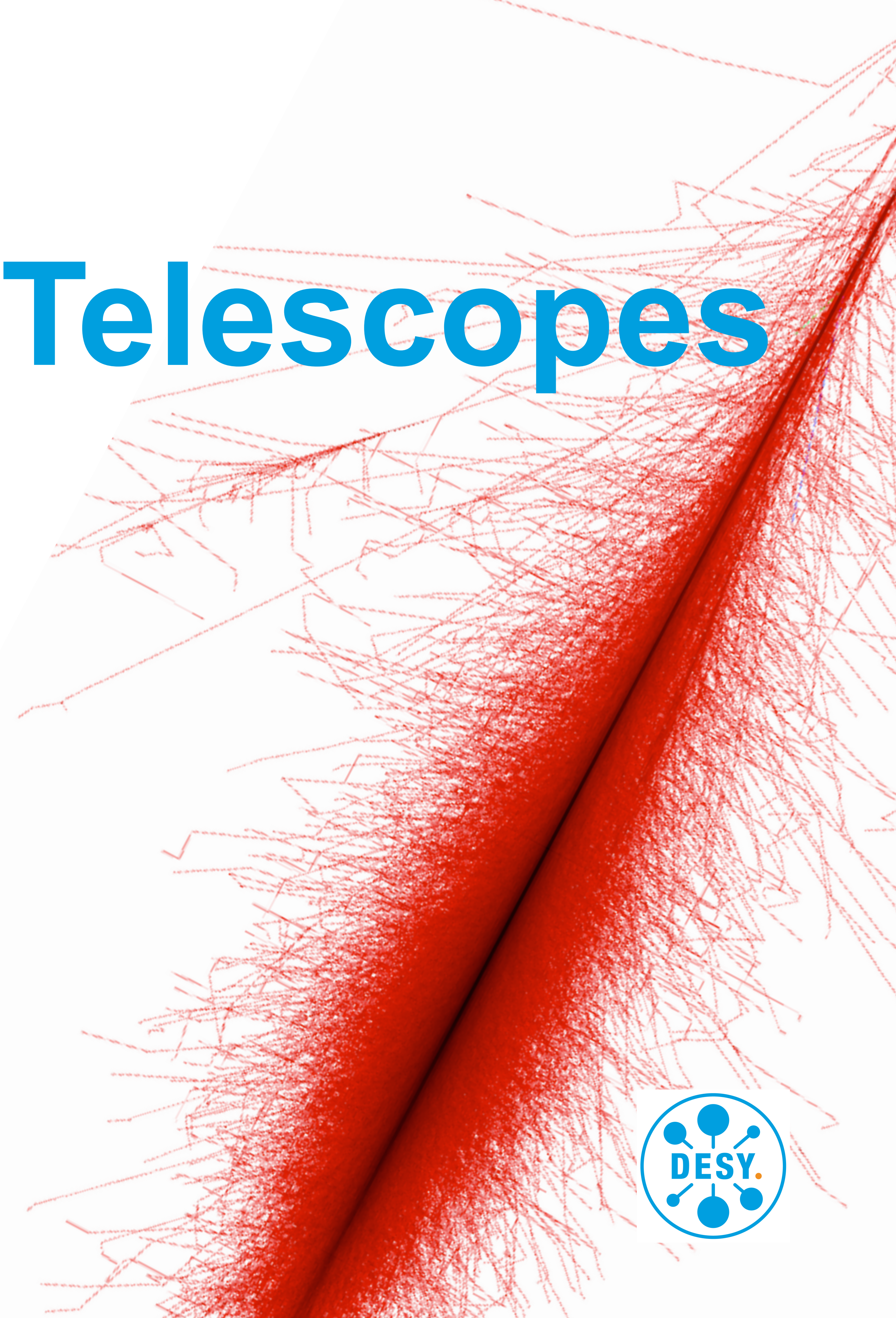
Optimising Cherenkov Telescopes

First MODE Workshop

6-8 September 2021

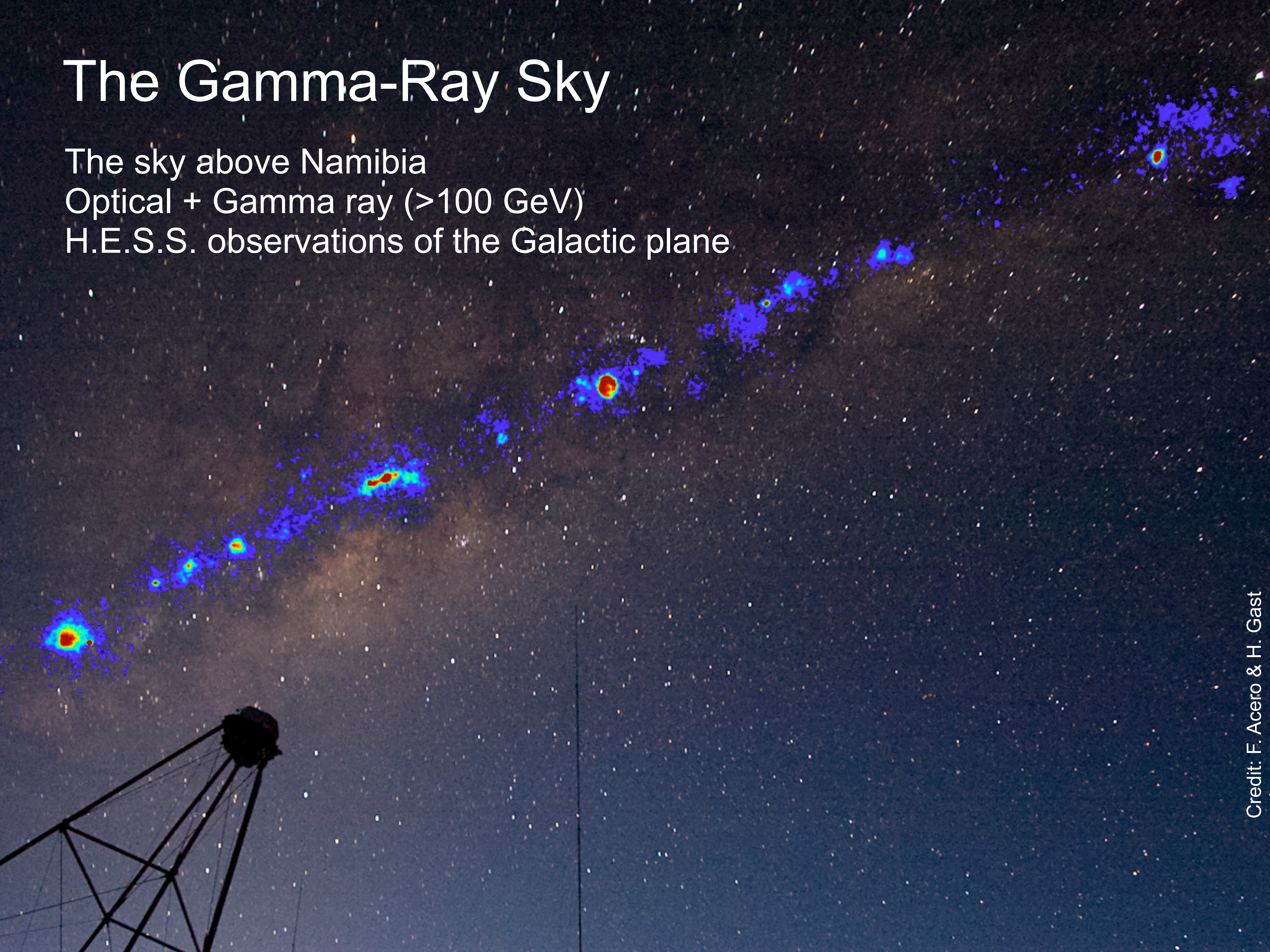
Gernot Maier



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

The Gamma-Ray Sky

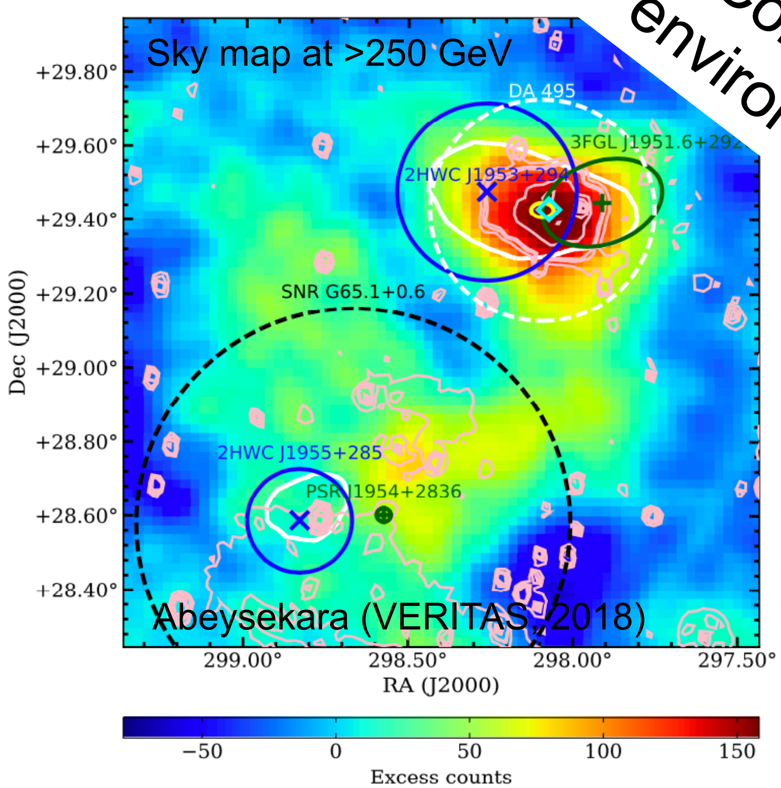
The sky above Namibia
Optical + Gamma ray (>100 GeV)
H.E.S.S. observations of the Galactic plane



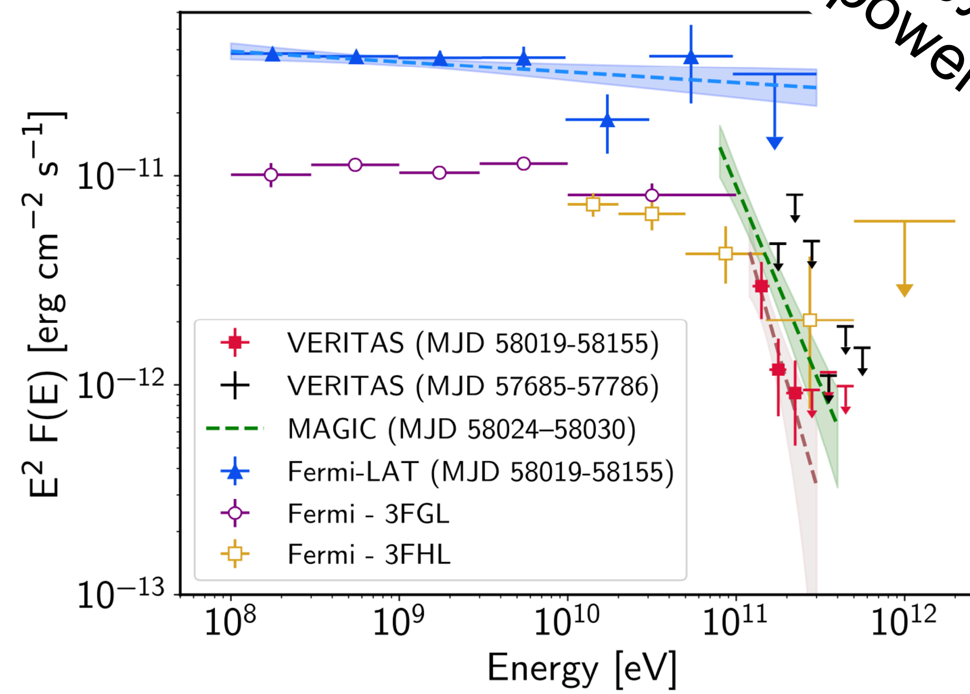
Gamma-ray Astronomy - Observations

Observables: Direction, Energy, Arrival Time

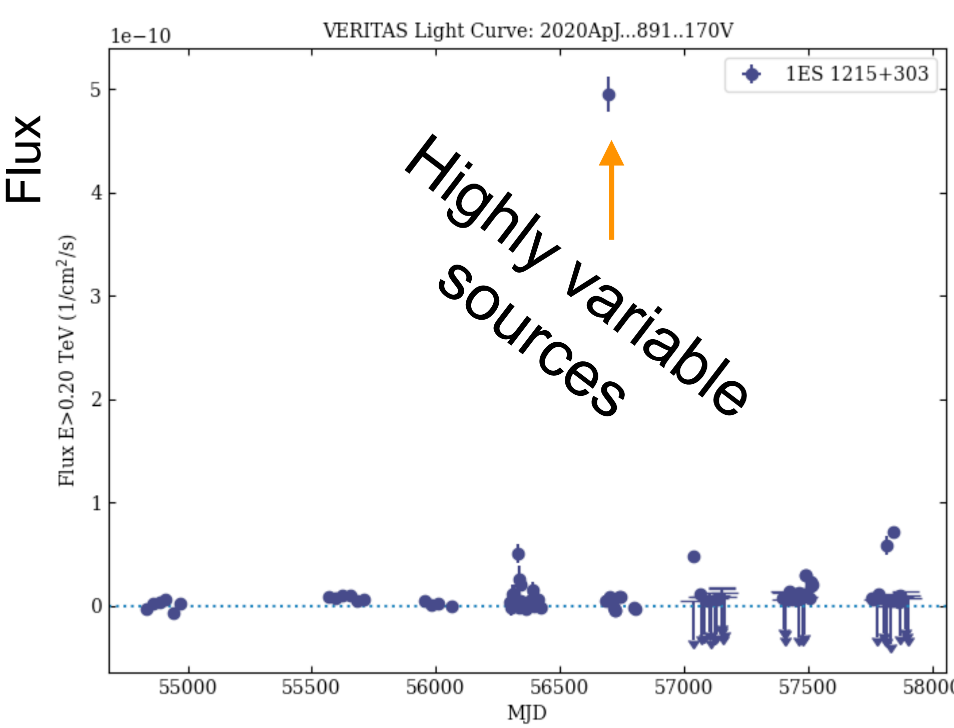
Complex environment



Energy spectra: power laws

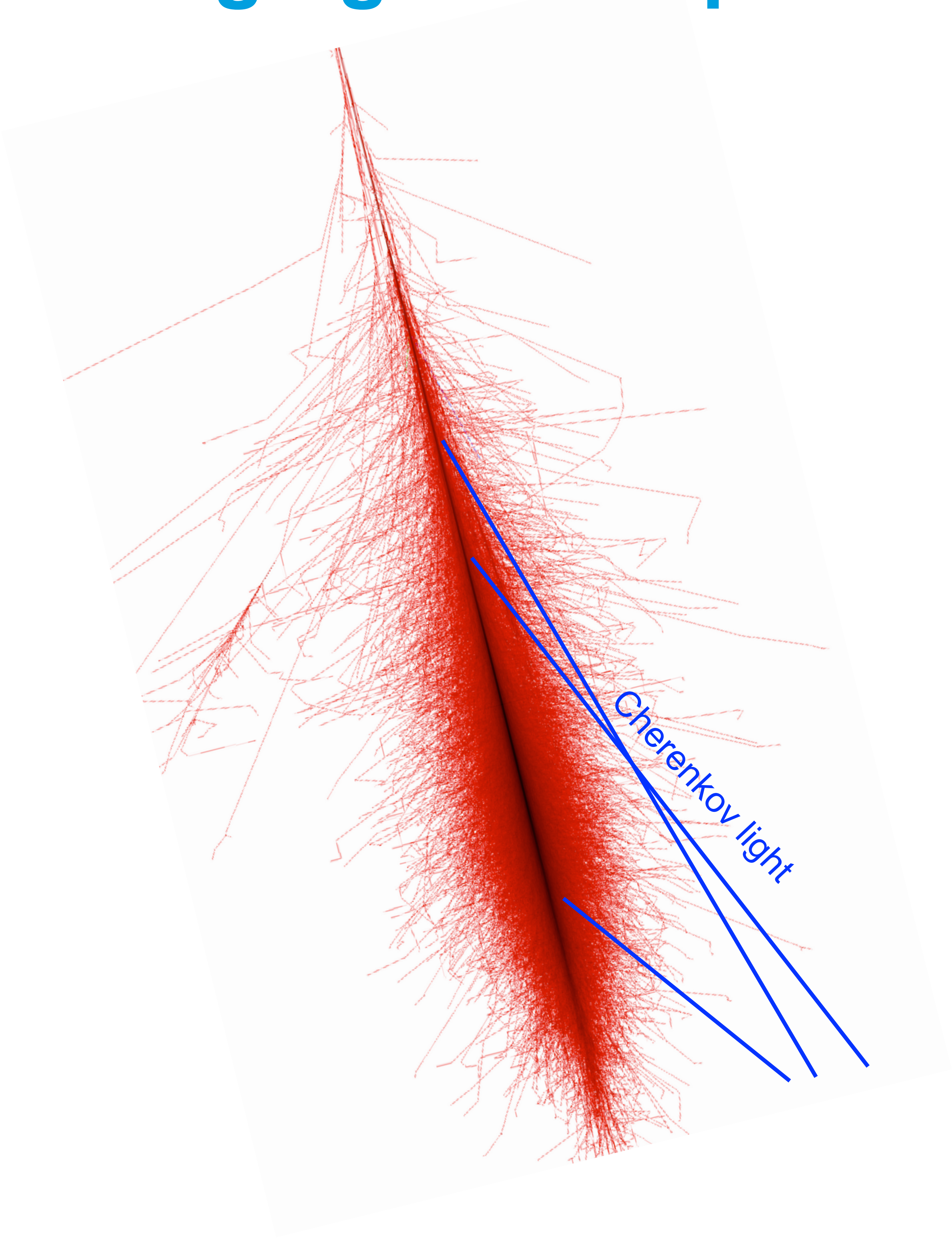


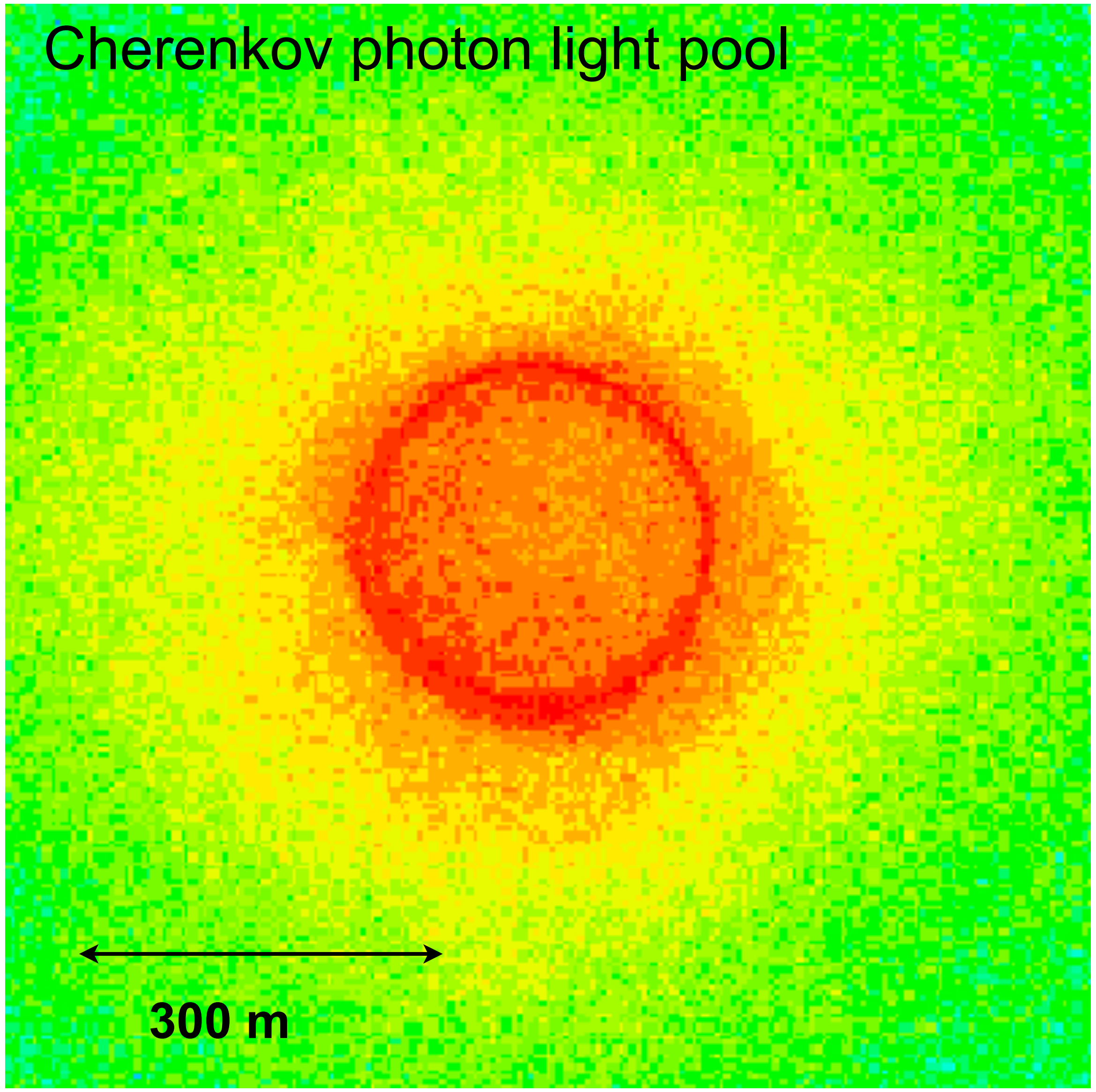
Highly variable sources



Low fluxes, high energies, variable sources, …

Imaging Technique - Air Showers





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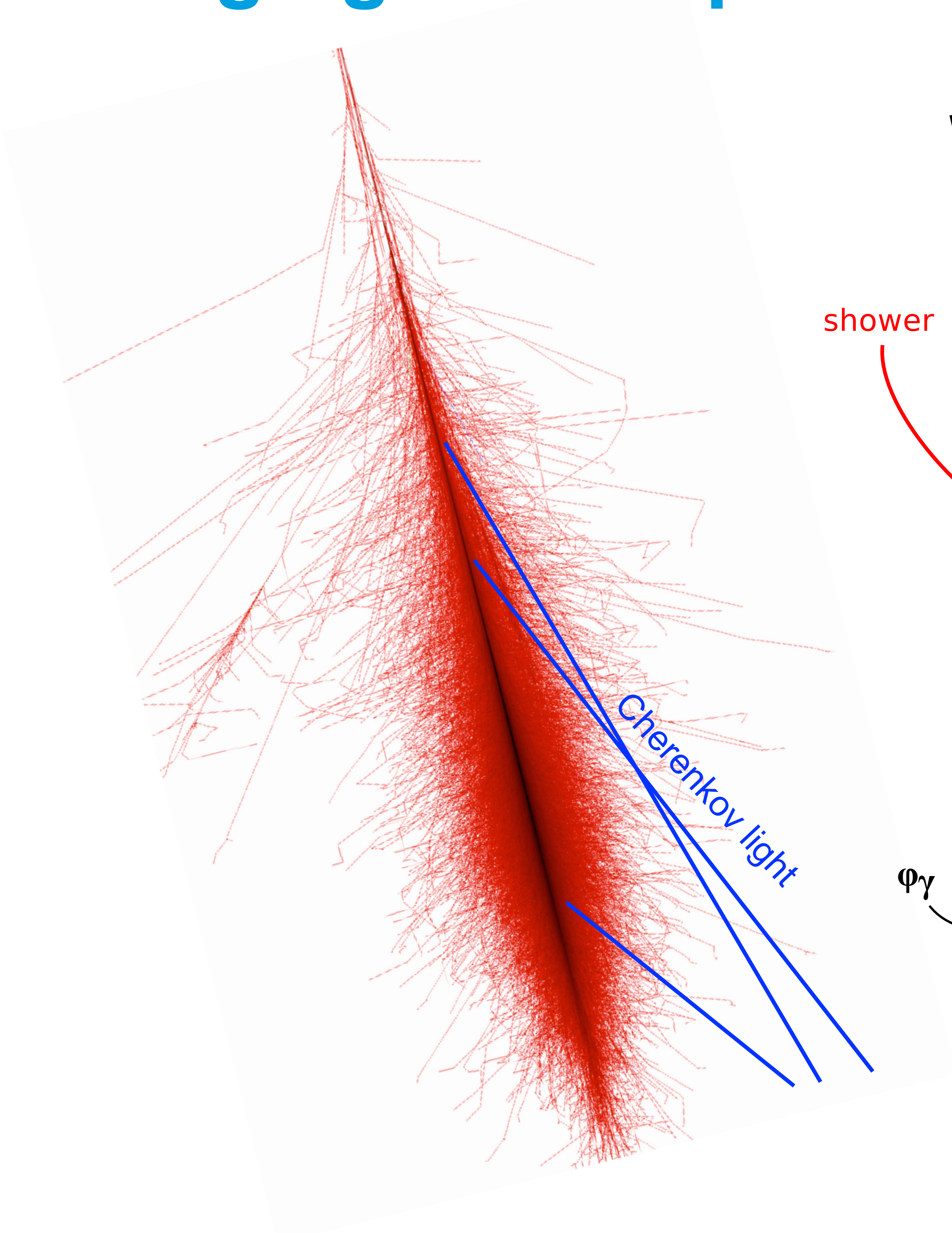
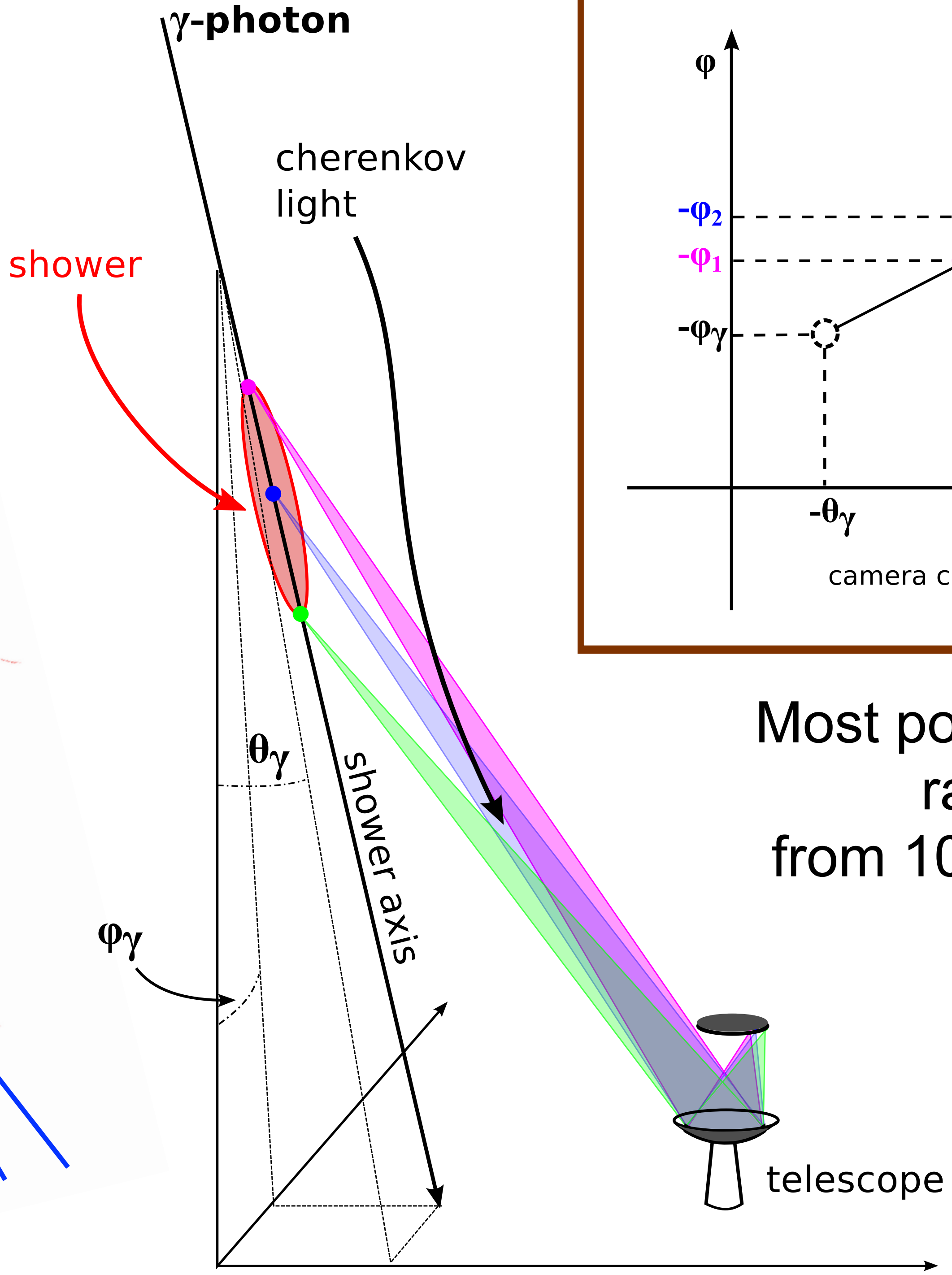
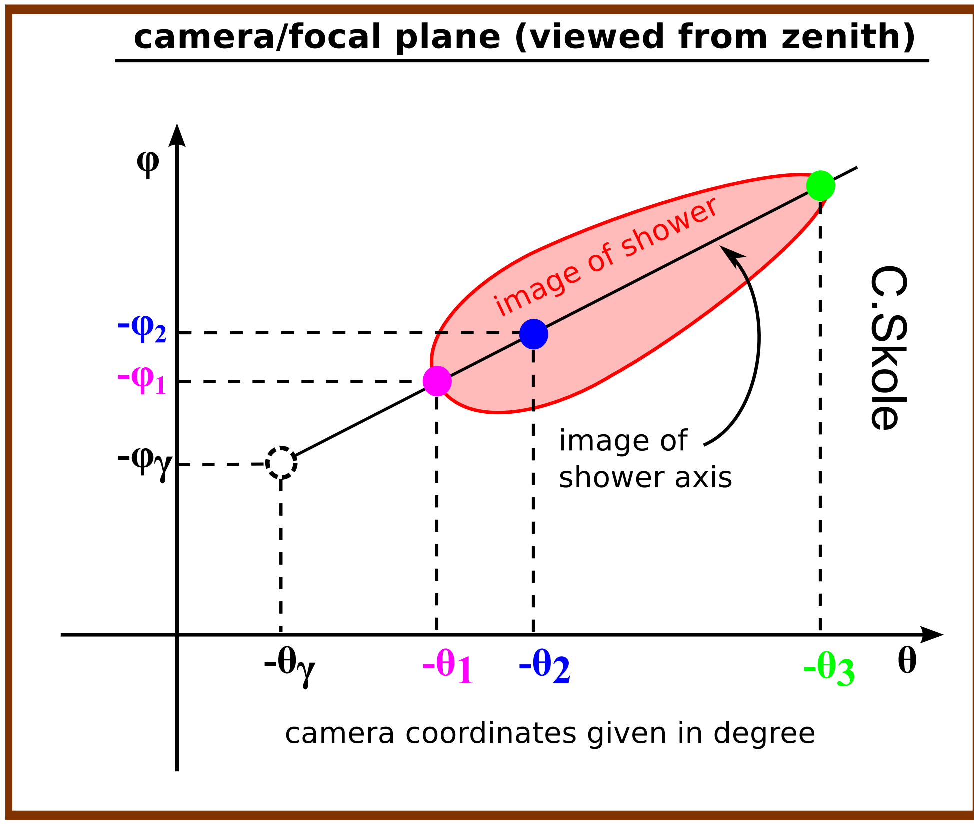


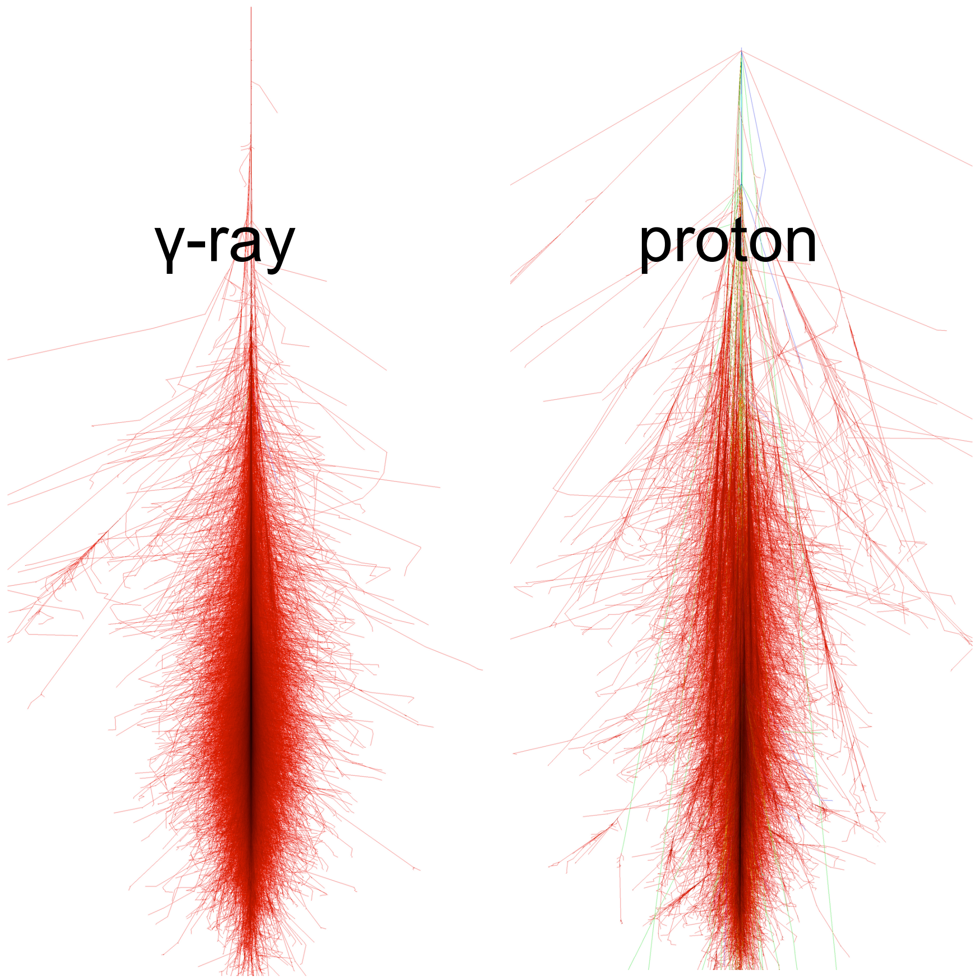




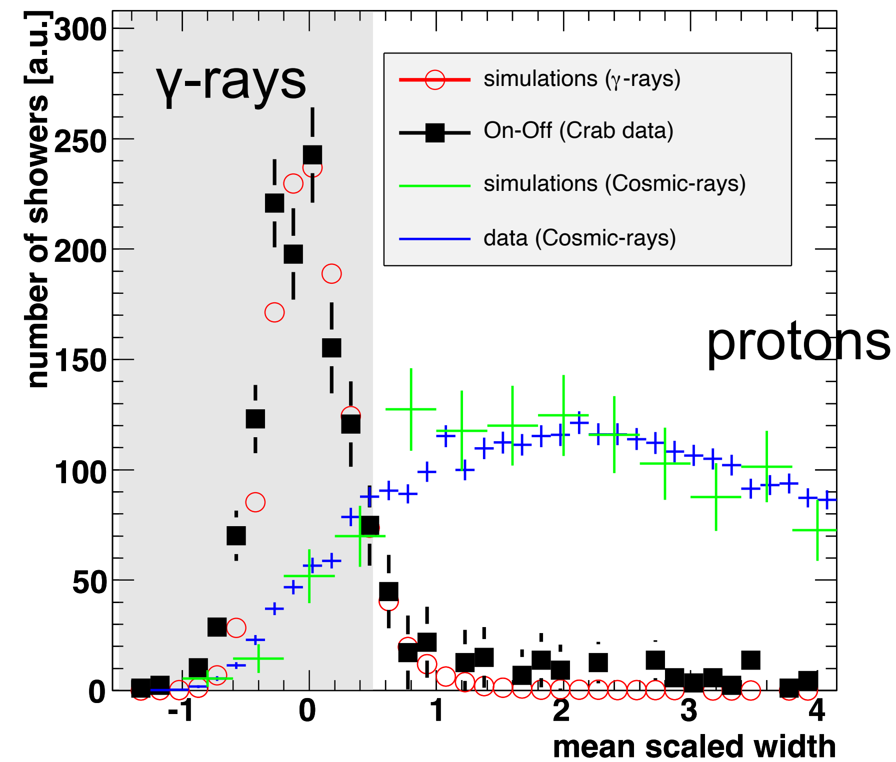
Most powerful at gamma-ray energies from 10 GeV to 300 TeV

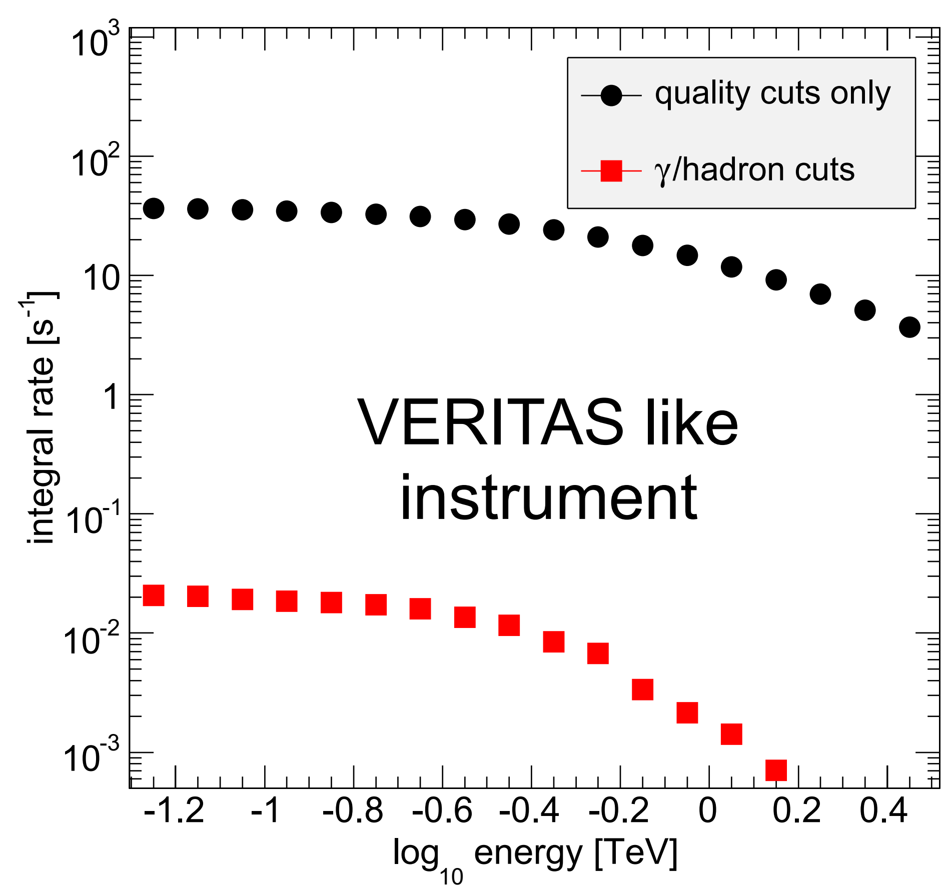
Cosmic Ray Background

ratio of signal/background
event rate 1:10³-10⁵



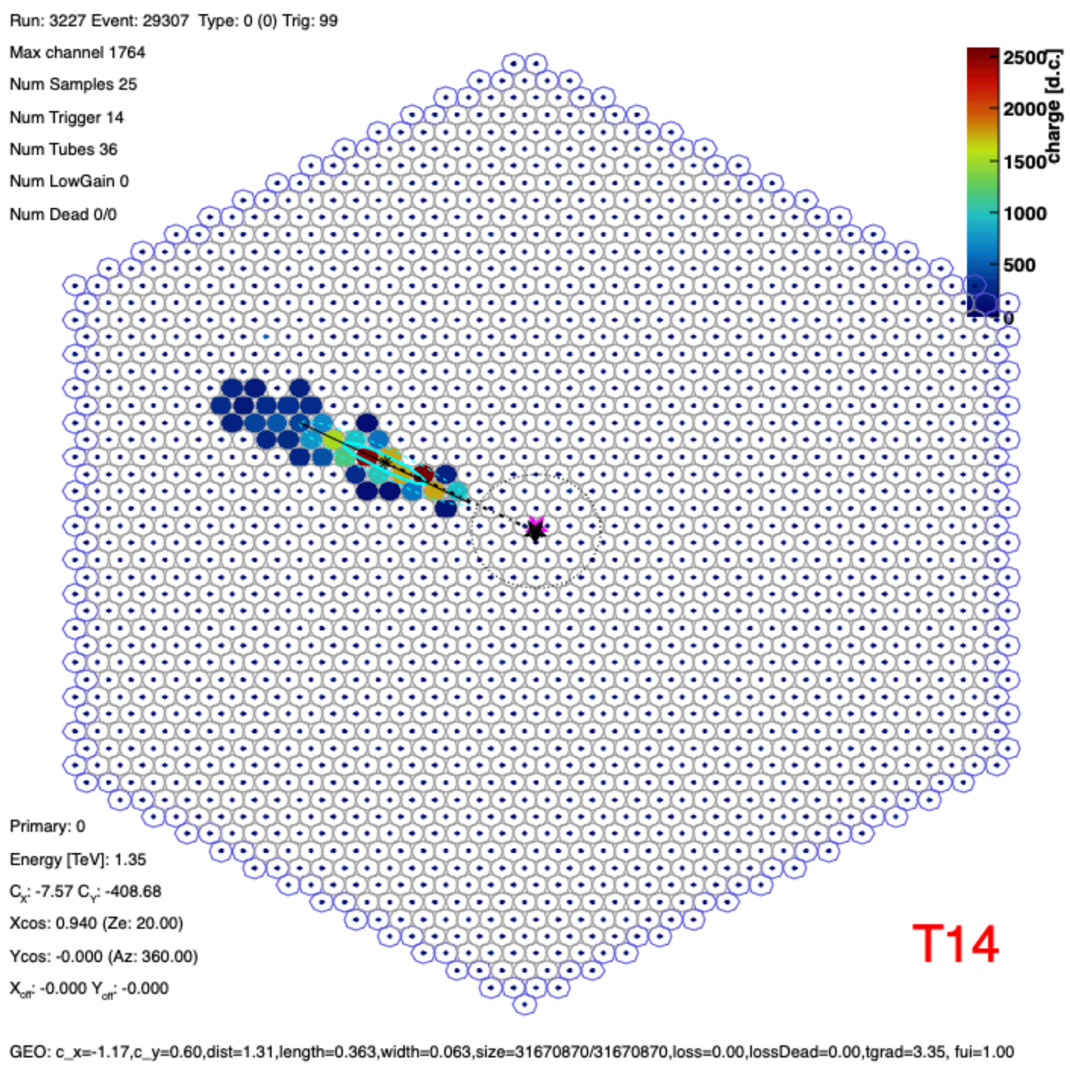
Signal events: ellipsoidal shape
Background: fuzzy, extended





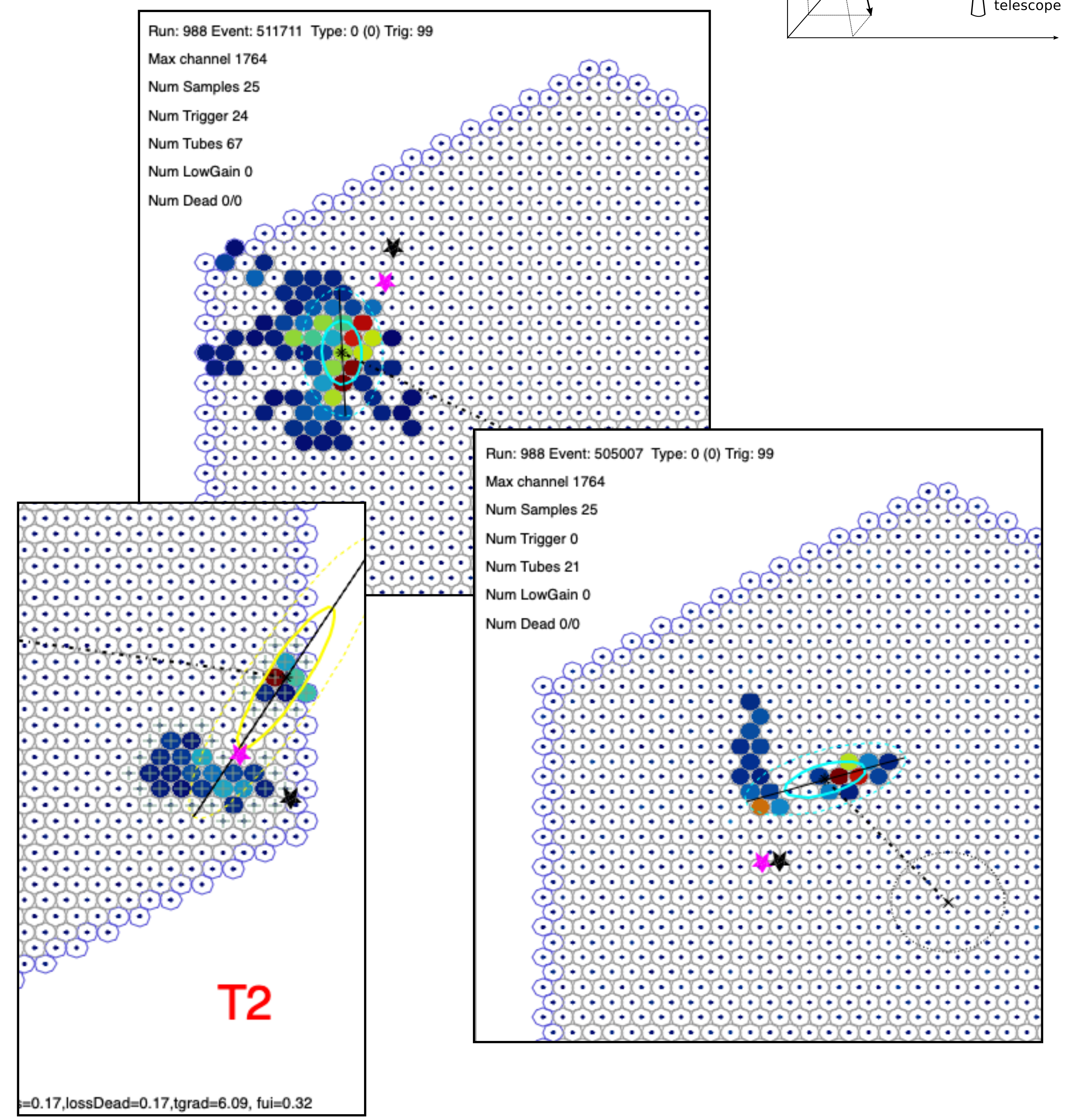
Imaging

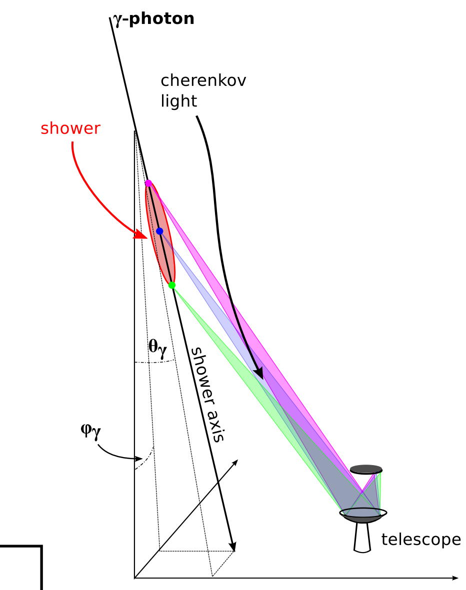
γ-ray



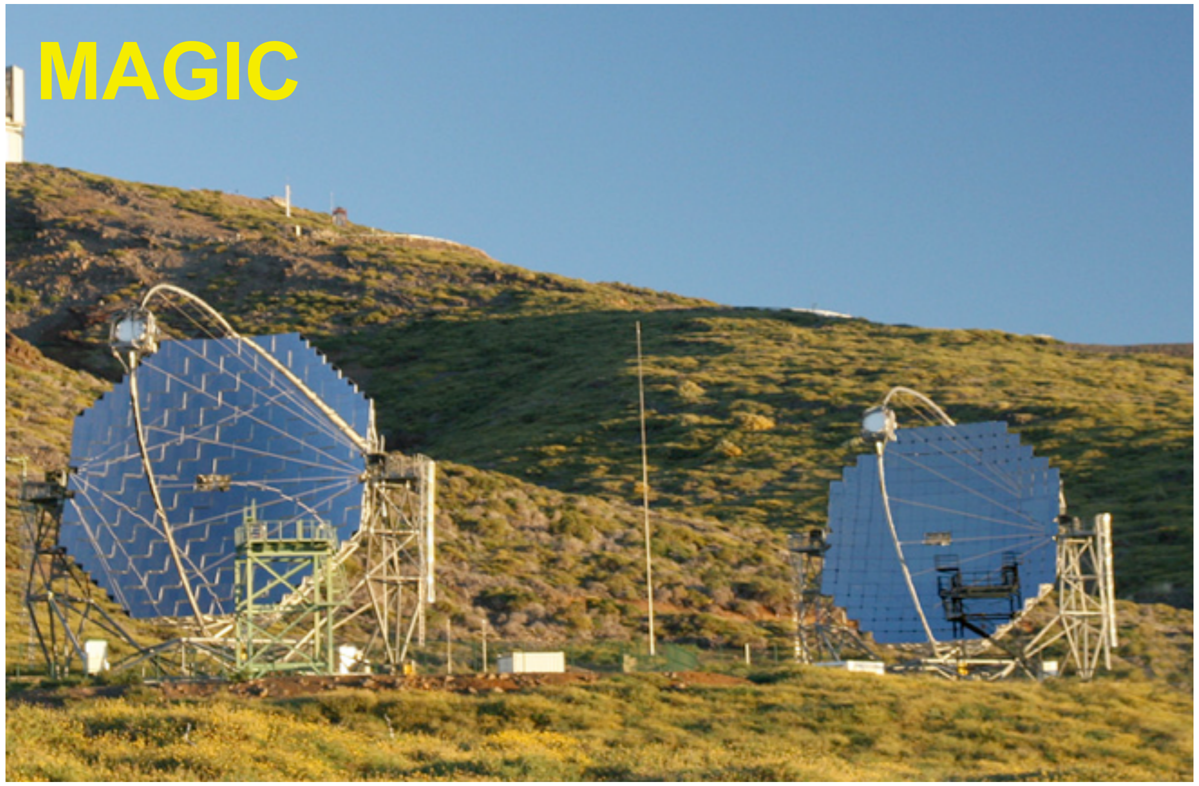
T14

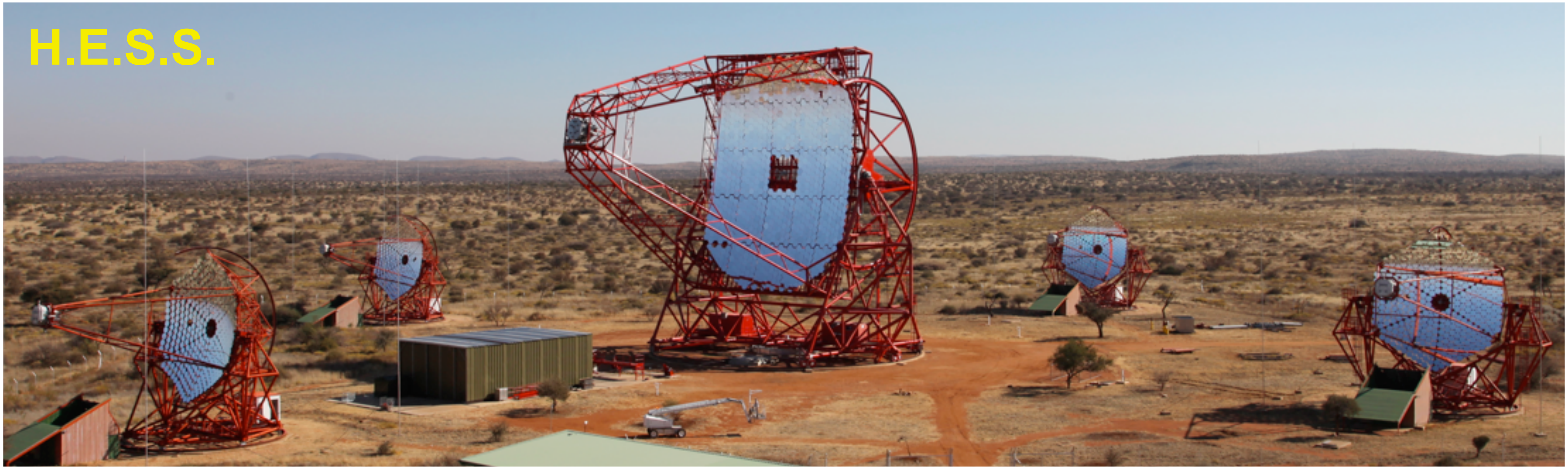
proton





Imaging Atmospheric Cherenkov Telescopes





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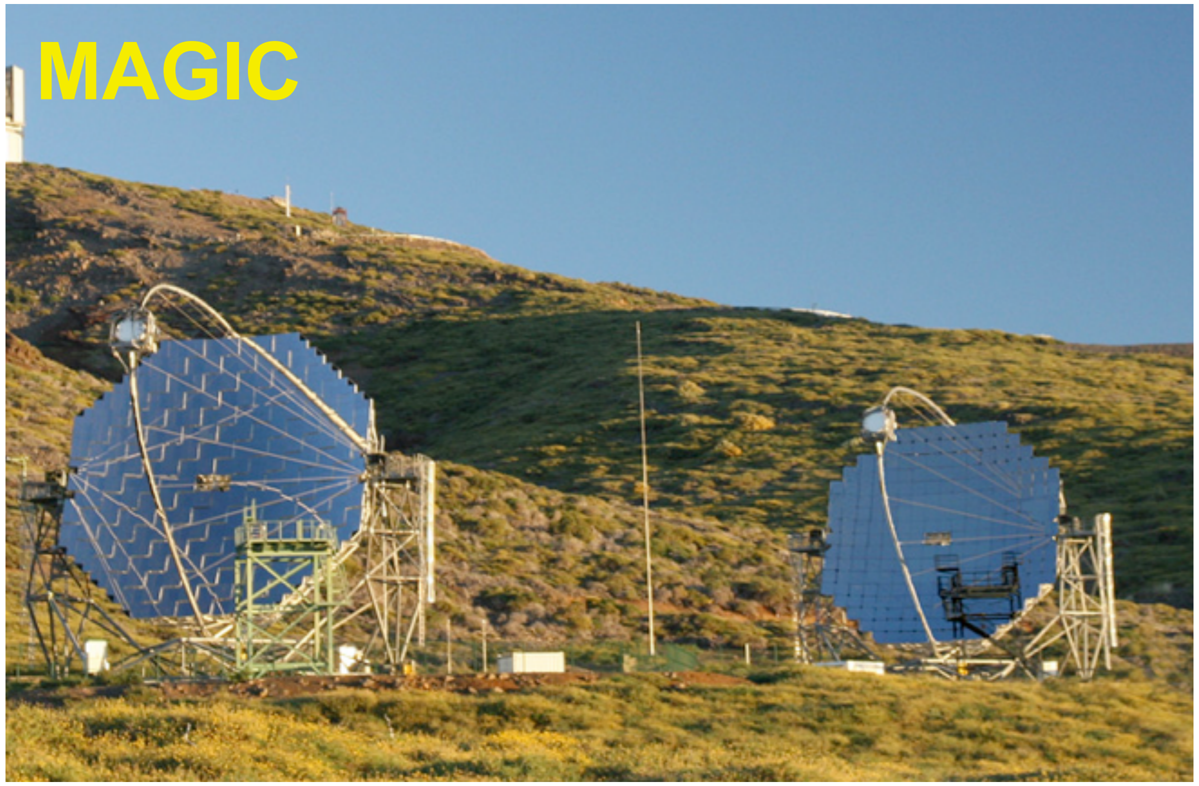
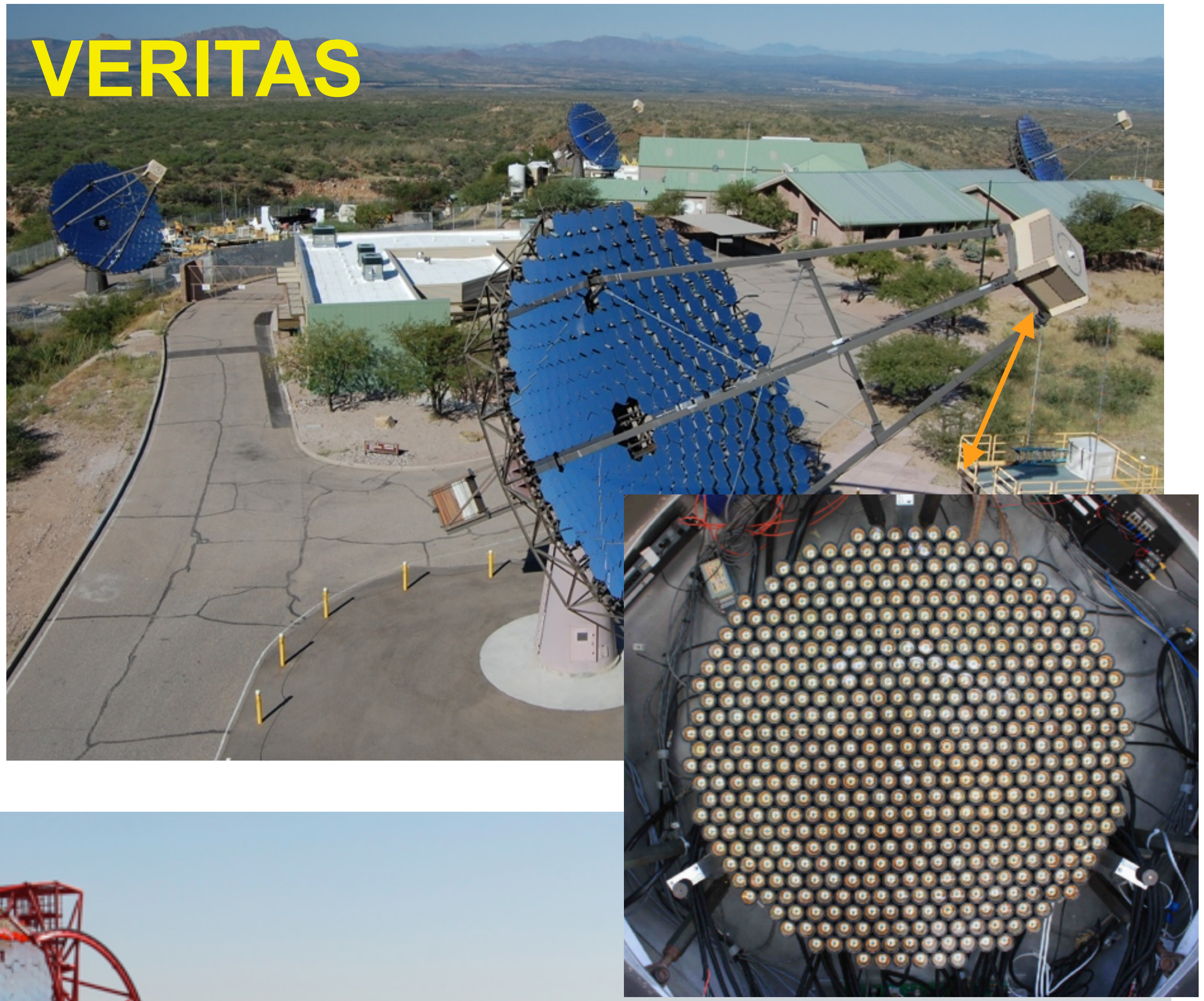
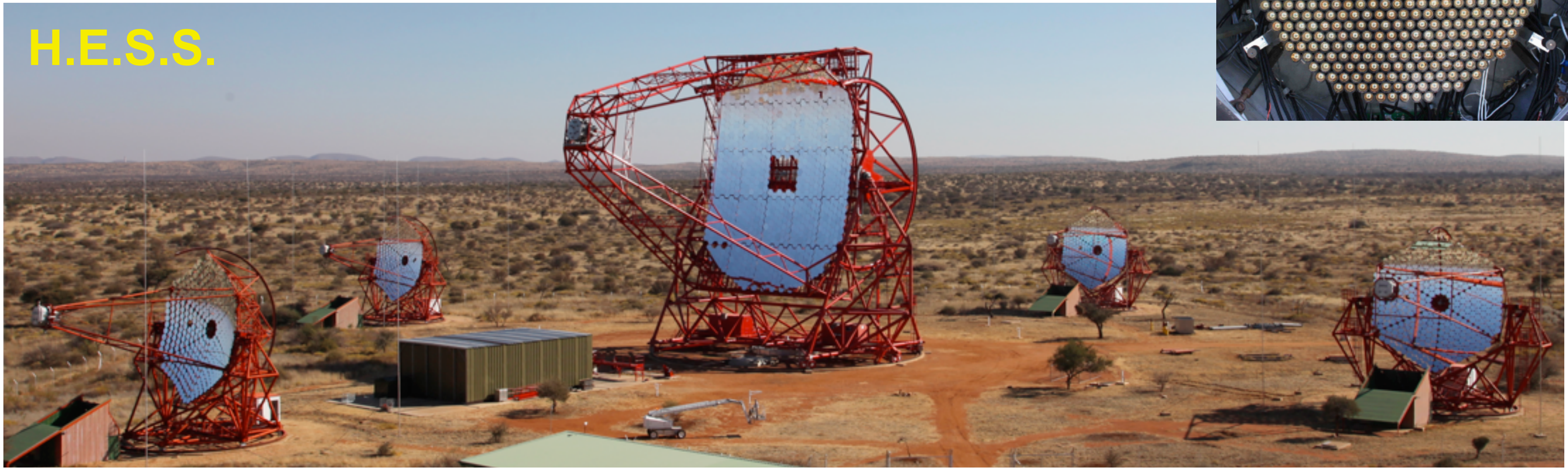
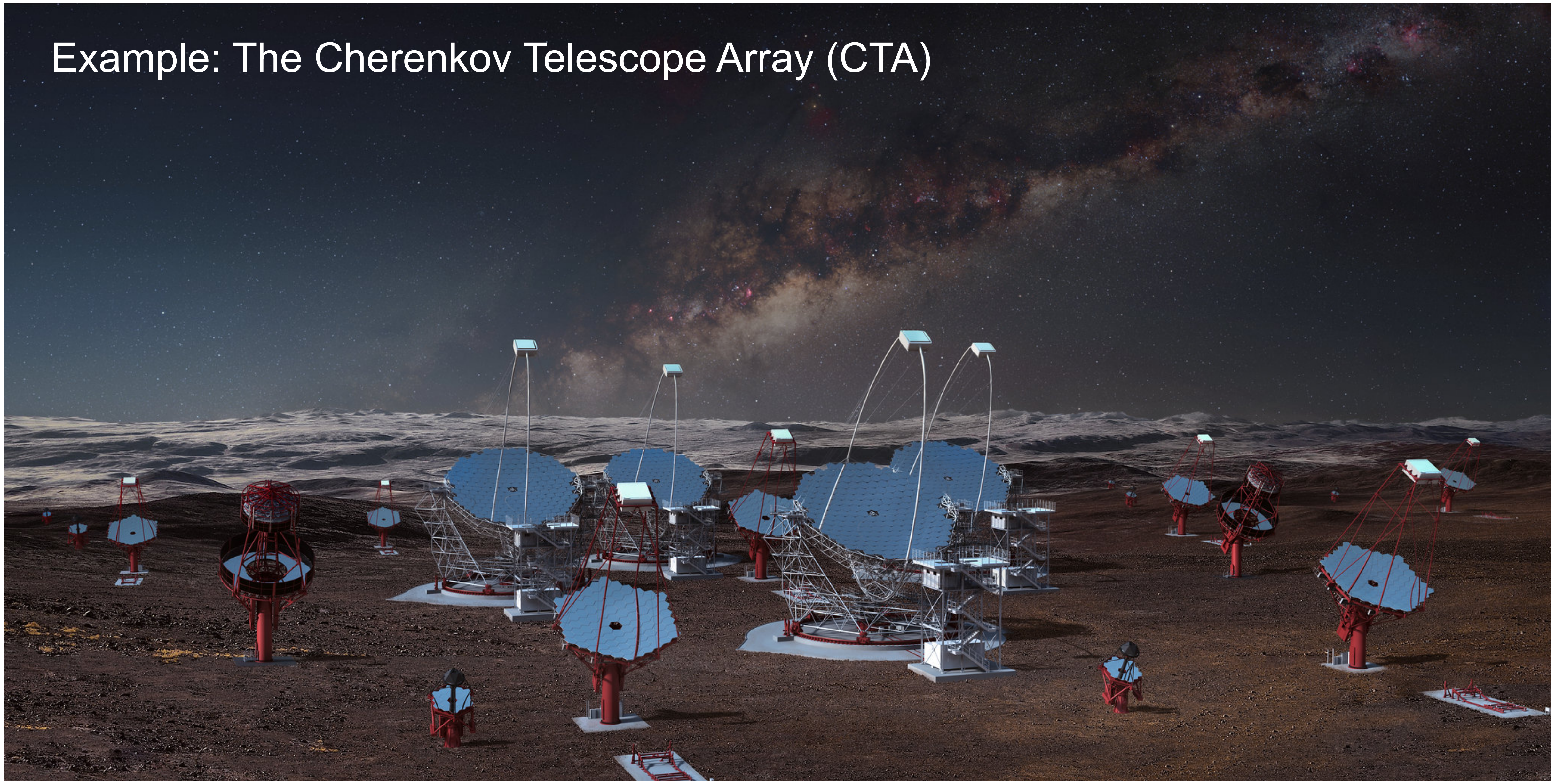






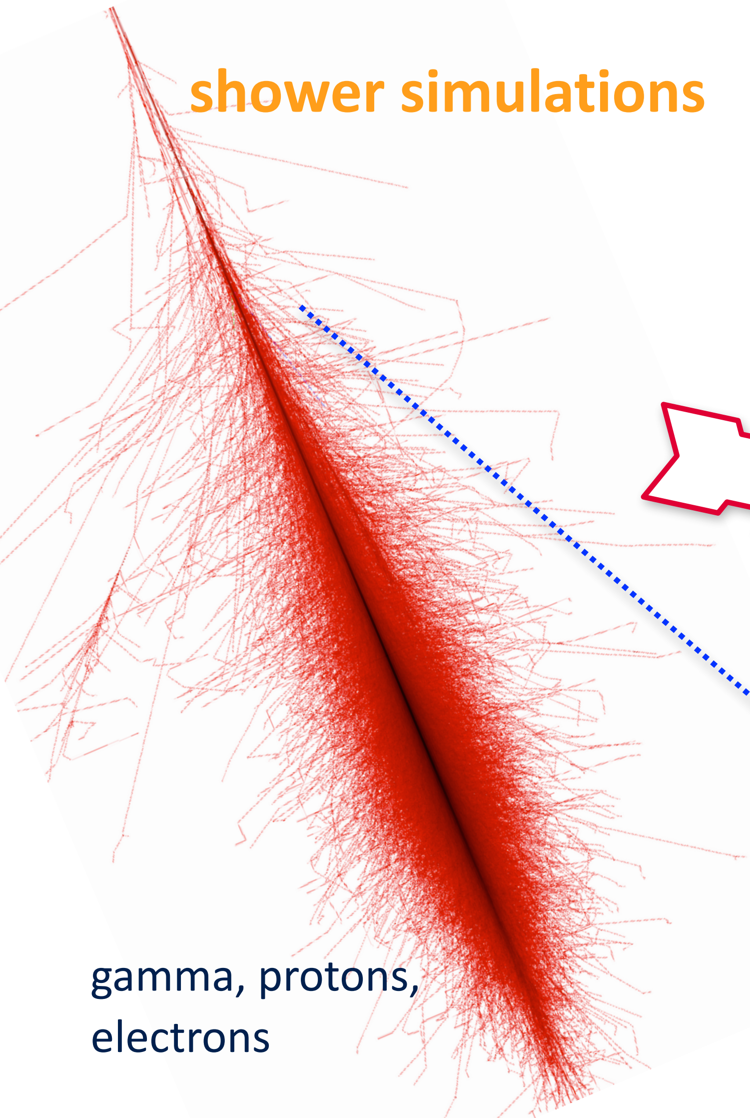
Development of Next-generation Instruments



Large (20-100) telescopes, several sites,
different telescope sizes and design, …

Simulation of Cherenkov Telescopes

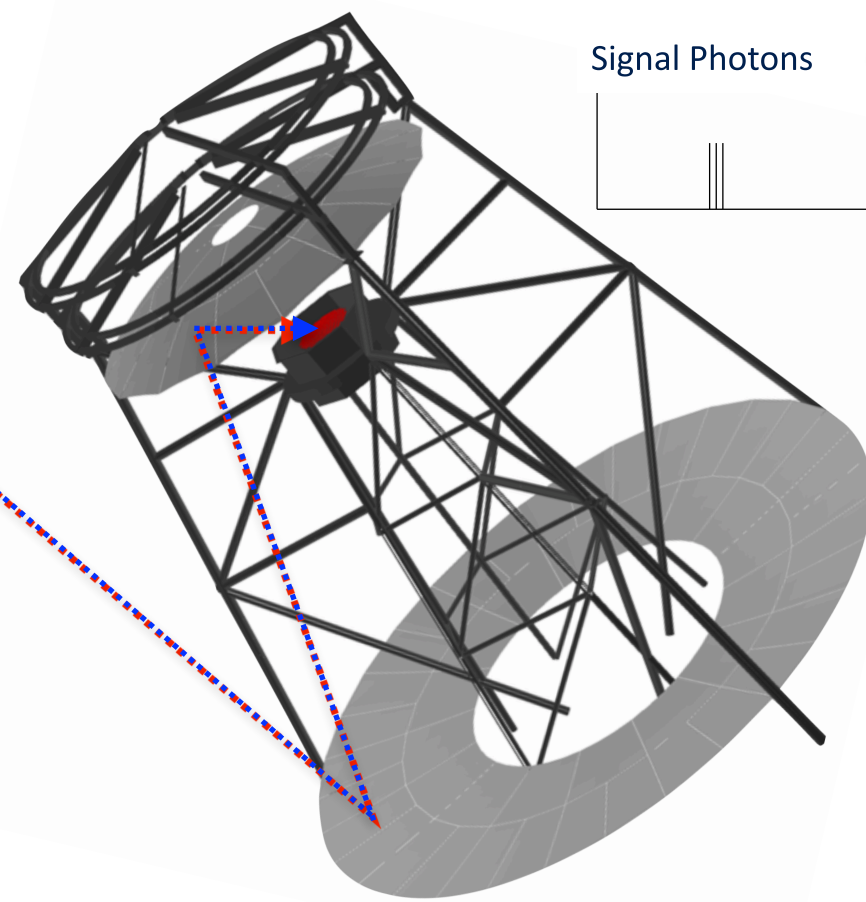
shower simulations



gamma, protons, electrons

shower physics, geomagnetic field, properties of the atmosphere (density profile, aerosols, molecular scattering)

optics - ray tracing

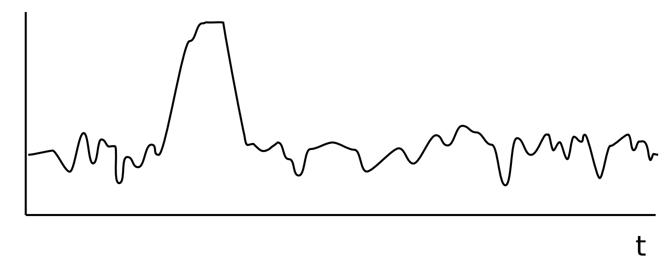


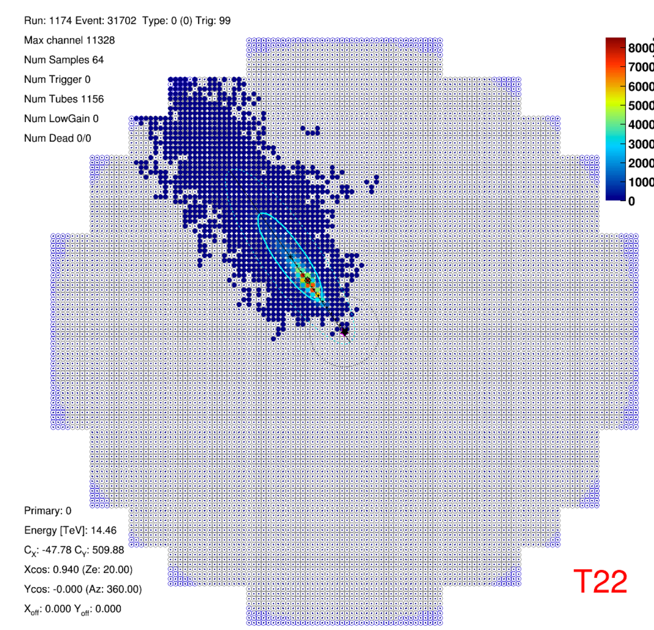
mirror reflectivity, alignment, shadowing, windows & light cones, …

photodetector - trigger - readout

Signal Photons

FADC noise + Max Signal + Pedestal





night-sky background, detection efficiency, SiPM optical cross talk, noise, pulse shapes, digitisation, trigger algorithms, readout, …

Simulation of Cherenkov Telescopes

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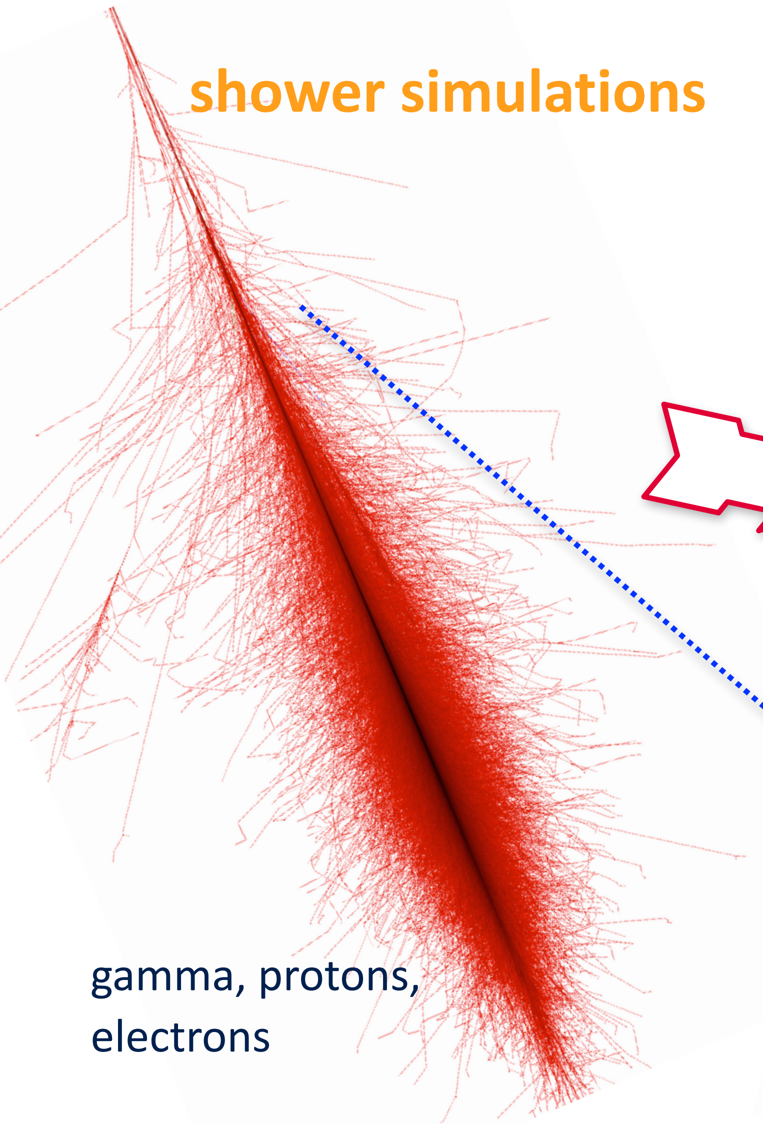

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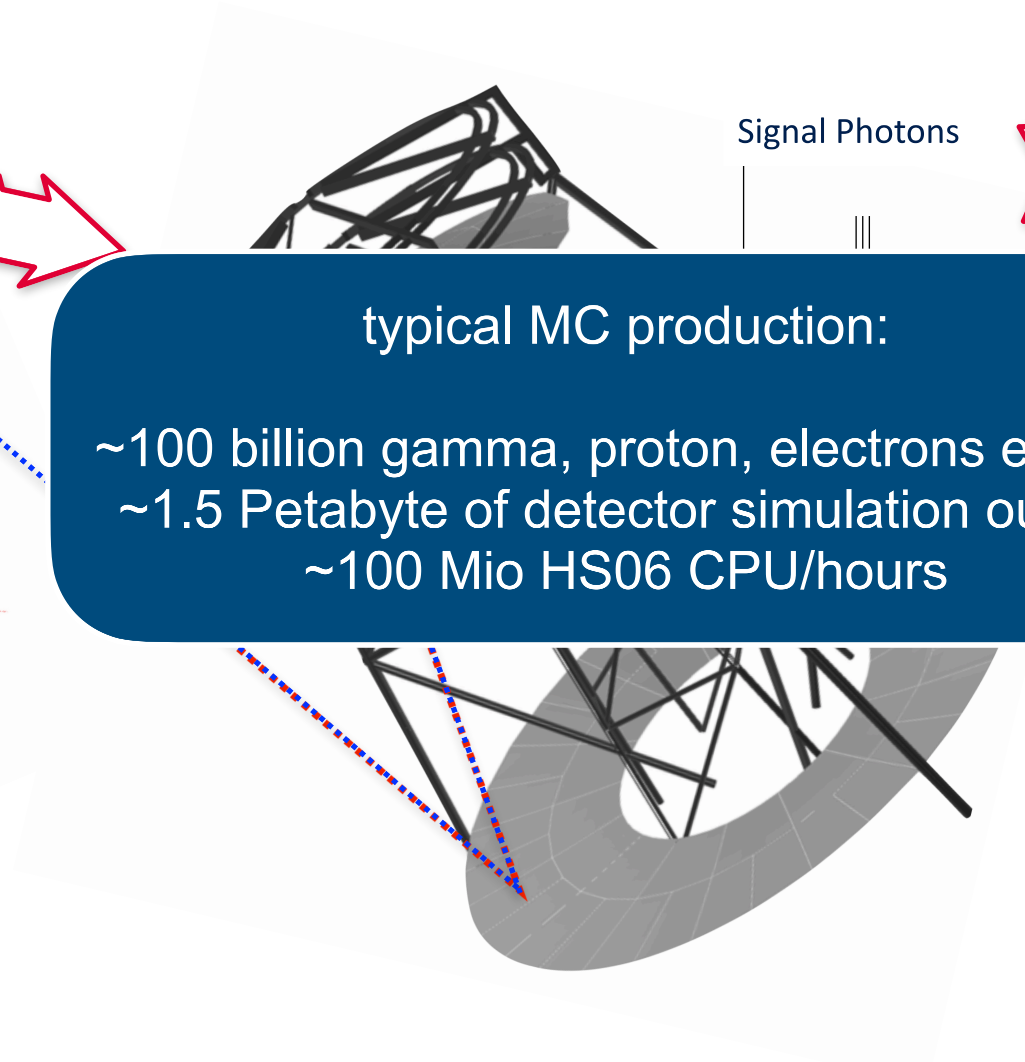
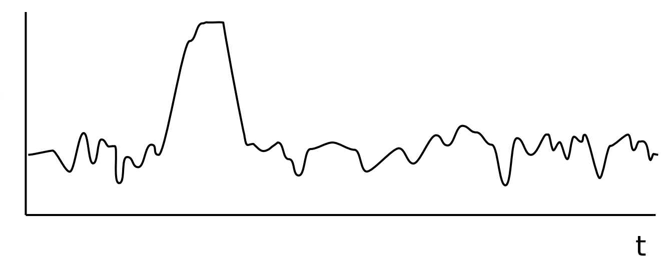


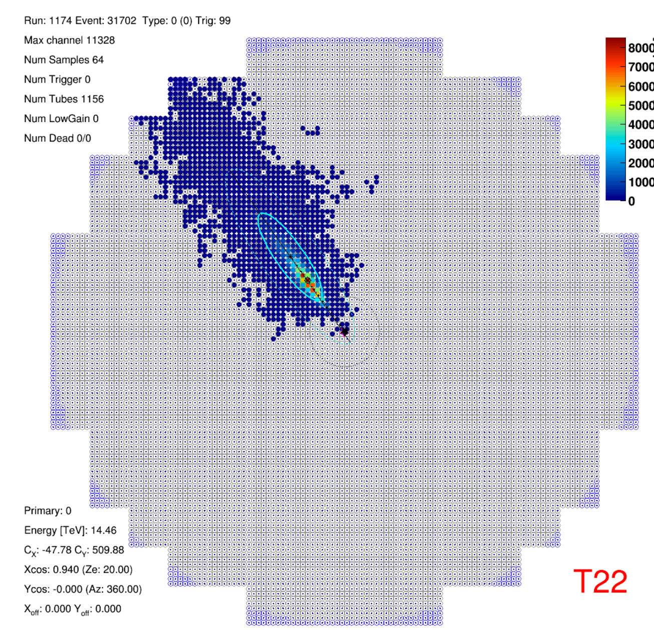
typical MC production:

~100 billion gamma, proton, electrons events
~1.5 Petabyte of detector simulation output
~100 Mio HS06 CPU/hours

mirror reflectivity, alignment, shadowing, windows & light cones, …

photodetector - trigger - readout





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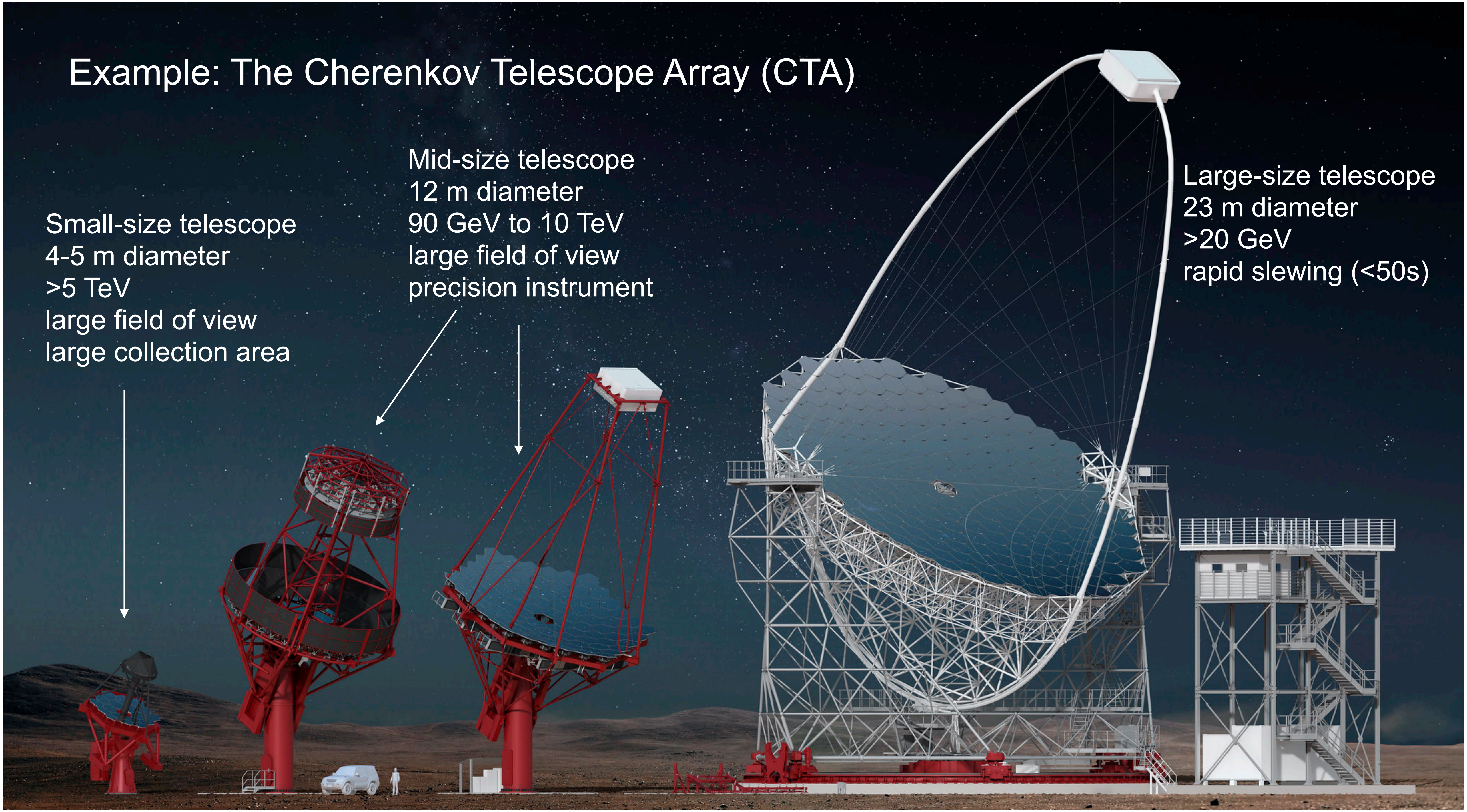
Types of Telescopes



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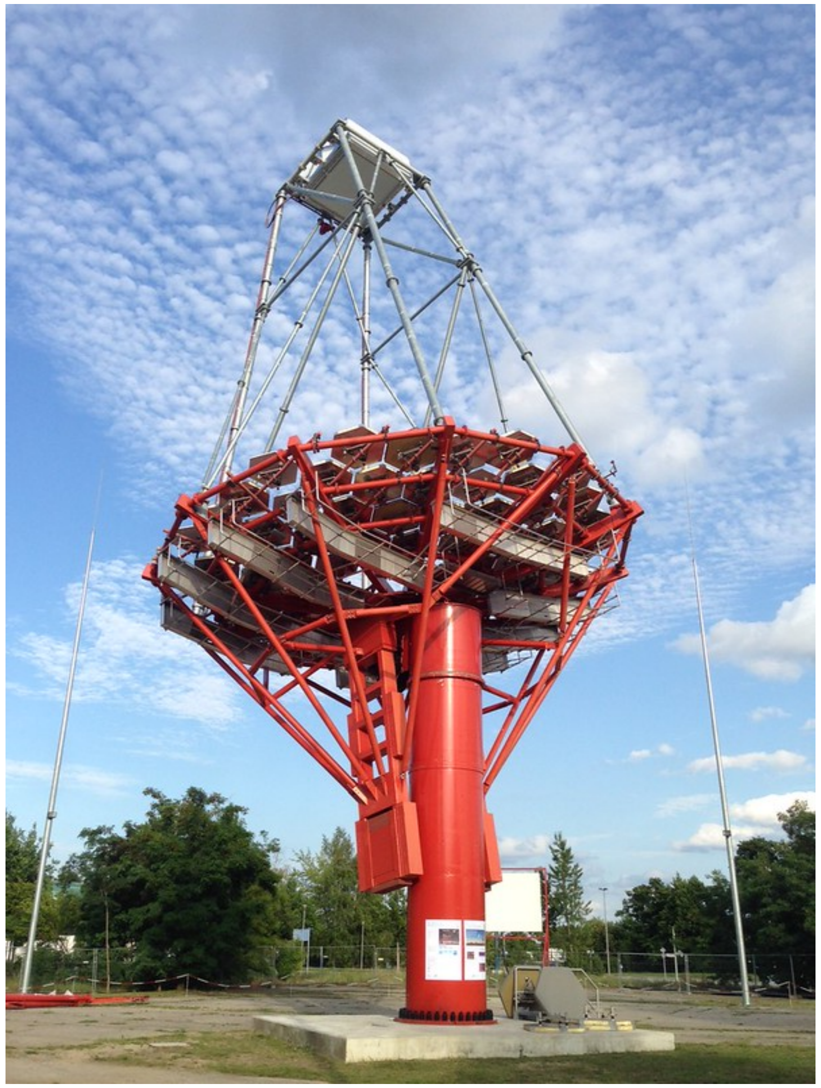
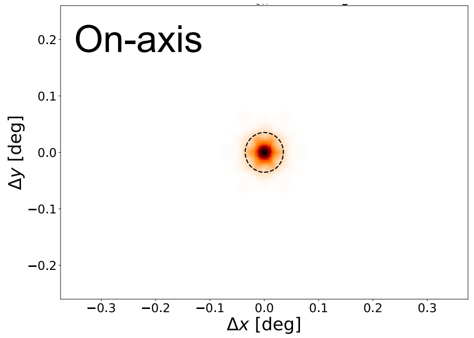
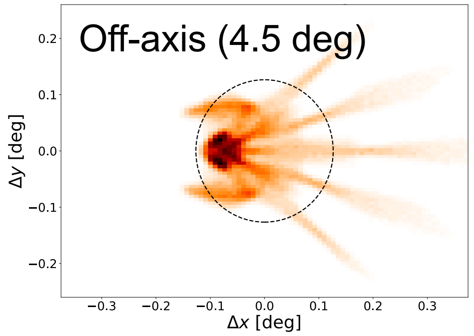
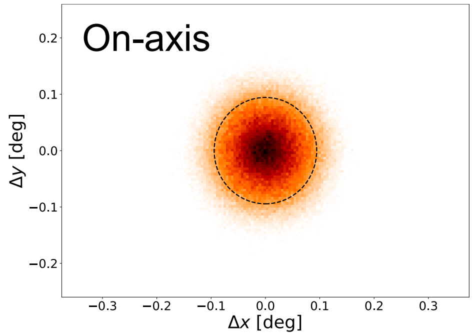








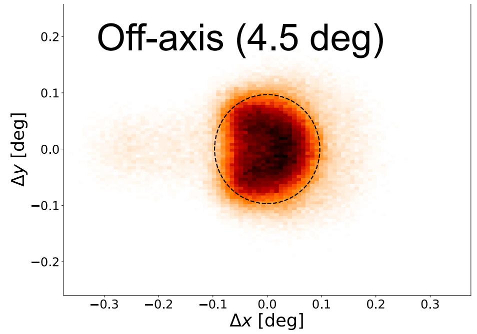
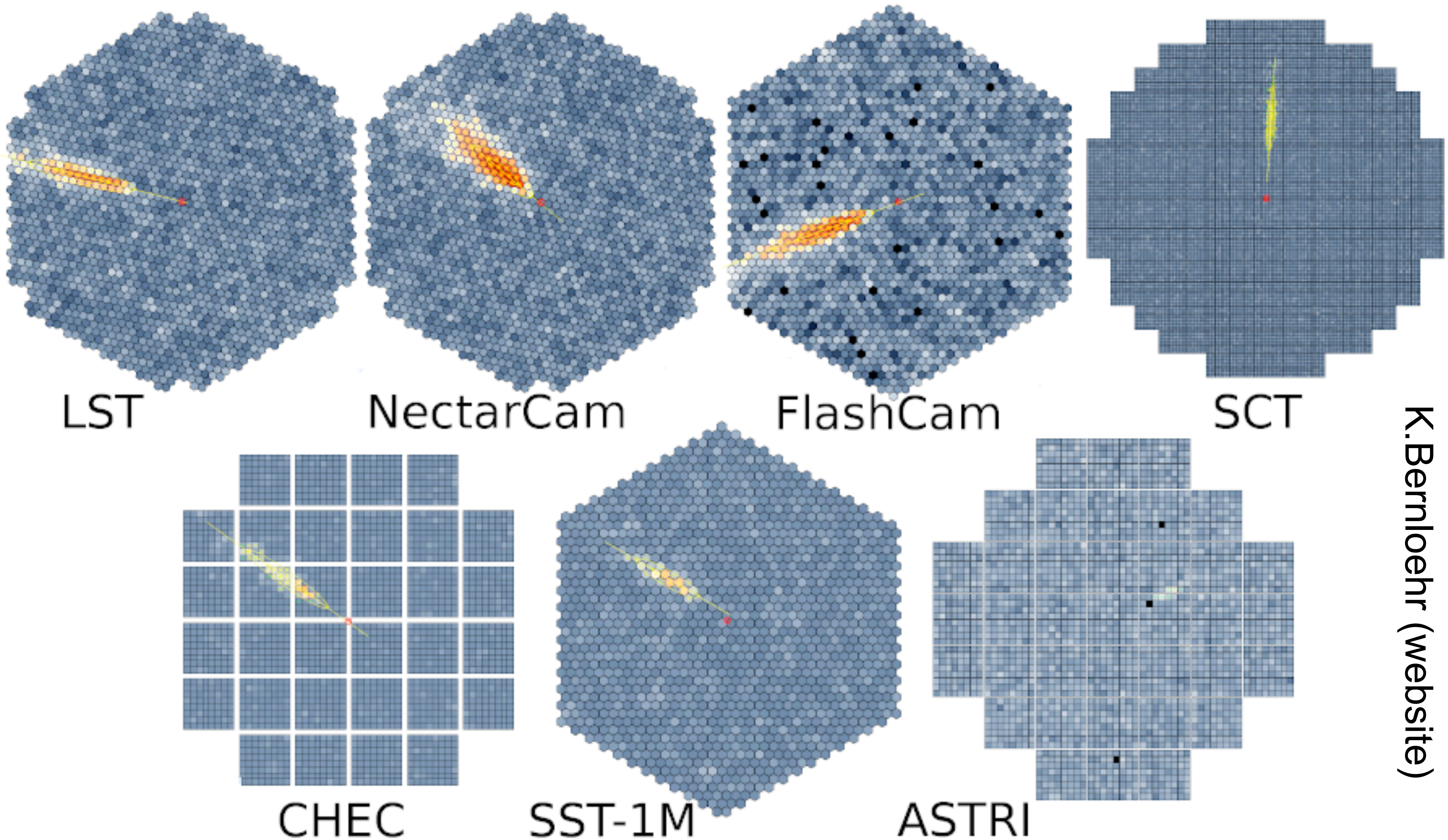


Illustration only - ignore units

Camera size & pixel size



K.Bernloehr (website)

Optimal pixel size determined from expected image shape and fluctuations
Confirmed by detailed simulations

Optimisation Procedure

Future application of differential programming

- **large parameter space to optimise**
  (close to 100D…)

- **“optimise” by common sense, first principle, guessing, brute force walk through the parameter space, green-table decisions**
  - split into smaller problems (if possible)

- **MC simulations and analysis**
  - detailed Monte Carlo Simulation of shower, telescope optics, trigger, and digitisation
  - image analysis, stereo reconstruction, background suppression including training of machine learners

- **discussion of technical and science teams on what is the ‘best’**

Main Variables

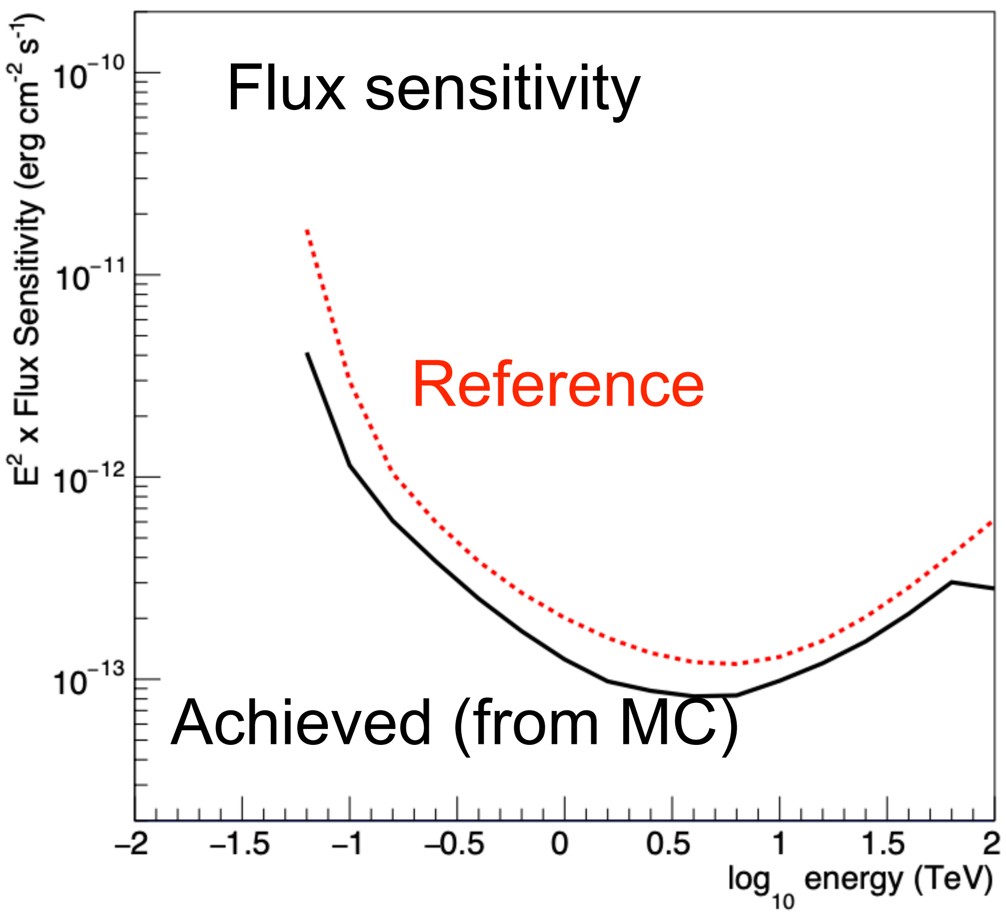
optimisation metric	main variable	current instruments	next-generation instruments
Flux Sensitivity	telescope number	2 - 5	30 - 100
Energy Range	telescope size, telescope distance	1-2 different sizes (12-28 m diameter)	3-4 different sizes (4-23 m diameter)
Angular and Energy Resolution	pixel size	0.15 deg	0.07-0.15 deg
Wide field of view	camera size	up to 5 deg	up to 9 deg
Rapid Slewing	telescope drive	20-80 s repositioning (100 tonnes!)	
Flexibility in operations	subarrays	(hardly possible)	e.g. monitoring arrays, etc.
Large Sky coverage	number of sites	1 site per observatory	multiple sites

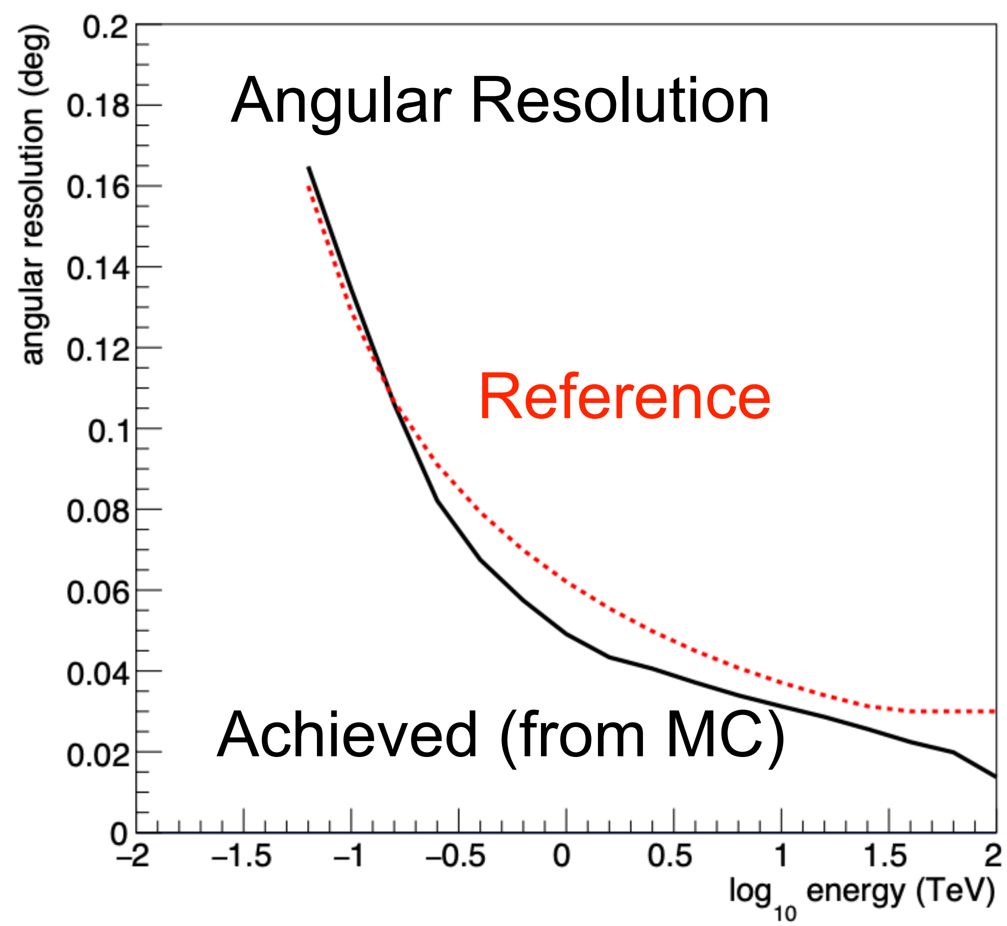
energy dependent correlation between almost all variables
constrains from site, budget, …

Optimisation Metrics

$$\mathrm{PPUT} = \left(\prod_{i=1}^{N} \frac{F_{ref}}{F_{array}}\right)^{1/N}$$

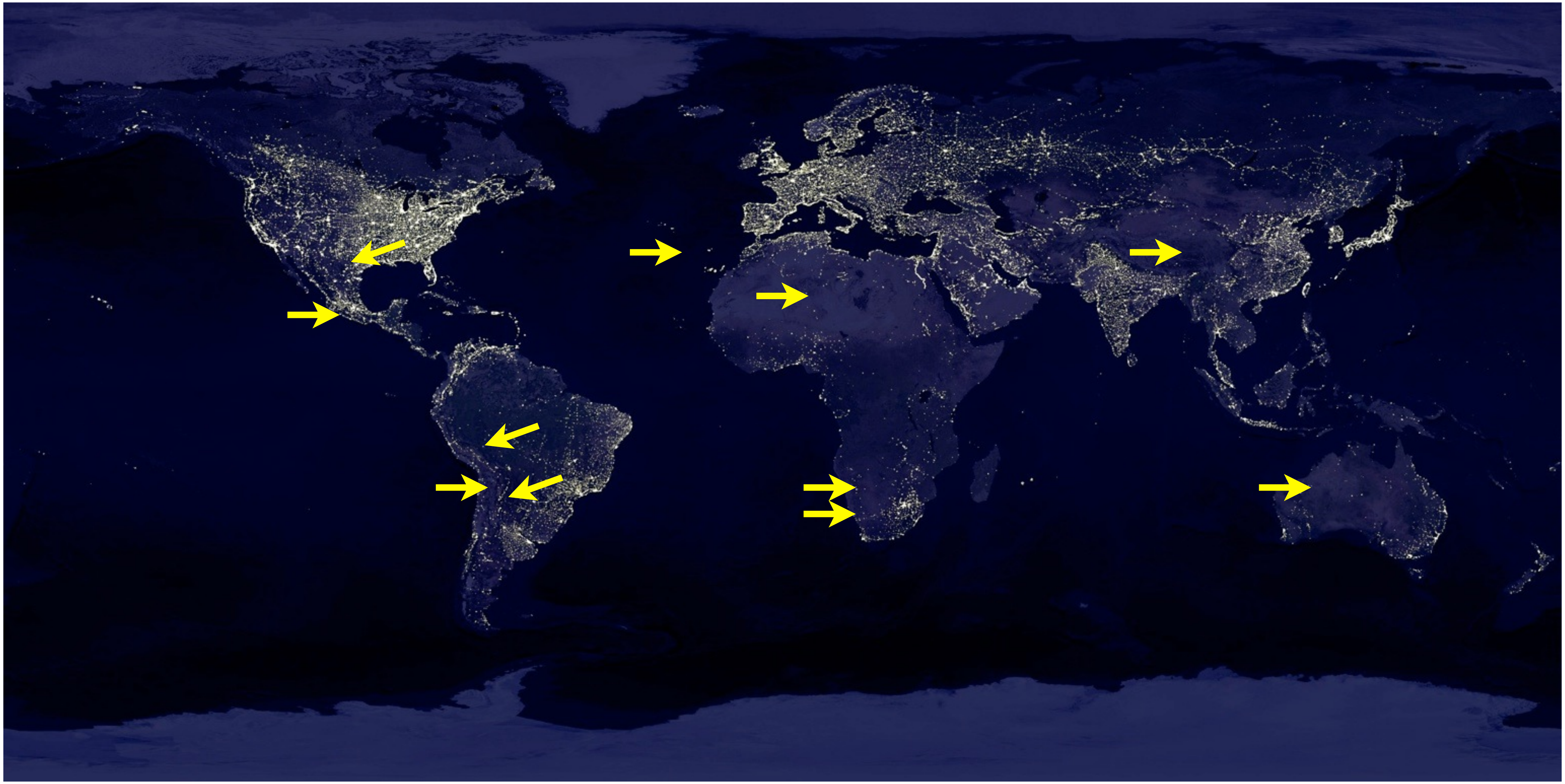
$$\mathrm{AP} = \left(\prod_{i=1}^{N} \frac{\Theta_{0.68;ref}}{\Theta_{0.68;array}}\right)^{1/N}$$





Optimise $\mathrm{AP}^{\mathrm{P}} \times \mathrm{PPUT}^{\mathrm{M}}$

Atmosphere above is part of the detector



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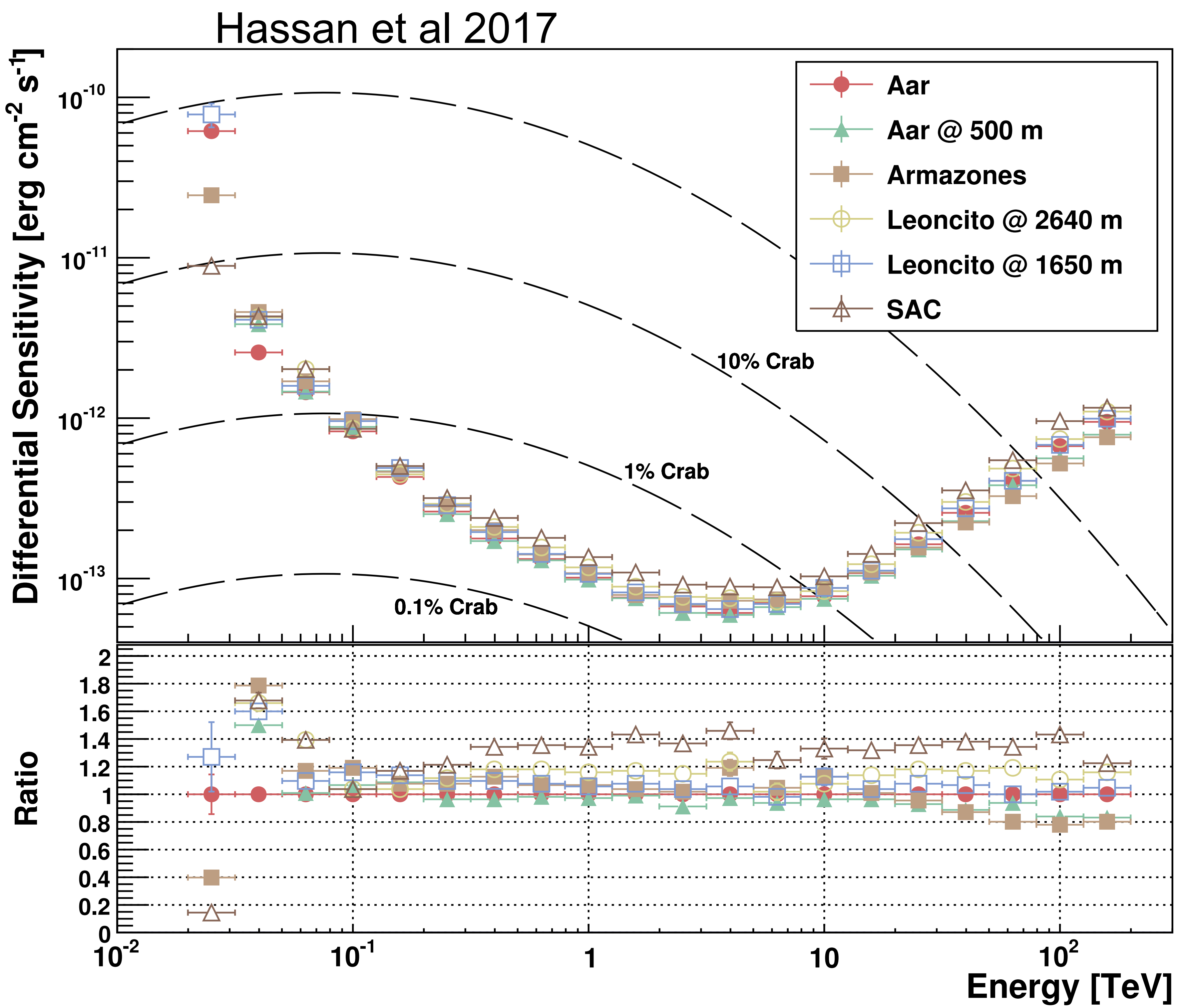
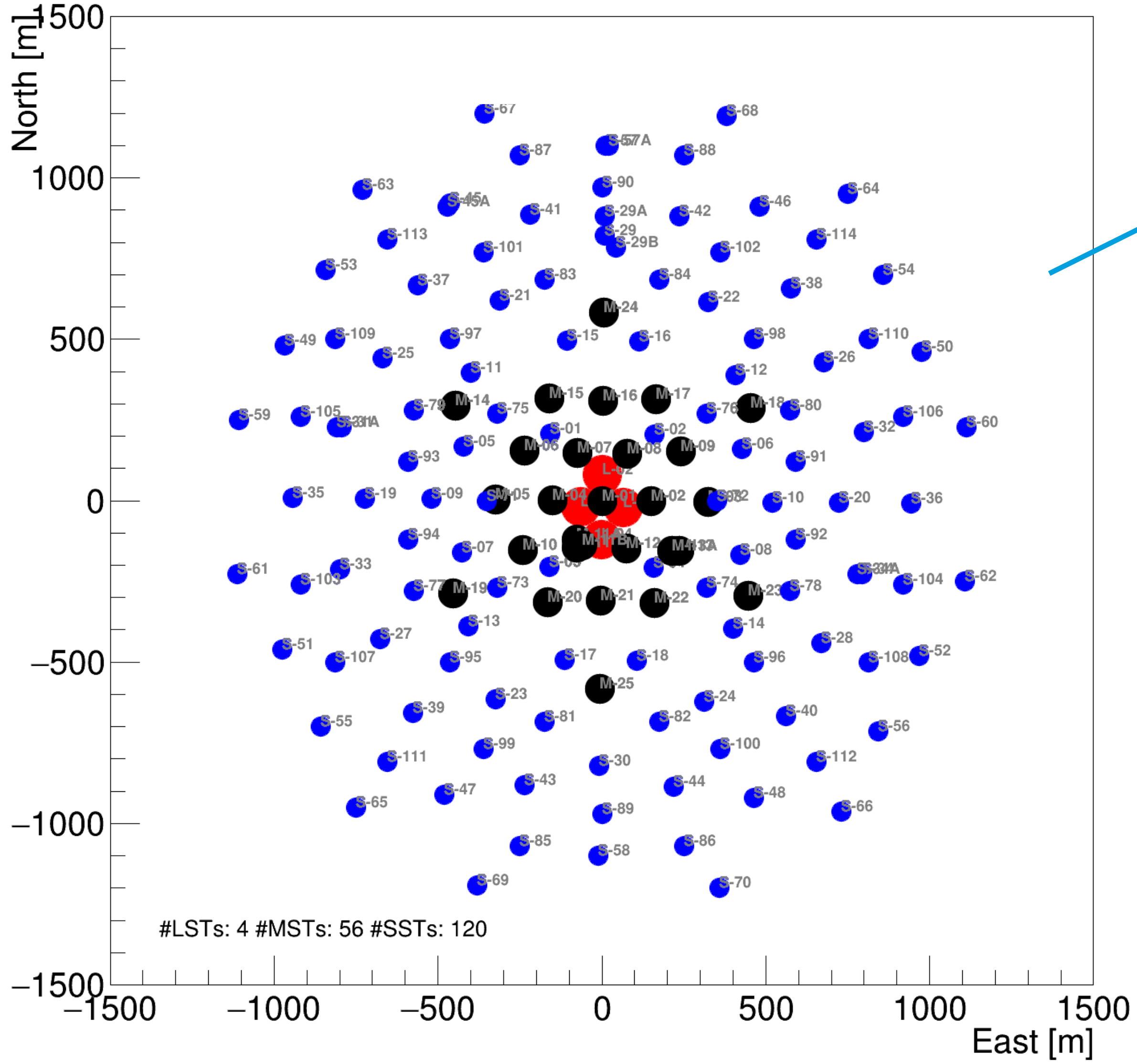


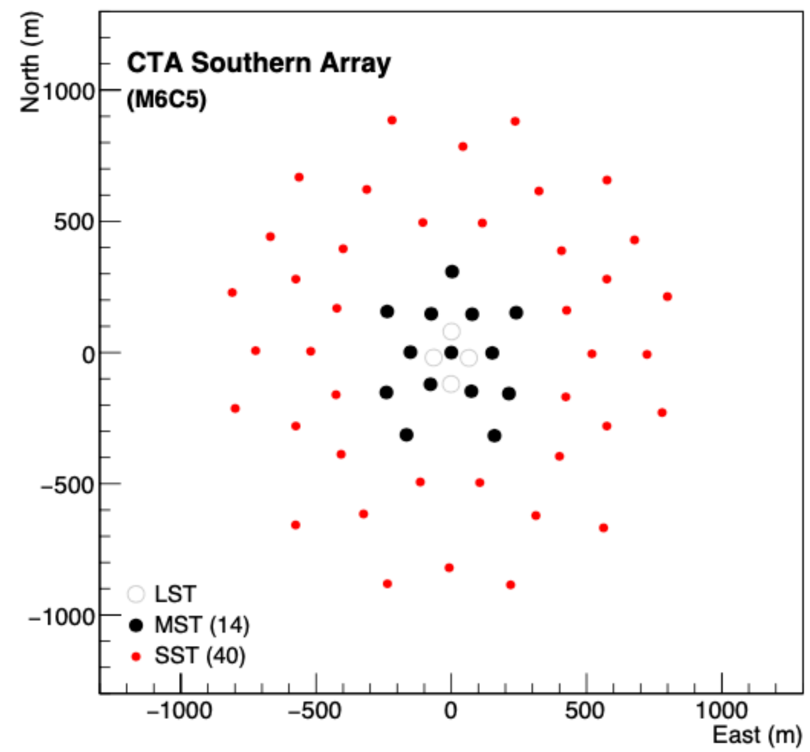
Telescope Arrangement - Layout

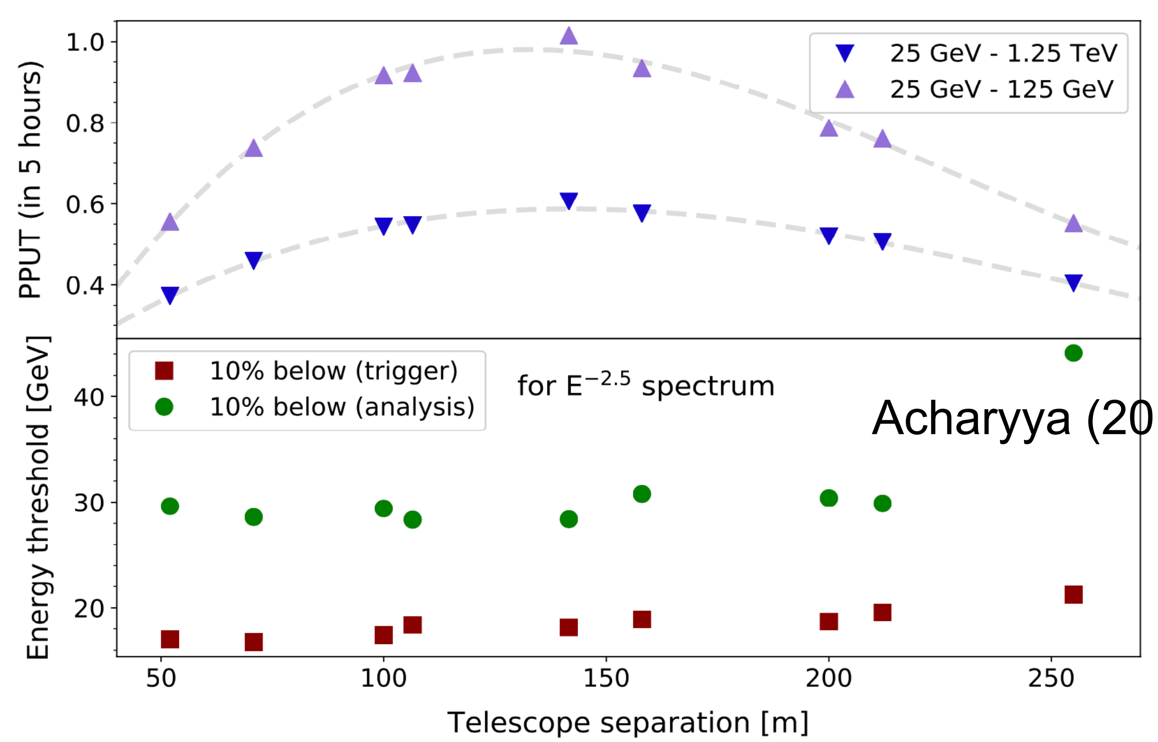
How to place the telescopes on the ground?
Competing metrics: collection area vs precision

Simulate ‘hyperarray’ of up to 900 telescopes



Gueta et al 2021





Acharyya (2019)

Summary

- **finding the optimise Cherenkov array is complex**
  - brute force simulation of even a small subset of the parameter space is very time consuming and obtained with enormous computational costs (but definitely worth spending it!)
  - no good way for fast simulations / estimations of background events found until now
- **long time scale of investigations are an issue**
  - technical development does not stop
  - funding constrains or political decisions sometimes appear / disappear on shorter time scales
  - software development for a planned instrument
- **locking desperately for a more efficient way to come to a conclusion for future instrument optimisation**
  - use case for differentiable simulators (but I honestly have no clue…)