Gamma-ray astronomy

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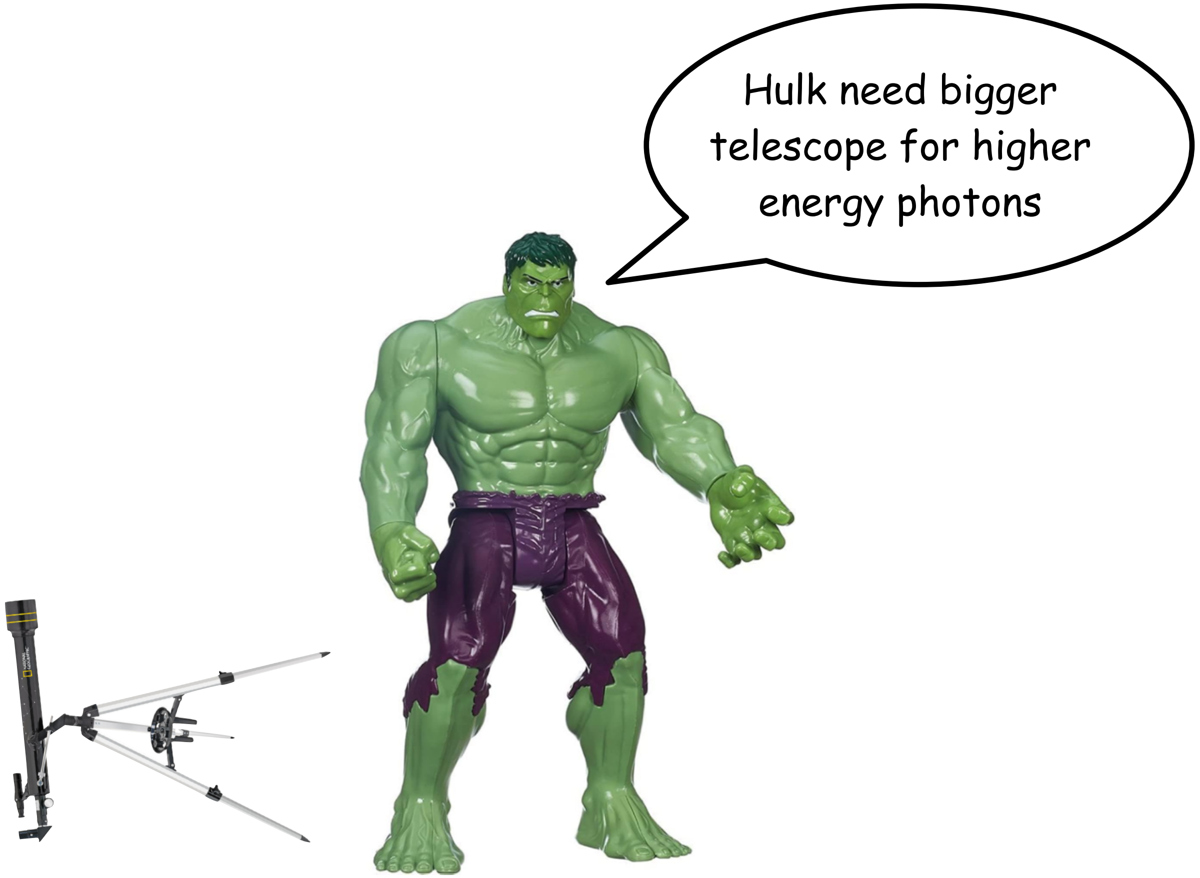
DESY summer students 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

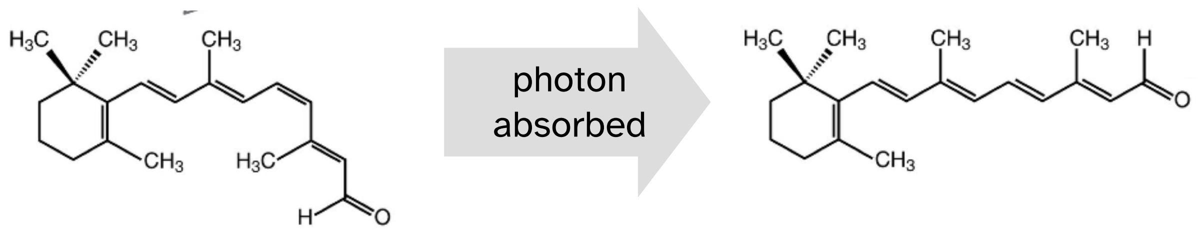
Part 2. How do we detect gamma rays?



How optical photons interact with matter

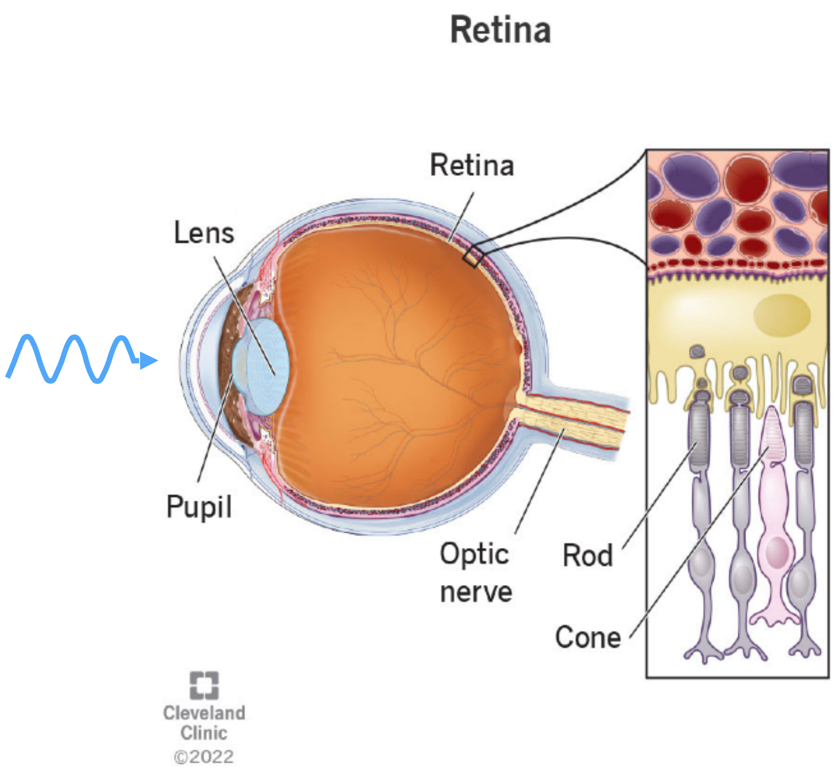
photons -> electric signals

The back of the human eye has photoreceptors that directly **absorb photons** at optical/visible wavelengths and convert them into electric signals



(a) 11-*cis*-retinal (b) all-*trans*-retinal

[Anatomy & Physiology, Connexions]

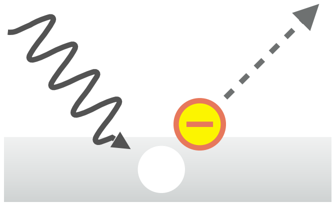


How do we do this for gamma rays?

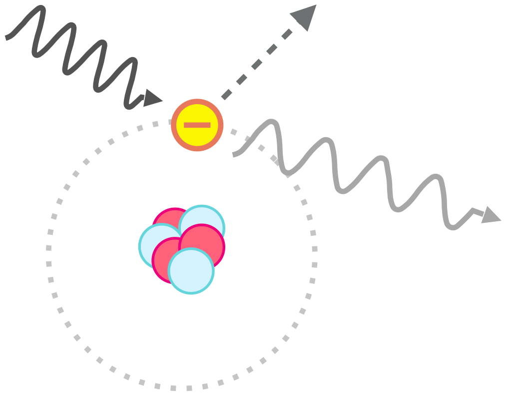
How gamma rays interact with matter

photons -> electric signals

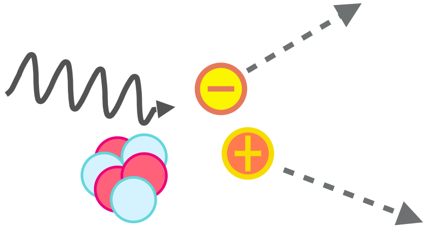
Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



photoelectric effect



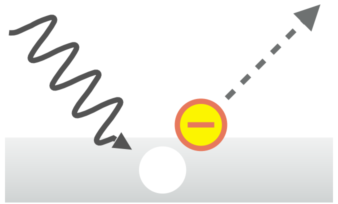
Compton scattering



pair production

How gamma rays interact with matter

Note: The exact shapes of these curves depend on the target material



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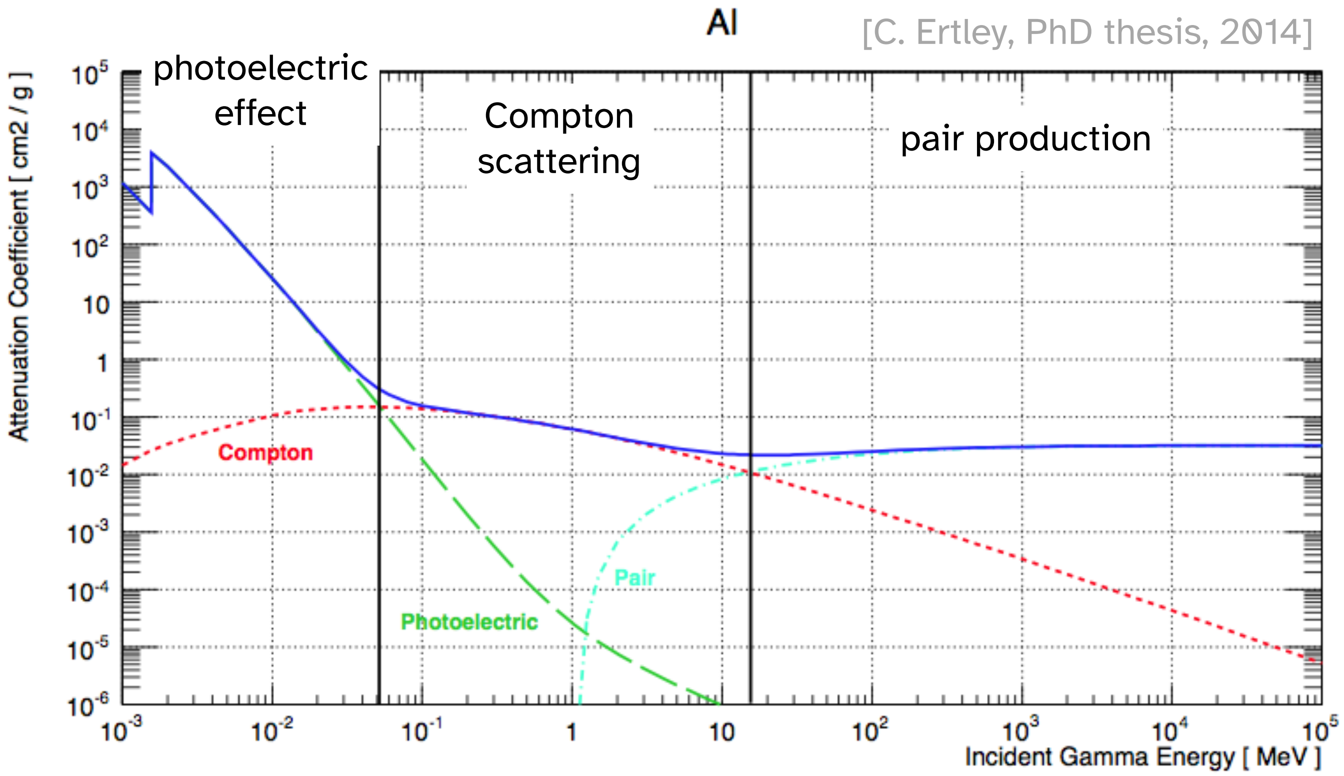

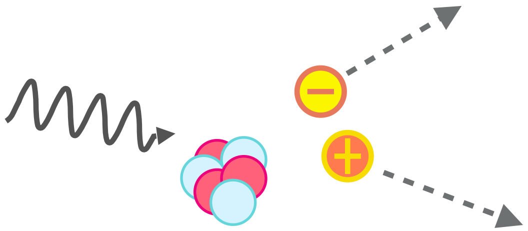

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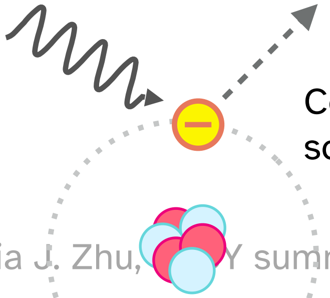

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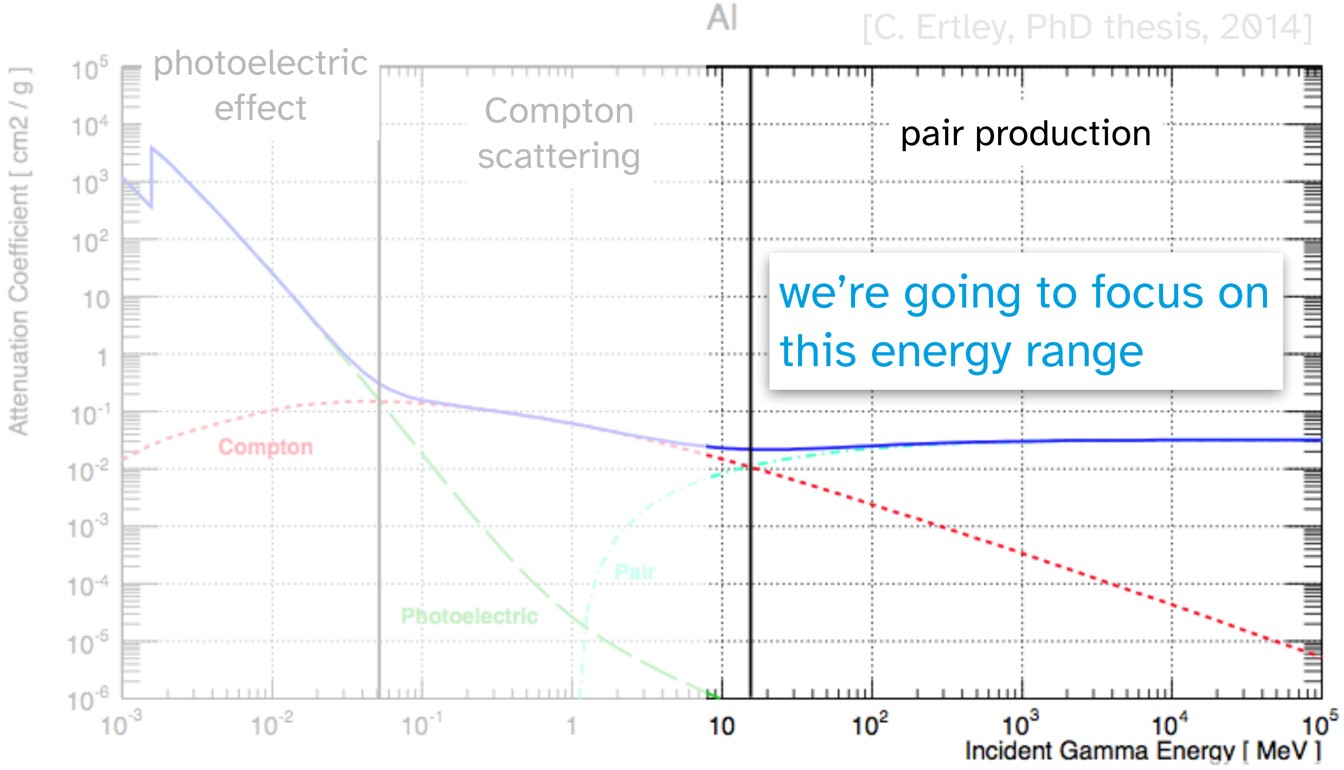

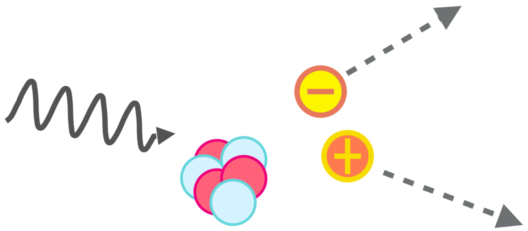

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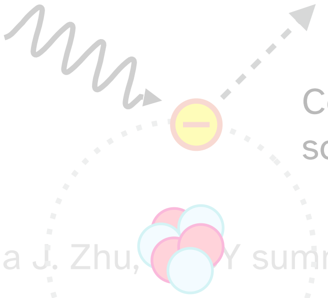
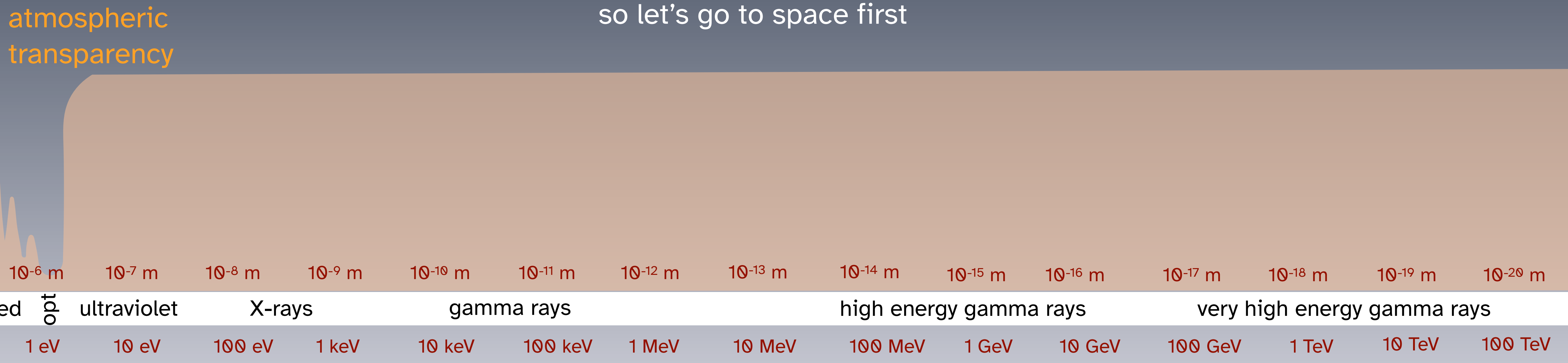


Compton scattering

The electromagnetic spectrum, continued

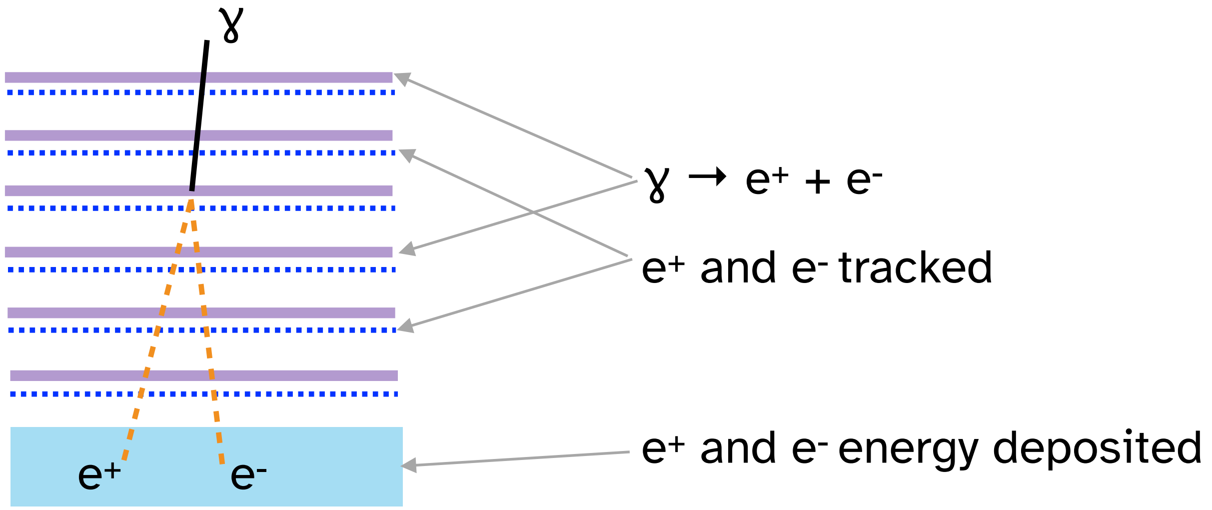
The atmosphere is opaque to gamma rays,
so let's go to space first

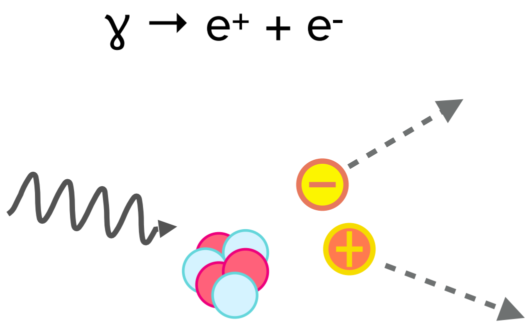


How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy





In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

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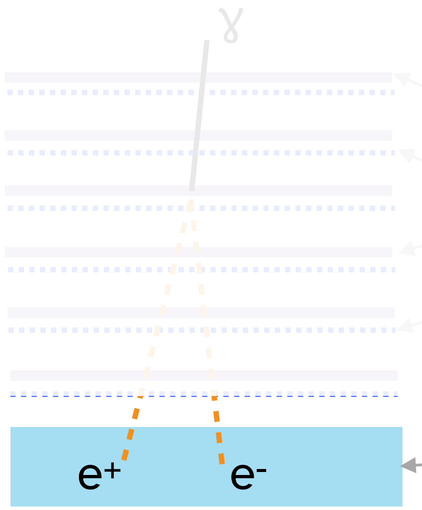

γ → $e^+ + e^-$

e^+ and e^- tracked

e^+ and e^- energy deposited

What exactly is happening here?

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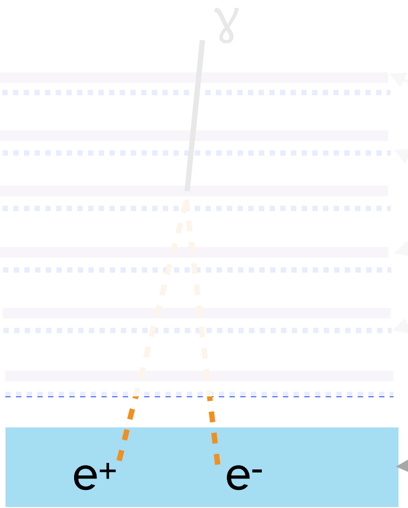

$\gamma \rightarrow e^+ + e^-$

e^+ and e^- tracked

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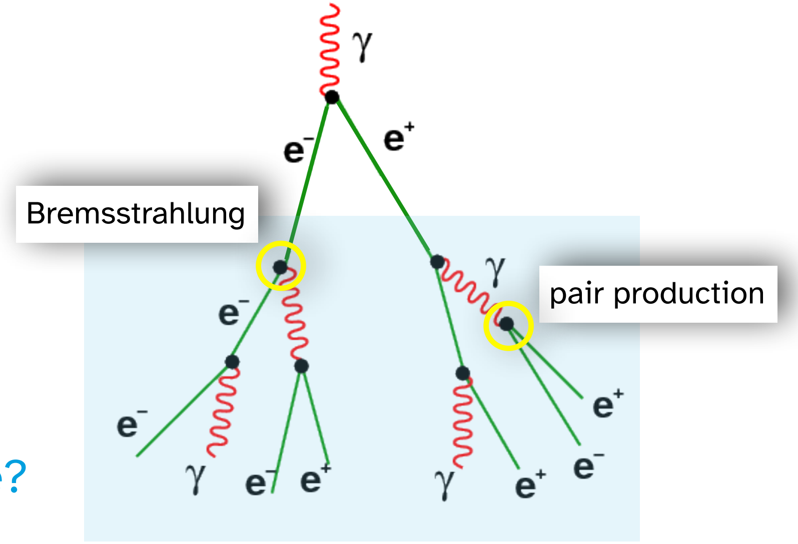
What exactly is happening here?

electromagnetic shower



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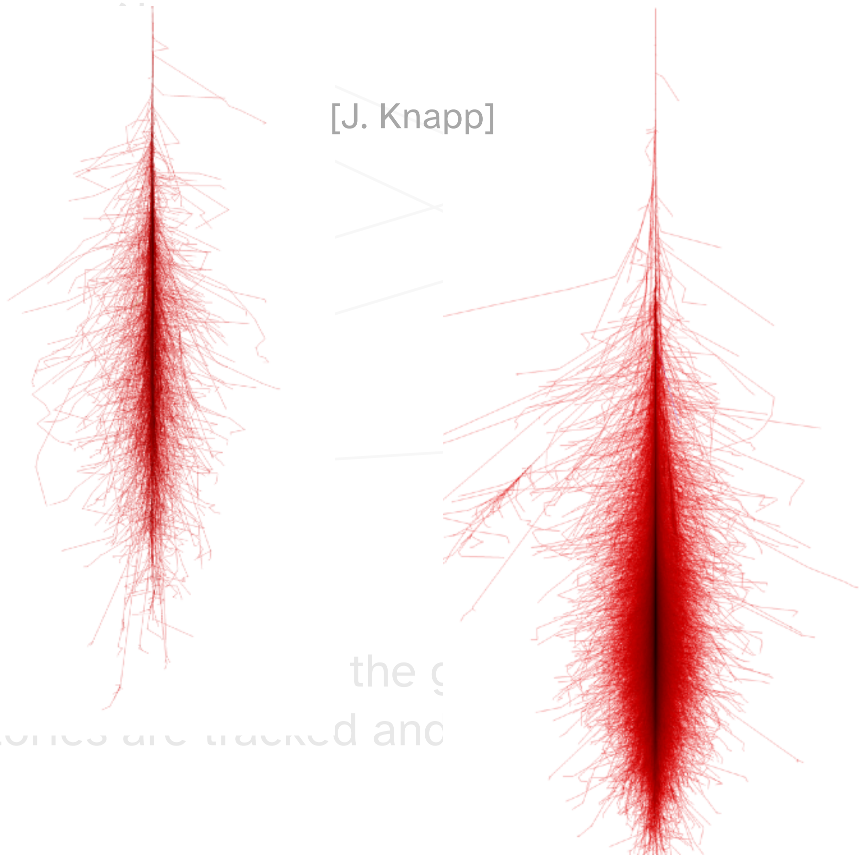
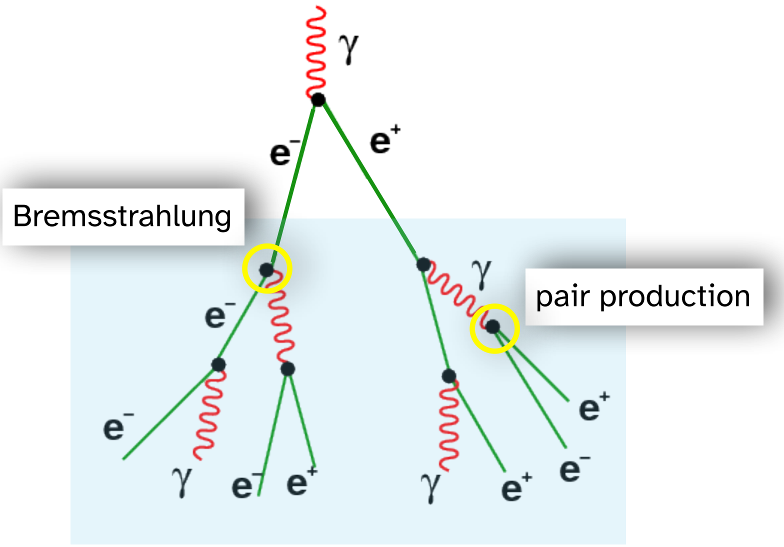


d

/ deposited



In pair-conve … the g … verted into electron-positron pairs, whose trajec… …d and … ured

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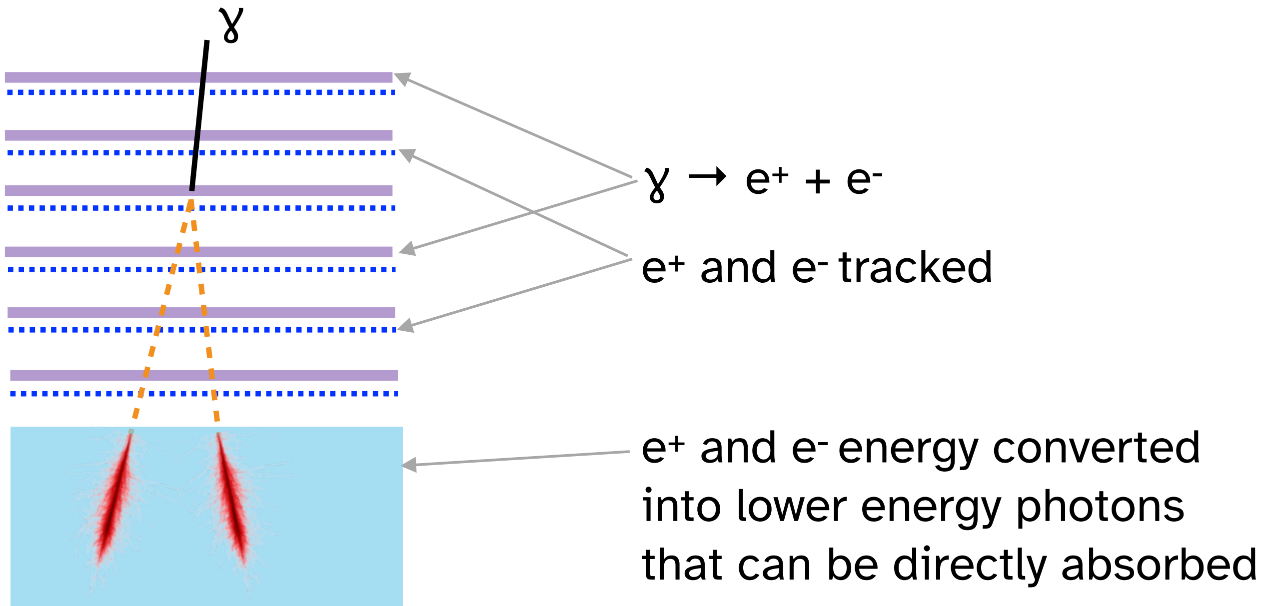

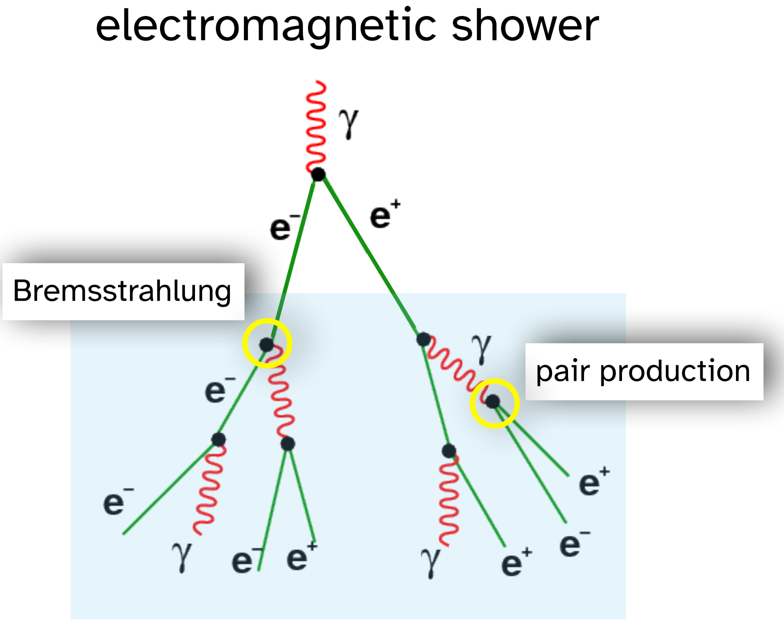

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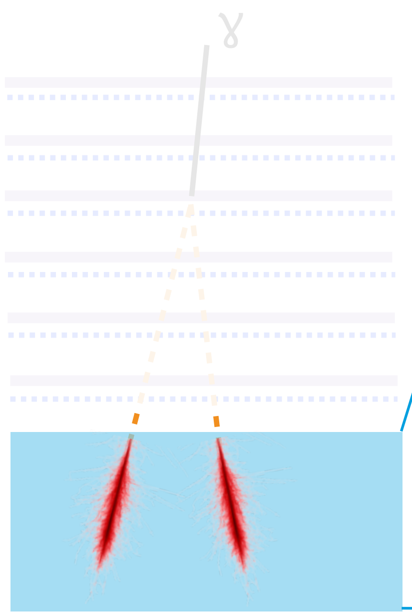
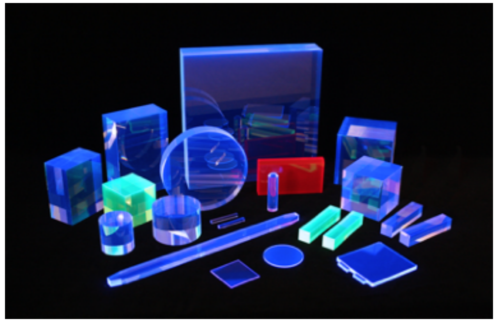
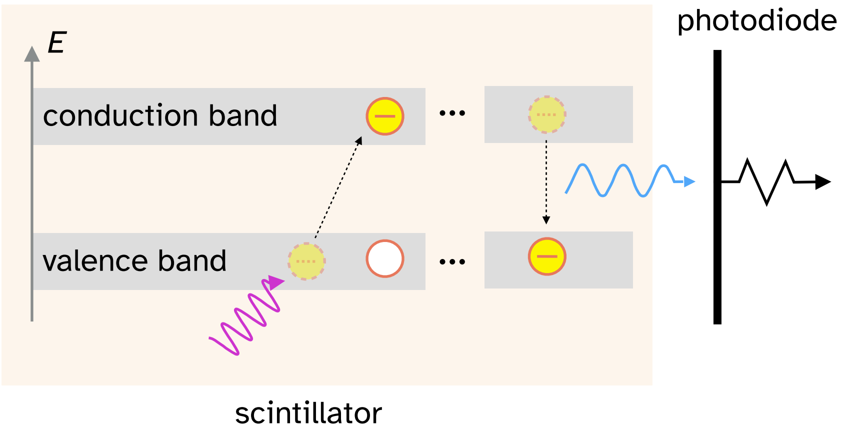


Scintillators absorb higher energy photons or charged particles, then reemit the energy in lower energy (UV, optical) photons



[Eljen Technology]



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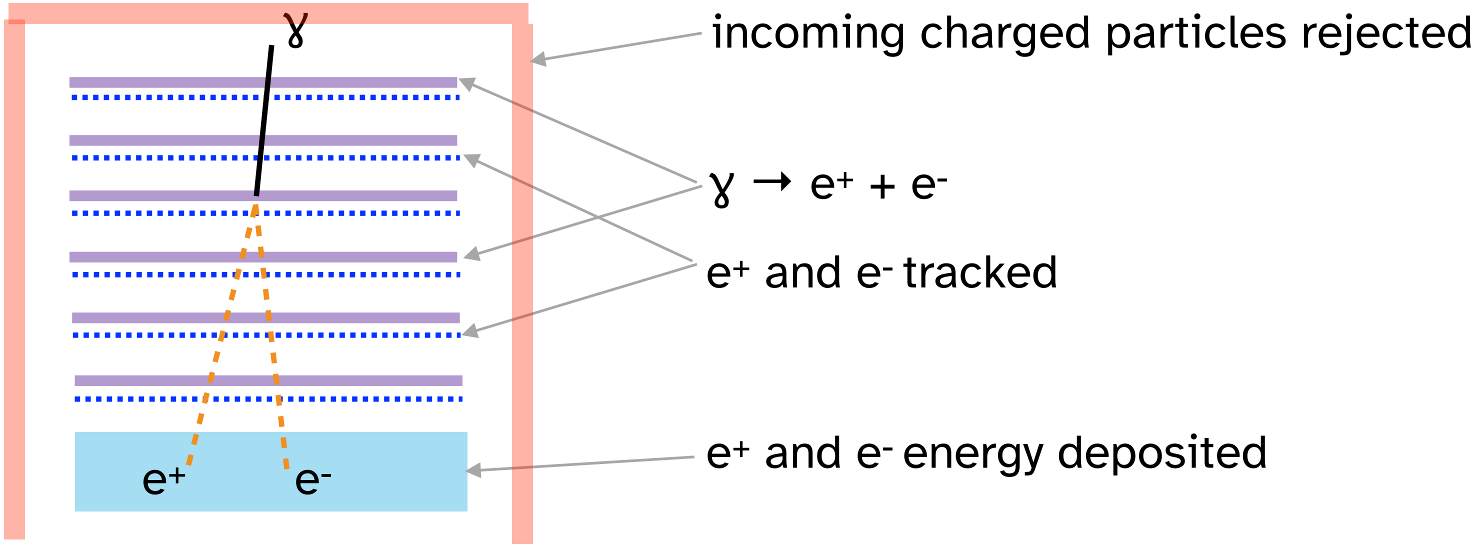

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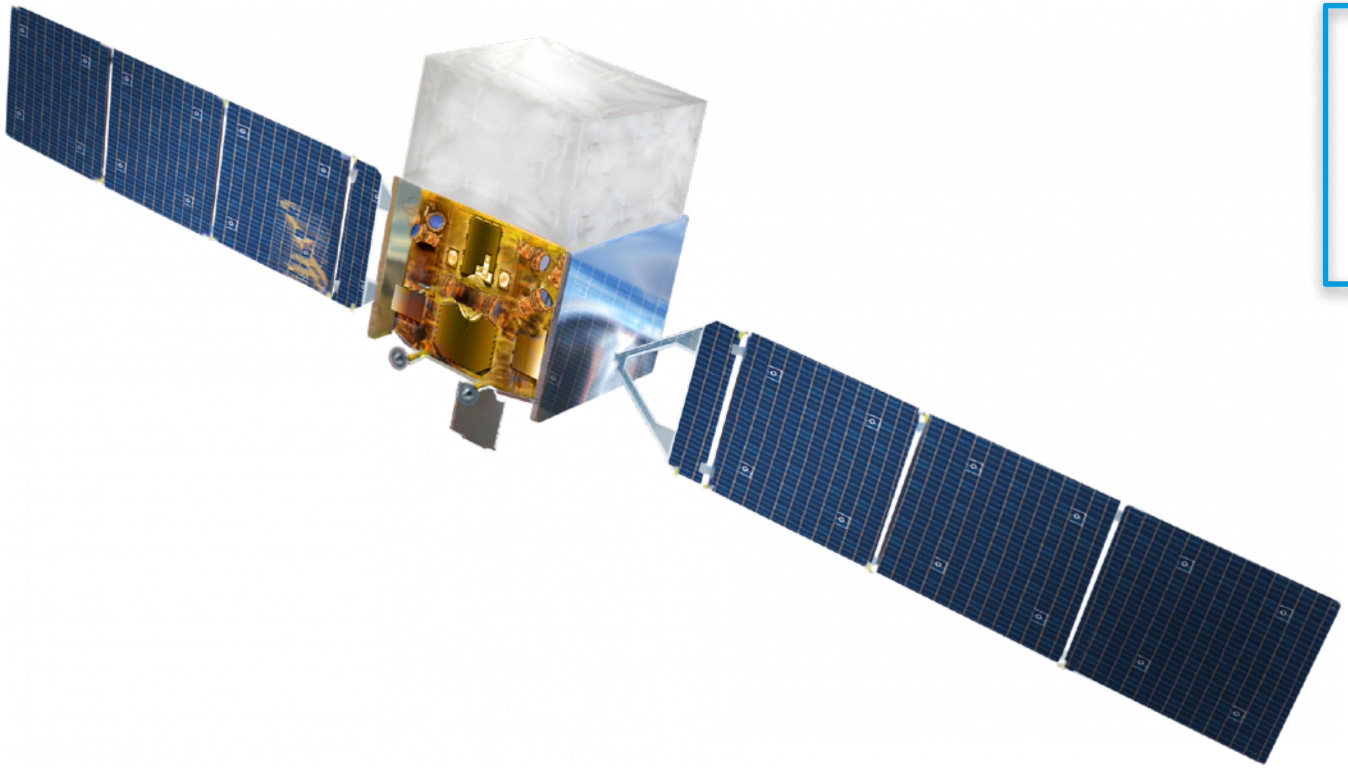

[NASA/DOE/Fermi-LAT]

Fermi Large Area Telescope

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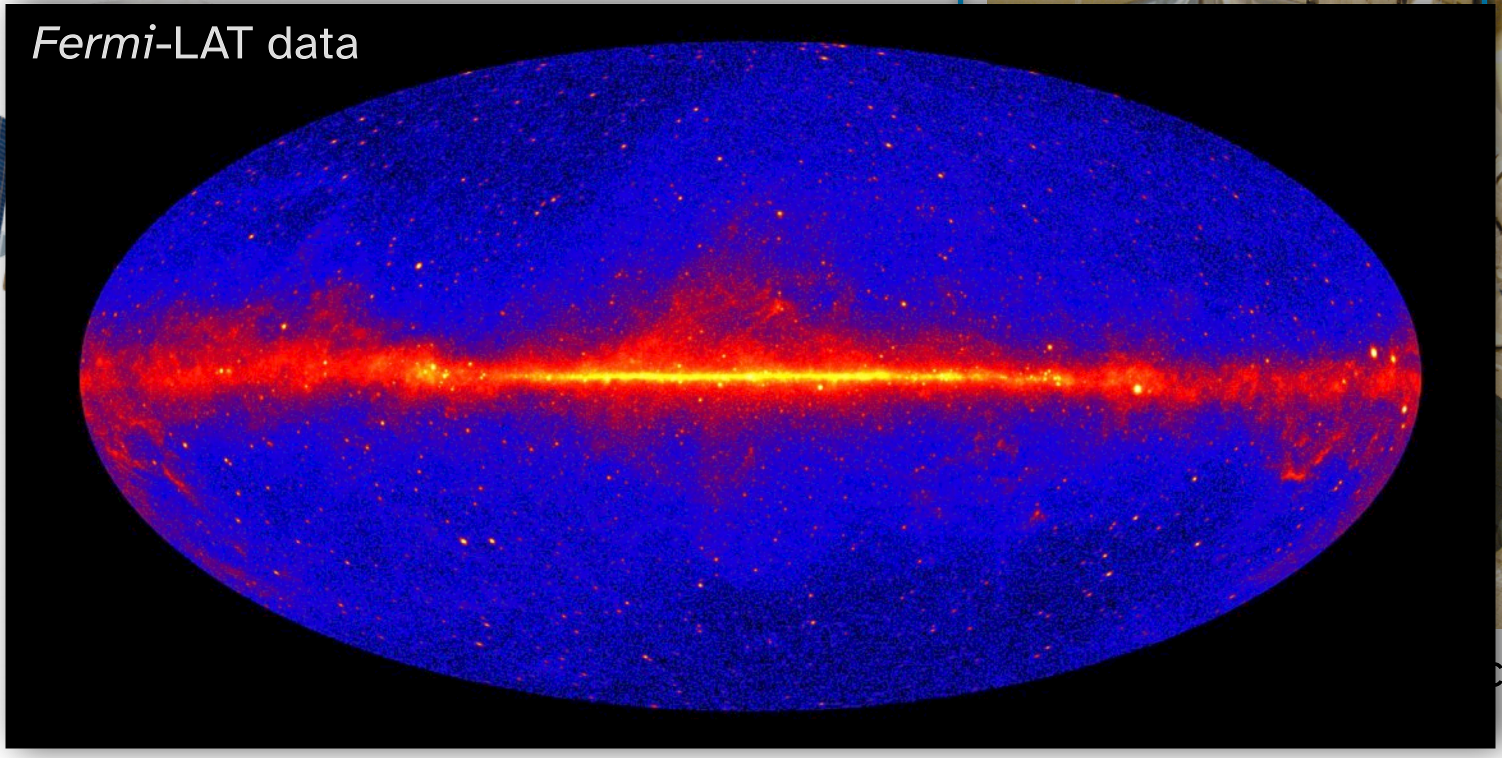
How gamma rays interact with matter: pair production

Pair-conversion telescopes

[NASA/DOE/Fermi-LAT]



cope

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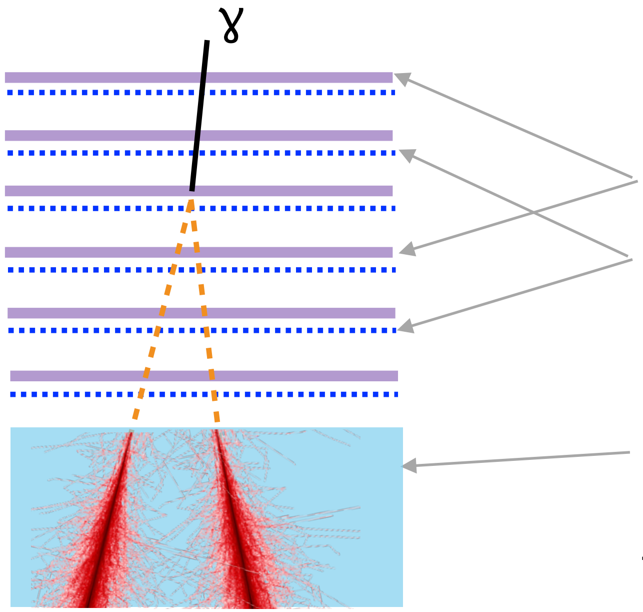
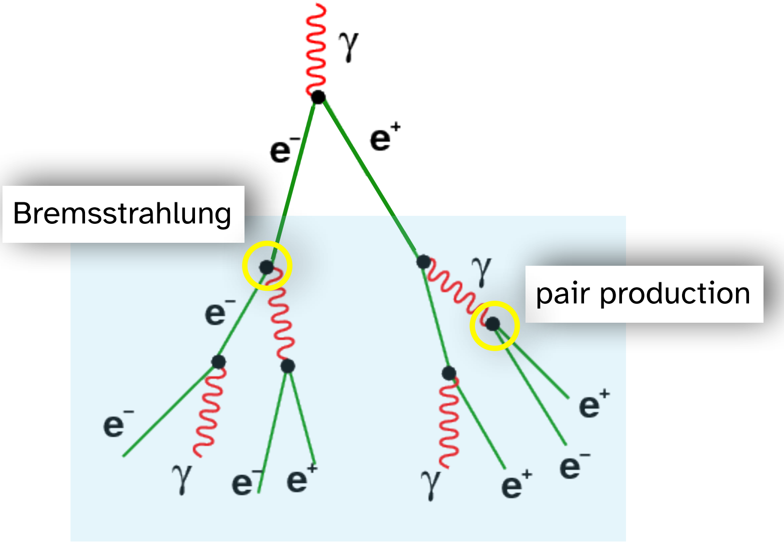
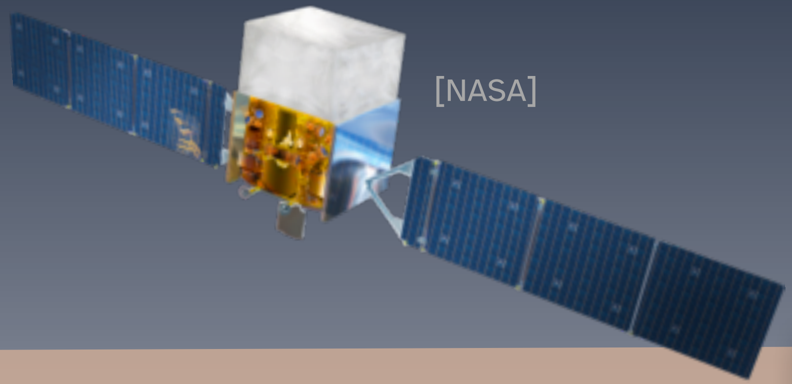


electromagnetic shower

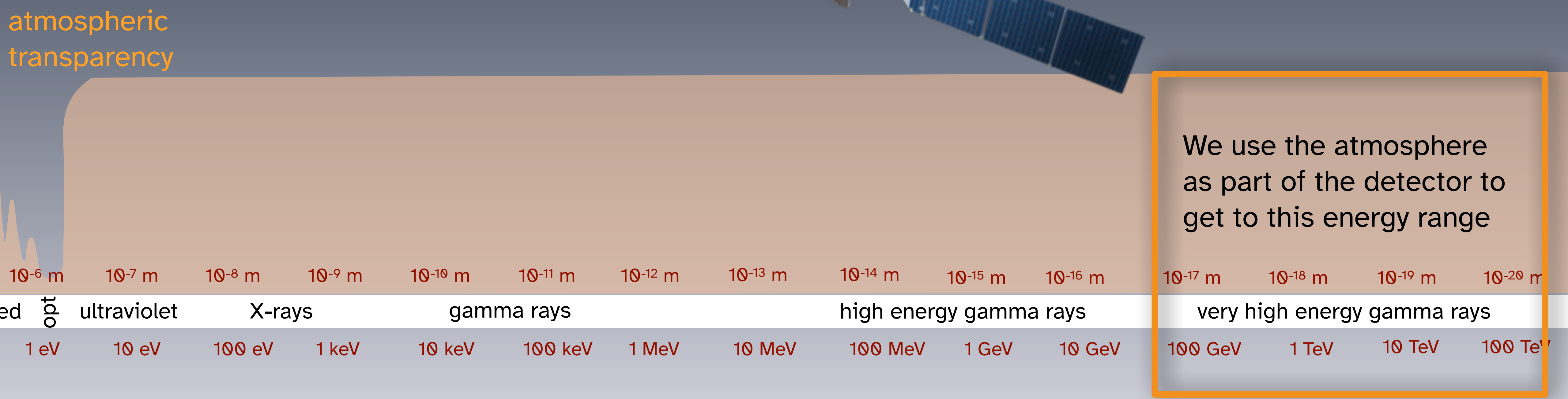


When the initial photon energy is too high, the shower can't be contained within the detector
-> space-based telescopes can't go above ~100s of GeV (plus the issue of collecting area)

The electromagnetic spectrum, continued



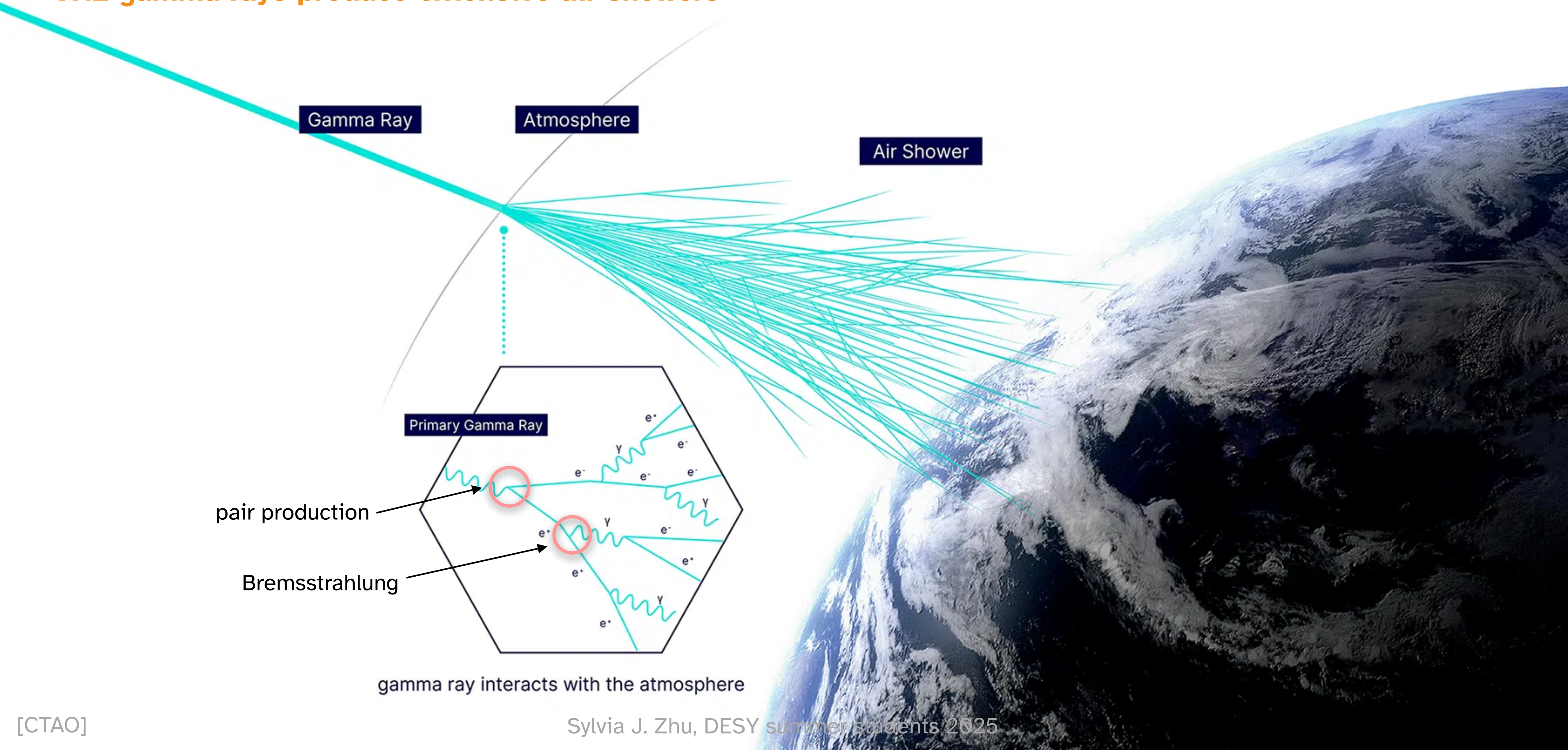
[NASA]



Use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers

VHE: Very High Energy
(>100 GeV)



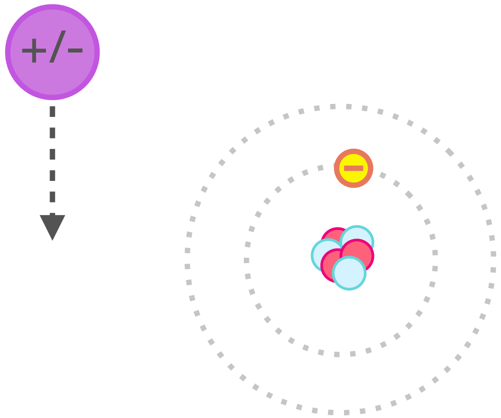
gamma ray interacts with the atmosphere

[CTAO]

Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

electromagnetic equivalent to a sonic boom



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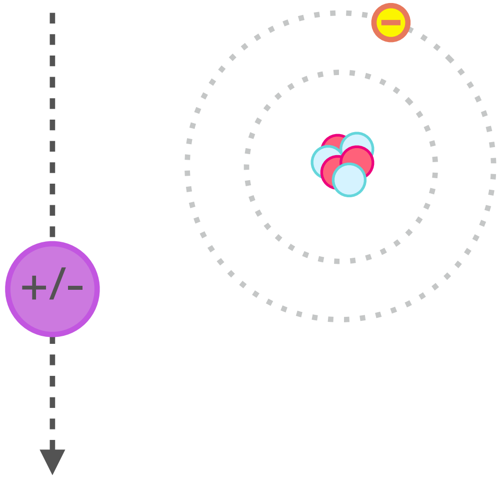

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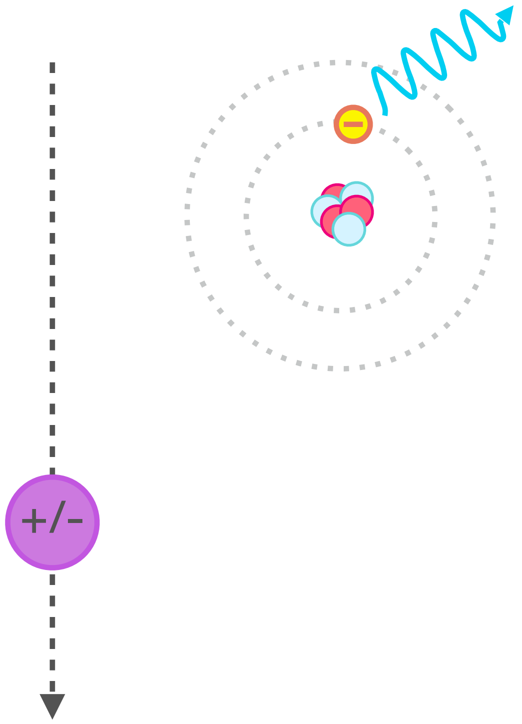

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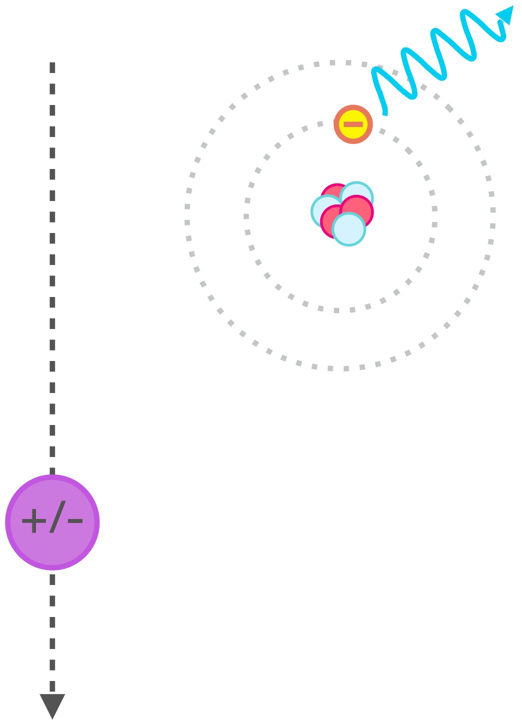


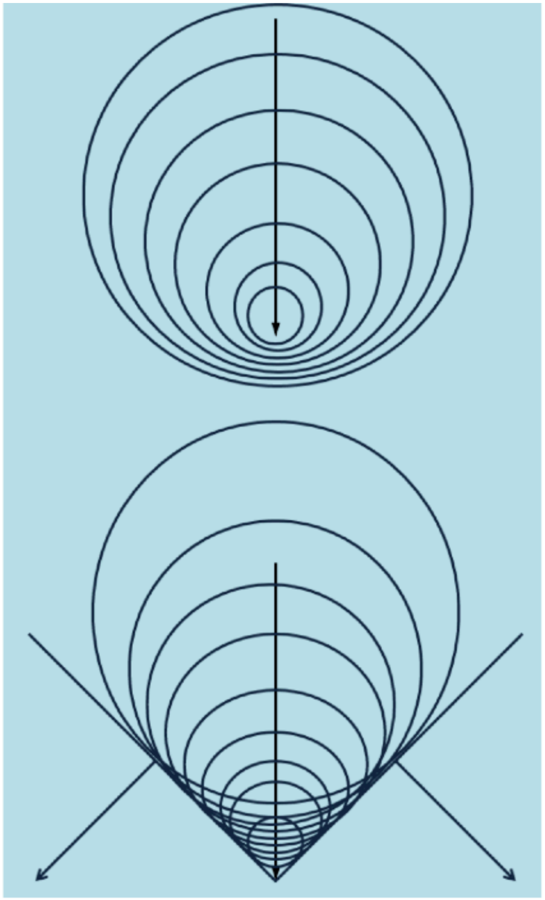
[J. Eckhard]

v < c/n:

no wavefront

v > c/n:

wavefront



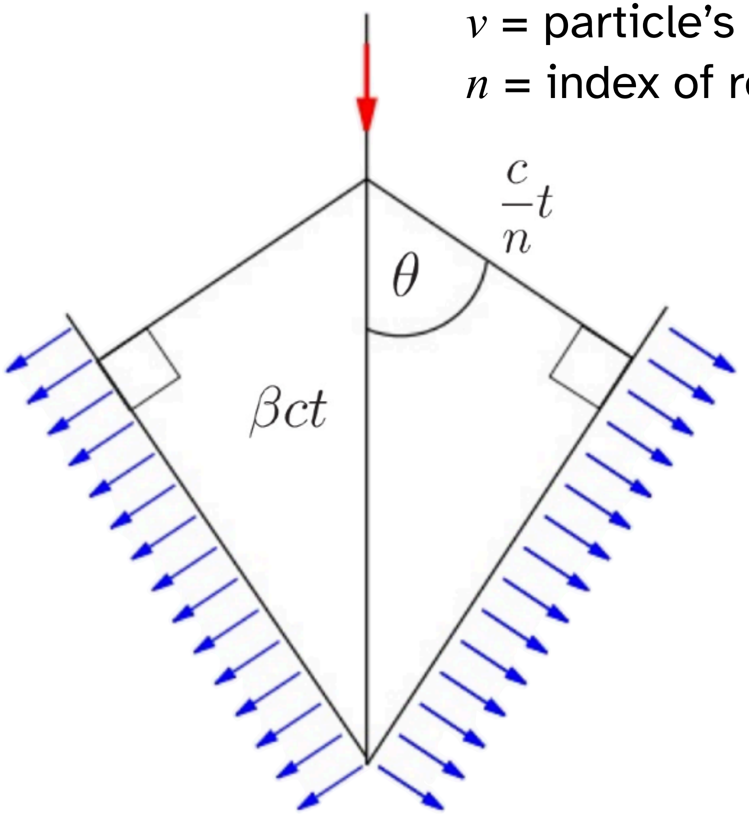
Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

electromagnetic equivalent to a sonic boom

v = particle's speed
n = index of refraction of air

$$\beta = \frac{v}{c}$$

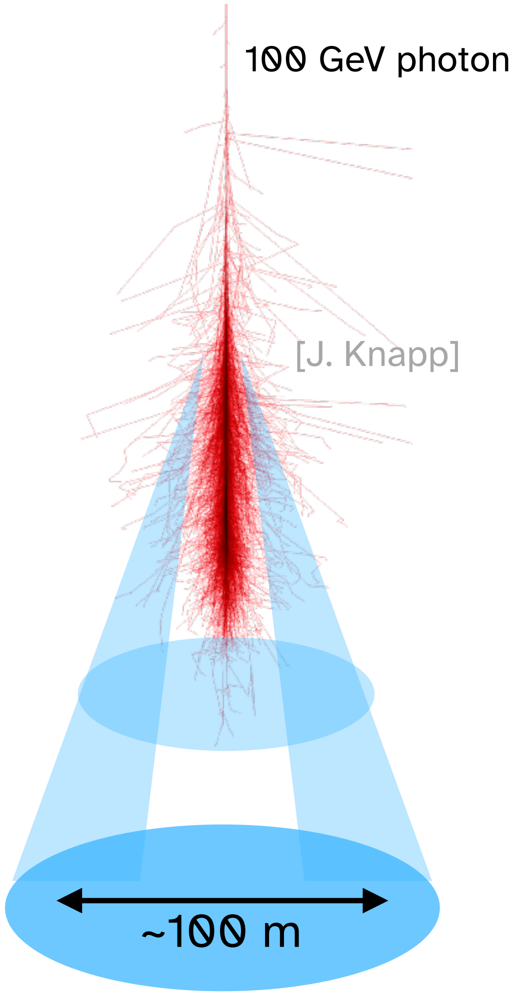


modified from [J. Eckhard]

$$\theta = \arccos \frac{1}{\beta n}$$

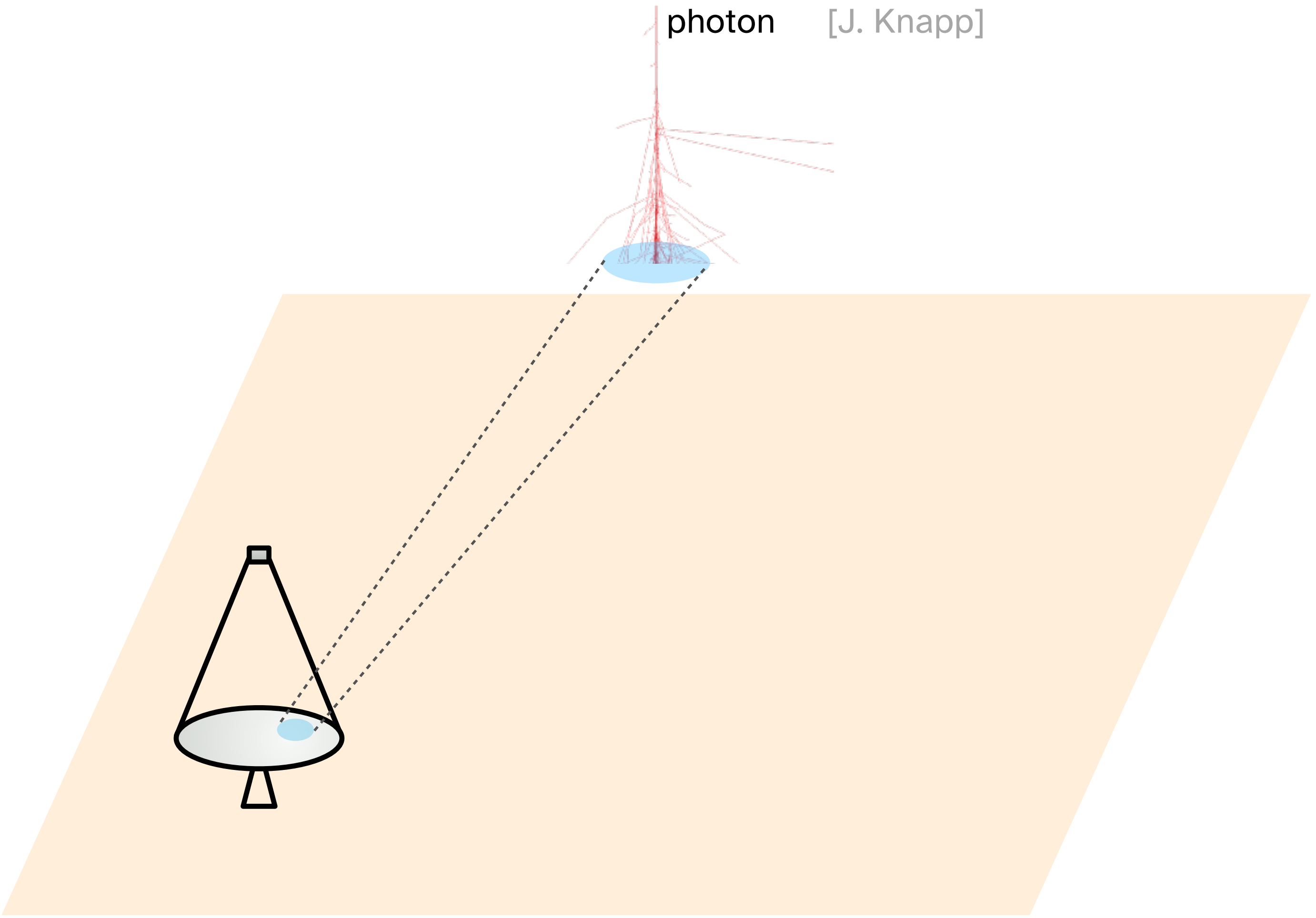
n ~ slightly larger than 1
β ~ 1
=> θ ~ 1°

if shower starts 10 km above ground,
Cherenkov light cone size will be ~100 m



Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a "snapshot" of the pool of Cherenkov light



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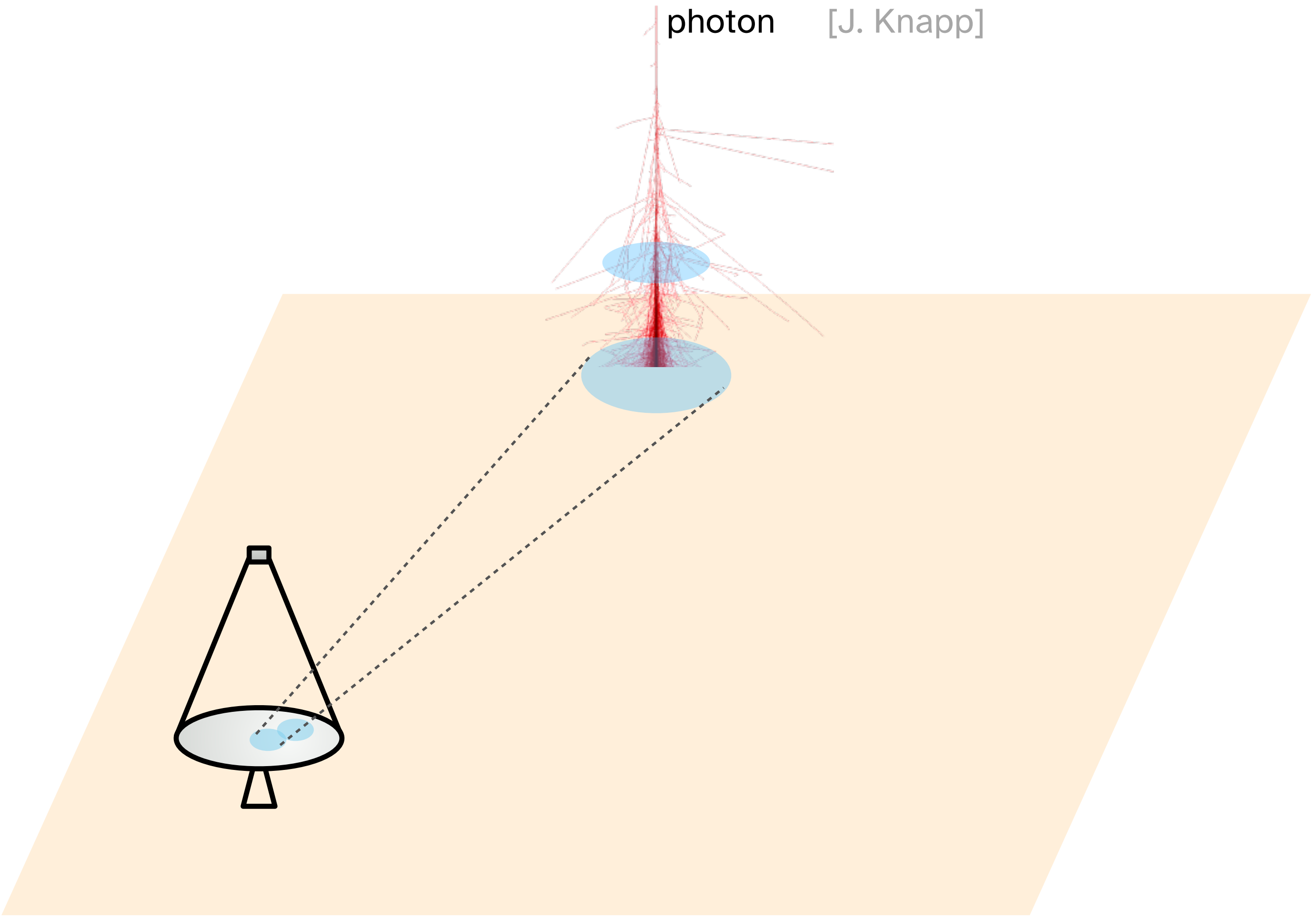

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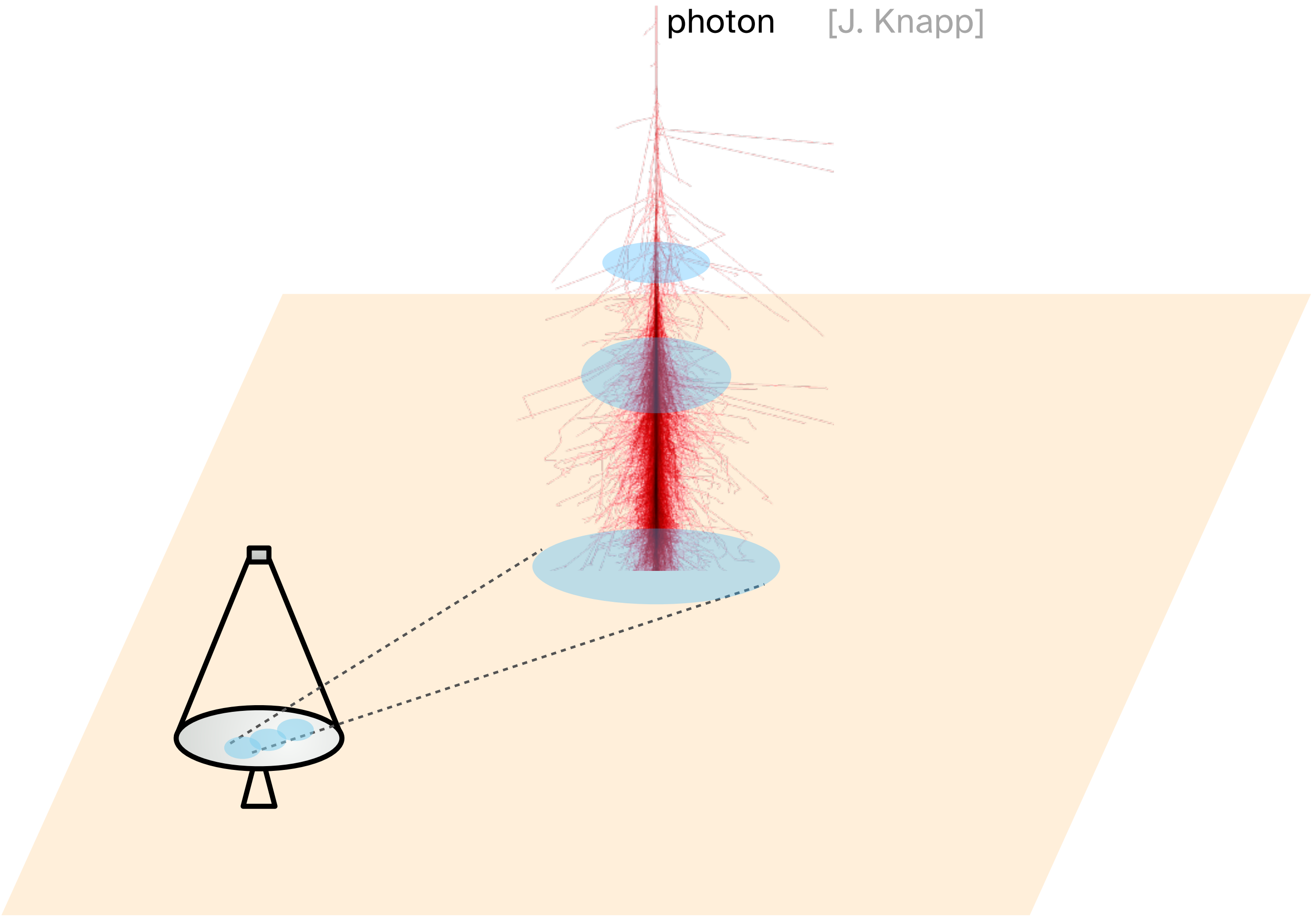

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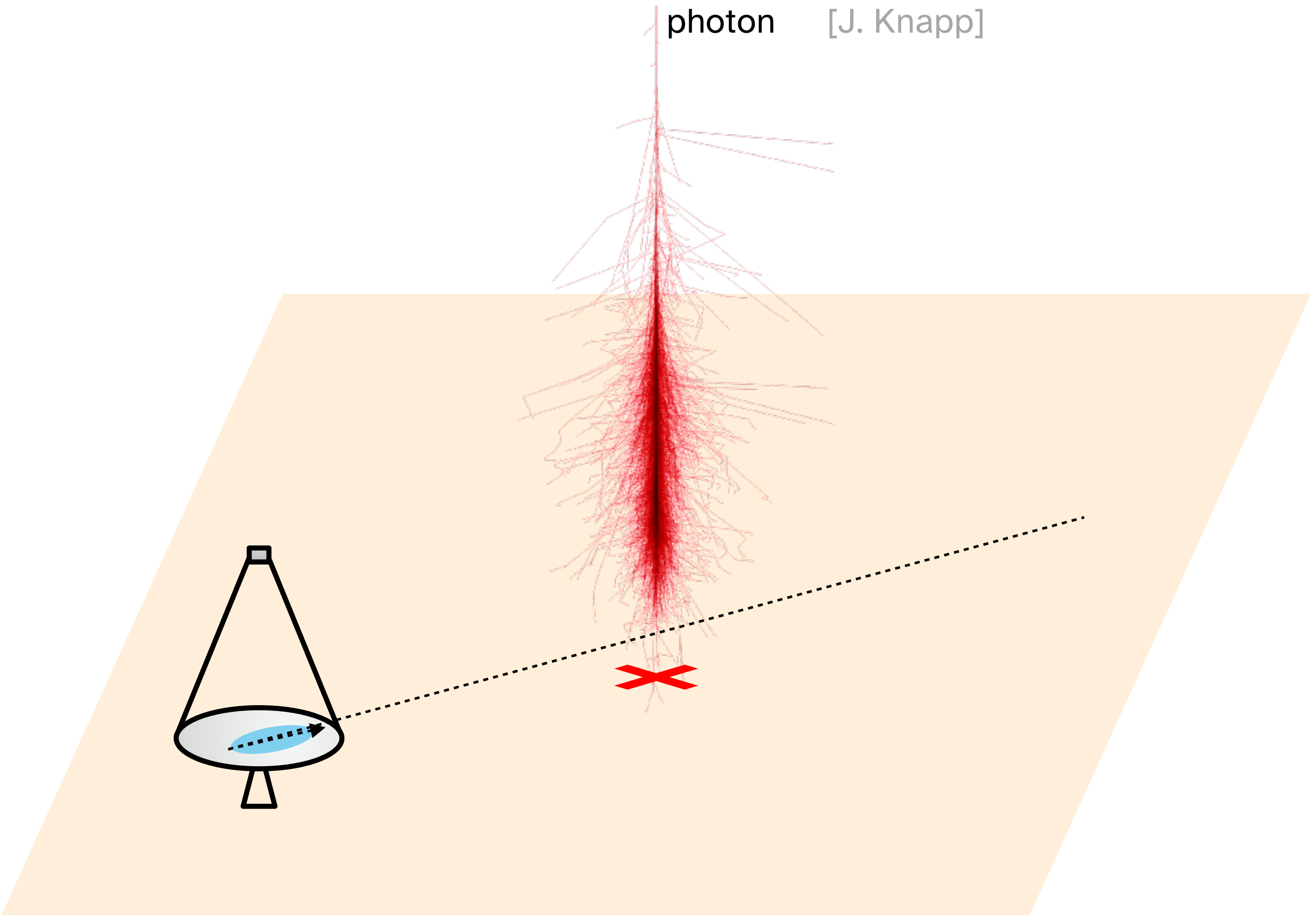

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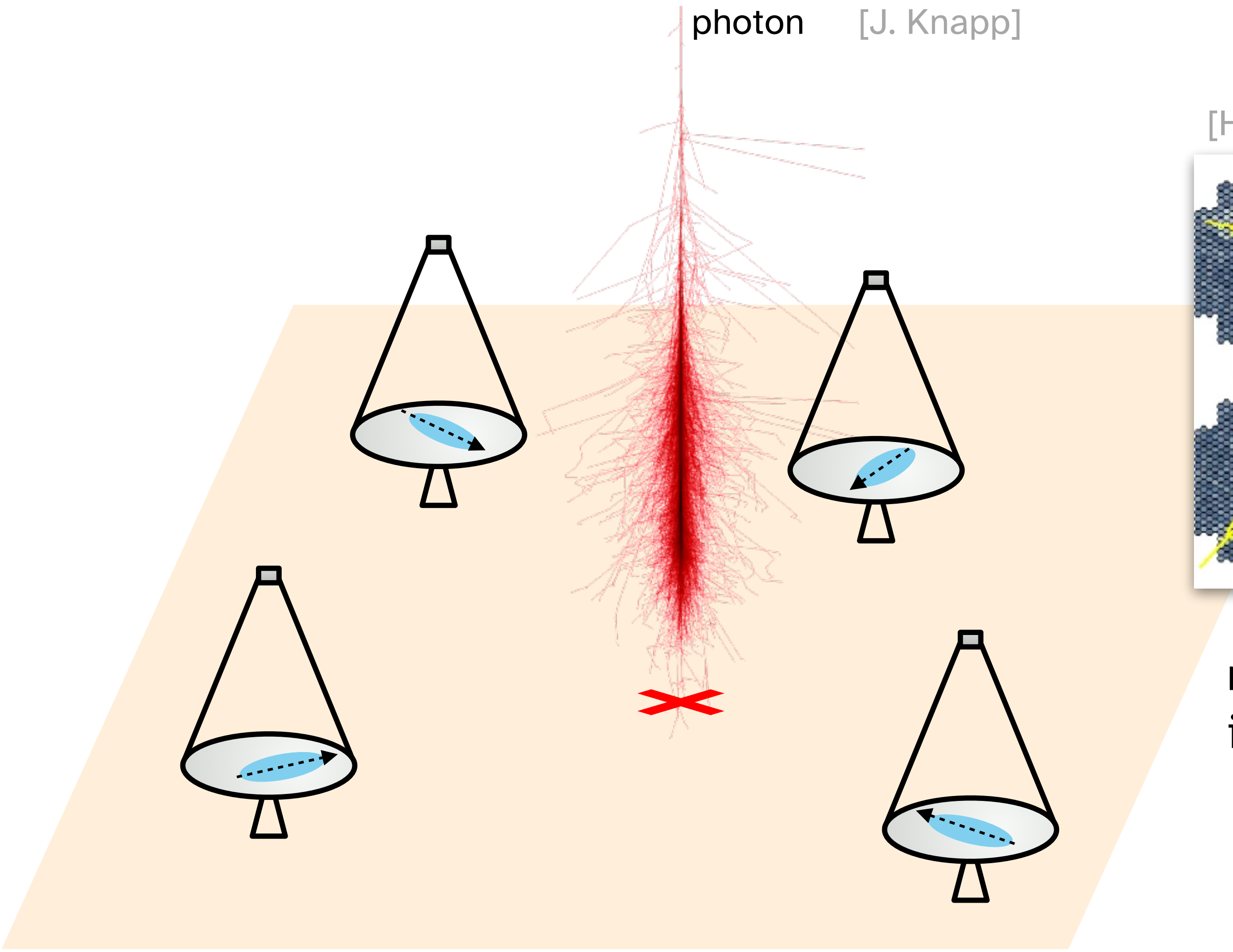
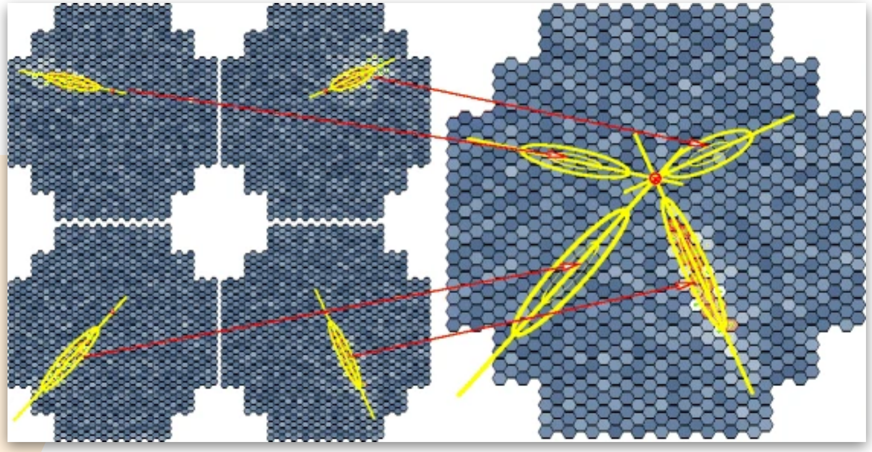


[J. Knapp]

[H. Völk & K. Bernlöhr, ExA 25 (2009)]



main axes -> photon direction
image intensity + geometry -> energy

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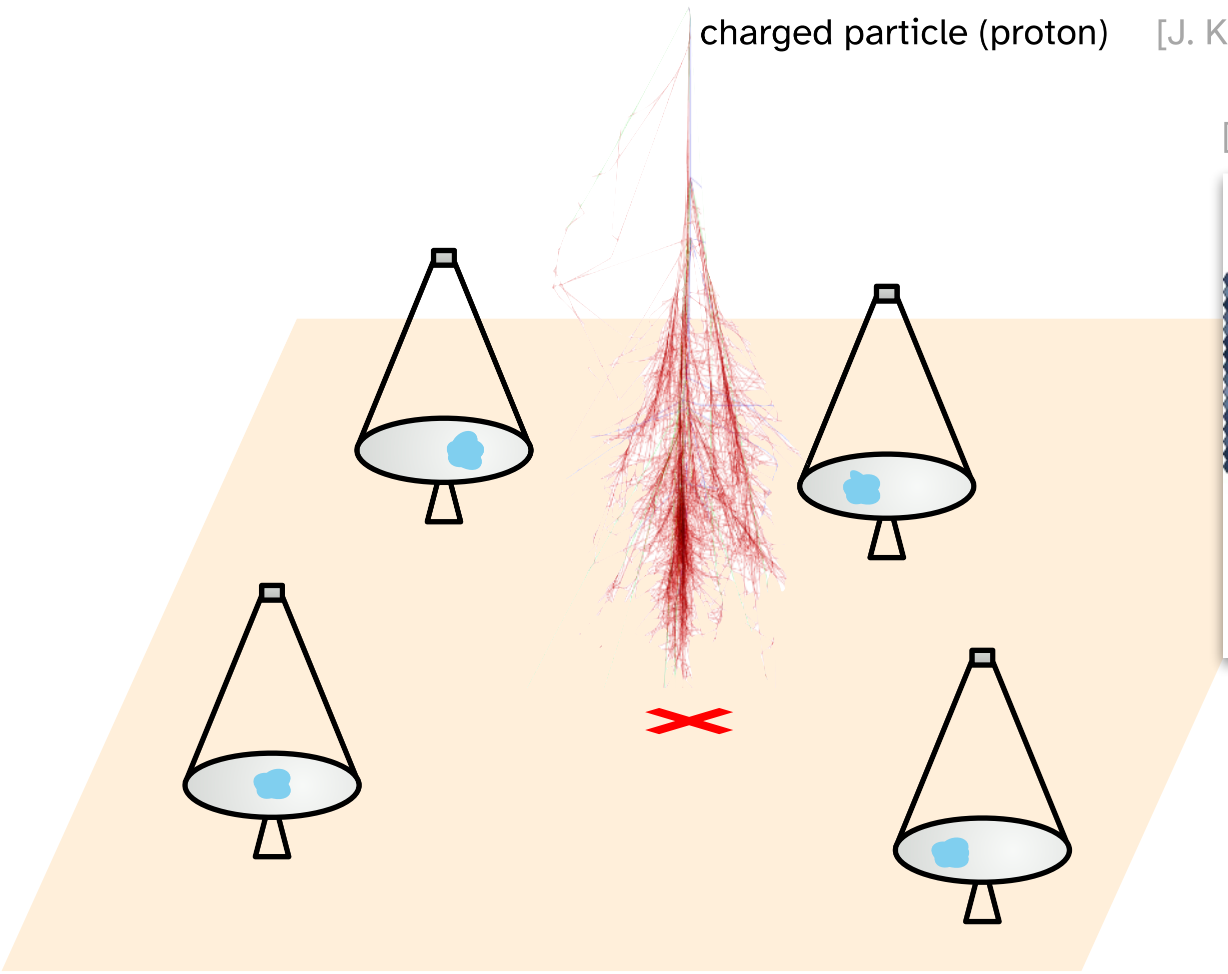
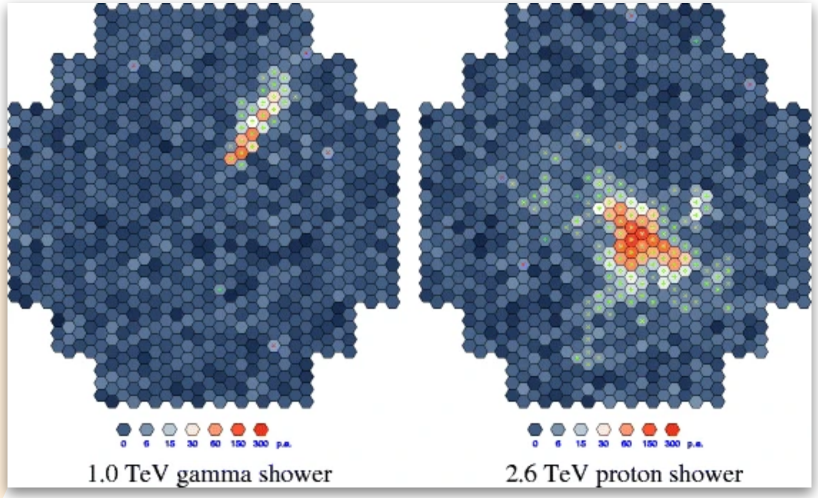


[H. Völk & K. Bernlöhr, ExA 25 (2009)]



main axes -> photon direction

image intensity + geometry -> energy

shape -> charged particle rejection

“gamma-hadron separation”

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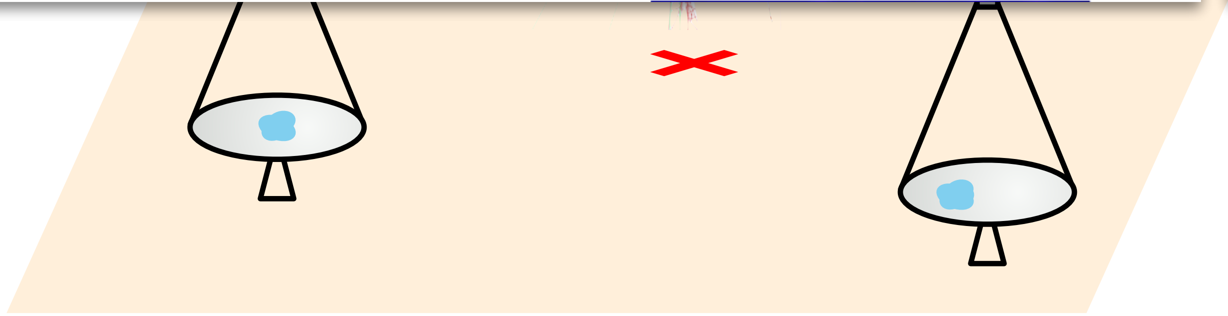
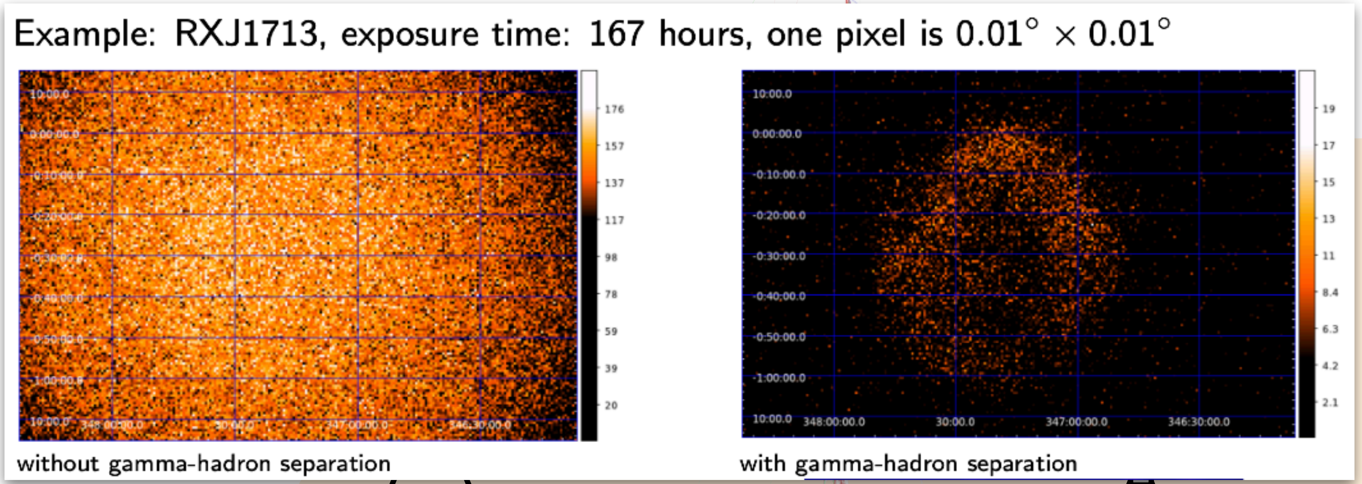


[R. Marx]



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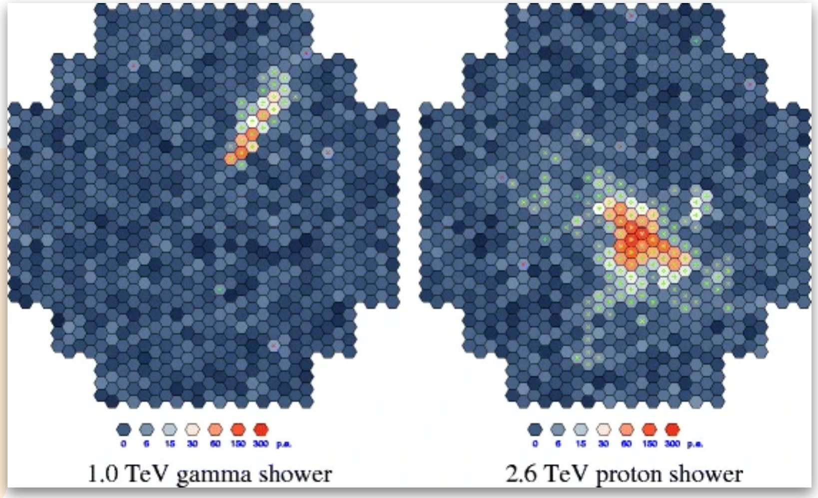


main axes -> photon direction
image intensity + geometry -> energy
shape -> charged particle rejection
"gamma-hadron separation"

IACT arrays

[Daniel R. Strebe]

IACT arrays

MAGIC (La Palma)

[Derek Strom, Giovanni Ceribella, MAGIC Collaboration]

2 x 236 m²
since 2003 / 2009

Major Atmospheric Gamma Imaging Cherenkov Telescope

VERITAS (Arizona, US)

VERITAS Collaboration

4 x 110 m²
since 2007

Very Energetic Radiation Imaging Telescope Array System

H.E.S.S. (Namibia)

[H.E.S.S., MPIK/Christian Föhr]

4 x 108 m² since 2007 + 1 x 614 m² since 2012

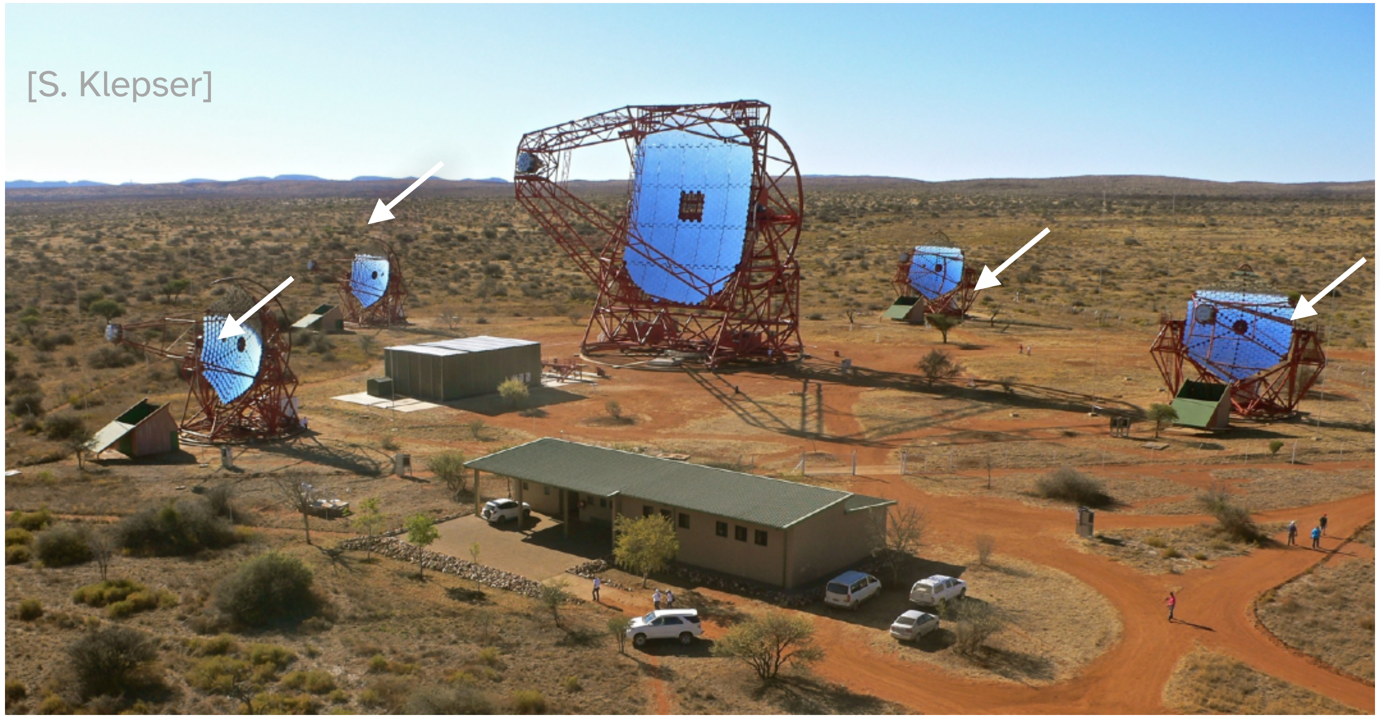
High Energy Stereoscopic System

H.E.S.S. telescopes

Physical scale

CT5 (big telescope)

CT1-4 (small telescopes)



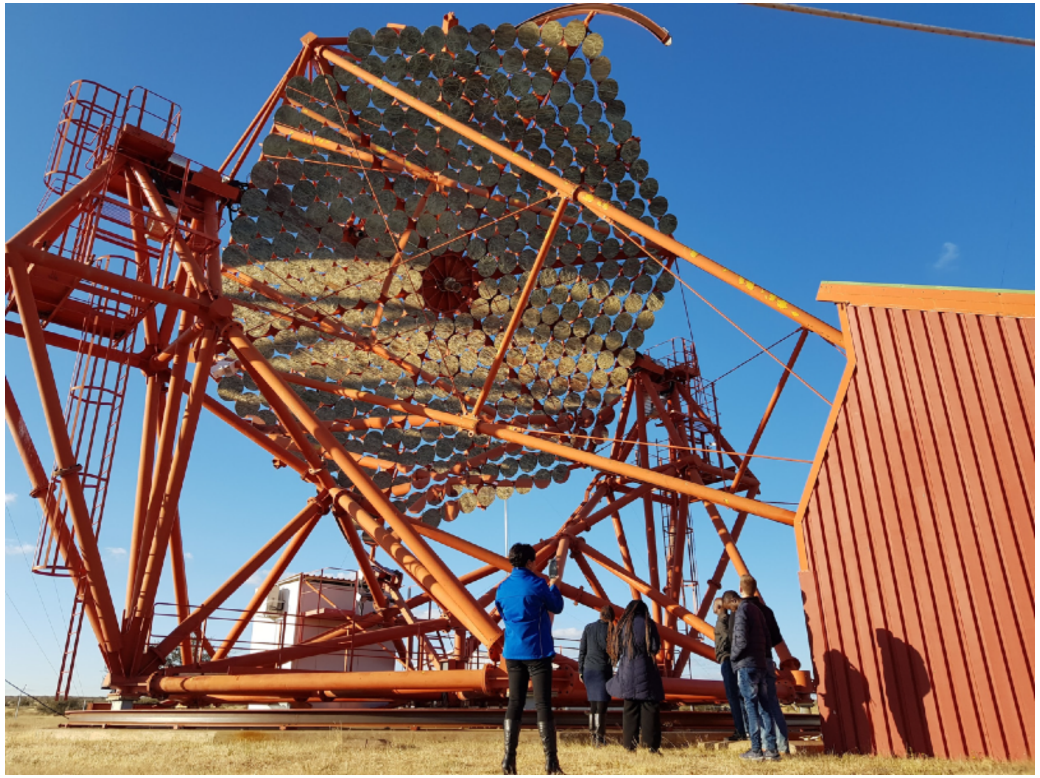
60 tons, ~25 m at tallest

600 tons, ~60 m at tallest

H.E.S.S. telescopes

Physical scale

CT1-4 (small telescopes)



$108\ m^2$ total mirror area (a large apartment)

CT5 (big telescope)

$614\ m^2$ mirrors (1.5 basketball courts)

H.E.S.S. telescopes

Physical scale

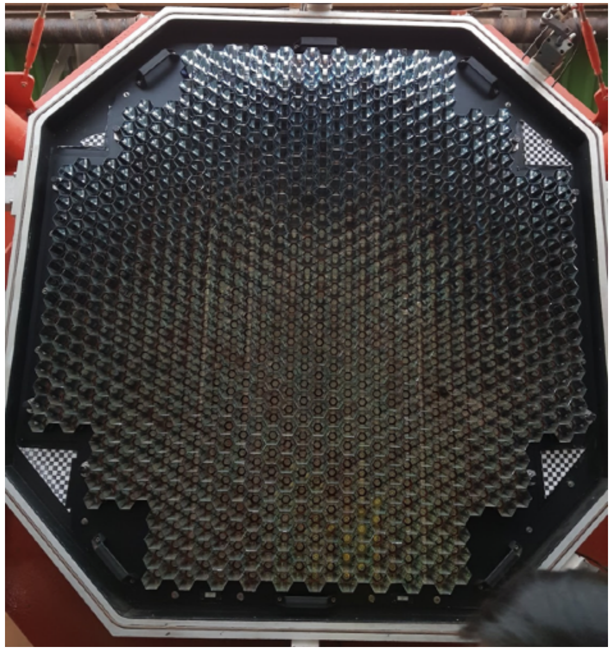
[Helmholtz Alliance for Astroparticle Physics / A. Chantelauze]

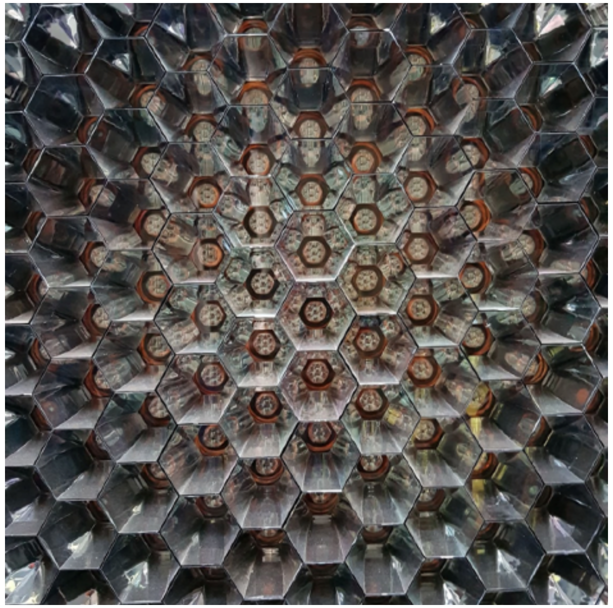
H.E.S.S. telescopes

Cameras (small telescopes)

H.E.S.S. telescopes

Cameras (small telescopes)

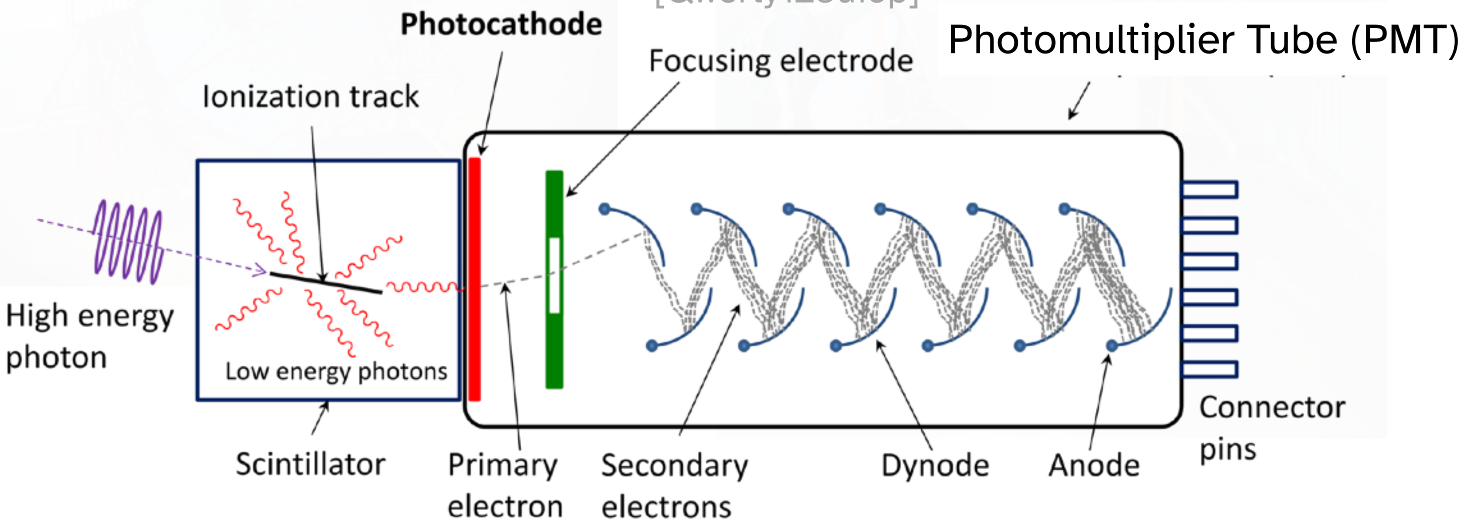


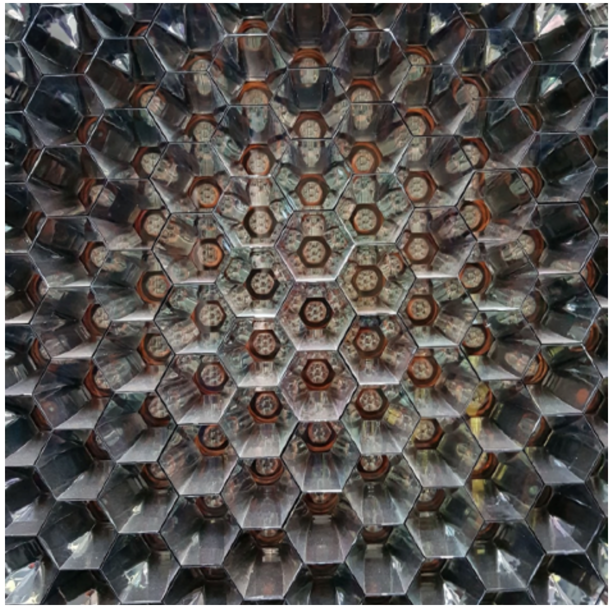


H.E.S.S. telescopes

Cameras (small telescopes)

[Qwerty123uiop]

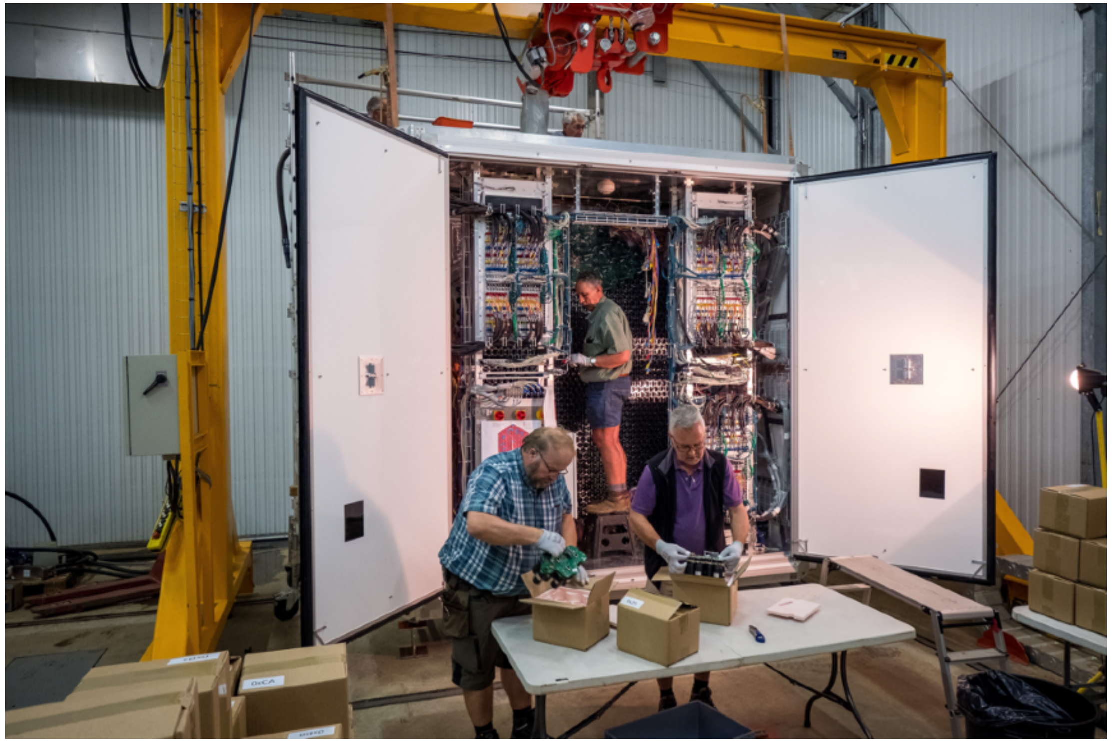




H.E.S.S. telescopes

Camera (big telescope)

[C. Föhr (MPIK)]



H.E.S.S. telescopes

Camera (big telescope)

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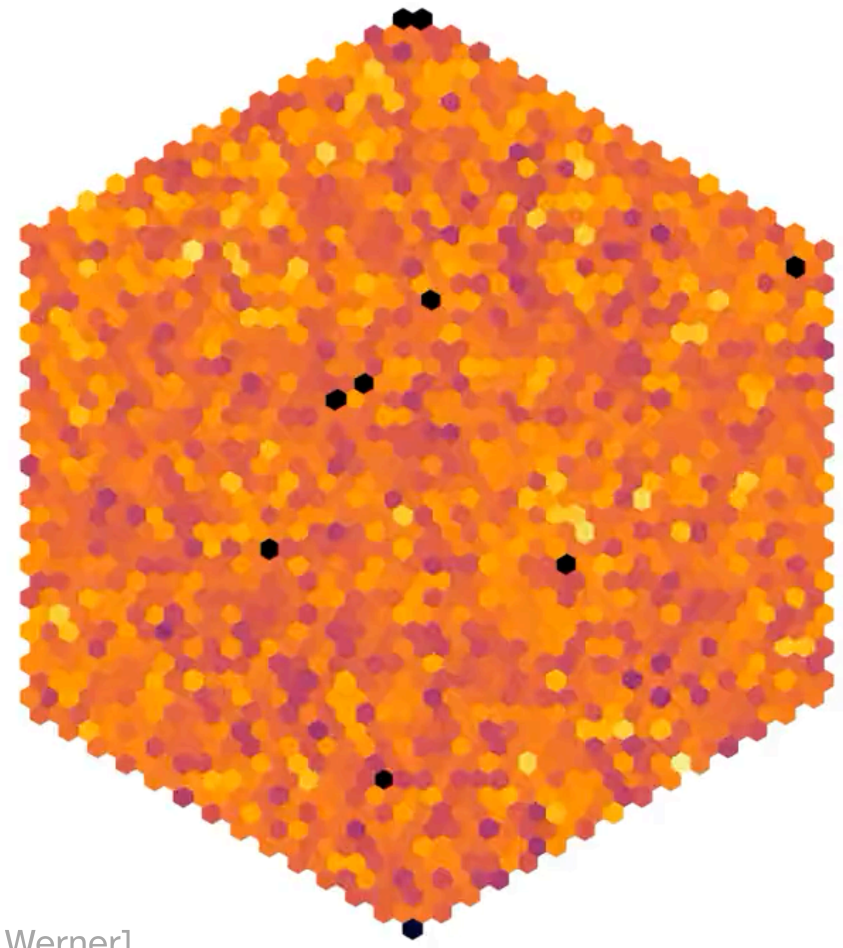
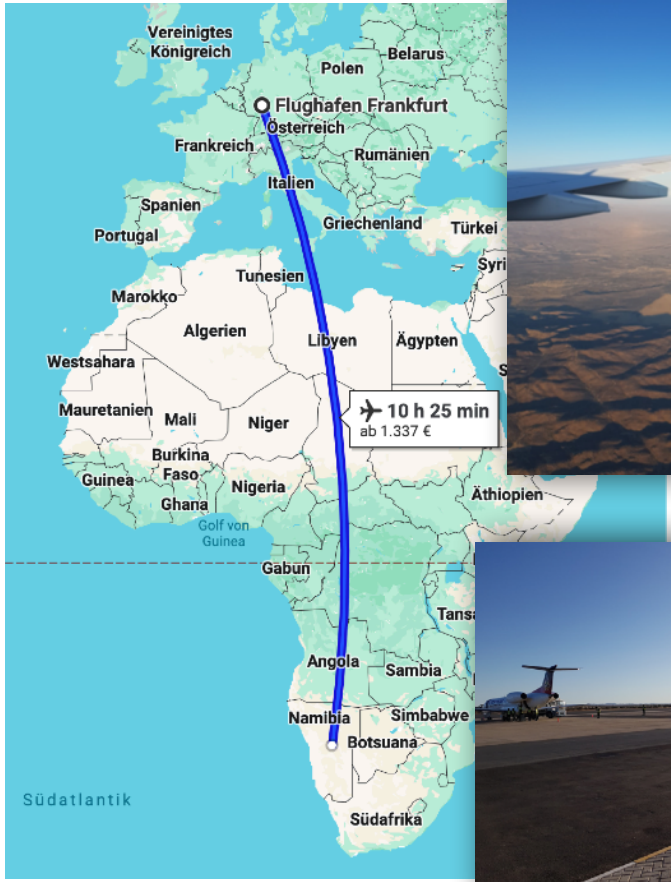


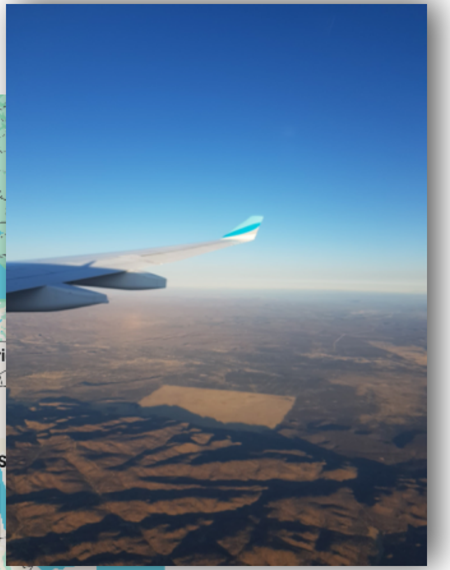
[F. Werner]

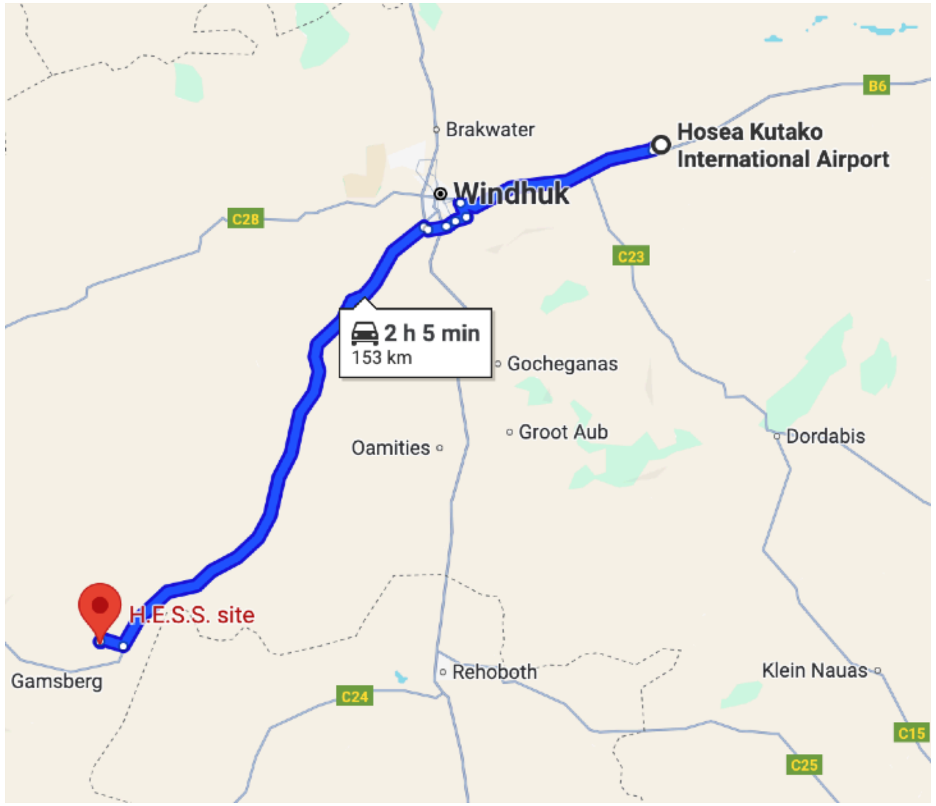
H.E.S.S. telescopes

What does a shift look like?

1-2 professional shifters + 2-1 students/post docs per shift (~25 days)
8-12 hours a night depending on the season







H.E.S.S. telescopes

What does a shift look like?

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pick up a truck and load it with 1-2 weeks worth of groceries

H.E.S.S. telescopes

What does a shift look like?

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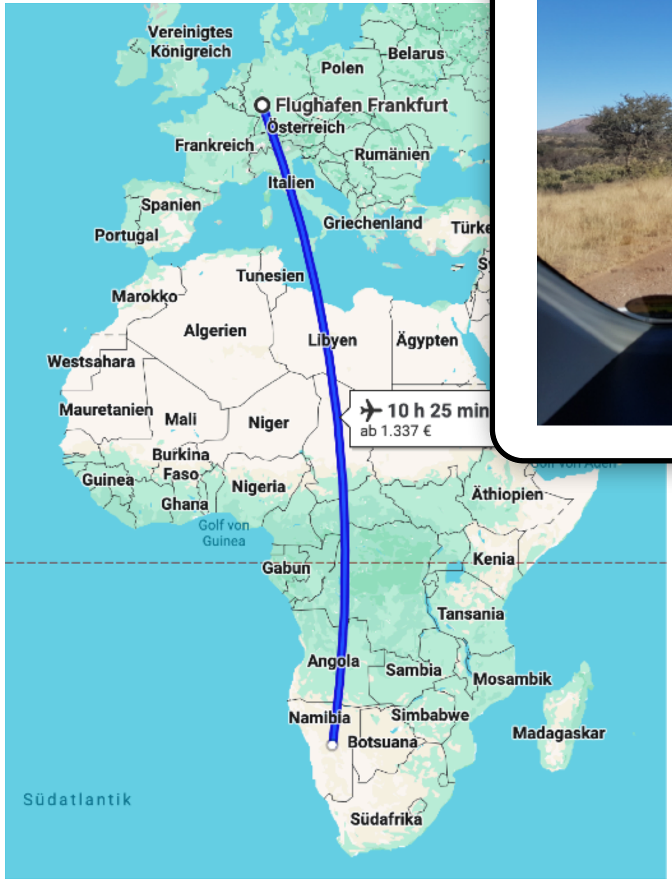
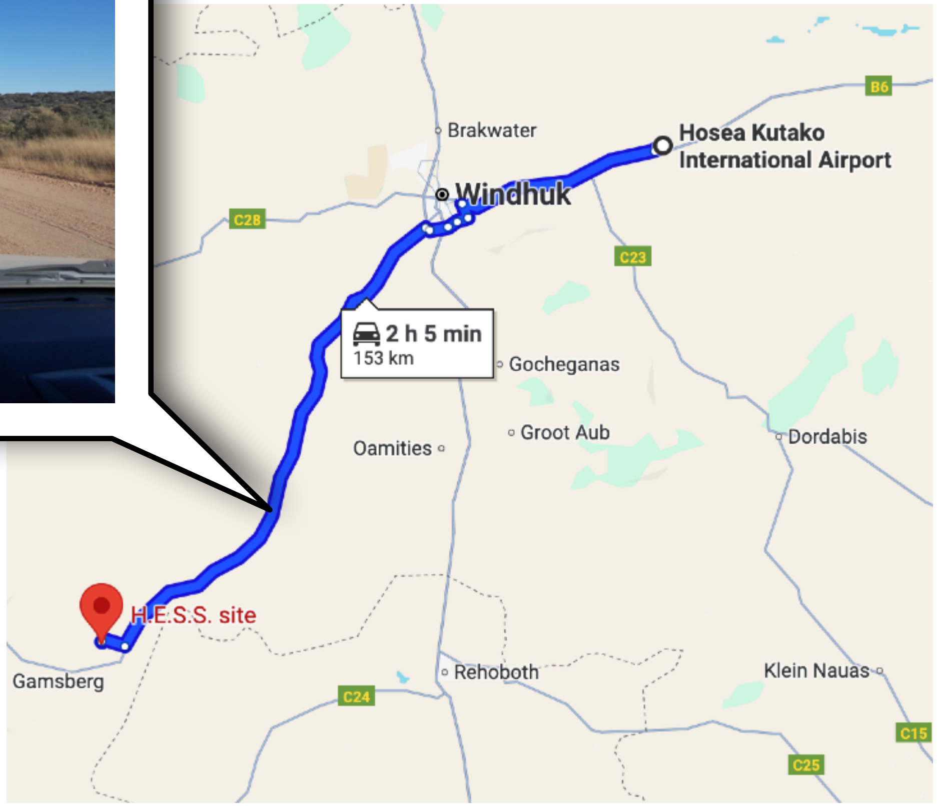
8-12 hours a night depending on



drive for a long time on a gravel road, start to doubt your sanity / sense of direction and time



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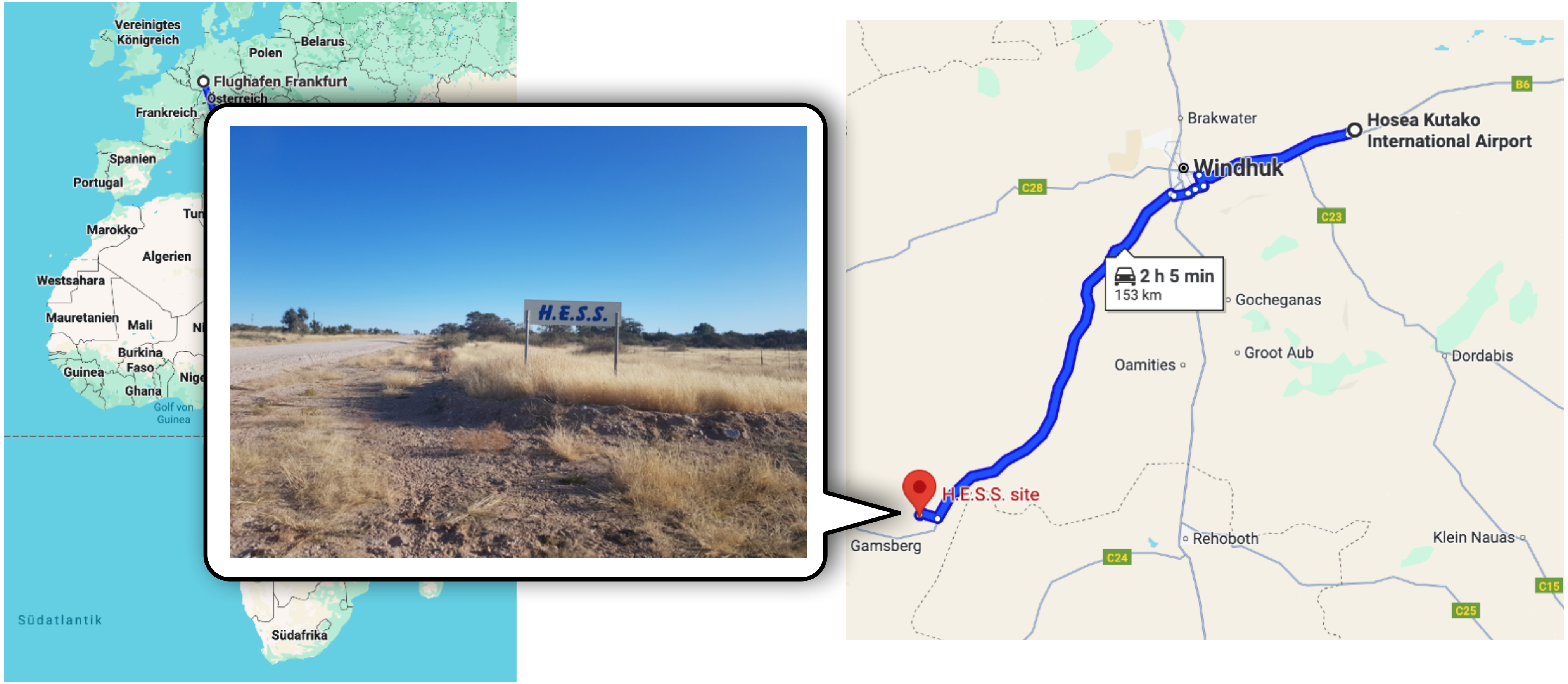

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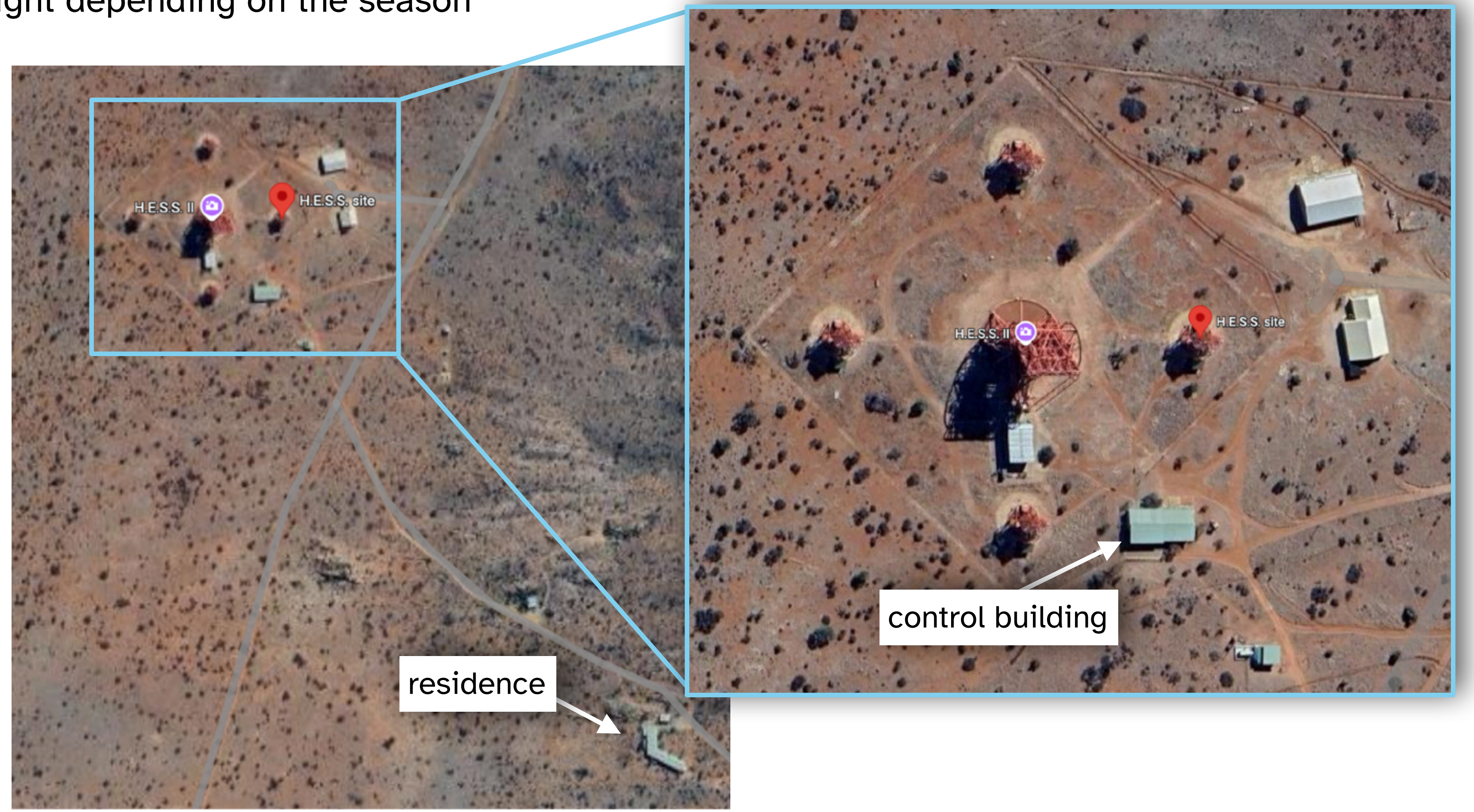

H.E.S.S. telescopes

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H.E.S.S. telescopes

What does a shift look like?

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8-12 hours a night depending on the season

control room

telescopes

MAGIC telescopes

Carbon fiber frames

~40 tons, ~30 m at tallest

[MAGIC collaboration]

[S. Schurig]

IACT arrays

When can they observe?

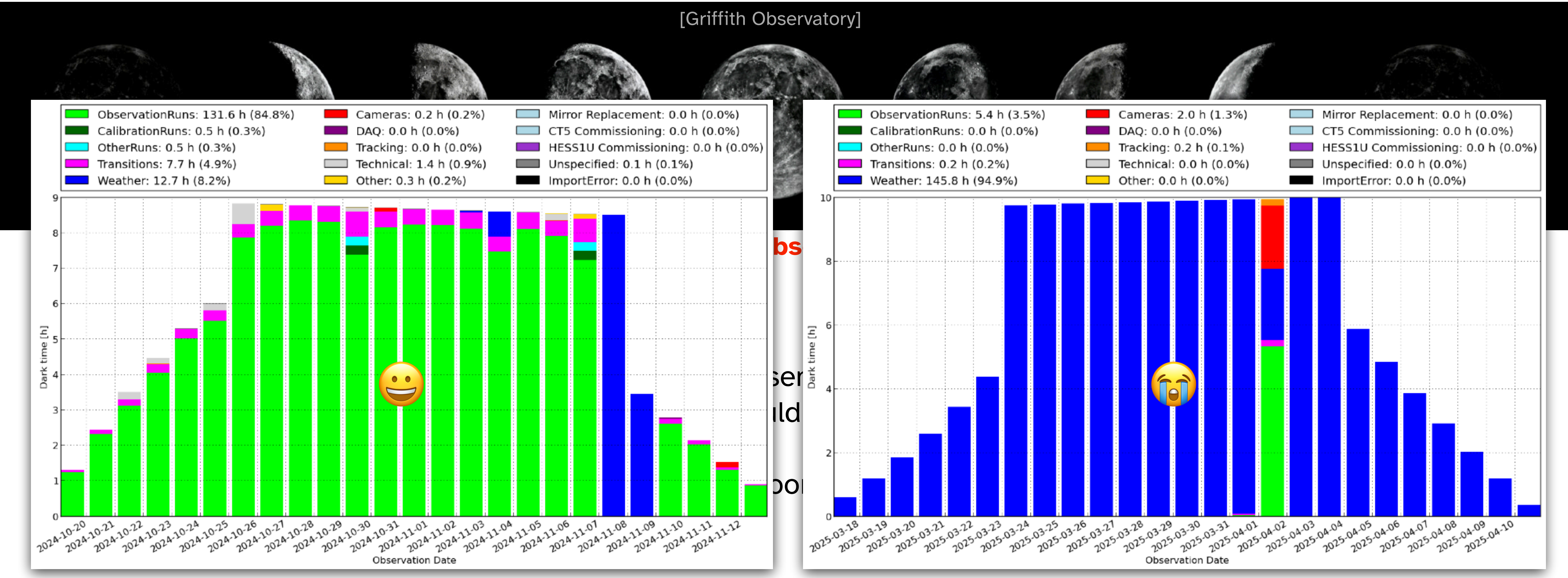
Best for observations | OK for observations | **Can’t observe** | OK for observations | Best for observations

Cherenkov flashes are dim -> cameras are extremely sensitive
If there is too much bright ambient light, cameras could get damaged

=> IACTs observe ~25 nights during every ~28 day moon cycle (**when weather is good**)

IACT arrays

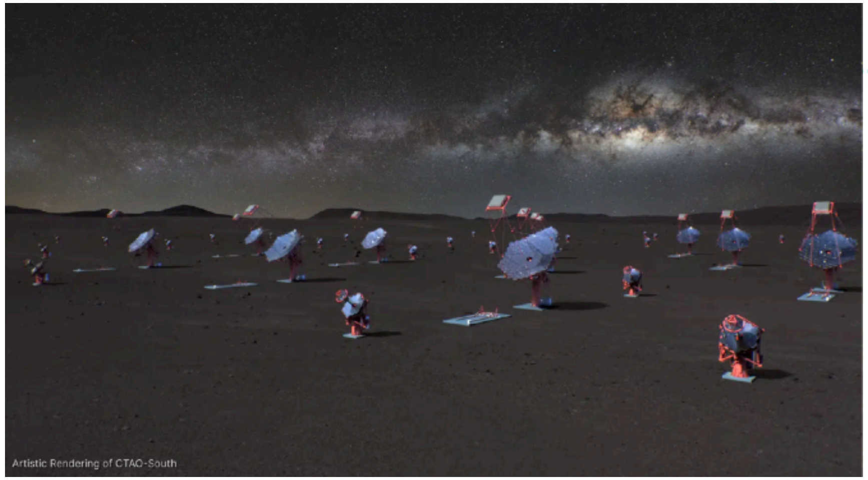
When can they observe?

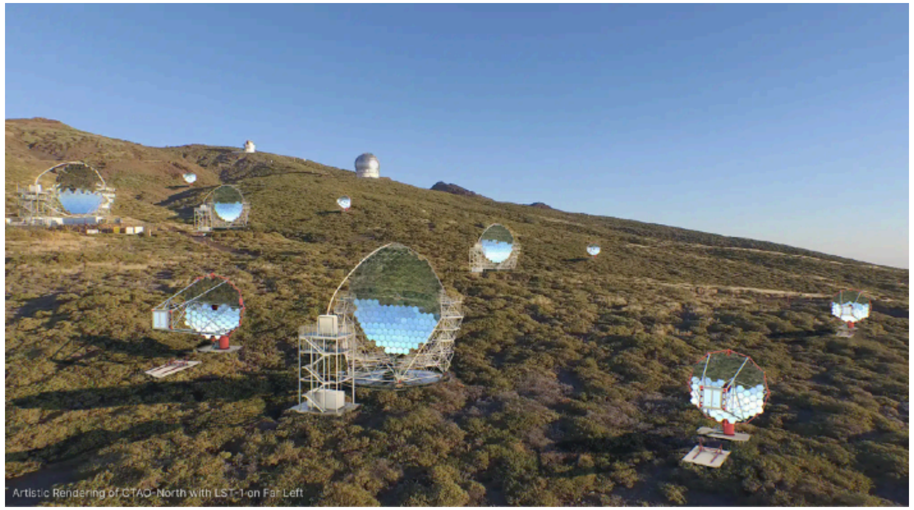


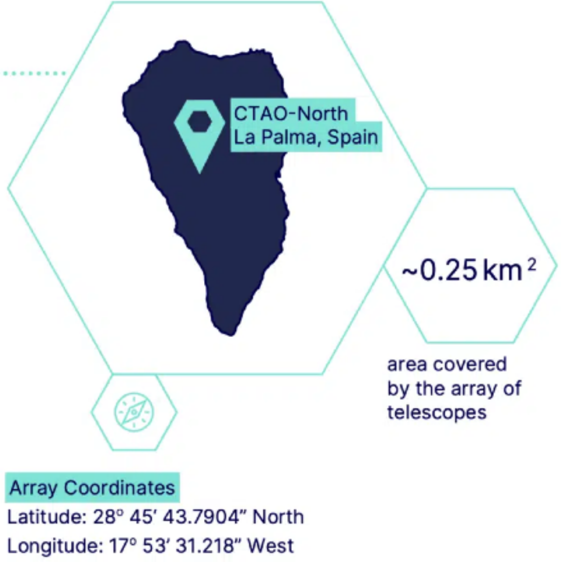
Two very different H.E.S.S. shifts

Cherenkov Telescope Array Observatory (CTAO)

Next generation IACT array







[CTAO]

IACT arrays

[Daniel R. Strebe]

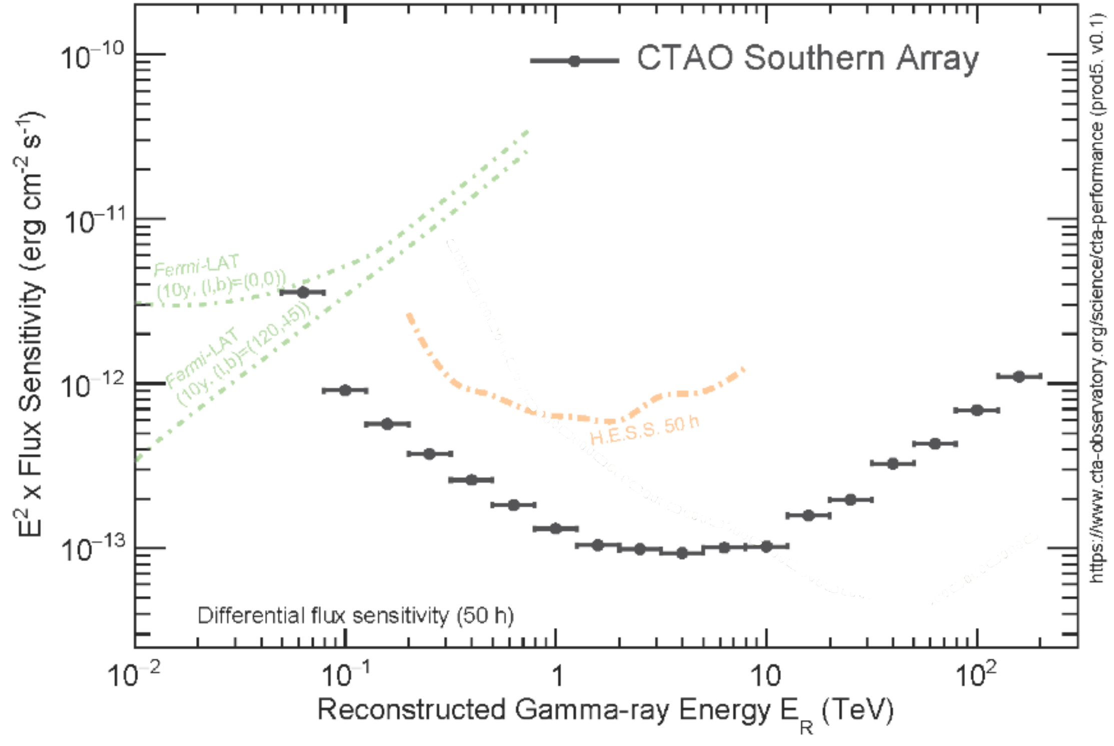
Cherenkov Telescope Array Observatory (CTAO)

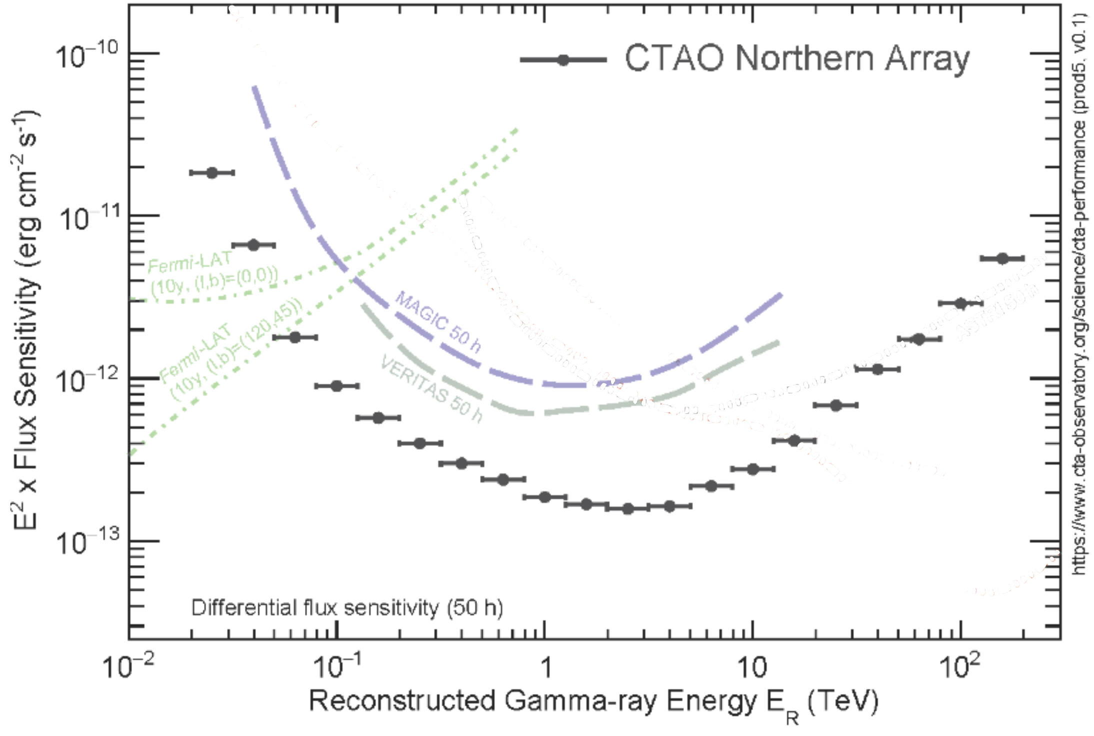
LST-1

Cherenkov Telescope Array Observatory (CTAO)

Next generation IACT array

CTAO will be 10x more sensitive than the current generation of IACT arrays

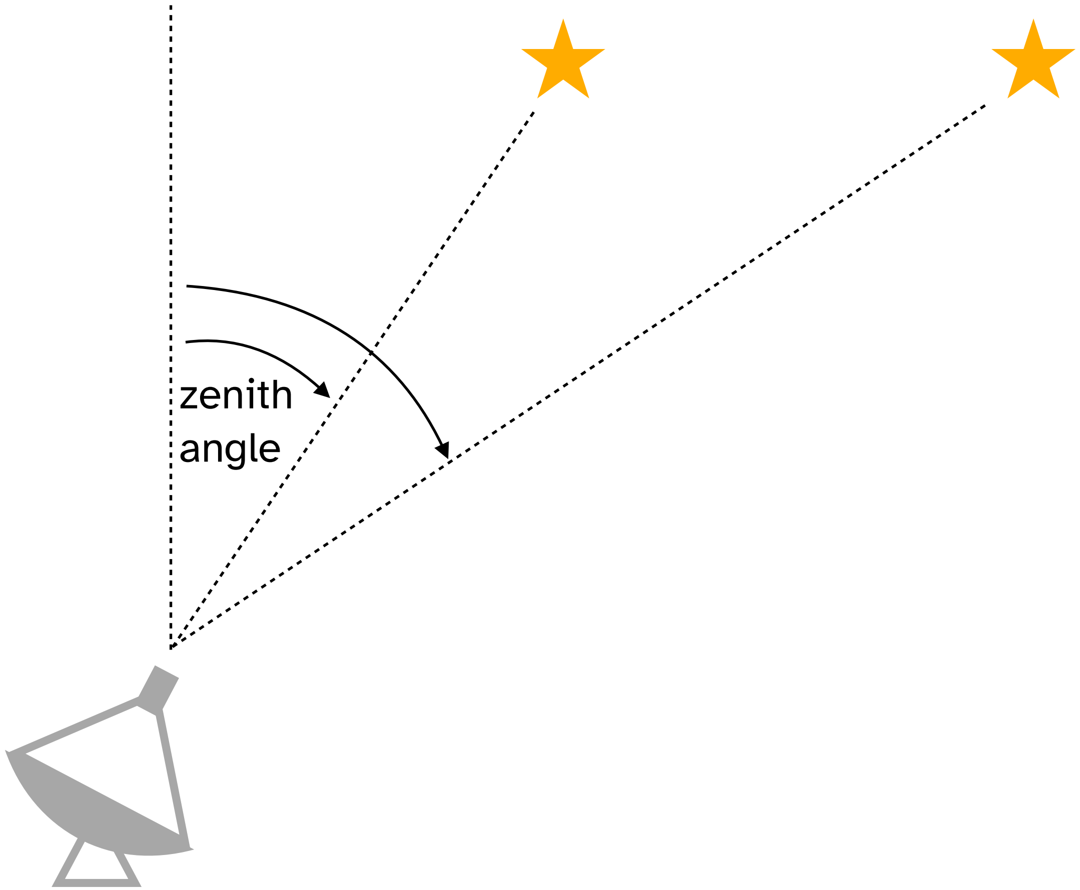




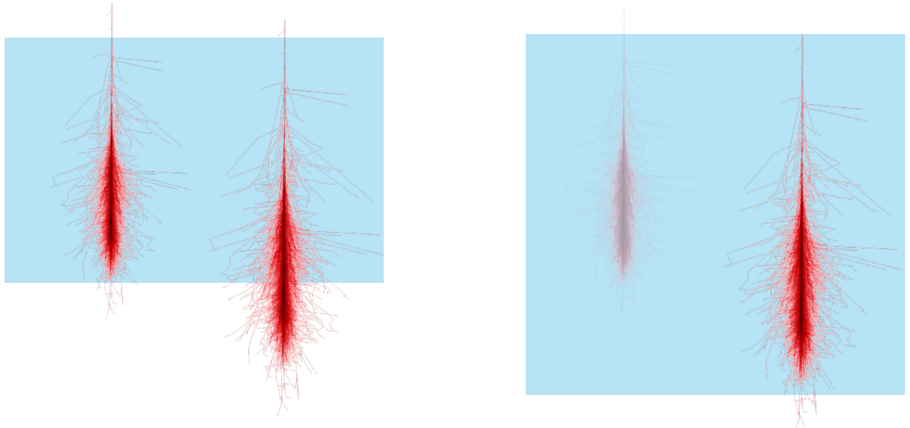
modified from [CTAO]

How do IACTs decide what to observe and when?

General considerations



1. When is it dark enough to observe?
2. When is the source high enough in the sky?
   (i.e., with sufficiently small zenith angle)

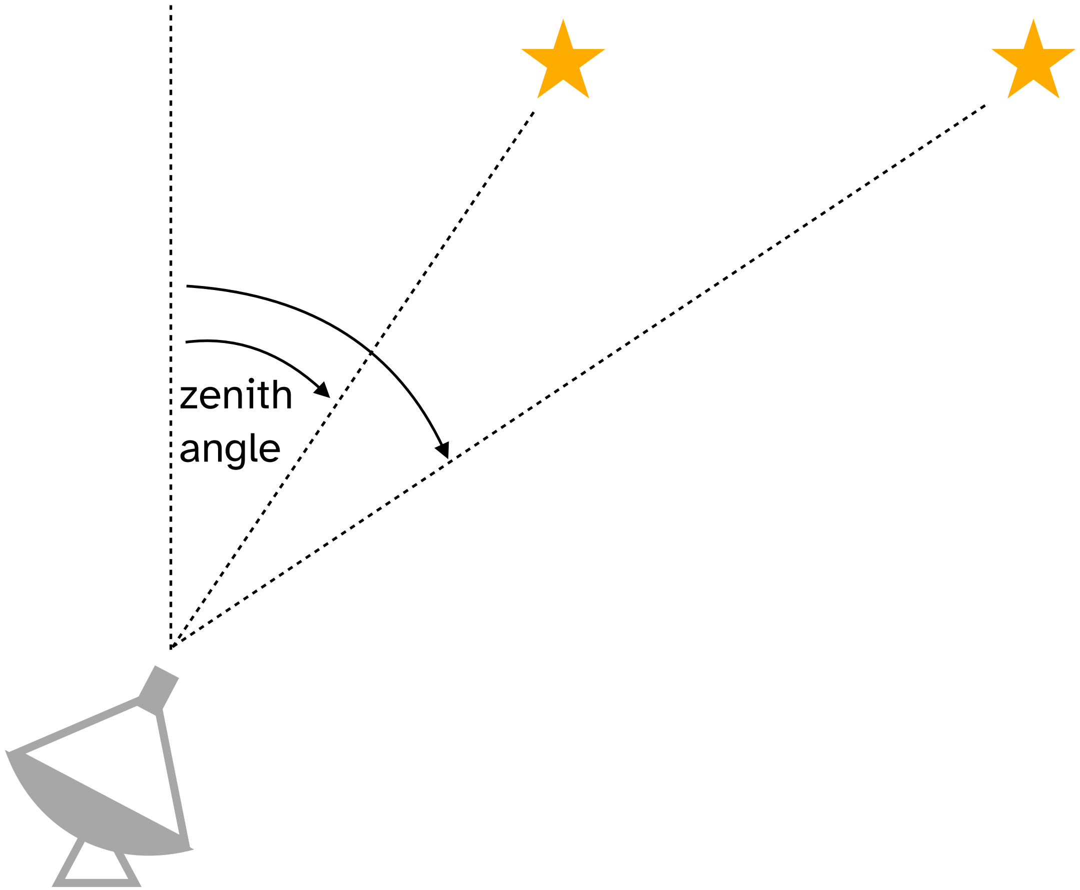


larger zenith angle -> more atmosphere to go through
-> more absorption of Cherenkov photons

How do IACTs decide what to observe and when?

General considerations

How far below the horizon do the Sun and Moon have to be? How bright can the Moon be? Are there certain parts of the sky that are too bright in general?



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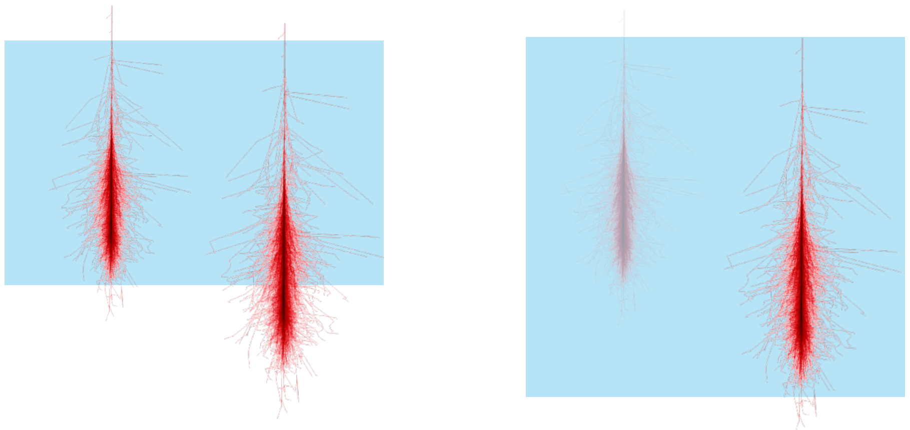

larger zenith angle -> more atmosphere to go through
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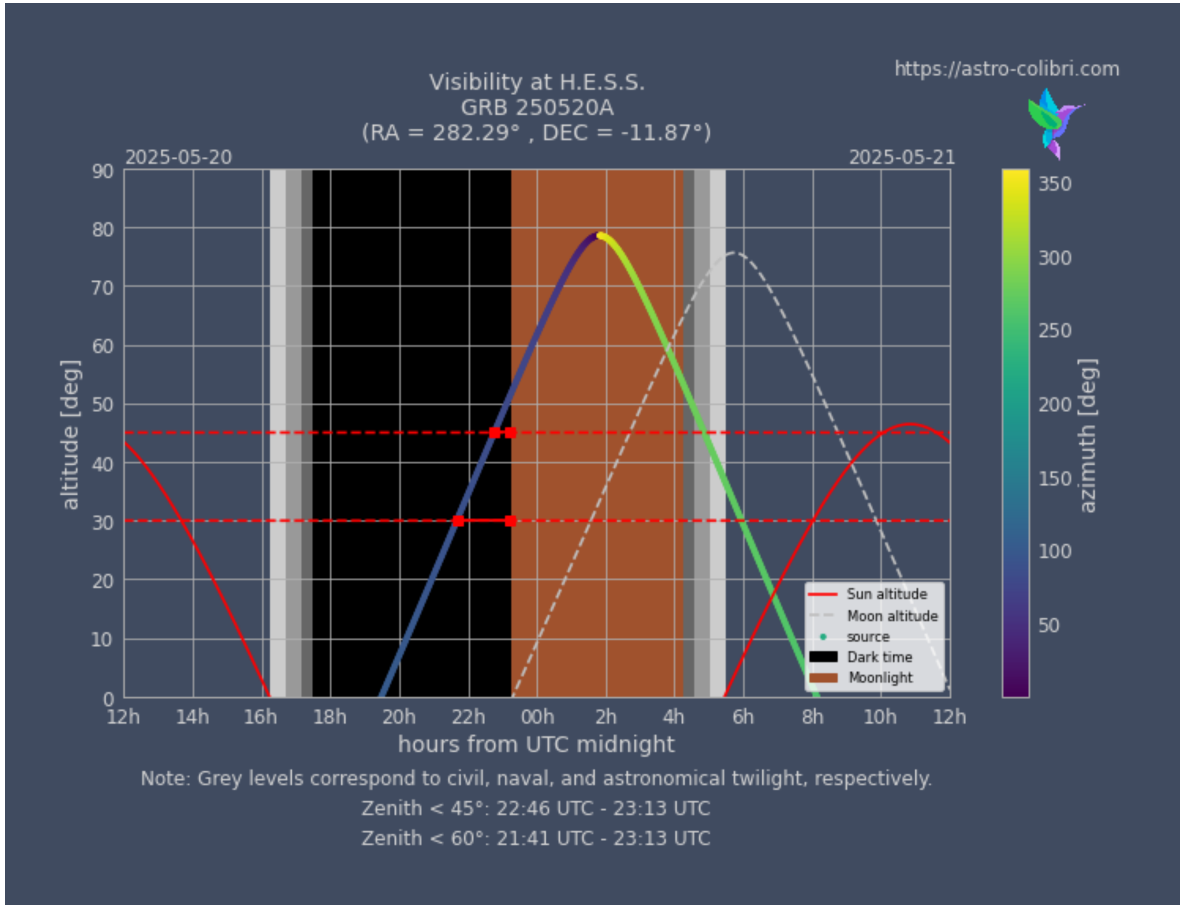
How do IACTs decide what to observe and when?

General considerations

Putting it all together:



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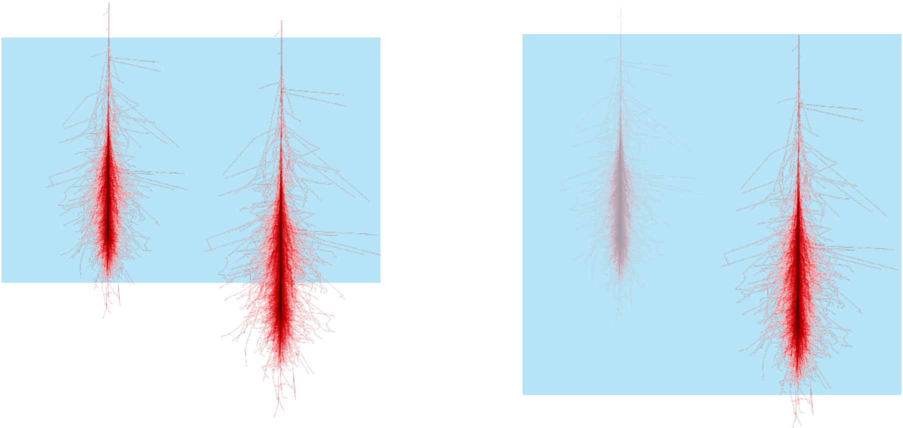
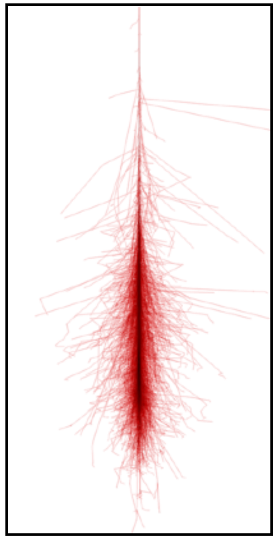


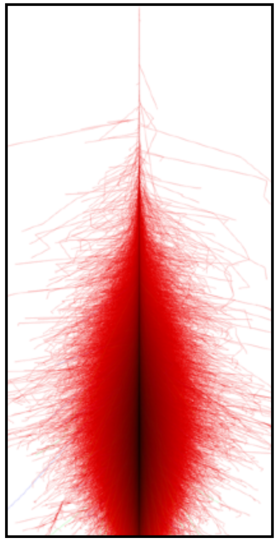
larger zenith angle -> more atmosphere to go through
-> more absorption of Cherenkov photons

Use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers

100 GeV gamma ray vs 100 TeV gamma ray





- most shower particles don't reach the ground
- detect them via Cherenkov light in air

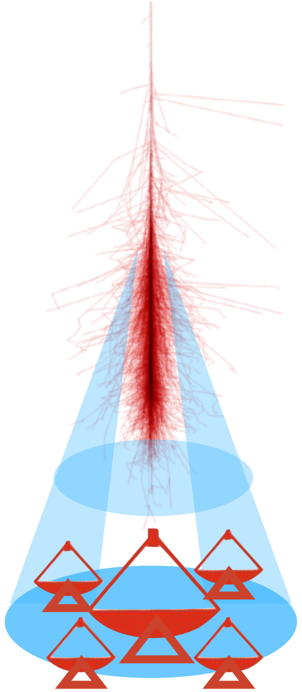
- many shower particles reach the ground
- detect them directly

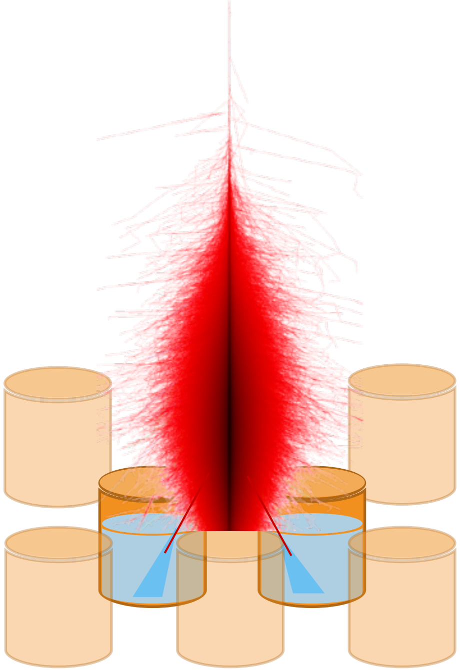
[J. Knapp]

Use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers

100 GeV gamma ray vs 100 TeV gamma ray





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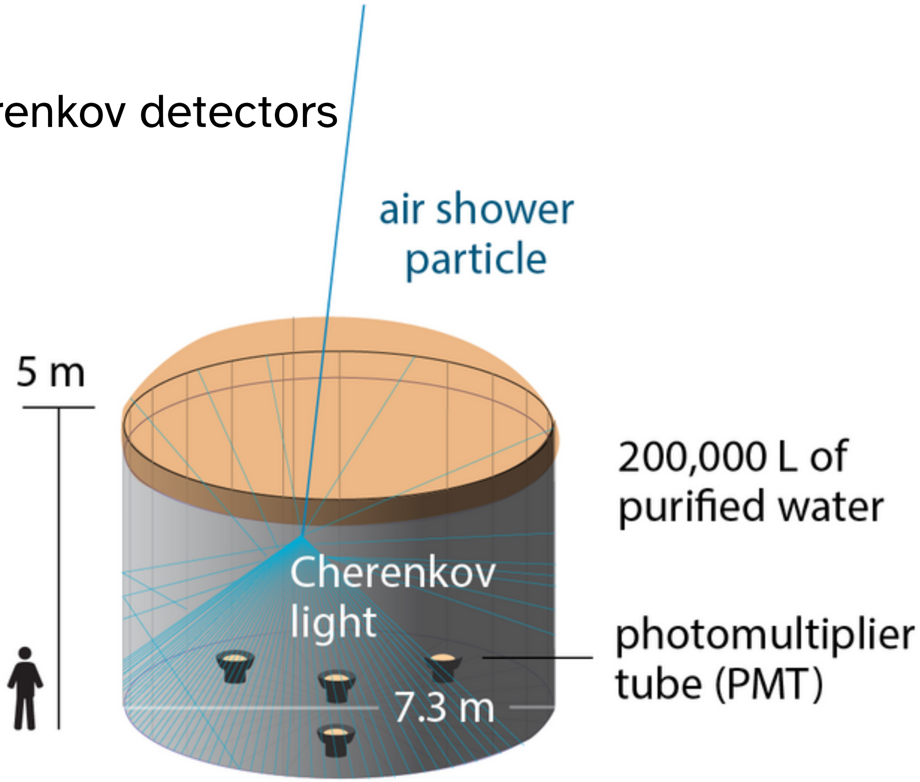
[J. Knapp]

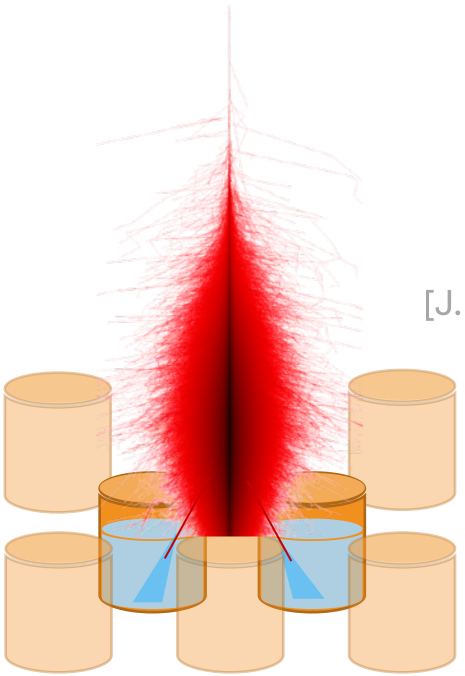
Particle detector arrays

Water Cherenkov detectors



[U. M. Nisa, HAWC]

100 TeV gamma ray

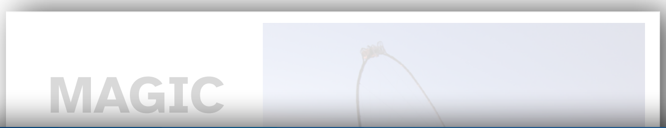


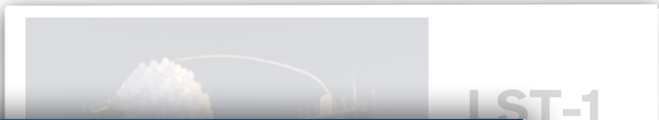
[J. Knapp]

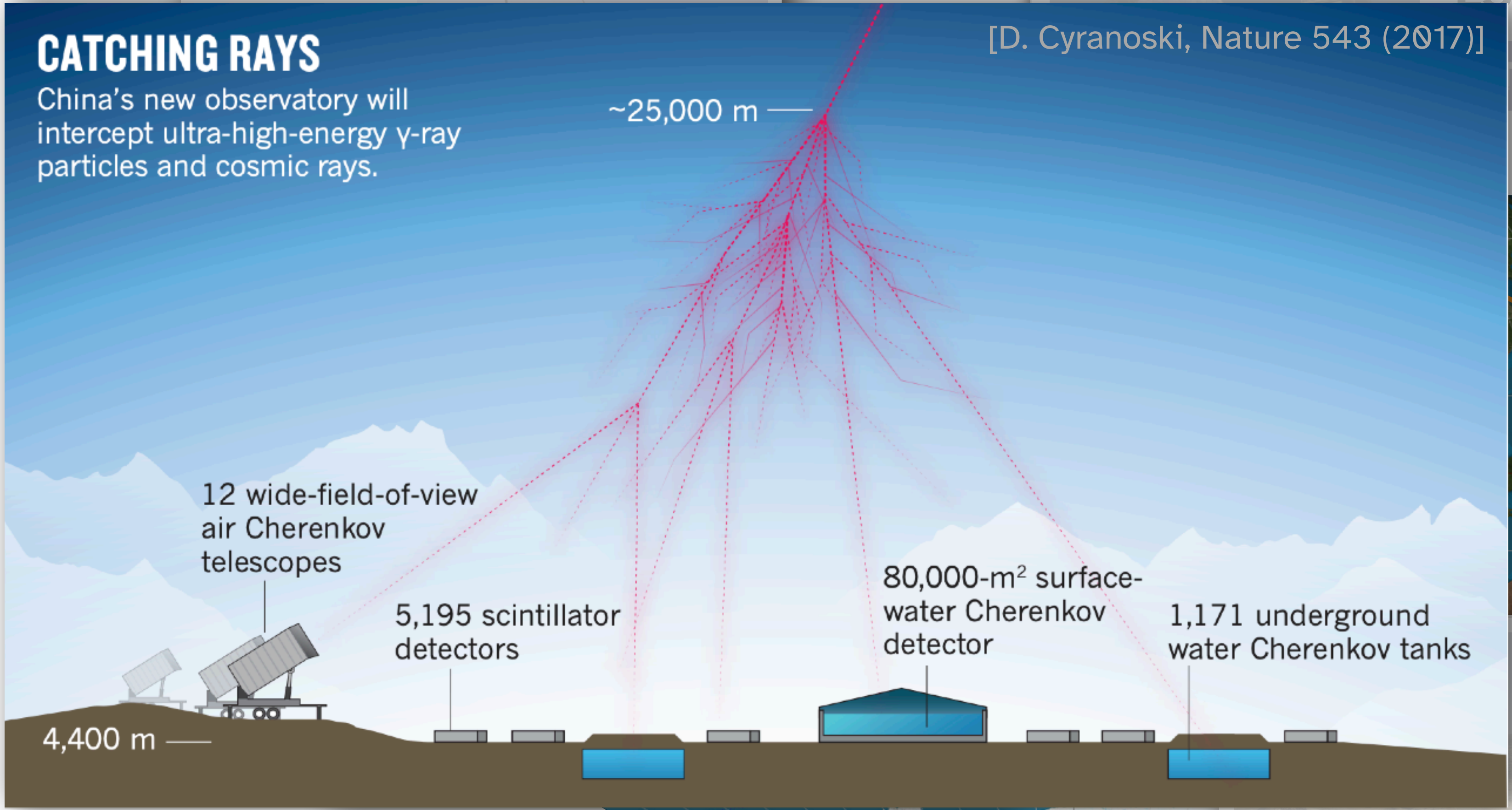
Particle detector arrays

[Daniel R. Strebe]

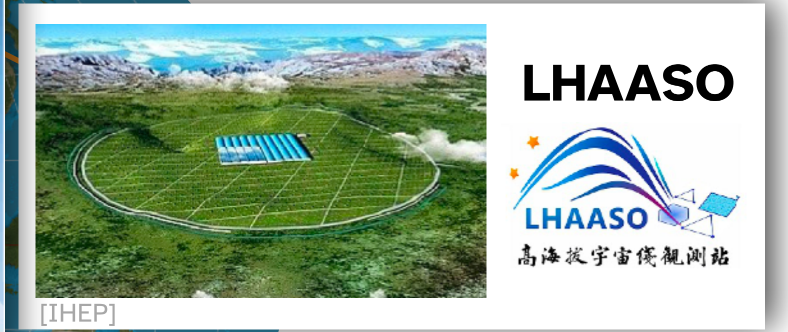
Particle detector arrays







[D. Cyranoski, Nature 543 (2017)]



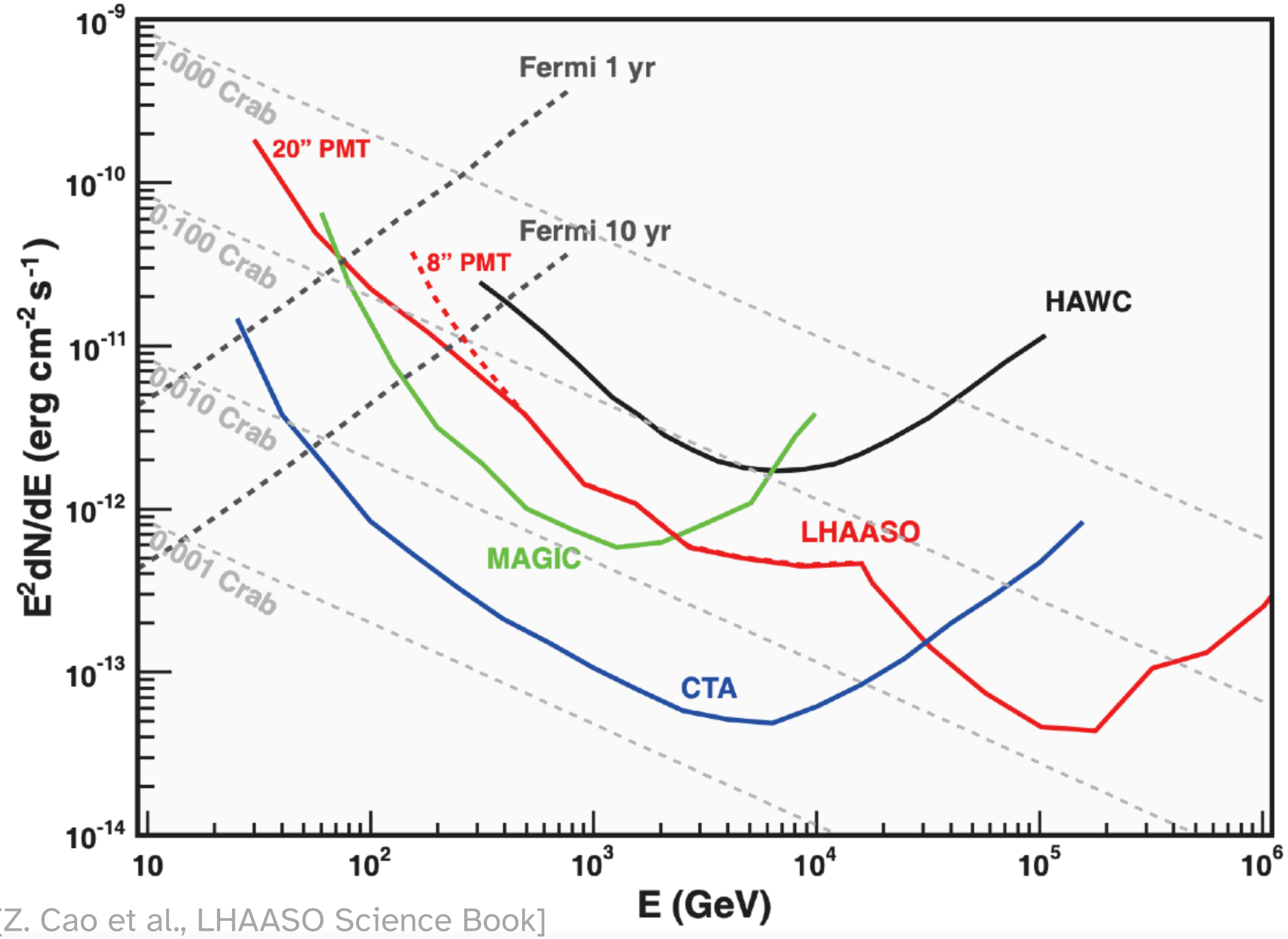
[IHEP]

[H.E.S.S., MPIK/Christian Föhr]

[Daniel R. Strebe]

Gamma-ray detectors

Comparing sensitivities



[Z. Cao et al., LHAASO Science Book]

Gamma-ray detectors

Complementary capabilities

	Fermi-LAT	IACT arrays (current gen)	CTAO	particle detector arrays
duty cycle	~95%	~15%	~15%	~90%
energy range	[10s of MeV, 100s of GeV]	[~25 to 100 GeV, 100 TeV]	[~20 GeV, >300 TeV]	[100s of GeV, >PeV]
field of view	>2 sr	~ 5°	~ 5°	>2 sr
angular resolution	~0.1° - 1°	< 0.1°	< 0.05°	~0.1° - 2°
energy resolution	~5 - 20%	~10 - 15%	~5%	~30 - 50%