Gamma-ray Astronomy

A brief introduction and history

David Green (CTAO), June 14th 2025

Brief History

The Electromagnetic Spectrum

Radio	Microwave	Infrared	Visible	UV	X-ray	γ-ray
10^{3} m	10^{-2} m	10^{-5} m	10^{-6} m	10^{-8} m	10^{-10} m	10^{-12} m
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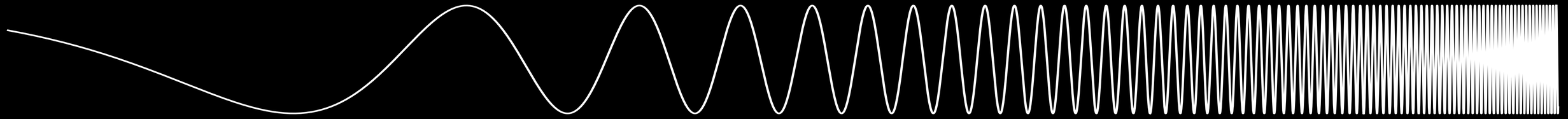

Penetrate Earth's Atmosphere

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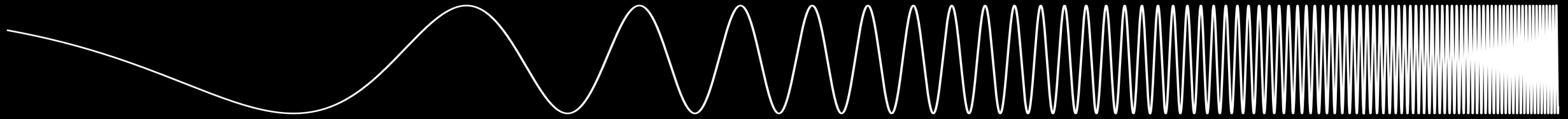

Penetrate Earth's Atmosphere

SKAO, GBT, VLA

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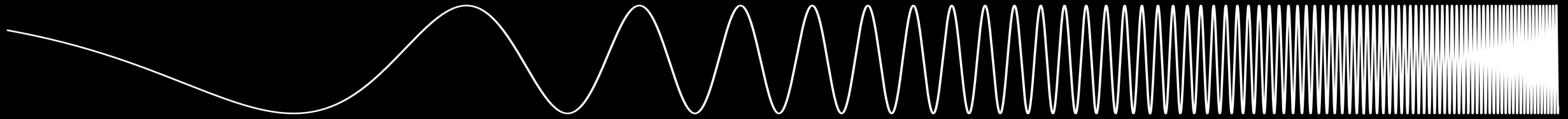

Penetrate Earth's Atmosphere

Y		N		Y	N

SKAO, GBT, VLA

ALMA

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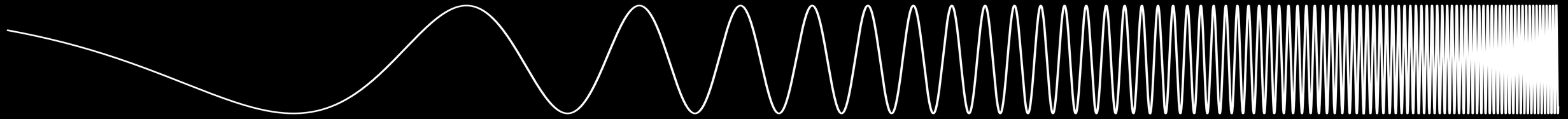

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SKAO, GBT, VLA

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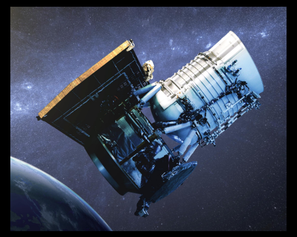

FIR: Spitzer, IRAS

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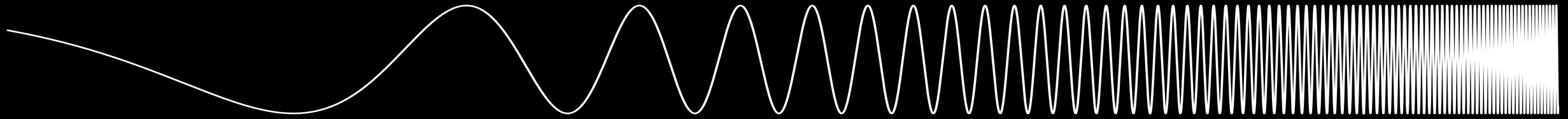

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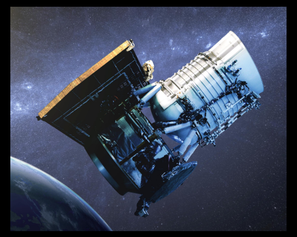

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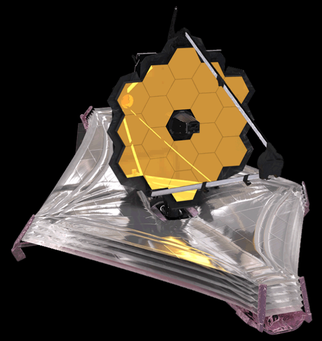

NIR: JWST, WISE, RST

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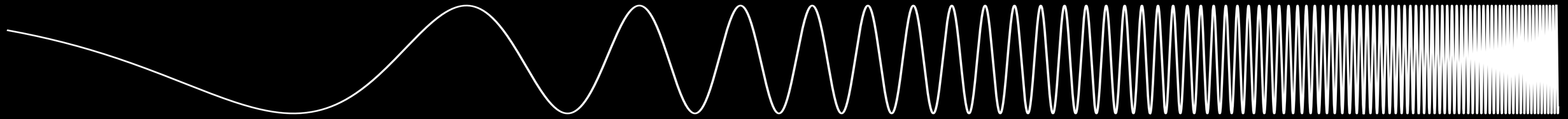

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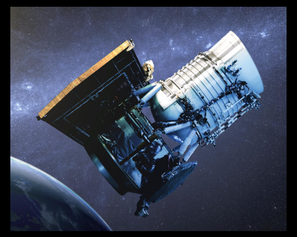

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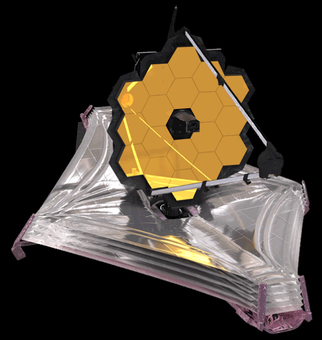
GTC, etc.



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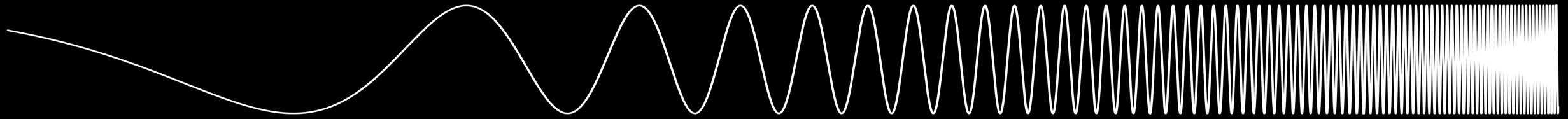

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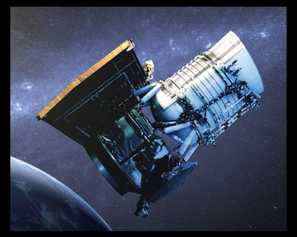

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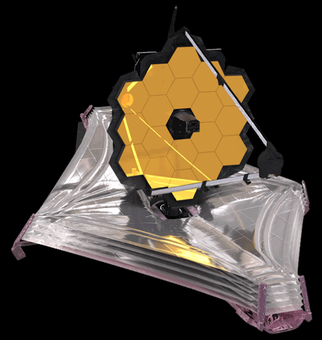

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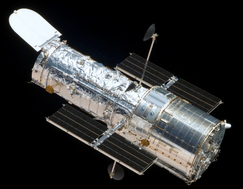

Hubble, AstroSAT

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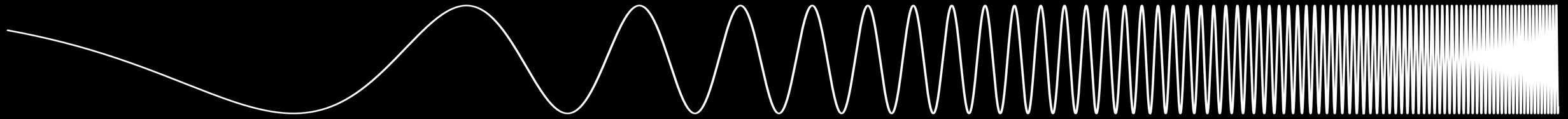

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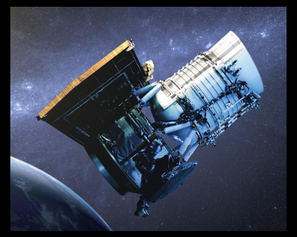

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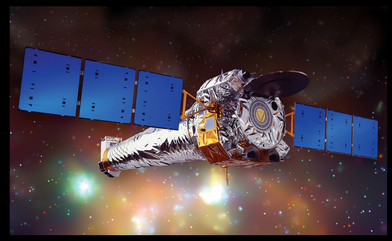
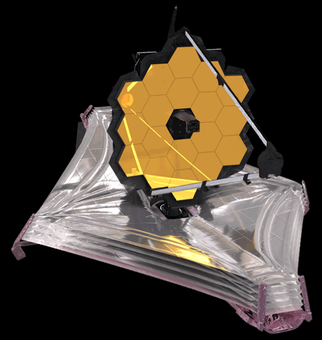


Chandra, XMM, Swift, Einstein Probe, etc.



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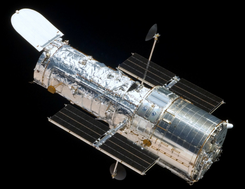

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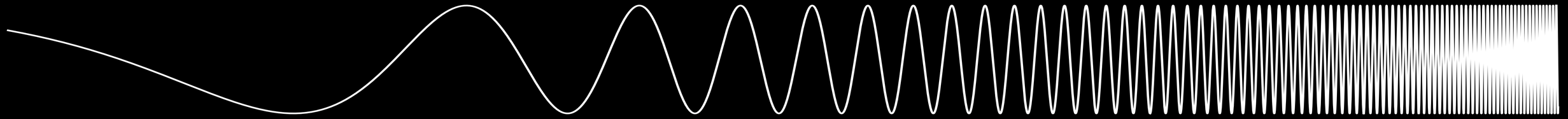

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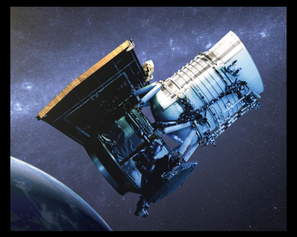

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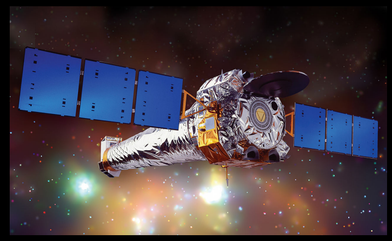

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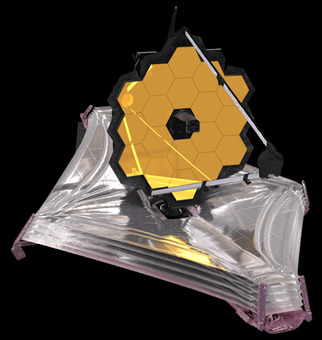

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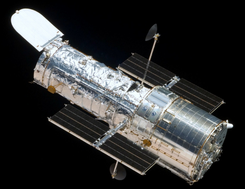

Hubble, AstroSAT

Let’s Extend The EM Spectrum

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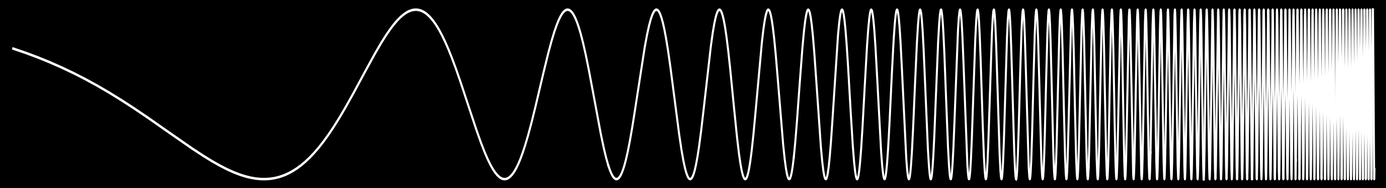

Penetrate Earth’s Atmosphere

Let’s Extend The EM Spectrum

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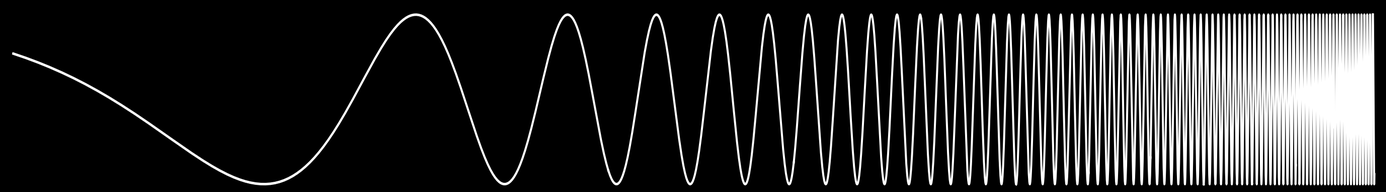

More γ-rays

Penetrate Earth’s Atmosphere

Let’s Extend The EM Spectrum

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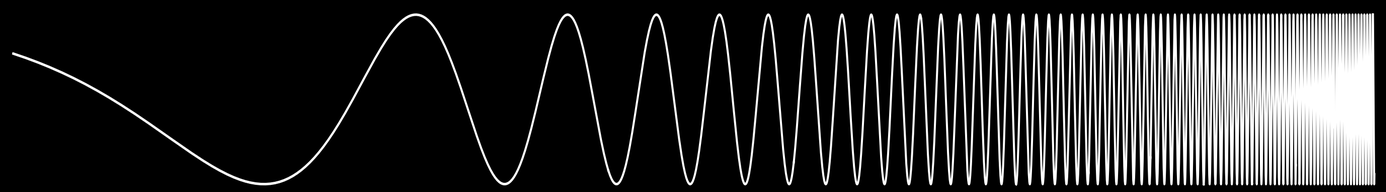

More γ-rays

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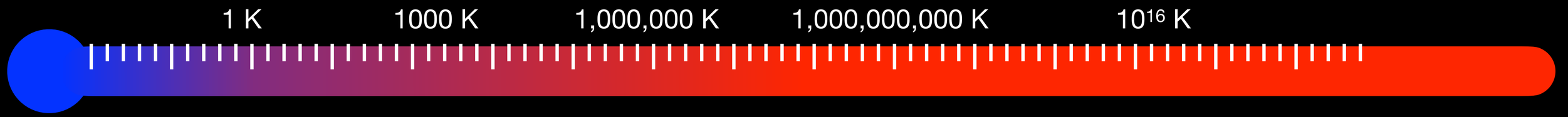

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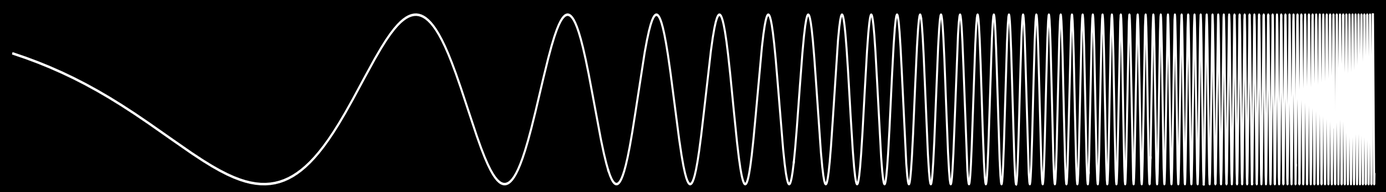

More γ-rays

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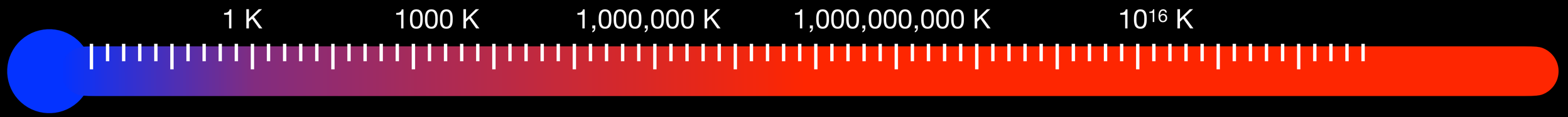


- Gamma rays cover 9 orders of magnitude in energy space
- If you convert their energy to black body radiation, they would require ridiculous energies
- Have to be made through non-thermal means == particle acceleration

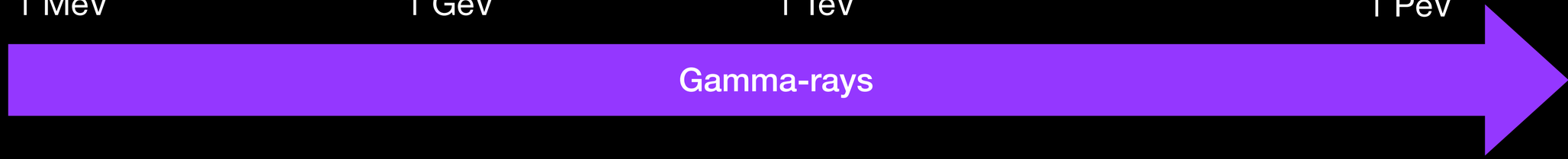
Let’s Zoom In

γ-ray
10^{-12} m
1 MeV

γ-ray
10^{-15} m
1 GeV

γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV



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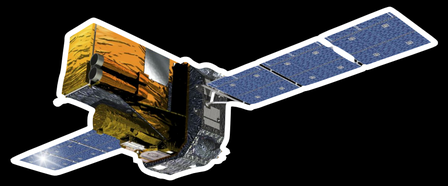
Gamma-rays



Integral

Let’s Zoom In

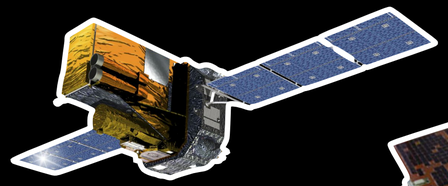
γ-ray
10^{-12} m
1 MeV

γ-ray
10^{-15} m
1 GeV

γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV

Gamma-rays



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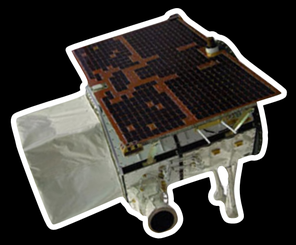

Agile

Let’s Zoom In

γ-ray
10^{-12} m
1 MeV

γ-ray
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γ-ray
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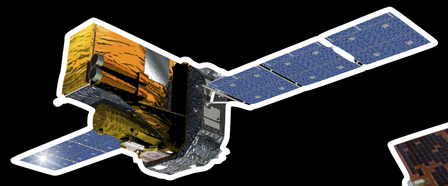
1 TeV

γ-ray
10^{-21} m
1 PeV

Gamma-rays



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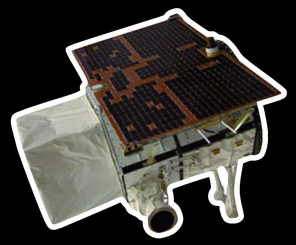

Agile

Fermi

Let’s Zoom In

γ-ray
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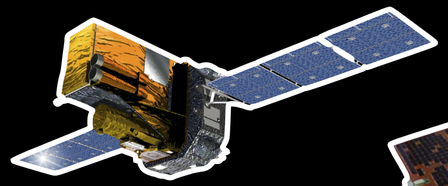
1 MeV

γ-ray
10^{-15} m
1 GeV

γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV

Gamma-rays



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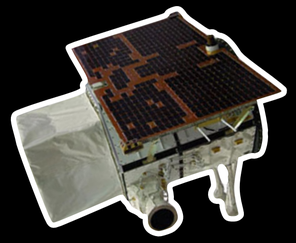

Agile

Fermi

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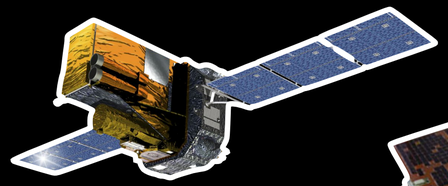
10^{-21} m
1 PeV

Gamma-rays



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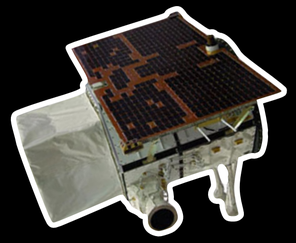

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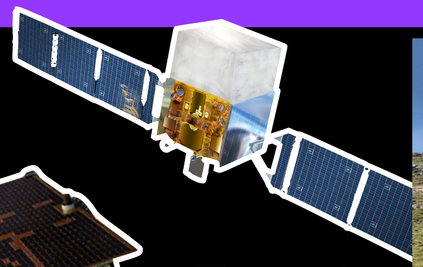


Fermi

HAWC

Let’s Zoom In

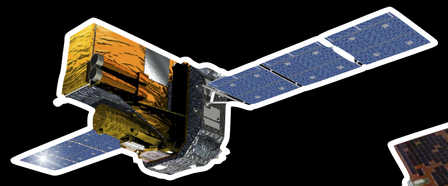
γ-ray
10^{-12} m
1 MeV

γ-ray
10^{-15} m
1 GeV

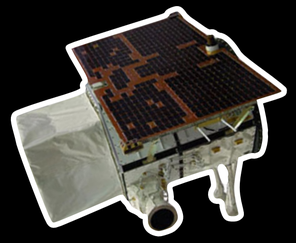
γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV

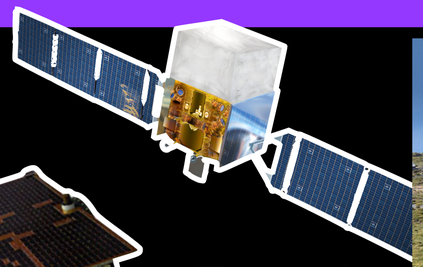
Gamma-rays



Integral



Agile



Fermi

HAWC

LHAASO

Let's Zoom In

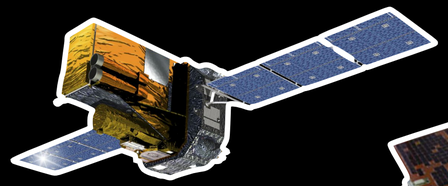
γ-ray
10^{-12} m
1 MeV

γ-ray
10^{-15} m
1 GeV

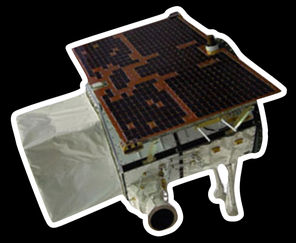
γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV

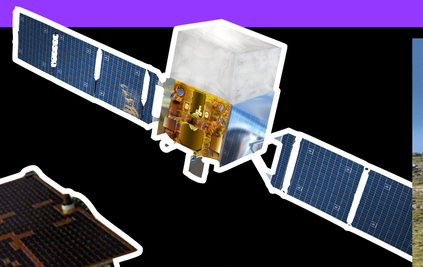
Gamma-rays



Integral



Agile



Fermi

HAWC

LHAASO

Detector Size and Collection Area

1000 cm^2

1 m^2

0.1 km^2

1 km^2

Let's Zoom In

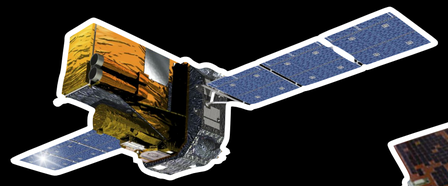
γ-ray
10^{-12} m
1 MeV

γ-ray
10^{-15} m
1 GeV

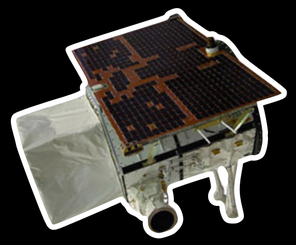
γ-ray
10^{-18} m
1 TeV

γ-ray
10^{-21} m
1 PeV

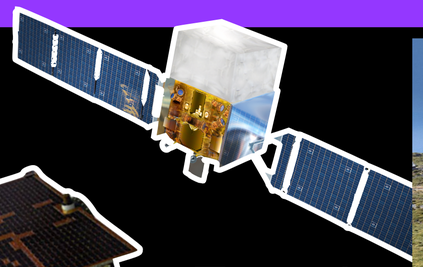
Gamma-rays



Integral



Agile



Fermi

HAWC

LHAASO

Detector Size and Collection Area

1000 cm^2

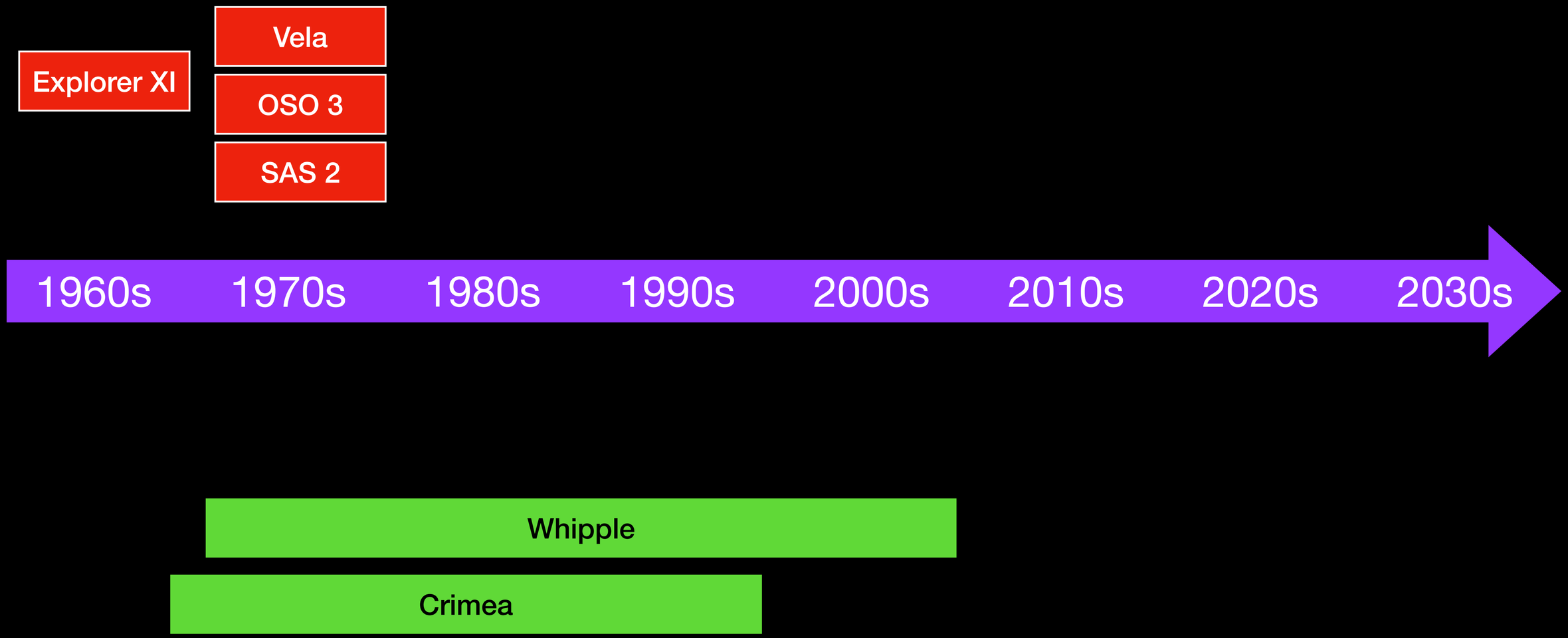
1 m^2

0.1 km^2

1 km^2

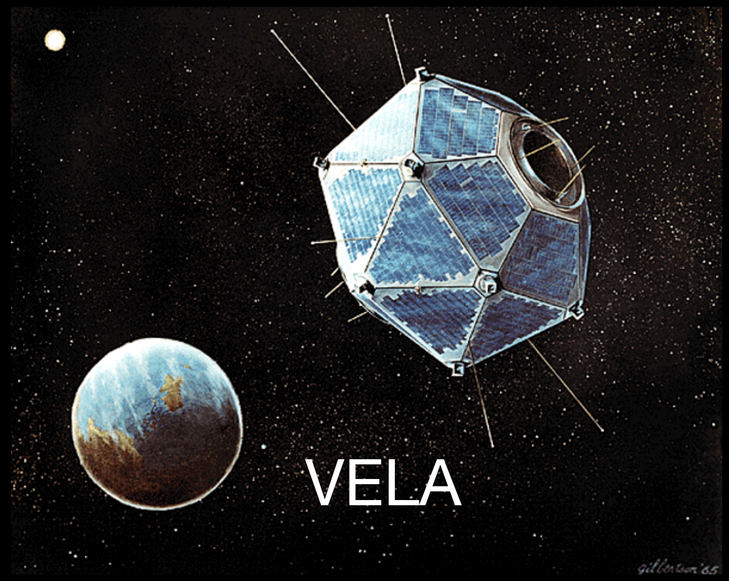
- Gamma rays cover 9 orders of magnitude in energy space
- Can be broken into Space Based and Ground Based

A Very Brief History

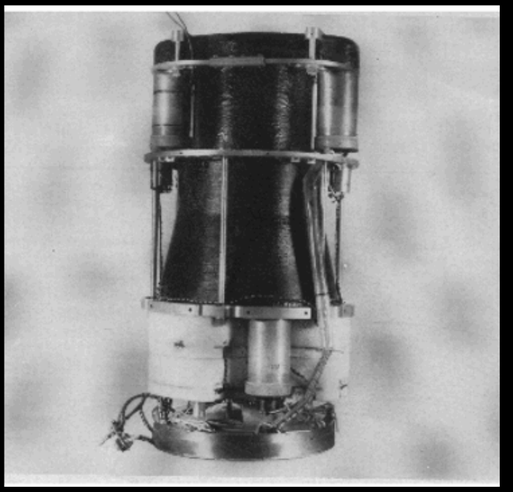


The Wild West (1960s & 1970s)

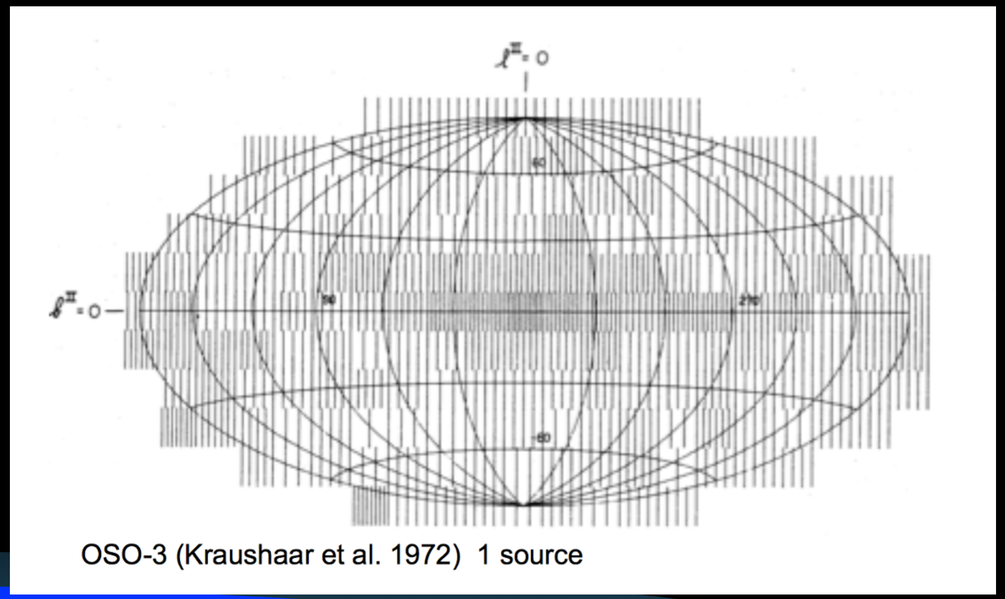
- In space, first ever measurement of gamma-rays from Explorer XI in 1968
  - Detected 22 gamma-rays above 50 MeV
- VELA detected first gamma-ray burst in the 70s
  - No localization ability
- First gamma-ray sky-map from OSO-3 in the 70s



Explorer XI

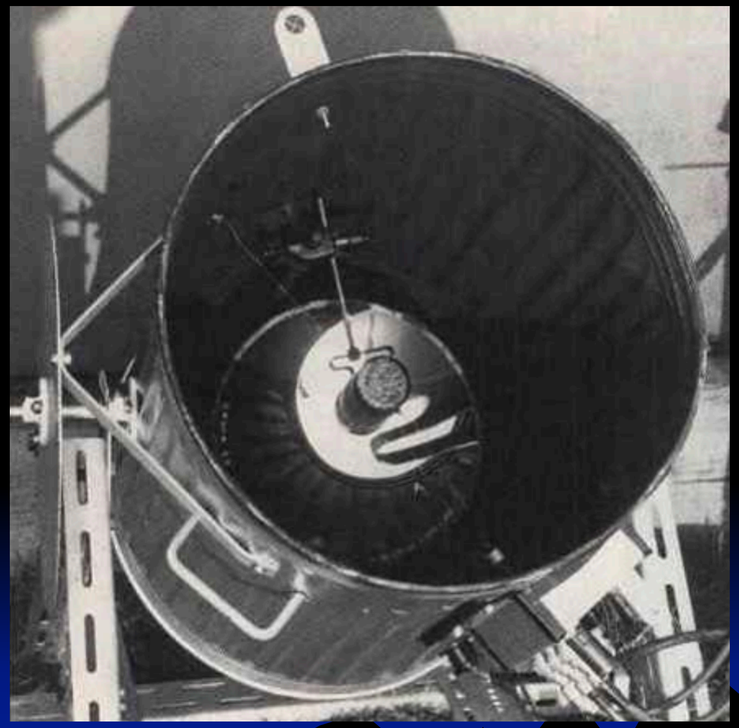


OSO-3

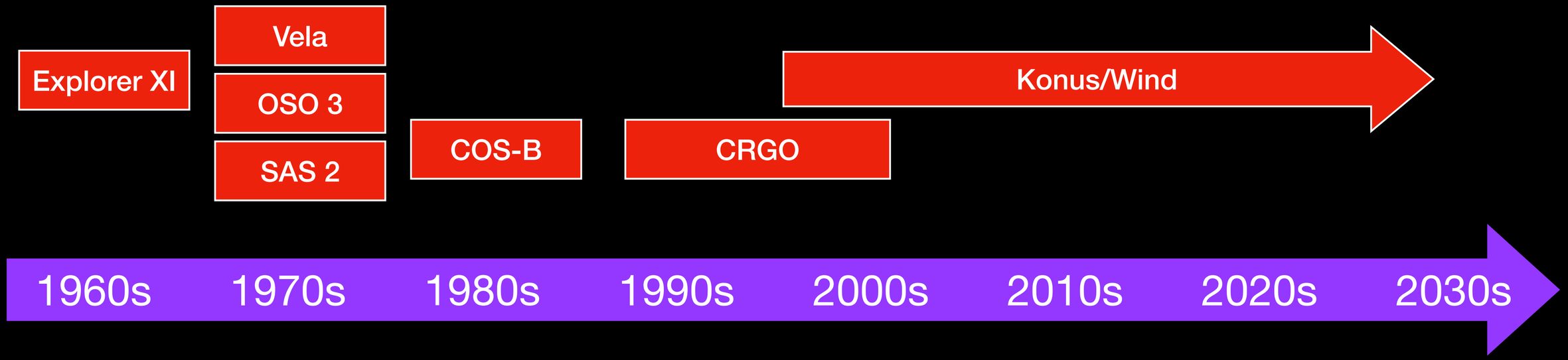


The Wild West (1960s & 1970s)

- On the ground, lots of experiments
- Many only lasting a few years, very fast development, improvement, and more development
- Main broken in American telescopes and Soviet telescopes
- At this time, mostly trying to detect Cherenkov photons at all, let alone detect sources



A Very Brief History



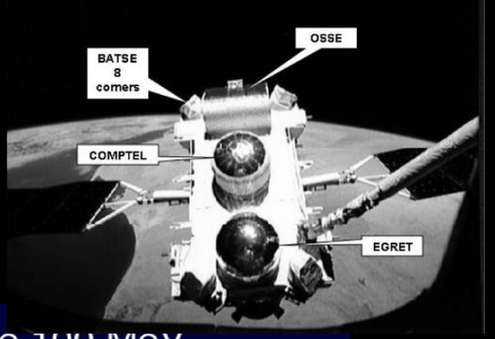
HEGRA

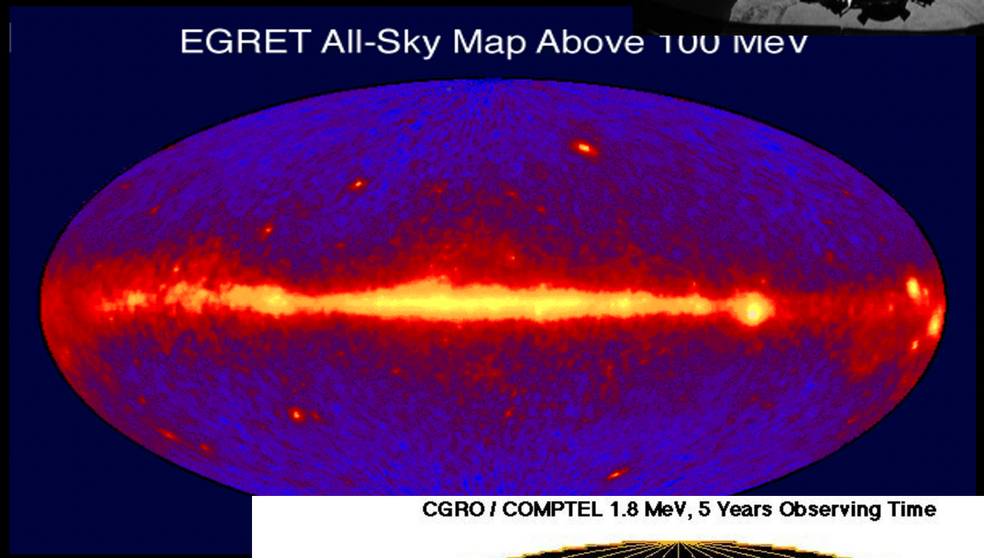
Whipple

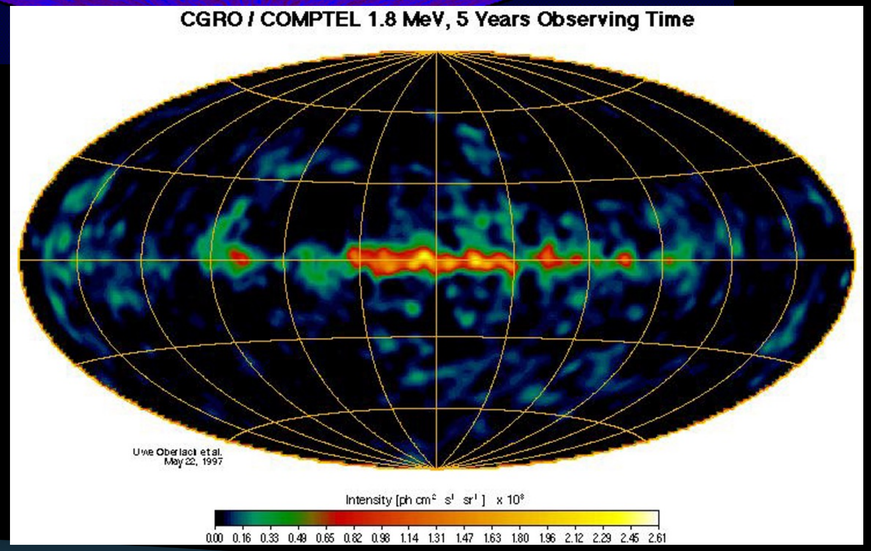
Crimea

The Pioneer Days (1980s & 1990s)

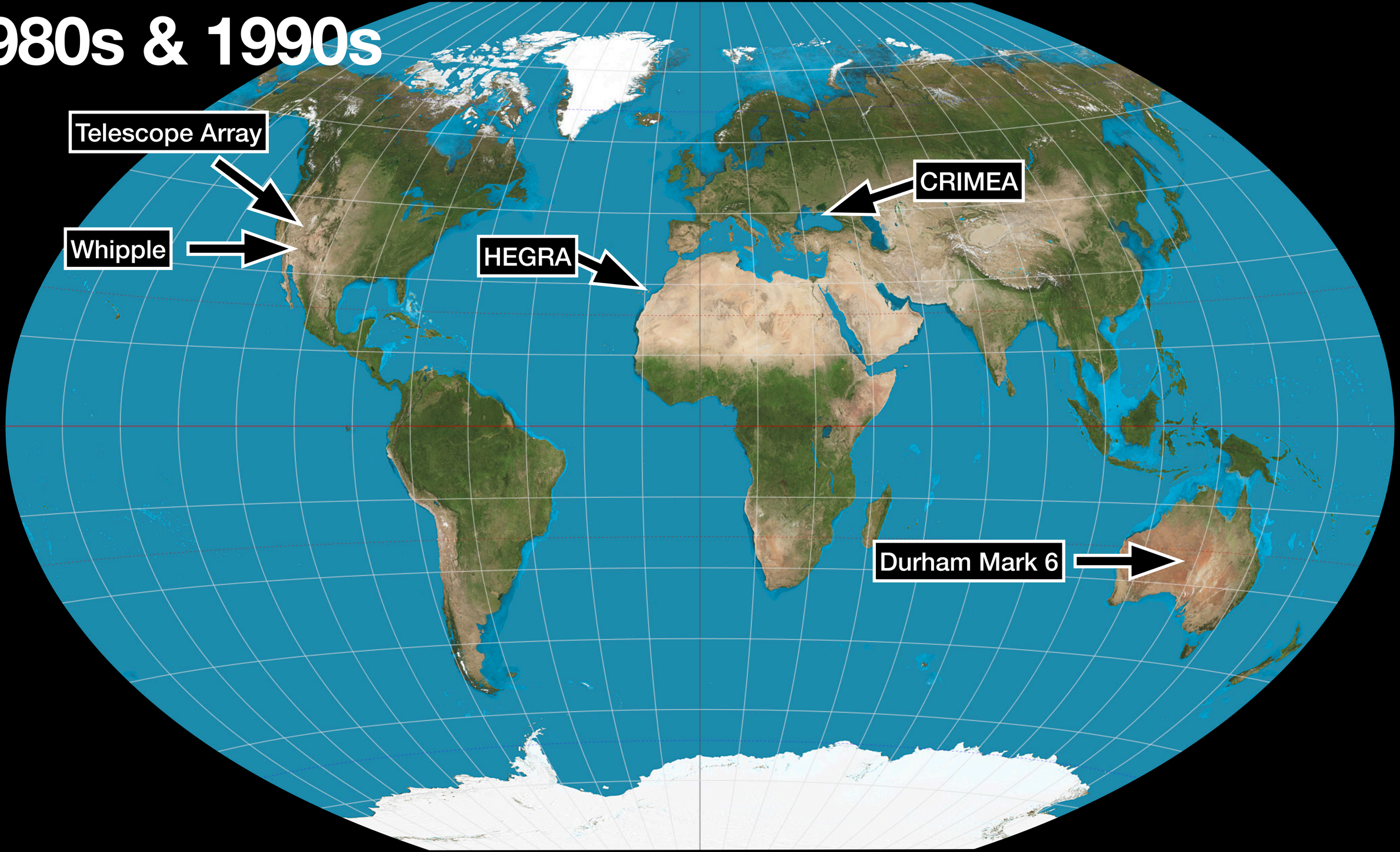
- New generation of satellites
  - COS-B and Compton Gamma-ray Observatory (CGRO)
  - First real surveys start to come out
  - Dozens of sources detected
  - A dynamic and highly energetic gamma-ray sky
  - Some confident source identifications both in and beyond the Galaxy





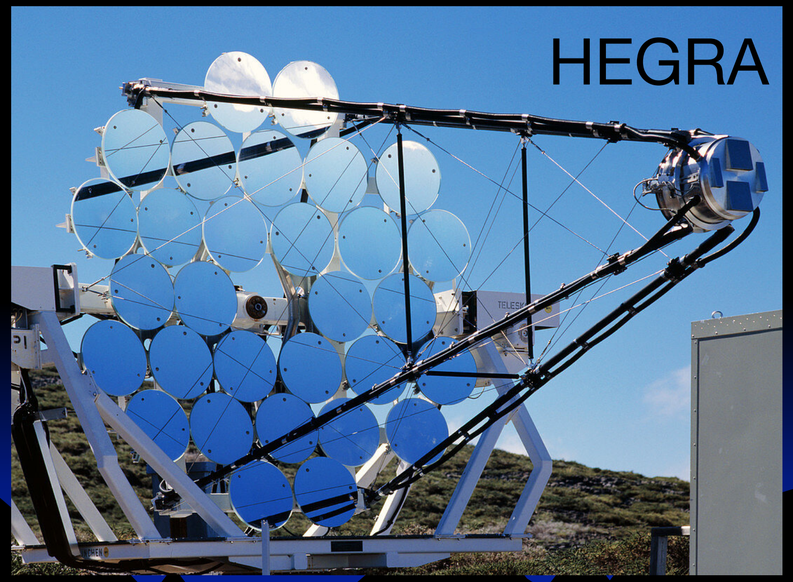


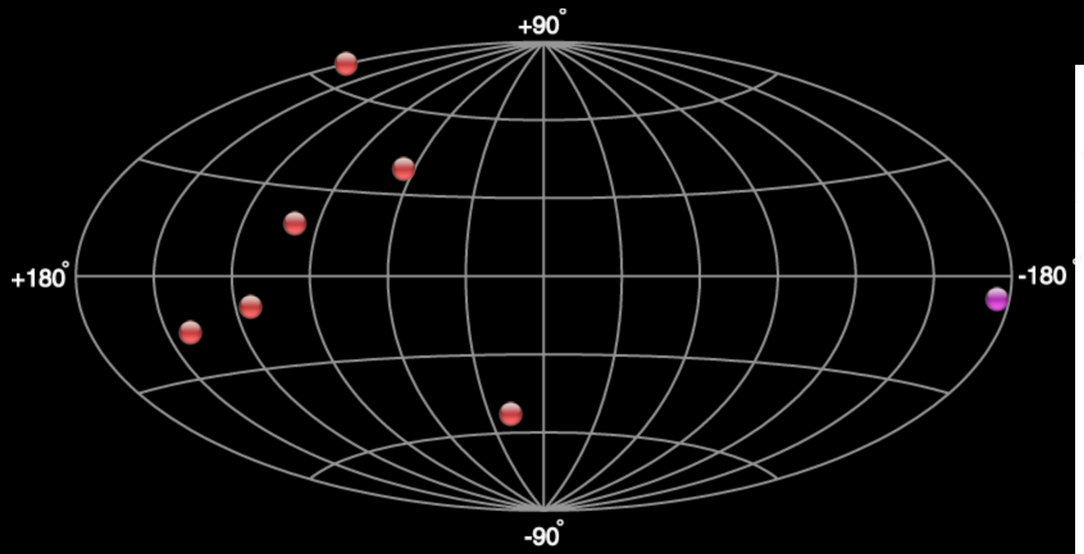
1980s & 1990s



The Pioneer Days (1980s & 1990s)

- IACTs start looking like IACTs we know and love
- Whipple discovered first VHE Source
  - Detected Crab in 1989
- Several new sources detected
  - Mrk 421/501, 1ES 2344, 1ES 1959, PKS 2155





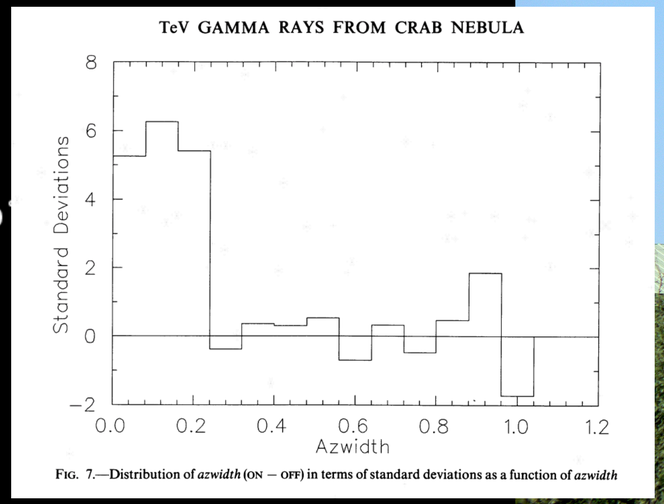
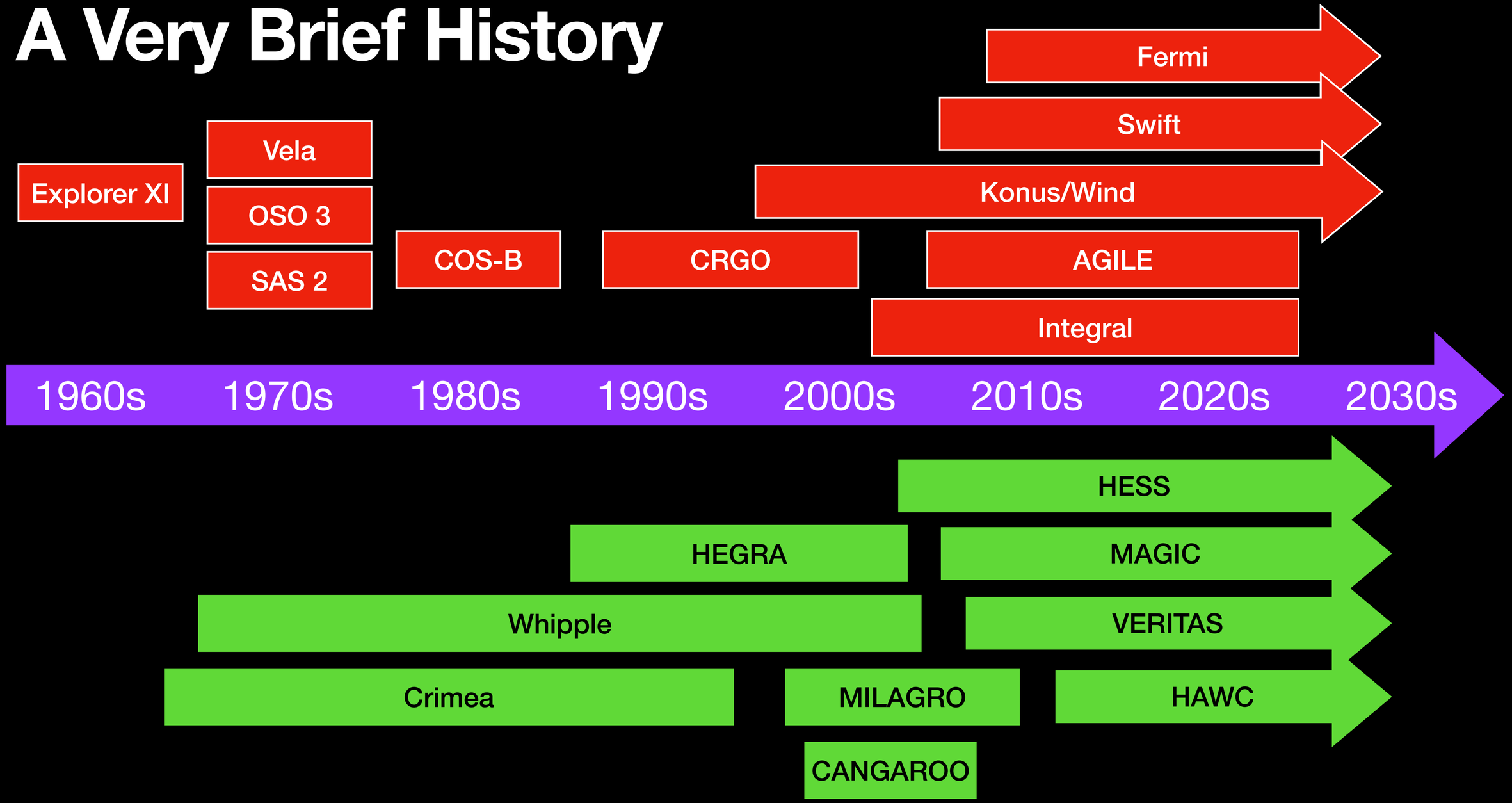


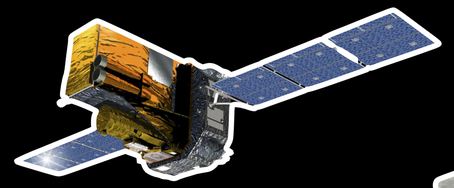
FIG. 7.—Distribution of *azwidth* (ON − OFF) in terms of standard deviations as a function of *azwidth*

A Very Brief History

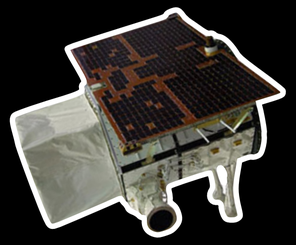


The Early Modern (2000s & 2010s)

- Many more telescopes:
  - Integral, Swift, AGILE, Fermi
  - 1000s of sources from Fermi
  - 1000s of GRBs
  - Entering the era of surveys, big data, and population studies

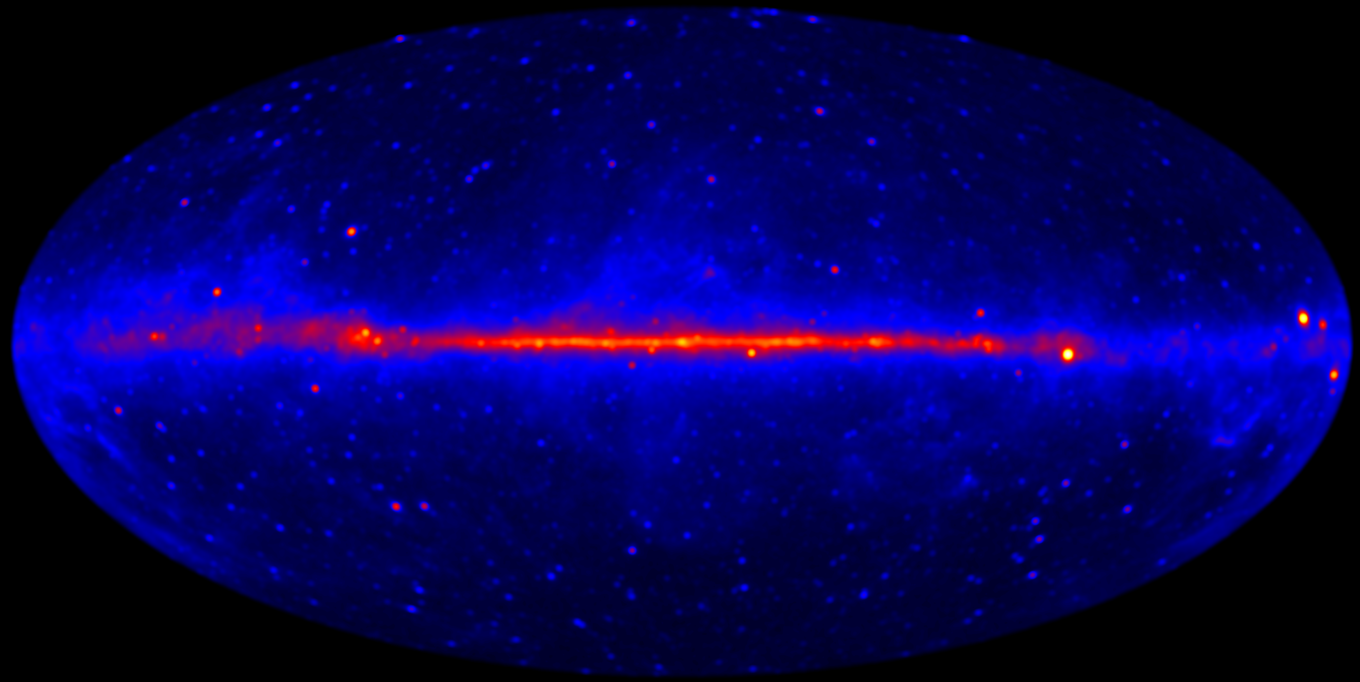


Integral

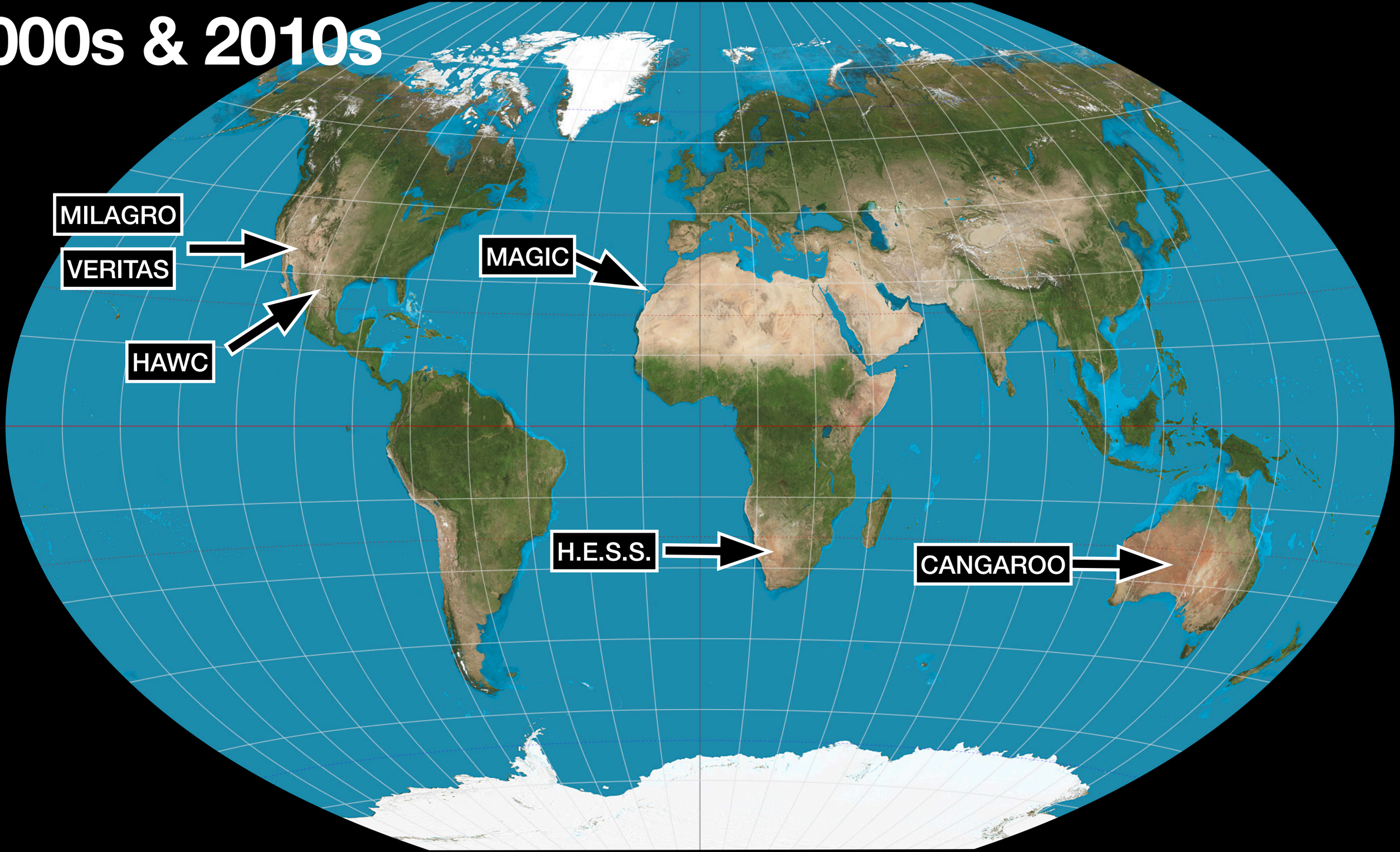


Agile

Fermi

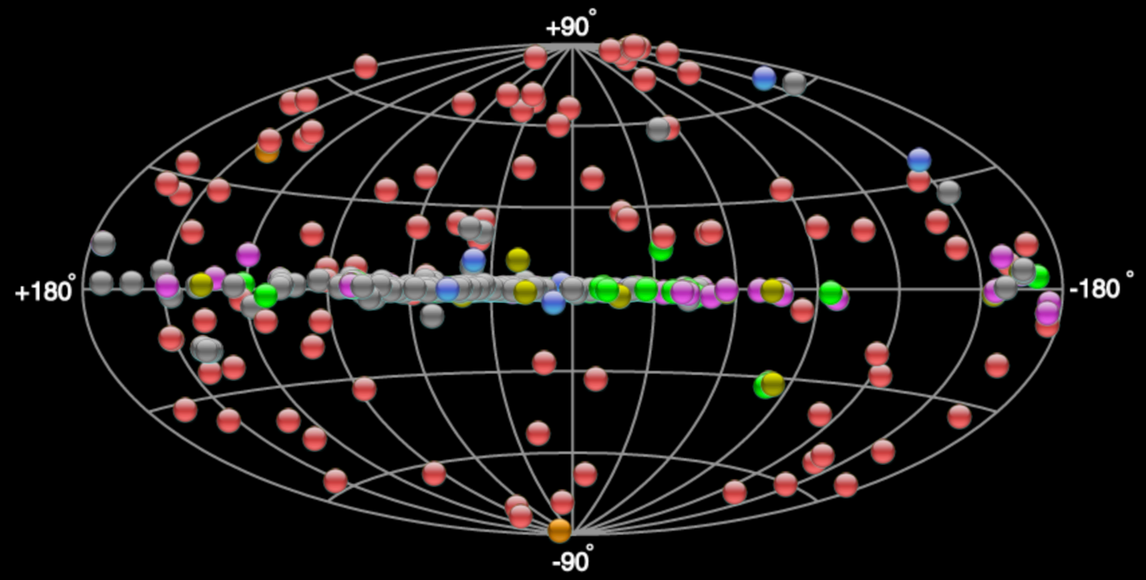


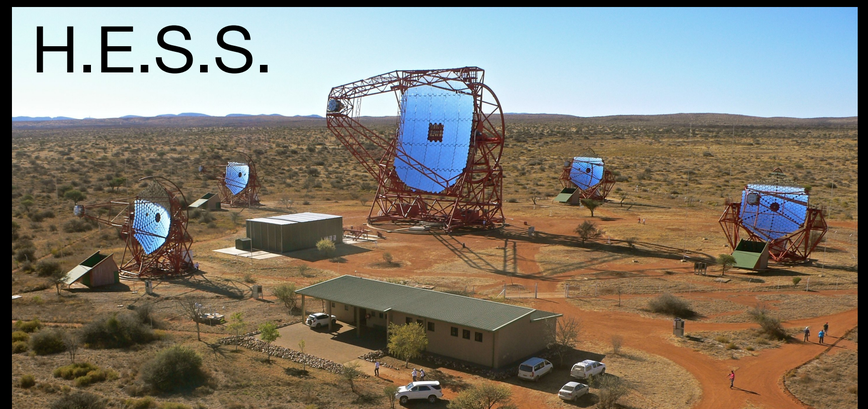
2000s & 2010s



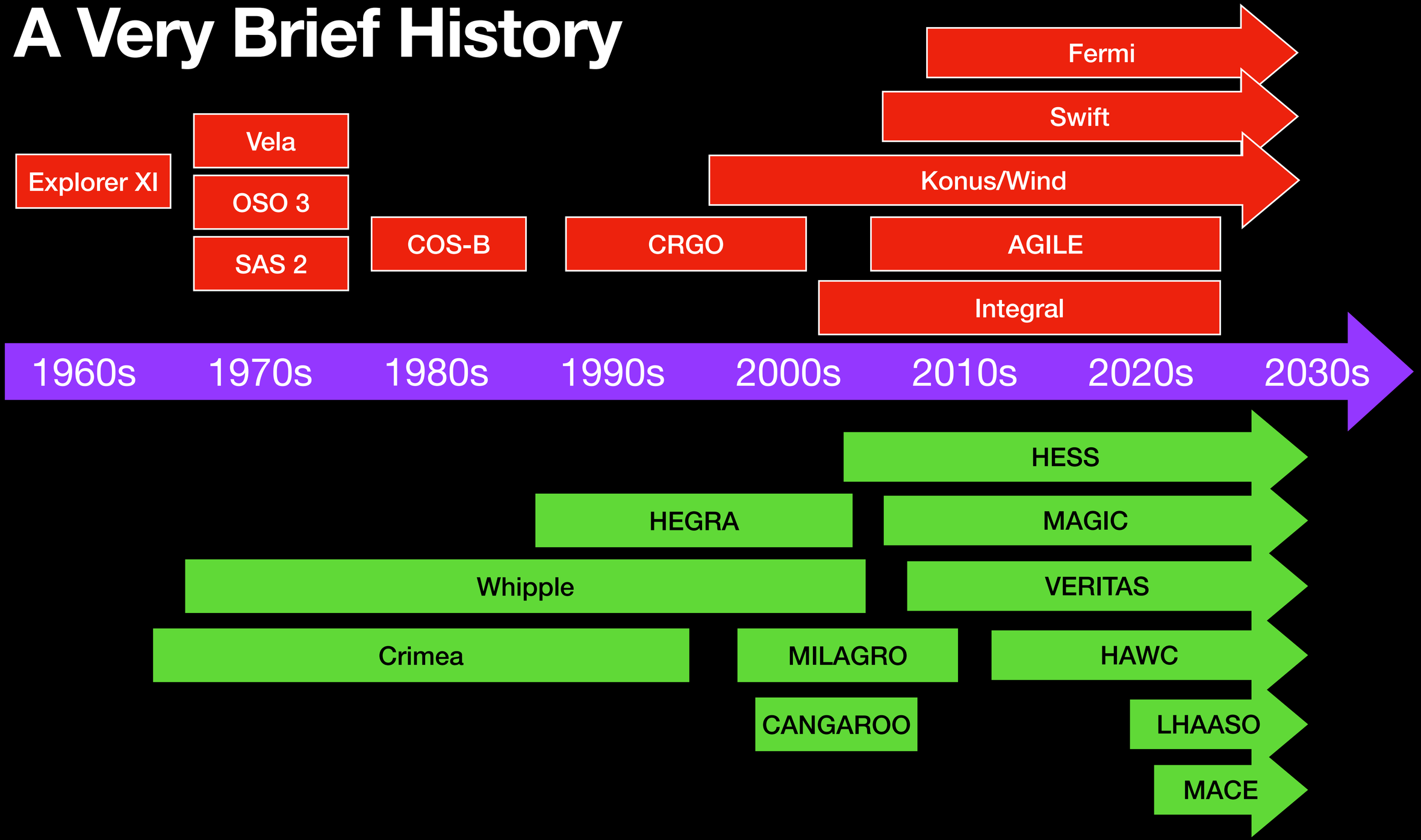
The Early Modern (2000s & 2010s)

- Explosion in telescopes:
  - H.E.S.S., MAGIC, VERITAS, MILAGRO, HAWC
- Explosion in Sources
  - 100s of sources
  - PWN, SNRs, AGN, diffuse emission, gamma-ray bursts, etc.





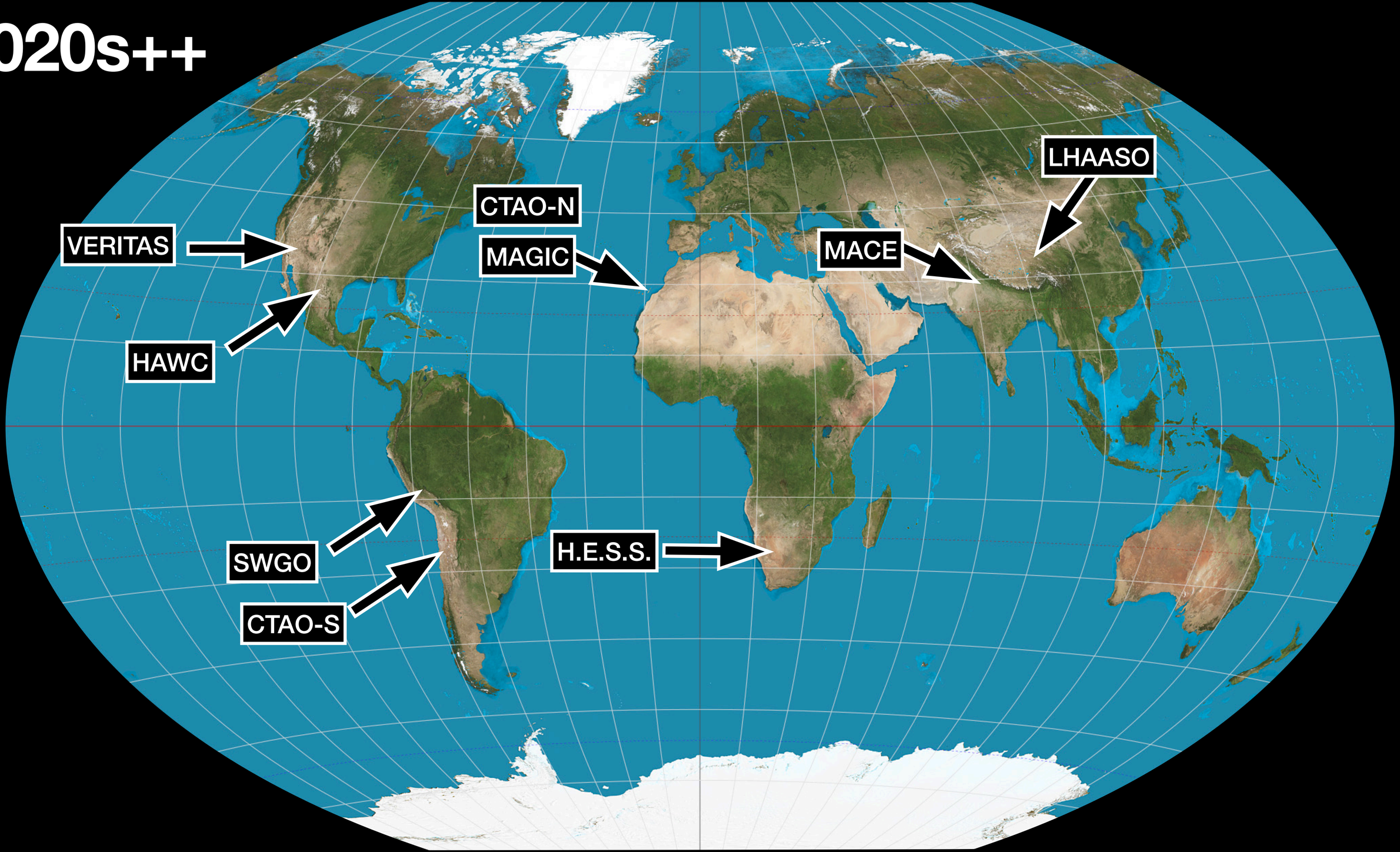
A Very Brief History



The Current Era and Future (2020s++)

- Fermi-LAT still taking data
  - 17 years and counting
- Many new telescopes under development:
  - COSI, AMEGO-X, e-Astrogram
  - Focusing on wide-field survey missions in the MeV energy range
    - Unexplored region since CGRO
  - Hopeful launch dates in the mid-late 2030s

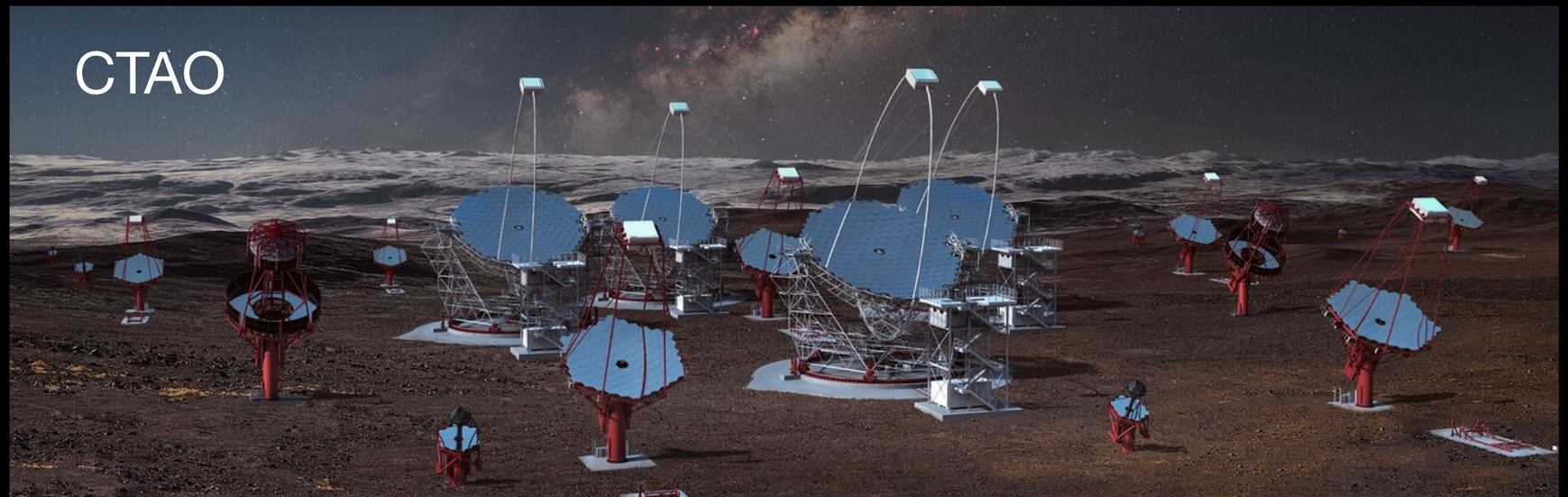
2020s++



The Current Era and Future (2020s++)

- IACTs and Arrays producing new exciting results
  - Pevatrons, microquasars, novae, and more
  - Multi-messenger - LIGO, IceCube
  - Time-domain - GRBs, GWs, AGN flares
- CTAO under construction

LHAASO



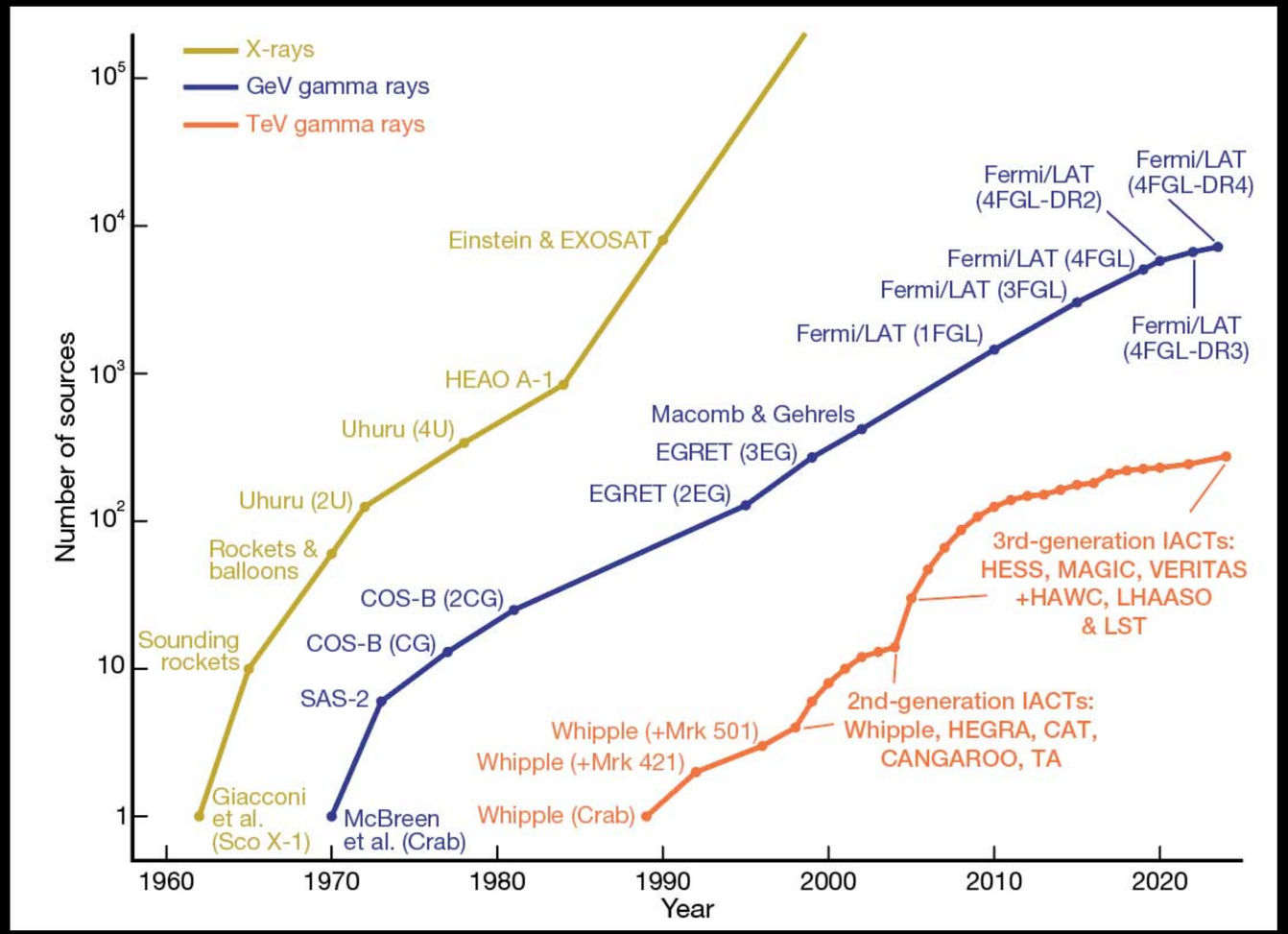
CTAO

MACE

The Current Era and Future (2020s++)

- Current High Energy Source:
  - 7195 from 4FGL-DR5
- Current VHE Sources:
  - 315 from TeVCat
- CTAO is expected to detect 1000+ sources

Source vs time



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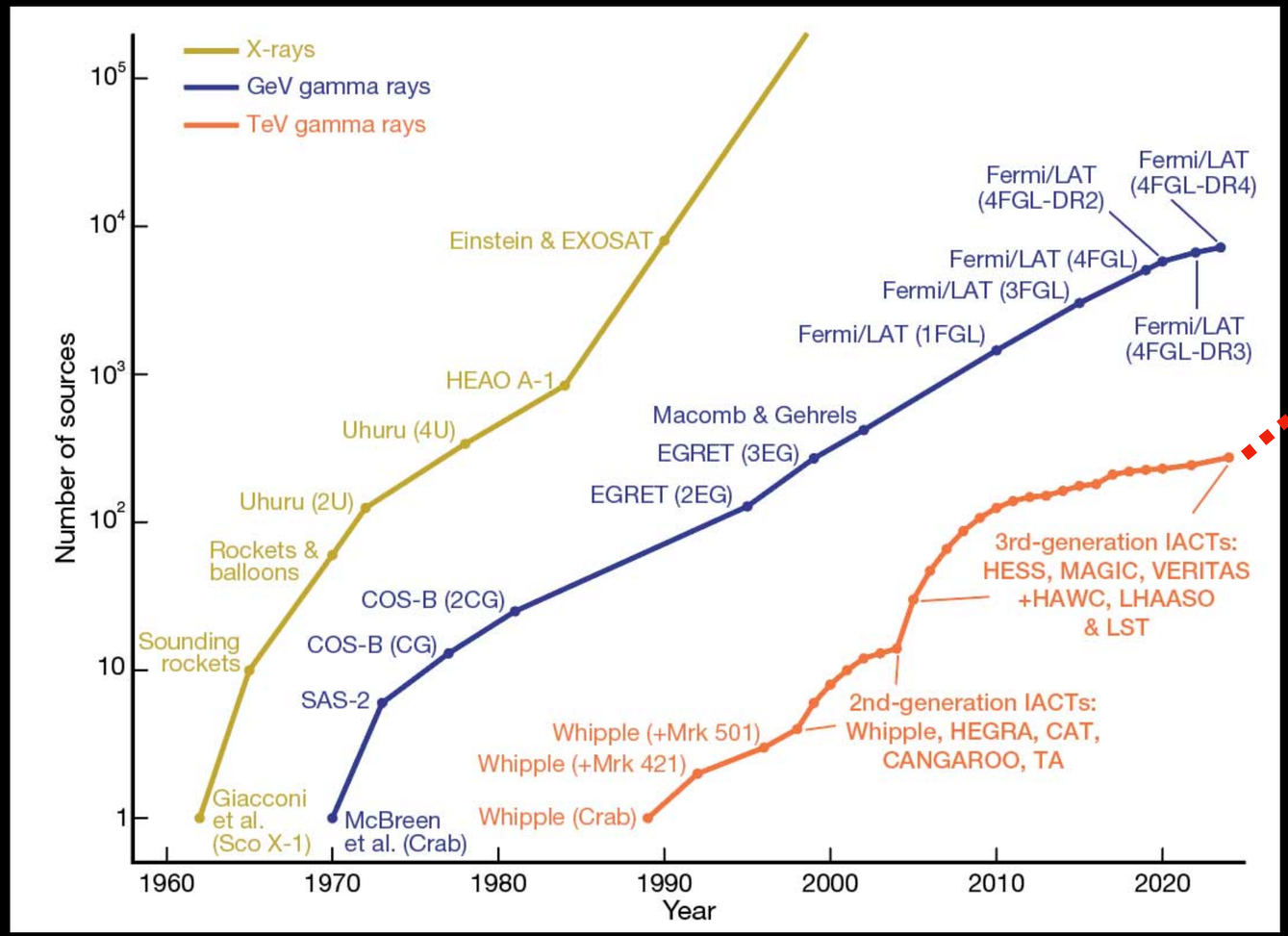
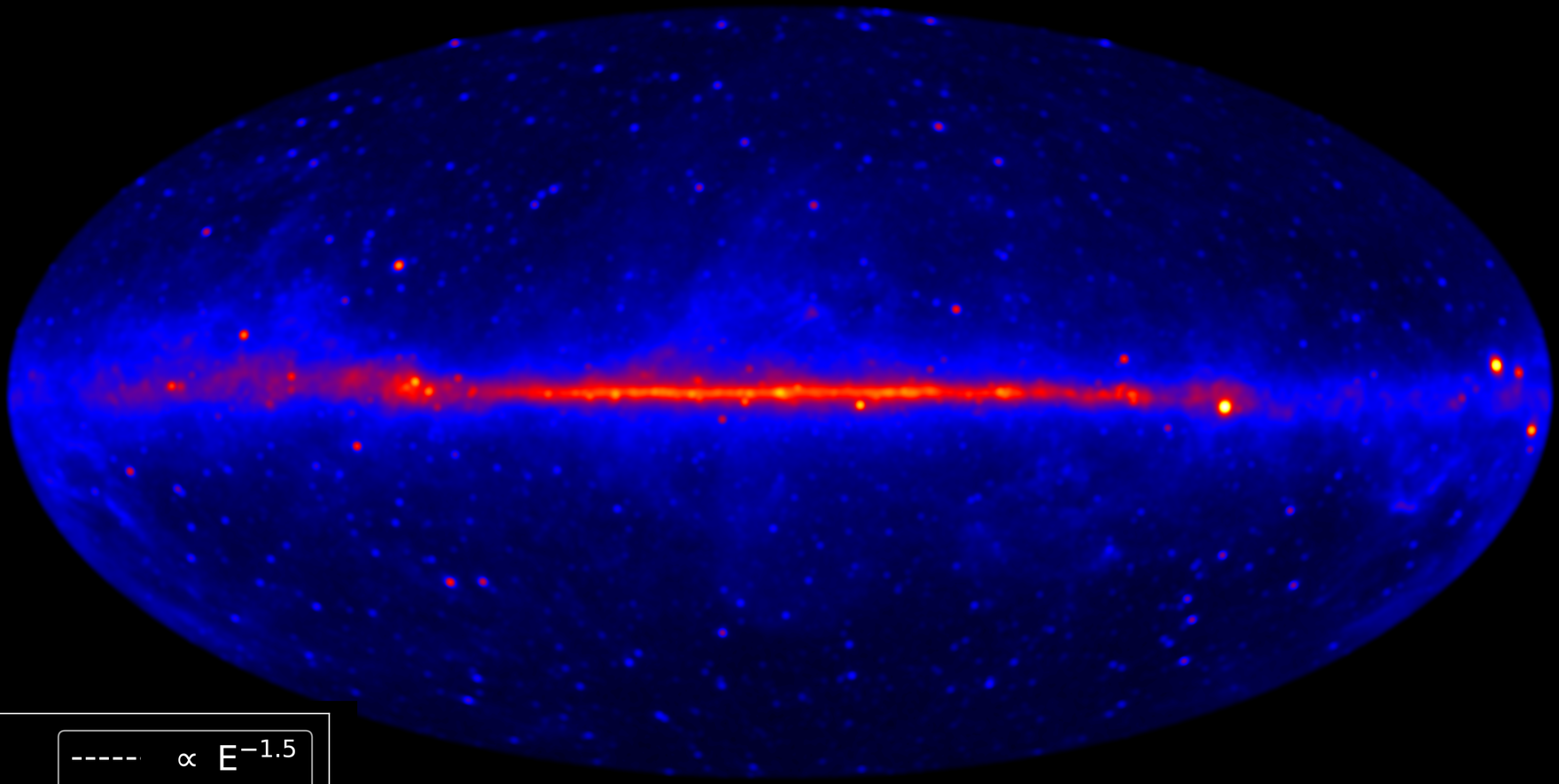
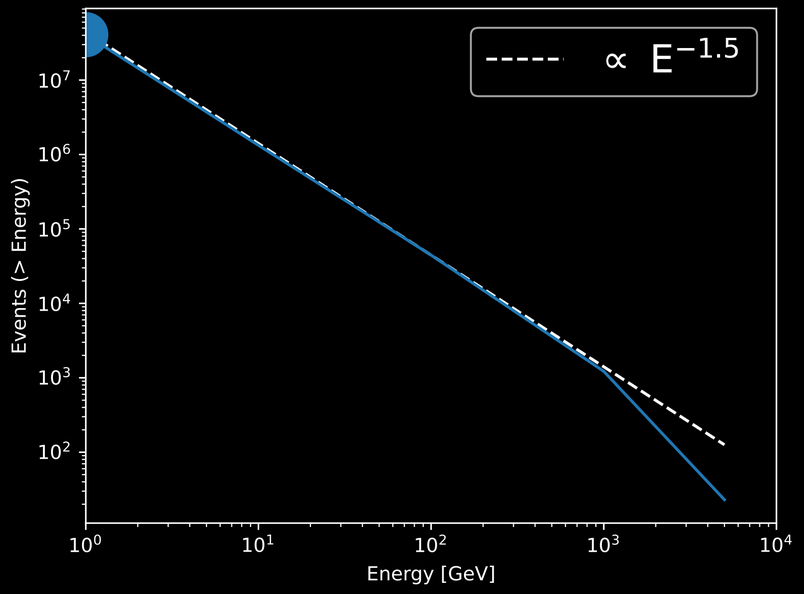


CTAO

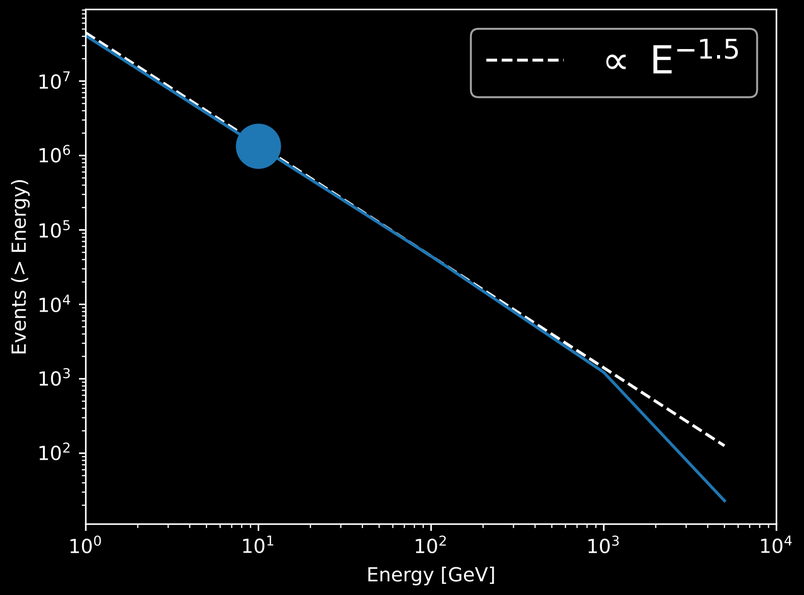
Brief Introduction





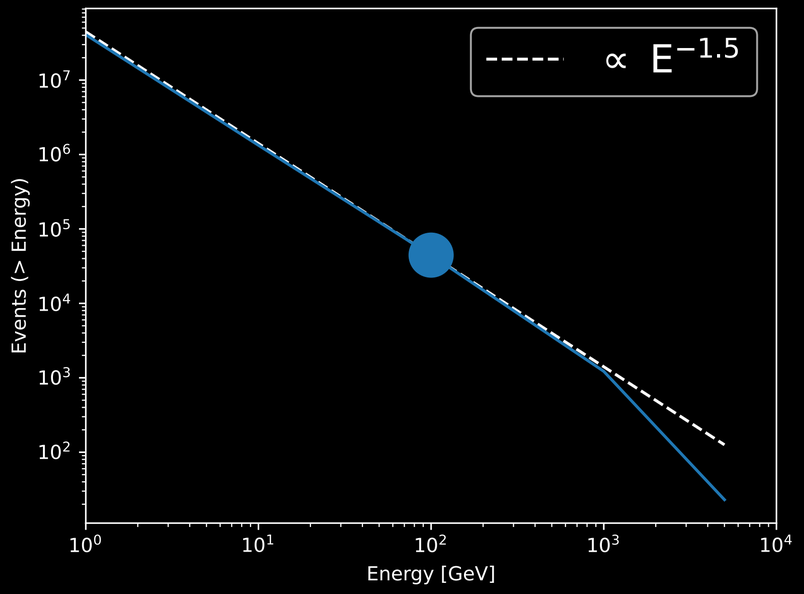
Energy > 1 GeV

- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)



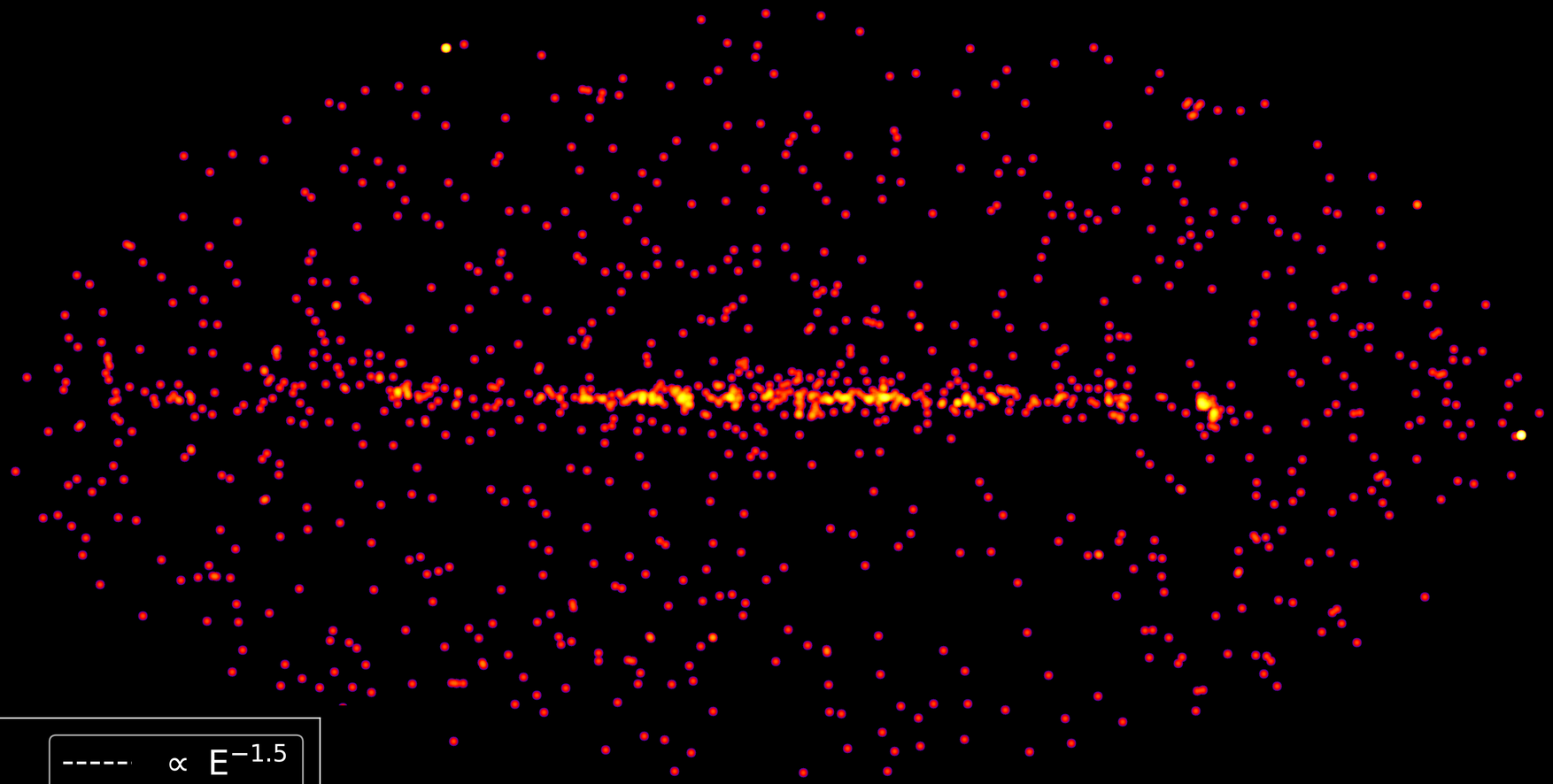
Energy > 10 GeV

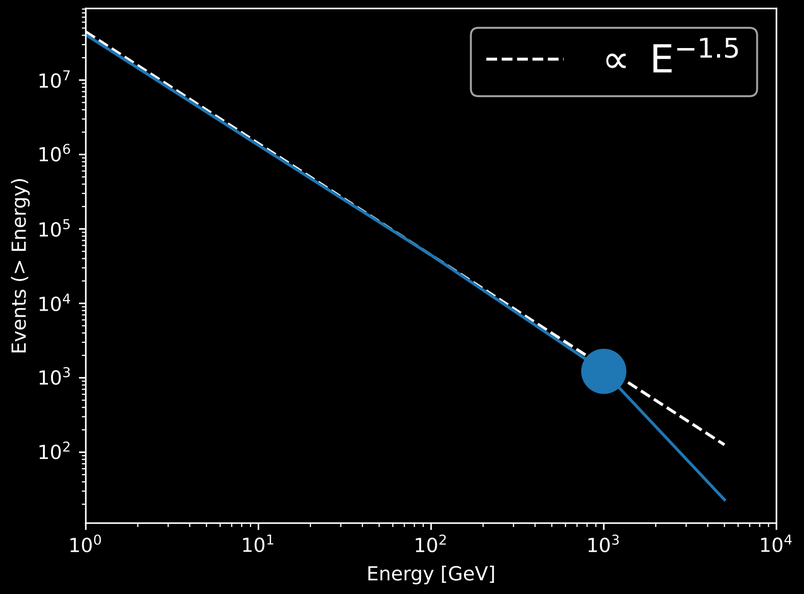
- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)



Energy > 100 GeV

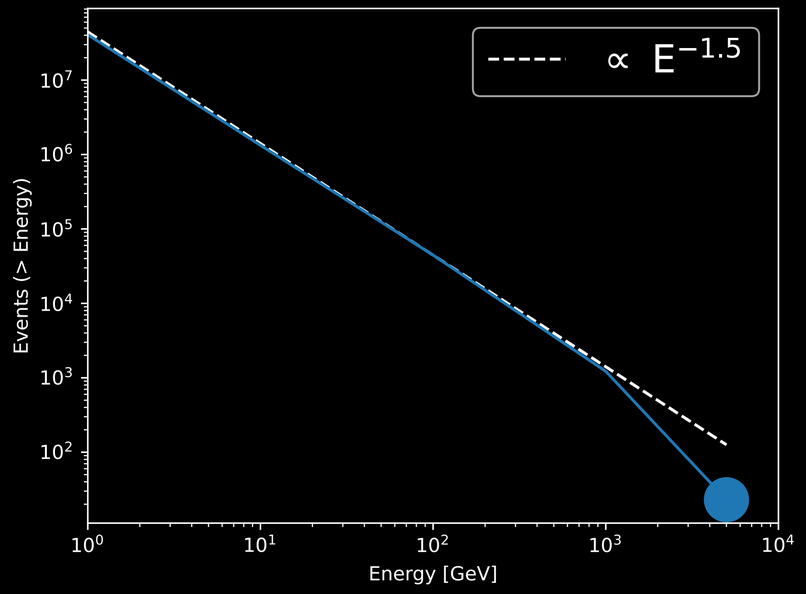
- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)





Energy > 1 TeV

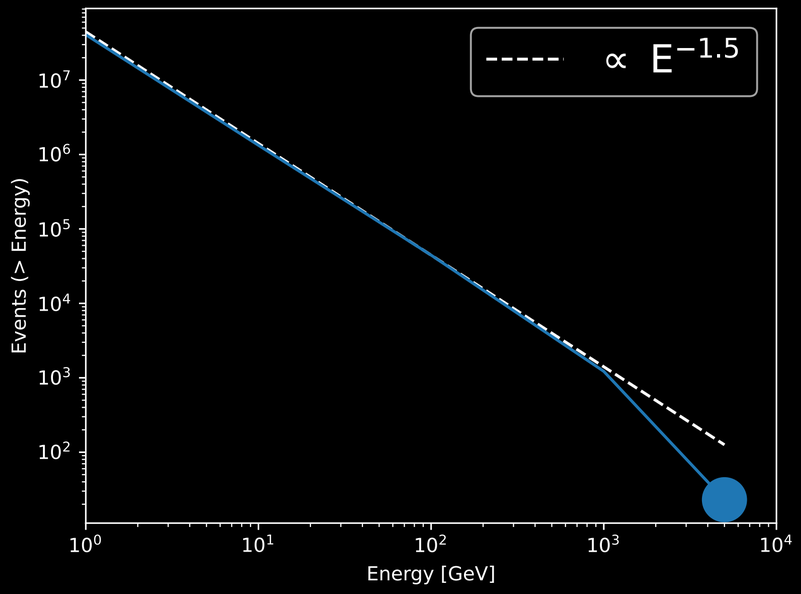
- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)



Energy > 5 TeV

- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)

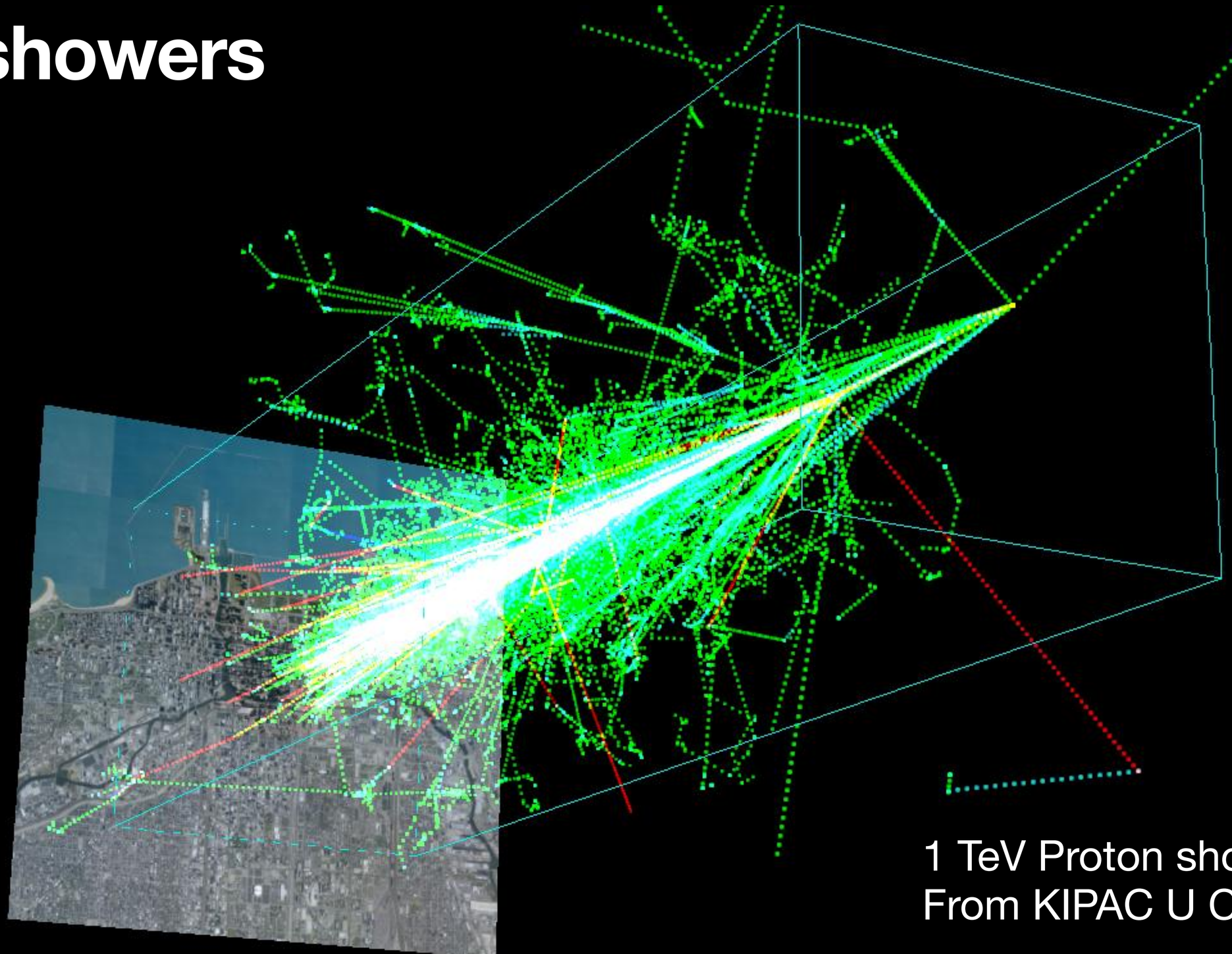
We need larger collection area!



Energy > 5 TeV

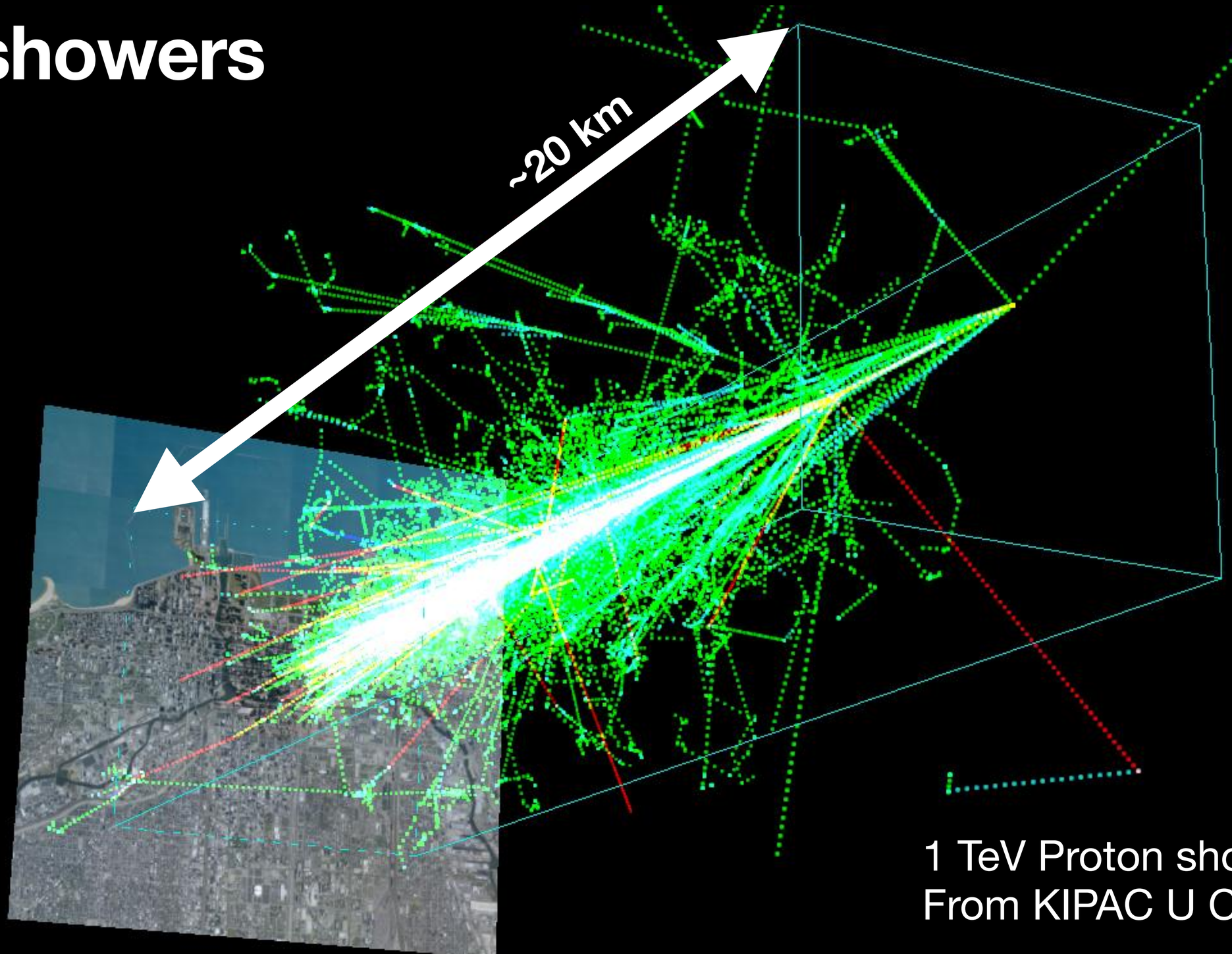
- Statistics drop quickly with energy (power-law spectrum)
- Very photons above 100 GeV (VHE)

Air showers



1 TeV Proton shower
From KIPAC U Chicago

Air showers



1 TeV Proton shower
From KIPAC U Chicago

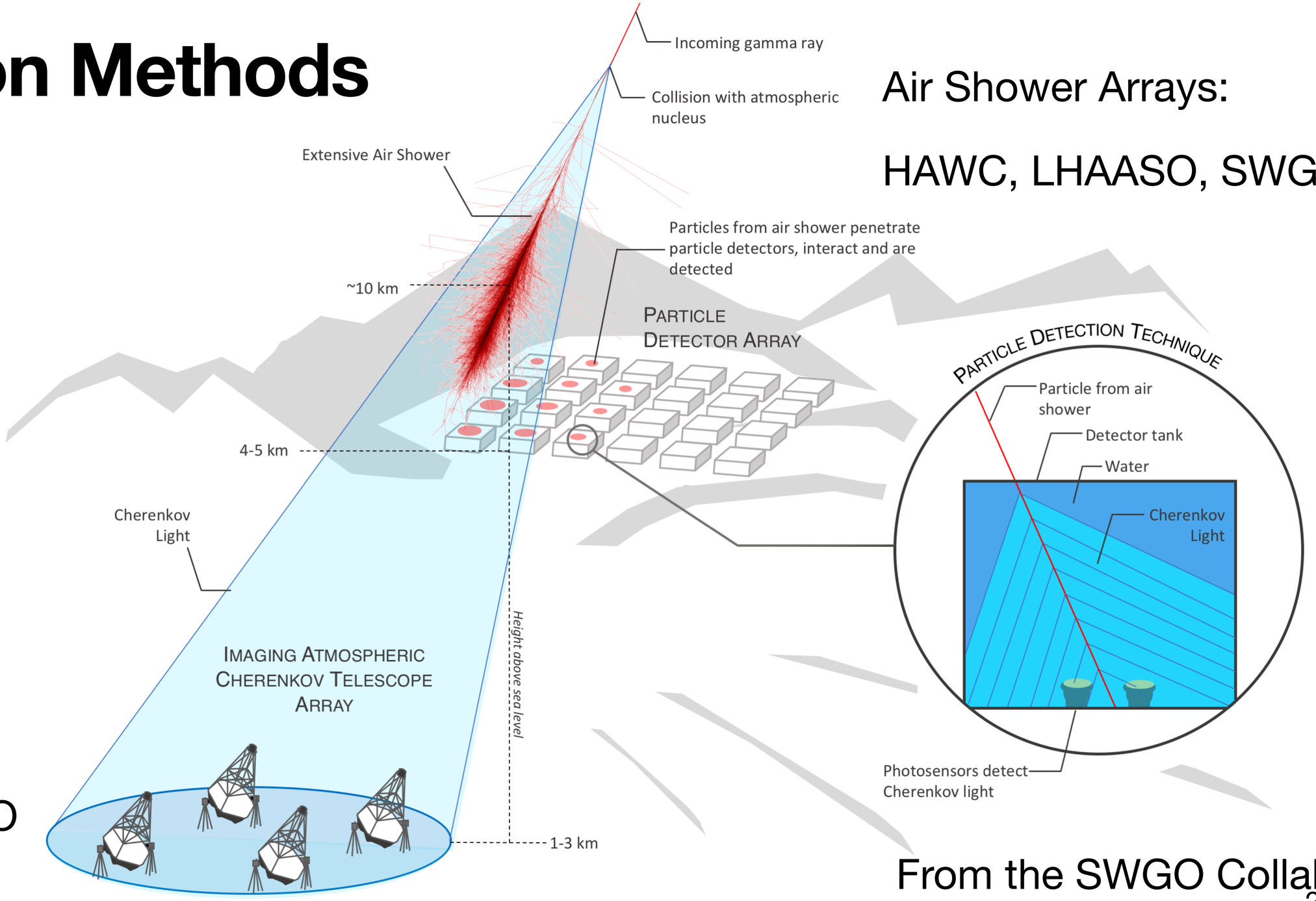
Detection Methods

Air Shower Arrays:

HAWC, LHAASO, SWGO

IACTs:

HESS, MAGIC, VERITAS, CTAO

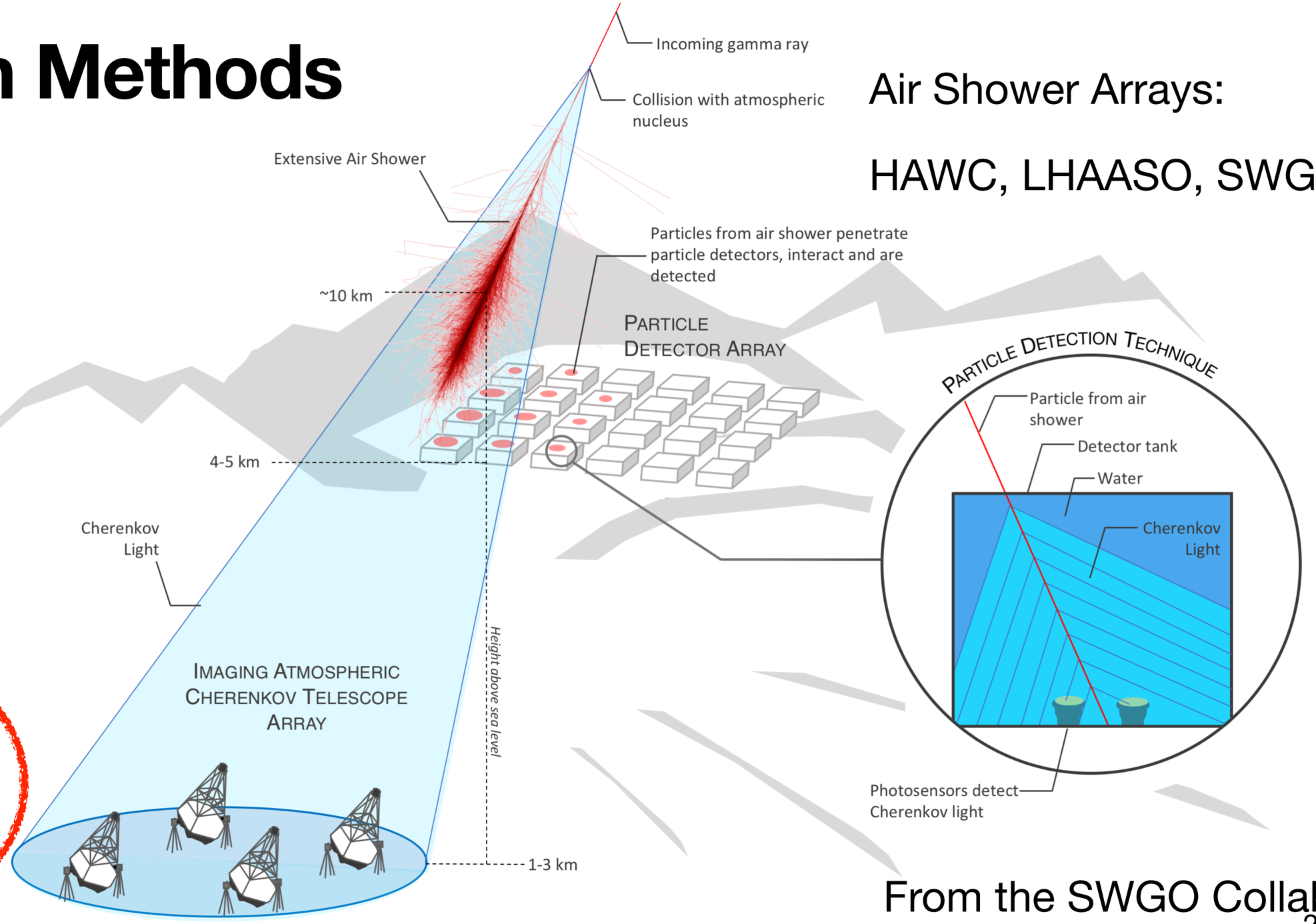


From the SWGO Collab

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

Detection Methods



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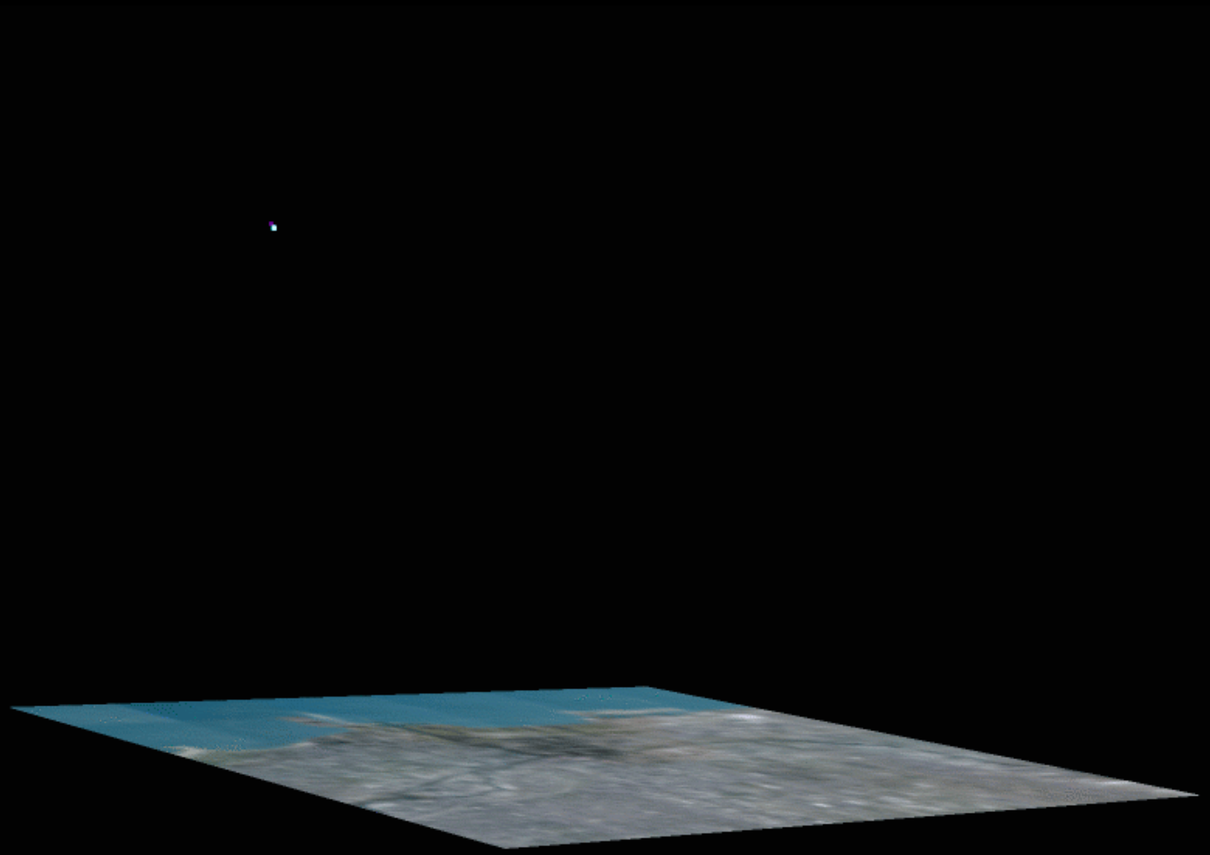
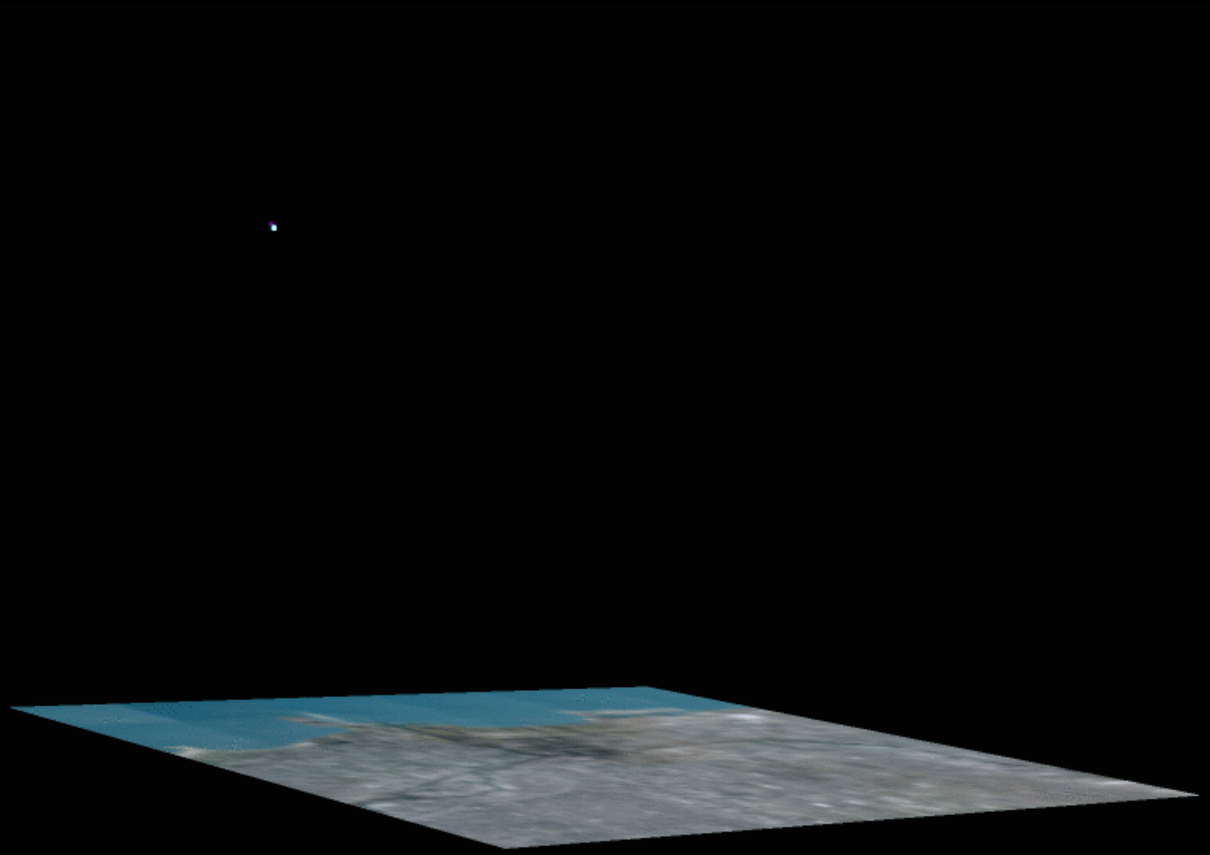
Not to scale

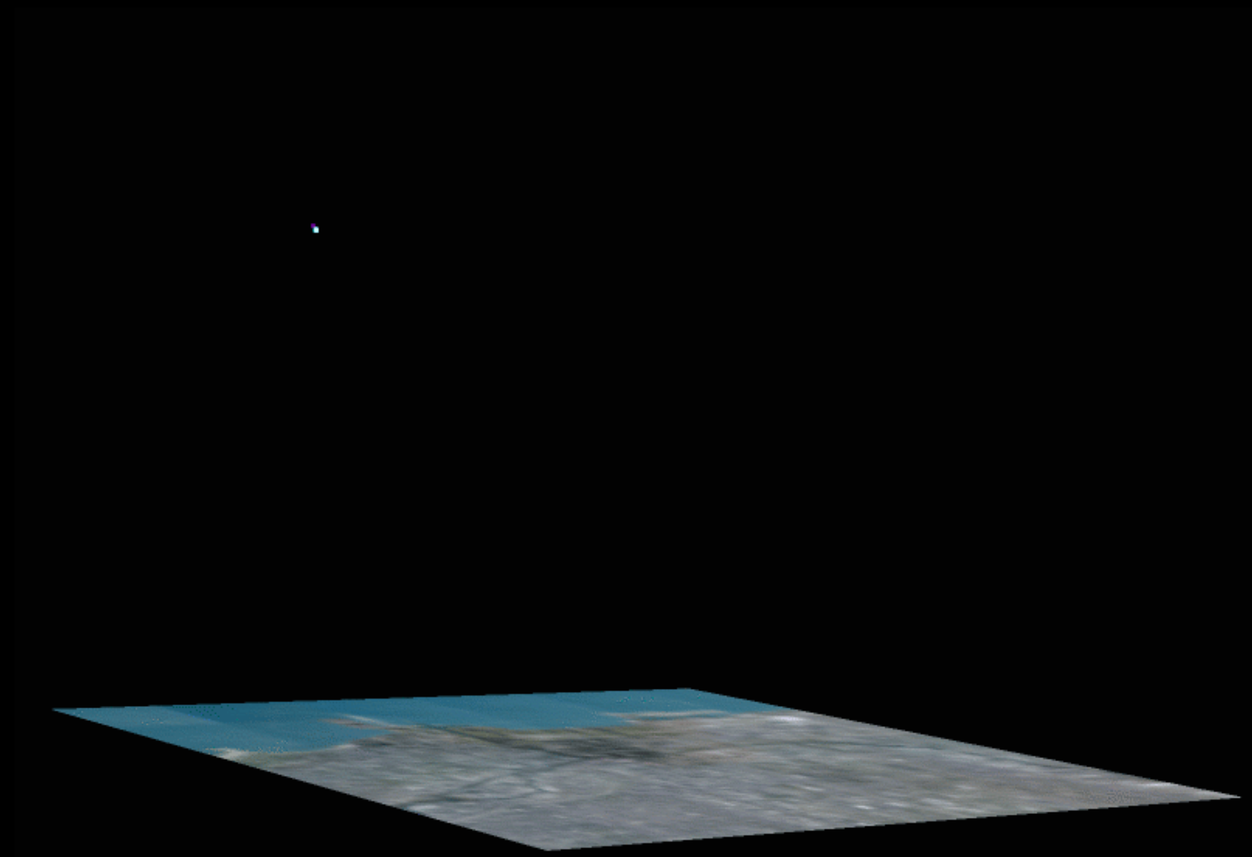
Atmospheric Cherenkov Radiation

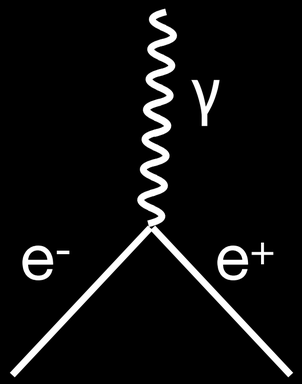


Atmospheric Cherenkov Radiation

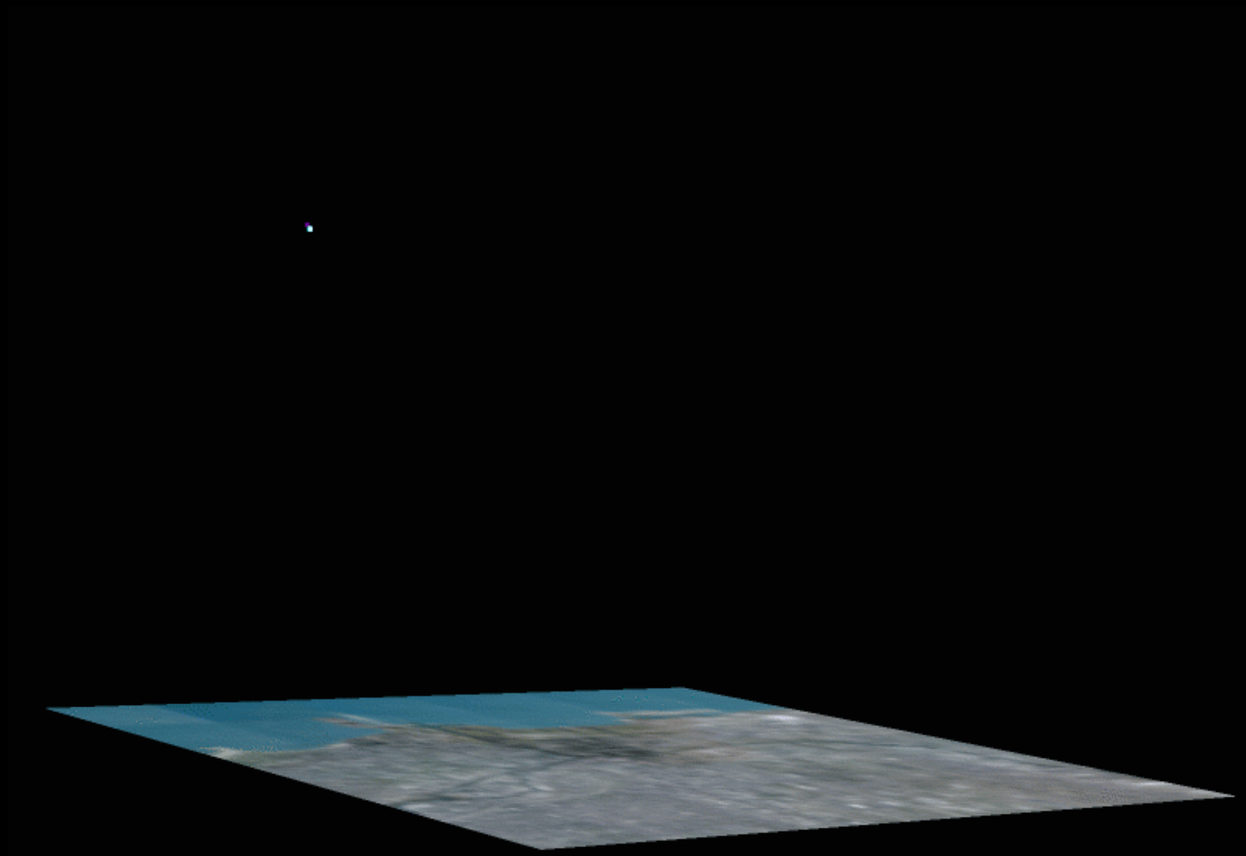


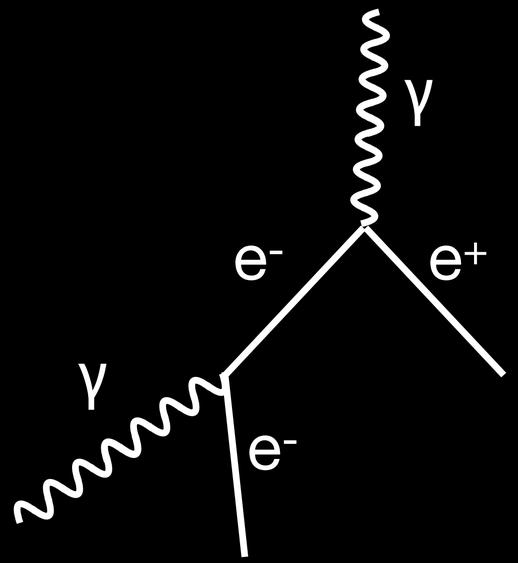
Atmospheric Cherenkov Radiation



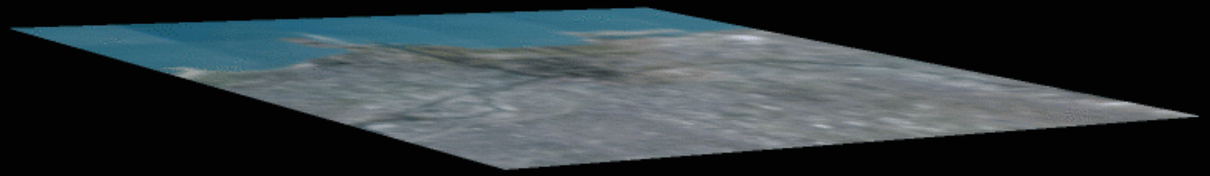


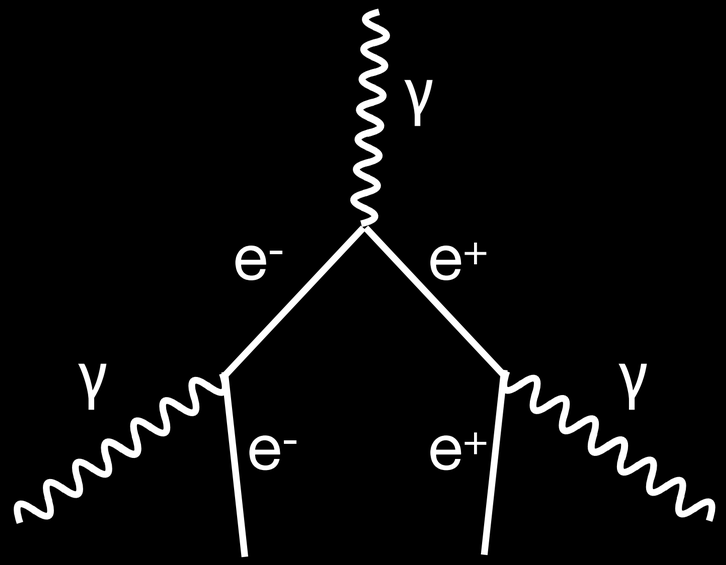
Atmospheric Cherenkov Radiation



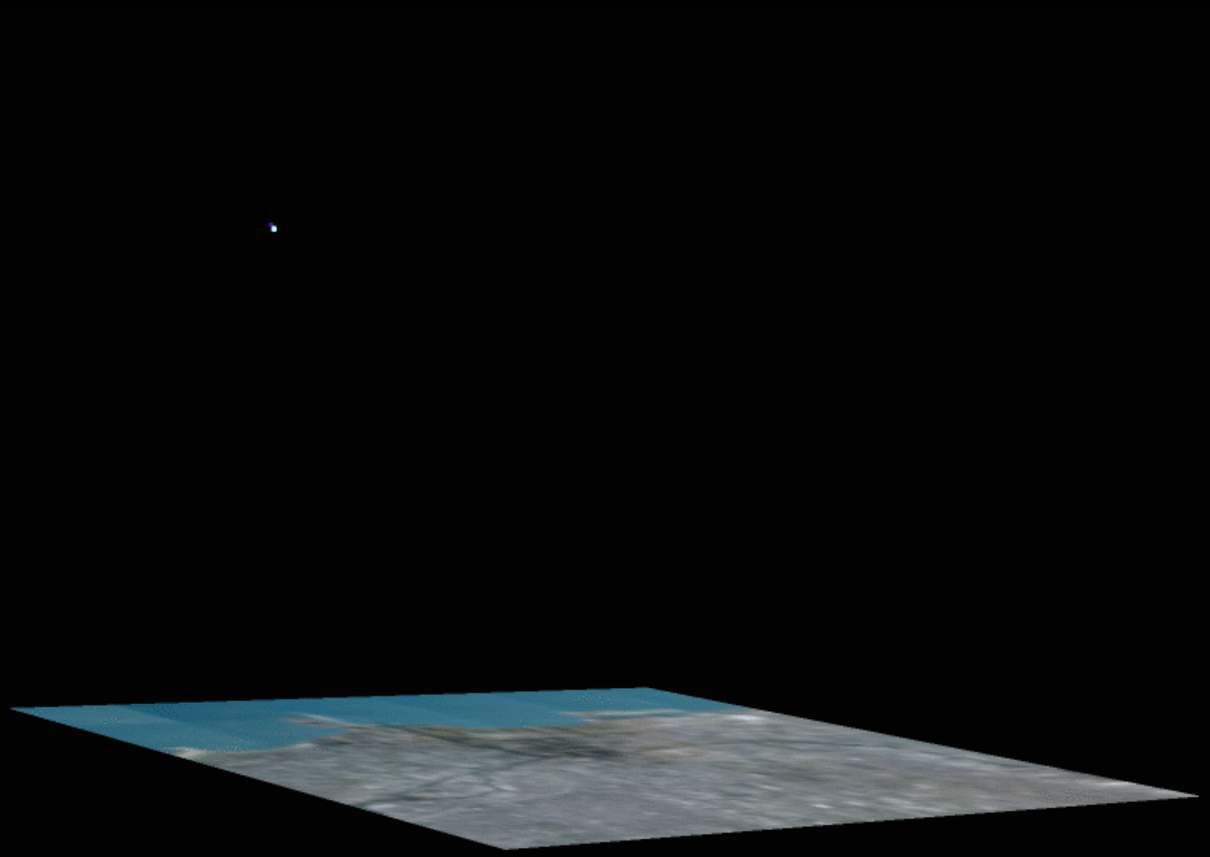


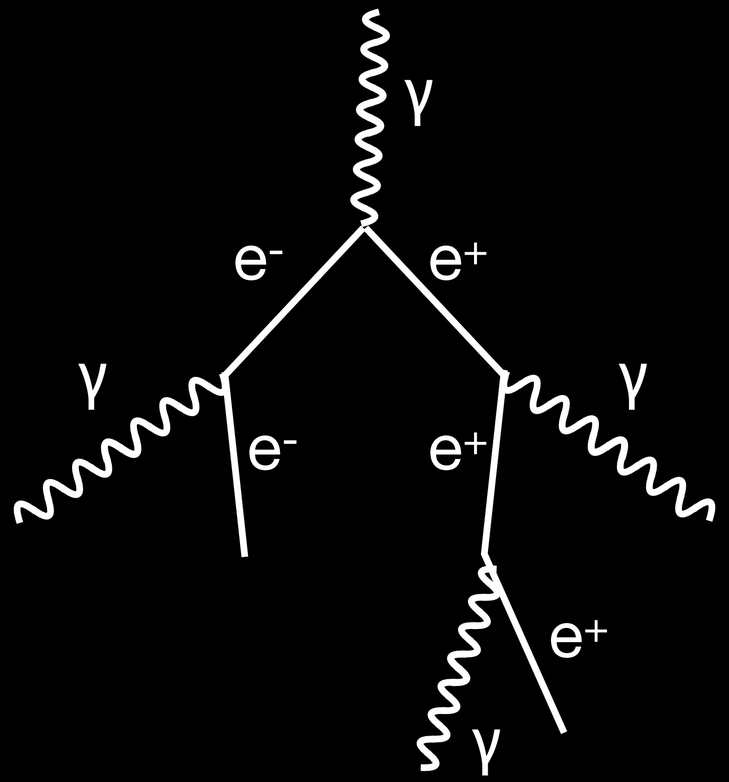
Atmospheric Cherenkov Radiation





Atmospheric Cherenkov Radiation





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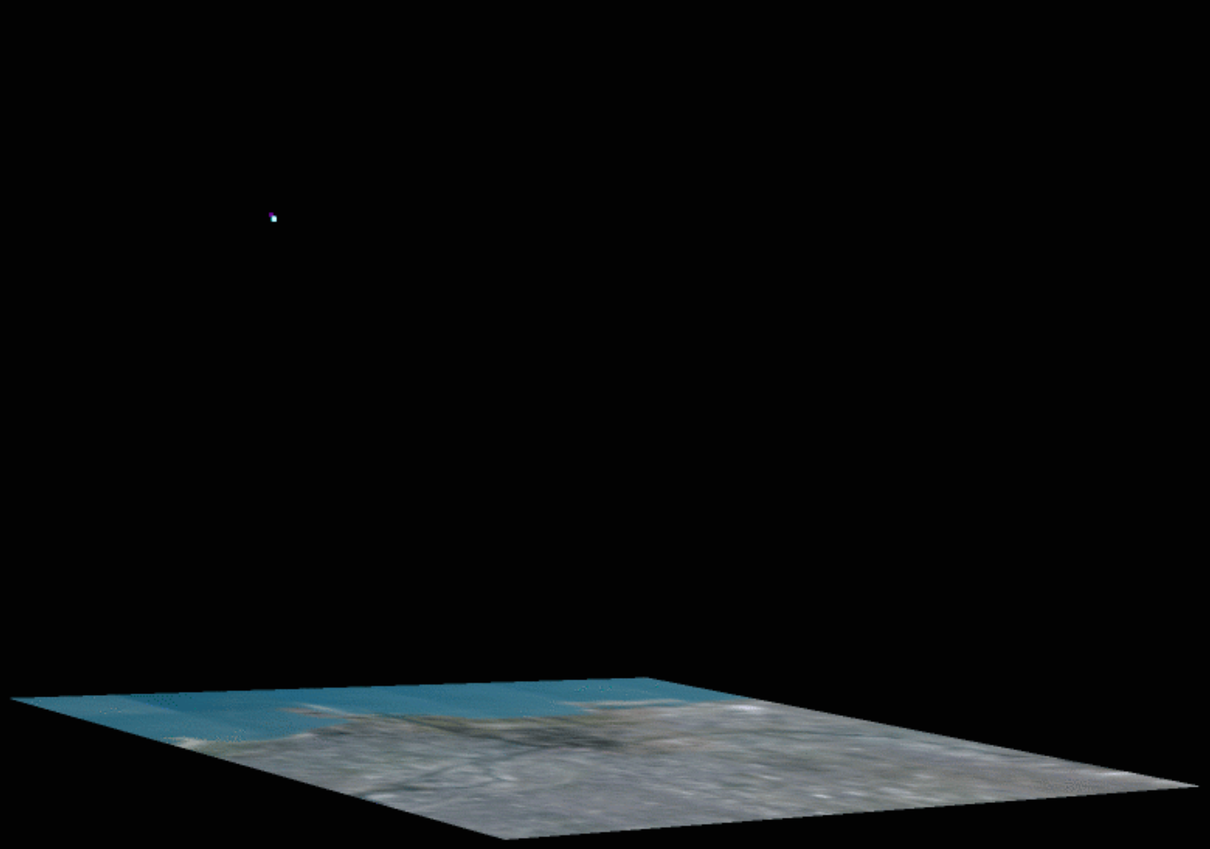

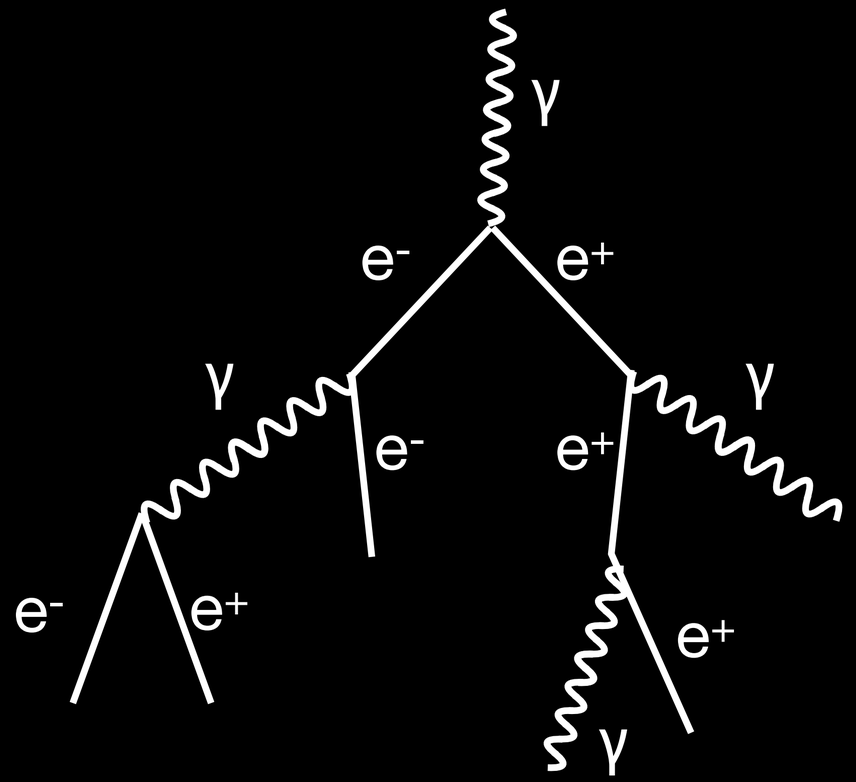

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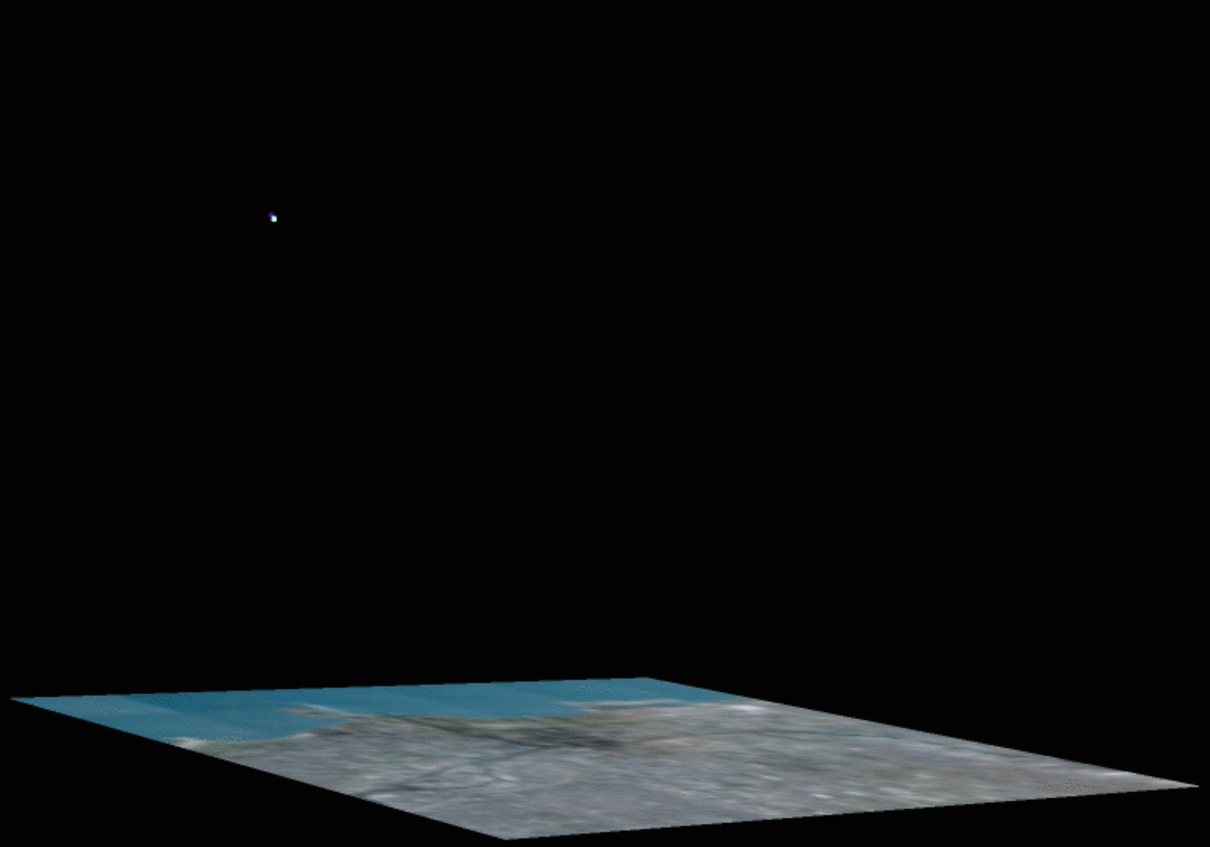
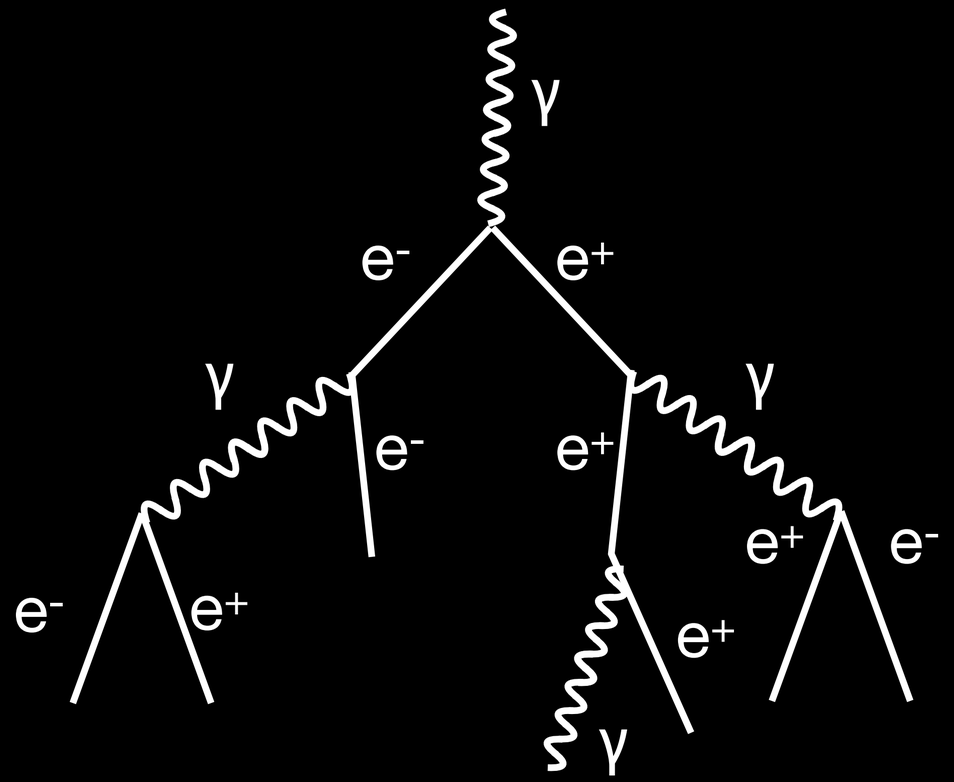
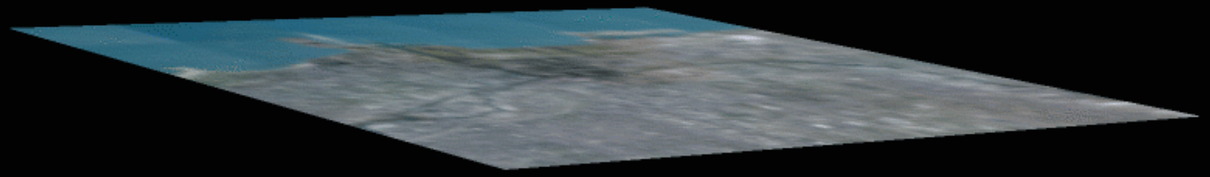
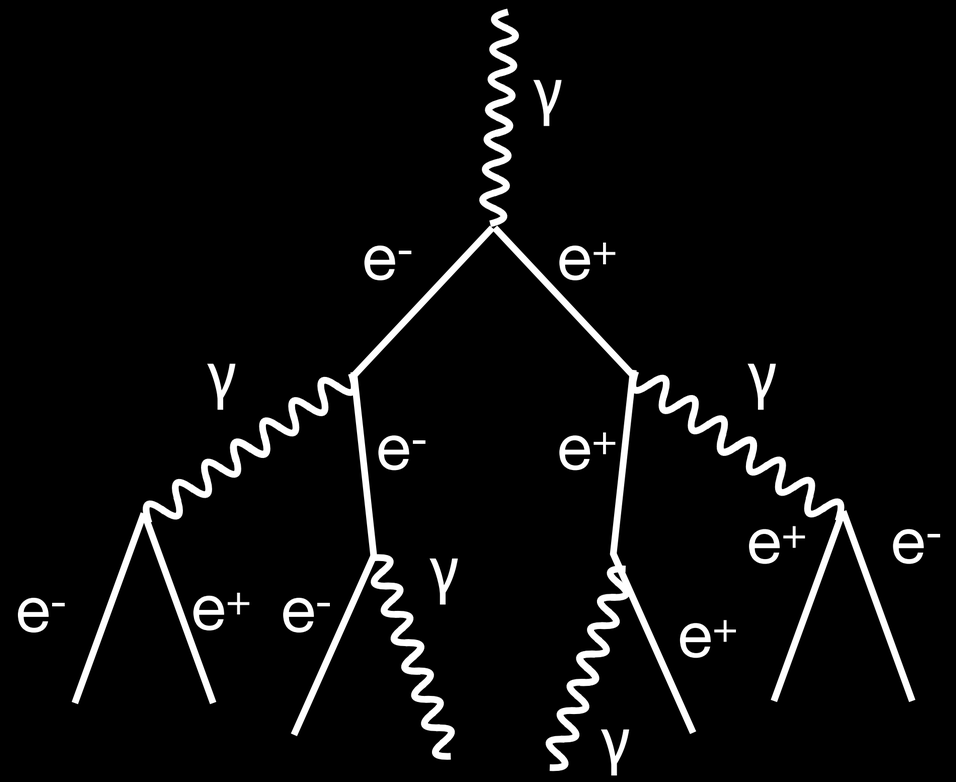


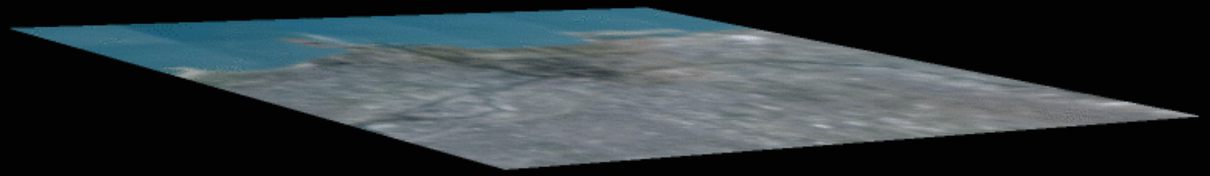


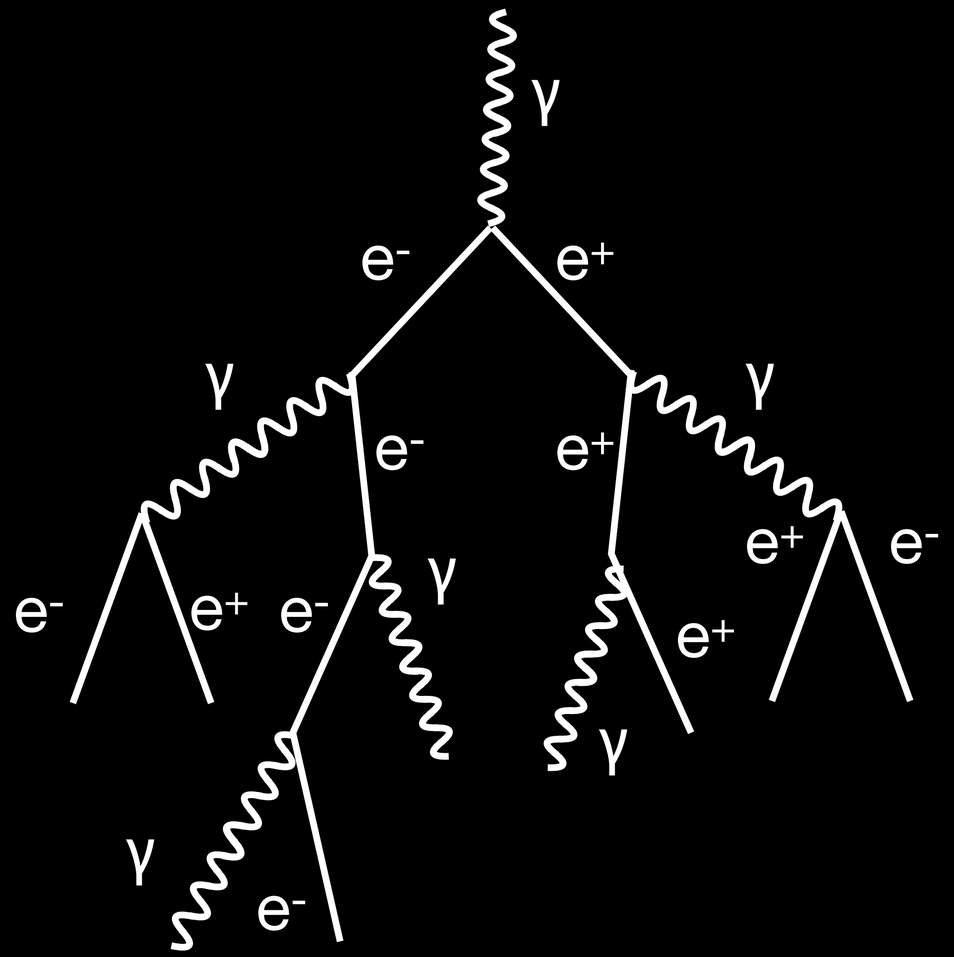
Atmospheric Cherenkov Radiation



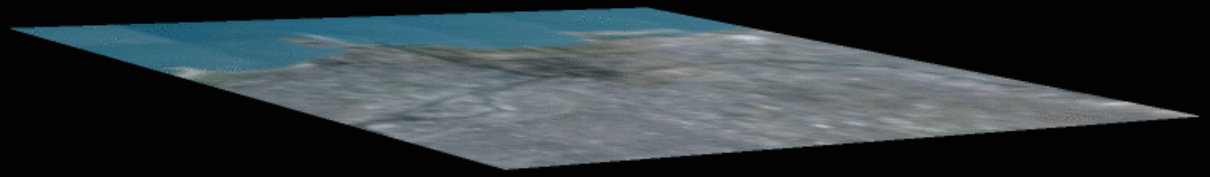


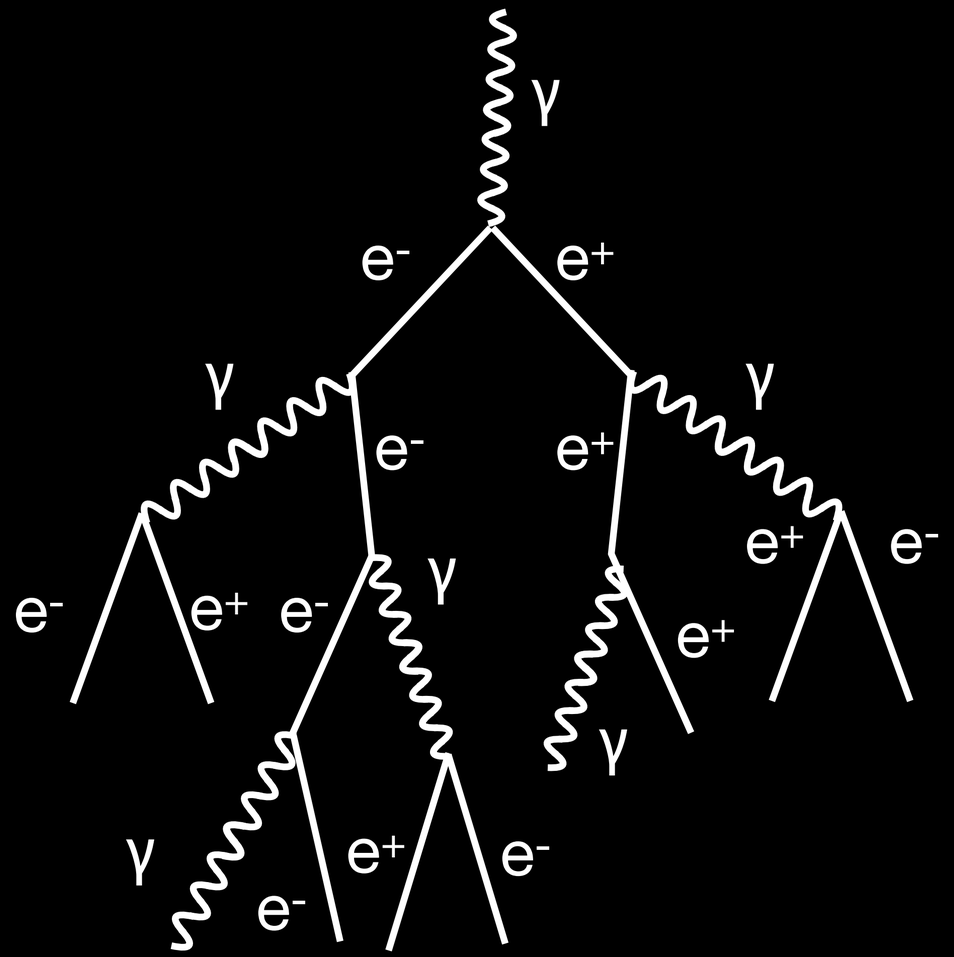
Atmospheric Cherenkov Radiation



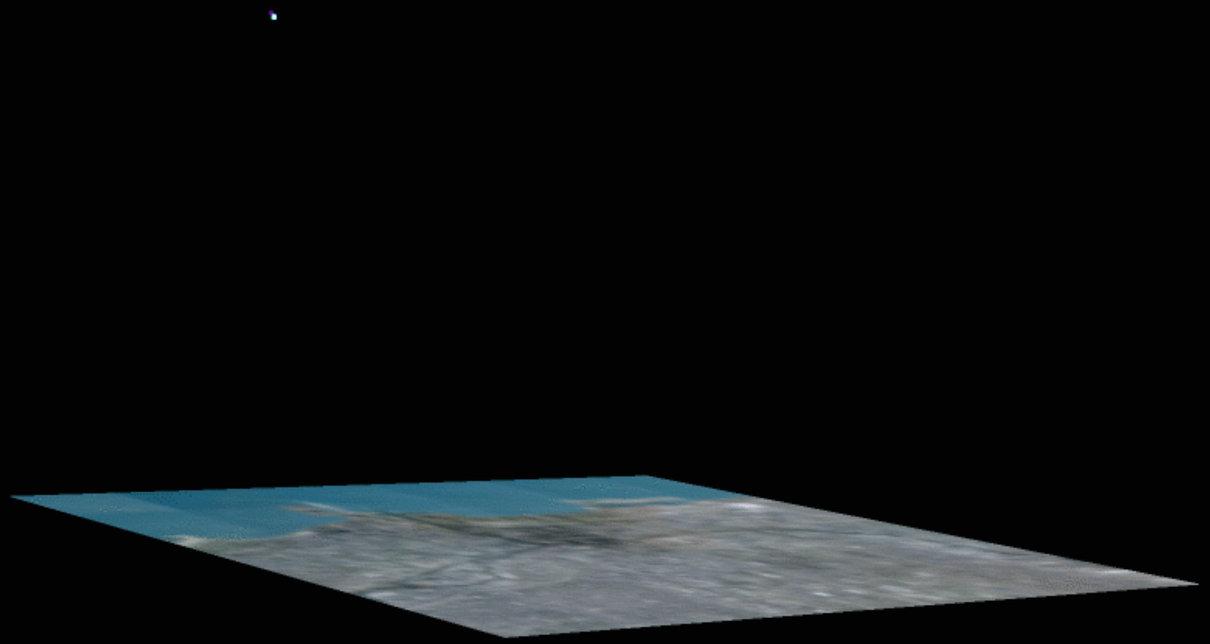


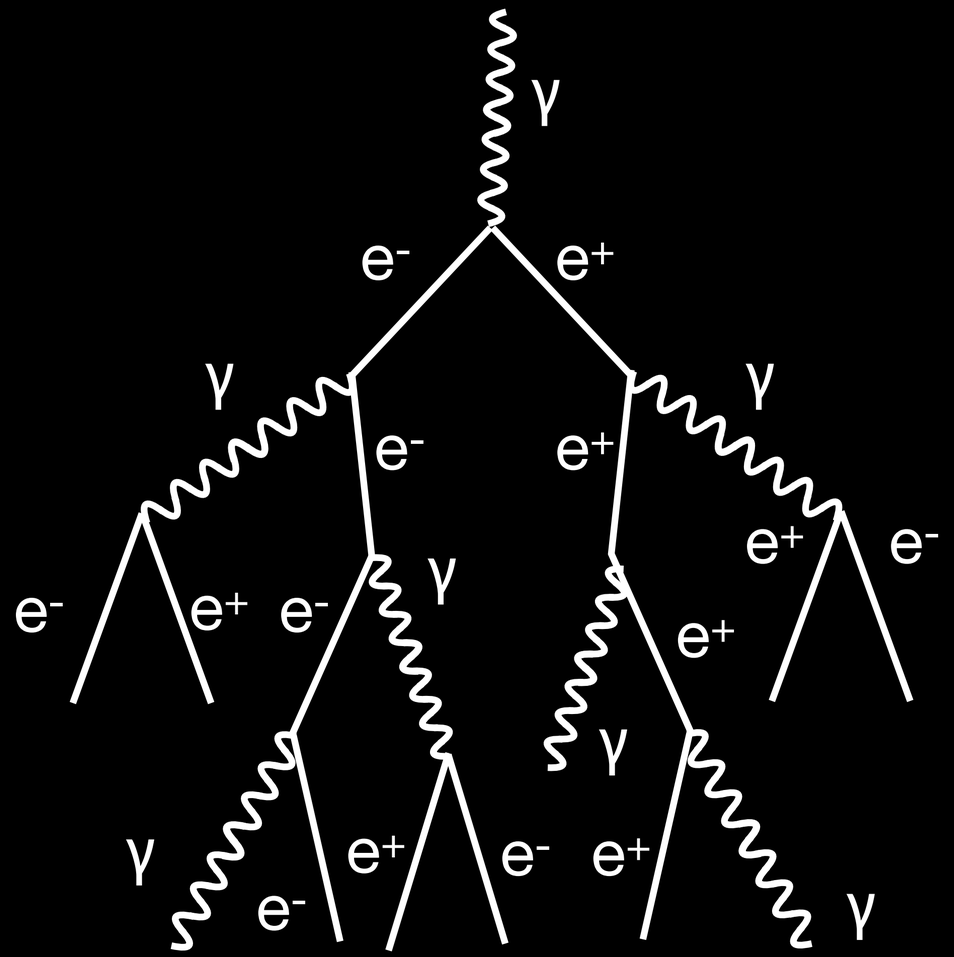
Atmospheric Cherenkov Radiation



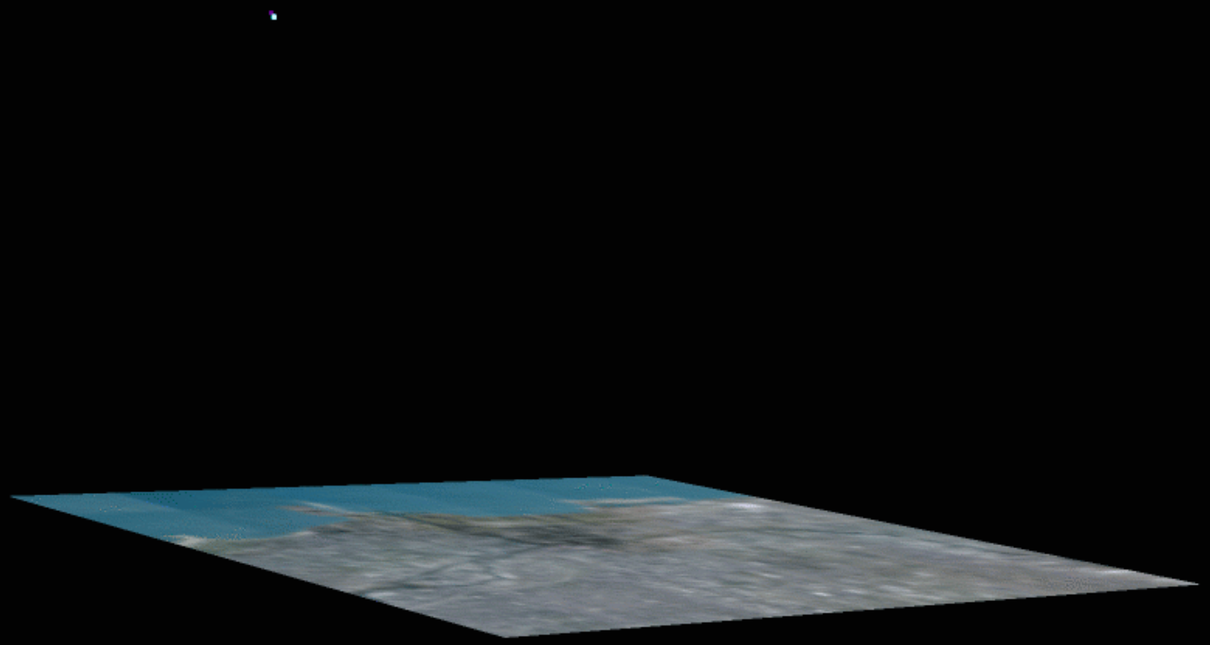


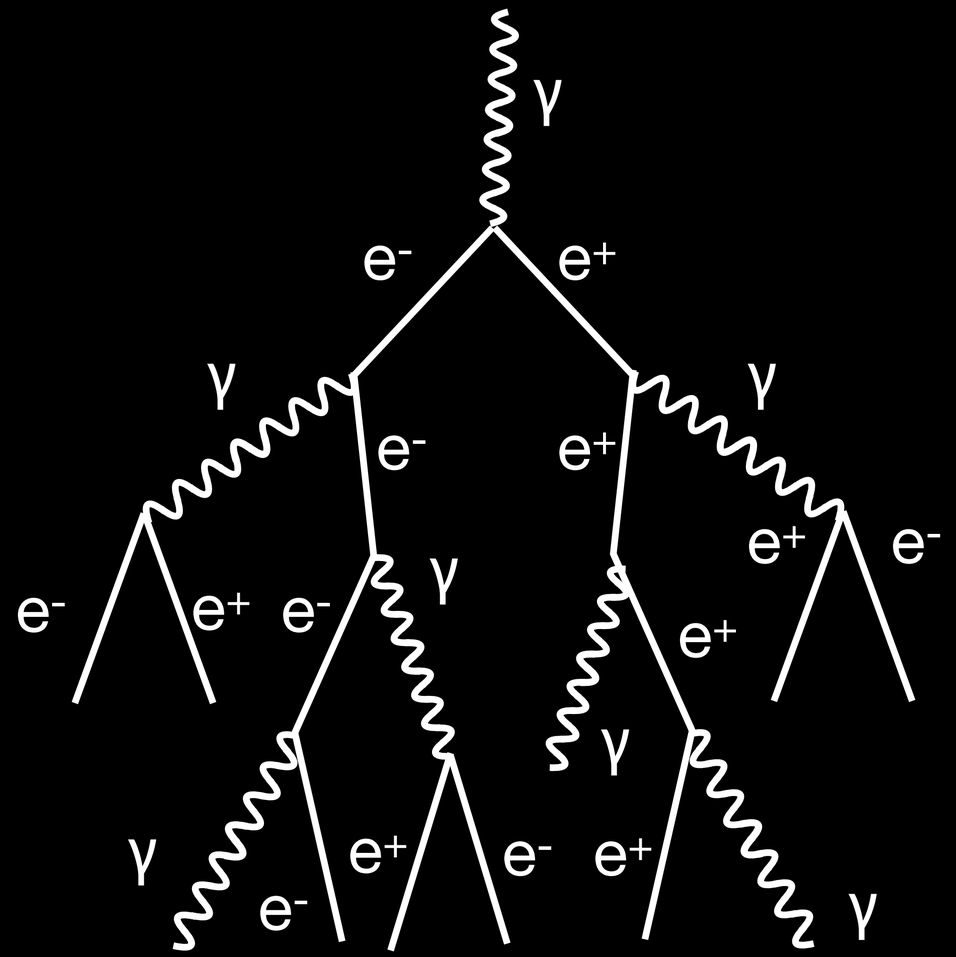
Atmospheric Cherenkov Radiation





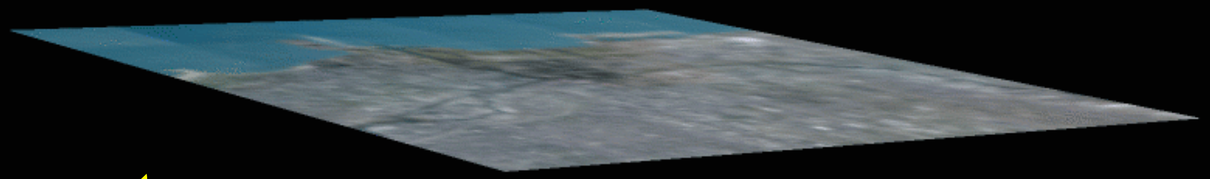
Atmospheric Cherenkov Radiation

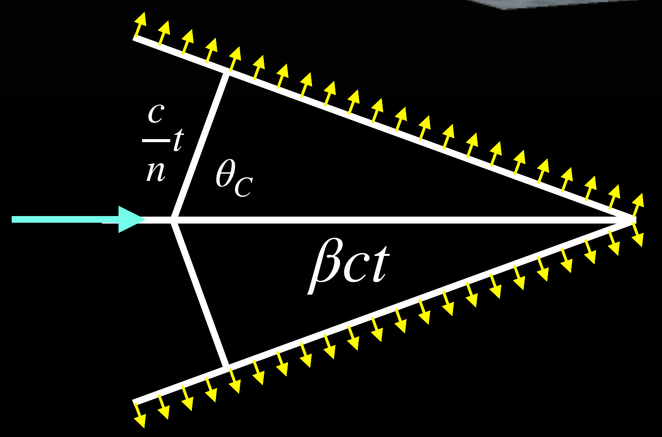




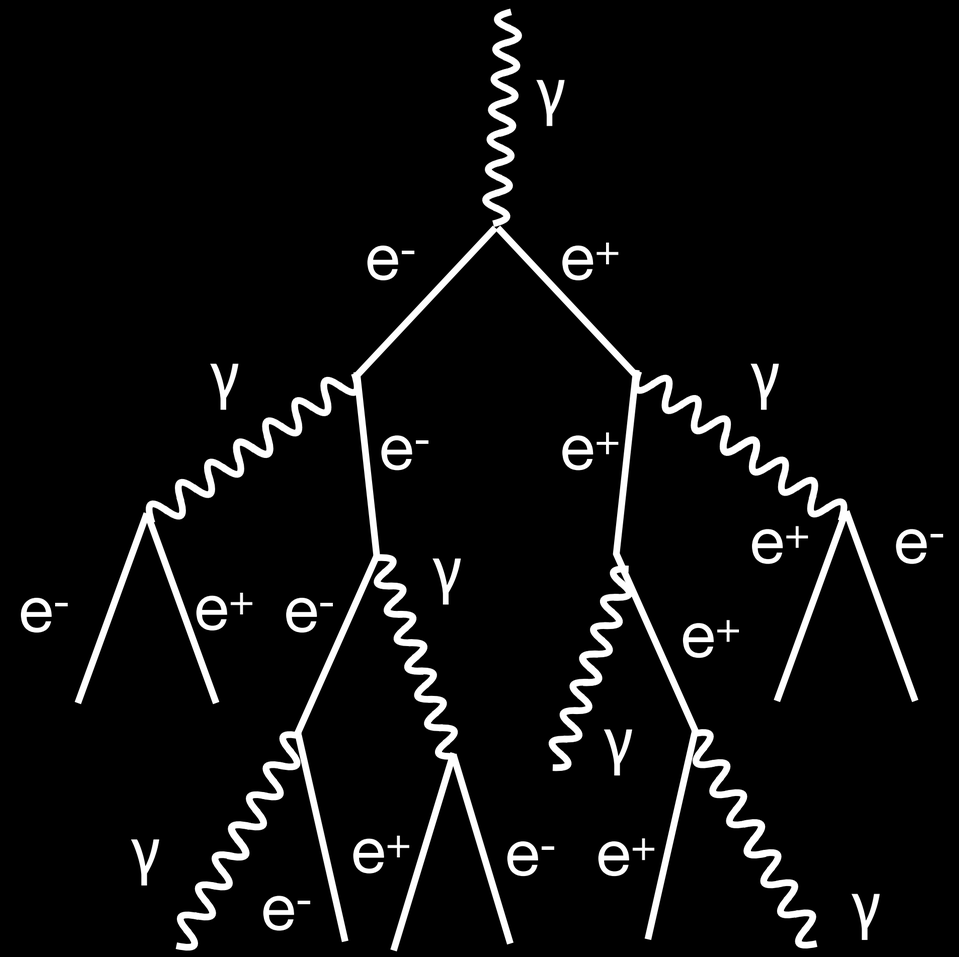
Cherenkov Condition: $v > \frac{c}{n}$

Atmospheric Cherenkov Radiation



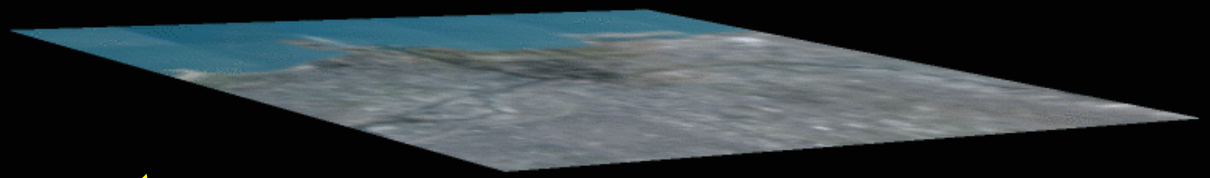


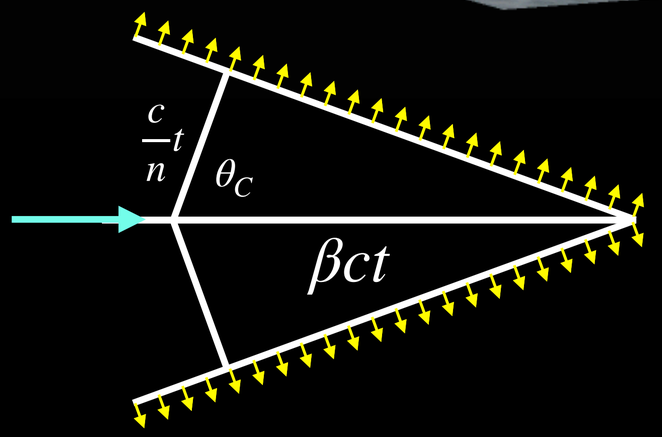
$$\cos(\theta_C) = \frac{1}{\beta n}$$



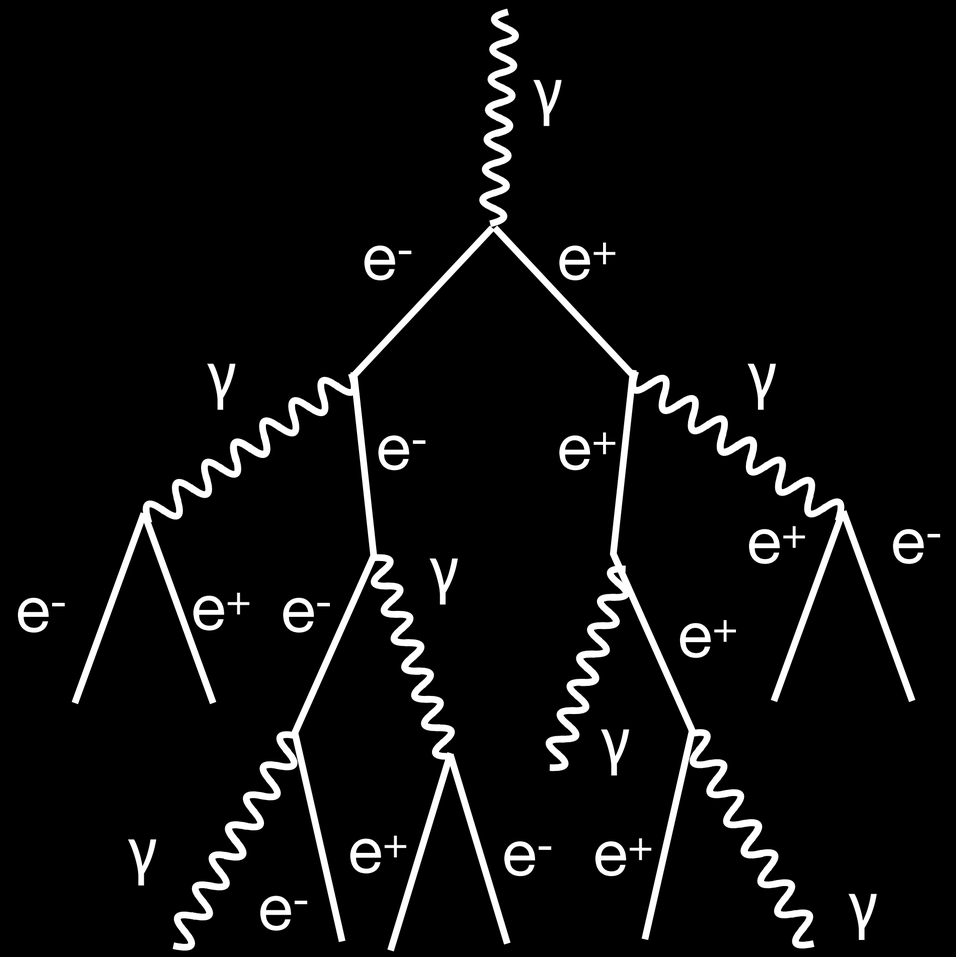
Cherenkov Condition: $v > \frac{c}{n}$

Atmospheric Cherenkov Radiation





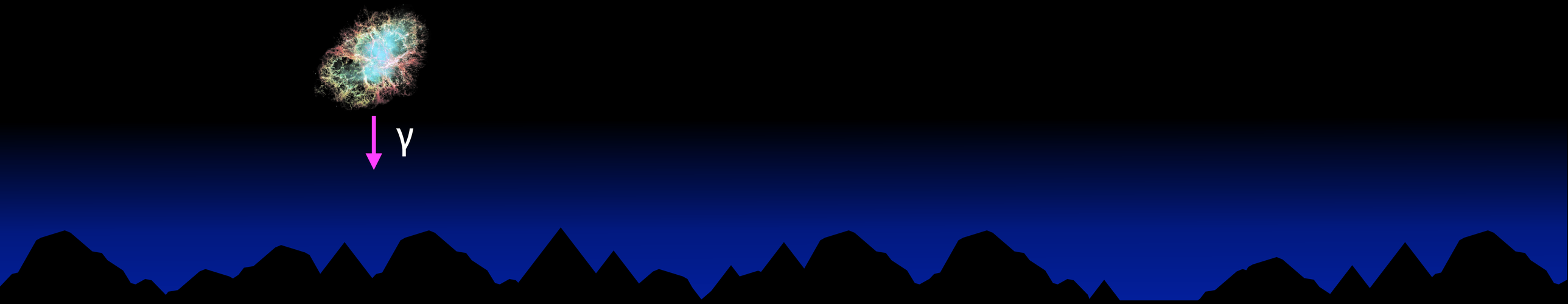
$$\cos(\theta_C) = \frac{1}{\beta n}$$



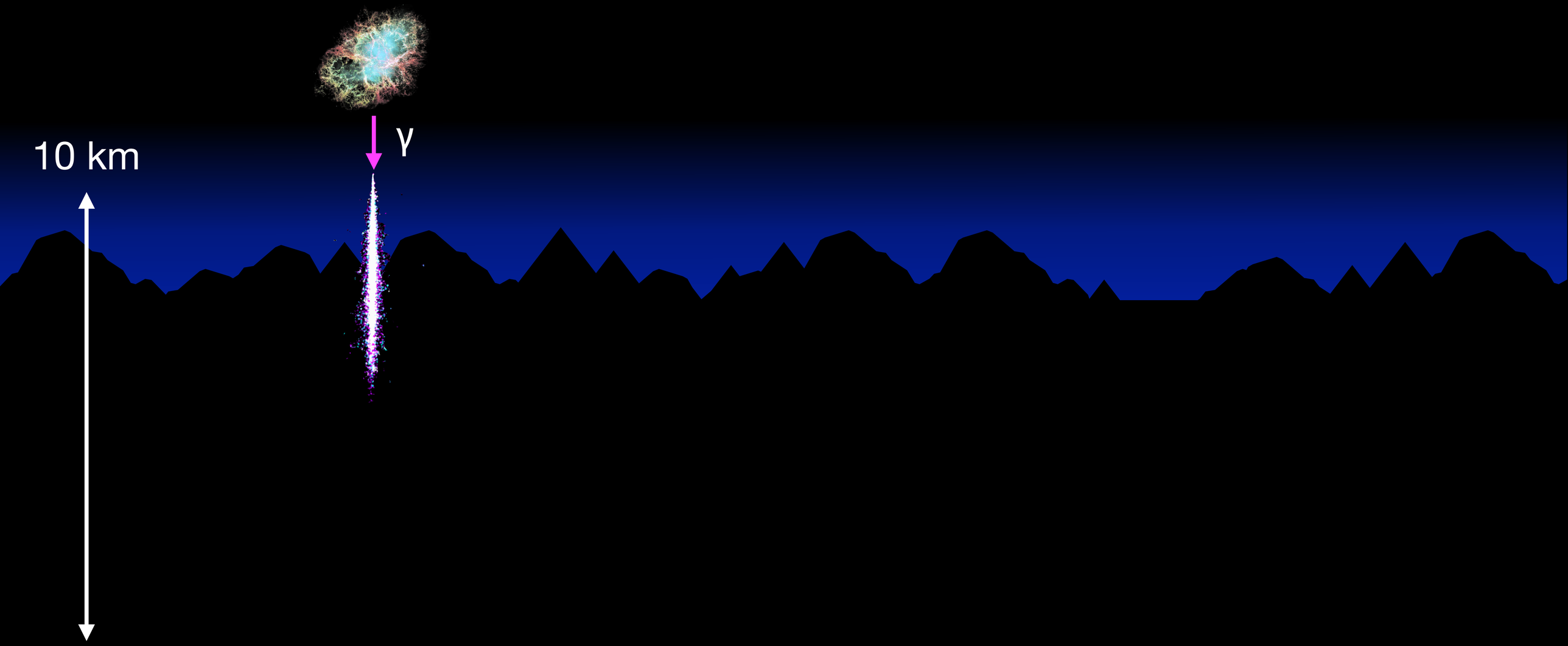
Cherenkov Condition: $v > \frac{c}{n}$

n~1.00029 (air) $\theta_C \approx 1.4°$

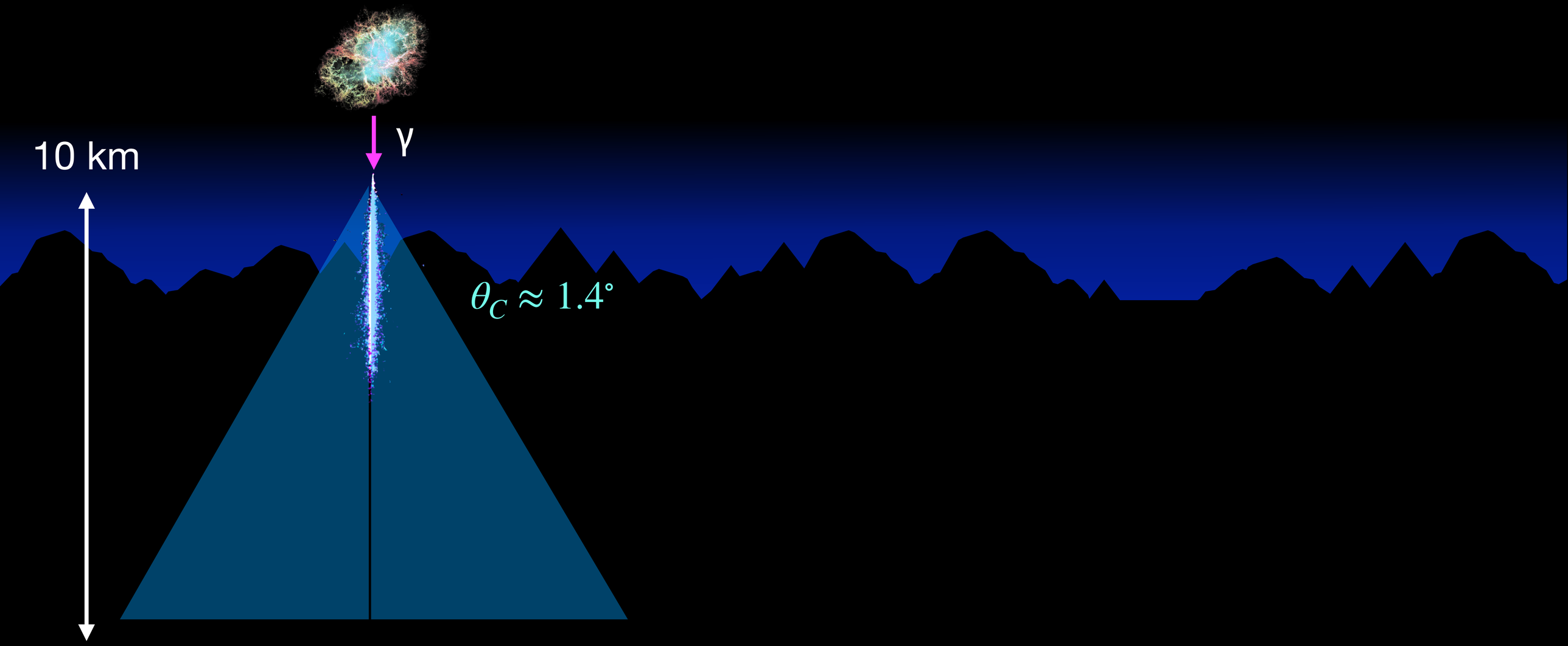
Atmospheric Cherenkov Radiation



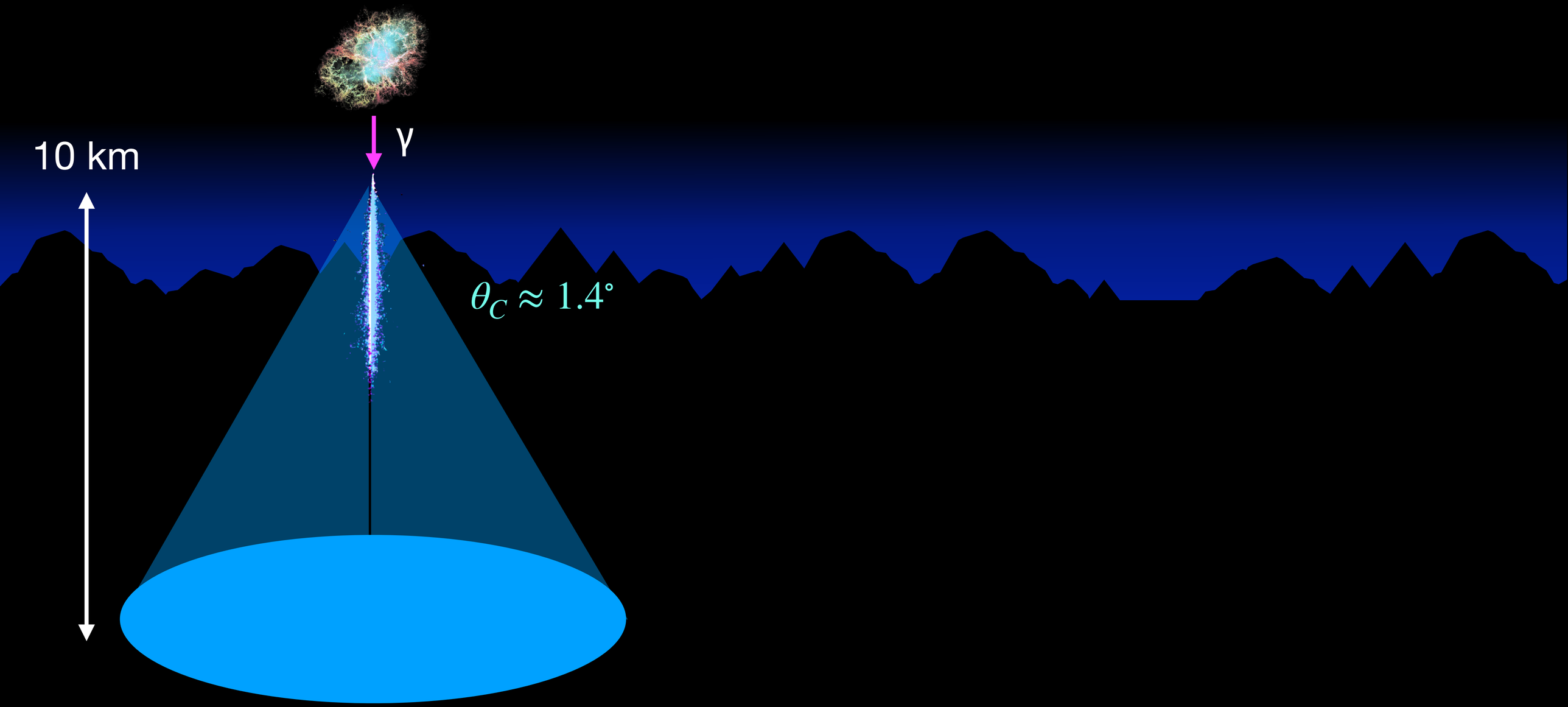
Atmospheric Cherenkov Radiation



Atmospheric Cherenkov Radiation



Atmospheric Cherenkov Radiation



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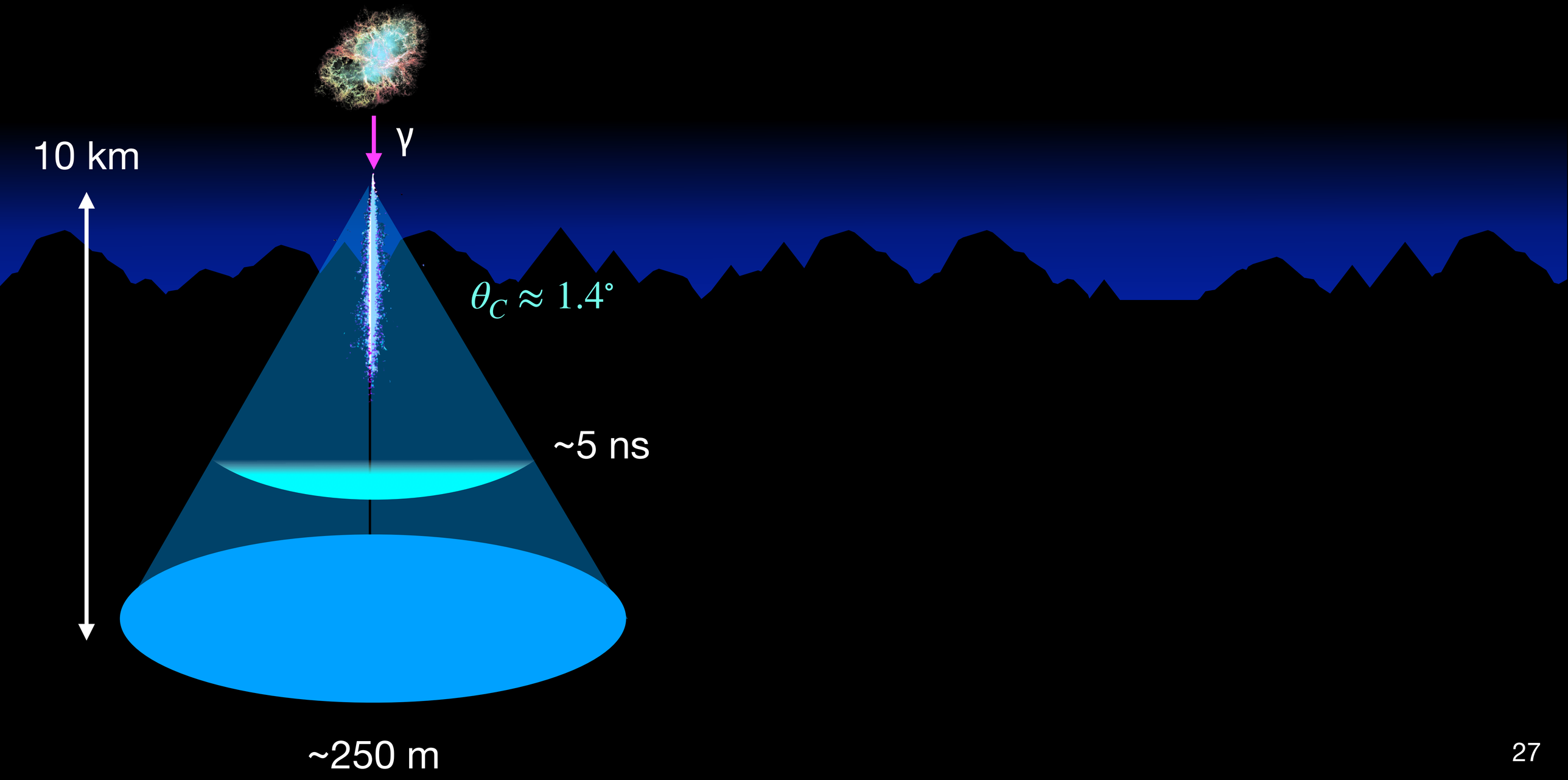
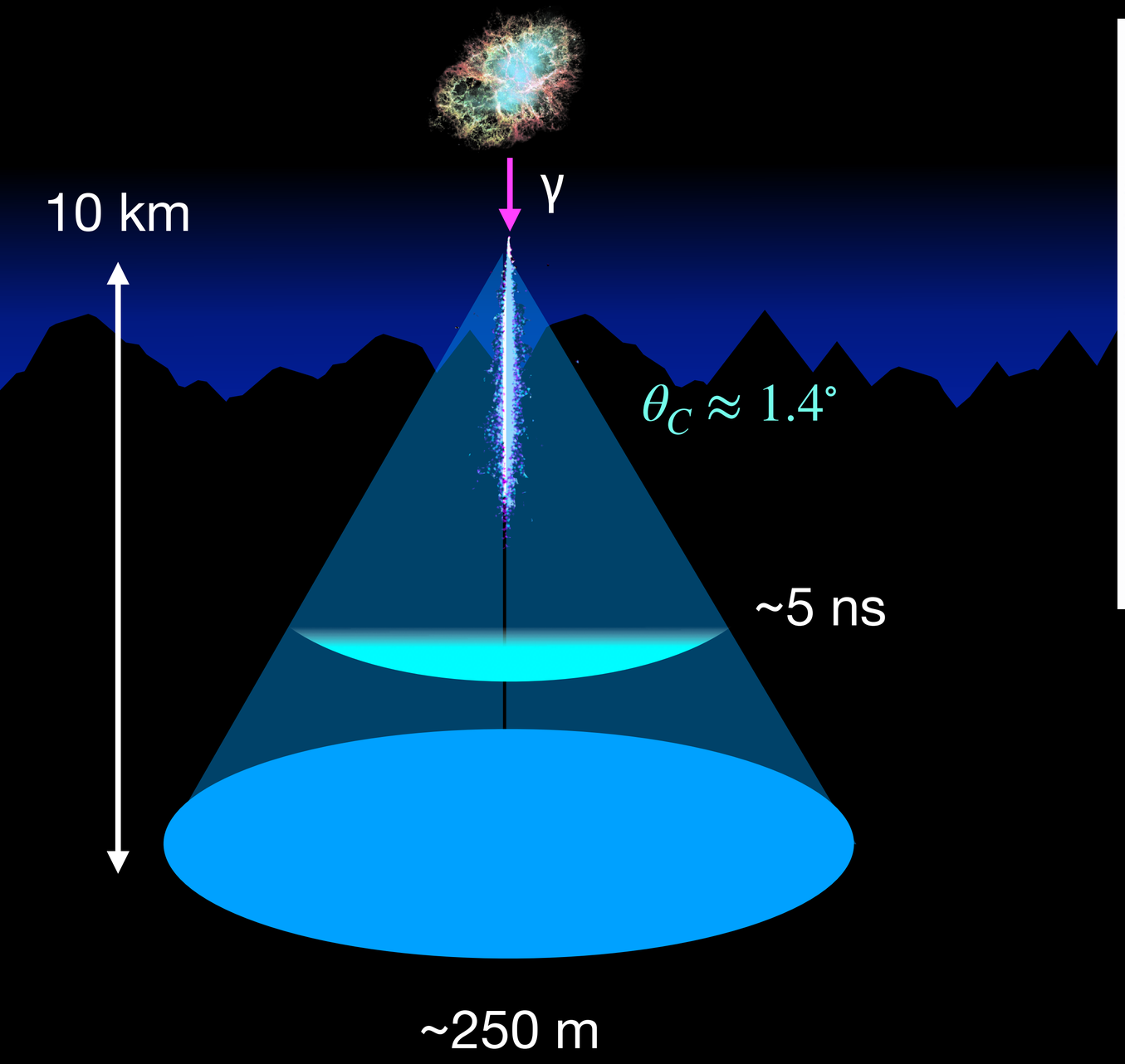
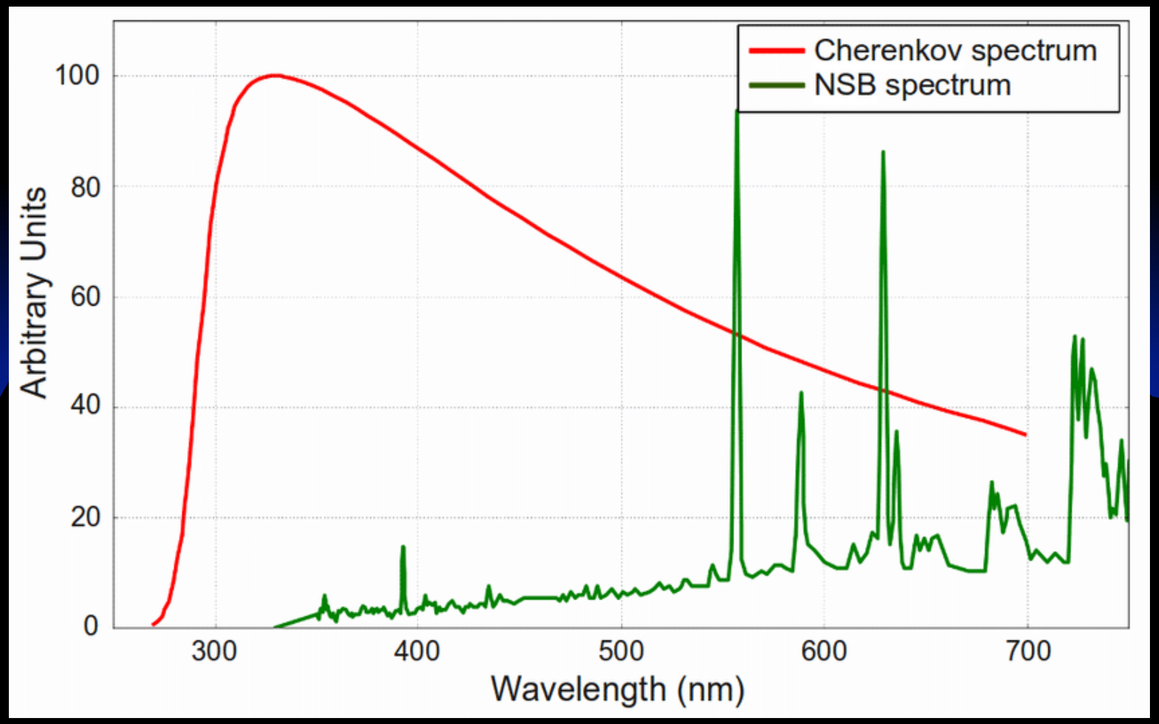
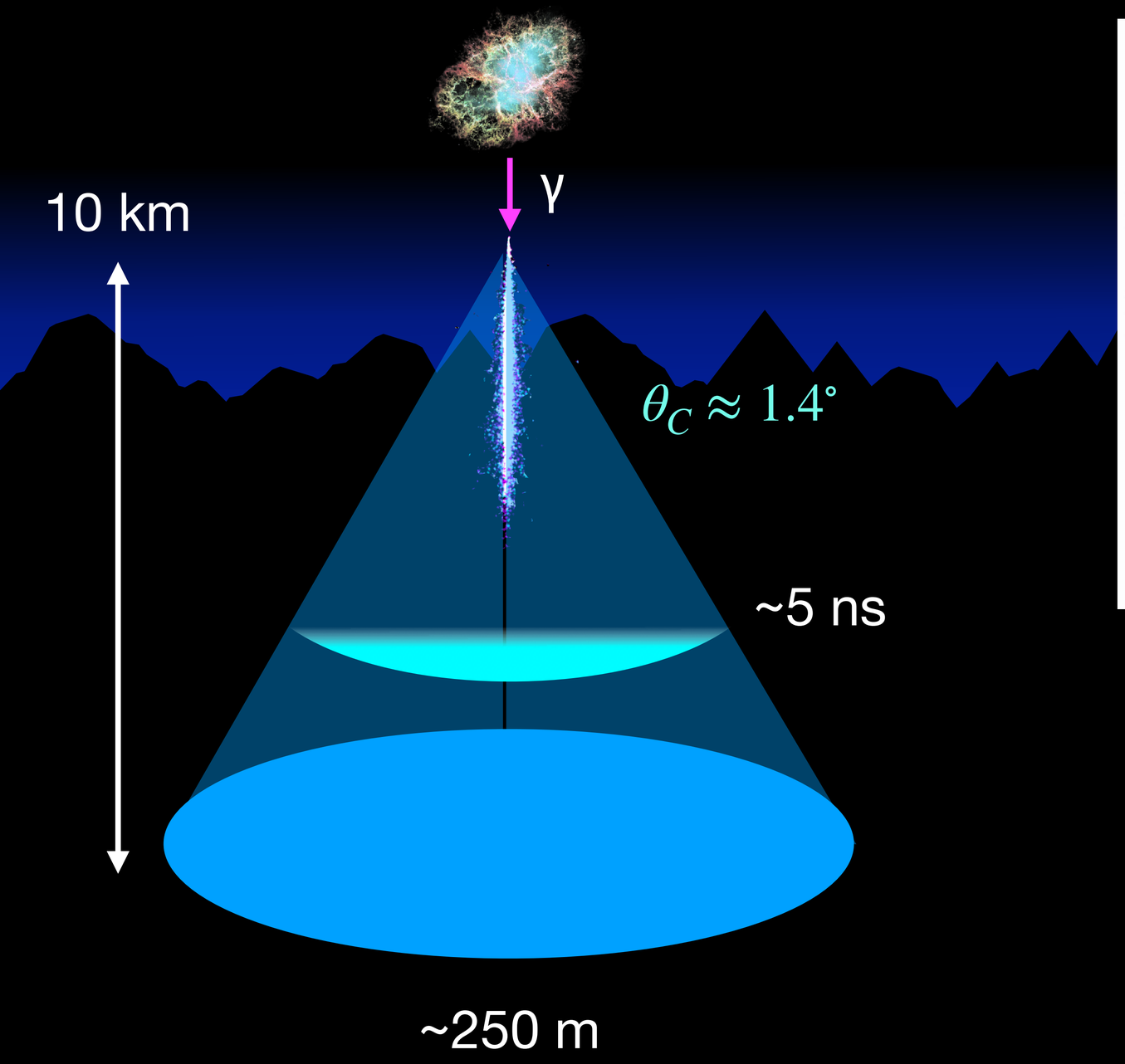


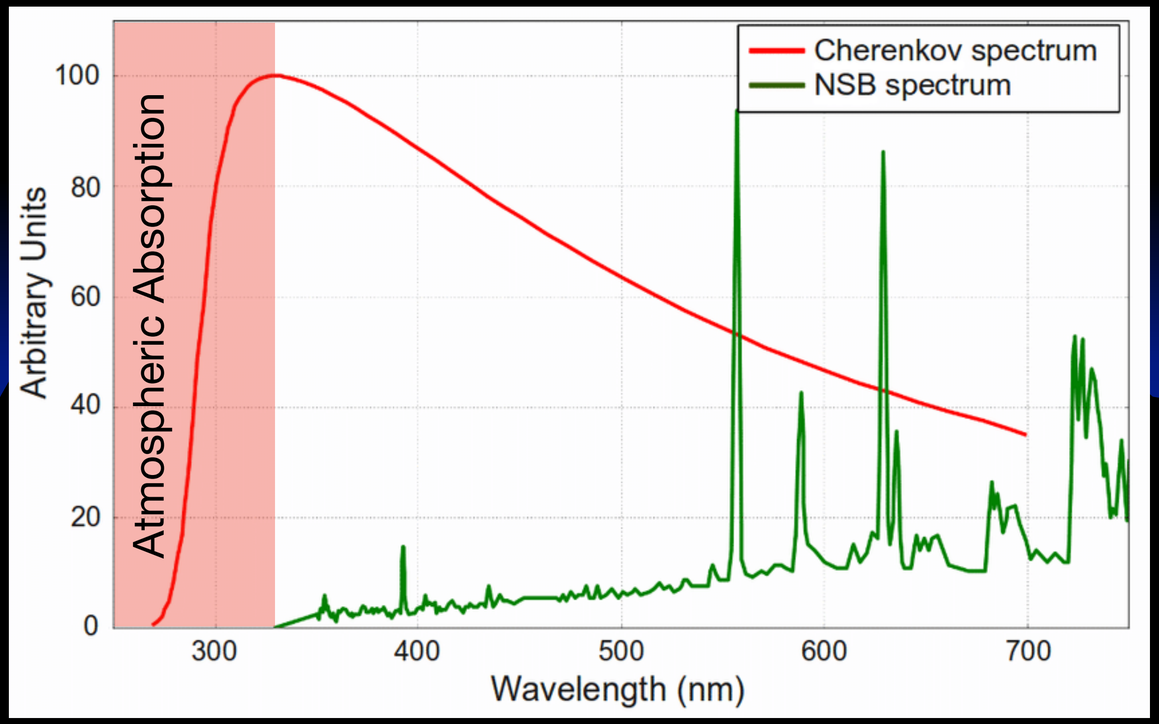
Atmospheric Cherenkov Radiation





Atmospheric Cherenkov Radiation





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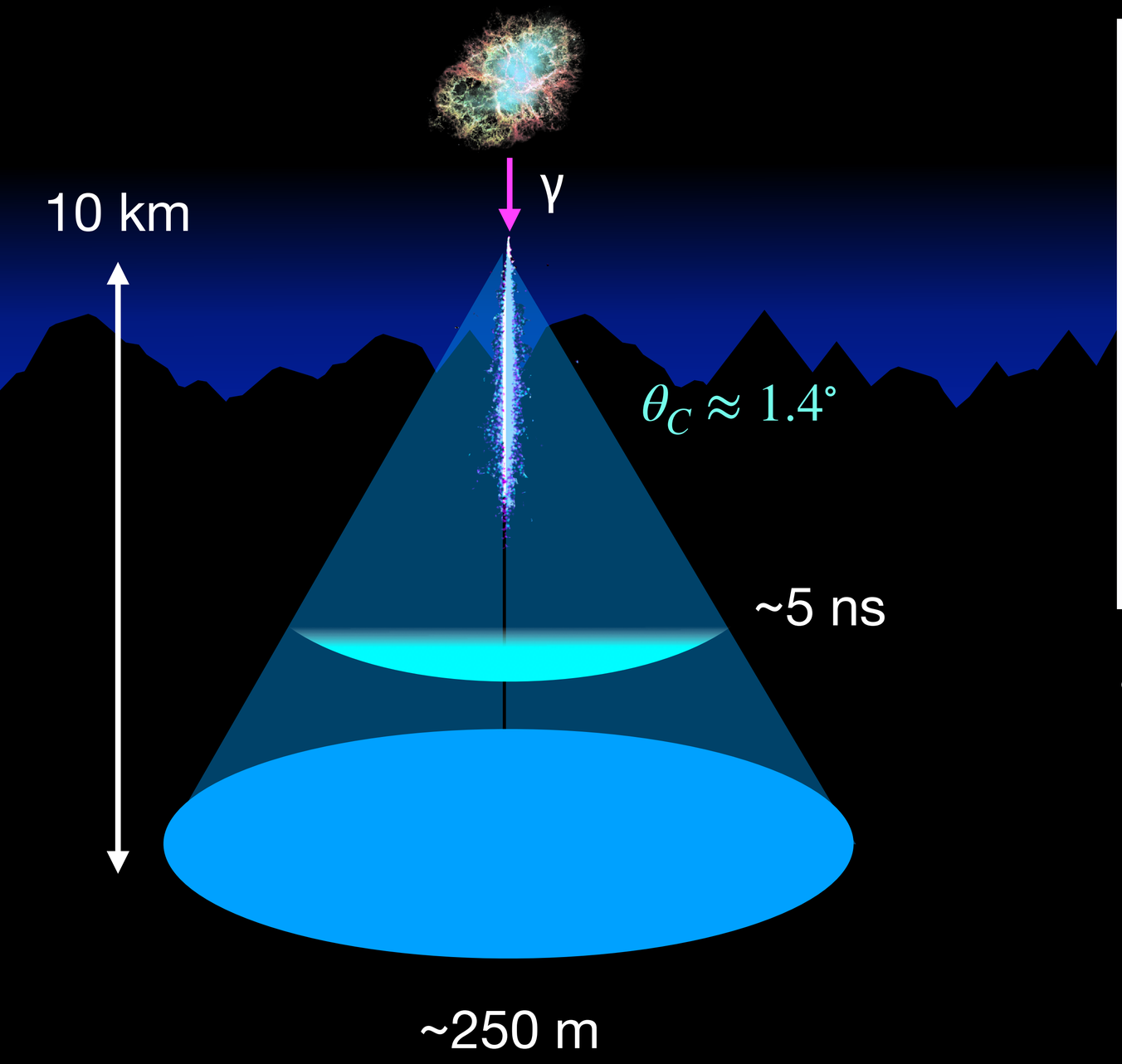
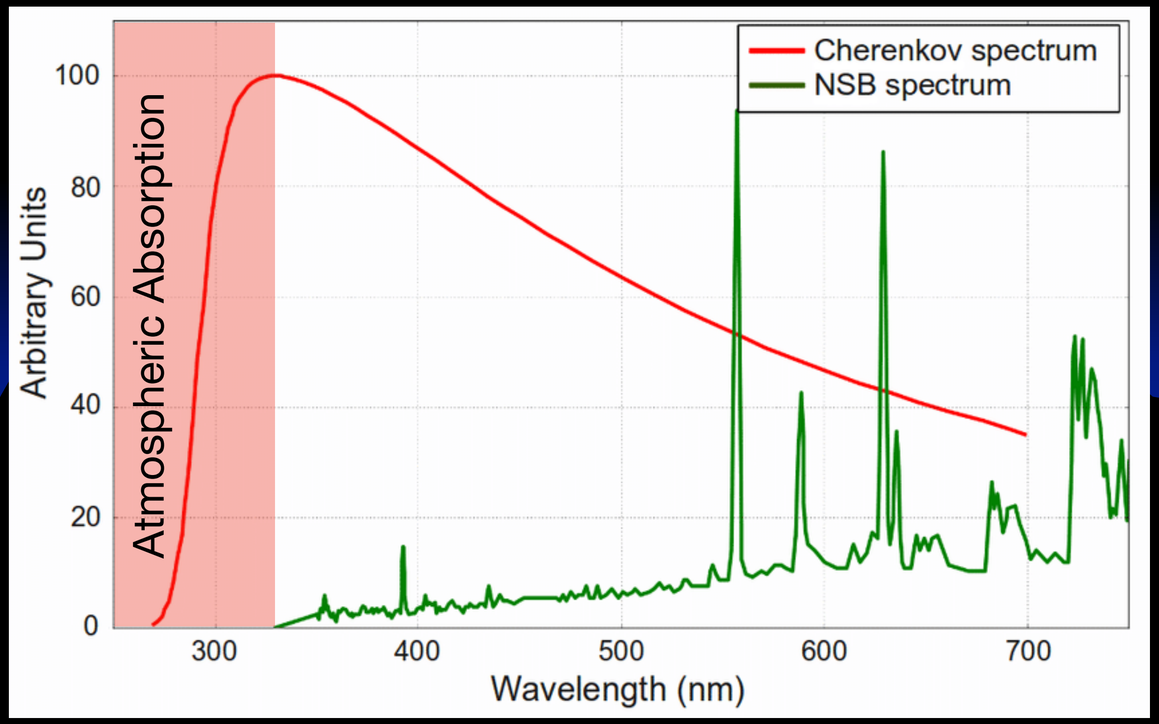
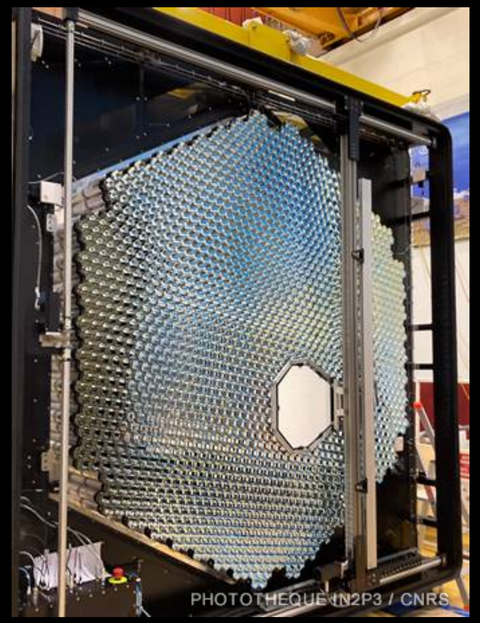


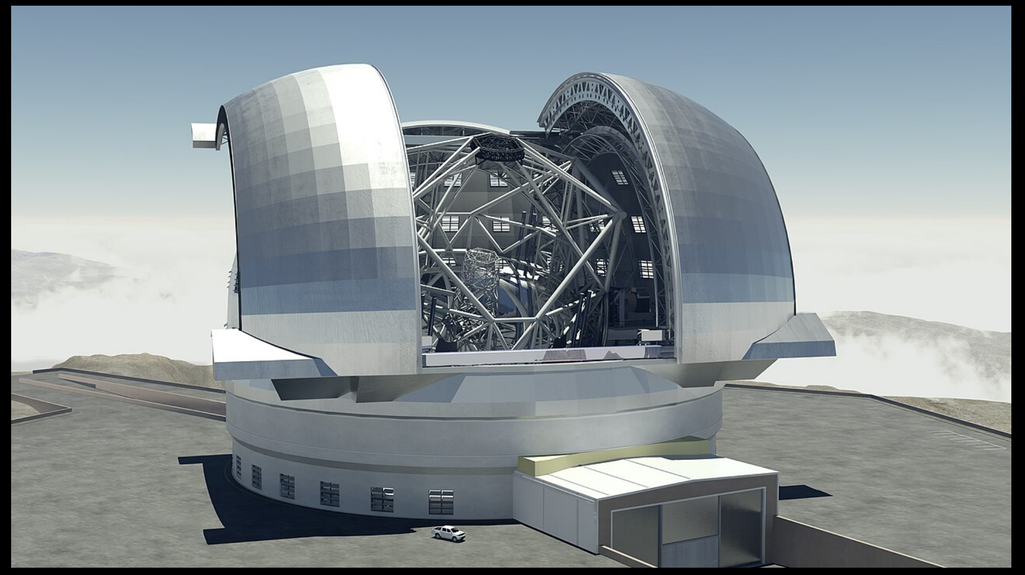


- An IACT needs to be:
  - Fast (ns time resolution)
  - Sensitive to Optical-UV (blue light)
  - Large Collection Area

Atmospheric Cherenkov Radiation

- Fast
  - Fairly Easy - Fast PMT have existed since the 80s. You just buy them
- Sensitive to Optical-UV (blue light)
  - Fairly Easy - Design your PMTs and cameras to be sensitive to blue light (i.e. high Quantum Efficiency at that frequency)
- Large Collection Area:
  - More difficult
  - A 250 m optical telescope is way too big.
  - ELT (largest optical telescope) had diameter of 40 m
  - But we can be clever and use multiple smaller telescopes





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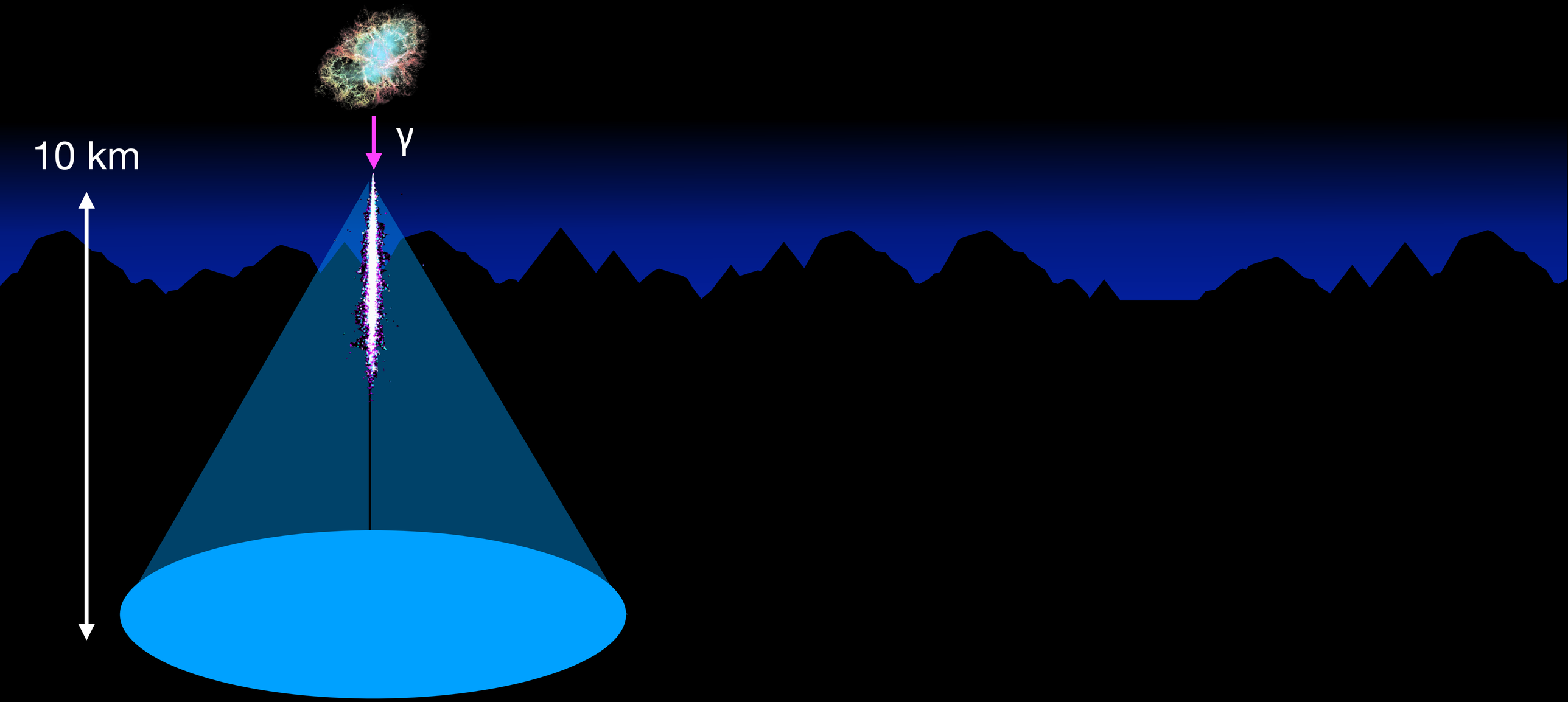

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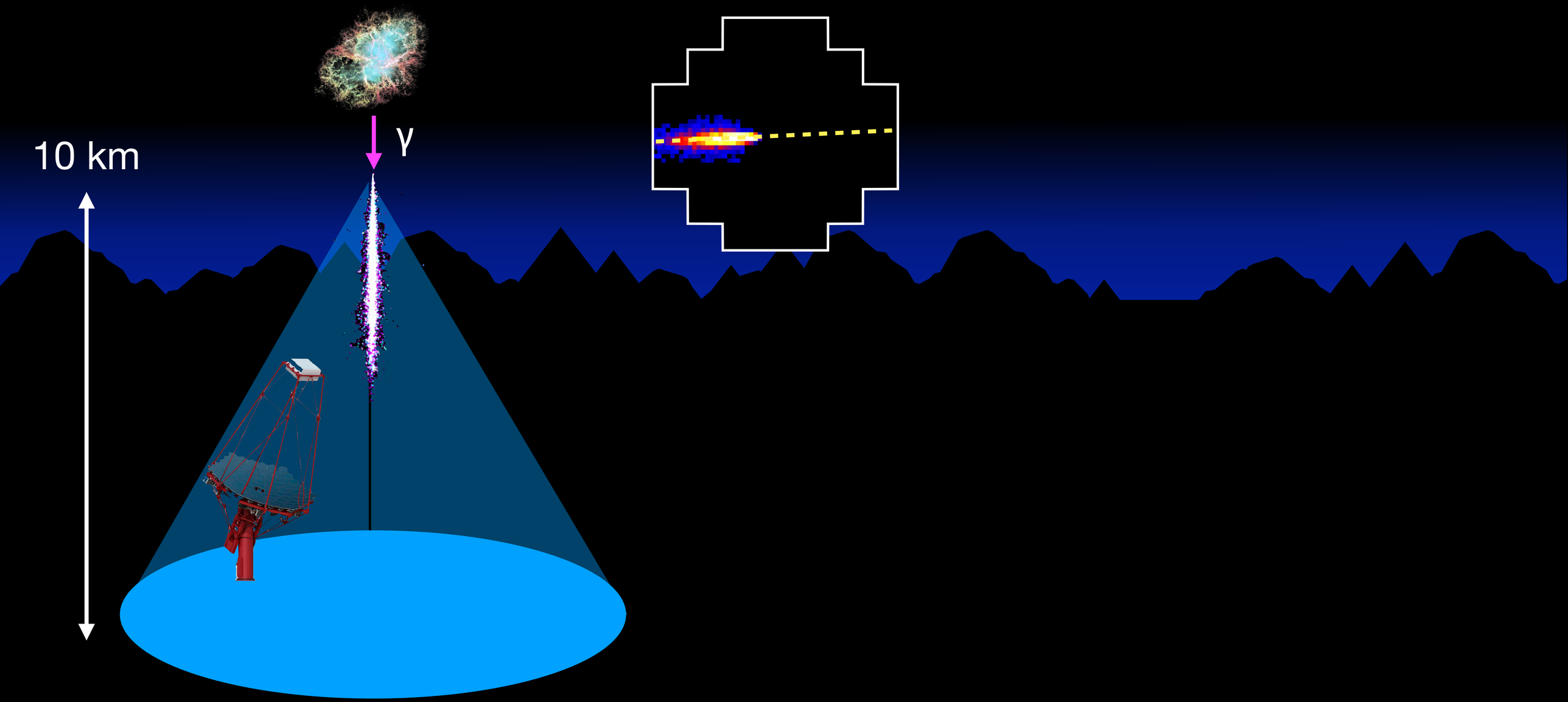

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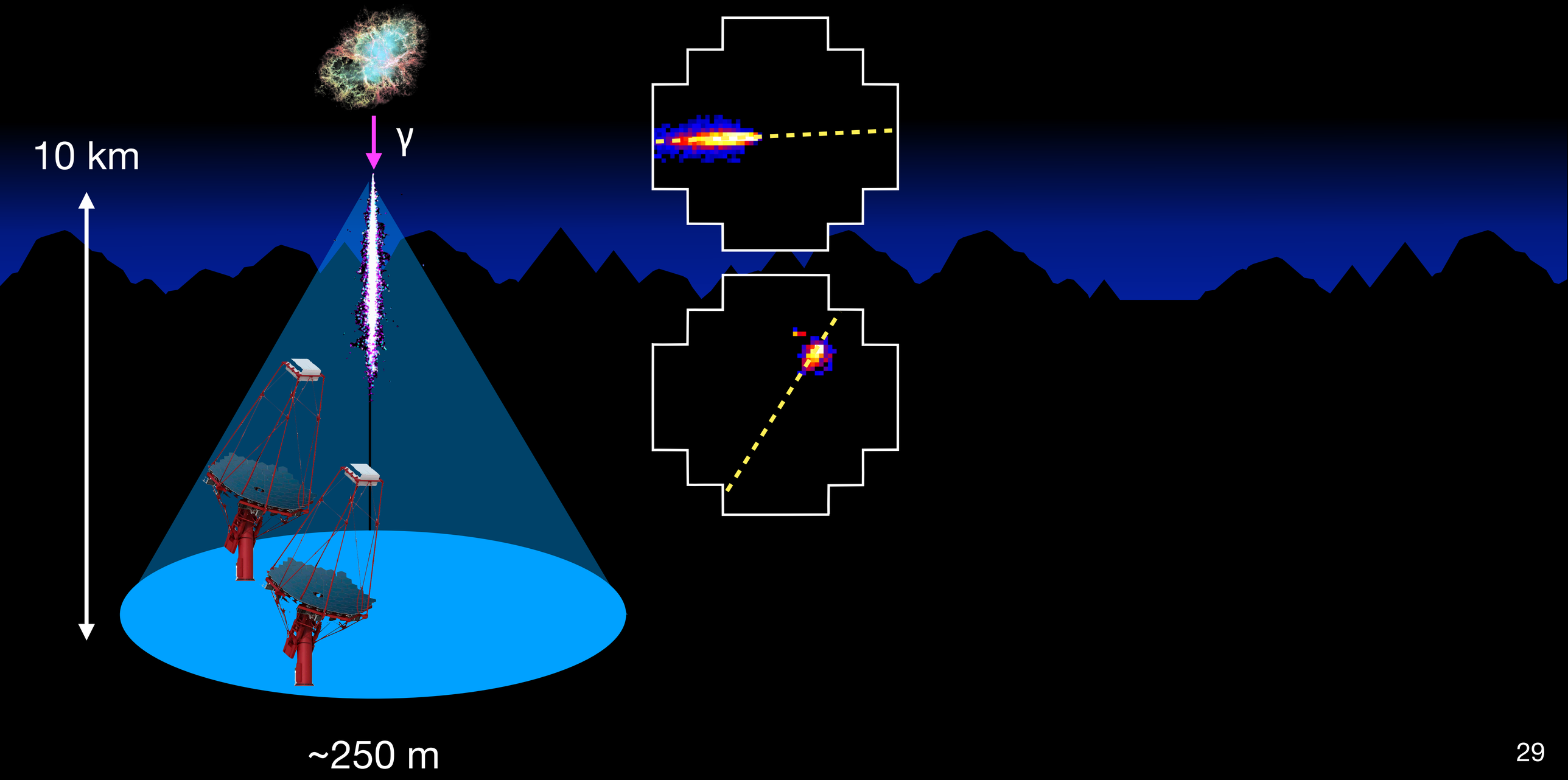
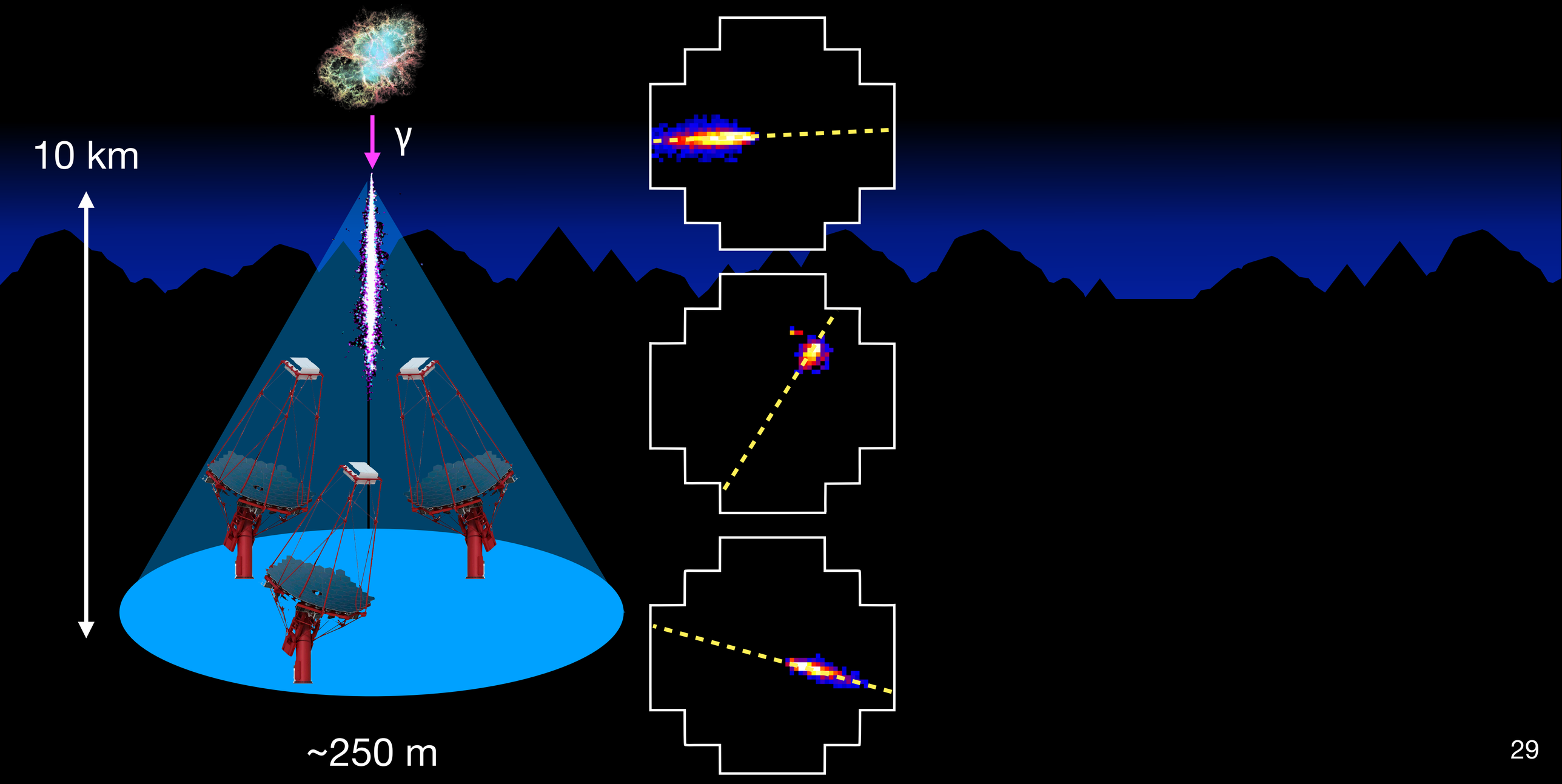
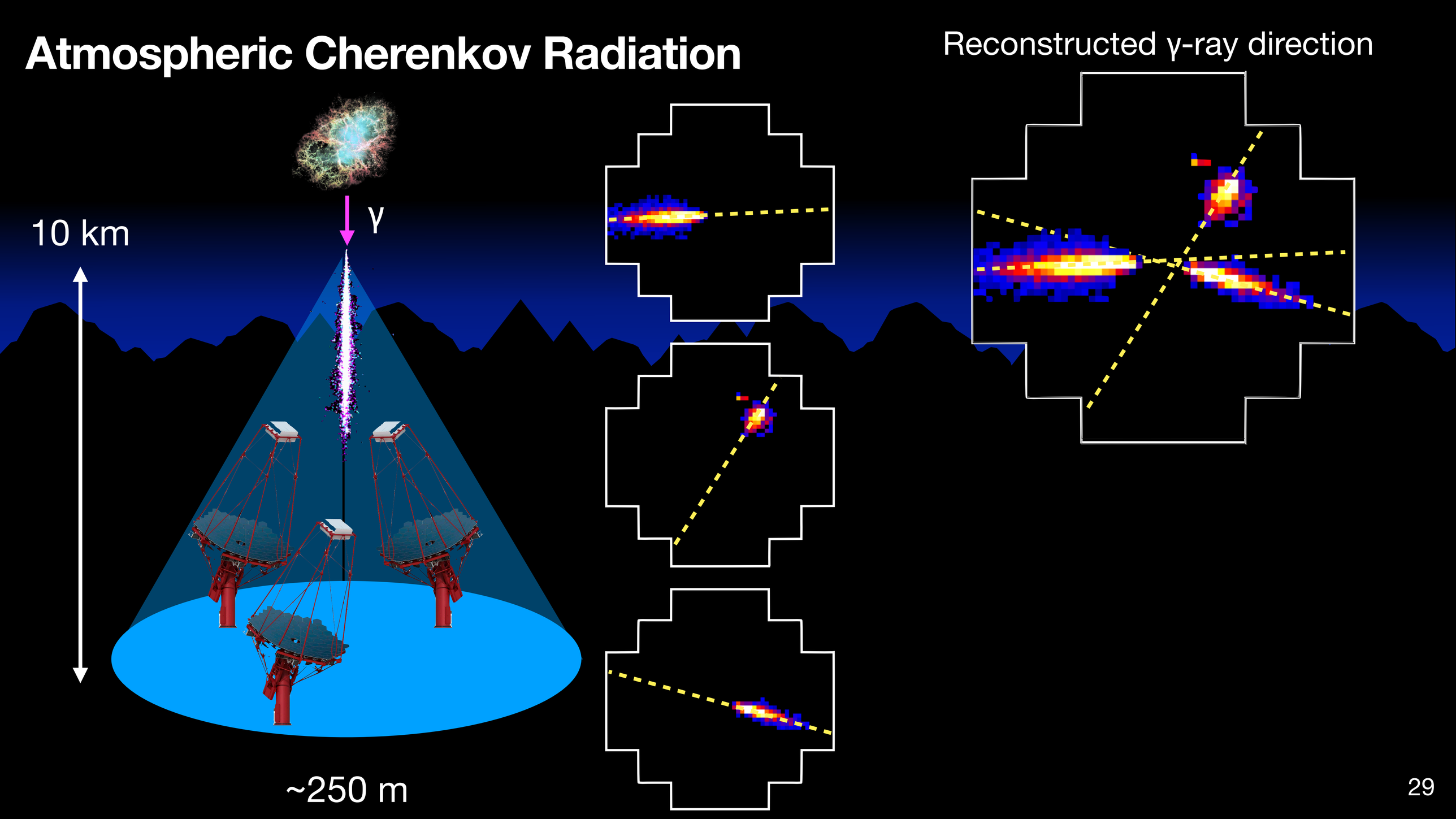


Atmospheric Cherenkov Radiation

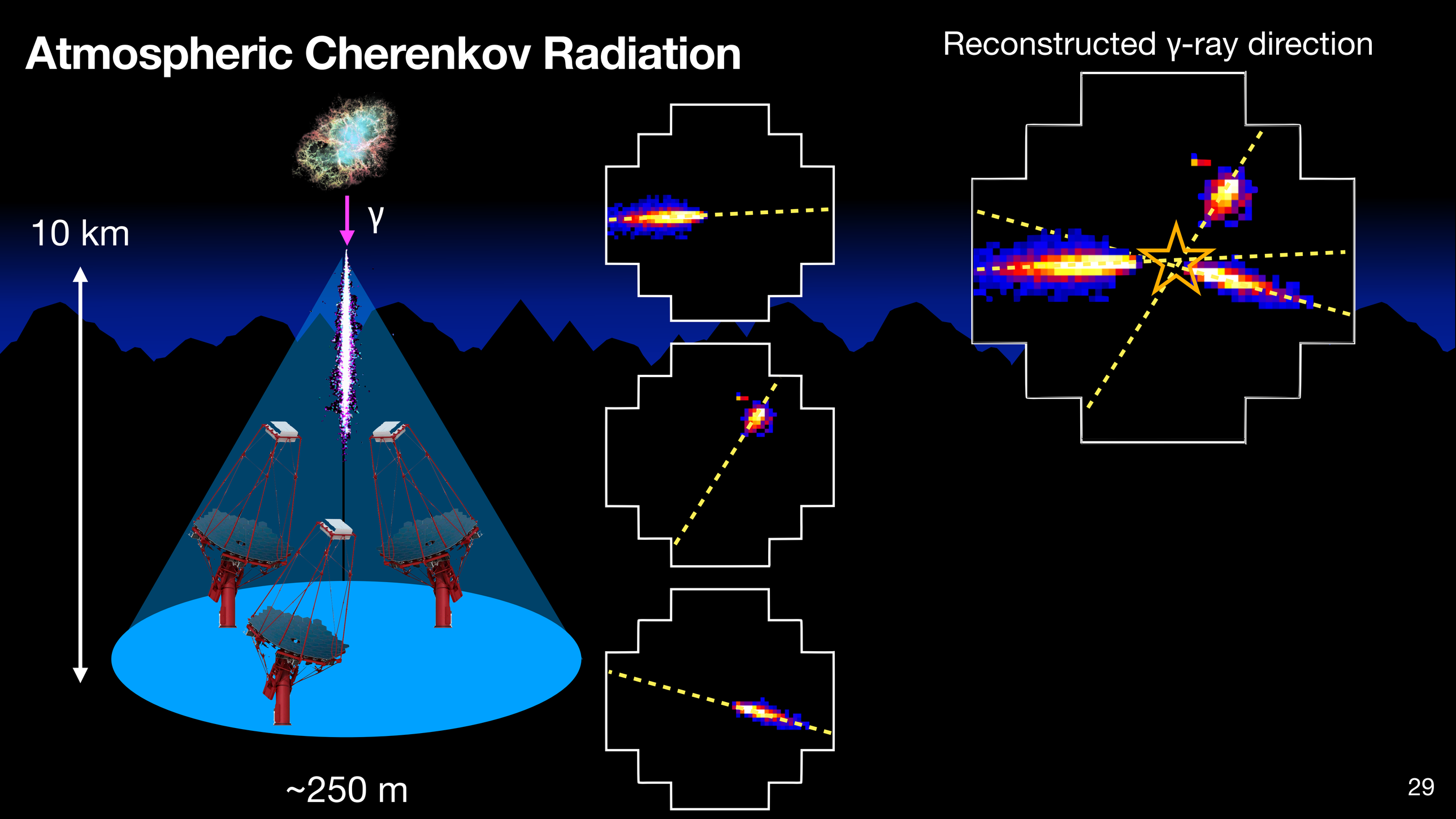


Atmospheric Cherenkov Radiation



Reconstructed γ-ray direction

Atmospheric Cherenkov Radiation



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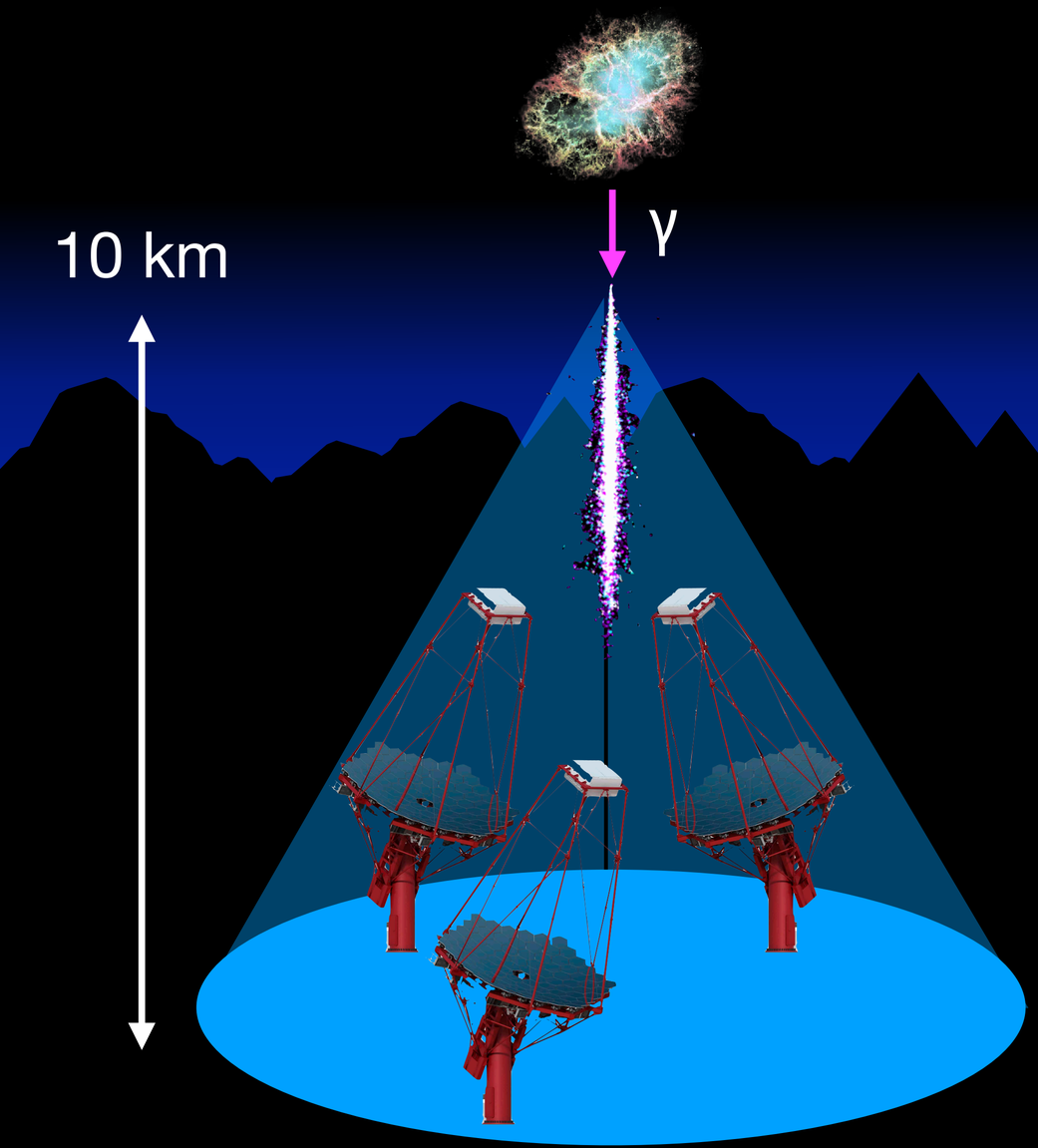
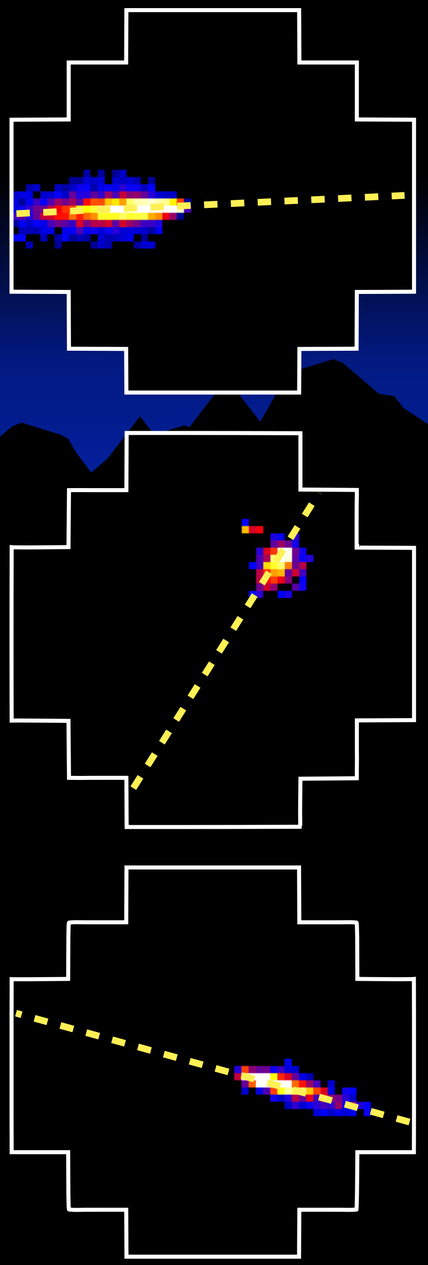
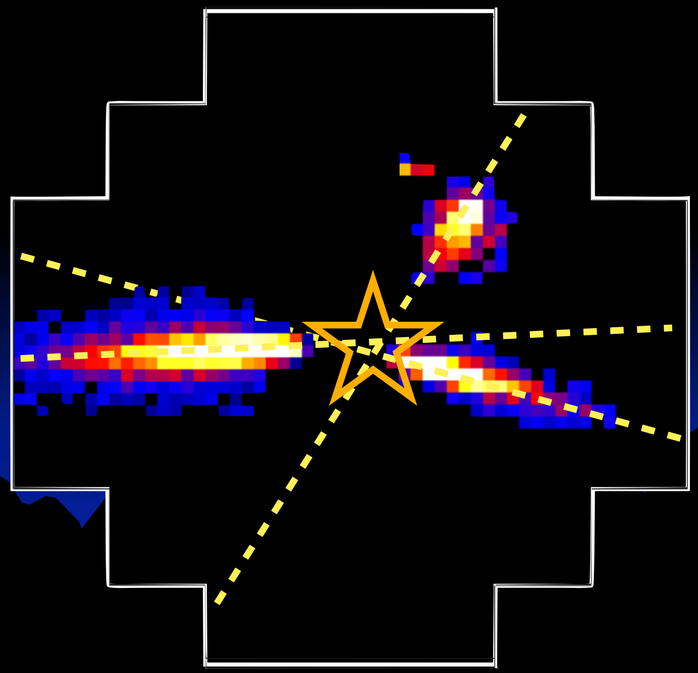
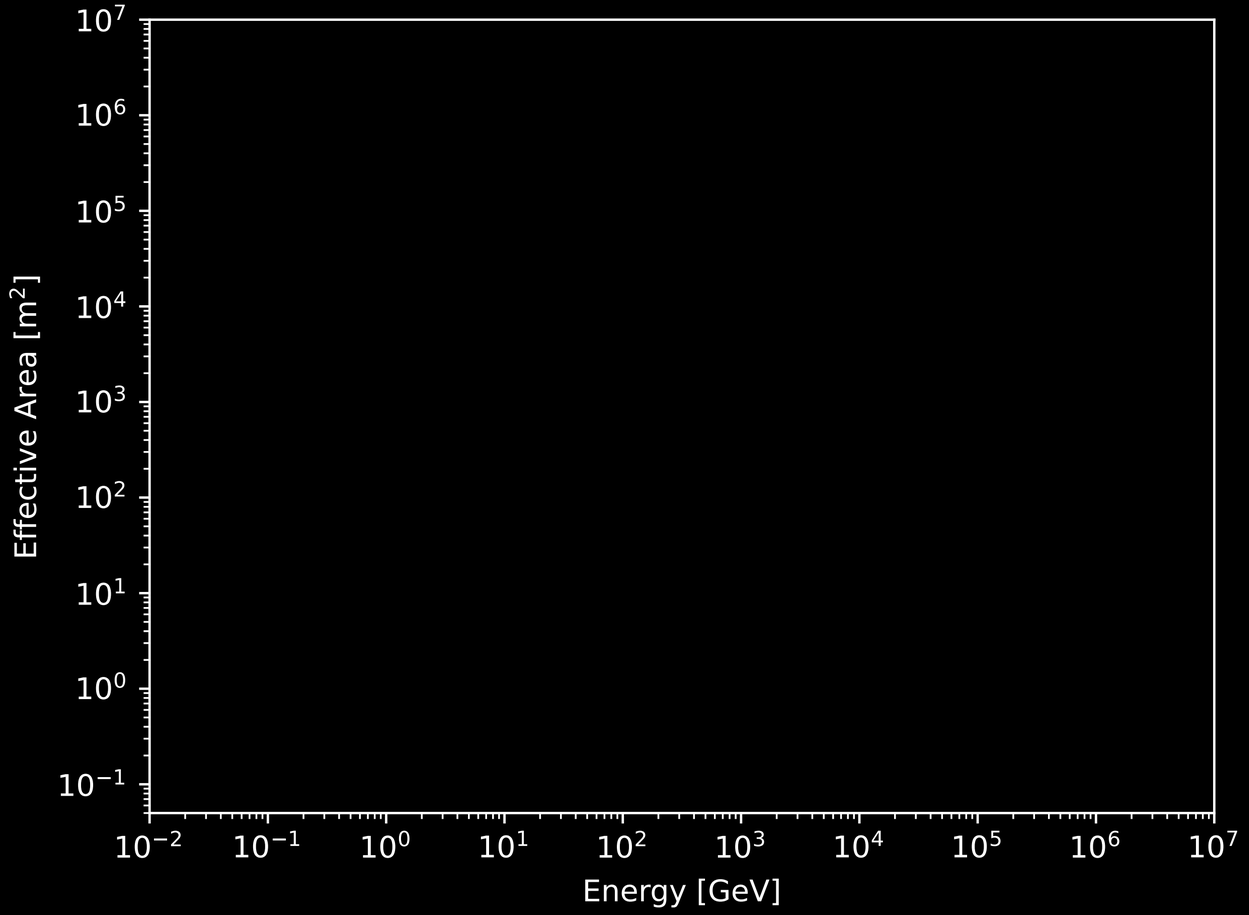


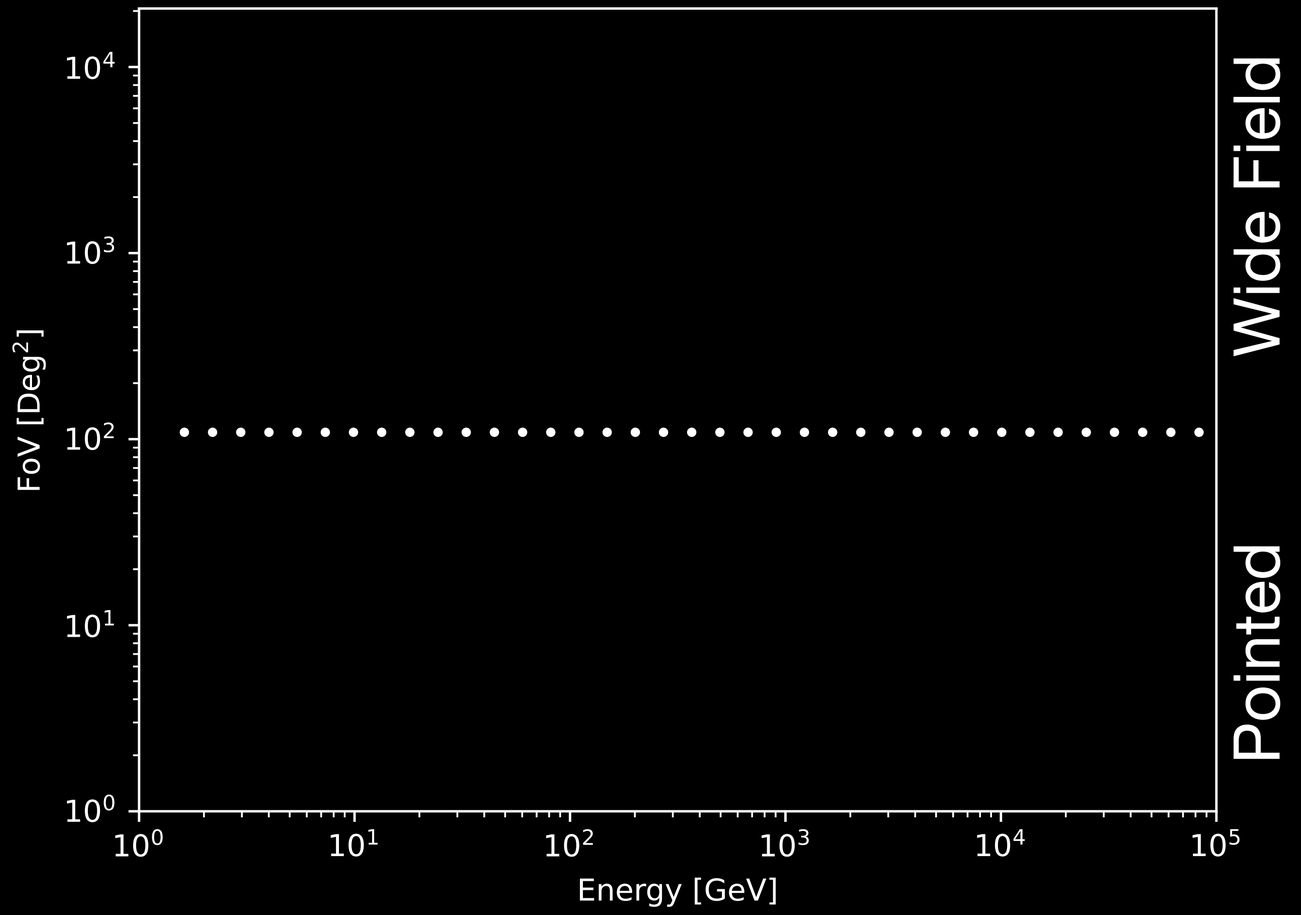


Reconstructed γ-ray direction

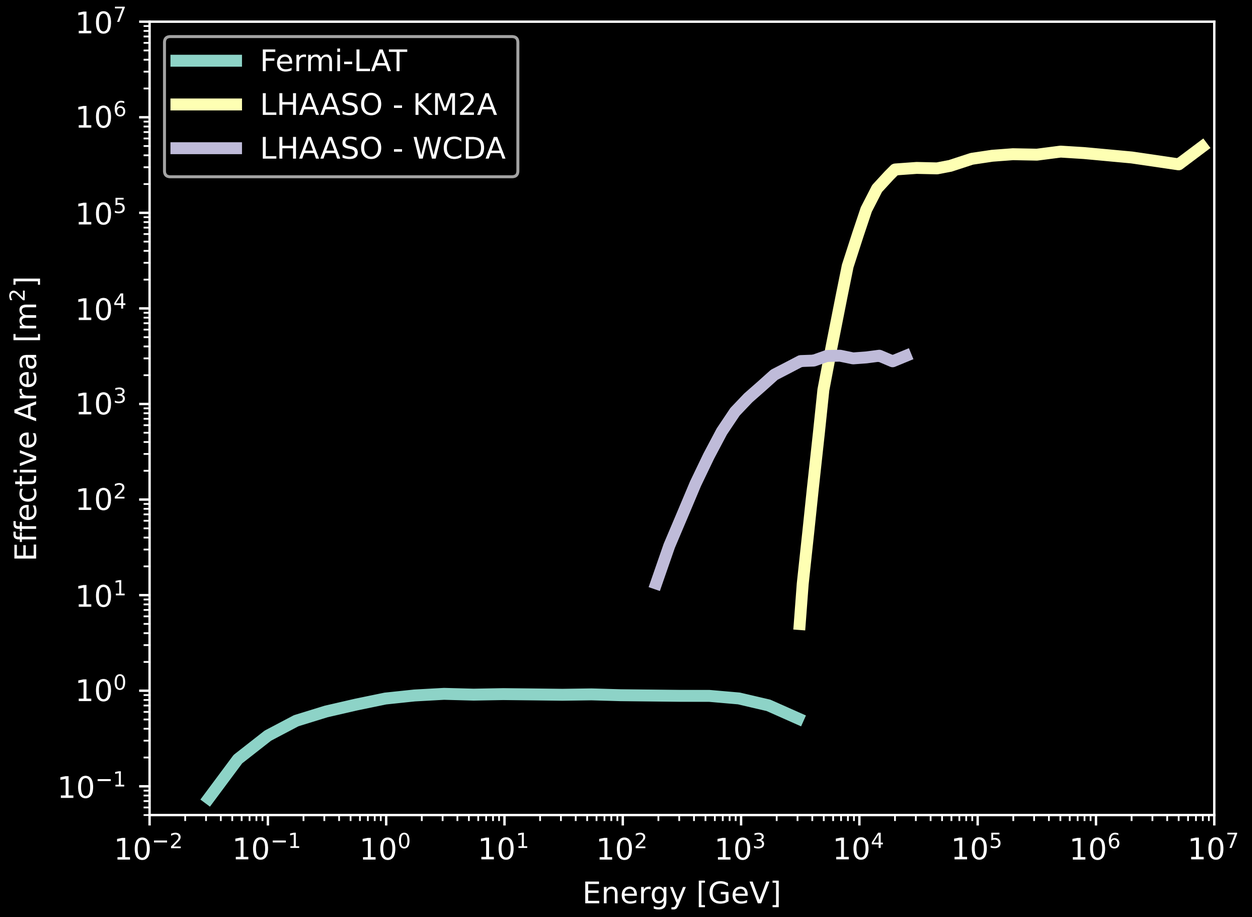


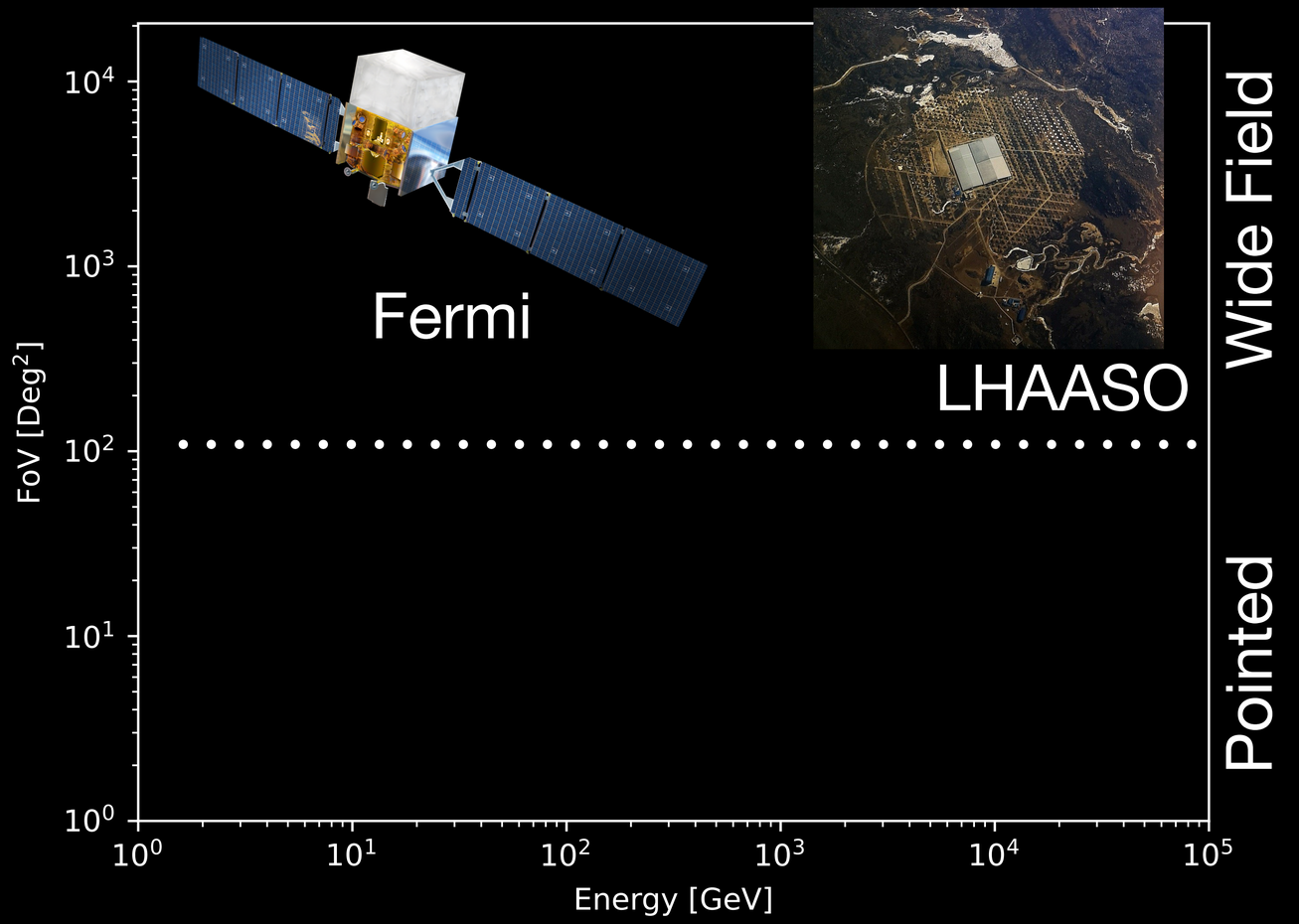
- Large γ-ray collection area (~10^5 m^2)
- High Cosmic-ray background
- Event Reconstruction from EAS
  - Primary type (γ-ray or CR)
  - Energy Estimation
  - Direction reconstruction





- Wide field (LAT, LHAASO) and Pointed (IACTs) provide complementary coverage from GeV to PeV
- IACTs provide deeper exposure with better PSF than wide field instruments





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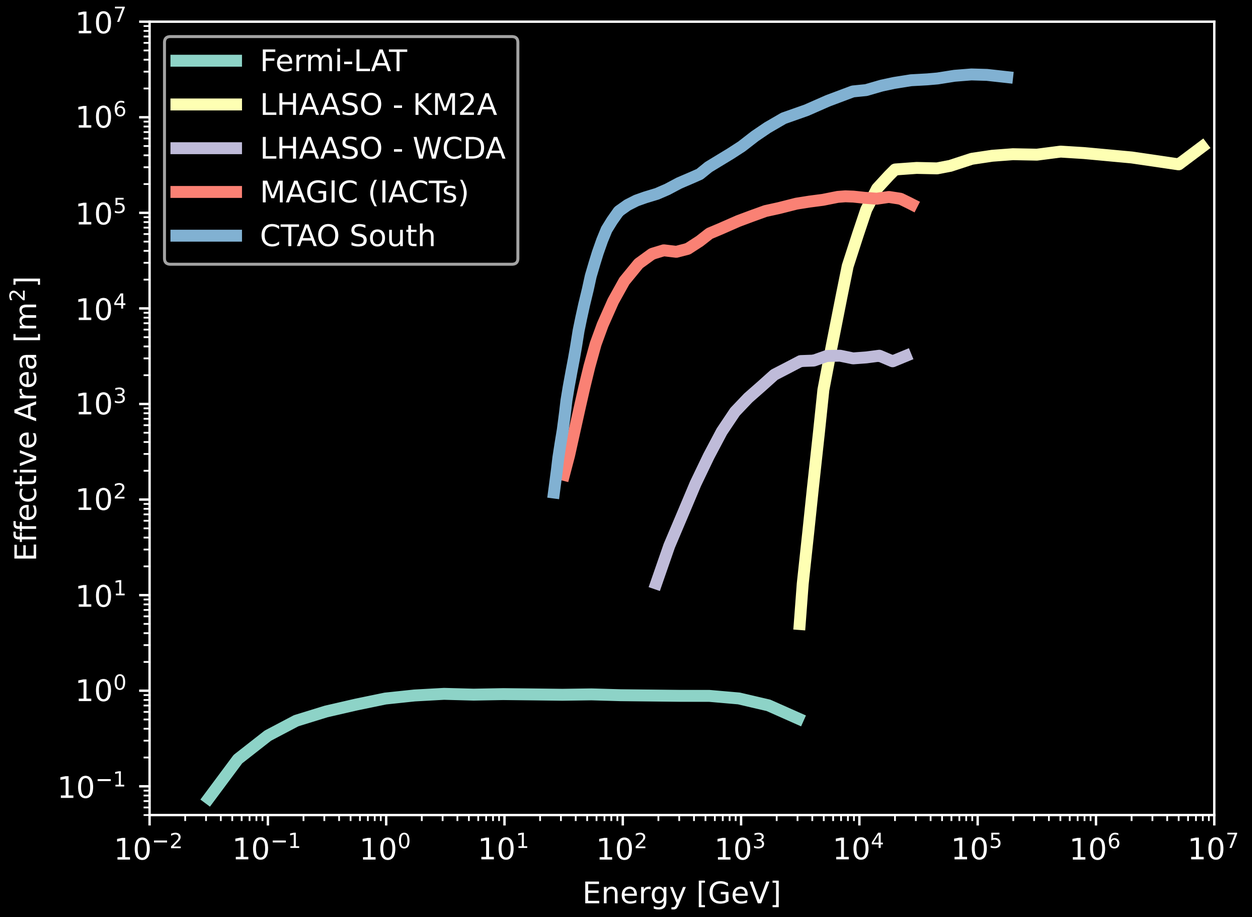
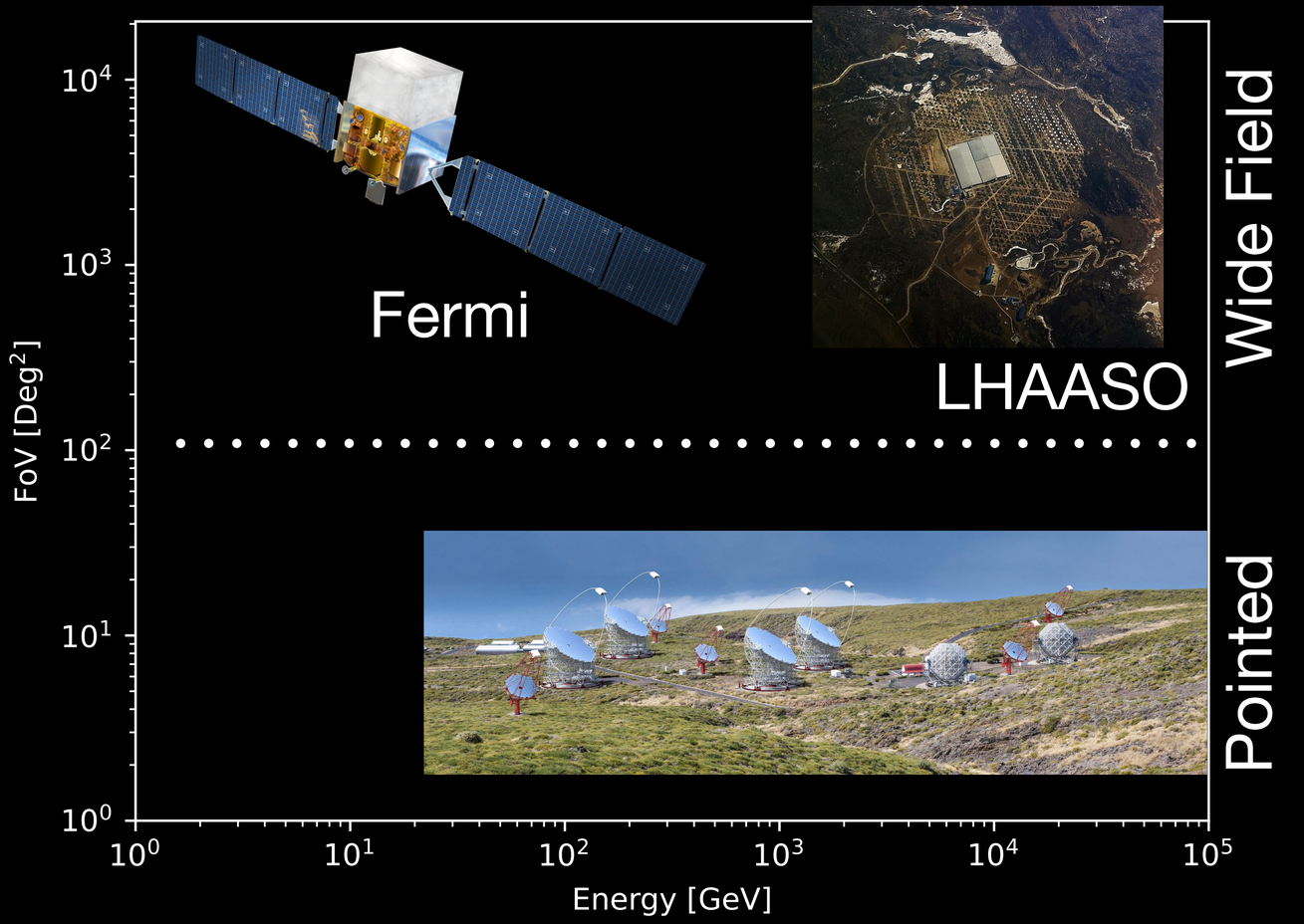
- IACTs provide deeper exposure with better PSF than wide field instruments

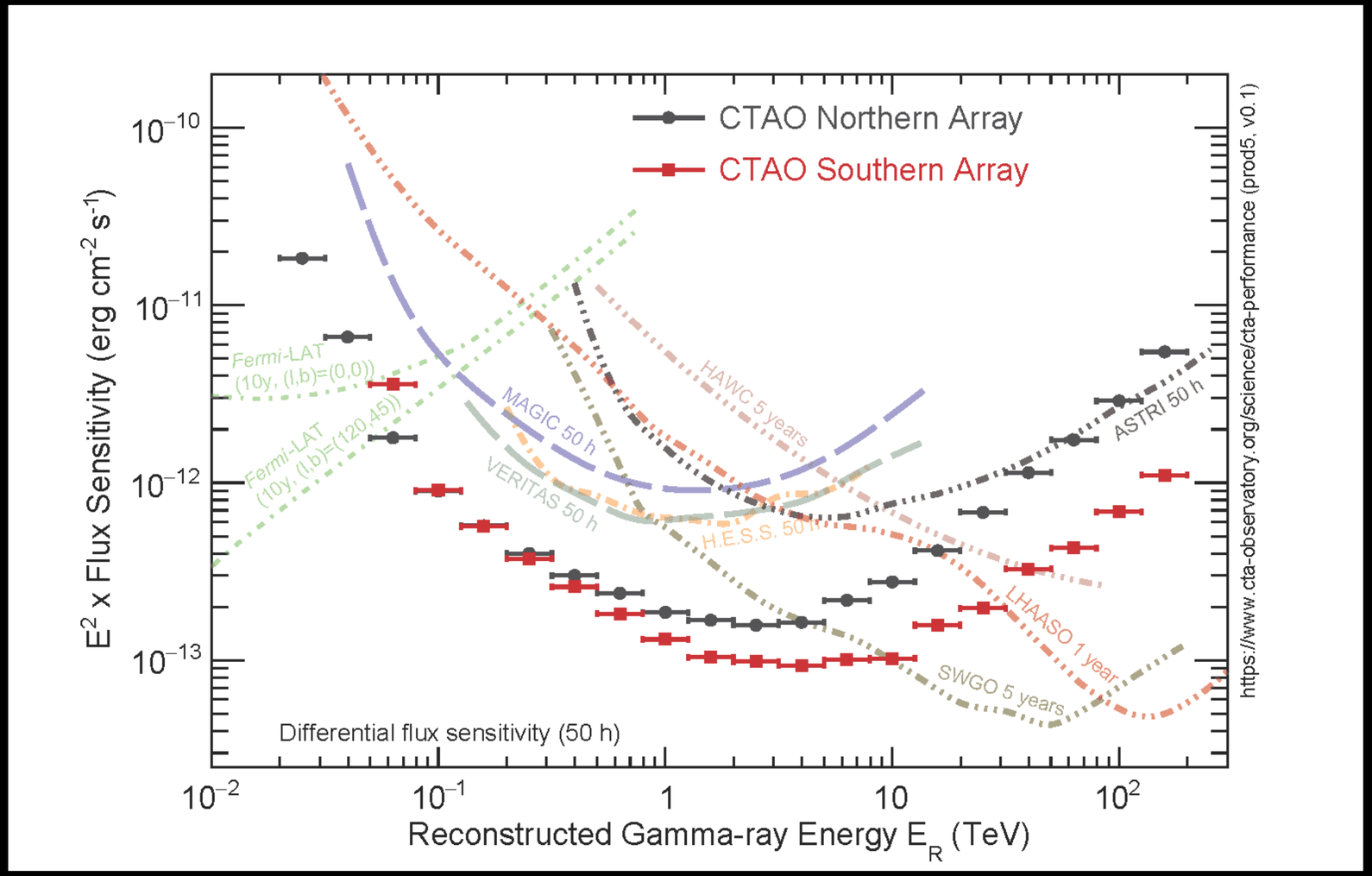




- Wide field (LAT, LHAASO) and Pointed (IACTs) provide complementary coverage from GeV to PeV
- IACTs provide deeper exposure with better PSF than wide field instruments

The Current Era and Future (2020s++)

- Complementary nature between wide field telescopes (LHAASO, SWGO) and pointed instruments (CTAO)
- CTAO has:
  - Deeper observations
  - Better short time-scale sensitivity
  - Improved PSF
- Wide Field telescopes have:
  - Better duty cycle
  - Wider Field of View
  - Natural survey capabilities



Conclusions

- Gamma-rays are relativity new field of astronomy
- Lots of discovery potential
- Complementary nature between different types of gamma-ray observatories/telescopes