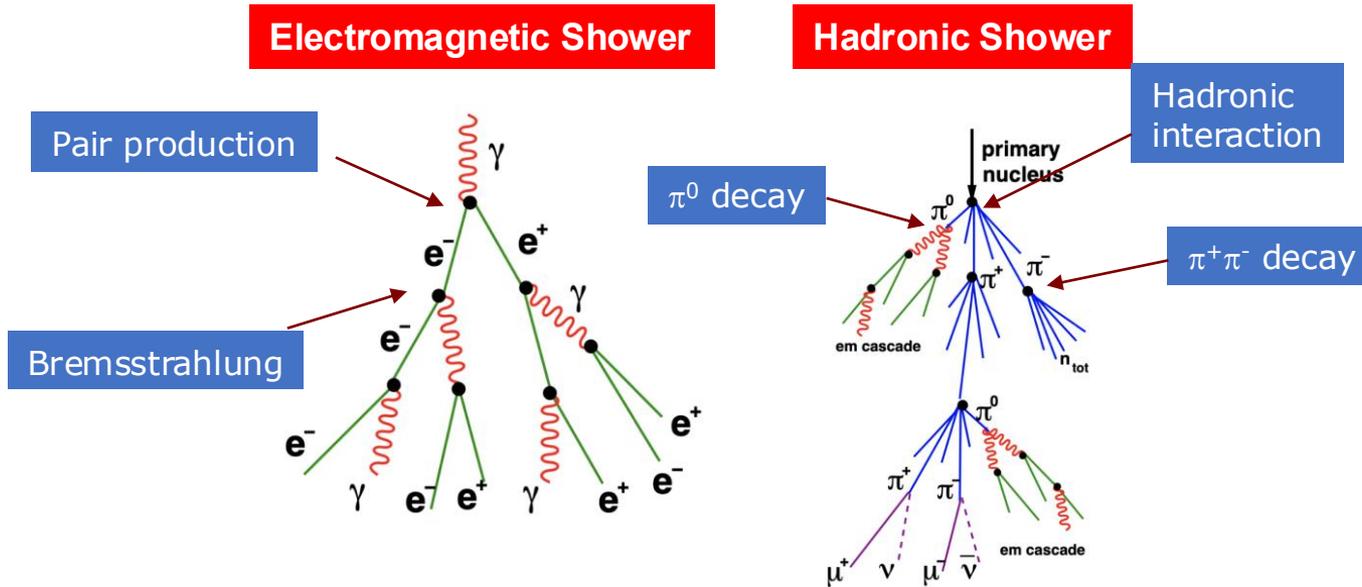


<u>Some key parameters for $\gamma$-ray atmospheric showers:</u>
- Atmosphere's vertical depth at sea level: 1024 gr/cm$^2$
- Pair production & bremsstrahlung dominate above: ~10 MeV,
- At lower E, $\gamma$-rays lose energy via Compton & photoelectric, and e$^-$/e$^+$ lose energy via ionization

# Atmospheric showers

• Unfortunately, γ-rays are not the only quanta of E>1 GeV arriving to the Earth.

• They are actually out-numbered by a huge flux of "cosmic rays" (protons and other nuclei) which also produce air showers.

• In other words, cosmic rays are a huge "background" for VHE γ-ray detection.

**Hadronic Shower**

Hadronic interaction

$\pi^0$ decay

$\pi^+\pi^-$ decay

# Atmospheric showers

**Electromagnetic Shower**

**Hadronic Shower**

Pair production

Bremsstrahlung

$\pi^0$ decay
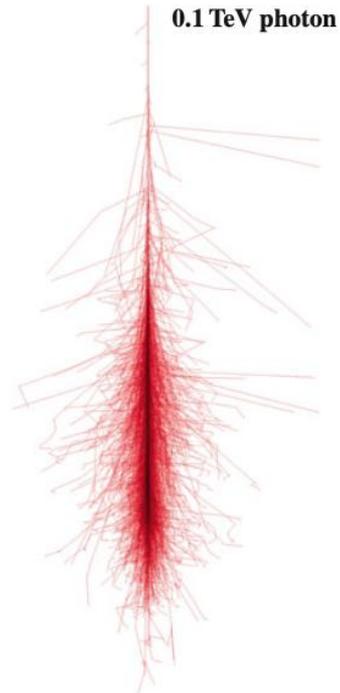
Hadronic interaction

$\pi^+\pi^-$ decay



Some key parameters for atmospheric showers:
- Atmosphere's vertical depth at sea level: 1024 gr/cm²
- Mean free path for pair production or bremsstrahlung: 40 gr/cm²
- Mean free path for hadronic interaction: 80 gr/cm²
- Pair production & bremsstrahlung dominate above: 10 MeV,
- At lower E, $\gamma$-rays lose energy via Compton & photoelectric, and $e^-/e^+$ via ionization
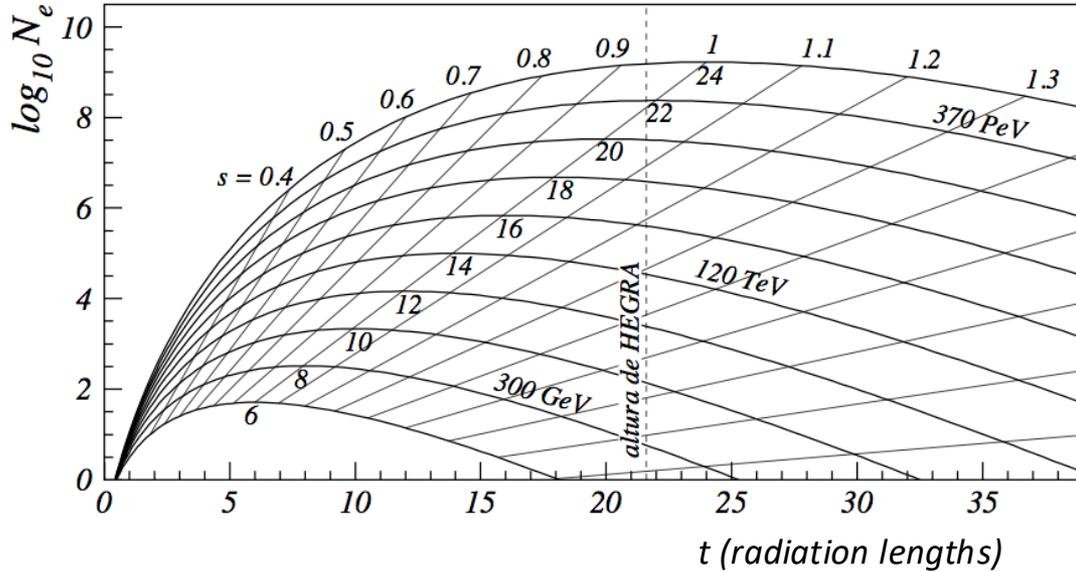
# Atmospheric showers

**Electromagnetic Shower**     **Hadronic Shower**

0.1 TeV photon          0.1 TeV proton
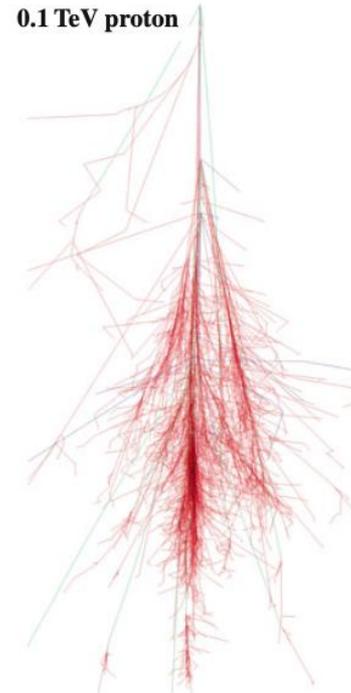
Actual simulations
(M. Errando, T. Saito,
Handbook of X-ray and γ-ray
astrophysics)

# Shower development

s = shower age
(0 in first interaction, 1 at $X_{max}$, 2 at the shower's end)

γ-ray shower:
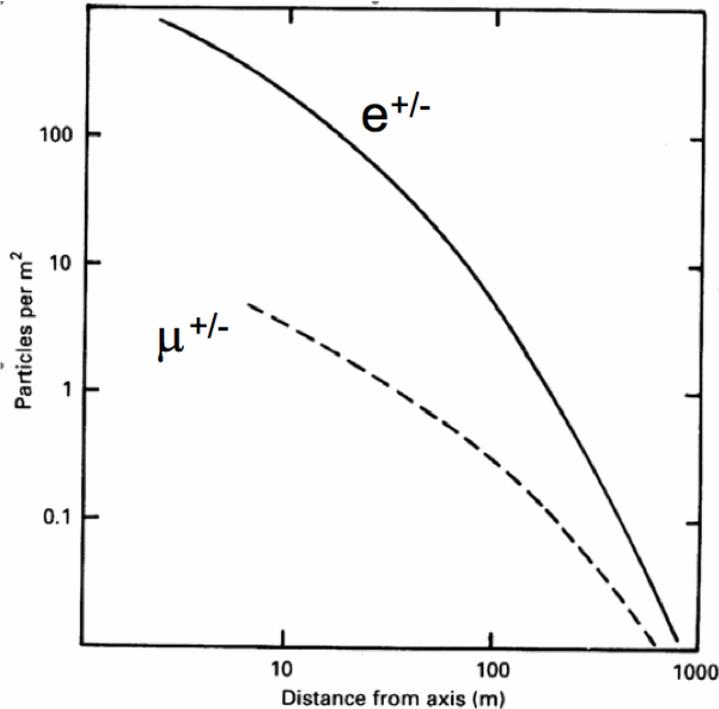$$X_{max}= X_0 \ln(E/E_c) / \ln 2 = 36.7 \text{ g/cm}^2 \ln(E/100 \text{ MeV})$$

Hadron shower (primary atomic mass A):
$$X_{max}=83 \text{ g/cm}^2 \ln(E/A \cdot 100 \text{ MeV})$$

# Shower lateral distribution

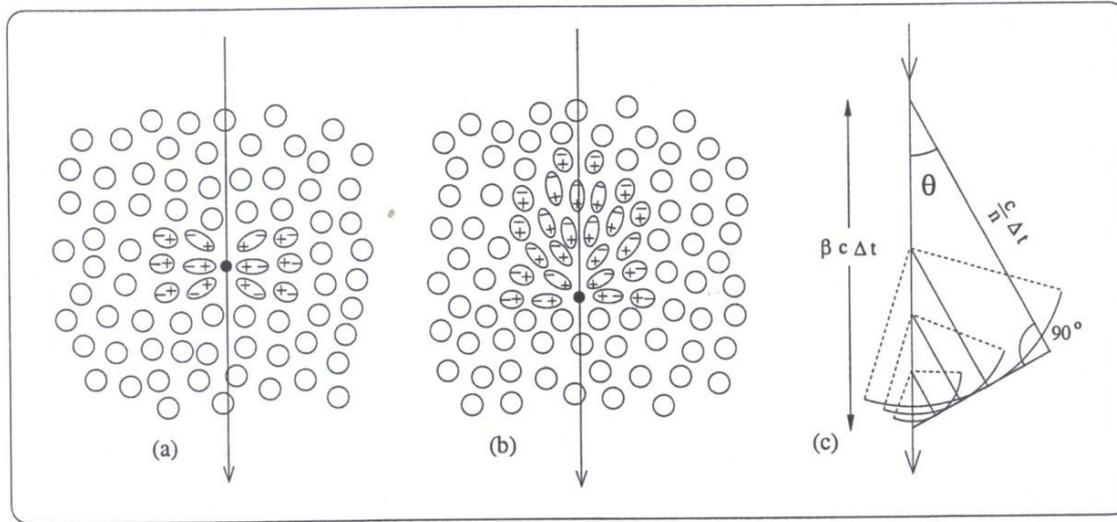Electron lateral distribution = Nishimura-Kamata-Greisen function:

$$\rho_e(r) = c(s)\, N_e/r_M^2\, (r/r_M)^{s-2}\, (1+r/r_M)^{s-4.5}$$

$r_M$ = Moliere's radius
(=79 m in the air at sea level)

s = shower age
(0 in first interaction, 1 at $X_{max}$,
2 at the shower's end)

c(s) = calibration factor

# Cherenkov effect



- Incident charged particle polarizes medium (air molecules).
- Molecules de-polarize and emit radiation, but there is constructive interference only when particle moves faster ($\beta c$) than light in medium ($c/n$): $\beta > 1/n$
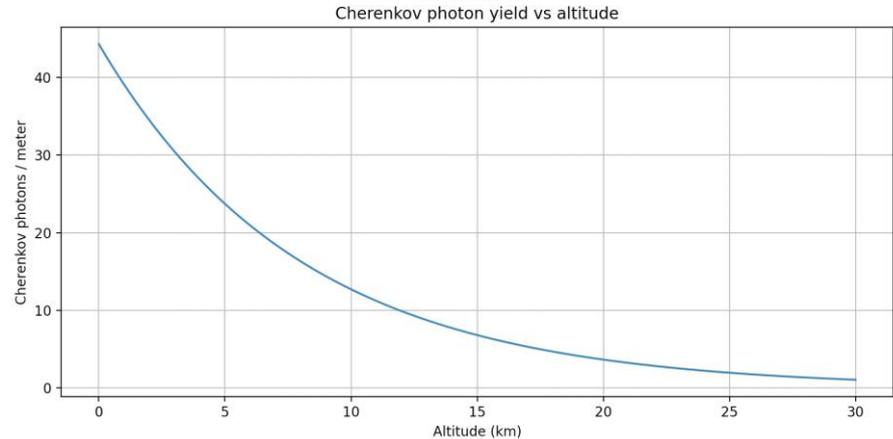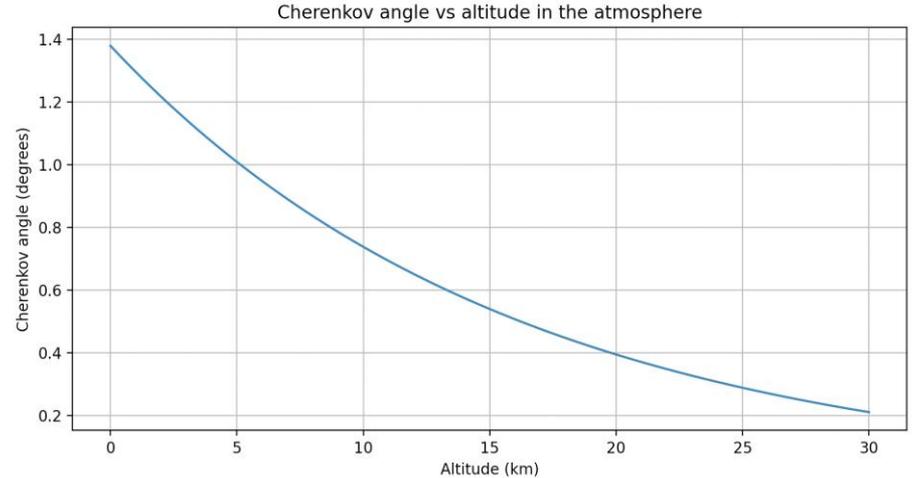
# Cherenkov light production

### Basic formulas:

$$\cos\theta = \frac{1}{n(\lambda)\beta}$$

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int\limits_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right)\frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int\limits_{\lambda_1}^{\lambda_2} \sin^2\theta(\lambda)\frac{d\lambda}{\lambda^2}$$

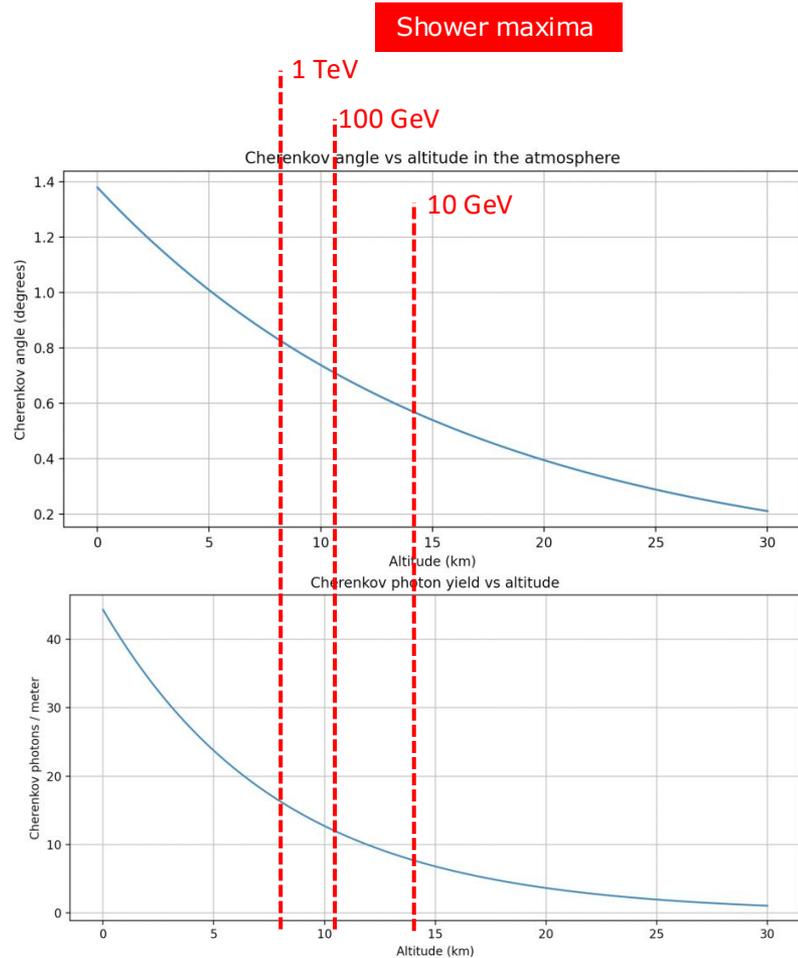Both emission angle and light yield grow as the shower goes deeper and deeper into the atmosphere.



Cherenkov angle vs altitude in the atmosphere



Cherenkov photon yield vs altitude
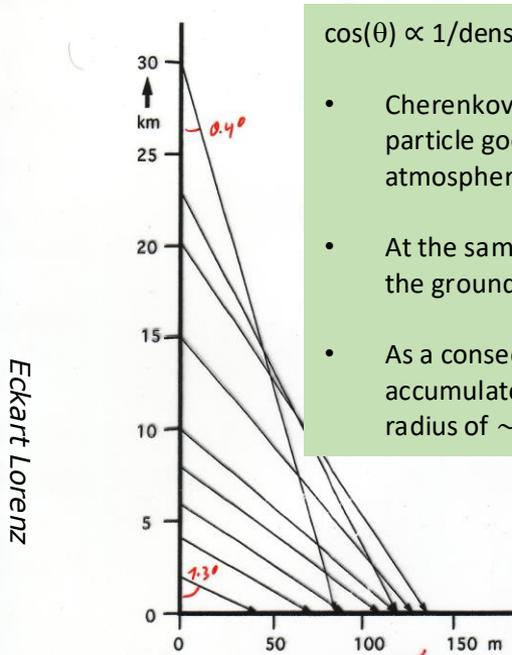
# Cherenkov light production

## Basic formulas:

$$\cos\theta = \frac{1}{n(\lambda)\beta}$$

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) \frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \sin^2\theta(\lambda) \frac{d\lambda}{\lambda^2}$$

Both emission angle and light yield grow as the shower goes deeper and deeper into the atmosphere.

Cherenkov light distribution generated by a charged particle



*Eckart Lorenz*

cos(θ) ∝ 1/density

- Cherenkov angle grows as the particle goes deeper into the atmosphere.

- At the same time, distance to the ground gets smaller.

- As a consequence, light accumulates up to a magic radius of ~ 120 m

Ground level



300 GeV
100 GeV
50 GeV
20 GeV

Particle speed is ~c so light and particles arrive almost at the same time on the ground: time spread is ~ 1-2 ns.

This is for an individual particle. But an electromagnetic shower = a lot of charged particles flying roughly parallel



250 m

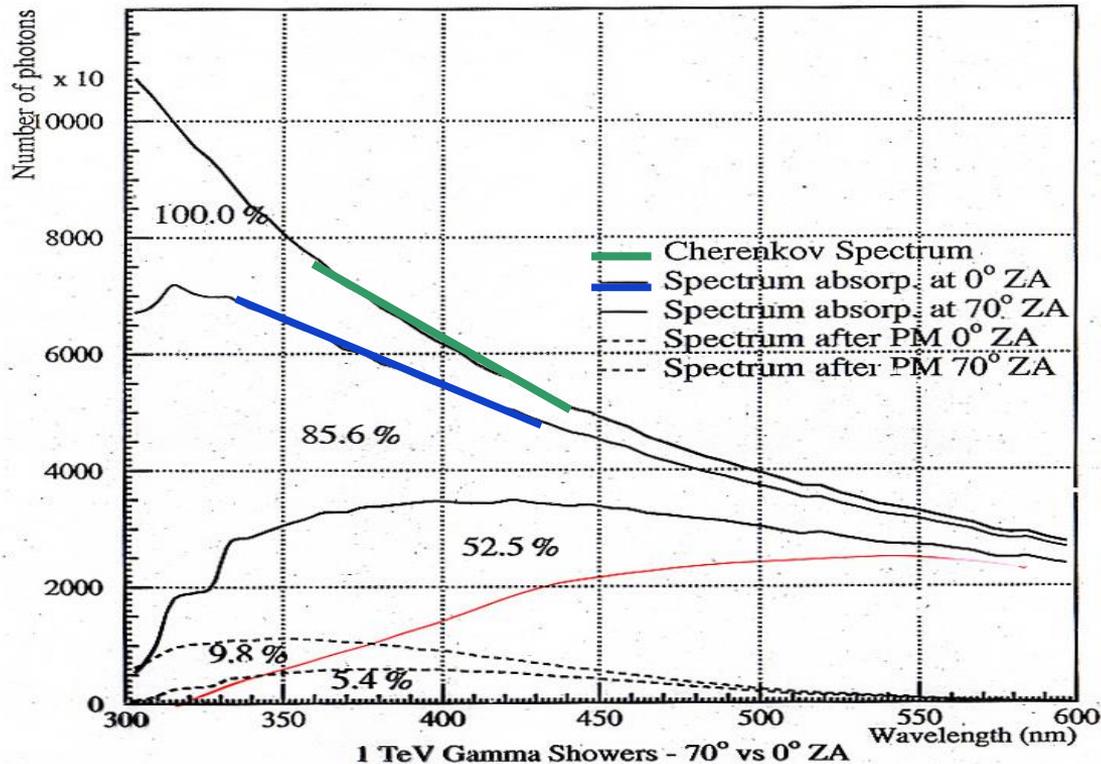"light pool"

*Konrad Berloehr*
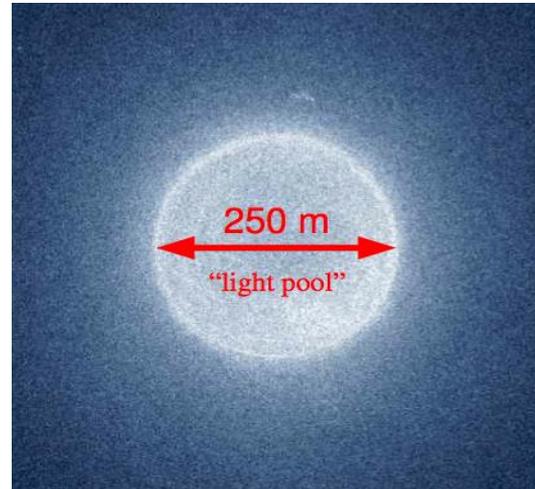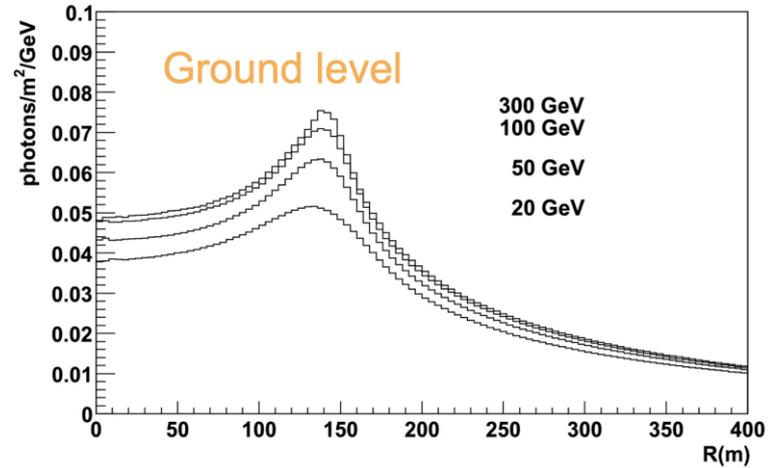
# γ-ray vs cosmic ray
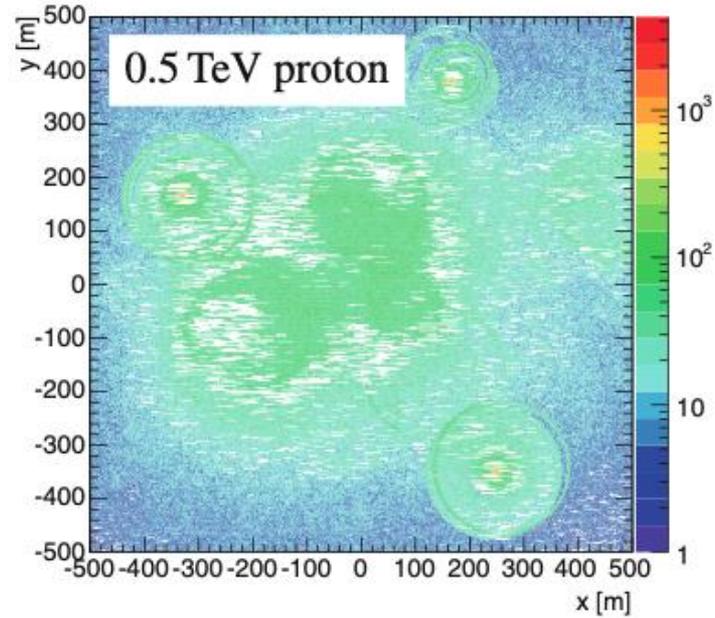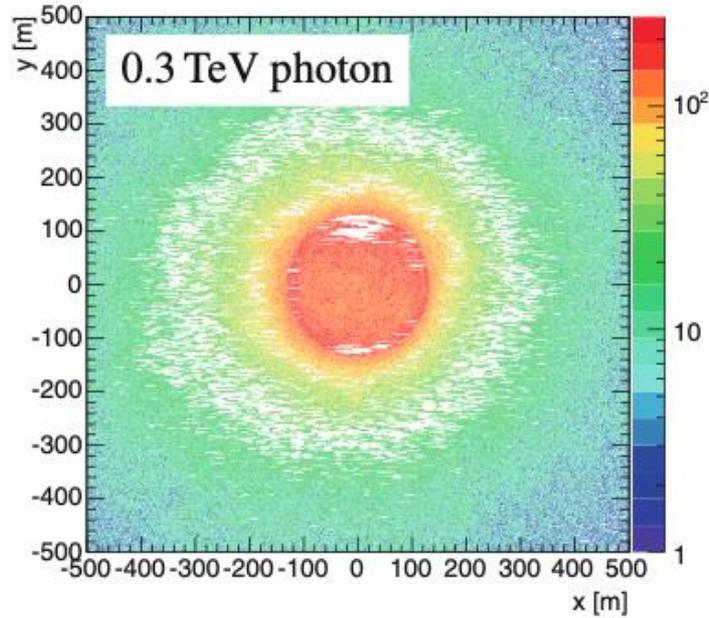


Handbook of X-ray and
γ-ray astrophysics

# Cherenkov spectrum on the ground



1 TeV Gamma Showers - 70° vs 0° ZA

▪ Cherenkov spectrum decreases with λ (emission peaks in near ultraviolet).

▪But atmospheric attenuation makes it more and more red as the zenith angle grows.

# Imaging Atmospheric Cherenkov Telescopes (IACTs)
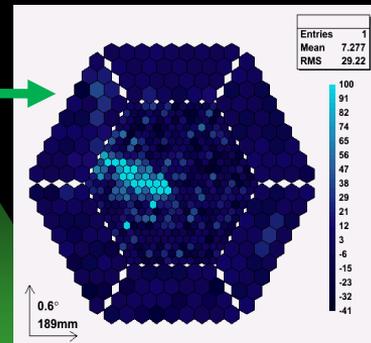
Gamma-ray

Particle shower

Cherenkov light

1°

~ 10 km

~ 120 m

Entries 1
Mean 7.277
RMS 29.22

100
91
82
74
65
56
47
38
29
21
12
3
-6
-15
-23
-32
-41

0.6°
189mm

# Optics / structure

- Simplest optics ever: one mirror, spherical/parabolic shape, camera located at focal plane.

- Low optical precision: ≲5 arcmin optical spot is enough.

- Tessellated reflectors: 10-20 meter diameters, tiles of 50 cm – 2 m size.

- Mirror tiles: as light and cheap as possible, >90% reflectivity in near UV-blue.

- Mirror support structure and positioning system: space frames to reduce weight and simplify construction.
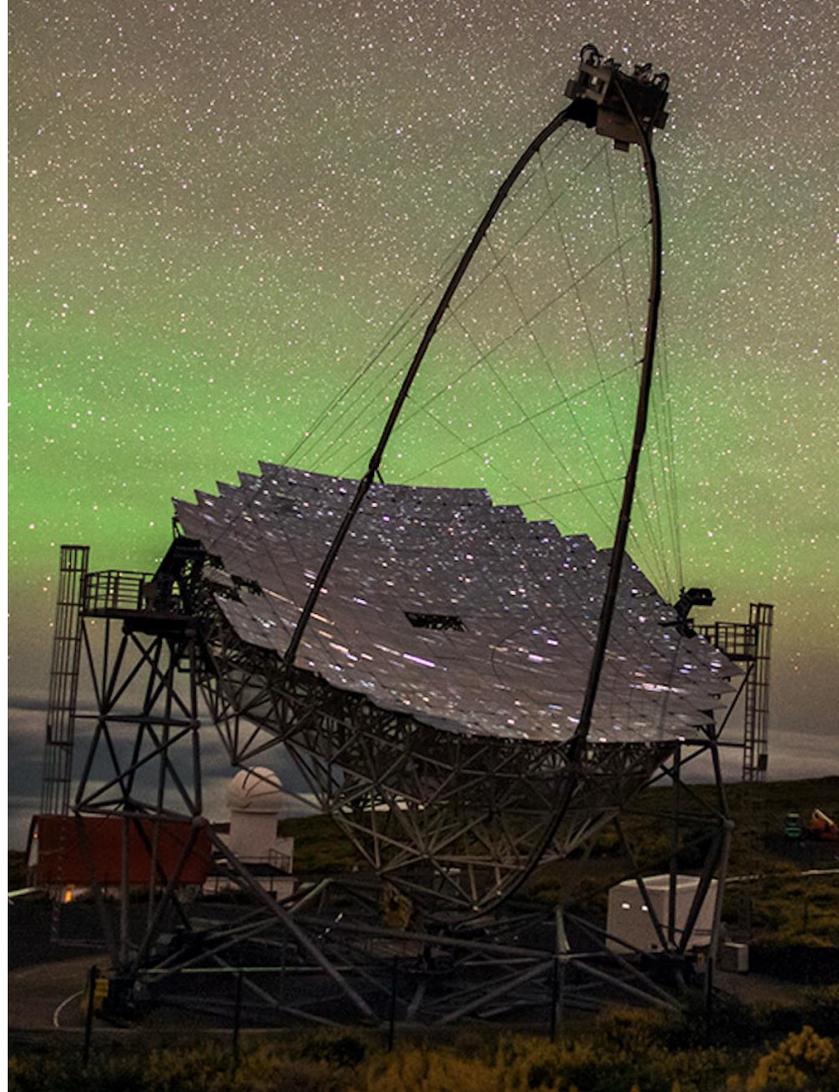


MAGIC telescope

# Cameras
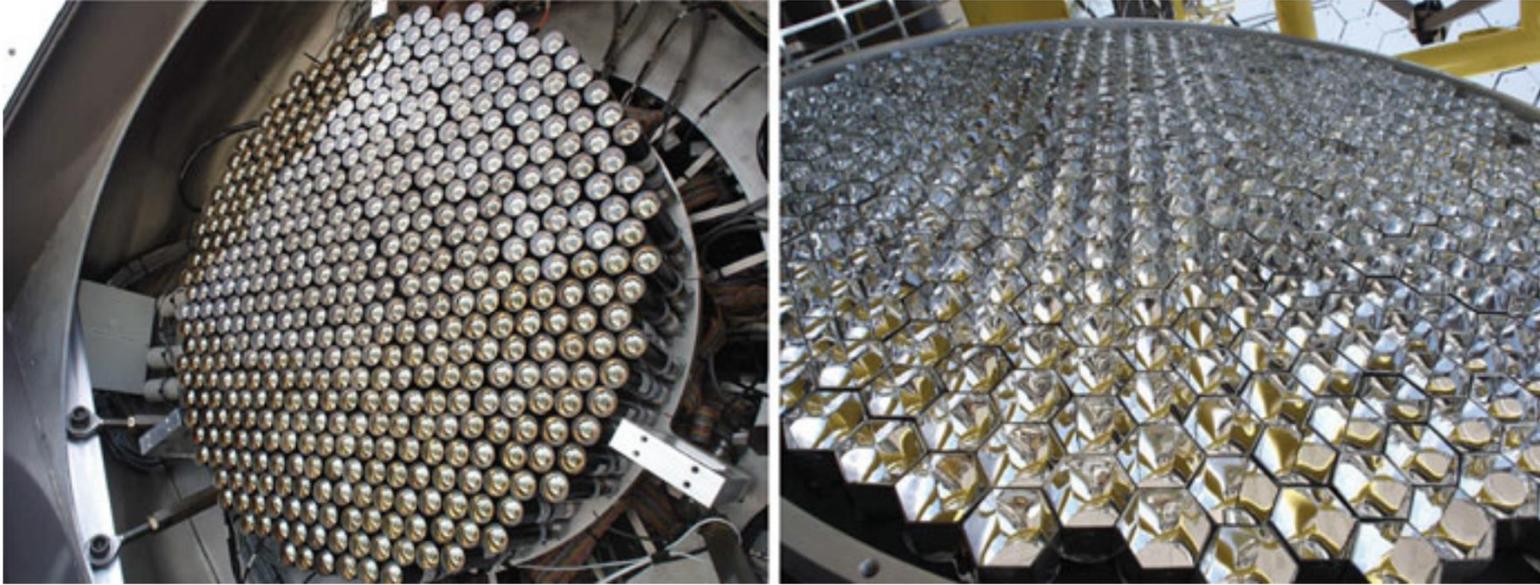


VERITAS telescope
(Handbook of X-ray and $\gamma$-ray astrophysics)

- Arrays of 1000-2000 PMTs with ~1 ns time response.
- Peak QE around 400 nm, QE ~20-40% in near UV-blue wavelength range.
- Each pixel: angular size ~0.1 deg, physical size ~2-3 cm

# Trigger and readout

- A shower is very short and produces light in only a few, typically contiguous pixels: dedicated electronics constantly monitor the PMT signals to identify clusters of fast signals. This is the so-called "telescope trigger". A second "stereo trigger" requires simultaneous telescope trigger in >1 telescope.

- Once a trigger signal is there, a second electronic system (Data Acquisition, DAQ) time samples the PMT pulses in the whole camera and saves them to disk.
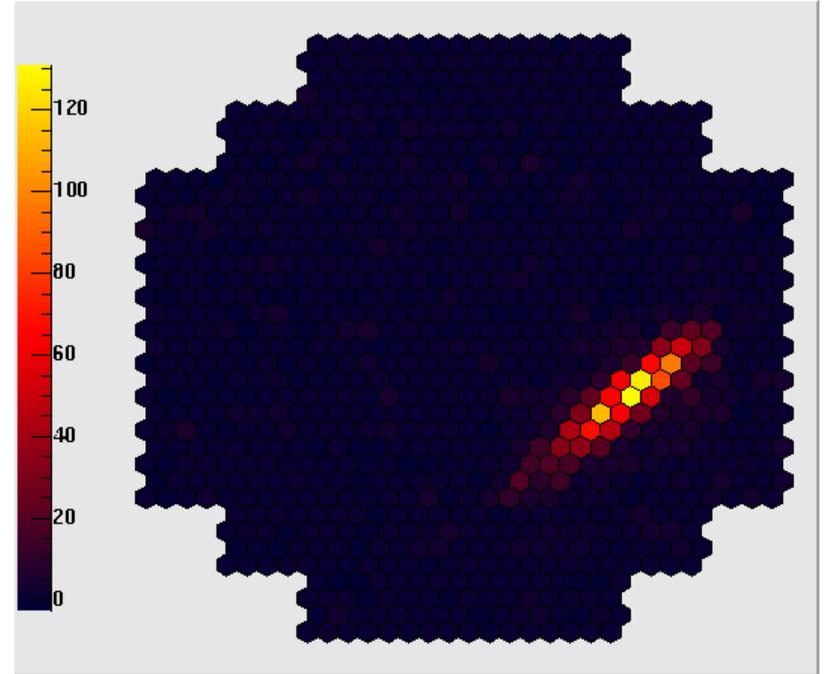


Events in a H.E.S.S. camera

# γ-ray detection and CR background

- As we shall see, from the images we can estimate energy and arrival direction of VHE γ-rays.

- However cosmic rays also produce showers.

- In fact they are much more numerous than γ-rays: for instance, for the brightest steady γ-ray source (Crab nebula) in the sky, we detect one γ-ray for every 1000 cosmic rays.

- We must find ways to eliminate this background. These are the so-called "γ/hadron discrimination techniques".

# Technique 1: Shape of shower images
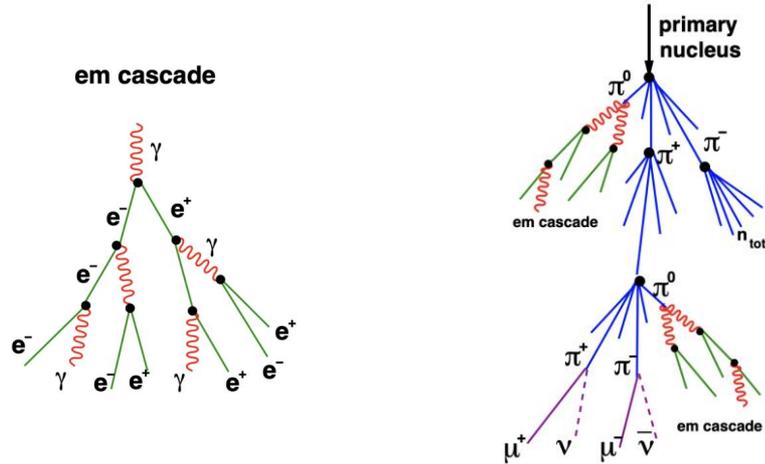


- Purely electromagnetic showers are more compact and regular than cosmic ray showers.

  - In a way, cosmic ray showers are a sum of many electromagnetic showers: every time a $\pi^0$ decays into two $\gamma$-rays, we get a new EM shower. But $\pi^0$ decay after a random path, so the shower may be shorter or longer.

  - On top of that, other charge particles produce Cherenkov light.

  - And hadronic interactions produce secondaries with a larger transverse momentum (angle), so the shower gets broader.

- All these effects reflect into the shape of the shower **image** on the telescope camera. Cosmic rays images are more irregular and flatter than $\gamma$-ray images.
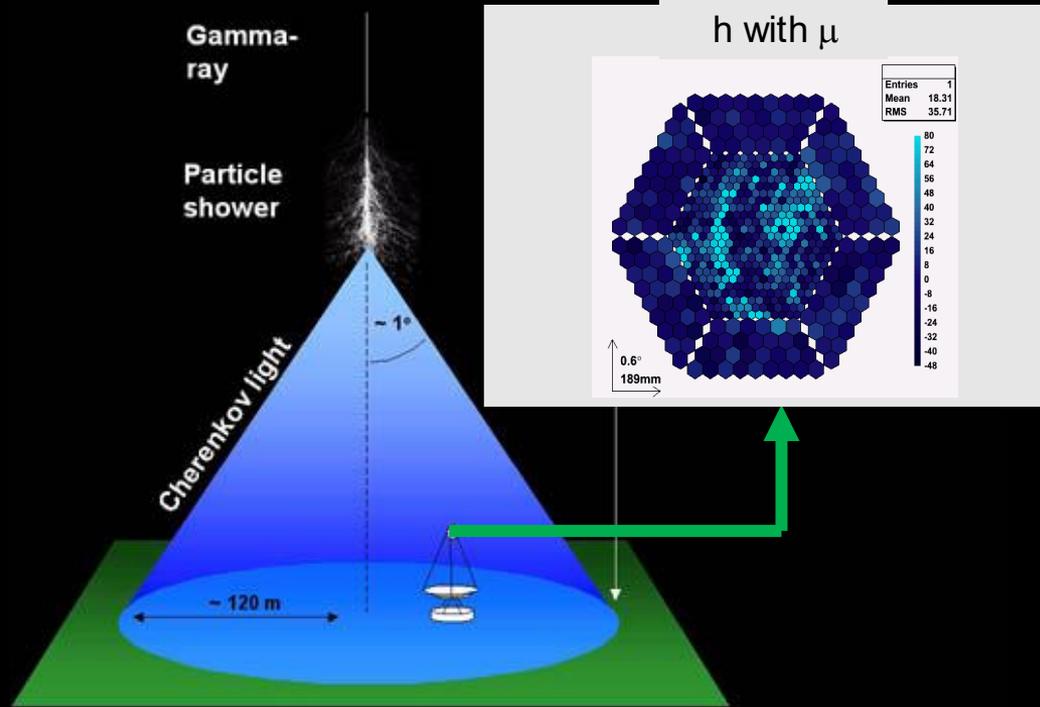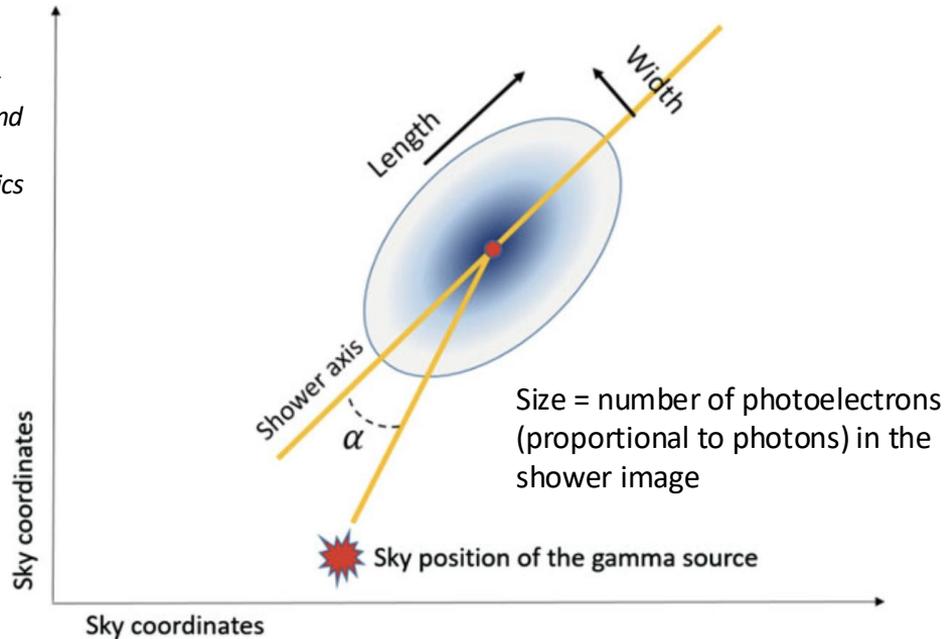
# Image parameters (1/2)

Shower images are described with the so-called "Hillas parameters": LENGTH, WIDTH, SIZE, ALPHA etc.



*Fig. from: Handbook of X-ray and γ-ray astrophysics*

Size = number of photoelectrons (proportional to photons) in the shower image
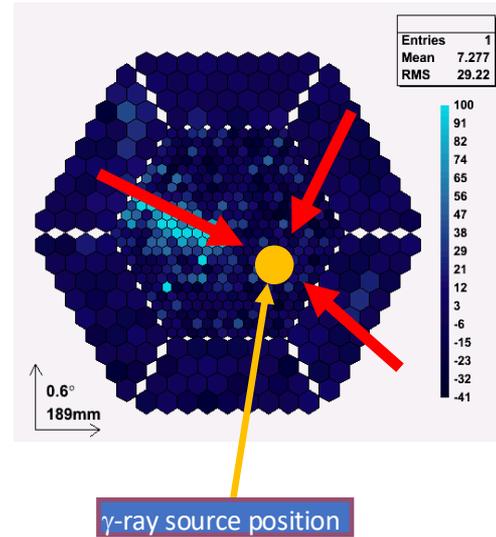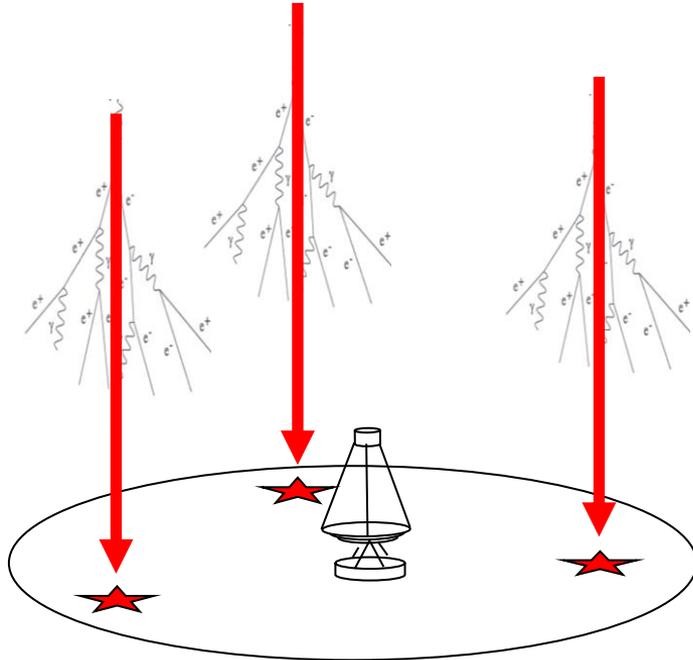
Size is roughly proportional to energy

γ-rays have smaller Length and Width for the same Size

# Technique 2: Orientation of the shower

- All showers coming from the same direction of the sky, i.e. a γ-ray source, are parallel.
- Their images will all point to the source's position in the camera, although at different places of the field of view.



γ-ray source position

# Technique 2: Orientation of the shower

- Conversely, cosmic rays come from any direction so their images will have random orientations in the camera.
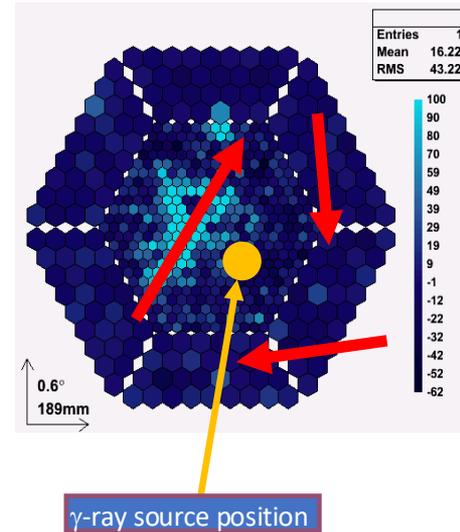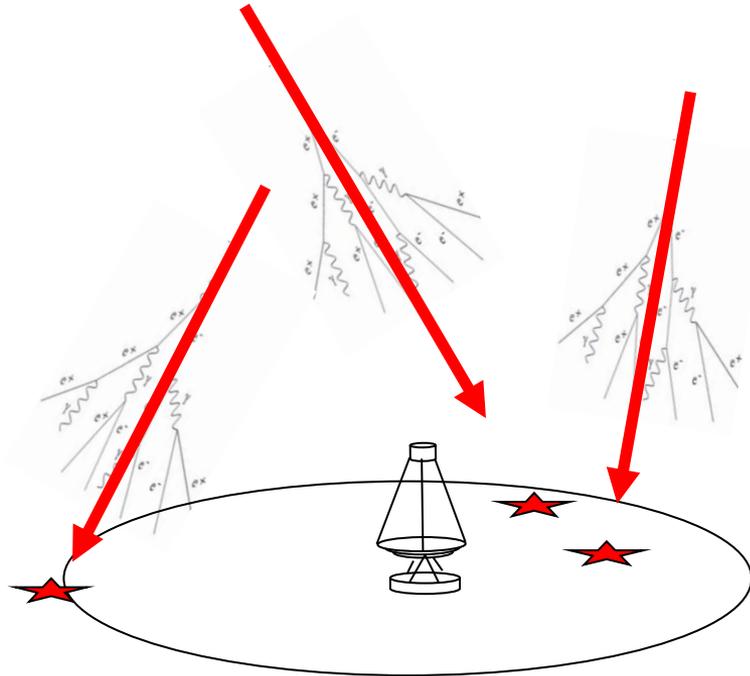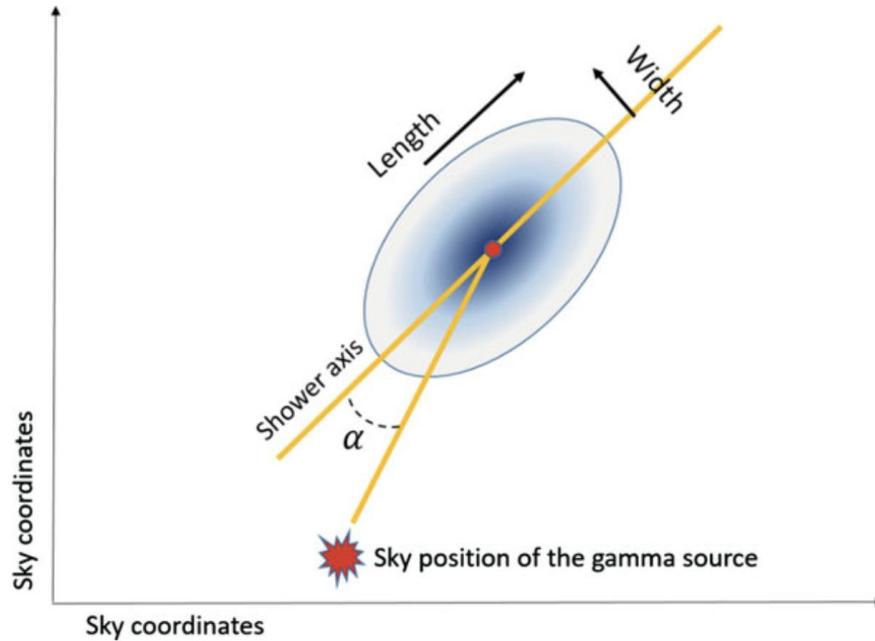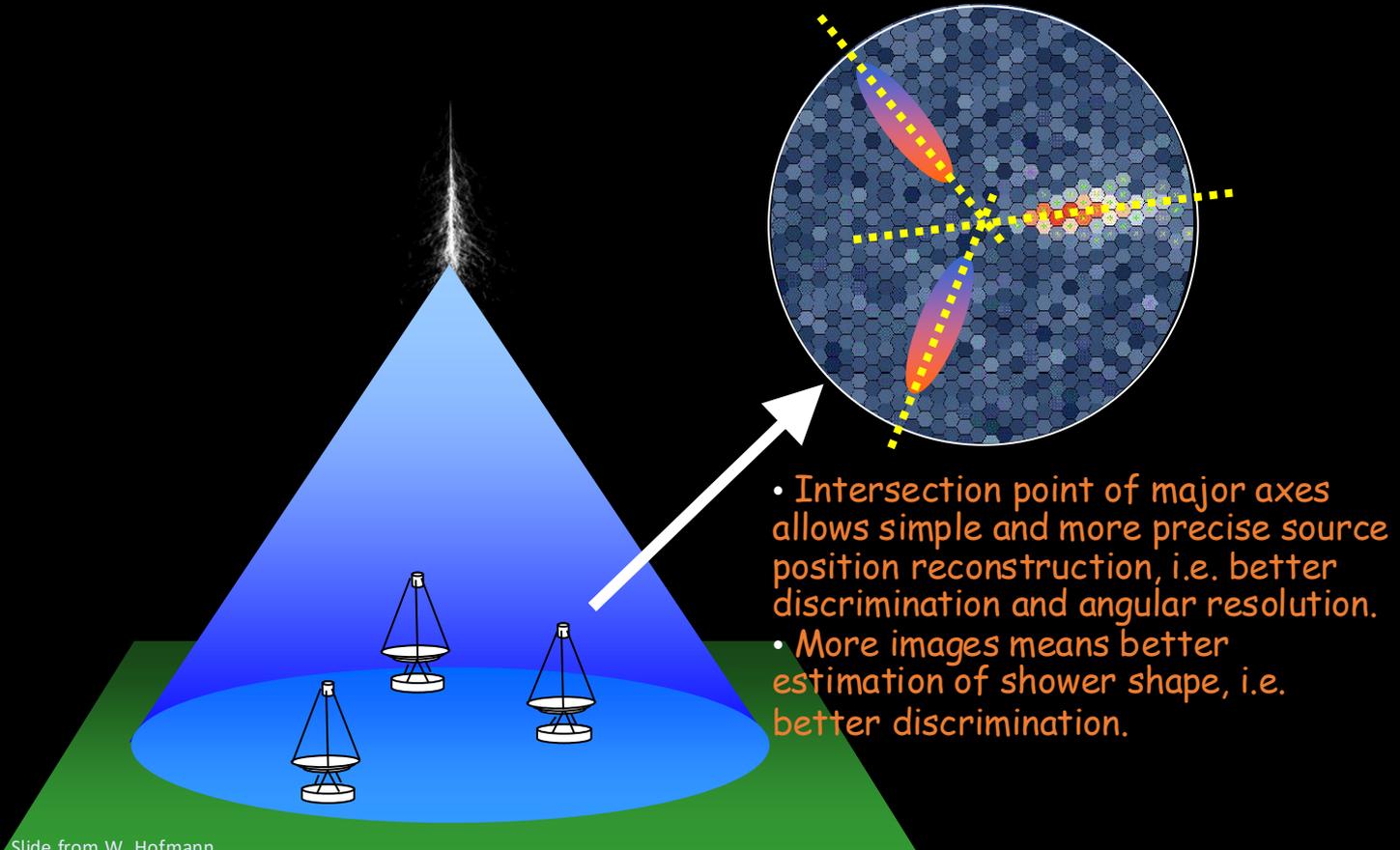- We just need to select showers which point to the source.



γ-ray source position

# Image parameters (2/2)



Length
Width
Shower axis
α
Sky coordinates
Sky coordinates
Sky position of the gamma source

γ-ray images have ALPHA~0. Cosmic ray images can have any ALPHA.

# Technique 3: Systems of IACTs



- Intersection point of major axes allows simple and more precise source position reconstruction, i.e. better discrimination and angular resolution.
- More images means better estimation of shower shape, i.e. better discrimination.

# IACT typical performance: angular resolution



$\Theta$ = Angular distance to the source
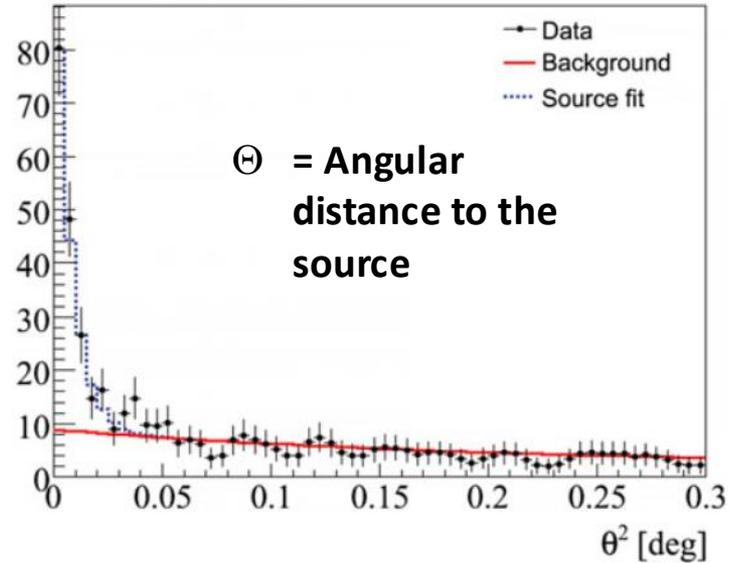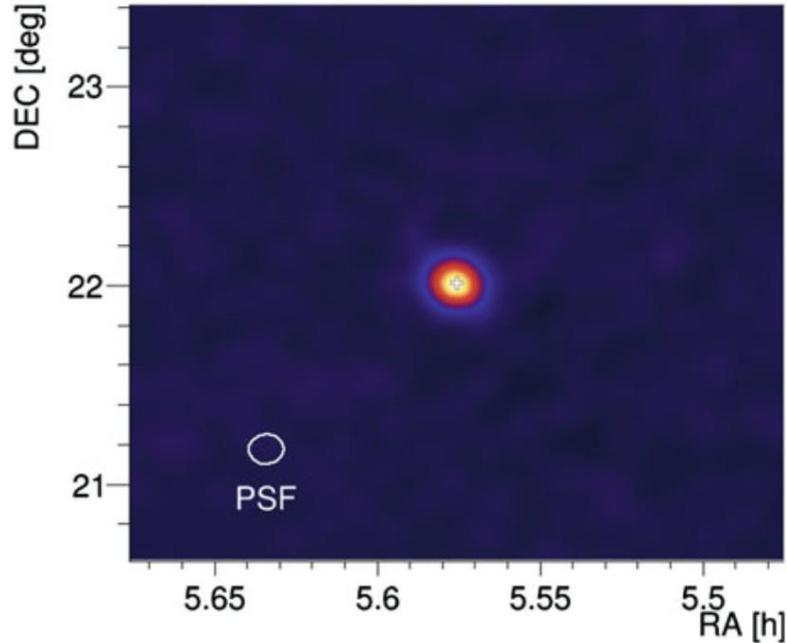
*Figures from:*
*Handbook of X-ray and γ-ray astrophysics*

# IACT typical performance: angular resolution
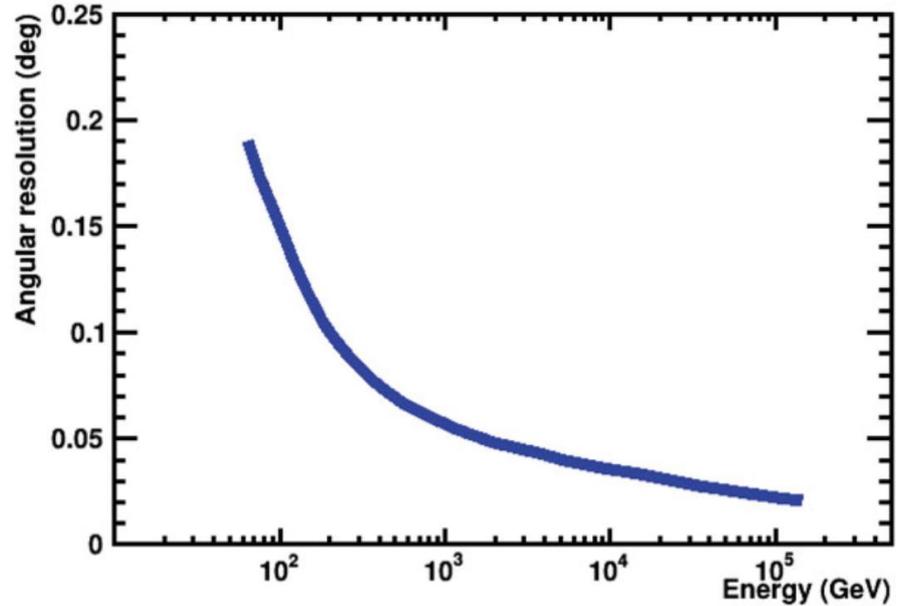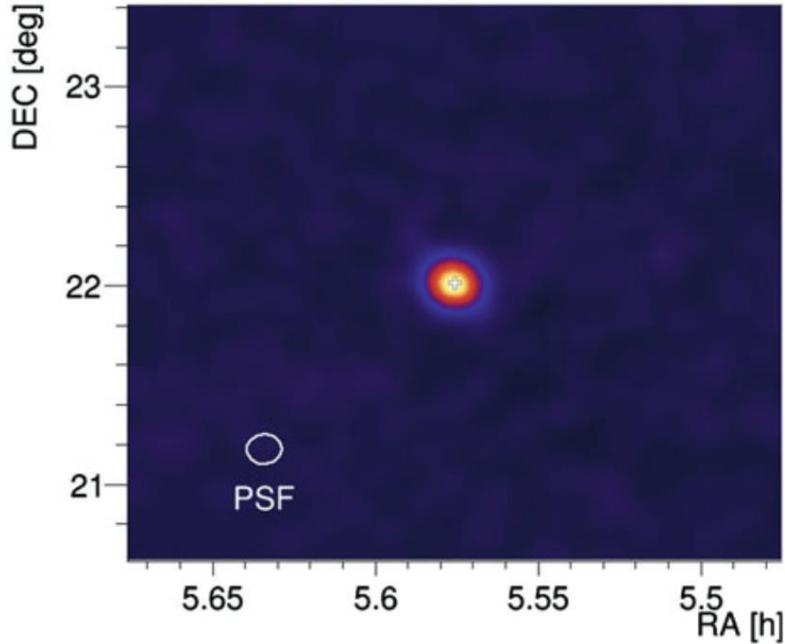


*Figures from:*
*Handbook of X-ray and $\gamma$-ray*
*astrophysics*

# Performance: sensitivity and spectral resolution
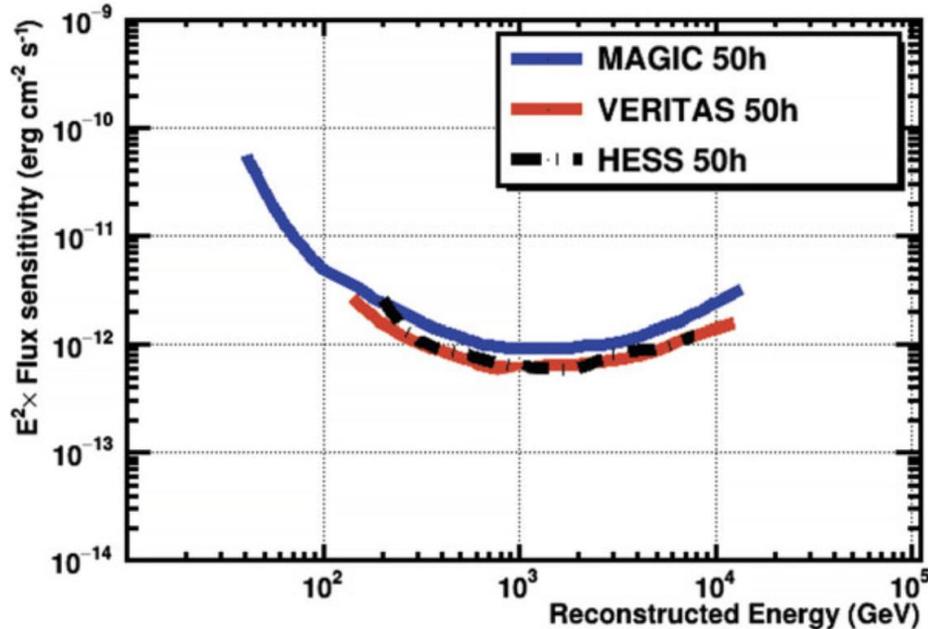


Flux sensitivity is the minimum flux of a $\gamma$–ray source that can be detected beyond a certain statistical significance (usually $5\sigma$) in a given amount of time (usually 50 h). Current IACTs have sensitivities of a few milicrabs at their optimal energy range.

Typical energy resolutions = 10 – 15%, improving with energy

# History:
# The pioneer
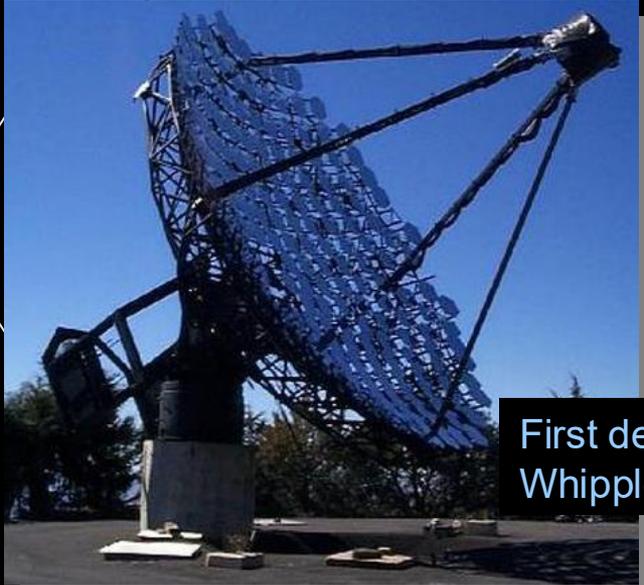


First detection of VHE γ-rays from the Crab Nebula:
Whipple Cherenkov Telescope (USA), 1989

# First generation of IACTs



CAT (1996-2003)

Whipple (1969!-2003)
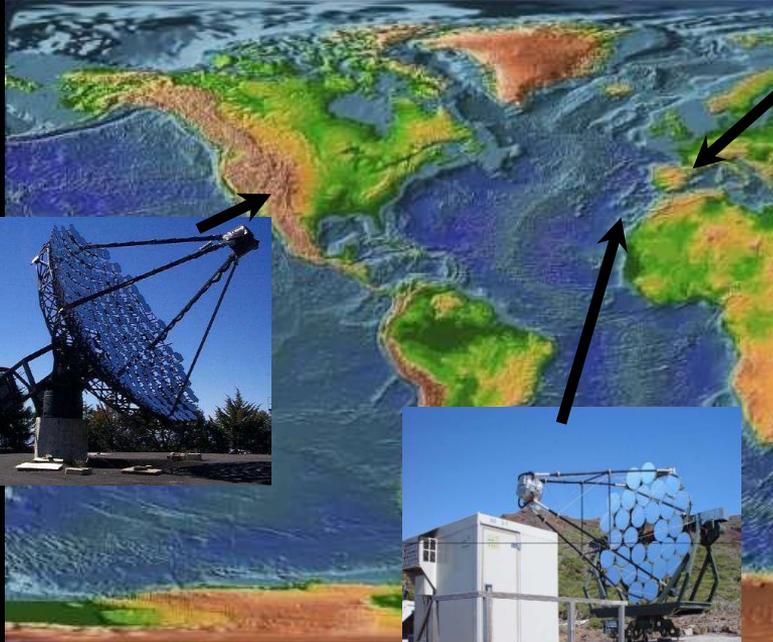
HEGRA (1993-2002)
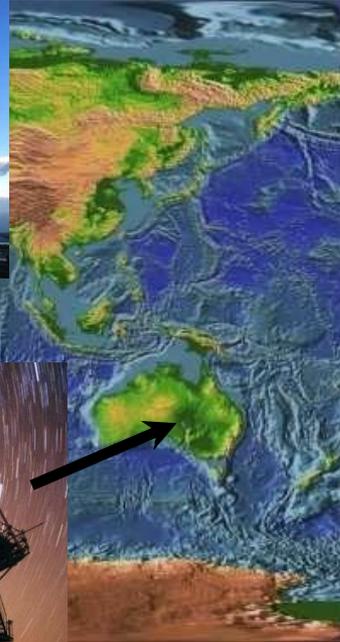
CANGAROO (1992-2001)

# 2nd generation



MAGIC

VERITAS
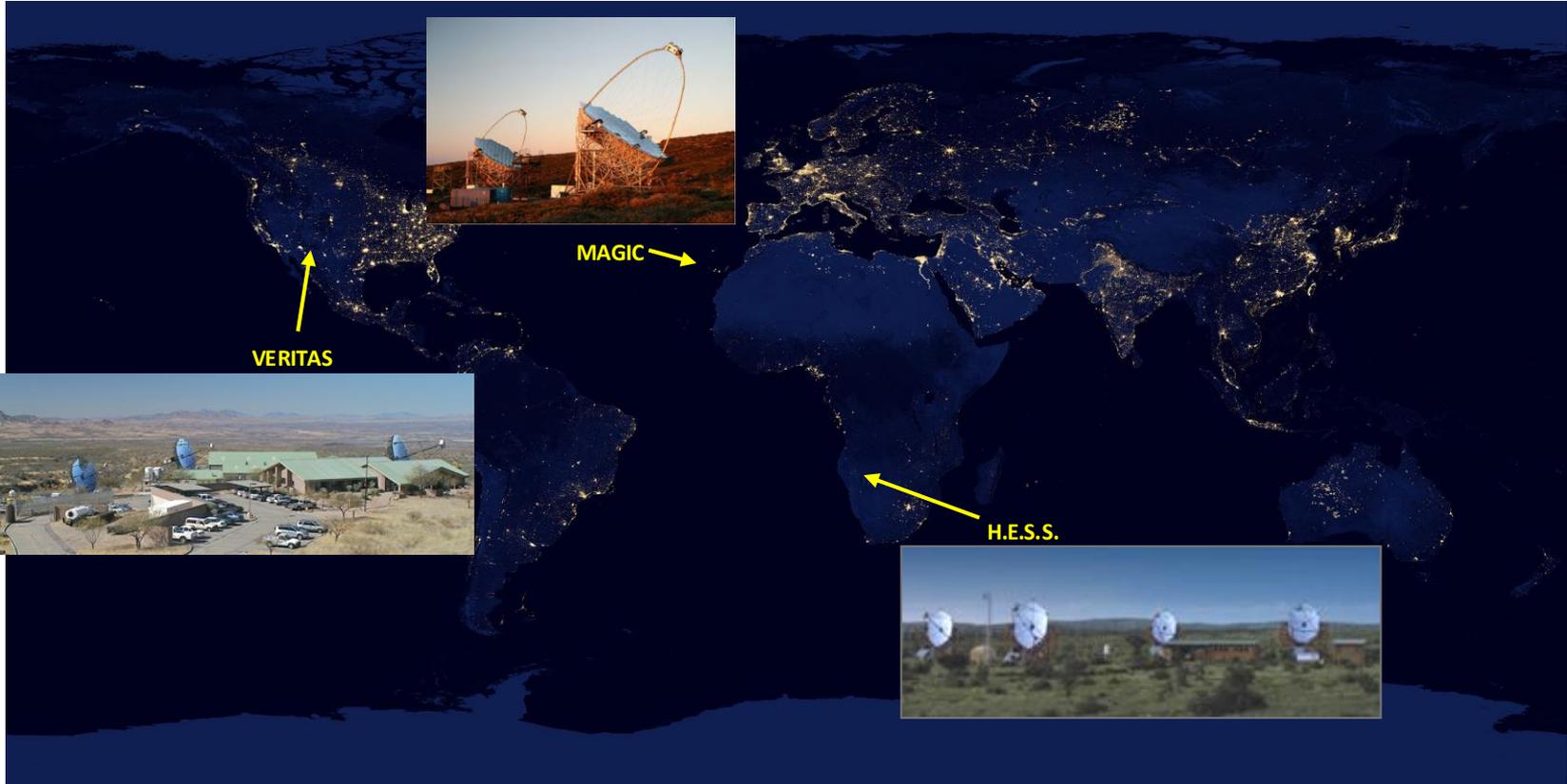
H.E.S.S.

# H.E.S.S.
## High Energy Stereoscopic System



- Array of 4 x 12 meter (100 m$^2$ mirror area) + 1 x 28 m (600 m$^2$) Cherenkov Telescopes
- Located at the Khomas Highland, Namibia (i.e. Southern Hemisphere)
- Fully operational since 2003

# The two MAGIC telescopes



Major Atmospheric Gamma-Ray Imaging Cherenkov telescopes
2 x 17 meter diameter telescopes
Located on the island of La Palma, Spain
First telescope in 2004, second telescope in 2009.

# VERITAS array



<u>V</u>ery <u>E</u>nergetic <u>R</u>adiation <u>I</u>maging <u>T</u>elescope <u>A</u>rray <u>S</u>ystem
4 x 12 m telescopes
Located in Arizona, US
First light in 2007.

# Towards the 3rd generation of IACTs

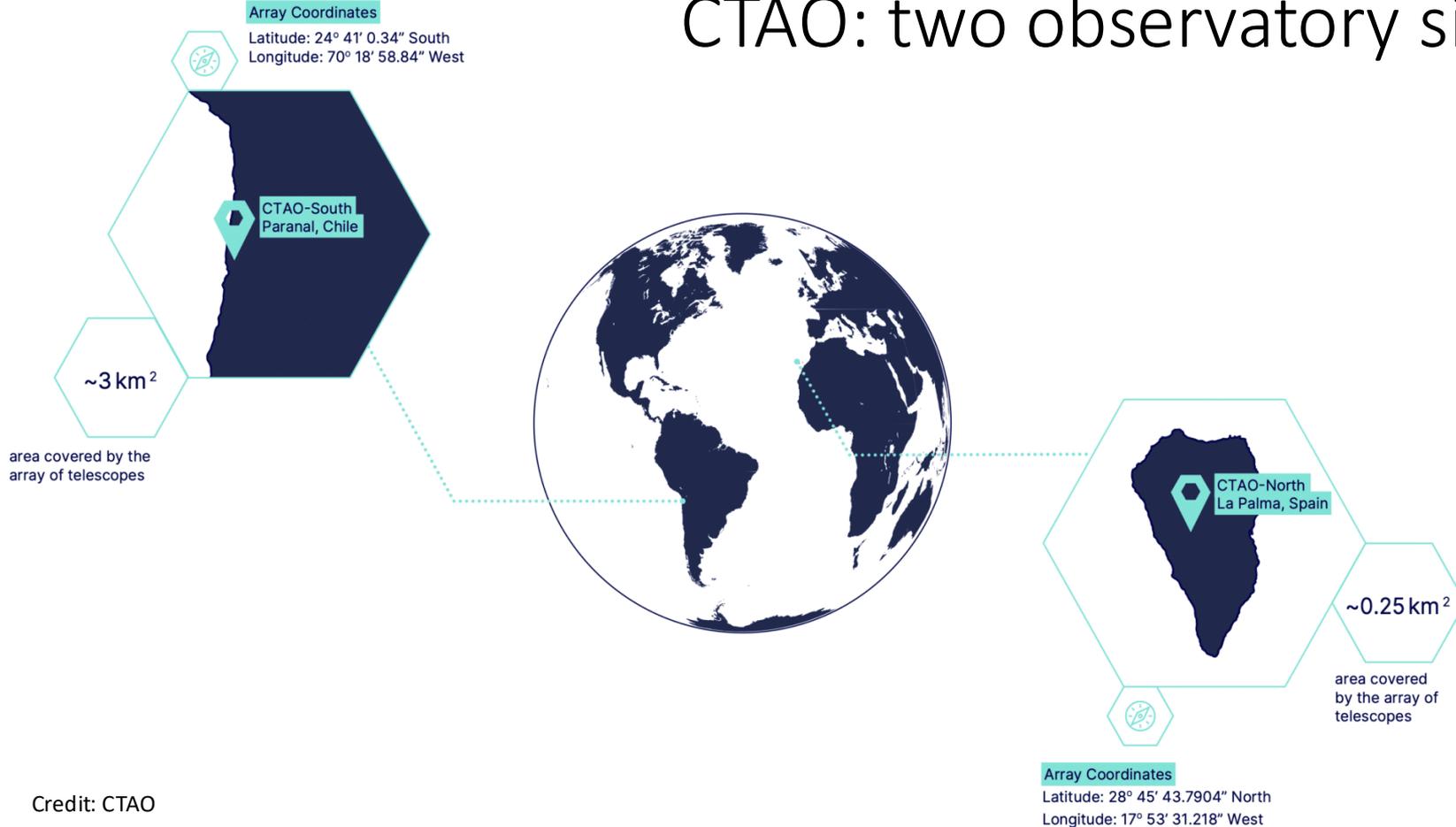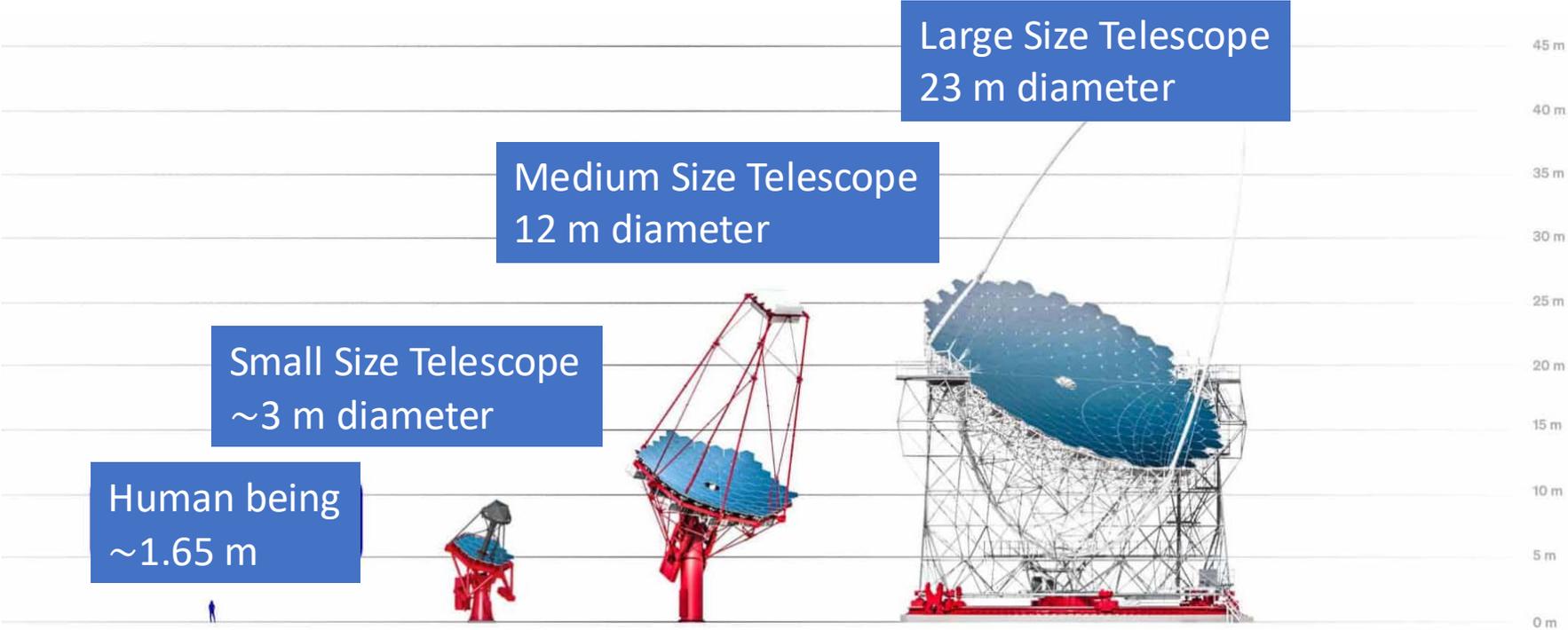- Expand energy range: reduce threshold energy to few tens of GeV but at the same time detect $\gamma$-rays from galactic sources up to the Knee of the CR spectrum, hundreds of TeV
    - Expand to lower energies: larger Cherenkov light collector -> **telescopes with larger mirrors**
    - Expand to higher energies: light collection not critical but need larger collection areas -> **smaller mirrors but many more telescopes**

- Improve sensitivity: better gamma-hadron separation **-> arrays of many telescopes**

- All sky coverage, i.e. north and south: build one observatory at each hemisphere

- Wider field of view: survey capability, serendipitous discoveries, source morphology **-> larger cameras**

- Fast repositioning for GRB follow-up **-> light structures**

- Access to any scientist in countries funding the observatory **-> open data, open analysis software, offer proposal evaluation system**

# CTAO: two observatory sites

Array Coordinates
Latitude: 24° 41' 0.34" South
Longitude: 70° 18' 58.84" West

CTAO-South
Paranal, Chile

~3 km²

area covered by the
array of telescopes

CTAO-North
La Palma, Spain

~0.25 km²

area covered
by the array of
telescopes

Array Coordinates
Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

Credit: CTAO

# CTAO: three different telescope sizes



Large Size Telescope
23 m diameter

Medium Size Telescope
12 m diameter

Small Size Telescope
~3 m diameter

Human being
~1.65 m

45 m
40 m
35 m
30 m
25 m
20 m
15 m
10 m
5 m
0 m

Credit: CTAO

# CTAO: array configurations – CTAO NORTH



LEGEND

Large-Sized Telescope
Medium-Sized Telescope
CTAO Operations Building & Other Calibration Devices
Weather Station
Stellar Photometer
Raman LIDAR
Road
Gradient
MAGIC Telescopes
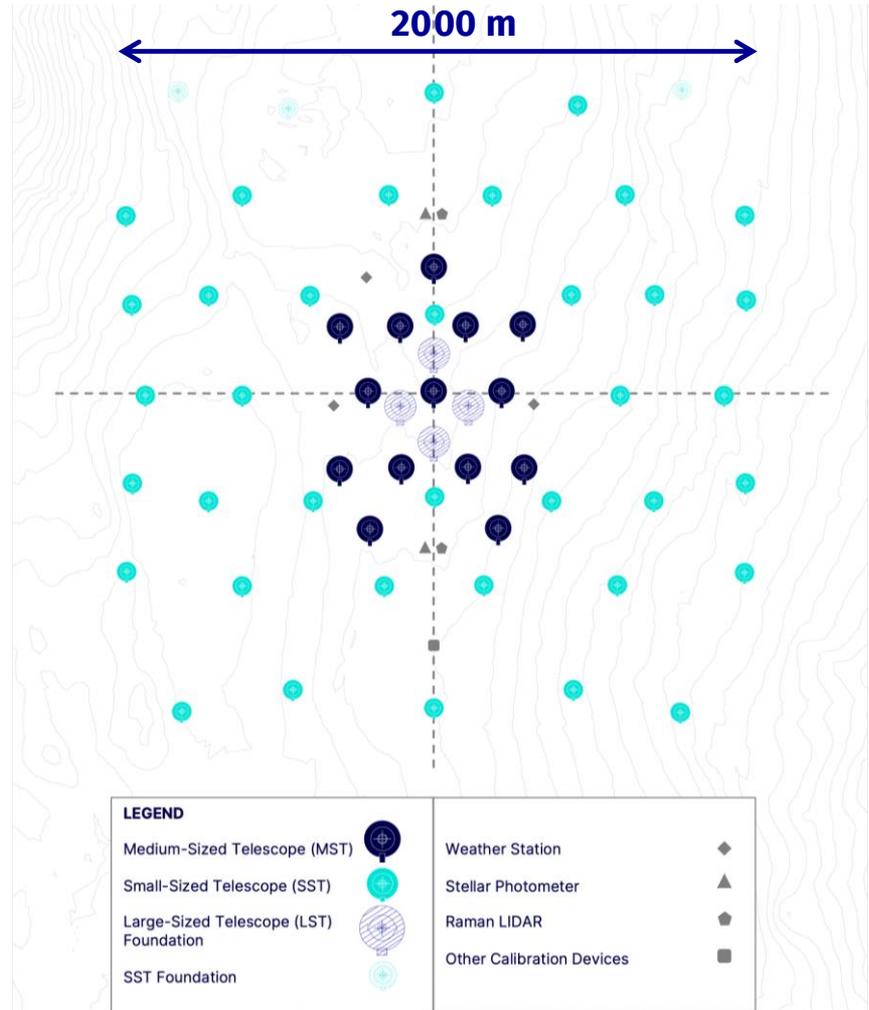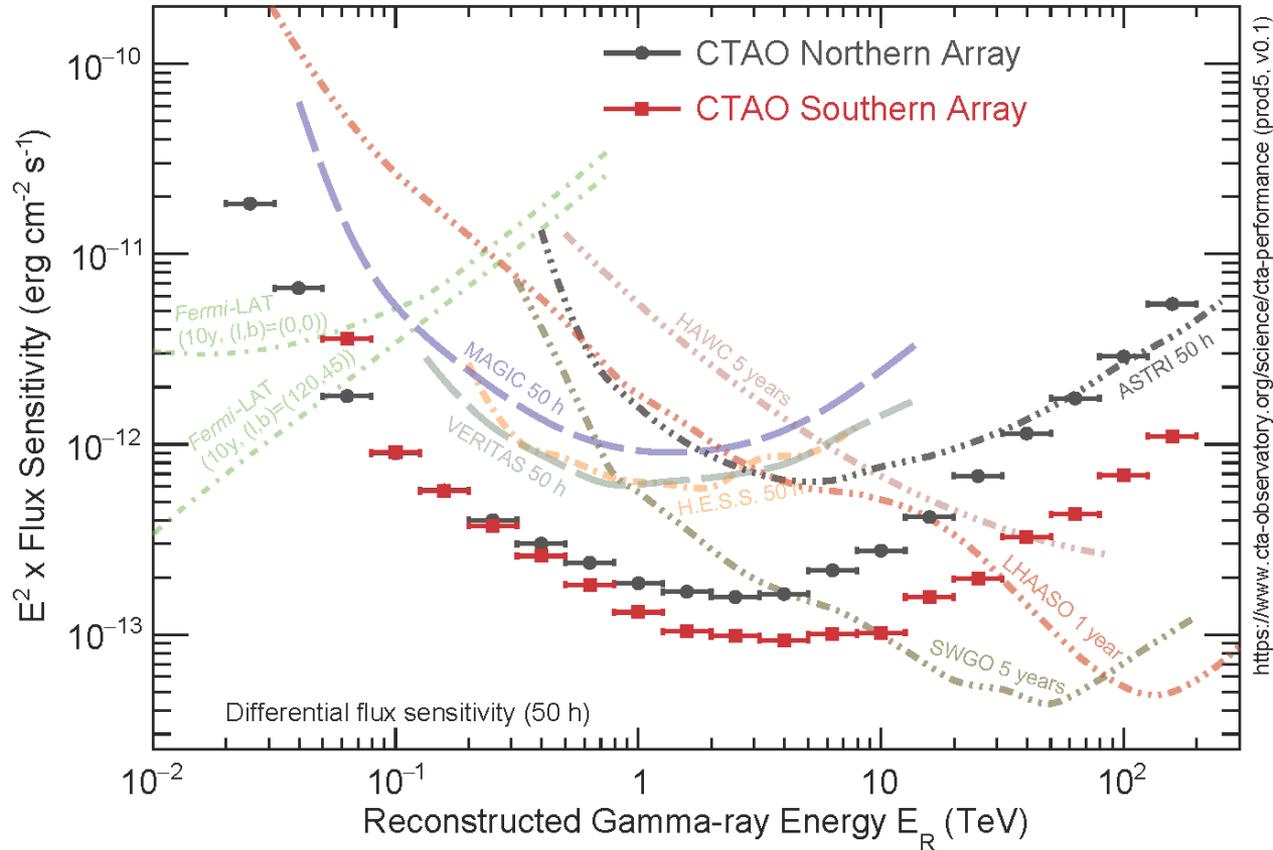External Facilities

600 m
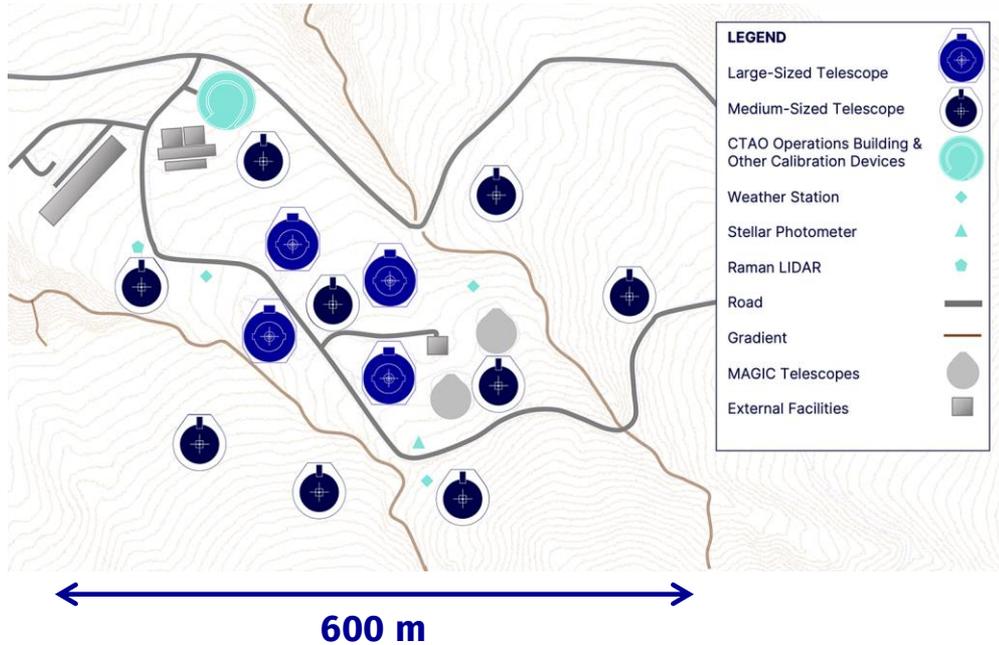
- Optimized for low- and mid-energy ranges from 20 GeV to 50 TeV
- Focus on extragalactic physics.

# CTAO: array configurations – CTAO SOUTH

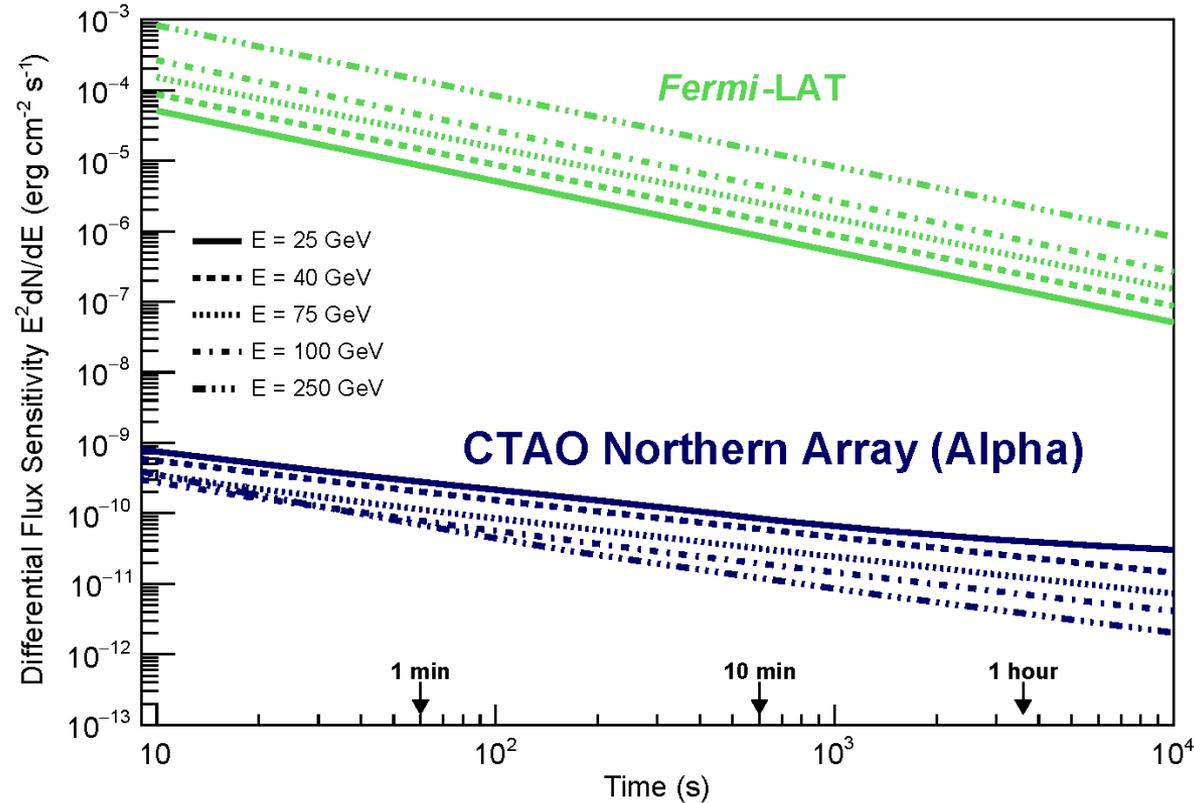- Optimized for the medium and high-energy ranges of the CTAO, from 80 GeV to 300 TeV
- Focus on Galactic targets.



**2000 m**

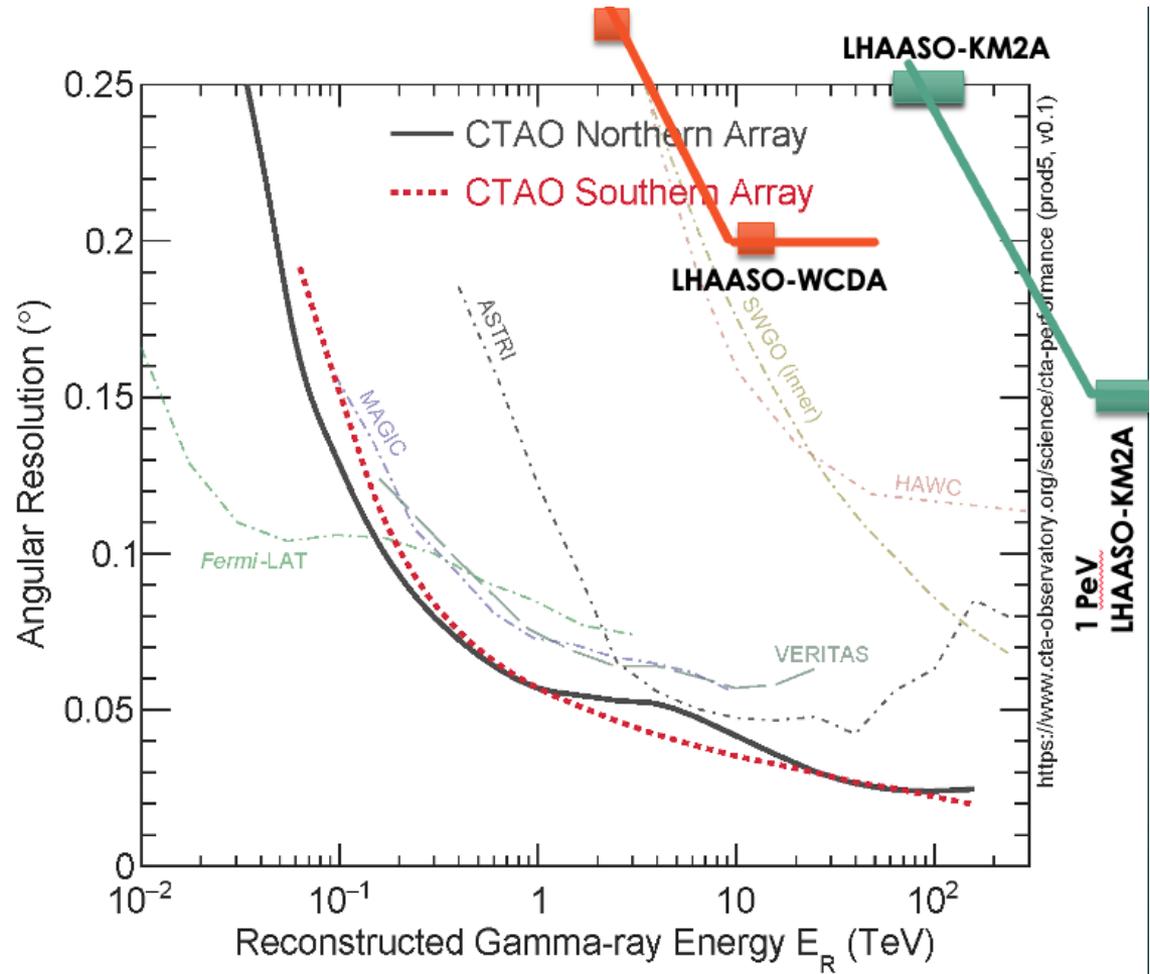**LEGEND**

| | | | |
|---|---|---|---|
| Medium-Sized Telescope (MST) | | Weather Station | ◆ |
| Small-Sized Telescope (SST) | | Stellar Photometer | ▲ |
| Large-Sized Telescope (LST) Foundation | | Raman LIDAR | ⬠ |
| SST Foundation | | Other Calibration Devices | ▪ |

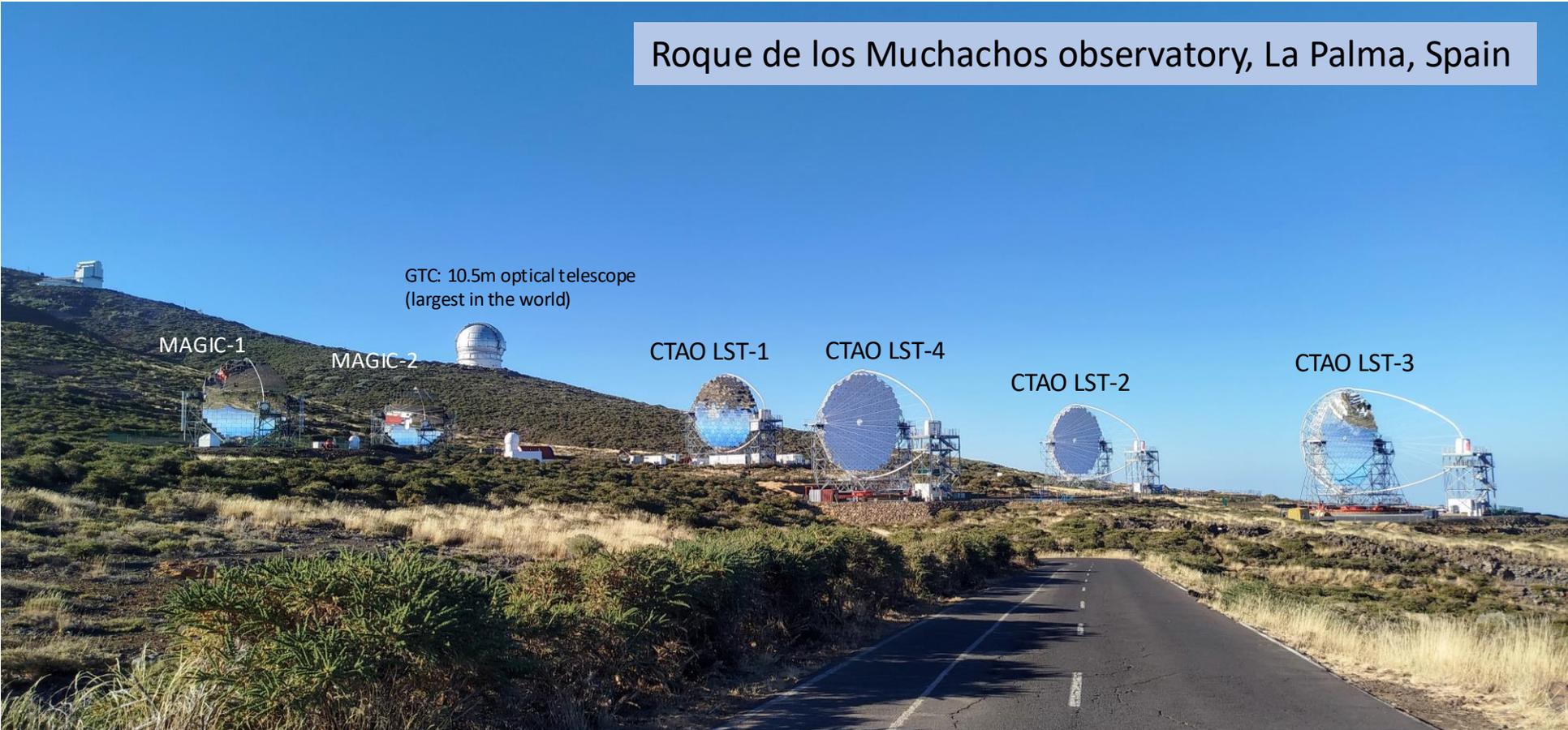# CTAO sensitivity

# Short term sensitivity

# Angular resolution



*LHAASO from: arXiv:2101.03508 and Chinese Phys. C **45**, 025002 (2021)*

# CTAO: under construction!



Roque de los Muchachos observatory, La Palma, Spain

GTC: 10.5m optical telescope (largest in the world)

MAGIC-1

MAGIC-2

CTAO LST-1

CTAO LST-4

CTAO LST-2

CTAO LST-3

# CTAO: status


CTAO-North

## CTAO-North:

- First LST installed in 2018, still under commissioning, but taking data in parallel

- LST sub-array to be completed this year (LST 1-4).

- First MST to be installed in 2027, next MSTs in the following years.

## CTAO-South:

- Infrastructure under deployment.

- First two MSTs and five SSTs to start installation this year.

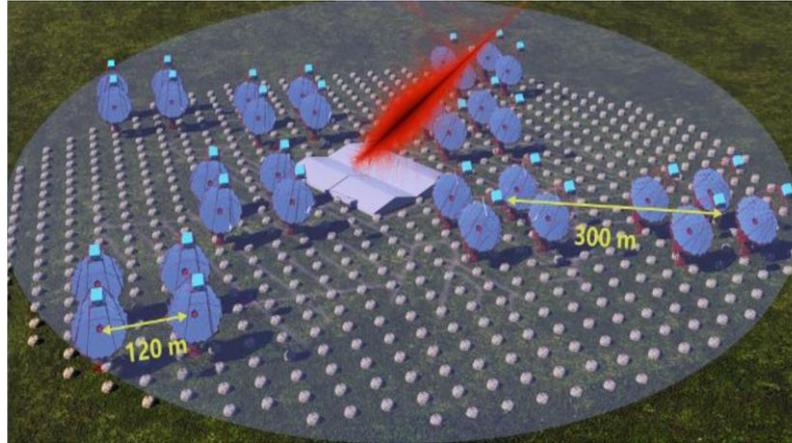- Next telescopes coming in the following years.


CTAO-South

# ASTRI Mini-array in Tenerife, Spain

- **A "spin-off" of CTAO.**
- 9 telescopes x 4 m diameter (very similar to CTAO SSTs in Chile)
- Energy range: ~1 -100 TeV

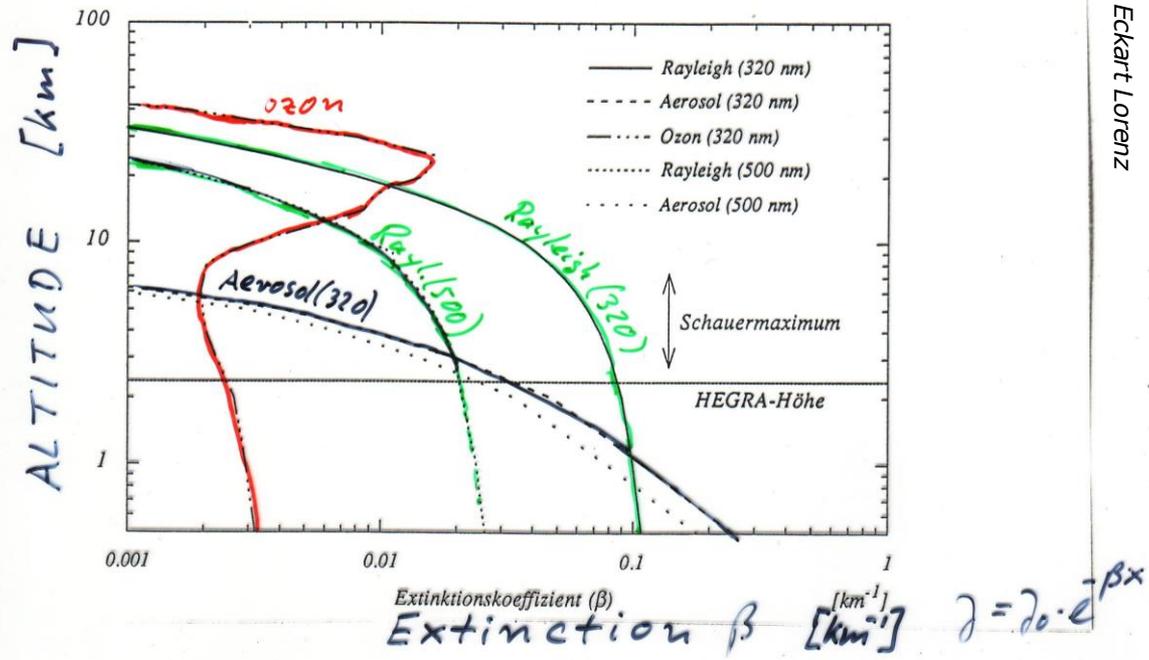# LACT: IACTs planned for Chinese LHAASO site



Qiang Yuan
ICRC 2025

- 8x4 telescope array
- 6 m diameter mirrors
- Two prototype telescope will soon see first light.

The end

backup

# Light attenuation in atmosphere