Gamma-ray Instruments

UNIVERSITÀ DEGLI STUDI DI PADOVA

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Shaping a World-class University

Padova, 25-29 September 2023

Program

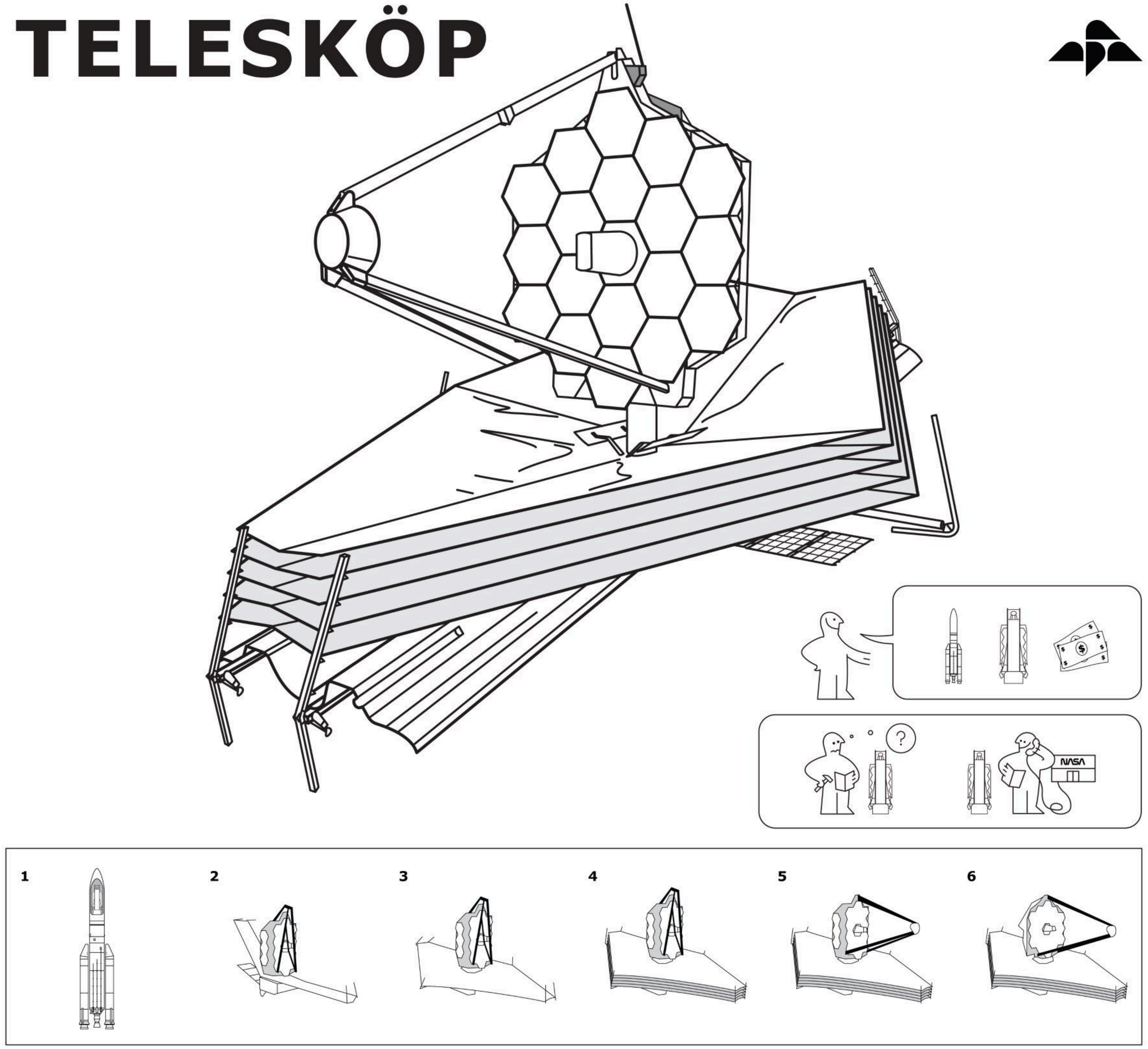
Gamma-rays in the e.m. spectrum

Experiments, comparison

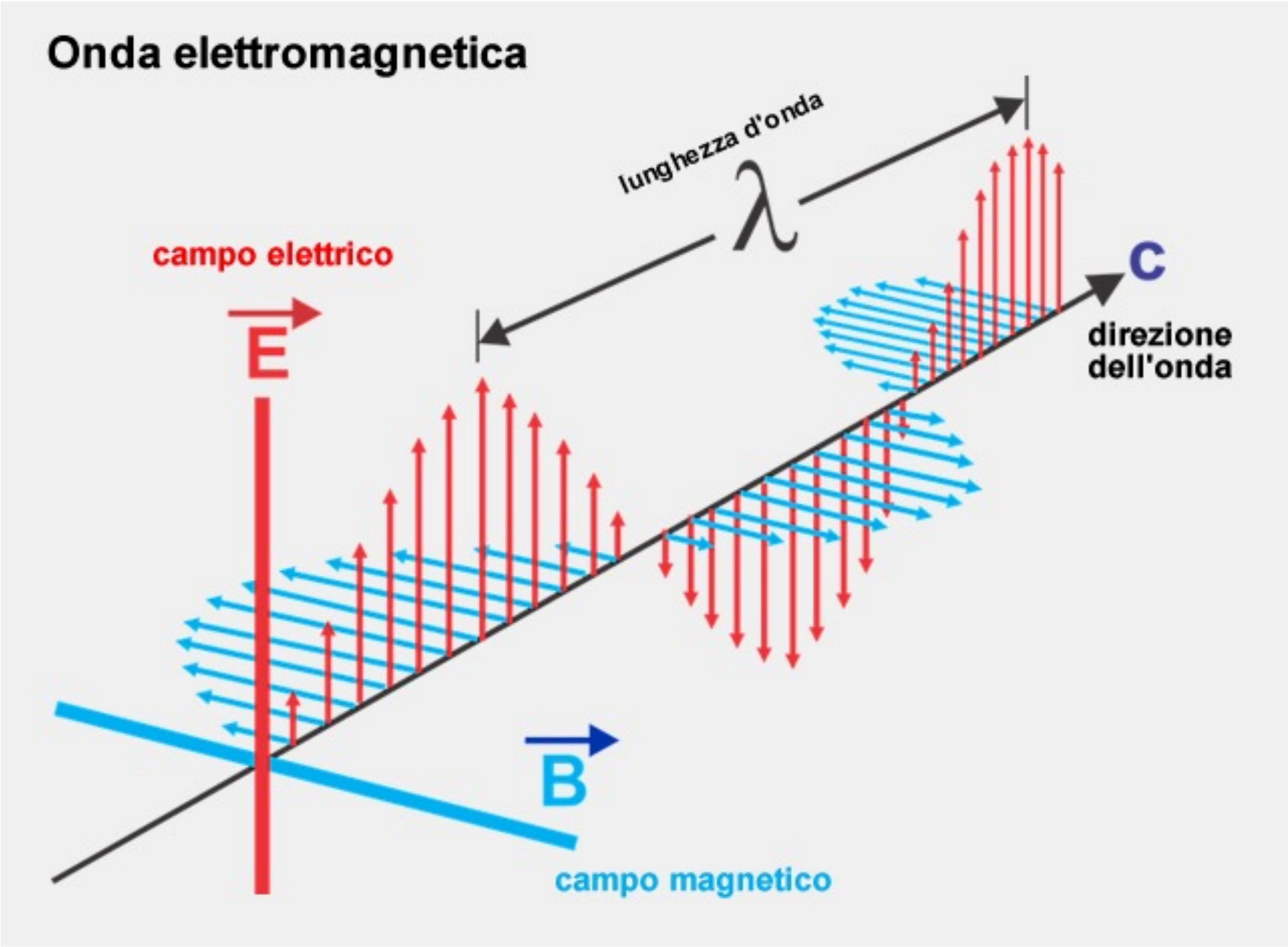
What is the best g-ray instrument?

Does not exist!
ONE Detector TO RULE
THEM ALL g–rays

Build your detector



The James Webb Space Telescope (JWST) is a space telescope being jointly developed by NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA).



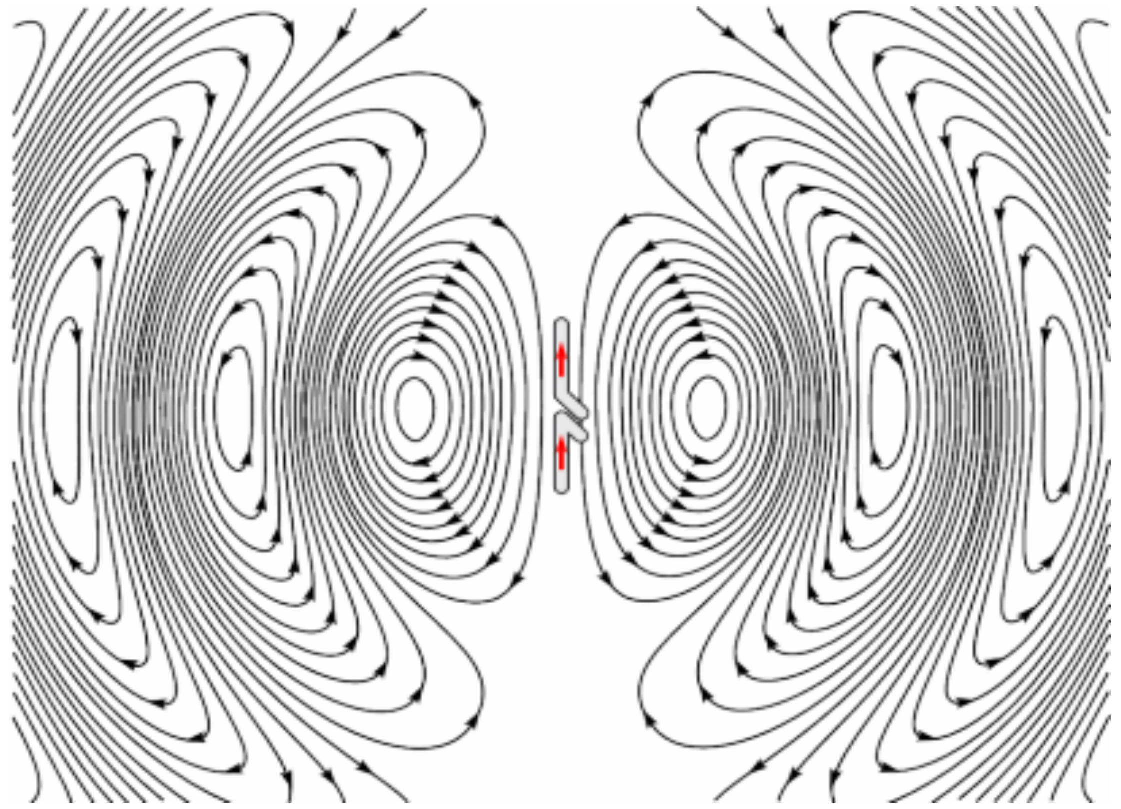
Wavelength λ

Frequency f

Energy E=hf

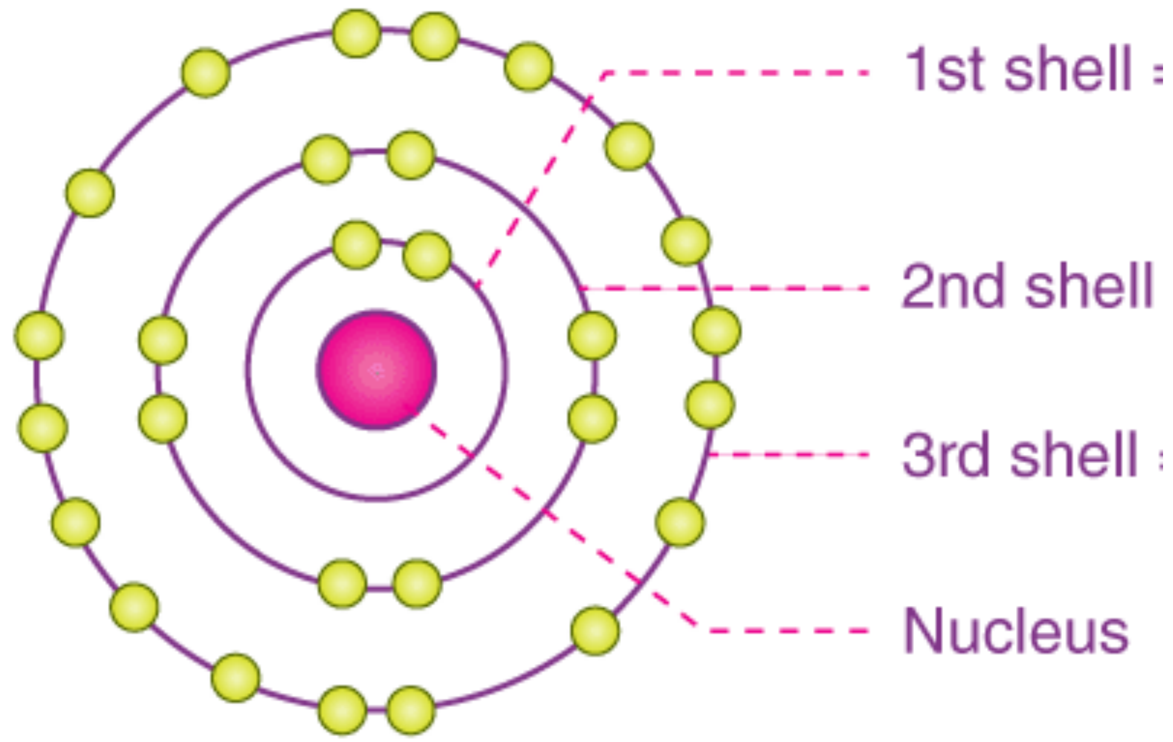
Speed c=299,792 km/s

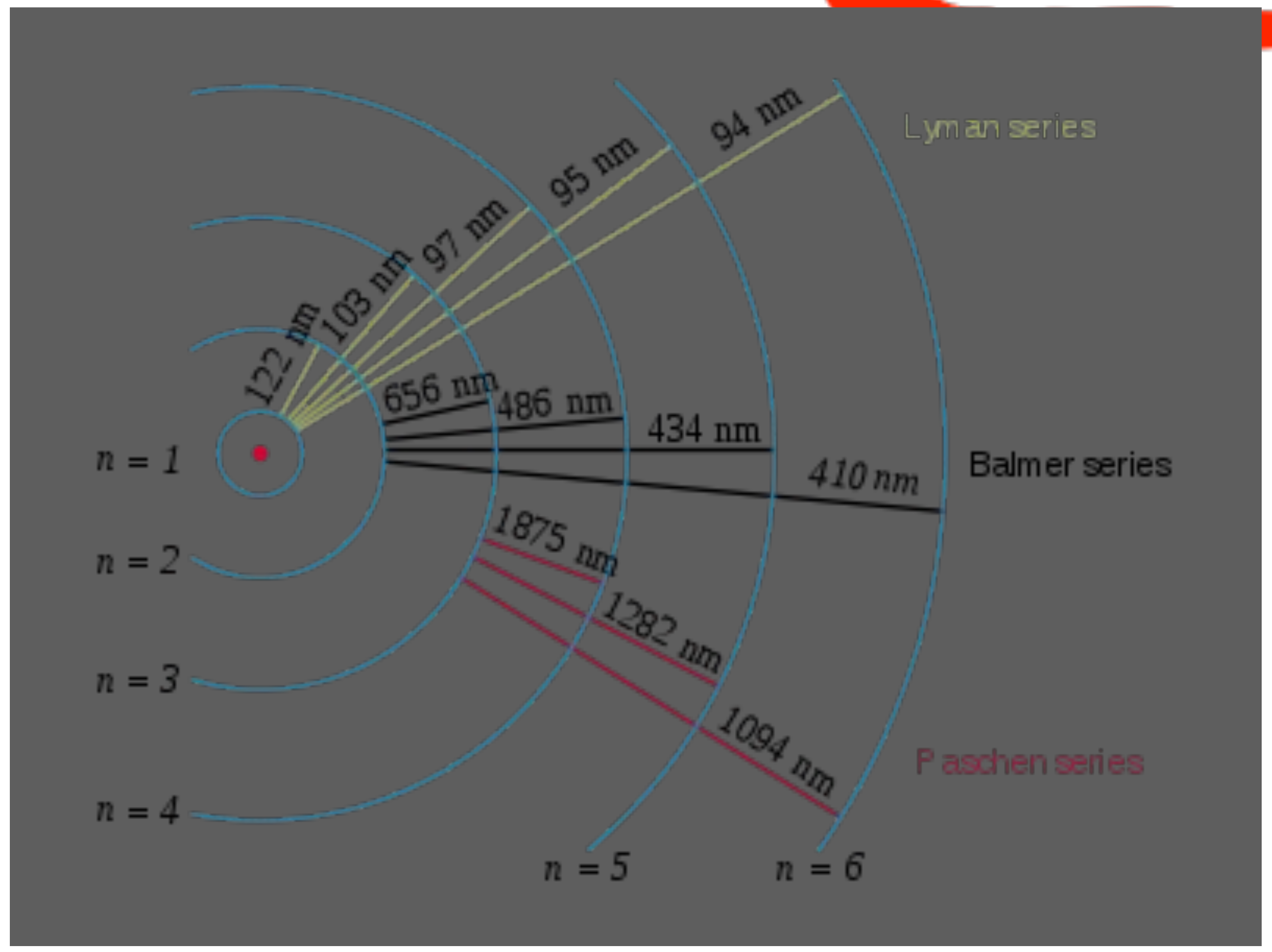
Do we know something more?



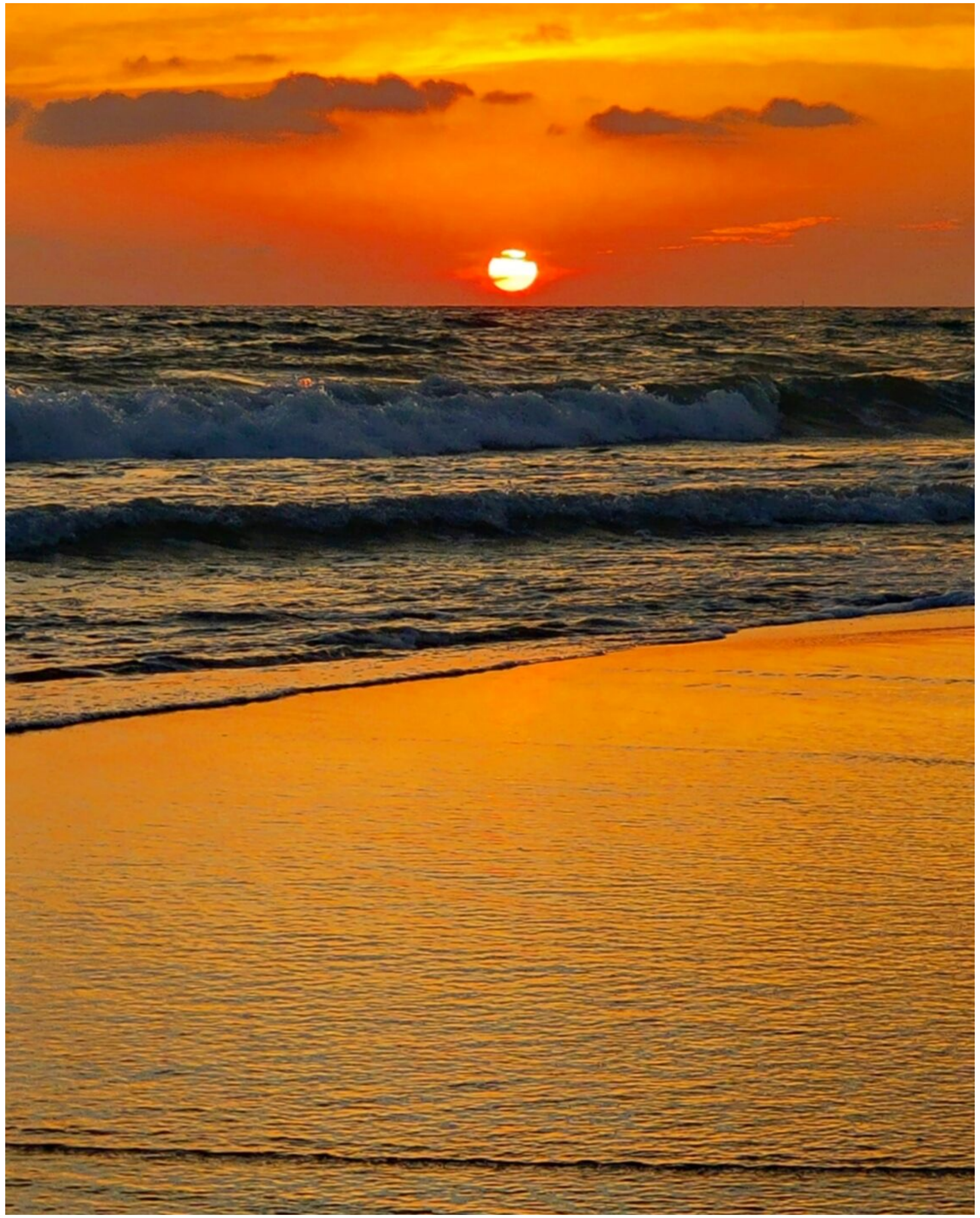
$$\textbf{Radio waveband}\; 3\ \text{MHz} \leqslant \nu \leqslant 30\ \text{GHz};$$
$$100\ \text{m} \geqslant \lambda \geqslant 1\ \text{cm}$$

HOW TO BUILD A RADIO TELESCOPE





1.4 Infrared waveband $3 \times 10^{12} \leqslant \nu \leqslant 3 \times 10^{14}$ Hz; $100 \geqslant \lambda \geqslant 1$ µm



Webb needs to be very cold ("cryogenic"),
with its mirrors at around -220 degrees

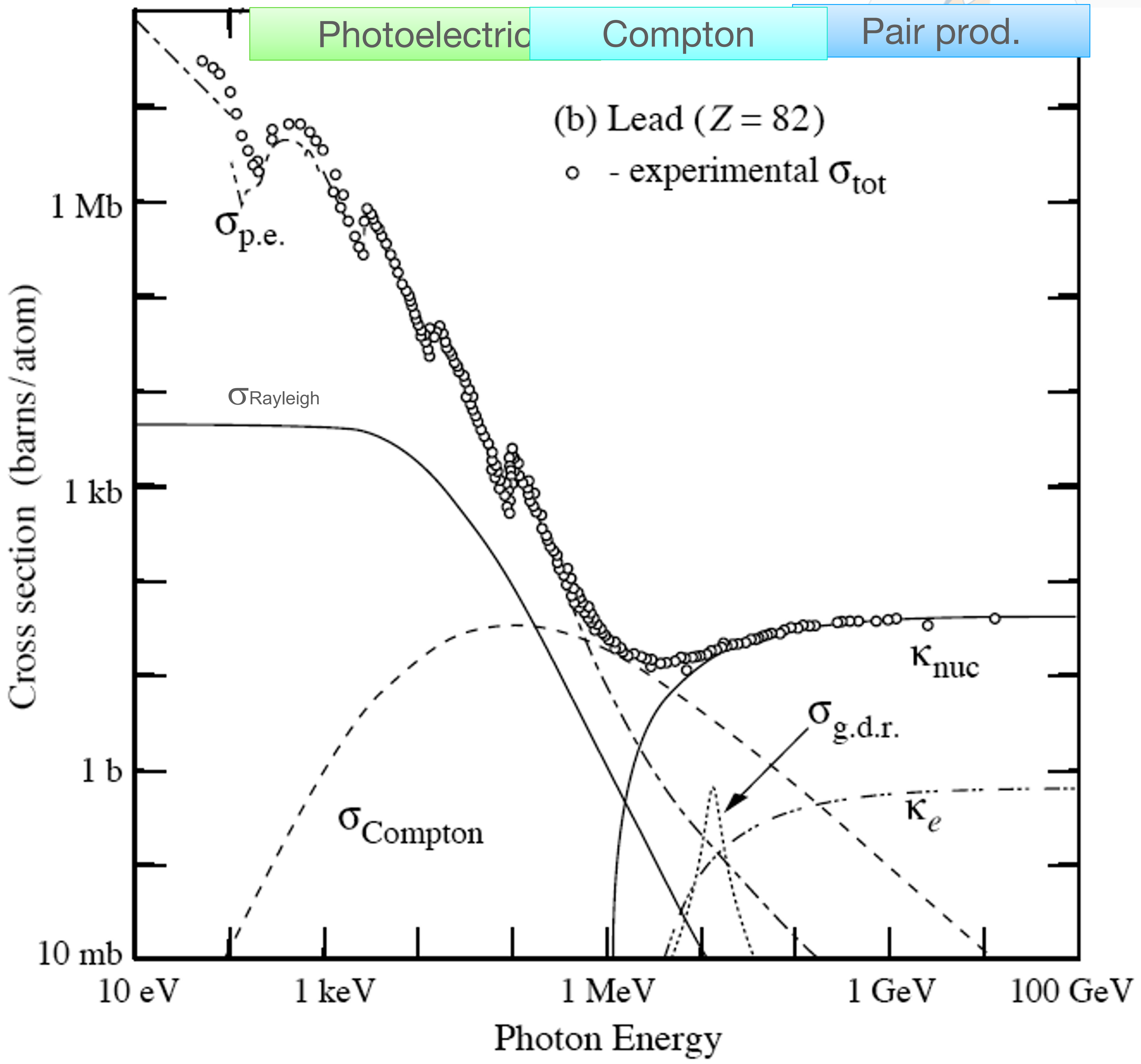
What about gamma-rays?

$$\gamma\text{-ray waveband } \nu \geqslant 3 \times 10^{19}\ \text{Hz};\ \lambda \leqslant 0.01\ \text{nm};$$
$$E \geqslant 100\ \text{keV}$$

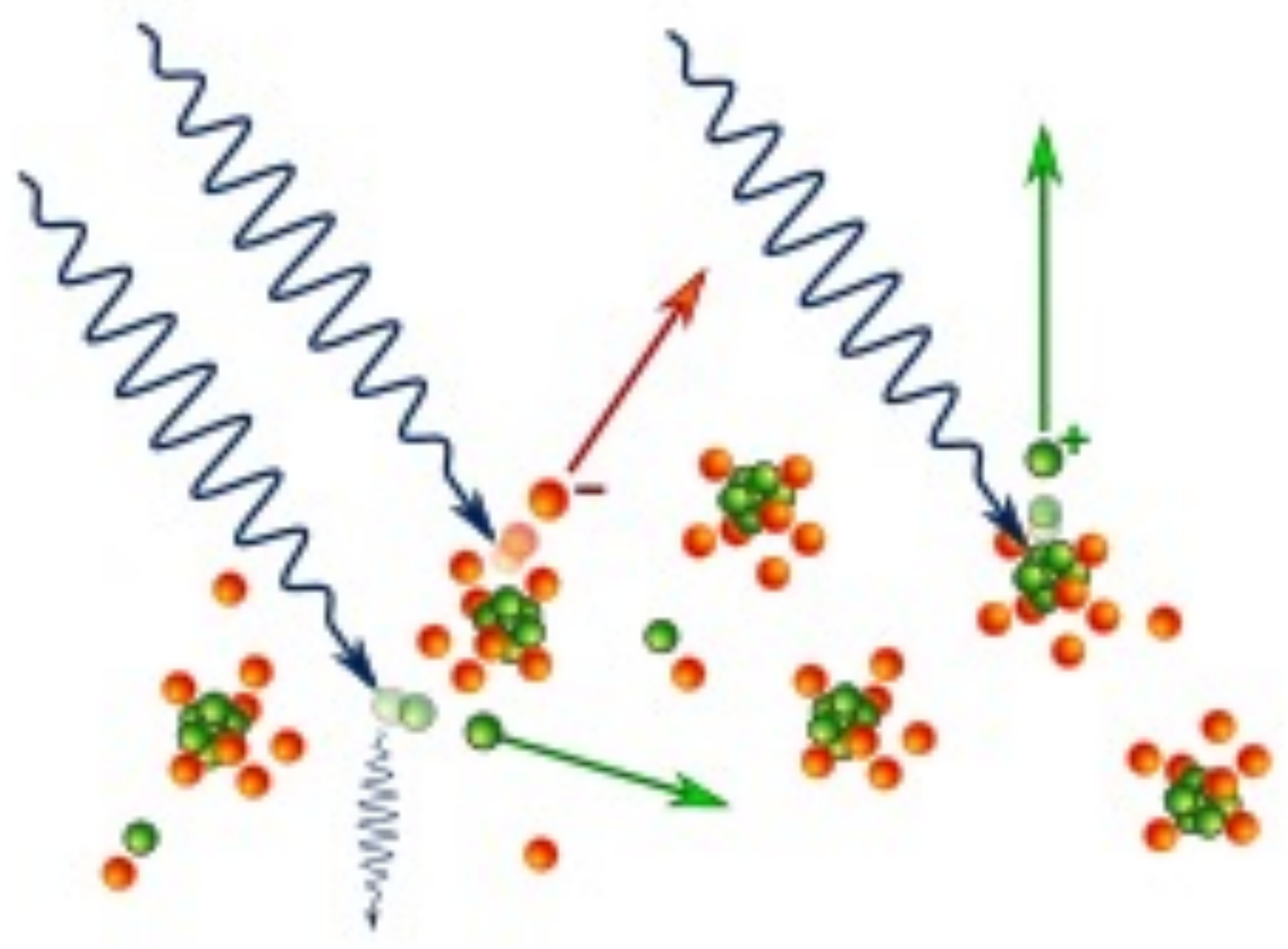
FACTS

- Facts:
  - Gamma-rays cannot be reflected, they too strongly interact with atoms/particles
- → check gamma-ray interaction with matter

Photon interactions in Pb



Compton effect



$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta),$$

where

- λ is the initial wavelength,
- λ' is the wavelength after scattering,
- h is the Planck constant,
- m_e is the electron rest mass,
- c is the speed of light, and
- θ is the scattering angle.

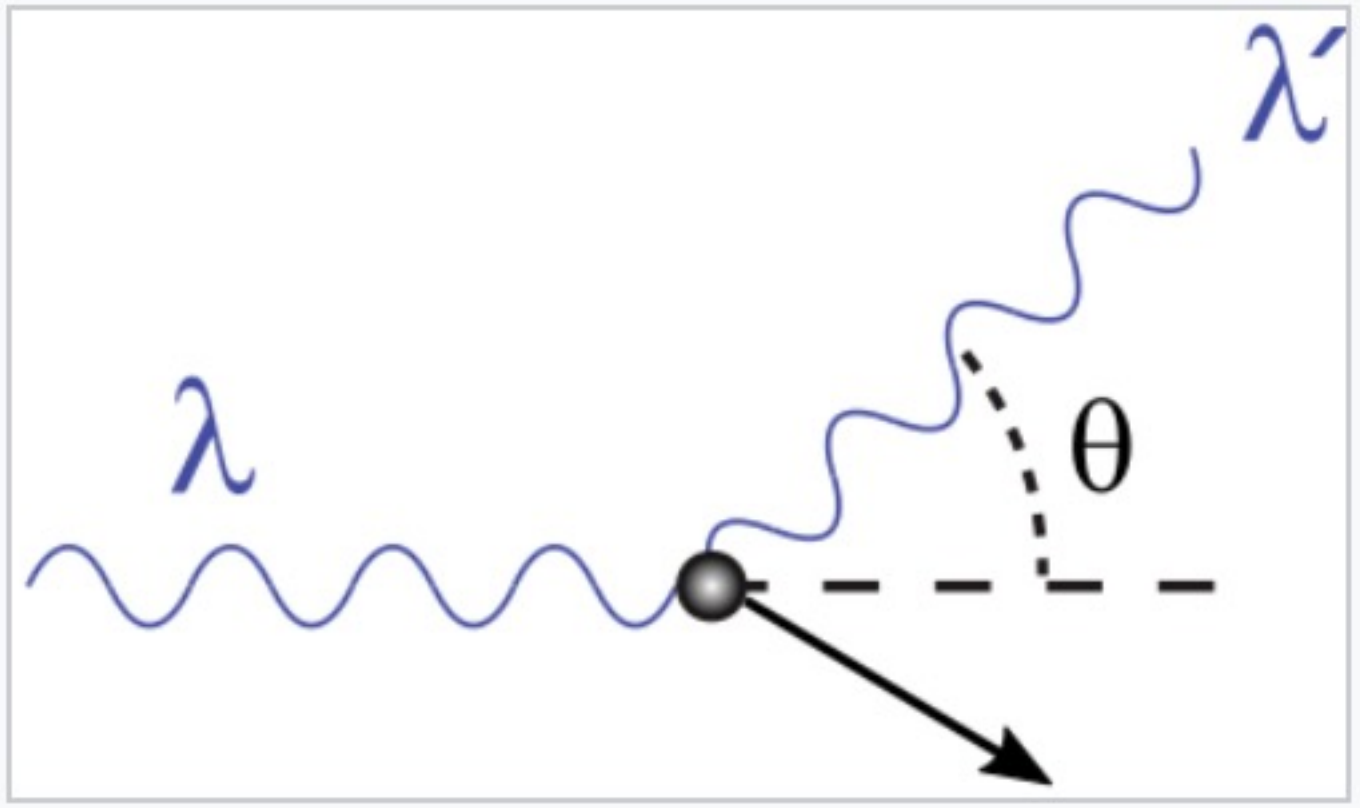
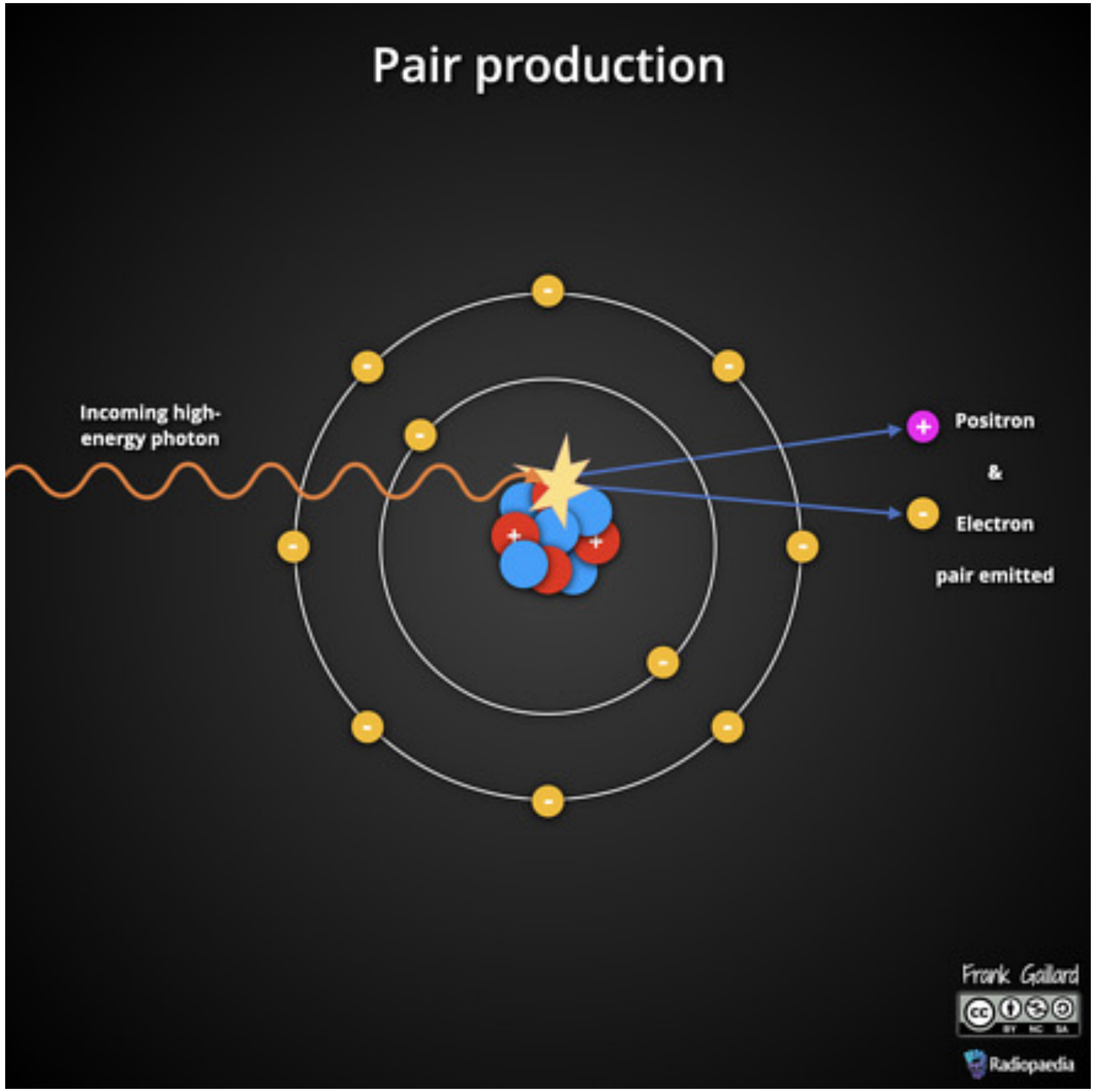


Fig. 2: A photon of wavelength λ comes in from the left, collides with a target at rest, and a new photon of wavelength λ' emerges at an angle θ. The target recoils, carrying away an angle-dependent amount of the incident energy.

- Scattering of a high frequency photon after an interaction with a charged particle, usually an electron.
- Decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma ray photon),

Pair production effect



- Two energetic photons can hit one another and become what they want (provided symmetries are respected)
- In particular it's very common they become electron/positron
- Also muon/antimuon, etc…

γ-rays from lightning
atmospheric nitrogen ^{14}N
Photonuclear reaction
neutrino
neutron
unstable nitrogen isotope ^{13}N
β⁺ decay
Scatterings in the atmosphere
stable carbon isotope ^{13}C
nitrogen ^{14}N
Annihilation
positron
electron
(n,p) reaction
Neutron capture
carbon isotope ^{14}C
nitrogen isotope ^{15}N
annihilation γ-rays at 0.511 MeV
Lightning!
300
Signal of

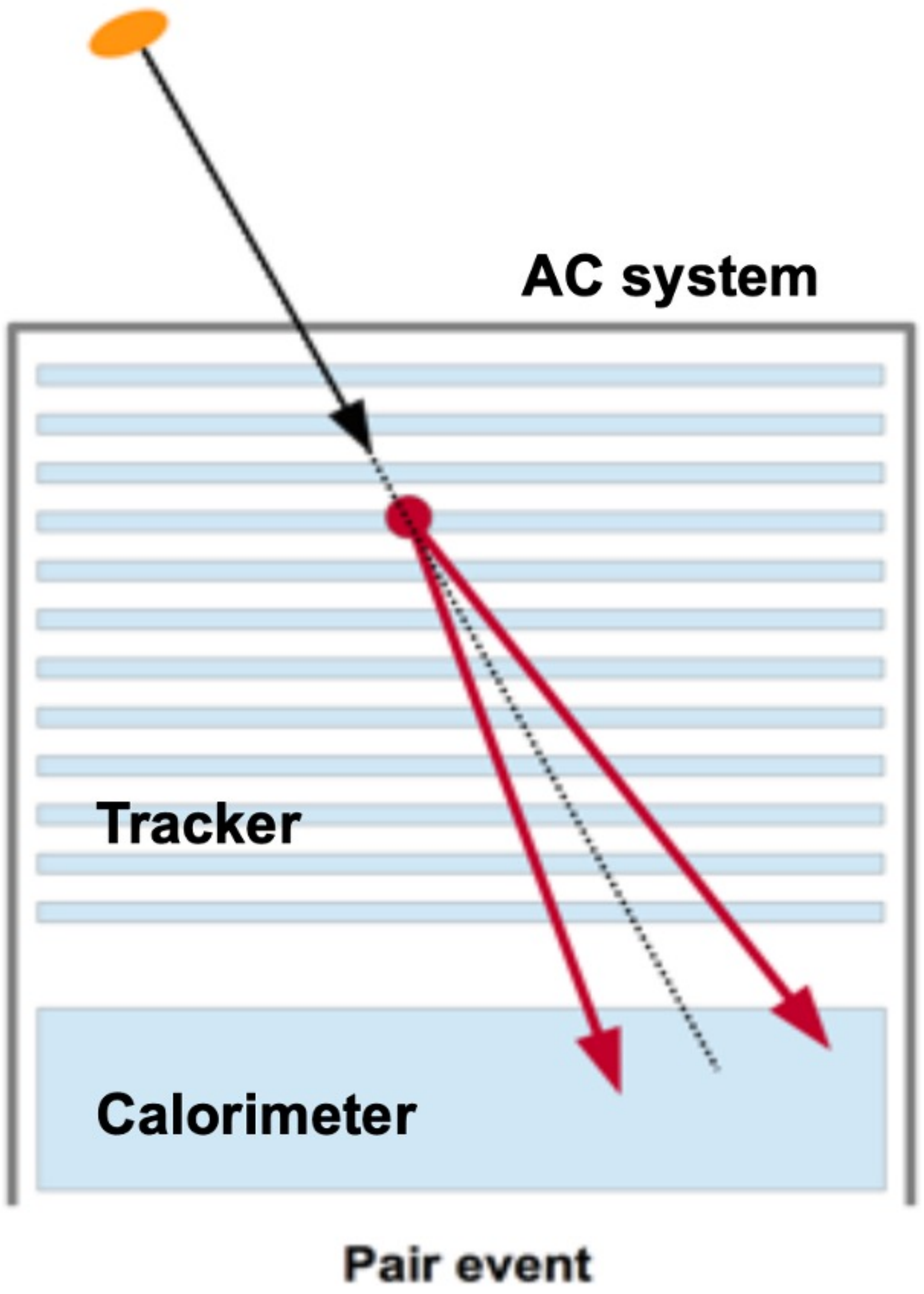
ATMOSPHERE is not transparent

- For same reason, atmosphere is not transparent to gamma-rays
- Btw, good for life
- Let’s go to space

FROM OUTSIDE THE ATMOSPHERE

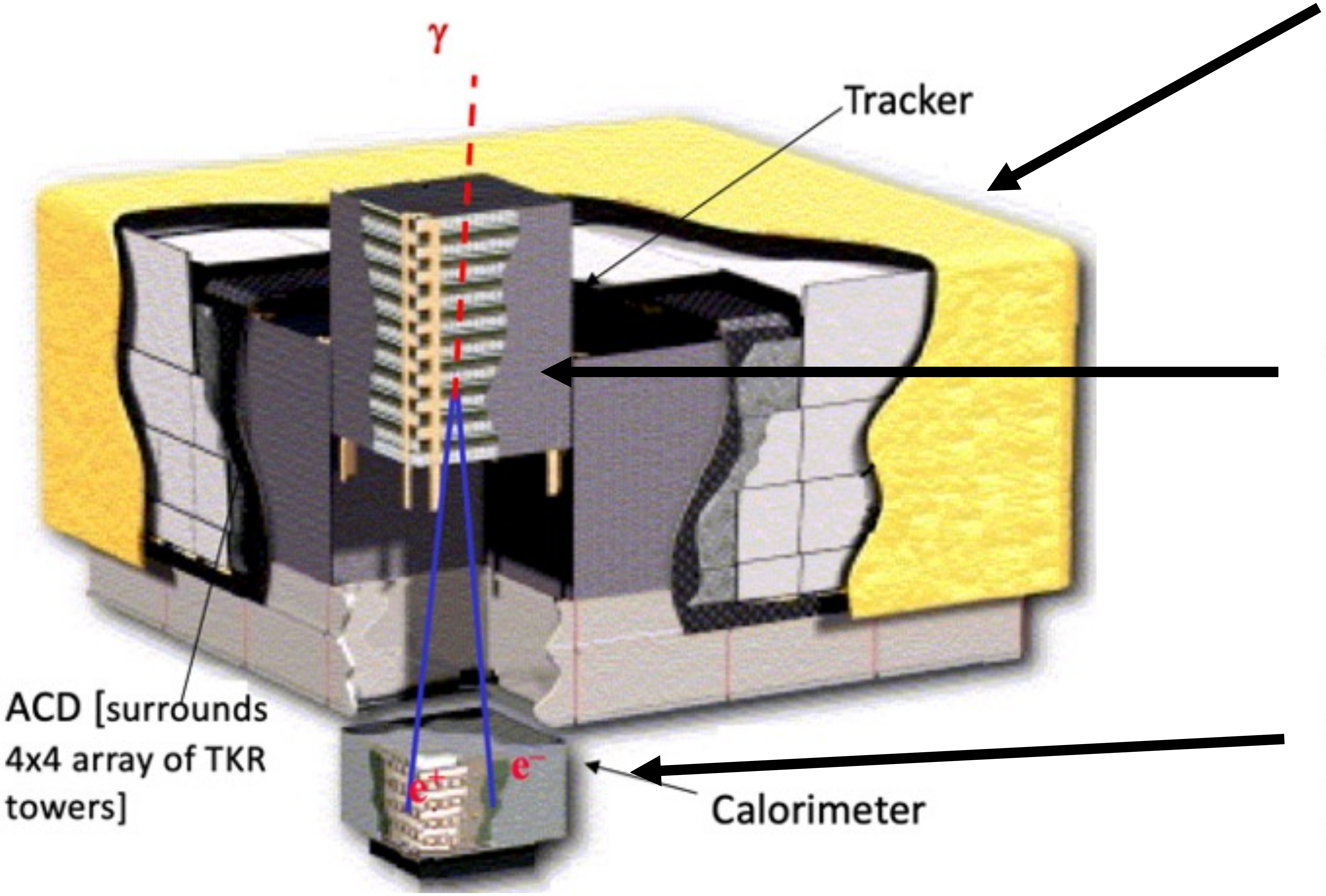
Better not go yourself
unless your are a crazy
Red Bull paracadutist!

Use pair production



- Gamma-rays are often searched for in accelerator / beam dump experiments
- Don't invent hot water again, go ask them particle physicists!

From accelerators to space

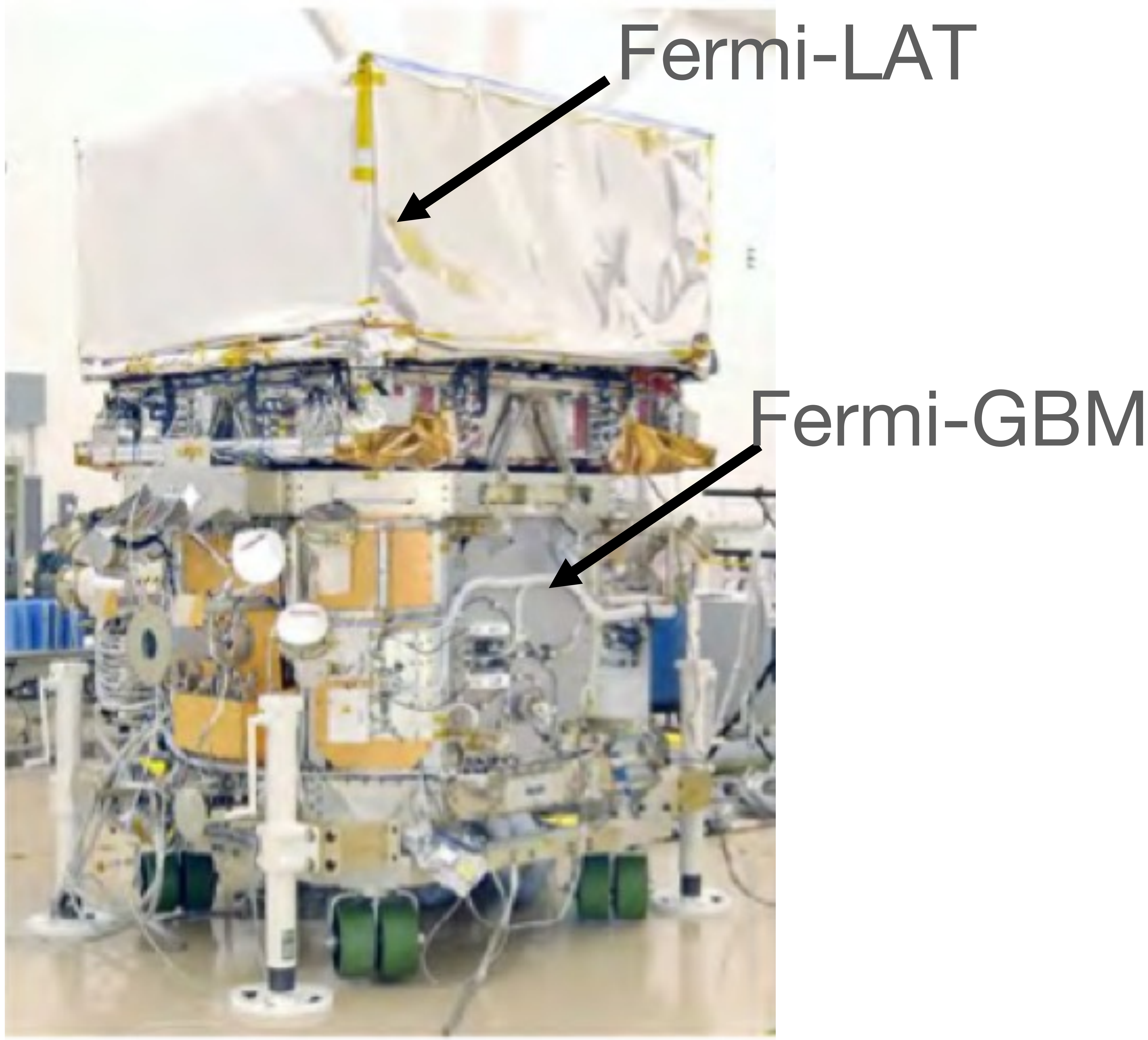


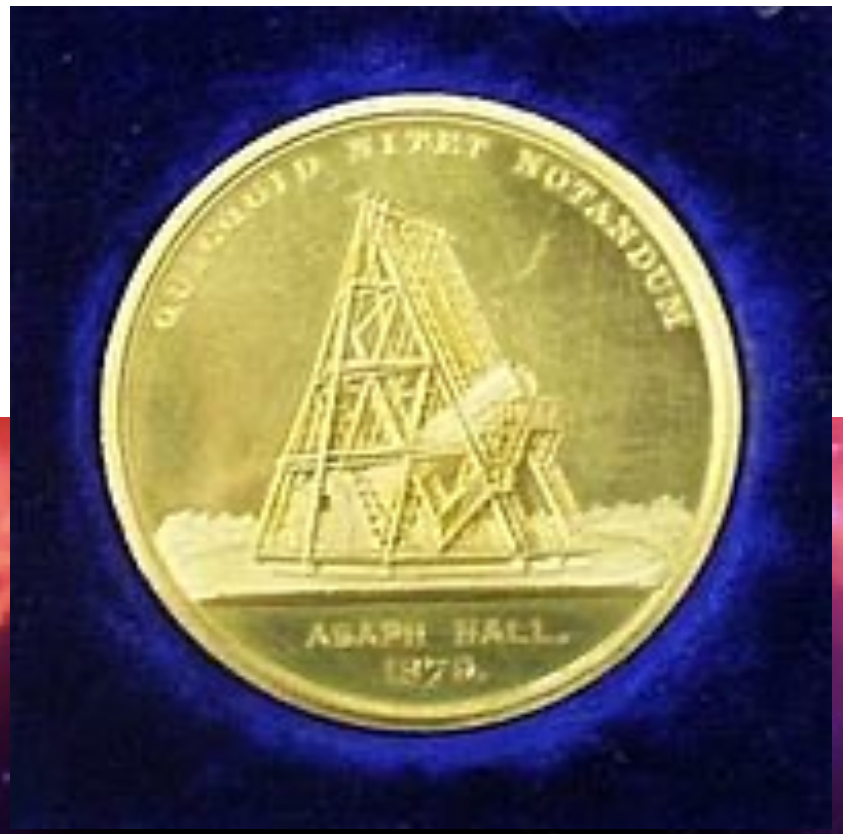
Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles.

Precision Si-strip Tracker (TKR)
70 m^2 of silicon detectors arranged in 36 planes. 880,000 channels.

Hodoscopic CsI Calorimeter(CAL)
1536 CsI(Tl) crystals in 8 layers, total mass 1.5 tons.

From design to construction





Fermi
Gamma-ray Space Telescope

Metrology of Fermi-LAT

- To first-year Physics students I teach metrology.
- What are Fermi-LAT metrological parameters (aka figure of merit)?

Sensitivity/ acceptance
- Minimum flux in given time
- Min/Max energy

Energy resolution

Angular resolution

Duty cycle

...

fermi.gsfc.nasa.gov
Projects
Didattica
Social
Utilities
Personale
Links
Reading List
URL Short INFN
Progettare un cor...
NASA
National Aeronautics and Space Administ
Goddard Space Flight Center
Fermi
Gamma-ray Space Telescope
Home
What is Fermi
Science
Fermi@10
Fermi's Decade of Gamma-ray Discoveri
Fermi's Decade of Gamma-ray Discove
Exploring the Extreme Universe
Supernova Remnants
Gamma-ray Bursts
Pulsar Wind Nebulae
Active Galactic Nuclei
Extragalactic Background
About Fermi
Click on the images or topic name for information about these science topics.
Catalogs
Binary Sources
Dark Matter
Pulsars
Terrestrial Gamma-ray Flashes
Diffuse Gamma Radiation
electronic catalog version provides gamma-ray pulsar ephemerides, properties and fit results to

Figure of merit of Fermi-LAT

LAT Characteristics

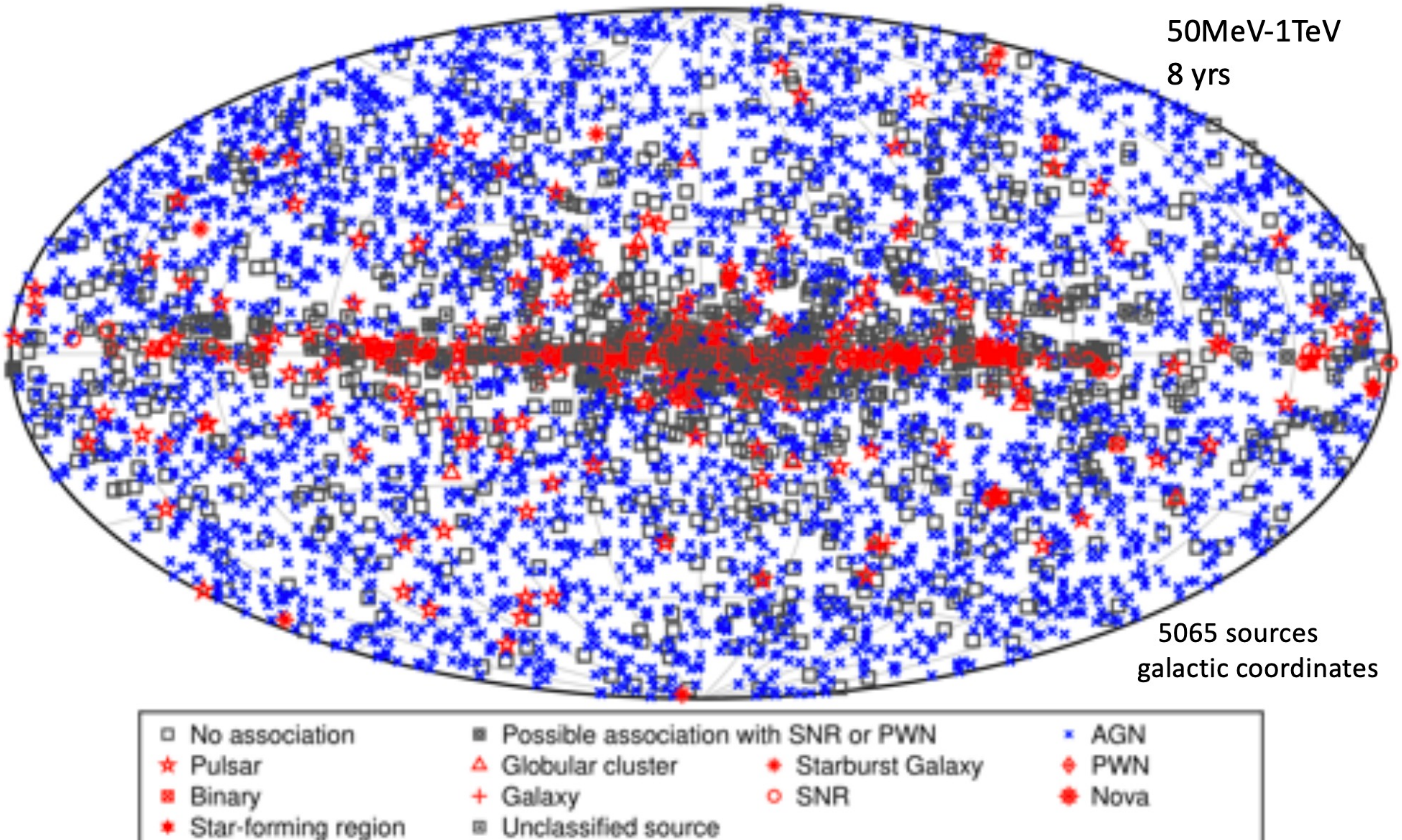
Parameter	Value or Range
Energy Range	~20 MeV to >300 GeV
Energy Resolution	<15% at energies >100 MeV
Effective Area	>8,000 cm^{2} maximum effective area at normal incidence
Single Photon Angular Resolution	<0.15ï¿½, on-axis, 68% space angle containment radius for E > 10 GeV; < 3.5ï¿½, on-axis, 68% space angle containment radius for E = 100 MeV
Field of View	2.4 sr
Source Location Determination	<0.5 arcmin for high-latitude source
Point Source Sensitivity	<6x10^{-9} ph cm^{-2} s^{-1} for E > 100 MeV, 5σ detection after 1 year sky survey
Time Accuracy	<10 microseconds, relative to spacecraft time
Background Rejection (after analysis)	<10% residual contamination of a high latitude diffuse sample for E = 100 MeV - 300 GeV.
Dead Time	<100 microseconds per event

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/LAT_overview.htm

- You can check these info yourself to 'understand' past and current experiments!

A lot of fun

The sky in gamma-rays 4th source catalog

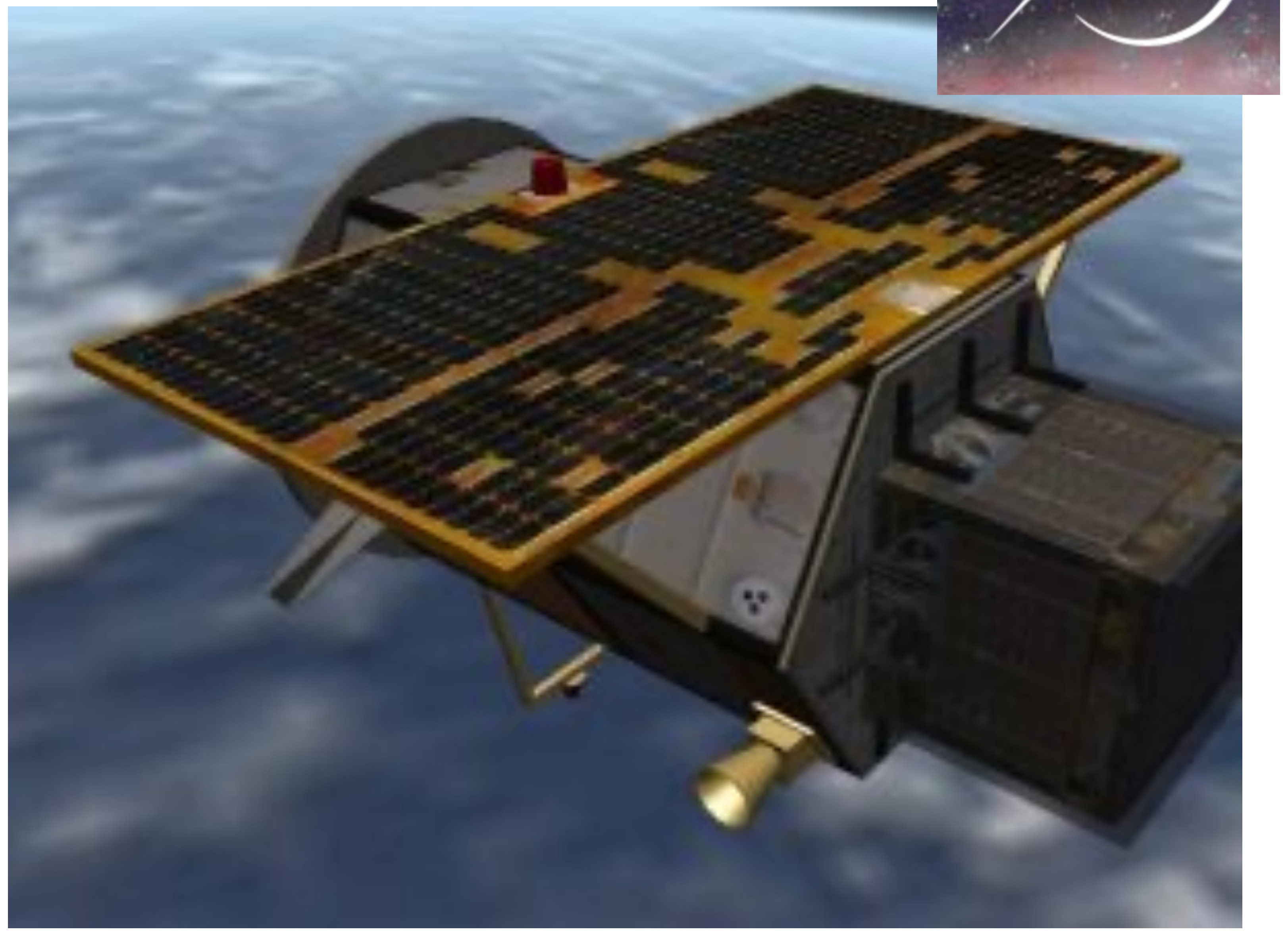


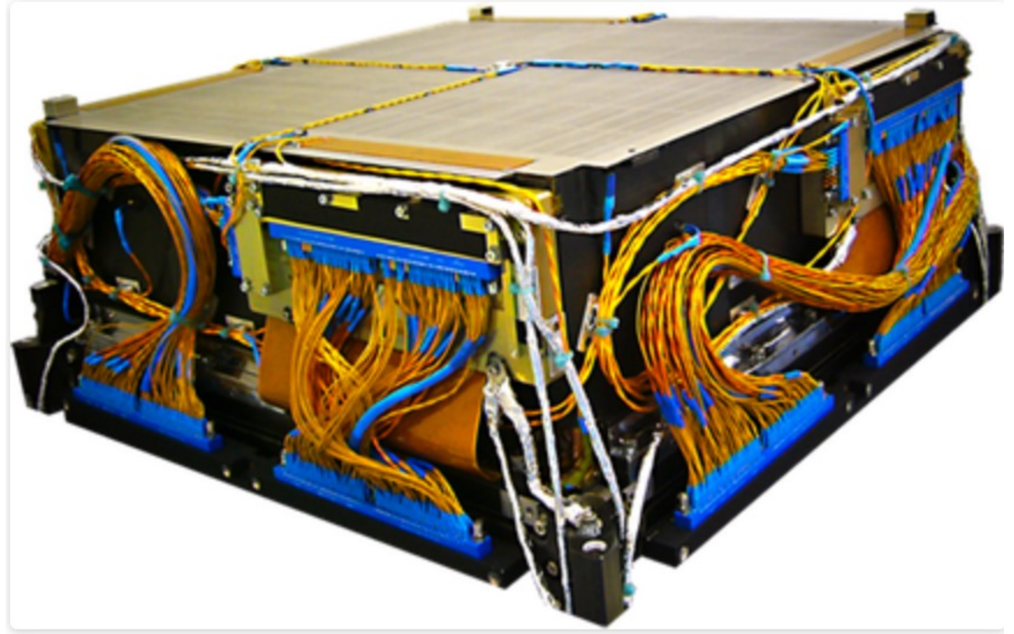
50MeV-1TeV
8 yrs

5065 sources
galactic coordinates

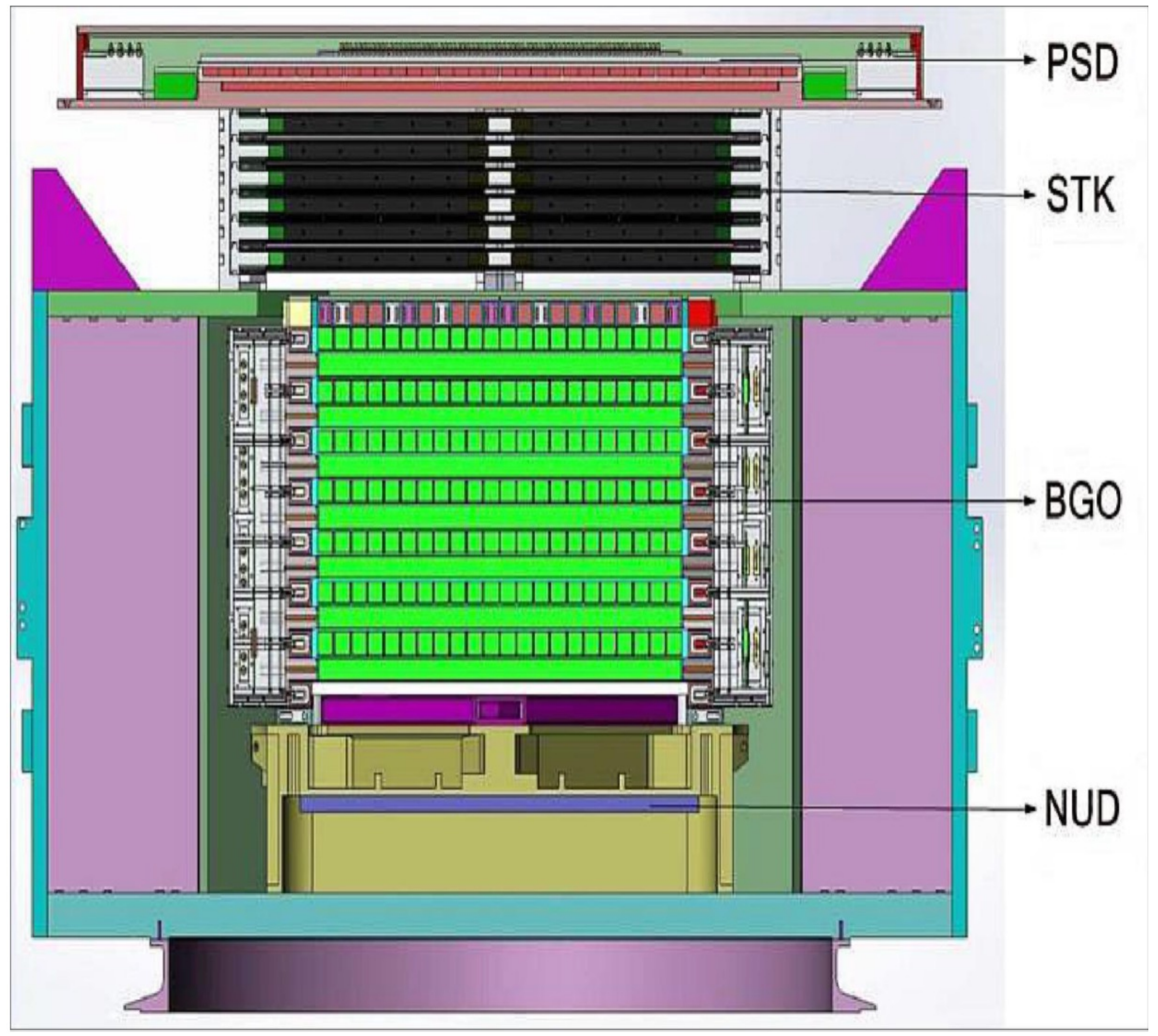
Type
Pulsars
Pulsar Wind Nebulae (PWNe)
Supernova Remnants (SNRs)
Candidate SNR/PWNe
Quasars (steep and soft spectrum)
BL Lac Blazars
Flat Spectrum Radio Quasars
Other Active Galactic Nuclei
Normal & Starburst Galaxies
Other*
Totals
Unassociated

AGILE





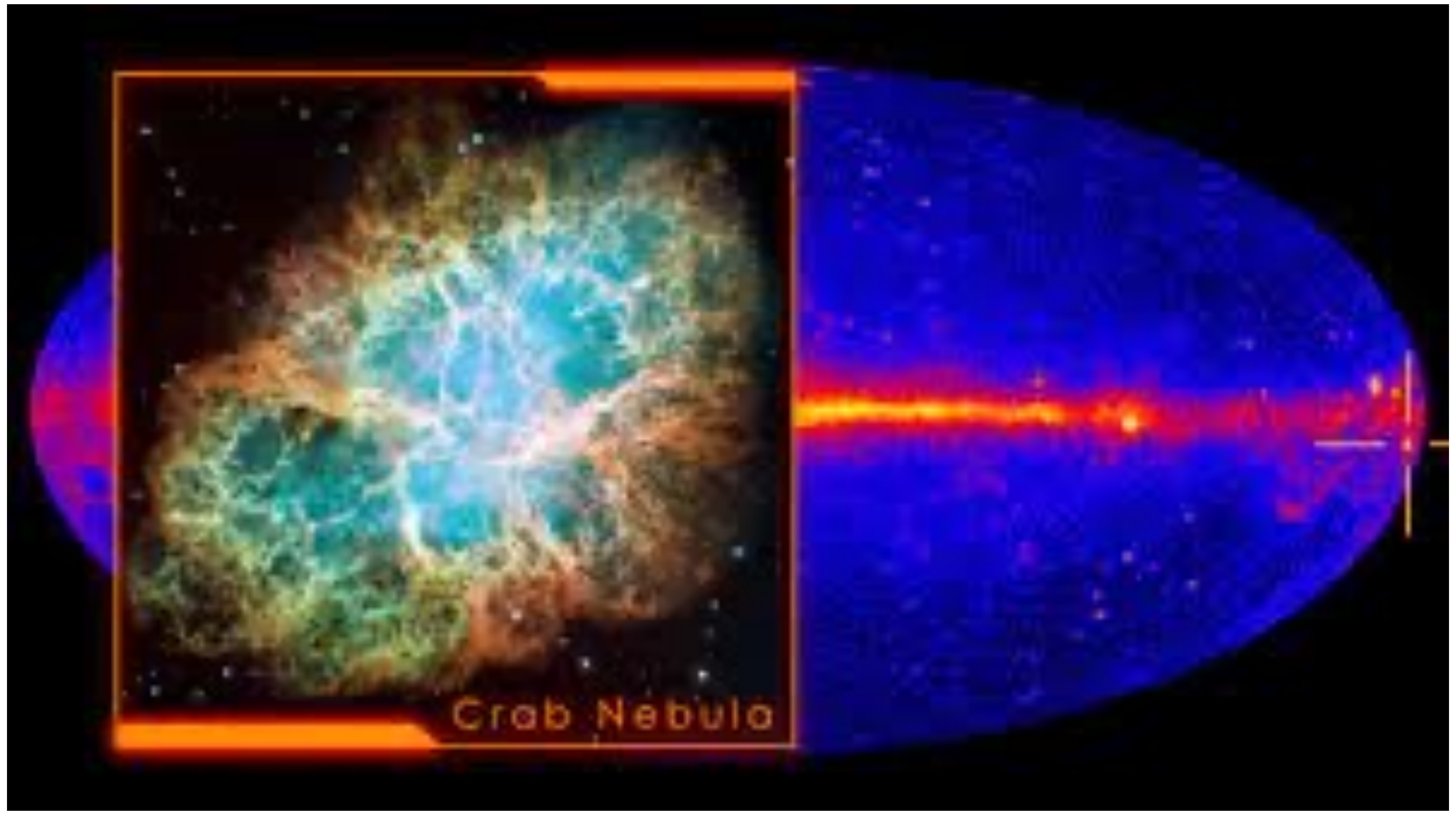
- Launched in 2007
- Should have been a precursor of LAT



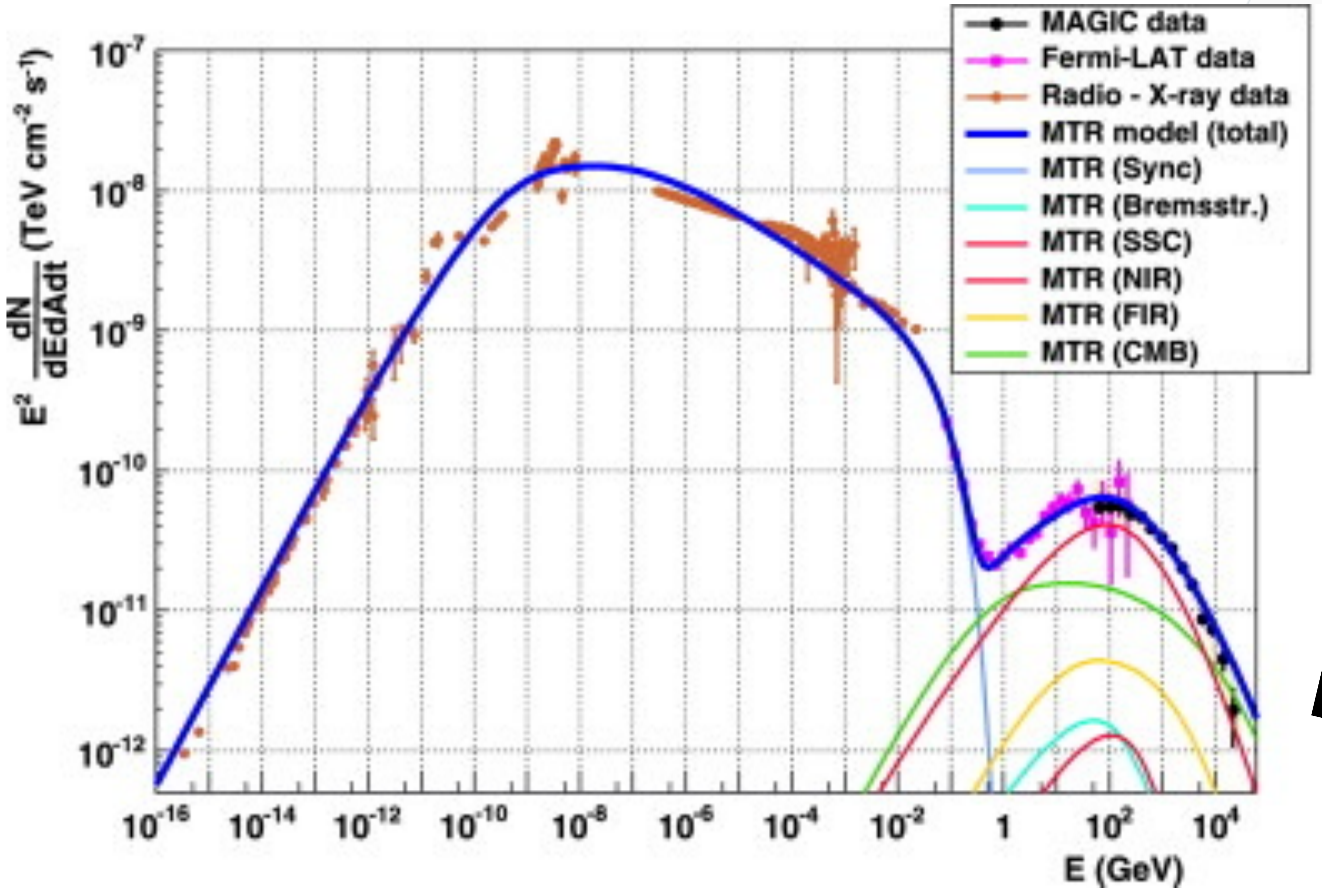
DAMPE (DARK MATTER PARTICLE EXPLORER)

Drawbacks

Take e.g. the Crab Nebula



Crab Nebula SED



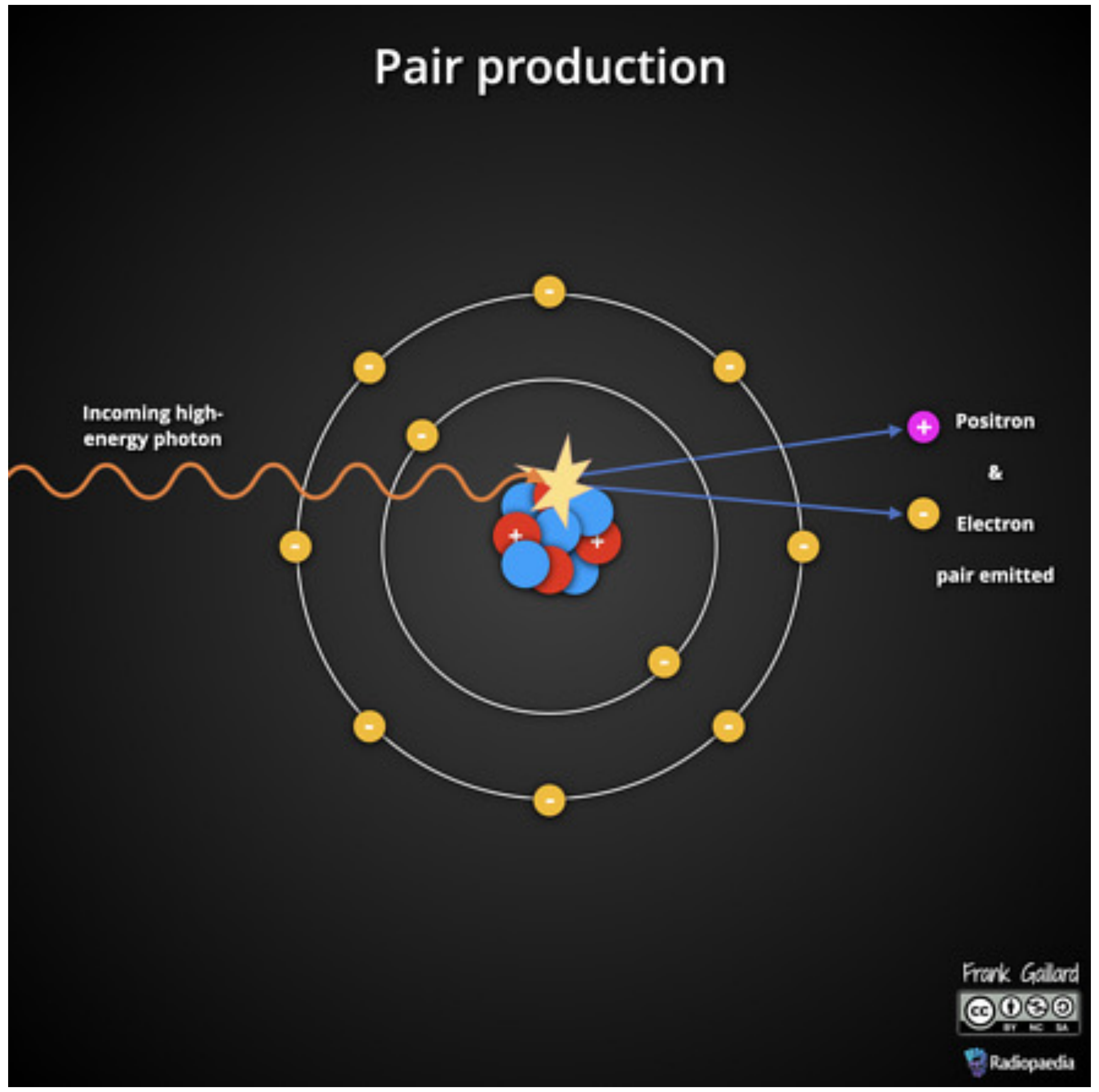
Very quickly Falling flux

Sensitive area is the geometrical area of the detector 2m^2, Houston we have a problem

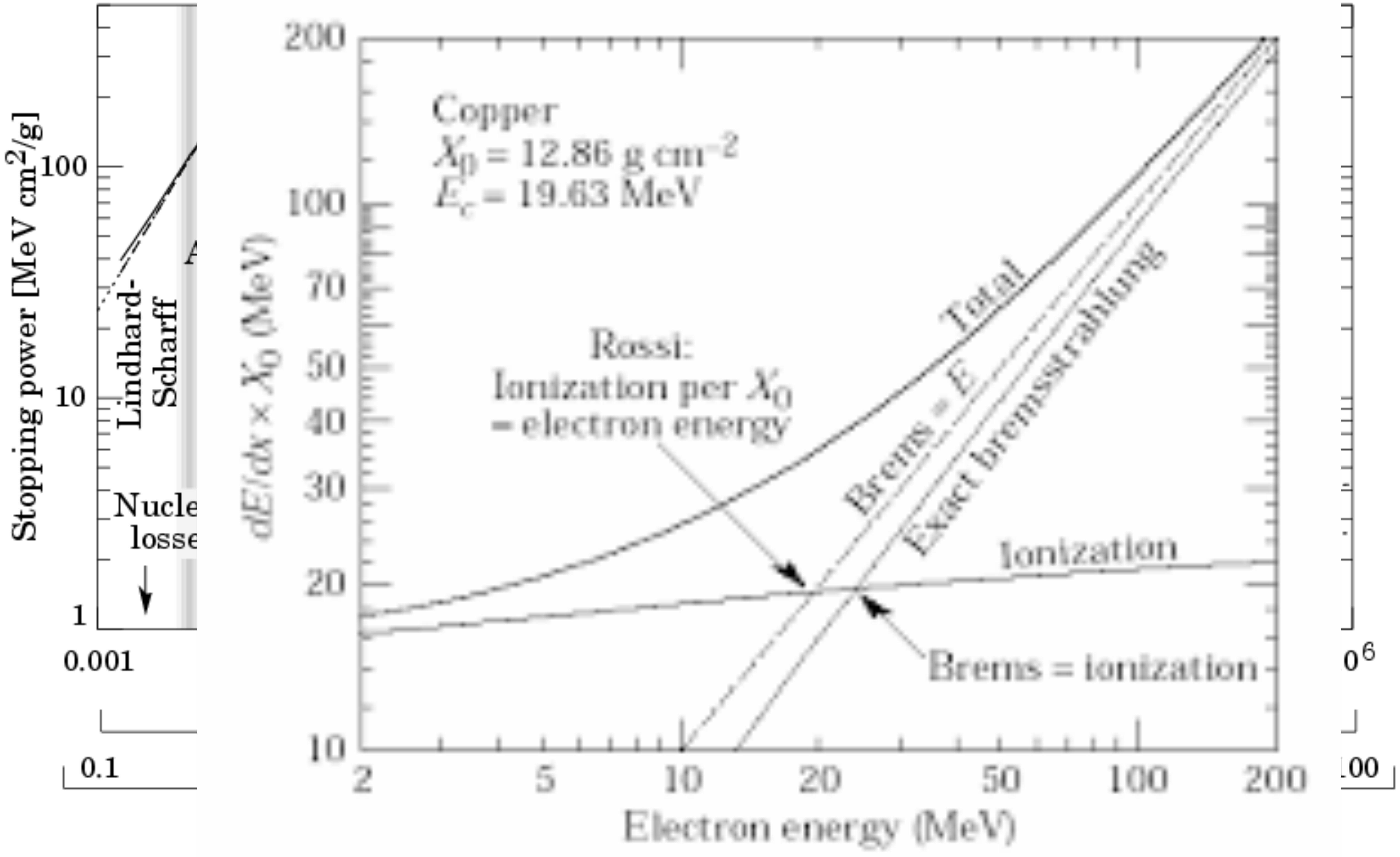
How to get to larger energies?

Solution is…to take a shower (not a joke)

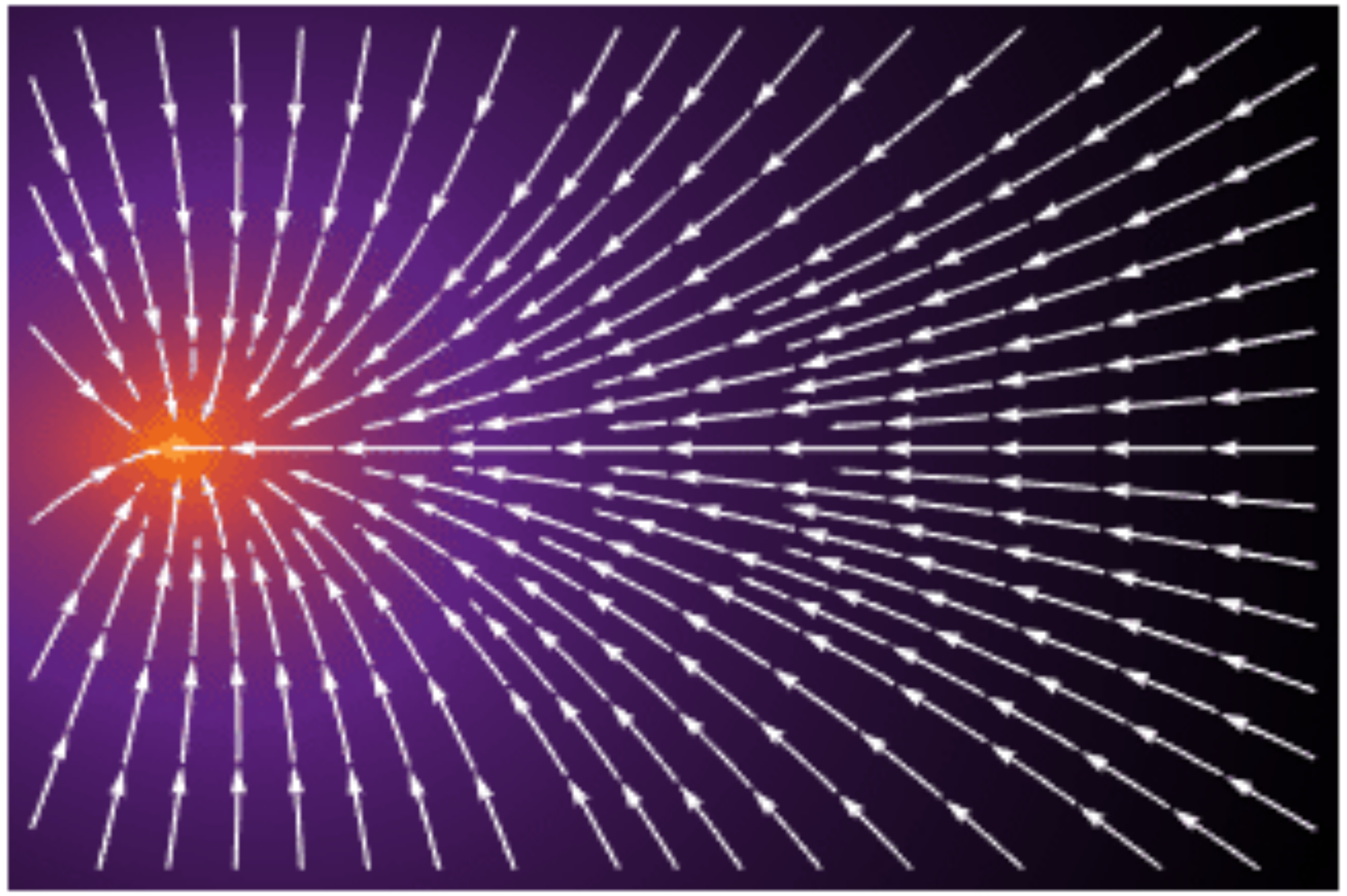
Remember pair production

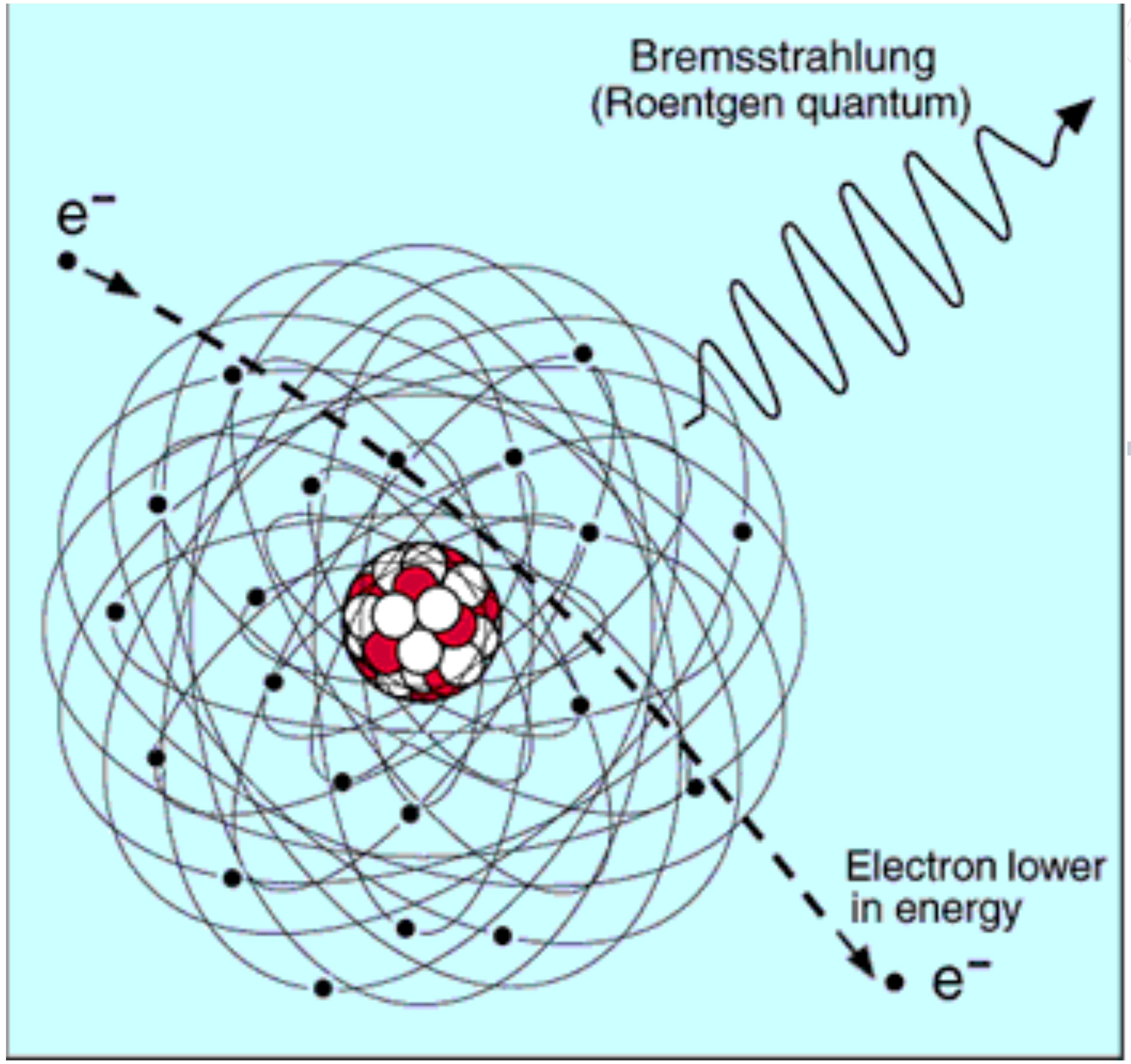


- Pair production can happen in the atmosphere, but are electron lost?



Decelerating charge: Breemstrahlung



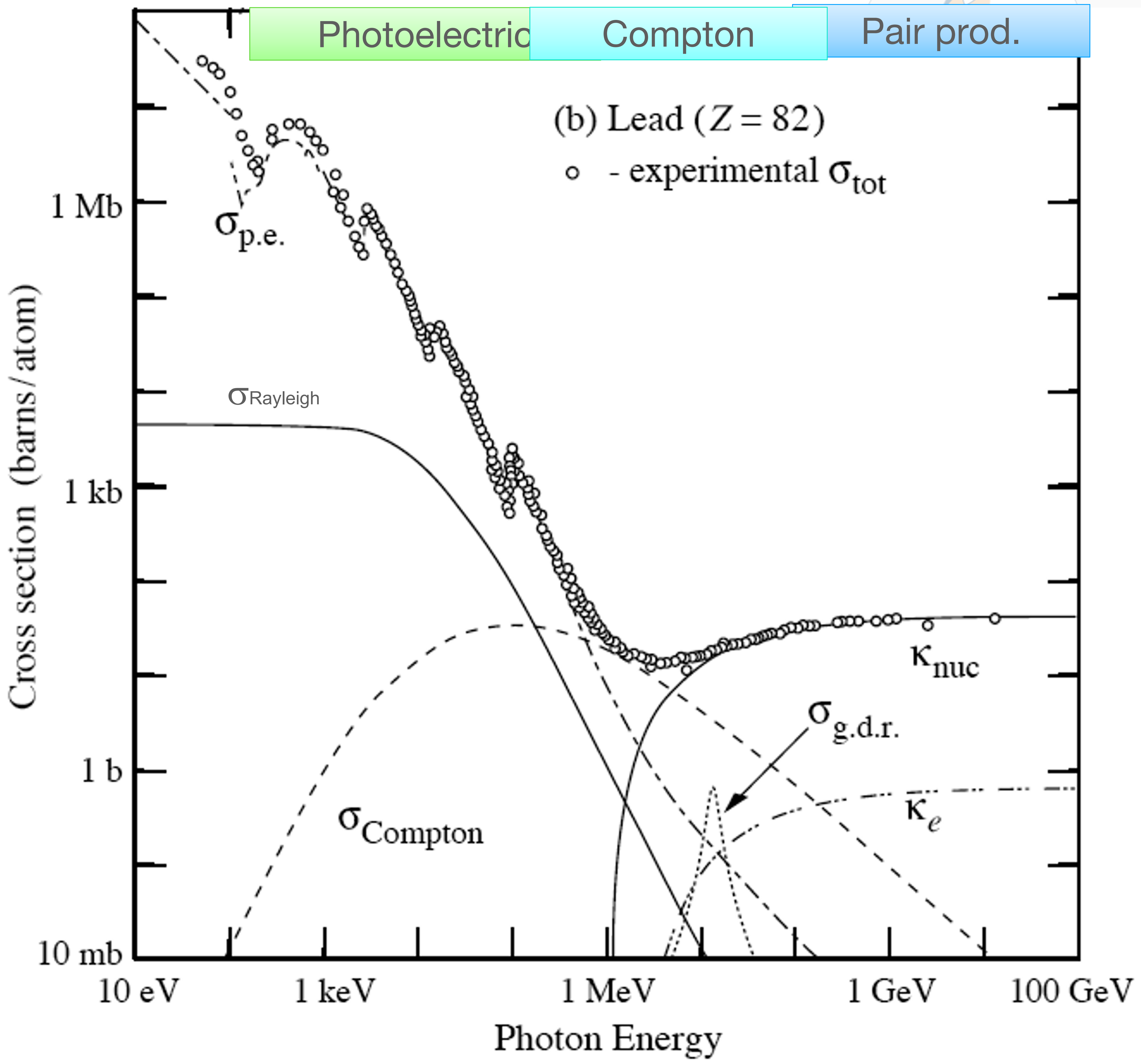


- From the first electron-positron pair → secondary emission of gamma-rays

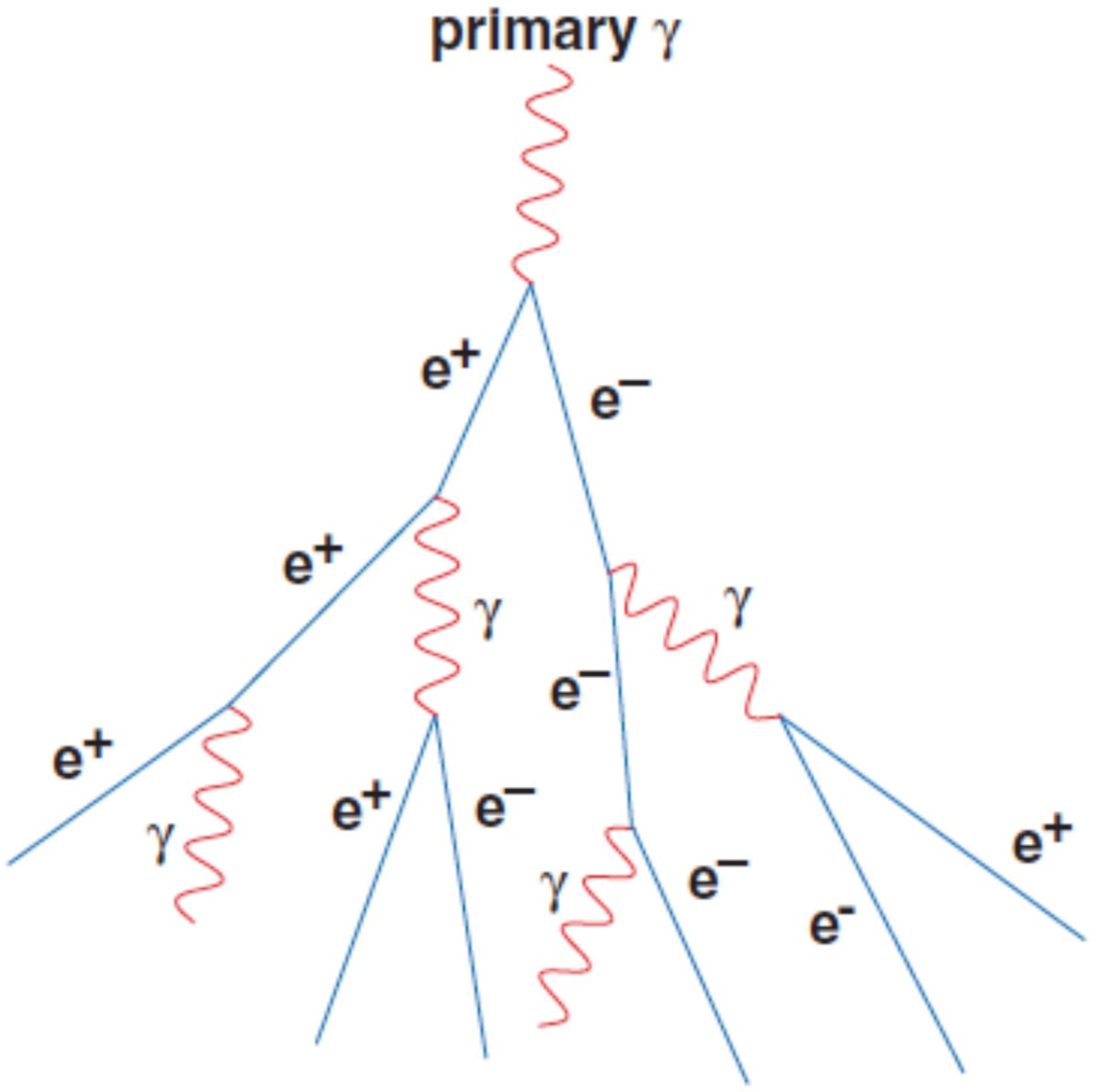
Wait…

- Didn't we say before gamma-rays interact with matter?
- Primary or secondary does not matter…

Photon interactions in Pb

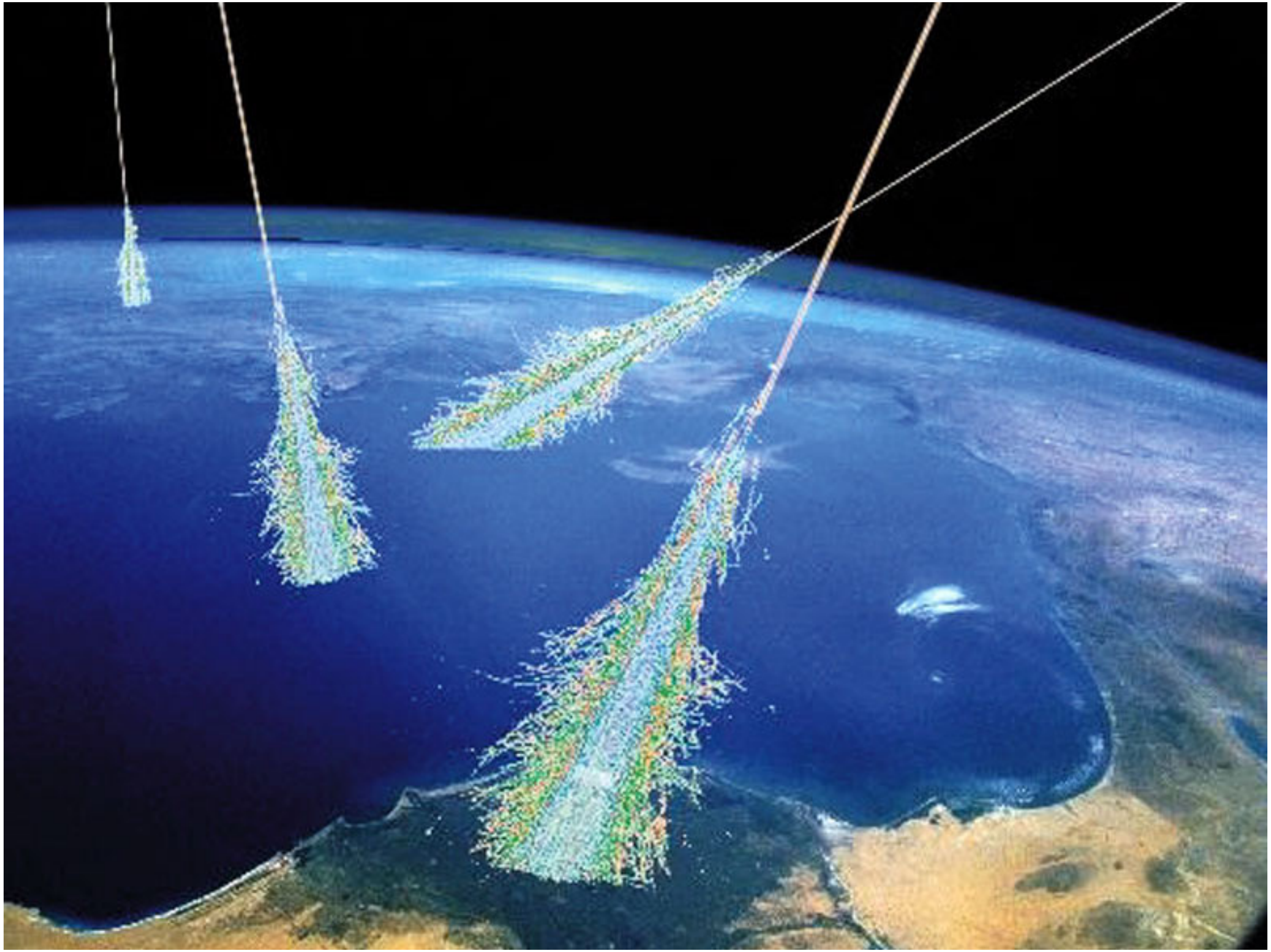


A “shower” of particles



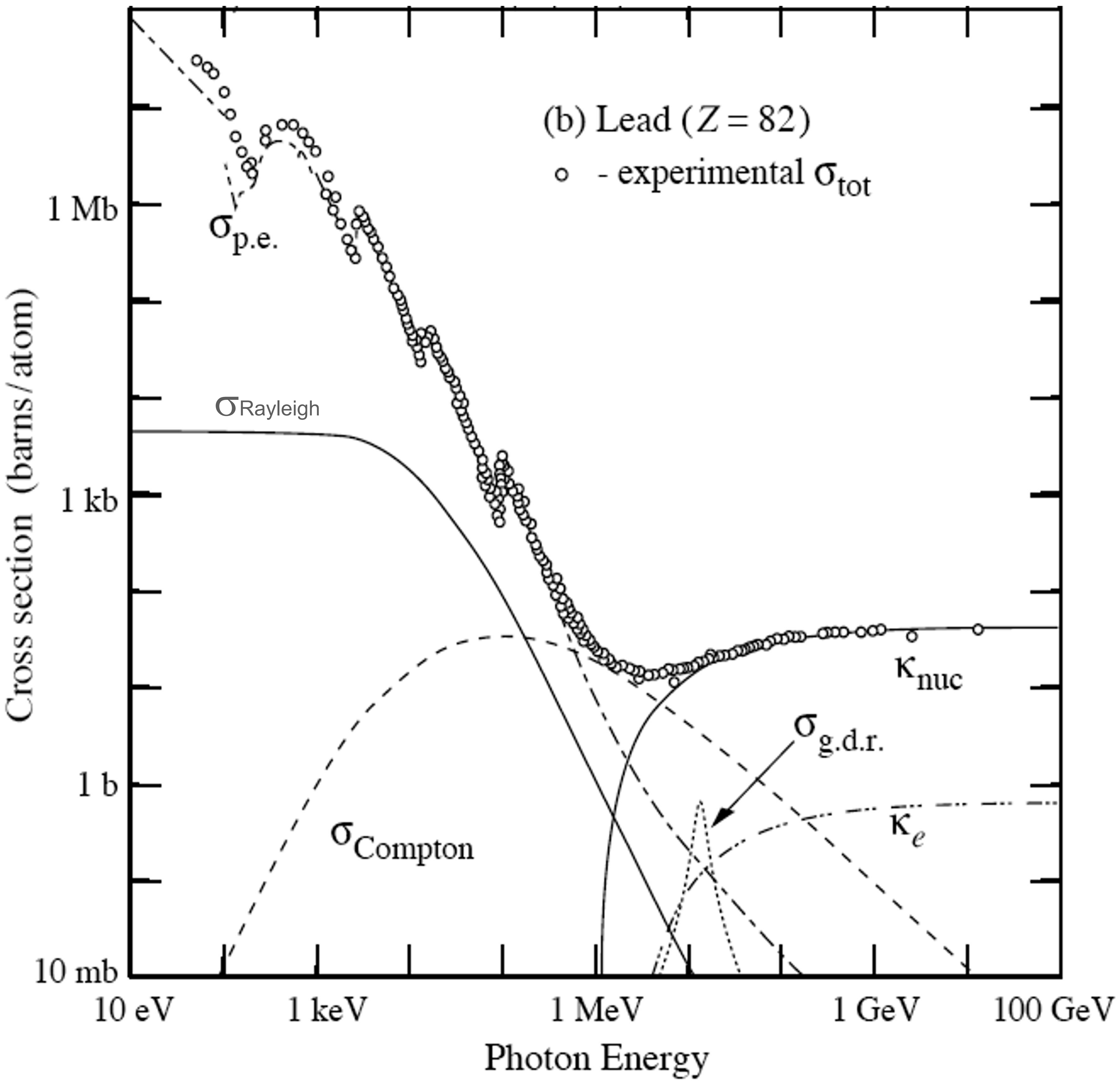
- A cascade of particles is born
- First studied by Bruno Rossi who dubbed them ‘docce’ (aka showers)

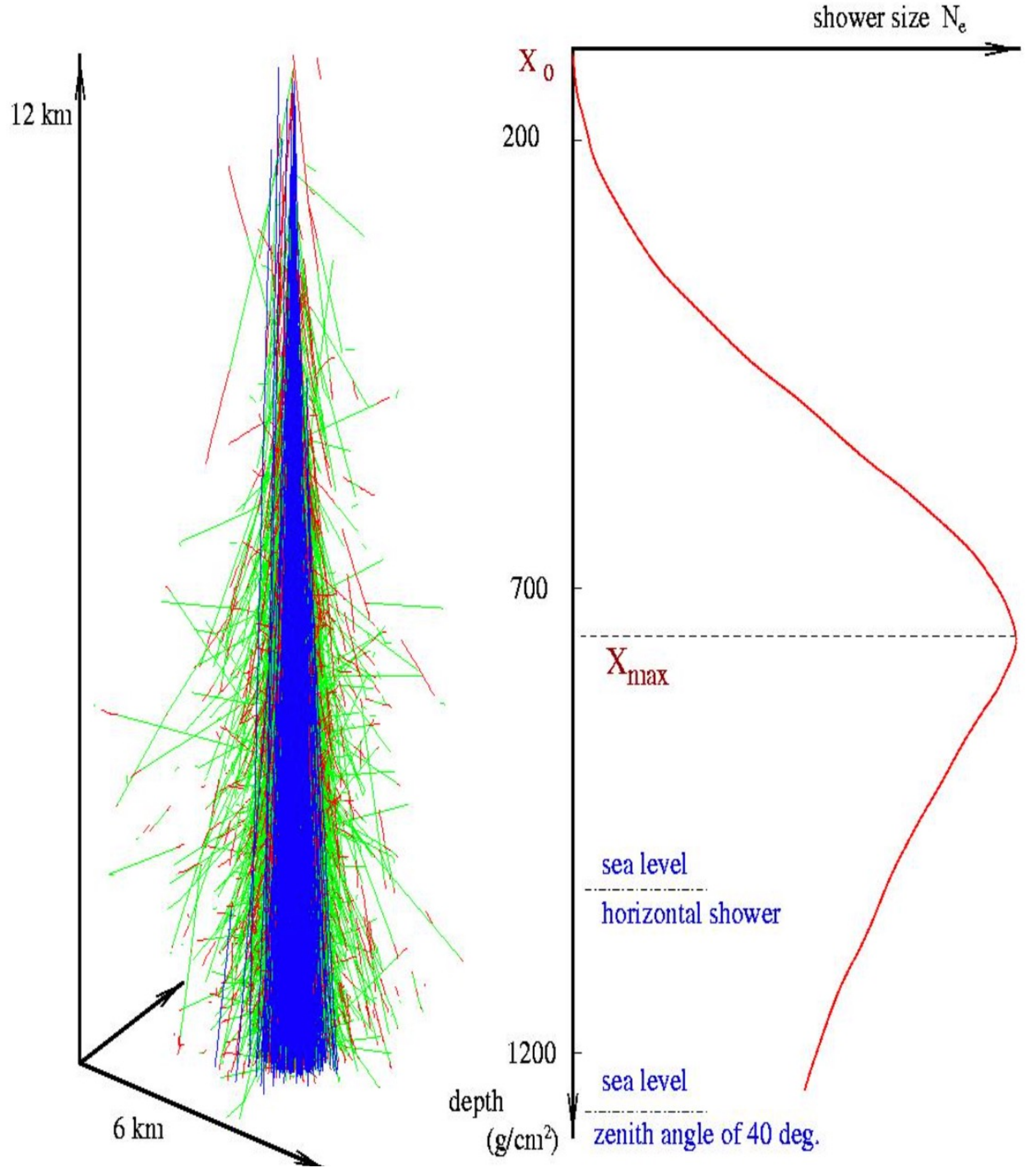
Bruno Benedetto Rossi



Gamma-rays hit the Earth atmosphere

The shower dies of photo-eletric effect



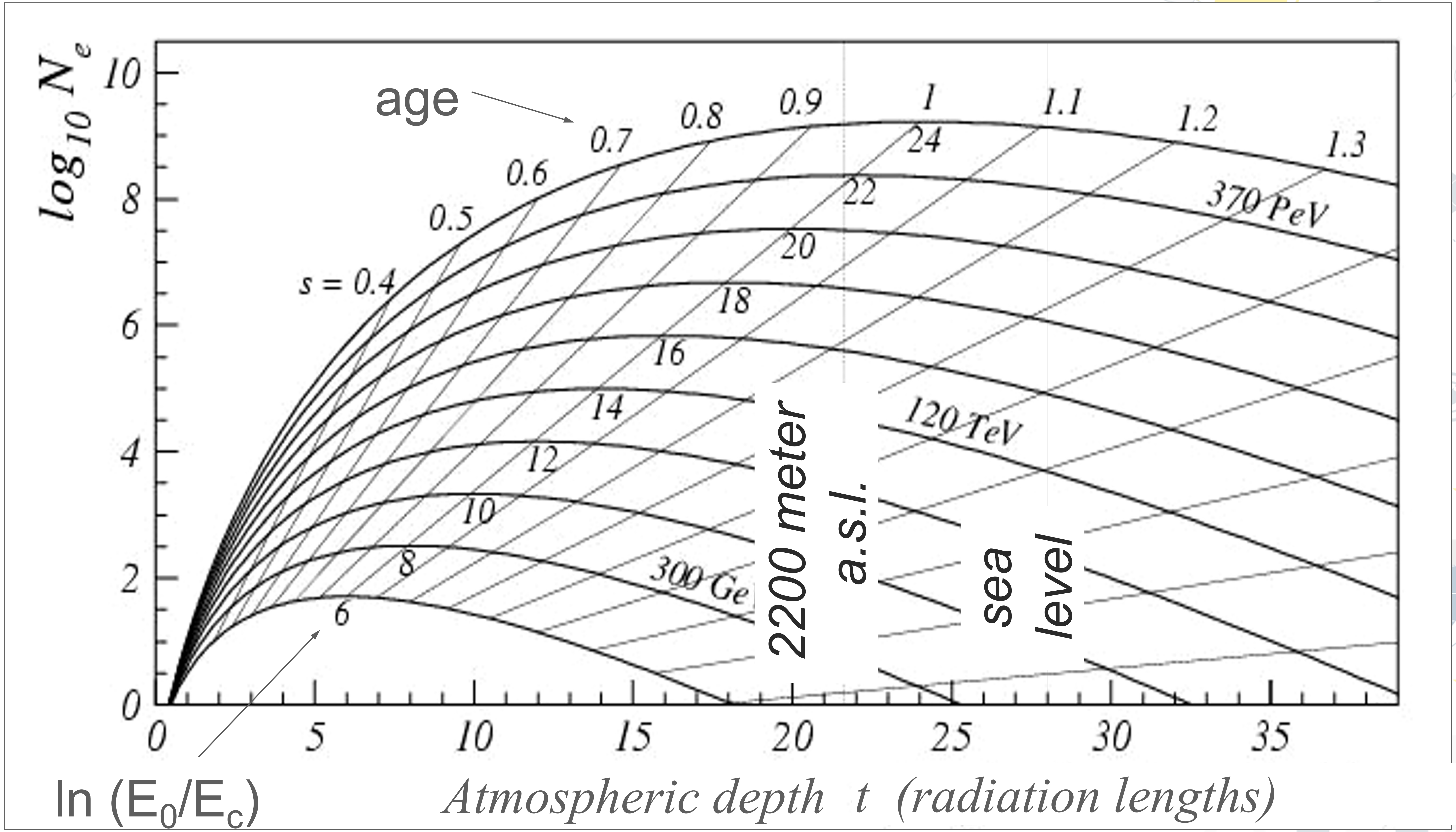


$$X(l) = \int_0^l \rho(x)dx$$

Longitudinal EM shower development

Rossi & Greisen approximation B

Bruno Rossi

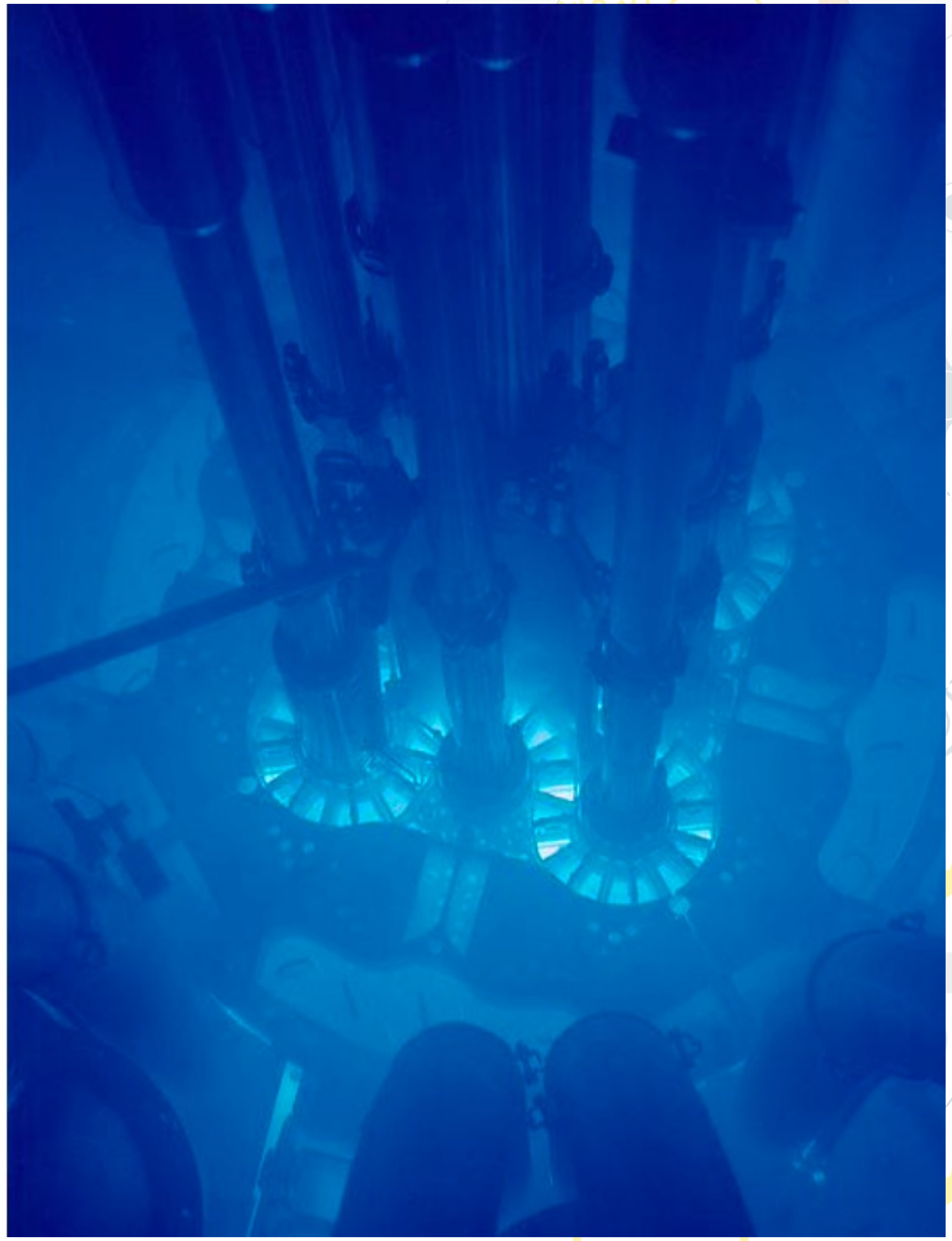


How can we see these showers?

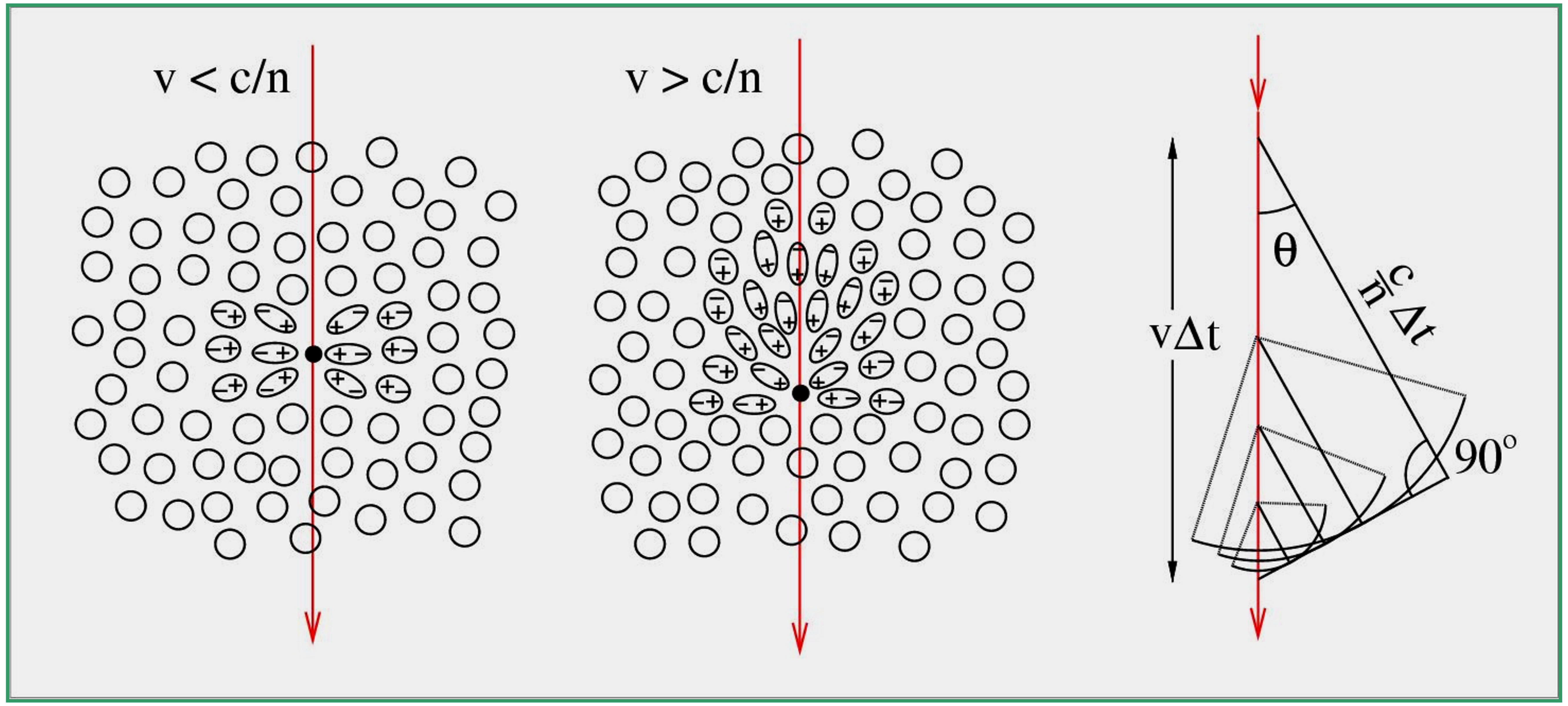
Will see not one but two ways…

Pavel Cherenkov

- Had to find the fluorescence nature of solvents of uranium salts, emitting bluish light
- Surprise that also water was sometimes emitting blue light
- Initially complaning about his tutor: he had to spend >1-1,5 hours in a dark, cold cellar, for accomodating his eyes
- He noticed that the emission is not chaotic, but is related to the track of moving particle.



Cherenkov Radiation – light ‘boom’



- Coherent reorientation of electric dipoles induced by the charge in the medium.

- Minimum energy for a charged particle to emit Cherenkov light

$$E_{min} = \frac{mc^2}{\sqrt{1-\beta^2}} > \frac{mc^2}{\sqrt{1-n^{-2}}}$$

- Assuming $\beta \sim 1$ the Cherenkov angle

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

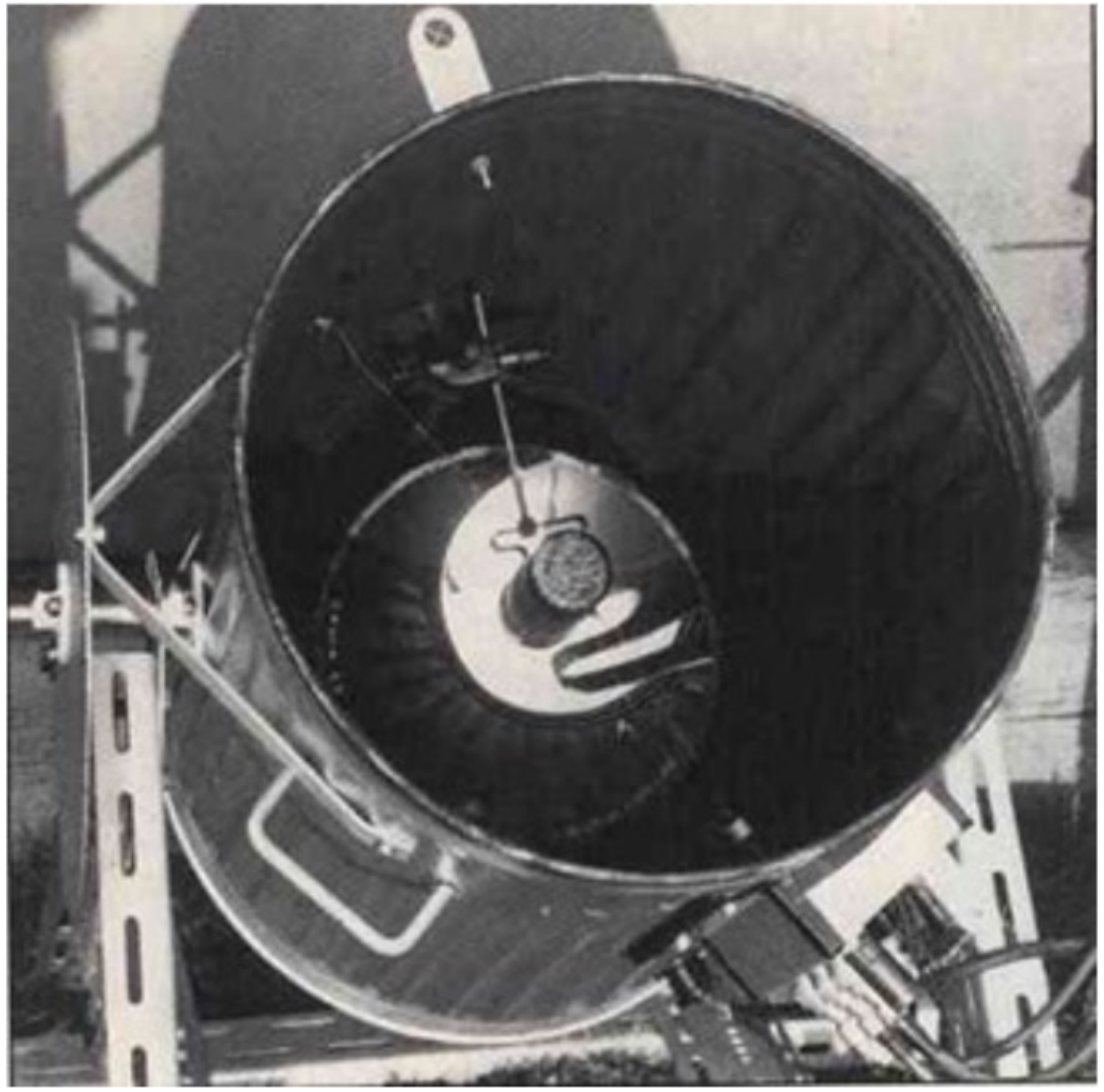
Cherenkov radiation in the atmosphere

In 1948, P.M.S. Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light

Pulses of Cherenkov light from air showers were first recorded by Galbraith and Jelley in 1953

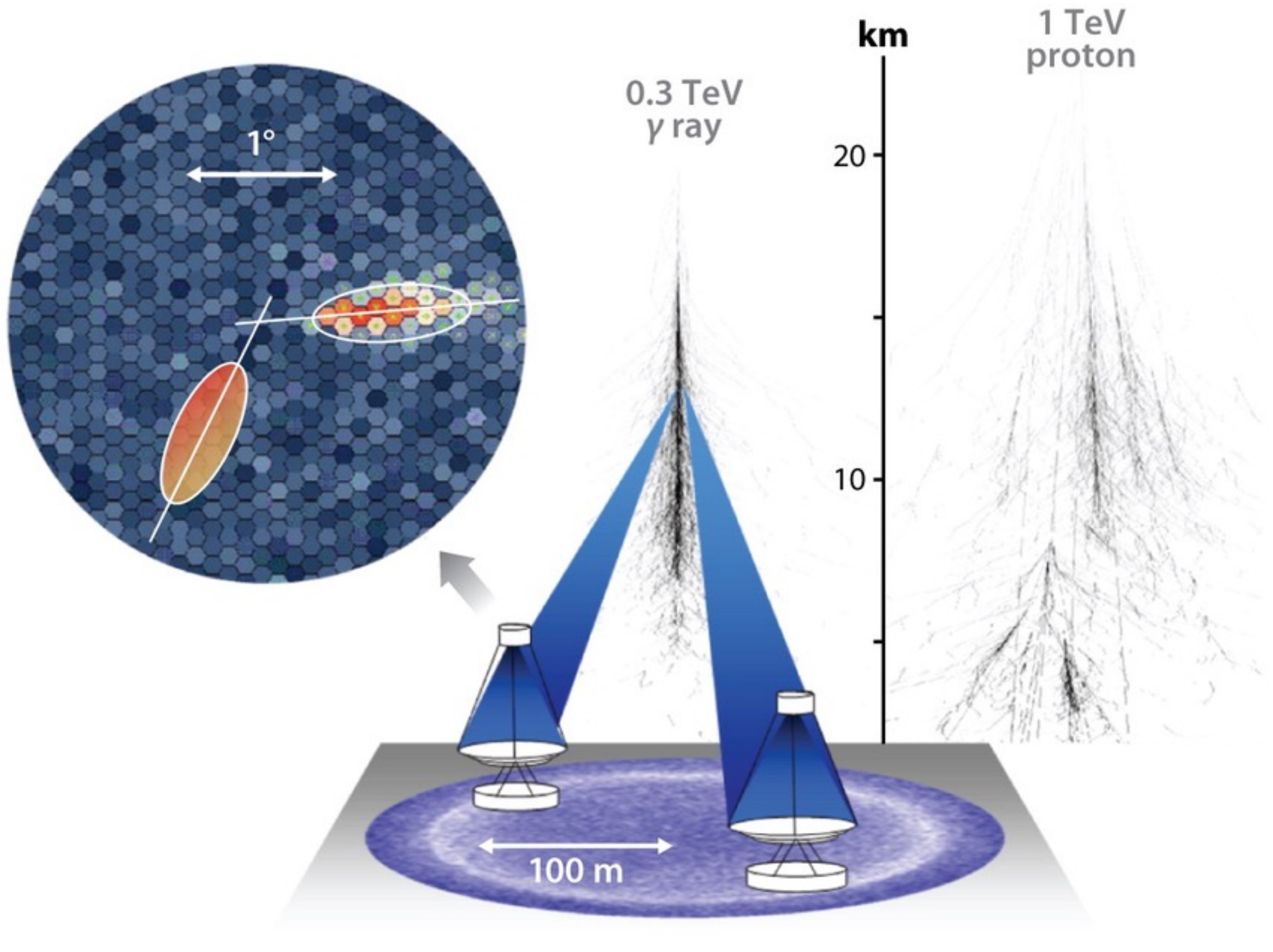
First attempt: UK and Crimea

Galbraith & Jelley, 1st telescope, 1953



Now…much better
Imaging Atmospheric Cherenkov Telescopes (IACTs)

How it works



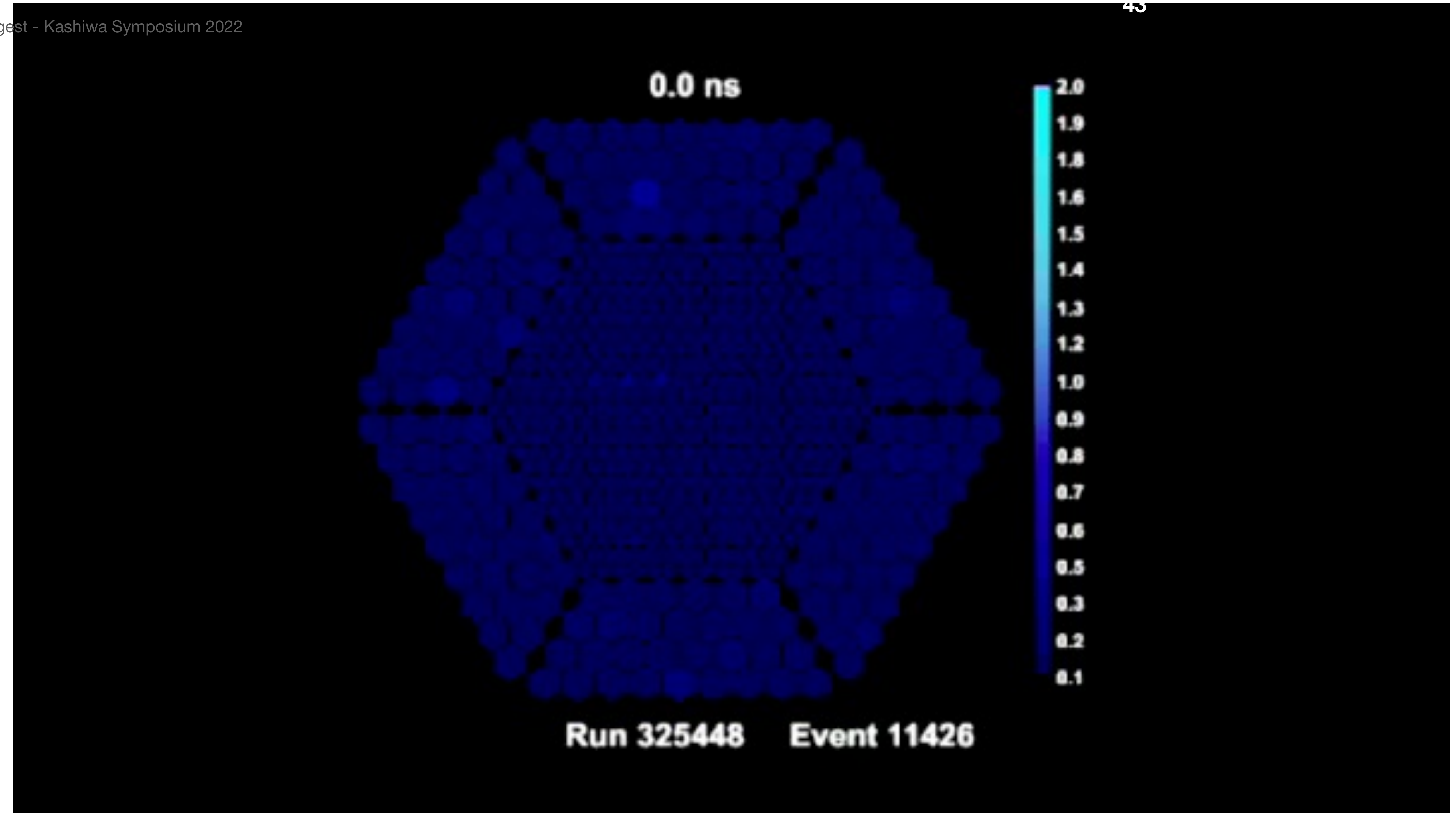
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

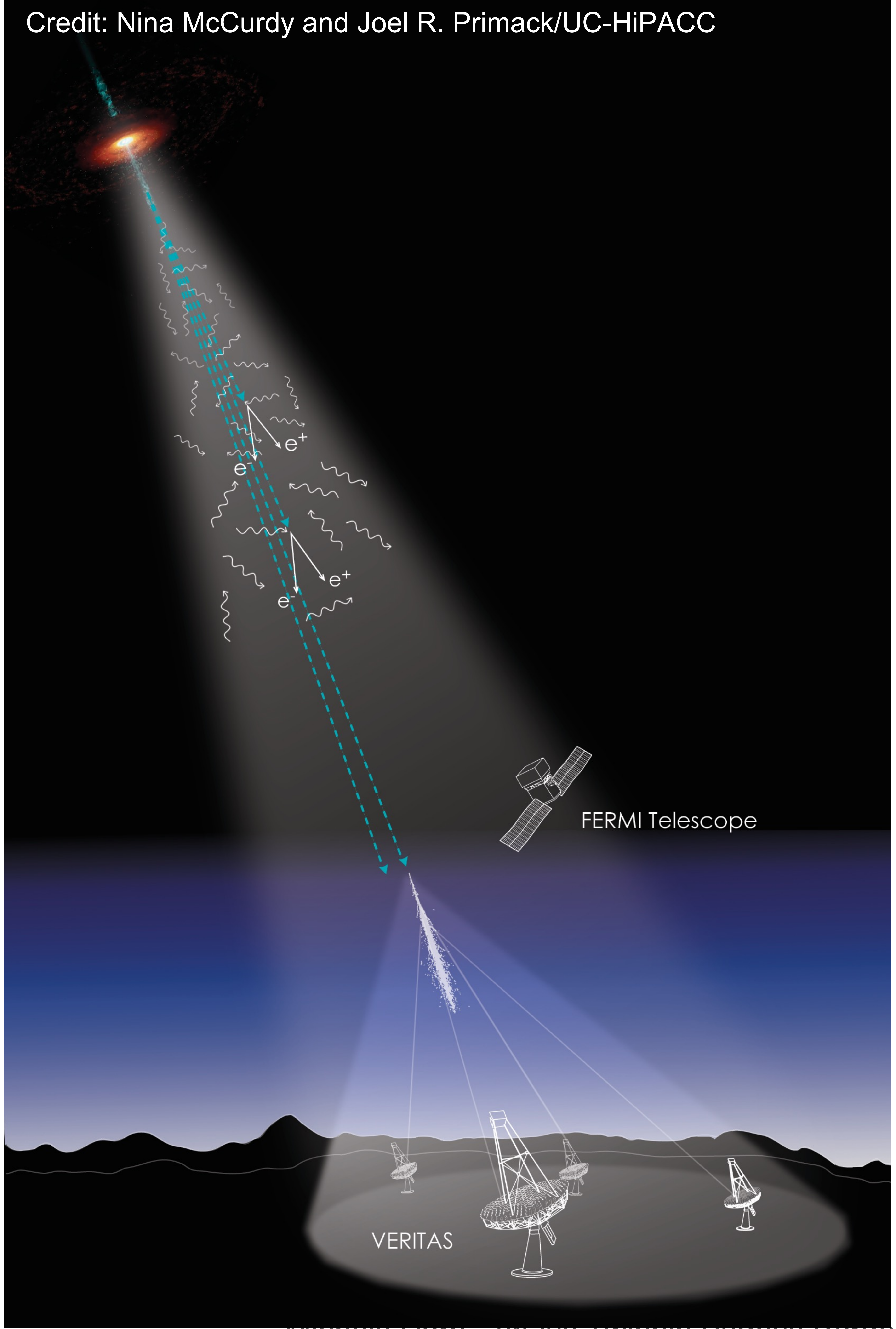
1. Primary gamma-rays pair-produce after few radiation lengths at 10-20 km asl
2. Shower of electrons dies off after few interaction lengths: particle do not reach ground
3. Cherenkov light emitted by ‘superluminal’ electrons v>c/n
4. Cherenkov photons pool at ground

~1 picture/sec

2 x 10^9 pictures/sec!

Non-commercial devices
- Photomultipliers tubes
- Fast electronics





Ground vs space

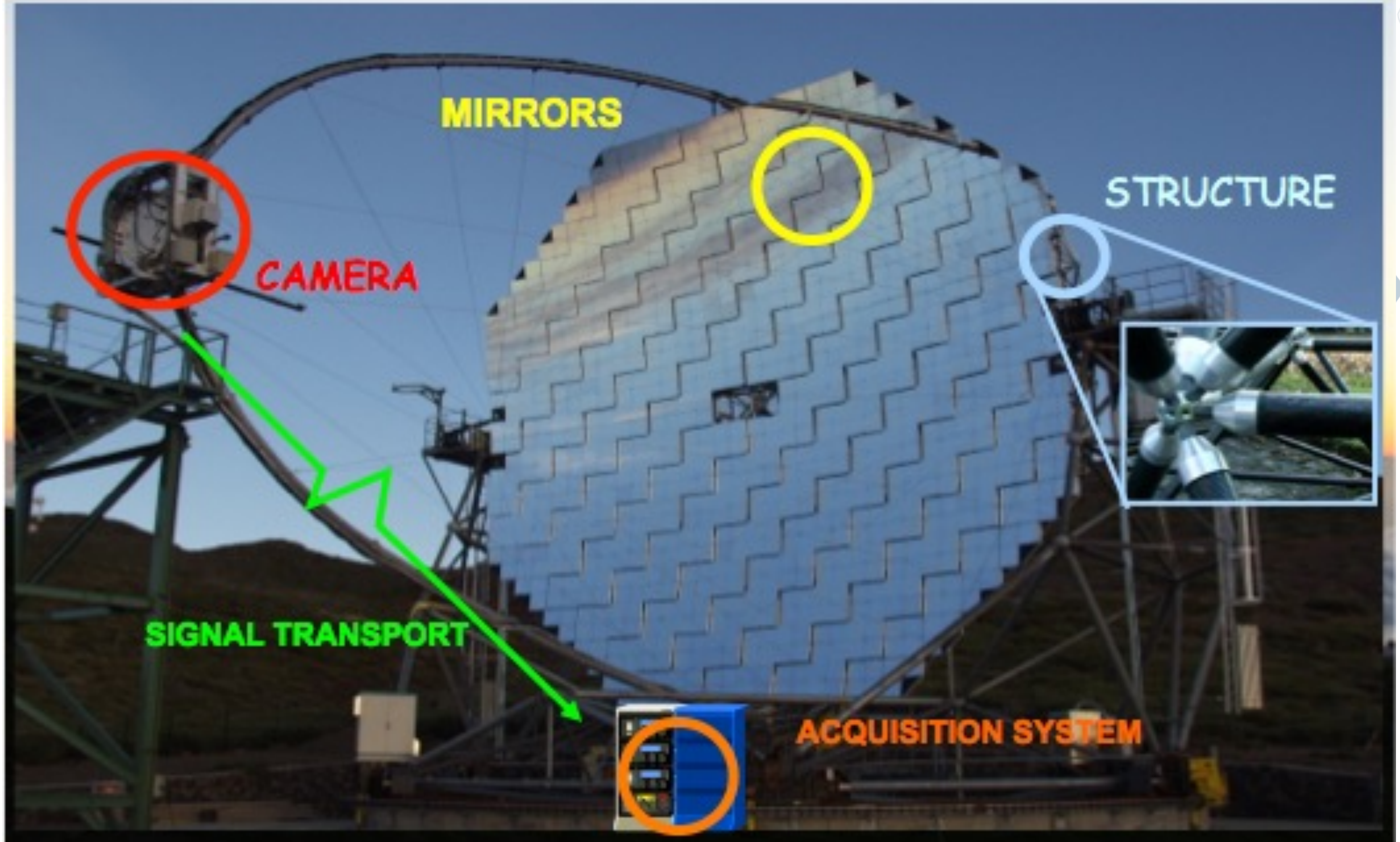
- Figure of merits of current generation:
  - FOV 5x5 deg
  - 50 GeV- 100 TeV
  - Eff.Area ~ 10^5-10^6 m^2
  - Dark time: ~1000 h/year
  - ~10-50 h source for detection
  - ~0.1 angular resolution
  - ~10-20% energy resolution

Current IACTs

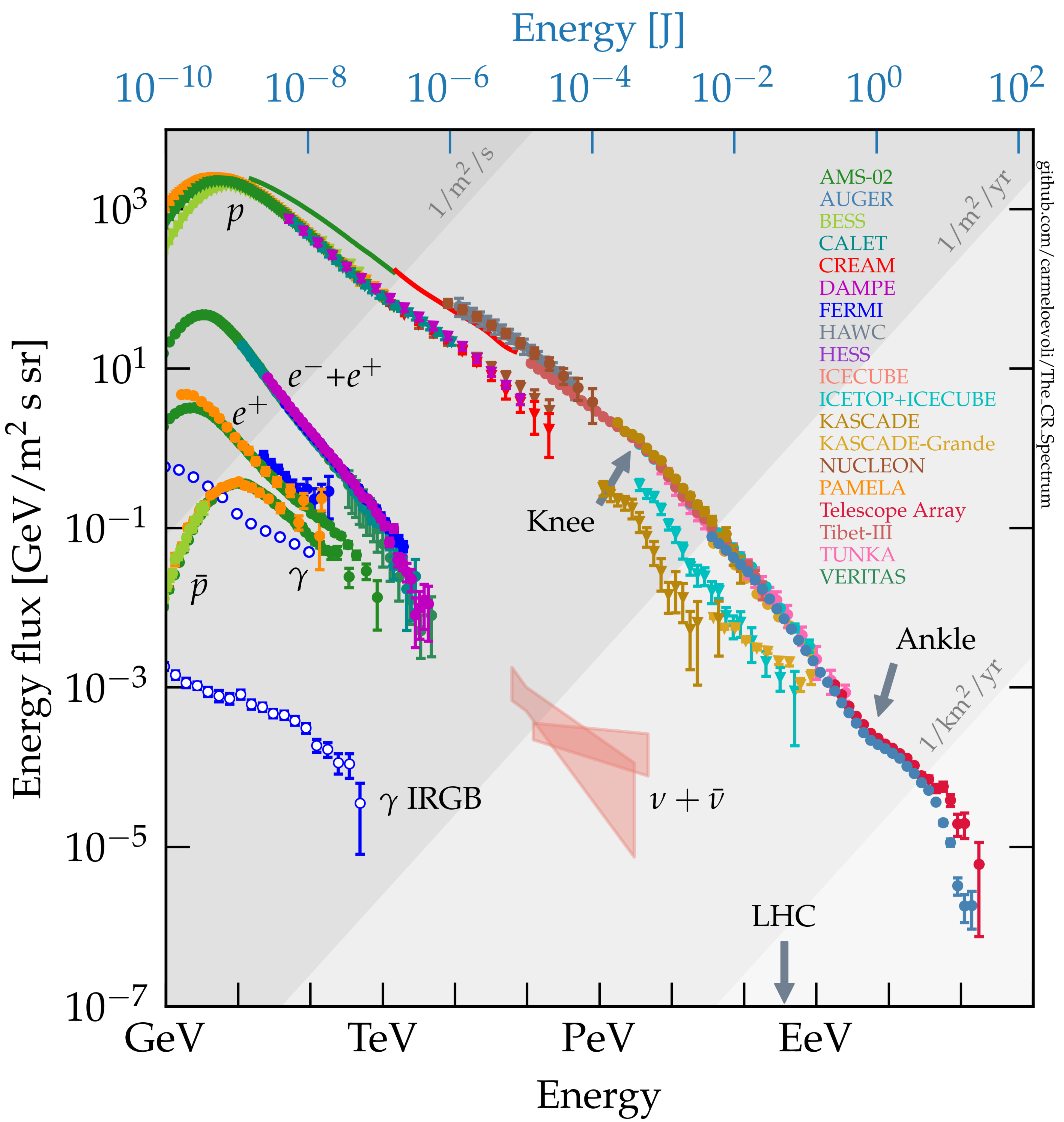
IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location. MD NIMA742 (2014) 99-106

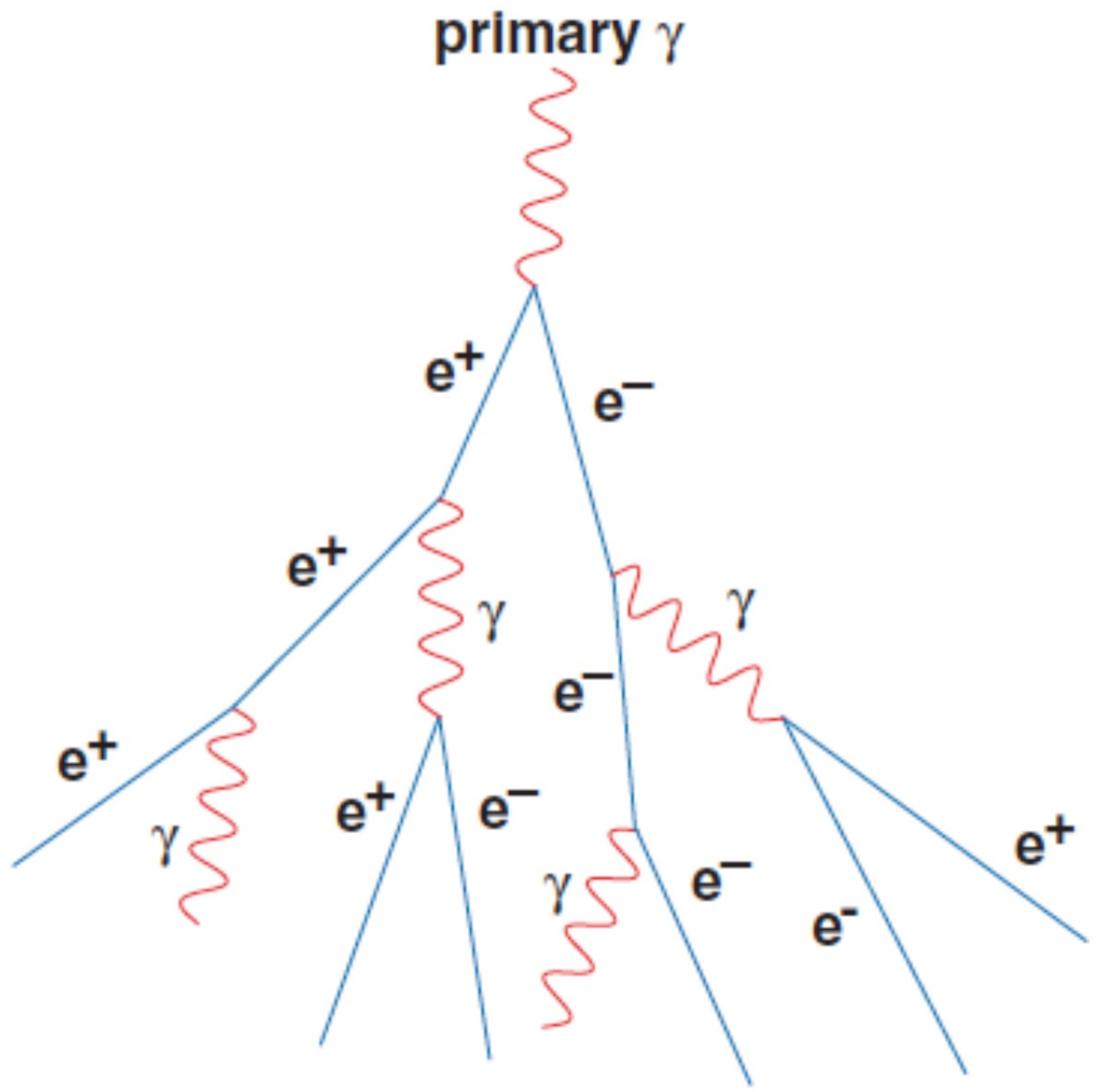
Key technological elements for MAGIC

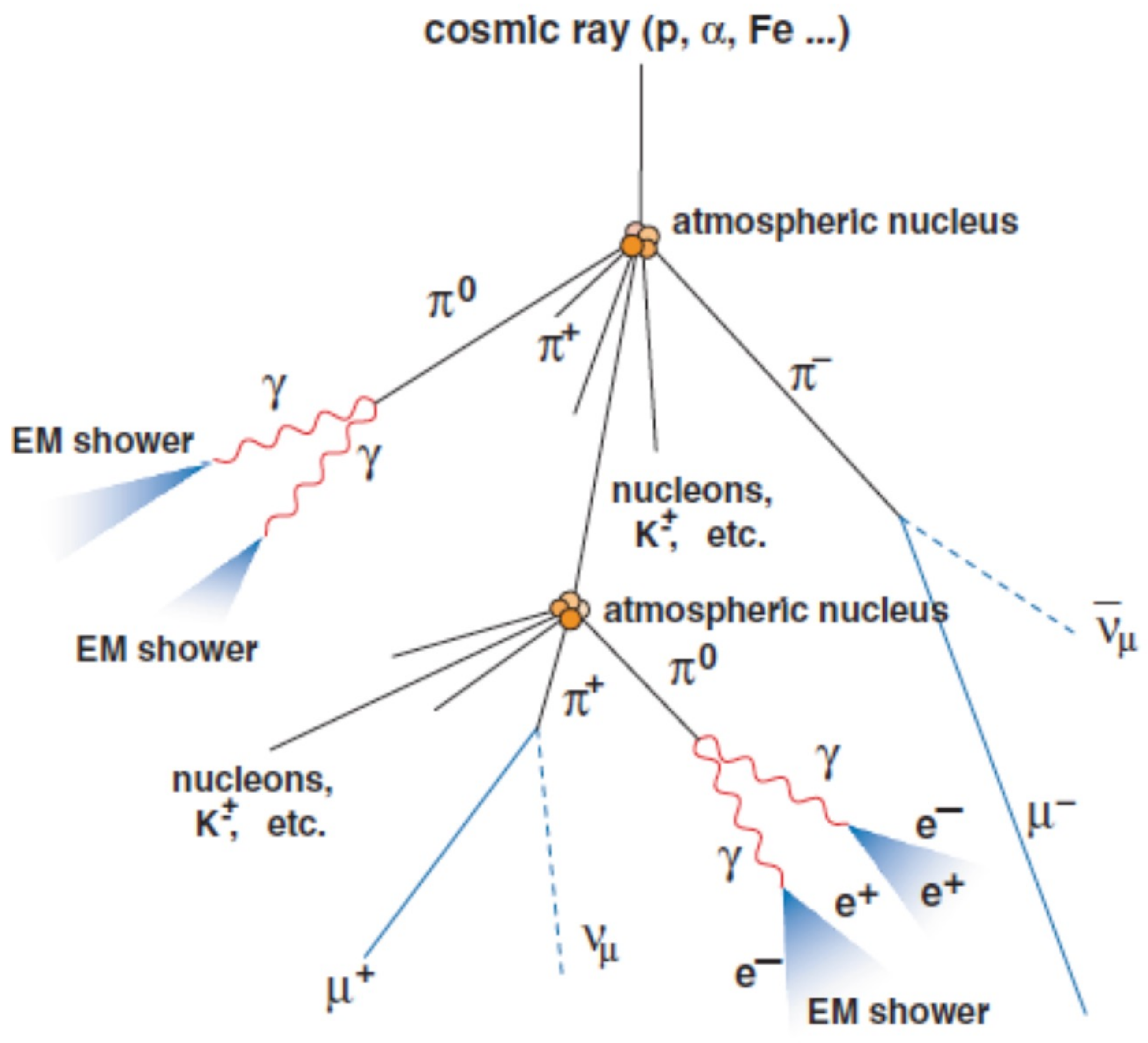


Drawback: also many cosmic rays



- Earth is hit by a constant flux of cosmic rays



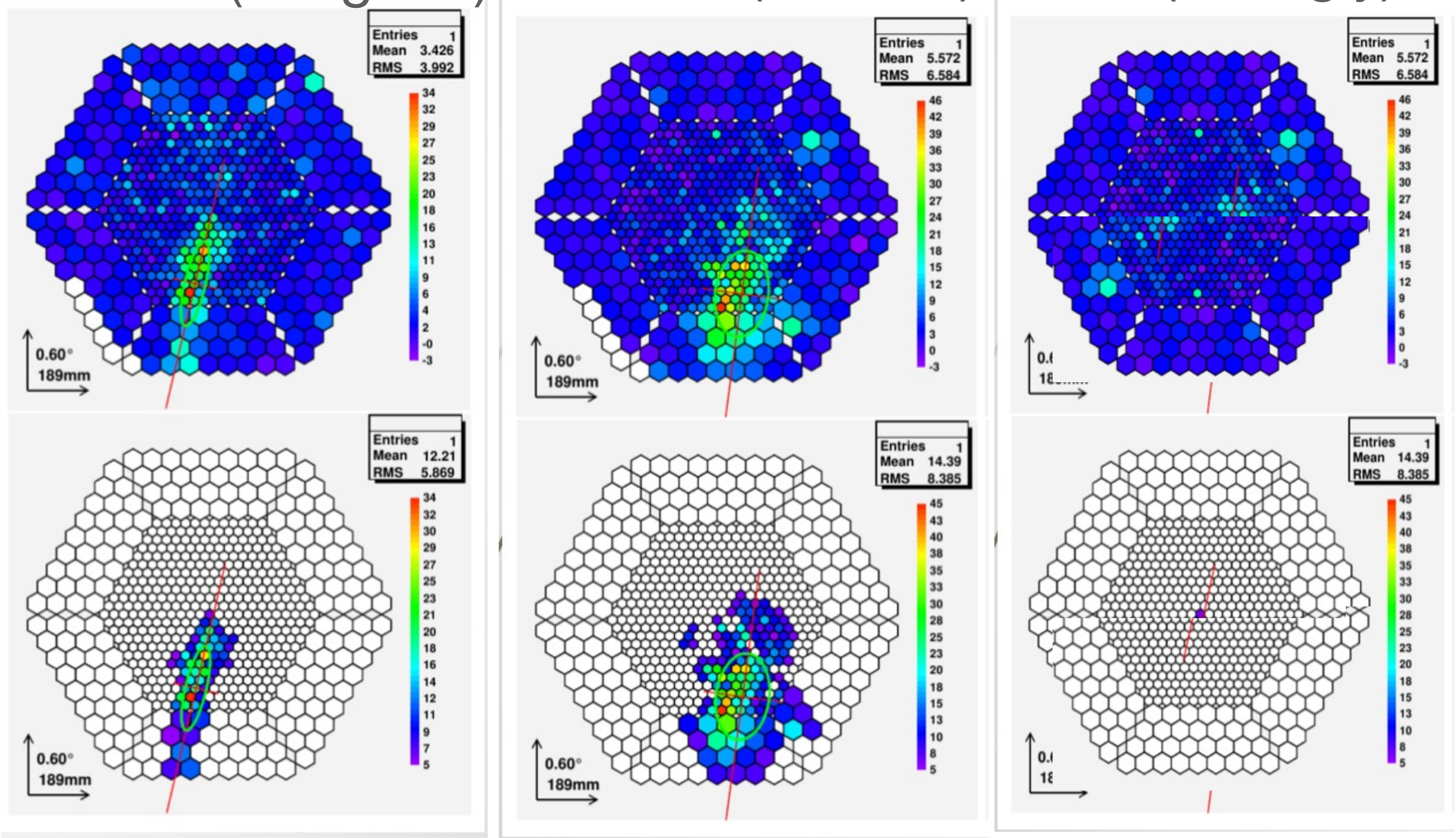


Events rate and selection

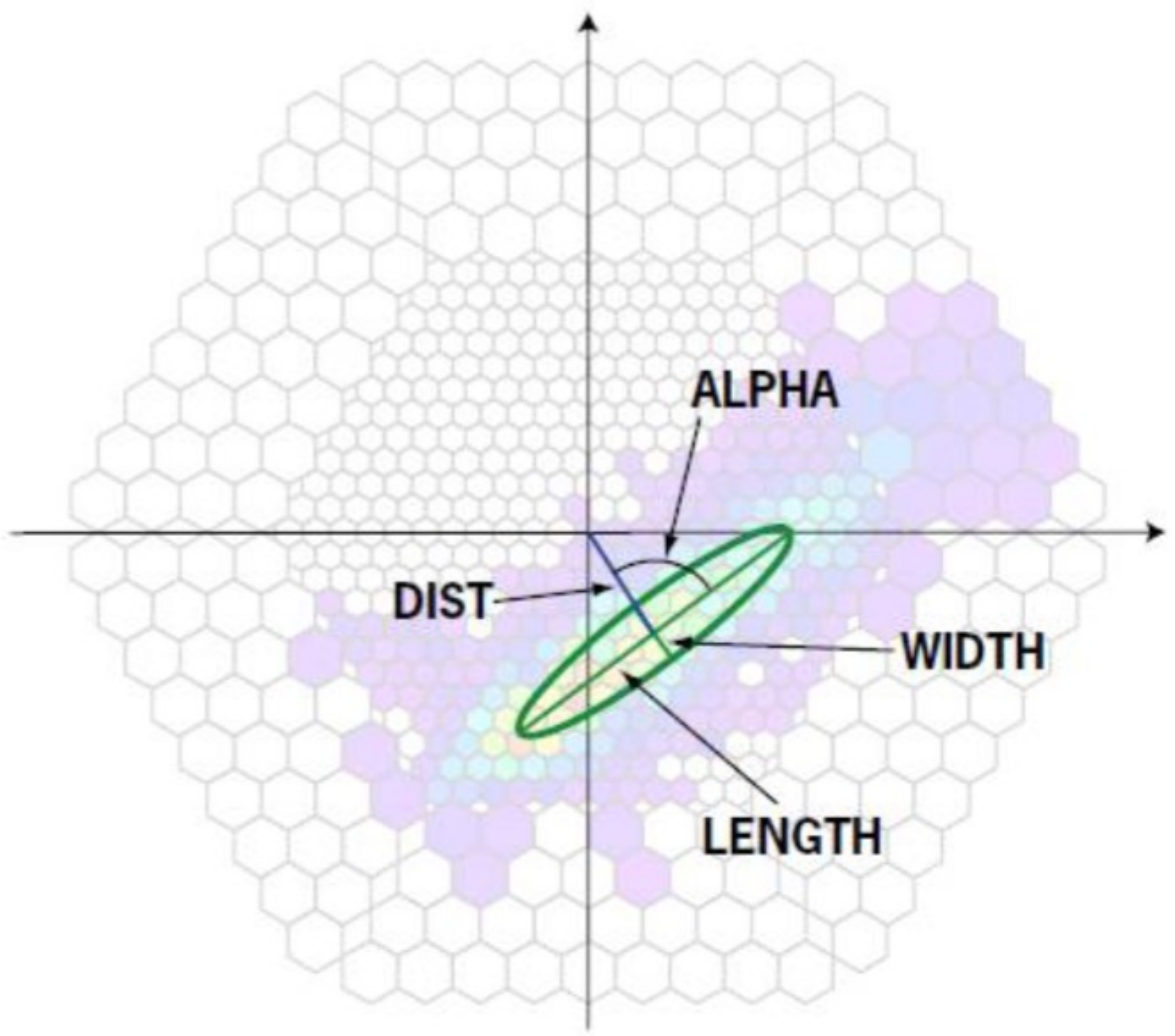
- During data-taking, e.g., MAGIC acquires @ **200 Hz**. *These are mostly hadronic showers. Gamma-rays are less than 1/1000 of this rate.*
- During data reconstruction**, only 1/1000 hadronic events survive** (very energy dependent)

Events classes

Gamma (the good) Hadron (the bad) NSB (the ugly)



Event tagging

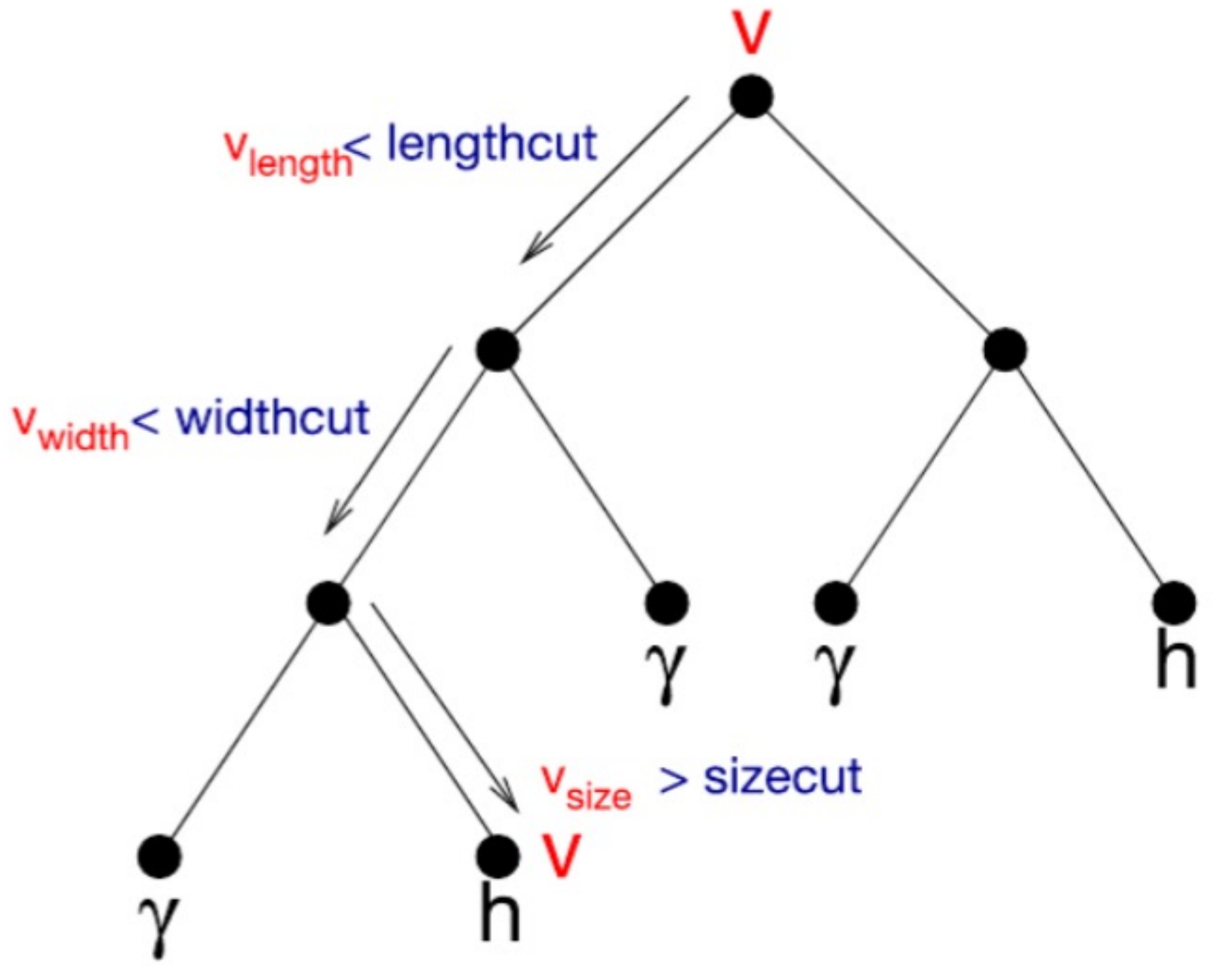


1

You "clean" the image and extract shape parameter

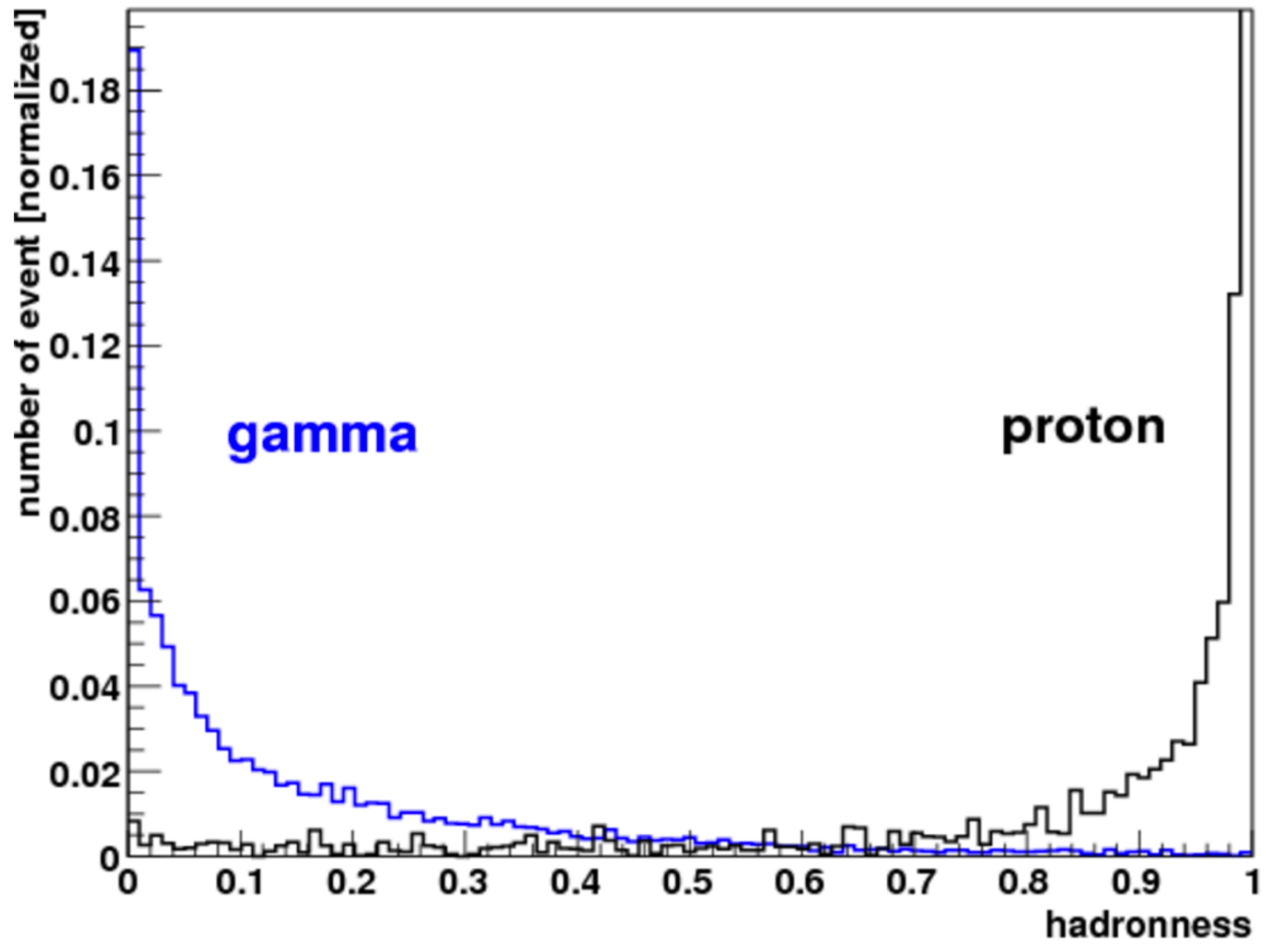
2

You make a Random Forest is a collection of decision trees, by comparing with Monte Carlo



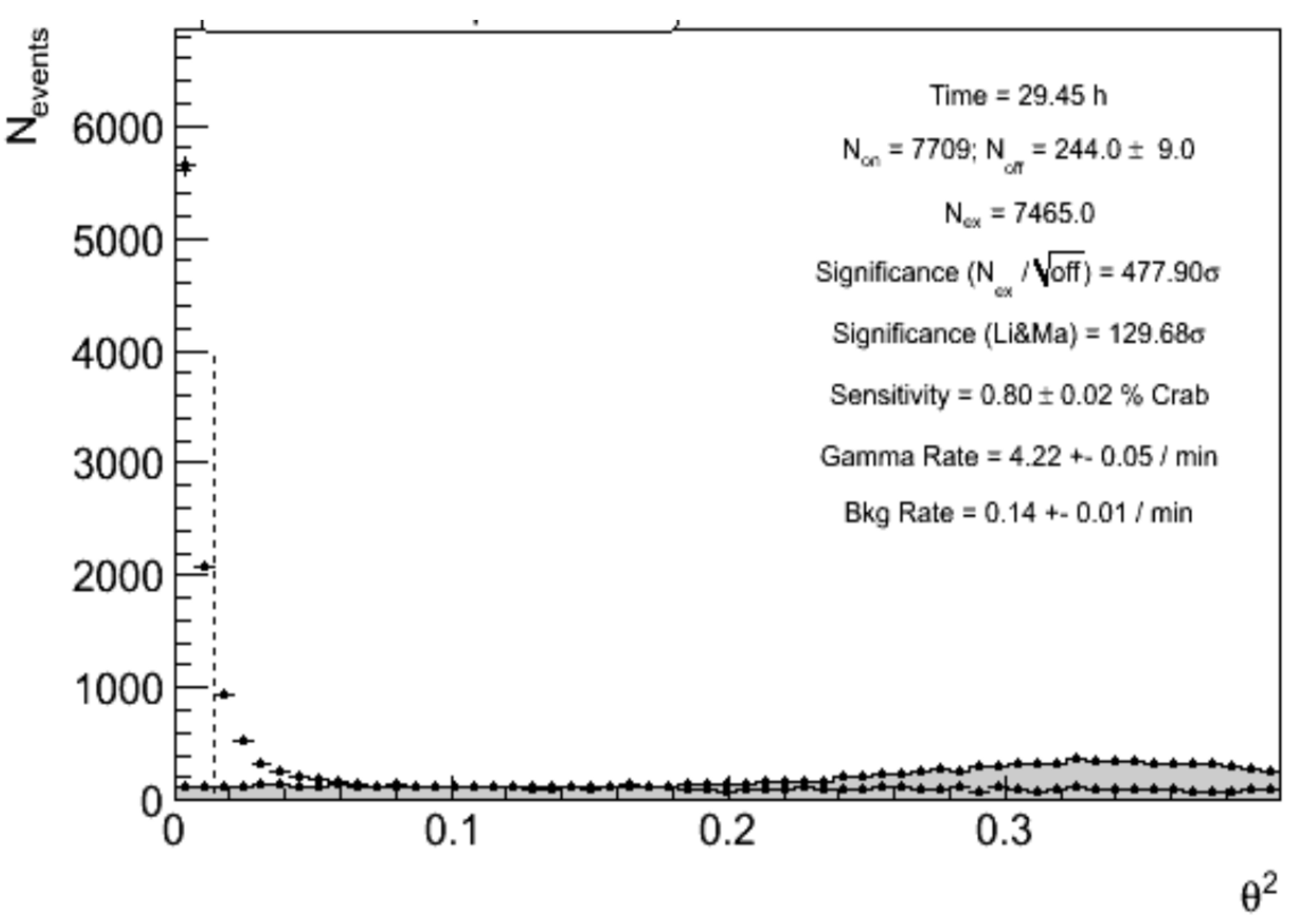
3

You have classified events according to "hadronness" and start to make cuts

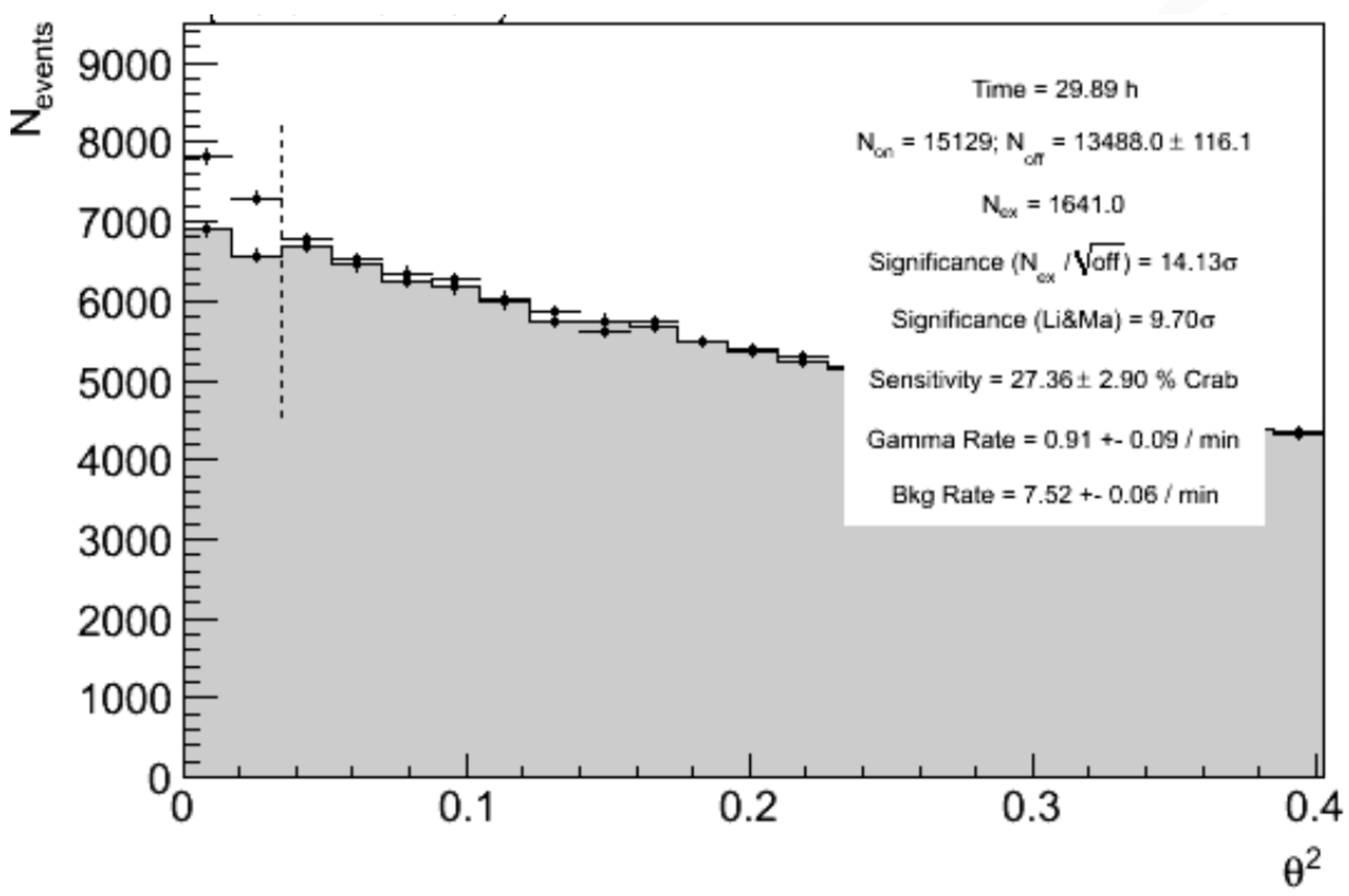


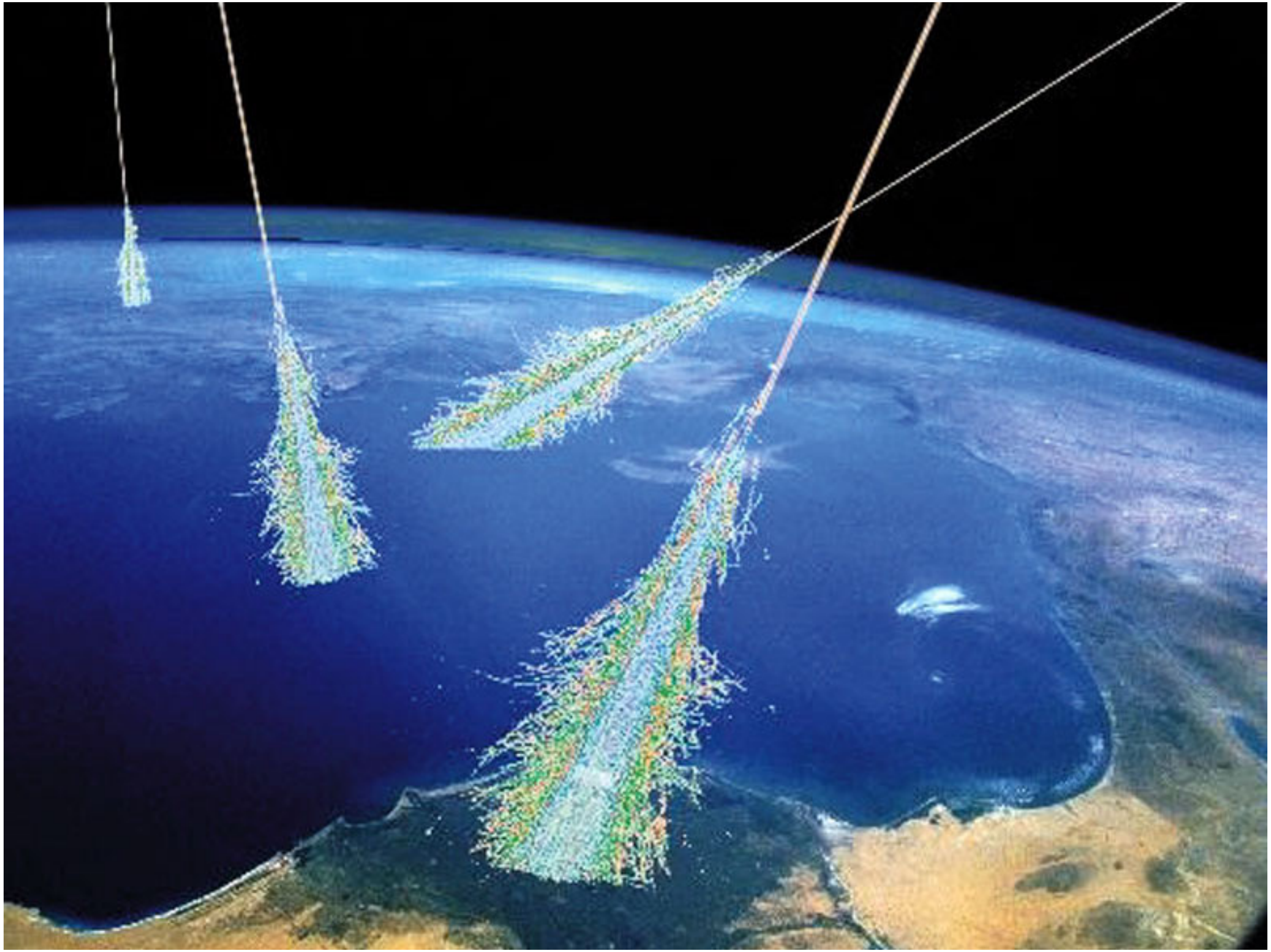
Some background survives

○ Strong!



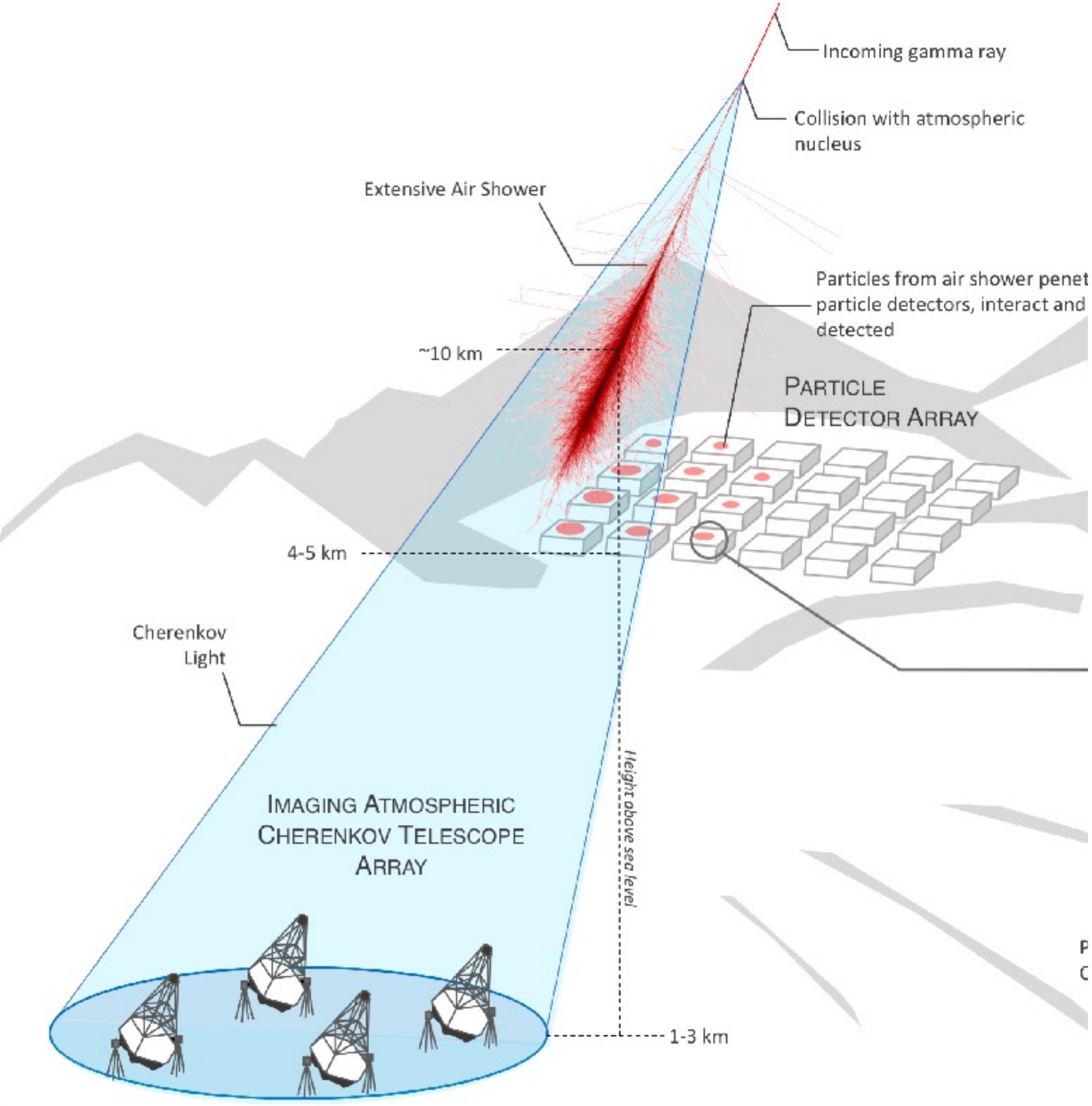
➡ Weak





A second way to get them

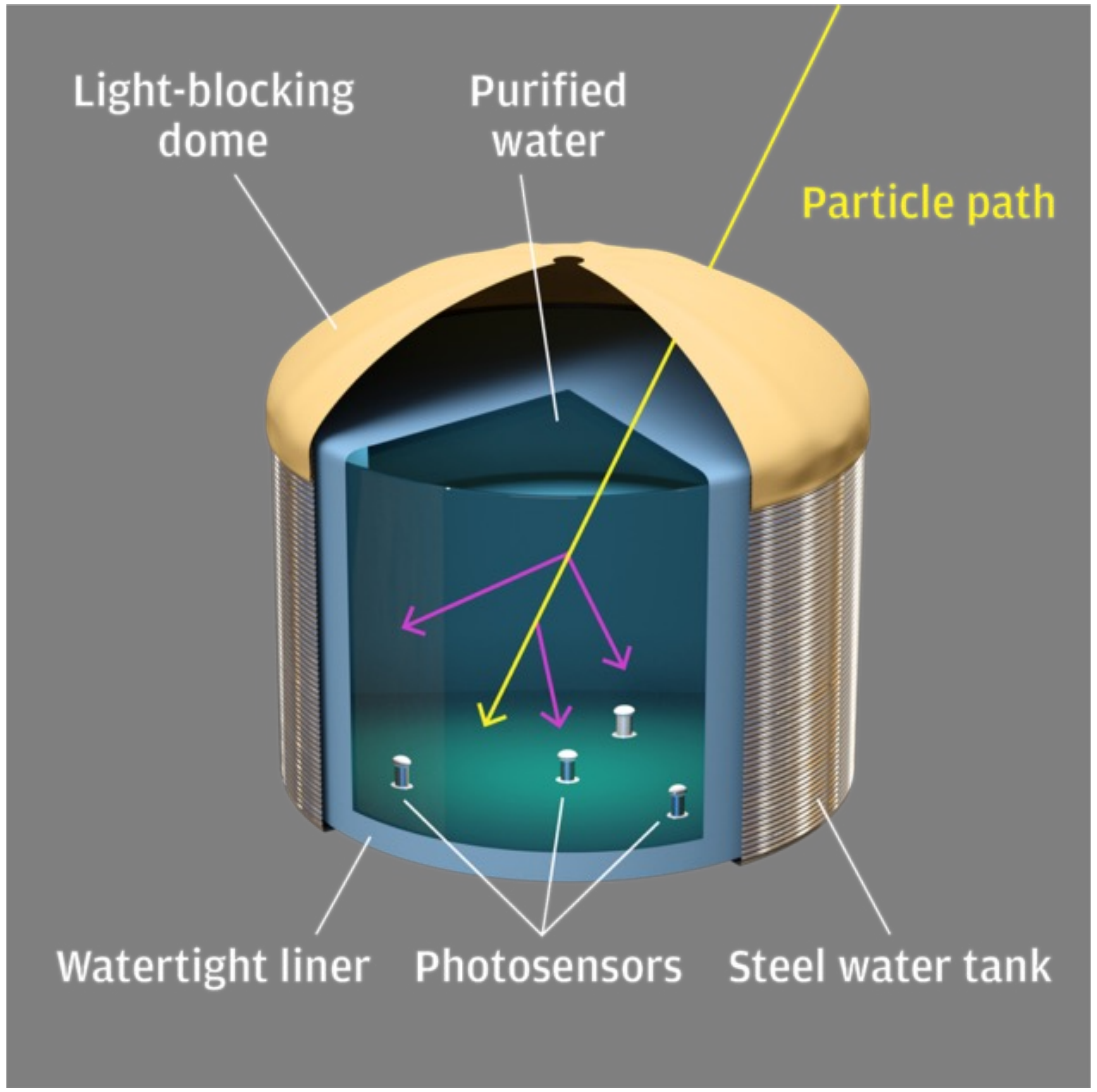
Shower Front Detectors



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

- If we go high-enough, we can detect _the particles_ of the showers directly!
- PRO and CONS?

Which detectors

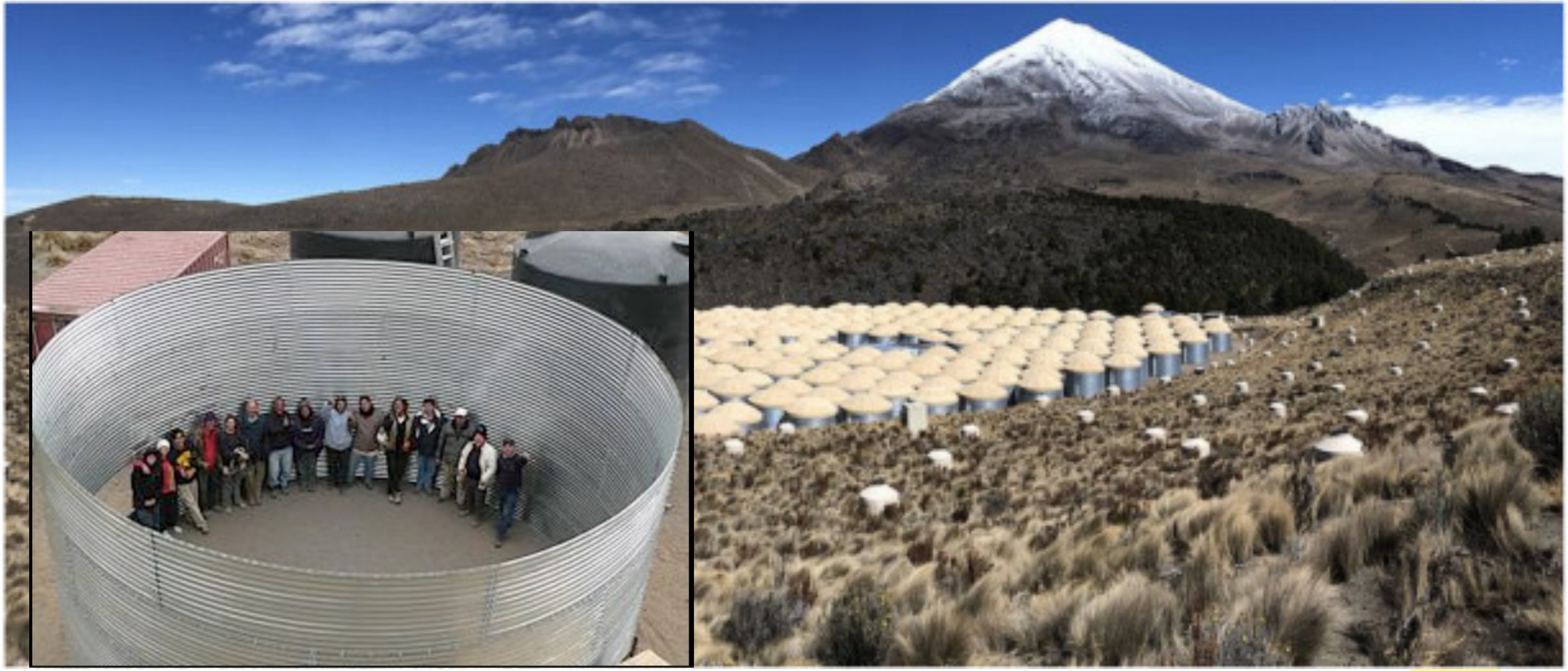


- Water tanks!

- Tank filled with water
- Photosensors within
- A charged particle emit Cherenkov light in the tank!

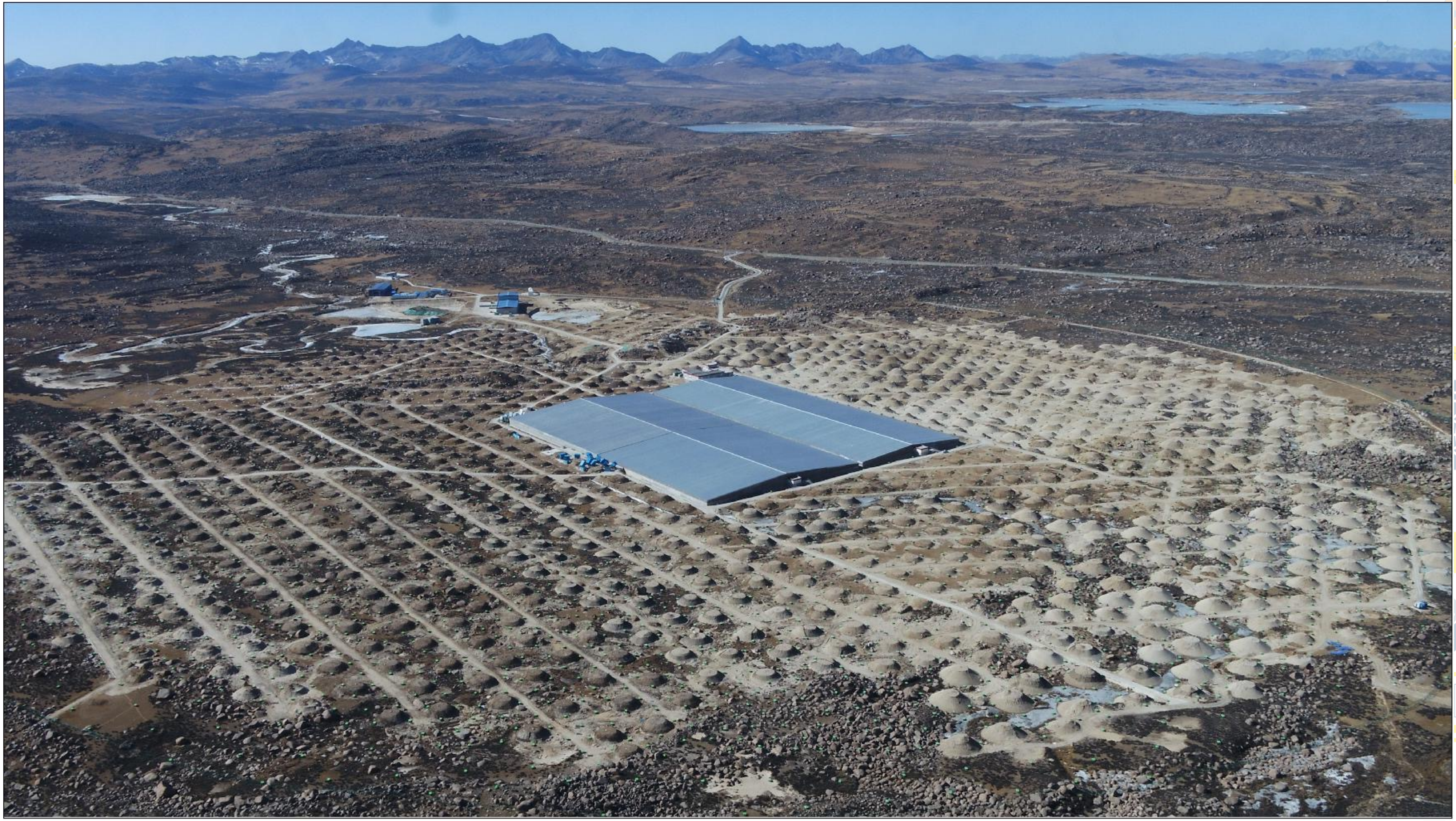
HAWC

Mexico



LHAASO

Sichuan-China

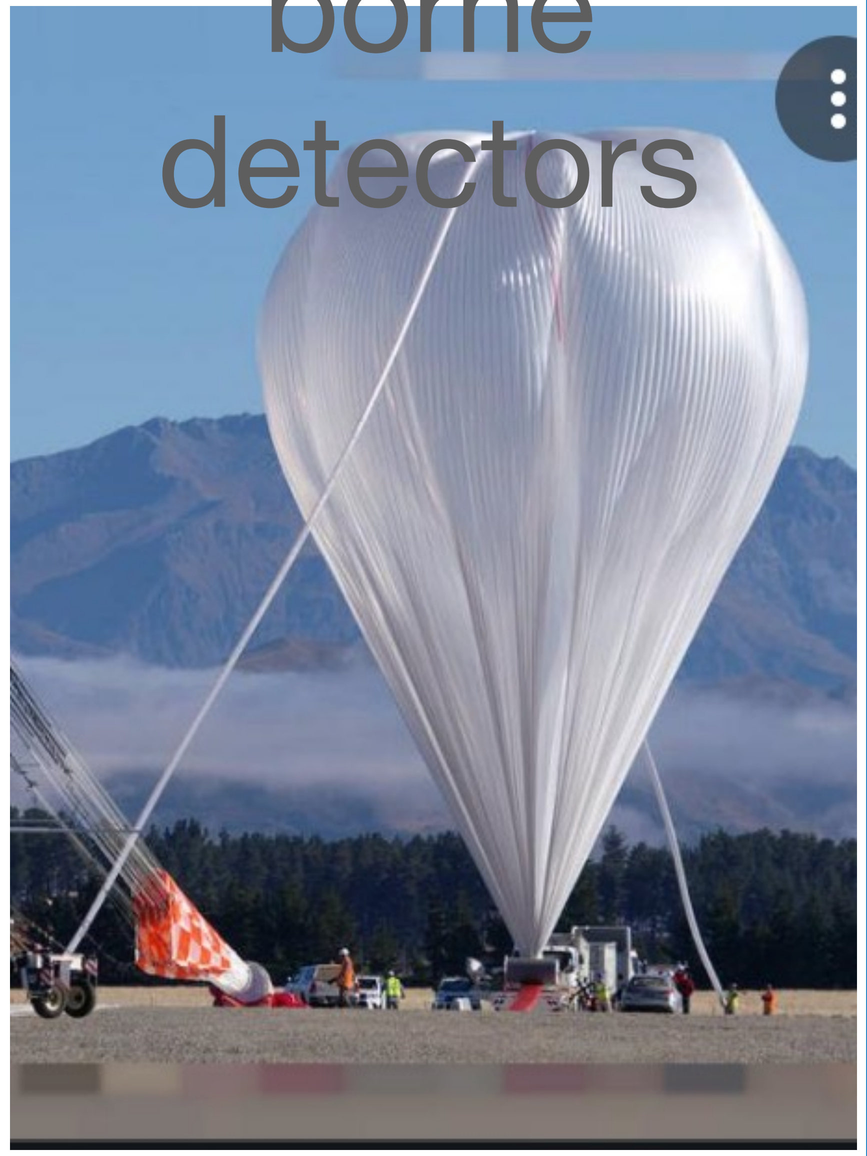


Recap

Gamma Ray (Cosmic-ray) detectors

ENERGY

<MeV range
Balloons-borne detectors

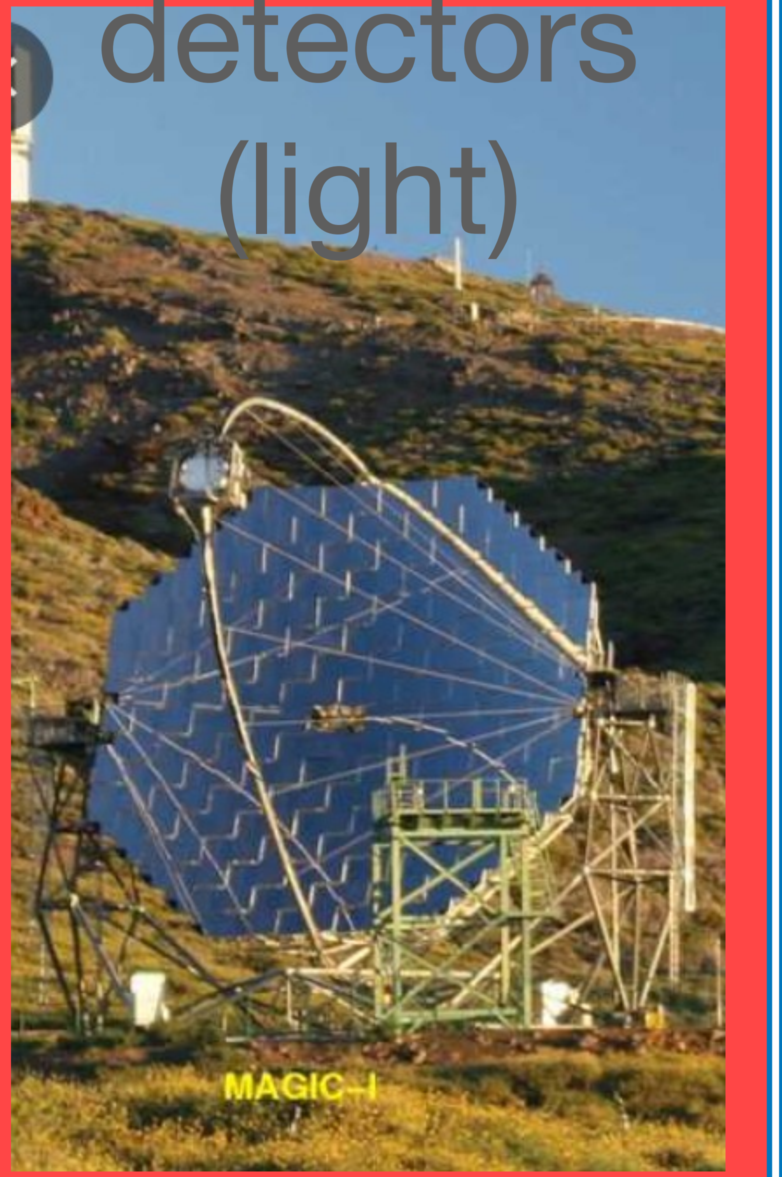


Just cosmic rays

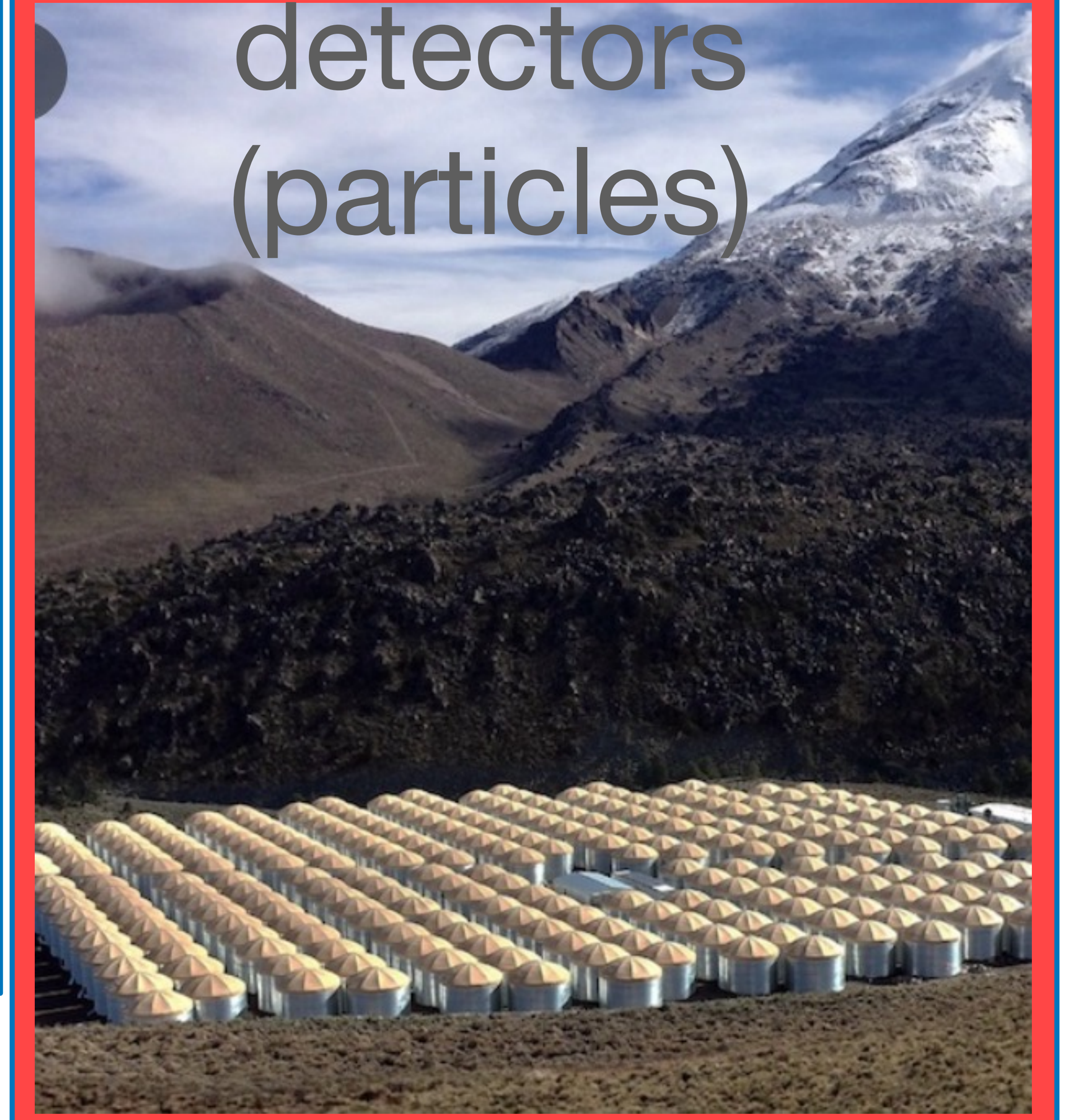
MeV-GeV range
Satellite-borne detectors

See talk by Regina Caputo earlier

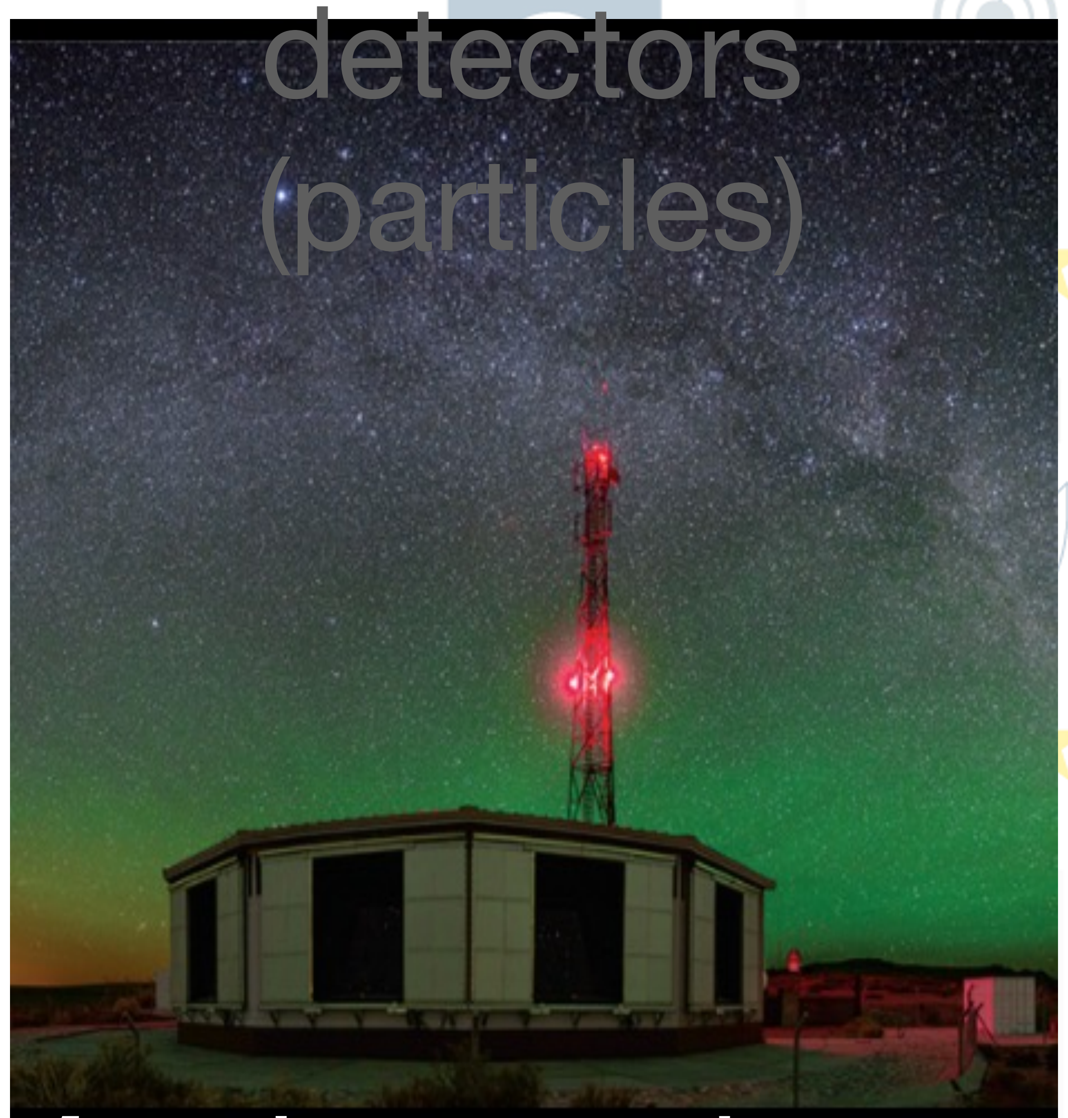
TeV range
Ground-based detectors (light)



TeV-PeV range
Compact Ground-based detectors (particles)



>PeV range
Wide Ground-based detectors (particles)

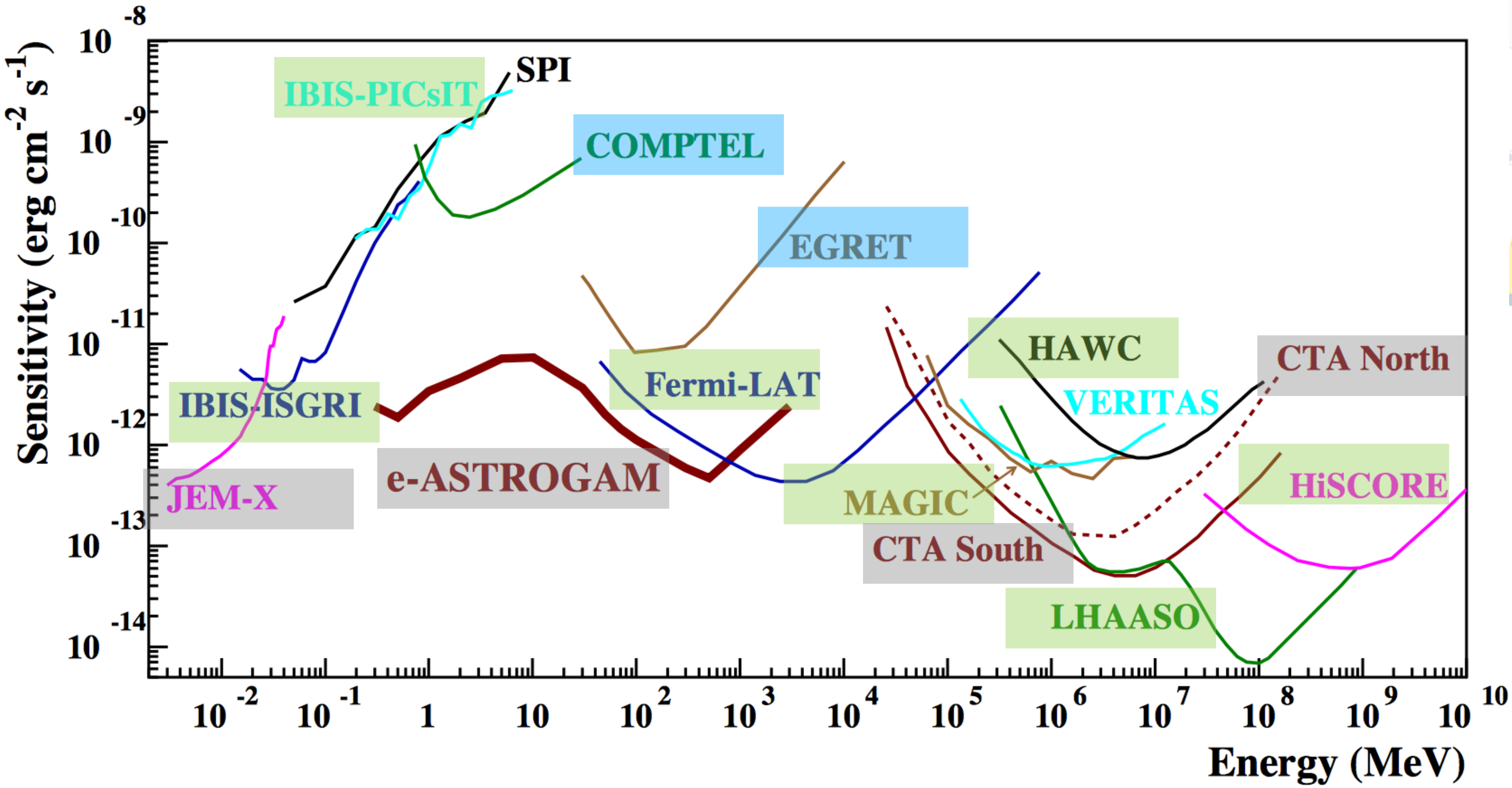


Mostly cosmic rays


Radio-galaxie s
GRB s
Blaz ar
FSR Qs
Gala xy clust ers
SNR s
PWN
Puls ars
Binar ies
Globula r clusters
Microq uasars
Nova e
Plasma
EBL
IGMF
Jet
Energy budget
Shocks
CR propag ation
CR acceler ation
BHs
Large scientific scope

Comparing experiments

Plot from https://arxiv.org/abs/1611.02232



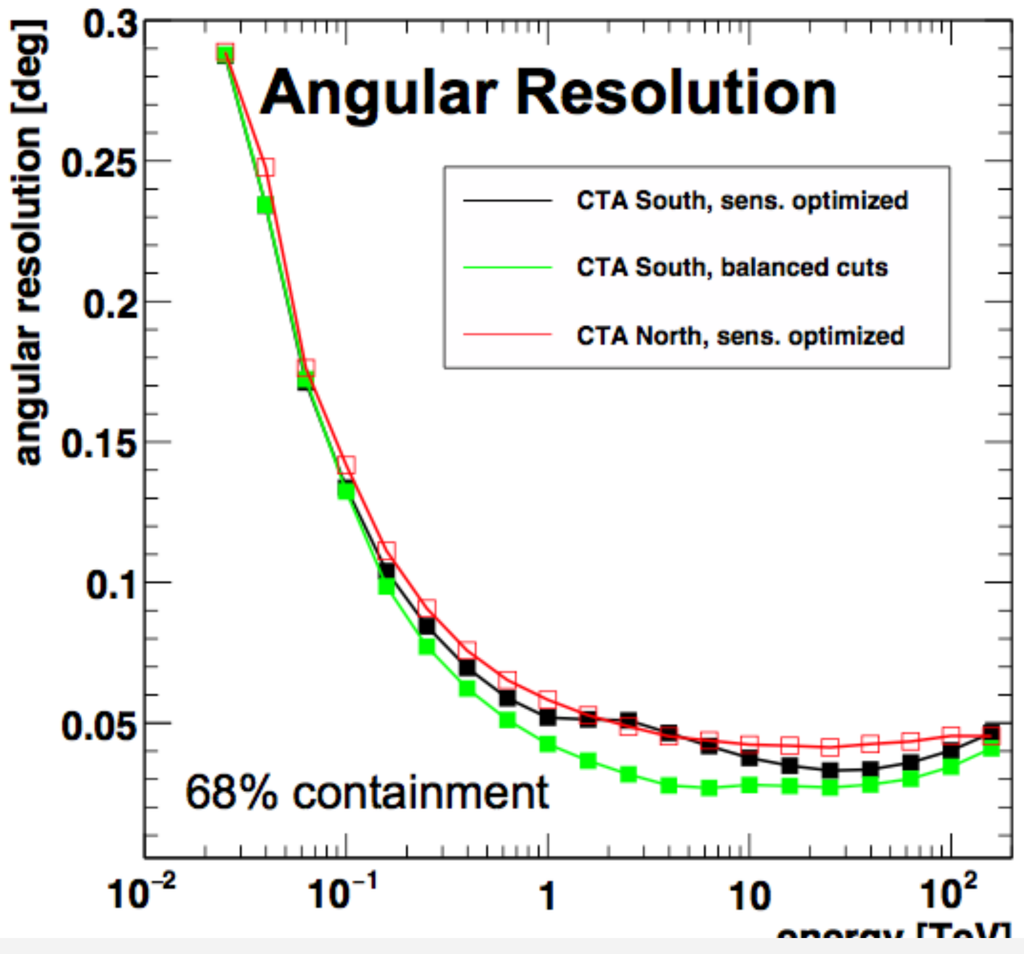
Past

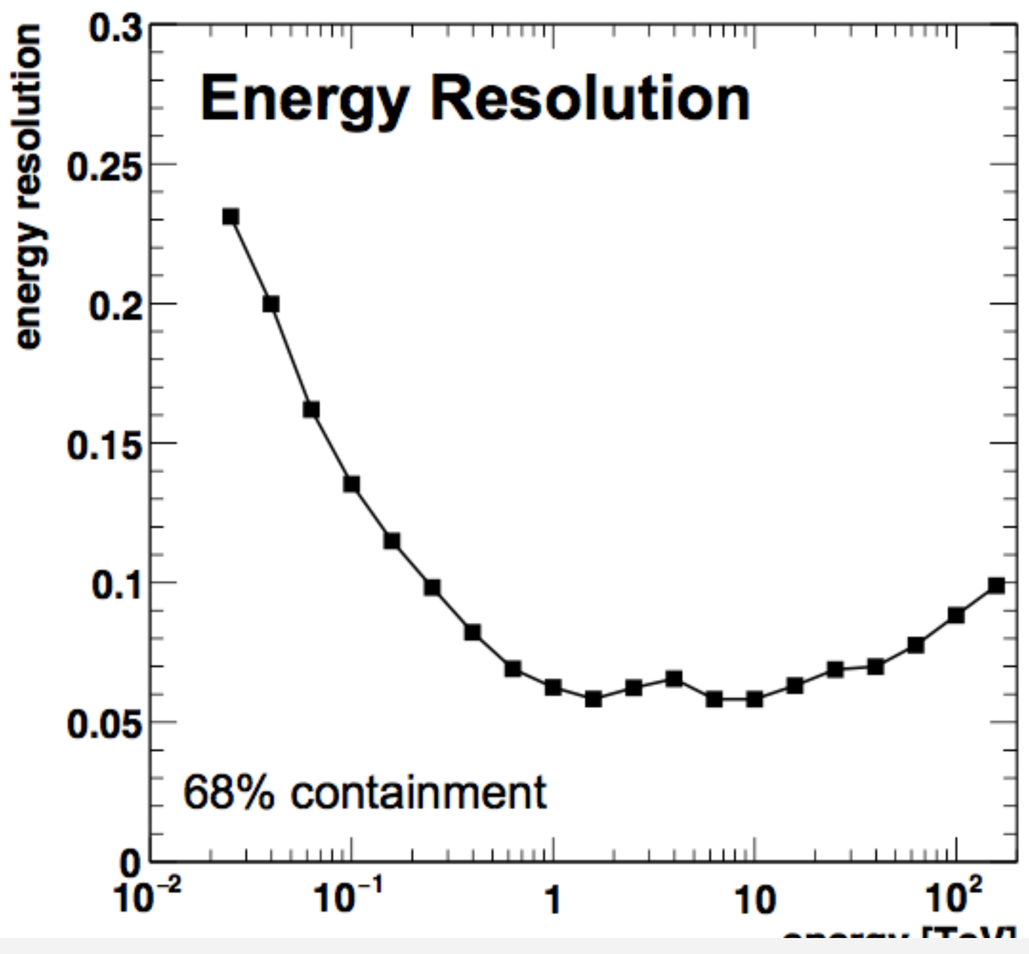
Present

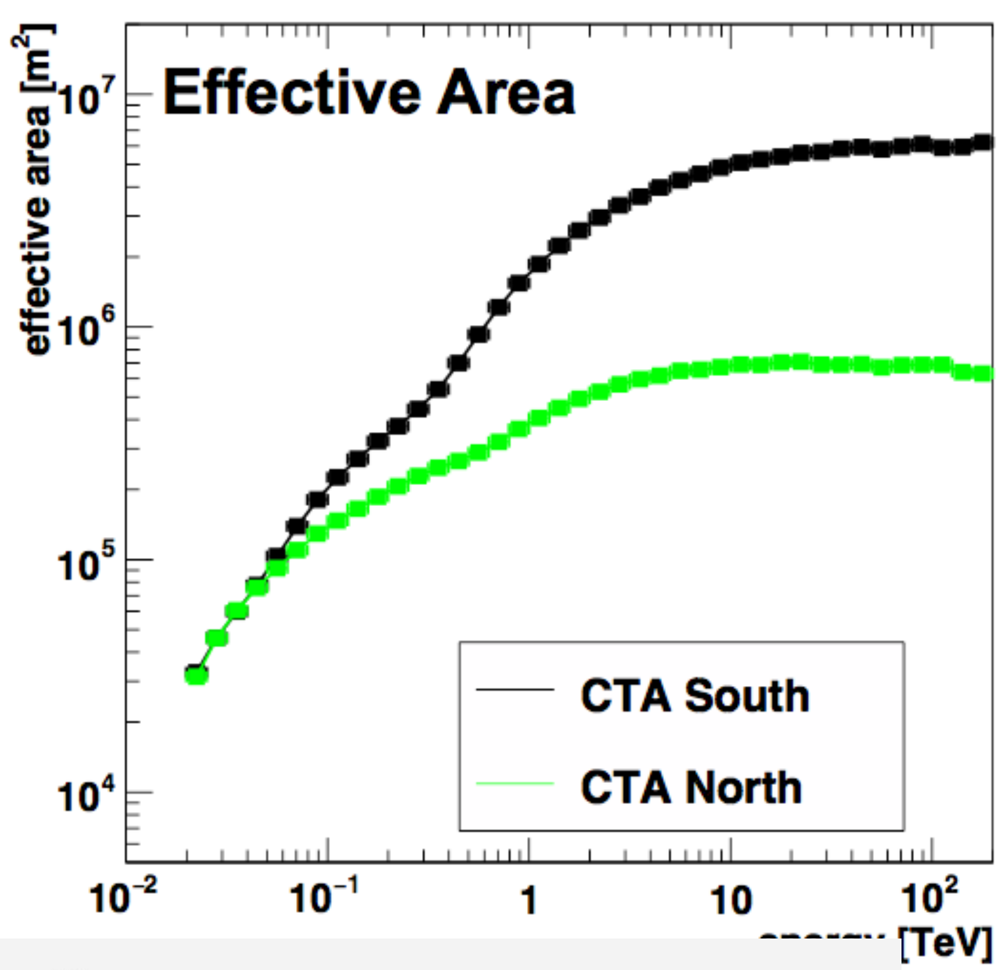
Fture

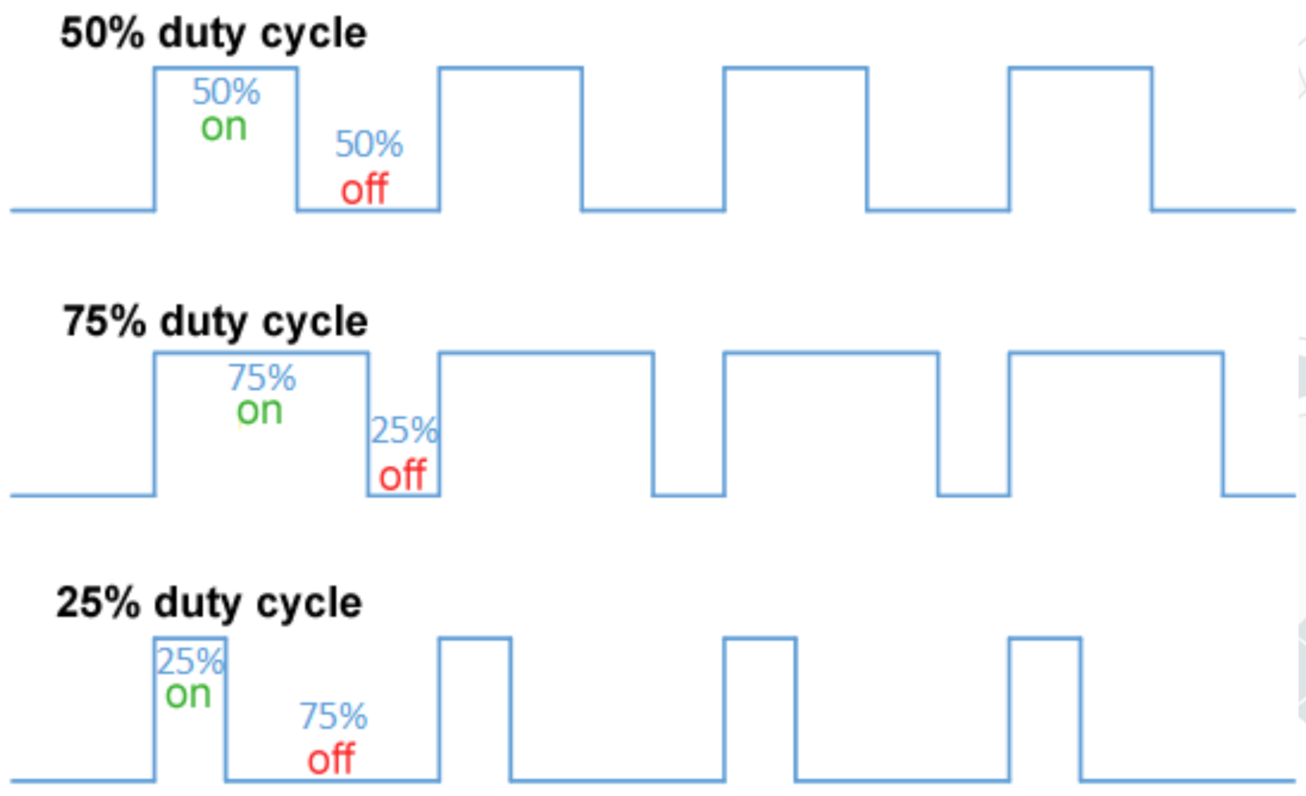
Sensitivity is not the only thing that matters

Ingredients to discovery



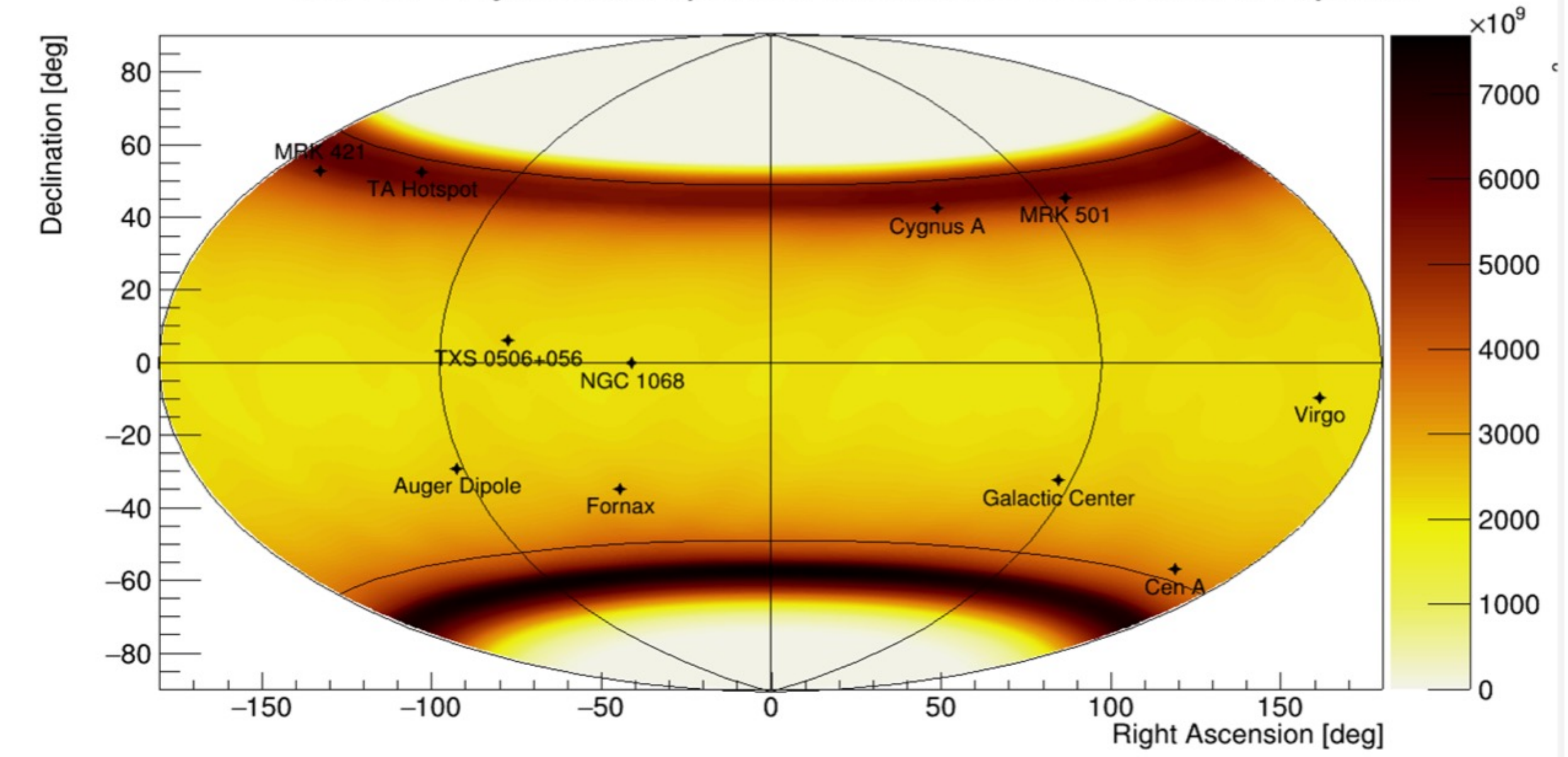






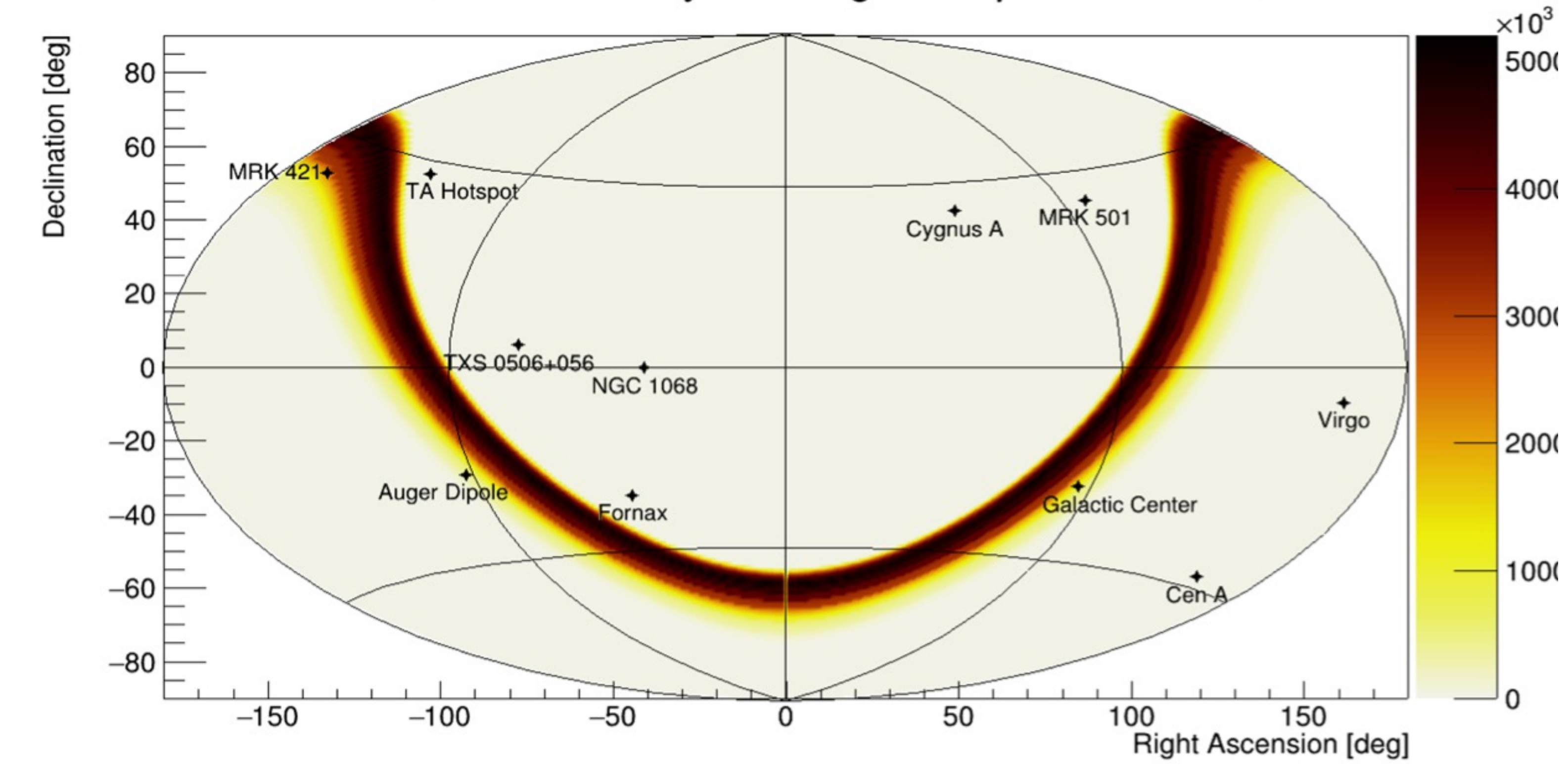
Annual

360 FoV Projection In Equatorial Coordinates Over 1 Year of Exposure



Daily

Instantanious Sky Coverage In Equatorial Coordinates



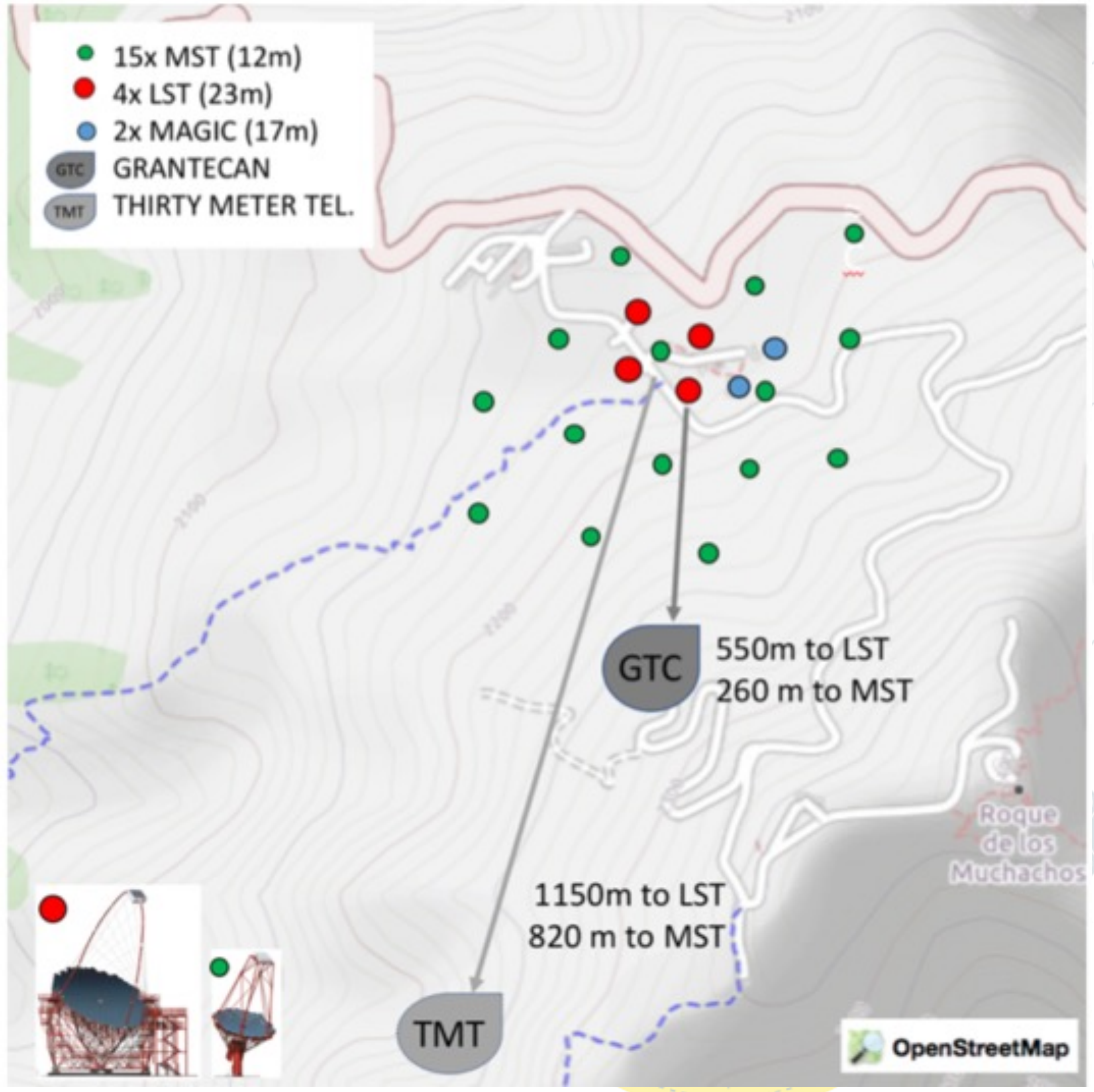
Not yet availbale

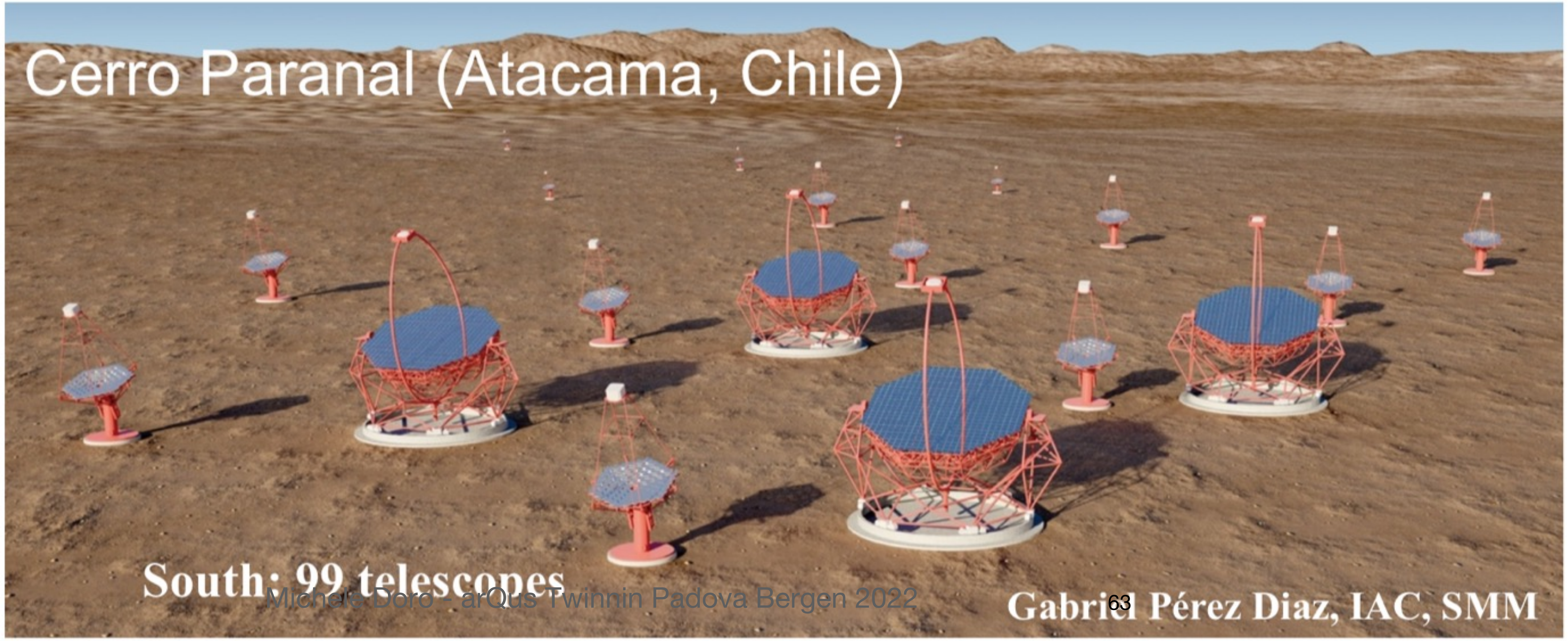
Other very interesting things to check

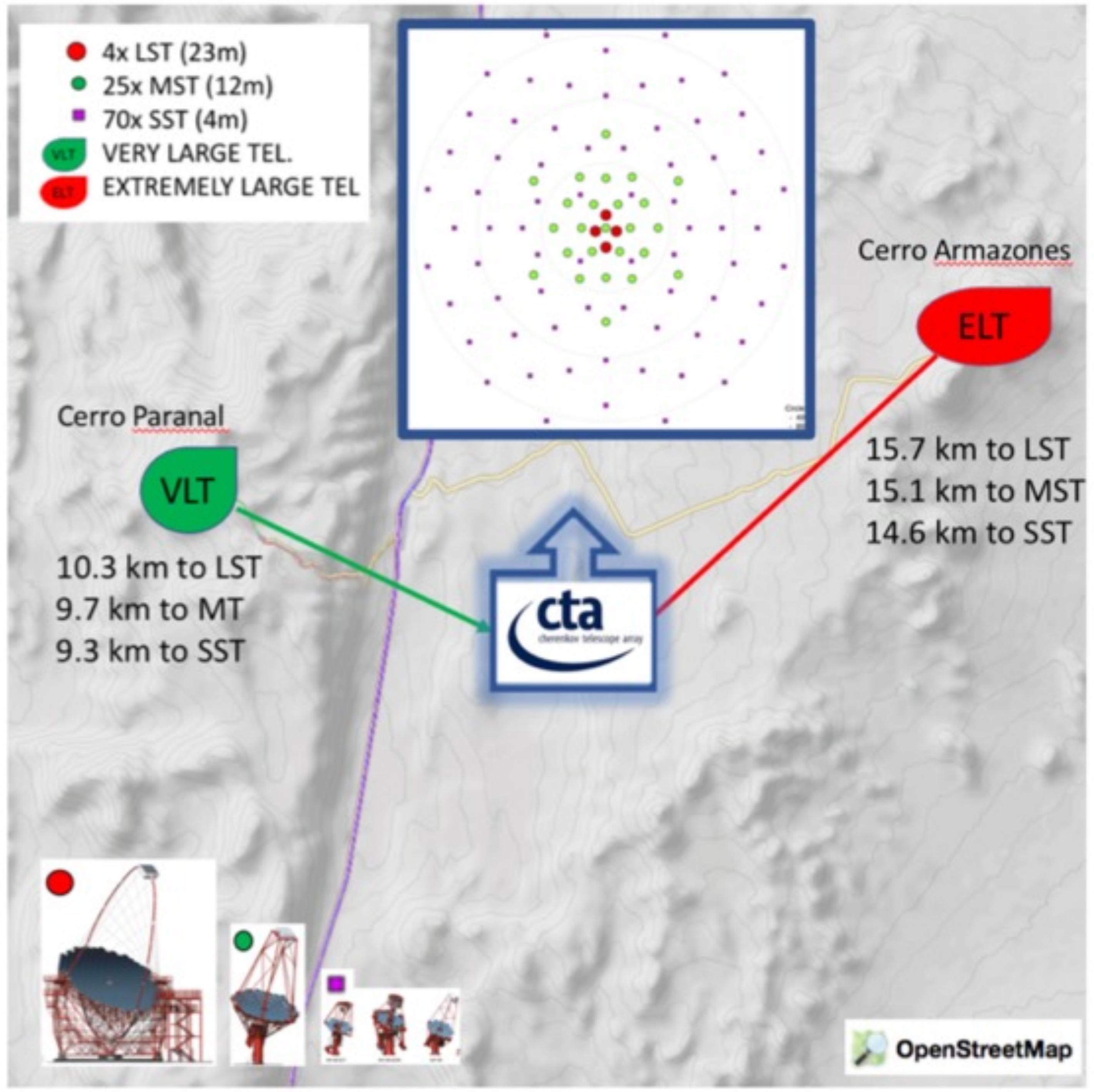
- Data
  - Are the data public/available?
  - Are data available with what delay?
- Software
  - Is there any instrument related software?
  - Is there a general astro-software?
- Science
  - Is there a guest observer program?

Two CTA arrays

M.Gaug, MD, MNRAS accepted 10.1093/mnras/sty2188→

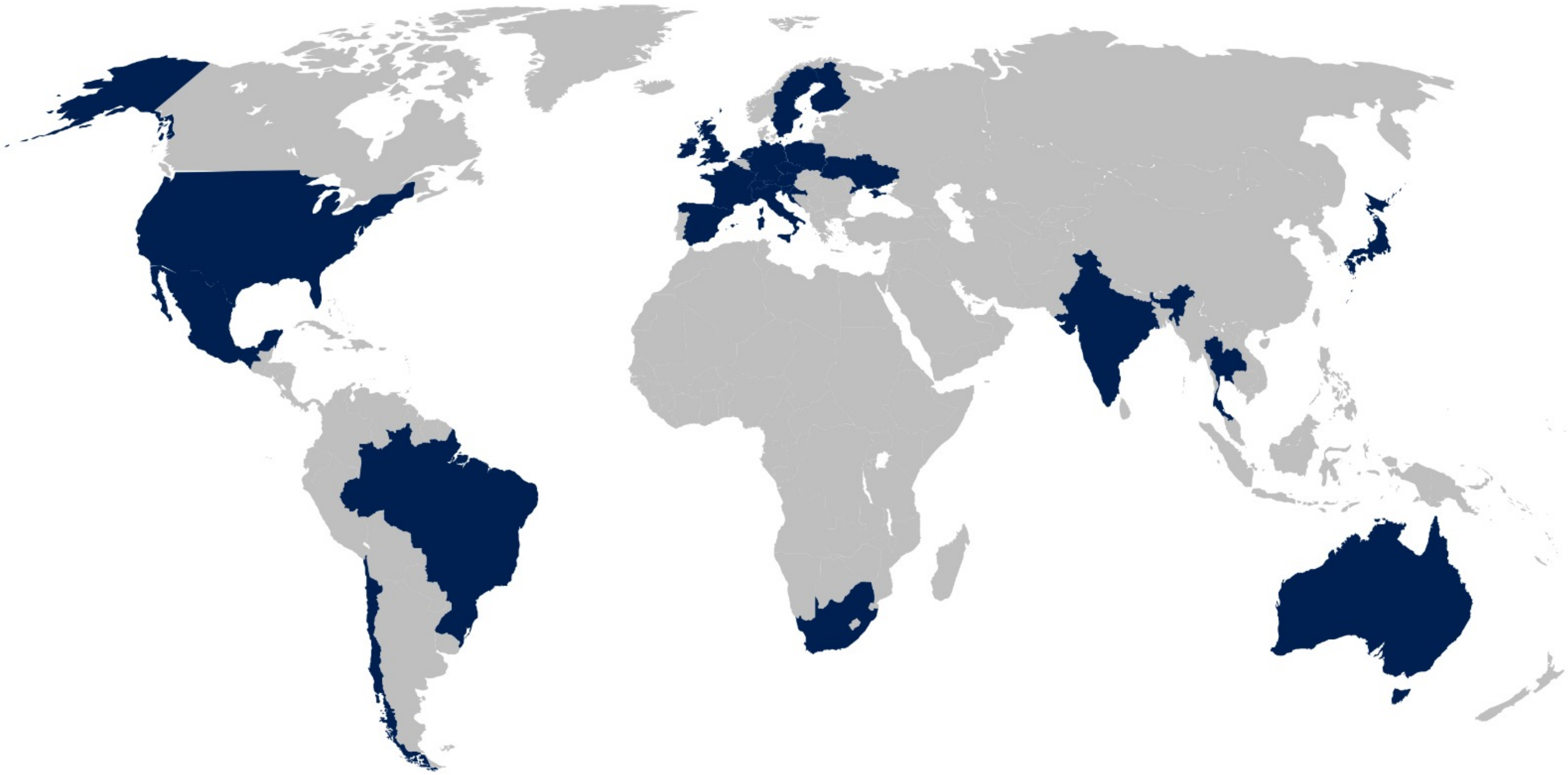






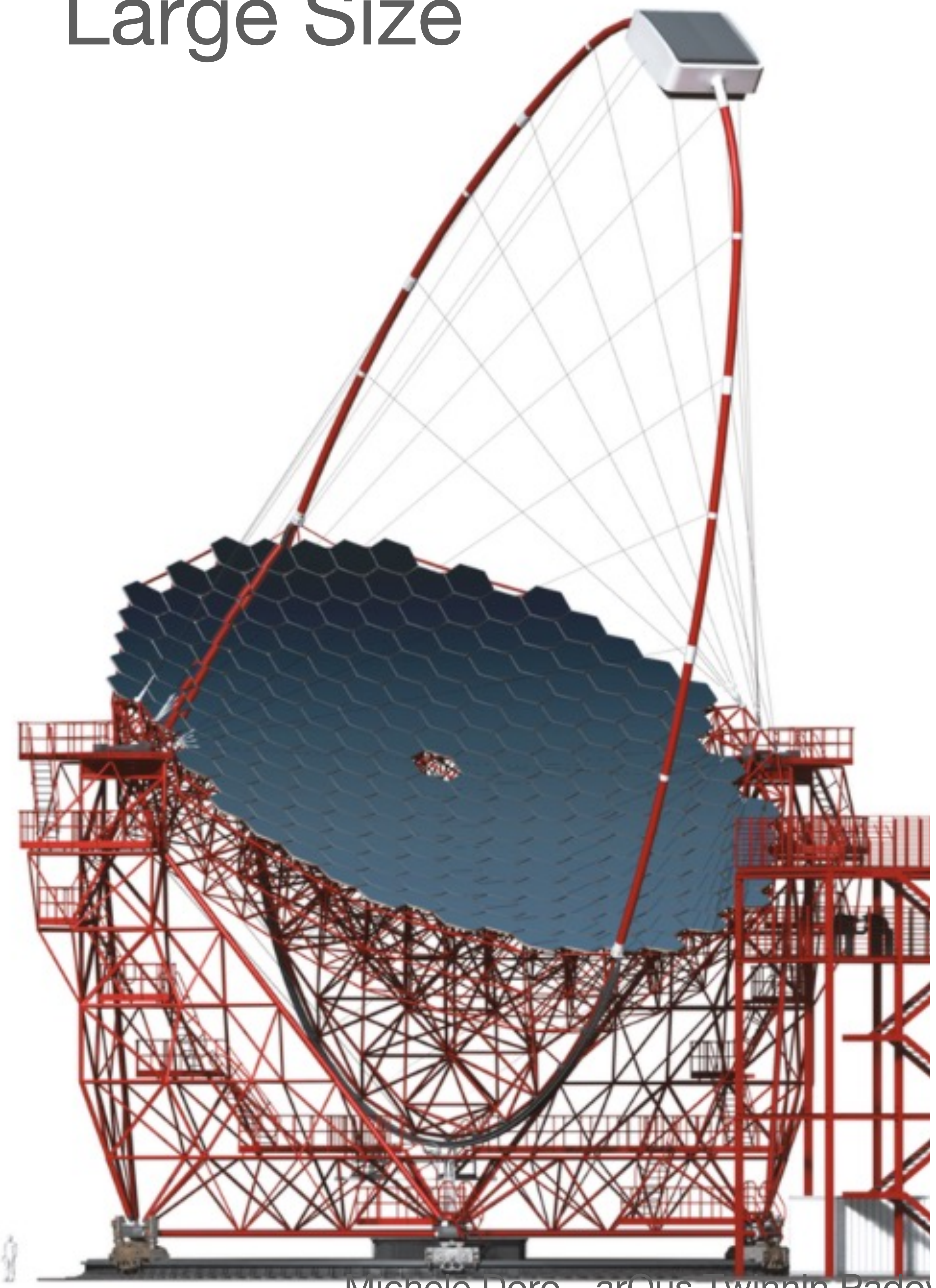
World-wide effort

»CTA is a global effort with more than 1,500 scientists and engineers from about 150 institutes in 25 countries involved in directing CTA's science goals and array design.«

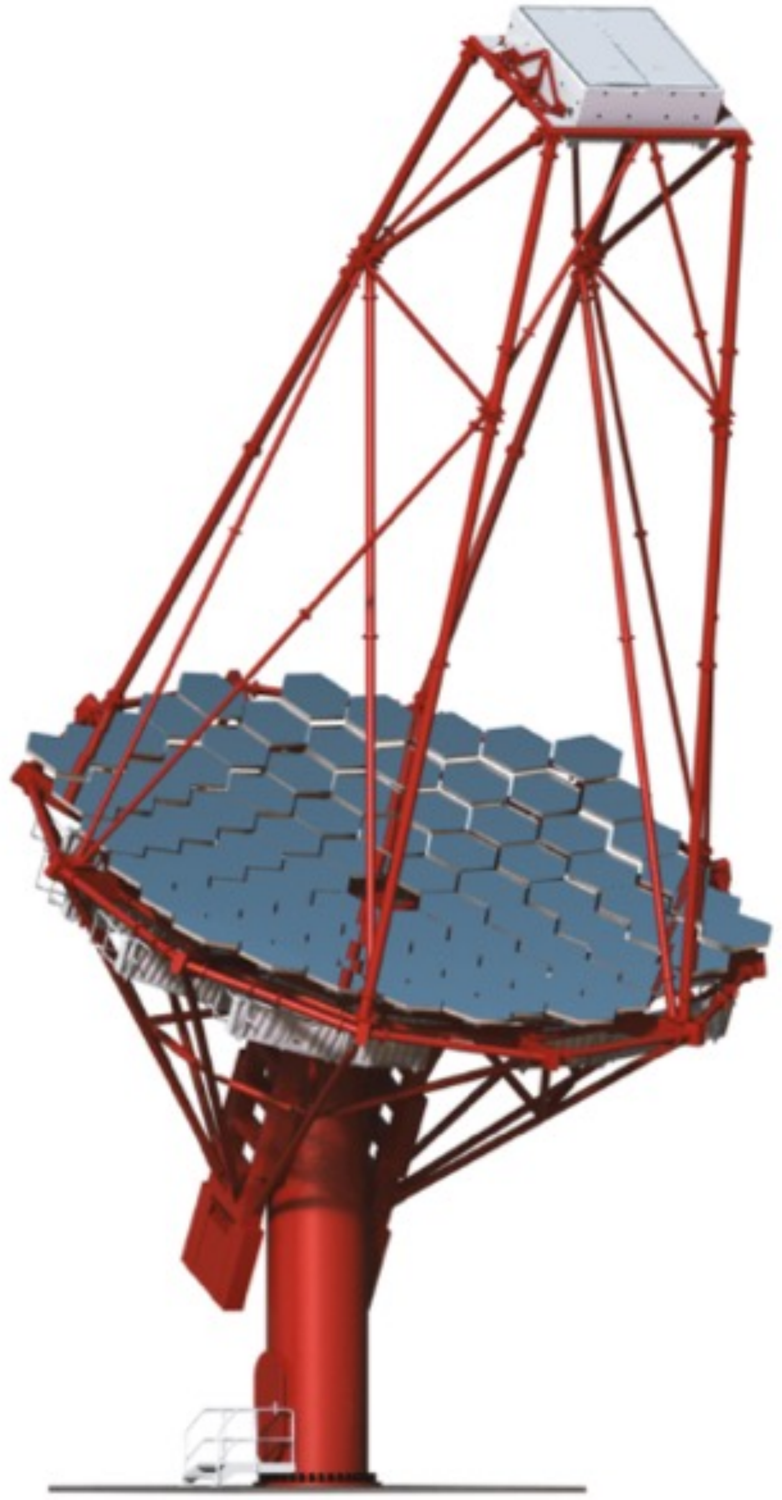


Three telescope sizes

Large Size



Medium Size



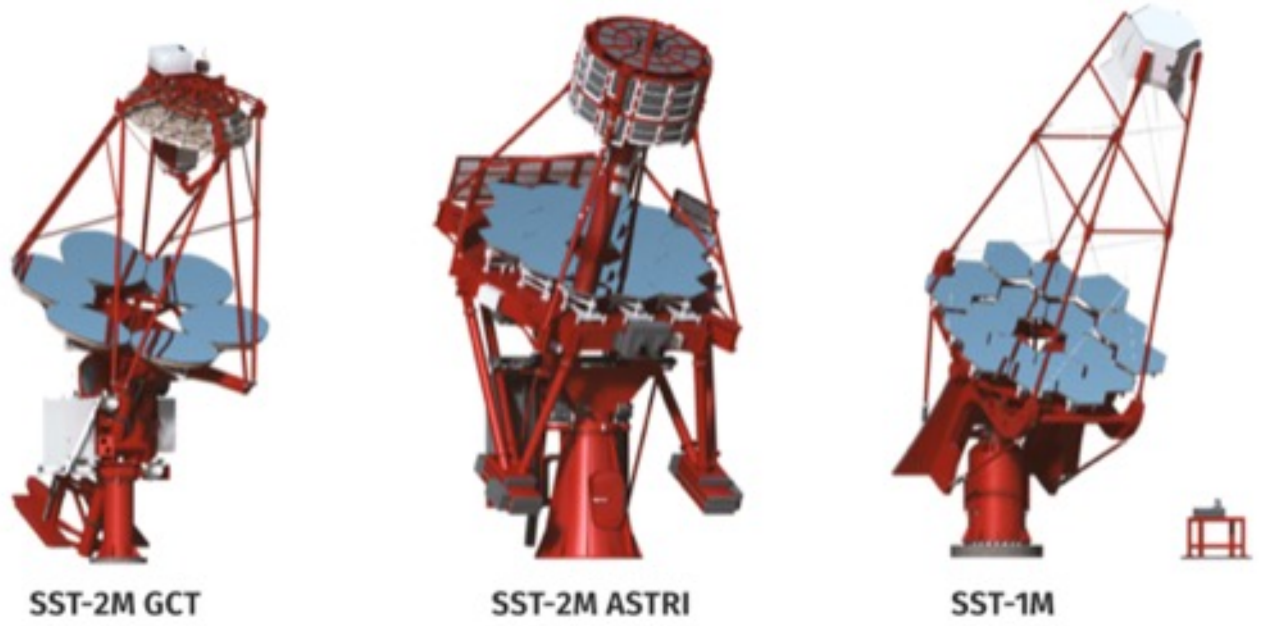
2017 Begin Pre-Construction

2022 Begin Operation

2022-25 Commissioning and Early Science

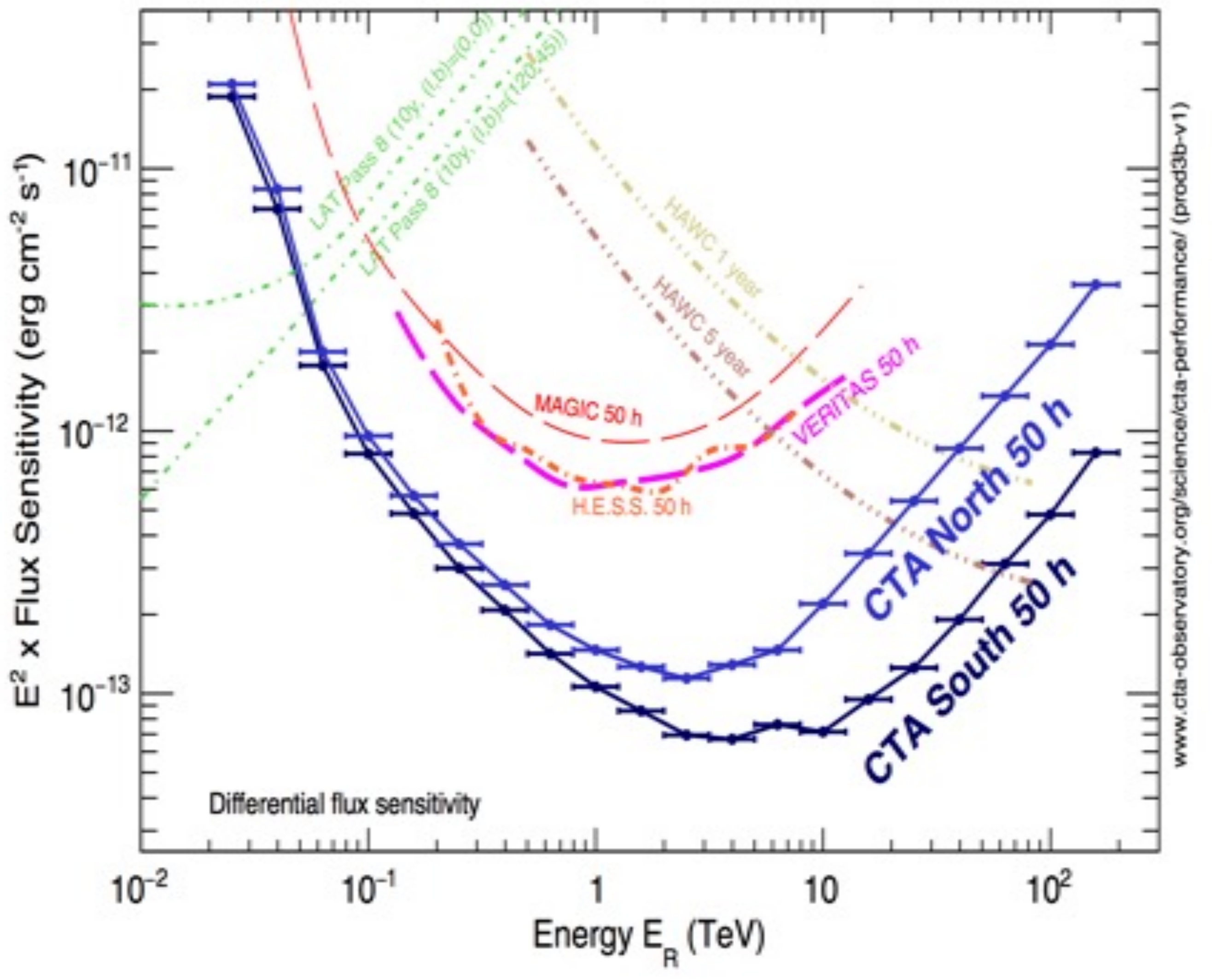
20xx Construction completion

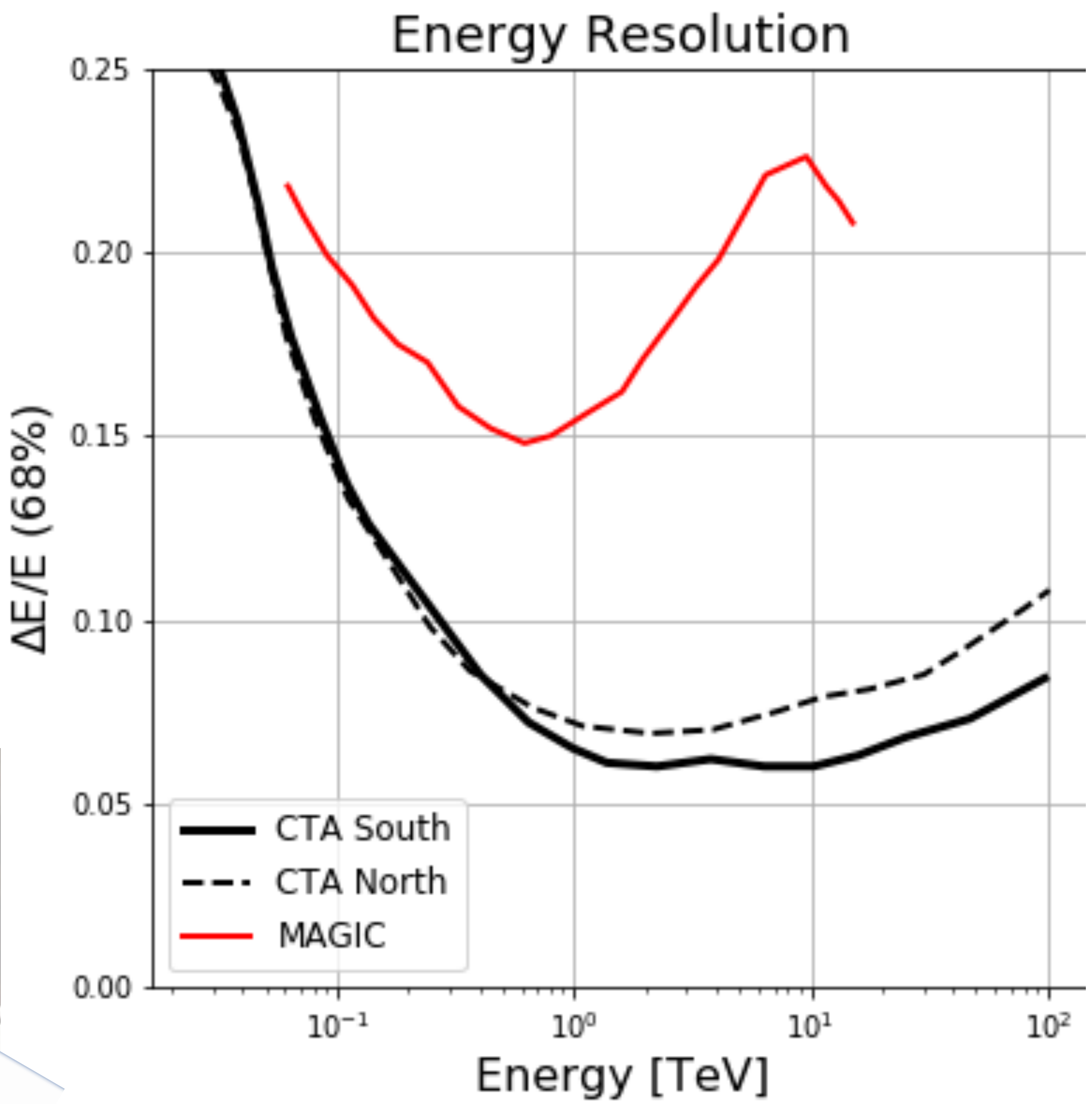
Small Size



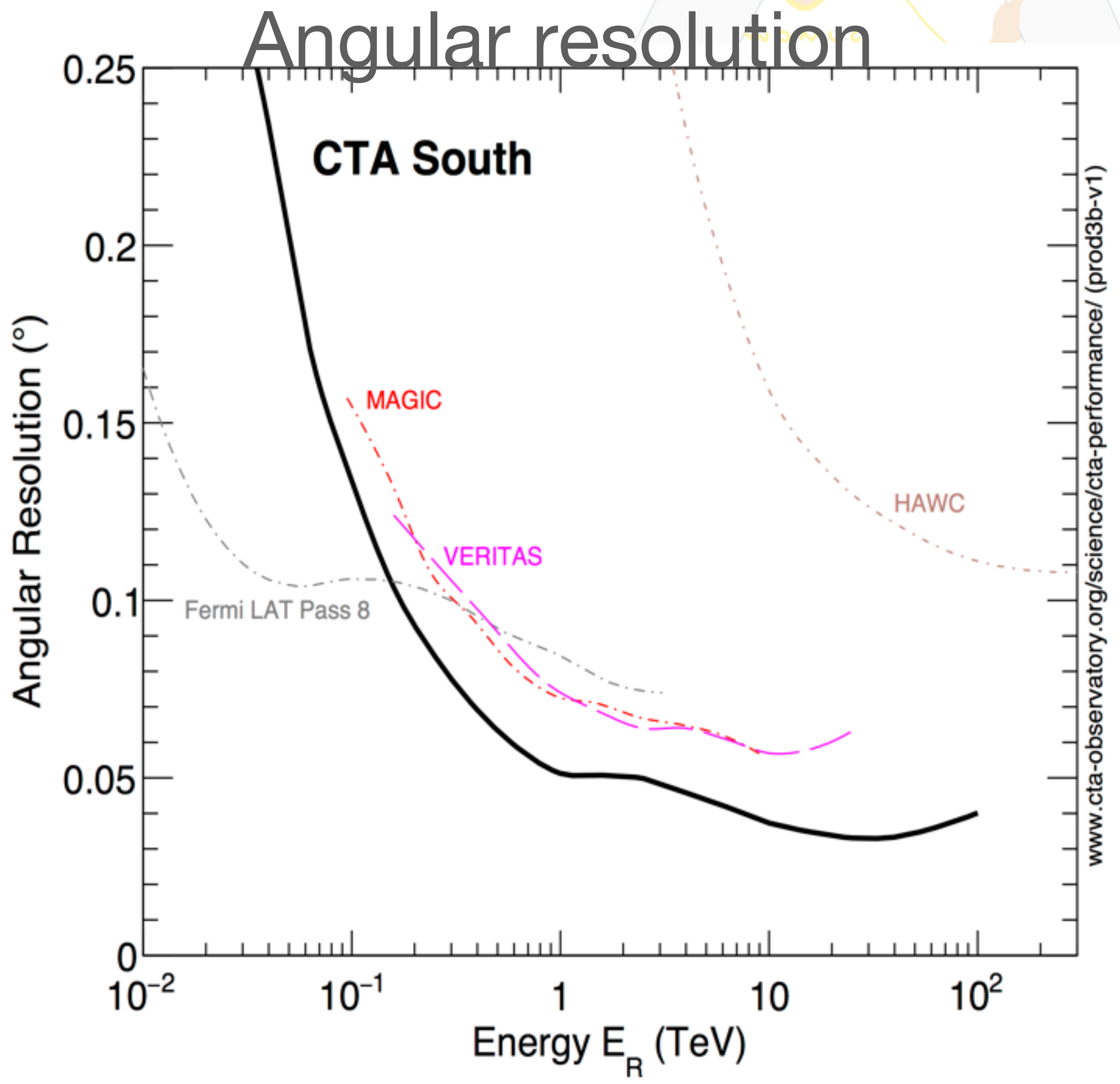
A sensitivity leap

CTA energy and angular resolution





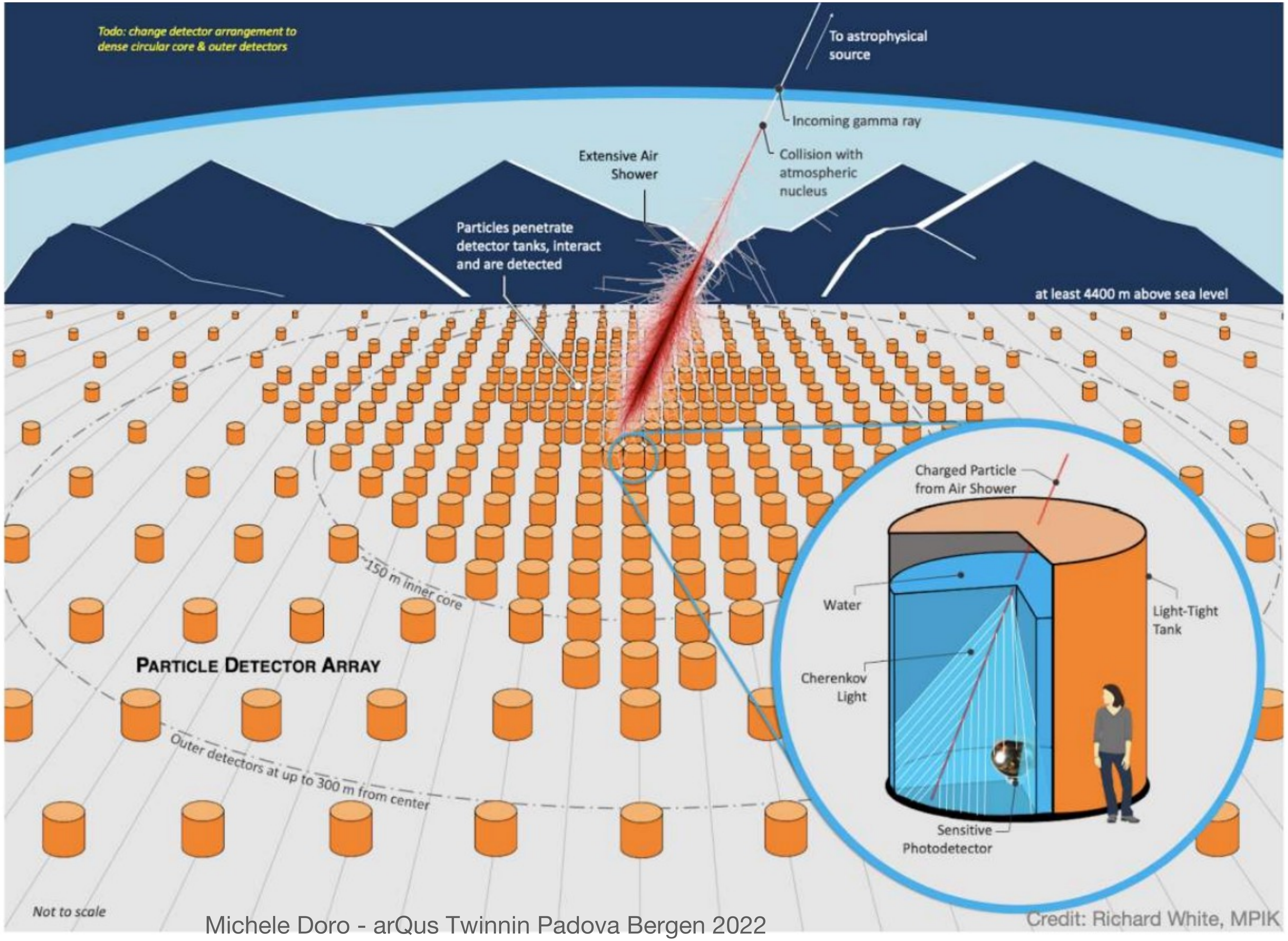
→spectral features



→ Morphology discrimination

- It would be even better if somebody told us where dark subhalos could be…
- Fermi-LAT follow ups?

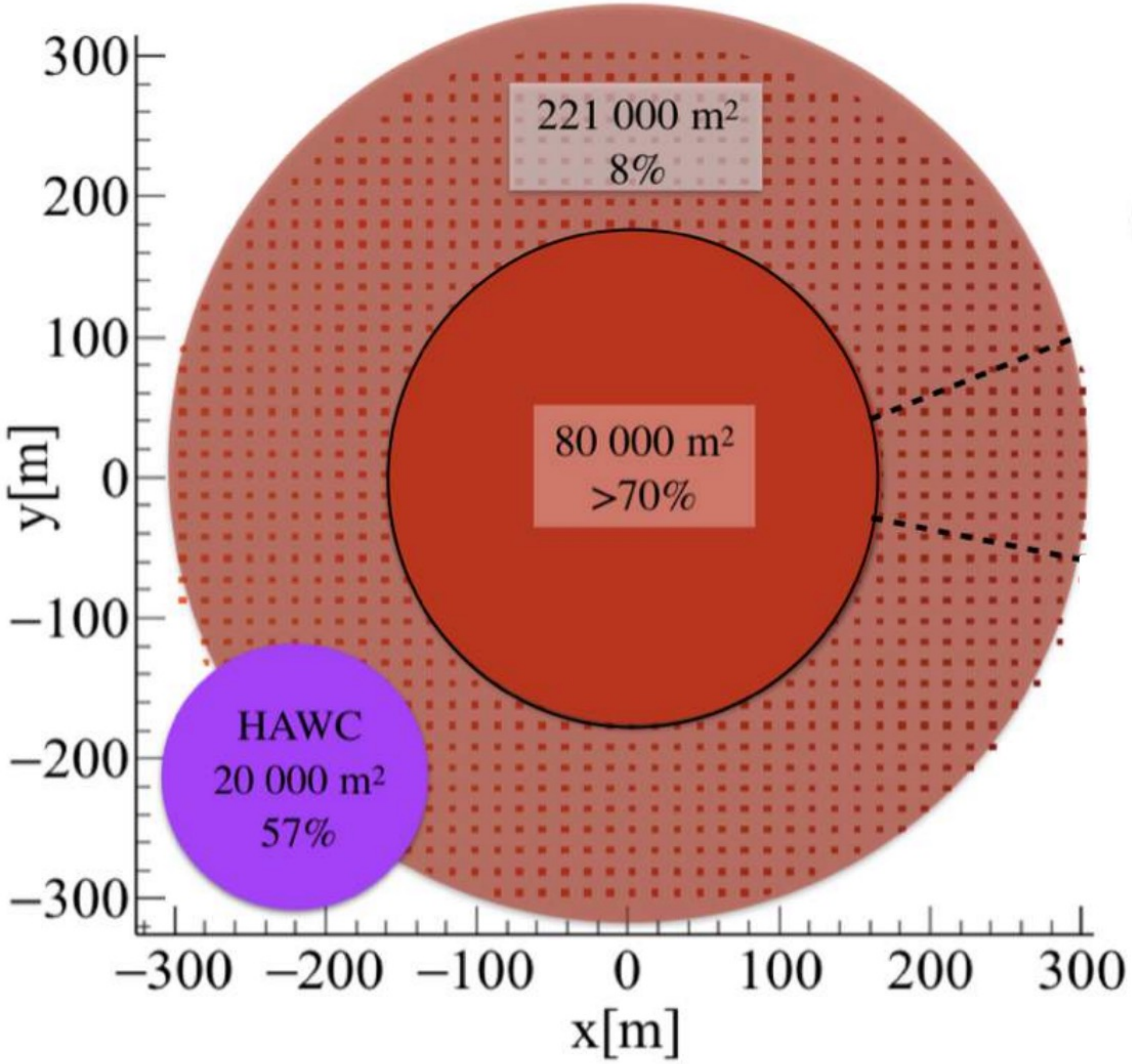
SWGO

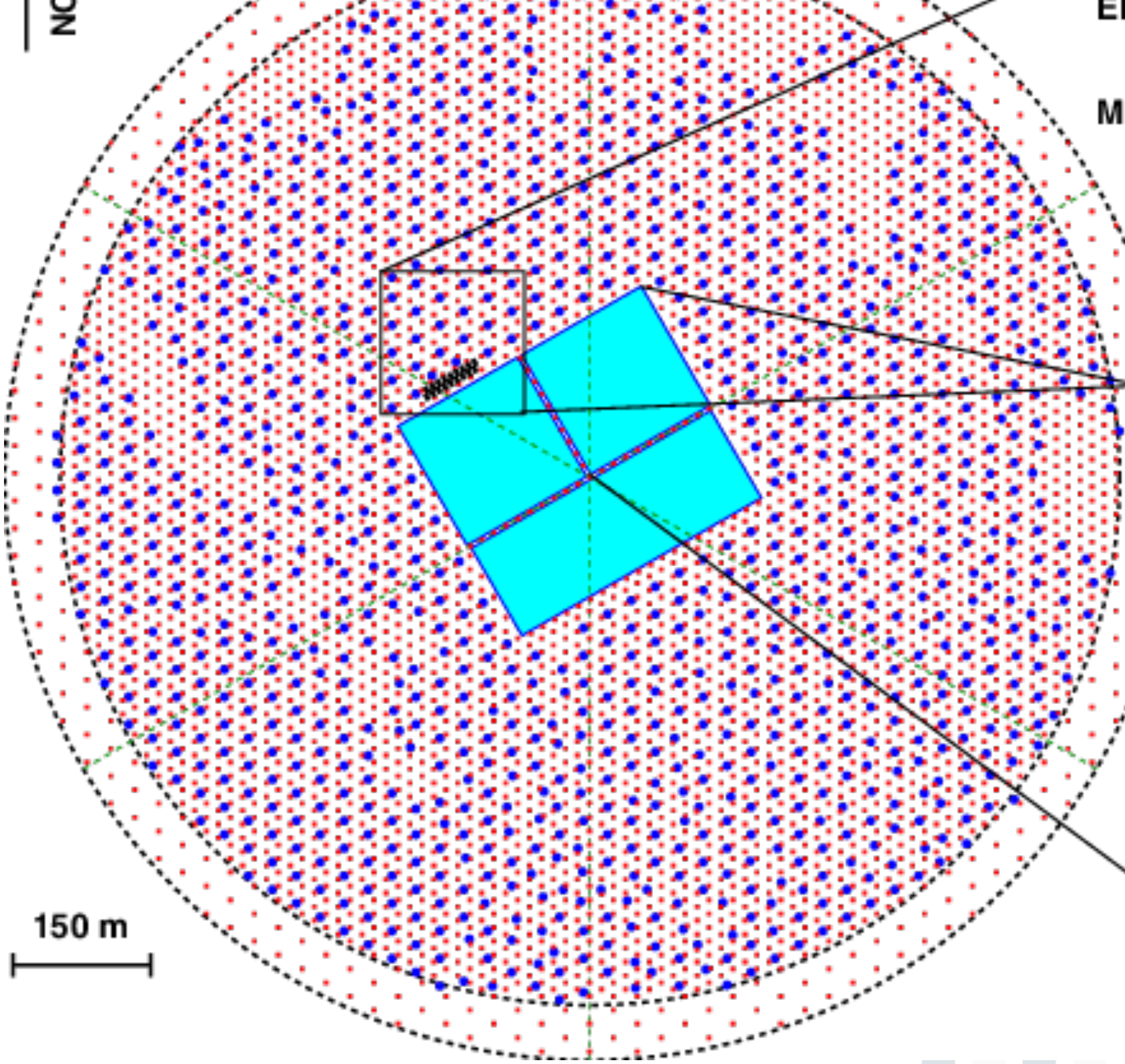


The Southern Wide-field Gamma-ray Observatory

- New project in South America

SWGO


221 000 m²
8%
80 000 m²
>70%
HAWC
20 000 m²
57%
y[m]
x[m]
300
200
100
0
−100
−200
−300
−300 −200 −100 0 100 200 300


150 m

Recap

1. There cannot be a single instrument to cover all energy-range
2. Instruments are bound to technology available, or technology development, and costs
3. Instruments improve with generations

Good bye and thanks!