Time-domain astronomy

CTAO summer school 2026

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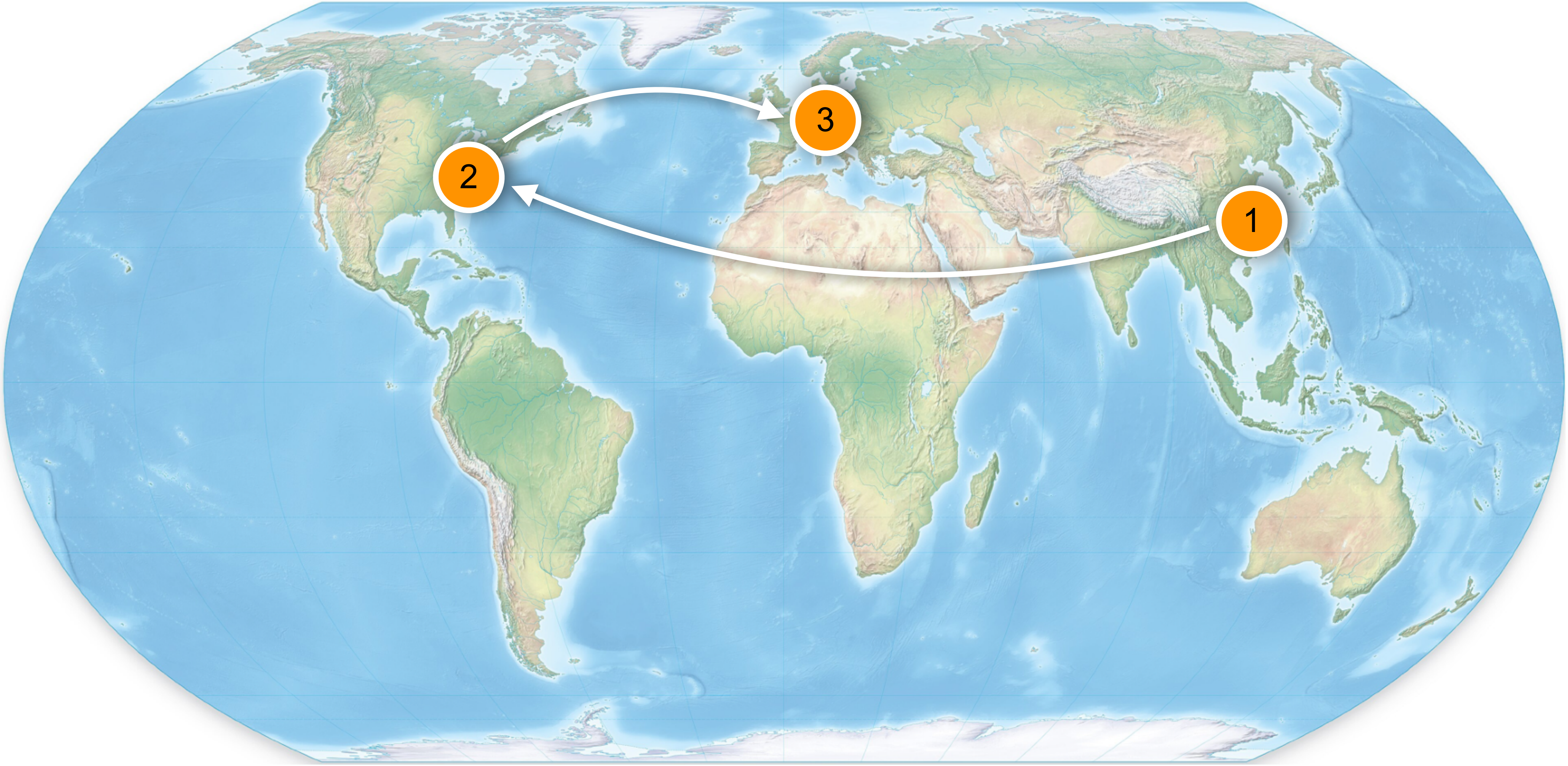
[she/her]

hello who am i



hello who am i and what do i do

Bachelors	PhD	Post doc 1	Post doc 2
¯_(ツ)_/¯			

hello who am i and what do i do

i'm bad at:

- theory
- IACT data analysis 👀
- coding
- not communicating like a millennial

Bachelors

Post doc 2

¯_(ツ)_/¯

Rough outline

Day 1: Intro + detectors

How are gamma rays produced and how do we detect them?

Day 2: Rapid transients

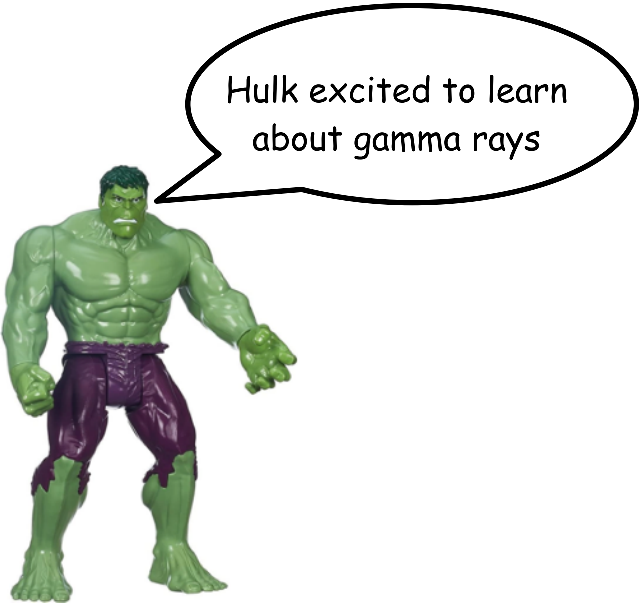
How do IACTs observe gamma-ray bursts and other rapidly fading transients?

Day 3: Longer duration transients

What else must be considered for longer duration transients like supernovae?

Part 1a. How are gamma rays produced?

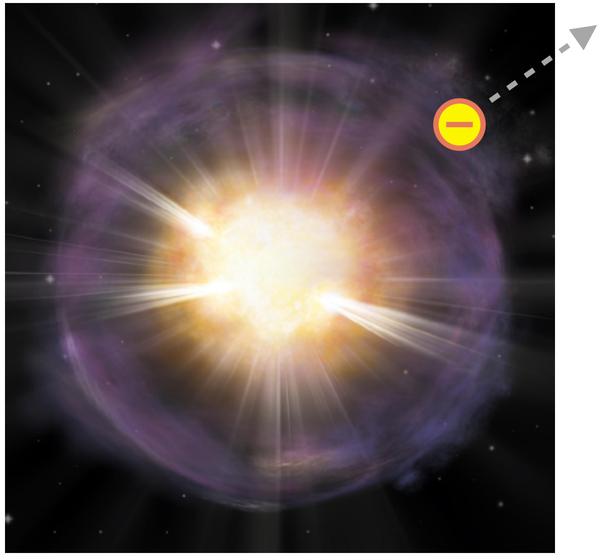
reviewing info from Giada's lectures yesterdays



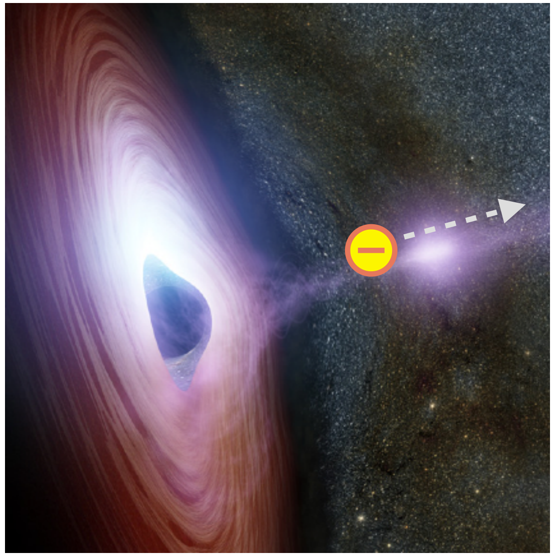
How do we get gamma rays?

Nonthermal emission

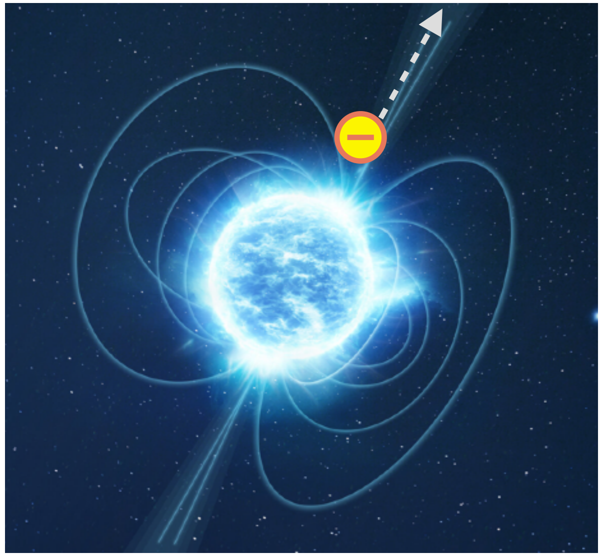
Charged particles are **accelerated** to high energies before radiating photons



[A. M. Geller/Northwestern/CTIO/SOAR/NOIRLab/NSF/AURA]



[NASA/JPL-Caltech]



[ESA]

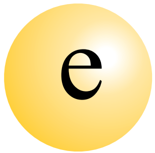
need an **energy source** and a way to **transfer this energy** to charged particles
(e.g., kinetic, gravitational, magnetic fields ...)

How do we get gamma rays?

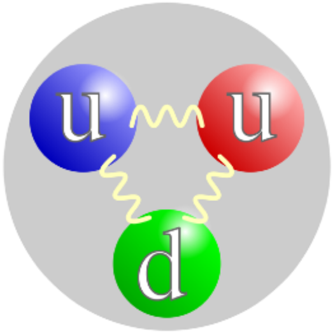
Nonthermal emission

Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)
-> the radiation processes can be **leptonic** and/or **hadronic**

electron



proton



[A. Horvath]

leptons are elementary particles

hadrons are made of quarks
-> can convert into other particles

How do we get gamma rays?

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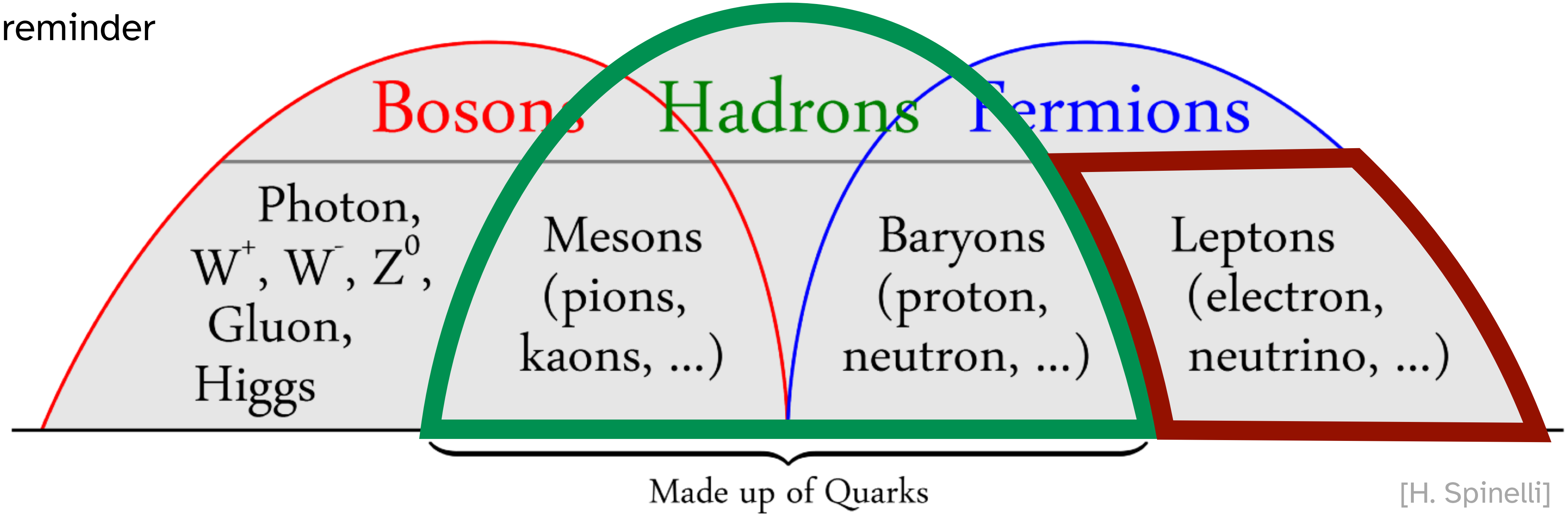
reminder



[H. Spinelli]

How do we get gamma rays?

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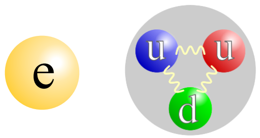
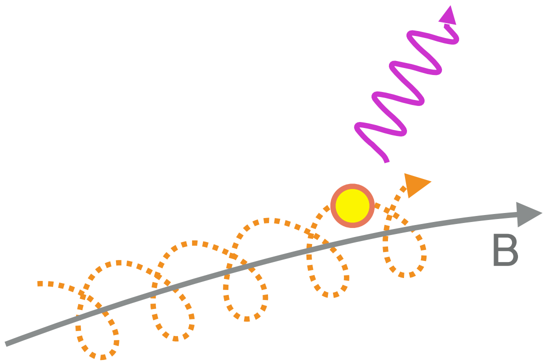
e.g., synchrotron





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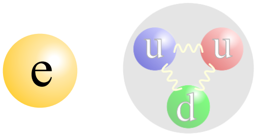
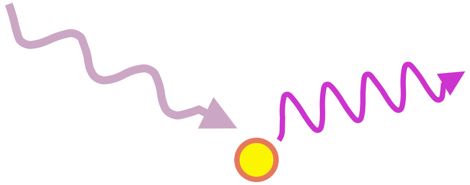
e.g., inverse Compton





How do we get gamma rays?

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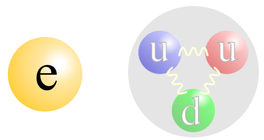
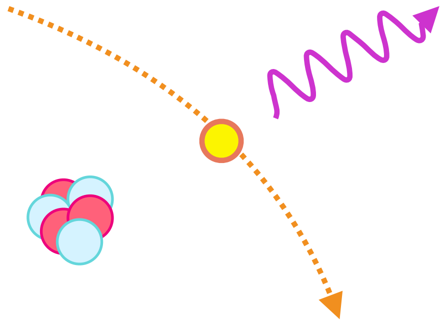
e.g., Bremsstrahlung





How do we get gamma rays?

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The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

-> the radiation processes can be **leptonic** and/or **hadronic**

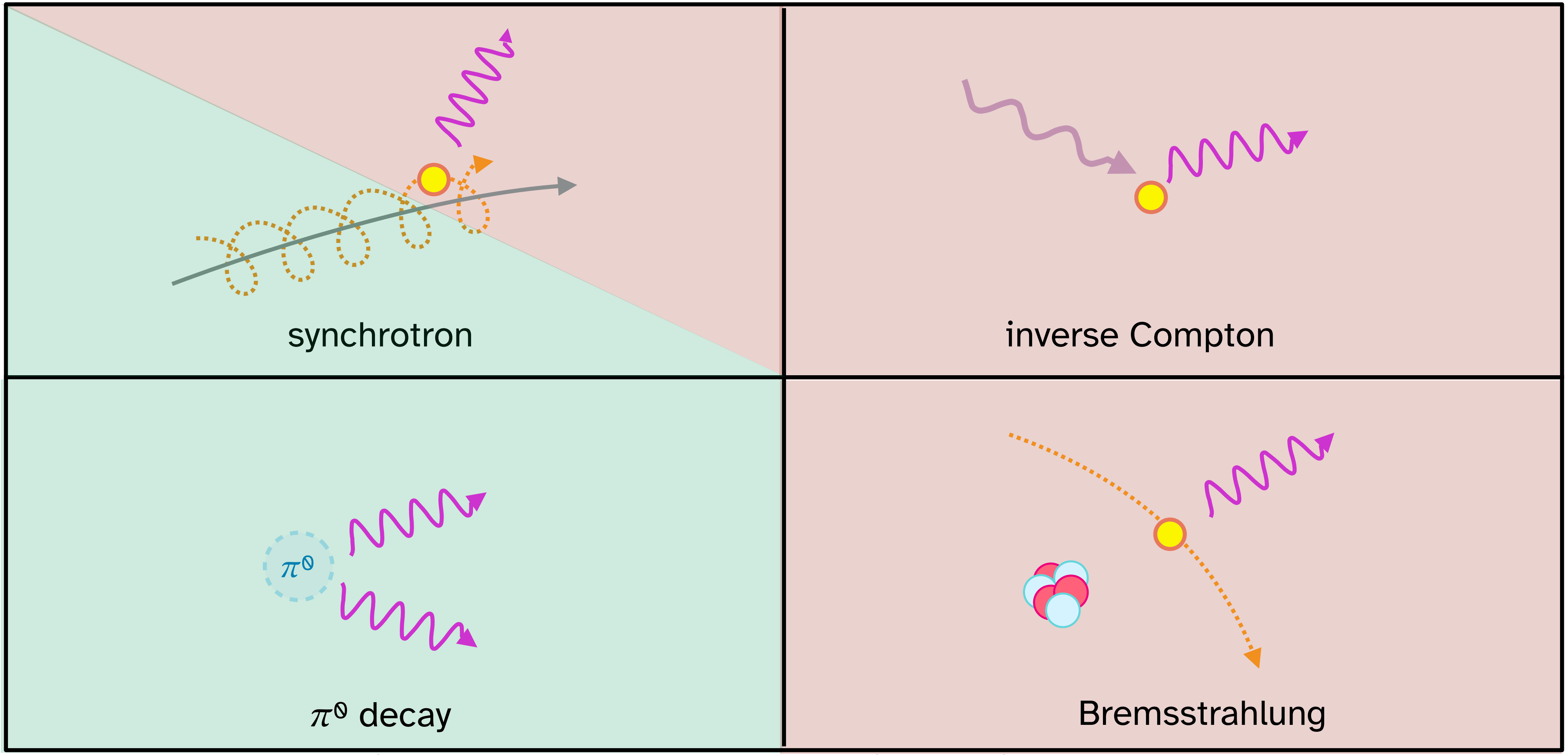
e.g., pion decay

How do we get gamma rays?

Nonthermal emission

(coloring indicates what is **most relevant to these lectures**)

Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)



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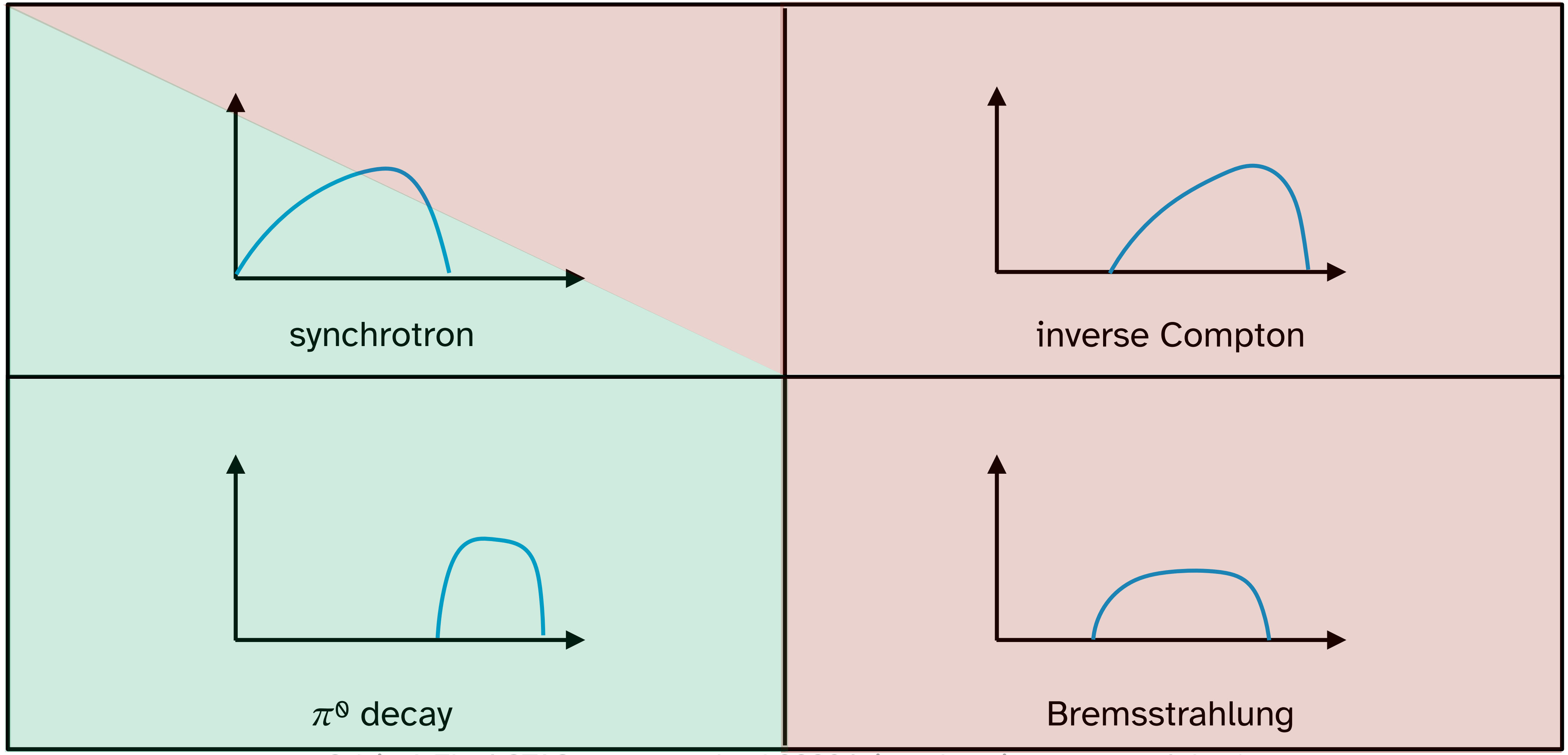

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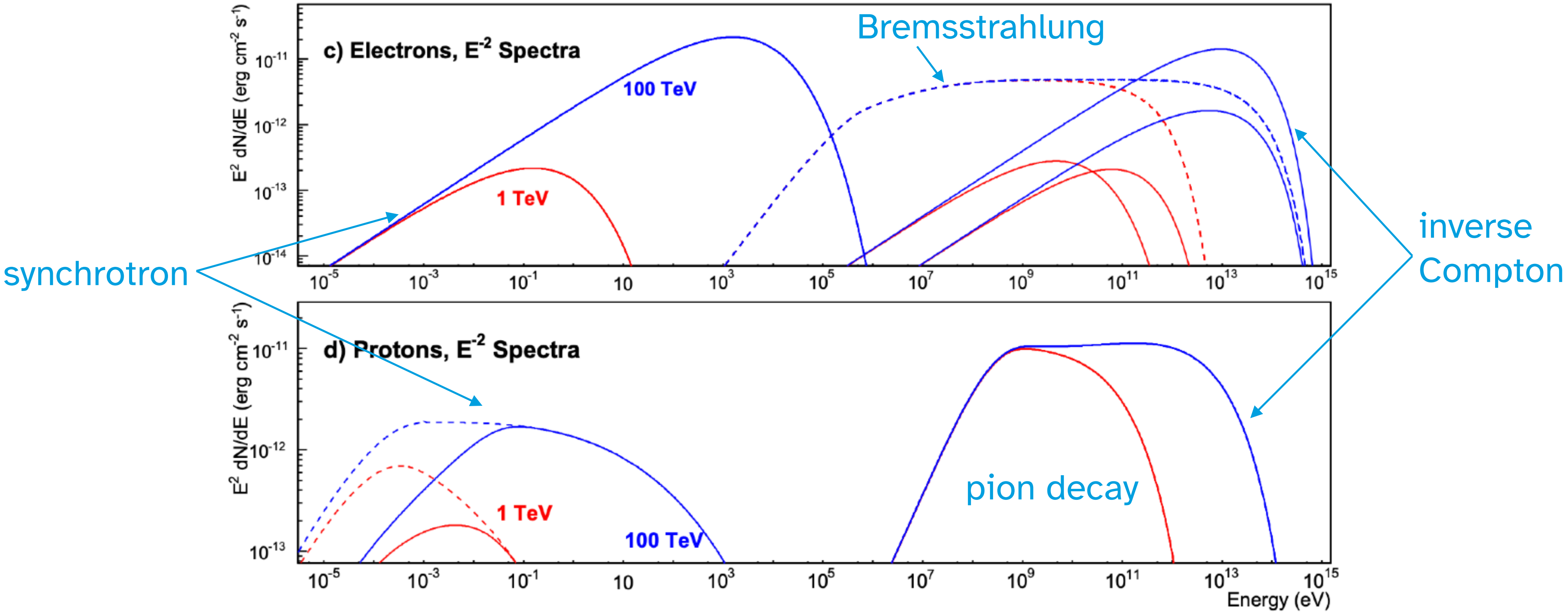
[J. A. Hinton & W. Hofmann, ARA&A 47 (2009)]

example spectra under common conditions

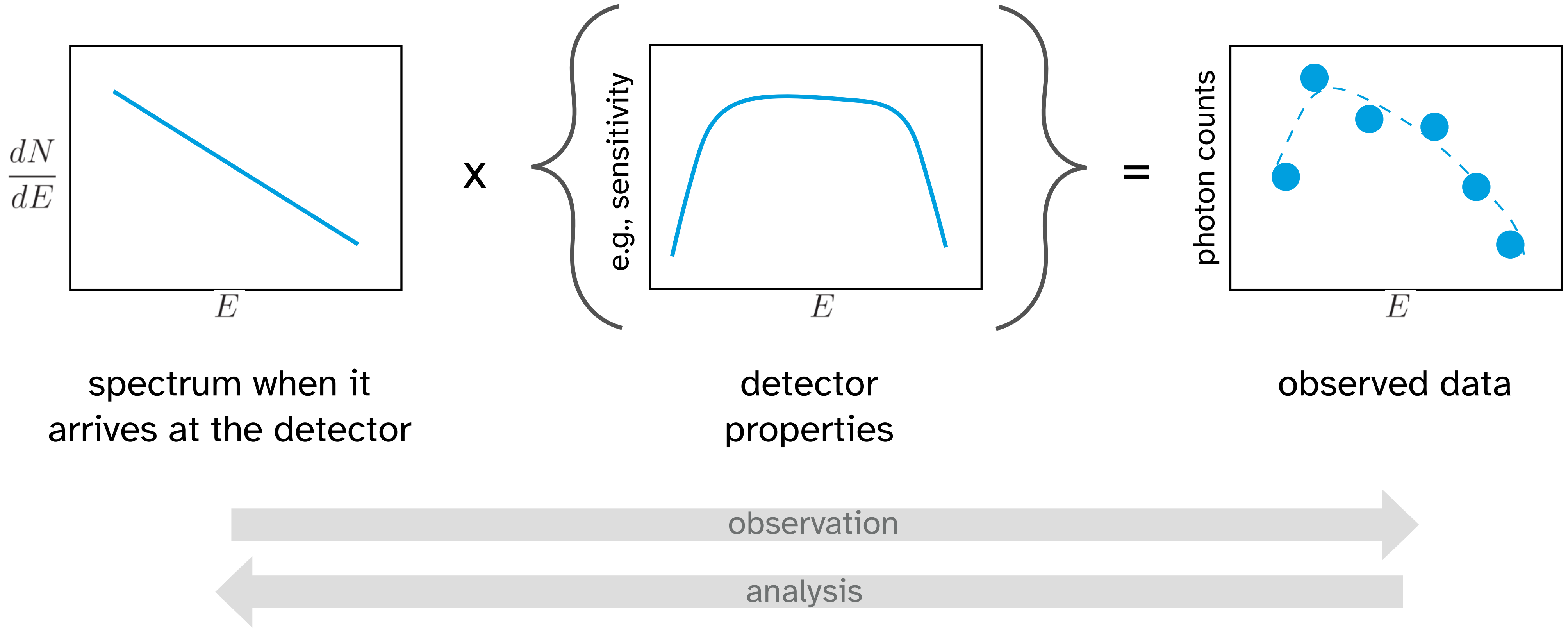


What exactly do we mean by “spectra”?

how much is emitted vs photon energy

$\frac{dN}{dE}$: number of photons per unit time*area*energy

example units: ph cm^{-2} s^{-1} keV^{-1}



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example units: ph cm^{-2} s^{-1} keV^{-1}

$E\frac{dN}{dE}$ tells us at what photon energy the largest number of photons is emitted

example units: ph cm^{-2} s^{-1}

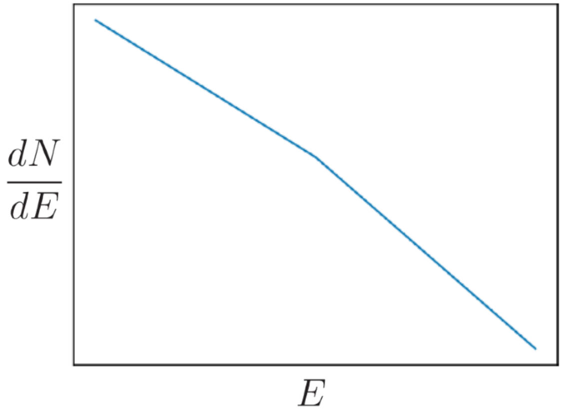
$E^2\frac{dN}{dE}$ tells us at what photon energy the largest amount of energy is emitted

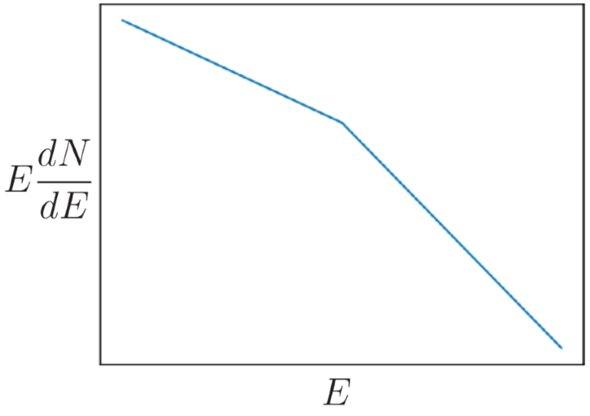
example units: erg cm^{-2} s^{-1}

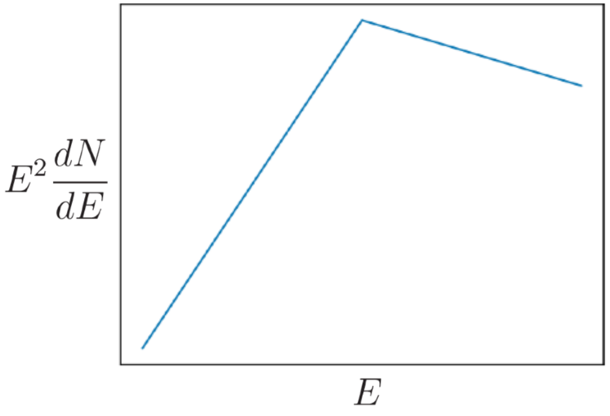
equivalently: νF_ν

(often seen in astronomy)

e.g.:



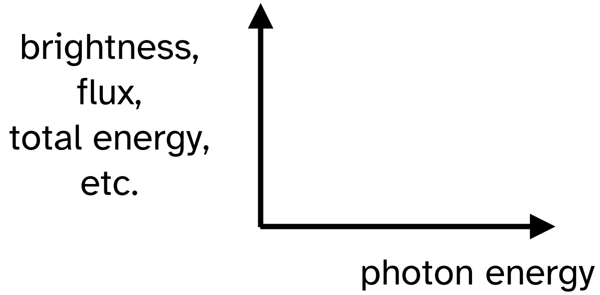


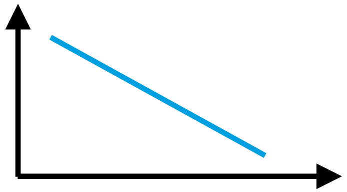


Spectra

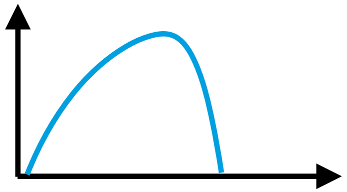
how much is emitted vs photon energy

The spectrum tells you something about the photon emission mechanism

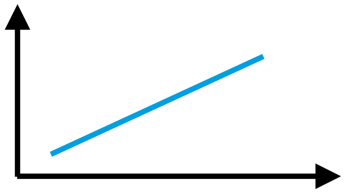




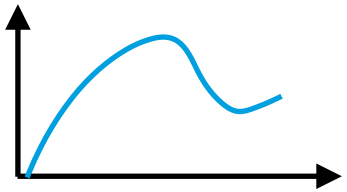
more energy emitted at lower photon energies ("soft spectrum")



there is a "peak" photon energy



more energy emitted at higher photon energies ("hard spectrum")

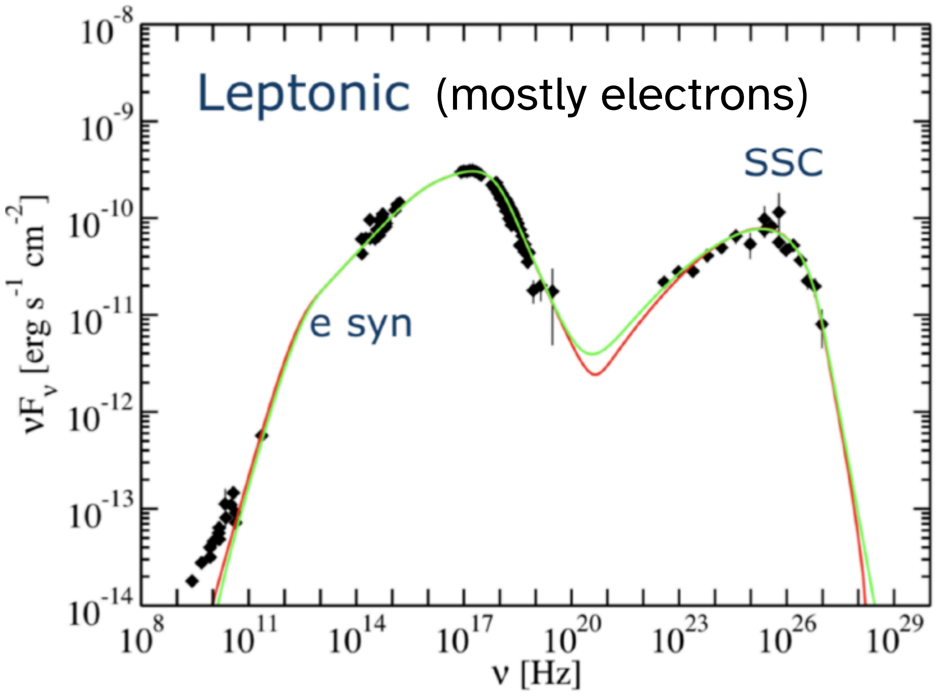


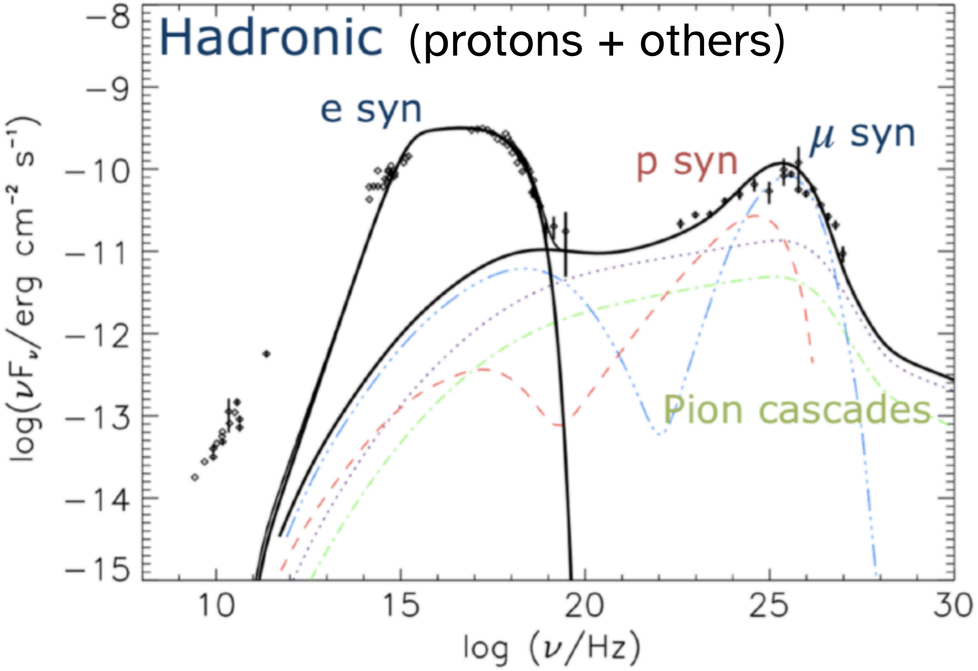
there are multiple emission mechanisms

Multiwavelength spectra

Combining the spectra across a wide range of photon energies allows us to better understand the photon emission mechanisms

[M. Cerruti, TAUP 2019] Markarian 421, an active galaxy





Light curves

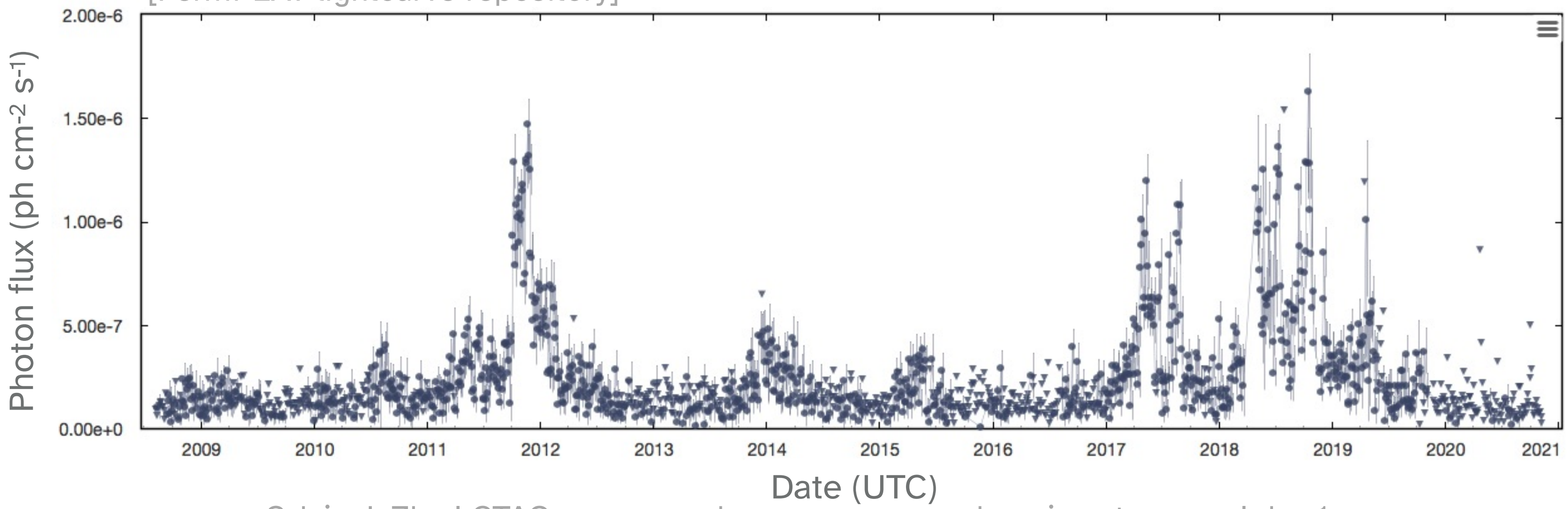
how much is emitted vs time

What if I want to see how the emission changes with time?

$$\int_{E_1}^{E_2} \left(\frac{dN}{dE}\right) dE$$: "(integral) photon flux," total number of photons detected over a photon energy range

$$\int_{E_1}^{E_2} E \left(\frac{dN}{dE}\right) dE$$: "(integral) energy flux," total energy detected over a photon energy range

[Fermi-LAT lightcurve repository]



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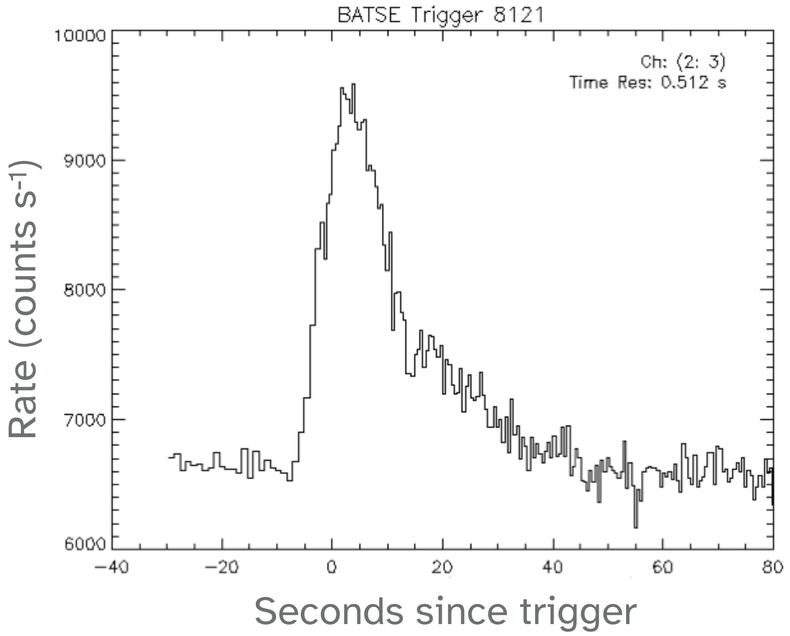
Or you can also simply plot the photon count rate over time



Light curves

how much is emitted vs time

What if I want to see how the emission changes with time?

$$\int_{E_1}^{E_2} \left(\frac{dN}{dE}\right) dE$$

$$\int_{E_1}^{E_2} E \left(\frac{dN}{dE}\right) dE$$

← Takes into account instrumental factors like changing detector sensitivity, but assumes a spectral model, and will change for different assumed spectra

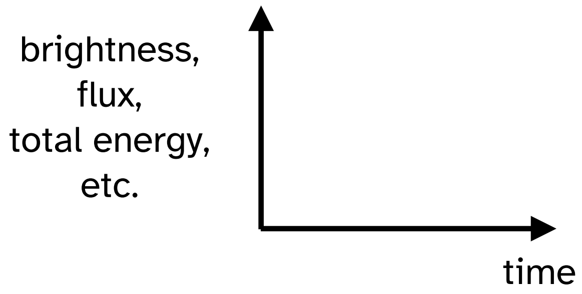
Or you can also simply plot the photon count rate over time

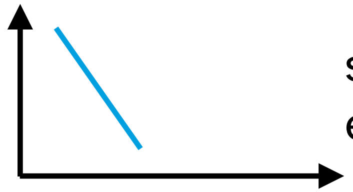
← Does not require any additional assumptions — except for the implicit assumption that the detector sensitivity is not greatly changing during this time

Light curves

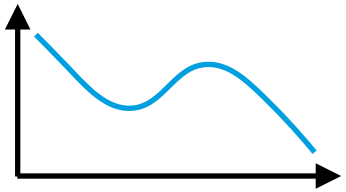
how much is emitted vs time

The lightcurve tells you about how the emission source is changing

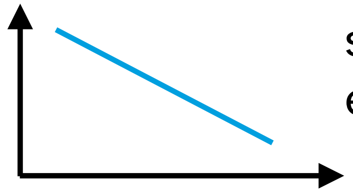




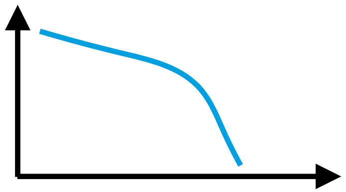
source is losing energy quickly



something has added additional energy into the system



source is losing energy slowly

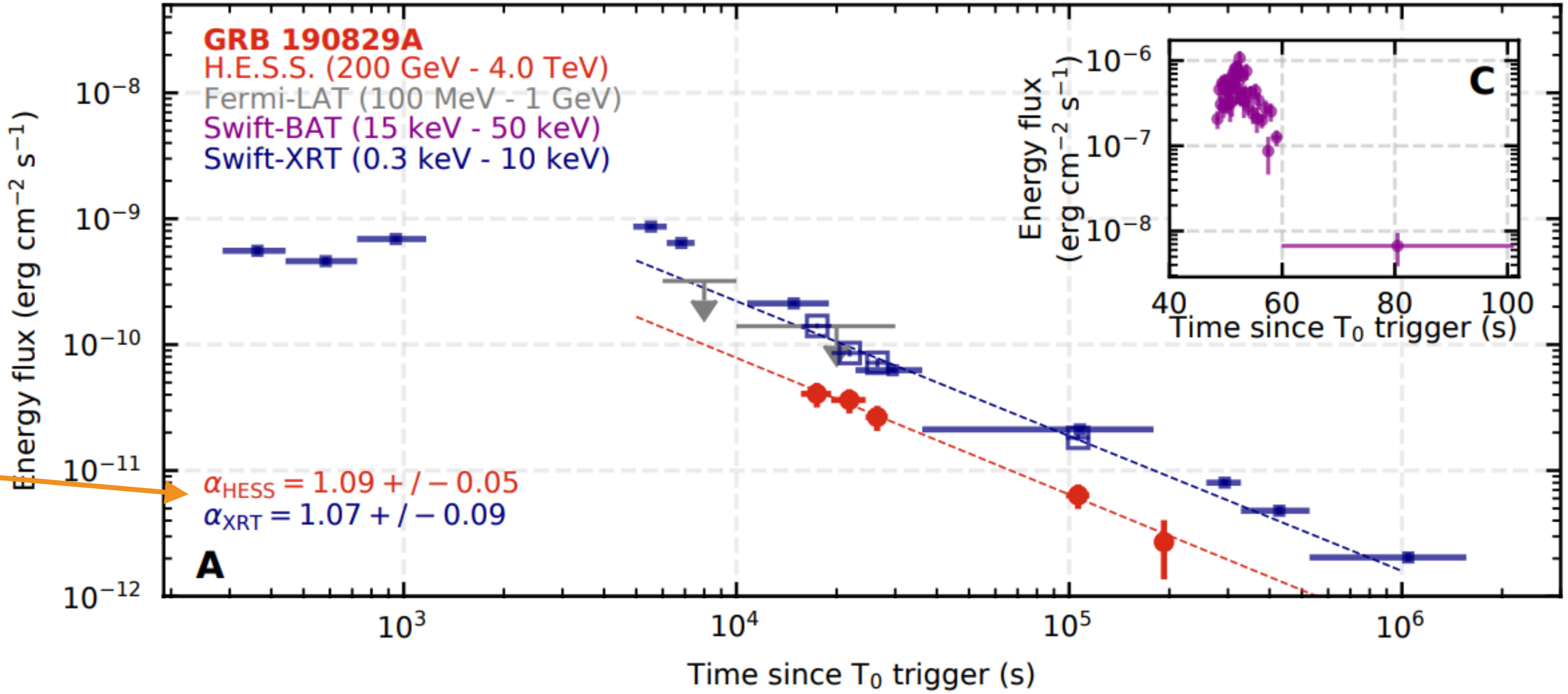


something that was providing energy is no longer doing so

Multiwavelength lightcurves

Comparing the lightcurves at different wavelengths gives information about how the system is evolving

X-ray and gamma-ray flux are decaying at the same rate
-> the same mechanism is likely producing both

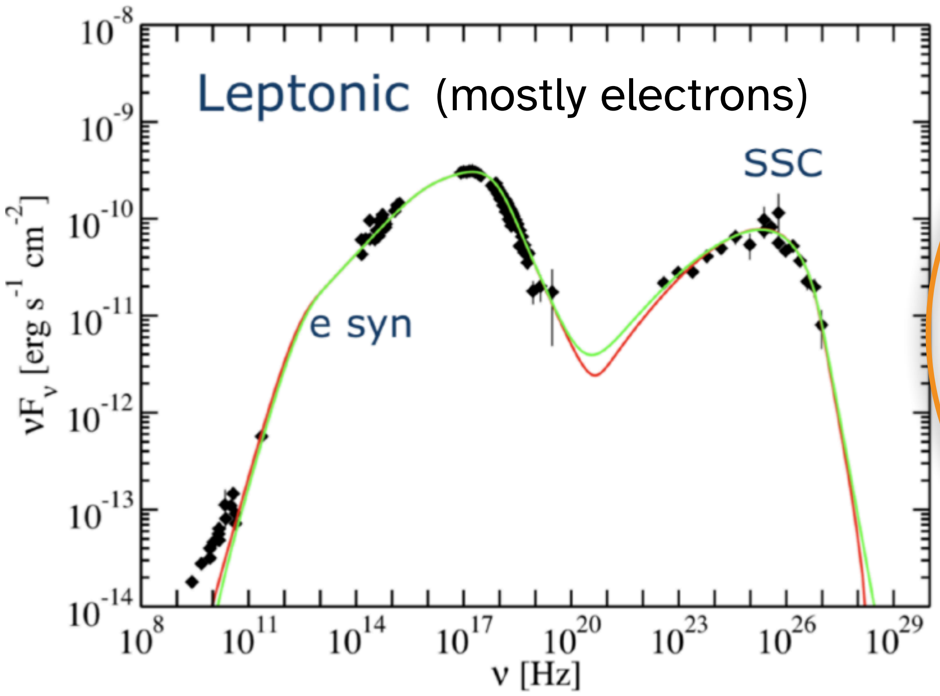


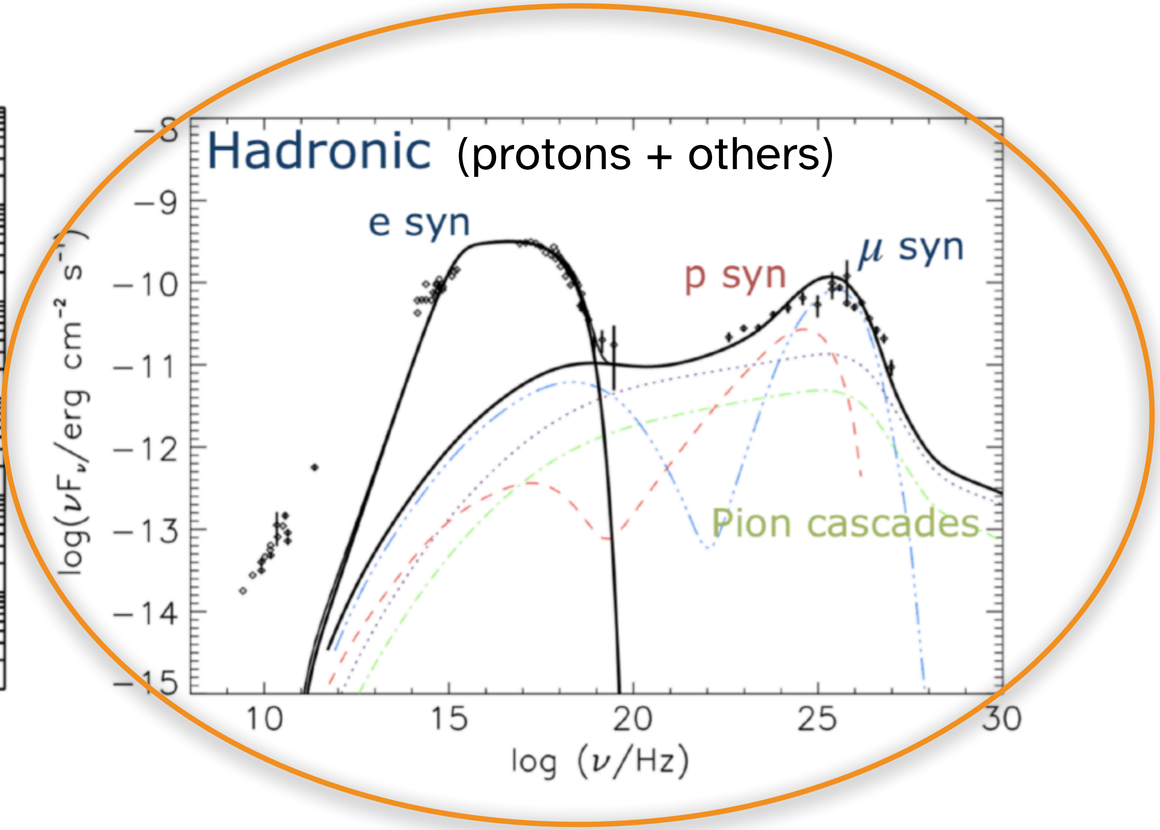
modified from [H. Abdalla et al., Science 372 (2021)]

Multiwavelength spectra

Combining the spectra across a wide range of photon energies allows us to better understand the photon emission mechanisms

[M. Cerruti, TAUP 2019]





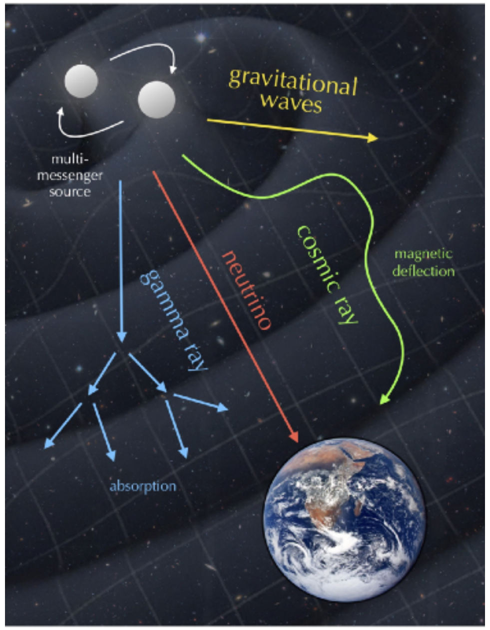
=> hadronic sources are sources of *cosmic rays*

hot take: I hate the term “cosmic rays”

fight me

Historical term, meaning: any kind of ionizing radiation from space (which technically includes gamma rays)
- nowadays we usually mean charged particles (protons, atomic nuclei, electrons/positrons)
  - but “cosmic ray” can also be neutrons + the secondary particles produced by the ones listed above
    - and as soon as we acknowledge cosmic-ray neutrons, then why not neutrinos too
      - so cosmic rays in principle encompass pretty much everything???? (╯°□°)╯︵ ┻━┻

Practically speaking, often we see some diagram like this ⟶



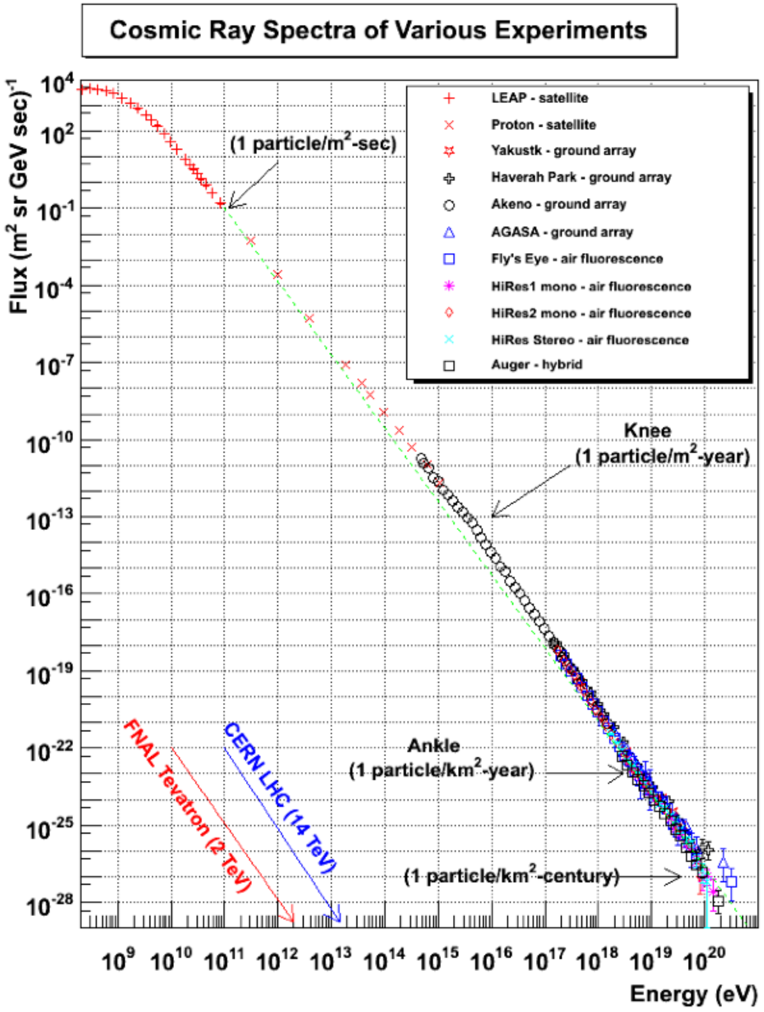
[Niels Bohr Institute]

so for gamma-ray purposes, sometimes we mean “charged particles”
although often we mean “charged hadrons” in particular
¯_(ツ)_/¯

so if someone says “cosmic ray” make sure it’s clear what they mean!!

ok great but what are cosmic rays

see Giada's lectures for more details



[M. Duldig, Science 314 (2006)]

cosmic rays are charged particles -> deflected by magnetic fields

mostly nuclei, a few % electrons

89% protons,
10% He,
1% heavier

How exactly do we go from cosmic rays to gamma rays?

Cosmic rays to gamma rays

see Giada's lectures for more details

$p + p \rightarrow p + p + \pi^0$

$p + p \rightarrow p + n + \pi^+$

$p + p \rightarrow p + p + \pi^+ + \pi^-$

$p + p \rightarrow$ etc.

$p + \gamma \rightarrow p + \pi^0$

$p + \gamma \rightarrow n + \pi^+$

$p + \gamma \rightarrow$ etc.

p	proton	**hadrons**
n	neutron	
π	pion (pi meson)	
γ	photon	
μ	muon	**leptons**
ν	neutrino	

Cosmic rays to gamma rays

see Giada's lectures for more details

π^0 decays in 10^{-16} s

$\pi^{+/-}$ decays in 10^{-8} s

$p + p \rightarrow$
- $p + p + \pi^0 \longrightarrow \gamma + \gamma$
- $p + n + \pi^+$
- $p + p + \pi^+ + \pi^-$
- etc.

$p + \gamma \rightarrow$
- $p + \pi^0 \longrightarrow \gamma + \gamma$
- $n + \pi^+$
- etc.

p	proton	hadrons
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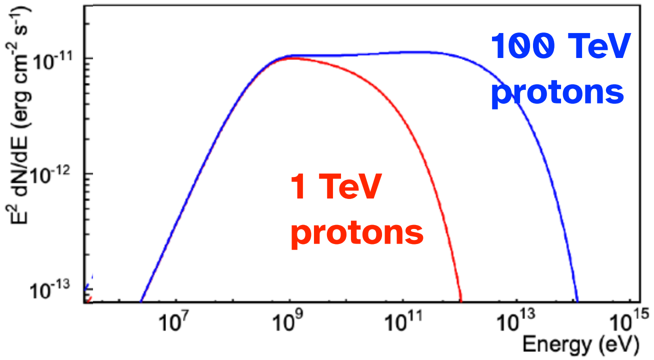
μ	muon	leptons
ν	neutrino	leptons

Cosmic rays to gamma rays

see Giada's lectures for more details

p + p → p + p + π^0 → $\gamma + \gamma$
p + p → p + n + π^+
p + p → p + p + π^+ + π^-
p + p → etc.



[J. A. Hinton & W. Hofmann, ARA&A 47 (2009)]

gamma rays can be produced by hadronic interactions, and the spectrum would be a characteristic "pion bump"

p + γ → p + π^0 → $\gamma + \gamma$
p + γ → n + π^+
p + γ → etc.

~10% of the original proton energy is transferred to the gamma rays

e.g., detect gamma rays with E_γ = 100 TeV
+ pion bump
= source can produce cosmic rays with E_{CR} = 1 PeV

congrats you found a pevatron

Cosmic rays to gamma rays

see Giada's lectures for more details

π^0 decays in 10^{-16} s

$\pi^{+/-}$ decays in 10^{-8} s

$p + p \rightarrow p + p + \pi^0 \rightarrow \gamma + \gamma$

$p + p \rightarrow p + n + \pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

$p + p \rightarrow p + p + \pi^+ + \pi^-$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

$p + p \rightarrow$ etc.

$p + \gamma \rightarrow p + \pi^0 \rightarrow \gamma + \gamma$

$p + \gamma \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$

$p + \gamma \rightarrow$ etc.

p	proton	hadrons
n	neutron	hadrons
π	pion (pi meson)	hadrons
γ	photon	
μ	muon	leptons
ν	neutrino	leptons

Neutrinos are the smoking gun for hadronic processes

Gamma-ray sources are multimessenger sources

TXS 0506+056 [IceCube et al., Science 361 (2018)]

Neutrinos are the smoking gun for hadronic processes

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

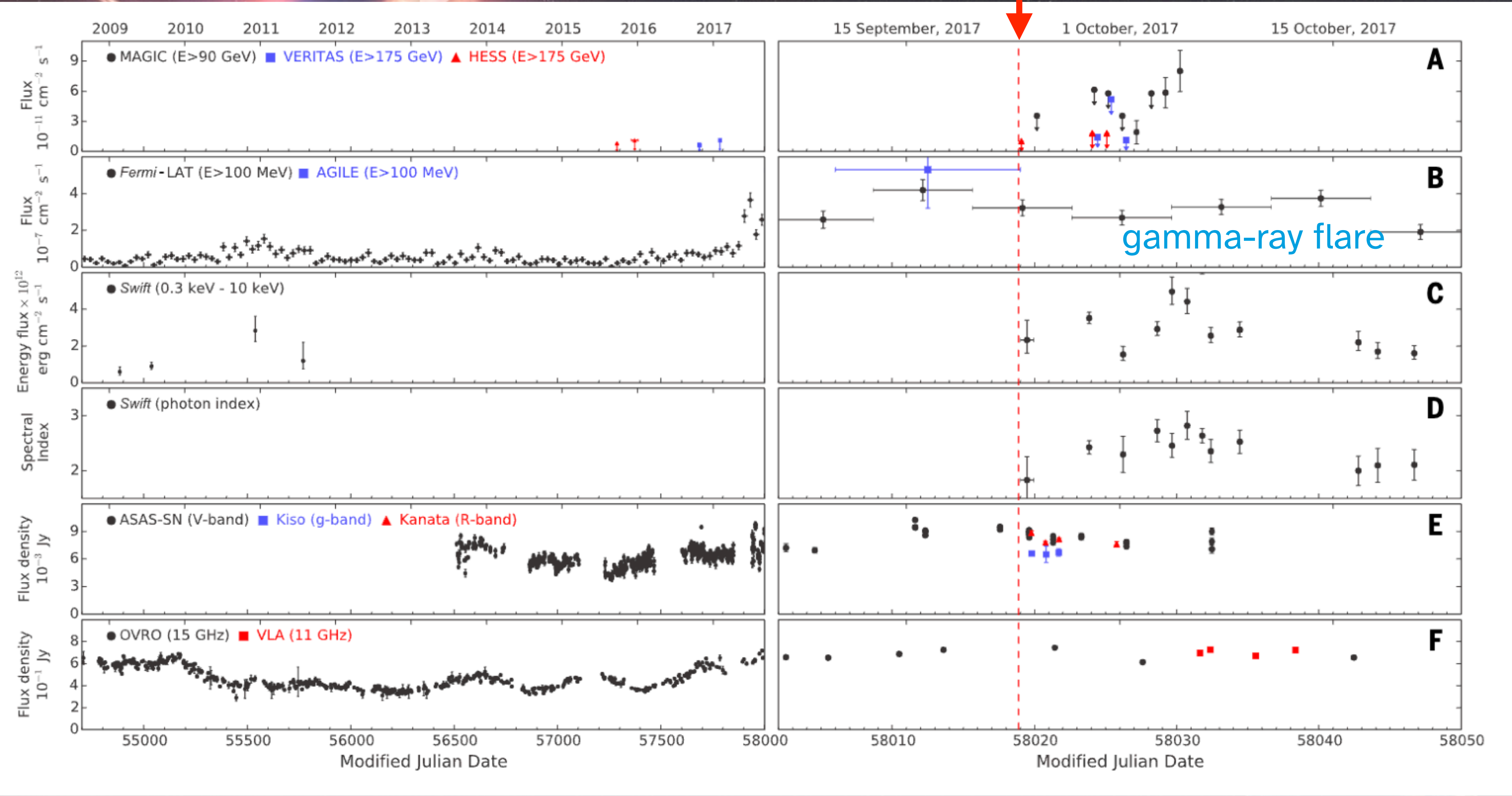
[IceCube et al., Science 361 (2018)]

[IceCube/NASA]

Gamma-ray sources are multimessenger sources

TXS 0506+056 [IceCube et al., Science 361 (2018)]

neutrino

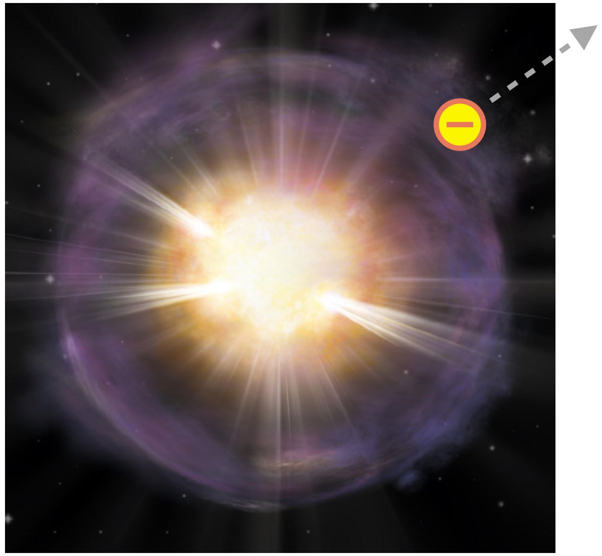


Lea will talk more about this on Thursday (I think)

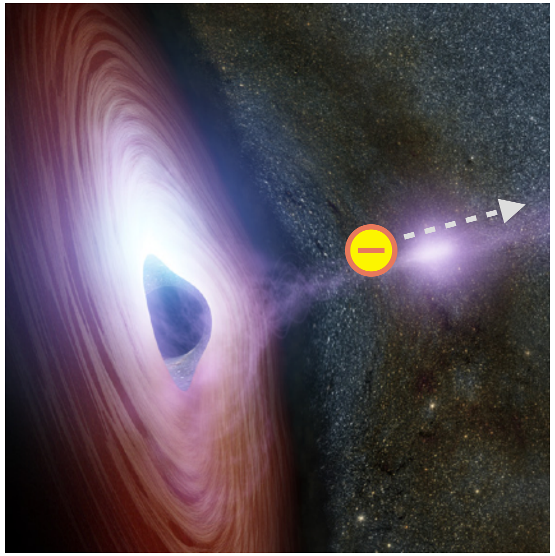
[IceCube/NASA]

Gamma-ray sources are multimessenger sources

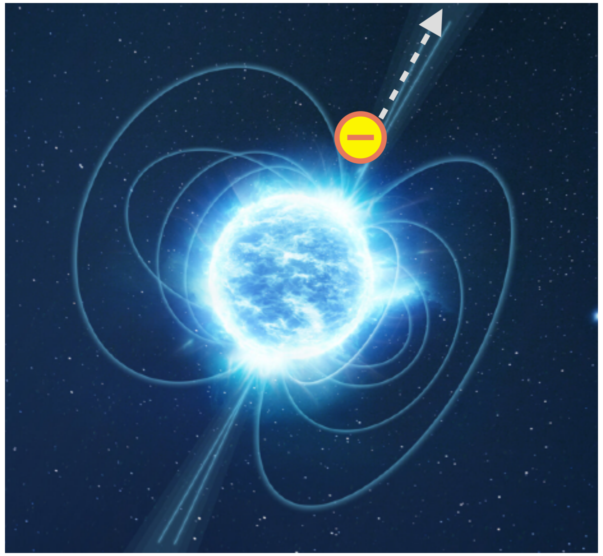
Charged particles are **accelerated** to high energies before radiating photons



[A. M. Geller/Northwestern/CTIO/SOAR/NOIRLab/NSF/AURA]



[NASA/JPL-Caltech]

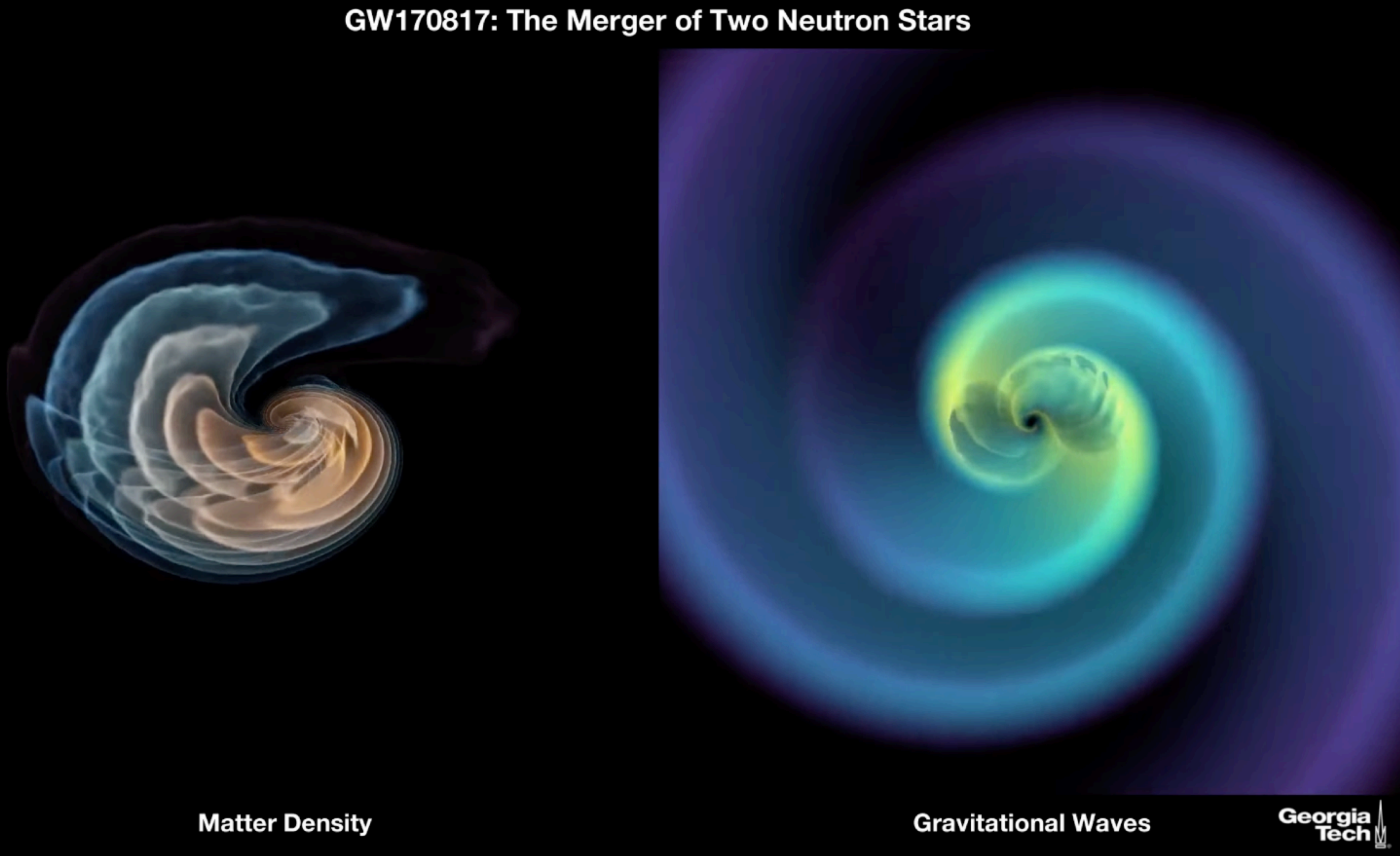


[ESA]

need a **large energy source** and a way to **transfer energy** to charged particles

=> **gamma-ray sources are often related to compact objects: black holes, neutron stars**

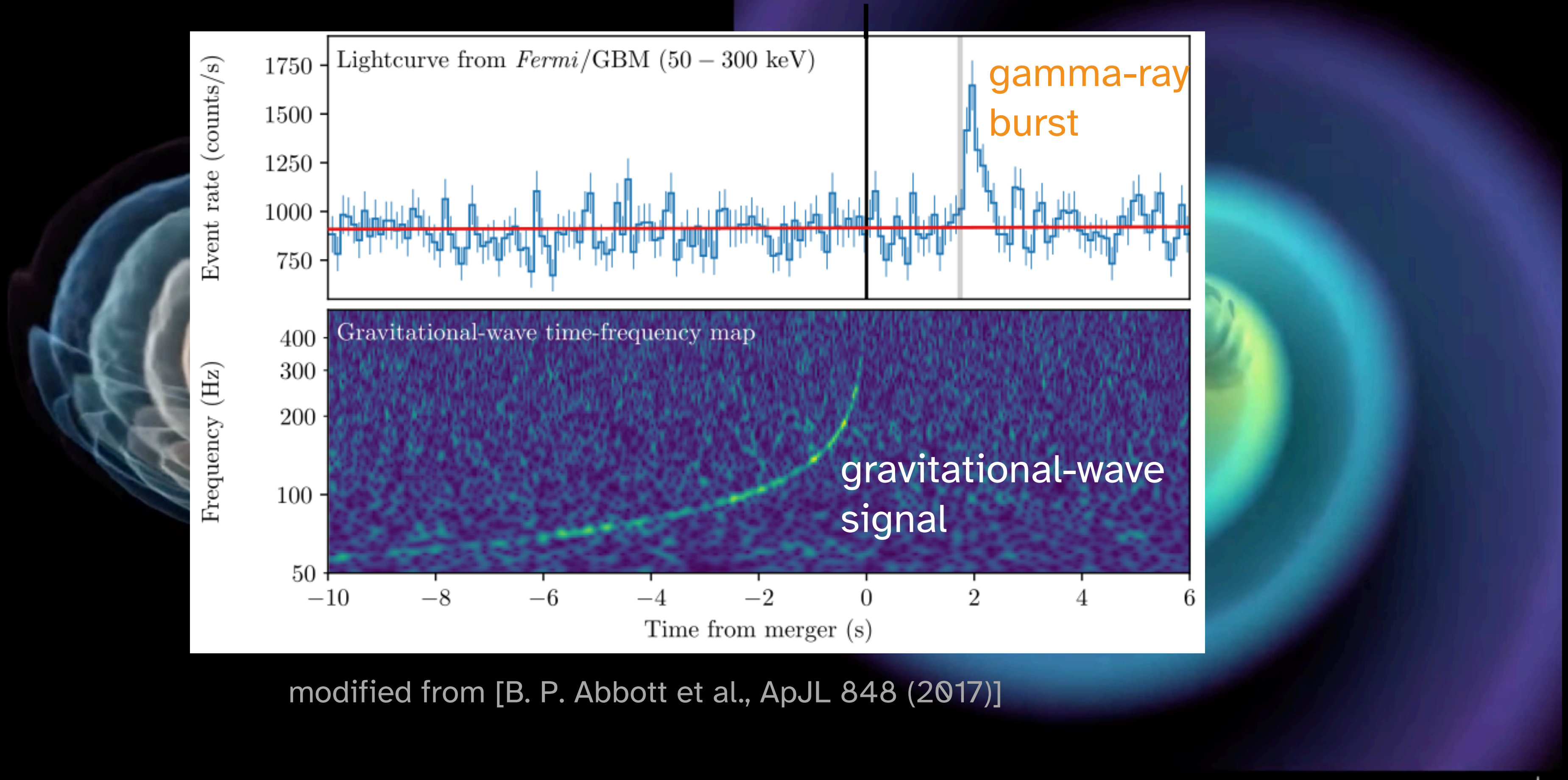
Gamma-ray sources are multimessenger sources



[Christopher W. Evans / Georgia Tech]

Gamma-ray sources are multimessenger sources

We'll talk more about this tomorrow

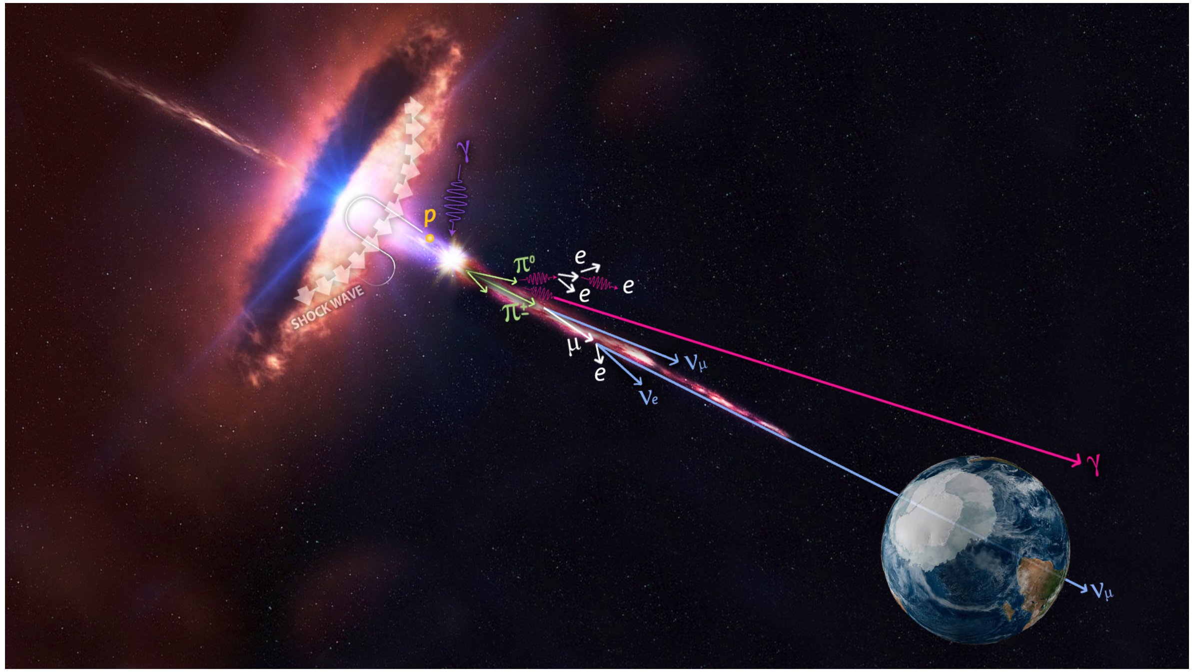


modified from [B. P. Abbott et al., ApJL 848 (2017)]

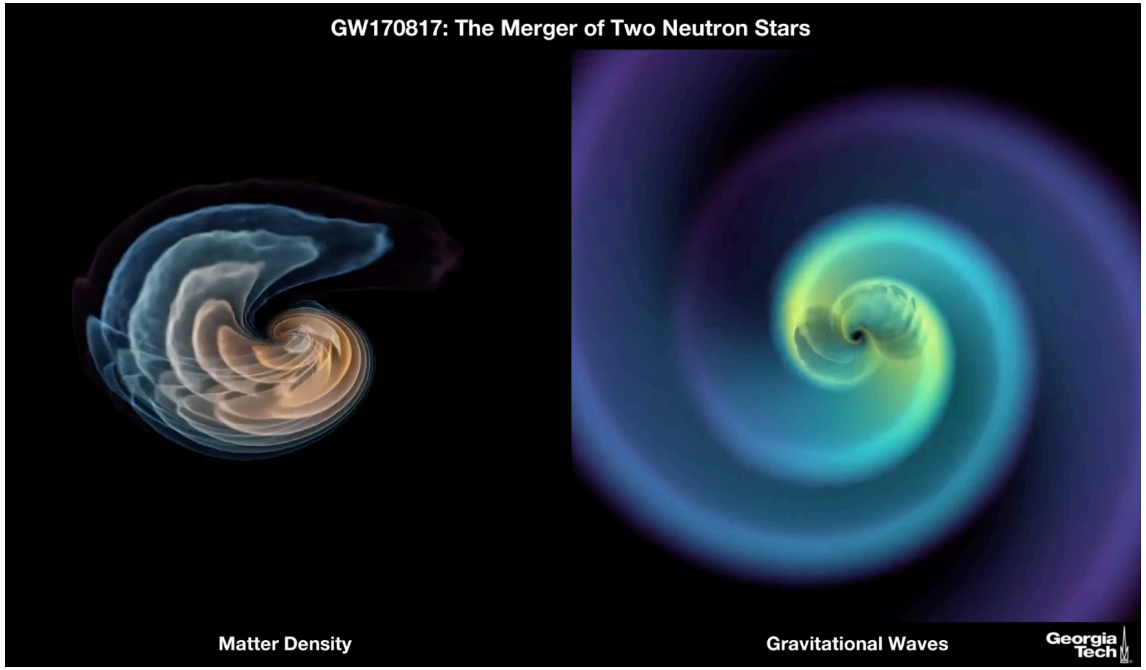
[Christopher W. Evans / Georgia Tech]

Time domain astronomy is the key to multimessenger science

(mostly (for now))



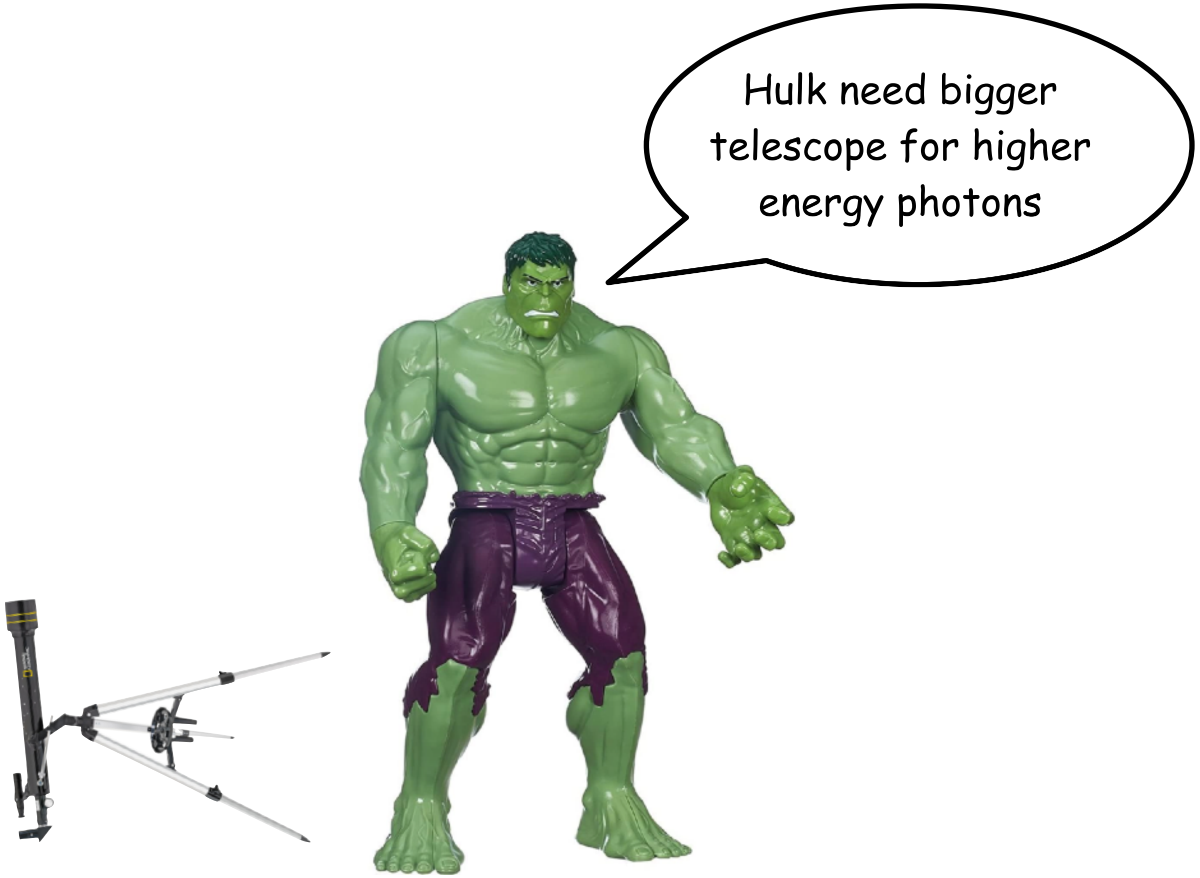
[IceCube/NASA]



[Christopher W. Evans / Georgia Tech]

Part 1b. How do we detect gamma rays?

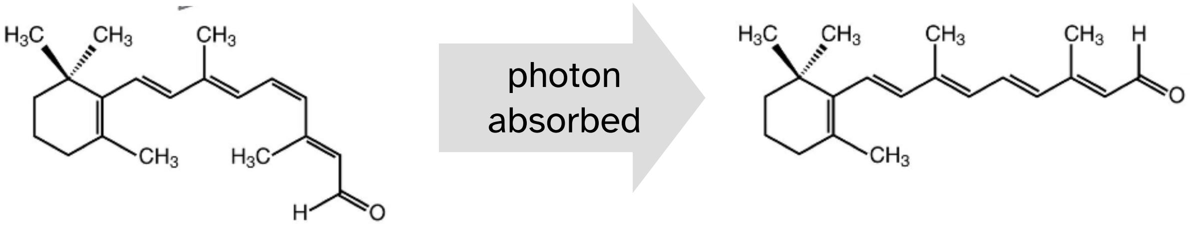
mostly a review of earlier lectures



How do our eyes detect photons?

photons -> electric signals

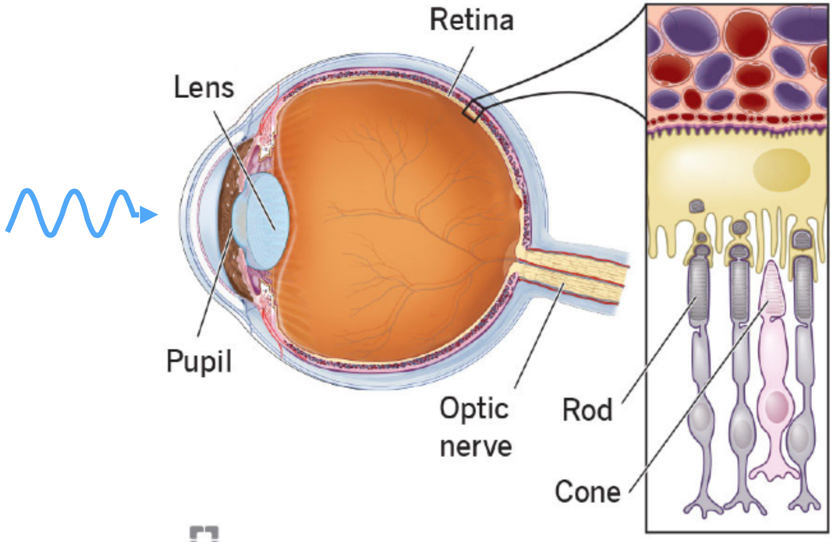
The back of the human eye has photoreceptors that directly **absorb photons** at optical/visible wavelengths and convert them into electric signals



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

[Anatomy & Physiology, Connexions]

Retina



Cleveland Clinic
©2022

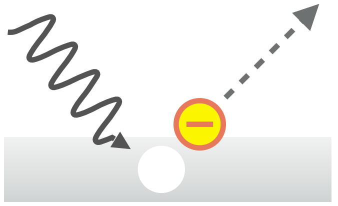
How do we do this for gamma rays?

Key: Convert high-energy photons into lower energy photons/particles that can be directly absorbed.

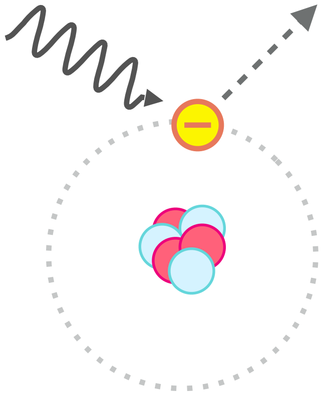
How gamma rays interact with **matter**

photons -> electric signals

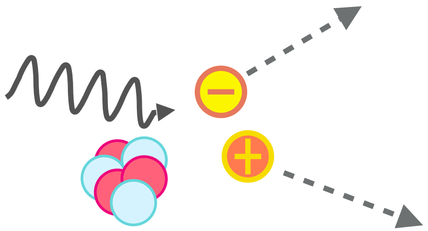
Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



photoelectric effect



Compton scattering

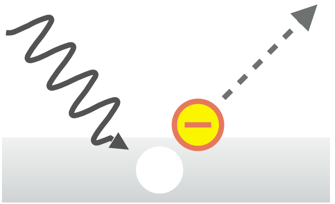


pair production

How gamma rays interact with matter

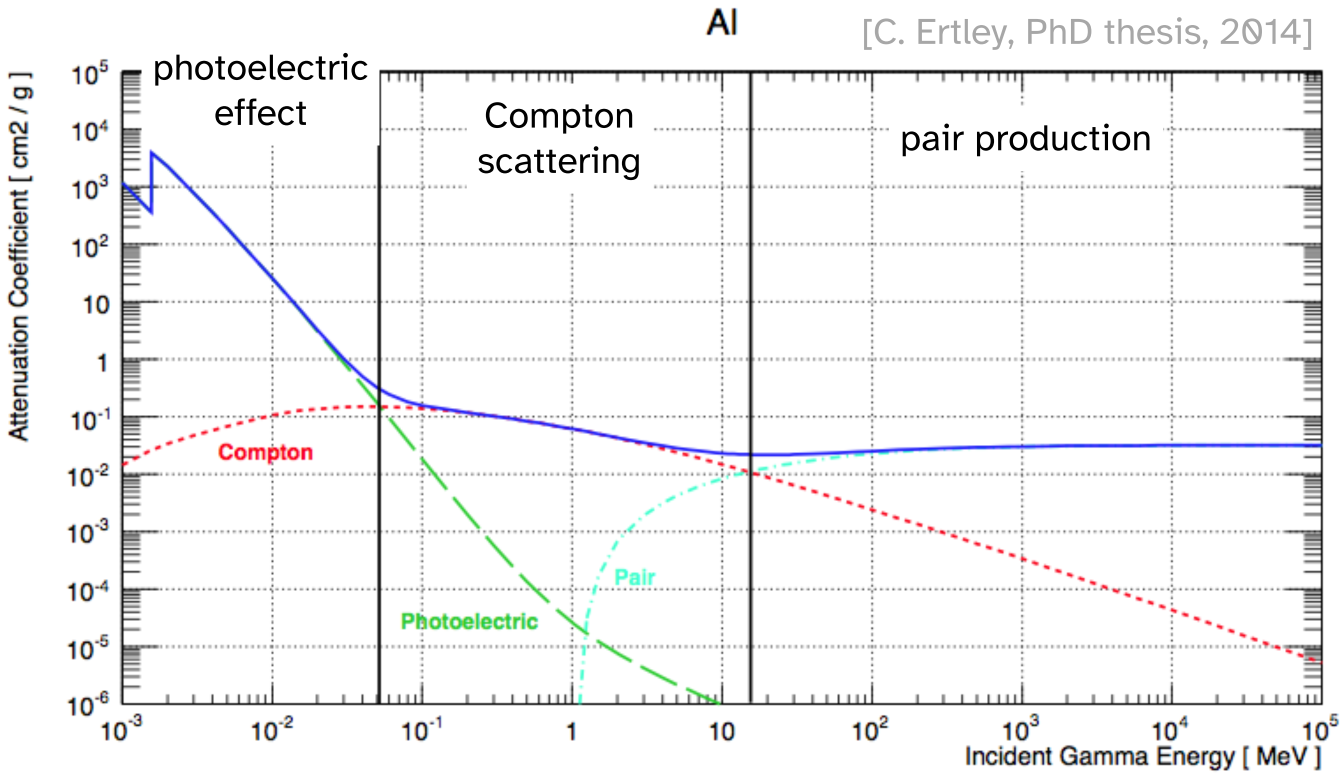
photons -> electric signals

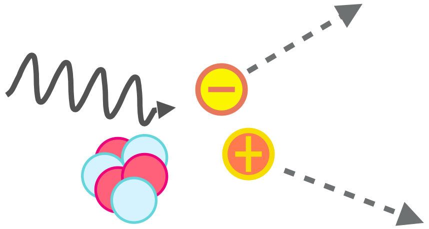
Note: The exact shapes of these curves depend on the target material



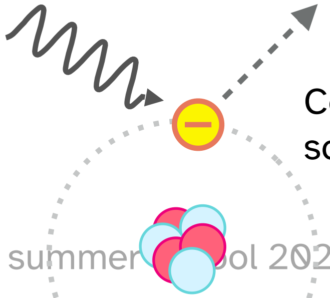
photoelectric effect

[C. Ertley, PhD thesis, 2014]





pair production



Compton scattering

How gamma rays interact with matter

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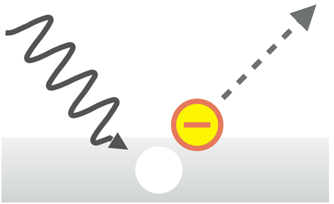
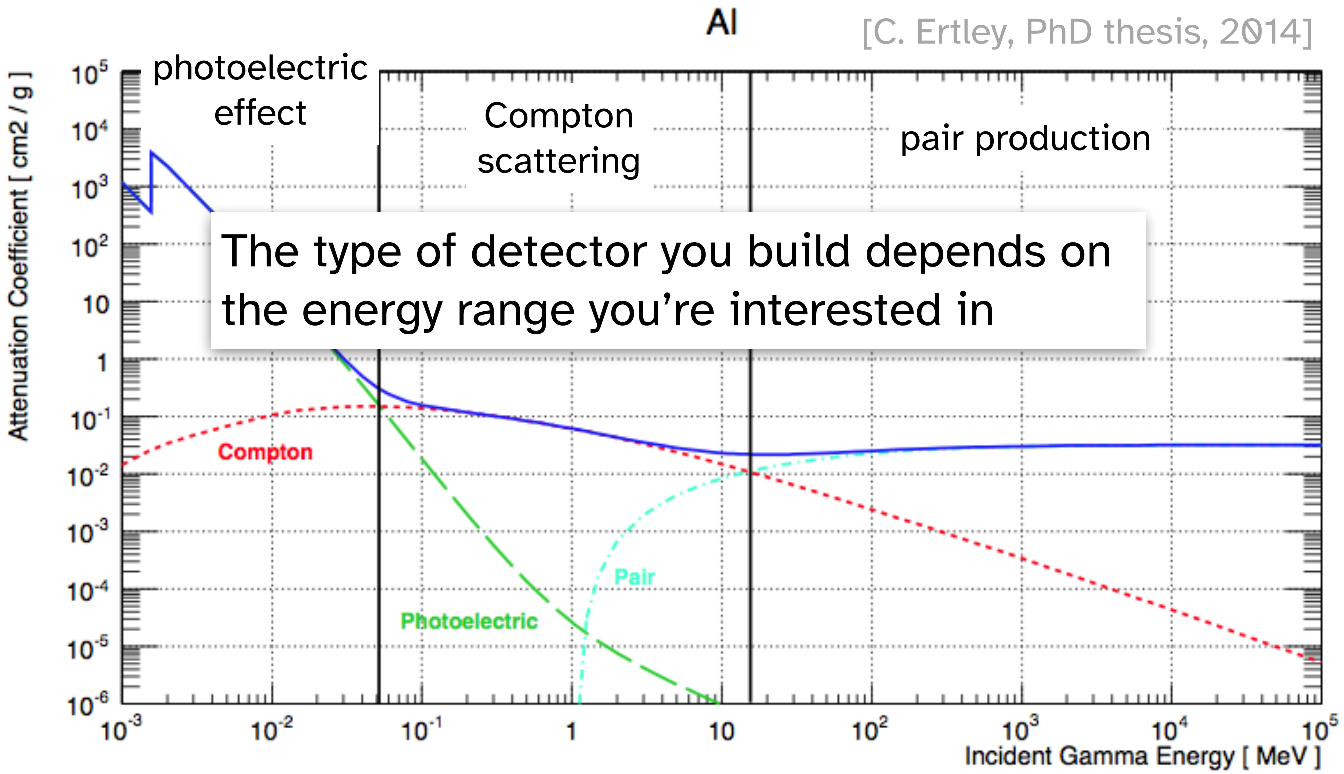
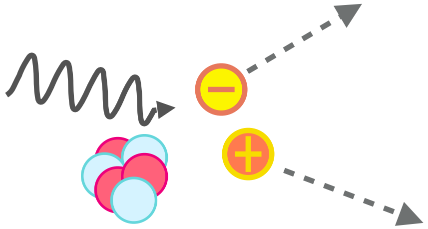


photoelectric effect

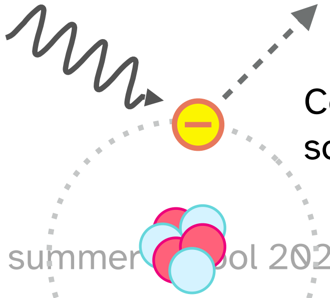
[C. Ertley, PhD thesis, 2014]



The type of detector you build depends on the energy range you're interested in



pair production

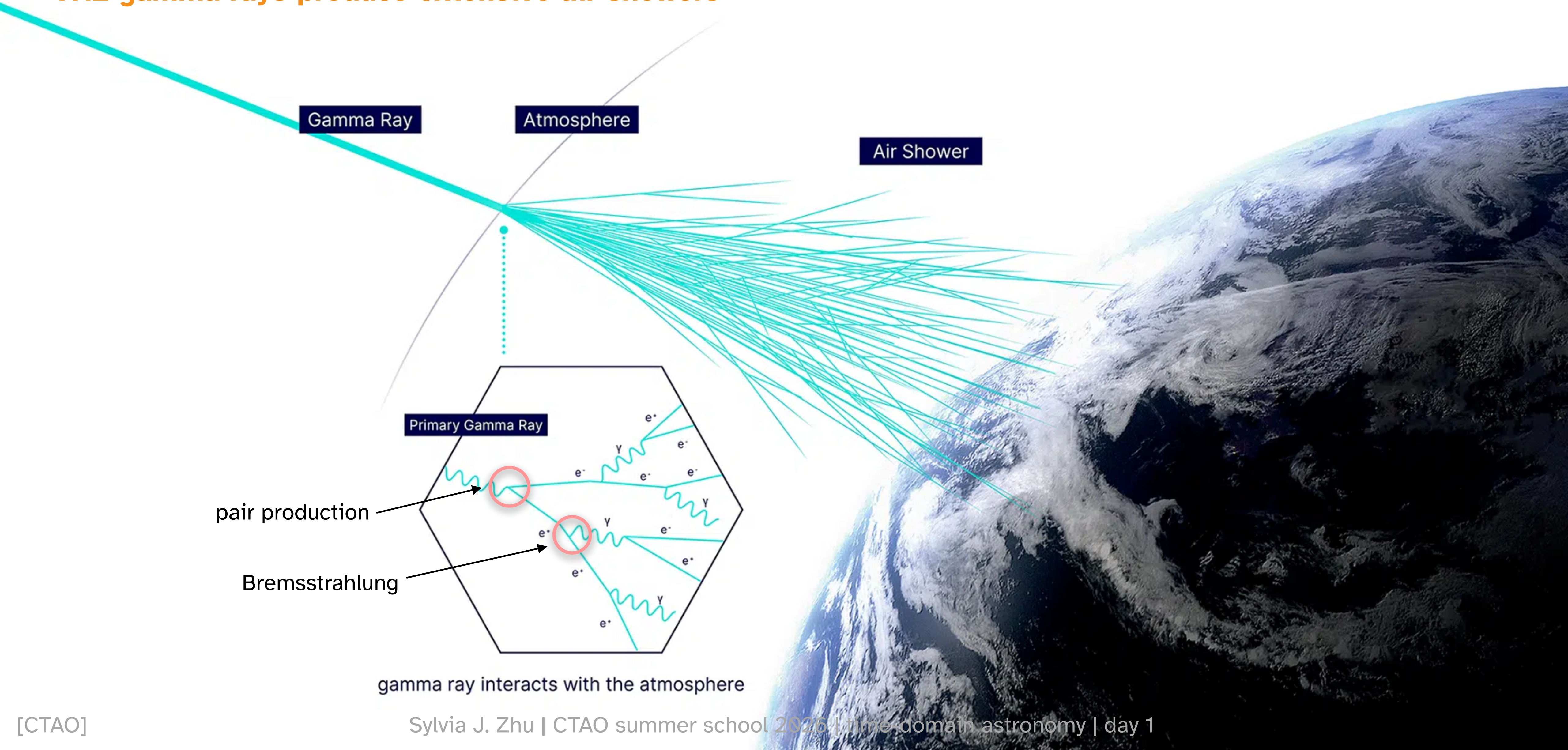


Compton scattering

CTAO

IACTs use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers



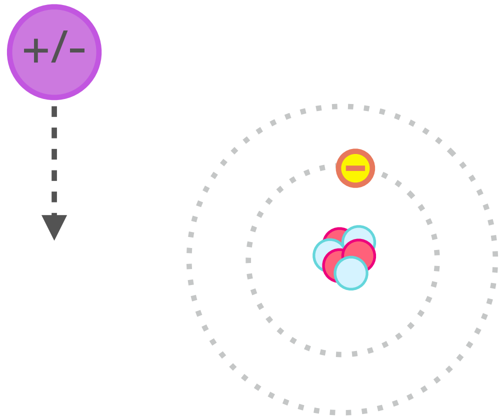
gamma ray interacts with the atmosphere

[CTAO]

Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

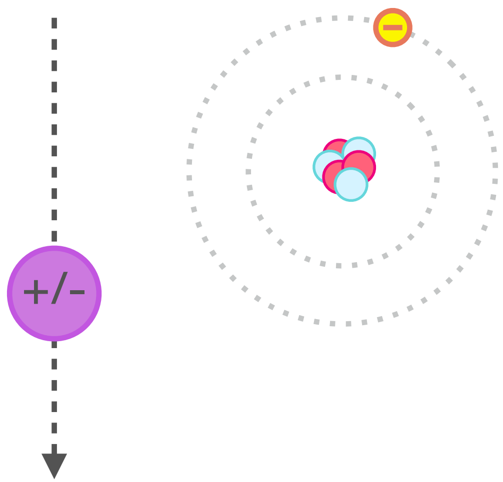
electromagnetic equivalent to a sonic boom



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

electromagnetic equivalent to a sonic boom



Use the atmosphere as part of the detector

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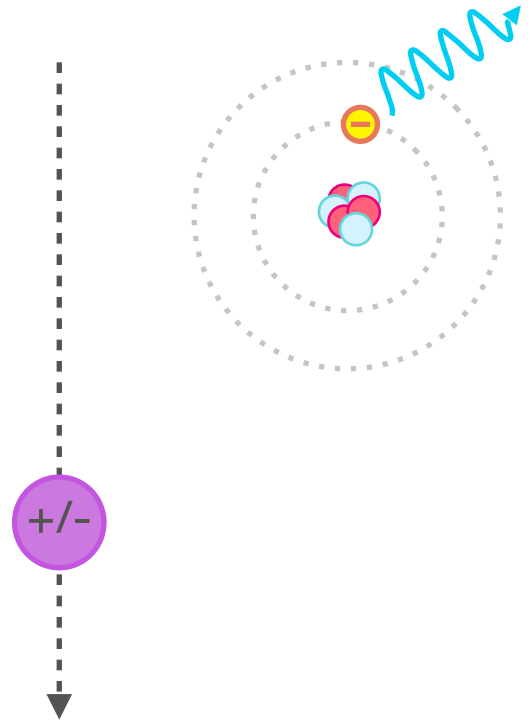
electromagnetic equivalent to a sonic boom



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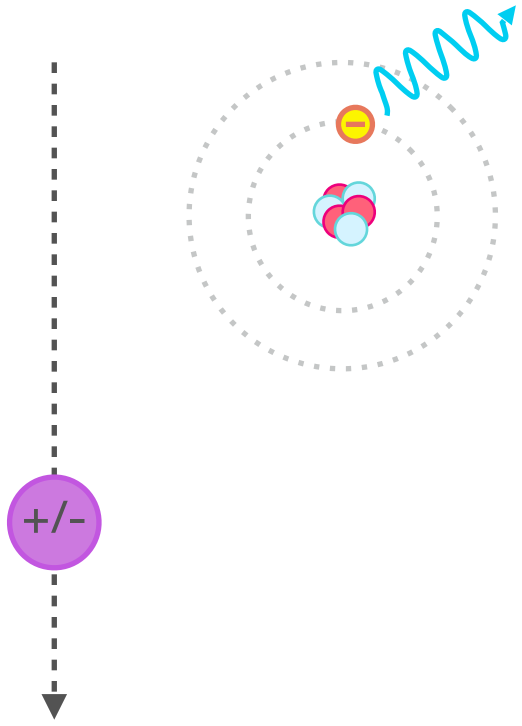
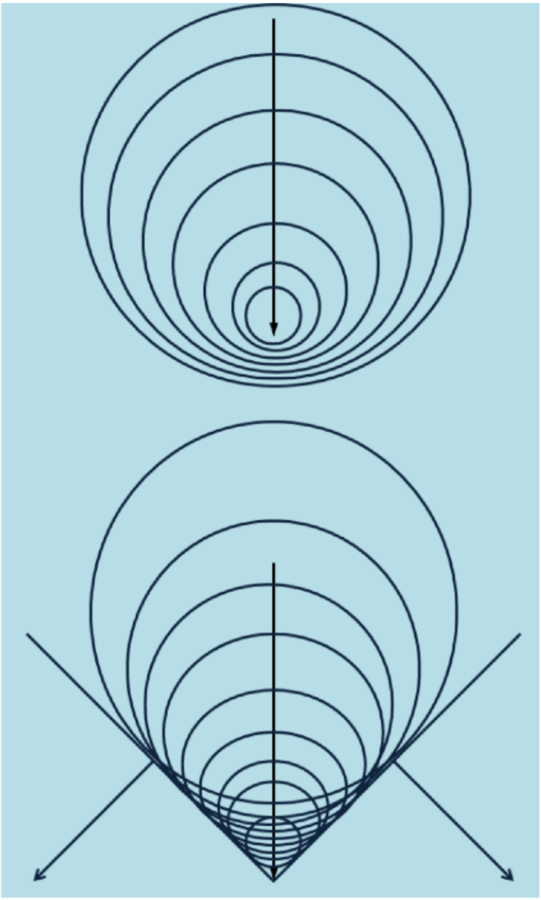


[J. Eckhard]

v < c/n:
no wavefront

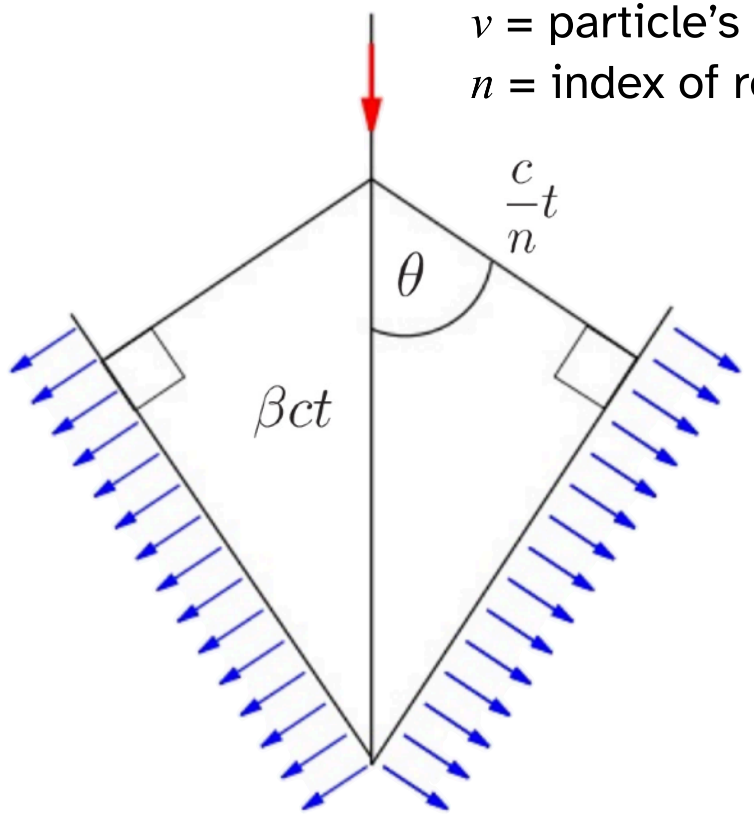
v > c/n:
wavefront



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

electromagnetic equivalent to a sonic boom



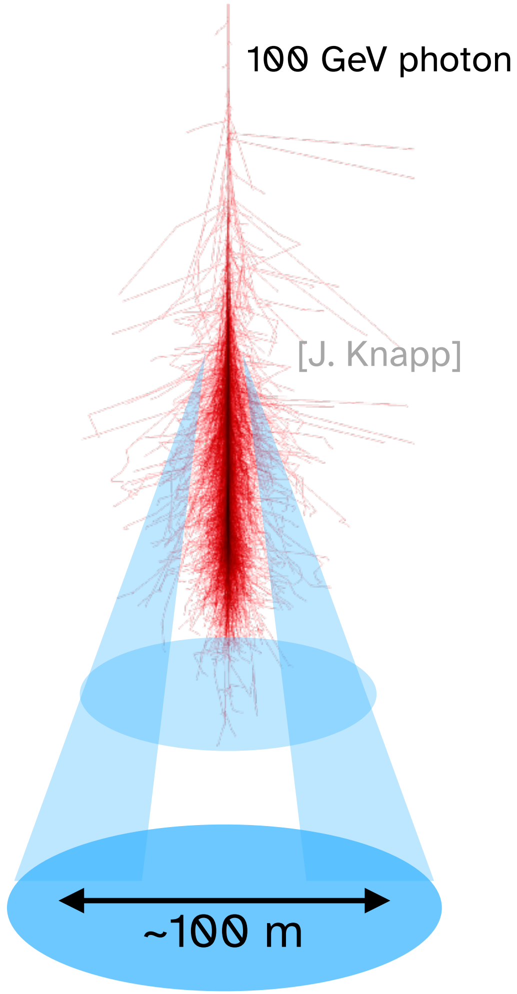
modified from [J. Eckhard]

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

$$\theta = \arccos \frac{1}{\beta n} \qquad \beta = \frac{v}{c}$$

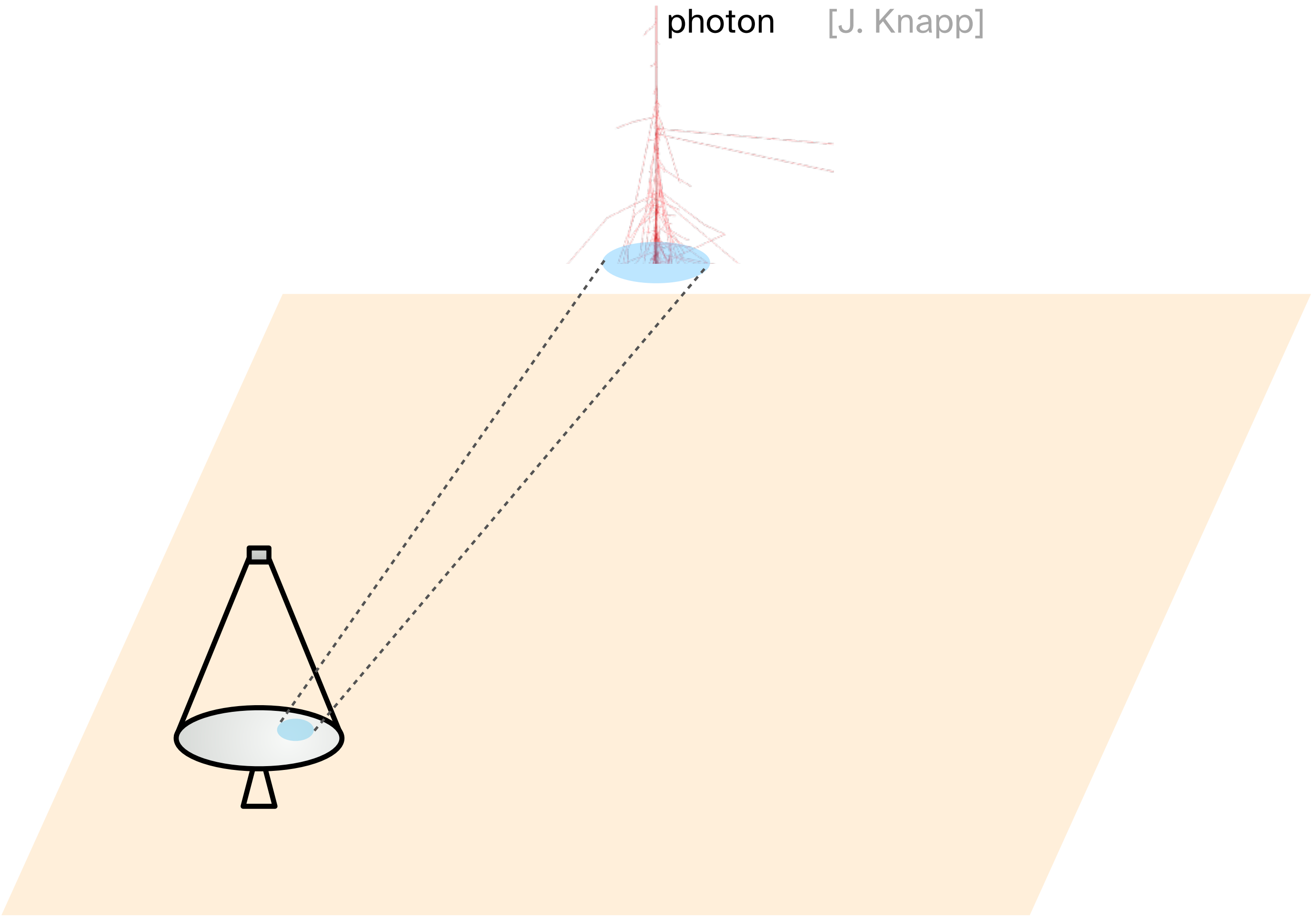
n ~ slightly larger than 1
β ~ 1
=> θ ~ 1°

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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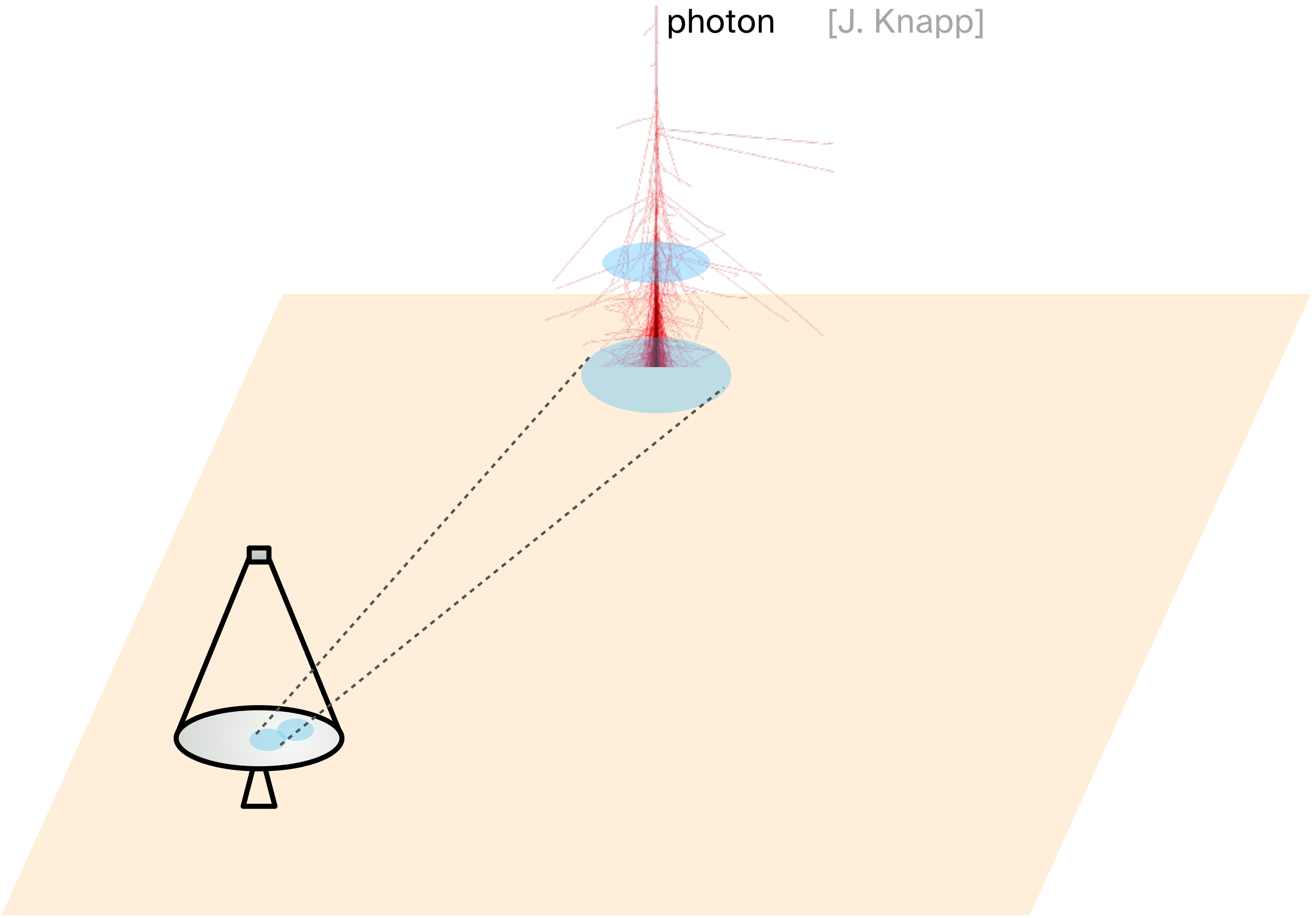

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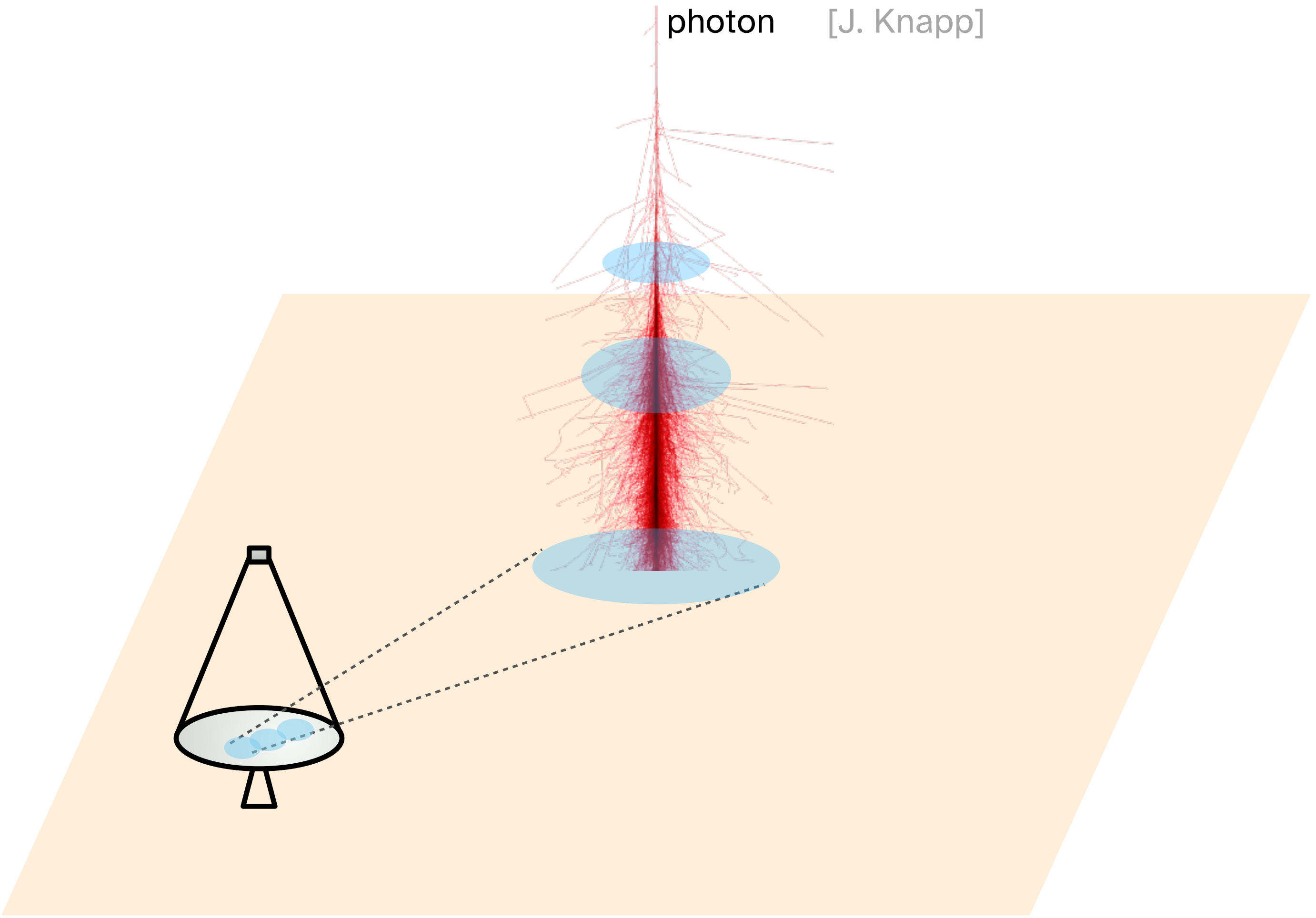

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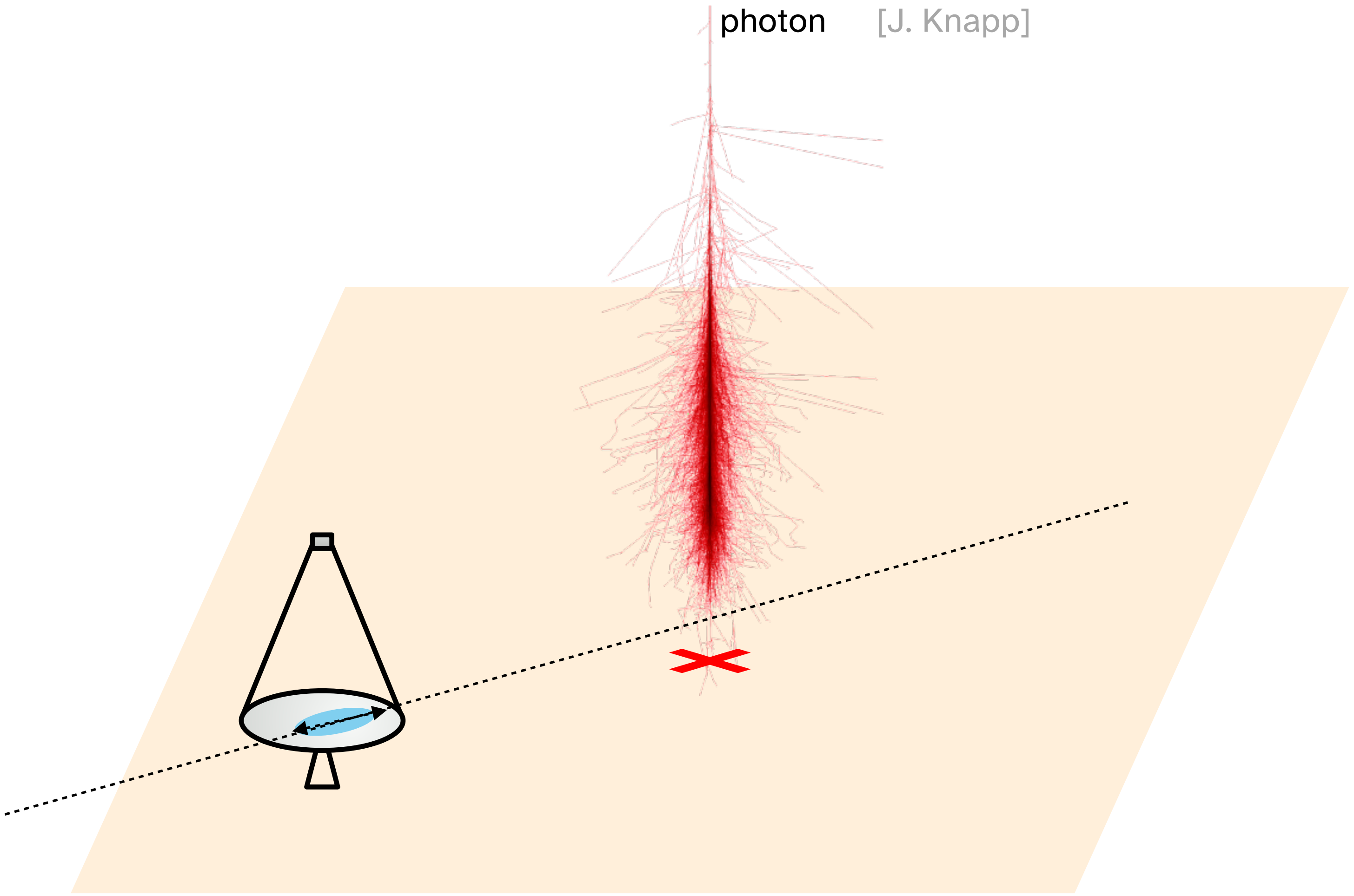

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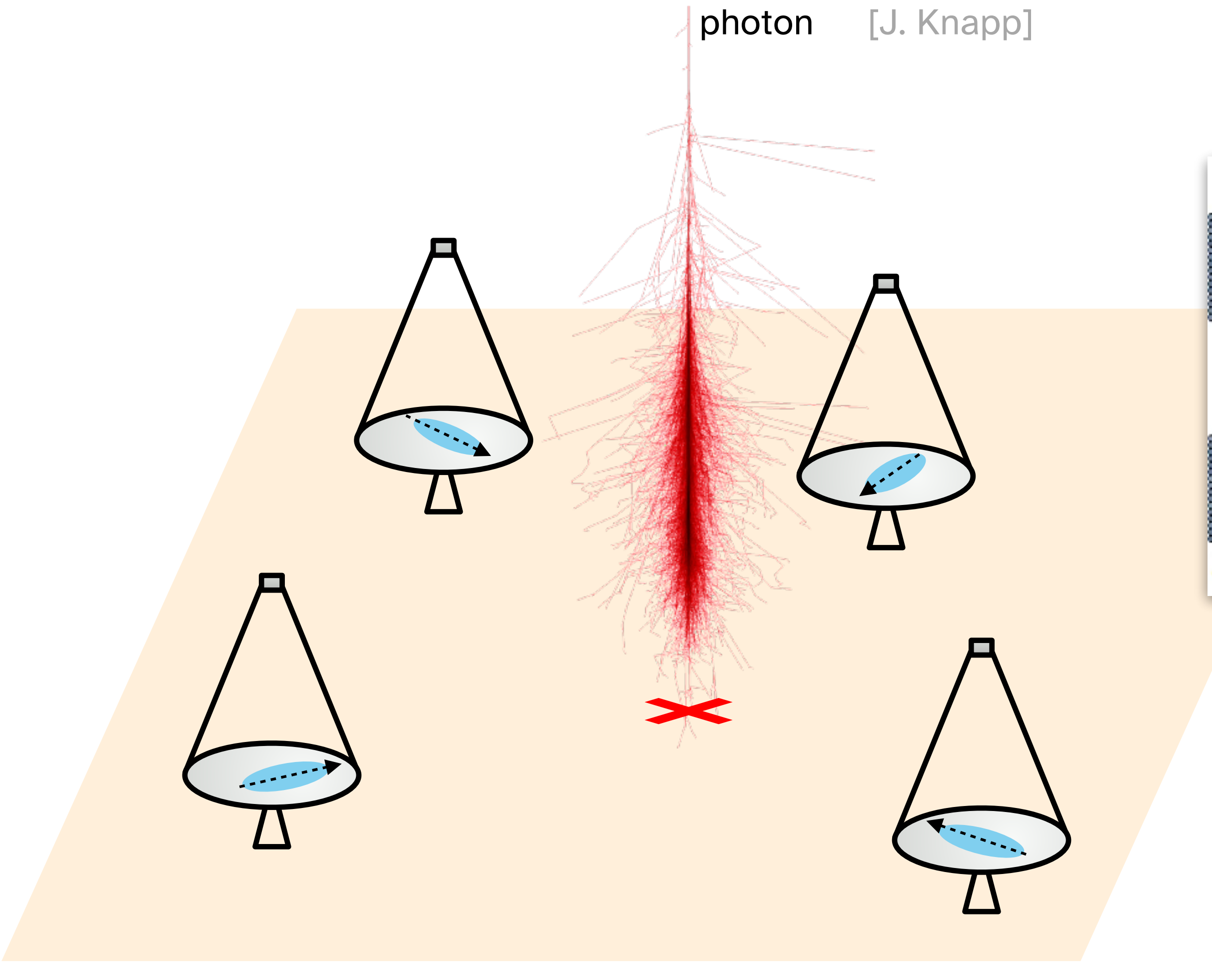
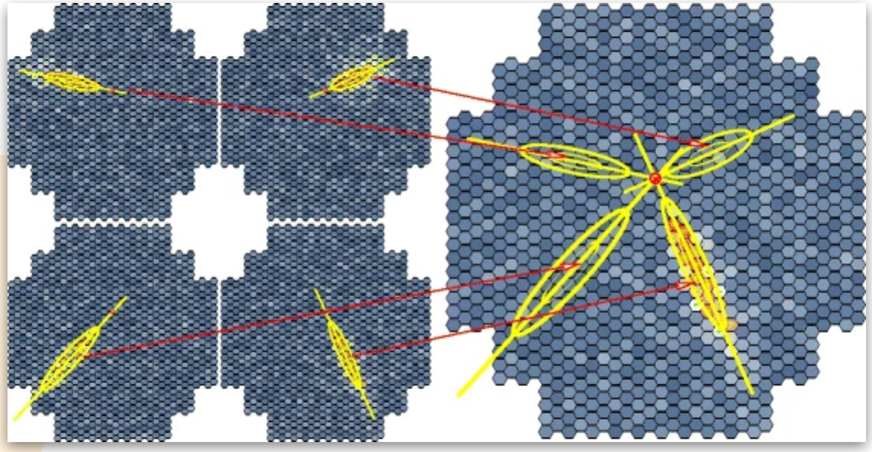


[J. Knapp]

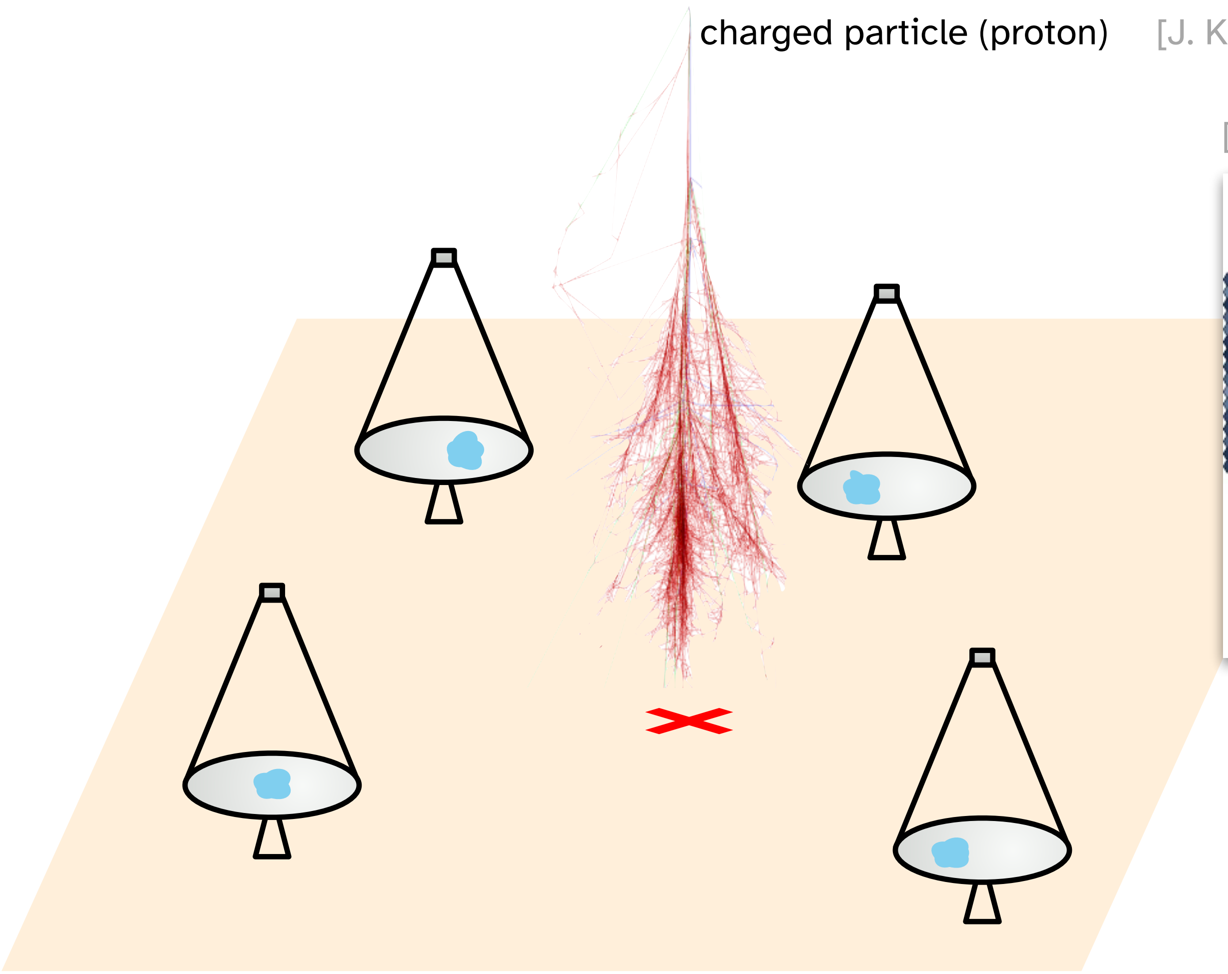
[H. Völk & K. Bernlöhr, ExA 25 (2009)]



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

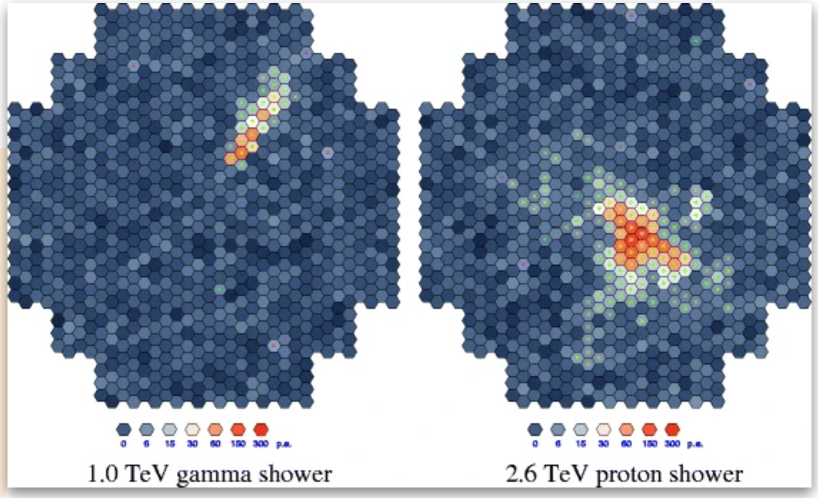
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light



[J. Knapp]

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



main axes -> photon direction

image intensity + geometry -> energy

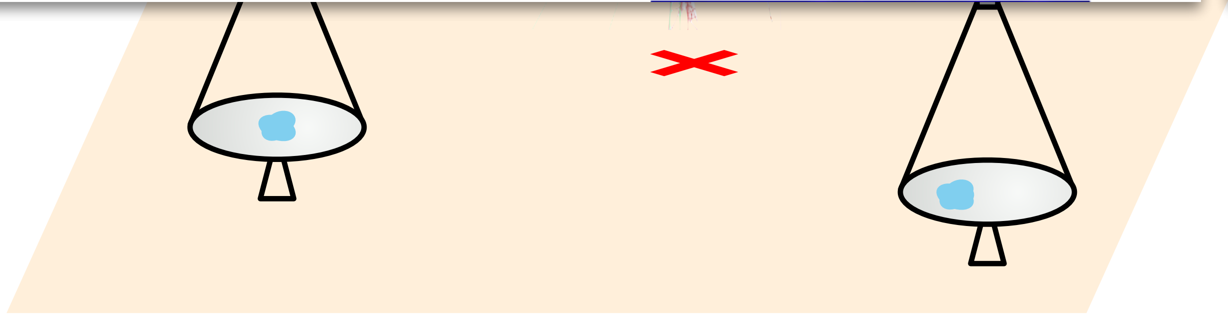
shape -> charged particle rejection

“gamma-hadron separation”

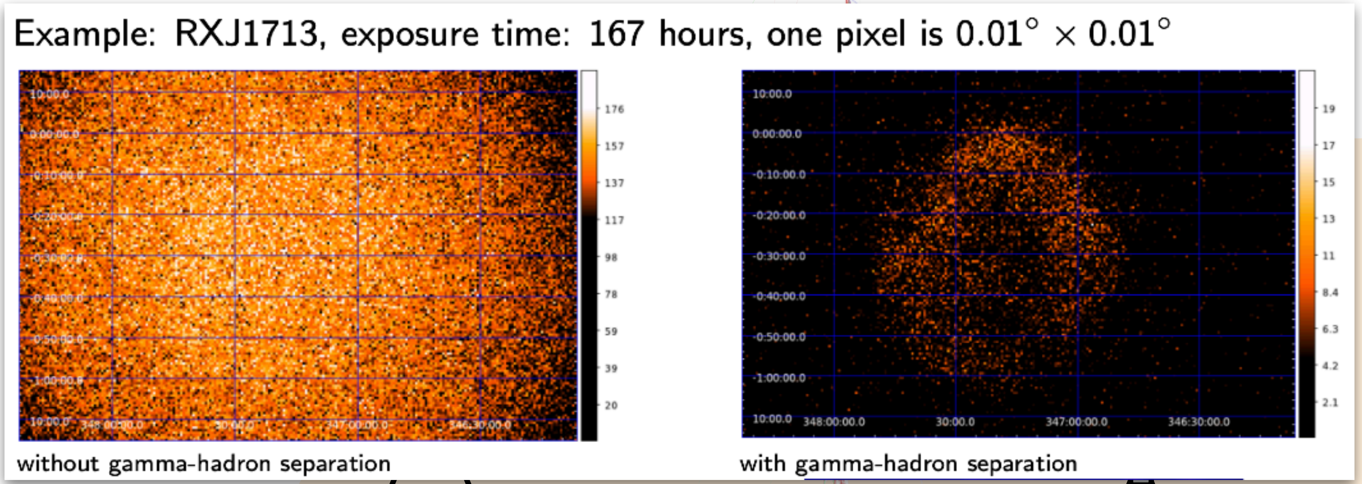
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light

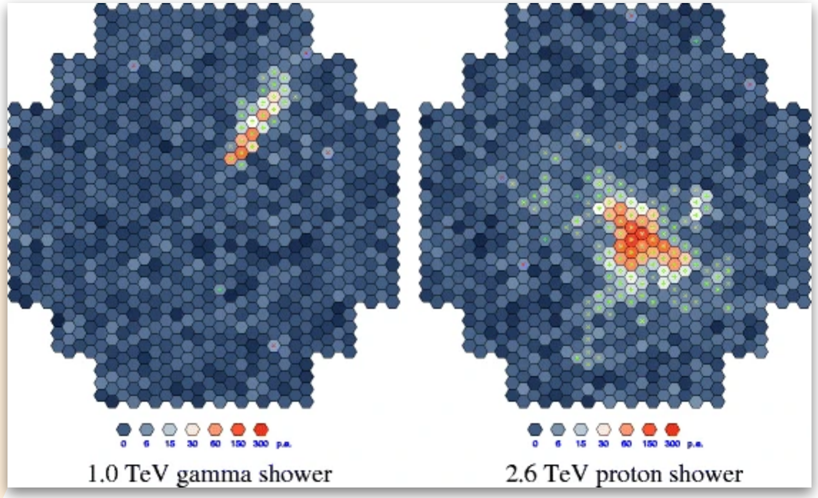
charged particle (proton)



[R. Marx]



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



main axes -> photon direction

image intensity + geometry -> energy

shape -> charged particle rejection

“gamma-hadron separation”

IACT arrays

When can they observe?

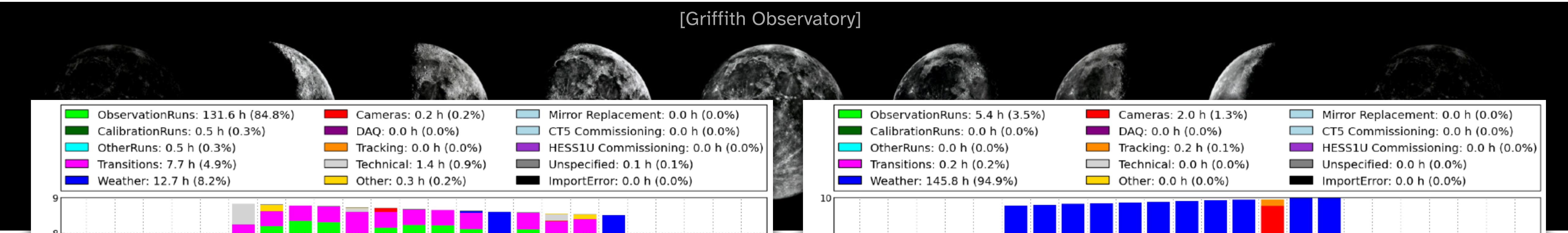
Best for observations | OK for observations | **Can't observe** | OK for observations | Best for observations

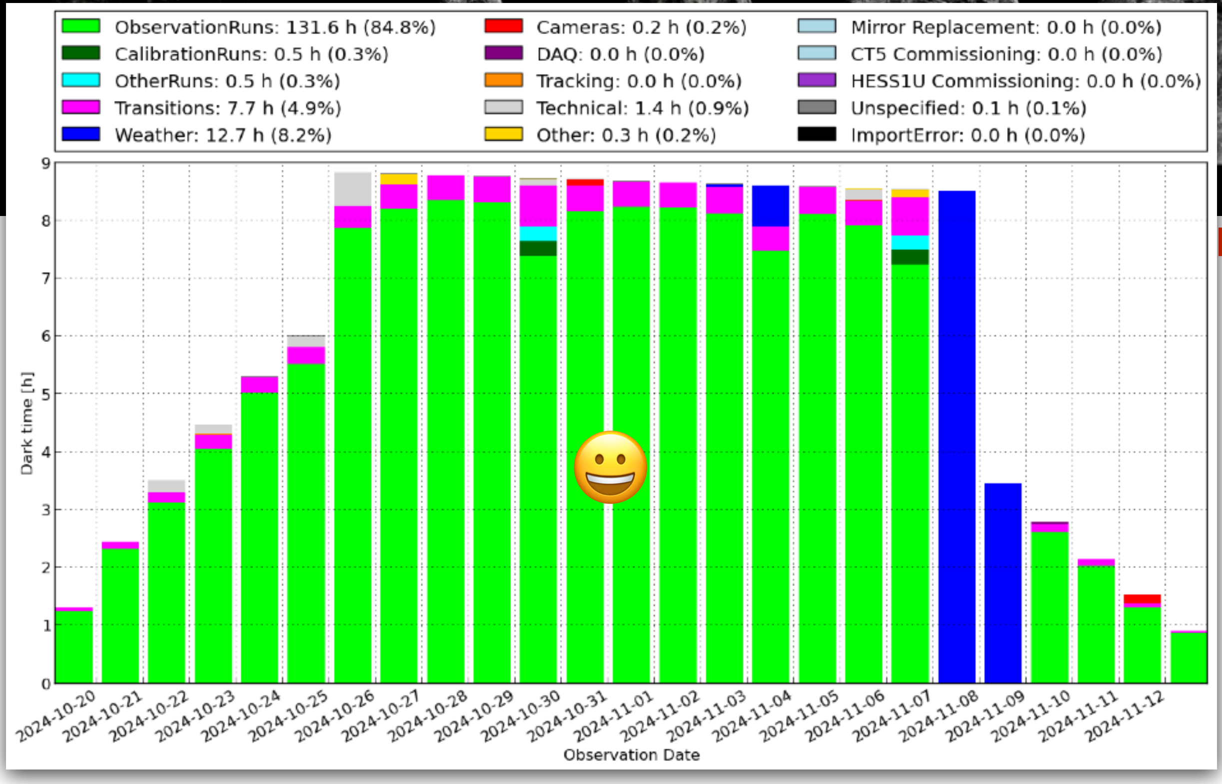
Cherenkov flashes are dim -> cameras are extremely sensitive
If there is too much bright ambient light, cameras could get damaged

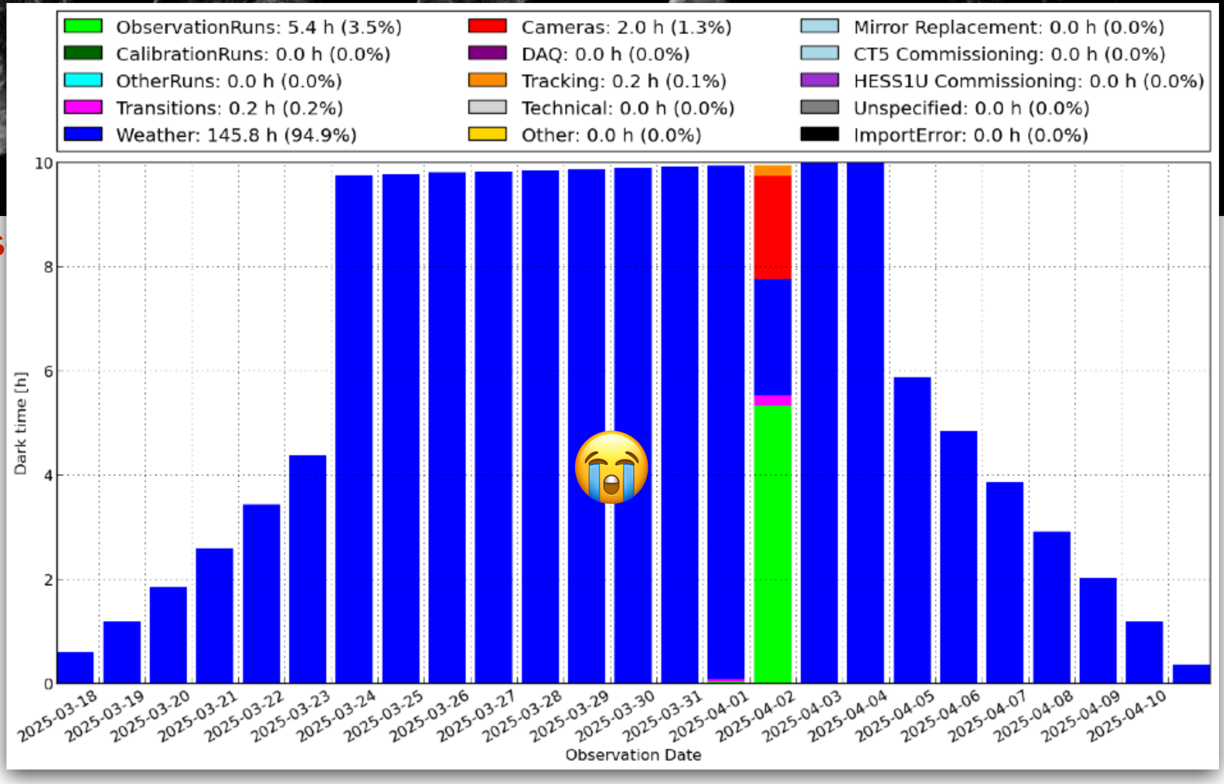
=> IACTs observe ~25 nights during every ~28 day moon cycle **(when weather is good)**

IACT arrays

When can they observe?





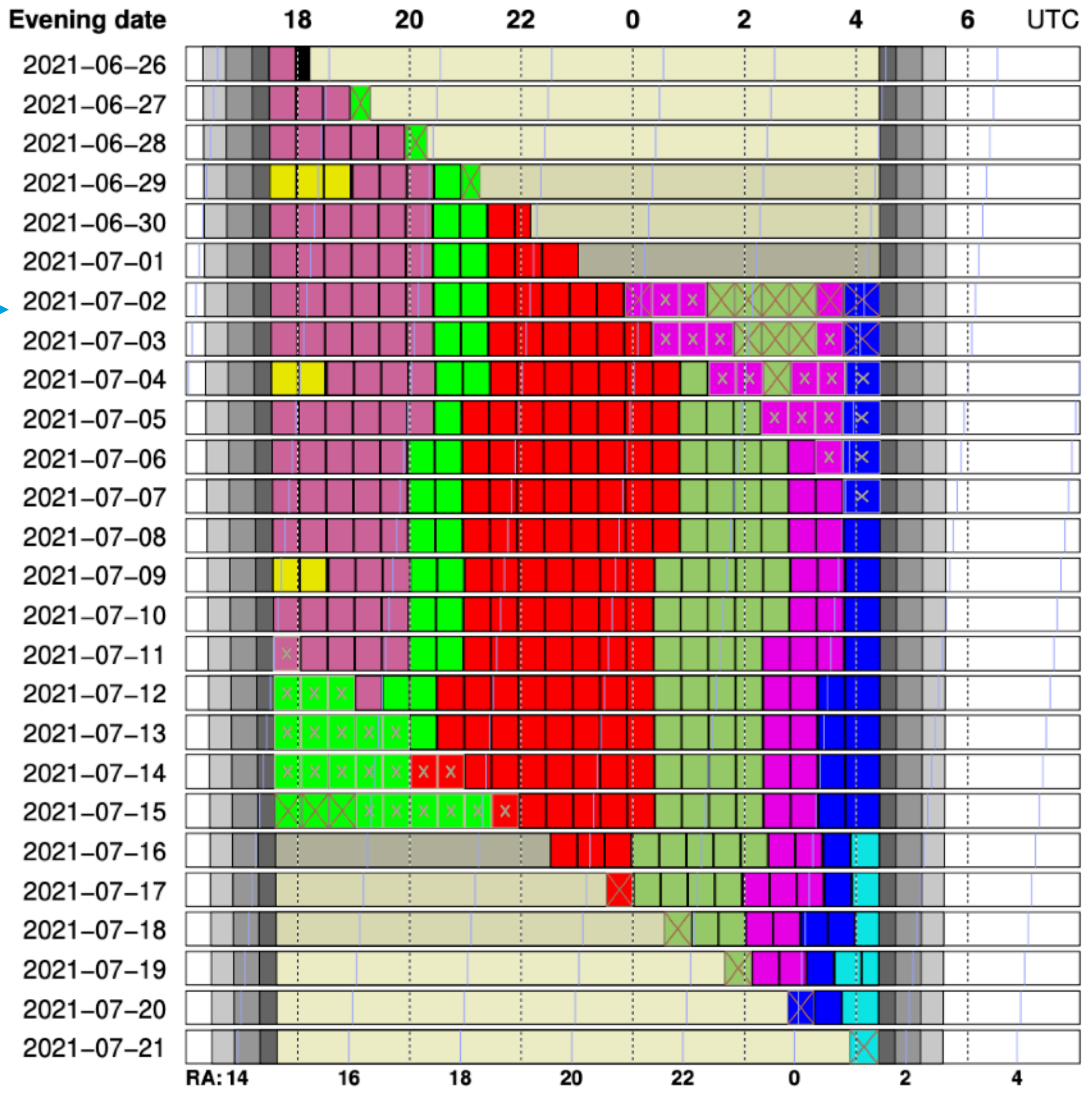


Two very different H.E.S.S. shifts

IACT arrays

When can they observe?

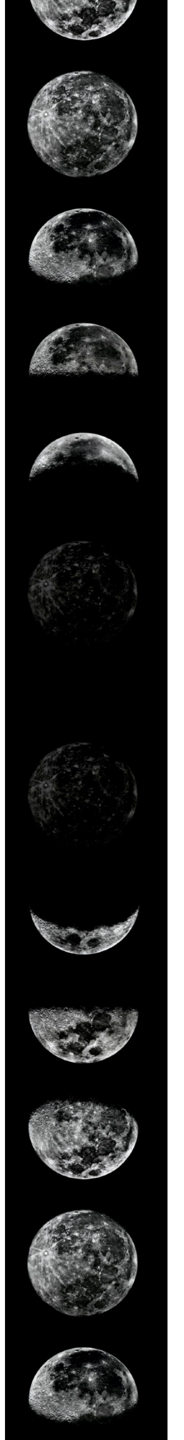
An example H.E.S.S. observing schedule →



of course, ToOs (Targets of Opportunity) will take precedence over these targets

Day light | Dusk/dawn | Moon light | Unused dark time

Moonlight...Run | Moon up but not a Moonlight...Run

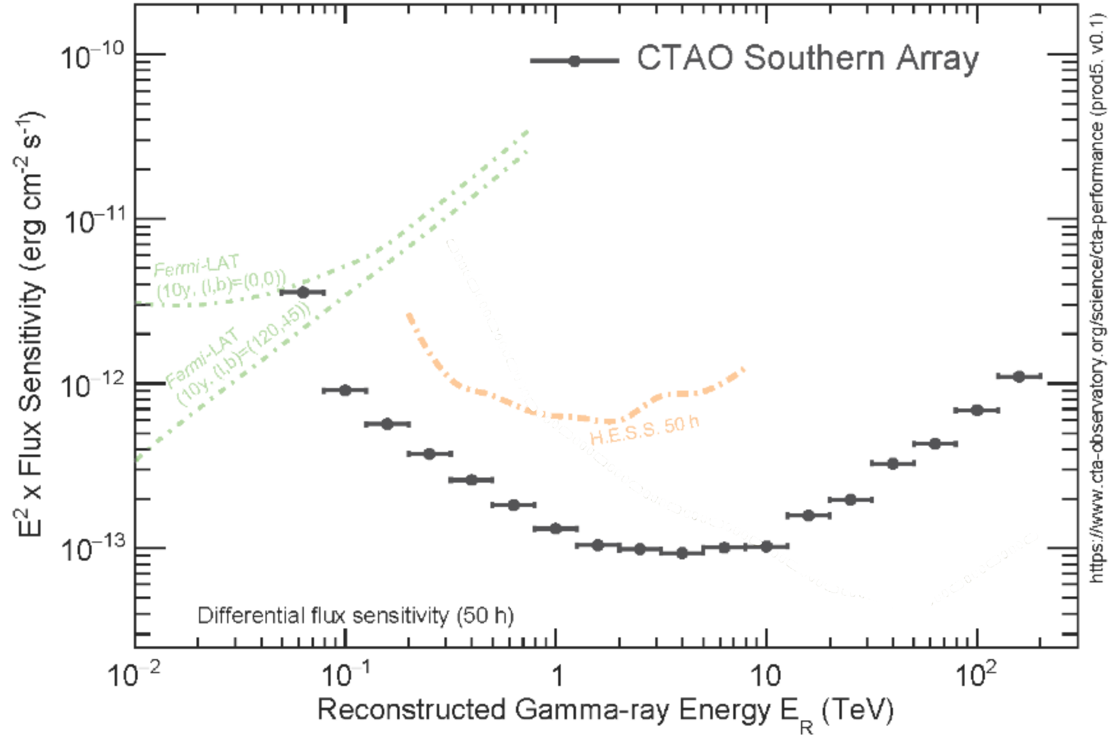


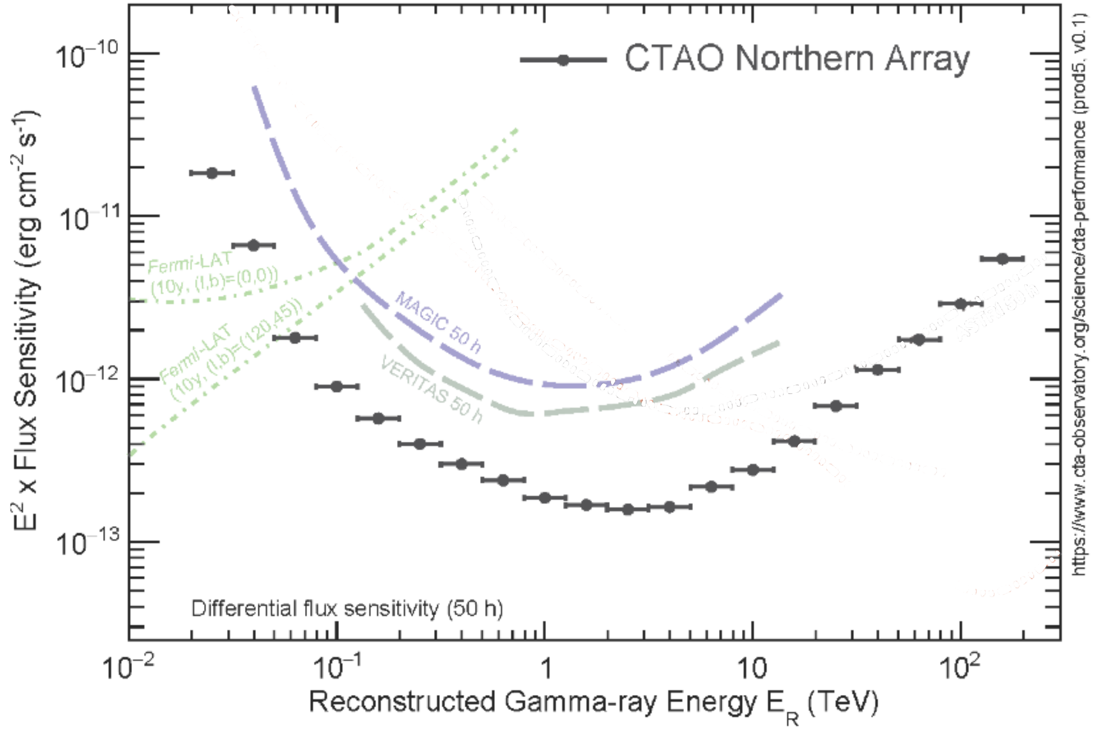
Cherenkov Telescope Array Observatory (CTAO)

Next generation IACT array

CTAO will be 10x more sensitive than the current generation of IACT arrays and cover a wider energy range

[CTAO]



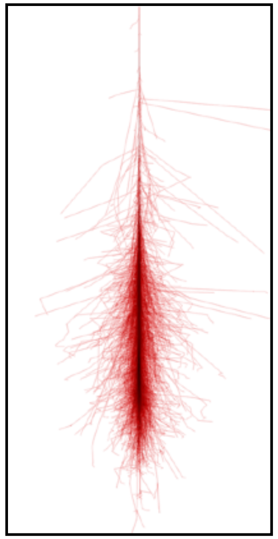


How do we get to higher energies (>100 TeV)?

Use the atmosphere as part of the detector

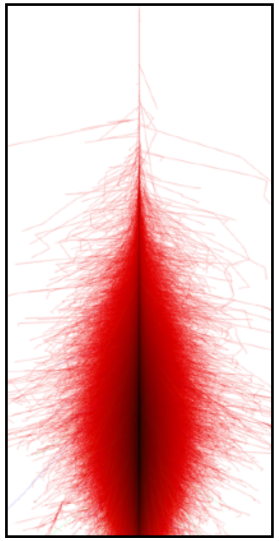
How do we get to even higher energies?

100 GeV gamma ray



vs

100 TeV gamma ray



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

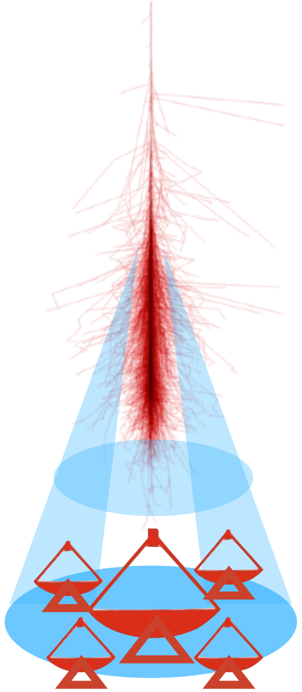
- many shower particles reach the ground
- detect the shower particles themselves

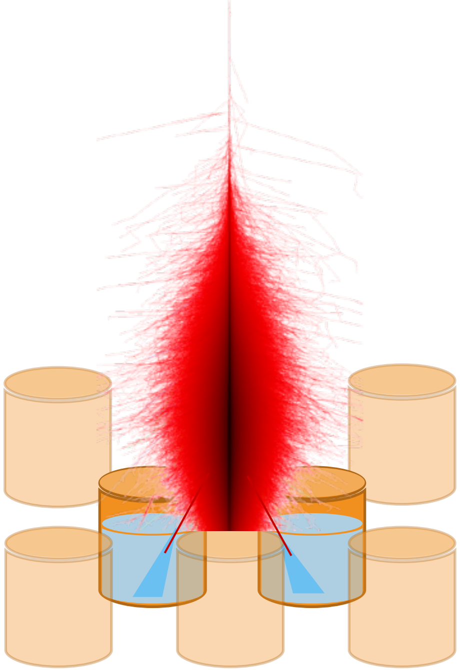
[J. Knapp]

Use the atmosphere as part of the detector

How do we get to even higher energies?

100 GeV gamma ray | vs | 100 TeV gamma ray





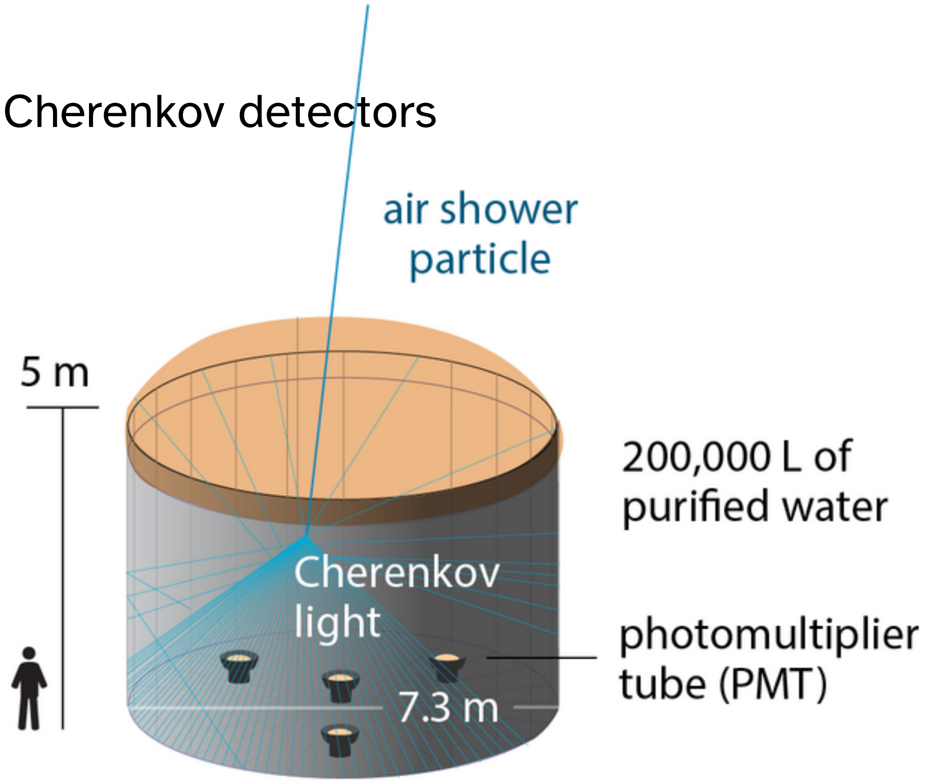
- most shower particles don’t reach the ground
- detect them via Cherenkov light in air

- many shower particles reach the ground
- detect the shower particles themselves

[J. Knapp]

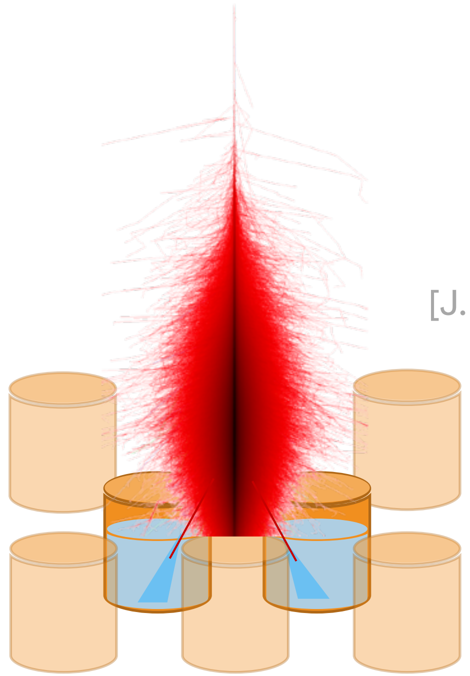
Particle detector arrays

e.g., Water Cherenkov detectors



[U. M. Nisa, HAWC]

100 TeV gamma ray



[J. Knapp]

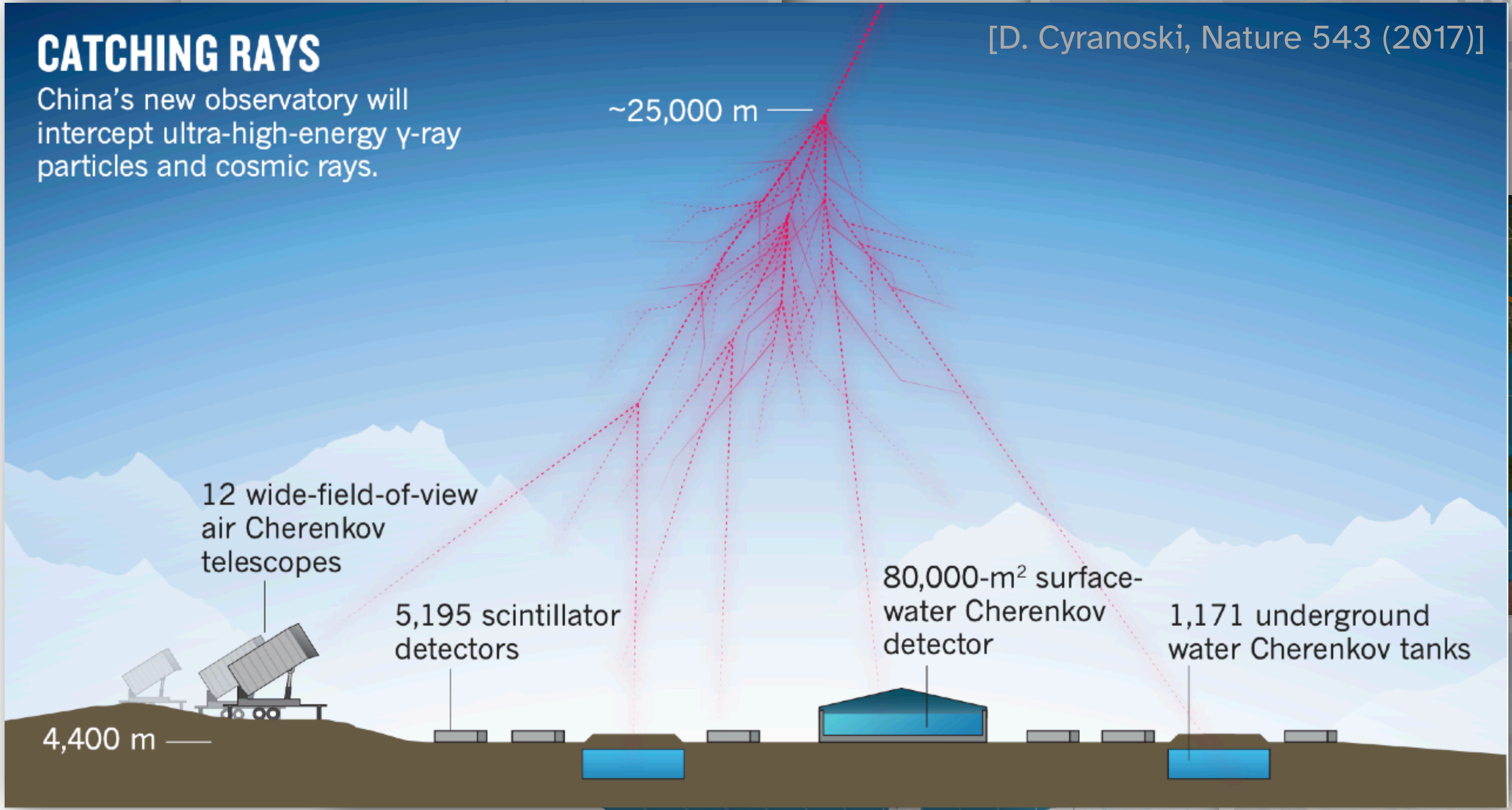
Particle detector arrays

[Daniel R. Strebe]

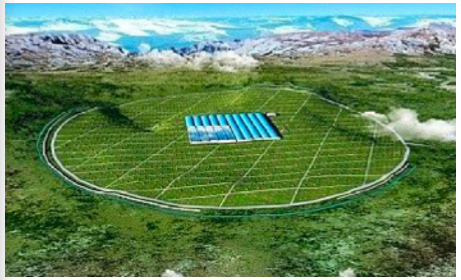
Particle detector arrays

MAGIC

LST-1



[D. Cyranoski, Nature 543 (2017)]



[IHEP]

LHAASO

LHAASO

高海拔宇宙线观测站

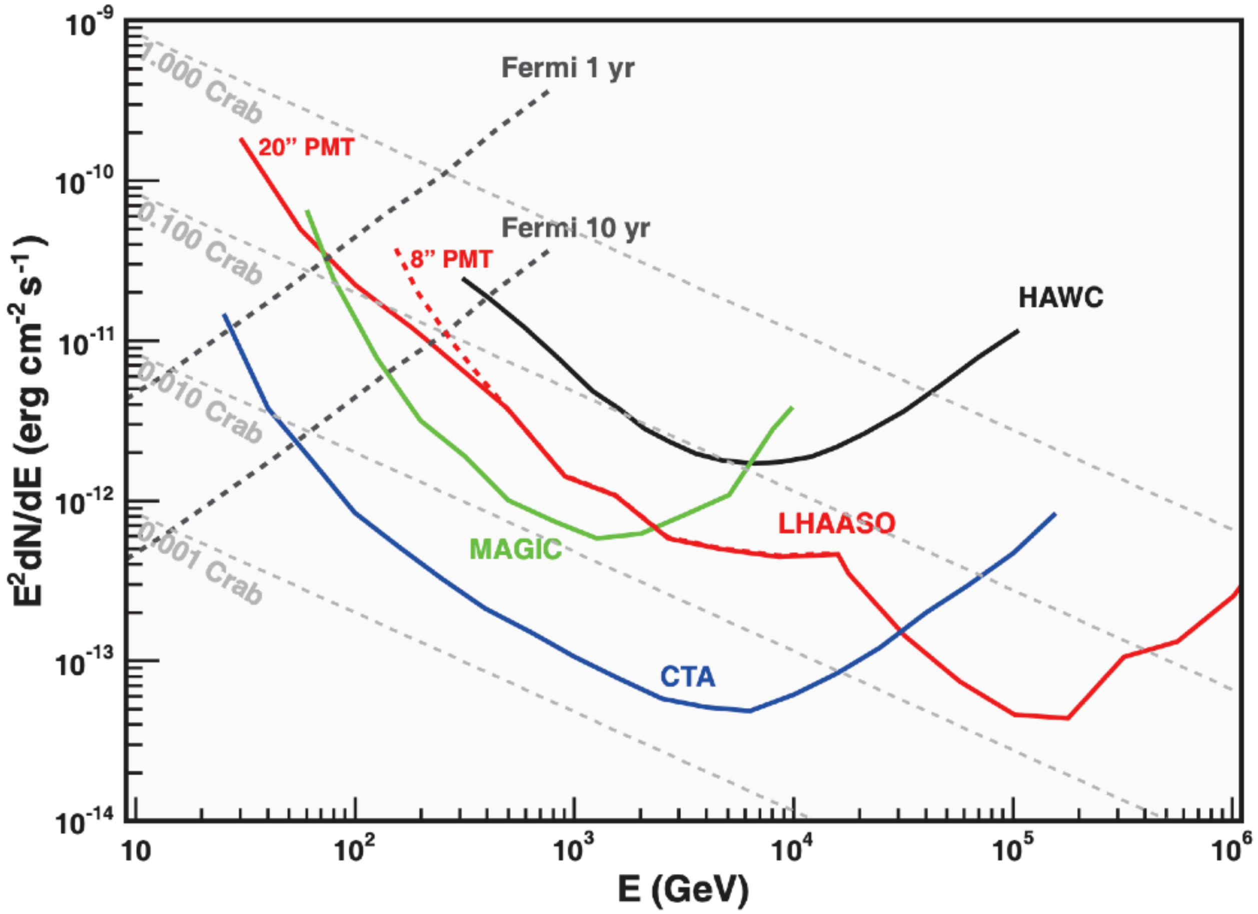
H.E.S.S.

[H.E.S.S., MPIK/Christian Föhr]

[Daniel R. Strebe]

Comparing gamma-ray detectors

Sensitivities

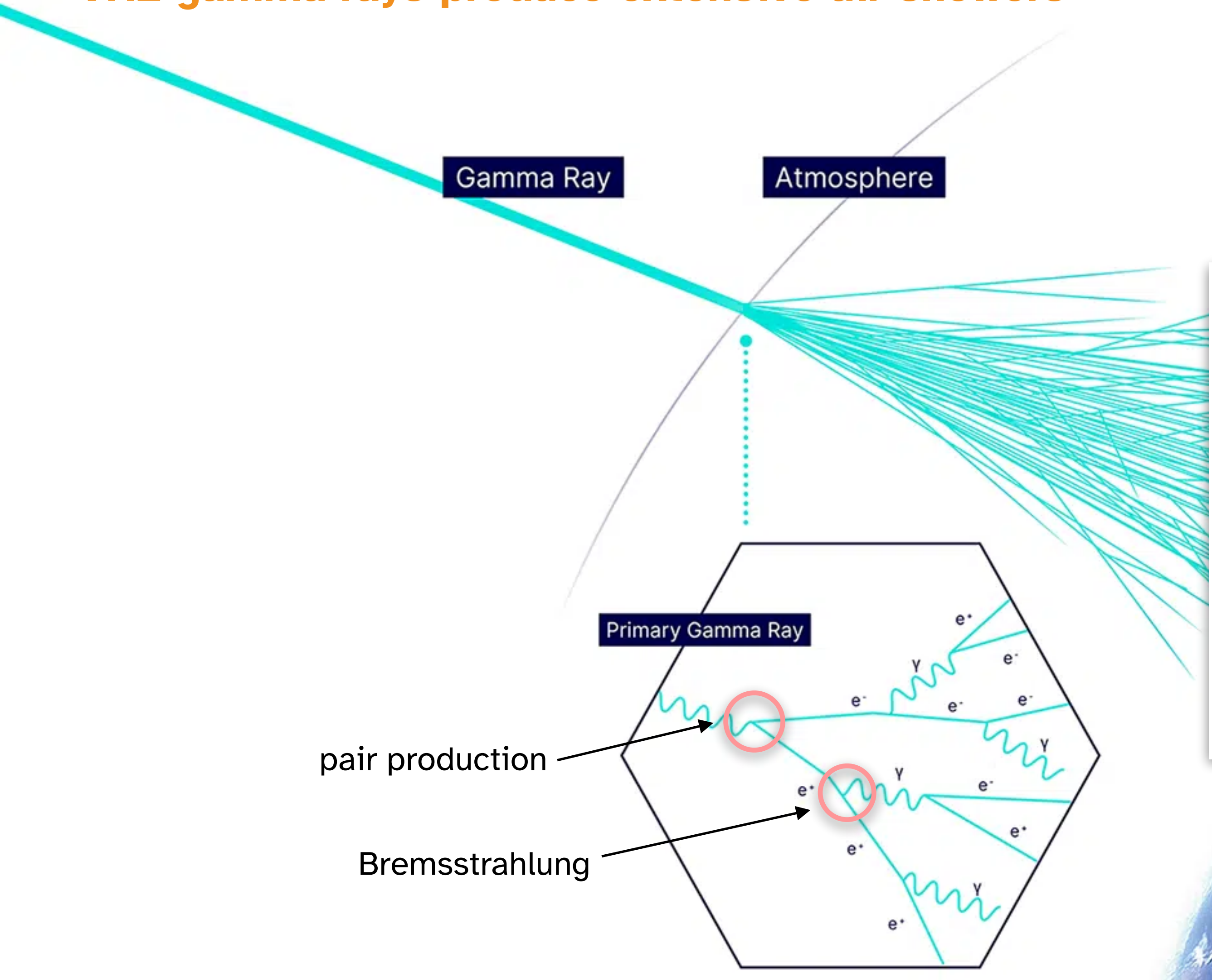


[Z. Cao et al., LHAASO Science Book]

How do we get to lower energies (<10s of GeV)?

IACTs use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers



gamma ray interacts with the atmosphere

Ground-based detectors like IACTs rely on the **atmosphere** for gamma-ray interactions with matter

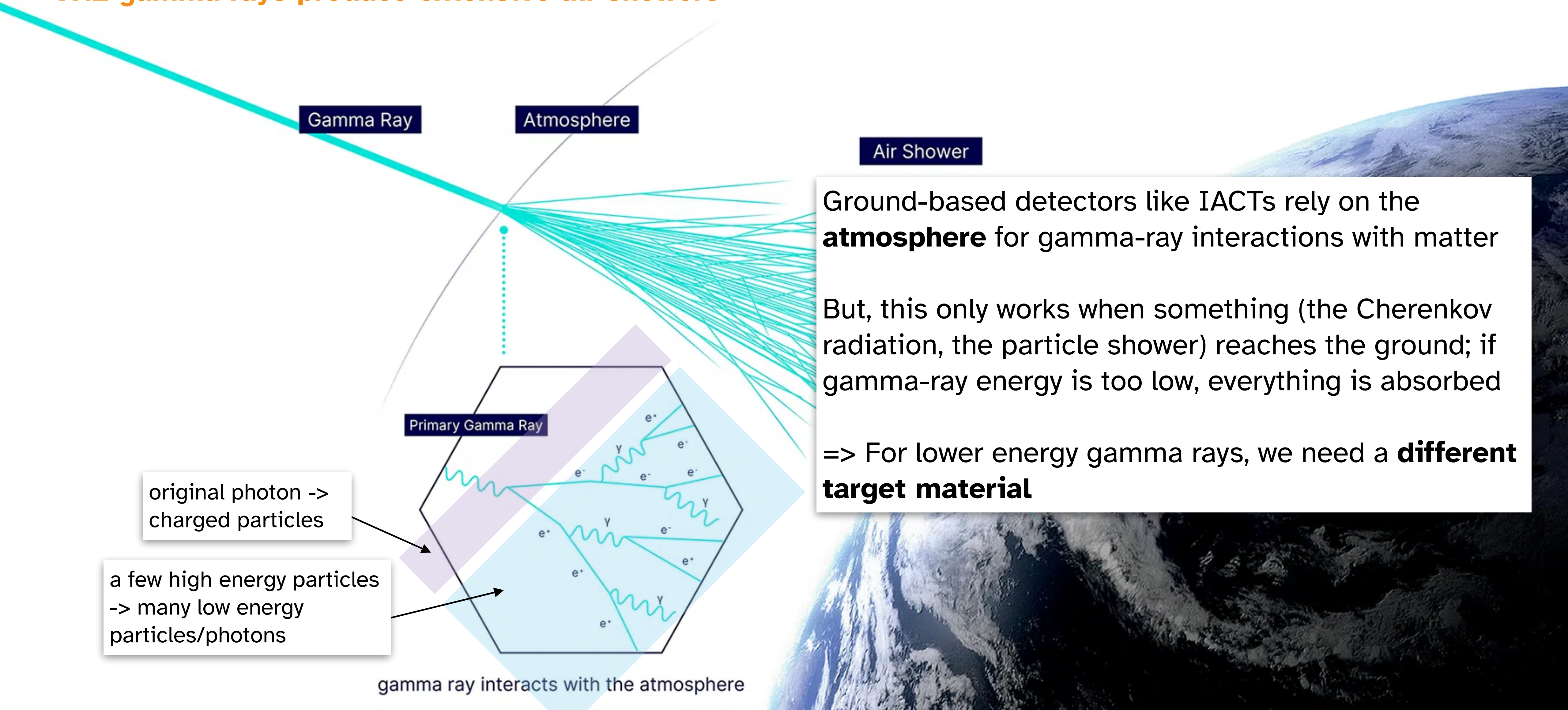
But, this only works when something (the Cherenkov radiation, the particle shower) reaches the ground; if gamma-ray energy is too low, everything is absorbed

=> For lower energy gamma rays, we need a **different target material**

[CTAO]

IACTs use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers



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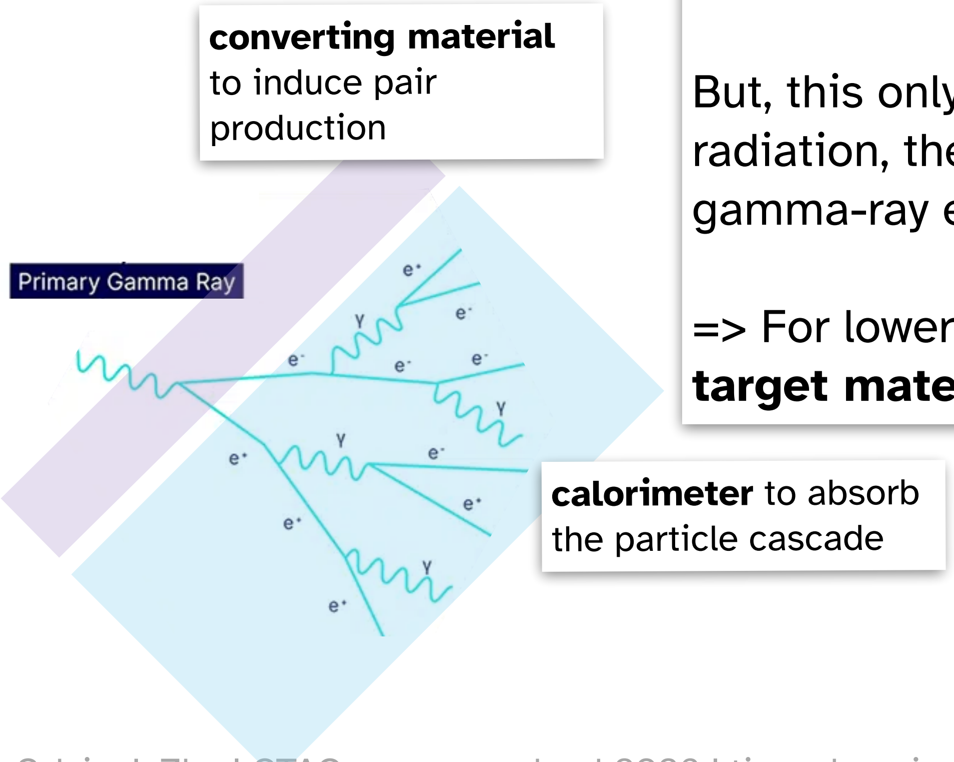
[CTAO]

Building a gamma-ray detector in space

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy
-> Convert gamma rays into charged particles



Ground-based detectors like IACTs rely on the **atmosphere** for gamma-ray interactions with matter

But, this only works when something (the Cherenkov radiation, the particle shower) reaches the ground; if gamma-ray energy is too low, everything is absorbed

=> For lower energy gamma rays, we need a **different target material**

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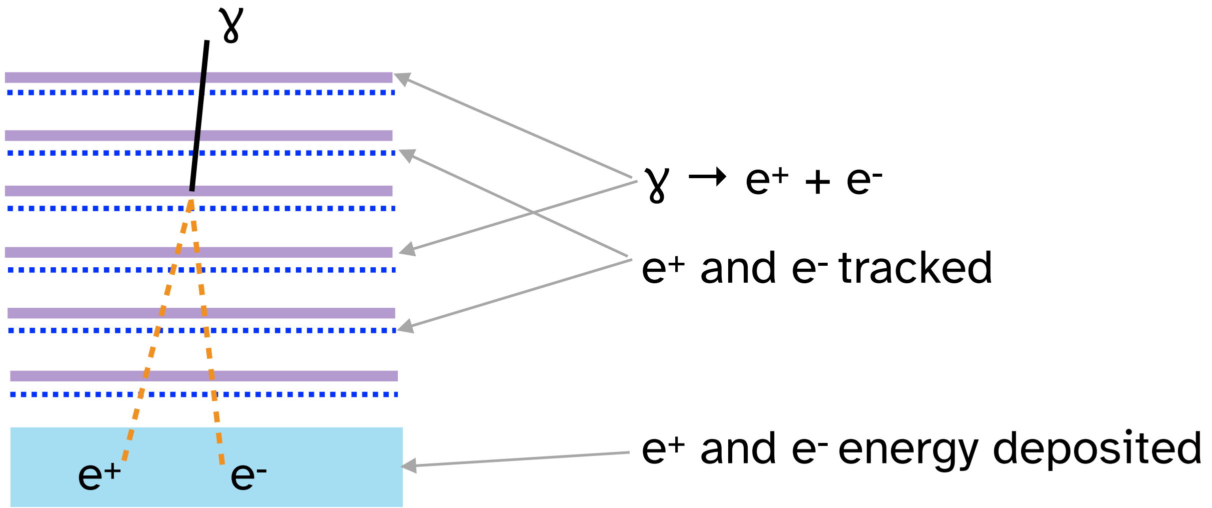

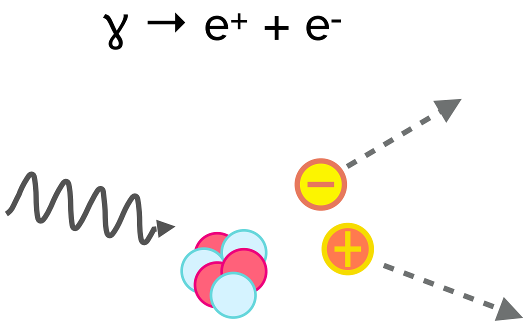

In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

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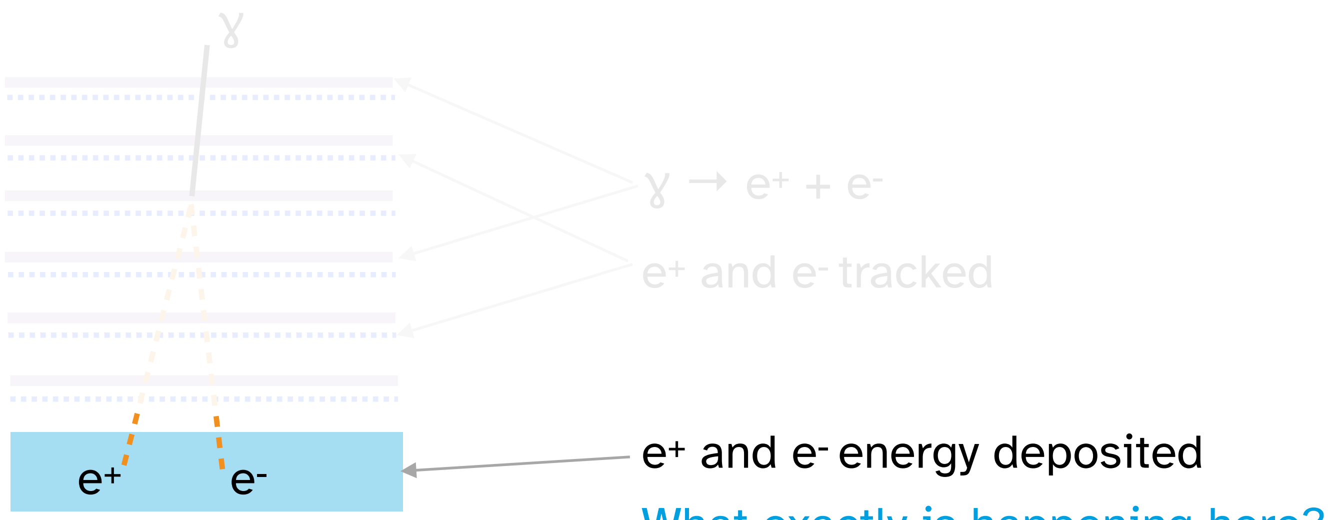

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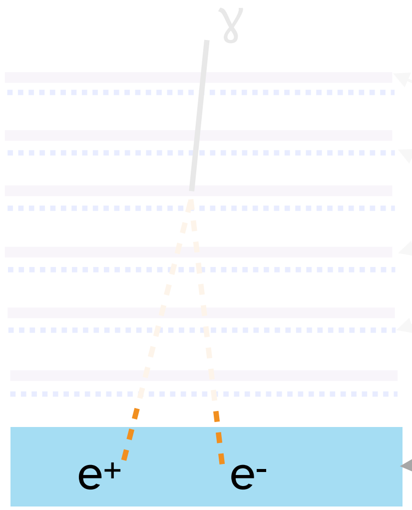


ɣ → e+ + e-

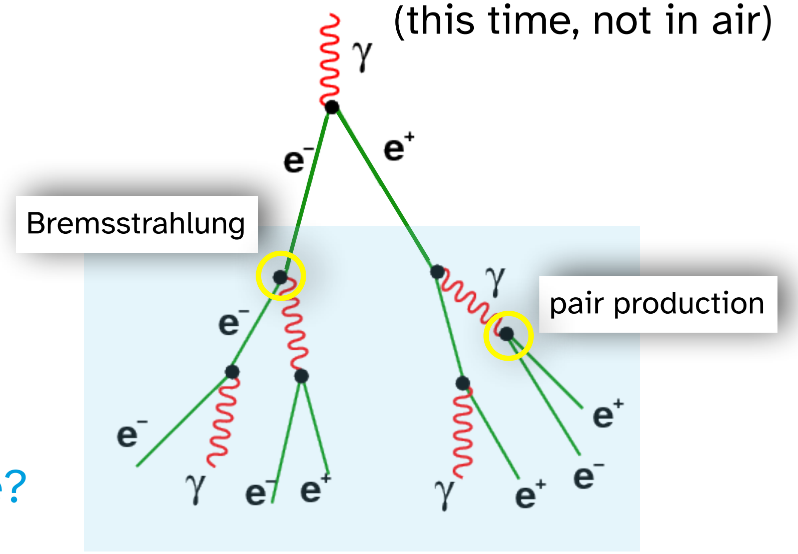
e+ and e- tracked

e+ and e- energy deposited

What exactly is happening here?

electromagnetic shower

(this time, not in air)



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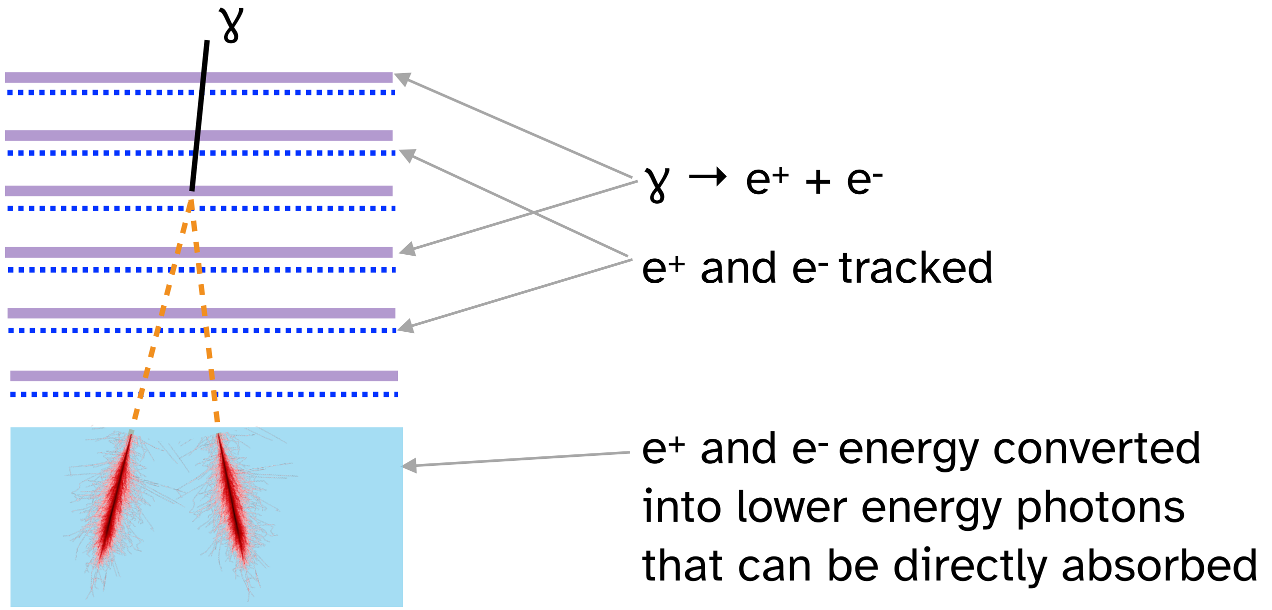

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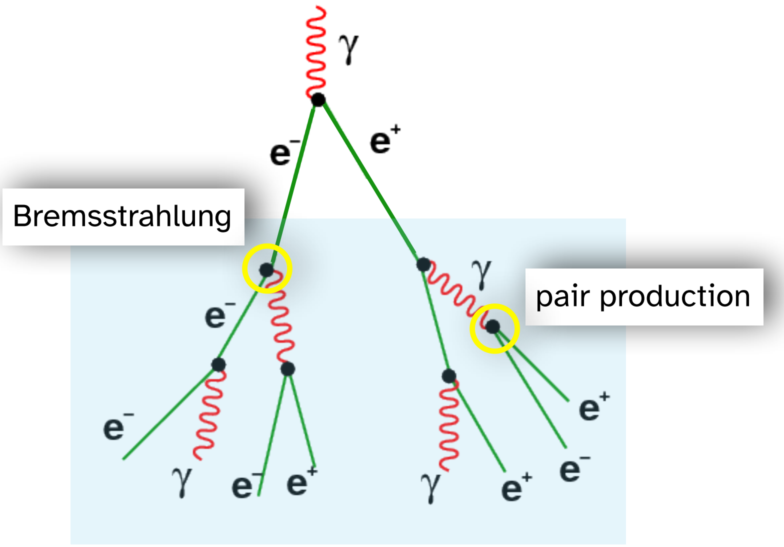

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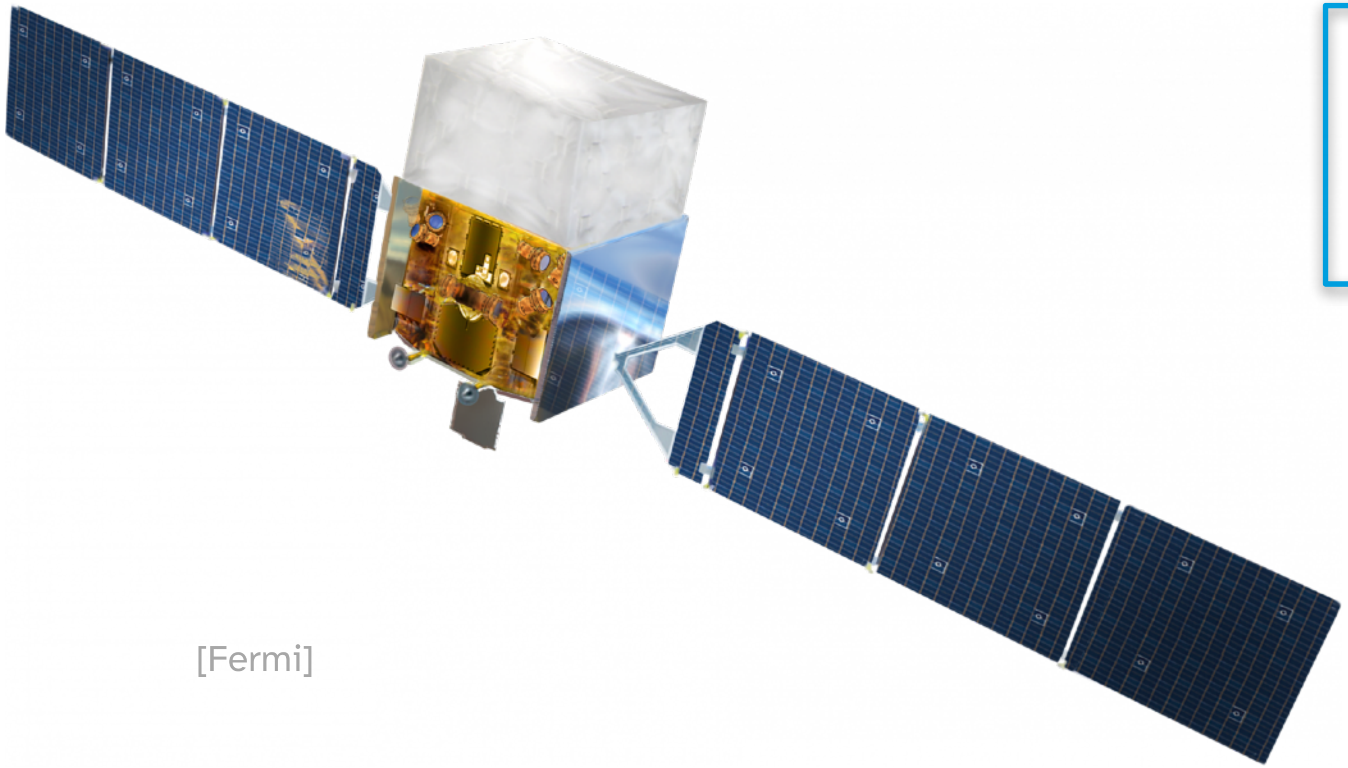

[Fermi]

[NASA/DOE/Fermi-LAT]

Fermi Large Area Telescope

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Building a gamma-ray detector in space

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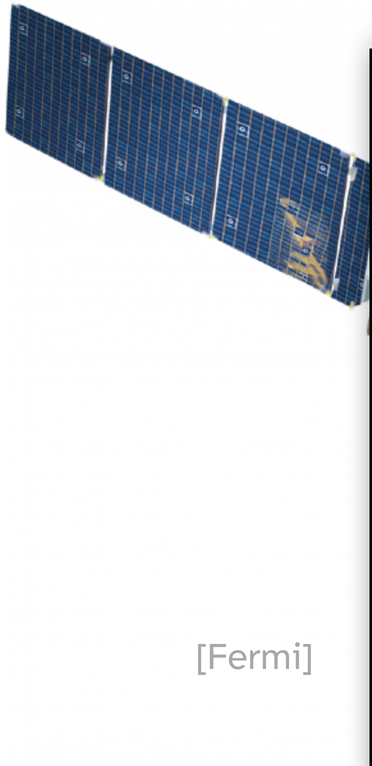

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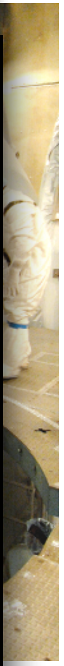
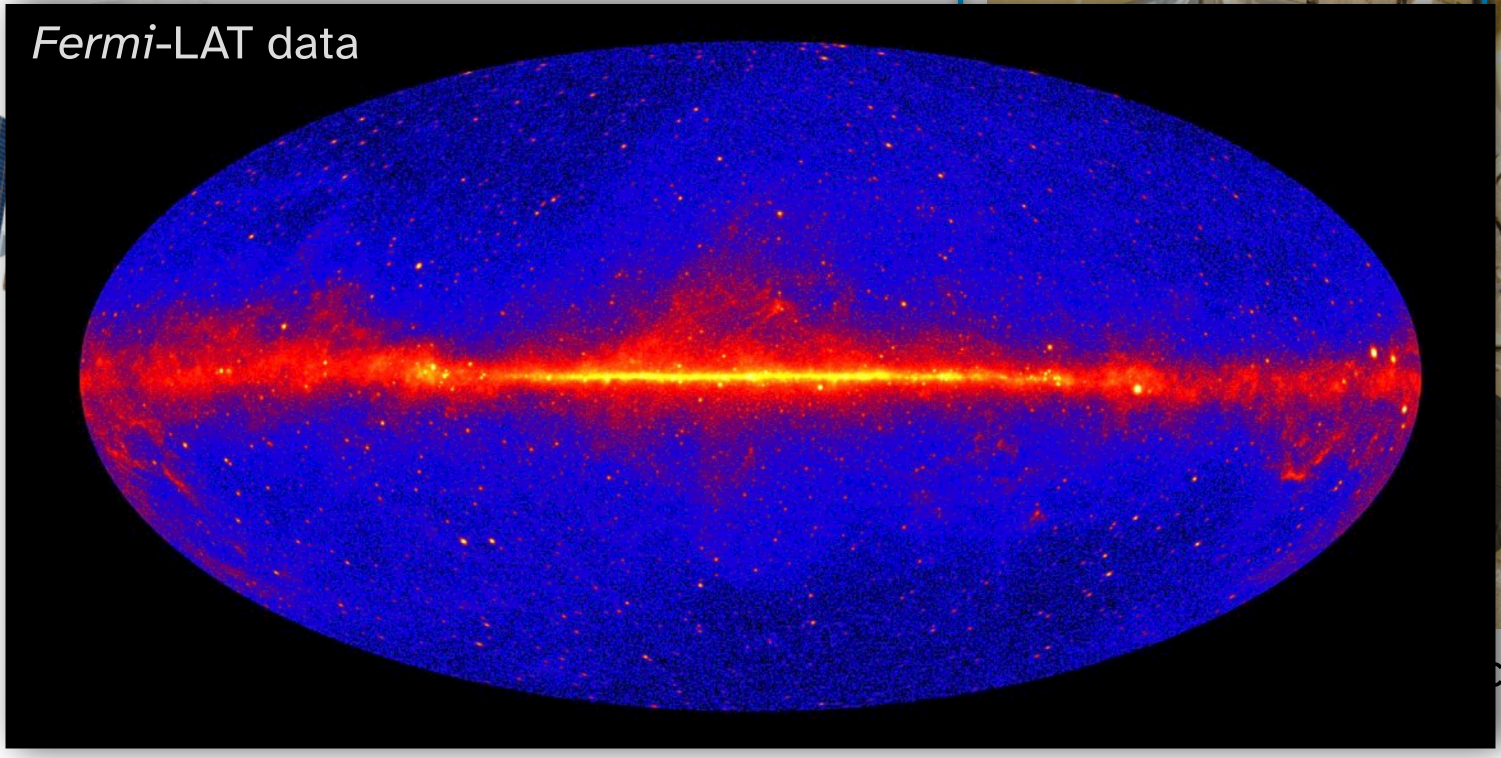


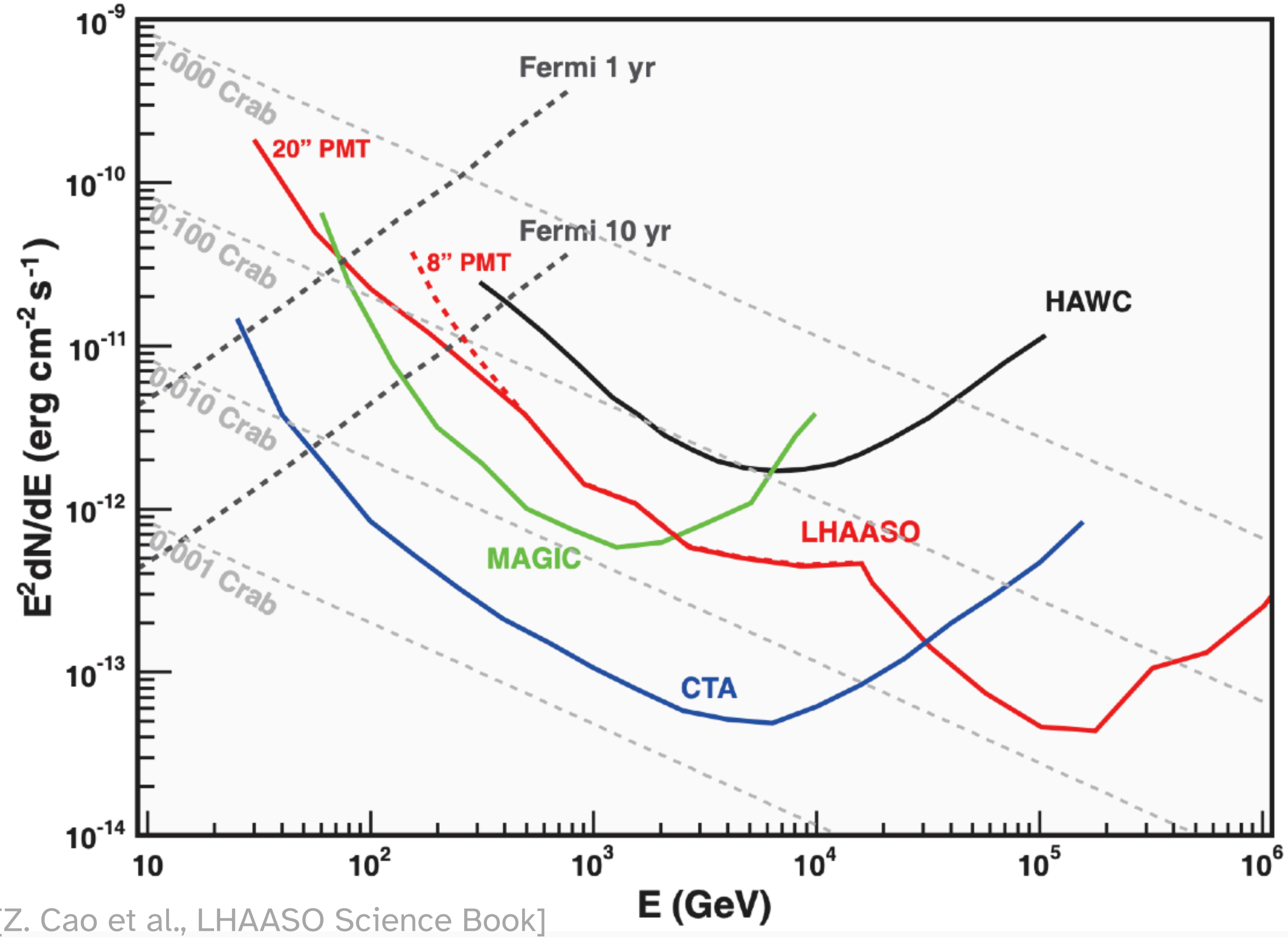


cope

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

Comparing gamma-ray detectors

Sensitivities

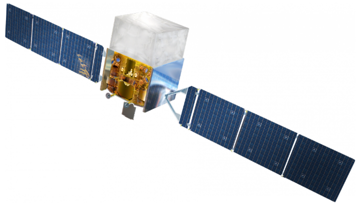


[Z. Cao et al., LHAASO Science Book]

Comparing gamma-ray detectors

Observational properties

	Fermi-LAT	IACT arrays (current gen)	CTAO	particle detector arrays (current gen)
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	all-sky	3.5 - 5°	3.5 - 5°	>2 sr
angular resolution	~0.1° - 1°	< 0.1°	< 0.05°	~0.1° - 2°
energy resolution	~5 - 20%	~10 - 15%	~5%	~30 - 50%



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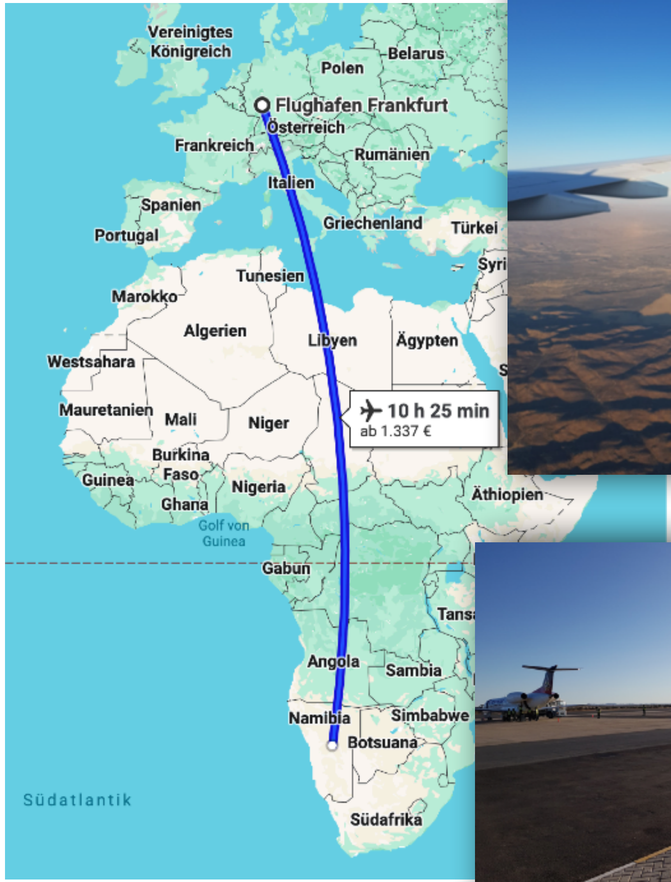
How do IACTs participate in time-domain astronomy?

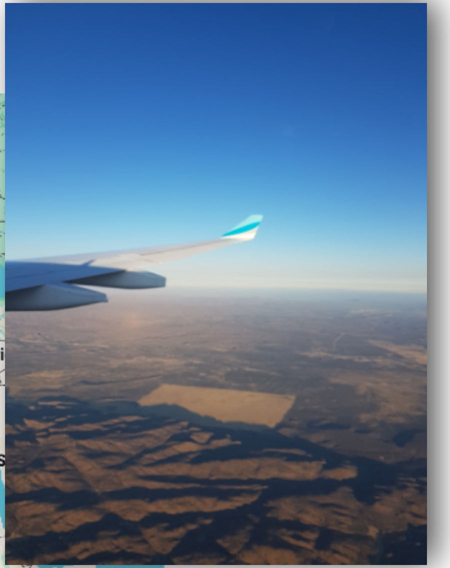
bonus H.E.S.S. pictures

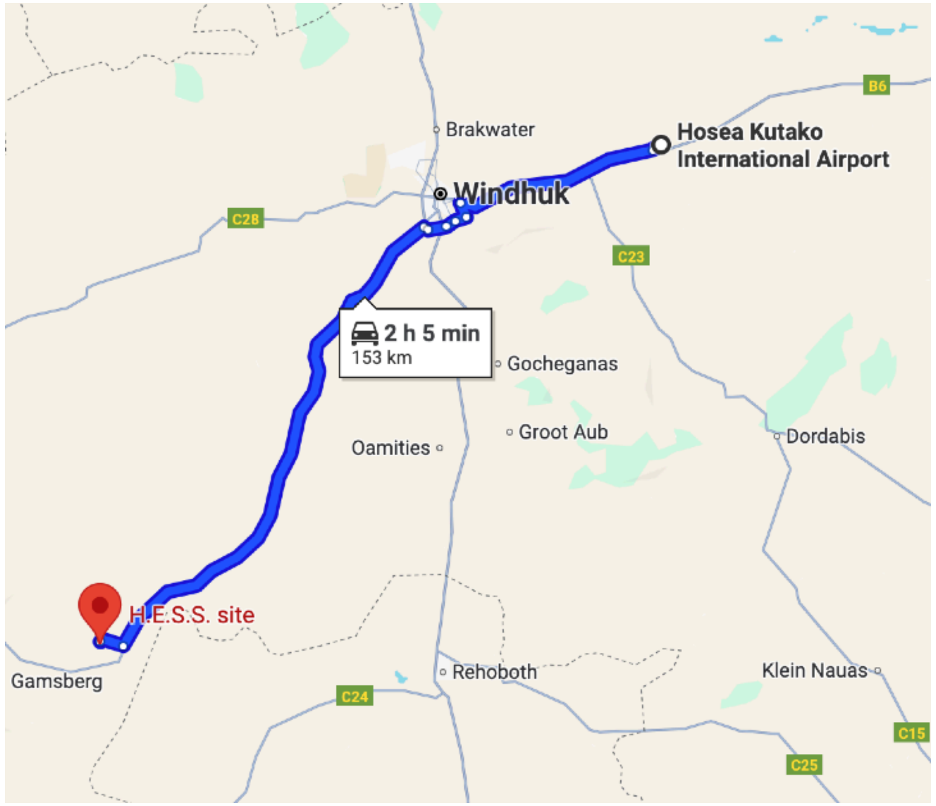
H.E.S.S. telescopes

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







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

H.E.S.S. telescopes

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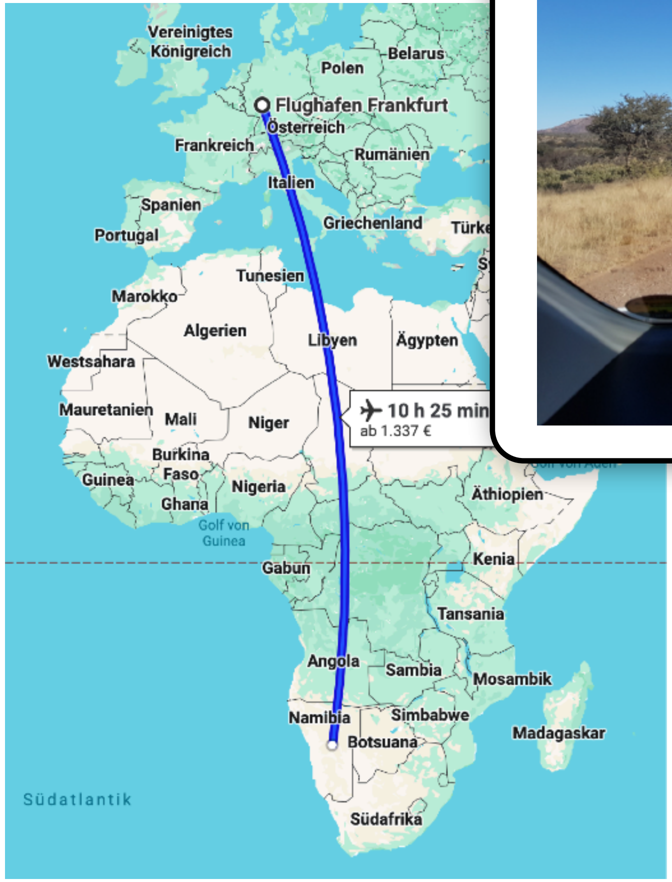
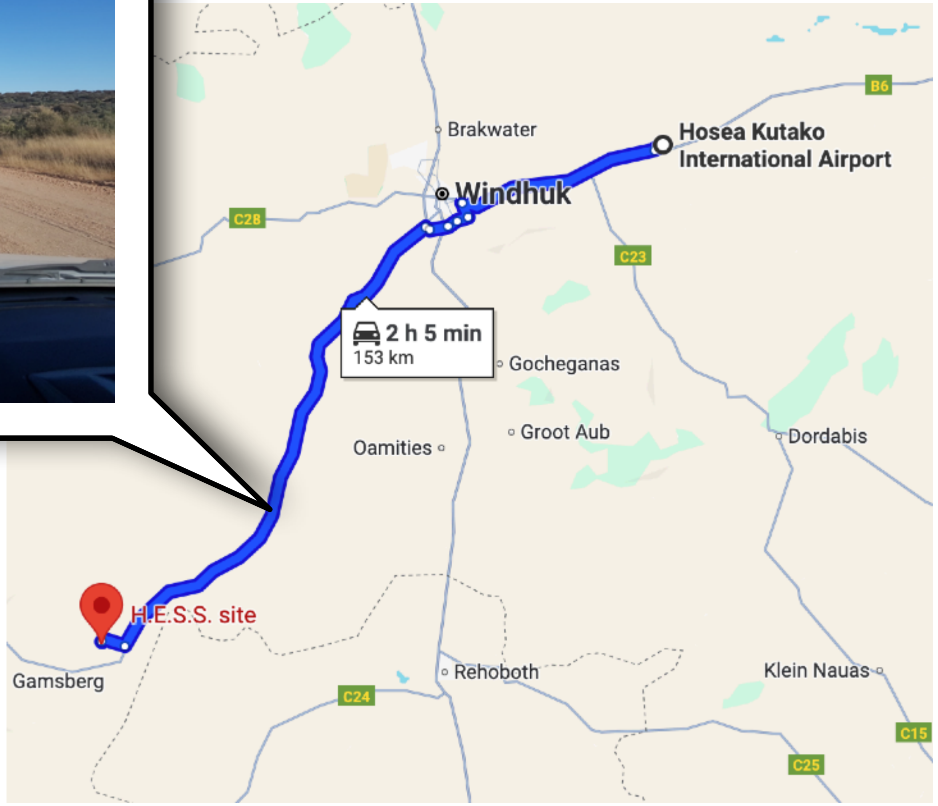
8-12 hours a night depending on



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



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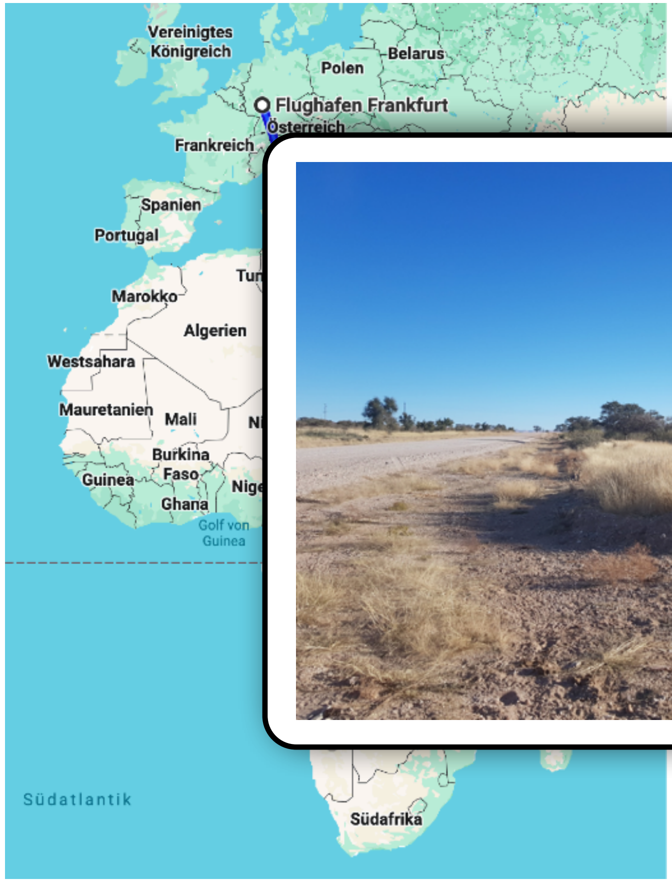

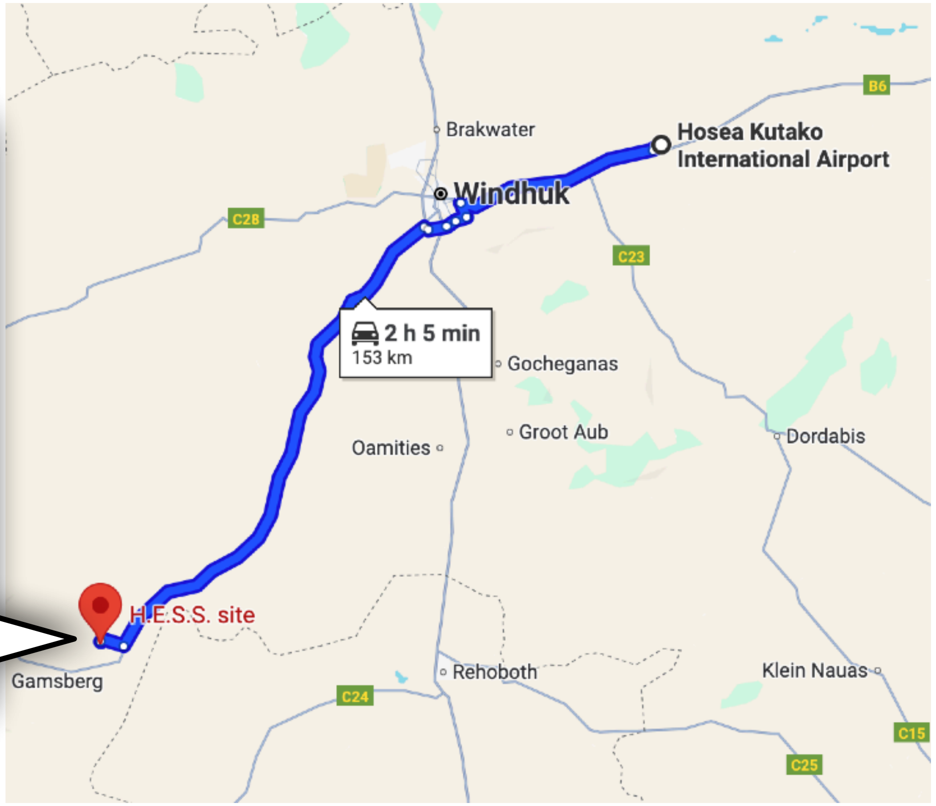

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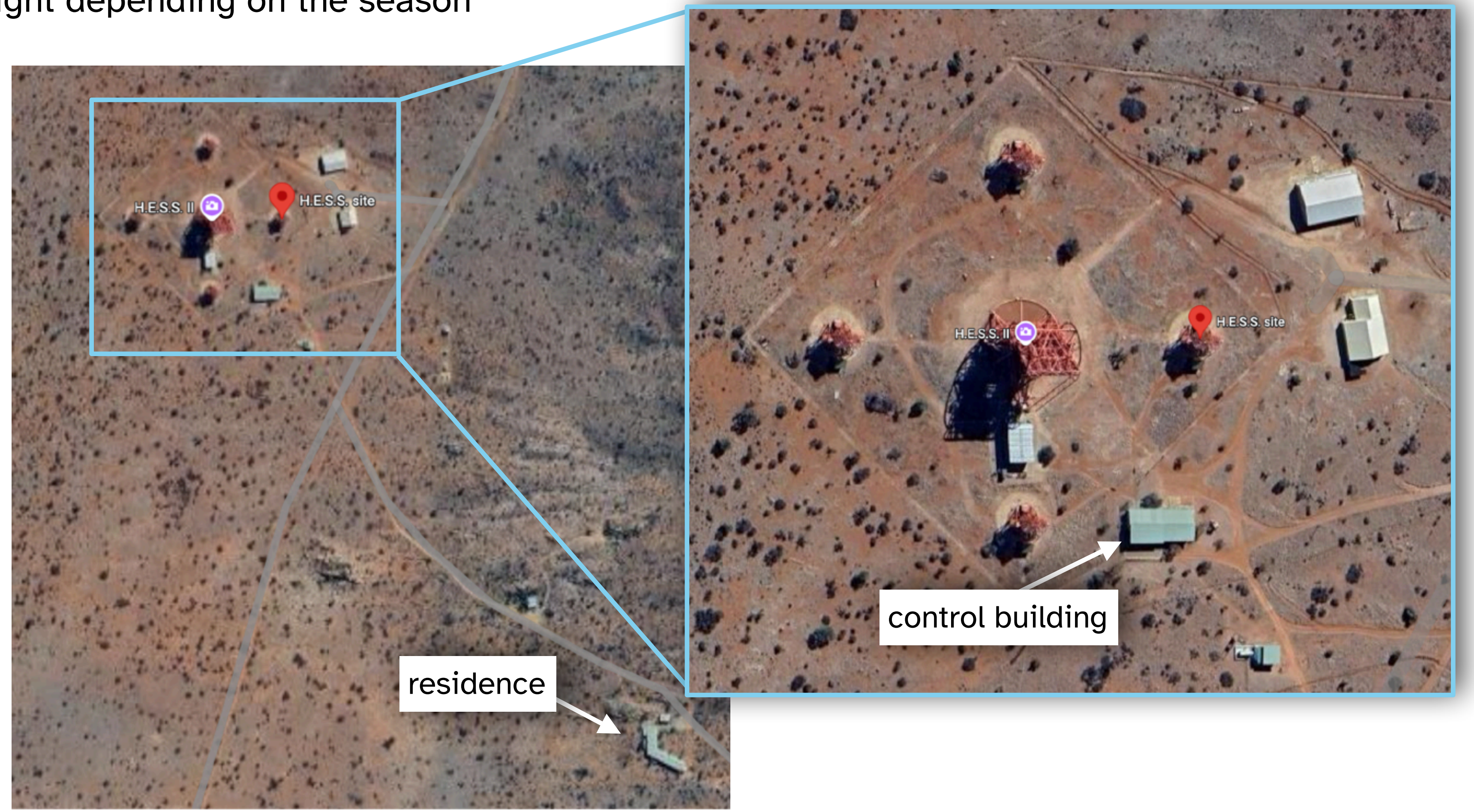

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control room


telescopes

I get to talk about gamma-ray bursts now


[DESY, Science Communication Lab]

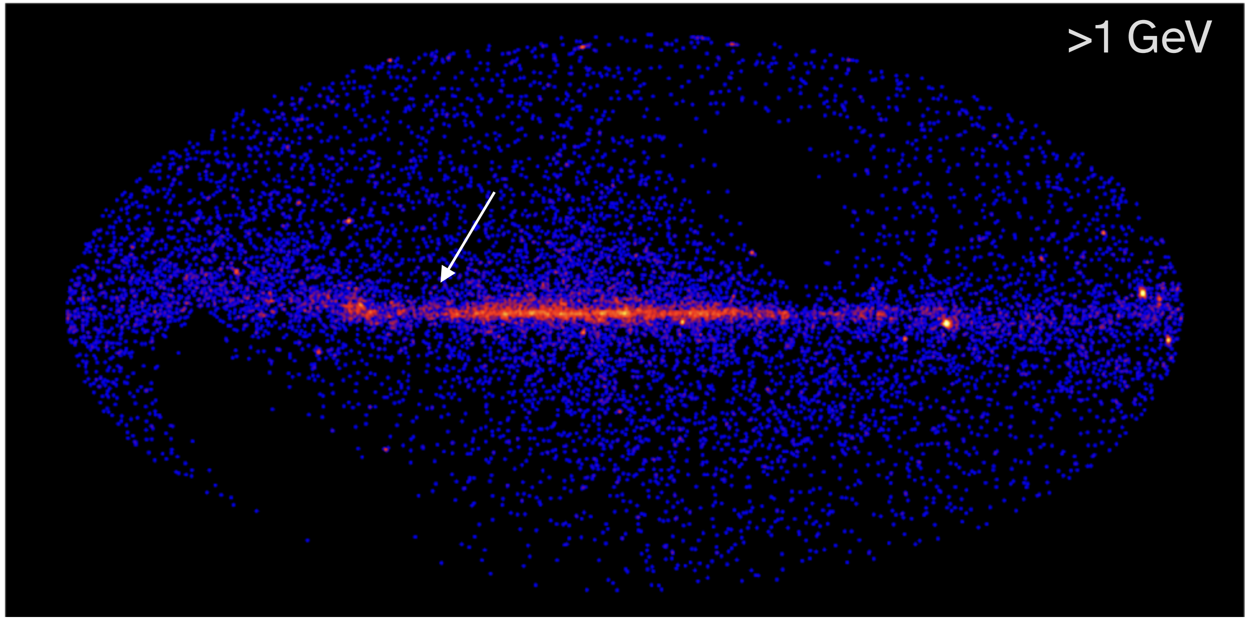
I’m going to focus on gamma-ray bursts with H.E.S.S. because that’s what I know best

CTAO will likely have a slightly different strategy but the broad concepts will be the same

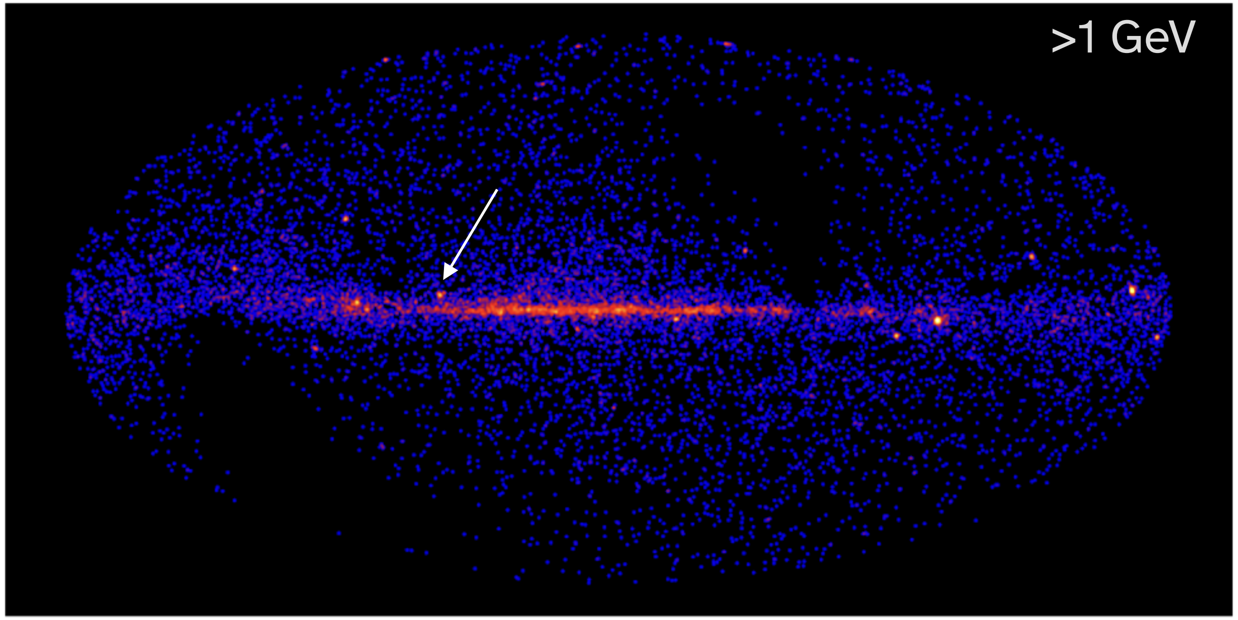
ok but what exactly *is* a “gamma-ray burst”?

Literally, a burst of gamma rays that easily outshines the rest of the gamma-ray sky for their brief existence

[D. Green]



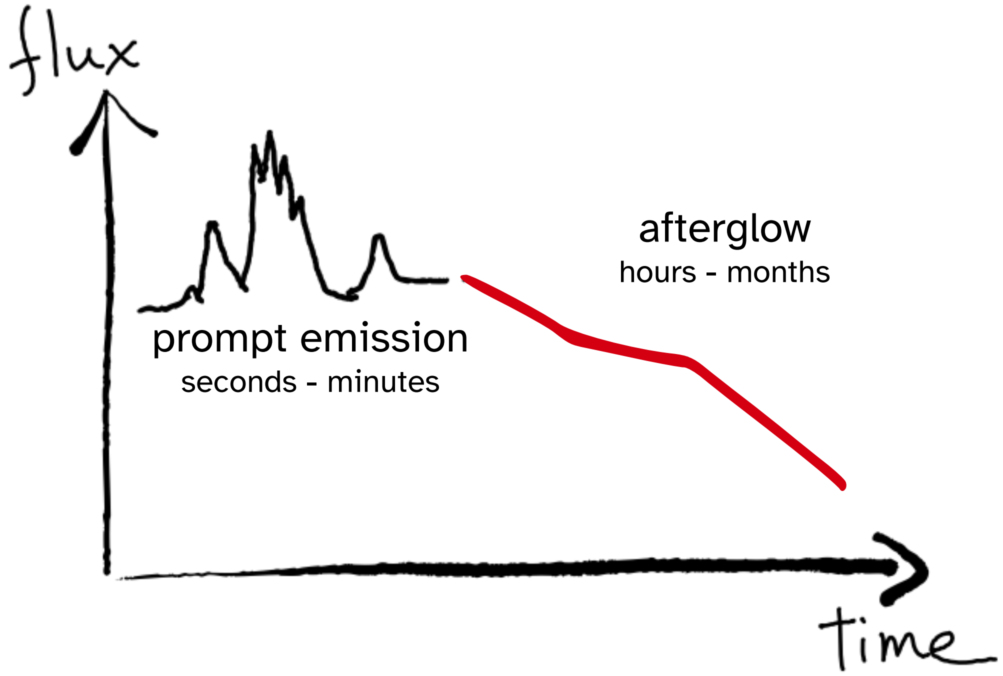
2 days before GRB



GRB + 2 days after

Gamma-ray bursts

What are they?



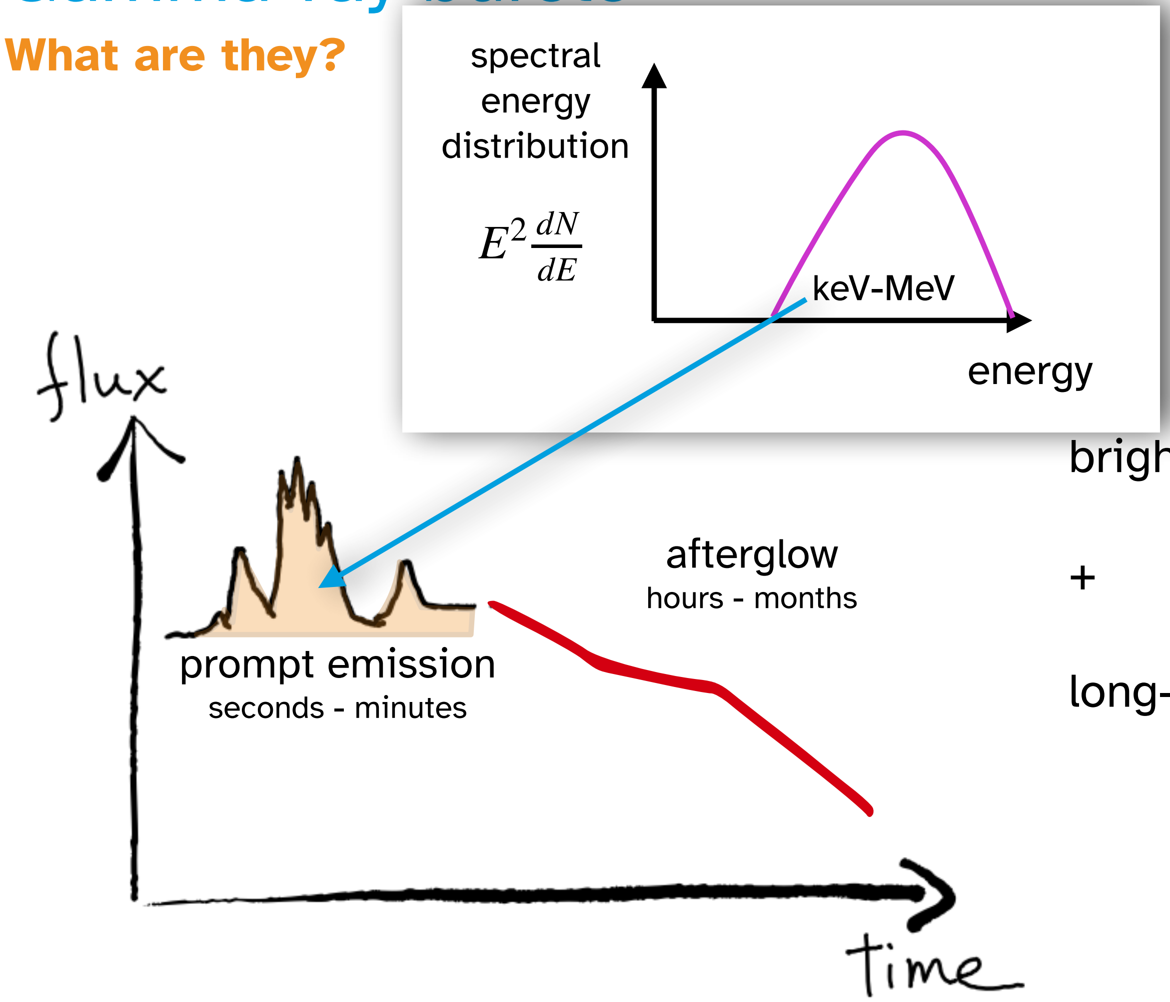
bright flashes of mostly gamma rays (prompt emission)

+

long-lived, slowly fading multiwavelength emission (afterglow)

Gamma-ray bursts

What are they?



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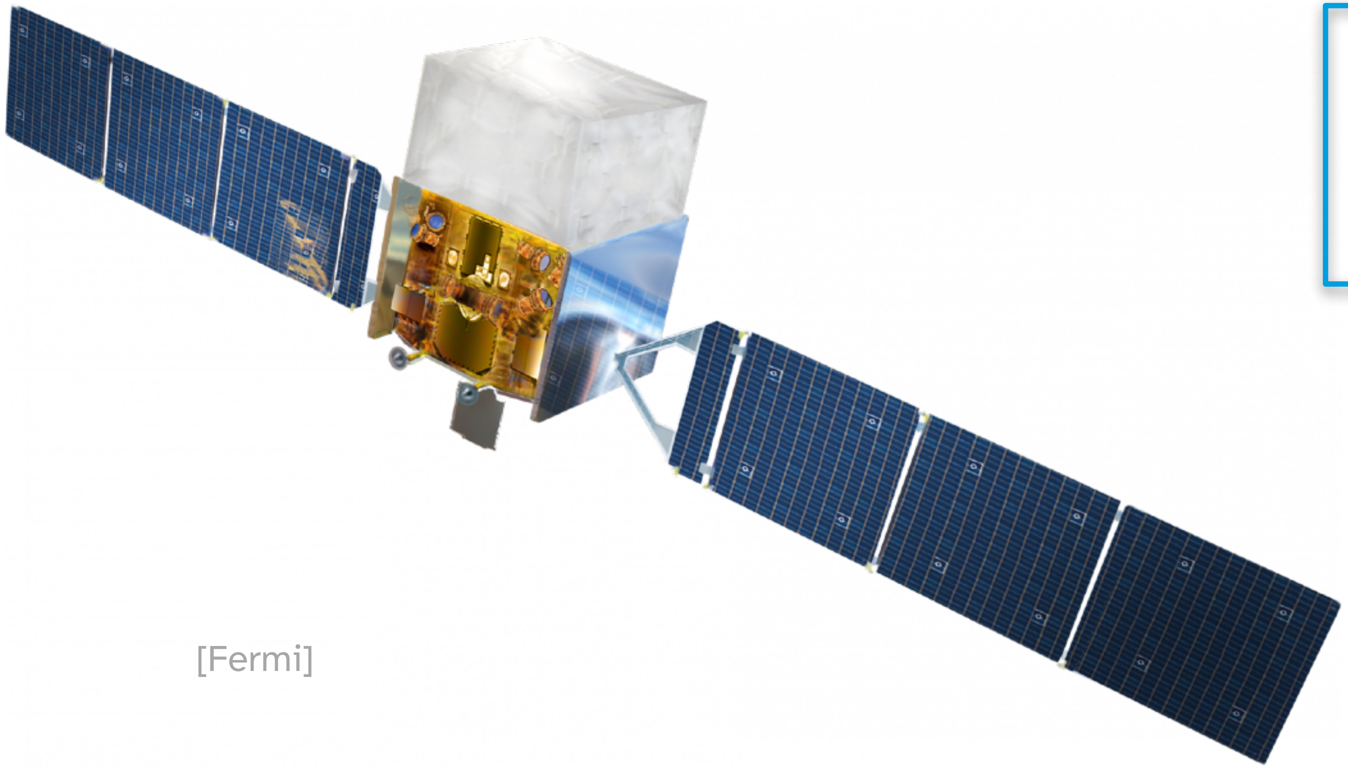
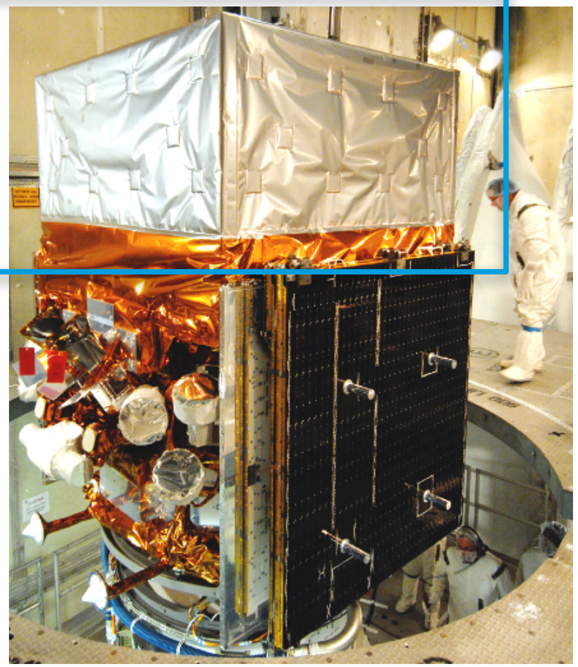
How are gamma-ray bursts detected?

Wide field-of-view gamma-ray monitors


[Fermi]

[NASA/DOE/Fermi-LAT]

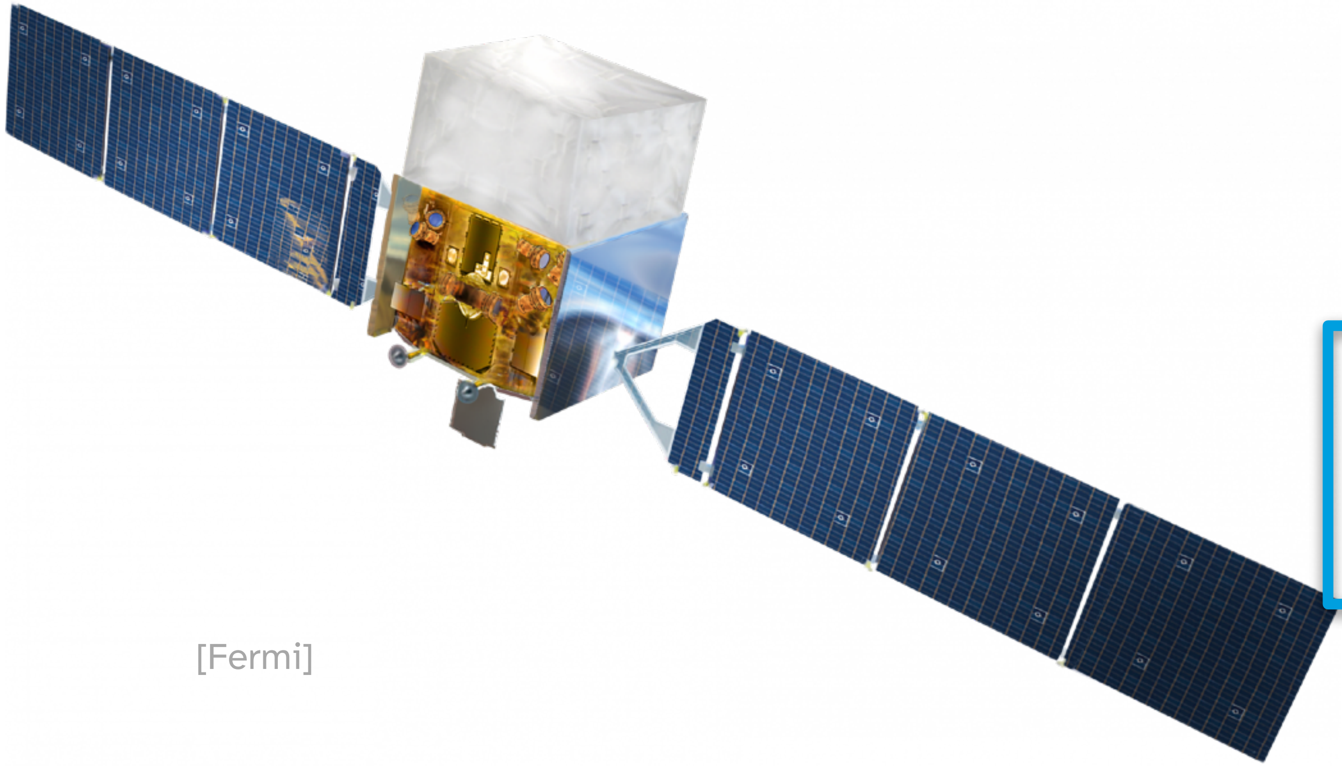


Fermi Large Area Telescope
MeV - GeV

10^{-6} m	10^{-7} m	10^{-8} m	10^{-9} m	10^{-10} m	10^{-11} m	10^{-12} m	10^{-13} m	10^{-14} m	10^{-15} m	10^{-16} m	10^{-17} m	10^{-18} m	10^{-19} m	10^{-20} m
ed opt	ultraviolet	X-rays		gamma rays				high energy gamma rays			very high energy gamma rays			
1 eV	10 eV	100 eV	1 keV	10 keV	100 keV	1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

How are gamma-ray bursts detected?

Wide field-of-view gamma-ray monitors



[Fermi]

[NASA/DOE/Fermi-LAT]

Fermi Gamma-ray Burst Monitor

keV - MeV

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ed | opt | ultraviolet | X-rays | gamma rays | high energy gamma rays | very high energy gamma rays

1 eV | 10 eV | 100 eV | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

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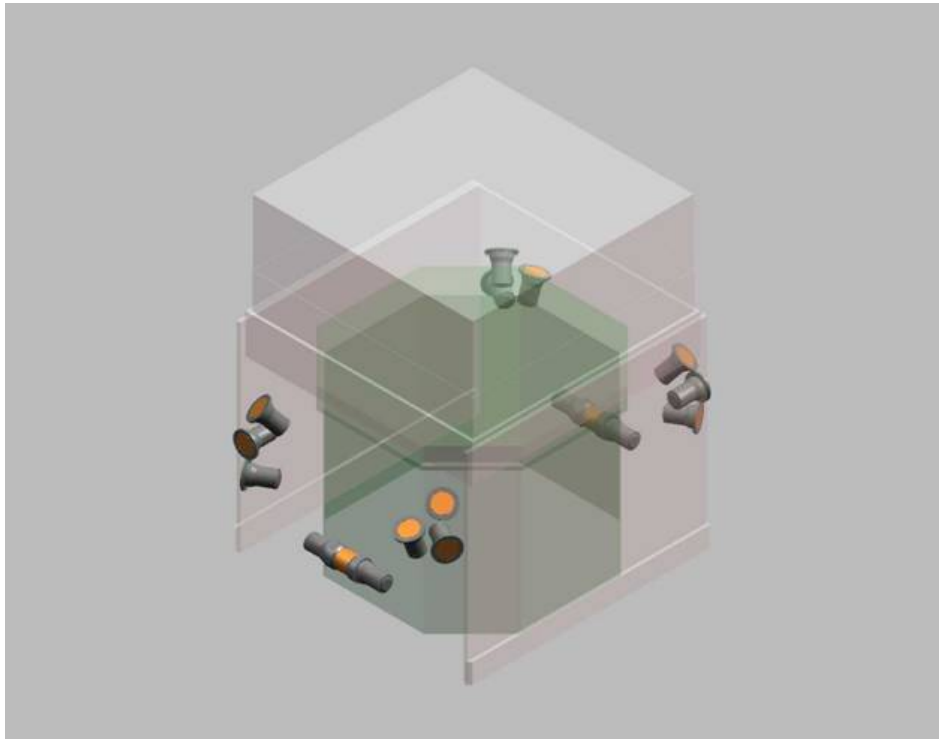

[NASA/DOE/Fermi-GBM]

[NASA/DOE/Fermi-LAT]

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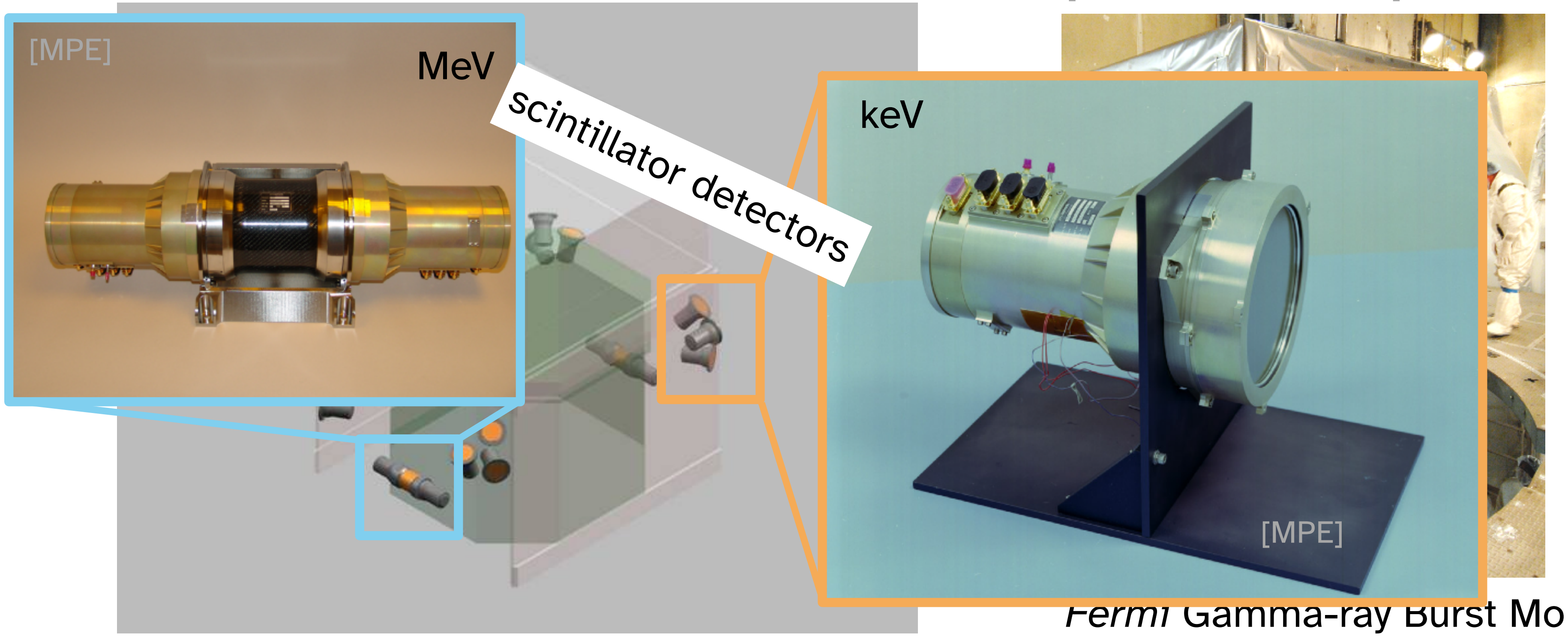
[NASA/DOE/Fermi-LAT]



[NASA/DOE/Fermi-GBM]

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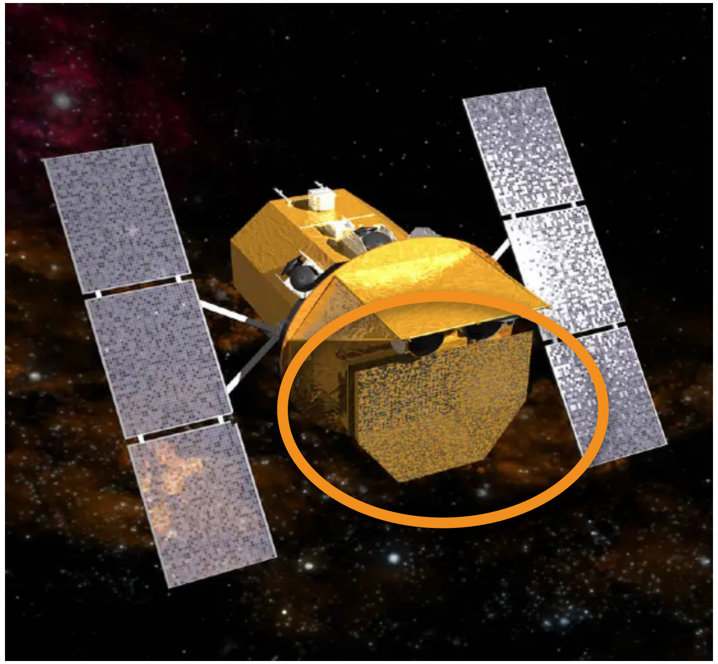
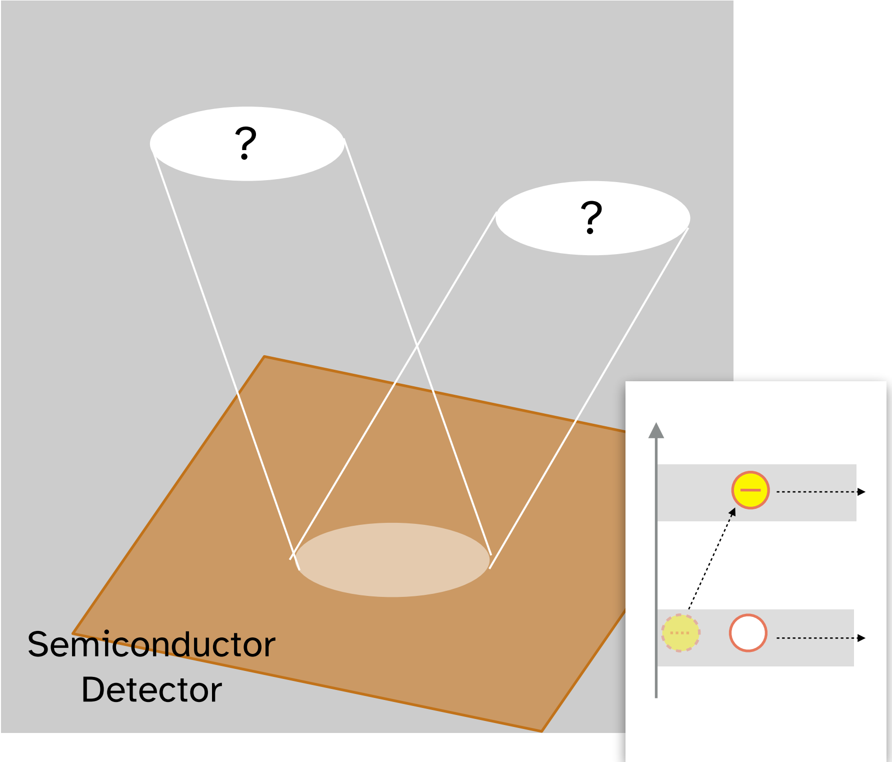
[NASA]



Swift Burst Alert Telescope

keV



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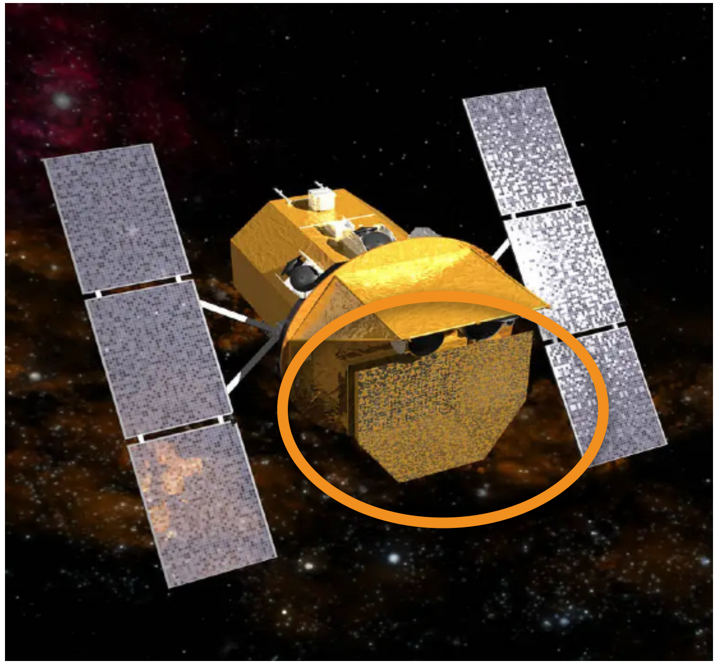
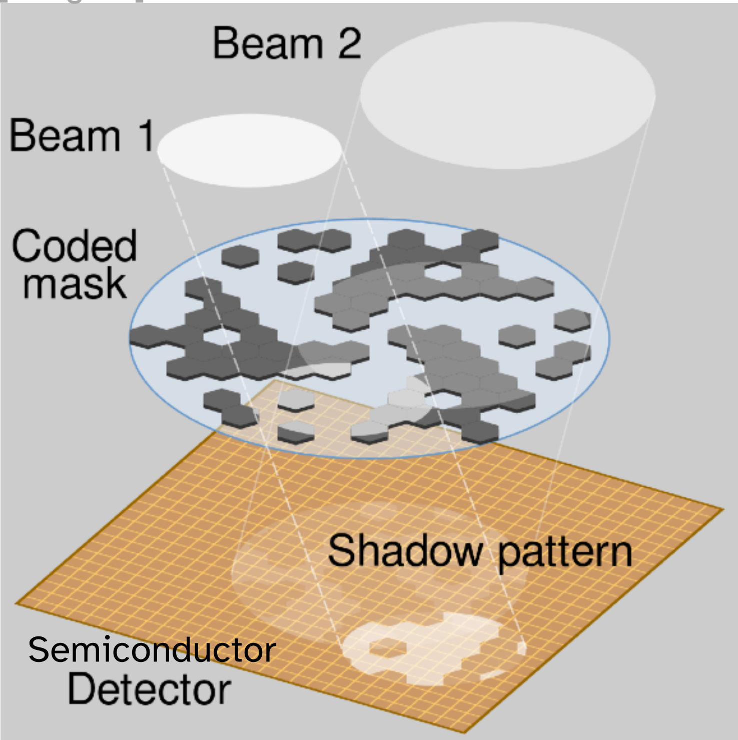
[NASA]



Swift Burst Alert Telescope

keV

[Cmglee]



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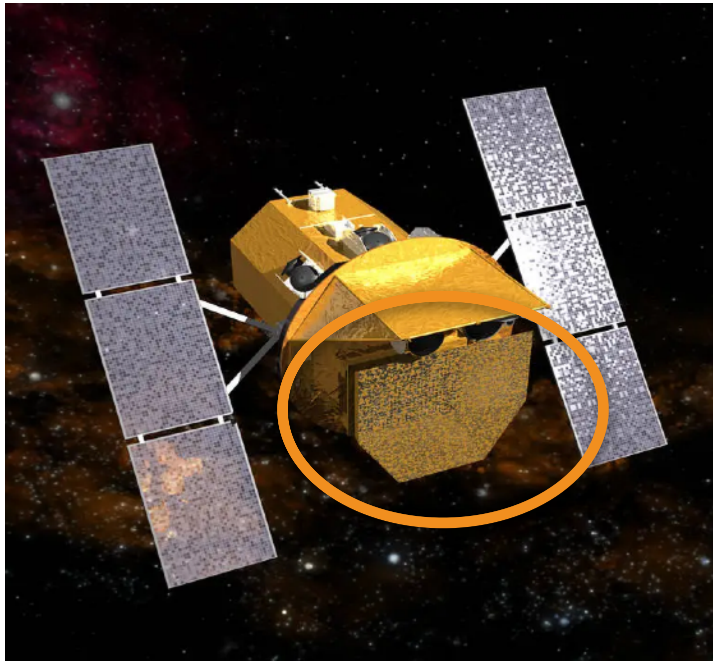

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keV

[NASA/DOE/Fermi-LAT]

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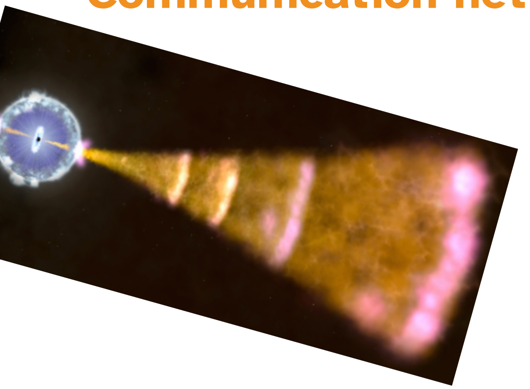
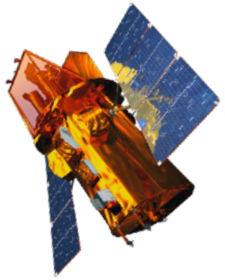
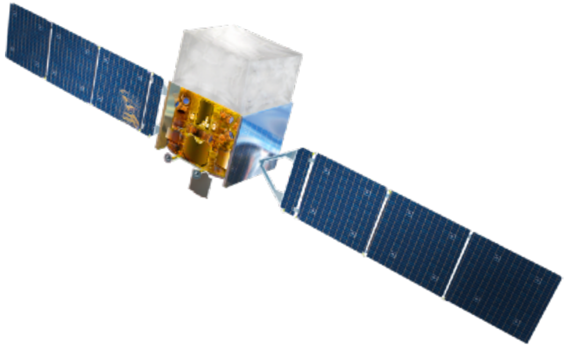
How are gamma-ray bursts detected?

Communication networks







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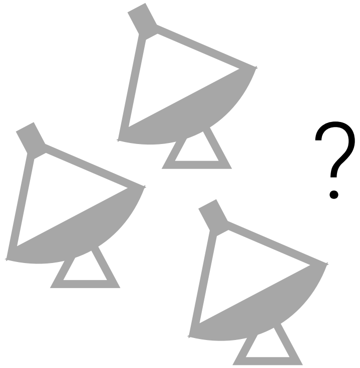

How are gamma-ray bursts detected?

Communication networks

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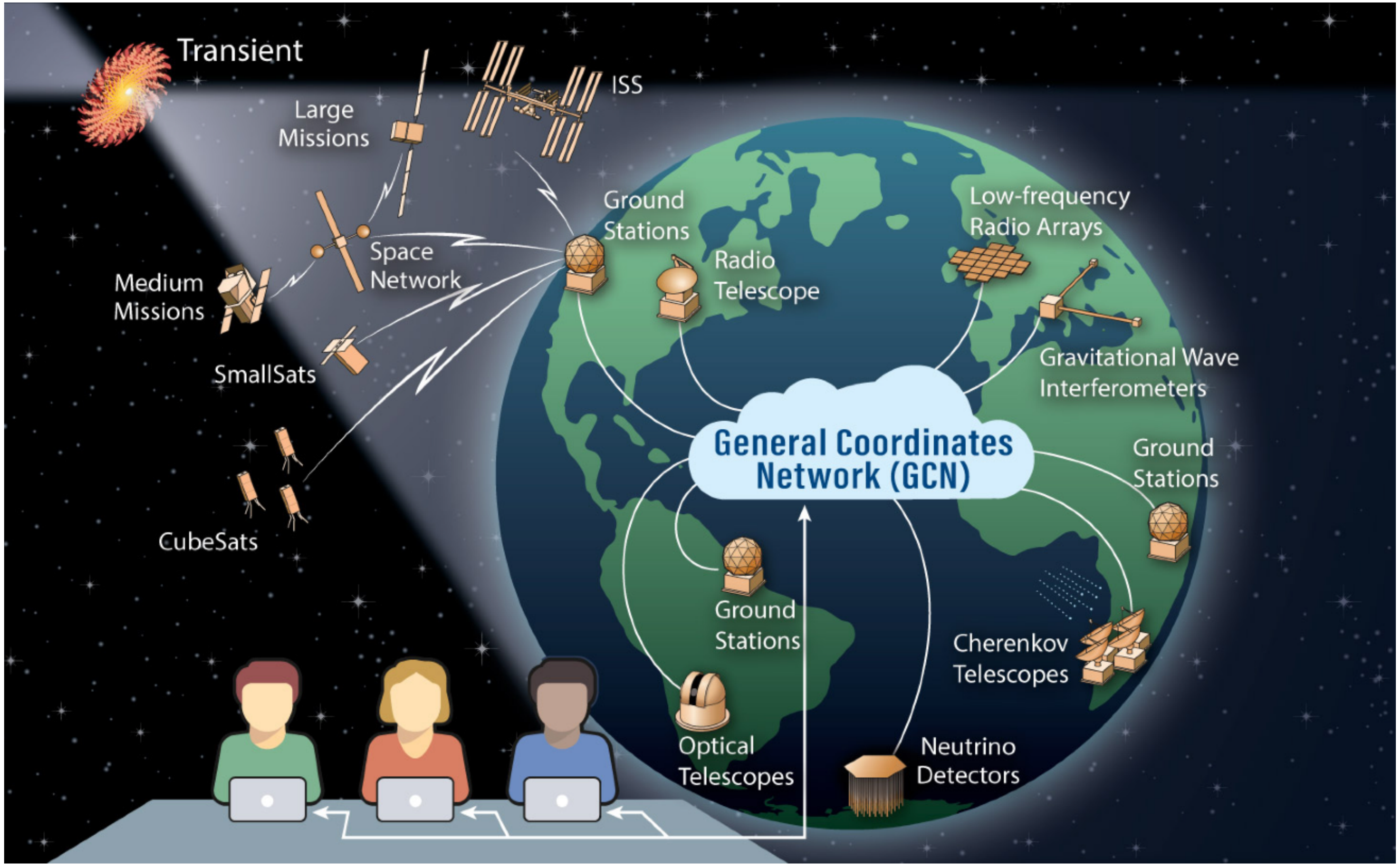


How do IACTs decide what to observe and when?

Transient follow-up systems

alert handling
- decision to observe
- communication with control software

What kind of alerts are we interested in?
From which telescopes?
When are the sources observable?
How do we want to observe them?

control software
- schedule observations

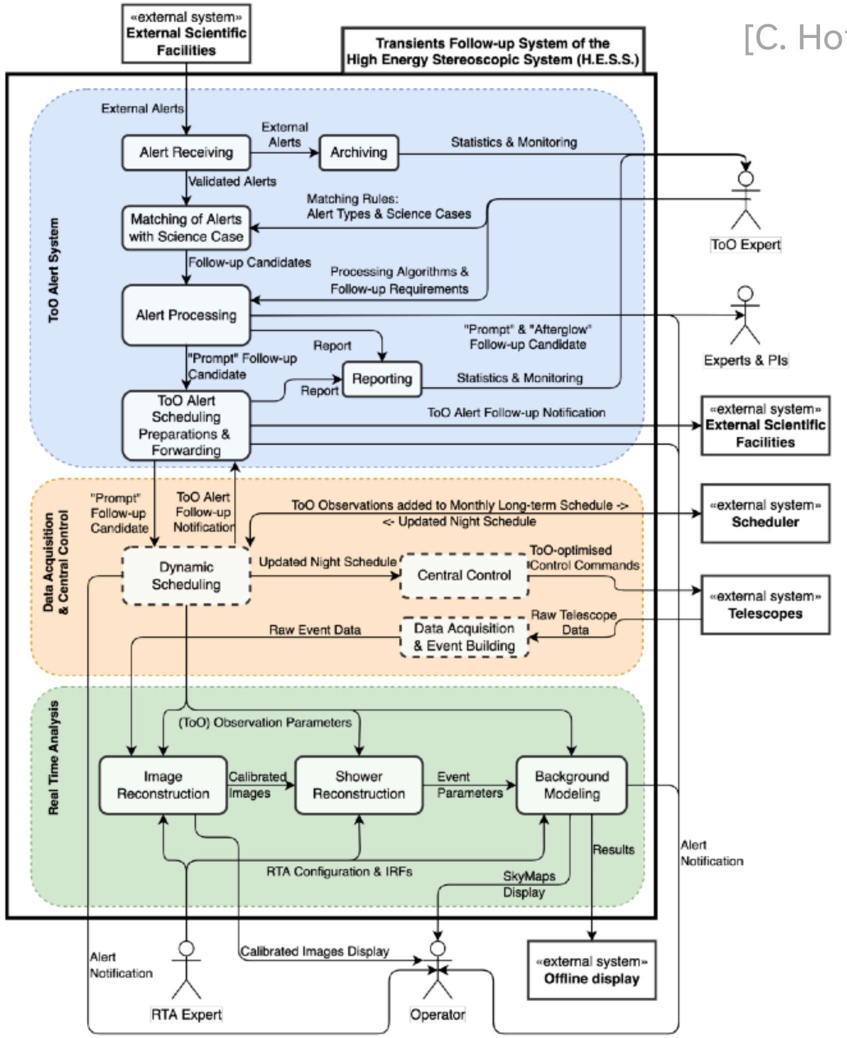
When do we insert the observation into the schedule?
Do the telescopes have to respond immediately?

realtime analysis
- low latency results

Did we detect anything?

How do IACTs decide what to observe and when?

Transient follow-up systems



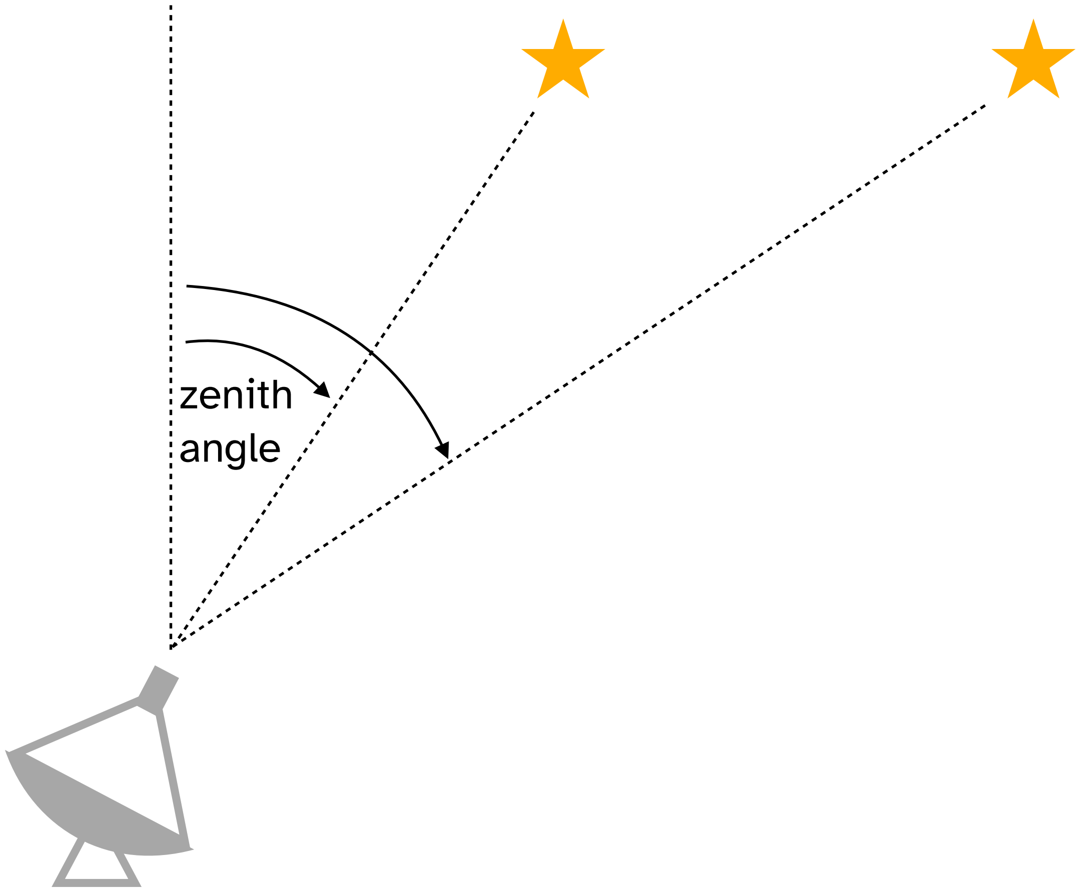
[C. Hoischen et al., A&A 666 (2022)]

Examples of subtleties that we might encounter:

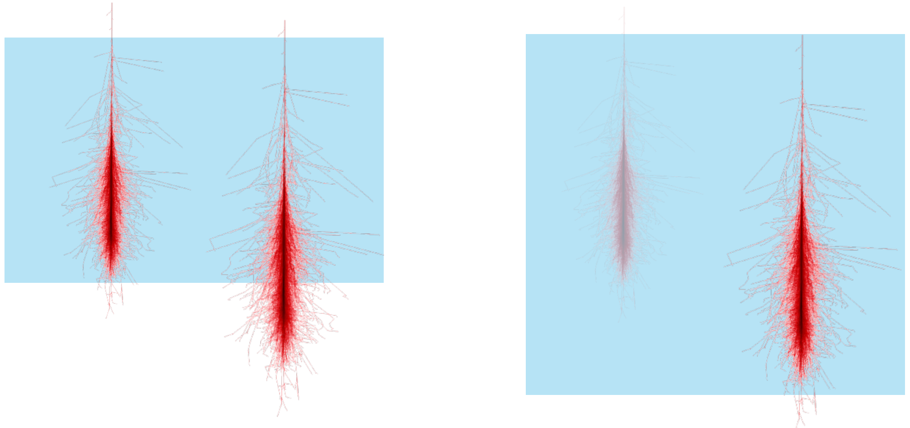
- What cuts might we need to include?
- What happens if two alerts come in at the same time?
- What happens if an alert comes in while the telescopes are taking calibration data?
- What happens if an alert comes in while the telescopes are transitioning between runs?
- If the array reacts automatically: How can we be sure nothing breaks?
- What kind of analysis do we want to run?

How do IACTs decide what to observe and when?

General considerations for IACT observations



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)

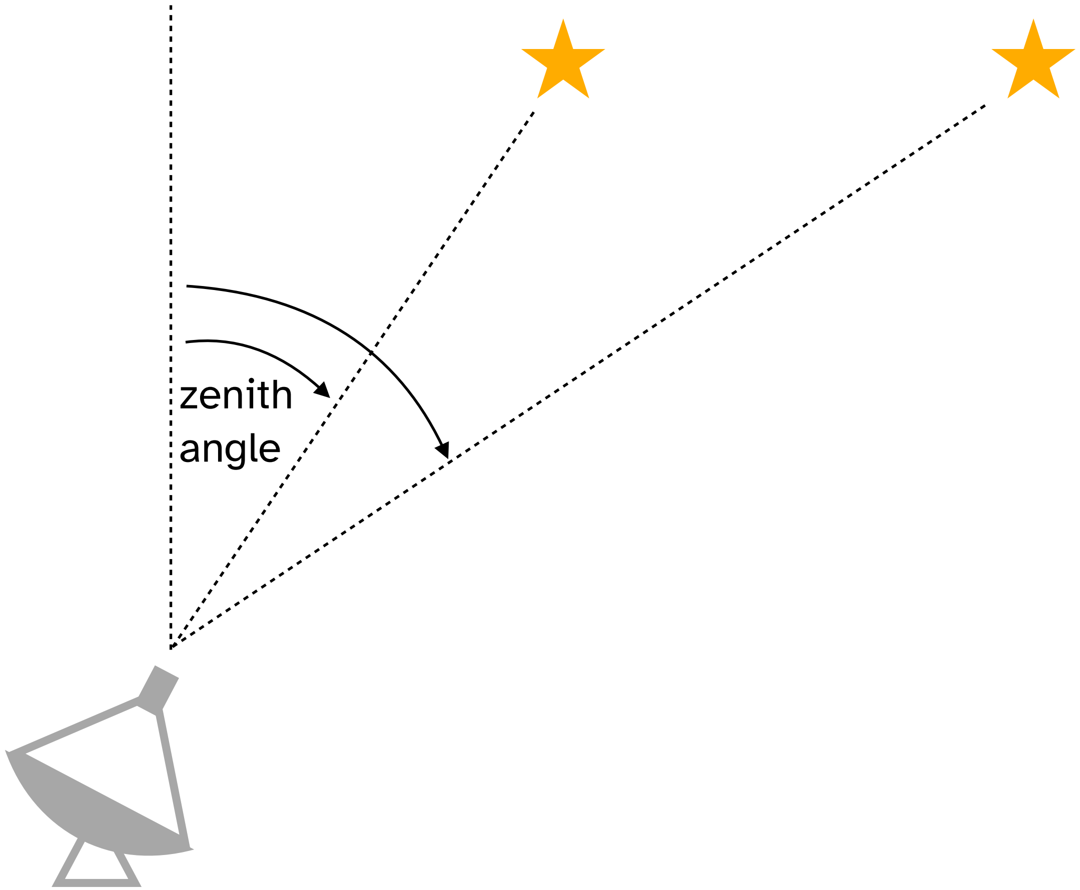


larger zenith angle -> more atmosphere to go through
-> more absorption of Cherenkov photons

How do IACTs decide what to observe and when?

General considerations for IACT observations

How far below the horizon do the Sun and Moon have to be? How bright can the Moon be? Are there certain regions of the sky where the night-sky background (NSB) is too bright in general?



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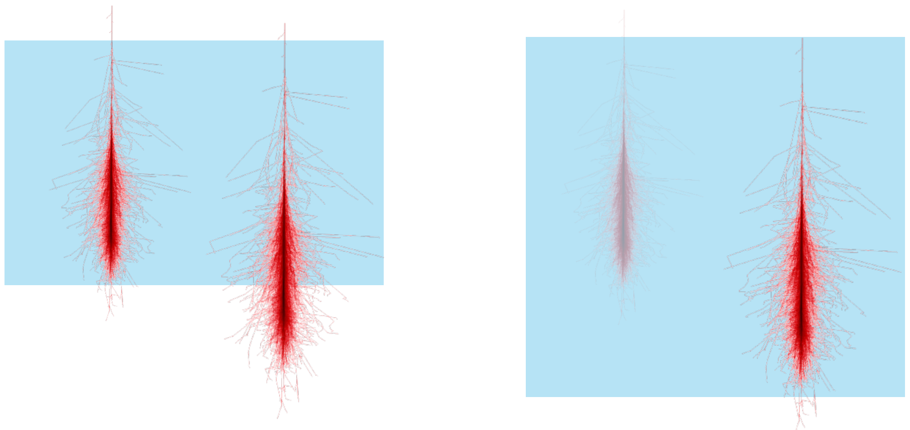

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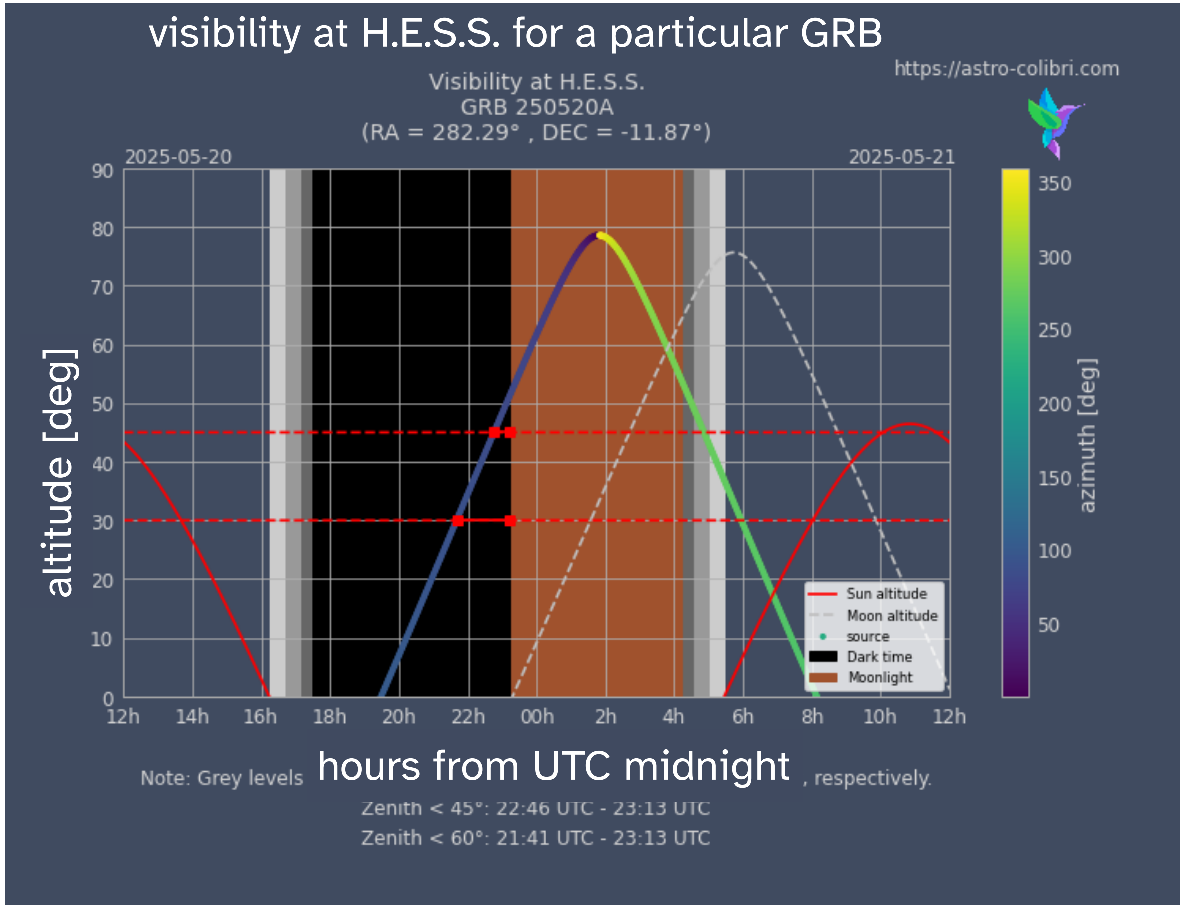
How do IACTs decide what to observe and when?

General considerations for IACT observations

Putting it all together:



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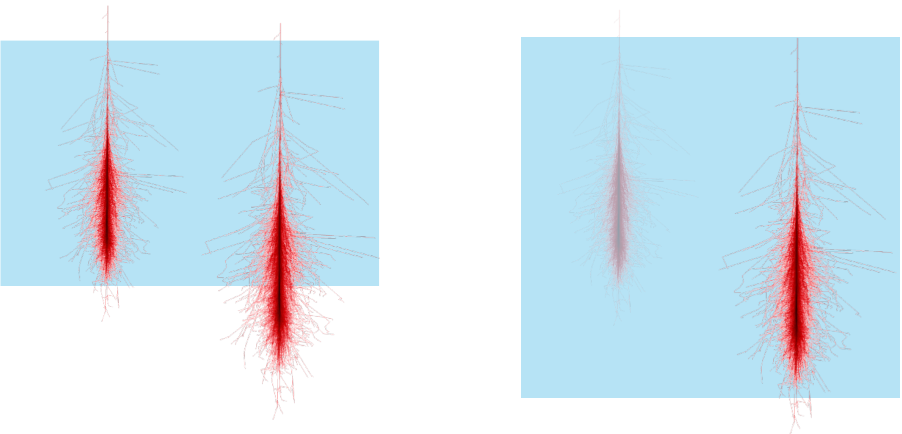

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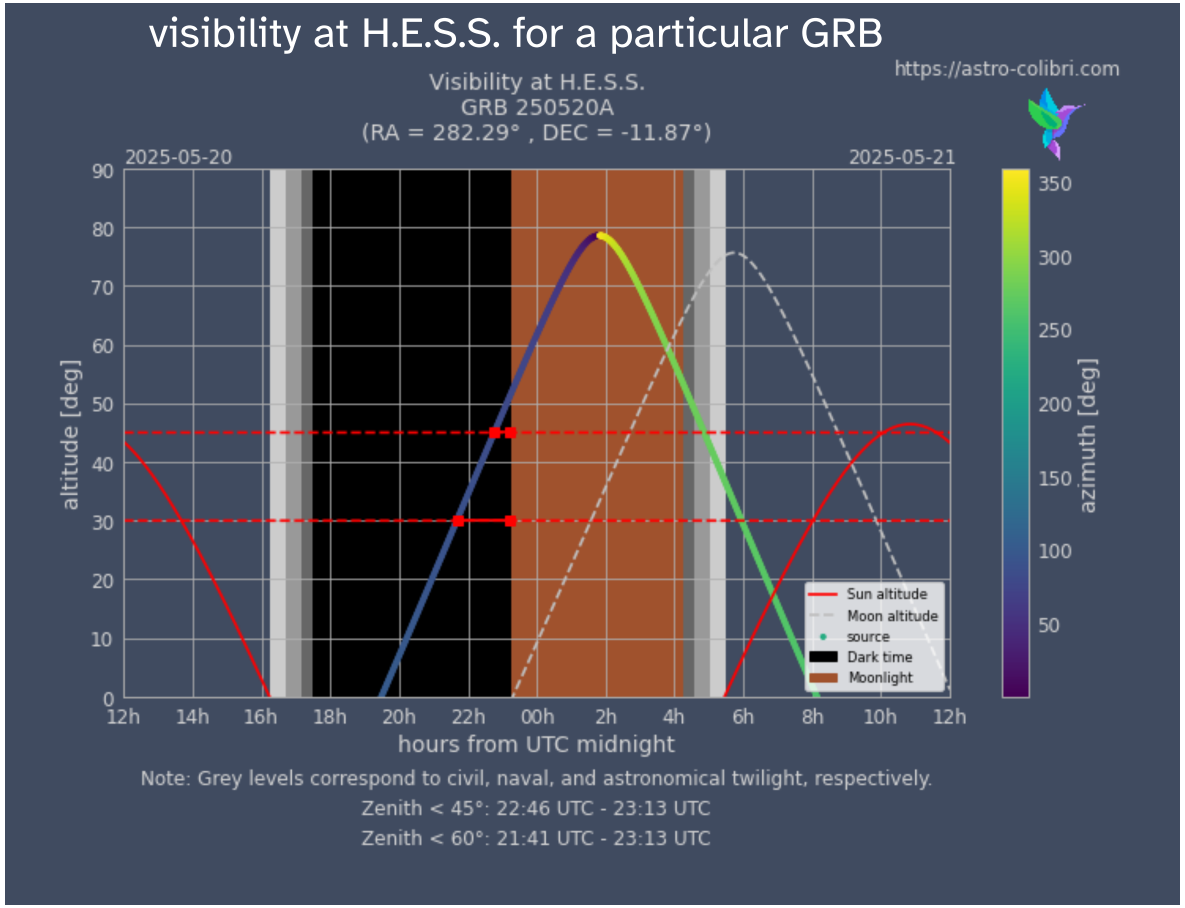
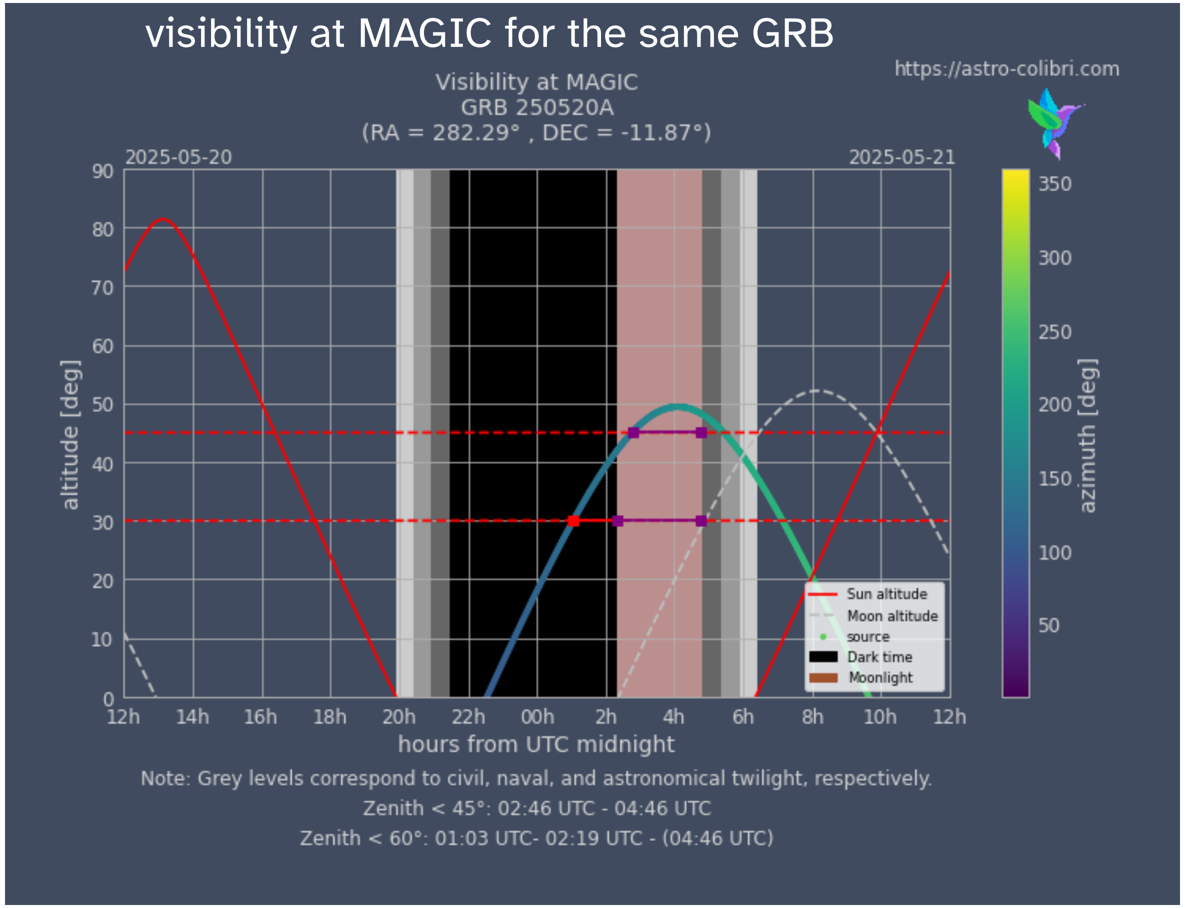
How do IACTs decide what to observe and when?

General considerations for IACT observations

The visibility will be different at different site locations





How do IACTs decide what to observe and when?

General considerations for IACT observations

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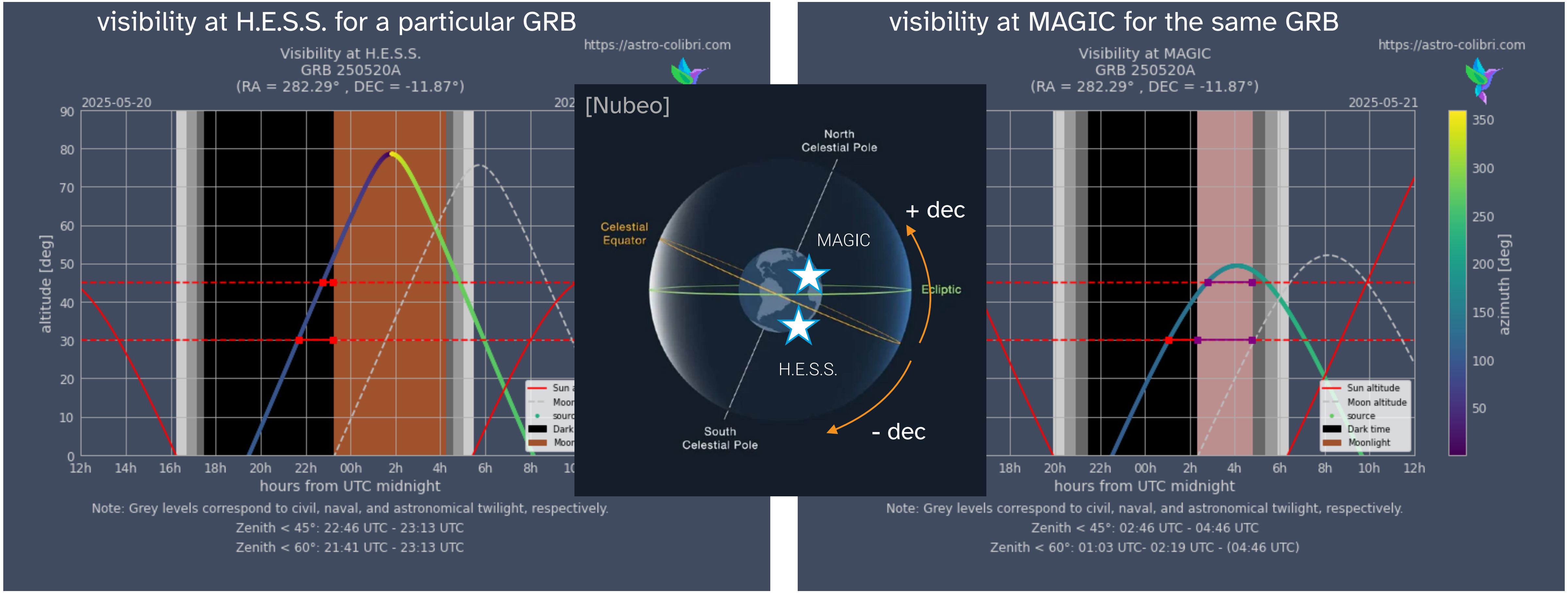


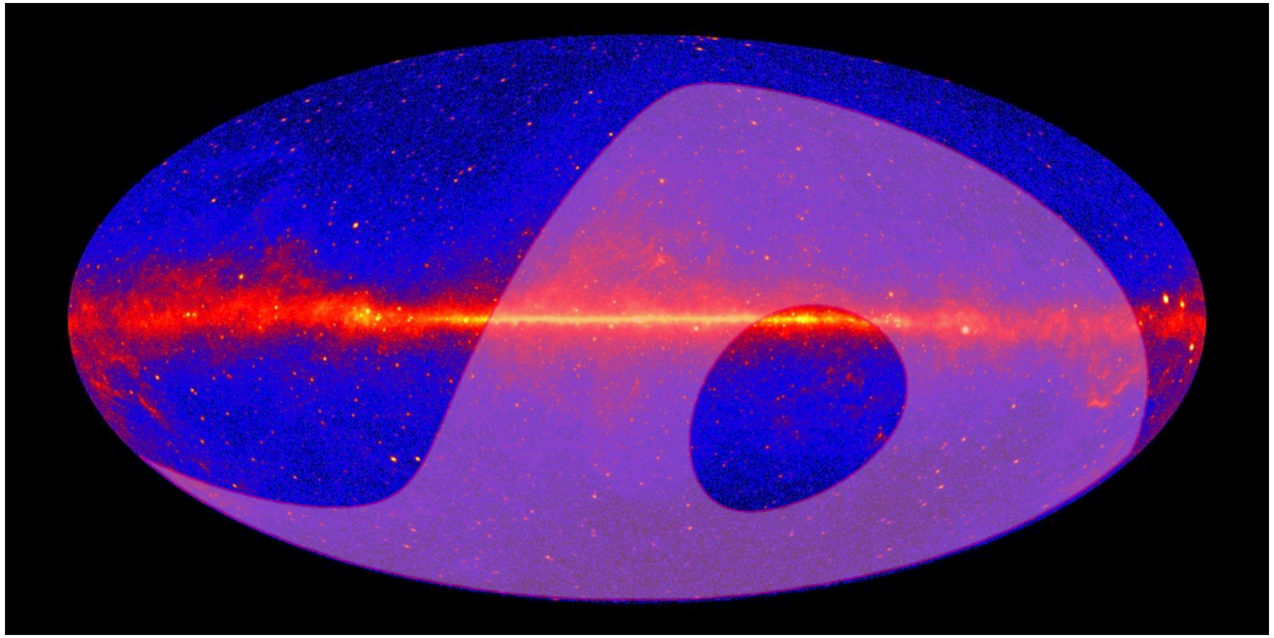
How do IACTs decide what to observe and when?

General considerations for IACT observations

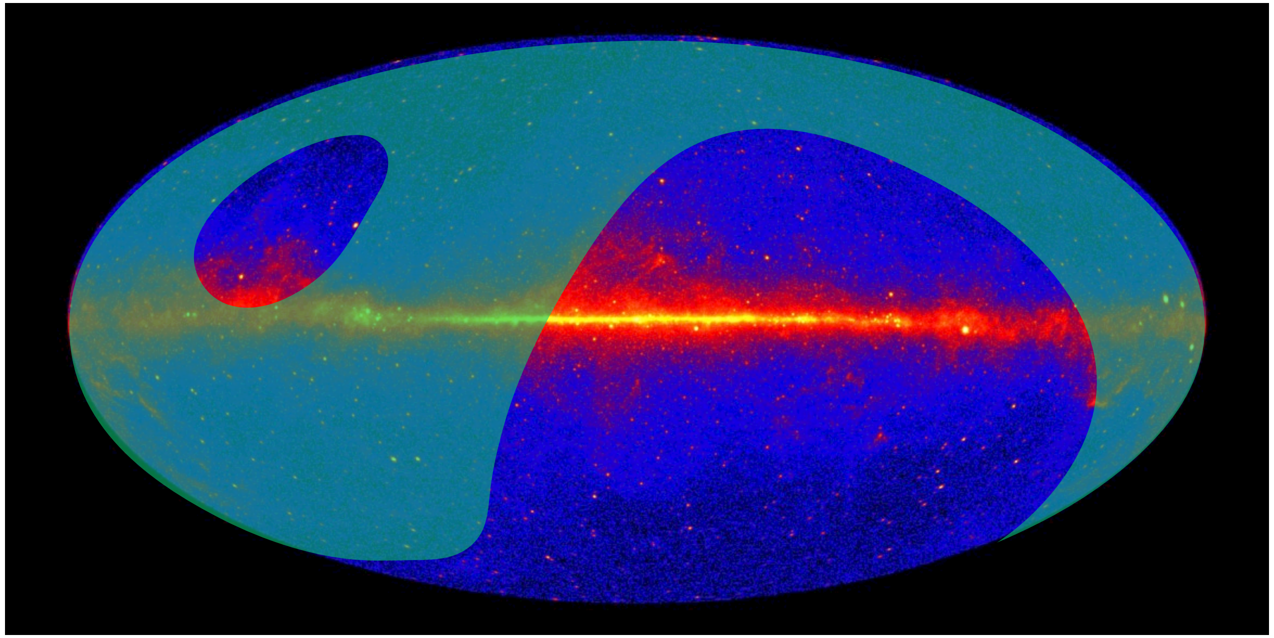
The visibility will be different at different site locations

(note: these particular contours are conservative)

H.E.S.S.



VERITAS/MAGIC



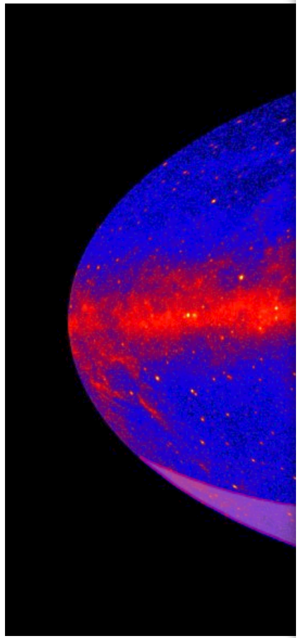
Shown here: Galactic coordinates (≠ ra, dec!)

contours made with the aid of [TeVCat]

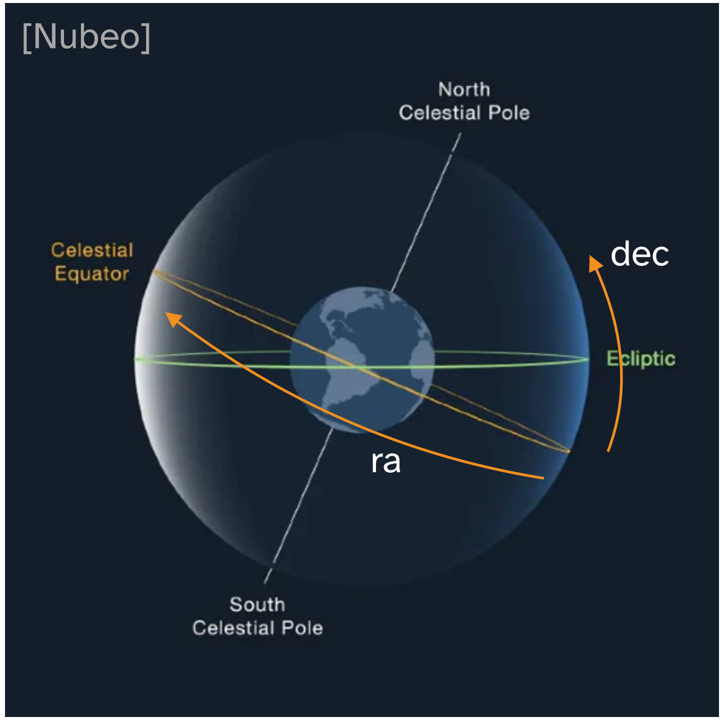
How do IACTs decide what to observe and when?

General considerations for IACT observations

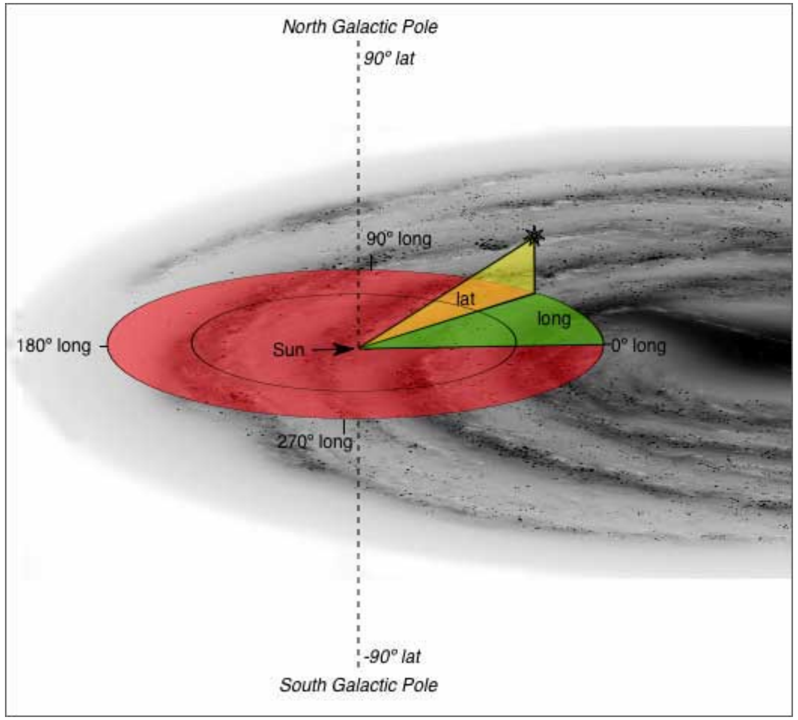
The visibil … vative)

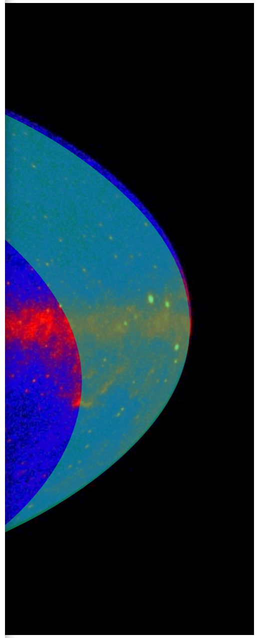


equatorial coordinates



galactic coordinates



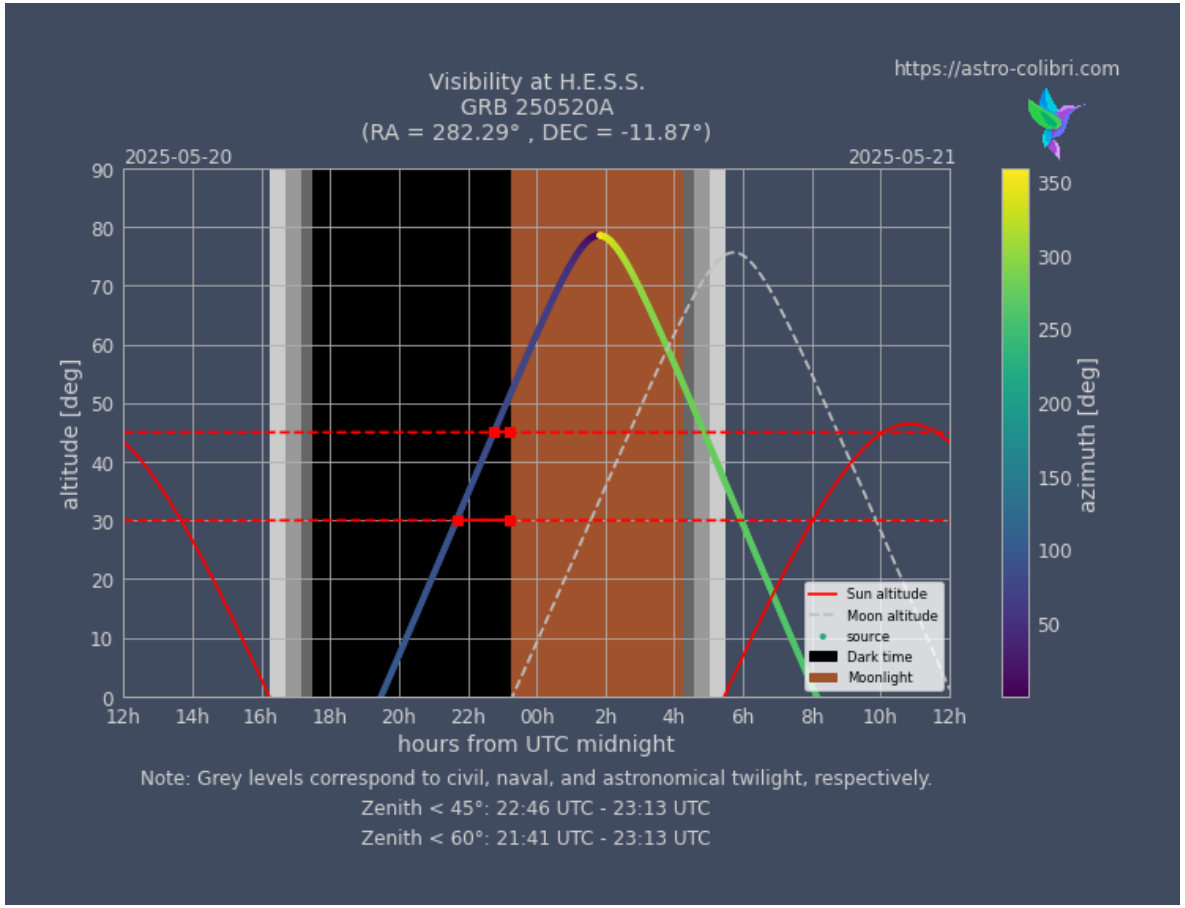


contours made with the aid of [TeVCat]

How do IACTs decide what to observe and when?

General considerations for IACT observations

Putting it all together:



1. When is it dark enough to observe?
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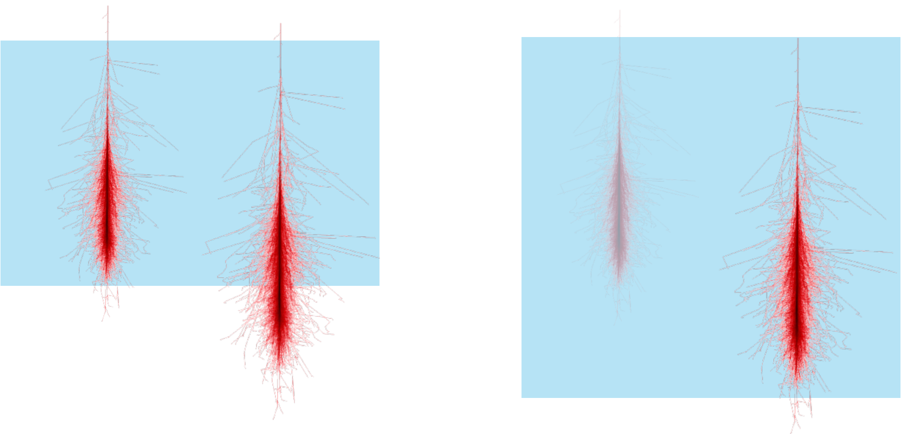

larger zenith angle -> more atmosphere to go through
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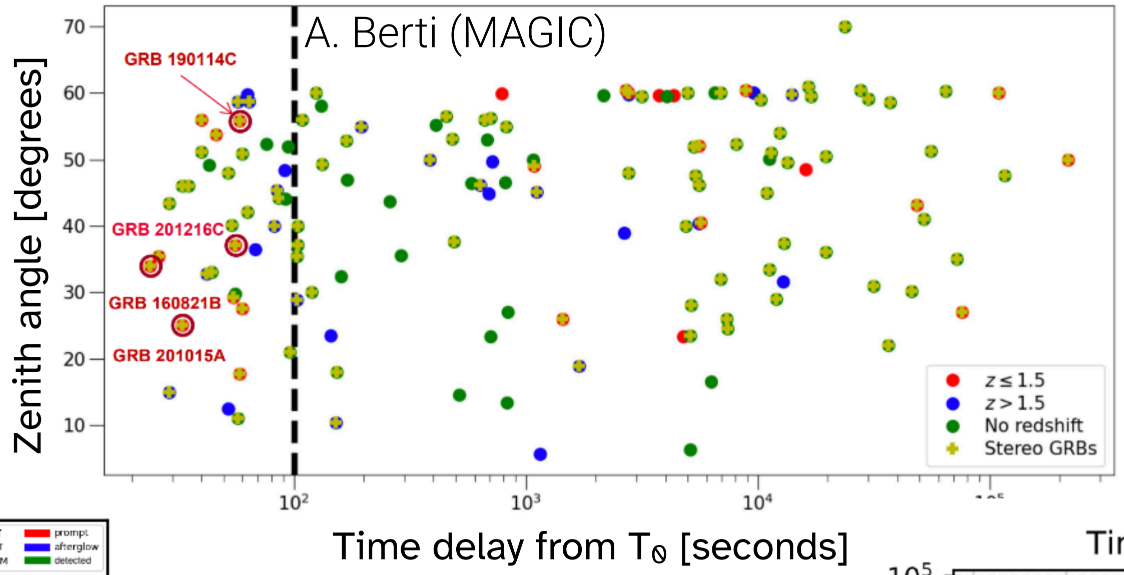
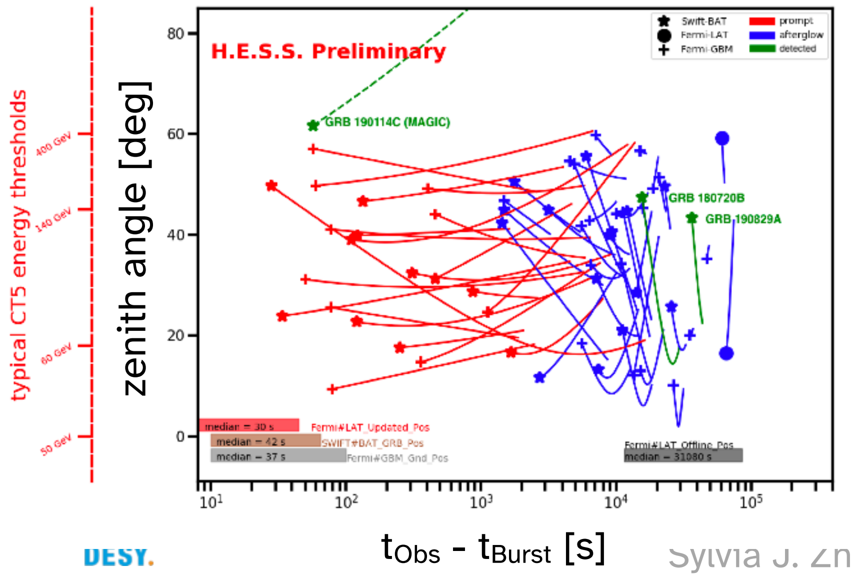
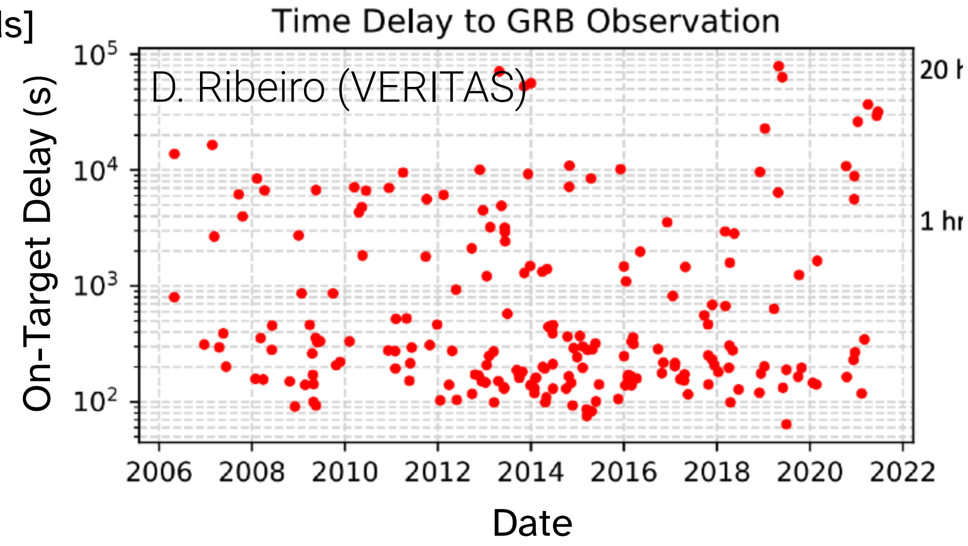
IACT GRB observations

summary of GRB programs

(note: these plots are a few years out of date!!)





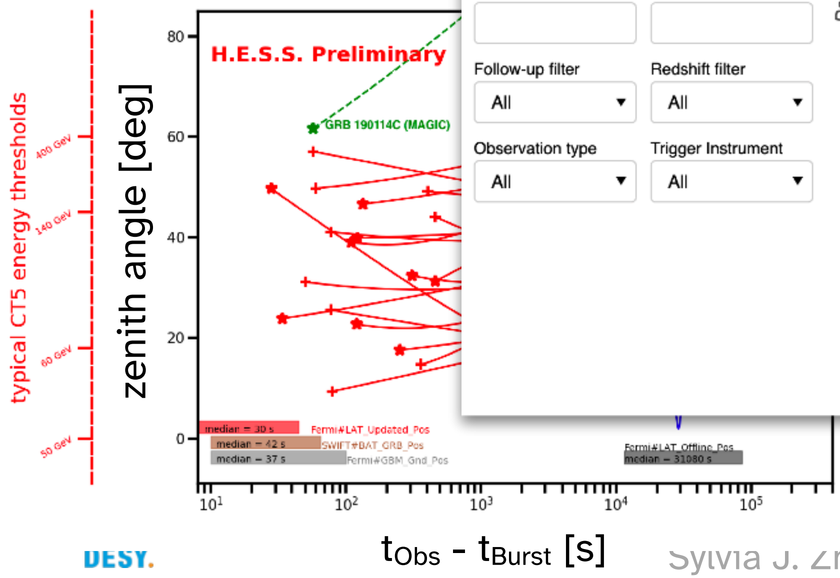


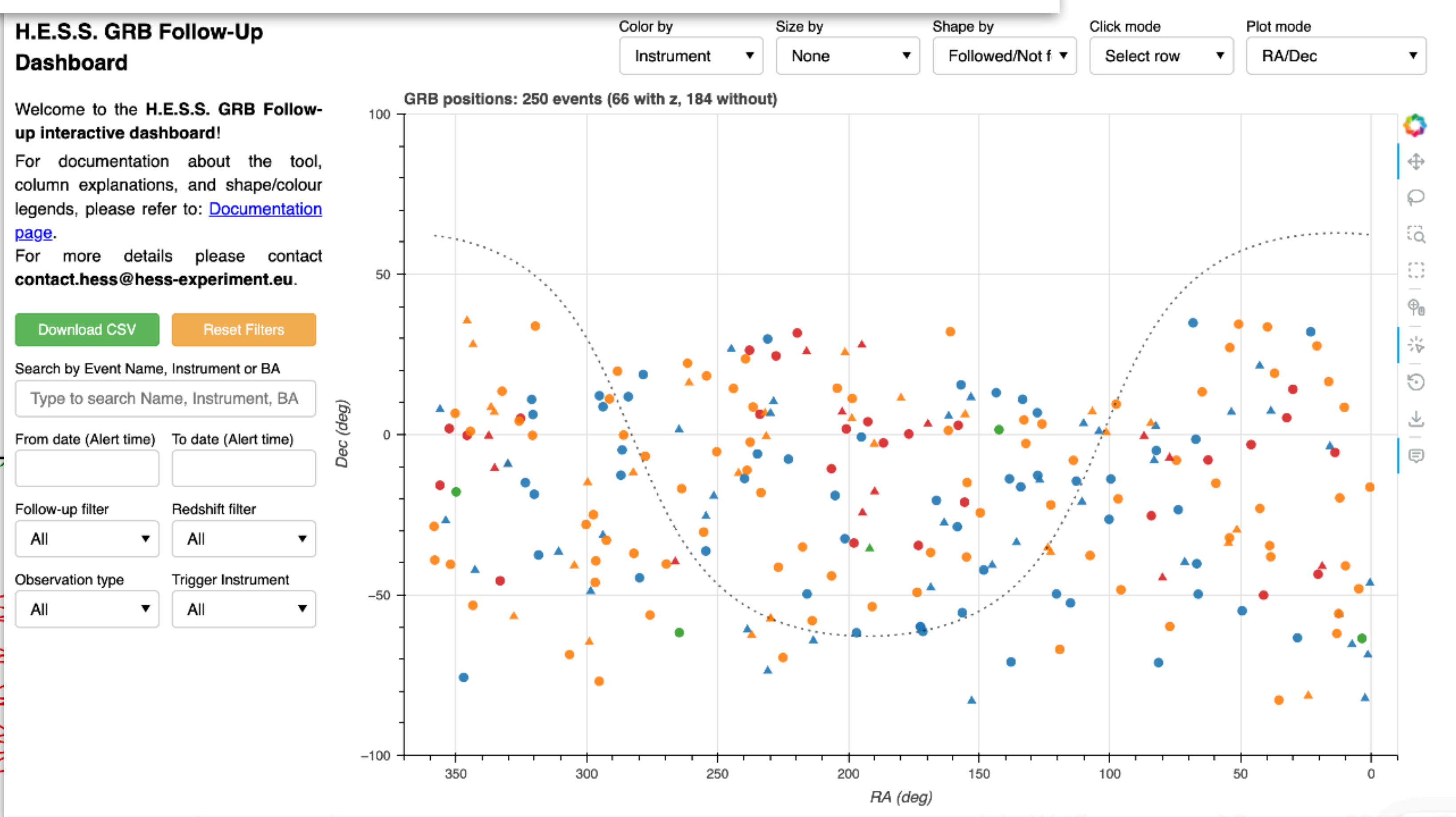
IACT GRB observations

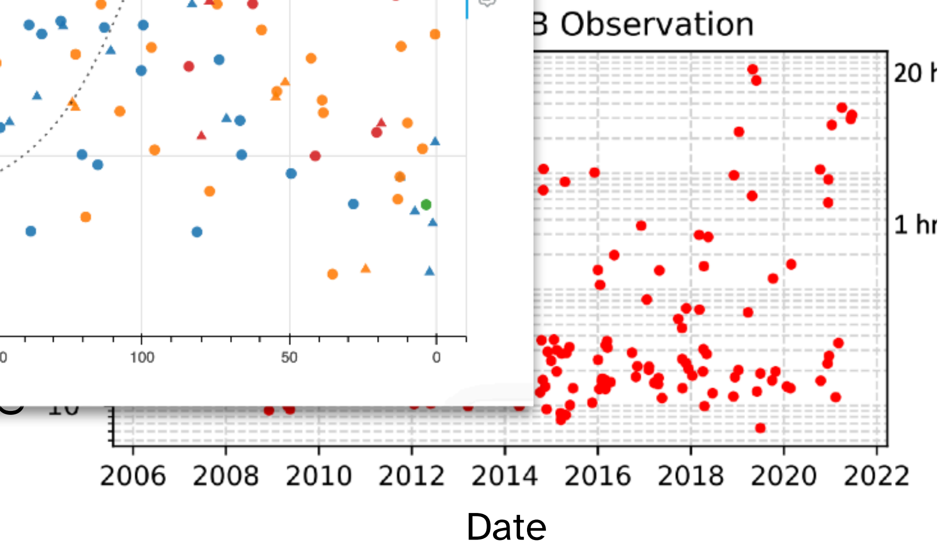
summary of GRB programs

(note: these plots are a few years out of date!!)

sidenote: there is a public H.E.S.S. GRB dashboard at hess-experiment.eu







IACT GRB observations

summary of GRB programs

(note: these plots are a few years out of date!!)

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H.E.S.S. GRB Follow-Up Dashboard

Color by: Instrument | Size by: None | Shape by: Followed/Not f | Click mode: Select row | Plot mode: RA/Dec

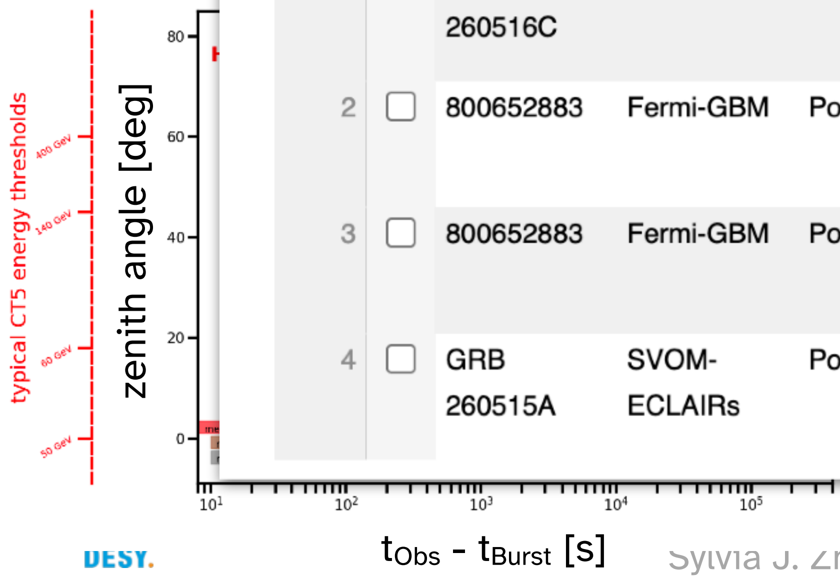
Welcome to the **H.E.S.S. GRB Follow-up interactive dashboard!**

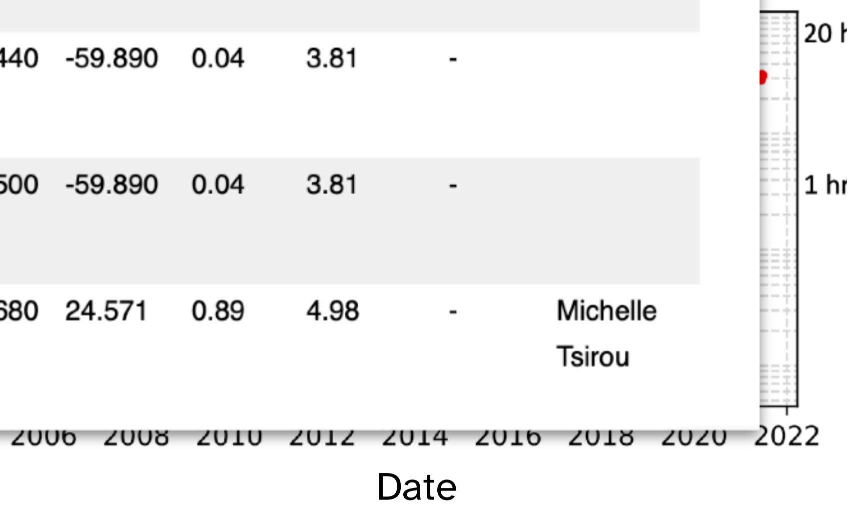
For documentation about the tool,

GRB positions: 250 events (66 with z, 184 without)

H.E.S.S. publicizes all of its GRB observations

#		Name	Instrument	Type	Alert Time (UTC)	Start Time (UTC)	End Time (UTC)	RA (deg)	Dec (deg	Delay (h	Exposure (	z	BA
0	☐	GRB 260516D	SVOM-Eclairs	Pointed	2026-05-16 20:38:28	2026-05-16 20:54:02	2026-05-17 02:25:06	233.849	6.373	0.26	5.52	-	Michelle Tsirou
1	☐	GRB 260516C	Fermi-GBM	Tiled	2026-05-16 19:34:38	2026-05-16 20:25:07	2026-05-16 23:20:31	171.520	-61.380	0.84	2.92	0.764	Michelle Tsirou
2	☐	800652883	Fermi-GBM	Pointed	2026-05-16 19:34:38	2026-05-16 19:36:50	2026-05-16 23:25:42	172.440	-59.890	0.04	3.81	-	
3	☐	800652883	Fermi-GBM	Pointed	2026-05-16 19:34:38	2026-05-16 19:37:01	2026-05-16 23:25:52	172.500	-59.890	0.04	3.81	-	
4	☐	GRB 260515A	SVOM-ECLAIRs	Pointed	2026-05-15 19:08:19	2026-05-15 20:01:50	2026-05-16 01:00:23	227.680	24.571	0.89	4.98	-	Michelle Tsirou



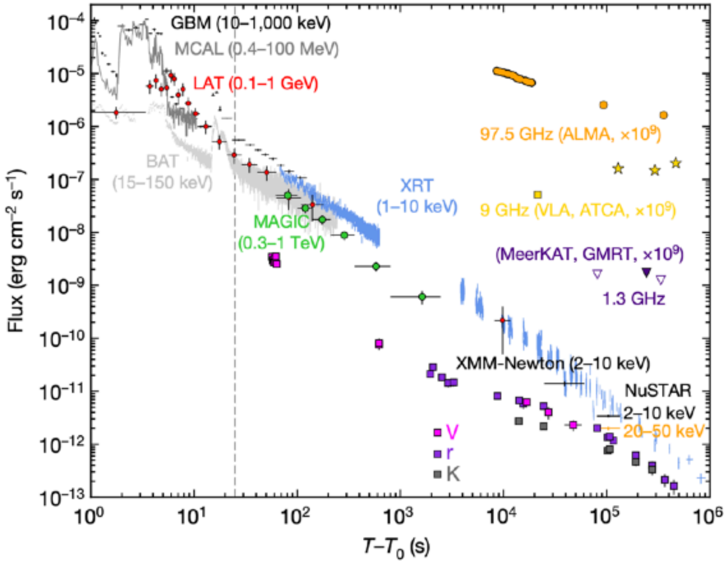


VHE GRB detections

$n < 10$

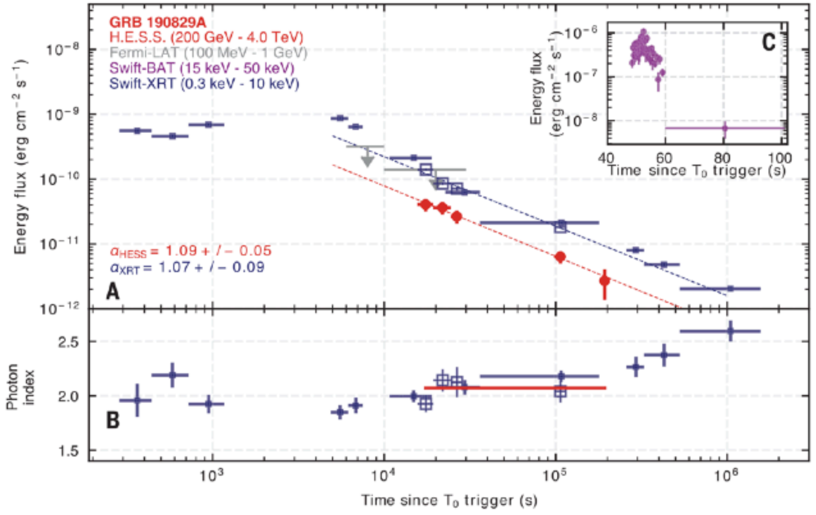
GRB 190114C

[MAGIC, Nature 575 (2019)]



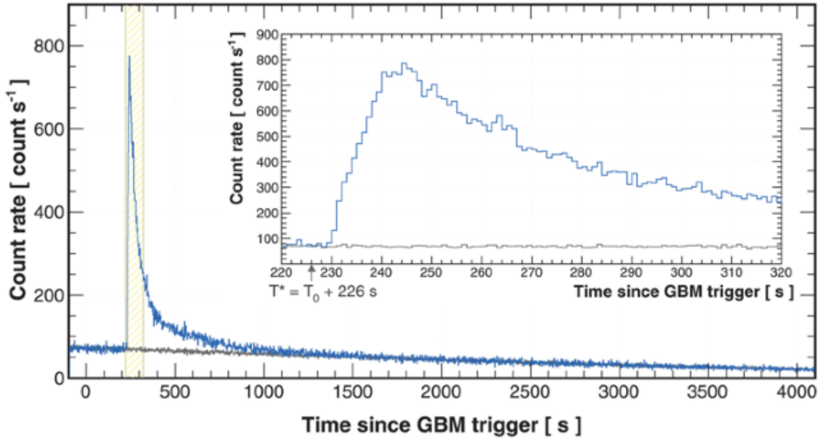
GRB 190829A

[H.E.S.S. et al., Science 372 (2021)]



GRB 221009A

[LHAASO, Science 380 (2023)]



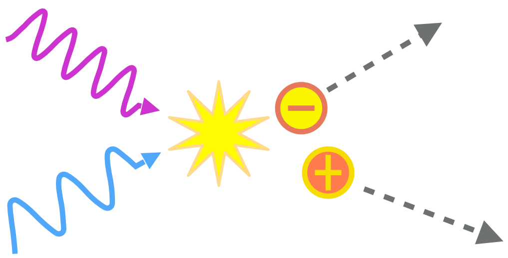
(We'll discuss these briefly later)

(plus a few more)

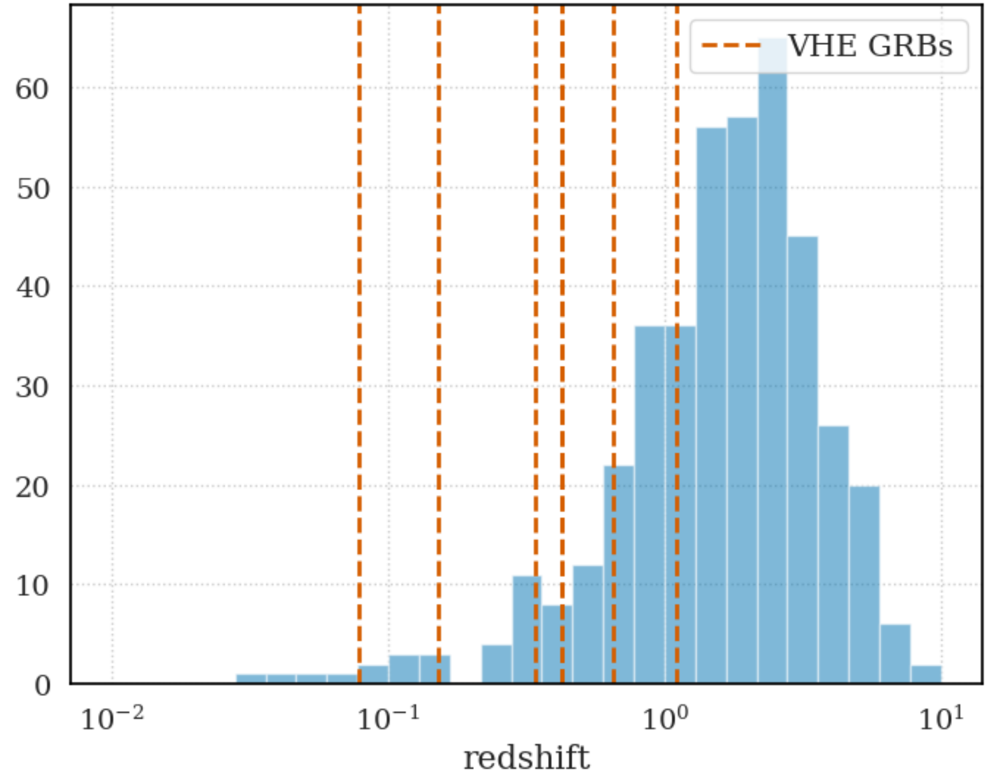
Why haven't we detected more VHE GRBs?

EBL absorption

The GRBs detected at VHE energies have all been very close (all redshifts $z \lesssim 1$)



$$\gamma + \gamma \longrightarrow e^+ + e^-$$



Gamma rays ≳100 GeV pair produce with the optical/infrared background (from star formation, active galaxies)

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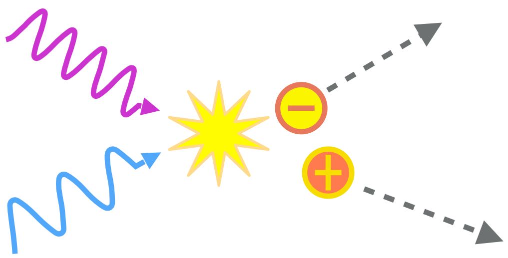

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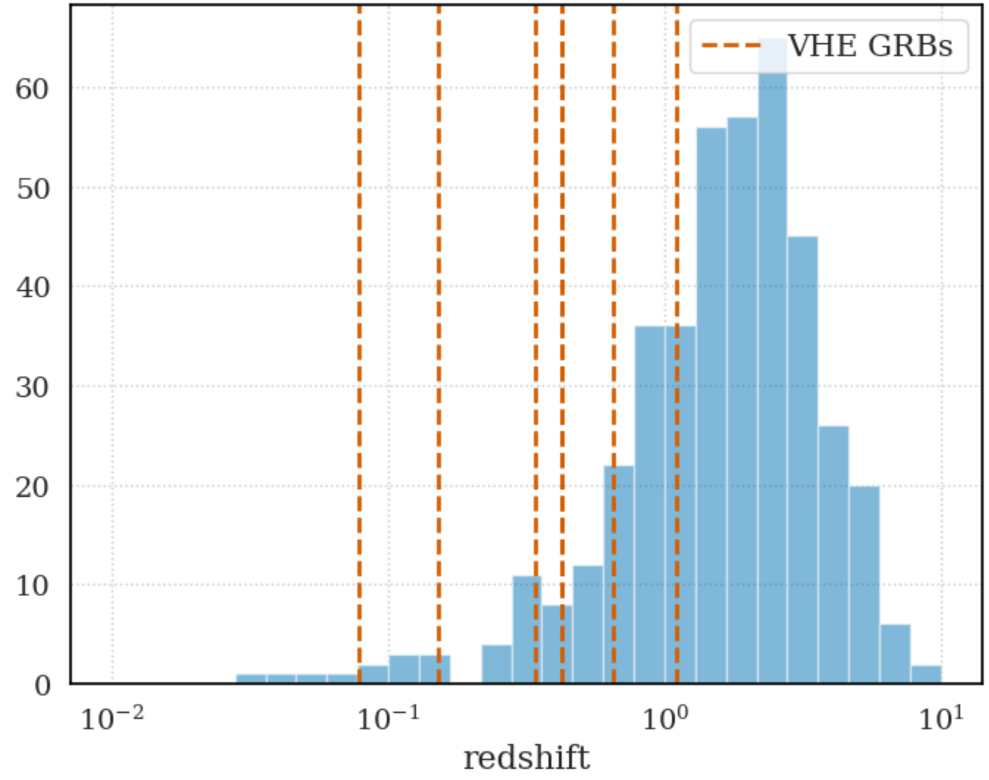


Gamma rays $\gtrsim$100 GeV pair produce with the optical/infrared background (from star formation, active galaxies)

rule of thumb for γ-γ pair production:

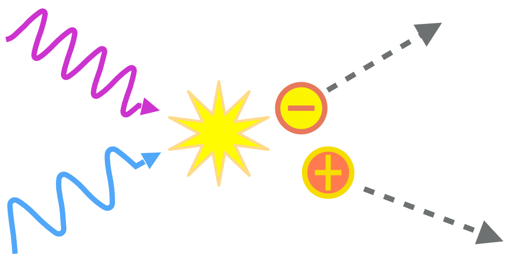
$E_1 E_2 \gtrsim (0.5\ \mathrm{MeV})^2$

for a derivation, see e.g. Frank Rieger's lectures

Why haven't we detected more VHE GRBs?

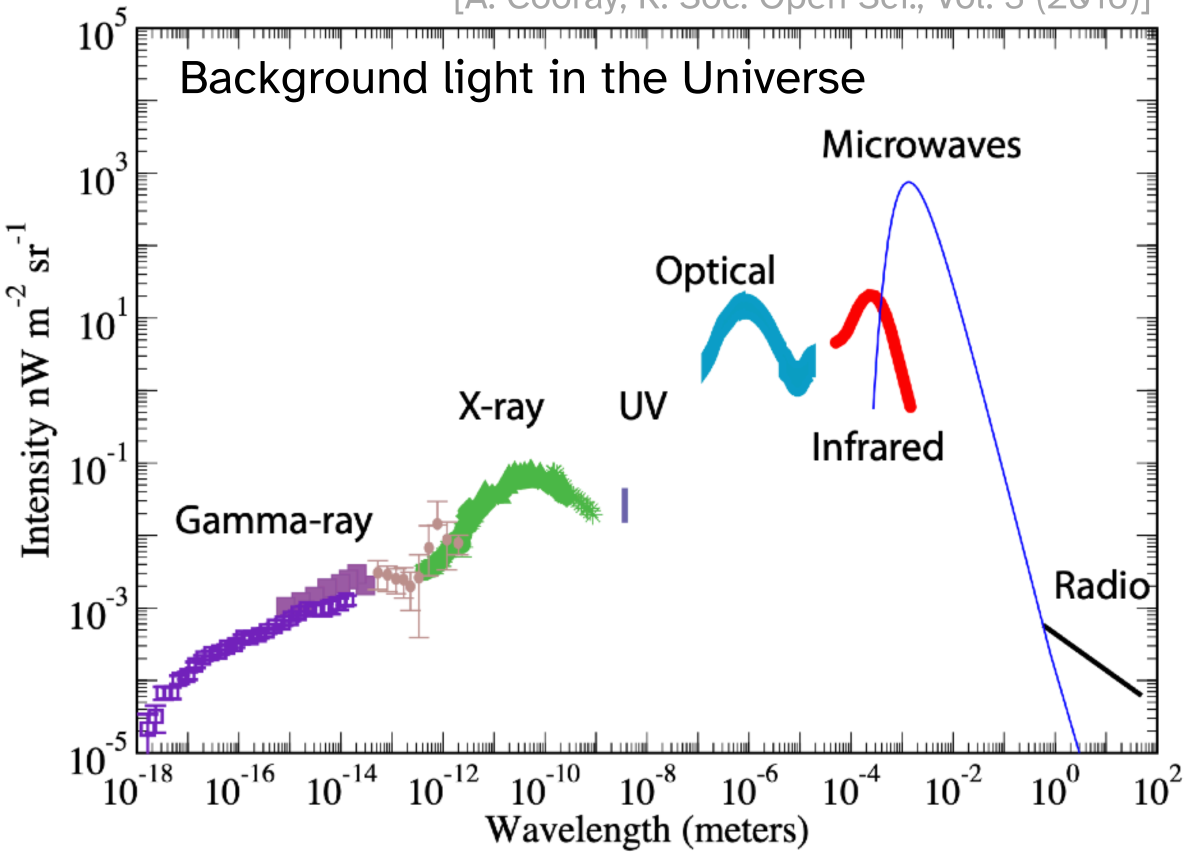
EBL absorption

The GRBs detected at VHE energies have all been very close (all redshifts $z \lesssim 1$)



$\gamma + \gamma \longrightarrow e^+ + e^-$

[A. Cooray, R. Soc. Open Sci., Vol. 3 (2016)]



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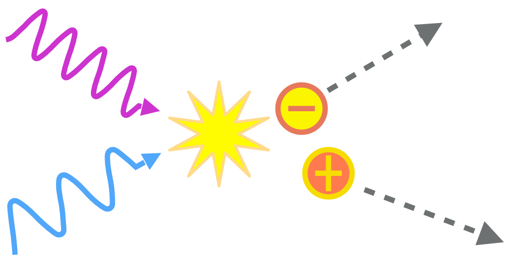

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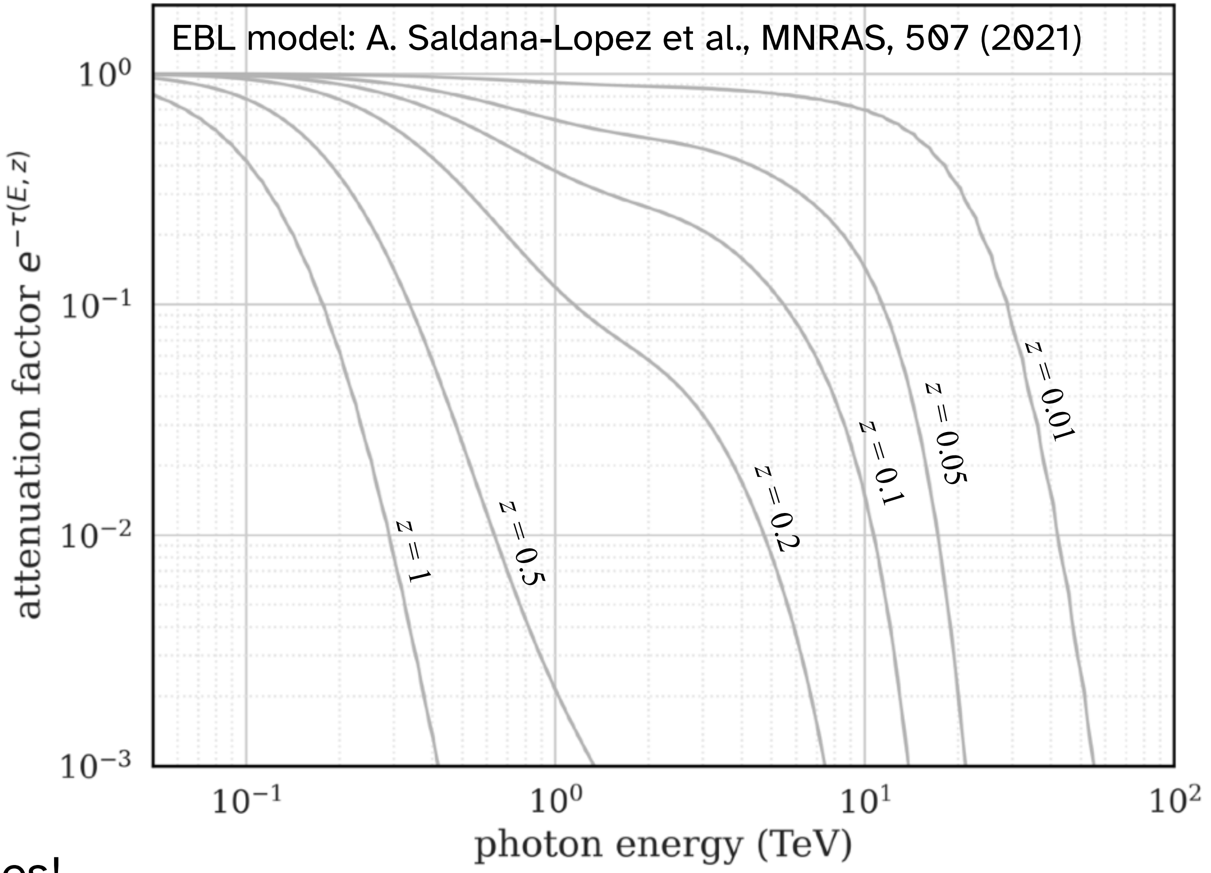


Gamma rays ≳100 GeV pair produce with the optical/infrared background (from star formation, active galaxies)

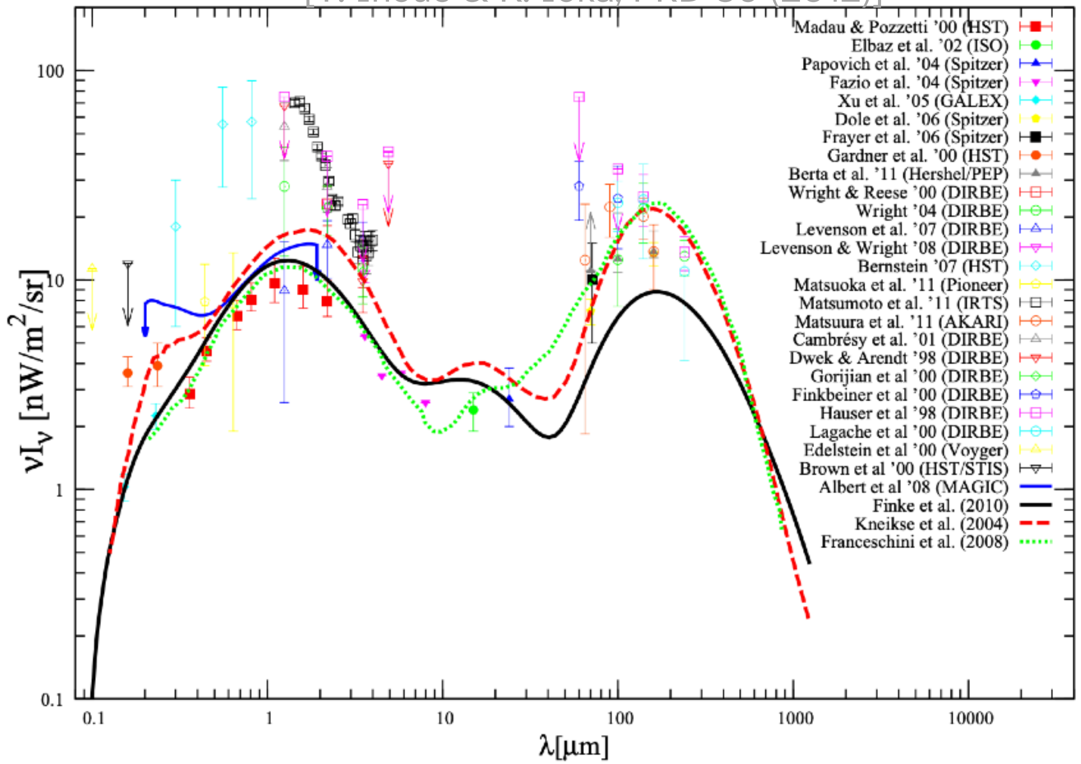
=> EBL is a major limiting factor in extragalactic sources!

Why haven't we detected more VHE GRBs?

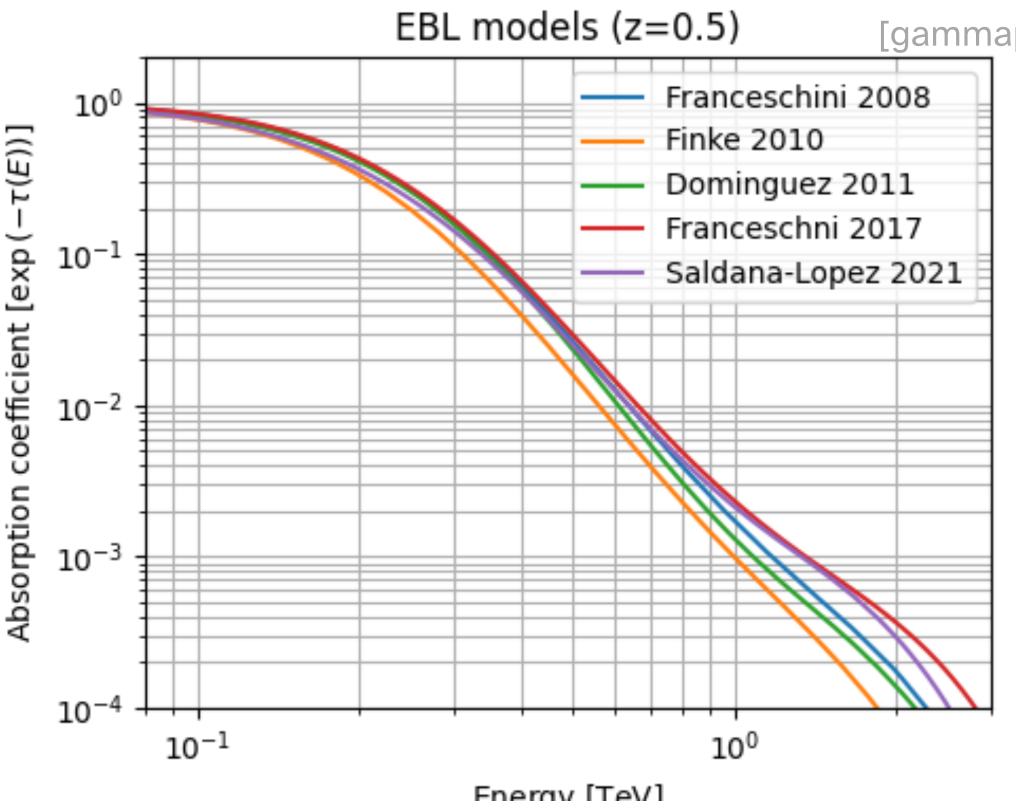
EBL absorption

There is a lot of uncertainty still in the EBL spectrum itself

[Y. Inoue & K. Ioka, PRD 86 (2012)]



[gammapy]

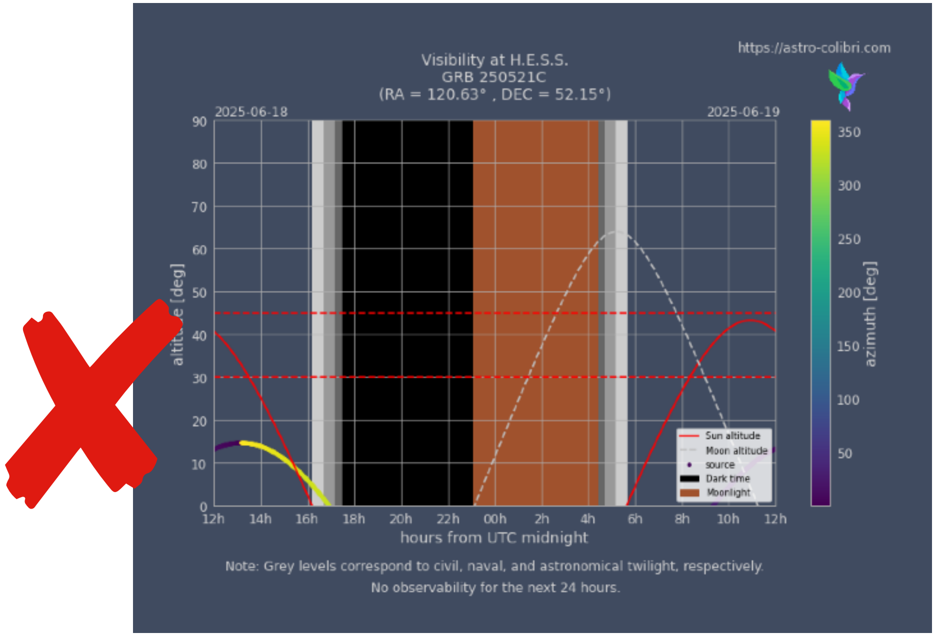


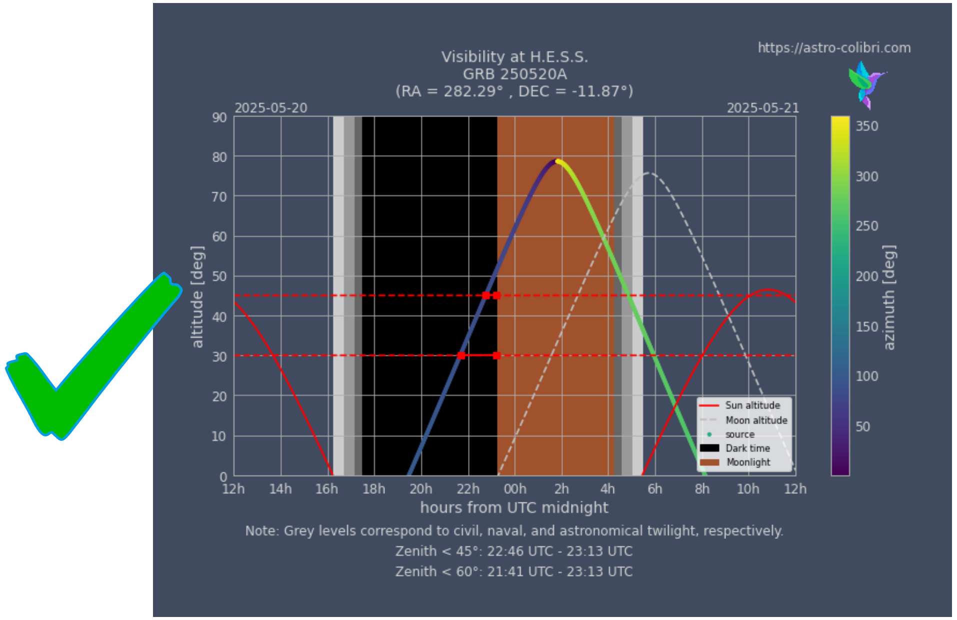
=> EBL is a major limiting factor in extragalactic sources, for both the **detection** and the **analysis**

Summarizing observation criteria

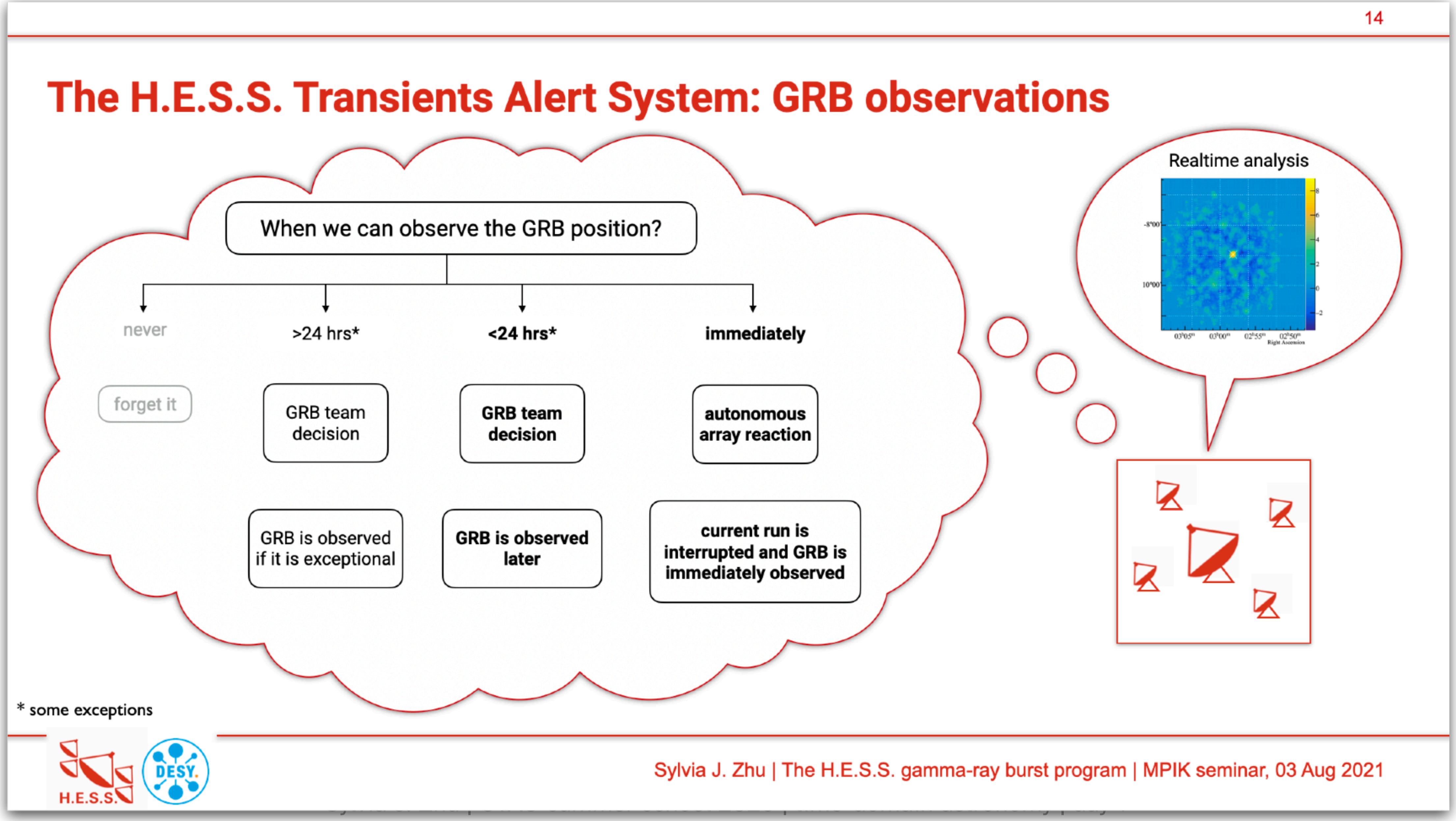
1. When is it dark enough to observe?
2. When is the source high enough in the sky?
   (i.e., with sufficiently small zenith angle)
3. If the redshift is known: Is it close enough?

plus:
4. Do we have any MWL information that might indicate it's particularly (un)interesting (e.g., z)?
5. When can we start observing it, and for how long?



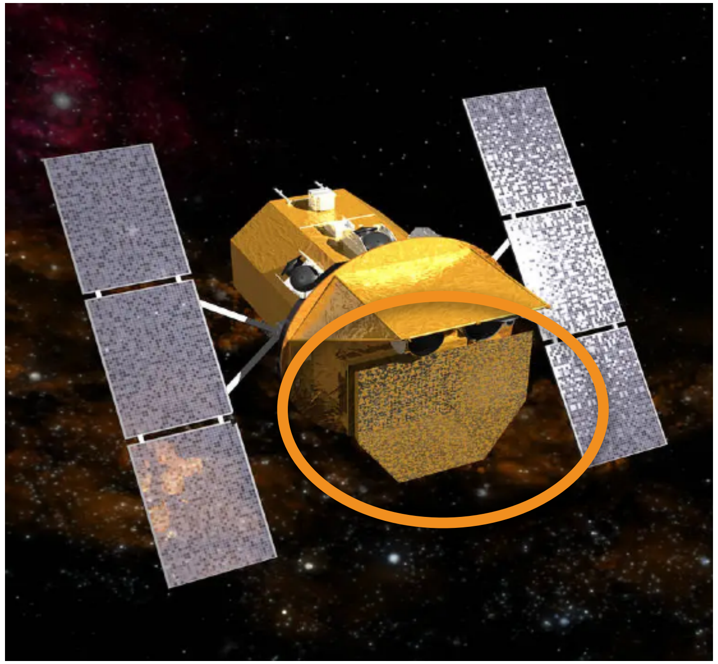


e.g., the H.E.S.S. GRB program



IACTs also observe poorly localized events

[NASA]



Swift Burst Alert Telescope

keV

Smaller field of view and narrower energy range

but

precise localizations

[NASA/DOE/Fermi-LAT]

Fermi Gamma-ray Burst Monitor

keV - MeV

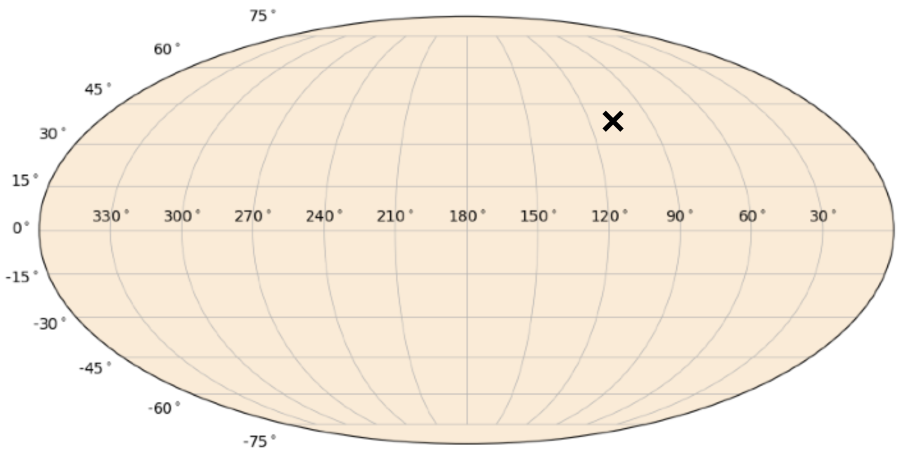
All-sky field of view and wider energy range

but

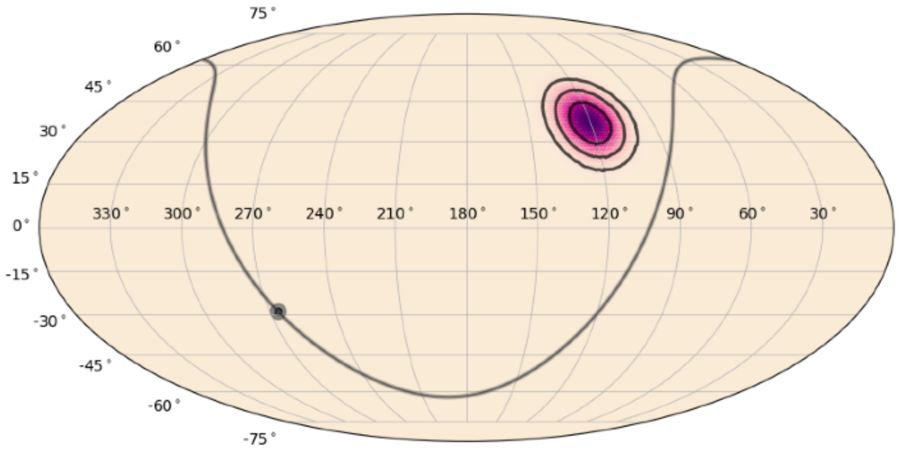
very uncertain localizations

IACT observations of large localization regions

(not just GRBs)



If the localization is smaller than the FoV of our telescope, we can just observe that sky position.

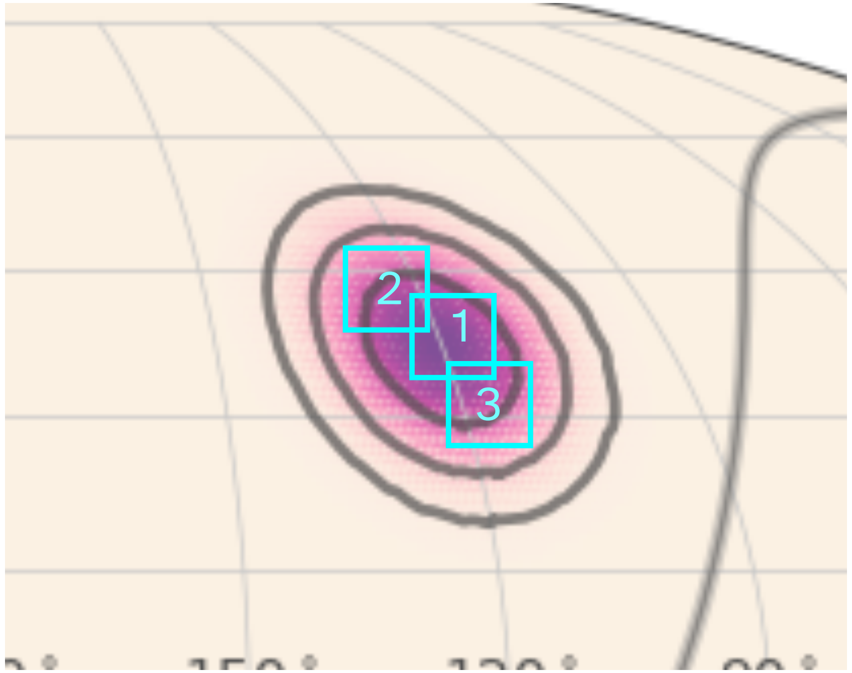


If the localization is *larger* than the FoV of our telescope, we can still **tile** the localization region.

IACT observations of large localization regions

Tiled observations

An example of what the tiling strategy might be for this particular localization region



Simplest: Cover the most probability within the time available

Additional things to potentially consider:

- Zenith angles (source is moving)
- Darkness conditions (moderate moonlight vs complete darktime)
- Prioritize regions where other observatories have found potential counterparts?
- Split up the region between multiple telescopes?
- (For gravitational-wave alerts) Prioritize maximizing the number of known galaxies covered? The most nearby galaxies? The most massive galaxies? see: [H. Ashkar et al., JCAP 2021 (2021)]

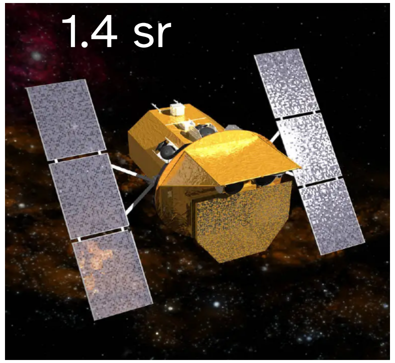
(more about gravitational-wave signals later)

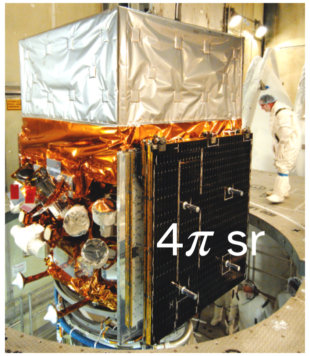
Multiwavelength and multimessenger triggers

a few deg diameter

Ultimately, IACT fields of view are small -> we rely on multiwavelength, multimessenger triggers

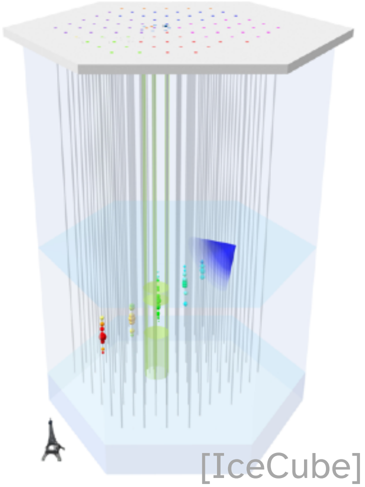
space-based gamma-ray telescopes





gravitational-wave detectors

optical surveys

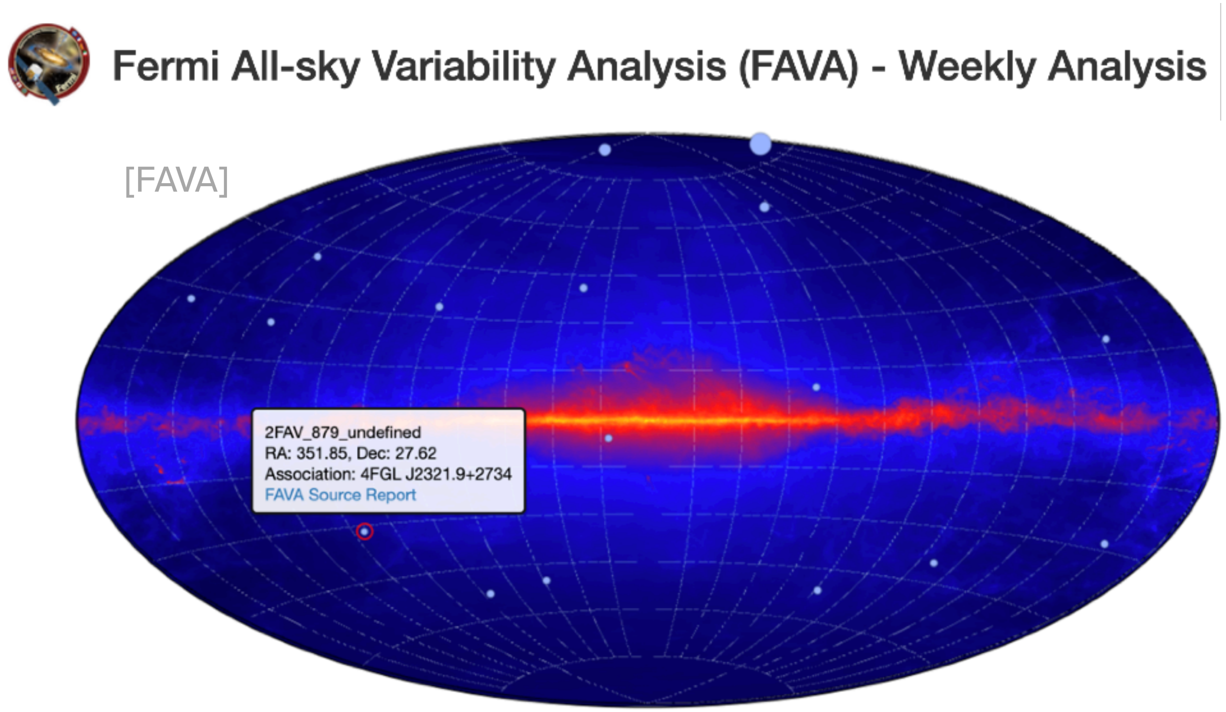


neutrino detectors

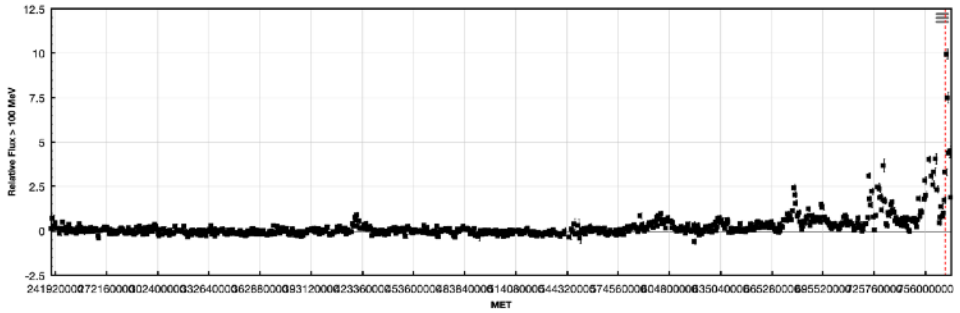
Multiwavelength and multimessenger triggers

Photometric Fermi-LAT analyses (e.g., for AGN flares)

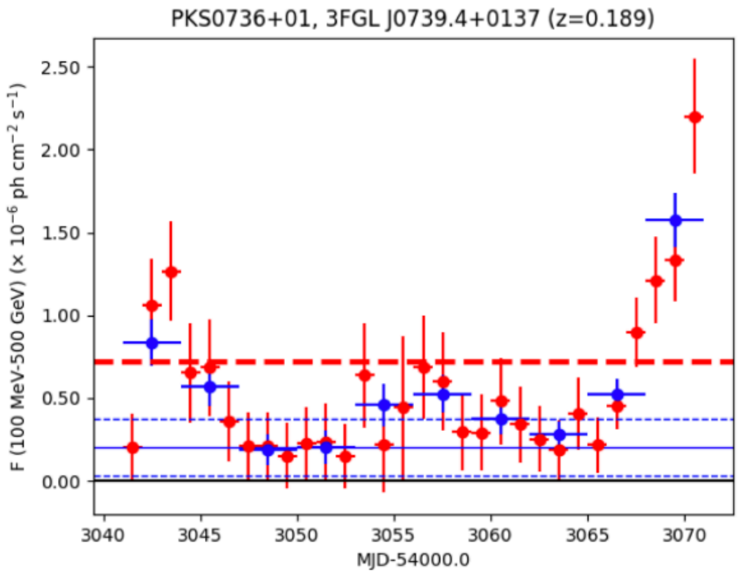
basically: counting photons



[FAVA]



FLaapLUC: finer time bins, predetermined sources



[J.-P. Lenain, Astronomy & Computing 22 (2018)]

Multiwavelength and multimessenger triggers

The Astronomer's Telegram (ATel)

[ATel]

Human-written summaries of interesting transients or flaring sources

Some examples:

Fermi-LAT detection of enhanced gamma-ray activity from the FSRQ PKS 0907-023

ATel #17133; *Adithiya Dinesh (Universidad Complutense de Madrid), Janeth Valverde (Marquette University) , on behalf of the Fermi Large Area Telescope Collaboration*

Enhanced HE and VHE gamma-ray activity from the FSRQ PKS 0346-27

ATel #15020; *S. Wagner (U. Heidelberg, Germany), for the H. E. S. S. collaboration and B. Rani (KASI, S. Korea), on behalf of the Fermi Large Area Telescope Collaboration*

The MAGIC telescopes detect a very-high-energy gamma-ray flare from OP313

ATel #16977; *David Paneque (Max Planck Institute for Physics), Axel Arbet-Engels (Max Planck Institute for Physics), Mireia Nievas Rosillo (IAC), Giacomo Bonnoli (INAF, Brera Astronomical Observatory), Jorge Otero Santos (INFN Padova) on behalf of the MAGIC collaboration*

VERITAS Follow-up of a Report of Enhanced Emission from 1ES 1727+502

ATel #17099; *Amy Furniss (UC Santa Cruz) for the VERITAS Collaboration*

ATELstream

Recently

17215 NICER sees declined X-ray activity of XB 1732-304 in Terzan 1
G. K. Jaisawal...

17201 SVOM/ECLAIRs detection of a thermonuclear burst in Terzan 1
S. Le Stum ...

Most Viewed

17227 6.7 GHz methanol maser flare in high-mass protostar G85.410+0.003
Ross A. Burns ...

17224 Spectroscopic Classification of PNV J06302516-6955014 as a Classical Nova
Yusuke Tampo ...

17226 Fermi-LAT detection of renewed gamma-ray activity from the FSRQ Ton 599 (4C +29.45)
S. Wagner ...

Fast Radio Burst

17195 Deep JWST/NIRCam Imaging of FRB 20250316A: Detection of Potential IR Counterparts
Peter K. Blanchard...

Supernovae

17225 Spectroscopic Classifications of Optical Transients with the Lick Shane telescope
Kishore C. Patra...

17223 Spectroscopic Classification of Astrophysical Transients with the Lick Shane Telescope
R. Kaur...

17210 Spectroscopic Classifications of Optical Transients with the Lick Shane telescope
Kishore C. Patra ...

17208 Spectroscopic classification of transients with the Lick Shane telescope
P. Arunachalam...

and tons of other source types

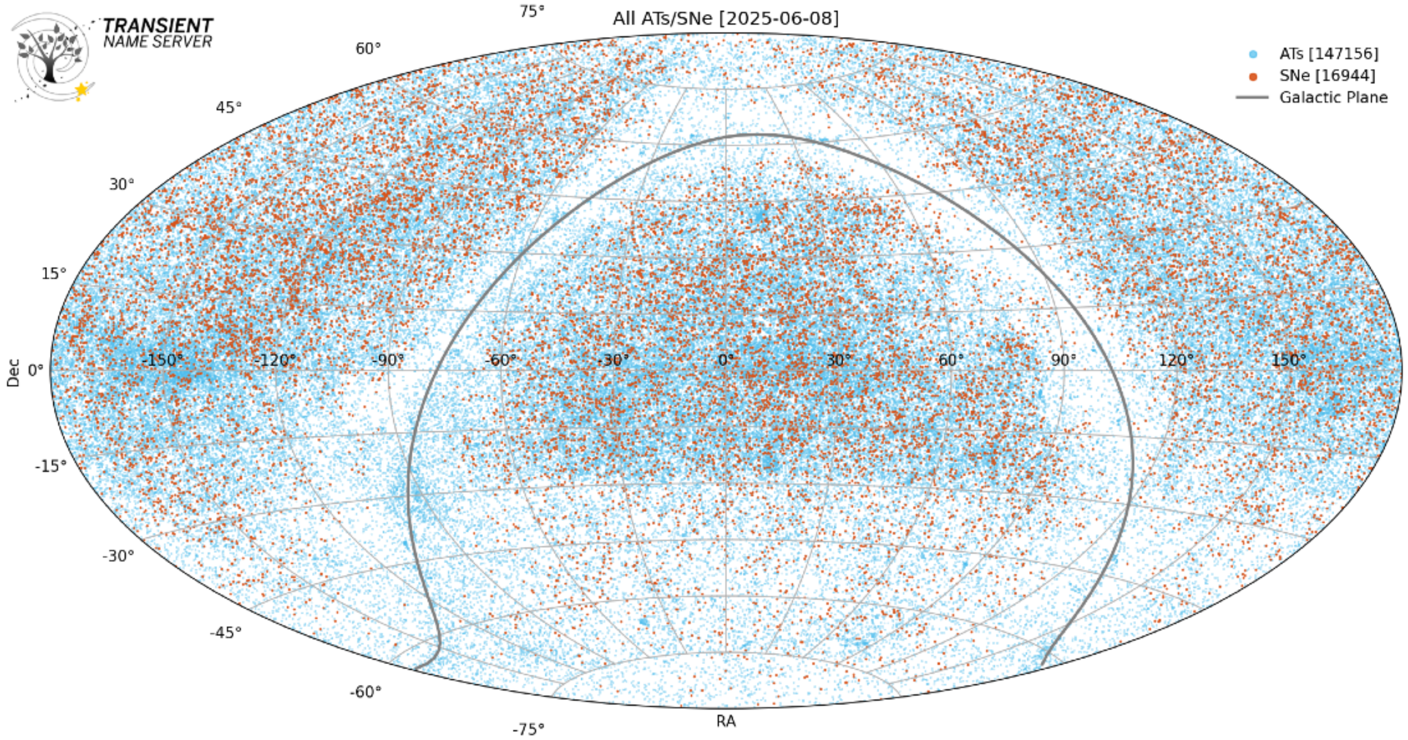
Multiwavelength and multimessenger triggers

Transient Name Server (TNS)

[TNS]

Human-submitted information on new transients

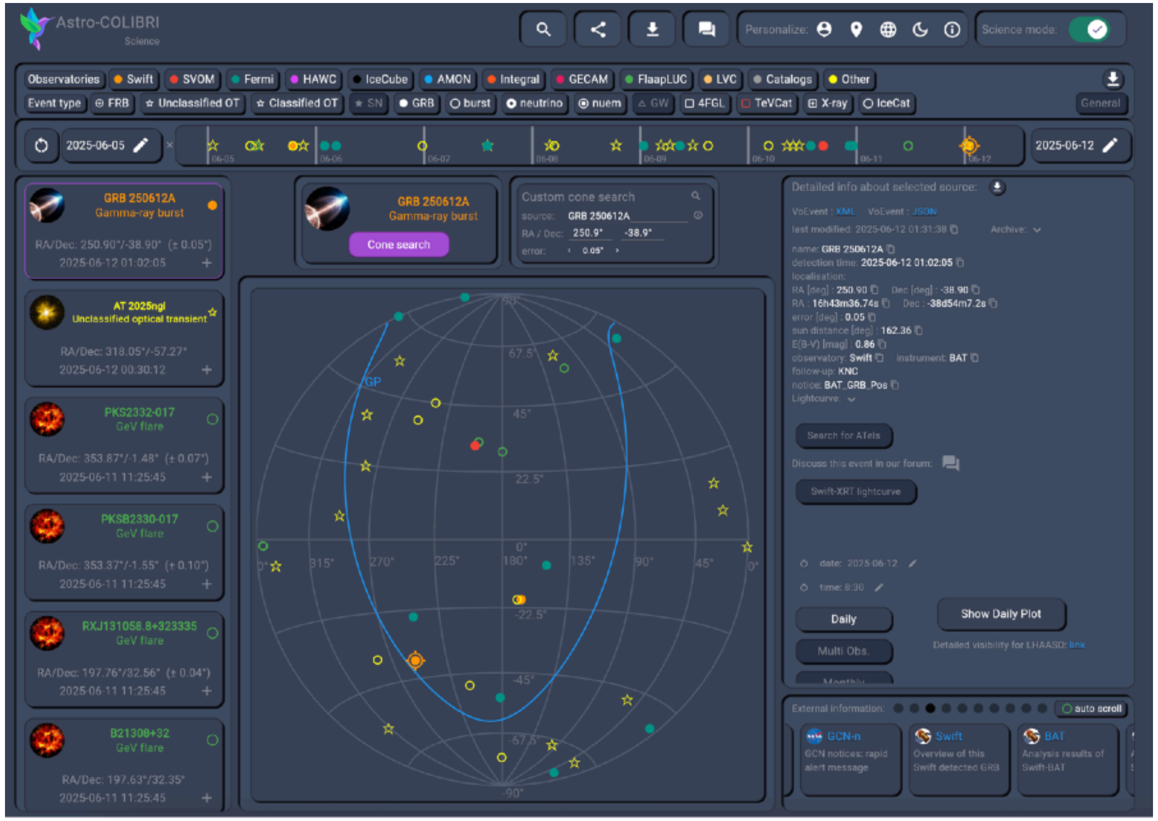
Also: The official way to get a supernova name

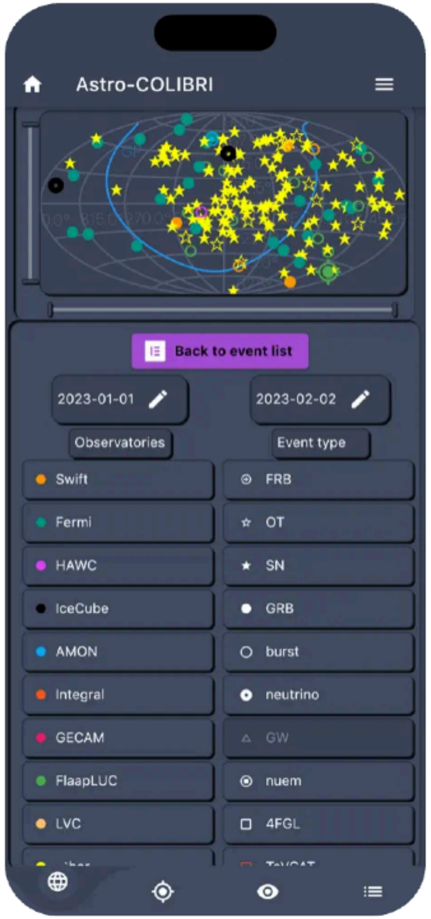


Multiwavelength and multimessenger triggers

Astro-COLIBRI [astro-colibri]

Platform for monitoring and communicating about transients;
also pulls information from other databases like TNS





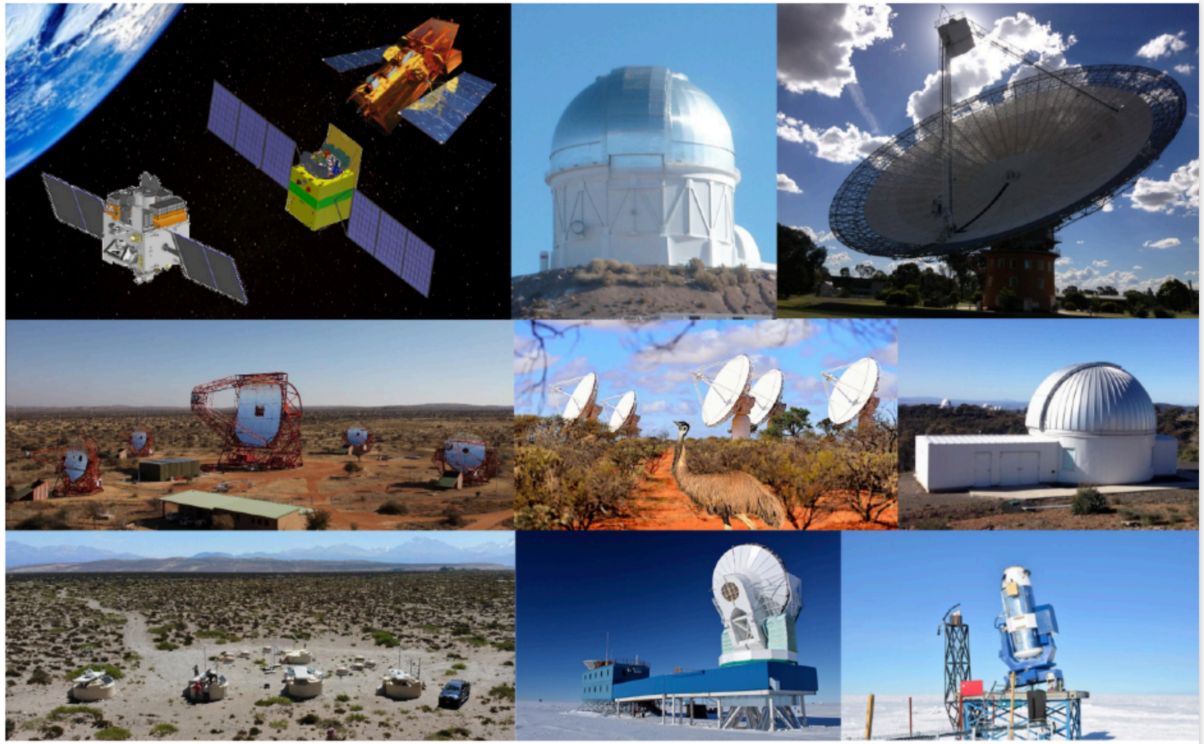
Coordinated observation campaigns

The Deeper, Wider, Faster program

Coordinated observations by ~70 telescopes of the same target fields

Searching for fast transients (ms to hours)

[J. Cooke]



Telescopes wide-field coordinated simultaneously include – *high-energy particles*: Pierre Auger Observatory, HAWC; *gamma-ray*: H.E.S.S., Swift; *X-ray*:, HXMT, Astrosat; *UV*: Astrosat; *optical*: CTIO DECam, Subaru HSC, KMTNet, AST3-2; *mm/sub-mm*: *South Pole Telescope*; *radio*: Parkes, ASKAP, MeerKAT, MWA; (also *GW*: LIGO/Virgo/KAGRA when online).

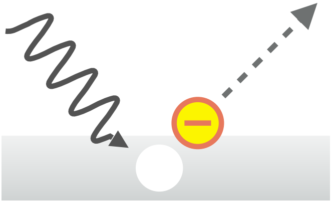
bonus stuff if you want to hear more about detectors

keV and MeV gamma rays???

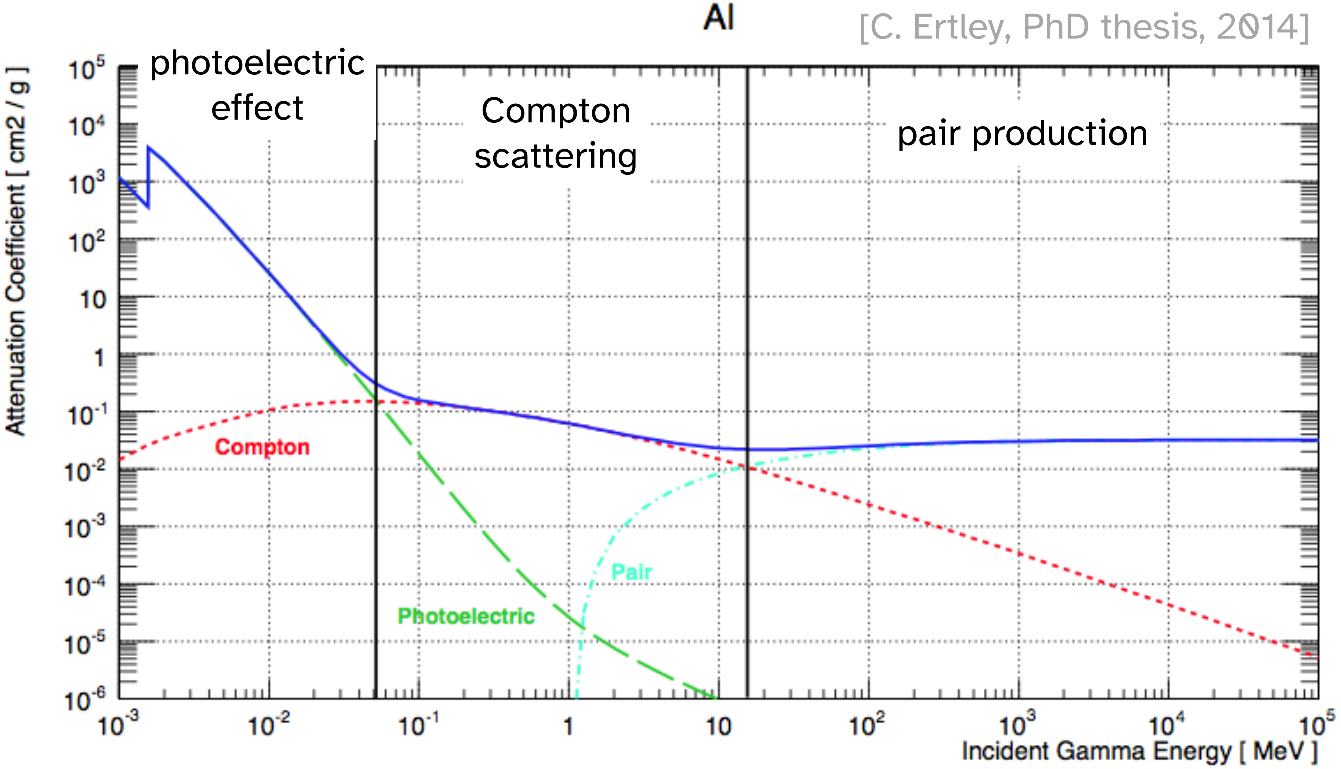
How gamma rays interact with matter

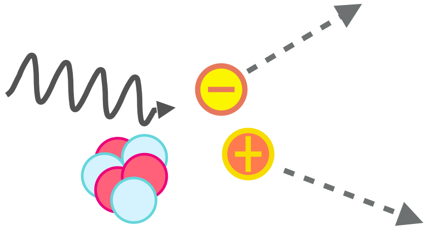
photons -> electric signals

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

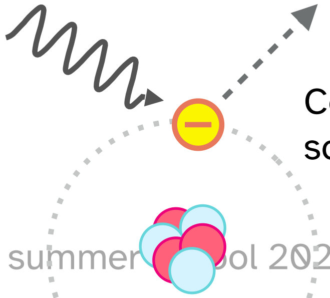


photoelectric effect





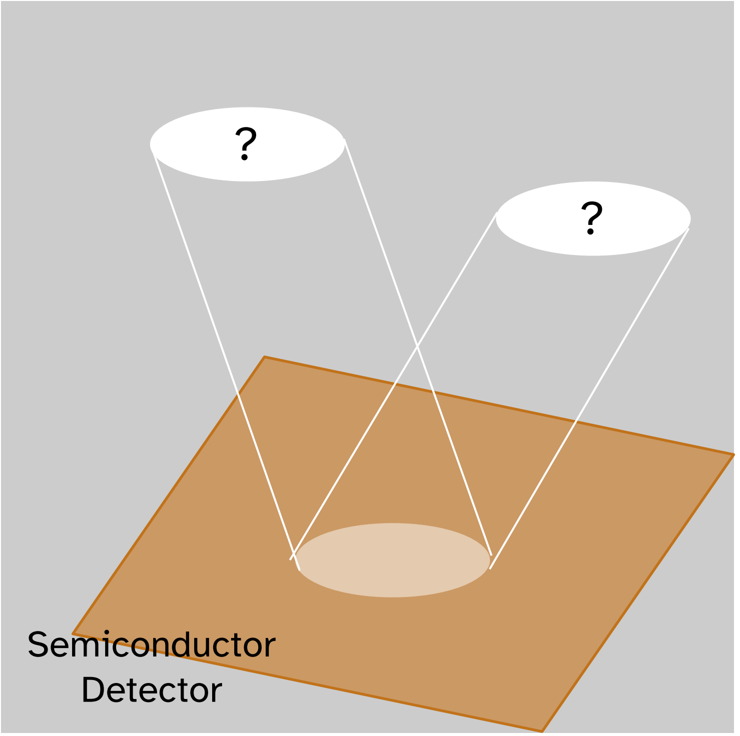
pair production



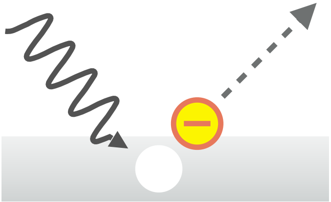
Compton scattering

How gamma rays interact with matter: photoelectric effect

Coded-aperture mask detectors, scintillator detectors



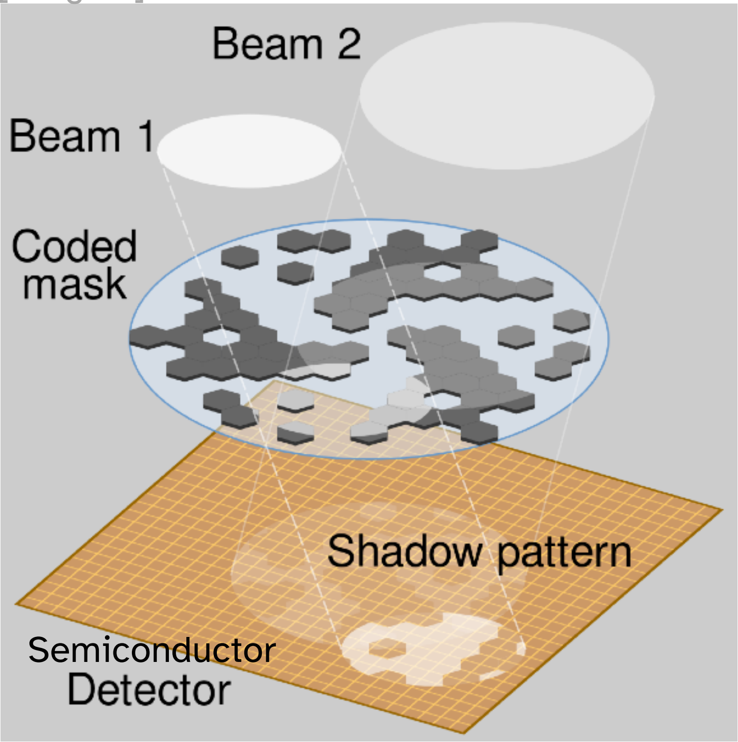
Semiconductor detectors can directly detect low energy gamma rays;



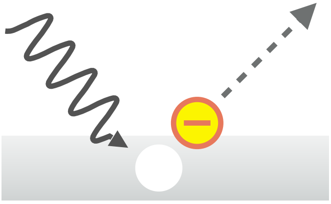
How gamma rays interact with matter: photoelectric effect

Coded-aperture mask detectors, scintillator detectors

[Cmglee]



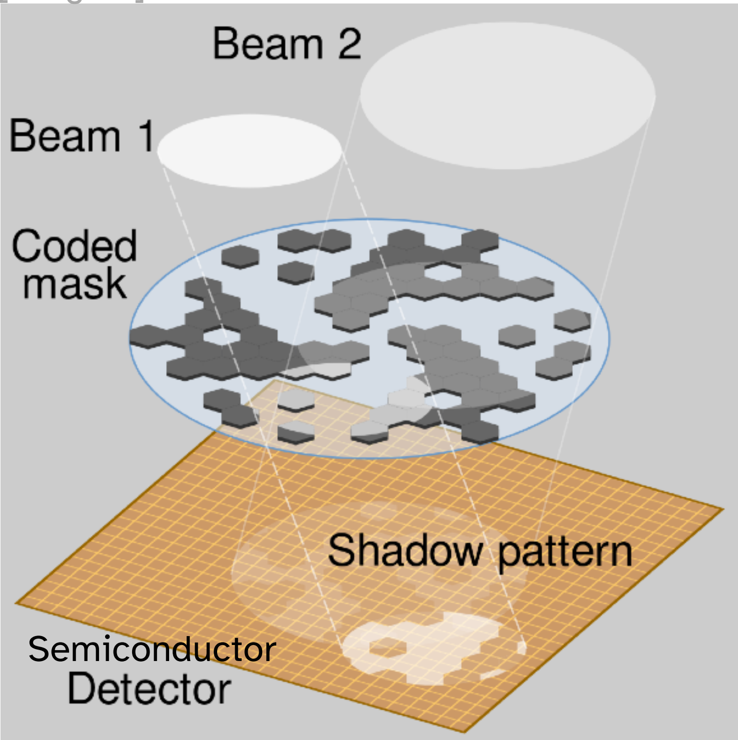
Semiconductor detectors can directly detect low energy gamma rays;
adding a coded-aperture mask allows for source localization



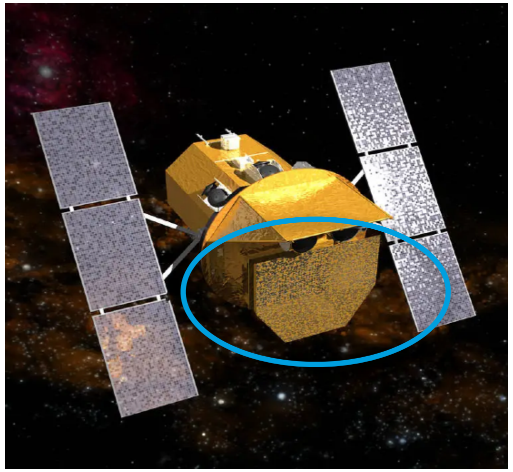
How gamma rays interact with matter: photoelectric effect

Coded-aperture mask detectors, scintillator detectors

[Cmglee]



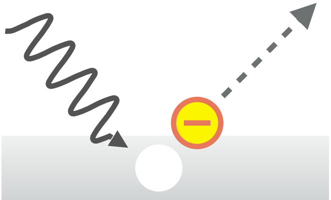
[NASA]



Swift Burst Alert Telescope

[NASA]

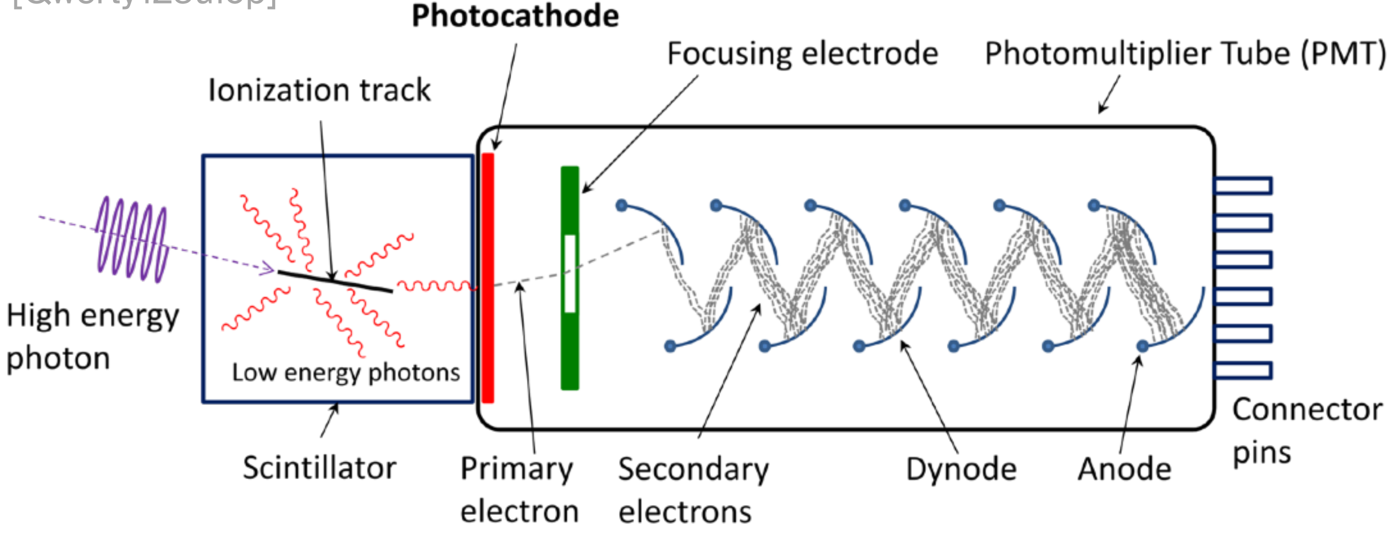
Semiconductor detectors can directly detect low energy gamma rays; adding a coded-aperture mask allows for source localization



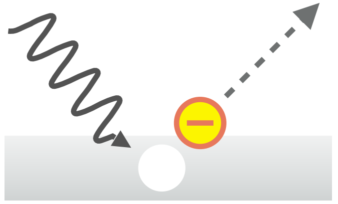
How gamma rays interact with matter: photoelectric effect

Coded-aperture mask detectors, **scintillator detectors**

[Qwerty123uiop]

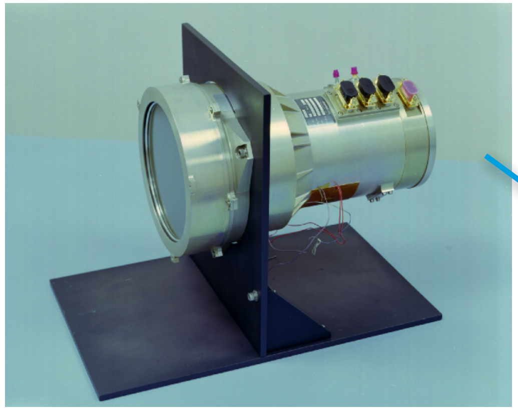


Scintillator detectors =
scintillator to convert high-energy photons into low energy photons
\+ **photomultiplier tube** to turn the photons into a measurable signal
They can't really determine directionality

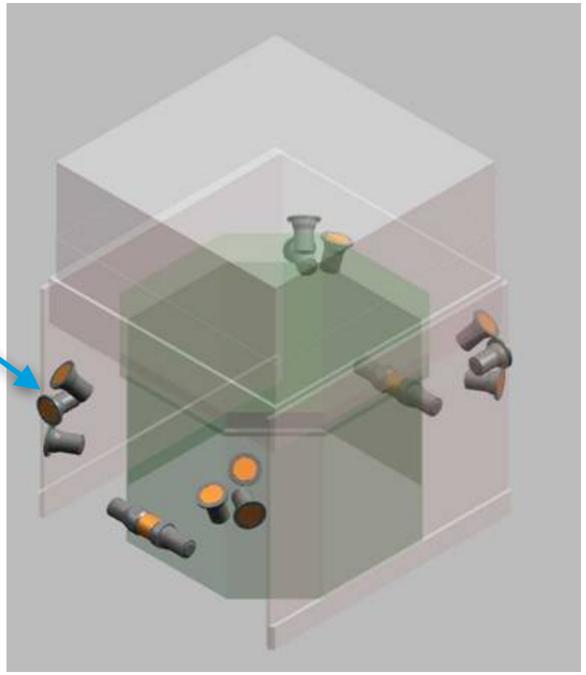


How gamma rays interact with matter: photoelectric effect

Coded-aperture mask detectors, **scintillator detectors**



[MPE]

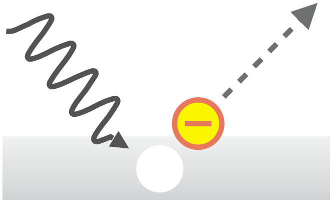


[NASA]

[NASA/DOE/Fermi-LAT]

Fermi Gamma-ray Burst Monitor

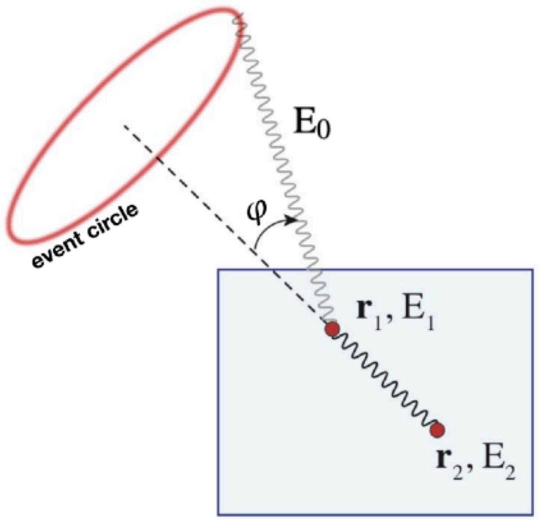
Scintillator detectors =
scintillator to convert high-energy photons into low energy photons
+ **photomultiplier tube** to turn the photons into a measurable signal
They can't really determine directionality,
so you need multiple ones to do some rough localization



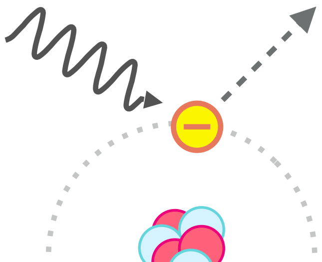
How gamma rays interact with matter: Compton scattering

Compton telescopes

[Kierans et al. (2022)]



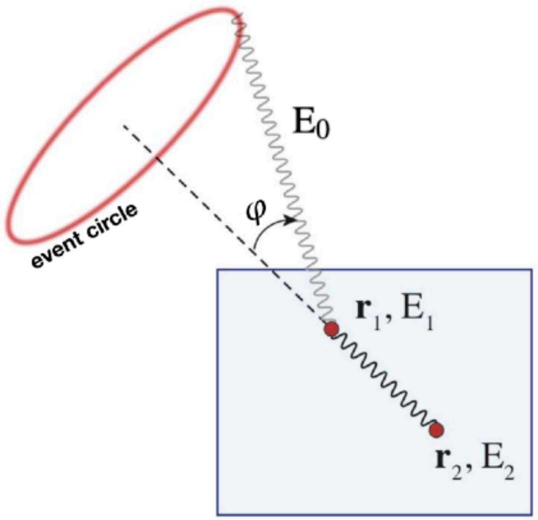
A photon undergoes multiple Compton scattering events in the detector,
and the initial scattering angle can be calculated from the energies before/after scattering

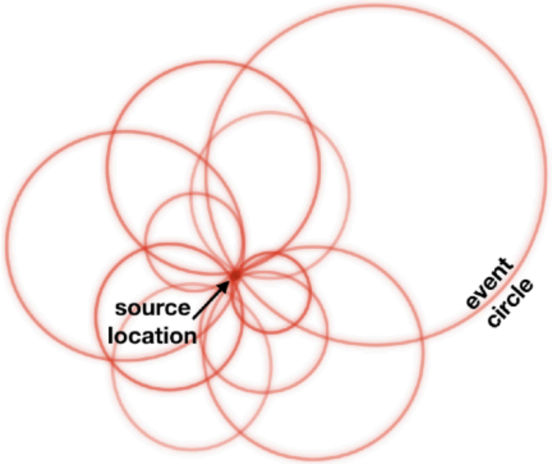


How gamma rays interact with matter: Compton scattering

Compton telescopes

[Kierans et al. (2022)]





A photon undergoes multiple Compton scattering events in the detector,
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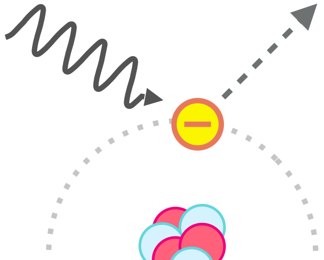
Multiple Compton events from the same source in the sky allow for source localization



How gamma rays interact with matter: Compton scattering

Compton telescopes

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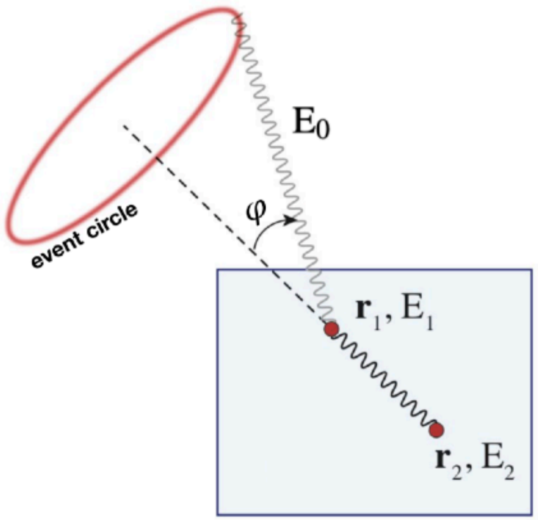
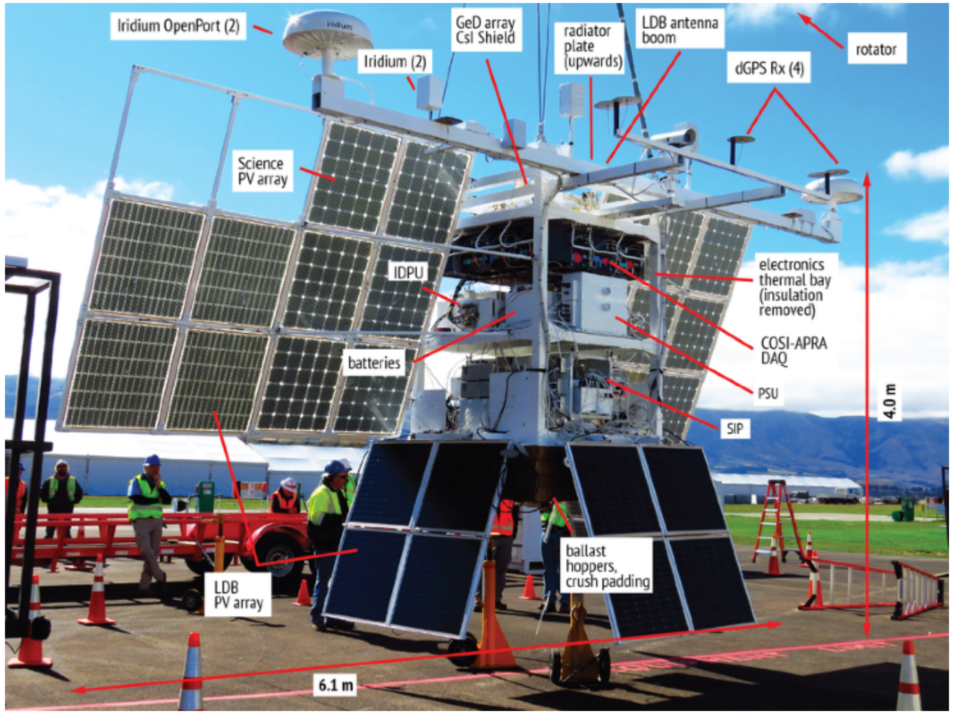


[Kierans et al., INTEGRAL2016]



Compton Spectrometer and Imager (balloon version)

A photon undergoes multiple Compton scattering events in the detector,
and the initial scattering angle can be calculated from the energies before/after scattering
Multiple Compton events from the same source in the sky allow for source localization