

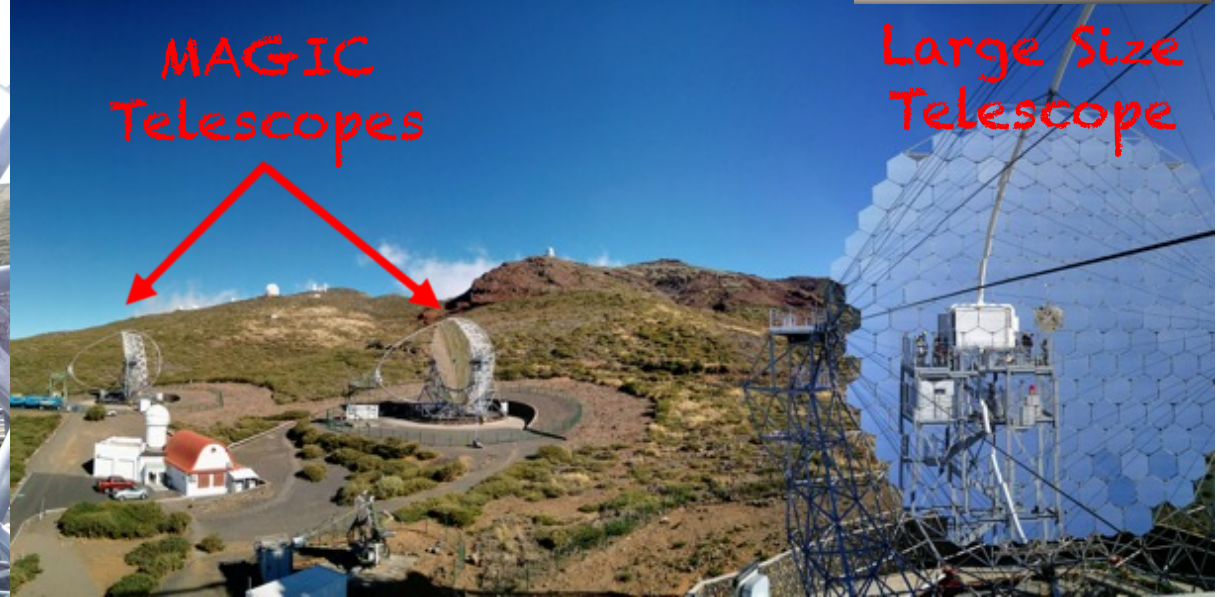
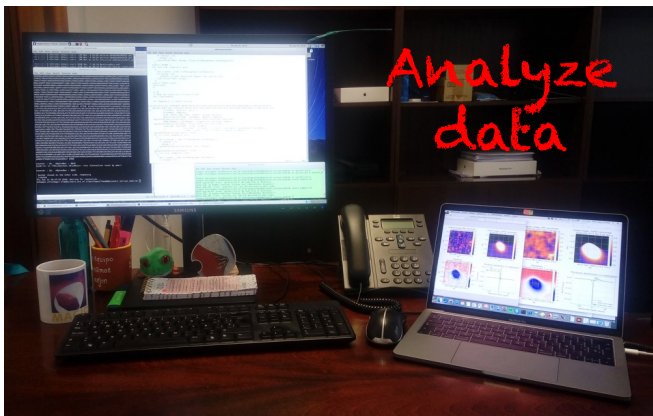
GAMMA-RAY ASTROPHYSICS DETECTORS

Daniela Hadasch

1

WHO AM I?

- Dr. Daniela Hadasch
 - dhadasch@ice.csic.es
- PhD here @ Institute for Space sciences (UAB)
- 1 year university assistance @University of Innsbruck, Austria
- 10 years @ The University of Tokyo (Institute for Cosmic Ray Research)
- Now: Staff Scientist at the Institute for Space sciences (ICE-CSIC)
- Working for MAGIC telescopes & Cherenkov telescope array & Fermi satellite
 - Construction & Galactic Science



OVERVIEW

- 8. July
 - How do we detect?
- 9. July
 - What do we detect in our Galaxy?
- 10. July
 - What do we detect outside our Galaxy?
- Some slides based presentations by Alicia López, Marcel Strzys, Liz Hays, Shoushan Zhang and Alison Mitchell.



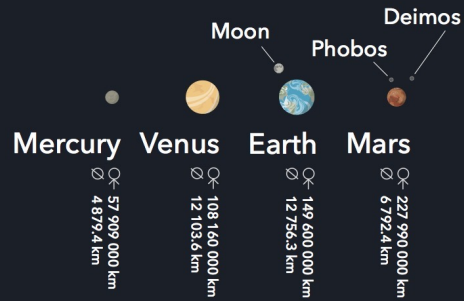
JOURNEY THROUGH OUR UNIVERSE

7/6/26

The Solar System:

Sun

☉ 1 392 684 km



Moons with colored frames are not to scale.

☉ = distance of the planet to the sun
 ∅ = average- or equatorial diameter

Vesta

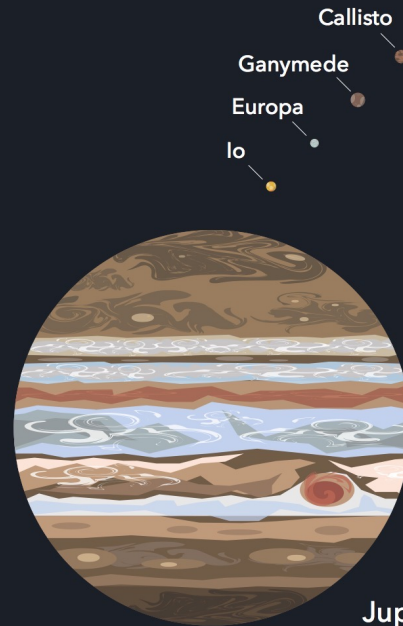
Juno

Asteroid belt

Ceres

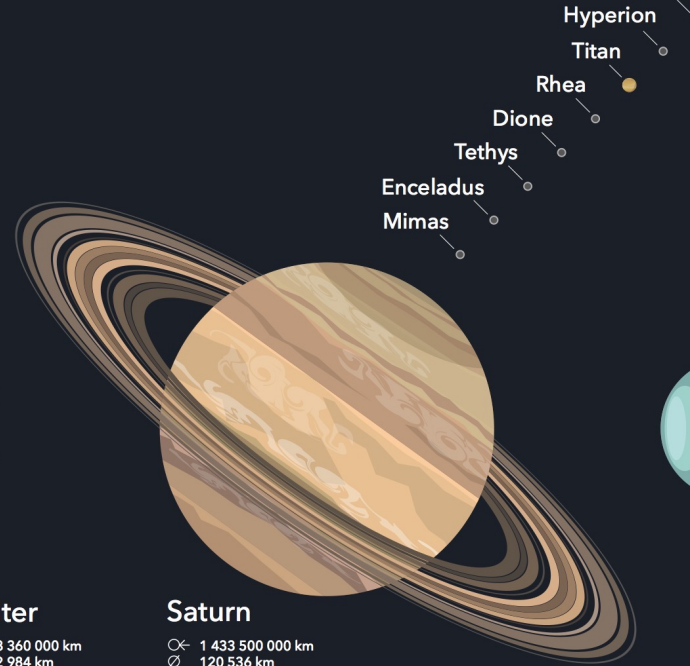
Pallas

The major objects in the belt; not in scale



Jupiter

☉ 778 360 000 km
 ∅ 142 984 km
 79 moons in total



Saturn

☉ 1 433 500 000 km
 ∅ 120 536 km
 62 moons in total



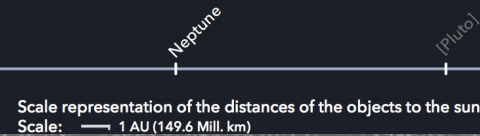
Uranus

☉ 2 872 400 000 km
 ∅ 51 118 km
 27 moons in total



Neptune

☉ 4 498 400 000 km
 ∅ 49 528 km
 14 moons in total



Kuiper belt

Makemake

Pluto
 Charon

Haumea

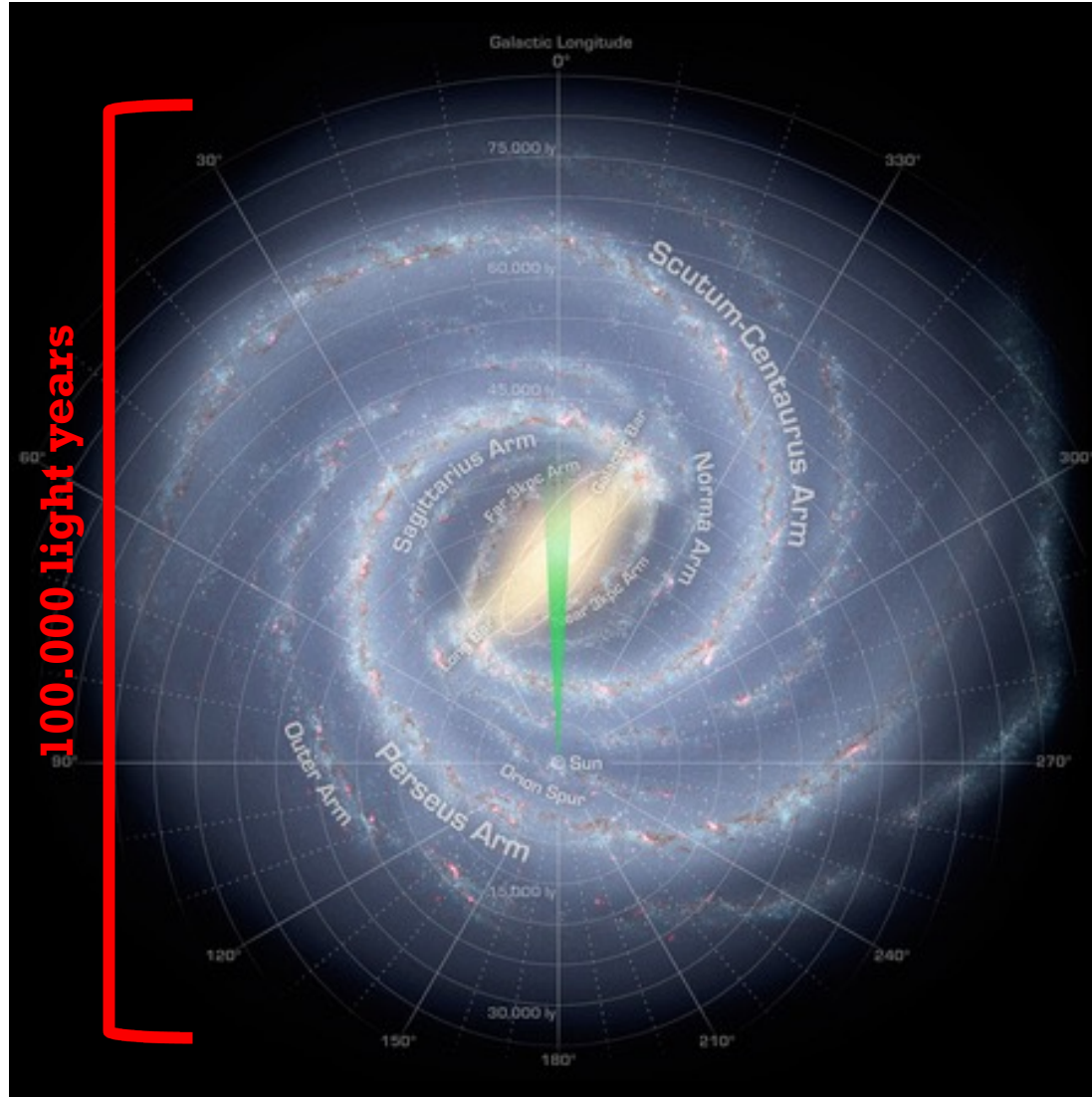
The major dwarf planets (including the biggest moon of Pluto); in scale.

4 498 400 00 km

OUR SOLAR SYSTEM

OUR GALAXY

- Milky Way
 - Spiral arm Galaxy

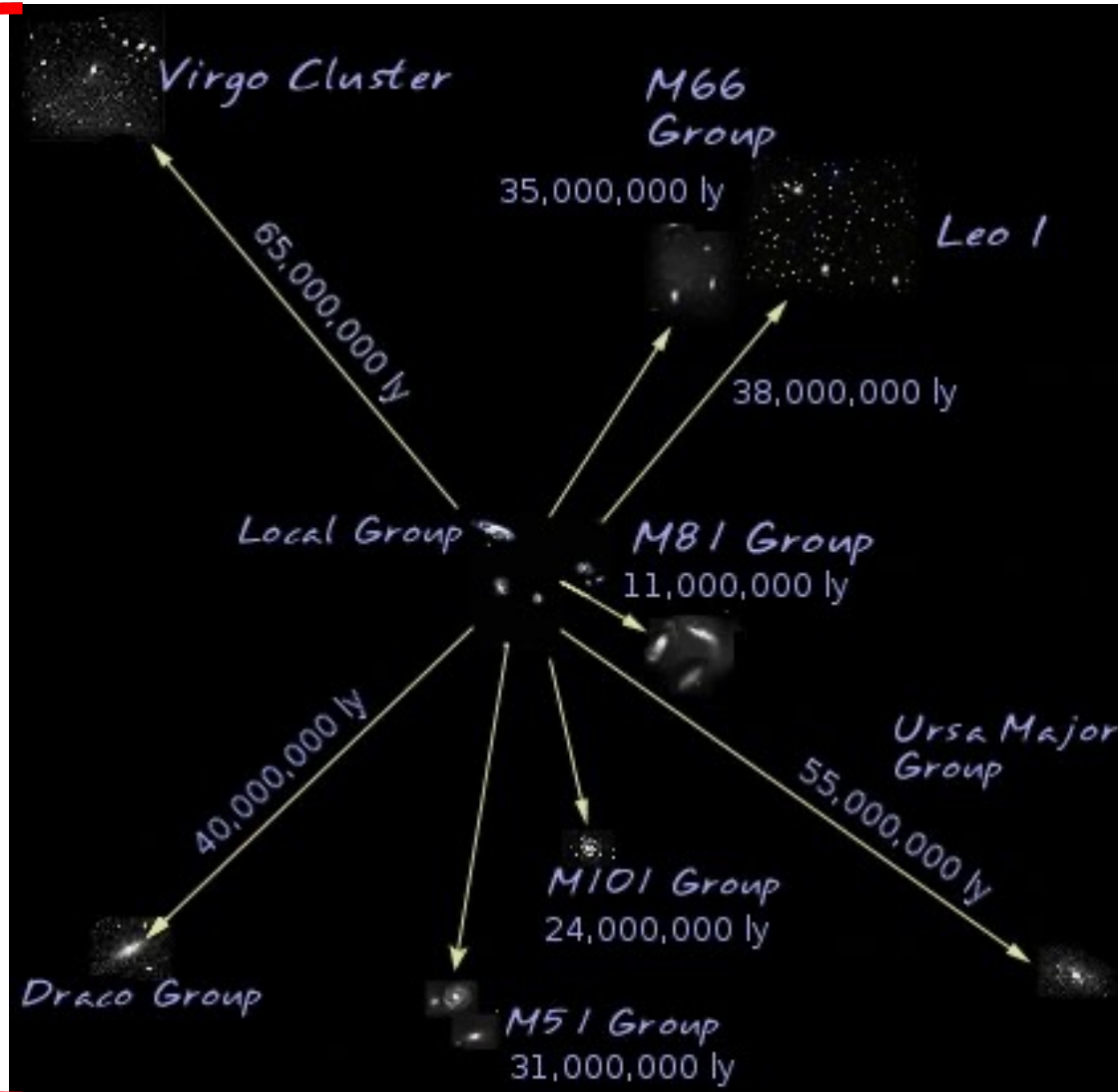


LOCAL GROUP OF GALAXIES

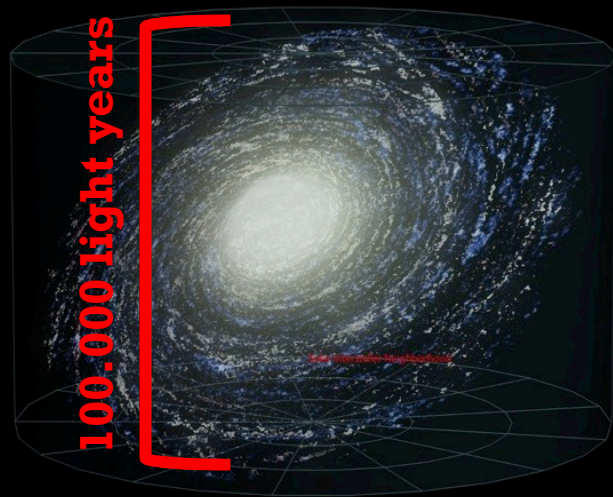


VIRGO SUPER CLUSTER

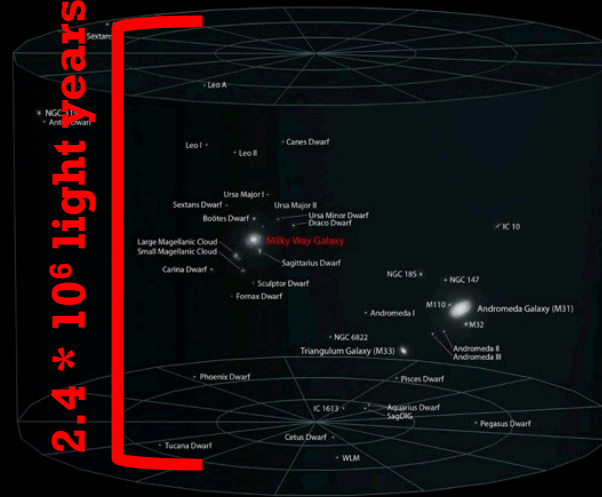
110 million light years



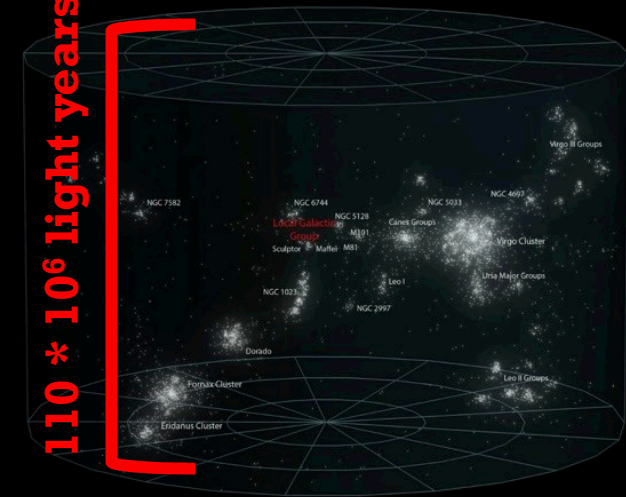
Milky Way Galaxy



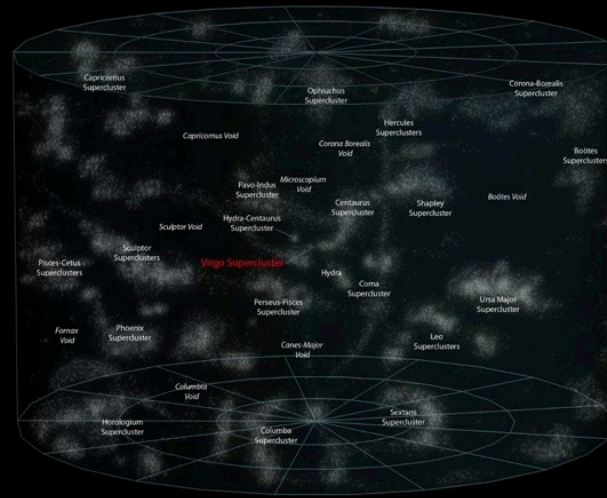
Local Galactic Group



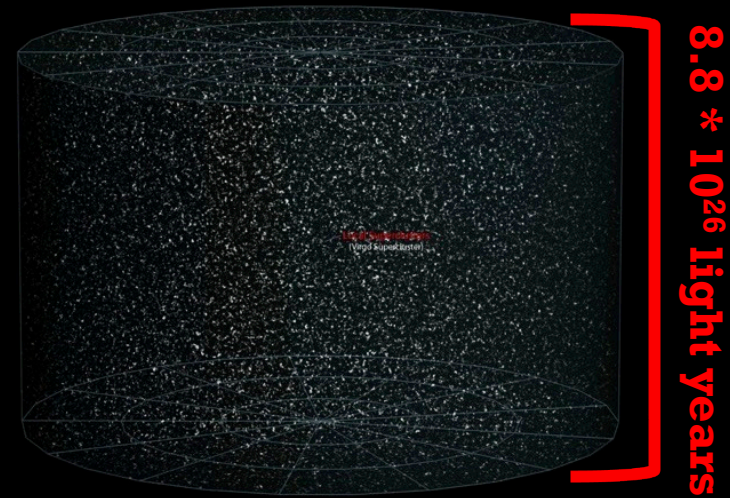
Virgo Supercluster



Local Superclusters



Observable Universe



JOURNEY THROUGH THE ELECTROMAGNETIC SPECTRUM



- Light is electromagnetic radiation.
- Relationship frequency, wavelength, energy
 - $\lambda\nu=c$ where λ is the wavelength, ν is the frequency and c is the speed of light.

$$c = \lambda \times \nu$$

$$E = h \times \nu$$

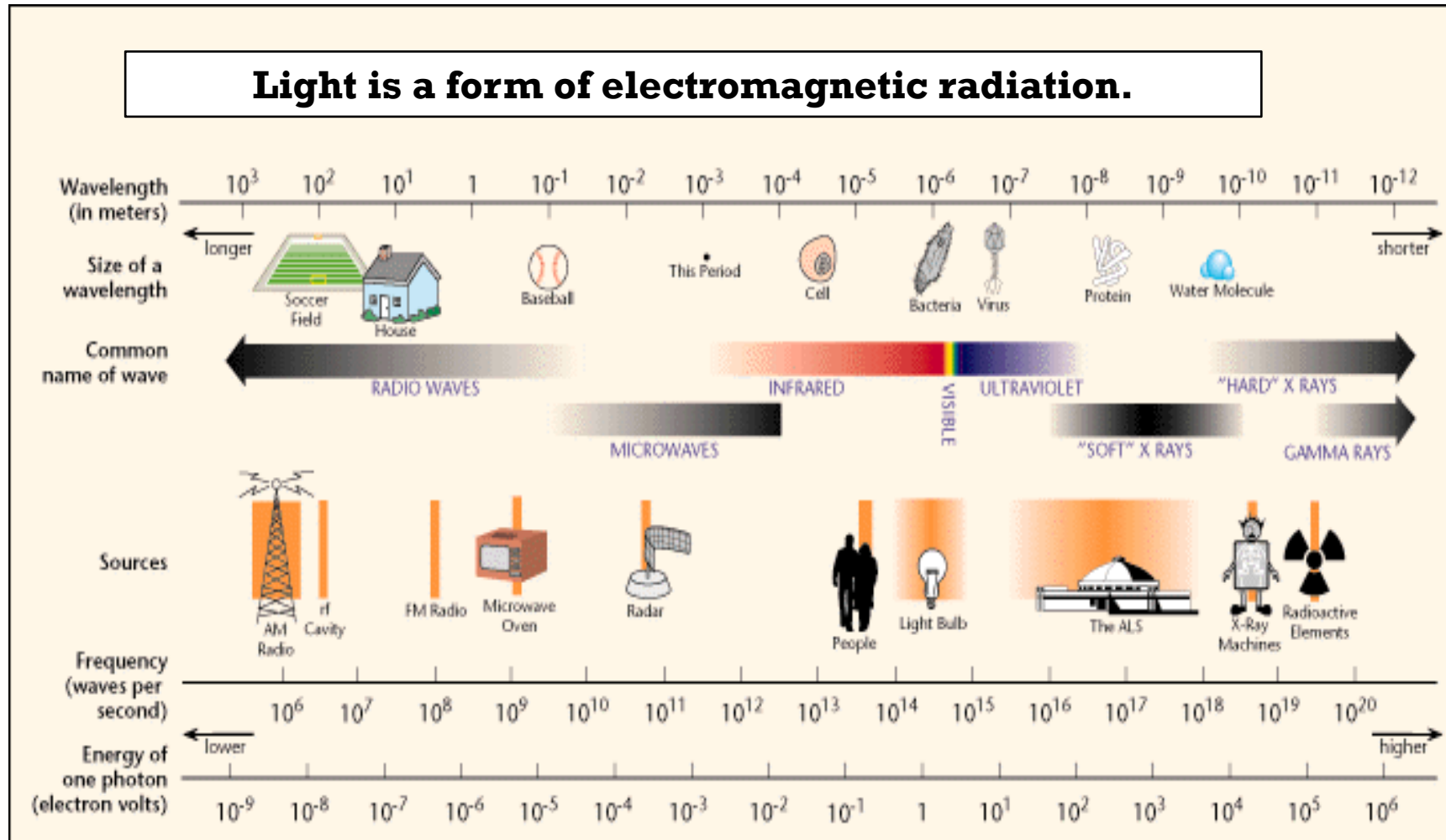
$$c = 3.00 \times 10^8 \text{ m/s}$$

$$h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$$

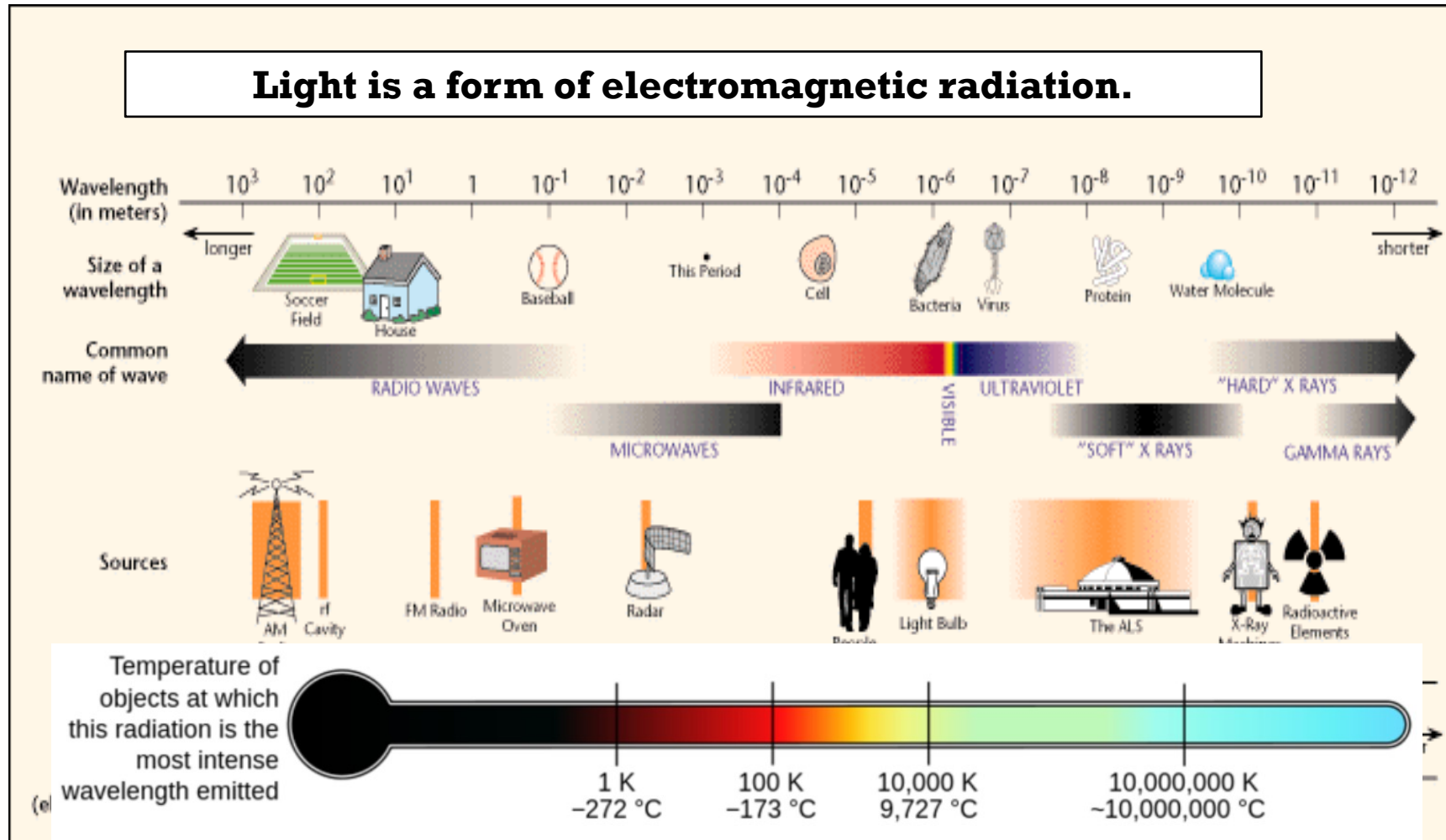
- **Electronvolt (eV)** is a unit of energy equal to approximately 1.6×10^{-19} joules (J).
 - An electronvolt (eV) is the energy gained by an electron accelerated through a potential difference of 1 volt.
 - $1\text{eV} = \text{Energy of the visible light}$

WHAT IS LIGHT?

THE ELECTROMAGNETIC SPECTRUM



THE ELECTROMAGNETIC SPECTRUM



GALACTIC PLANE AT DIFFERENT WAVELENGTHS



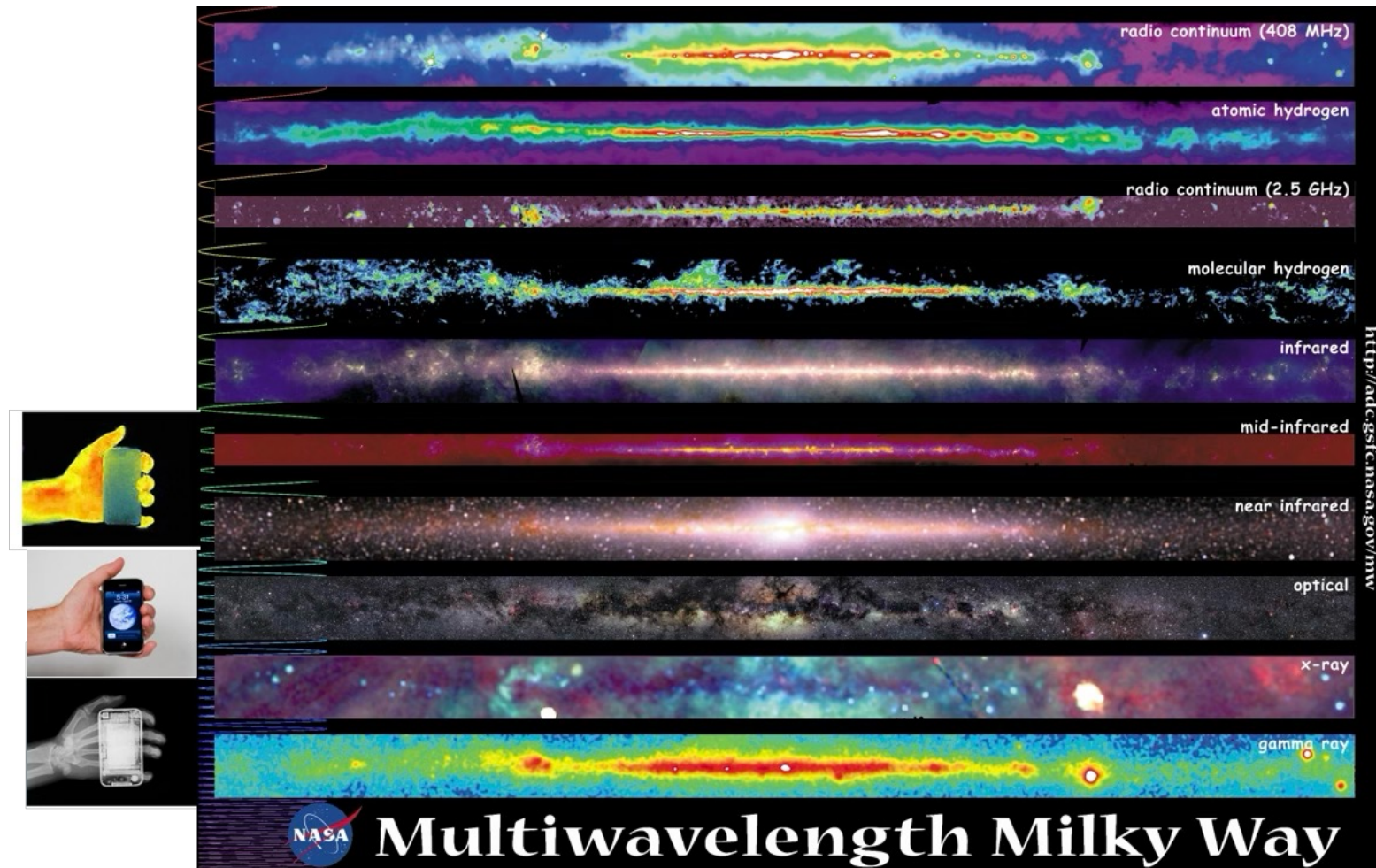
GALACTIC PLANE AT DIFFERENT WAVELENGTHS



GALACTIC PLANE AT DIFFERENT WAVELENGTHS

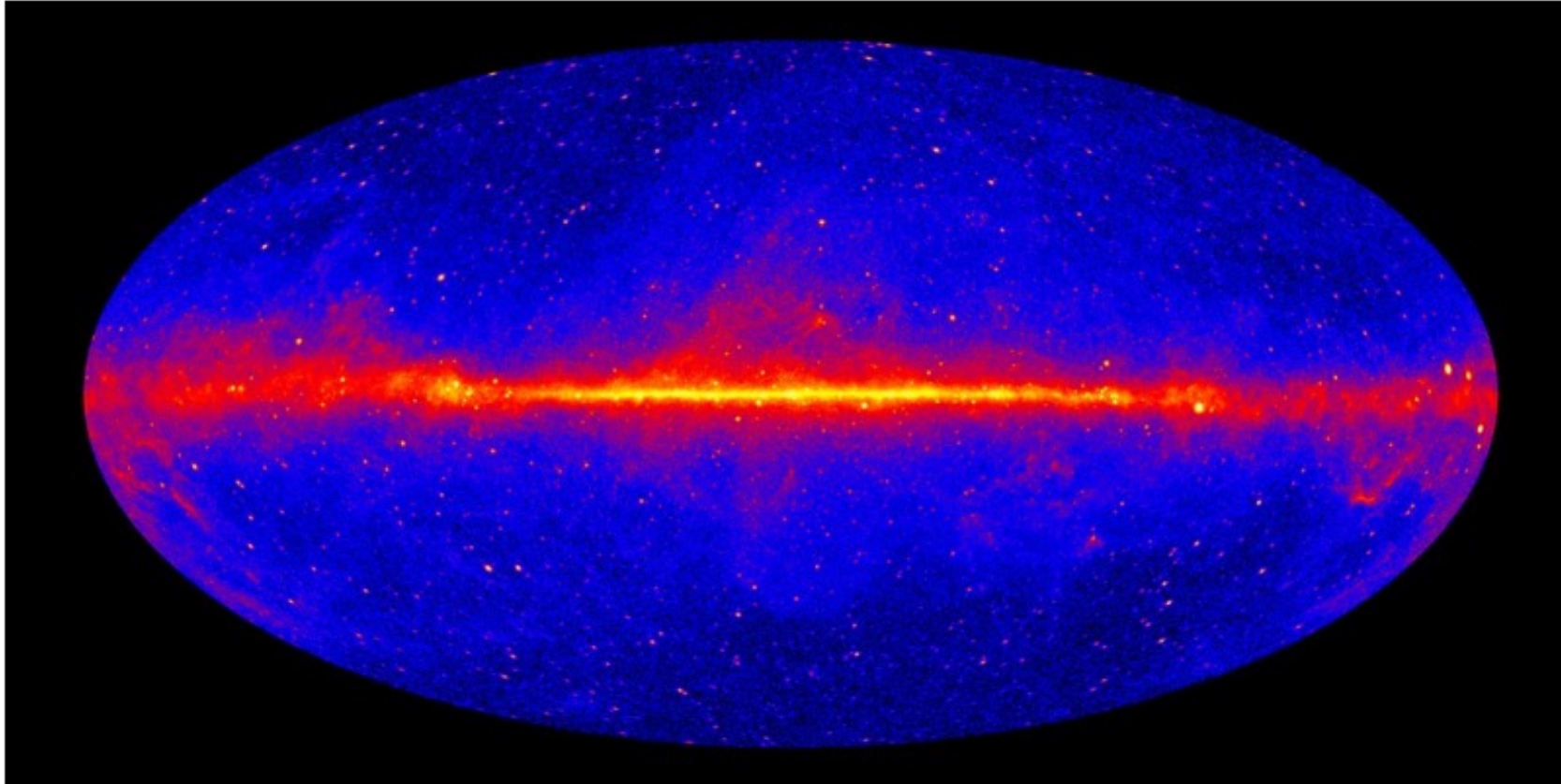


GALACTIC PLANE AT DIFFERENT WAVELENGTHS



THE SKY IN GAMMA-RAYS

γ -ray sky observed by Fermi-LAT >1 GeV over 12 years

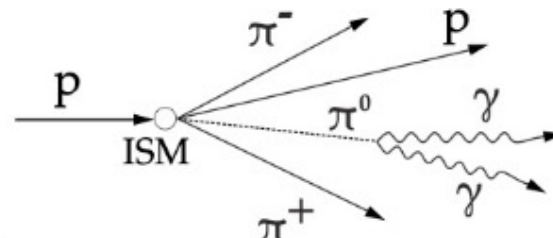
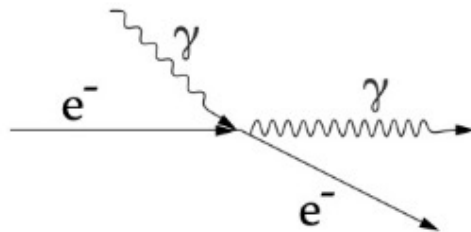
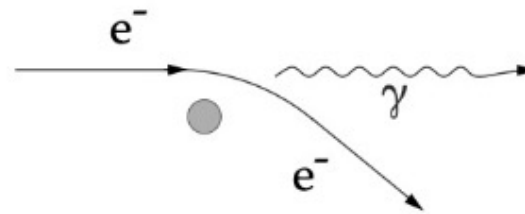
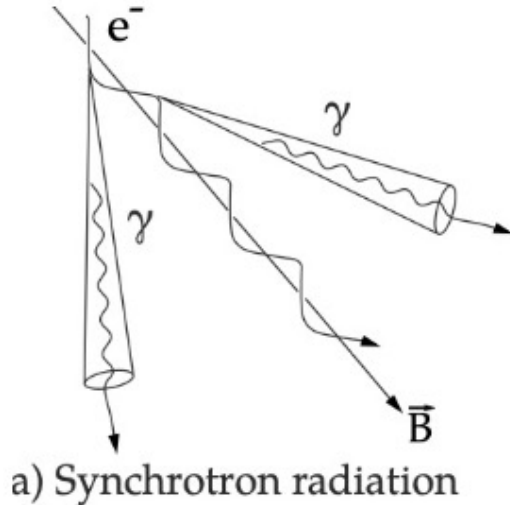


[Credit: NASA/DOE/Fermi LAT Collaboration]

- Temperatures:
Hot stars $\sim 1 \times 10^4$ K,
hottest gas 1×10^7 K
- To produce γ -rays of 1 MeV,
we need a temperature of
 2×10^9 K
- We see γ -rays throughout
the Galaxy constantly
- How are they produced?

GAMMA-RAY ASTRONOMY – ASTRONOMY OF AND WITH PARTICLES

Non-thermal processes



- Gamma rays are generated via particle interactions
- By electrons or hadrons (protons and heavier nuclei)
- Gamma rays show interaction of high energetic particles with surrounding medium

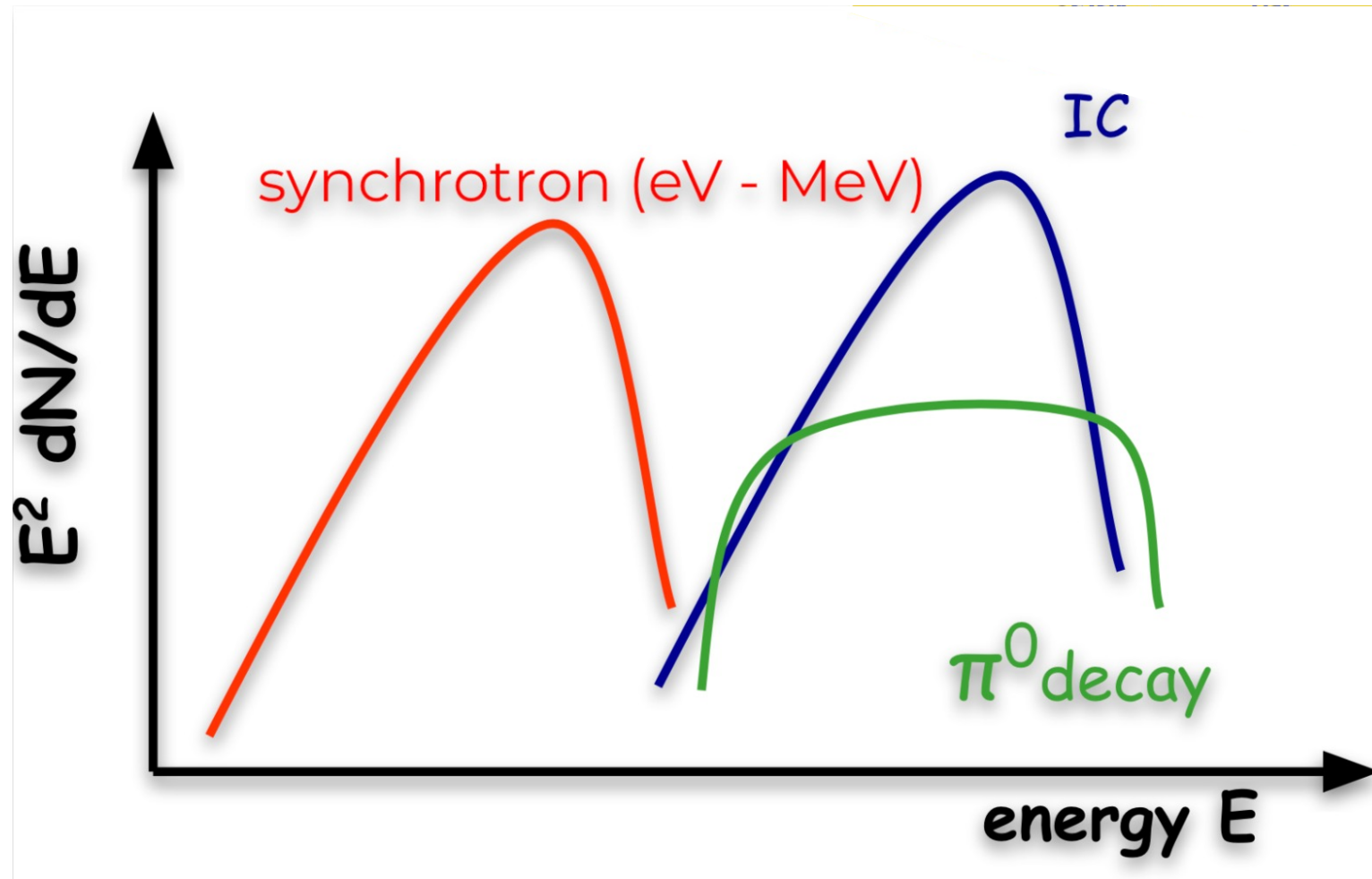
[Strzys PhD Thesis 2020
based on N. Tonello 2005]

Summer School 2026

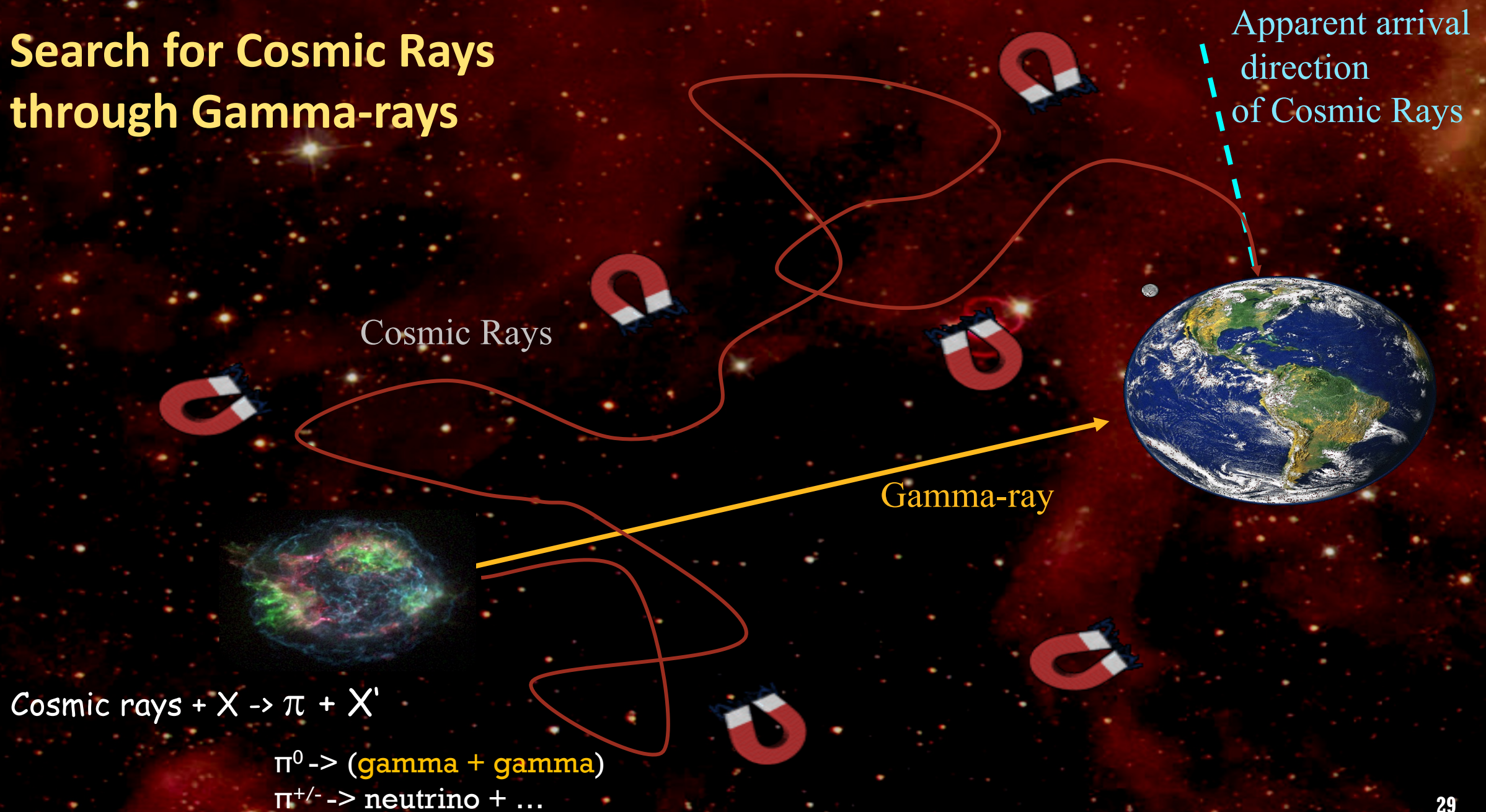
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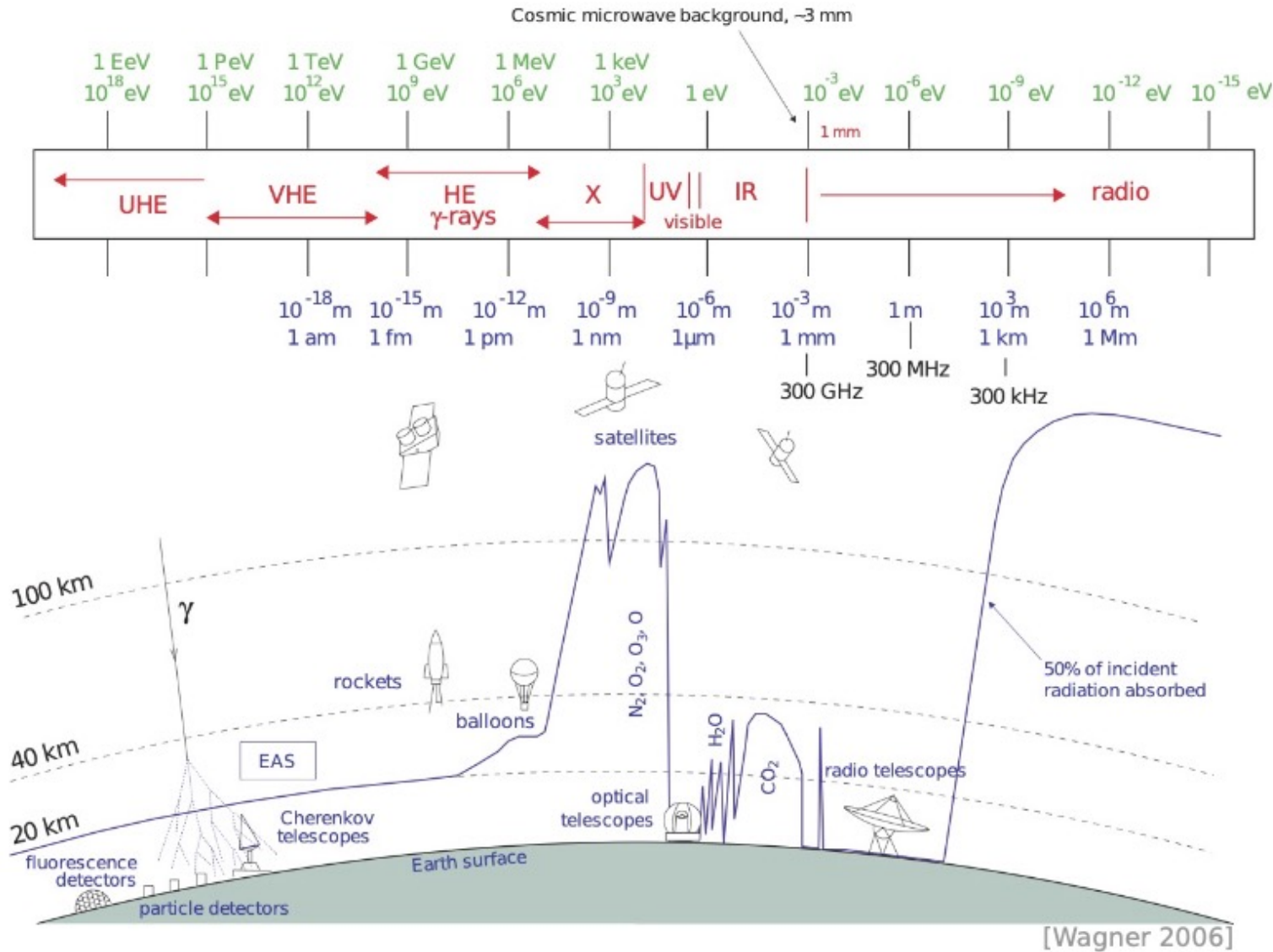
NON-THERMAL PROCESSES



Search for Cosmic Rays through Gamma-rays

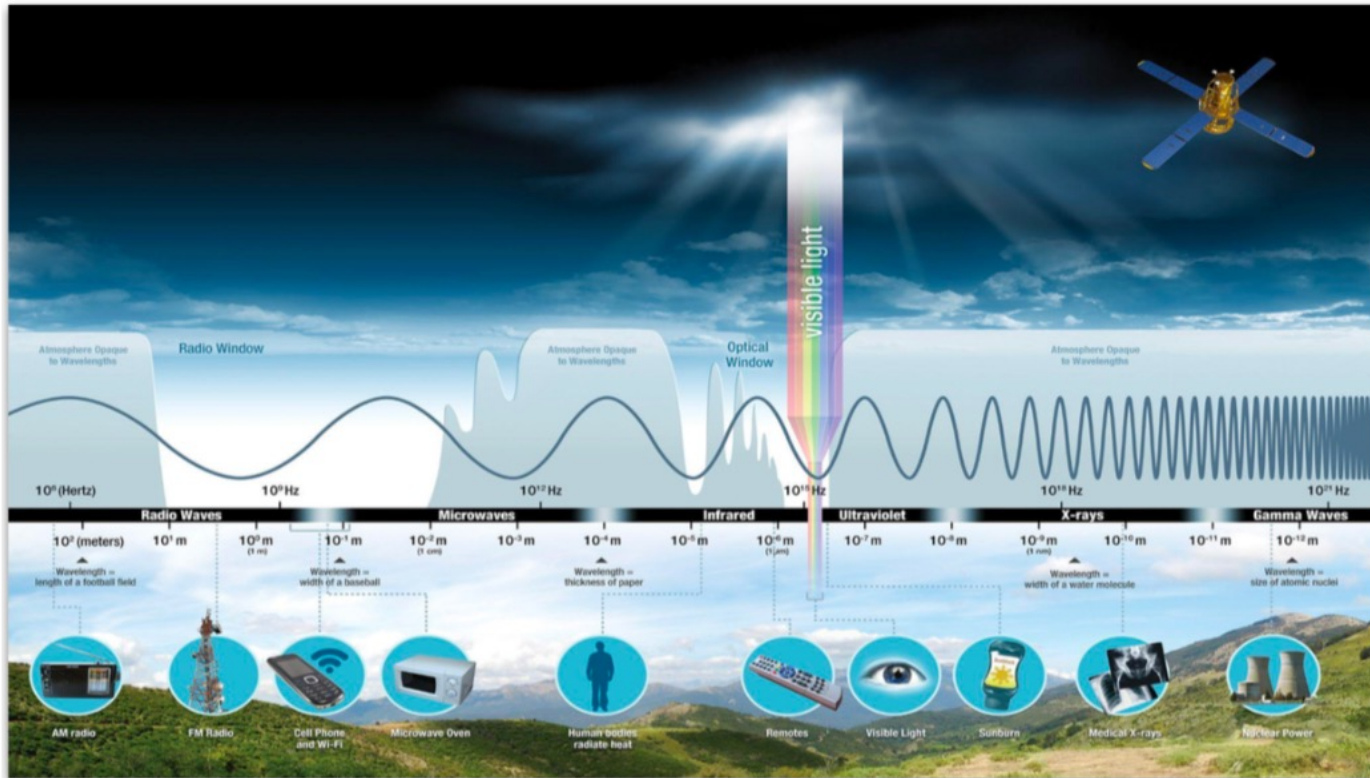


TRANSPERENCY OF THE EARTH'S ATMOSPHERE



- Atmosphere transmission heavily depends on the wavelength
- Two important observational “windows”:
optical & radio window

CLASSIFICATION & 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 $\sim 1/\text{km}^2/\text{day}$)

CLASSIFICATION & 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

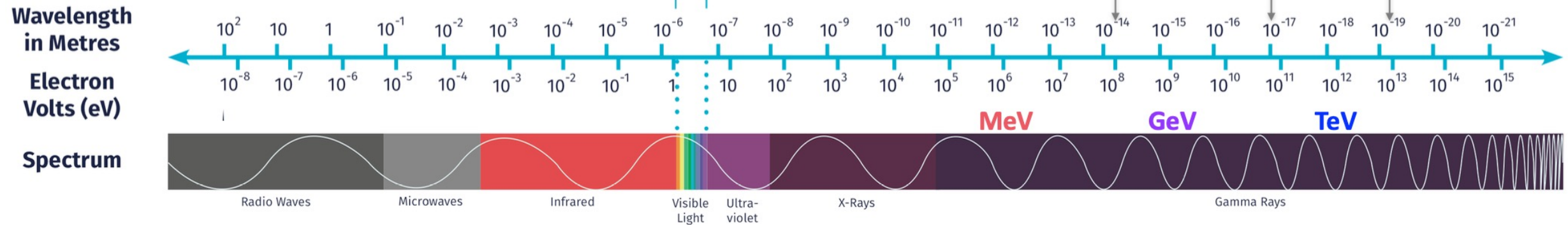
-> Particle (EAS) detectors (LHAASO, HAWC)



HE
E > 100 MeV
(Fermi-LAT)

VHE
E > 100 GeV
(IACTs)

UHE
E > 10 TeV
(Detectors)



Quantity	<i>Fermi</i>	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	$4\pi/5$	$5^\circ \times 5^\circ$	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1% Crab (1 GeV)	1% Crab (0.5 TeV)	0.5 Crab (5 TeV)



HOW TO DETECT GAMMA-RAYS SPACE BASED?

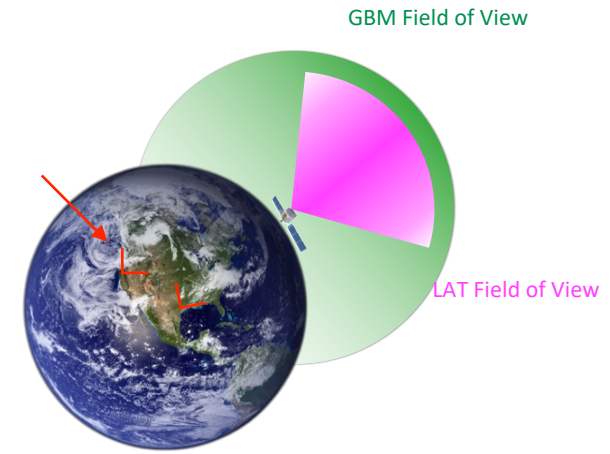
THE FERMI I

Large Area Telescope (LAT)

Large field of view

- 1/5 of the sky
- >85% of the sky in 3 hrs

Broad energy range
(20 MeV - >300 GeV)



Gamma-ray Burst Monitor (GBM)

Views entire unocculted sky

NaI: 8 keV - 1 MeV

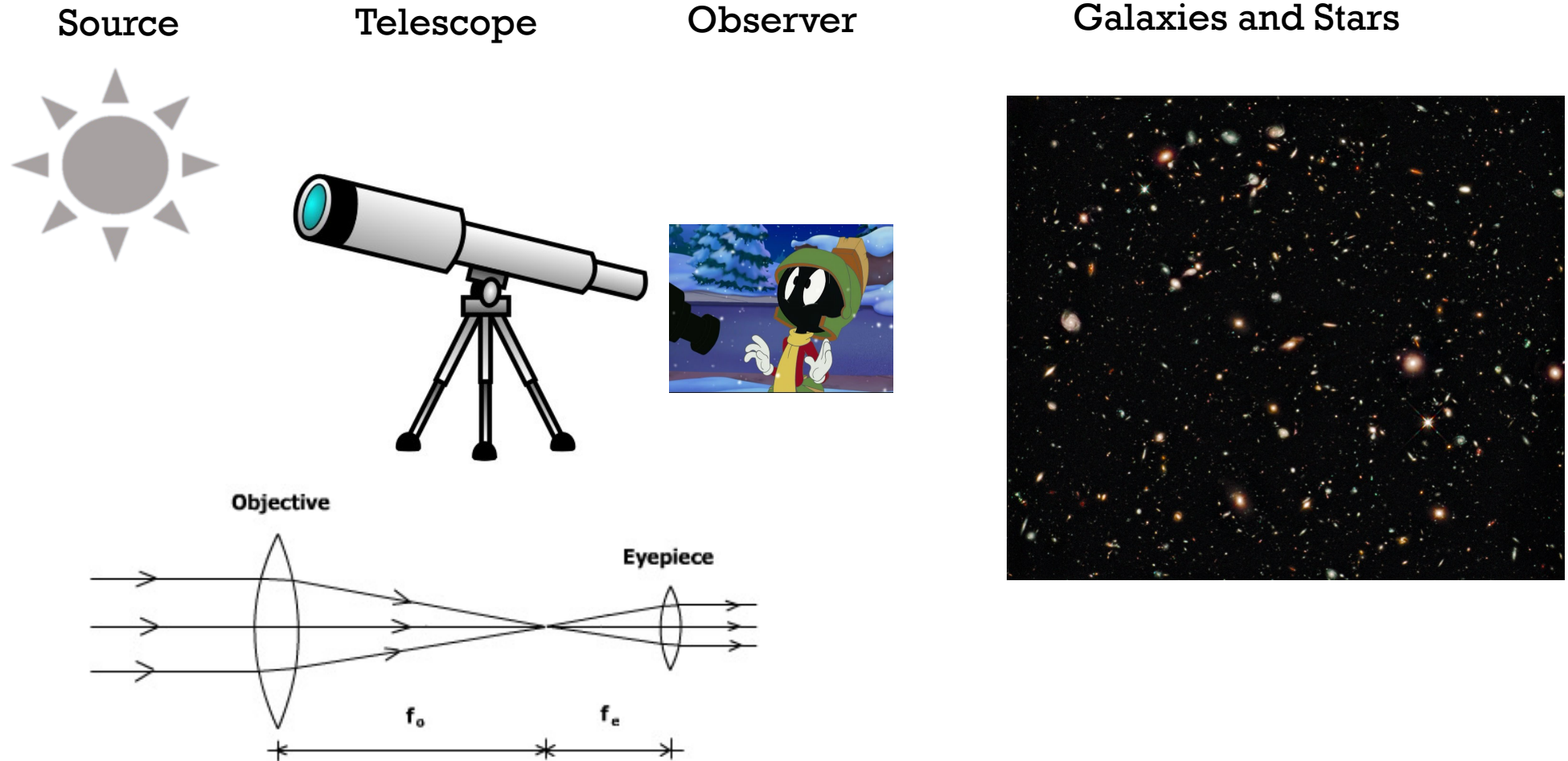
BGO: 150 keV - 30 MeV



WAIT A MINUTE...



YOU MAY THINK OF A TYPICAL TELESCOPE LIKE THIS



Collect light through reflection or refraction and record the image



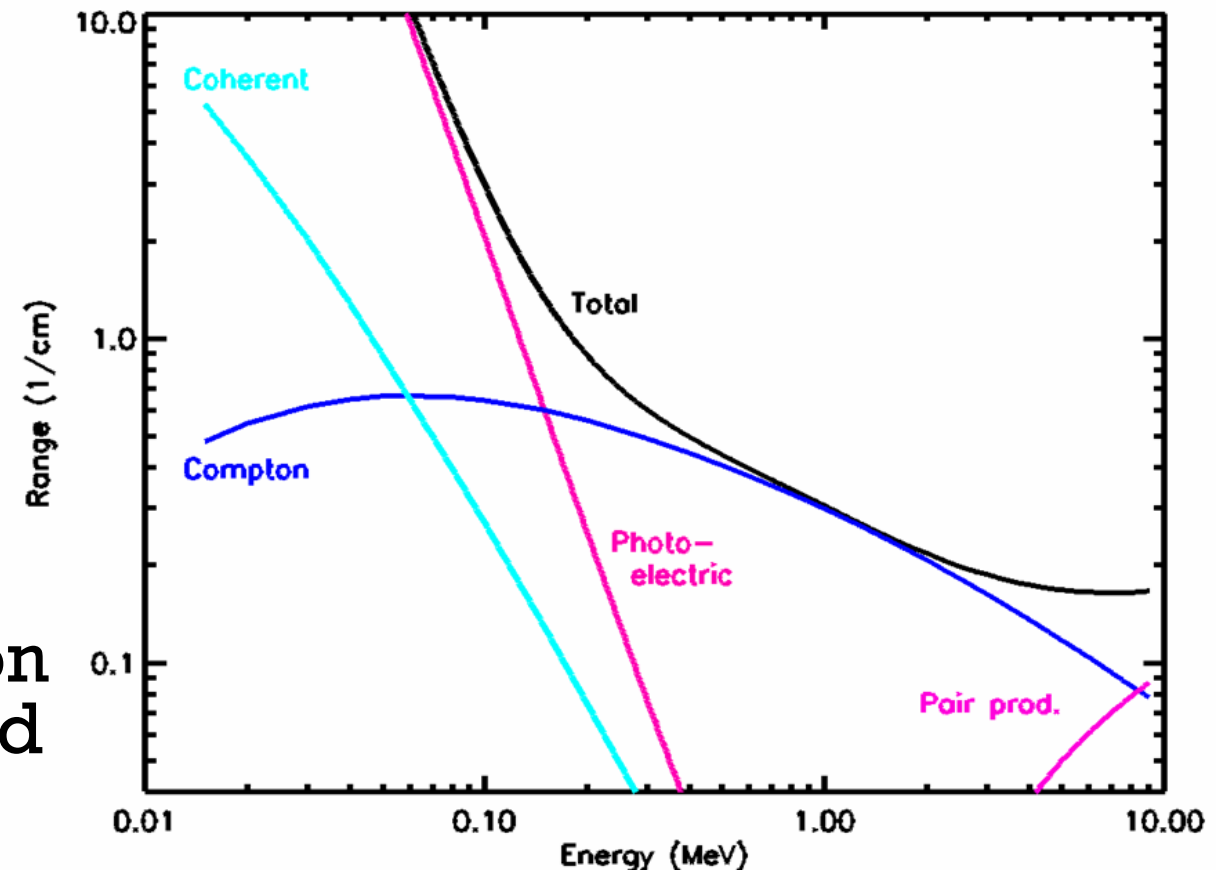
GAMMA RAYS DO NOT REFLECT OR REFRACT EASILY

Difficult to focus onto a camera or even detect. Blame physics!

Gamma rays are scattered and absorbed in matter

- Coherent Scattering (electron remains bound to atom)
- Photoelectric Effect
- Compton Scattering
- Electron (e^-) positron (e^+) Pair Production
- Details depend on composition and density of the material and photon energy

Gamma-ray attenuation in Germanium



Credit: Richard Kroeger



GAMMA-RAY TELESCOPES ARE MORE LIKE THIS

Source

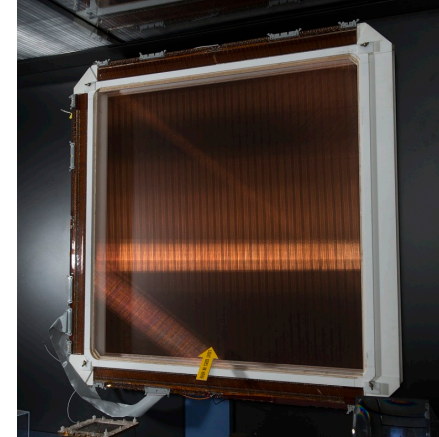


Matter

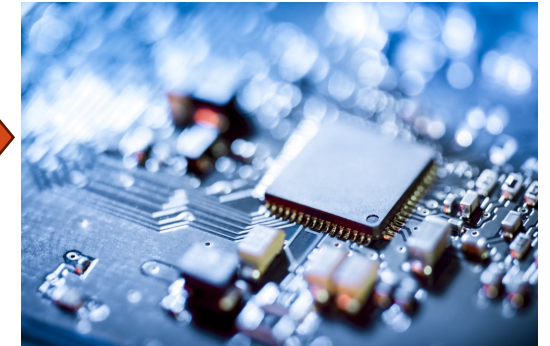
Radiation

Electron
Electron + Positron
Photons

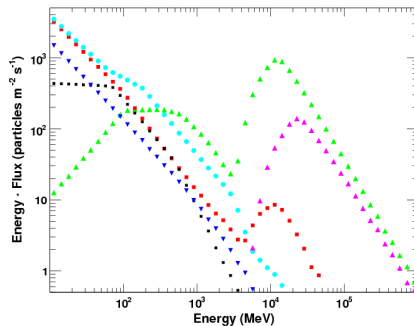
Sensors/Electronics



Computers



Instrument
simulations,
background models



More computers

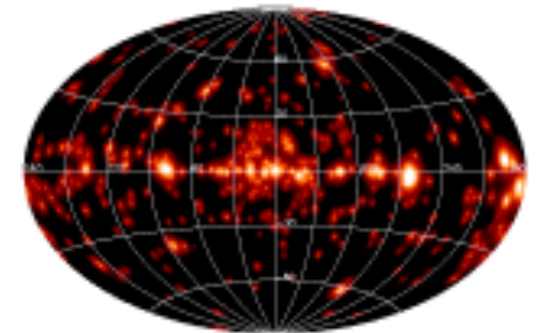


Black Holes, compact objects
Observer effects of stellar explosions...

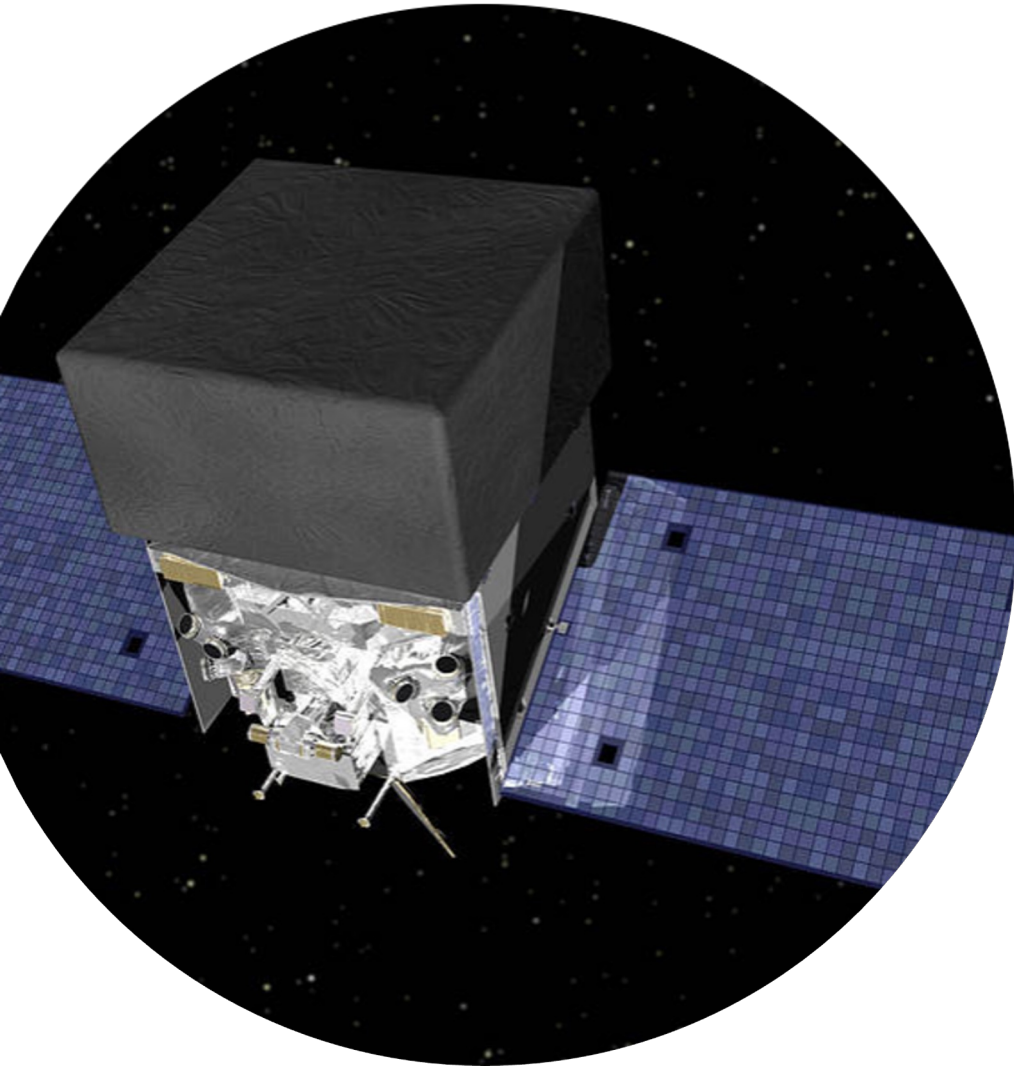
Observer



Collecting light through creative
absorption



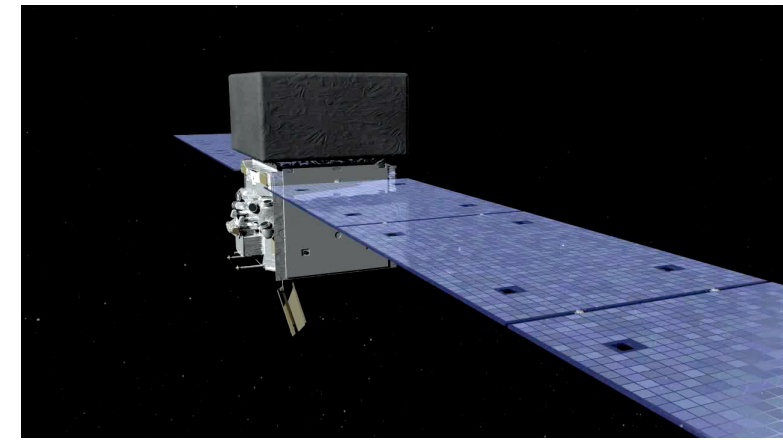
OBSERVATORY STATUS



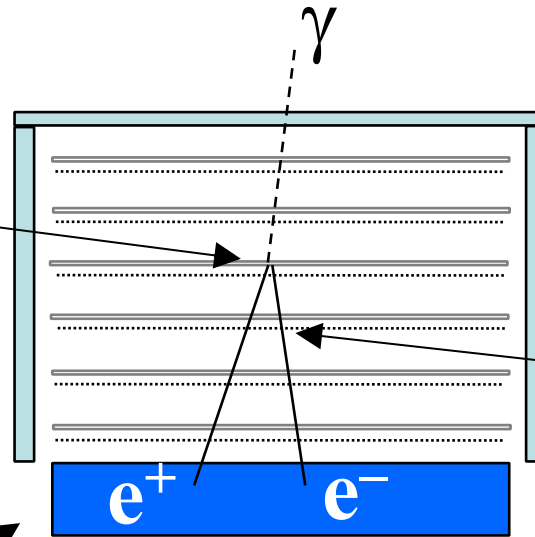
- *Fermi* continues to operate extremely smoothly and to perform at full capability
- On orbit for 17 years
- No consumables
- No degradation of science performance
- Improved due to software (LAT Pass 8) and configuration changes (GBM Continuous Time-Tagged Event data)



LAT is a Pair Conversion Telescope



Gamma ray **converts** to an $e^+ e^-$ pair in a high density foil layer.

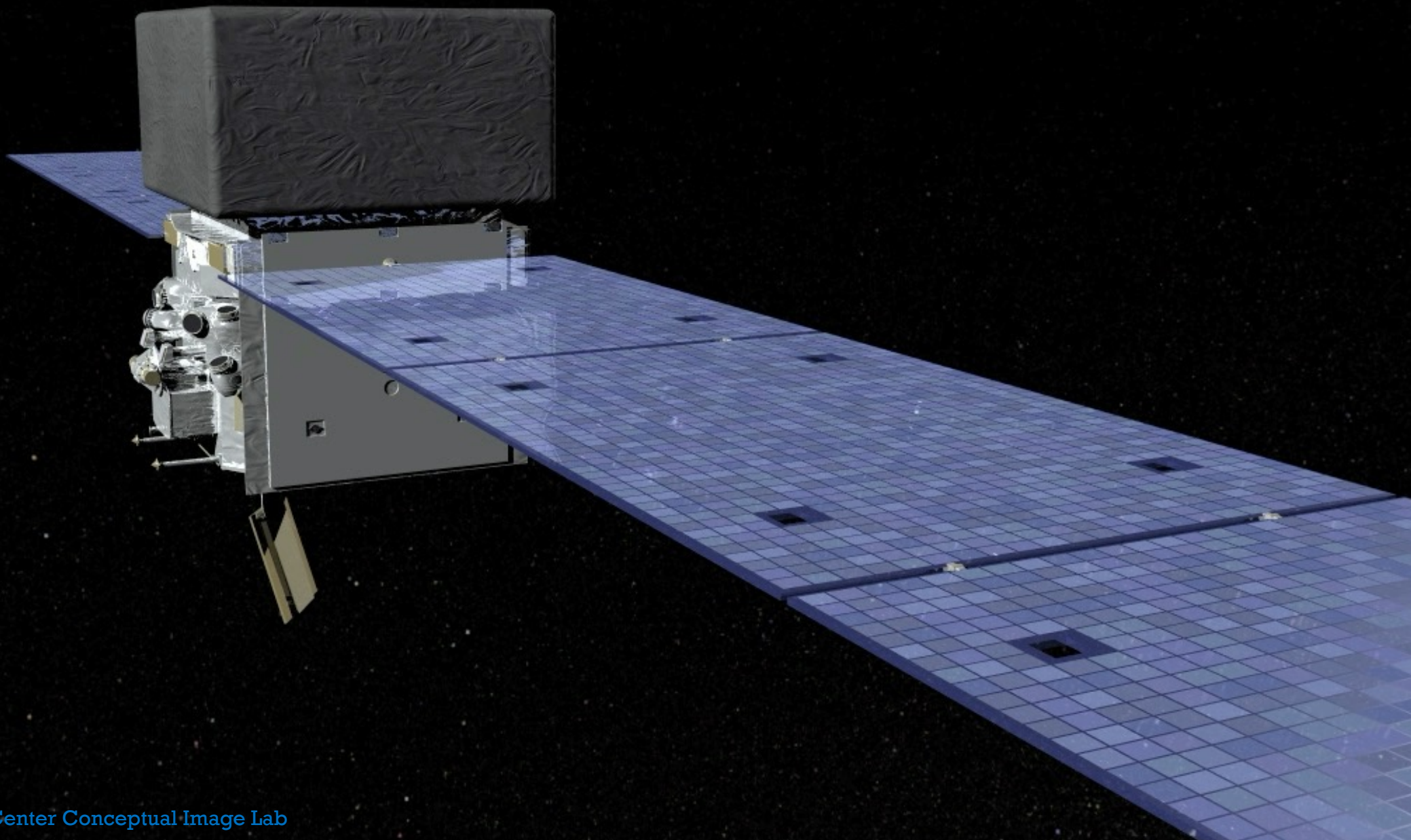


An **anti-coincidence detector** identifies and rejects incoming charged particles.

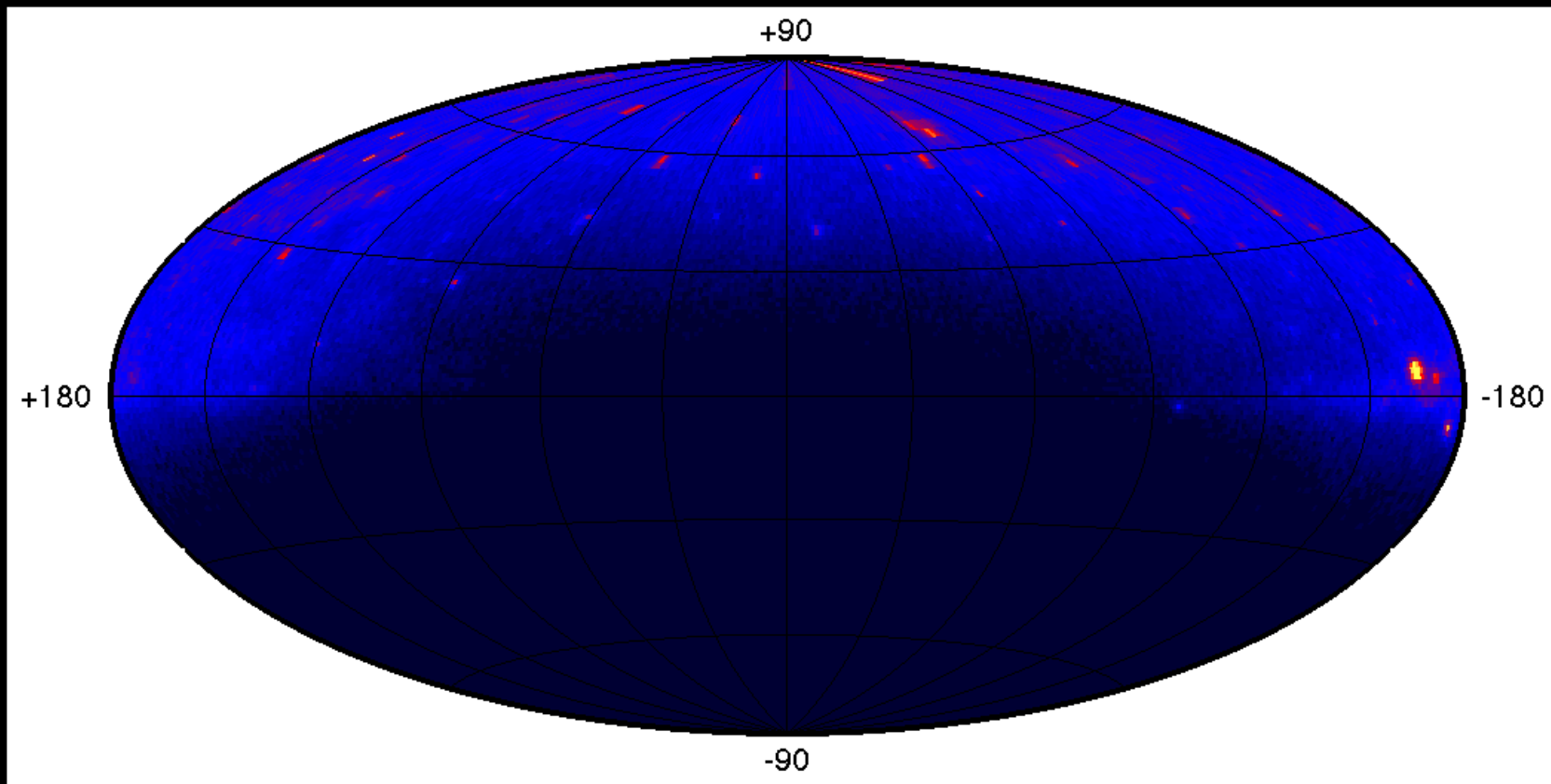
The **tracks** of charged particles in the instrument are recorded by sensors.

The photon energy is determined from measured energy deposited in the **calorimeter**.

The tracks are used to determine the direction of the gamma-ray source.



LAT SKY COVERAGE



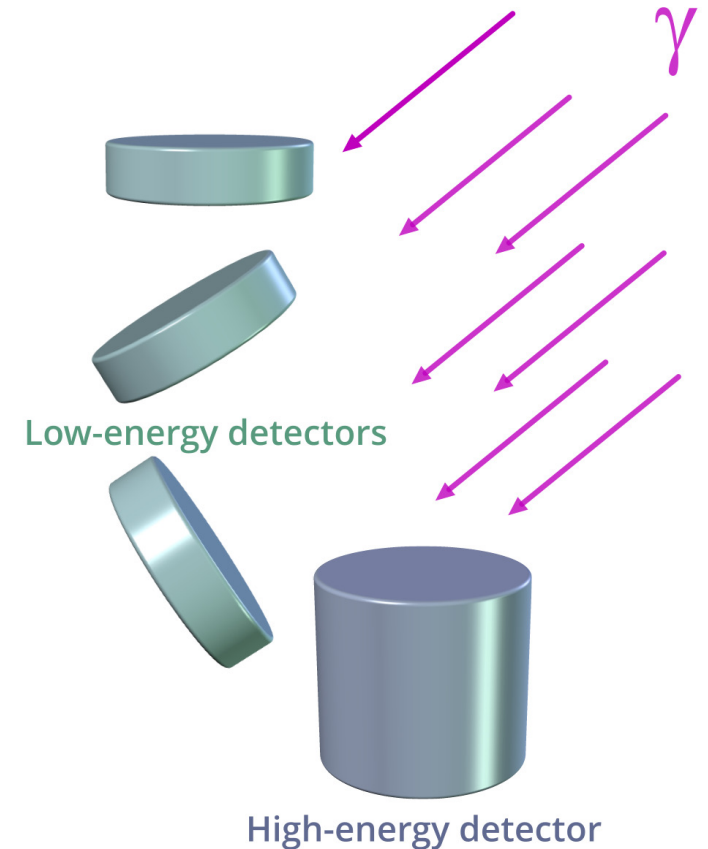
GAMMA-RAY BURST MONITOR DETECTORS



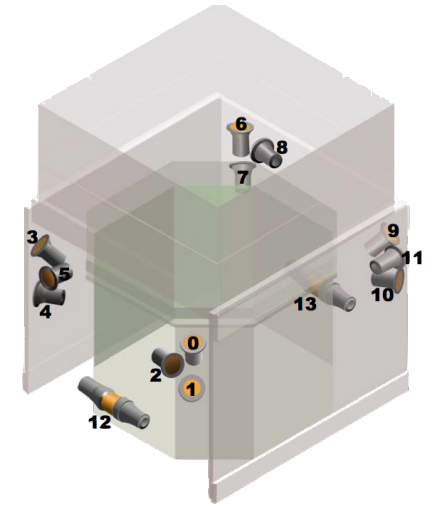
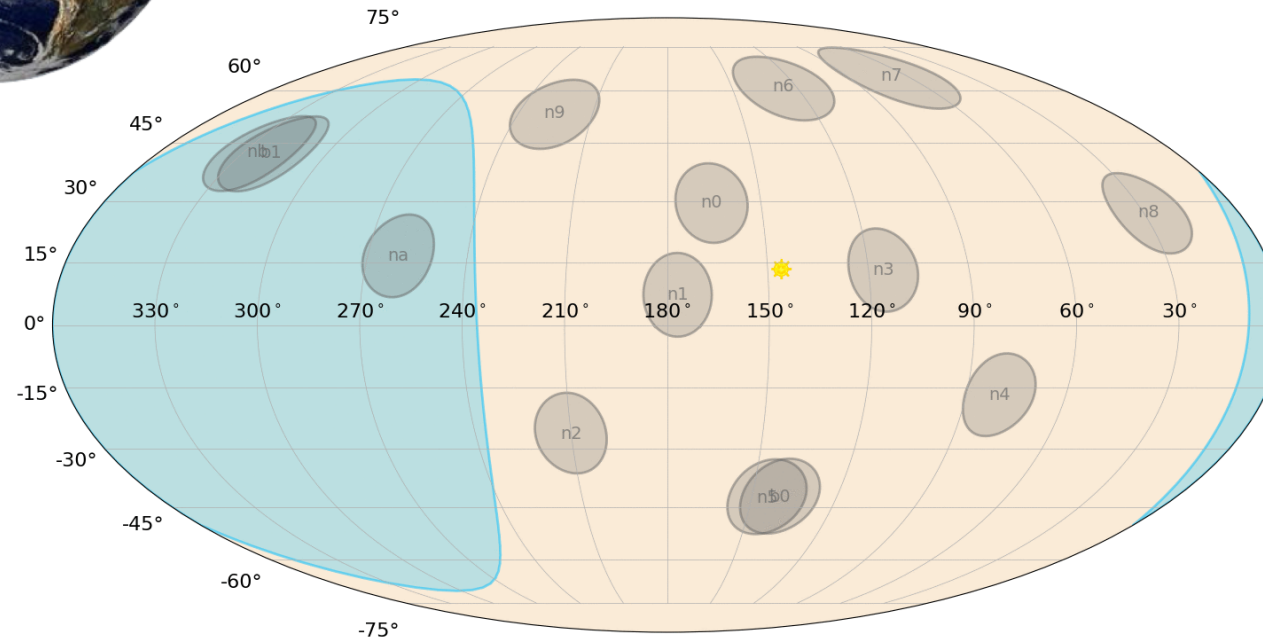
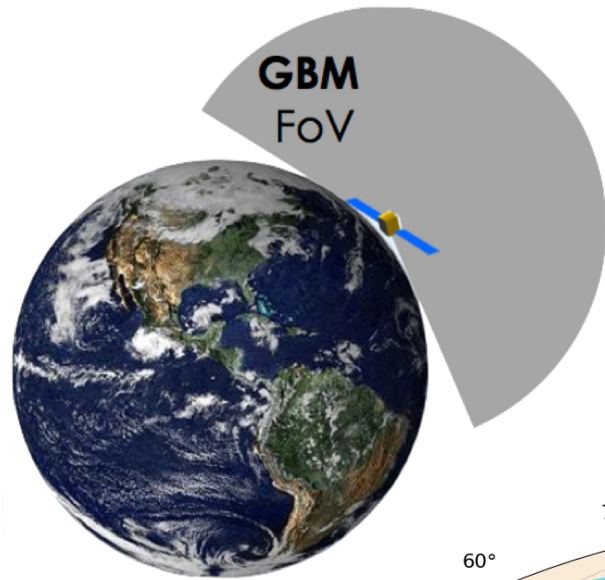
The GBM detectors are made of scintillator material, sodium iodide (NaI) or bismuth germanate (BGO), that produce light when gamma rays strike them.

The low-energy detectors (NaI) are placed in different positions and directions. Transients are located using the difference in gamma-ray rates.

The high-energy detectors (BGO) provide sensitive spectral information that overlaps with the NaI detectors and extends measurements to higher energy.



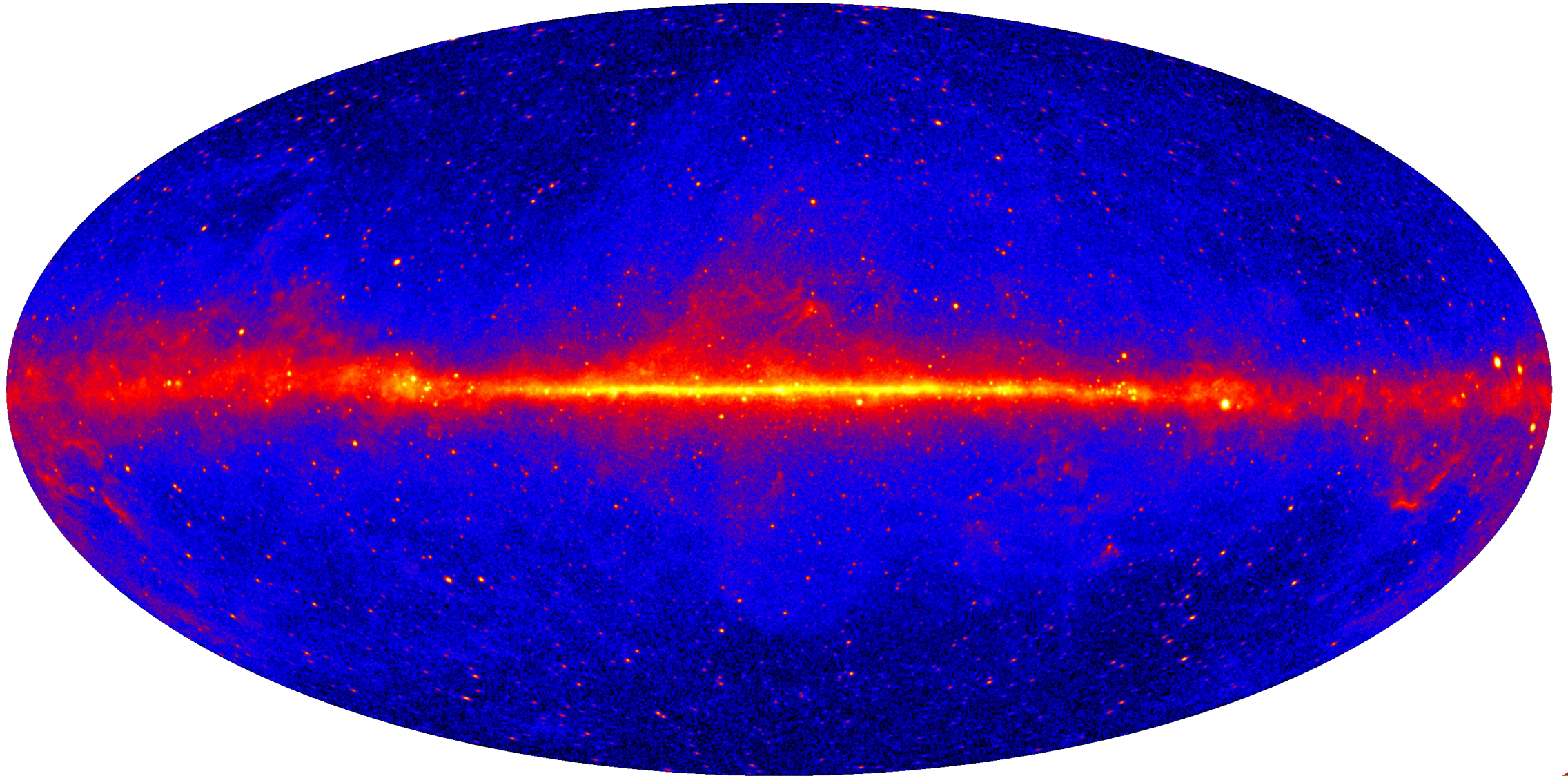
GBM SKY COVERAGE



GBM instantaneous field of view: ~70% of the sky
~87% uptime (off during South Atlantic Anomaly)

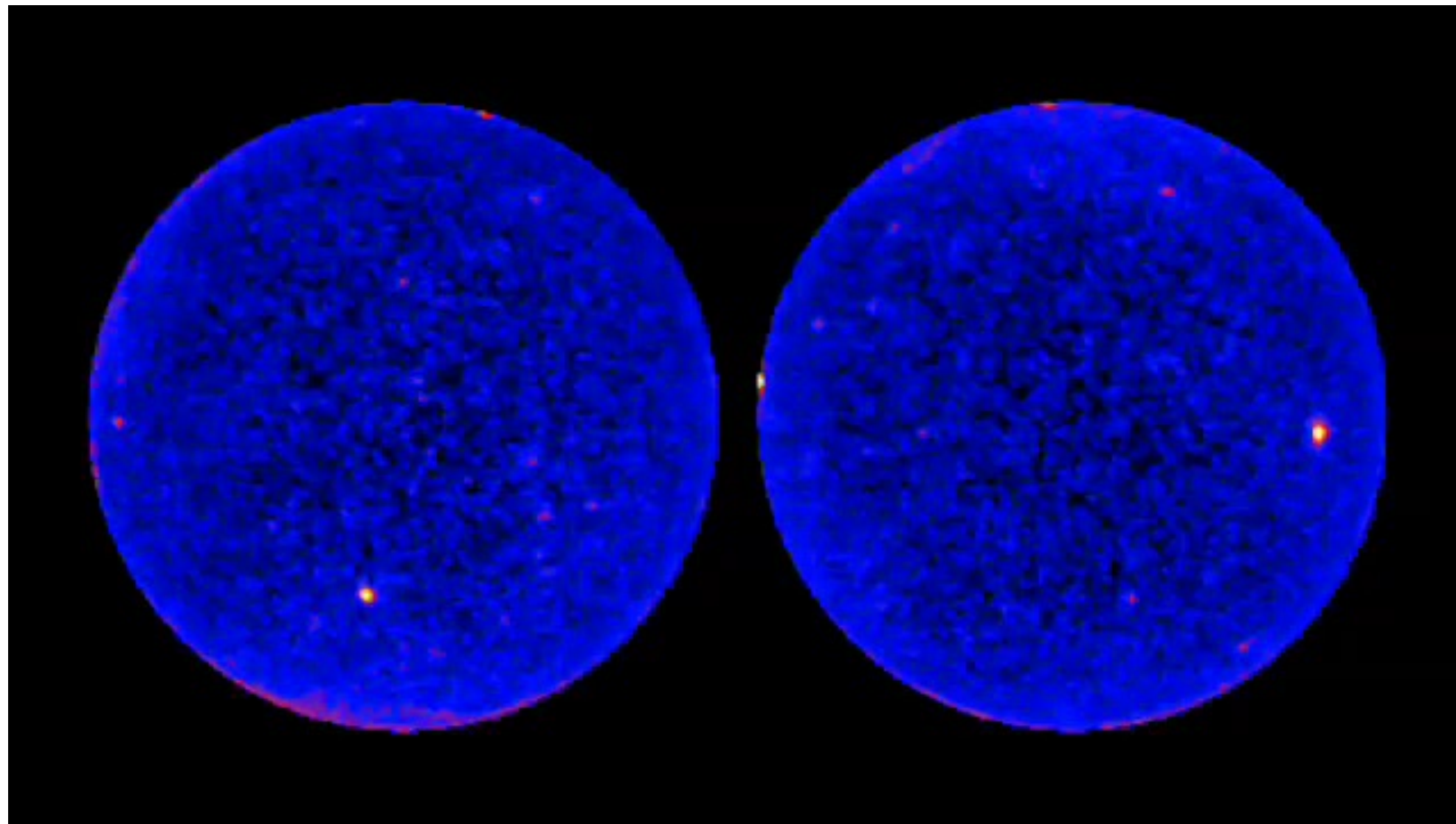


THE FERMI SKY



Fermi LAT, Energy > 1 GeV, 12 years of data (7,464,664 photons)

THE DYNAMIC GAMMA-RAY SKY



This movie
shows 1 day
frames of
LAT data
over 1 year

Northern Hemisphere

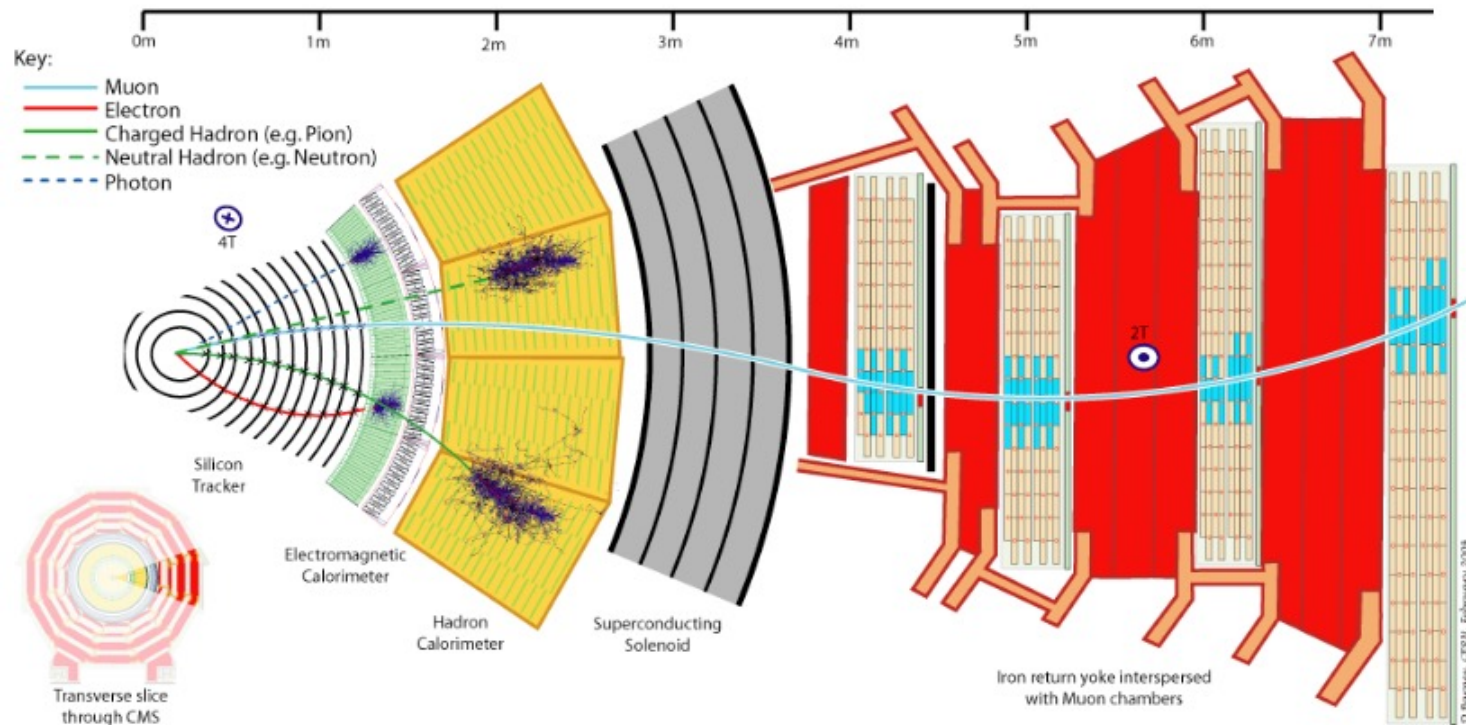
Southern Hemisphere



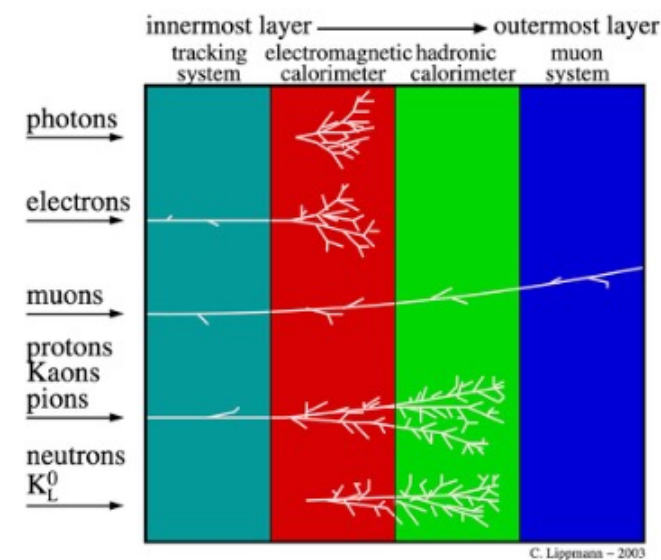
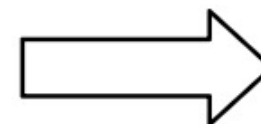


HOW TO DETECT GAMMA-RAYS GROUND BASED?

PARTICLE DETECTORS - SCHEMATIC

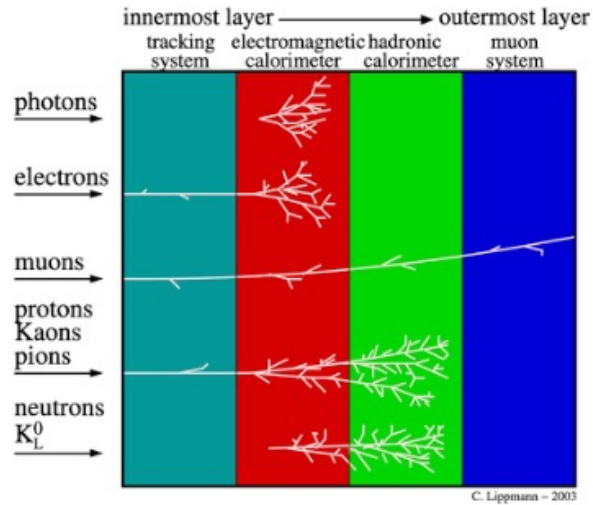


Simplify



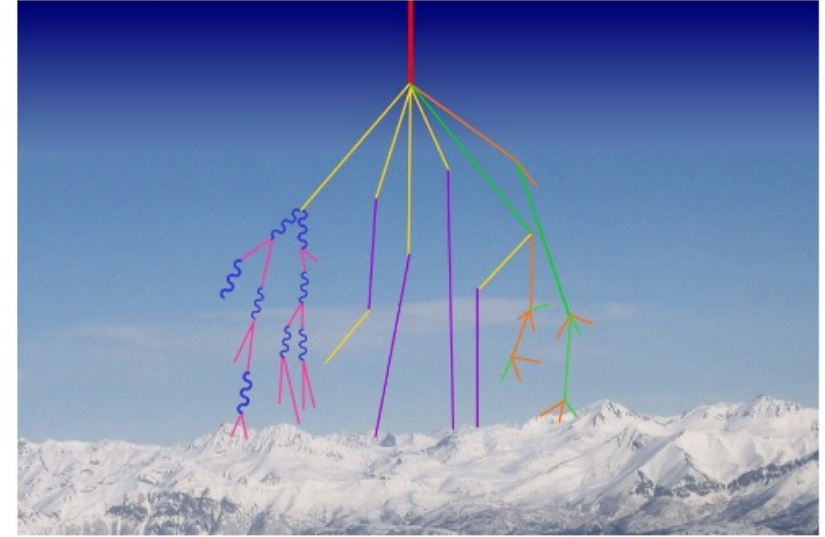
Different particles interact with matter differently, and particle detectors are built in layers to exploit those differences.

ATMOSPHERIC AIR SHOWERS



→
All in one

[<https://scied.ucar.edu/image/cosmic-ray-air-shower>]



- Particles interact with molecules in the atmosphere and generate particles, which in turn again can generate particles
- Particle cascade develops
- Atmosphere works as a combined calorimeter systems
- Discovered in 1912 by V. Hess

The Nobel Prize in Physics 1936

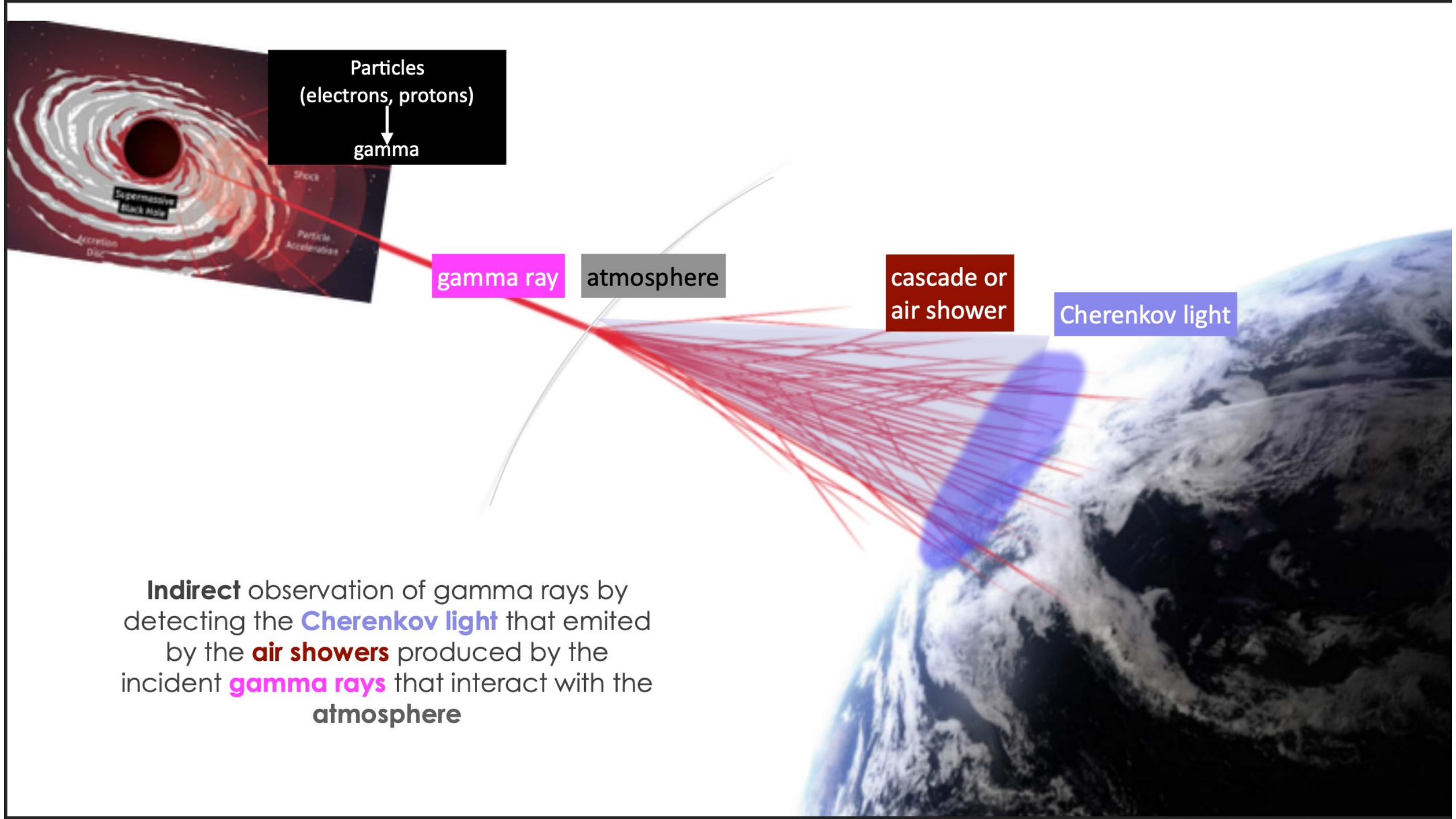


Photo from the Nobel Foundation archive.
Victor Franz Hess
Prize share: 1/2



Photo from the Nobel Foundation archive.
Carl David Anderson
Prize share: 1/2

[nobelprize.org]



Particles
(electrons, protons)
↓
gamma

gamma ray

atmosphere

cascade or
air shower

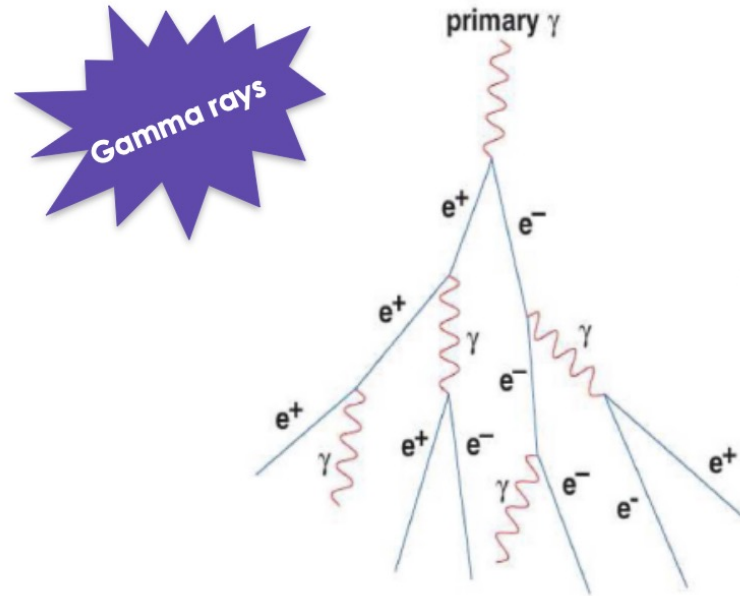
Cherenkov light

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

PARTICLE CASCADES IN THE ATMOSPHERE – AIR SHOWER

Primary γ -ray

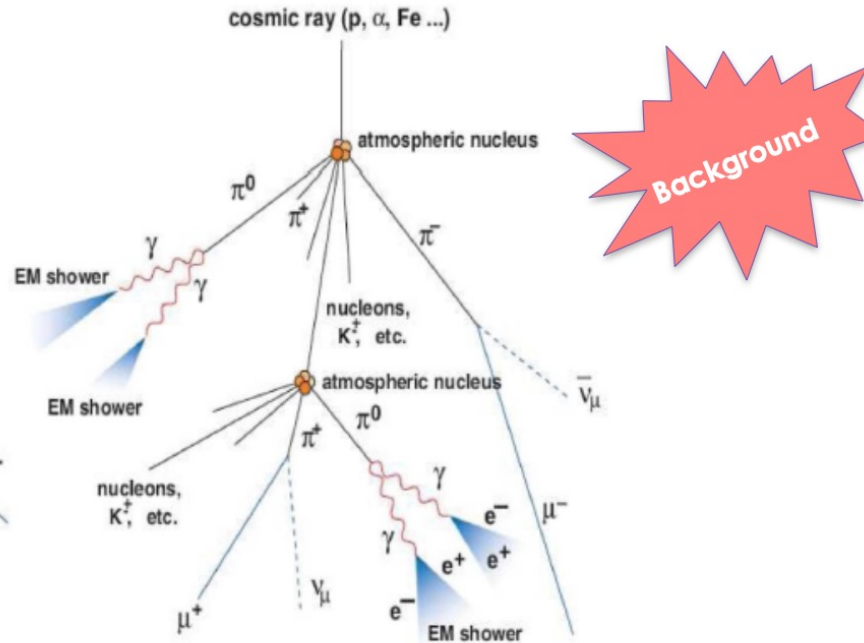
GAMMA RAYS Electromagnetic Shower



Pair production + bremsstrahlung

1 gamma - 1000 cosmits

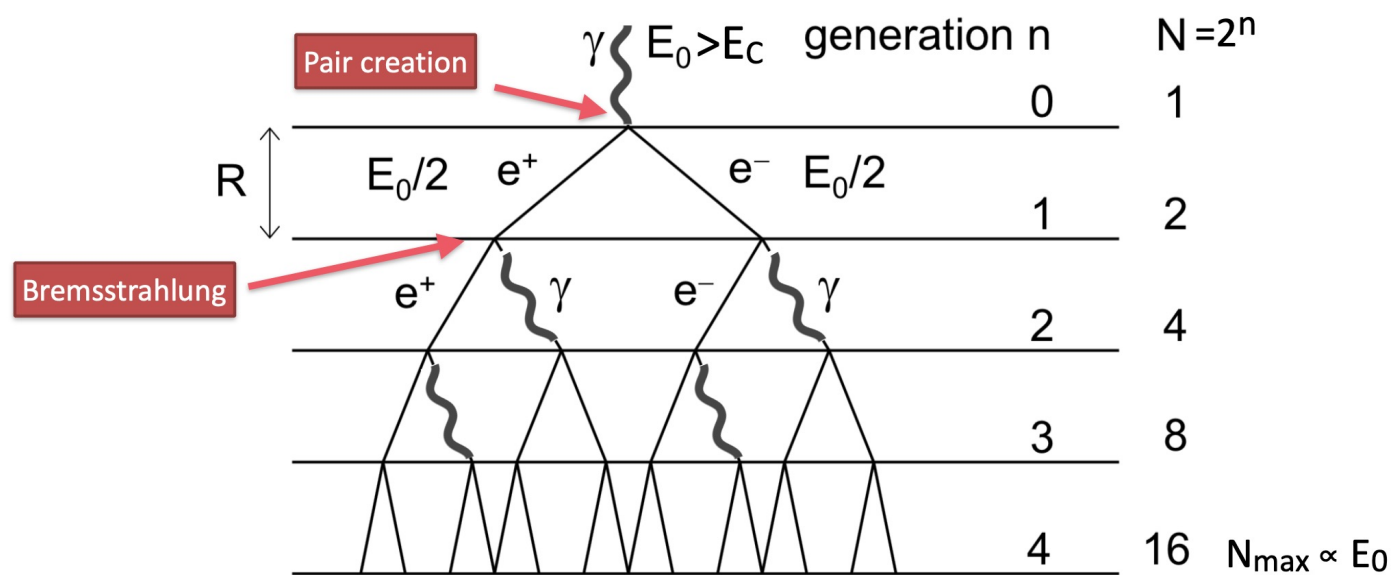
Cosmic rays Hadronic Shower



Hadronic interaction + sub-showers
from π^0 decay

- Gamma rays create pure electromagnetic cascades via pair production and bremsstrahlung
- Hadronic particles (protons & heavier nuclei) initiate cascades with additional hadronic & muon components
- Gamma-ray like hadronic cascades form huge background for ground-based gamma-ray detectors

HEITLER MODEL



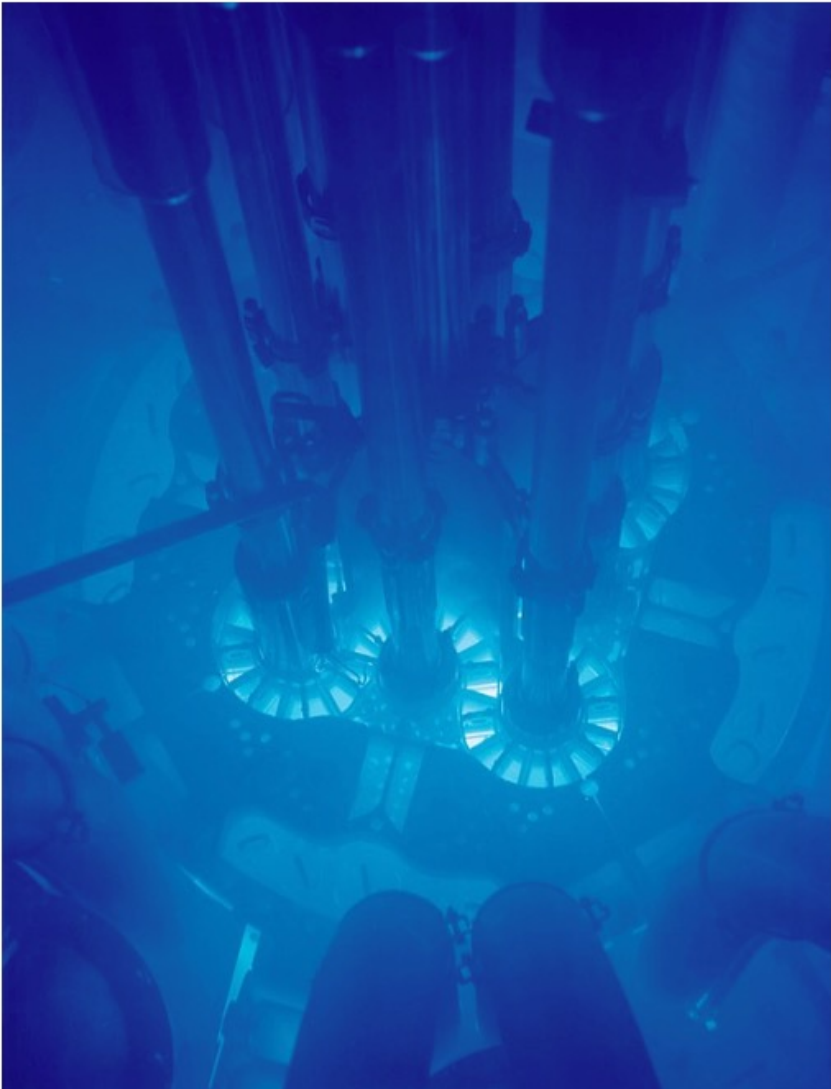
$E_c(\text{air}) \approx 85 \text{ MeV} \rightarrow$ shower stops at $E < E_c$ (ionization loss > bremsstrahlung)

- Simple model of cascade named after W. Heitler from 1938
- Assume:
 - Mean free path pair production = radiation length electrons (distance over which electron lose 50% energy)
 - Energy is split 50:50
 - Cascade stops when energy of each particle drops below critical energy (air $\sim 85 \text{ MeV}$; below ionization dominates over bremsstrahlung)
- Shower size proportional to primary energy

$$E_0 = \xi_c^e N_{\max}$$
- Depth of shower in atmosphere increase logarithmically with primary energy

$$X_{\max} = \lambda_r \ln(E_0 / \xi_c^e)$$
- Number of electrons wrong by $\sim 10x$
- Nowadays we use event simulations

CHERENKOV LIGHT – CAN SOMETHING BE FASTER THAN LIGHT?



The Nobel Prize in Physics 1958



Photo from the Nobel
Foundation archive.

Pavel Alekseyevich
Cherenkov

Prize share: 1/3



Photo from the Nobel
Foundation archive.

Il'ja Mikhailovich
Frank

Prize share: 1/3



Photo from the Nobel
Foundation archive.

Igor Yevgenyevich
Tamm

Prize share: 1/3

[nobelprize.org]

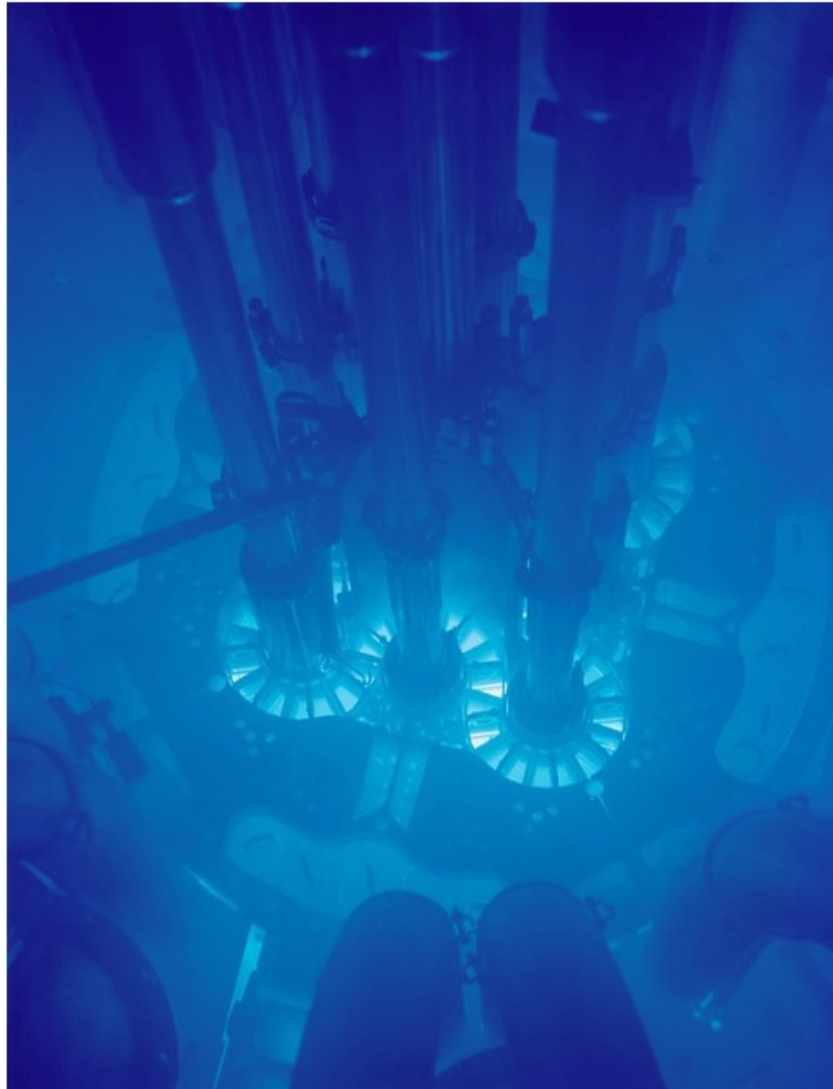
- Particles faster than phase velocity of light in medium emit light:

$$v = c / n \Rightarrow v = 0.75 \cdot c \text{ (water)}$$

n = refractive index

- Discovered 1938

CHERENKOV LIGHT – CAN SOMETHING BE FASTER THAN LIGHT?



The Nobel Prize in Physics 1958



Photo from the Nobel
Foundation archive.
Pavel Alekseyevich
Cherenkov

Prize share: 1/3



Photo from the Nobel
Foundation archive.
Il'ja Mikhailovich
Frank

Prize share: 1/3



Photo from the Nobel
Foundation archive.
Igor Yevgenyevich
Tamm

Prize share: 1/3

[nobelprize.org]

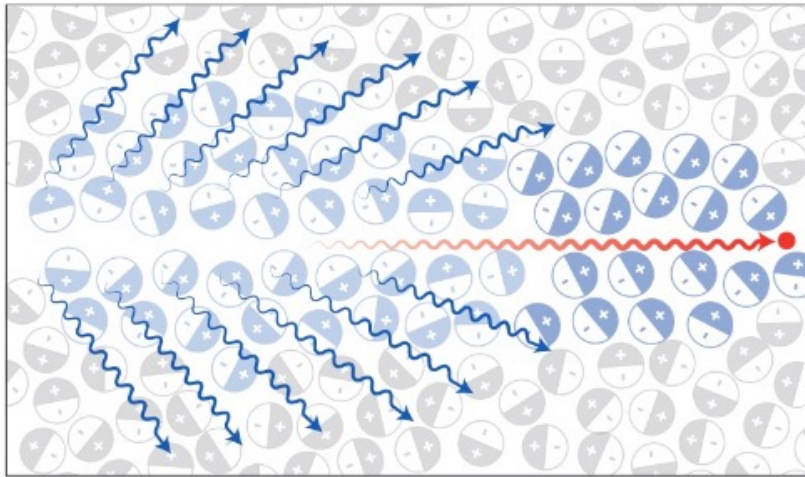
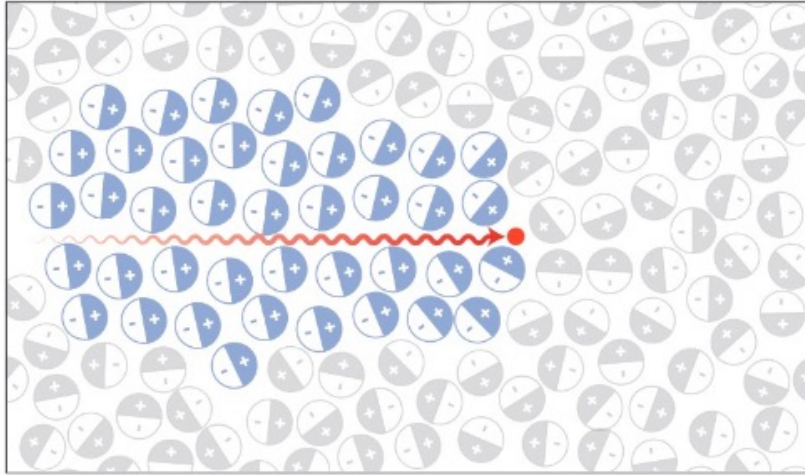
Charged particles moving faster than light
propagates in a medium emit Cherenkov radiation

$$v_{\text{particle}} > \frac{c}{n}$$

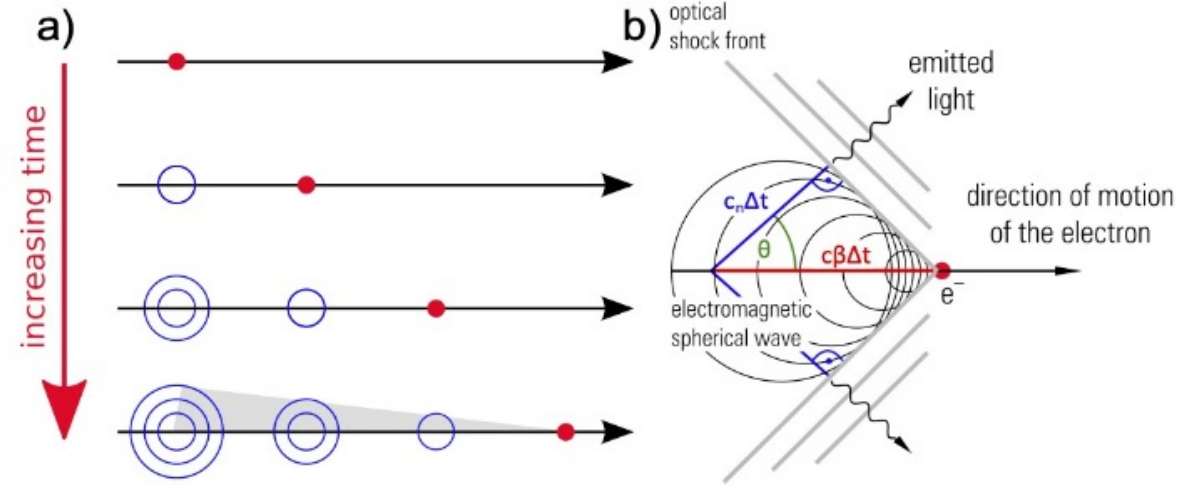
For water, $n \approx 1.33$, so the threshold is $v > 0.75c$.

Discovered 1938

THE CHERENKOV EFFECT



[<https://doi.org/10.1038/nnano.2016.301>]



- Energy of the particles must be larger than:

$$\beta \cdot c \geq \frac{c}{n} \Rightarrow E_{th} = m_0 \frac{c^2}{(1 - n^{-2})}$$

- Waves interfere constructively at an angle of

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

$$\beta = v/c$$

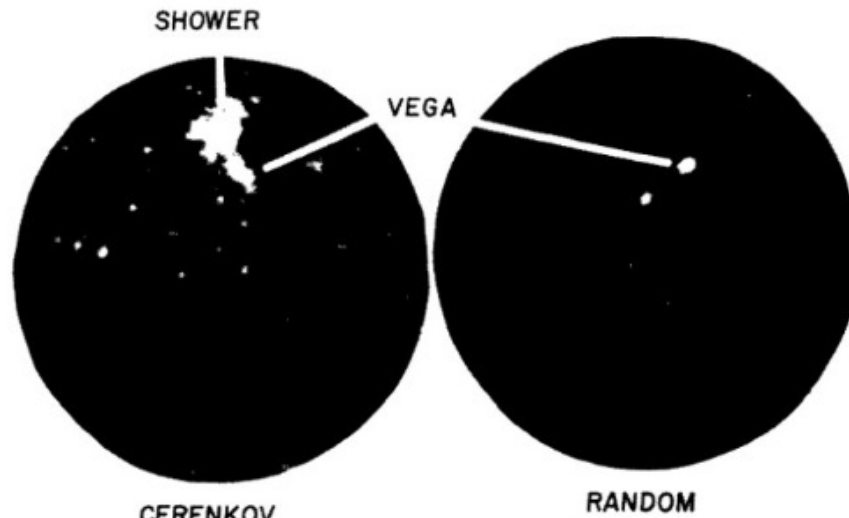
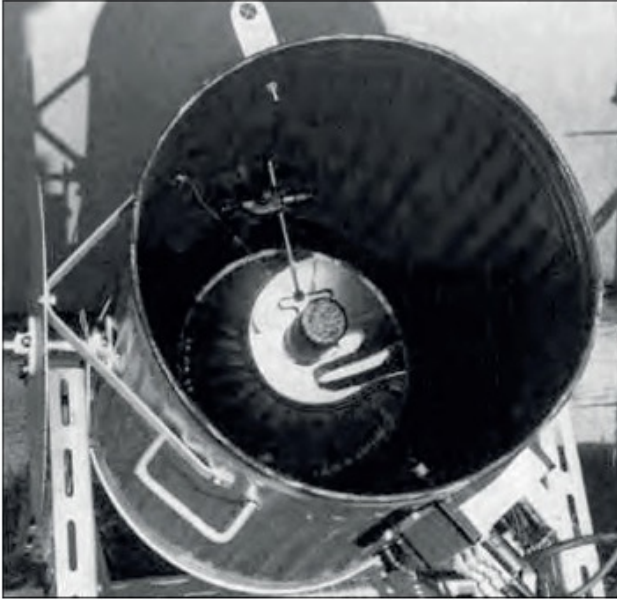
The background of the slide is a dark, starry night sky. A prominent, ethereal blue glow, resembling an aurora or a large-scale atmospheric phenomenon, stretches across the middle of the frame. In the foreground, the silhouettes of numerous radio telescope dishes are visible, arranged in a field on a dark, hilly landscape. The text is overlaid on the upper portion of the image.

How do we detect them?

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

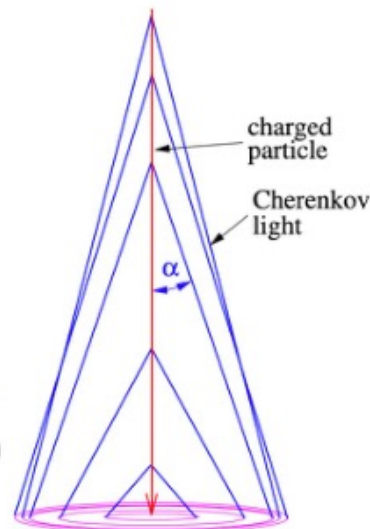
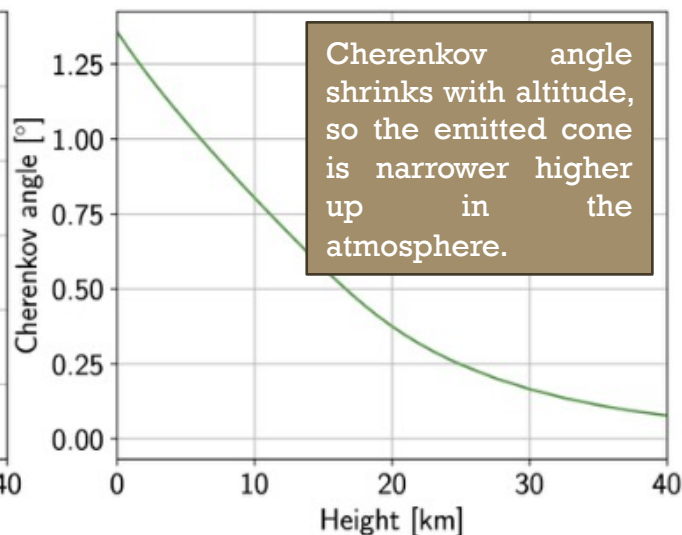
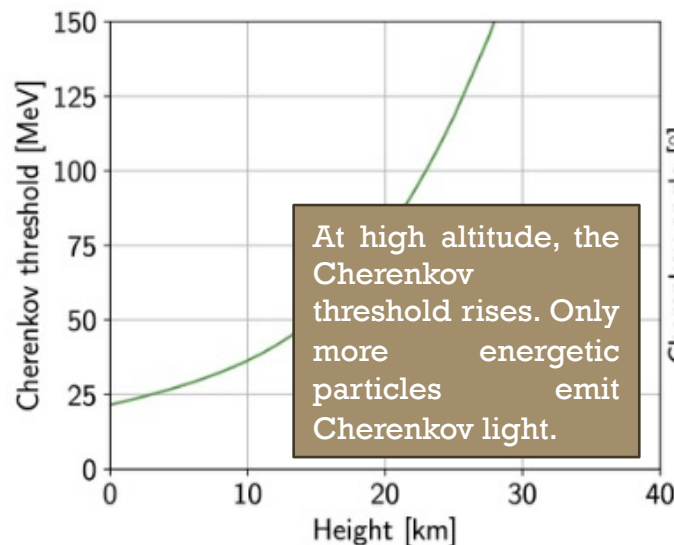
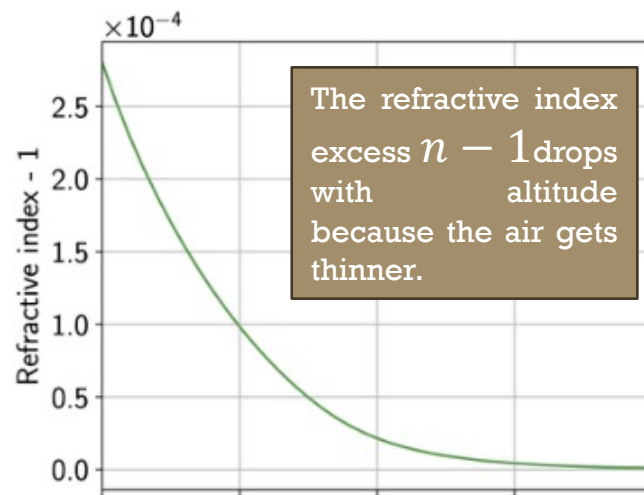
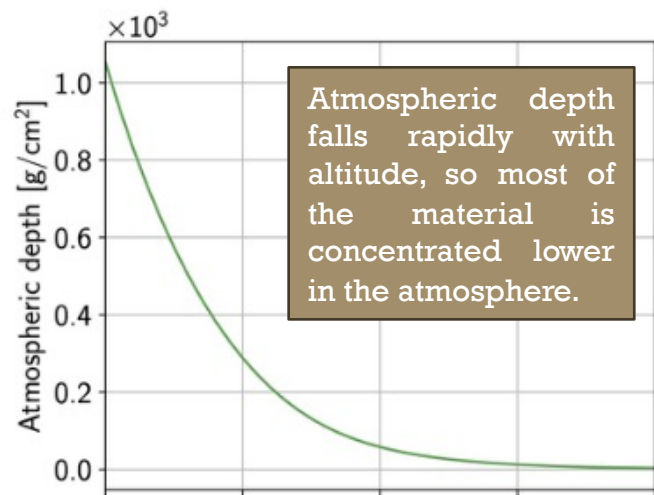
FIRST ATMOSPHERIC CHERENKOV TELESCOPE

[<https://doi.org/10.3390/universe8040219>]

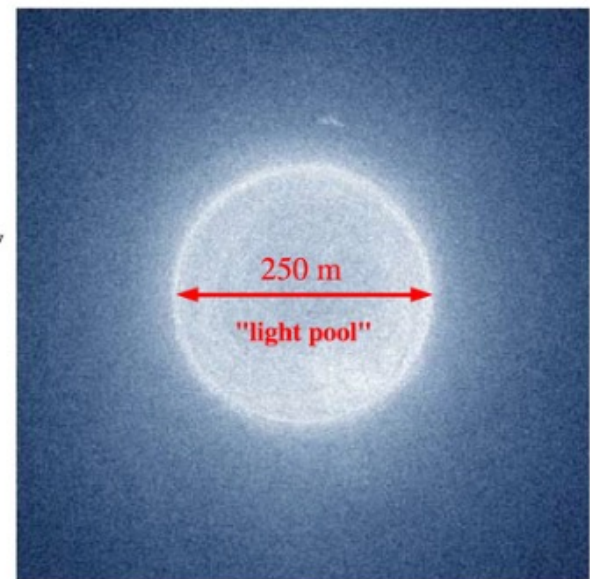


- Atmosphere filled with Cherenkov light predicted by Patrick Blackett (NP 1948)
- William Galbraith and John Jelley detected it in 1953
- 25 cm mirror, PMT, dustbin in combination with Geiger-Müller counter array
- First image from 1961 pointing to the Crab Nebula; J. Jelly & N. A. Porter

THE ATMOSPHERE AS A TOOL



- Refractive index of the air changes with height
- Change of Cherenkov angle
- Can use to map the shower



[<https://doi.org/10.1007/s10686-009-9151-z>]

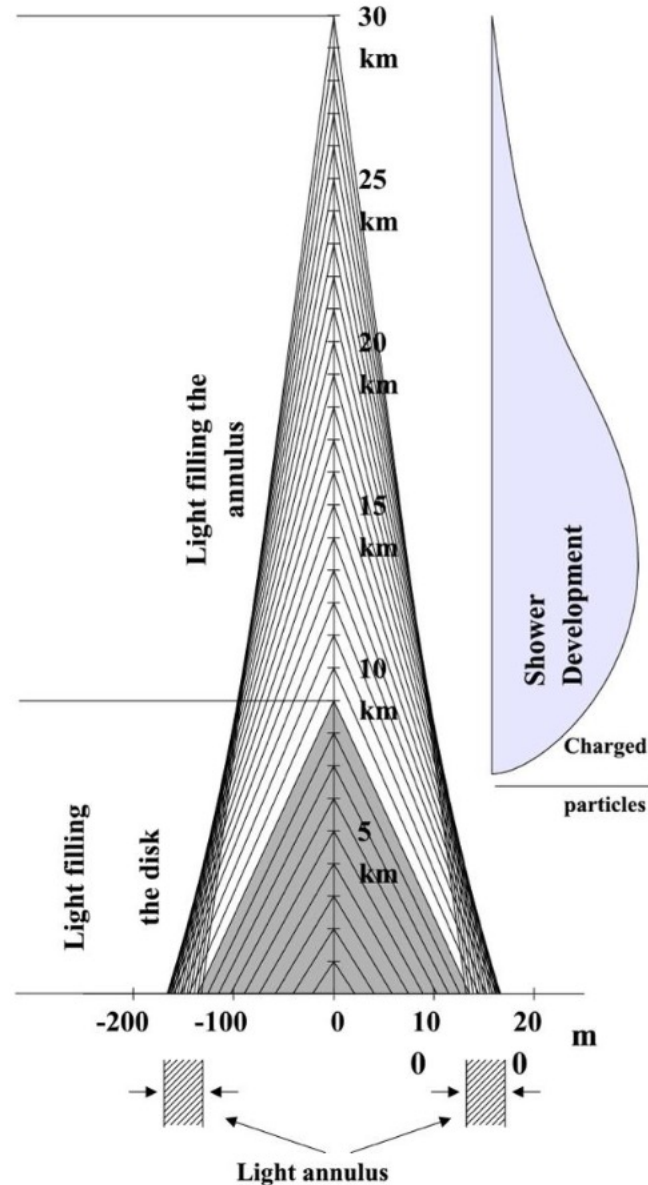
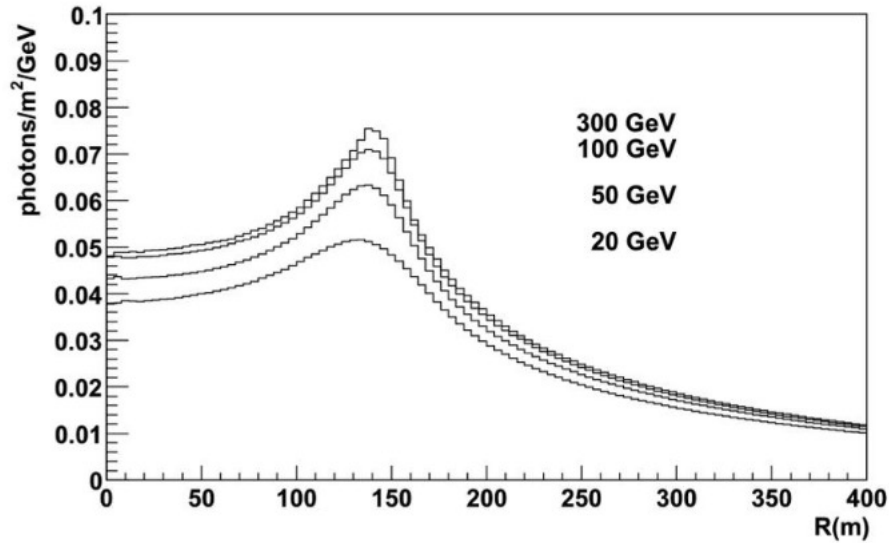
[Strzys PhD Thesis 2020]

Summer School 2026

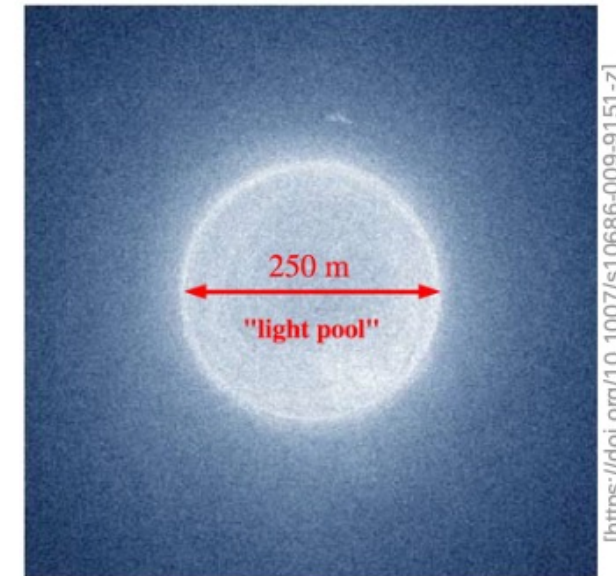
7/8/26

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THE ATMOSPHERE AS A TOOL

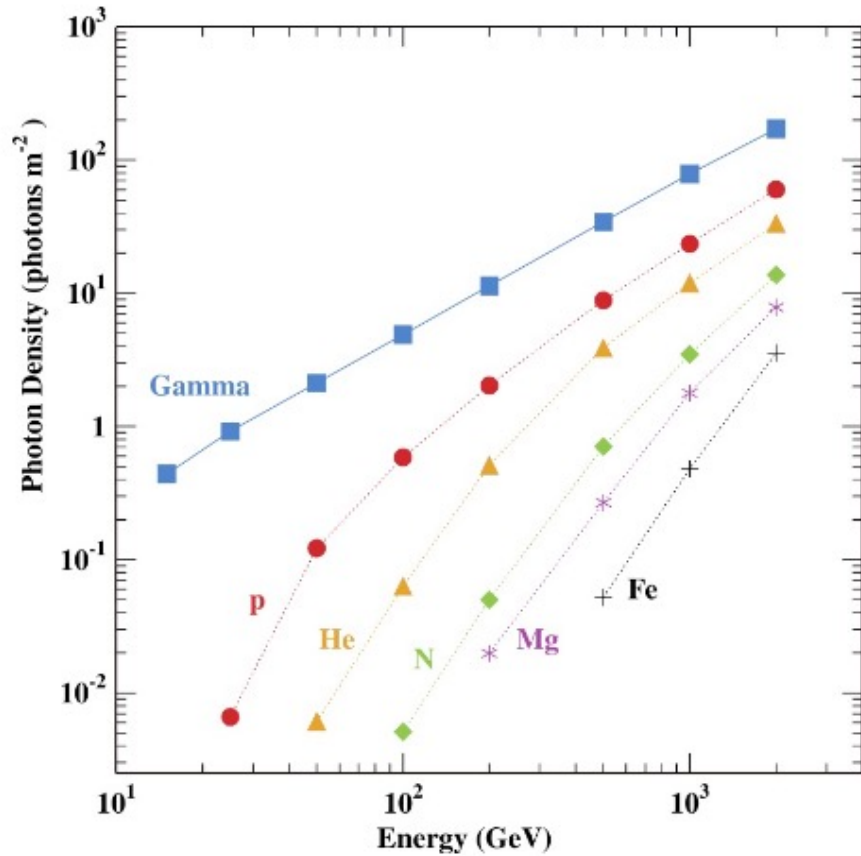


- Refractive index of the air changes with height
- Change of Cherenkov angle
- Can use to map the shower



[<https://doi.org/10.1007/s10686-009-9151-z>]

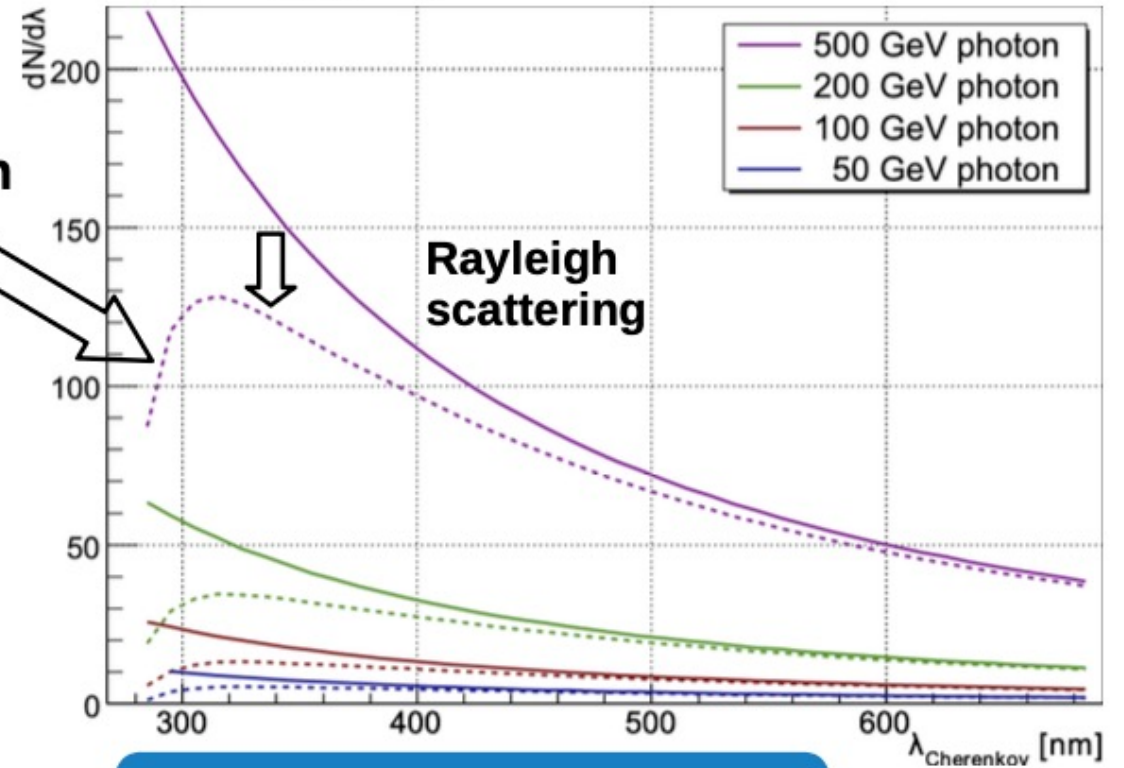
SPECTRUM OF THE CHERENKOV LIGHT



Emission spectrum

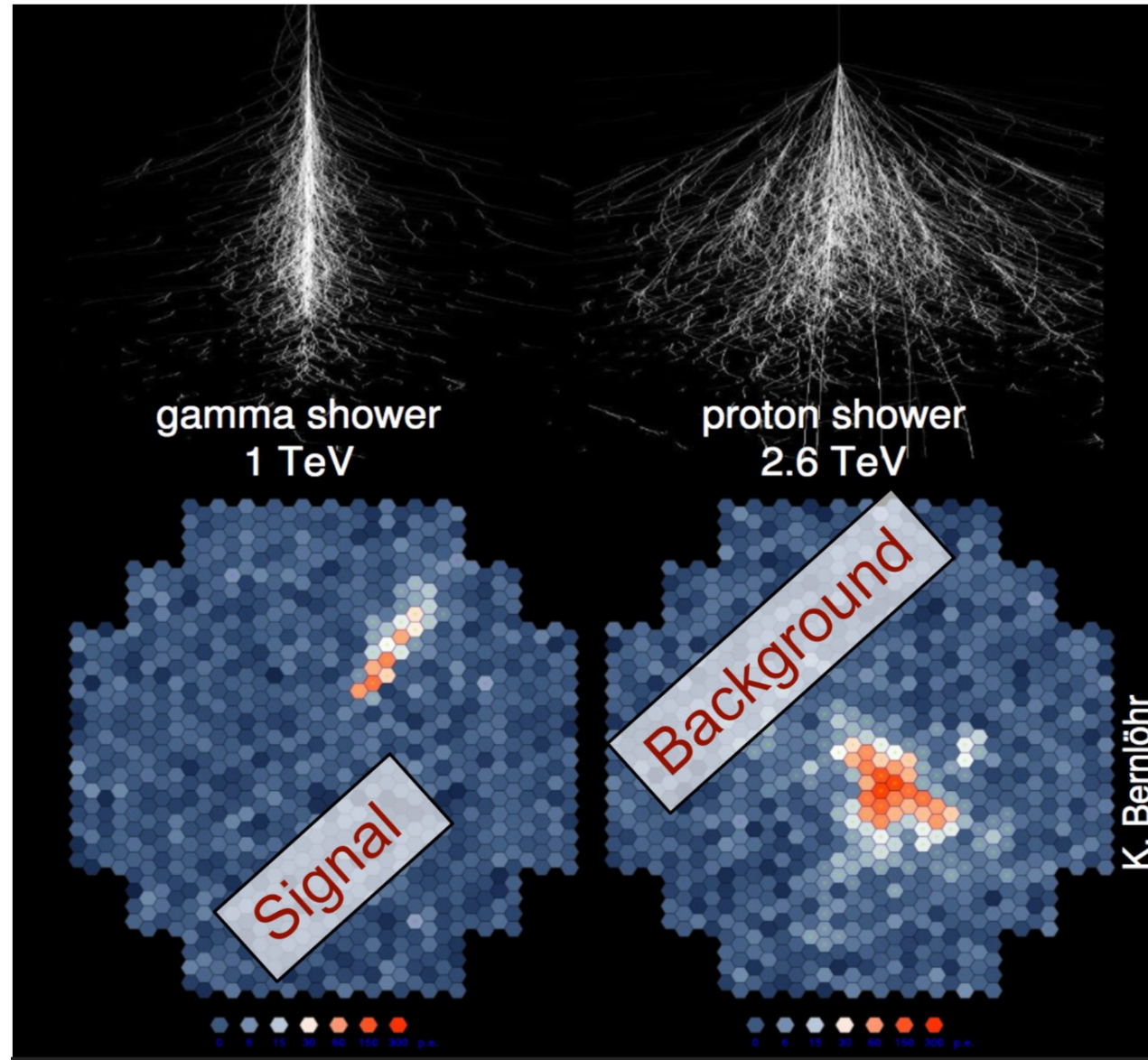
$$\frac{dN}{dx d\lambda} \propto \frac{1}{\lambda^2}$$

Ozone absorption

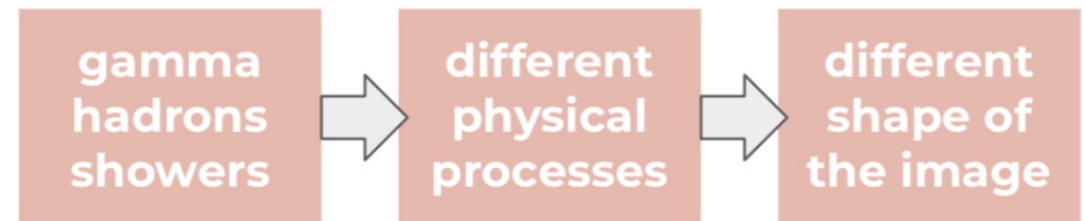
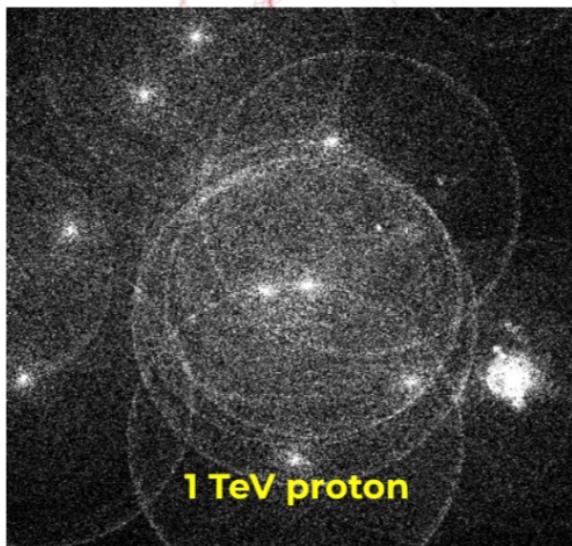
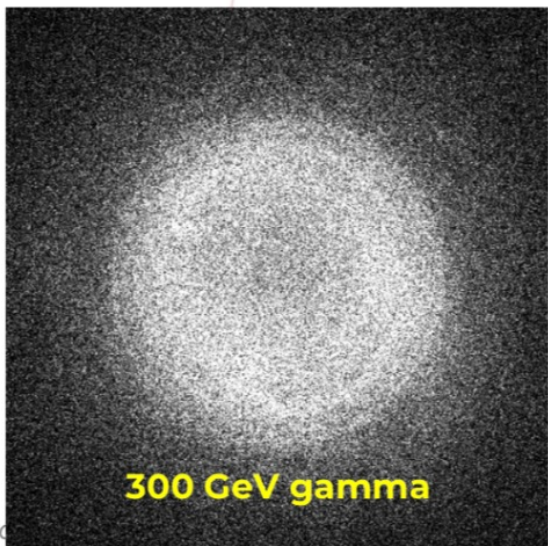
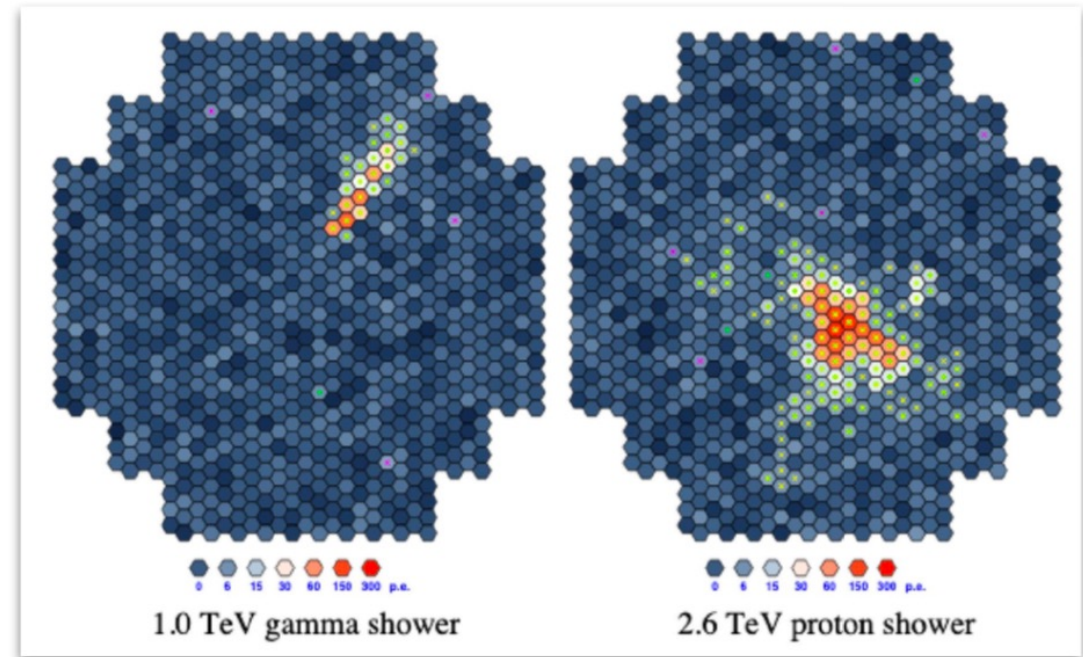
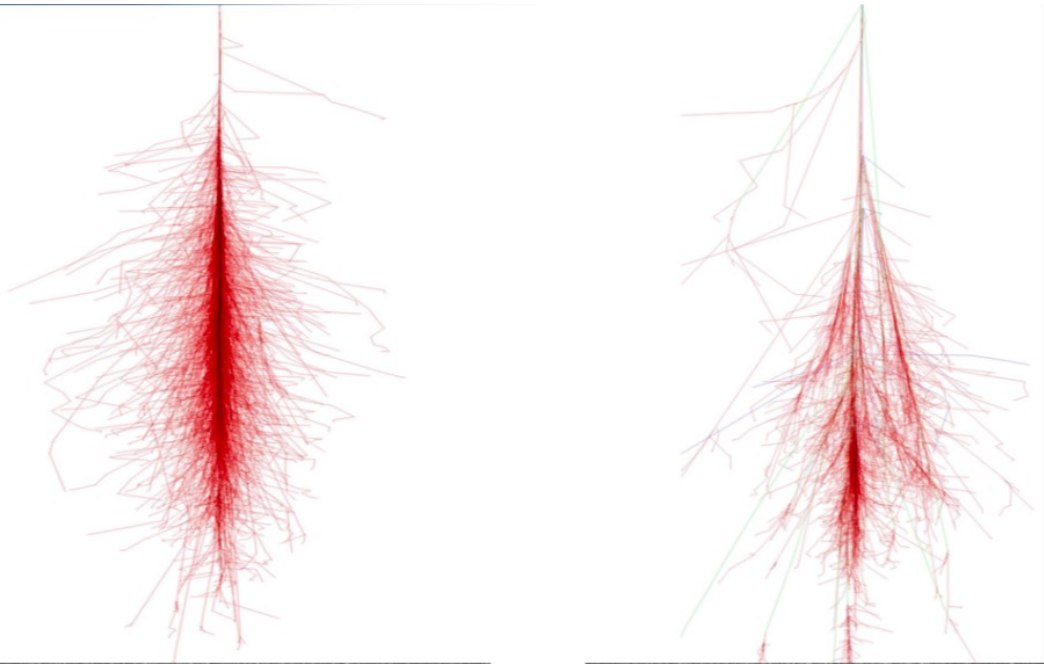


Cherenkov light is predominantly blueish

EXTENSIVE AIR SHOWERS (EAS)

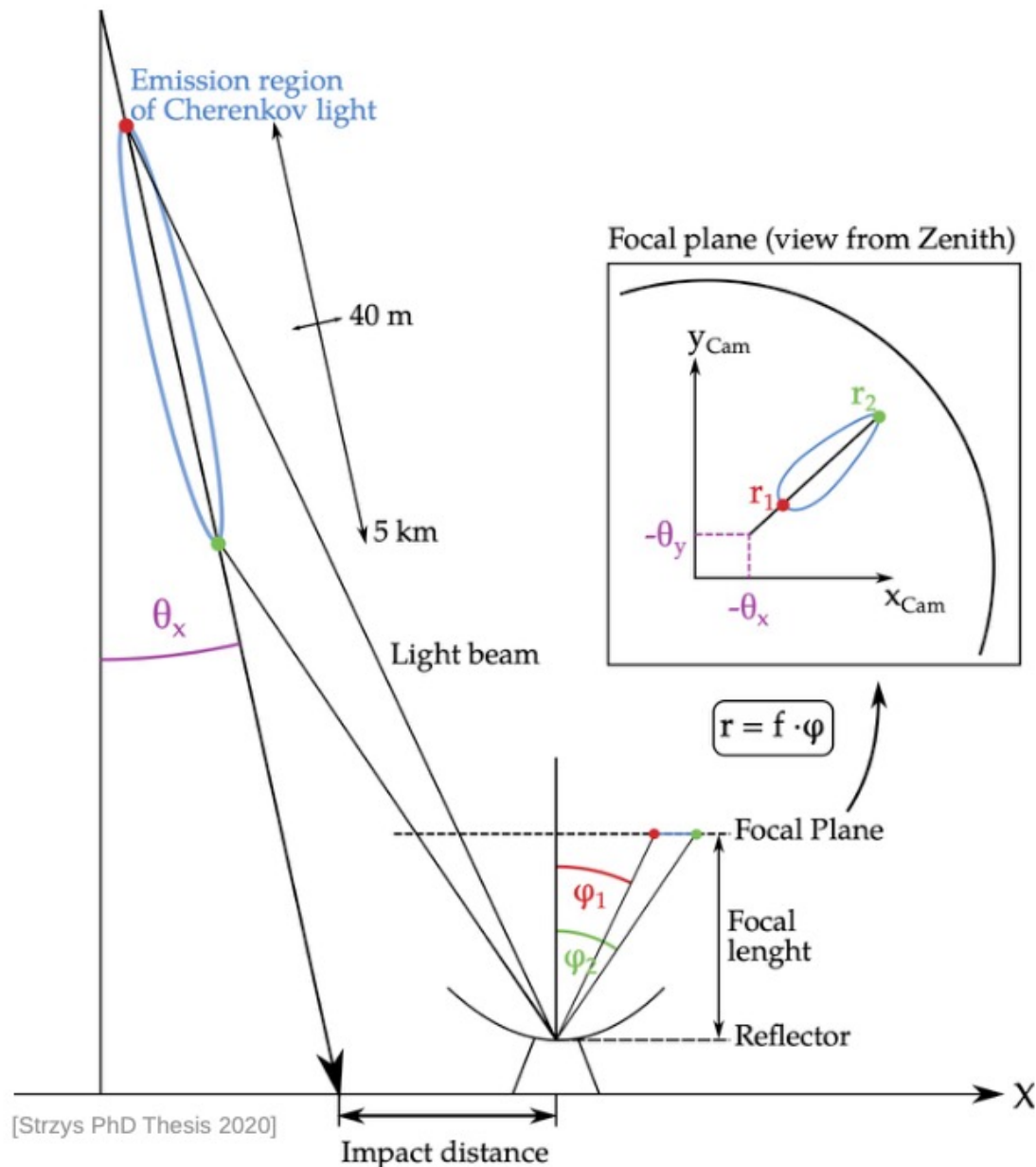
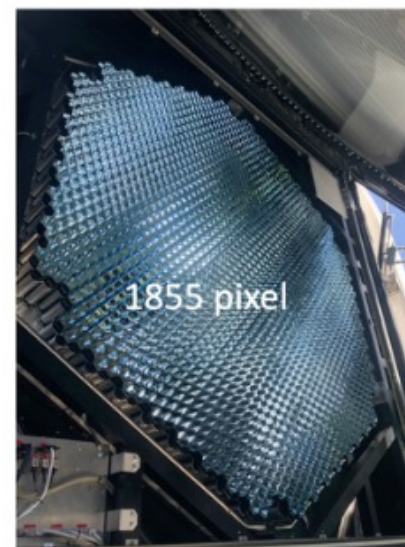


EXTENSIVE AIR SHOWERS (EAS)

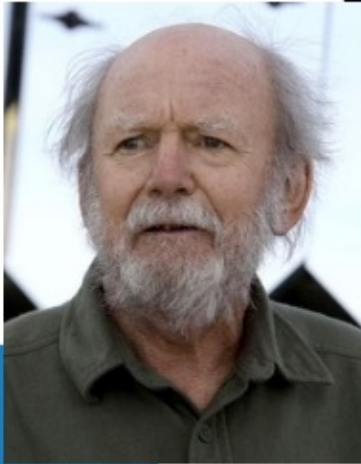


FUNCTION OF THE TELESCOPE

- Telescope focusses light into focal plane
- Angles get converted to positions in the camera
- Different angles mean different locations in the camera
- Get an image of the shower
- Duration of Cherenkov flashes very short ~ 10 ns
- Need ultra-fast cameras or not detectable against bright night sky



FIRST DETECTION OF A SOURCE WITH AN IACT



Trevor Weekes
(1940-2014)

- Started working in the field from 1966



- Whipple was located at Mt. Hopkins, Arizona at 2300m height
- Detected the first gamma ray source: the Crab Nebula
- ~75 m² mirror area and 37 pixel camera

Comparison LST:
~420 m²
1855 Pixel camera

IMAGE PARAMETRIZATION

- Keep only pixels with signal above the background light fluctuations
- Calculate a set of parameters describing the image:
 - Size (total # of photo-electrons)
 - main axis
 - Width, Length (2nd order moments – "Hillas parameters")
 - time gradient along major axis...

A. M. Hillas
(1932 - 2017)

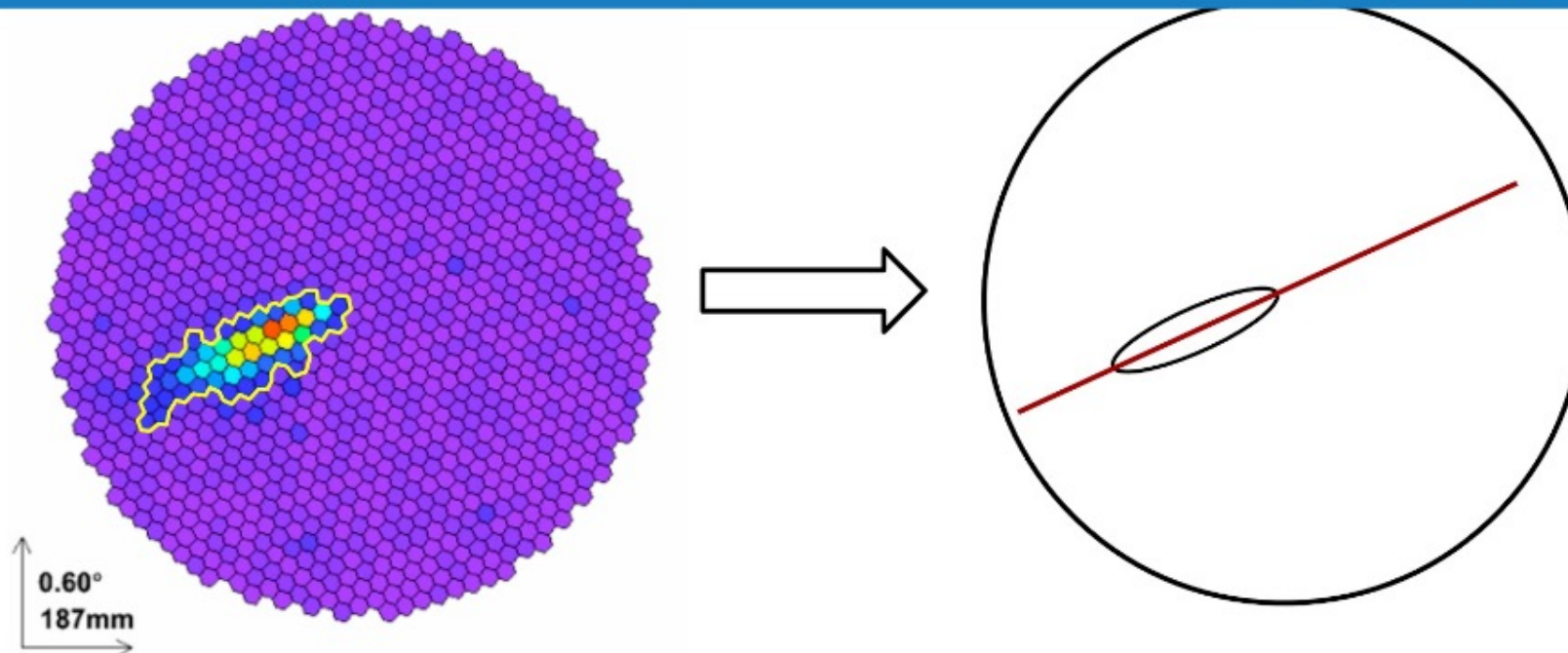
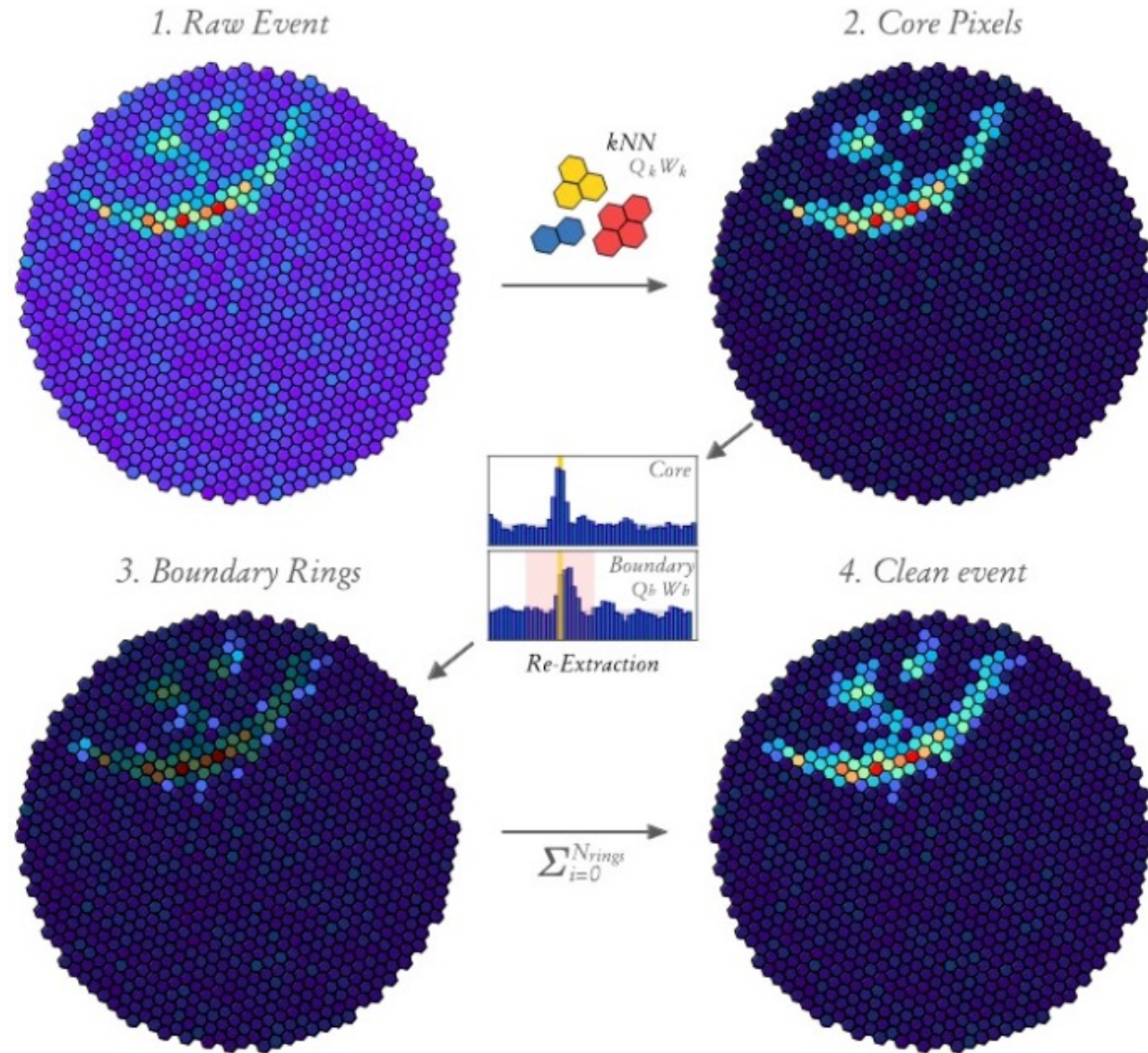


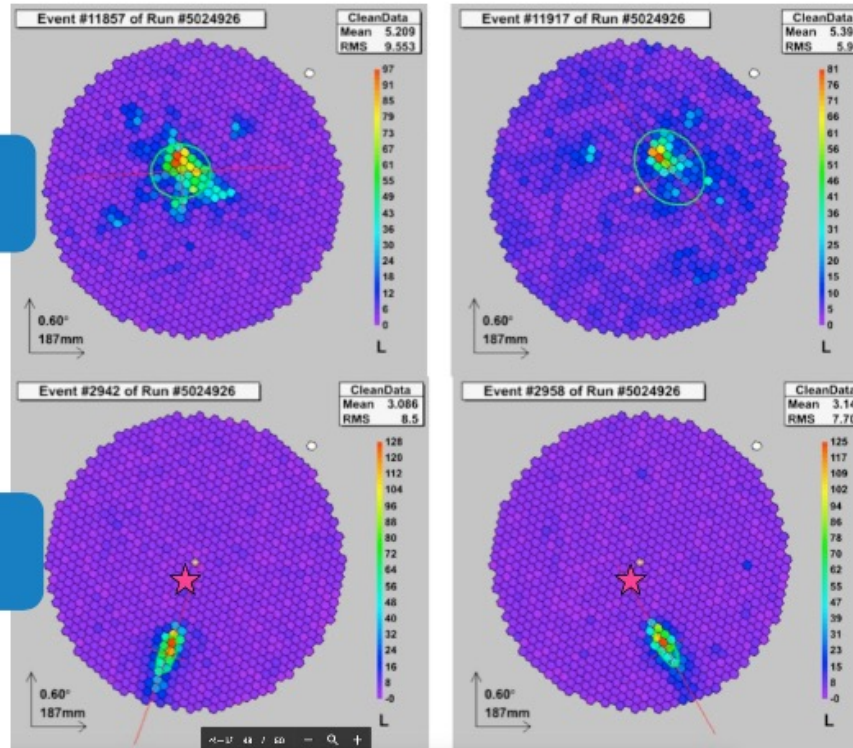
IMAGE CLEANING



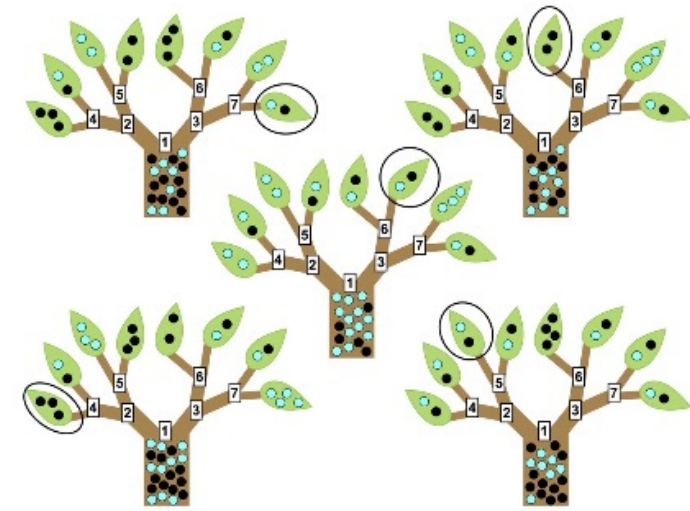
DISTINGUISH GAMMA-RAY AND BACKGROUND EVENTS

Hadronic event candidate

gamma-ray event candidate

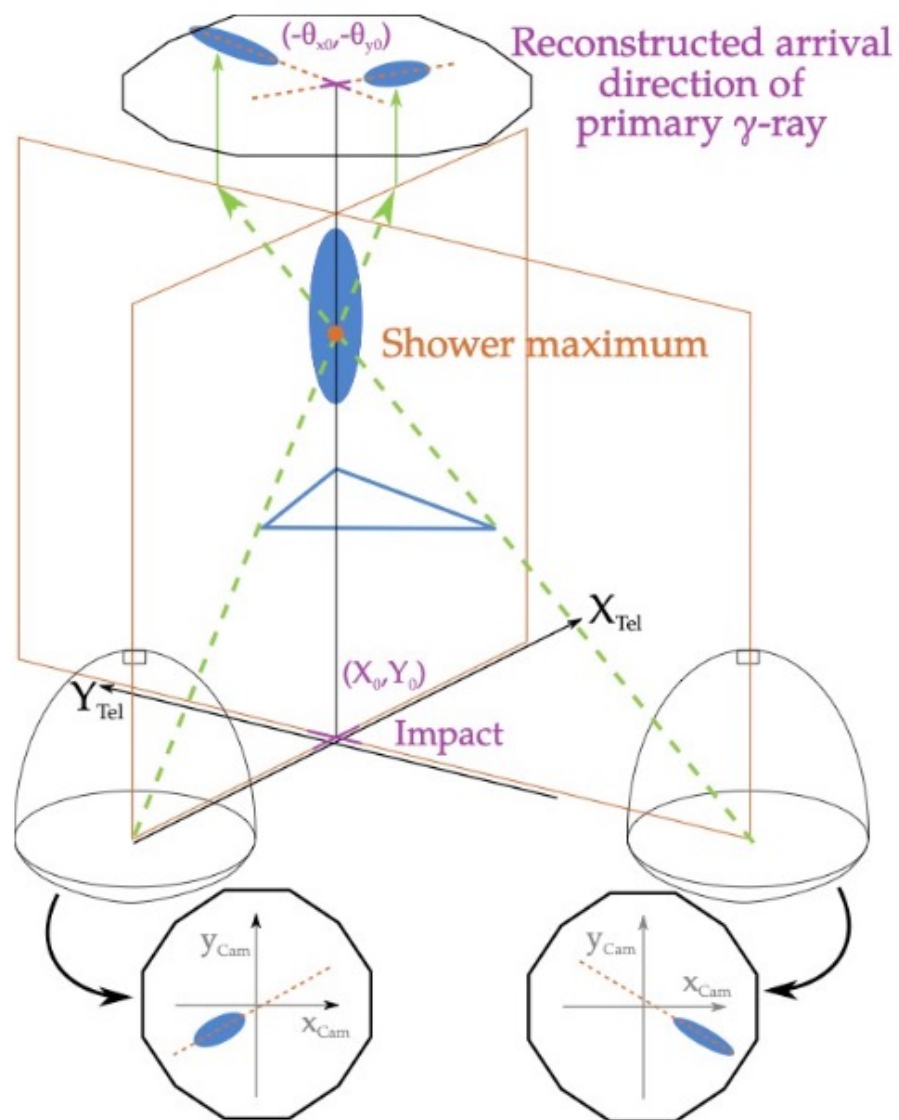


- After image parametrization events are classified by machine learning algorithms (we use random forrest classifier)
- For training these classifiers accurate simulations are needed



[<https://doi.org/10.1103/PhysRevD.91.062004>]

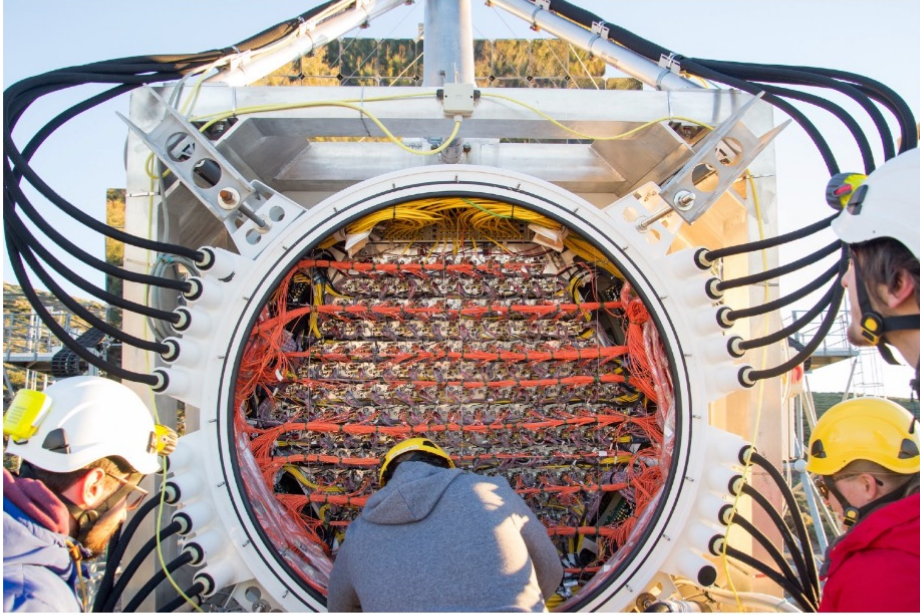
STEREO OBSERVATIONS WITH IACTS



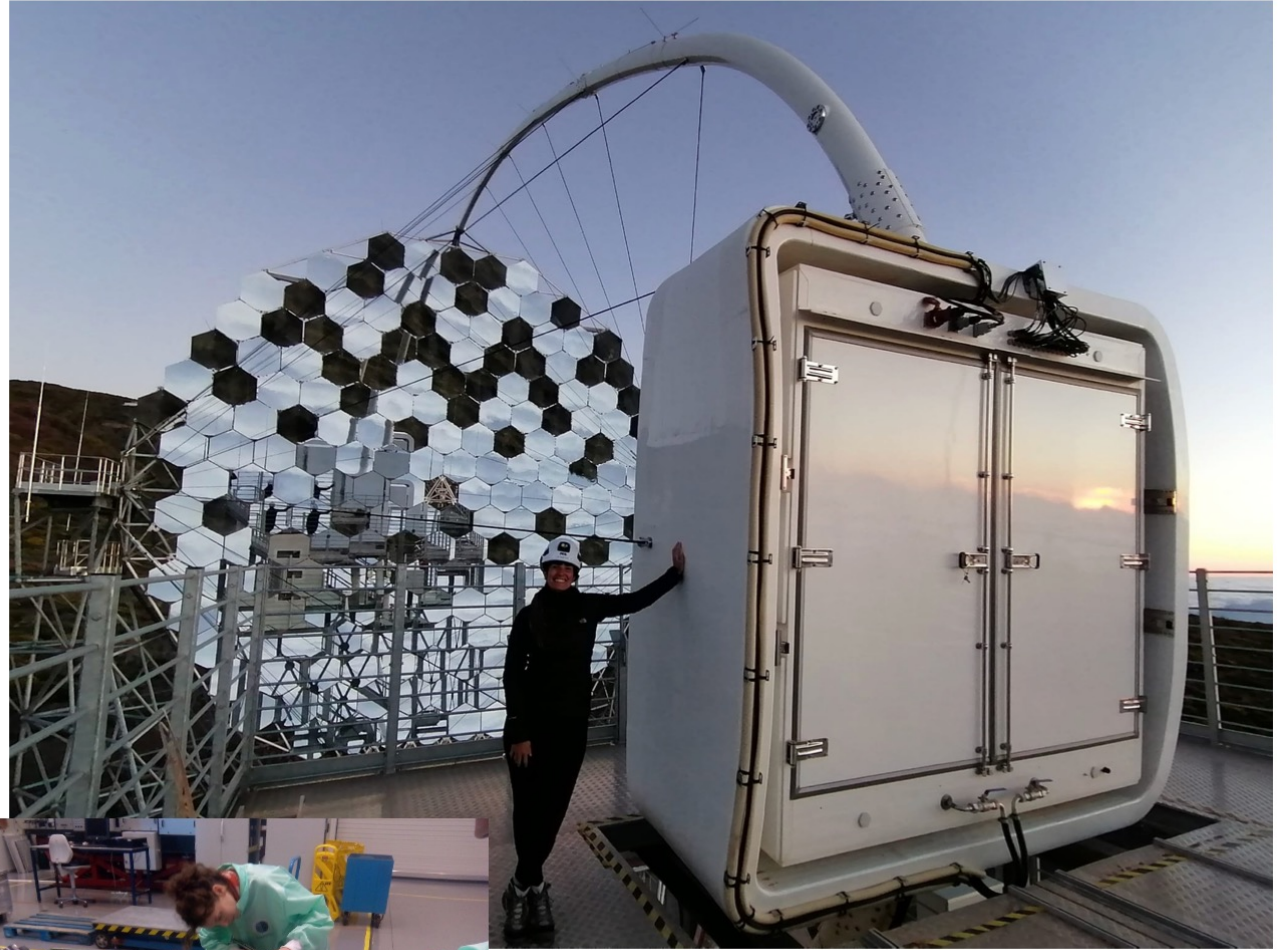
[Strzys PhD Thesis 2020]

- Seeing shower from multiple side allows reconstruction of the shower axis
- Each Hillas ellipse determines the shower in one plane
- Two telescopes determine the axis
- Extending main axis in the ground frame determines the Impact point
- Projecting images into one camera image determines the arrival direction relative to that frame
- Furthermore stereo observation provide stereo image parameters
- Improved background rejection

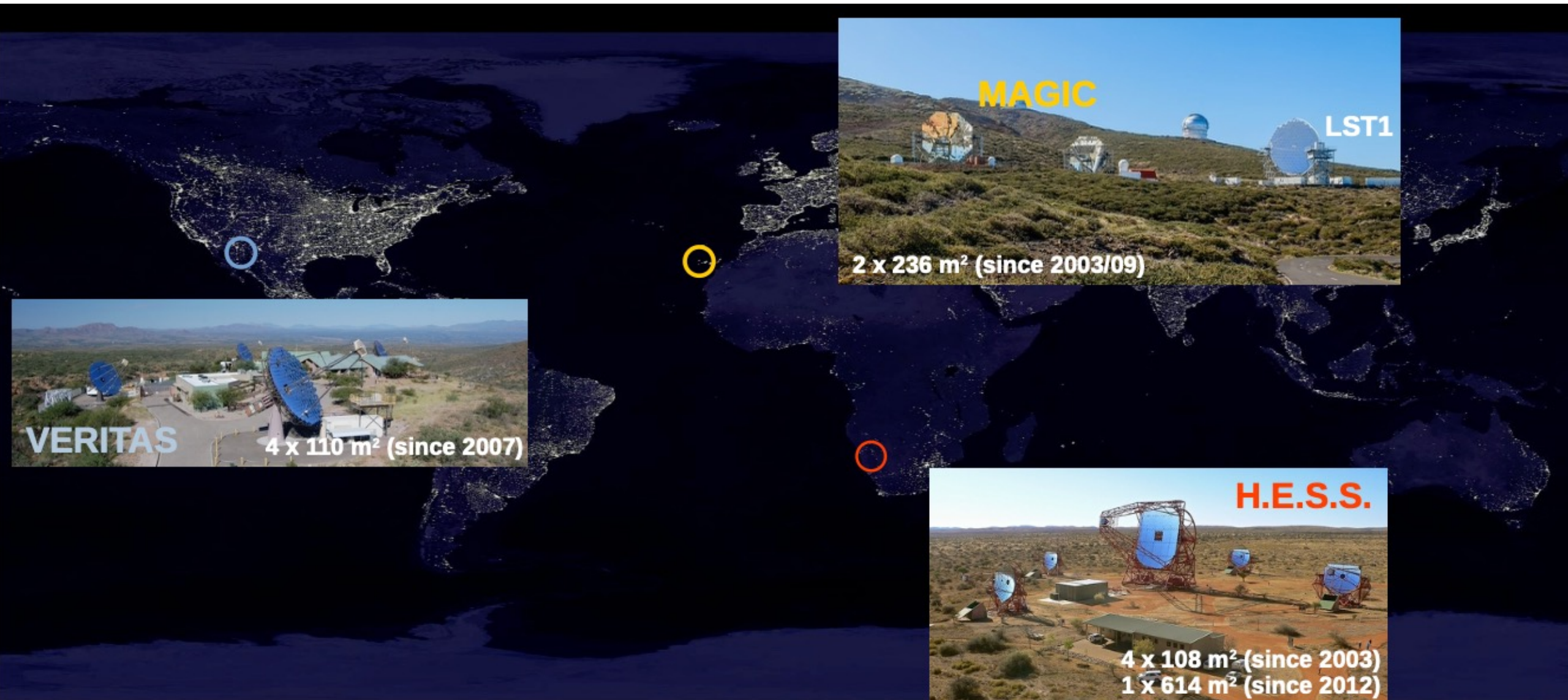
MAGIC-II camera



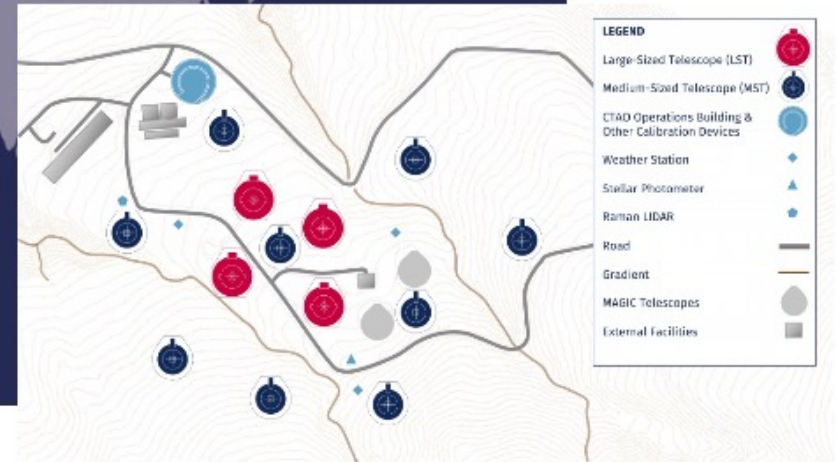
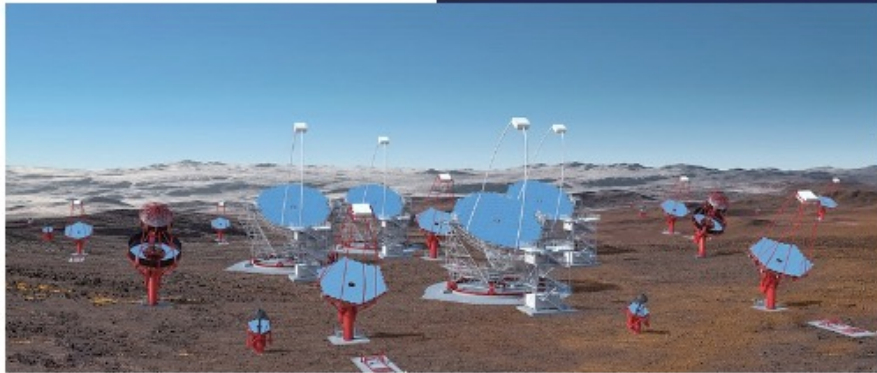
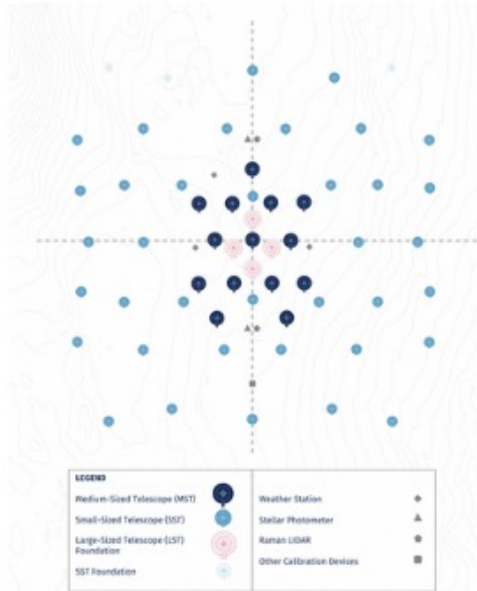
LST1 camera



CURRENT GENERATION OF IACTS



THE FUTURE OF IACTS: THE CHERENKOV TELESCOPE ARRAY OBSERVATORY





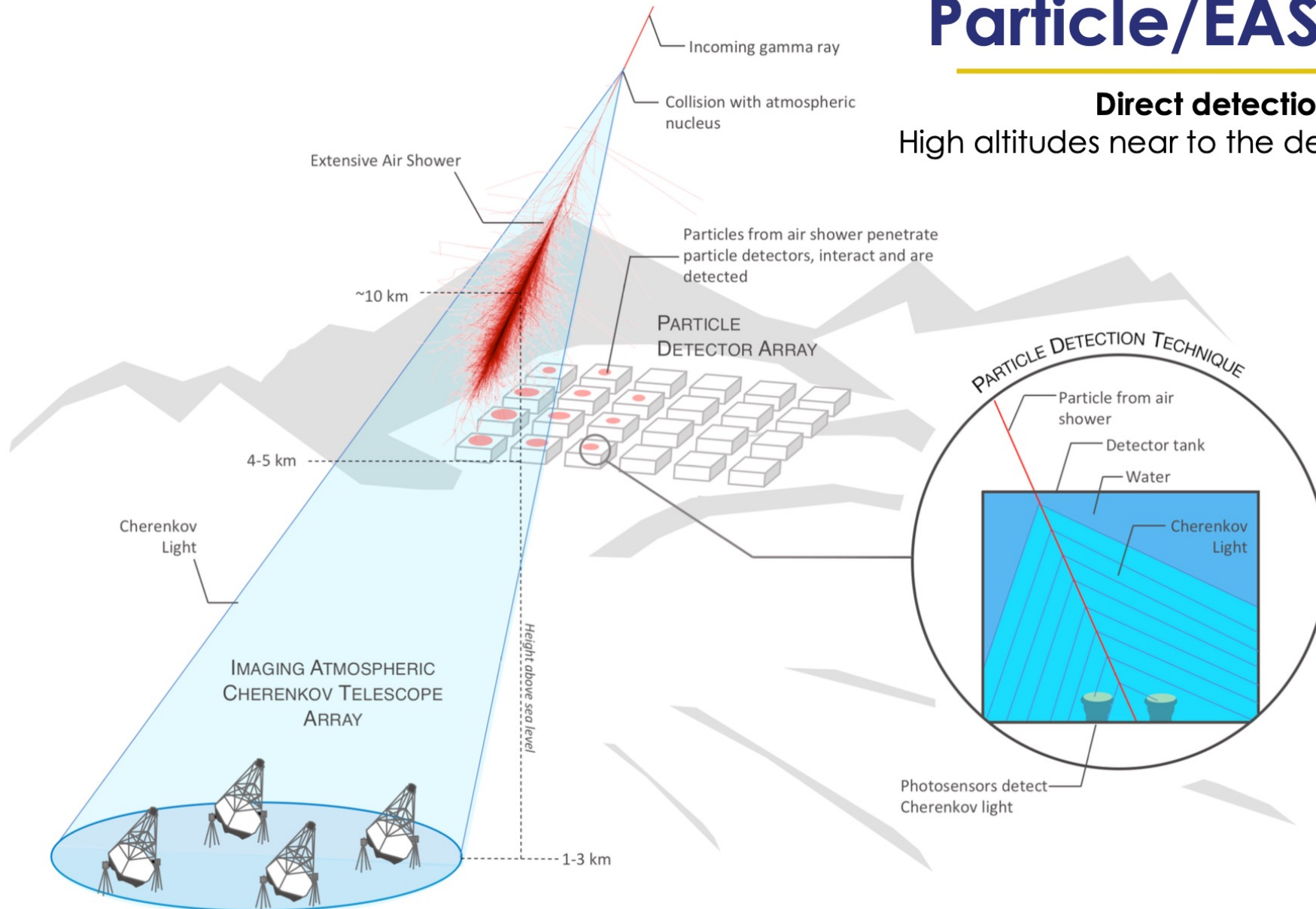
Aerial photo of LHAASO taken in 2022. Photo: Courtesy of the Institute of High Energy Physics

PARTICLE DETECTORS (UHE)

Particle/EAS detectors: UHE

Direct detection of secondary particles of the EAS

High altitudes near to the depth of the shower maximum X_{max}



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>

Not to scale

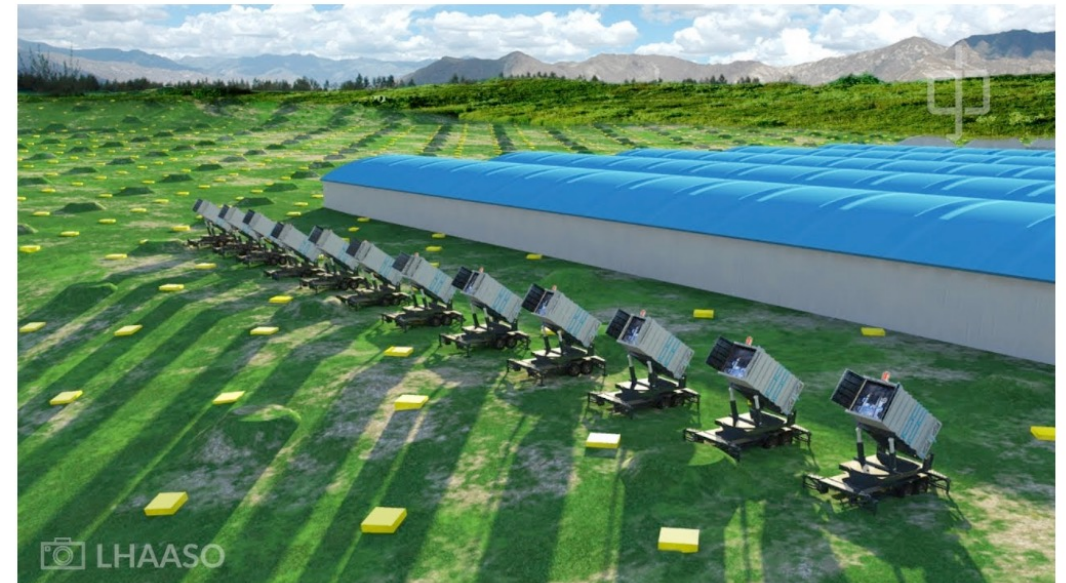
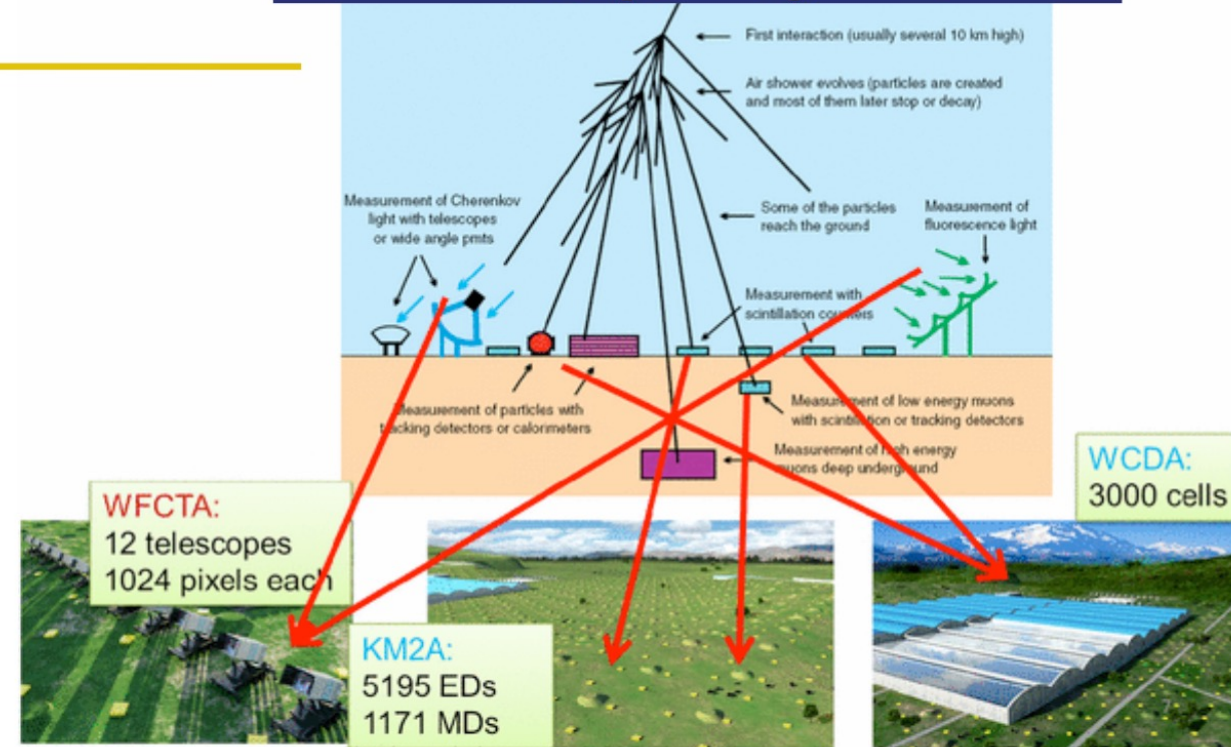
Particle/EAS detectors: UHE

HAWC (México): 4100 m



Water Cherenkov Detector (WCD)

LHAASO (China): 4410m



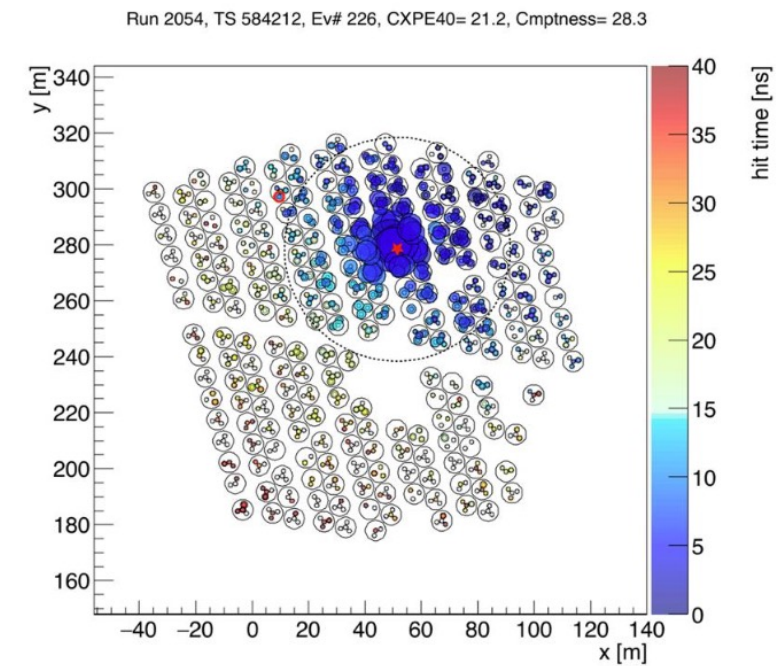
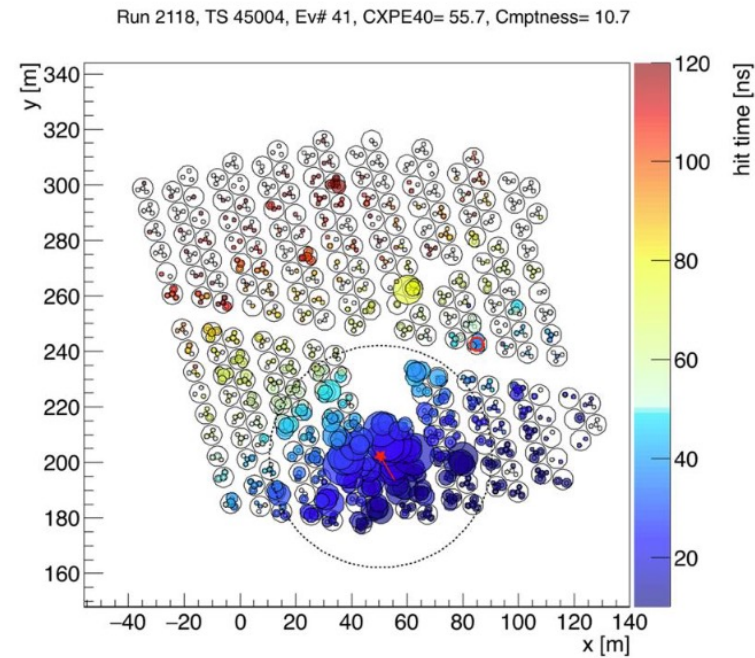
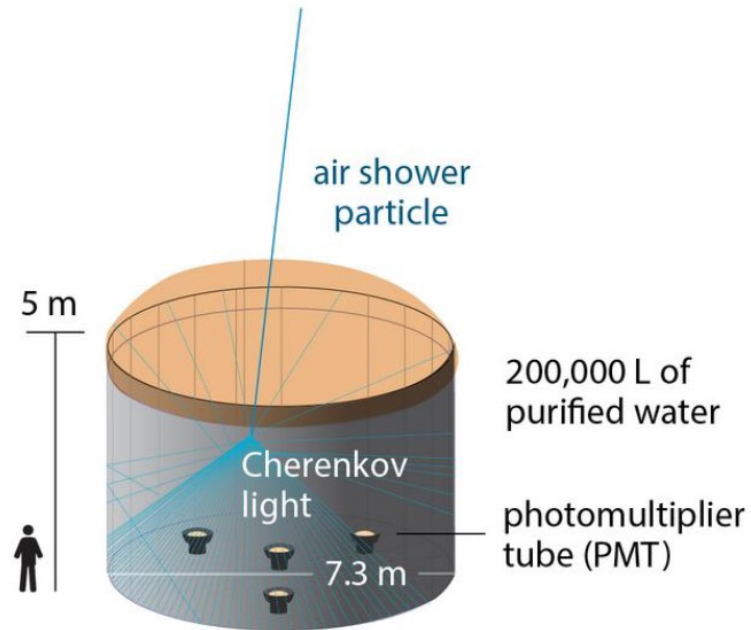
WATER CHERENKOV DETECTORS (WCDS)

e.g. HAWC located in Mexico

Array of 300 WCDs at 4100m above sea level.

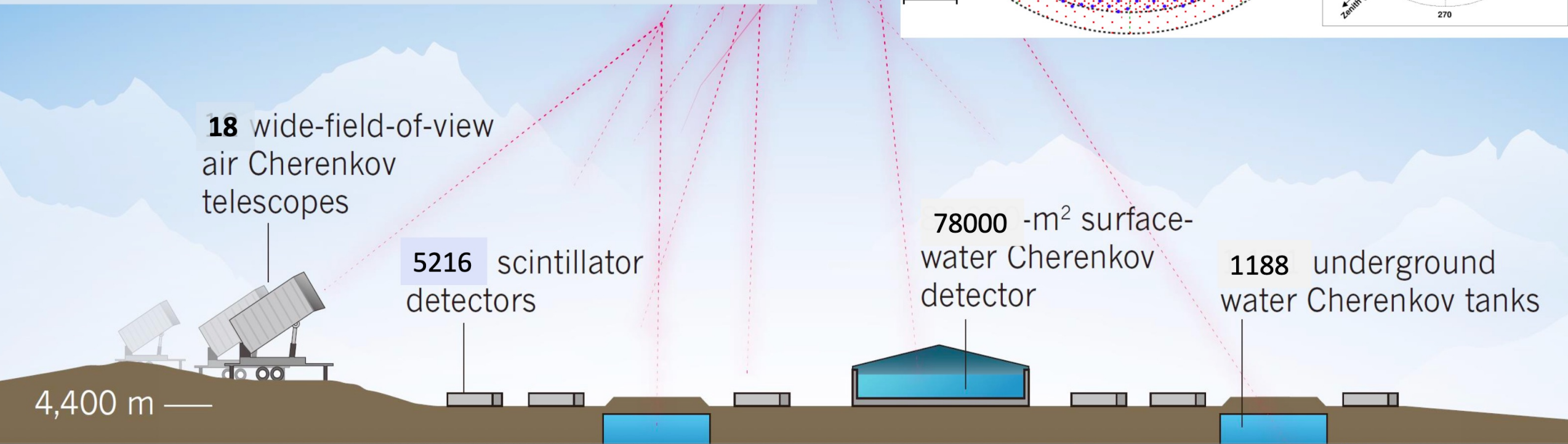
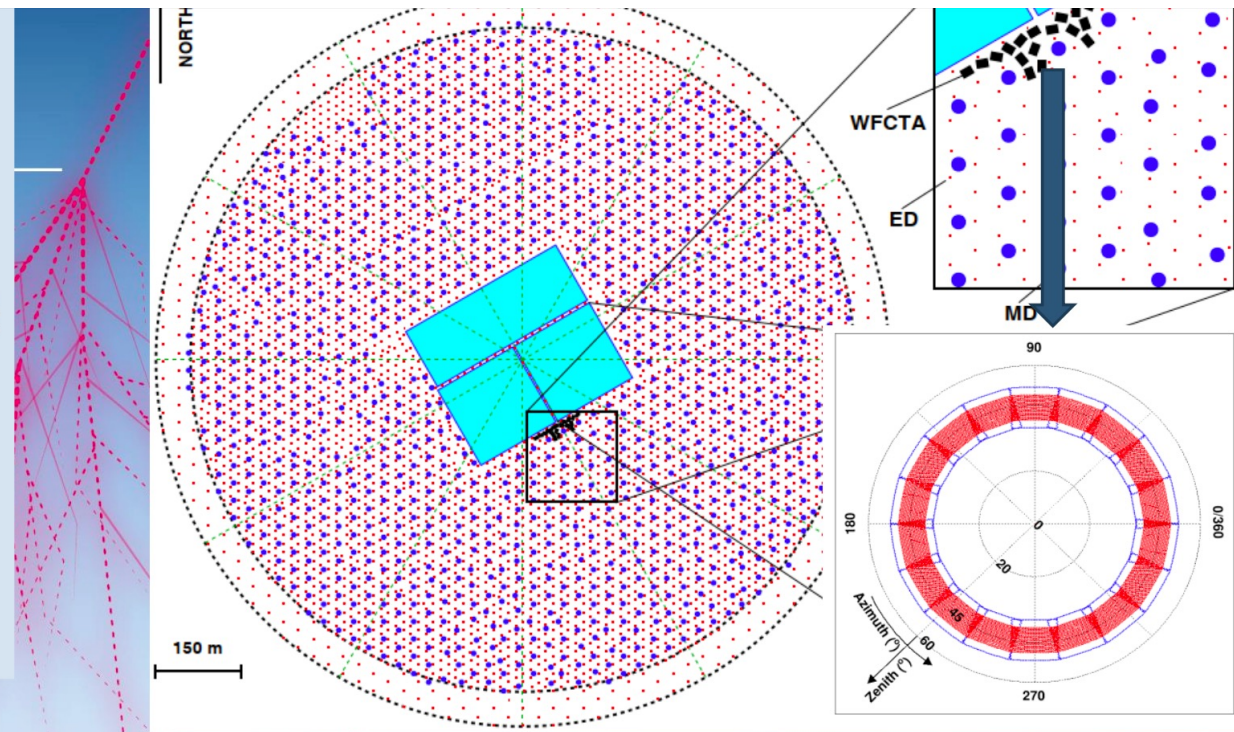
Air shower events trigger across array – can operate during day and night.

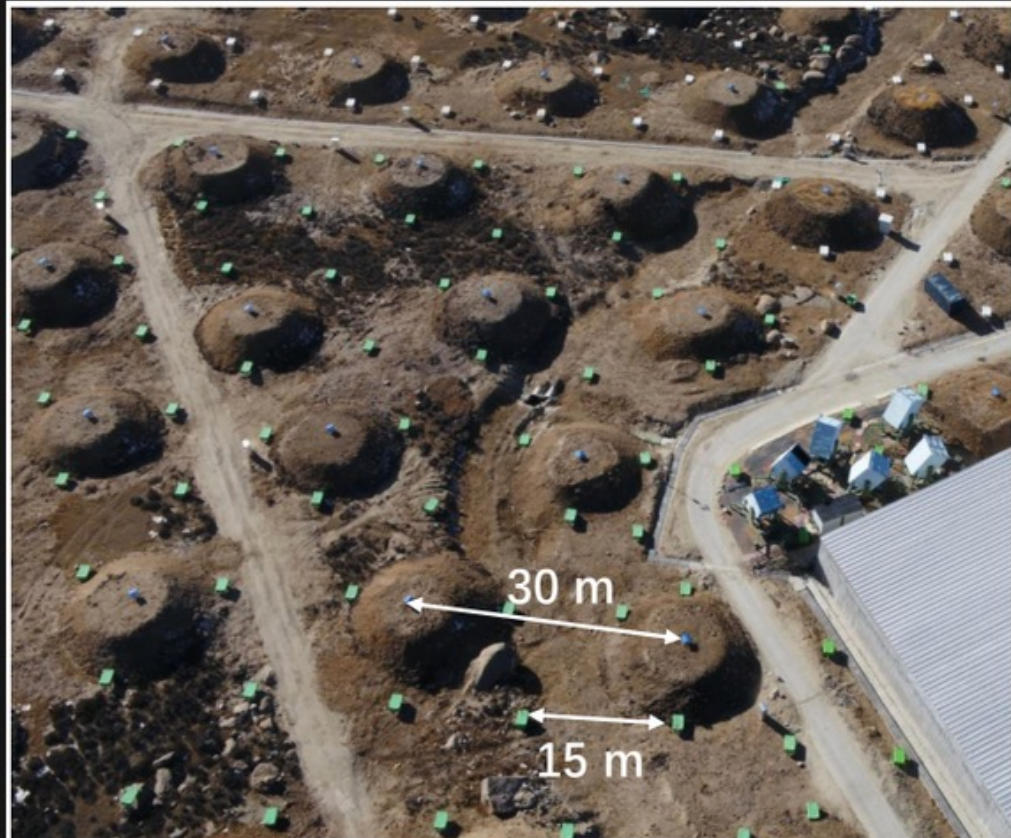
Gamma-ray vs Cosmic Ray ?



Multi-type detectors

- 1188 muon detector (KM2A-MD)
- 5216 electromagnetic detector (KM2A-ED)
- 18 Widefield of view Cherenkov telescope array (WFCTA)
- 78000 m² water Cherenkov detector array (WCDA)
- To improve the composition discriminative capabilities
- To reduce the effects of high energy hadronic interaction models

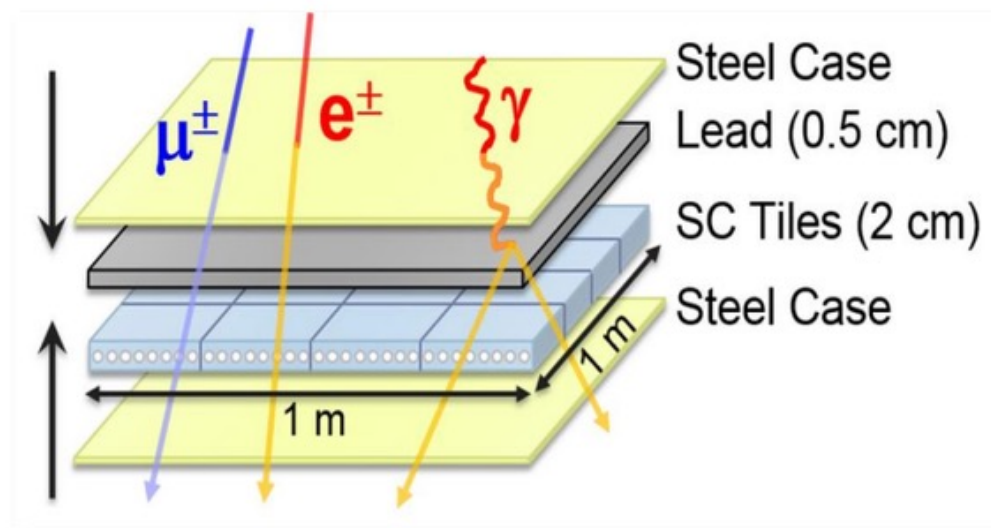




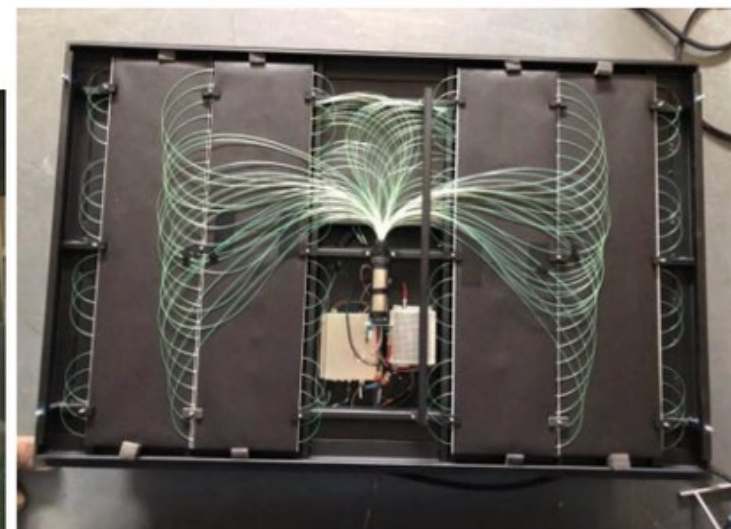
KM2A: 1.36 (km)²

- 5195 EDs
 - 1 m² each
 - 15 m spacing
- 1188 MDs
 - 36 m² each
 - 30 m spacing

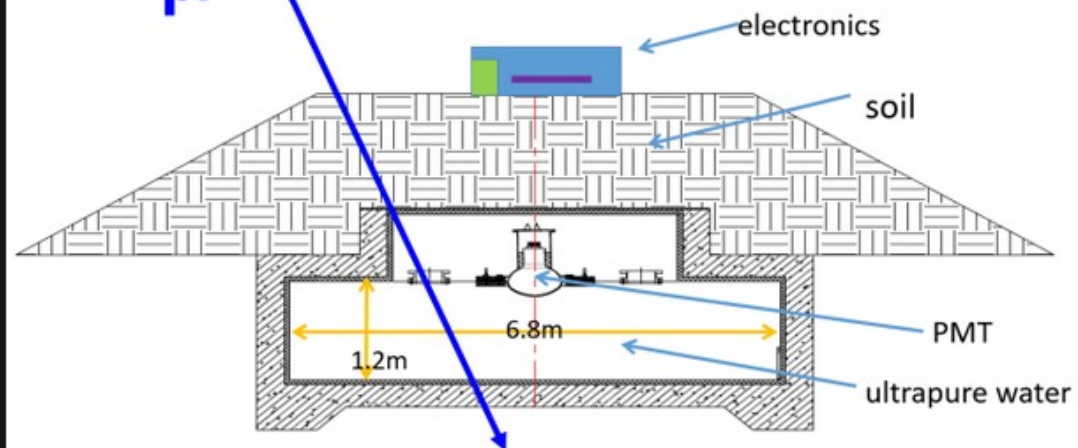
Scintillator Detectors (ED)



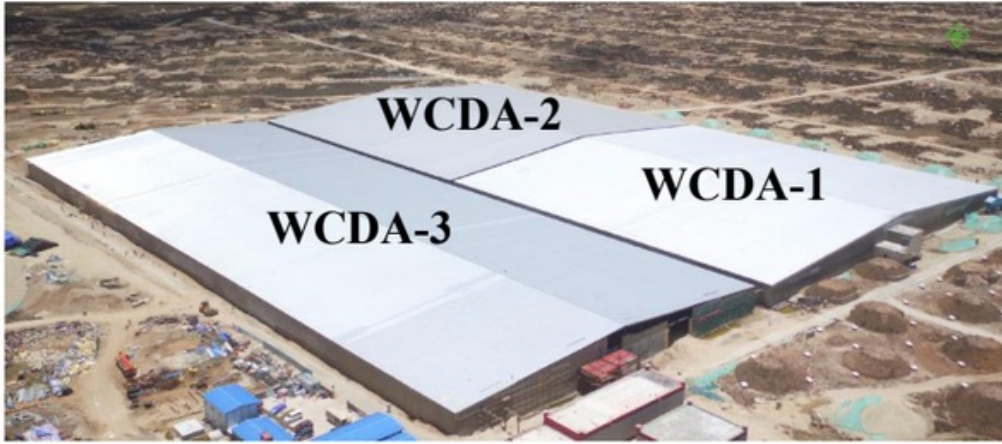
Inner View of one ED



Muon detector (MD)

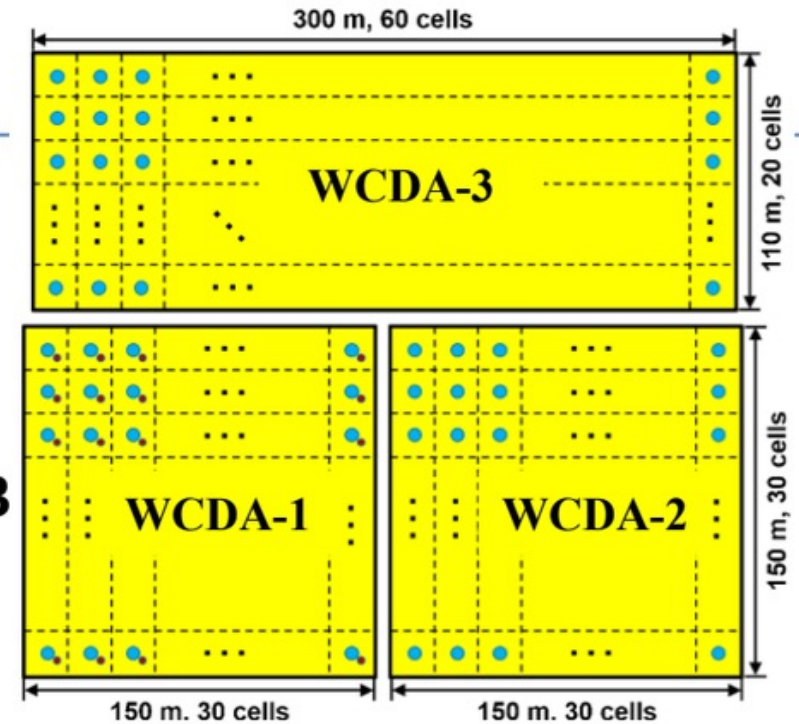


Water Cherenkov Detector Array (WCDA)

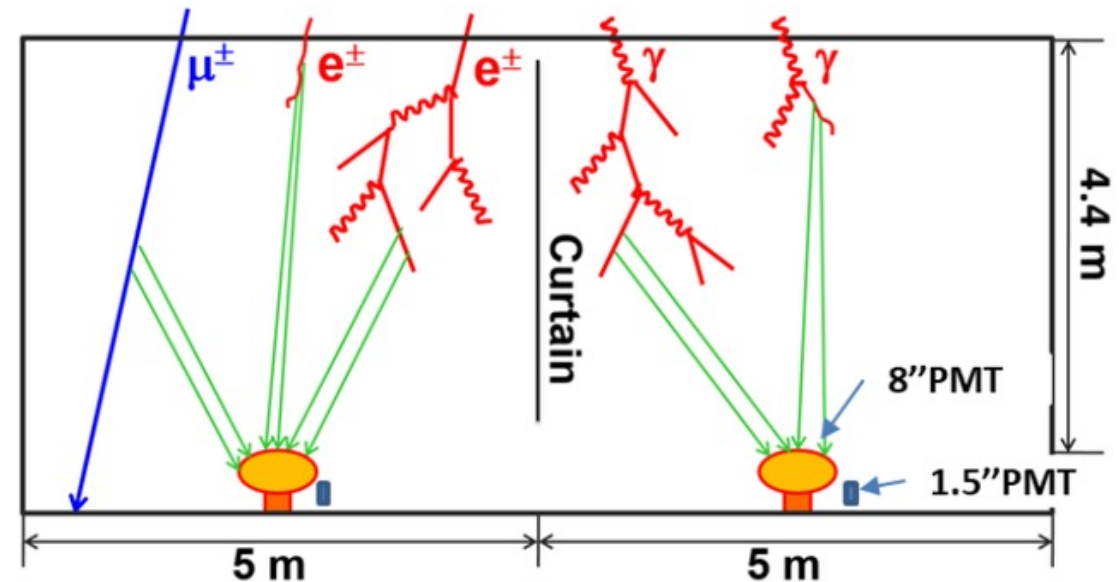


Energy rang

- ◆ WCDA-1
 - 300 GeV – 10 TeV
- ◆ WCDA-2 and WCDA-3
 - 100 GeV - 10 TeV

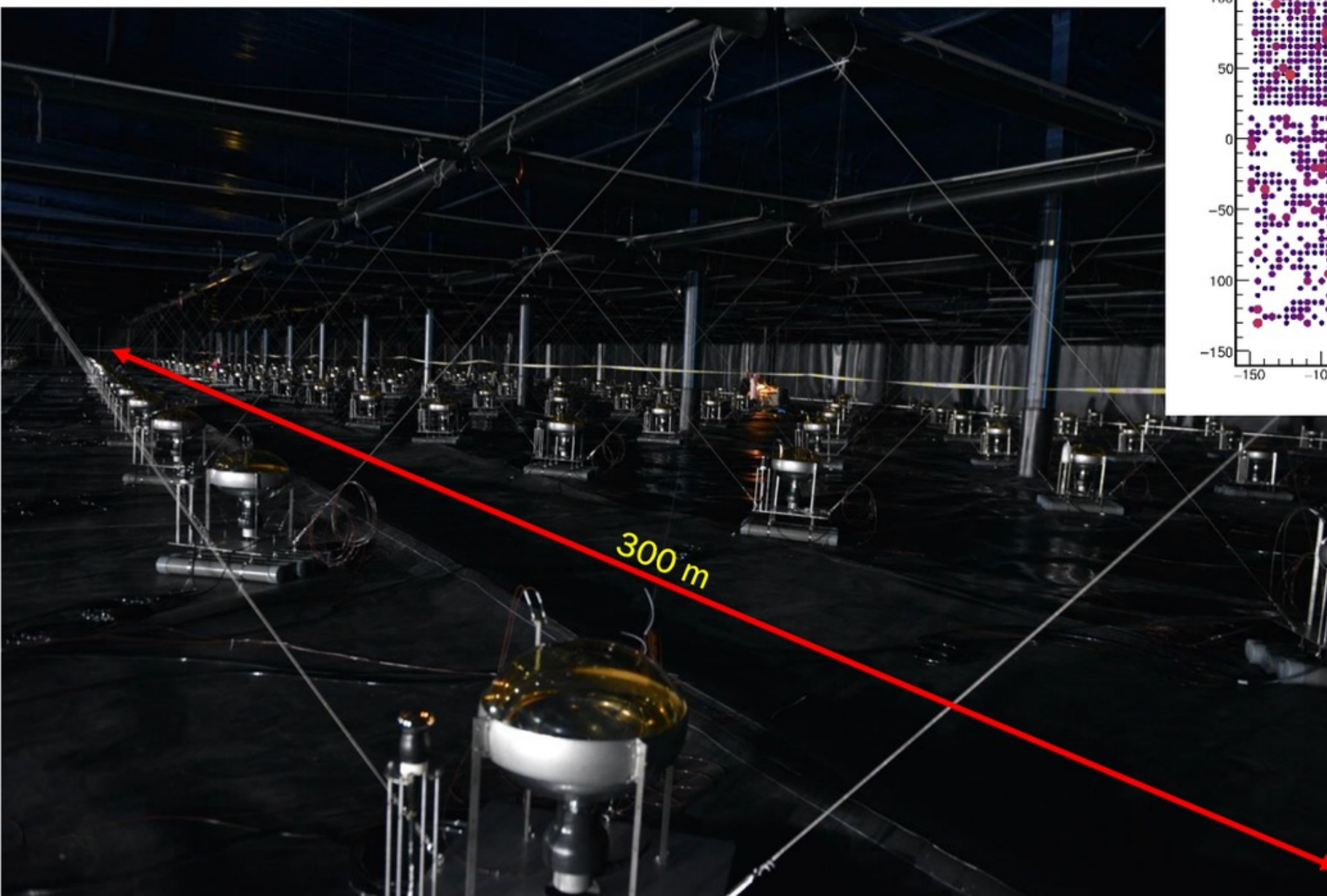


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two type of PMTs in each unit:
 - 8 inches and 1.5 inches for WCDA-1
 - 20 inches and 3 inches for WCDA-2 and WCDA-3

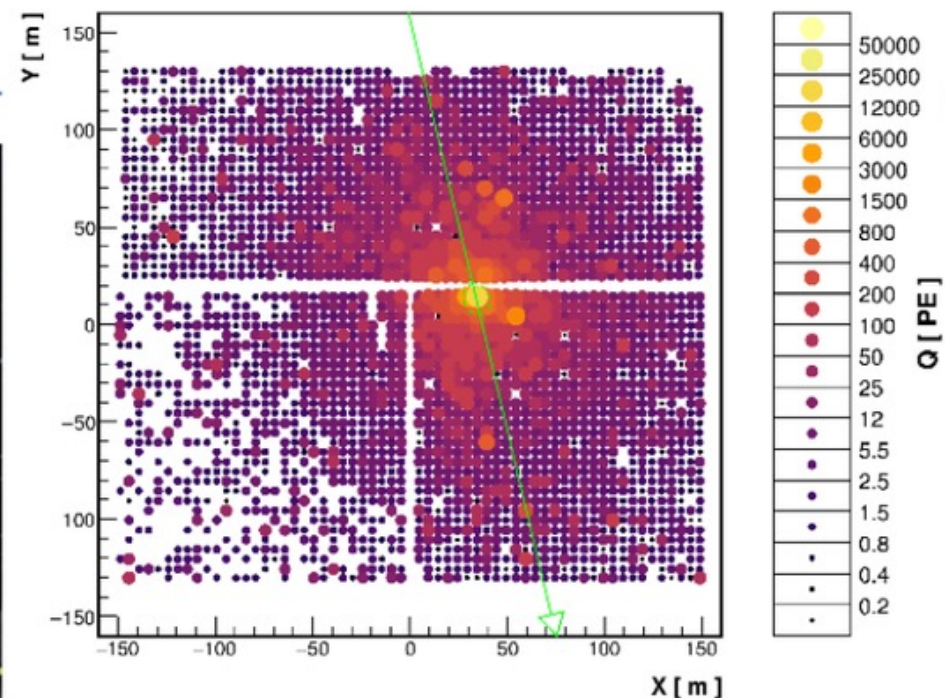




Inside of WCDA-3

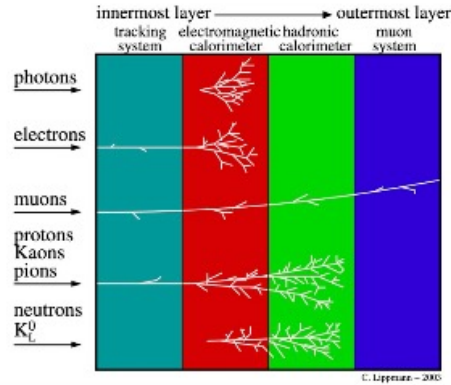


20210511/131236/0.554789897: nTrig=-1, $\theta=37.81\pm0.02^\circ$, $\phi=103.39\pm0.02^\circ$



- ◆ WCDA-1 started operating in April 2019
- ◆ WCDA-2 started operating in January 2020
- ◆ WCDA-3 started operating in March 2021

COMPARISON OF DIFFERENT GAMMA-RAY INSTRUMENTS



Method 1: go to space

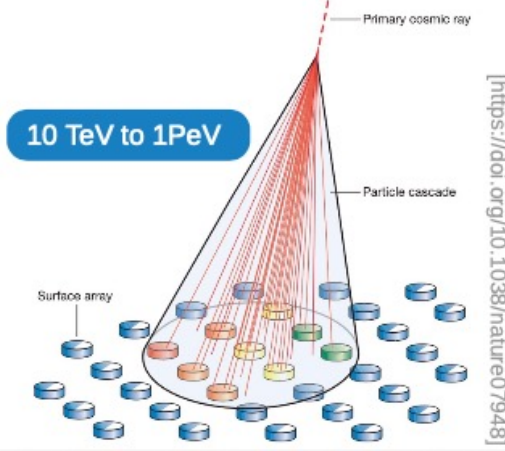
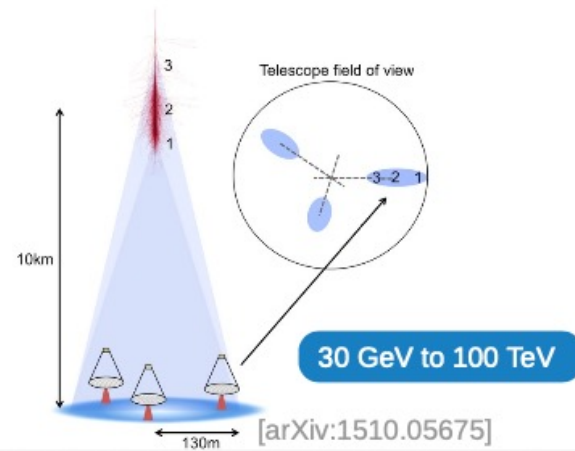
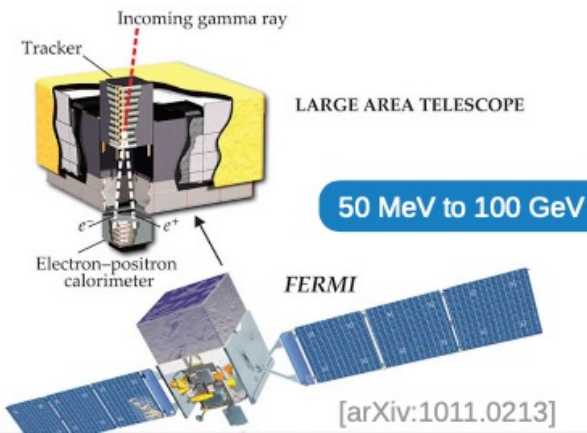
- + Background control
- + All sky coverage
- Direction reconstruction
- Detector size

Method 2: use a trick

- + Direction reconstruction
- + Detector size
- Calibration
- Needs good weather / night
- Field of view

Method 2: wait till shower reaches you

- + Detector size
- + Runs all the time
- Field of view
- Direction reconstruction



Instruments

Cherenkov
telescopes
50GeV - 50TeV



VERITAS

HAWC
100GeV - 100TeV



HAWC



MAGIC

CTA-LST1

LHAASO

H.E.S.S.



Fermi



Fermi-GBM
8keV - 30MeV
Fermi- LAT
100MeV - 300GeV



LHAASO
1TeV - 1PeV

Adapted M. Strzys

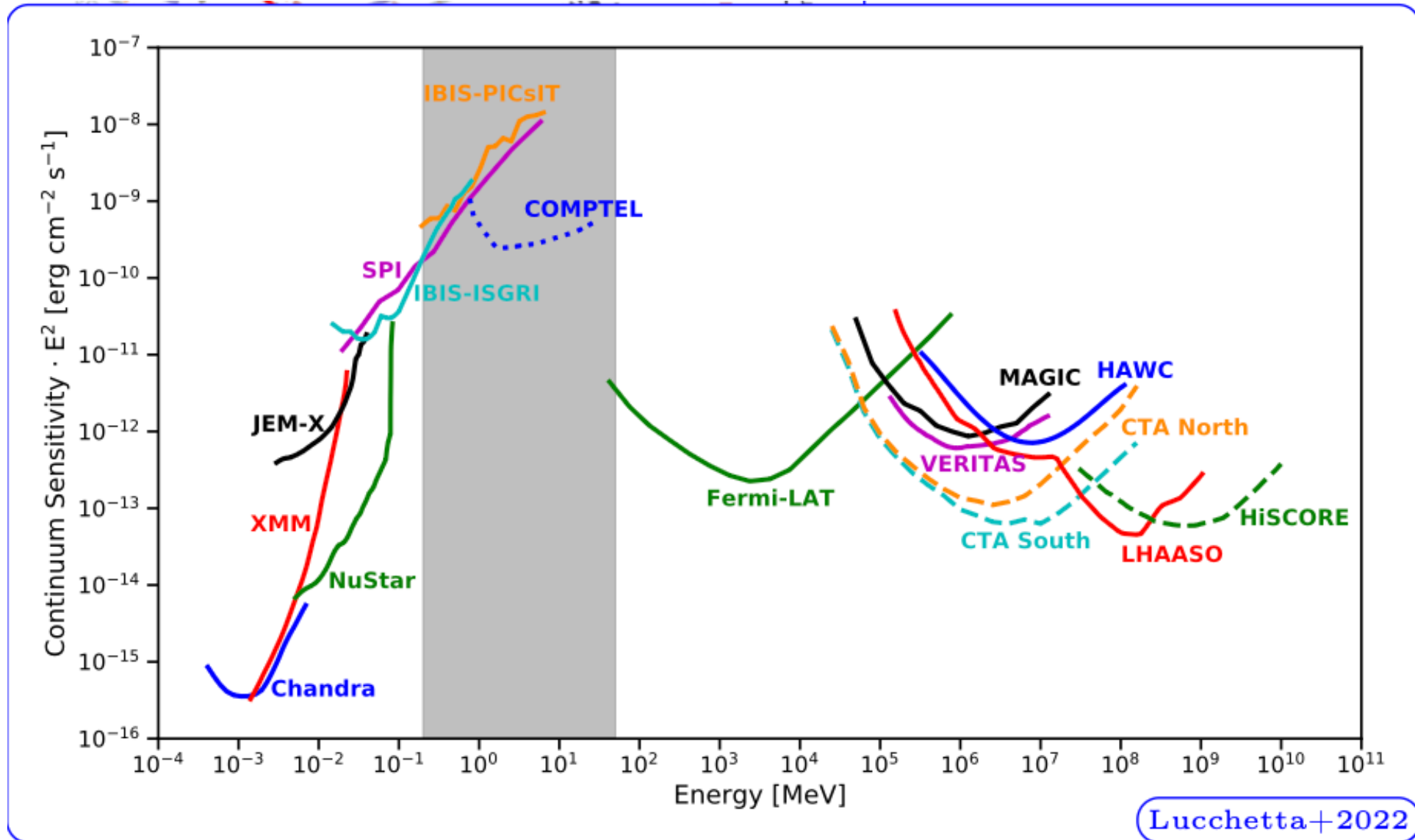
THANK YOU

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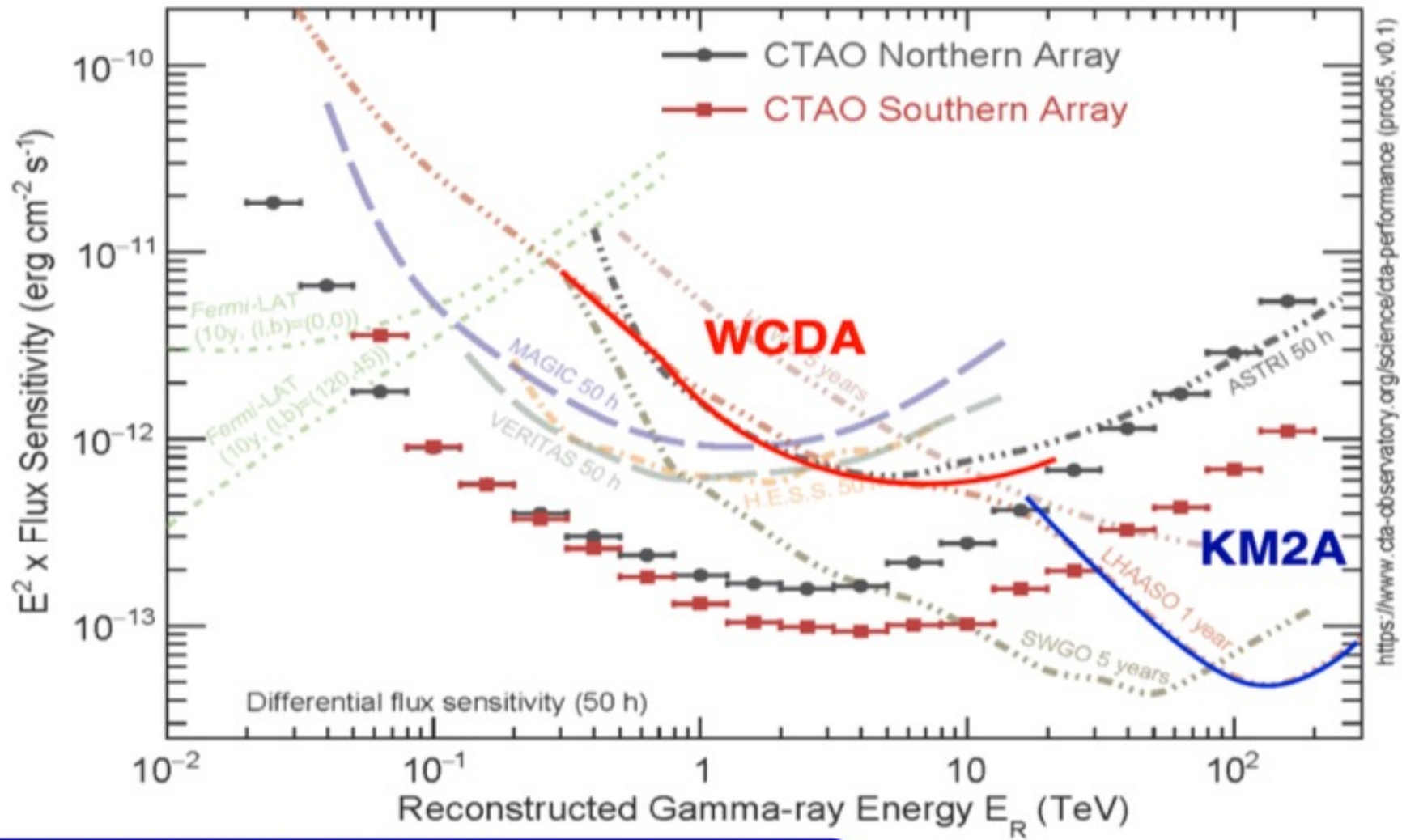
BACK UP

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SENSITIVITIES

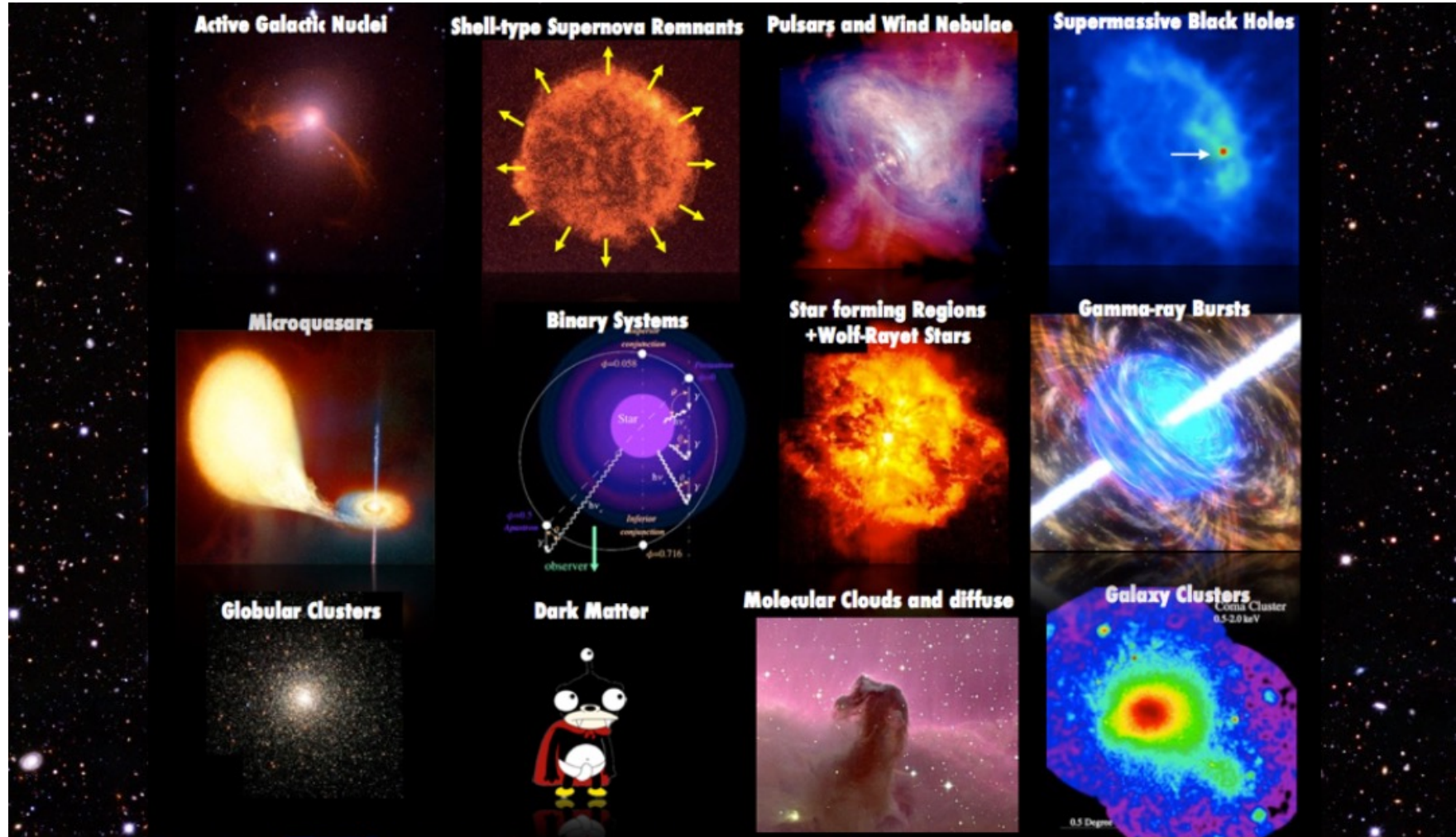


SENSITIVITIES



della Volpe, LHAASO Collaboration (2022)

NON-THERMAL UNIVERSE



THE MULTI-WAVELENGTH UNIVERSE

