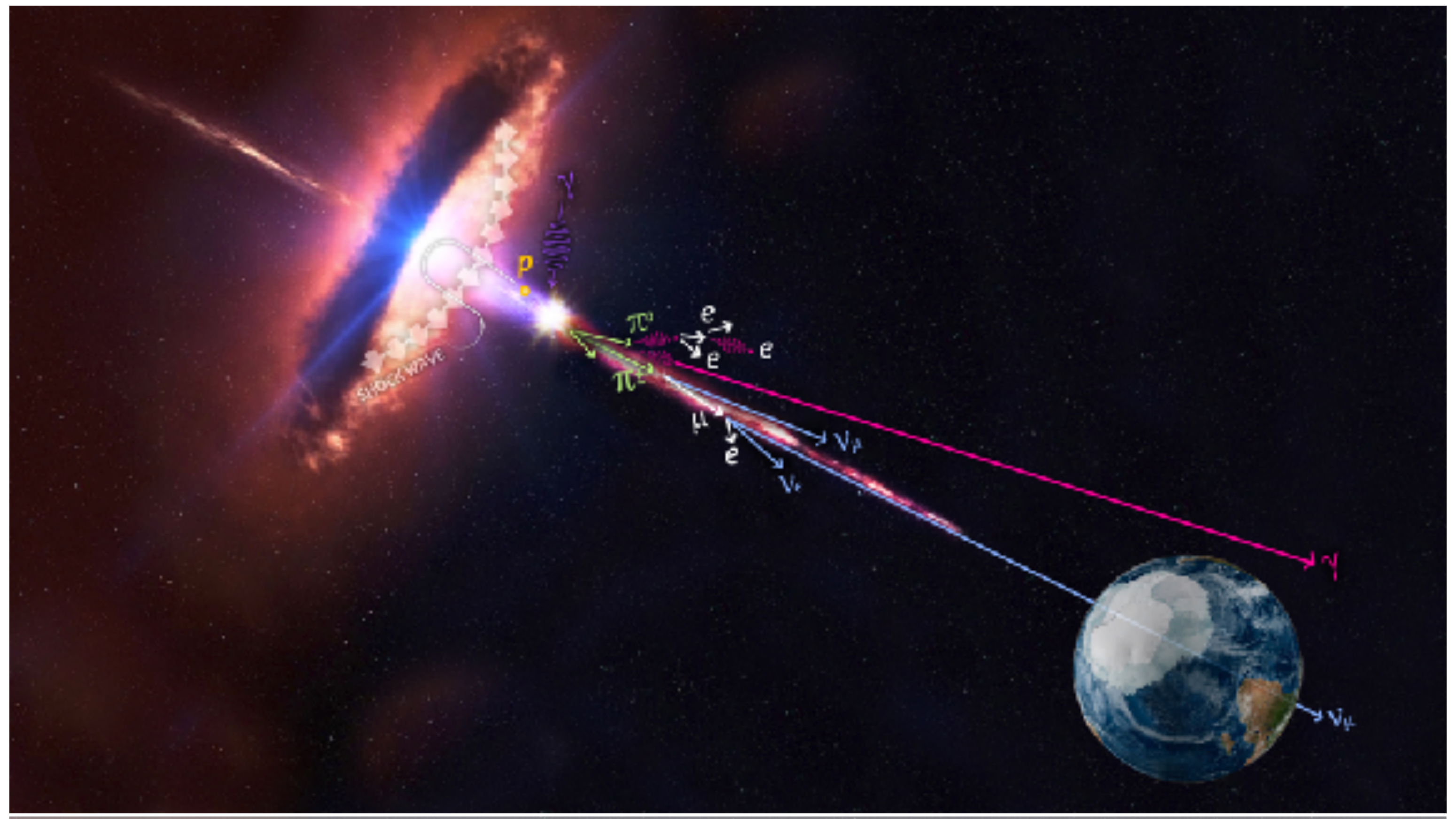
第30回
ICEPP シンポジウム

Hardware Stereo Trigger

Joshua R. Baxter (ICRR, University of Tokyo)

Gamma-ray Observations

Gamma-ray Astronomy & Astrophysics

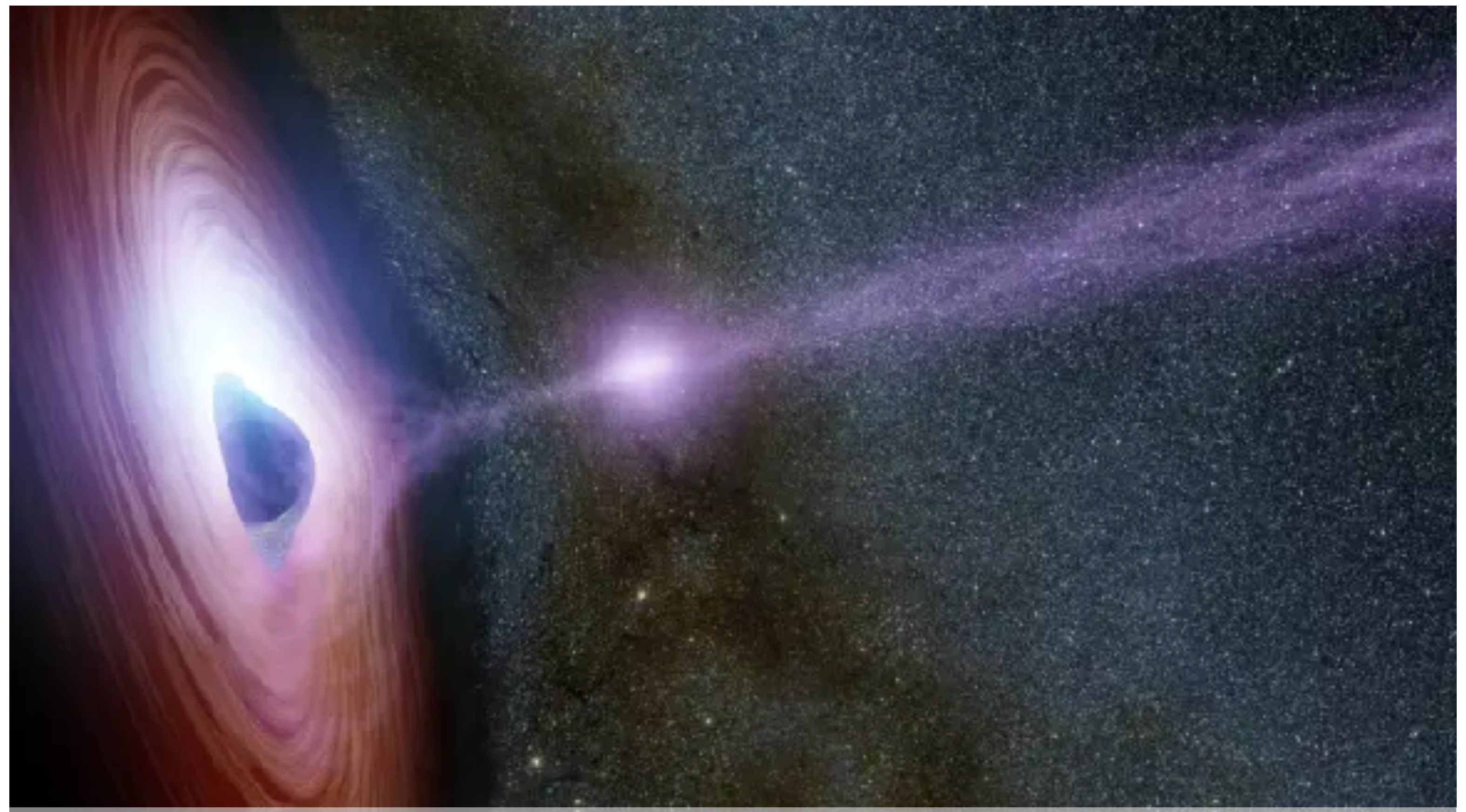


Origin of comic rays

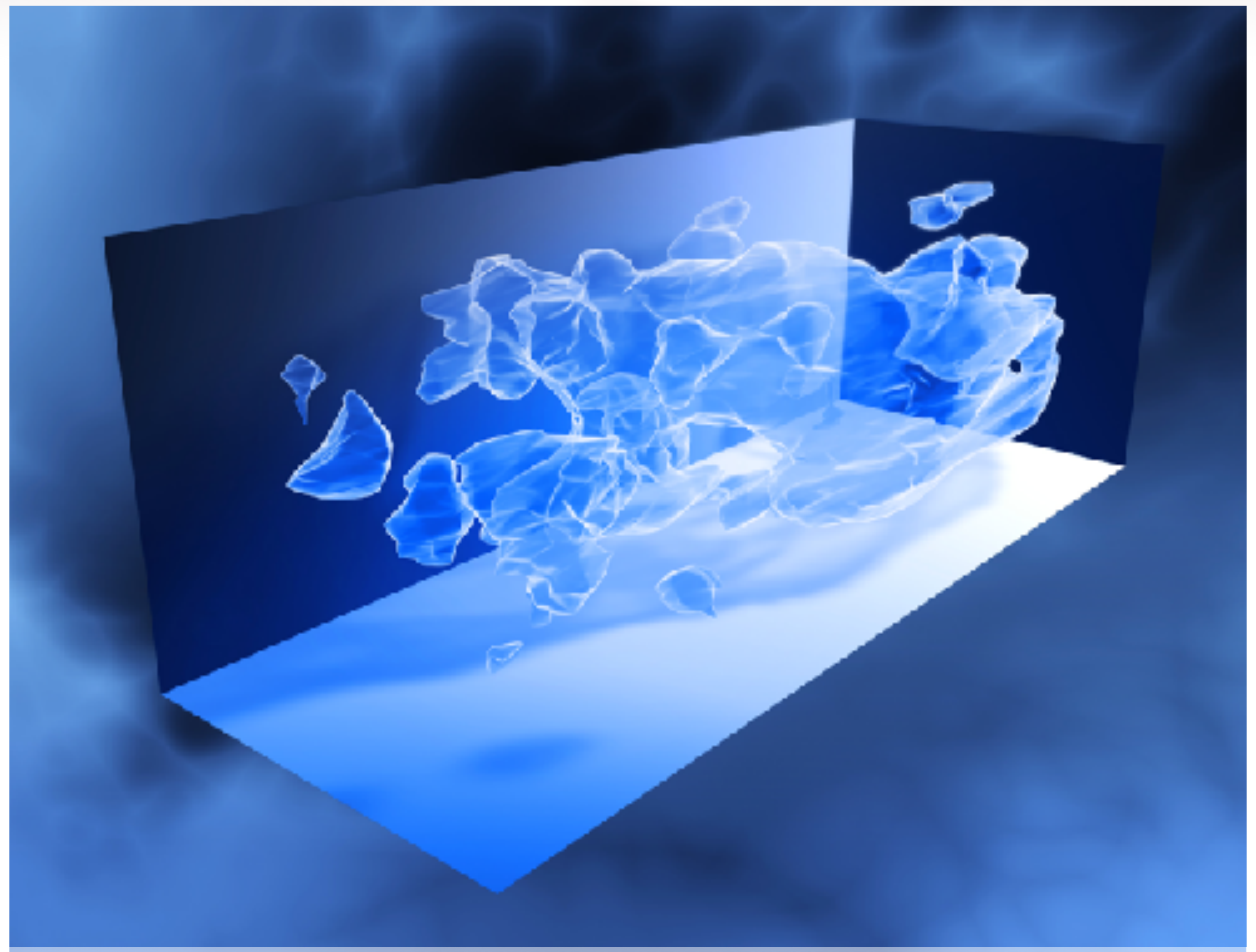
Supernova Remnant

Supermassive Black Hole

Gamma-ray Burst

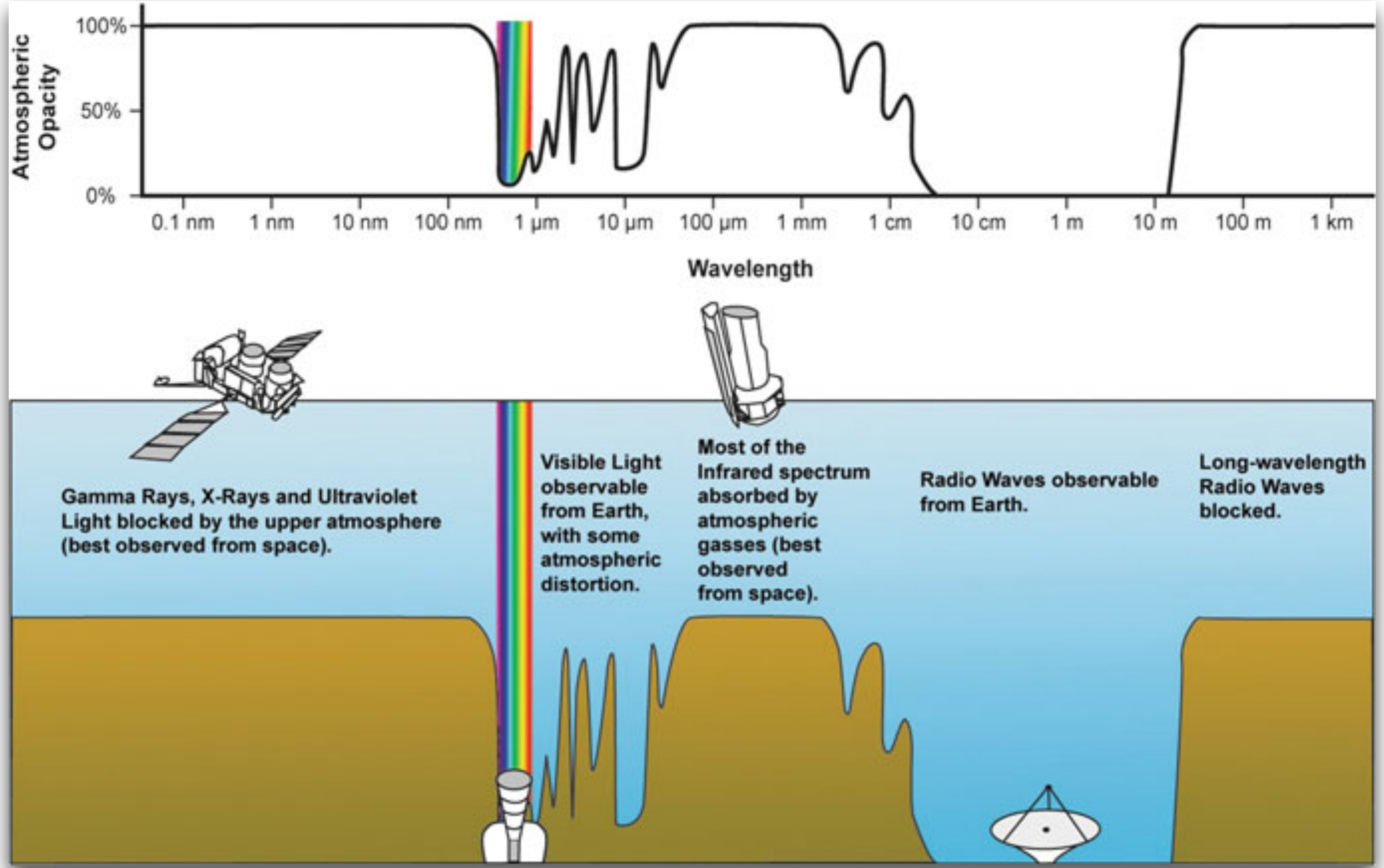


Active Galactic Nuclei



Dark Matter

Opacity of the Universe



Gamma ray Observation: Fermi-LAT

- Gamma-ray observation satellite, part of a NASA project.
- equipped with two gamma-ray detectors: a large-area telescope (LAT) and a gamma-ray burst monitor (GBM).
- It detects gamma rays by pair-conversion in the calorimeter.
- Energy range: 20 MeV- 300 GeV
- Due to the limitation of the effective area, very-high-energy (VHE) gamma rays are observed with ground-based telescopes.

50ms exposure
(human eye)


5ms exposure
Moon
Aldebaran
Betelgeuse
Rigel

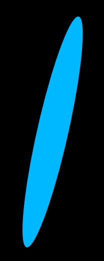
0.5ms exposure

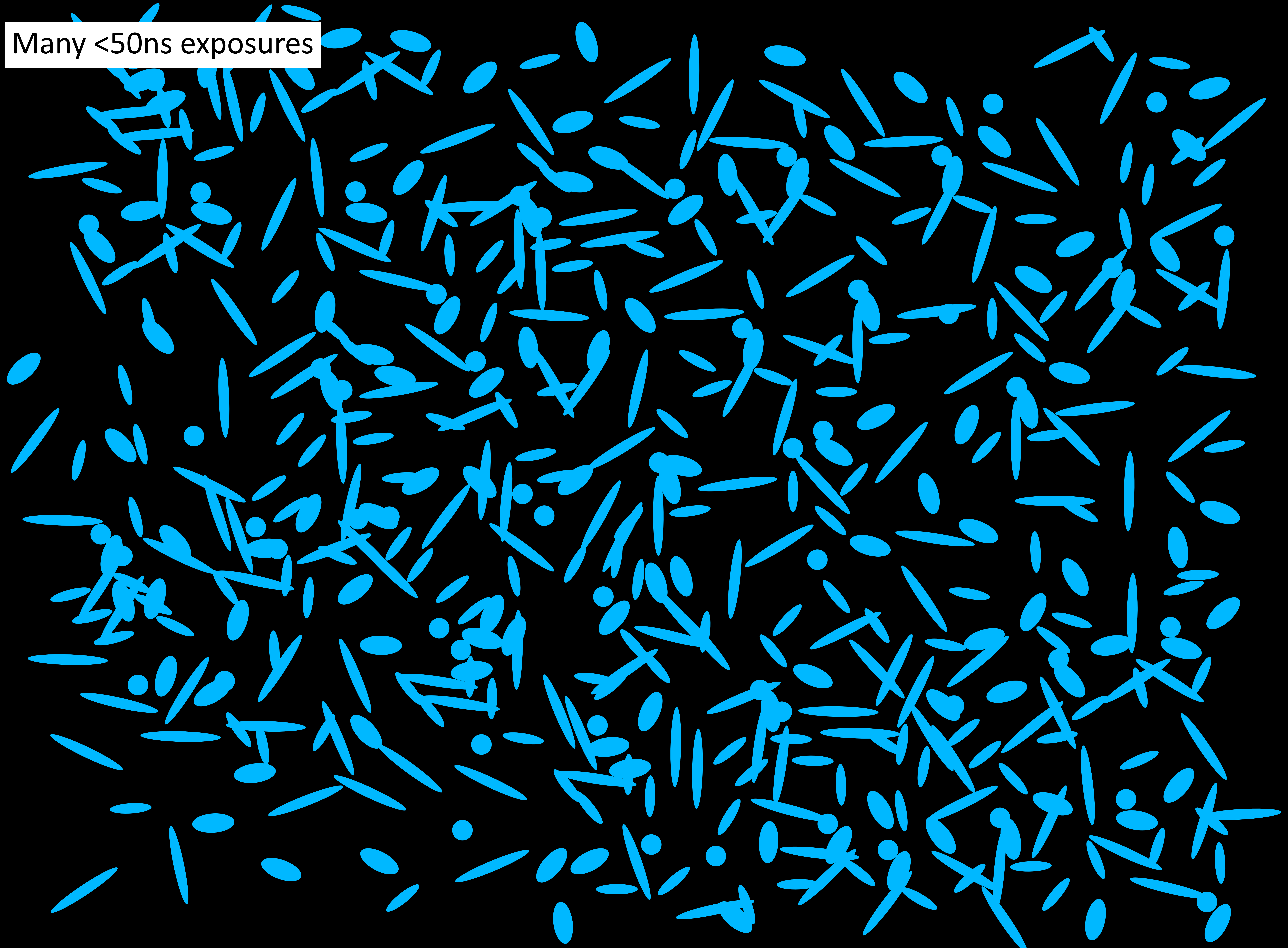
50µs exposure

5μs exposure

0.5μs exposure

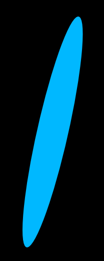
<50ns exposure



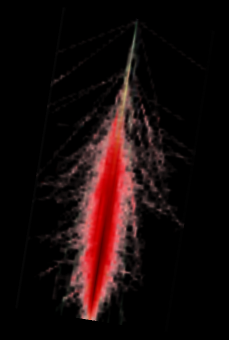

Many <50ns exposures

50ms exposure
(human eye)

<50ns exposure

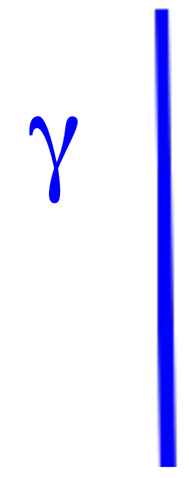


<50ns exposure



Imaging Atmospheric Cherenkov Telescope

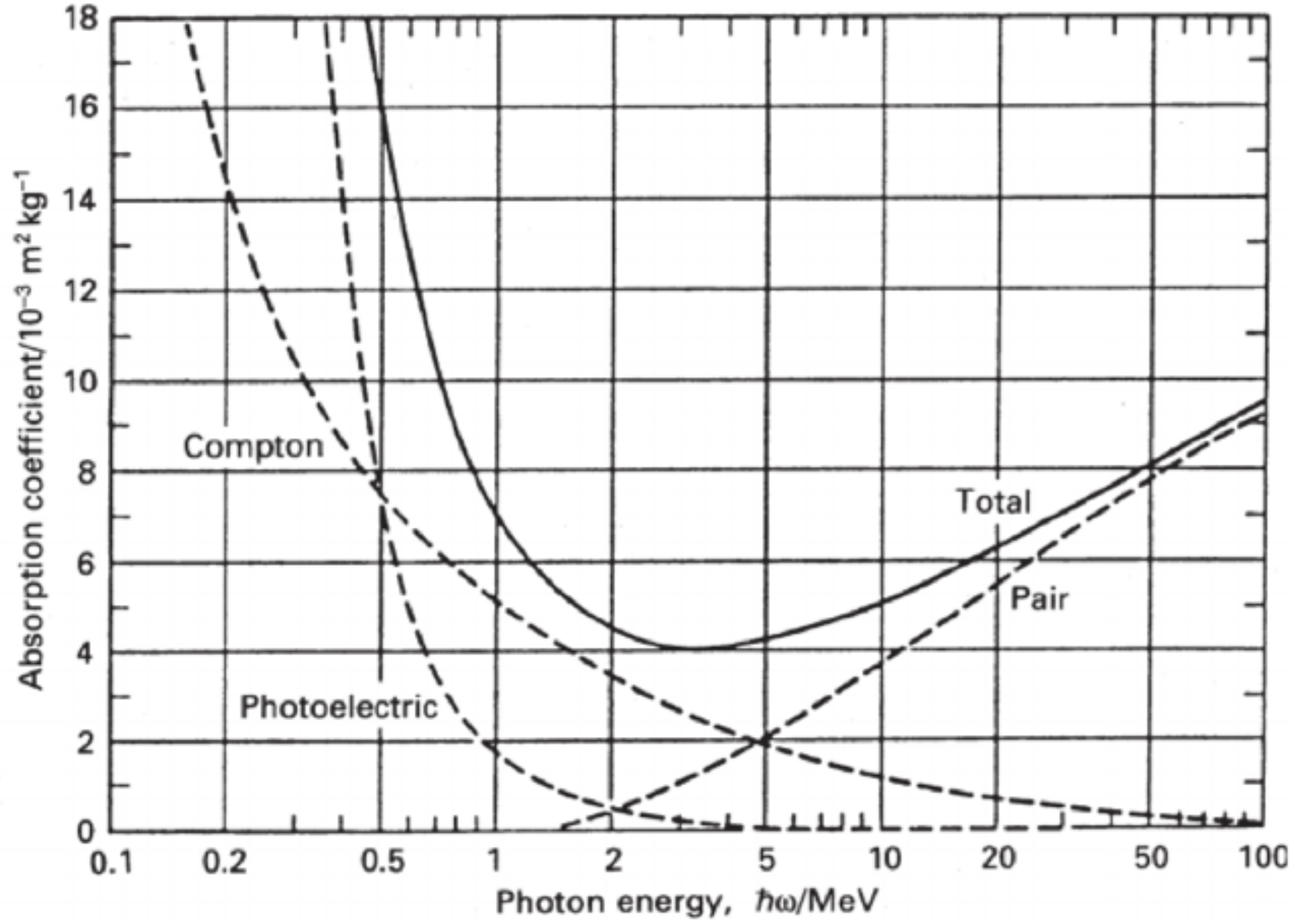
What happens when a very high energy gamma-ray enters the atmosphere?



Imaging Atmospheric Cherenkov Telescope

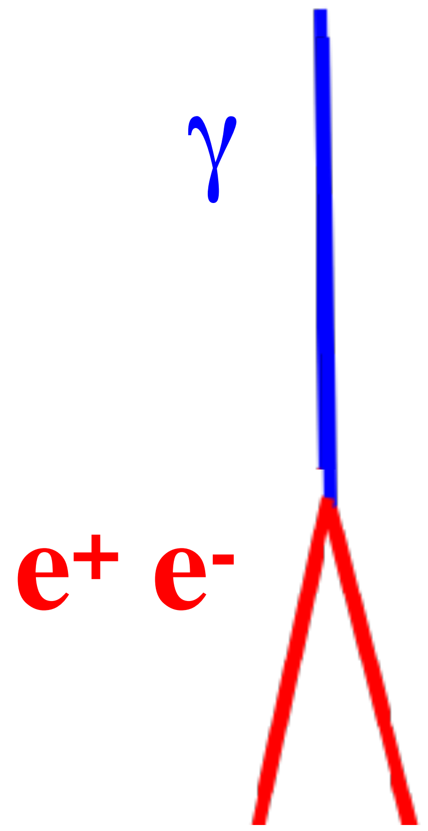
What happens when a very high energy gamma-ray enters the atmosphere?

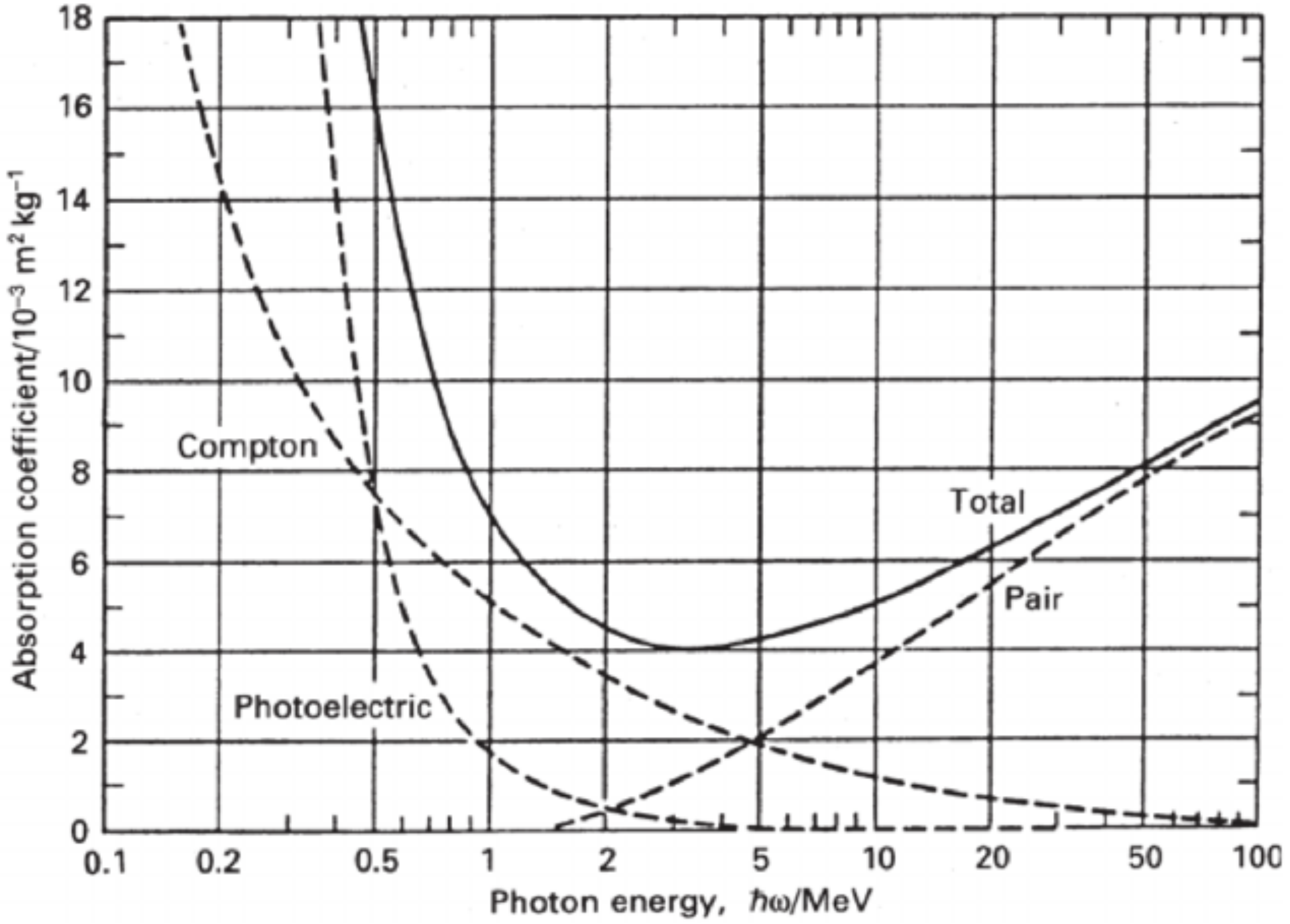
γ



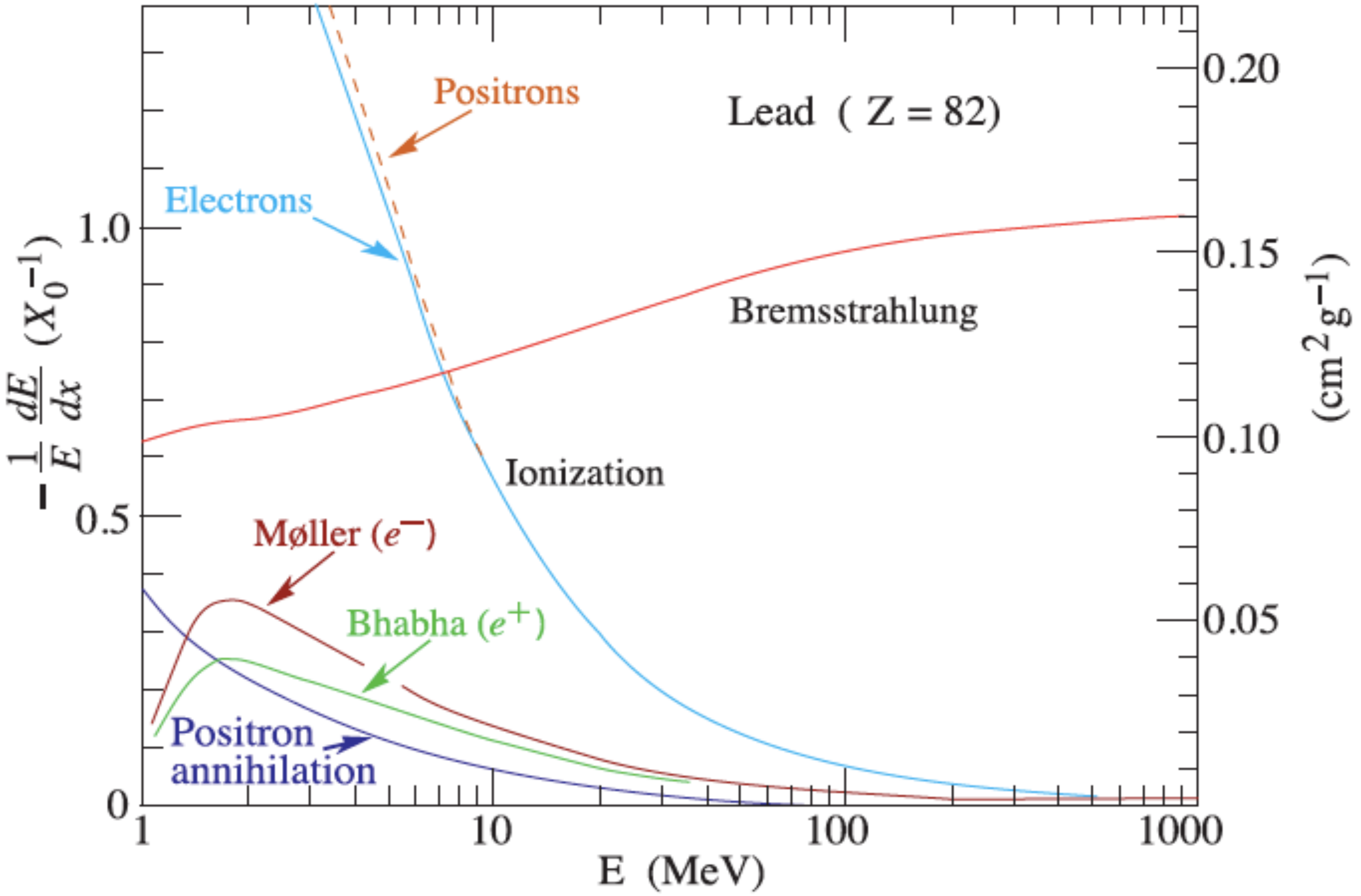
Imaging Atmospheric Cherenkov Telescope

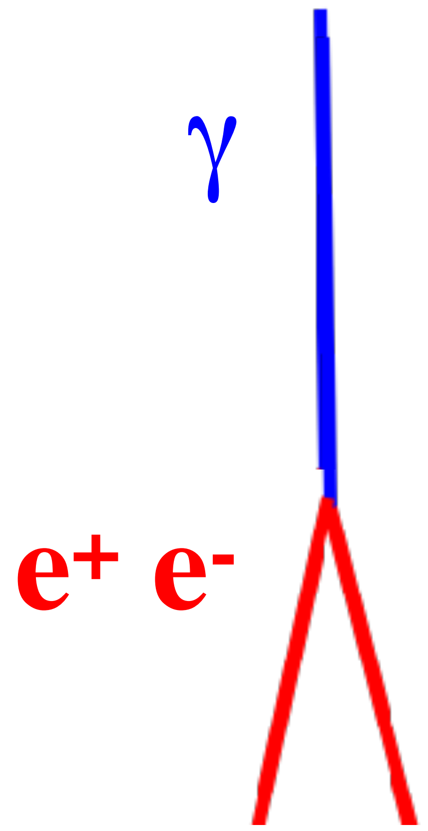
What happens when a very high energy gamma-ray enters the atmosphere?





What happens when a very high energy gamma-ray enters the atmosphere?

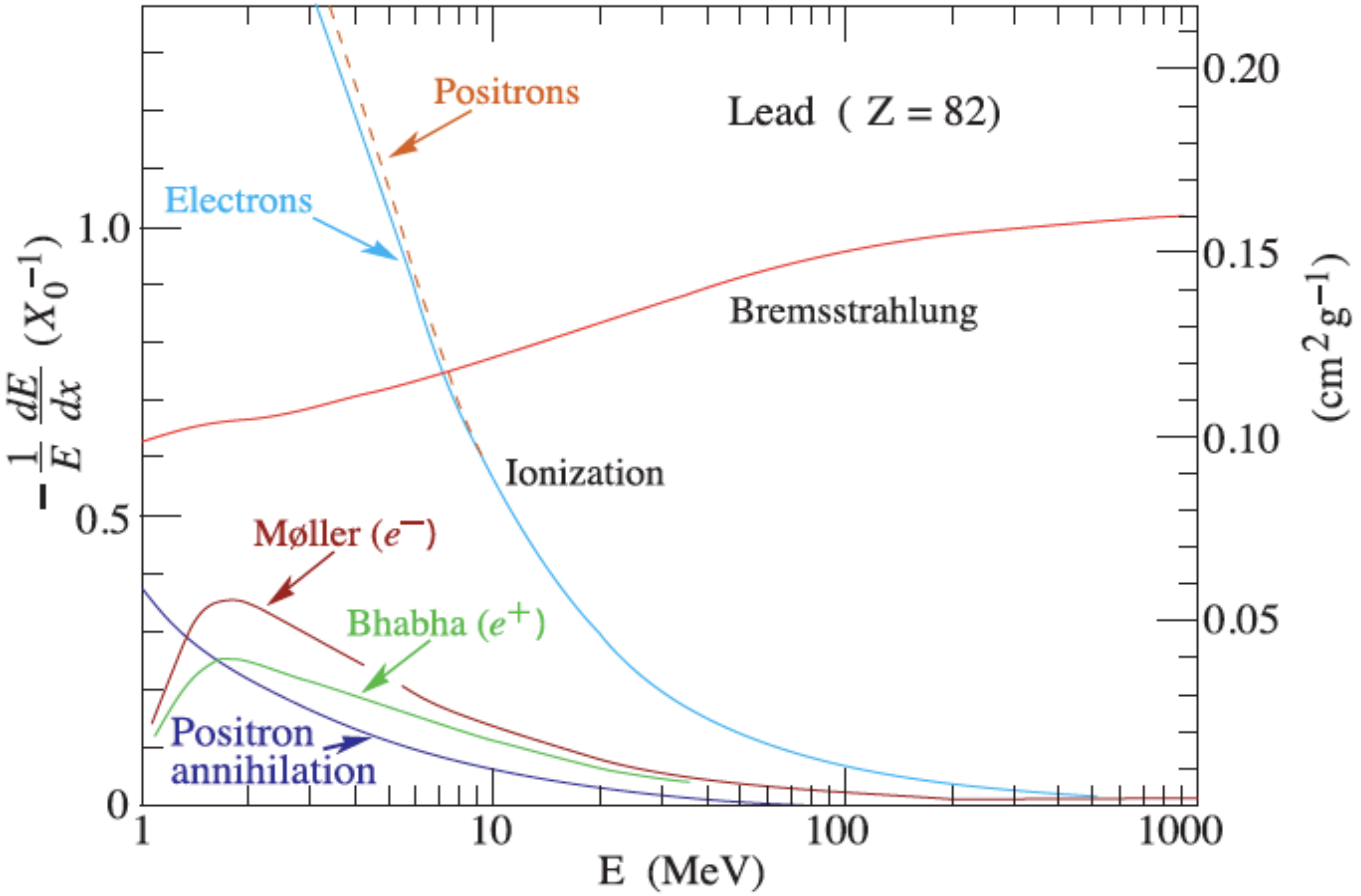


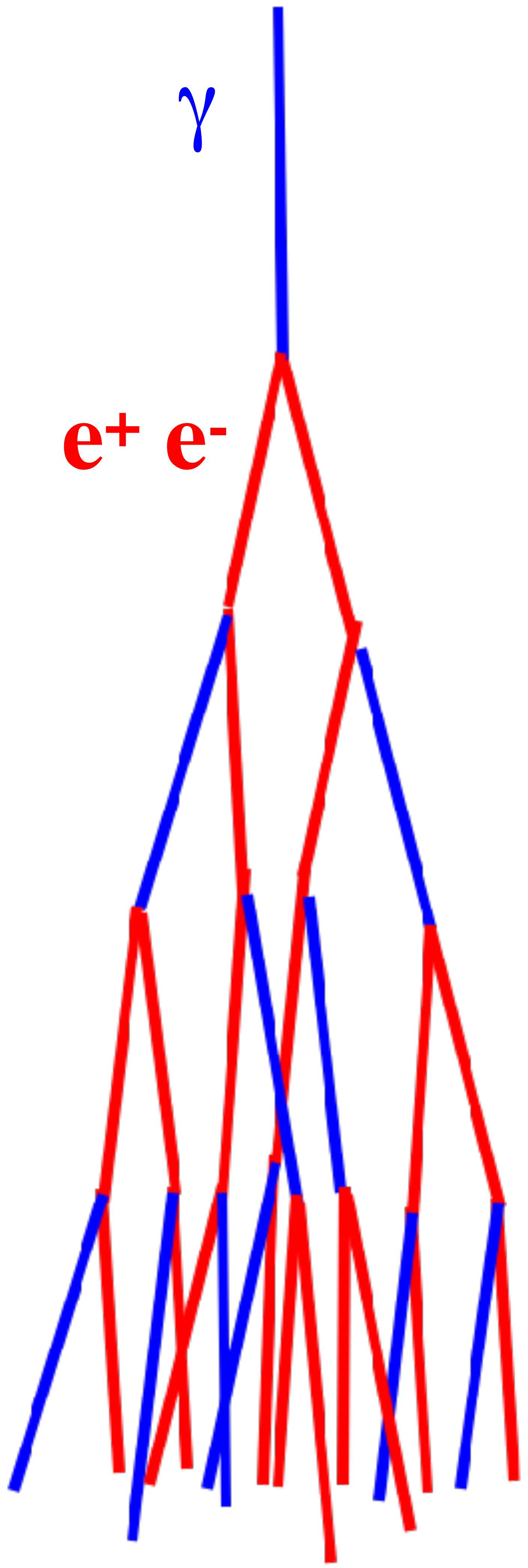


Ionization takes over at the 'Critical energy'= 560 MeV/Z
Z of air = 7 (nitrogen)
Critical energy in air = 560/7=80 MeV

Imaging Atmospheric Cherenkov Telescope

What happens when a very high energy gamma-ray enters the atmosphere?

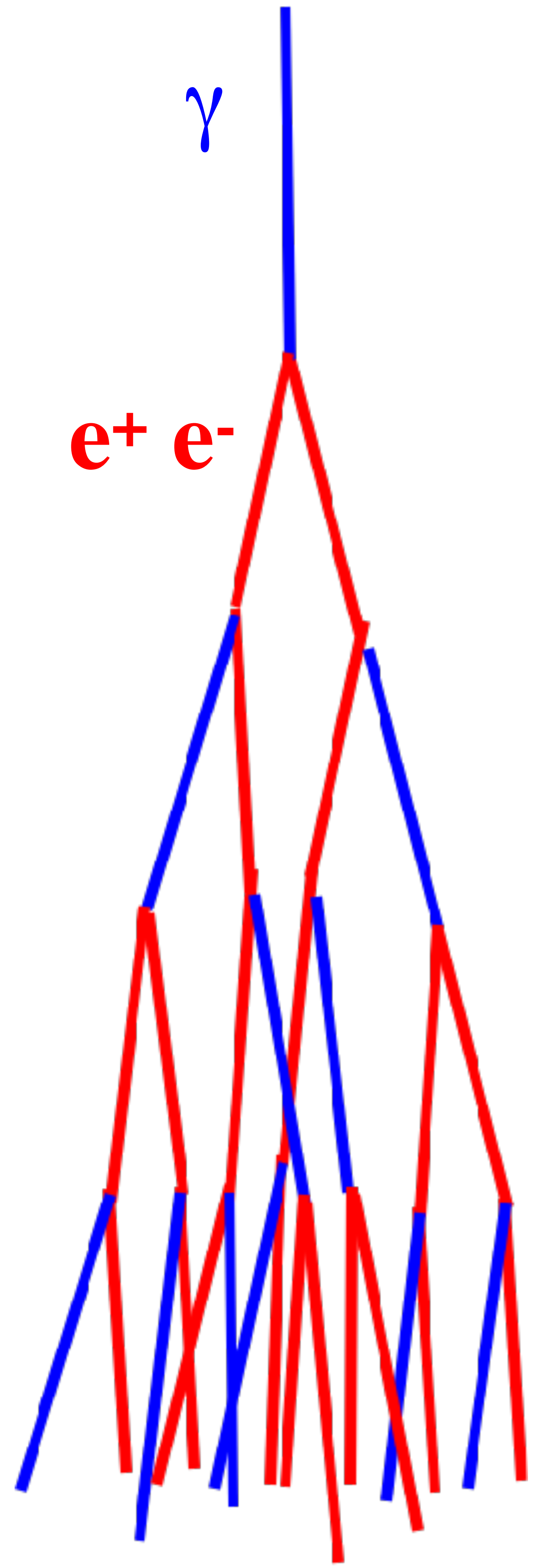




Ionization takes over at the 'Critical energy'= 560 MeV/Z
Z of air = 7 (nitrogen)
Critical energy in air = 560/7=80 MeV

Imaging Atmospheric Cherenkov Telescope

What happens when a very high energy gamma-ray enters the atmosphere?

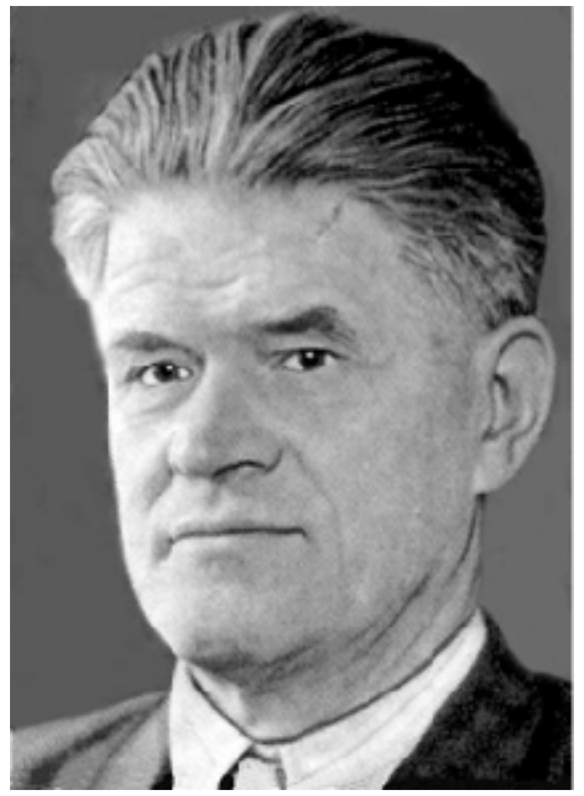


- What is the maximum number of products (electrons, positrons & photons) for a 1 TeV gamma-ray?
- 1 TeV / 80MeV = 12500 products
- 1 PeV / 80MeV = 12,500,000 products
- The charged particles produce **Cherenkov** radiation

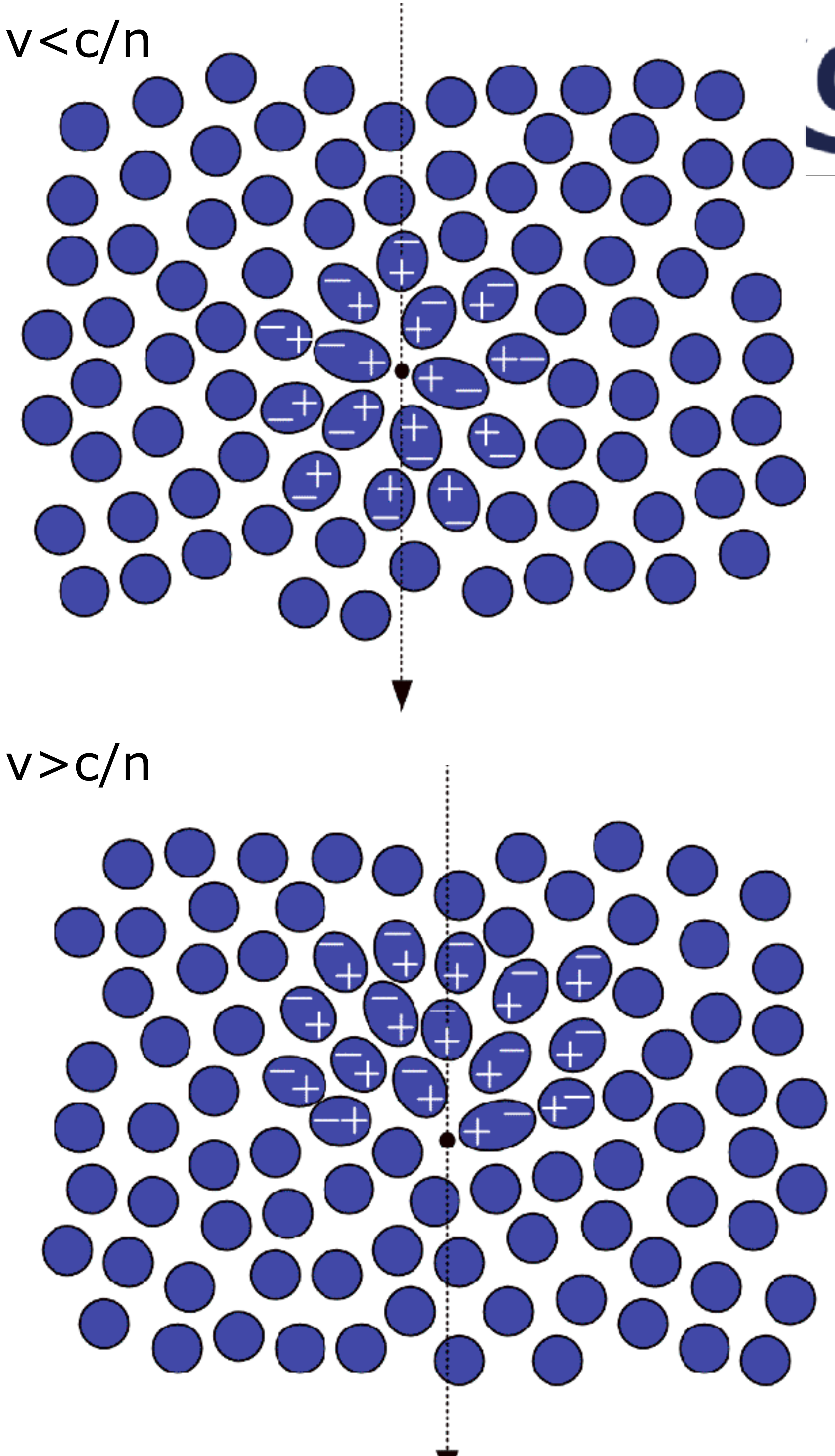
Imaging Atmospheric Cherenkov Te

Cherenkov radiation

- The charged particles in the shower are moving faster than the speed of light in air or water (=c/n)
- A moving charge causes atoms to become polarised
- When the particle is moving quickly, the polarization is not symmetrical along the axis of motion, resulting in a pulse of radiation



Pavel Alekseyevich Cherenkov (Nobel 1958)

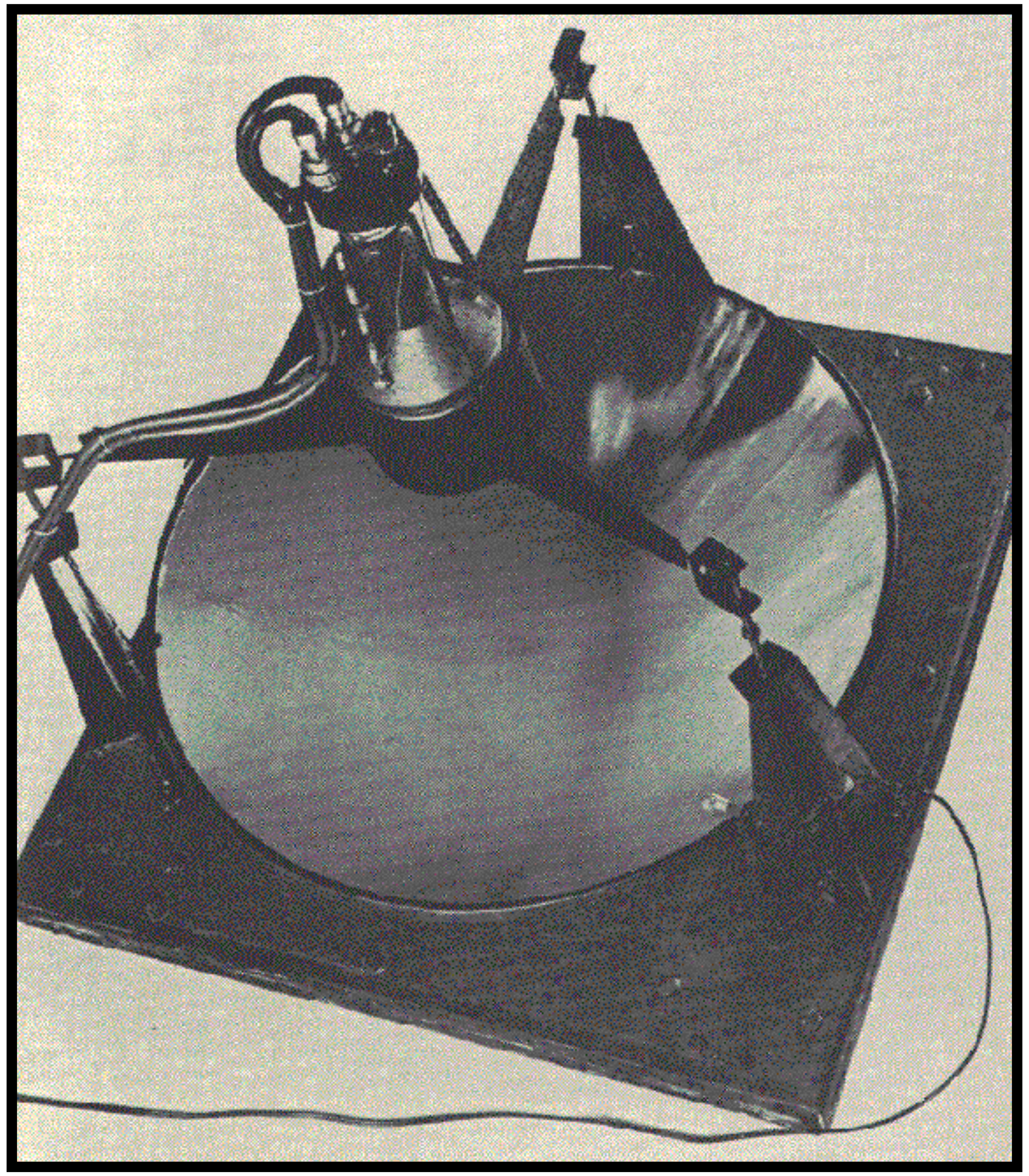


Imaging Atmospheric Cherenkov Telescope

- Useful rule-of-thumb:
  - A 1 TeV shower produces 100 photons/m^2
- Assume we detected pulses ~few hundred mV
- 1 photo-electron produces ~5mV
- So let's say 100 photo-electrons
- PMT photon to photo-electron conversion efficiency is ~20%
  - So this corresponds to 100/0.2=500 photons
- If Mirrors are ~0.25*0.25*pi = 0.2m^2
- So showers has 500/0.2 = 2500 photons/m^2
- So their energy us 2500/100 = 25 TeV

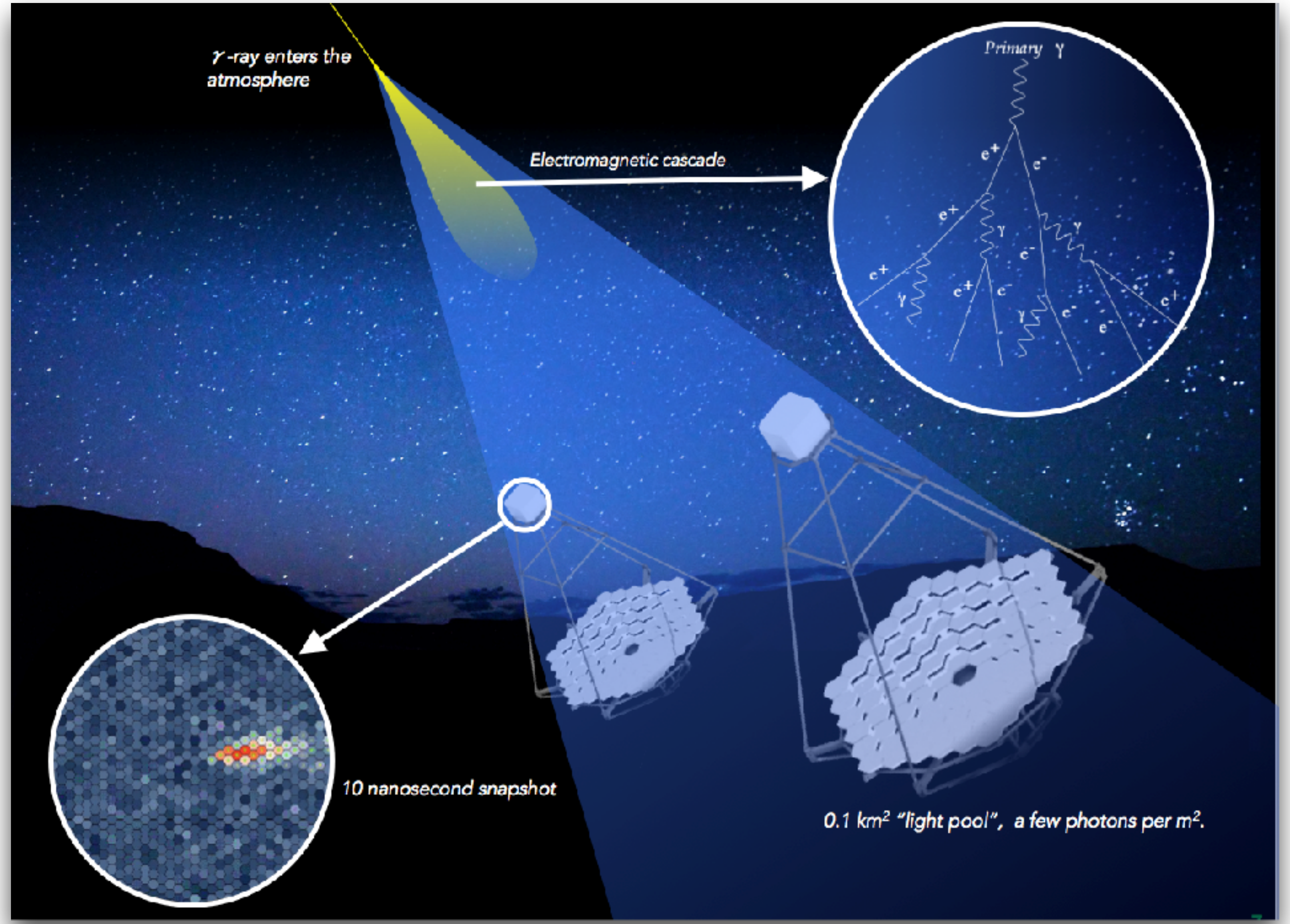
- Very rough – but probably in the right ball-park (photon yield is lower for cosmic ray showers)

The Jelley & Galbraith light bucket (1952)



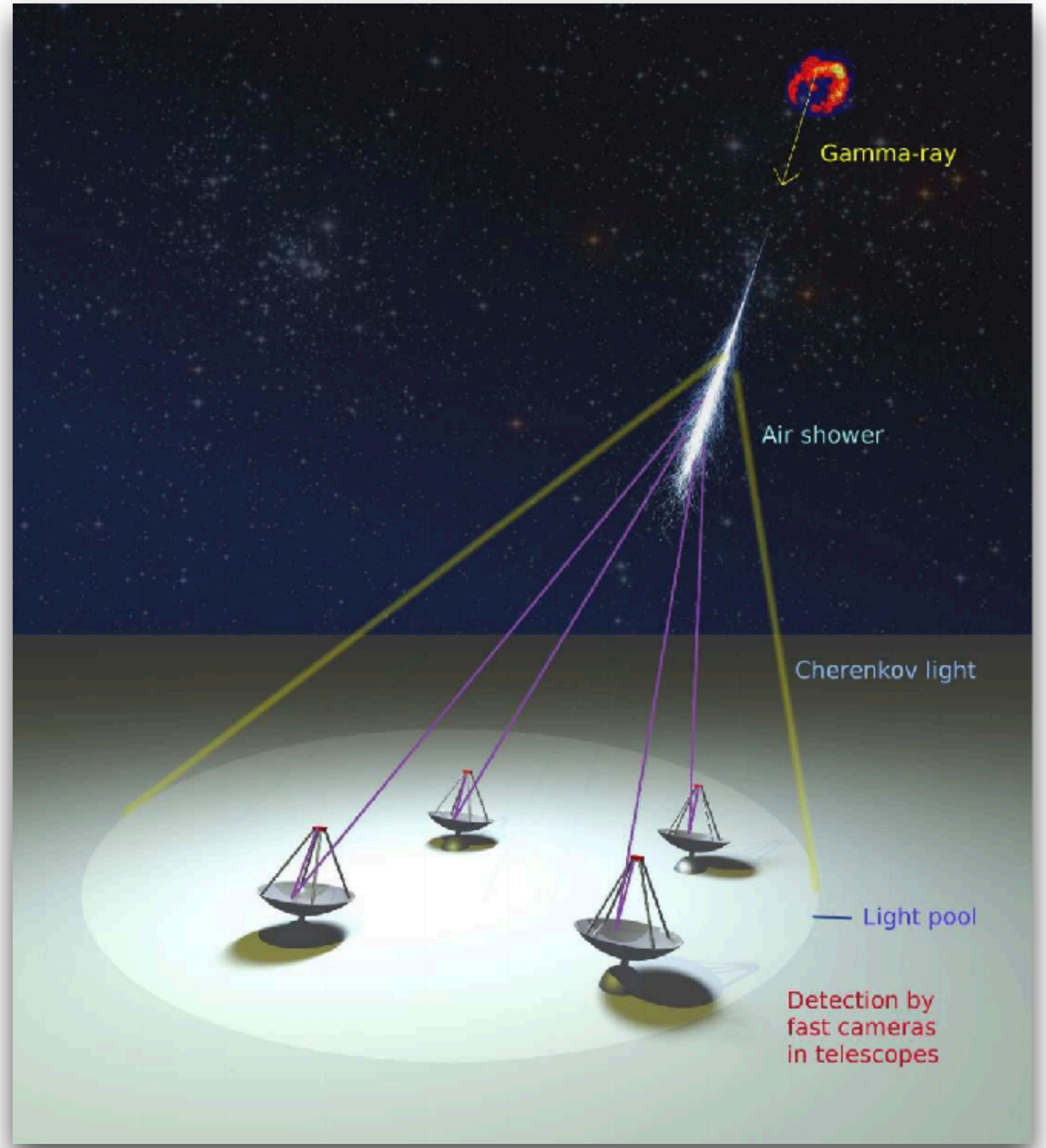
Imaging Atmospheric Cherenkov Telescope

Next generation ground-based instrument for gamma-ray astronomy at very-high energies

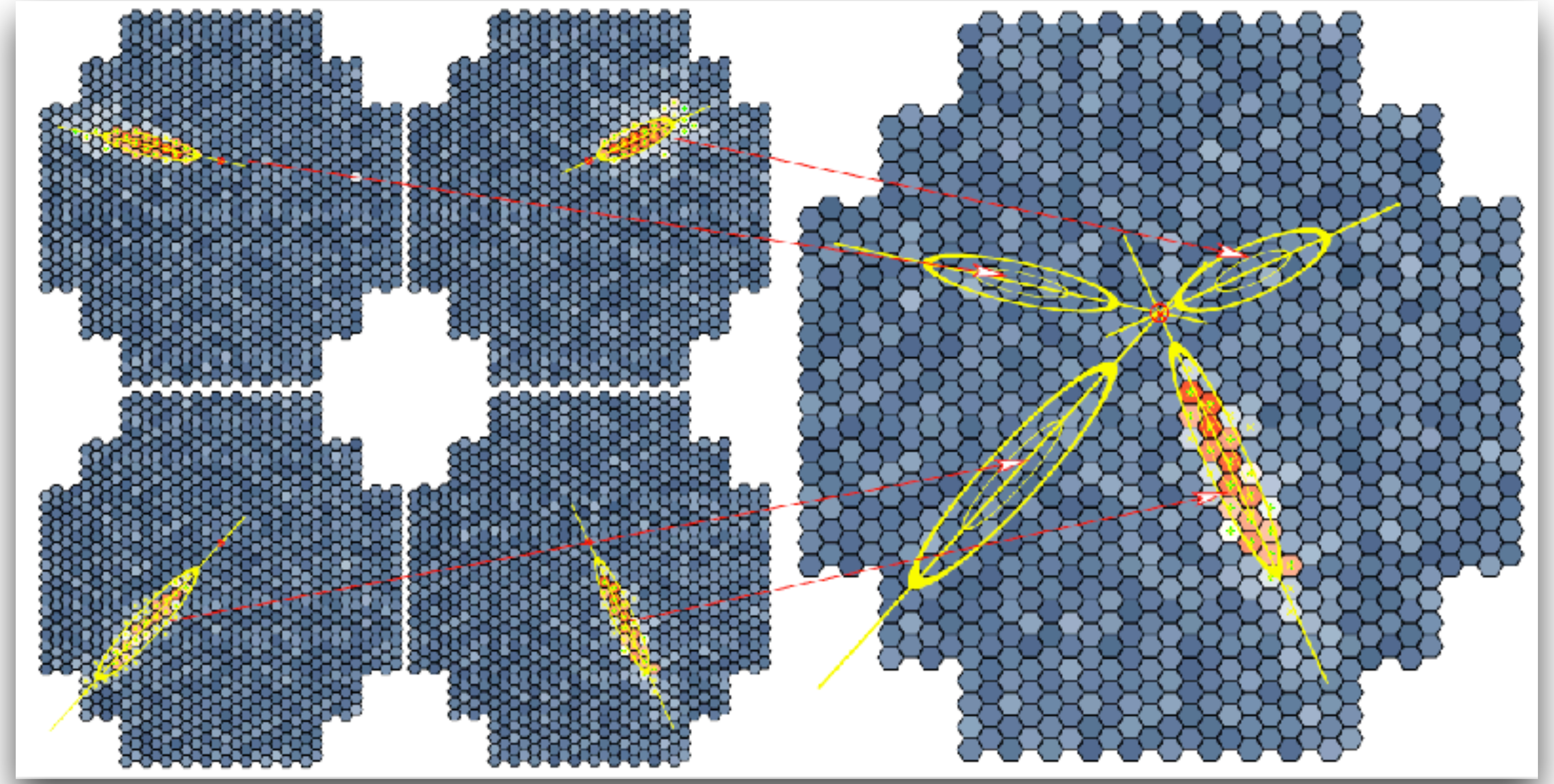


- Gamma rays interact with the atmosphere → Cherenkov radiation
- IACT reflects Cherenkov light through a mirror and captures the image with a focal plane camera
- The energy and direction of arrival of the gamma rays are reconstructed from the image information.
- We call our telescope: IACT

Stereo Reconstruction



Heinrich J. V¨olk and Konrad Bernl¨ohr. Imaging Very High Energy Gamma-Ray Telescopes.
Exper. Astron., Vol. 25, pp. 173–191, 2009.



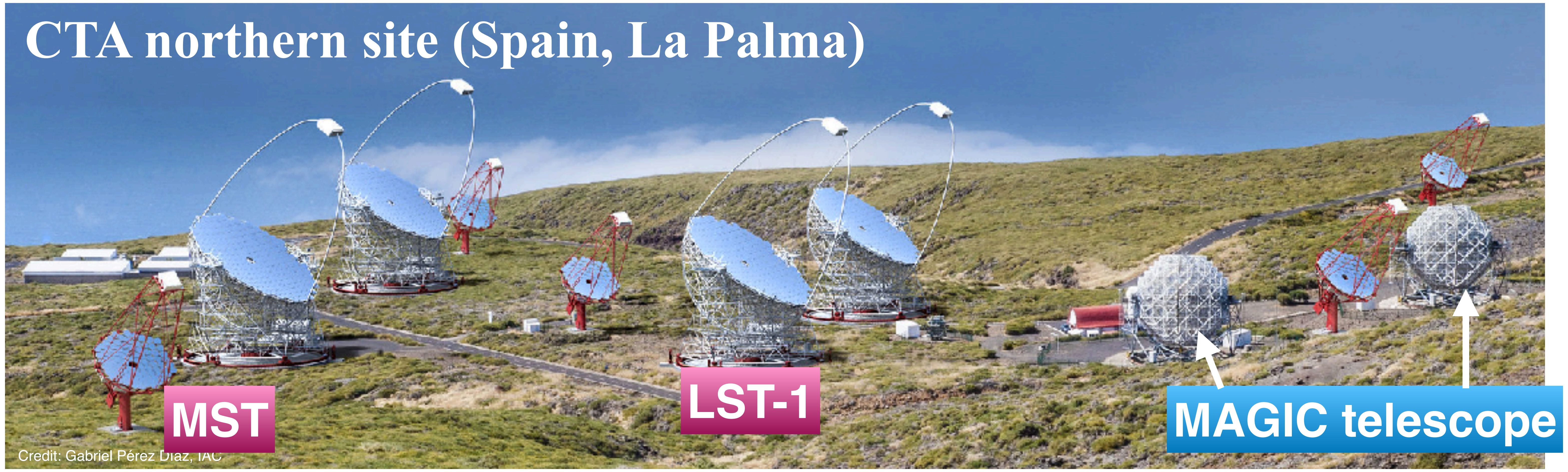
Heinrich J. Voelk, Konrad Bernloehr., Exp.Ast.25:173-191 (2009)

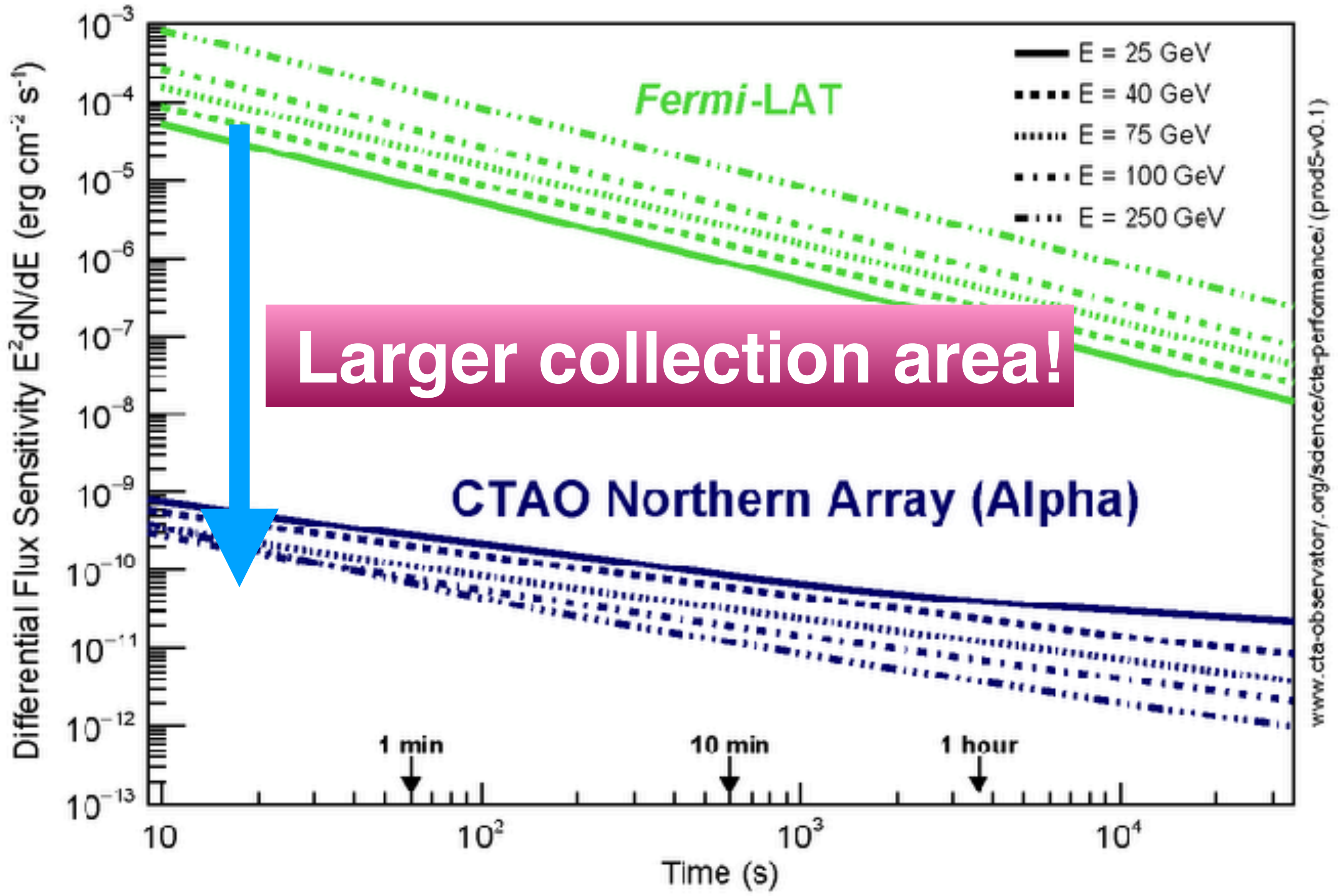
- Better angular and energy resolution than a single unit : **stereo reconstruction**
- Better background noise suppression performance than a single unit: **triggering system**

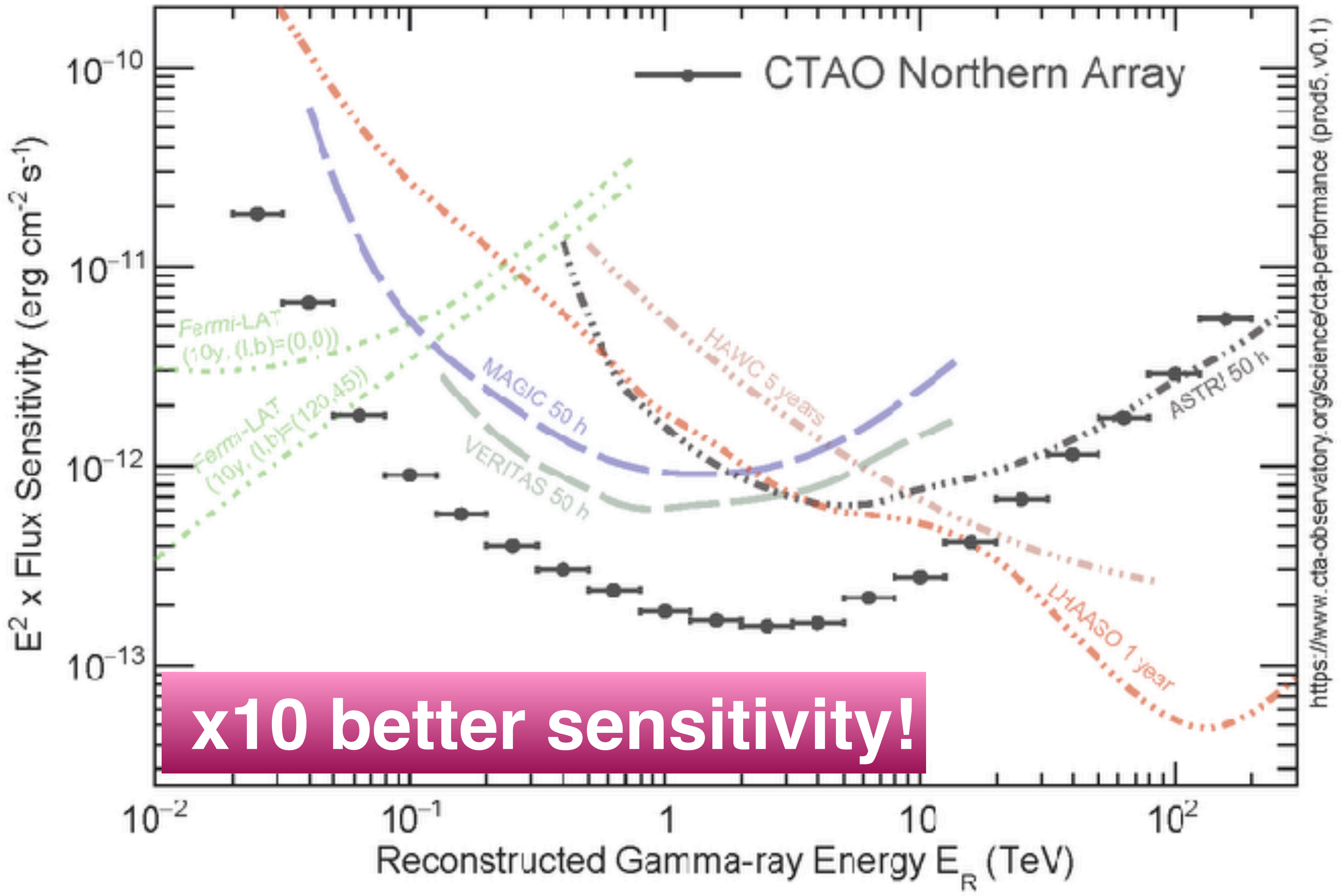
Cherenkov Telescope Array (CTA)

Next generation ground-based instrument for gamma-ray astronomy at very-high energies

- Located in the northern and southern hemispheres with 71 telescopes
- Northern CTA: 4 Large-Sized Telescopes + 9 Medium-Sized Telescopes
- **x10 better sensitivity + wide energy coverage of 20 GeV-300 TeV**
- LST-1 started observation since 2020





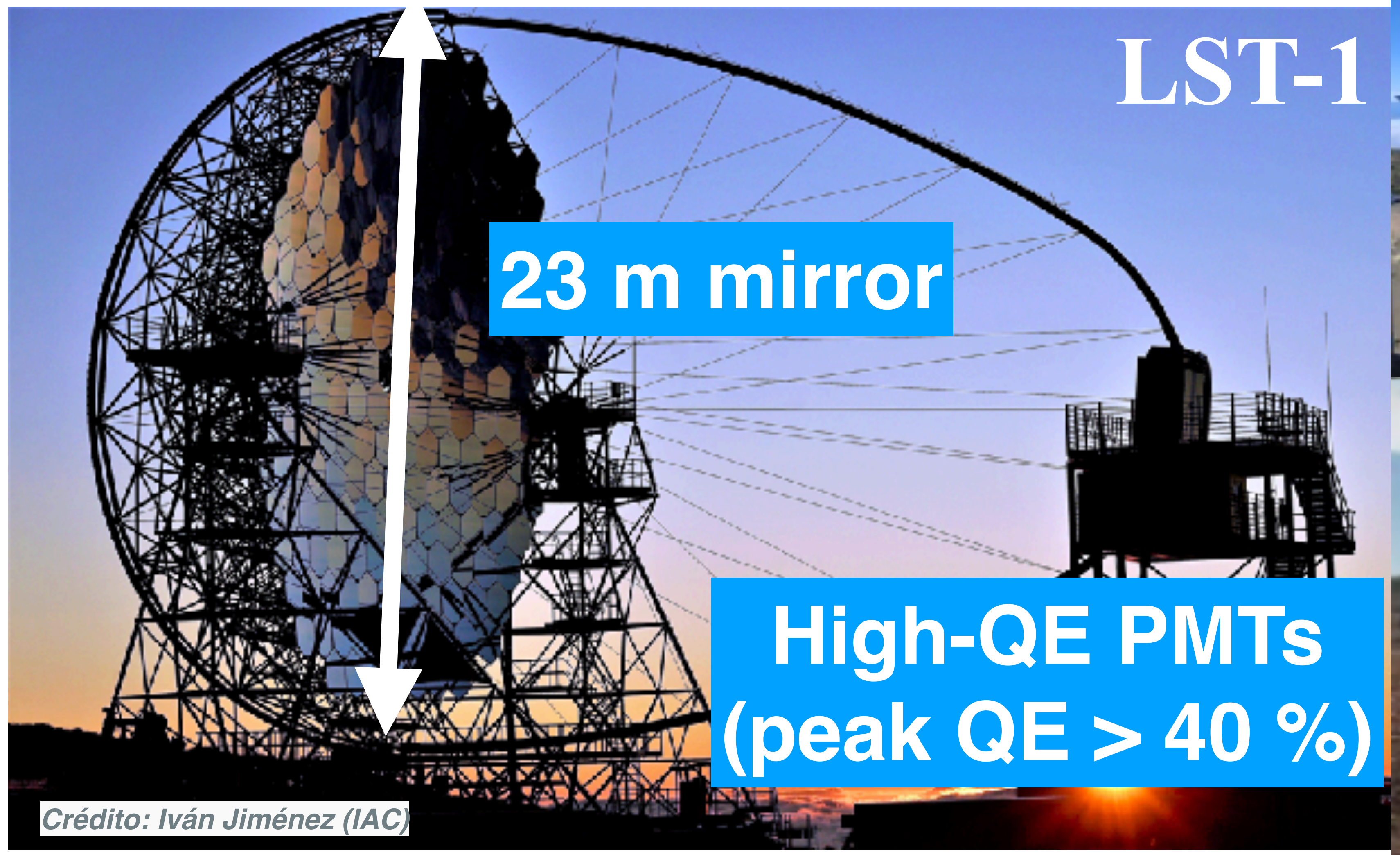


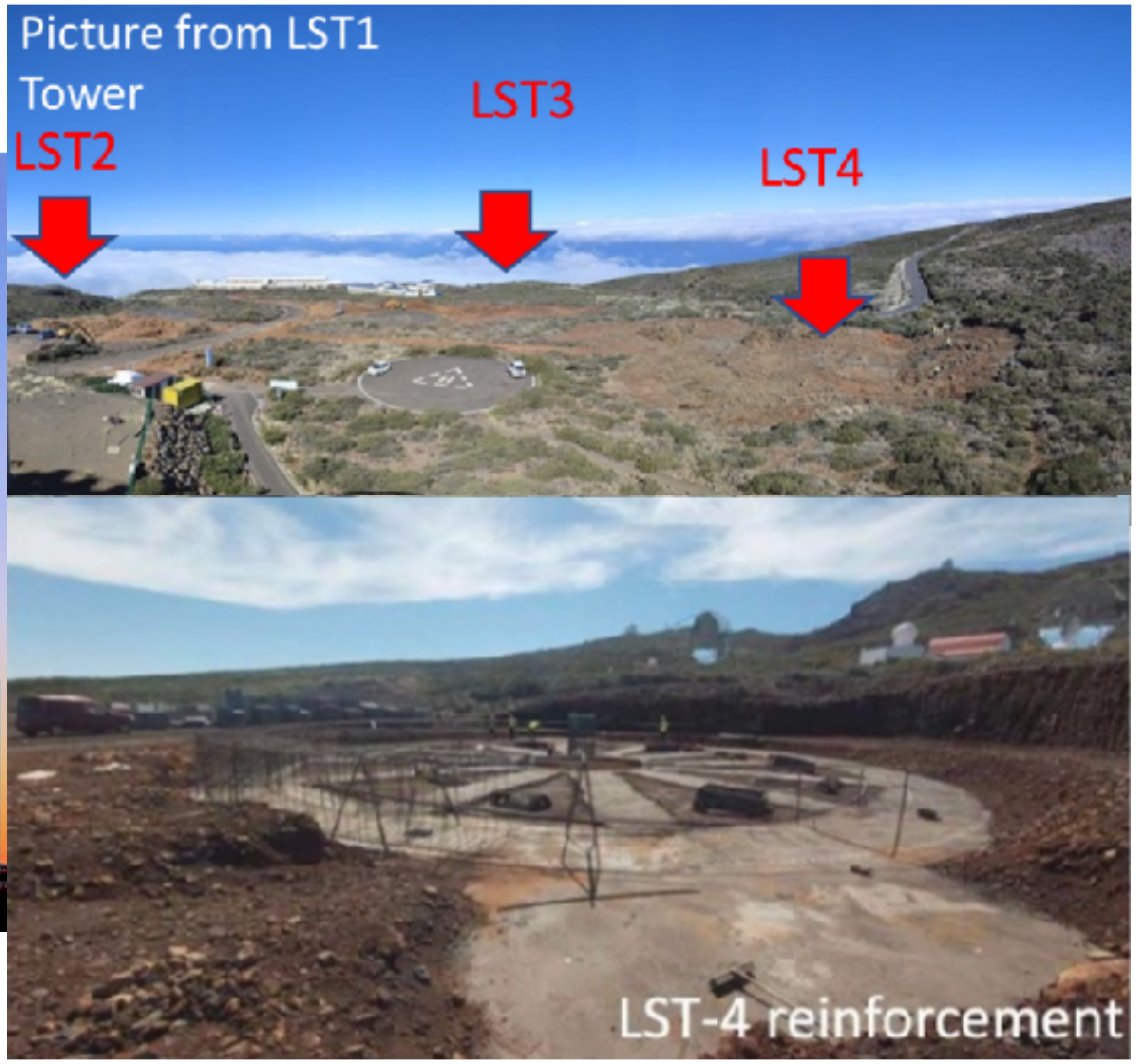
Large-Sized Telescope (LST)

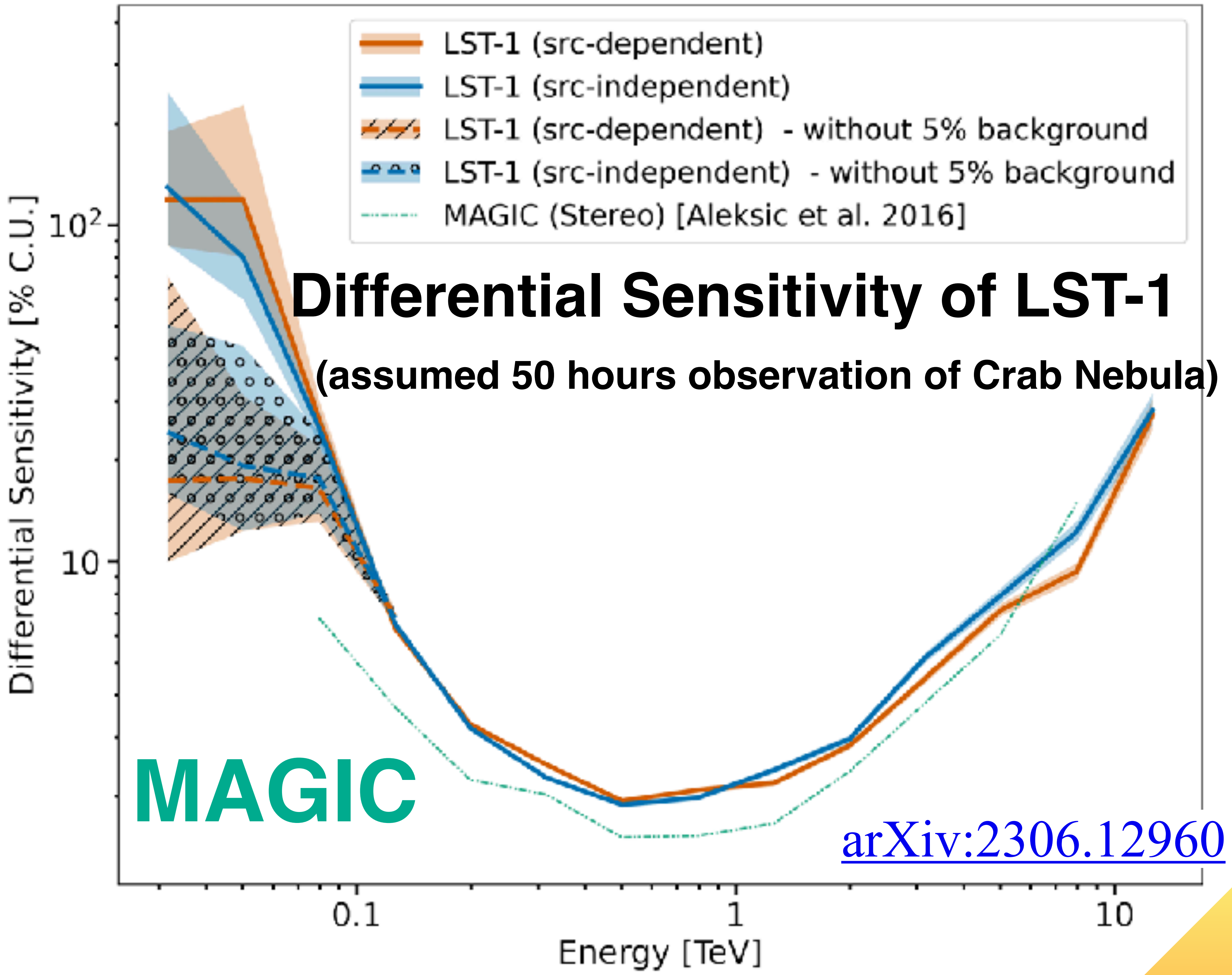
cherenkov telescope array

LSTs are designed to give optimal performance in the lowest region of the energy range covered by CTA, down to ≃ 20 GeV

- Reposition to any point in the sky **within 20 seconds**
- A performance paper on LST-1 was published based on the observational data of the Crab Nebula
  - The energy threshold at trigger level estimated to be **20 GeV**, increasing to ≃ **30 GeV after data analysis**
- Suitable for **transient/soft/distant** sources





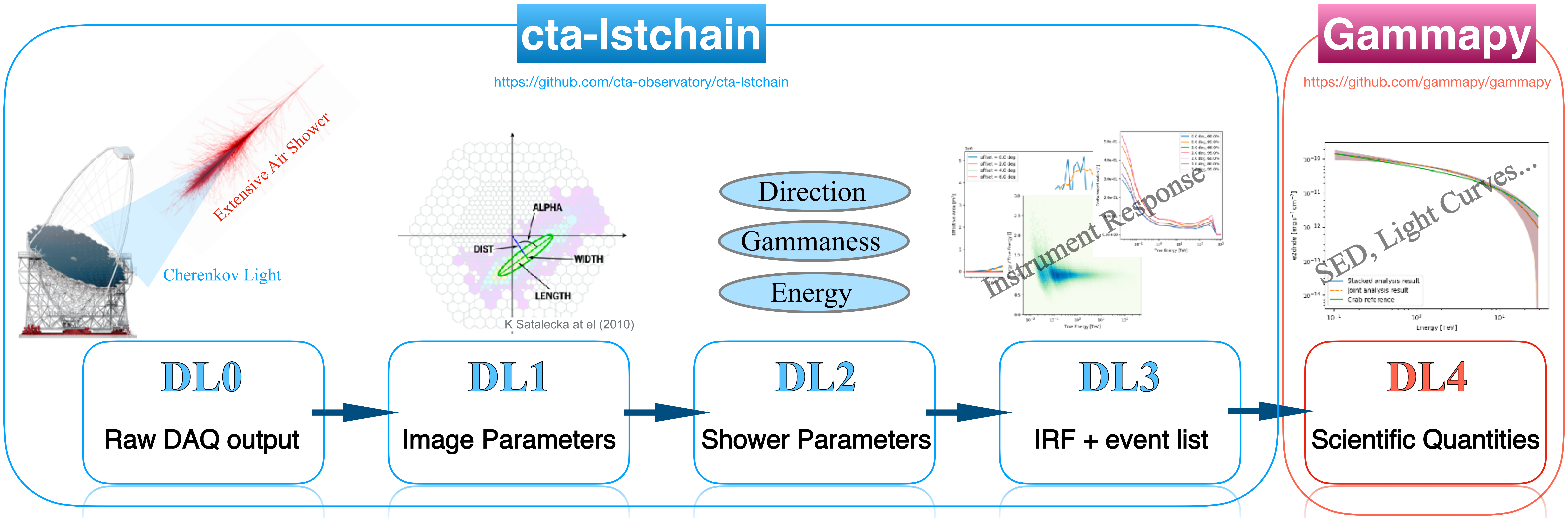


arXiv:2306.12960

LST-1 Data Analysis Method

We used cta-lstchain for creating IRFs and event list, and Gammapy for subsequent processes

- Python-based pipeline **cta-lstchain v0.9.12/0.9.13** (dedicated analysis tool for LST data)
- For the generation of high-level visualizations, including SED and Light Curves, we employed **Gammapy v1.0.1**
  - **Gammapy**: open-source Python package for gamma-ray astronomy built on Numpy, Scipy and Astropy

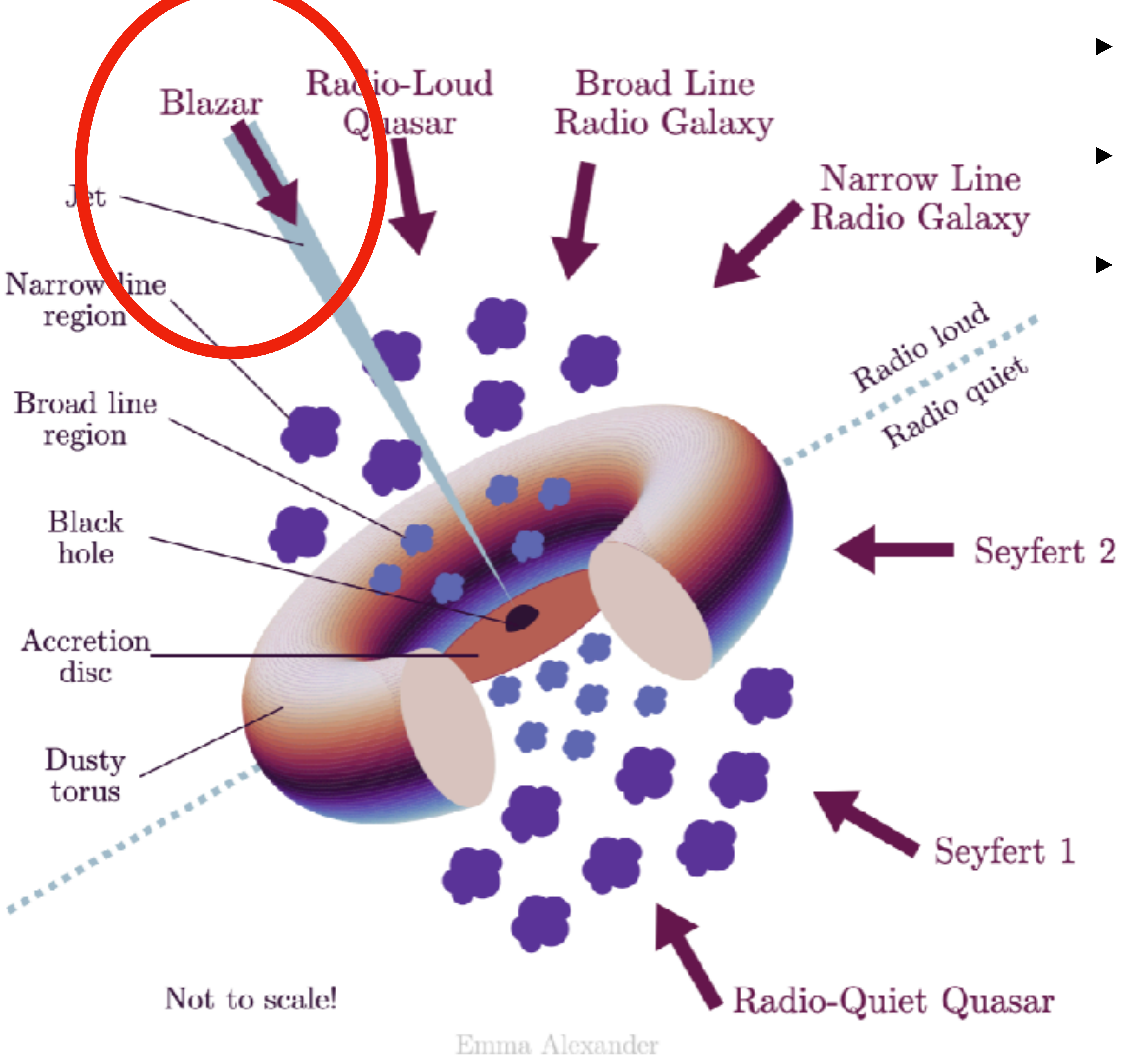


Motivation of the study

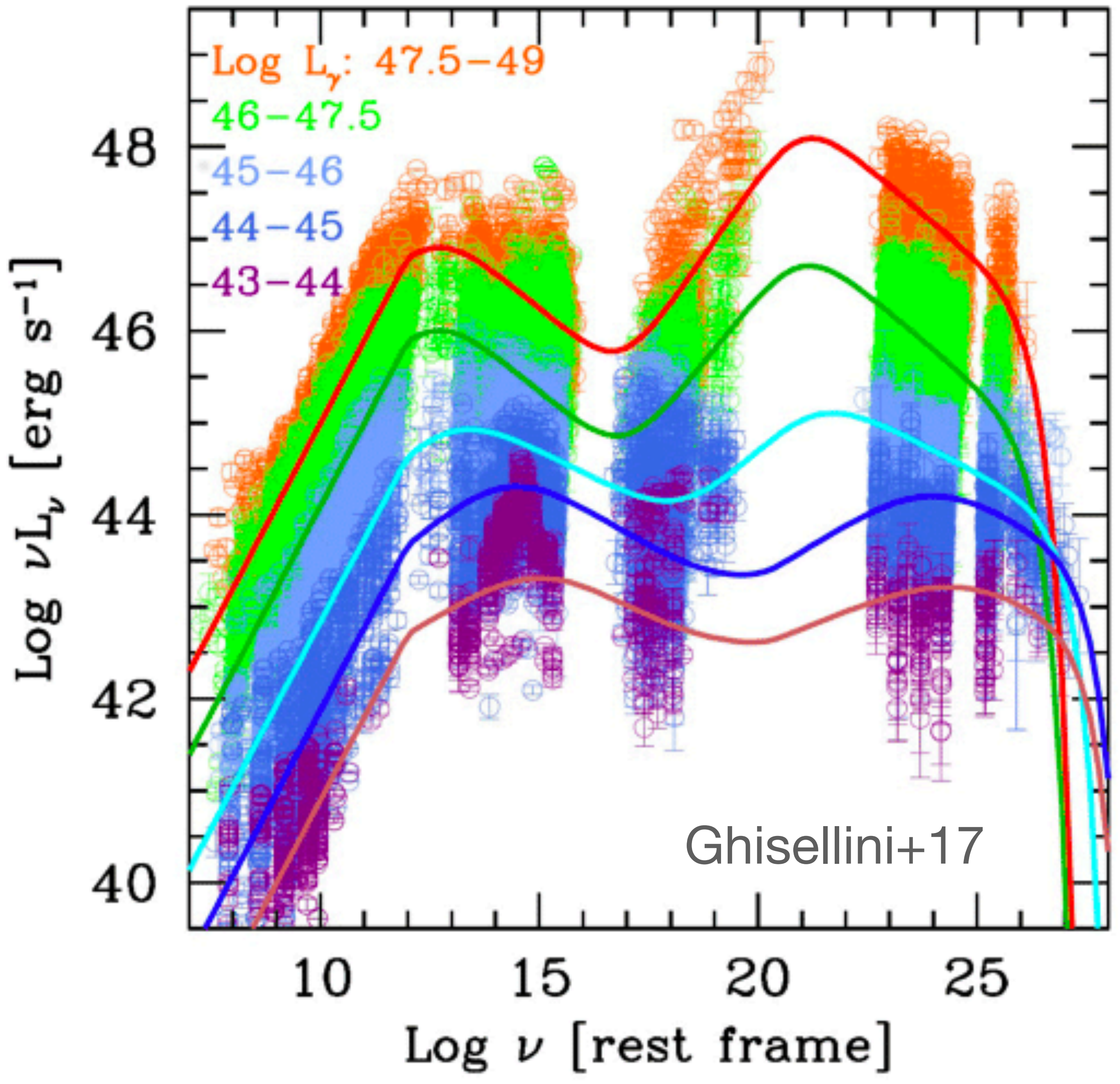
Blazars: Active Galactic Nuclei (AGN) jet pointing towards us

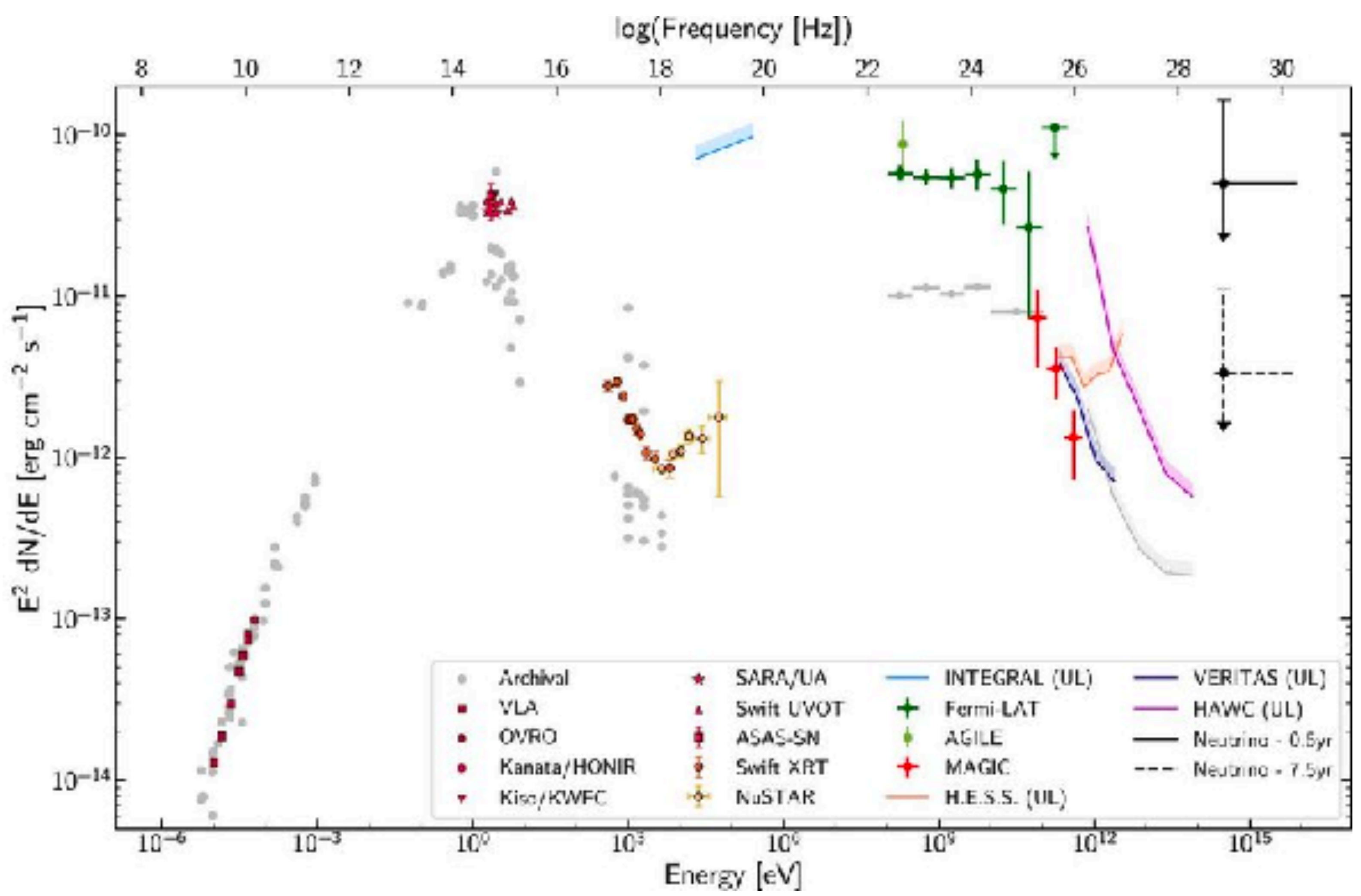
cta cherenkov telescope array

Only ~0.1% of all AGN



- Dominates the **HE/VHE extragalactic sky**
- **Significant variability** across the entire EM spectrum
- This talk will focus on **GeV-TeV** in particular as an individual engaged in VHE experiments (Cherenkov Telescope Array, CTA)



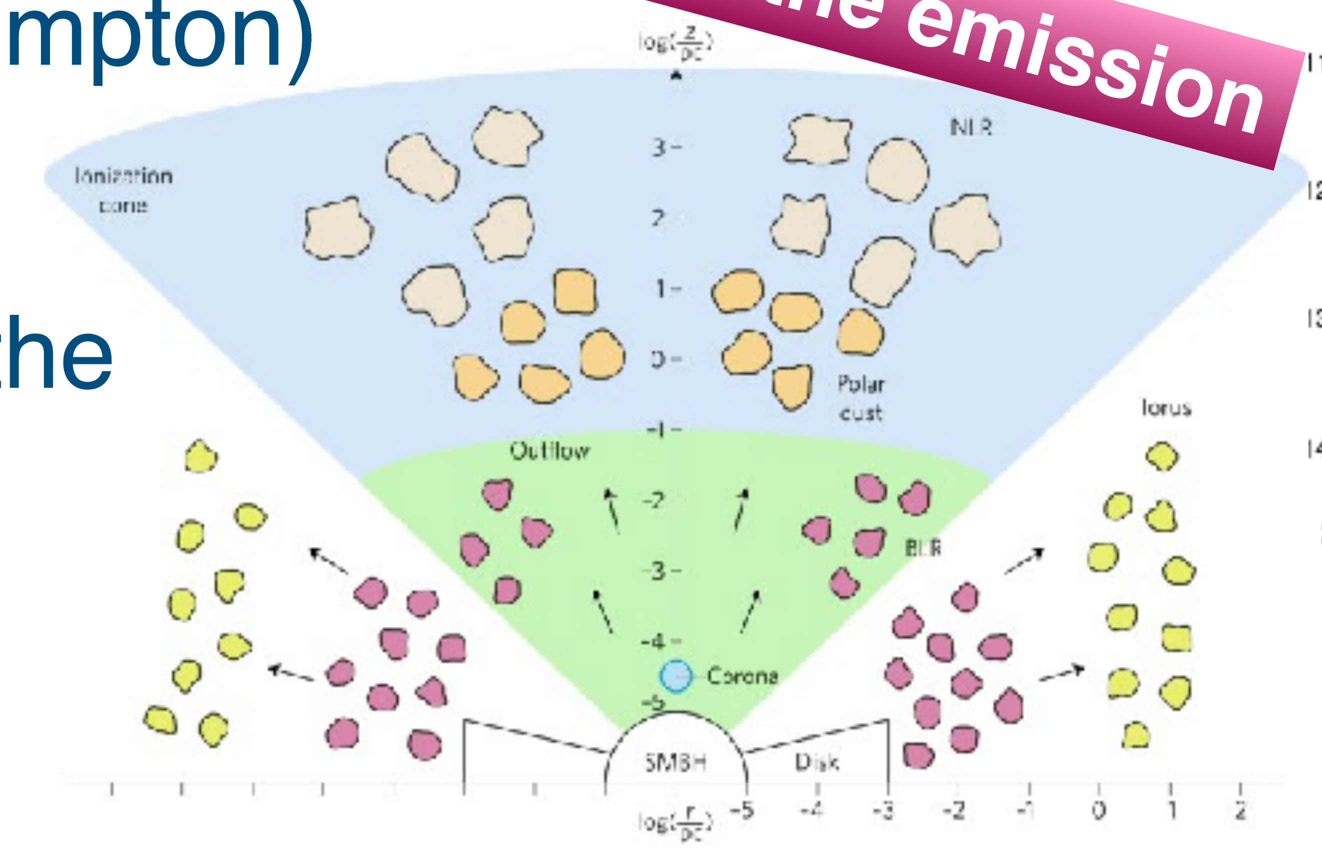


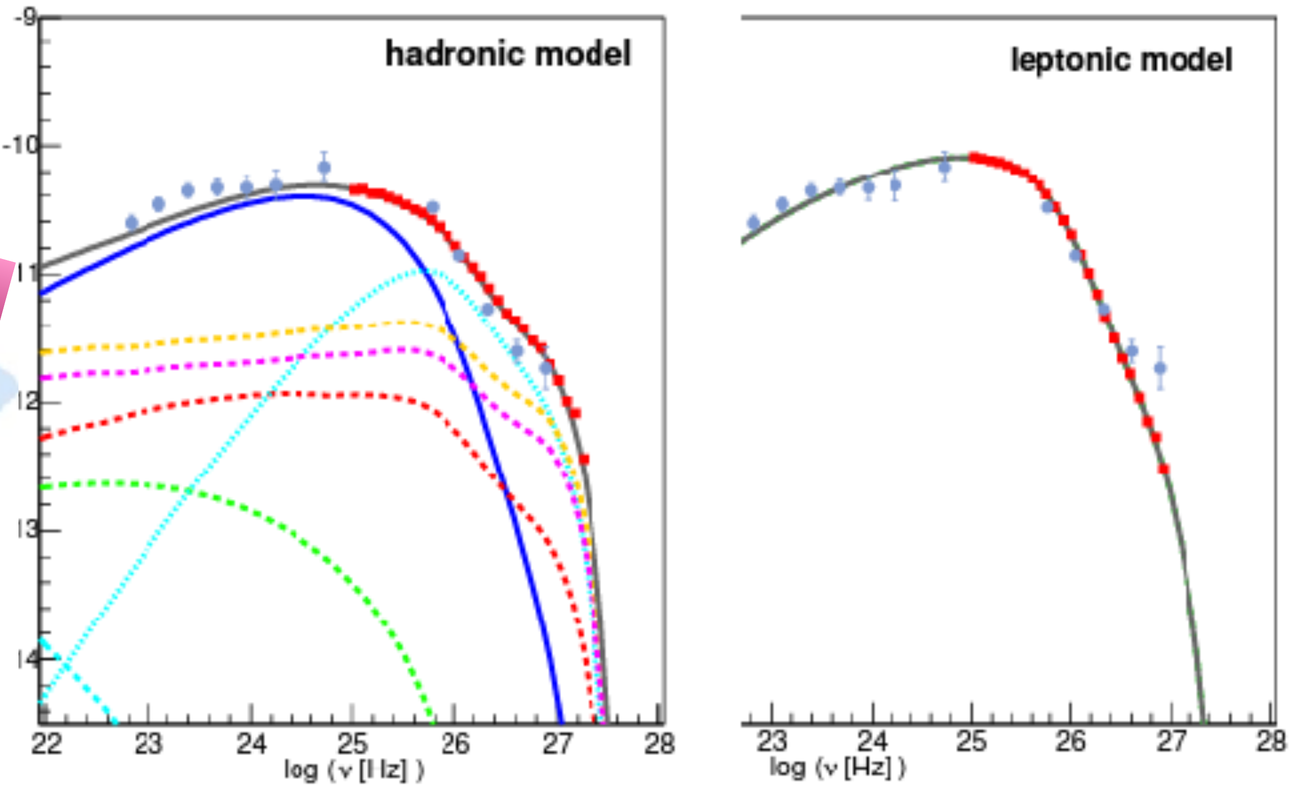
IceCube2018

What do we anticipate elucidating through the observation of blazars?

- Astrophysical studies:
  - Leptonic (Synchrotron Self-Compton, External Compton) or hadronic (Proton synchrotron, Photomeson...)?
  - What is the structure/role of the magnetic field in the jets?
  - Where along the jet HE/VHE emission produced?
- Cosmological, fundamental physics:
  - Validation of galaxy and star formation models in the universe (Extragalactic Background Light)
  - Does the intergalactic magnetic field exist?
  - Axion-Like Particle?
  - Towards the Hubble crisis; cosmological parameter measurement

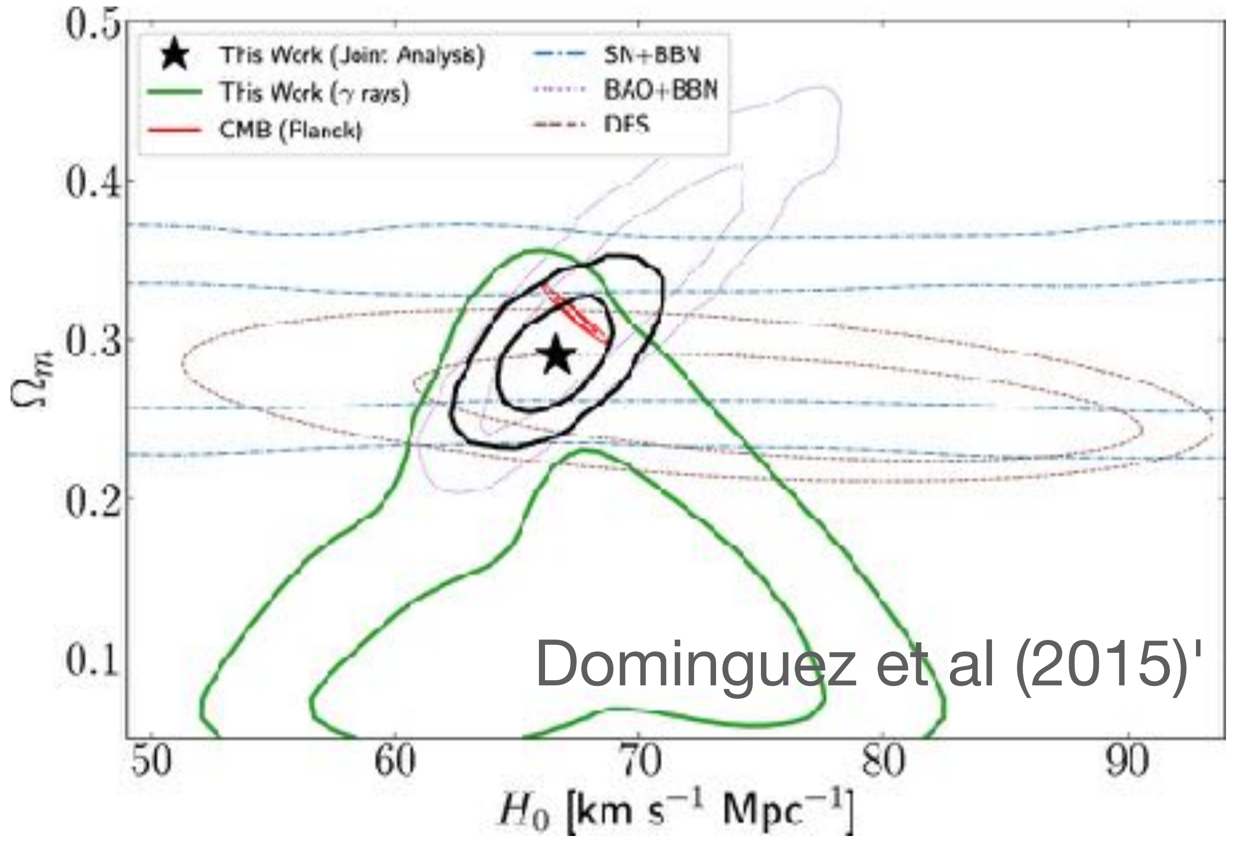
Location of the emission



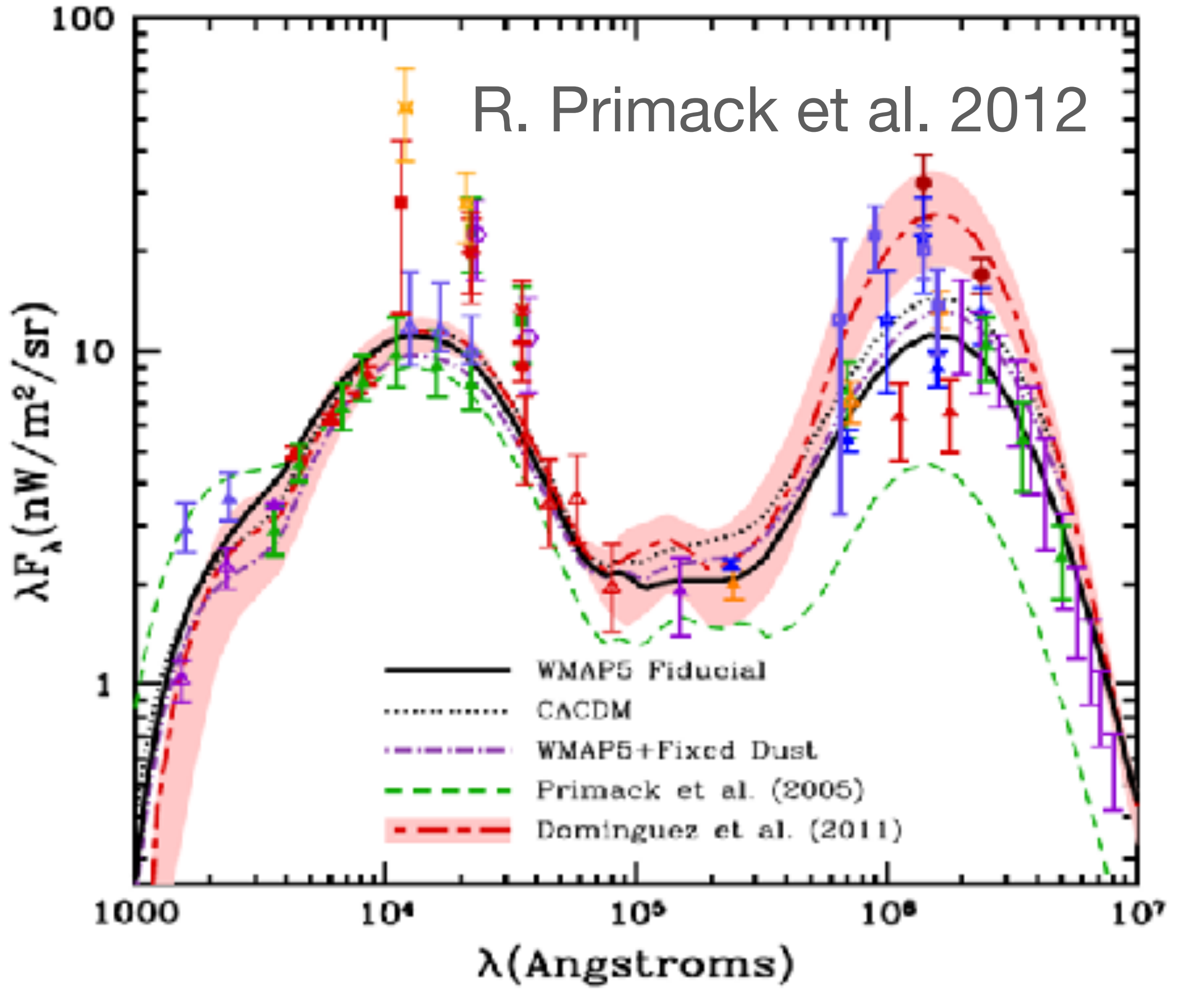


Hadronic vs Leptonic

Measurements of H0,Ωm



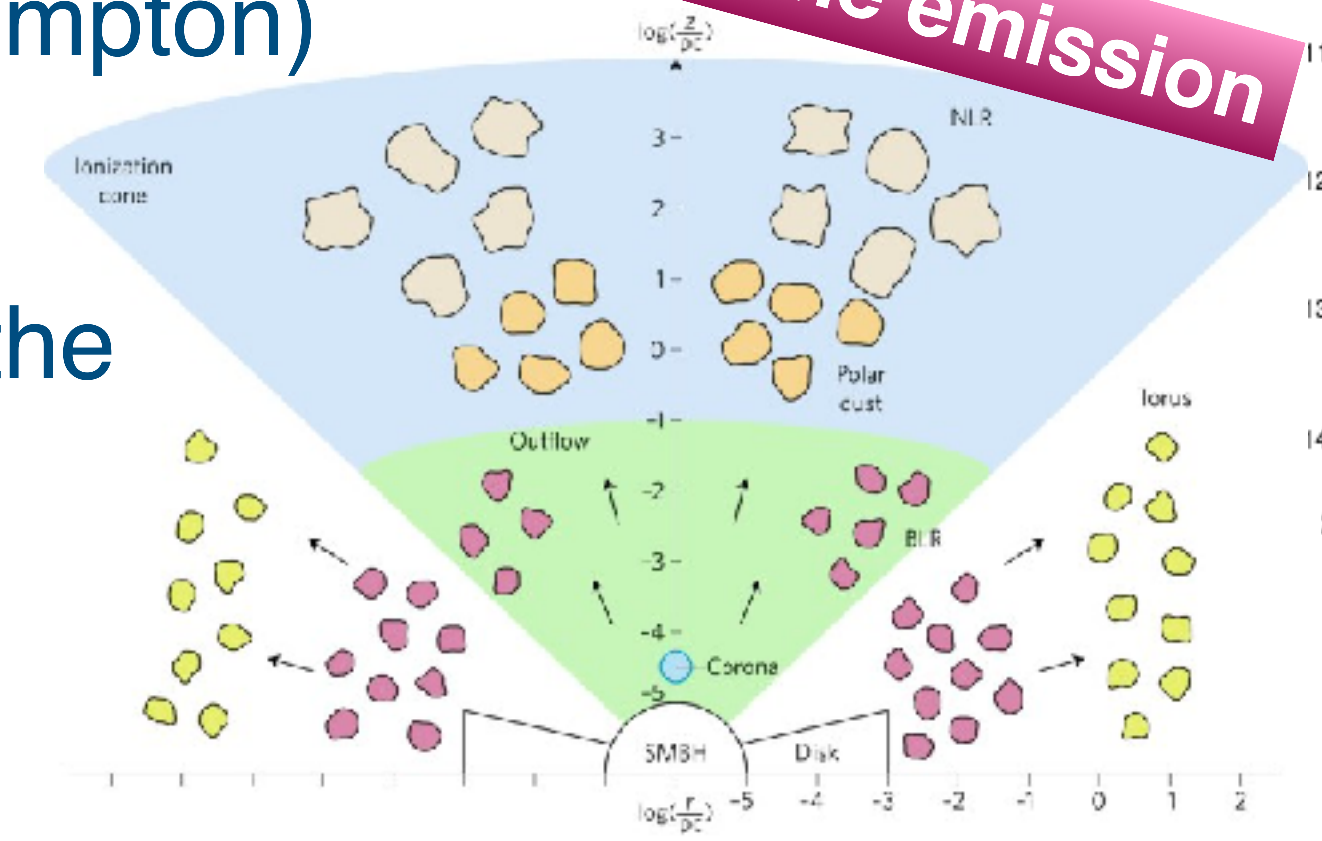
Measurements of EBL

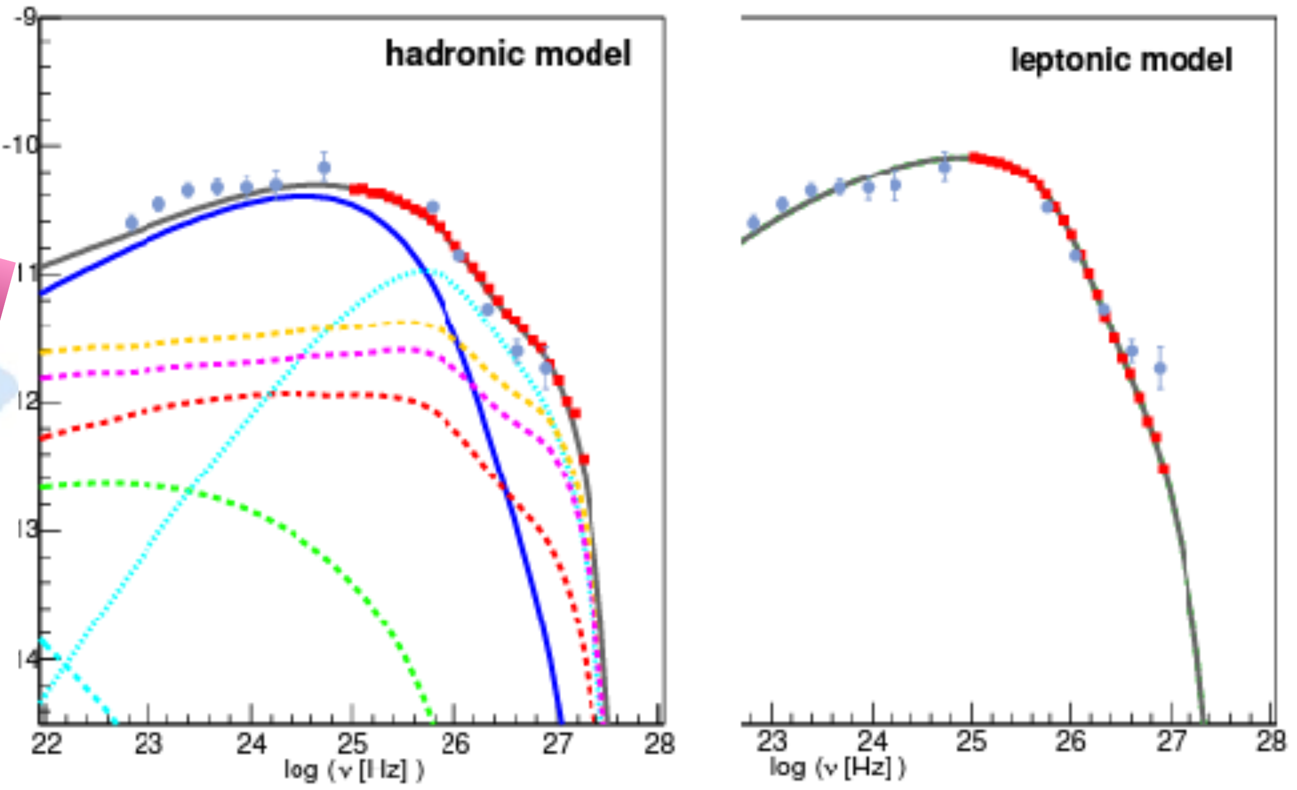


What do we anticipate elucidating through the observation of blazars?

- Astrophysical studies:
  - Leptonic (Synchrotron Self-Compton, External Compton) or hadronic (Proton synchrotron, Photomeson...)?
  - What is the structure/role of the magnetic field in the jets?
  - Where along the jet HE/VHE emission produced?
- Cosmological, fundamental physics:
  - Validation of galaxy and star formation models in the universe (Extragalactic Background Light)
  - Does the intergalactic magnetic field exist?
  - Axion-Like Particle?
  - **Towards the Hubble crisis; cosmological parameter measurement**

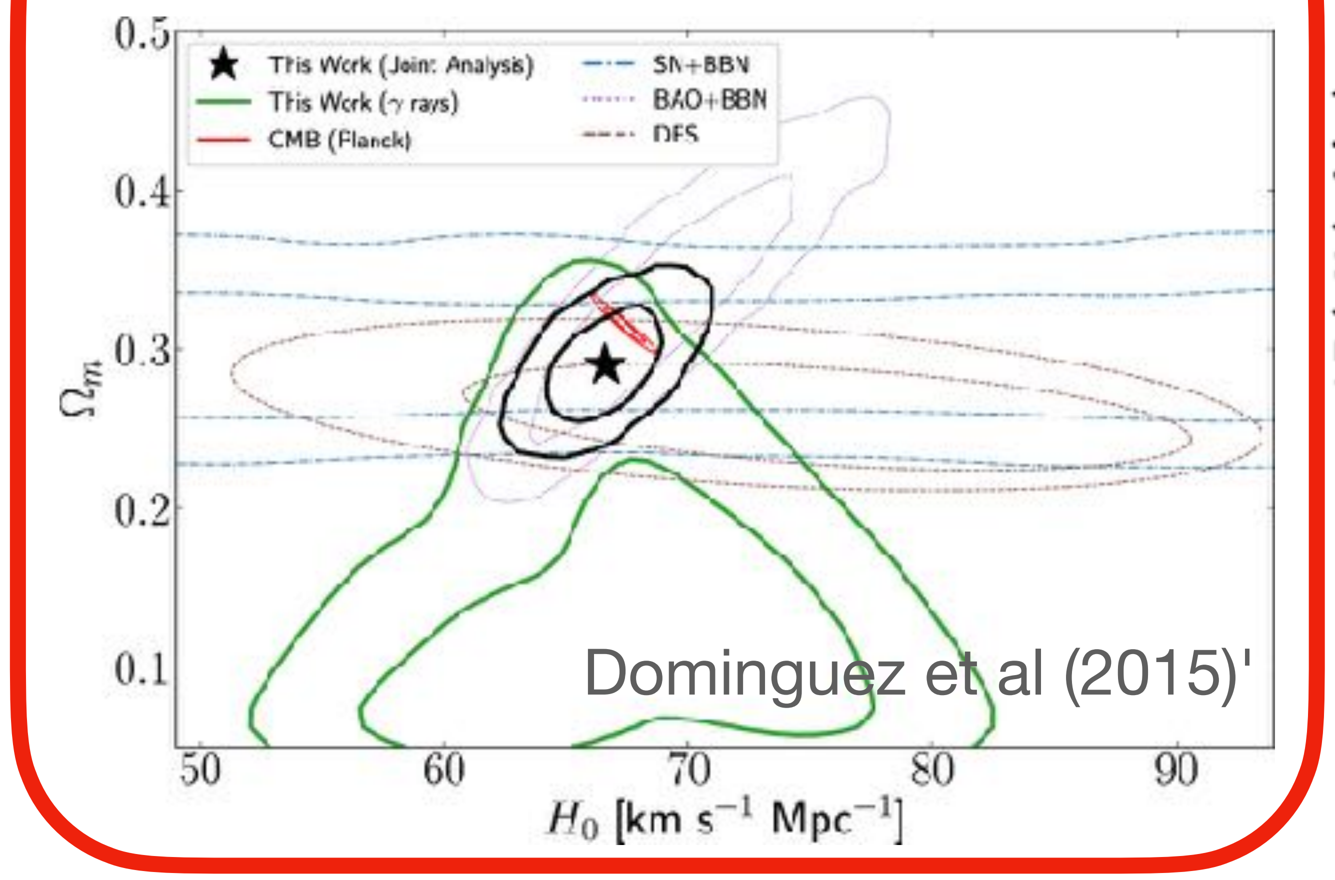
Location of the emission



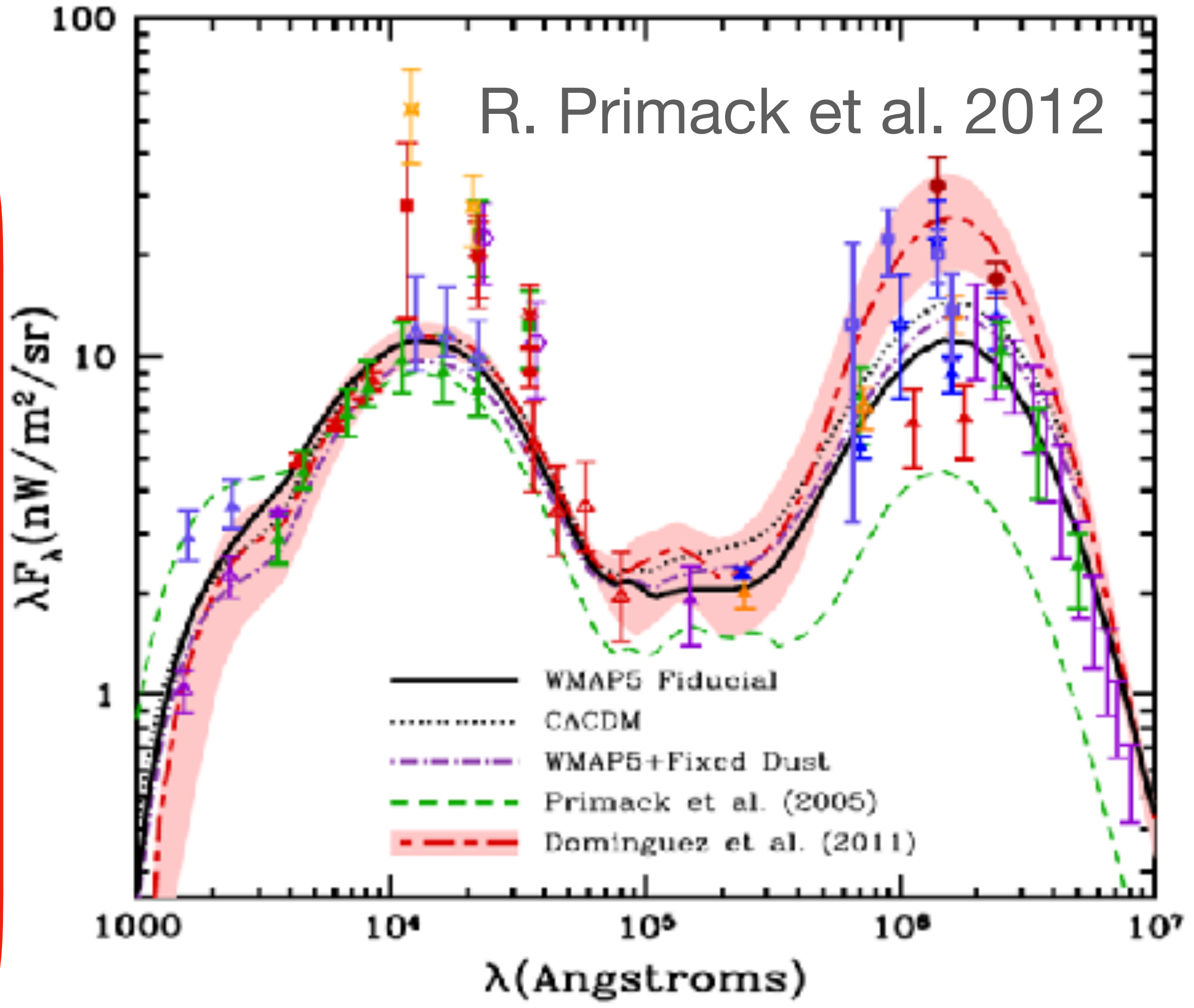


Hadronic vs Leptonic

Measurements of H0,Ωm

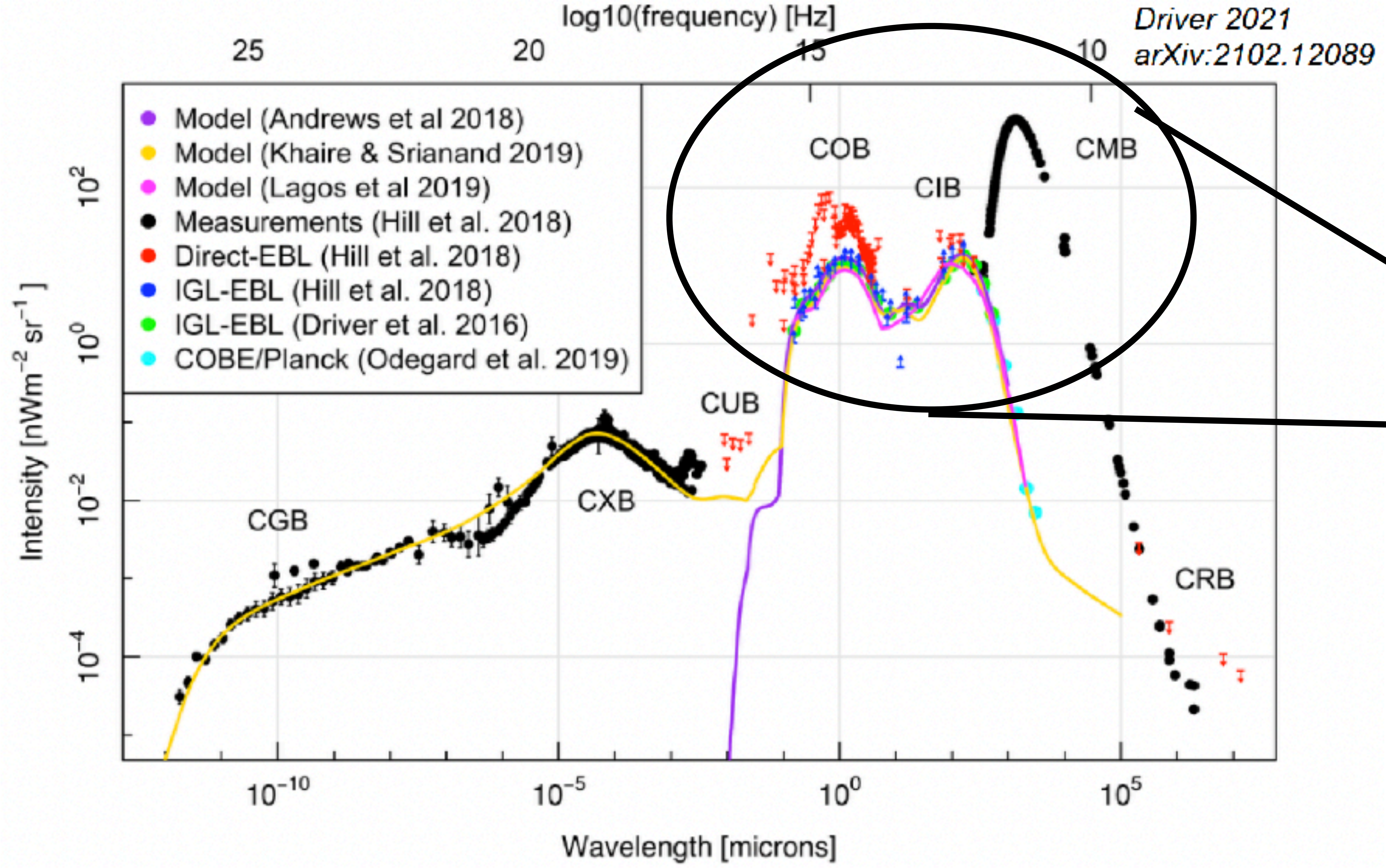


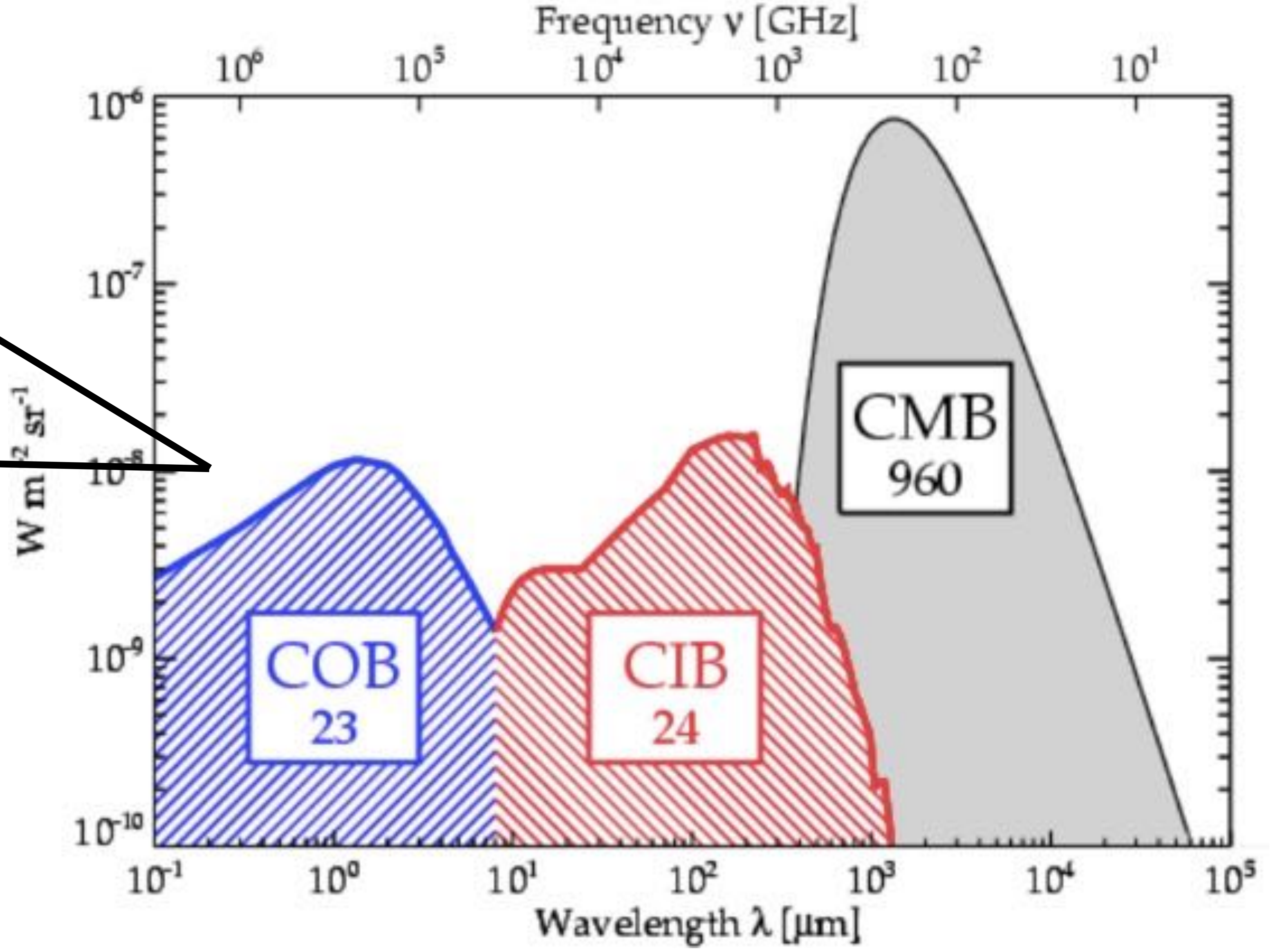
Measurements of EBL



A gamma-ray journey through cosmic ages

- Extragalactic background light (EBL)
  - a diffuse radiation field accumulated in UV and IR wavelengths since the birth of stars and galaxies.
  - Second most intense diffuse photon field (after CMB)
- Two main components : Cosmic Optical Background (COB) and Comic Infrared Background(CIB)

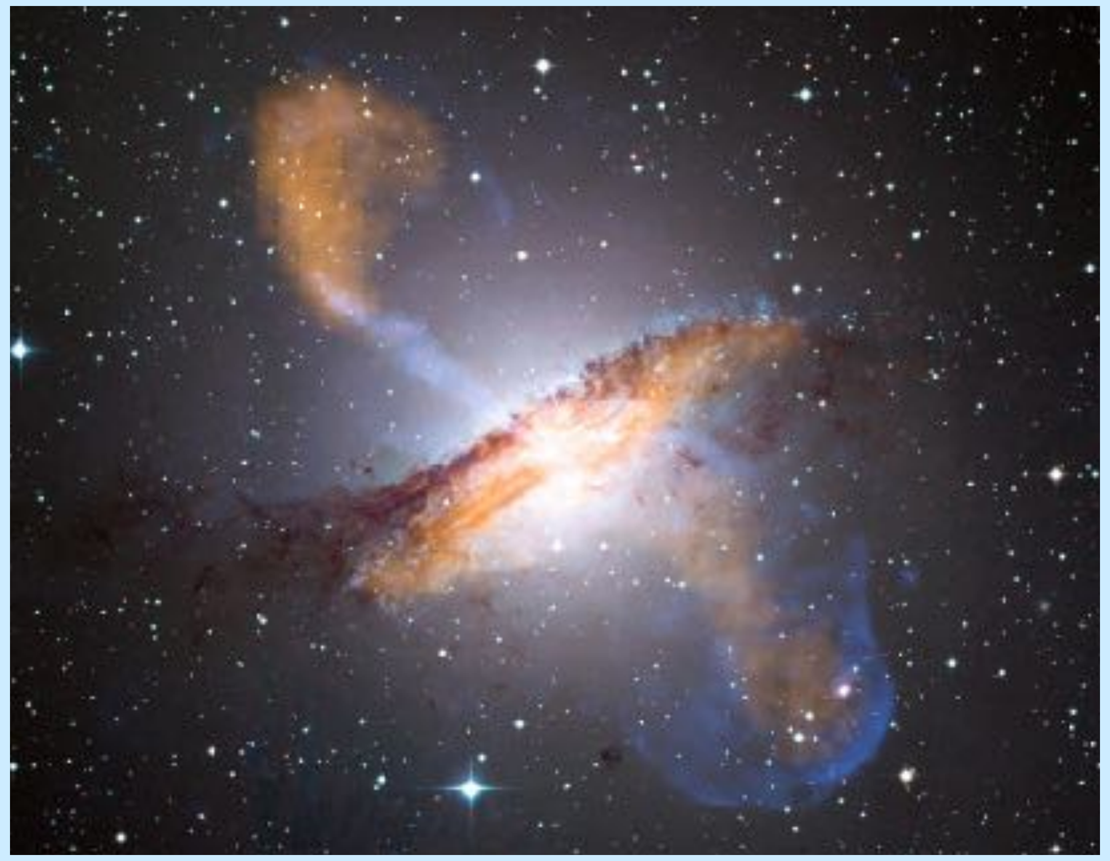




A gamma-ray journey through cosmic ages

cherenkov telescope array

✳ **Extragalactic background light (EBL)**
- a diffuse radiation field accumulated in UV and IR wavelengths since the birth of stars and galaxies.



EBL photon

γ rays

Attenuated γ rays

Mean Free Path

$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^\infty d\epsilon' \frac{dn(\epsilon', z)}{d\epsilon'} \int_{-1}^{1} d\cos\theta' \frac{1-\cos\theta'}{2} \sigma_{\gamma\gamma}(\beta')\, \Theta(\epsilon' - \epsilon'_{th})$$

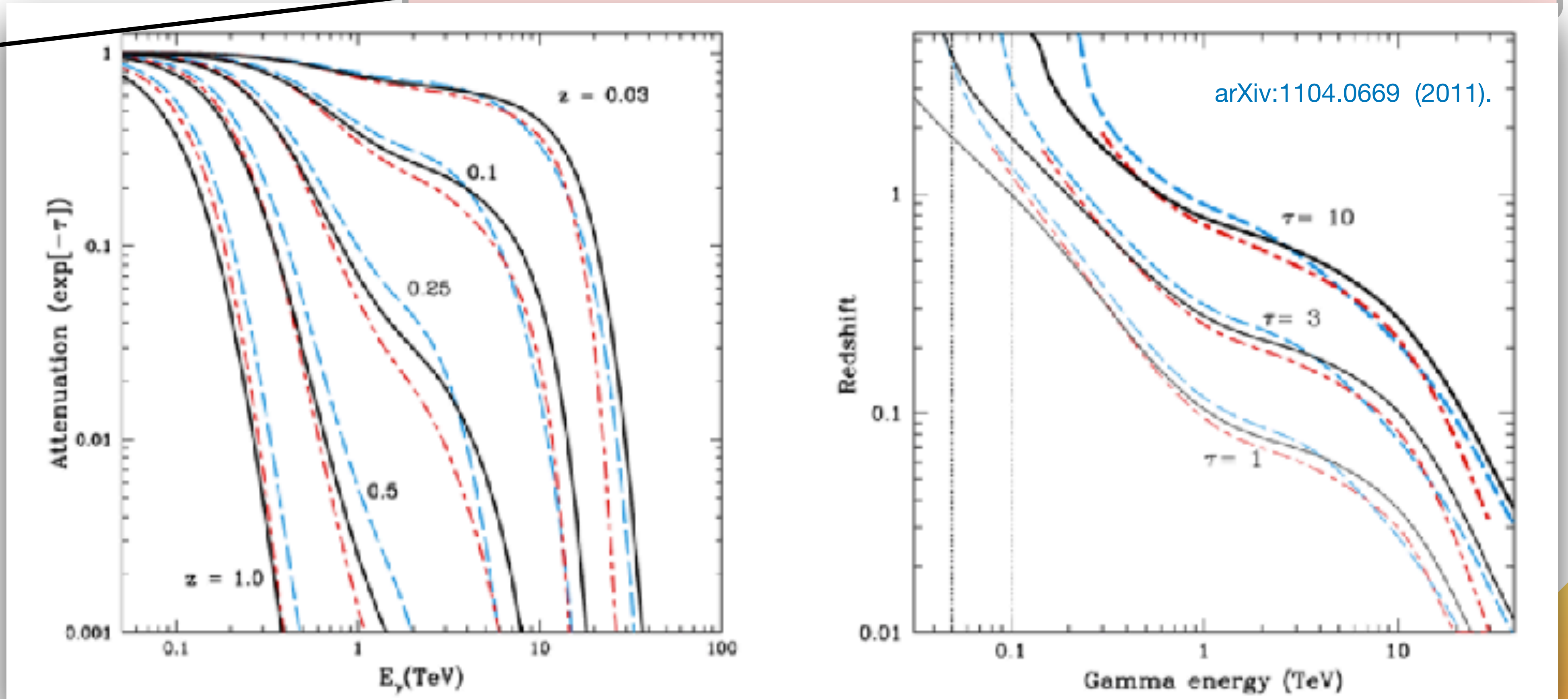
$$\beta'^2 = 1 - 2\left(m_e c^2\right)^2 / \left[E'\epsilon'(1-\cos\theta')\right]$$

$$\Phi_{obs}(E_\gamma, z) = e^{-\tau(E_\gamma, z)} \times \Phi_{int}(E_\gamma)$$

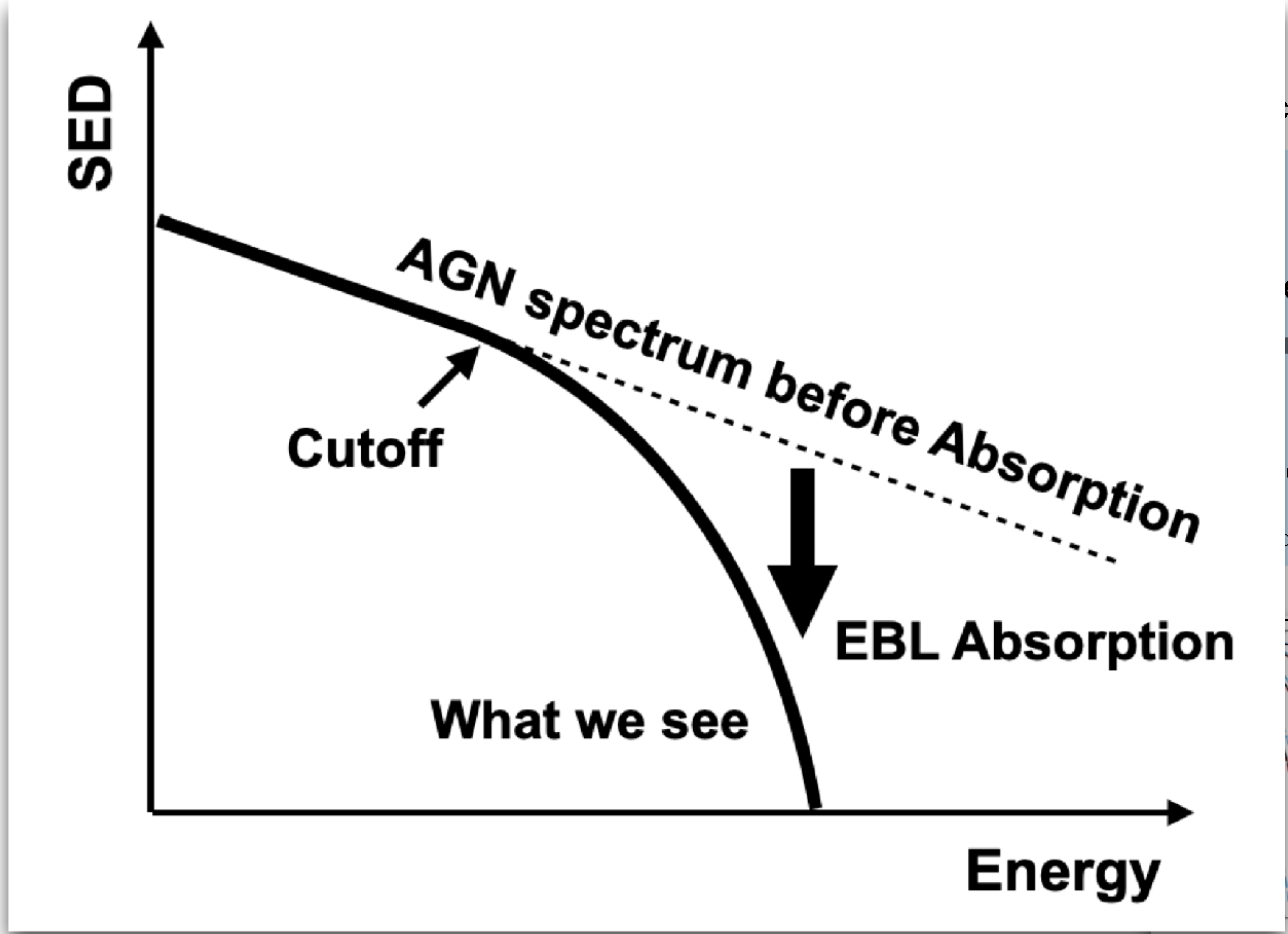
The gamma-ray absorption, quantified by the optical depth

$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} \Gamma_{\gamma\gamma}^{-1}(E(1+z), z) \frac{d\ell(z)}{dz}\, dz$$

line-of-sight integral up to the redshift of the source over the mean-free path



A gamma-ray journey through cosmic ages



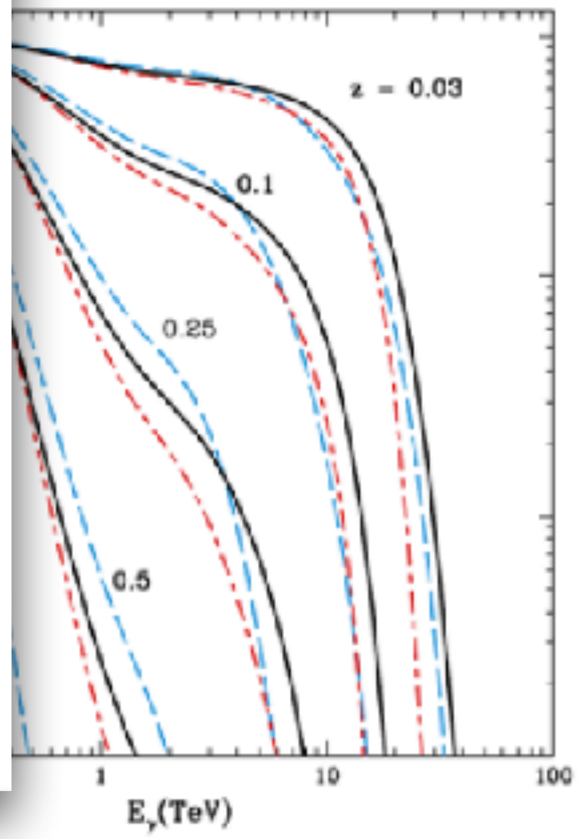
ce the birth of stars and galaxies.

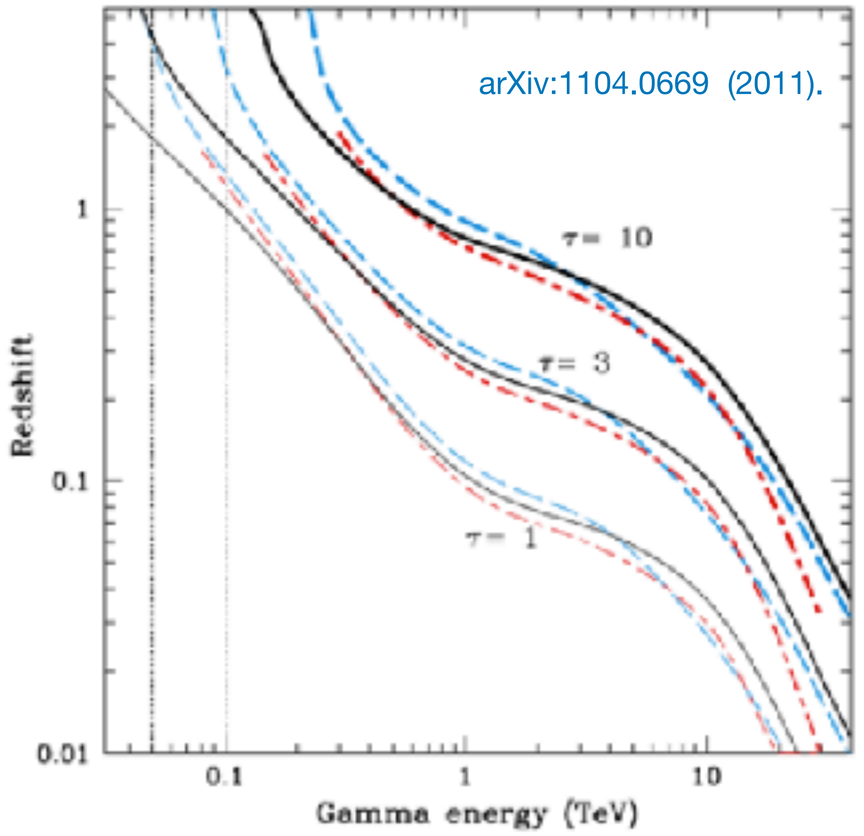
ed γ rays

$\Theta\left(\epsilon' - \epsilon'_{\text{th}}\right)$

$\text{os}\,\theta')]$

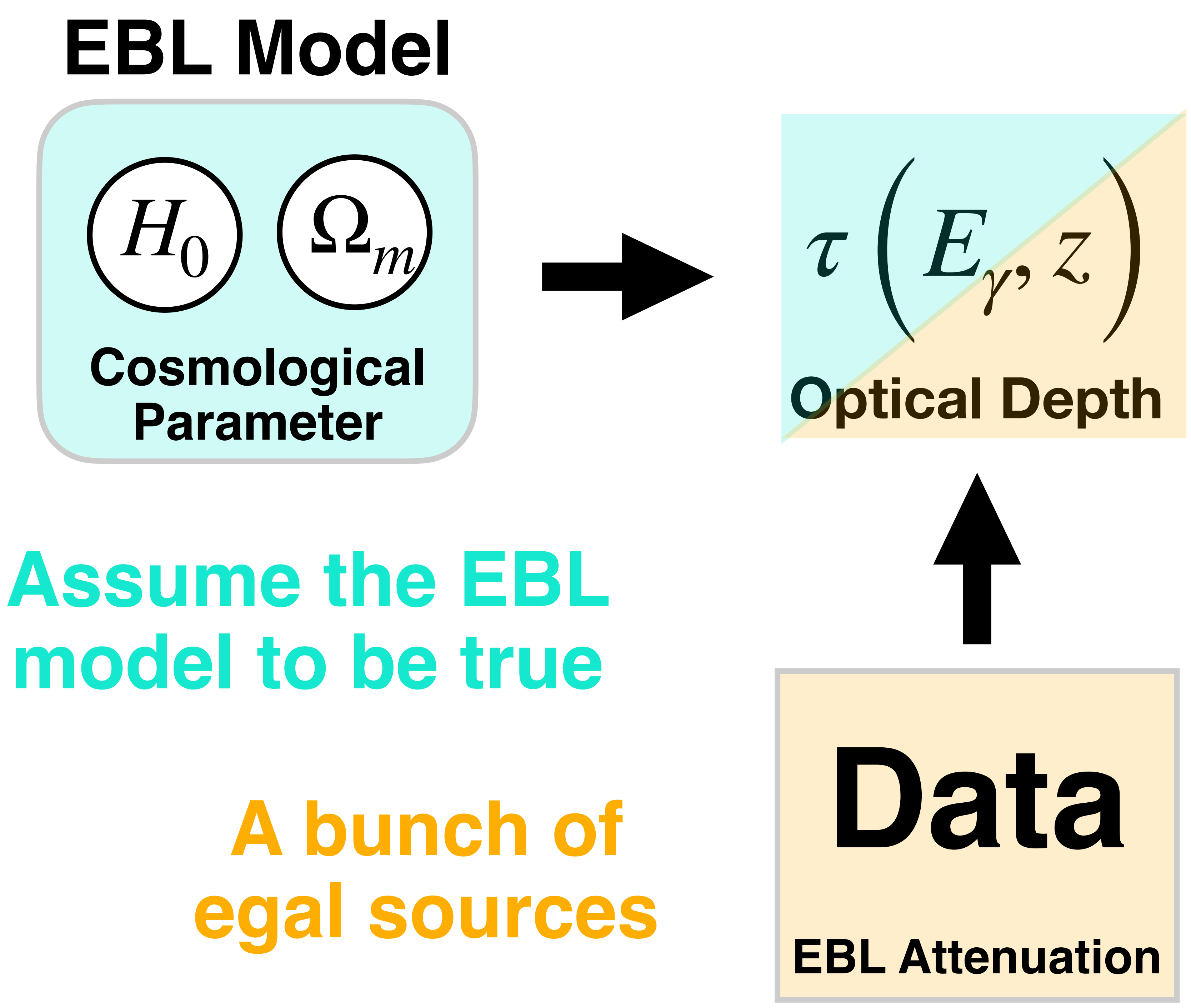
$$\Phi_{\text{obs}}\left(E_\gamma, z\right) = e^{-\tau\left(E_\gamma, z\right)} \times \Phi_{\text{int}}\left(E_\gamma\right)$$

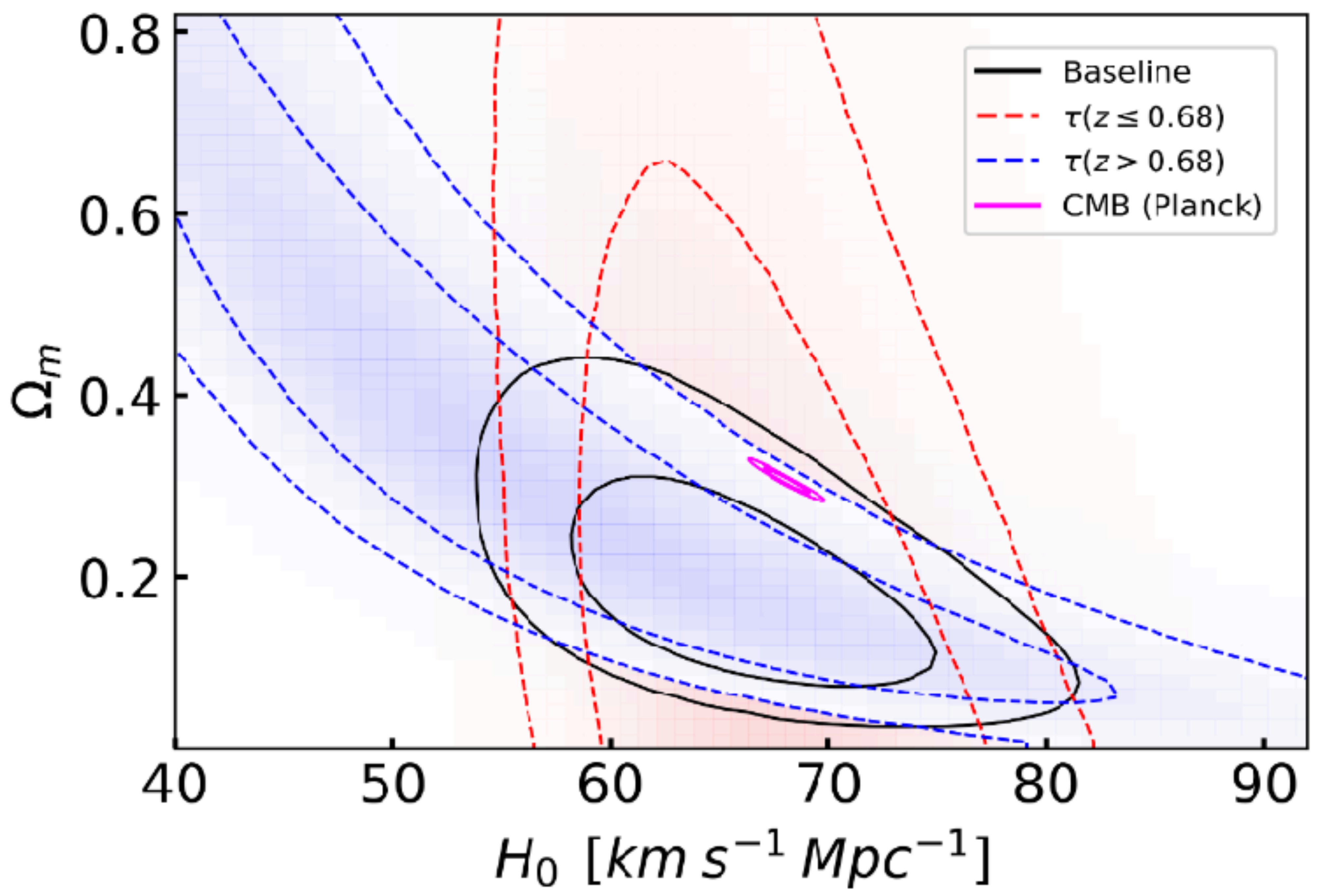




Estimation of the Hubble constant from γ-ray attenuation

- The opacity of gamma rays against Extragalactic background light (EBL) depends on H_0 and Ω_m
  By using this fact in reverse, they gave constraints on H_0 and Ω_m from the EBL attenuation data
- In this paper, H_0 and Ω_m of the universe are measured using the γ-ray attenuation results (Abdollahi et al. 2018, Desai et al. 2019) from Fermi-LAT and Cherenkov telescopes (IACT)
- For the EBL model, they used the latest developed empirical model Saldana-Lopez et al. 2021 (S21)





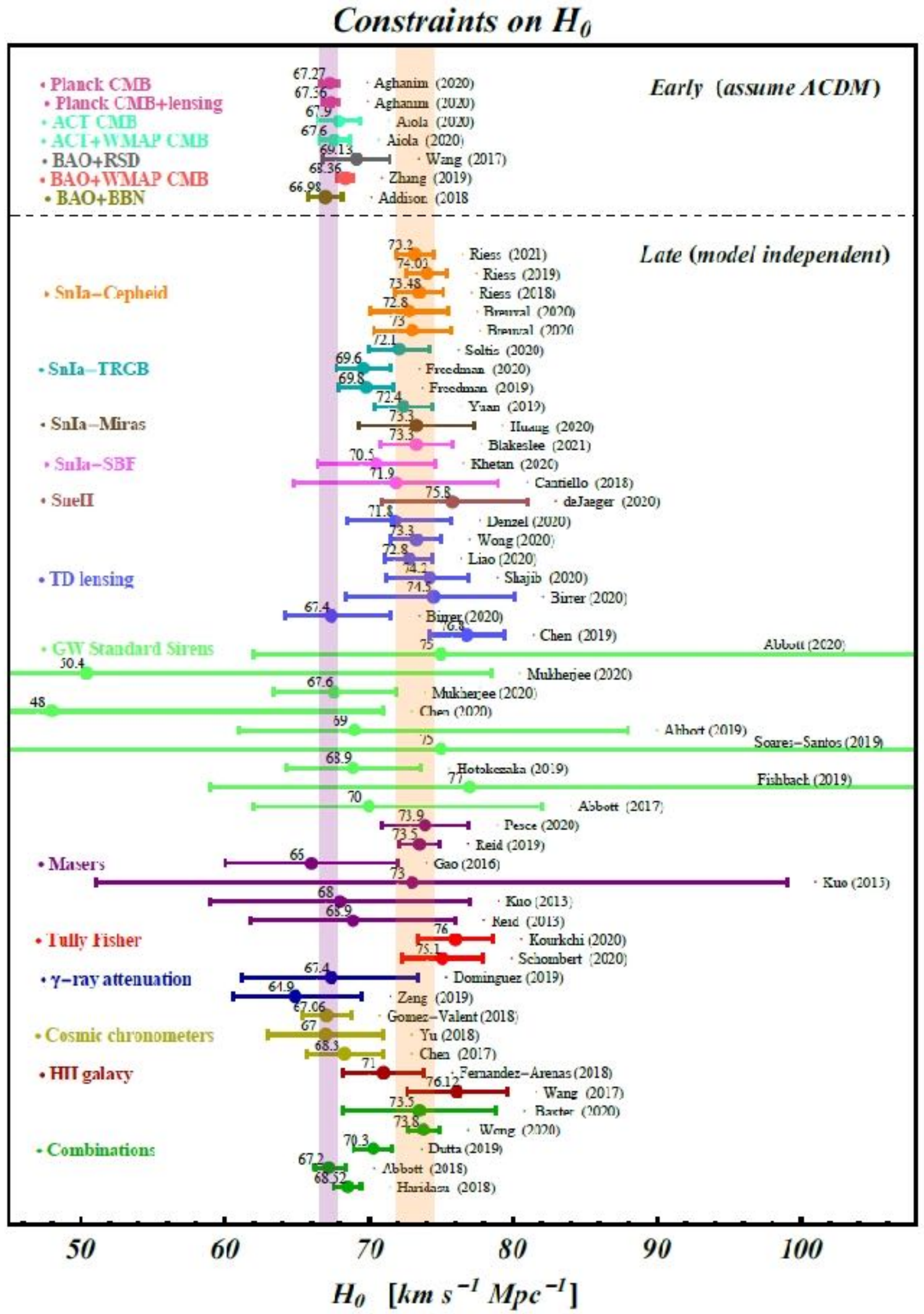
Hubble Crisis

- To assess and control systematic uncertainties

  - The Hubble constant is a too significant physical quantity to be measured by an independent method, as it is related to dark energy and the curvature of the universe.

- Hubble Crisis (Much more motivated physically!)

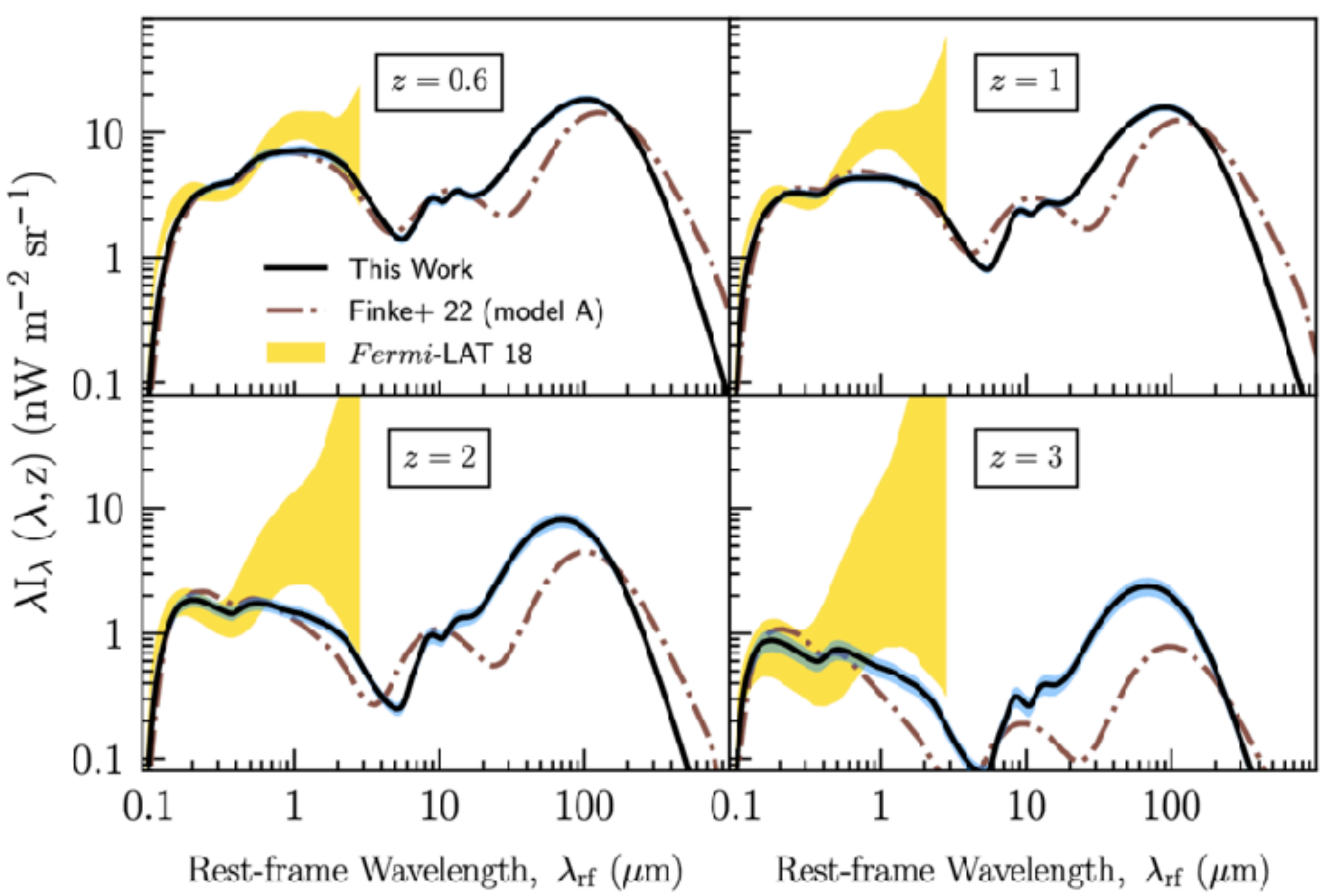
  - Discrepancy between the Hubble constant inferred from the cosmic microwave background radiation (CMB) and those from type Ia supernovae with distance calibration from Cepheids.

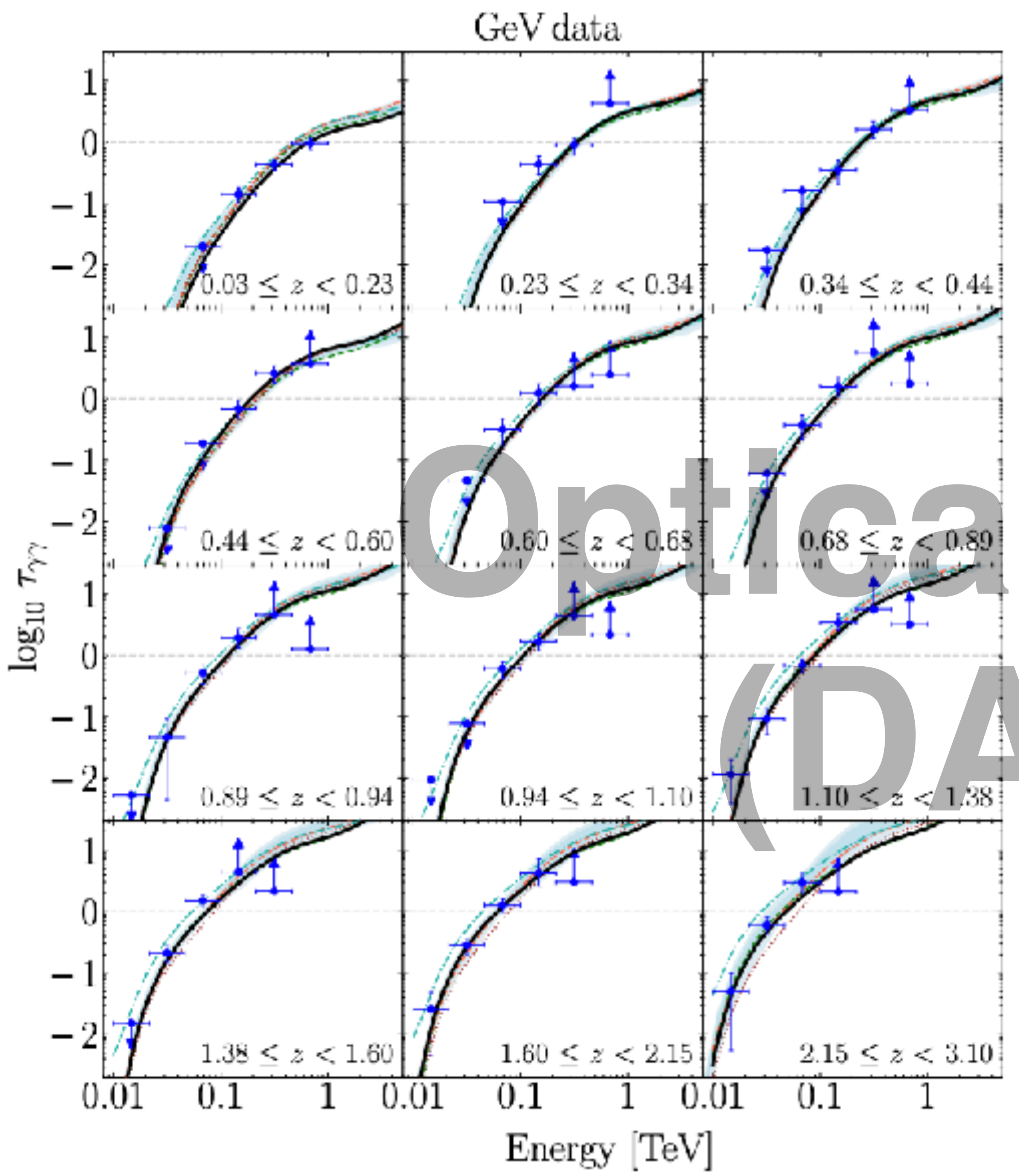


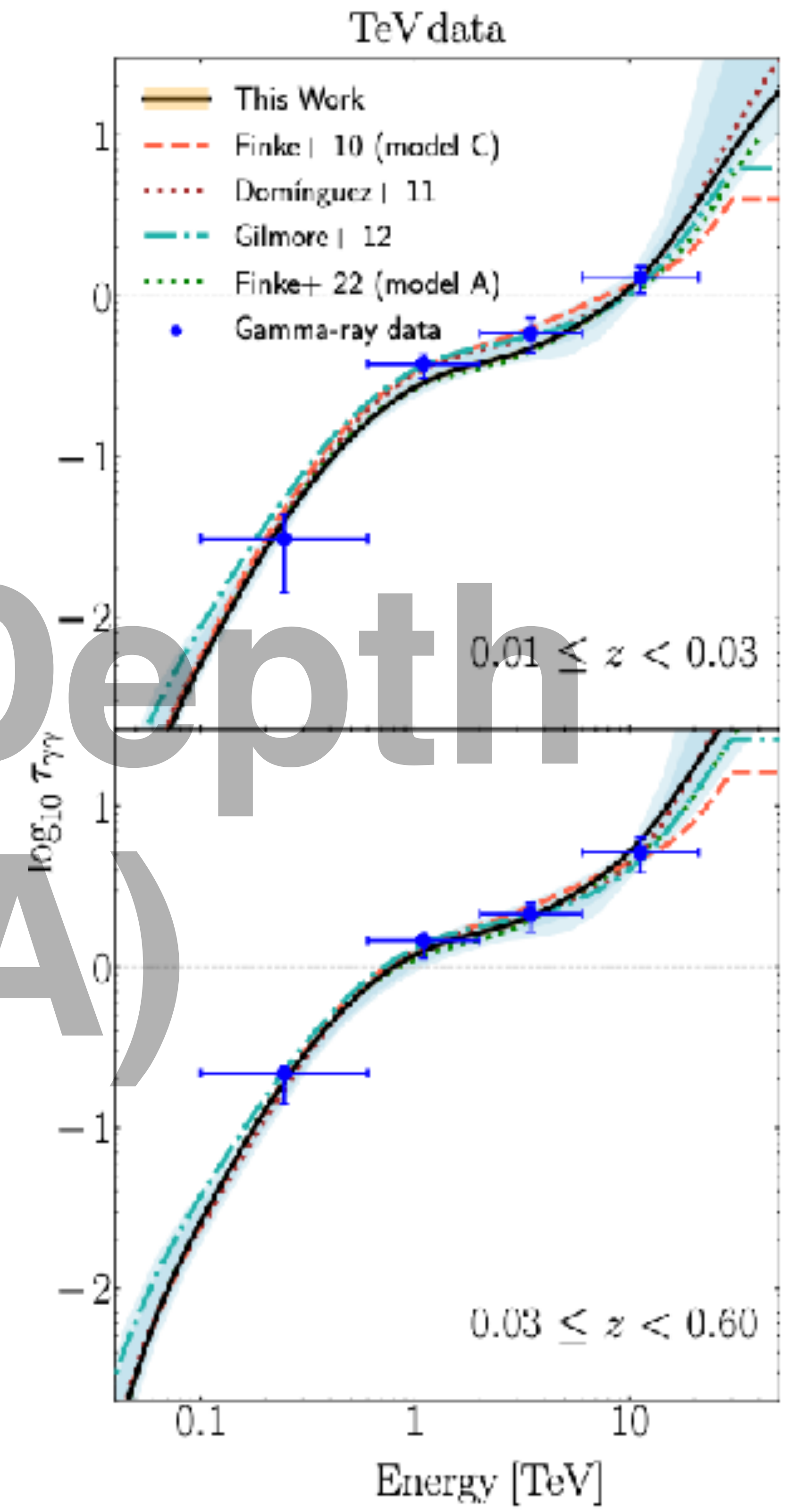
Estimation of the Hubble constant from γ-ray attenuation

- The opacity of gamma rays against Extragalactic background light (EBL) depends on H_0 and Ω_m
  By using this fact in reverse, they gave constraints on H_0 and Ω_m from the EBL attenuation data
- In this paper, H_0 and Ω_m of the universe are measured using the γ-ray attenuation results (Abdollahi et al. 2018, Desai et al. 2019) from Fermi-LAT and Cherenkov telescopes (IACT)
- For the EBL model, they used the latest developed empirical model Saldana-Lopez et al. 2021 (S21)

EBL Model





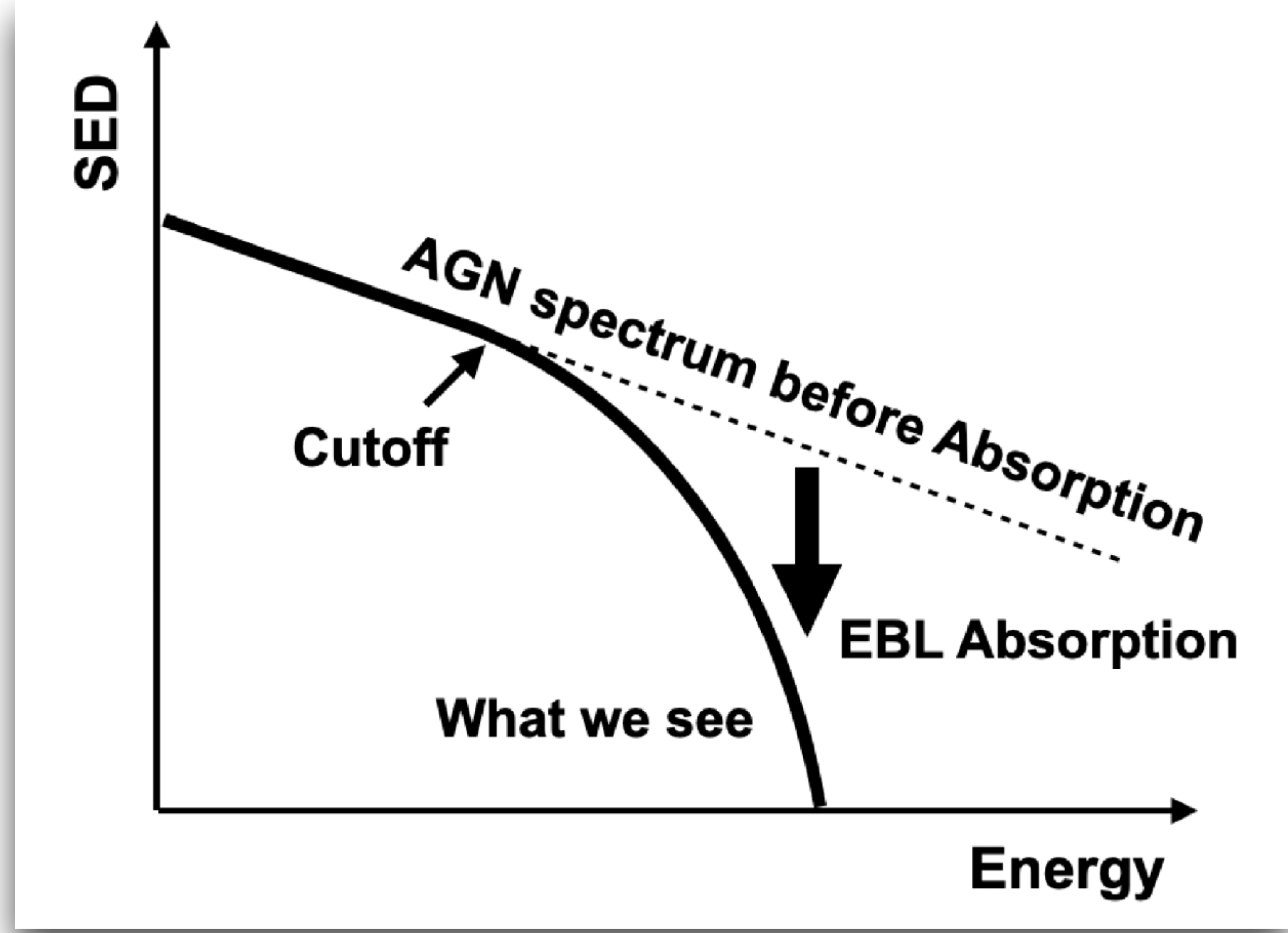


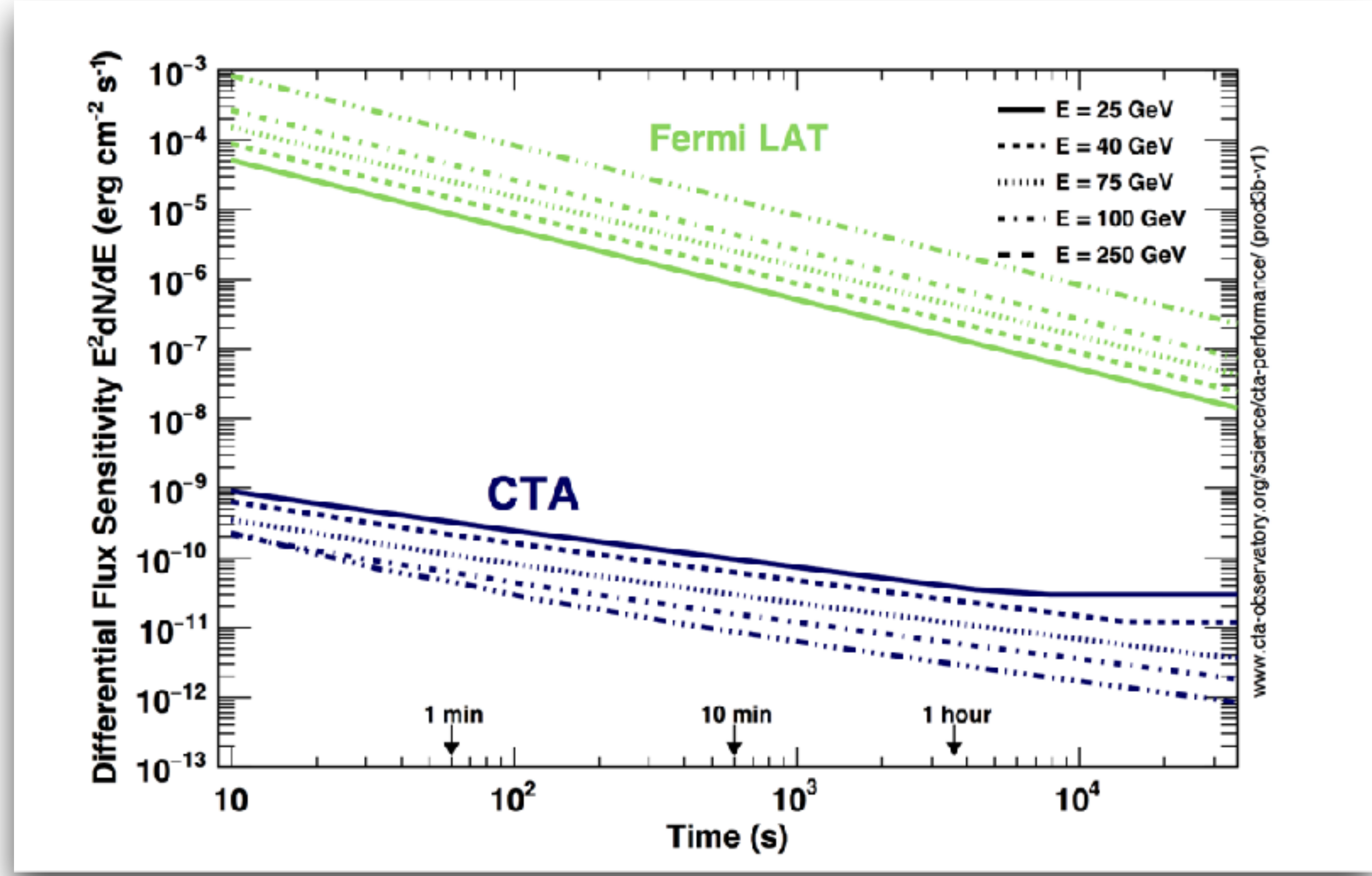
Optical Depth (DATA)

What kind of performance do we need for the IACT

- To conduct cosmological studies through gamma-ray observations, the required telescope performance includes observing gamma rays before they begin to be absorbed by the EBL.
- This significantly impacts the estimation of the intrinsic spectrum

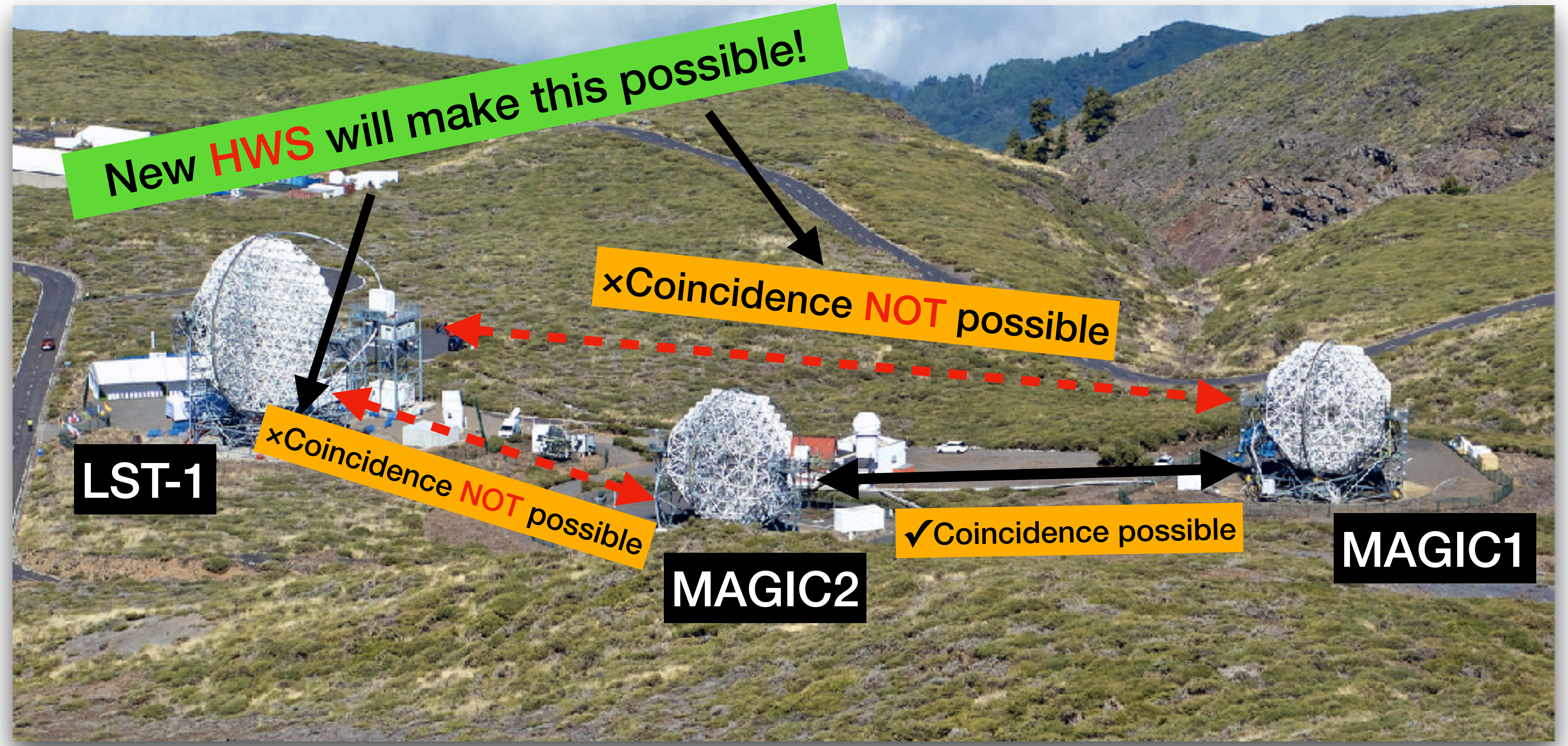
Highlighting the importance of lowering the energy threshold for IACTs!



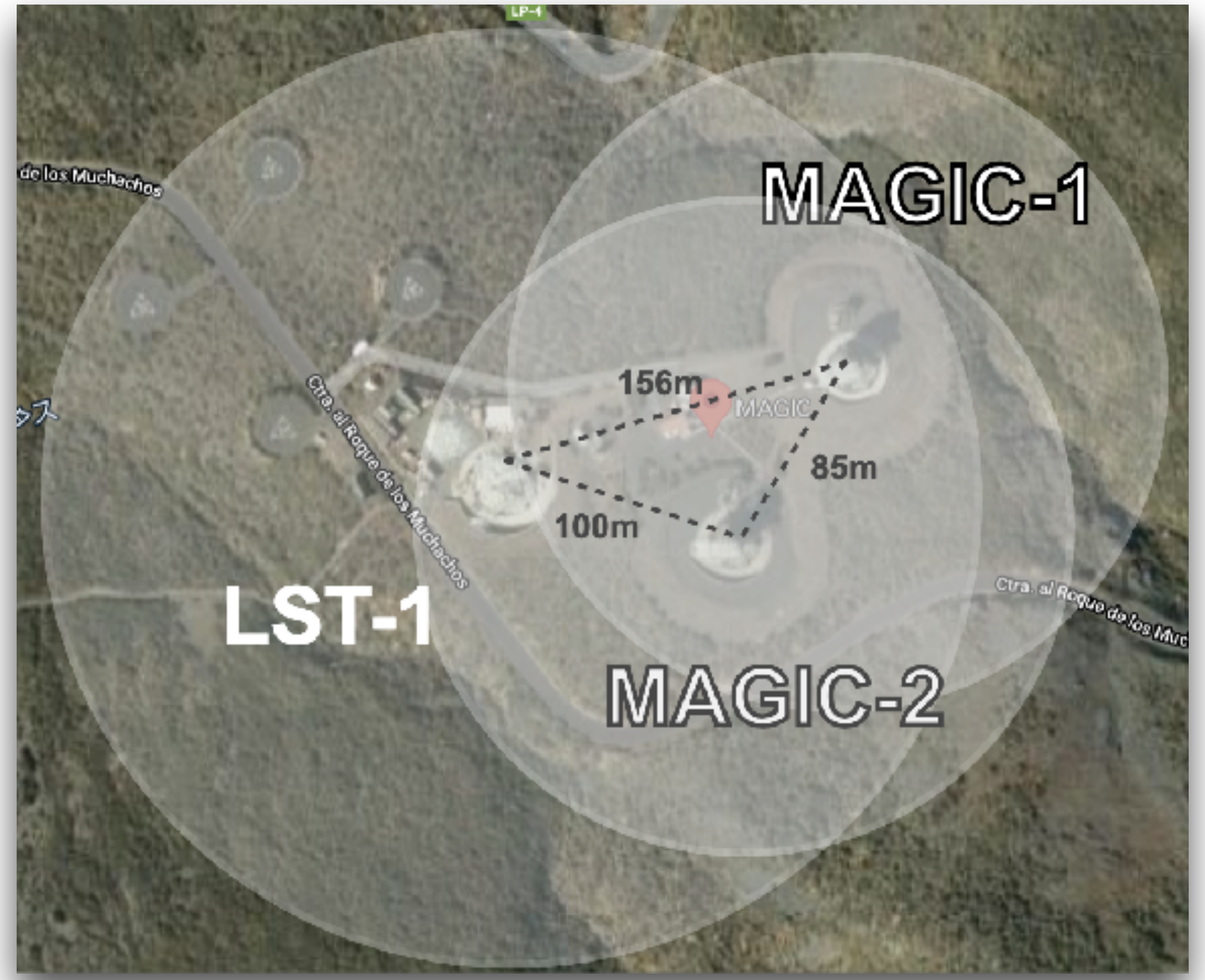


Hardware Stereo Trigger between MAGIC and LST-1

Implementation of the Hardware Stereo Trigger



MAGIC telescopes and LST-1



Aerial photography of MAGICs and LST-1

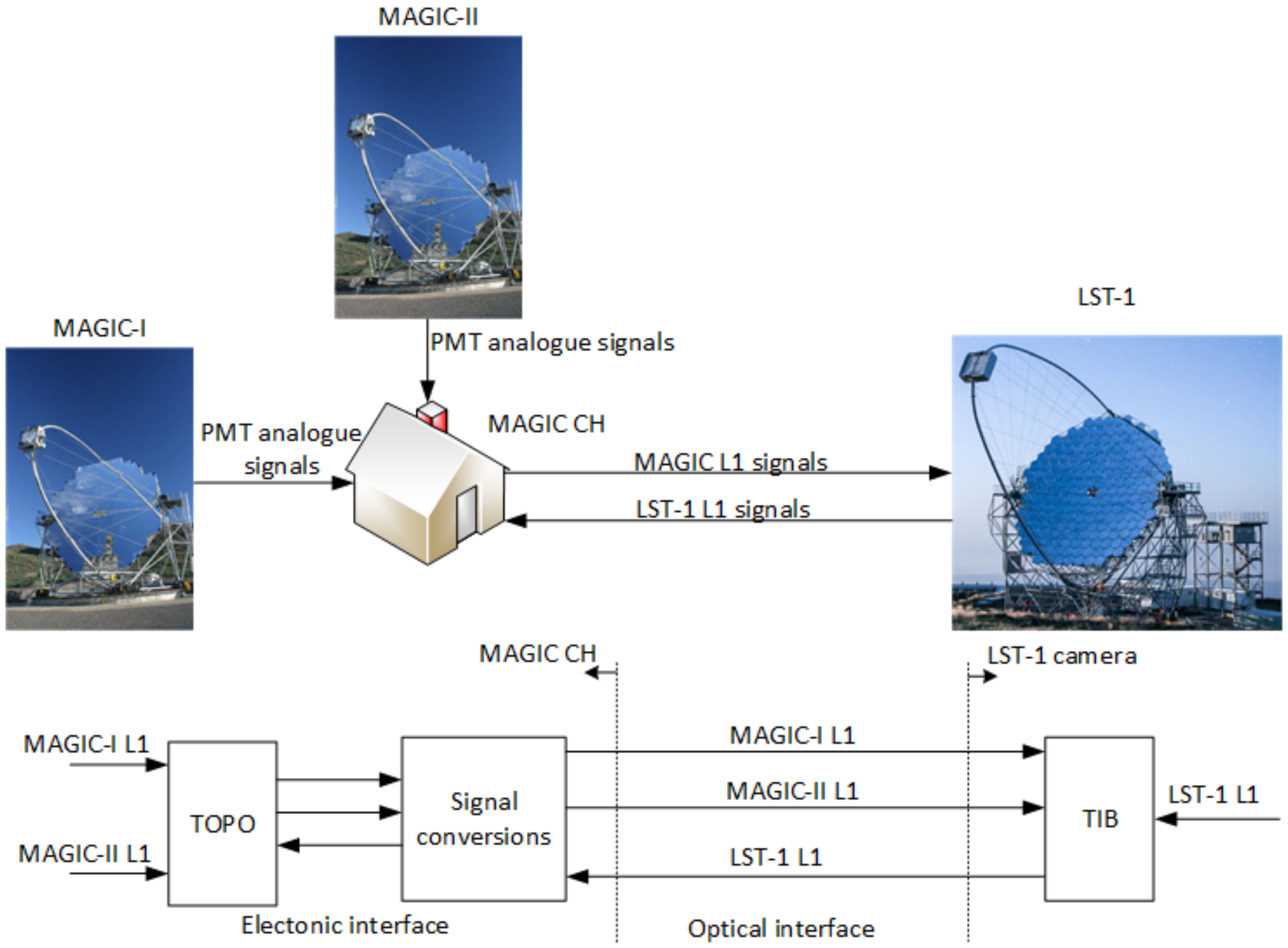
- MAGICs: Two stereo reconstructions possible
  LST-1: Low energy threshold than MAGIC, i.e. ~20 GeV
- If there is an HWS that exchanges trigger signals among MAGIC and LST-1, we will have lower energy threshold than the current MAGIC and will be more sensitive.

Joint Observation of the Hardware Stereo Trigger

✦ Schematic view of the HaST system

- Electro Optical Transceiver (EOT), LVDS-CMOS Converter, HaST (TOPO board) in MAGIC CH

- LST-1 does not require new hardware stereo board to be implemented, but uses an existing trigger interface board

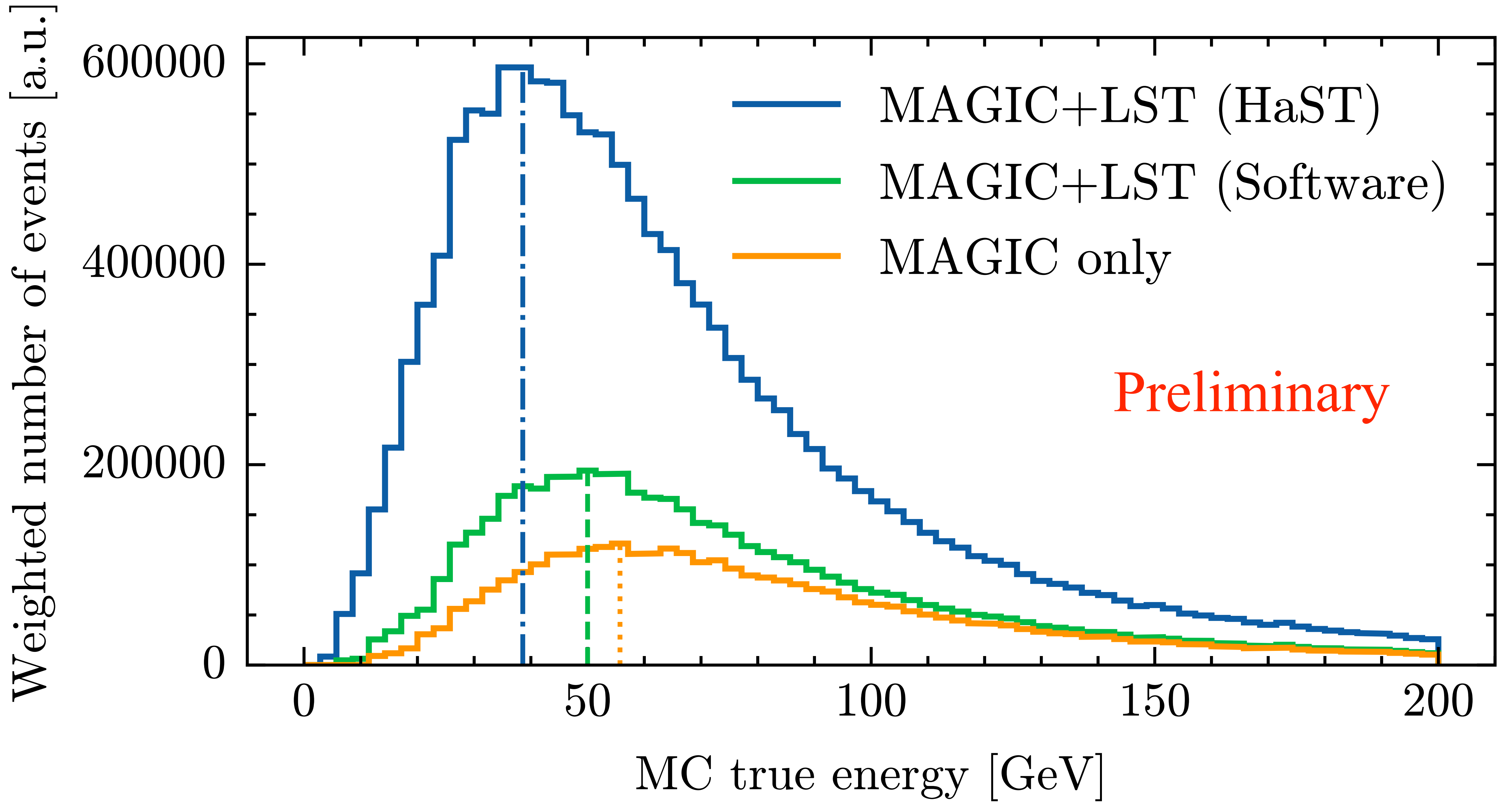


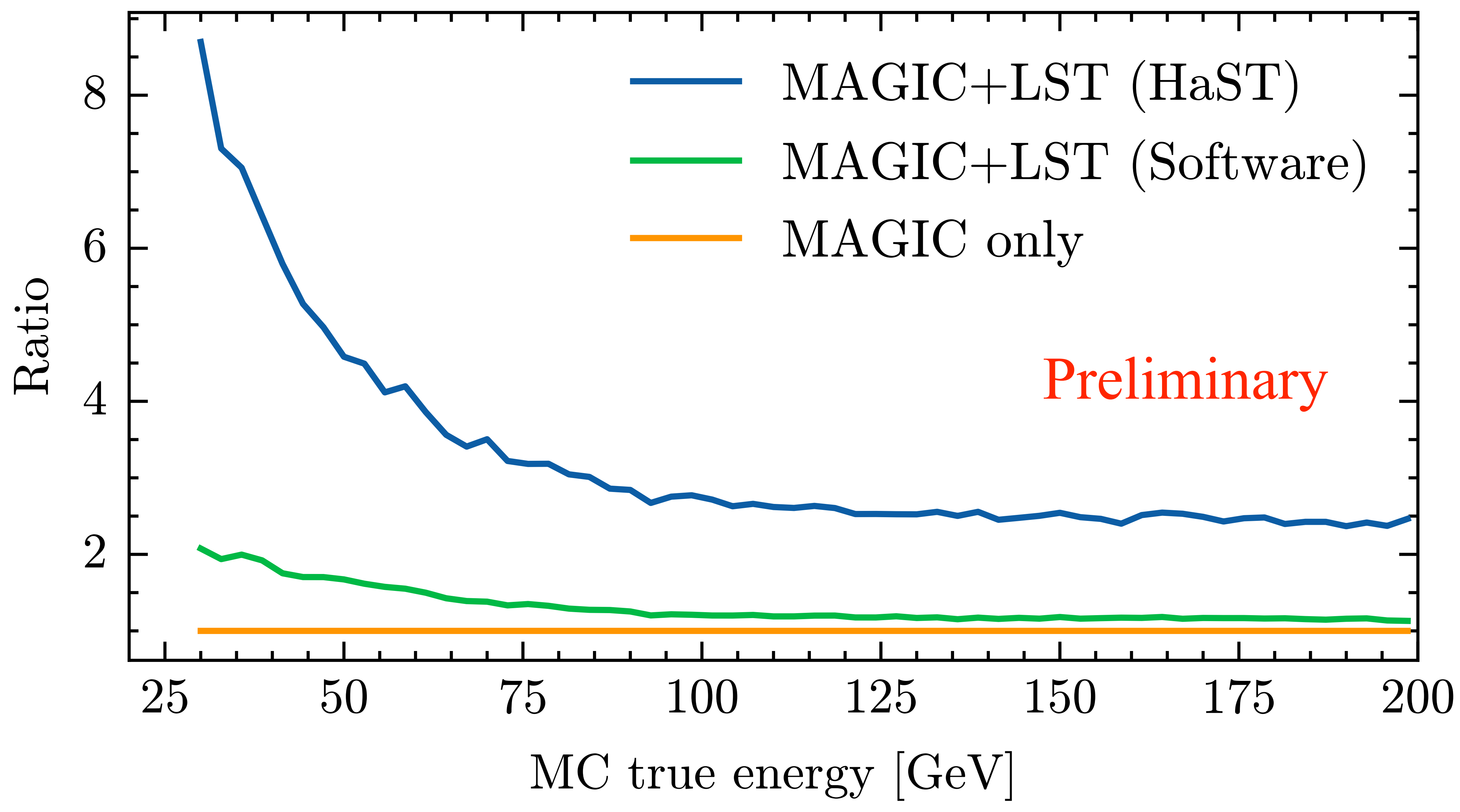
Sketched by ALEJANDRO PEREZ

Performance Estimation of the Hardware Stereo Trigger

✦ Energy Threshold of the HaST system vs Software Coincidence approach and MAGIC-only

- The respective energy thresholds are estimated to be ~ 39 GeV for HaST, ~49 GeV for SC, and ~56 GeV for MAGIC only, namely, HaST system presents an improvement of about 20% over SC, and roughly 30% over MAGIC only
- The ratio of triggered events clearly shows the effect of effective area expansion by the HaST system, as seen in the fact that the HaST system increases the number of triggered events by another 3-4 times more than the SC method, which itself enhances the event count by up to twice that achieved solely with MAGIC

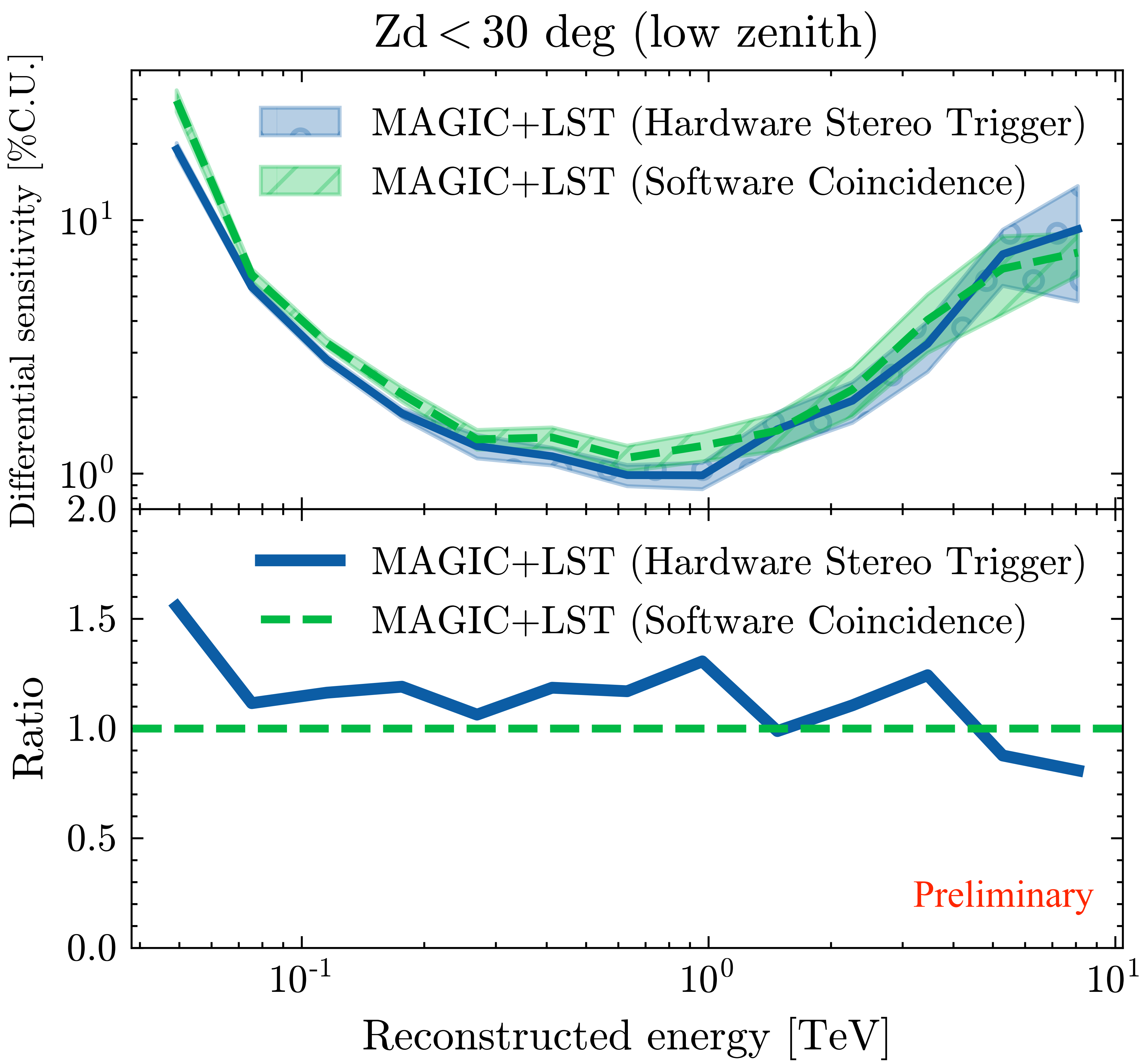


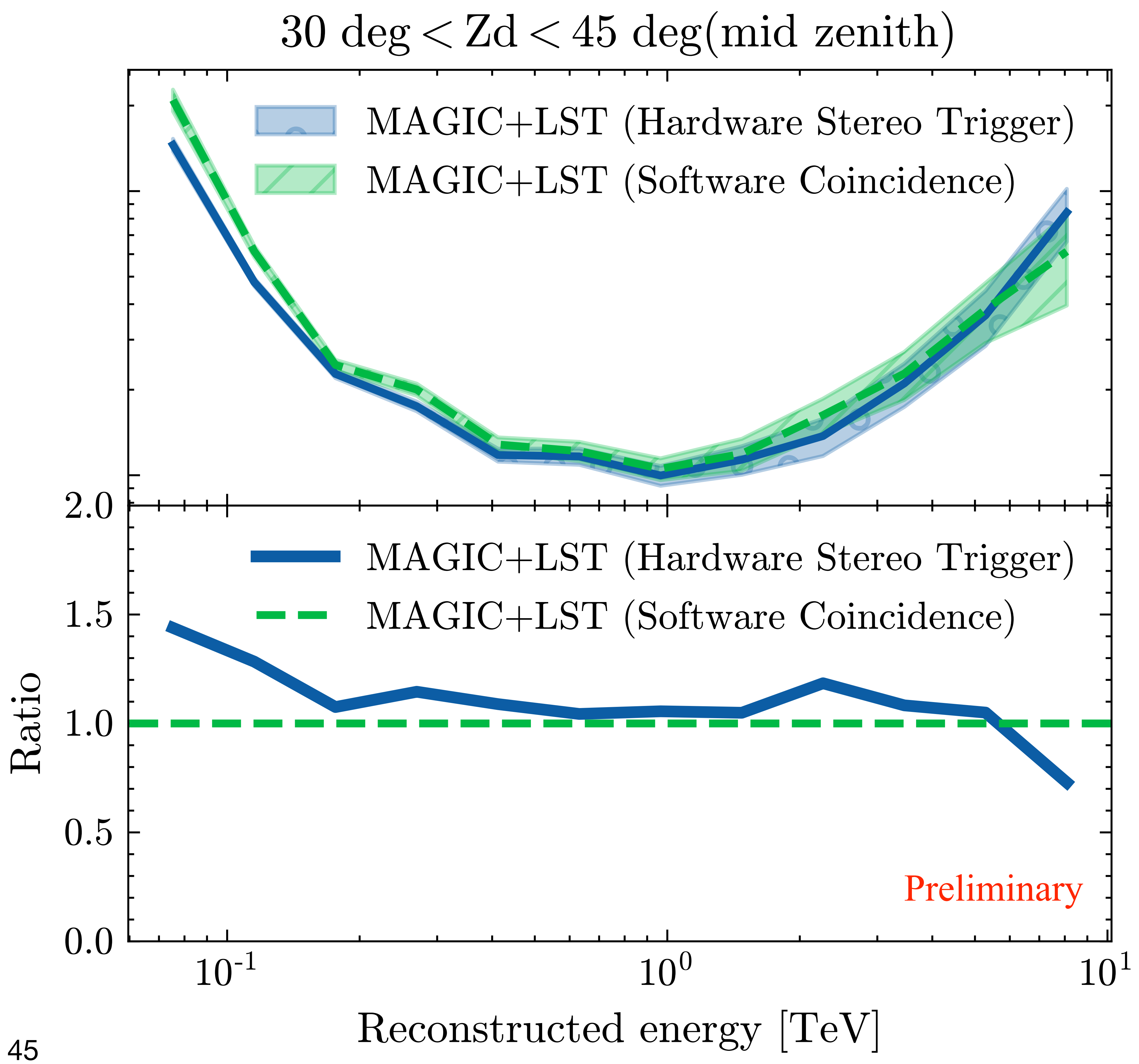


Performance Estimation of the Hardware Stereo Trigger

✦ Sensitivity of the HaST system vs Software Coincidence approach

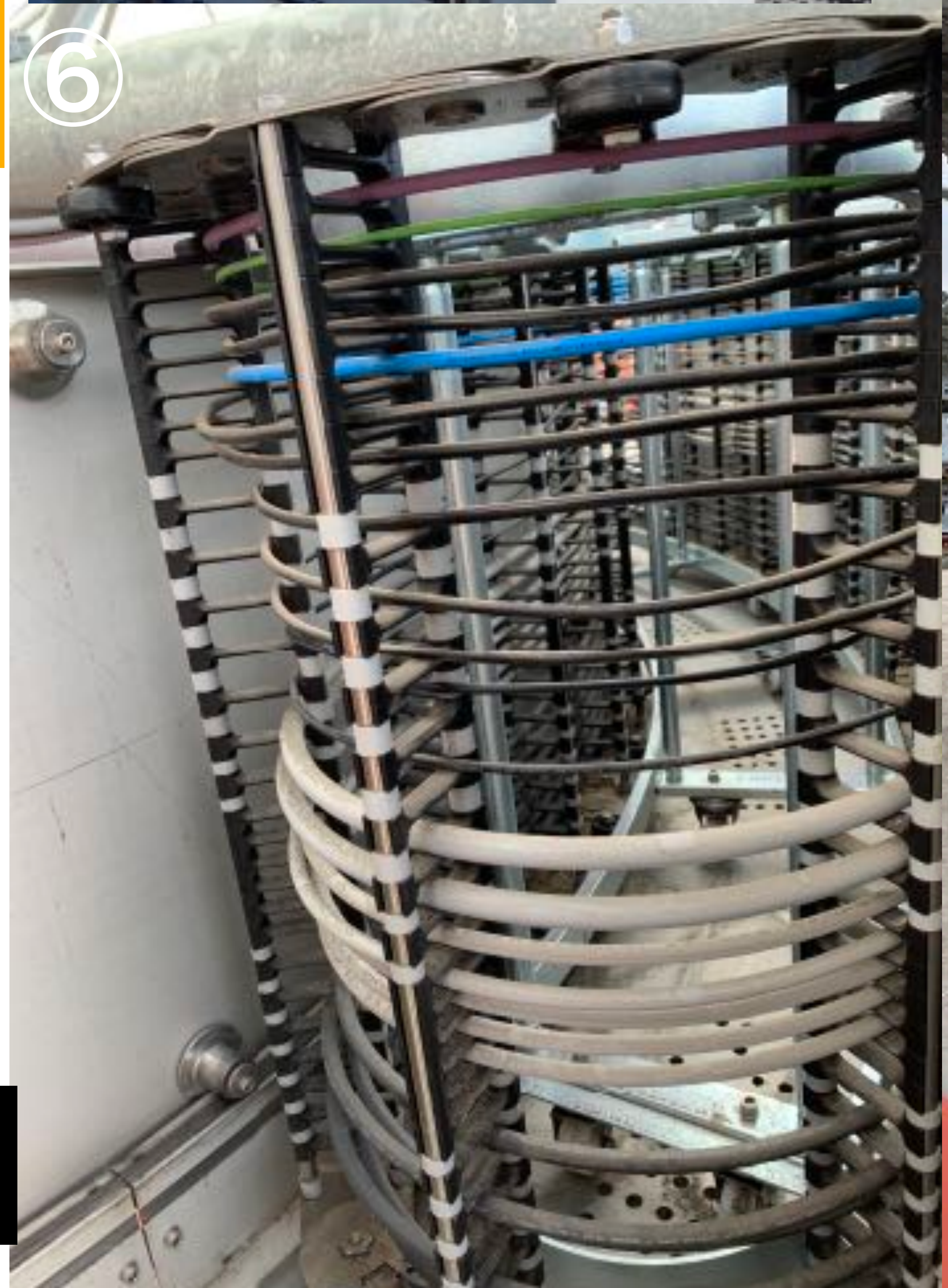
- The improvements in the effective area and energy threshold provided by the HaST system result in a overall sensitivity enhancement; particularly in the lowest energies ~100 GeV





Cabling towards MAGIC telescope

going along the tension cable
(before arch and dish)



Test Observation with the Hardware Stereo Trigger

- Observations of the Crab Nebula were conducted with HaST activated
- Effective observation time ~ 2 hours after quality cut
- Data analyzed using traditional SC method for comparison
- Implementation of HaST confirmed to effectively lower energy threshold