The Cherenkov Telescope Array:

astronomy at the extreme end of the rainbow

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LPHNE seminar, 28th February 2022

For the next 45…

- Where it all started….
- Why gamma-rays? What is our motivation?
- Ground-based gamma-ray astronomy
- The future! What is the Cherenkov Telescope Array?
- The challenges CTA presents us with…

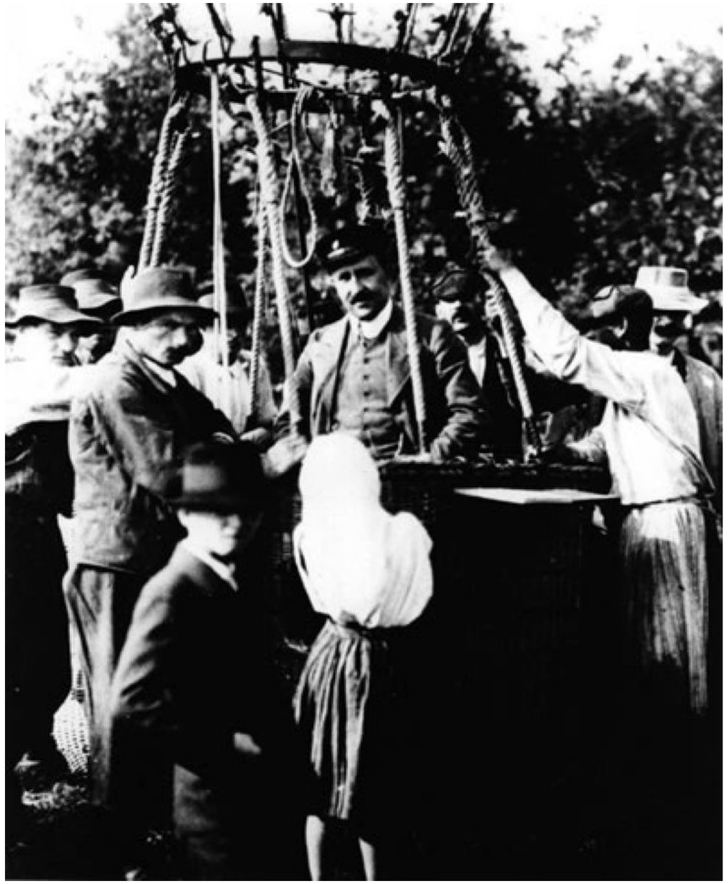
…And how we aim to solve them!

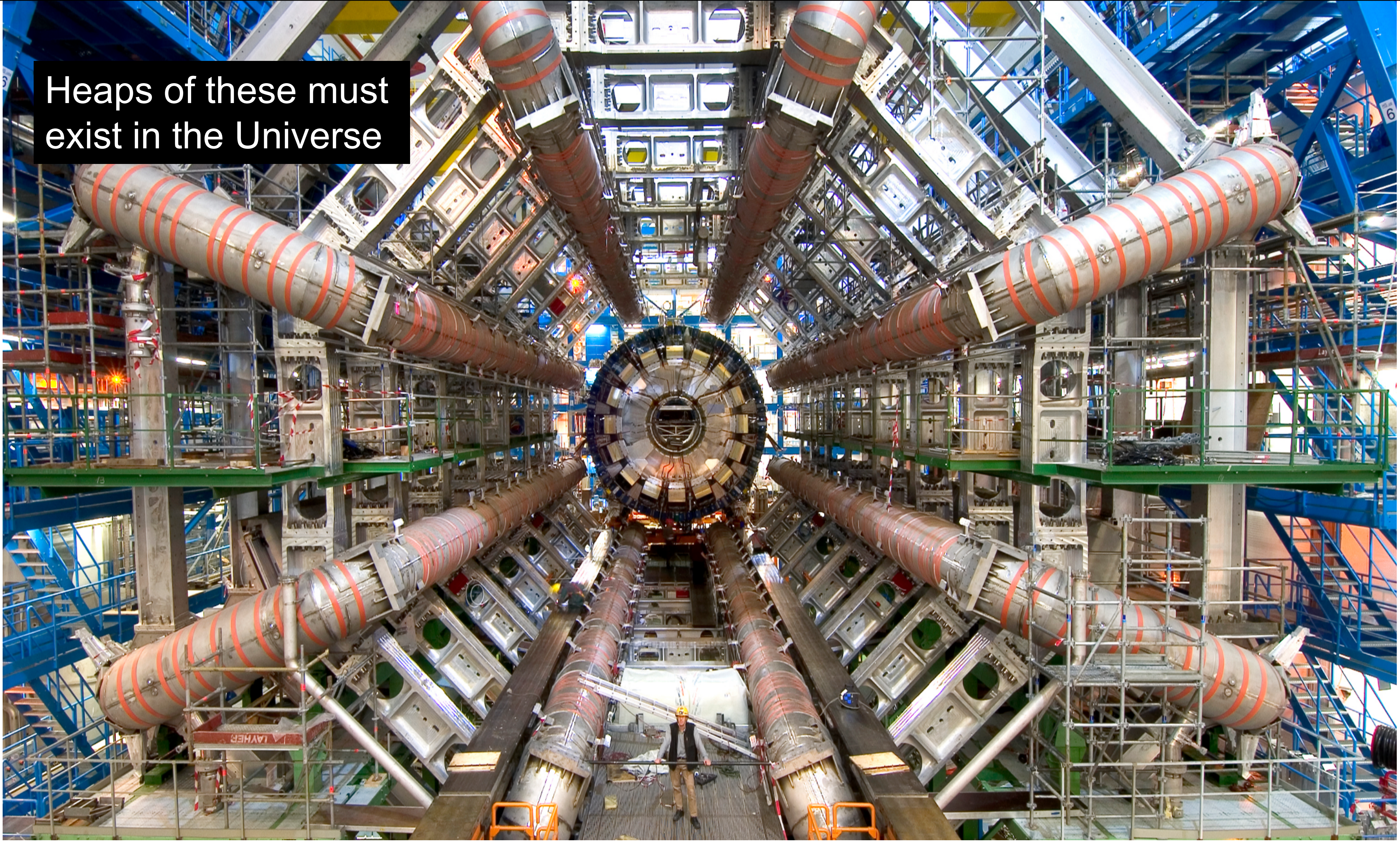
It started with cosmic rays…

1909 Wulf
1911 Pacini
1912 Hess

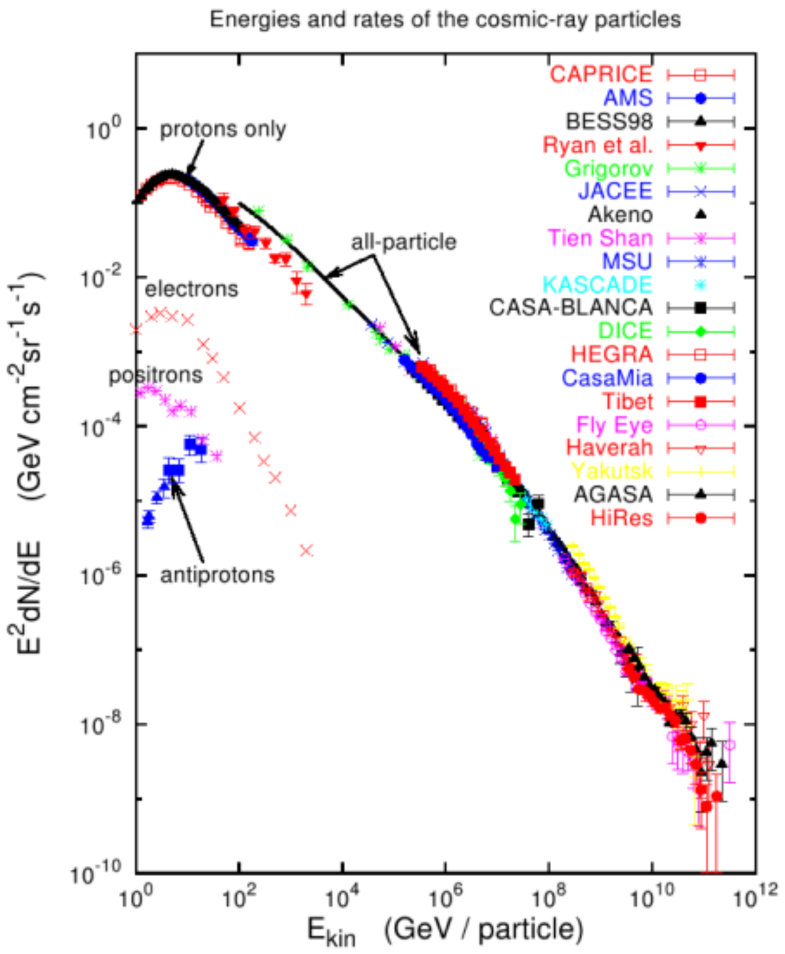
All measured variation in ionization as a function of altitude

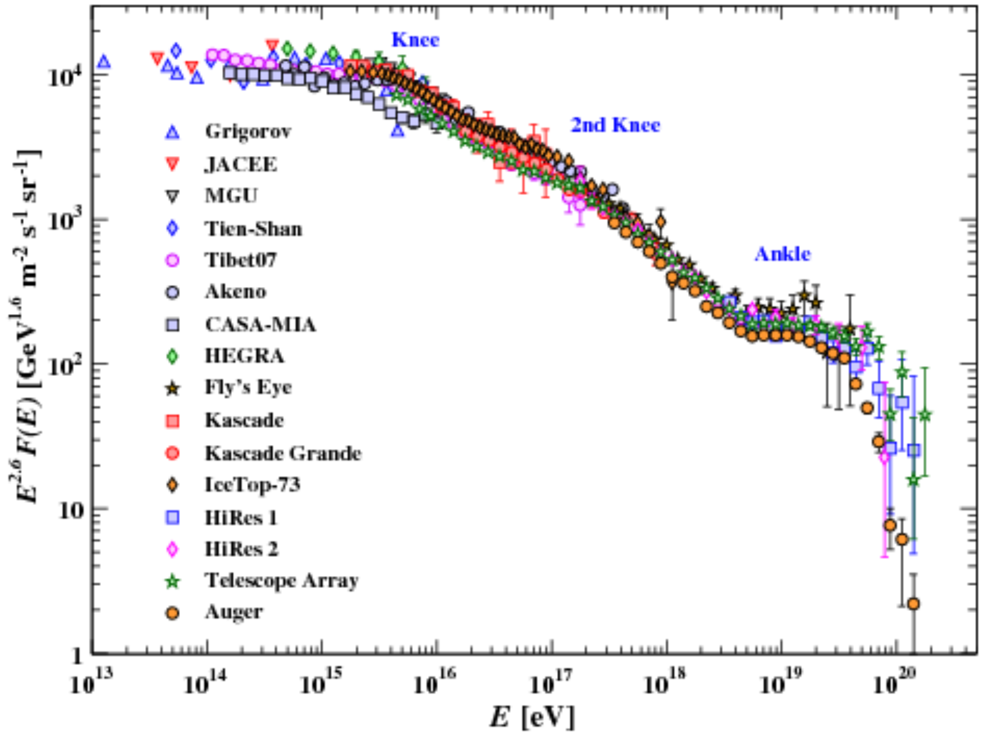
Evidence pointed to a source of charged particles, some with enormous energy, outside of our atmosphere
=> Cosmic rays!



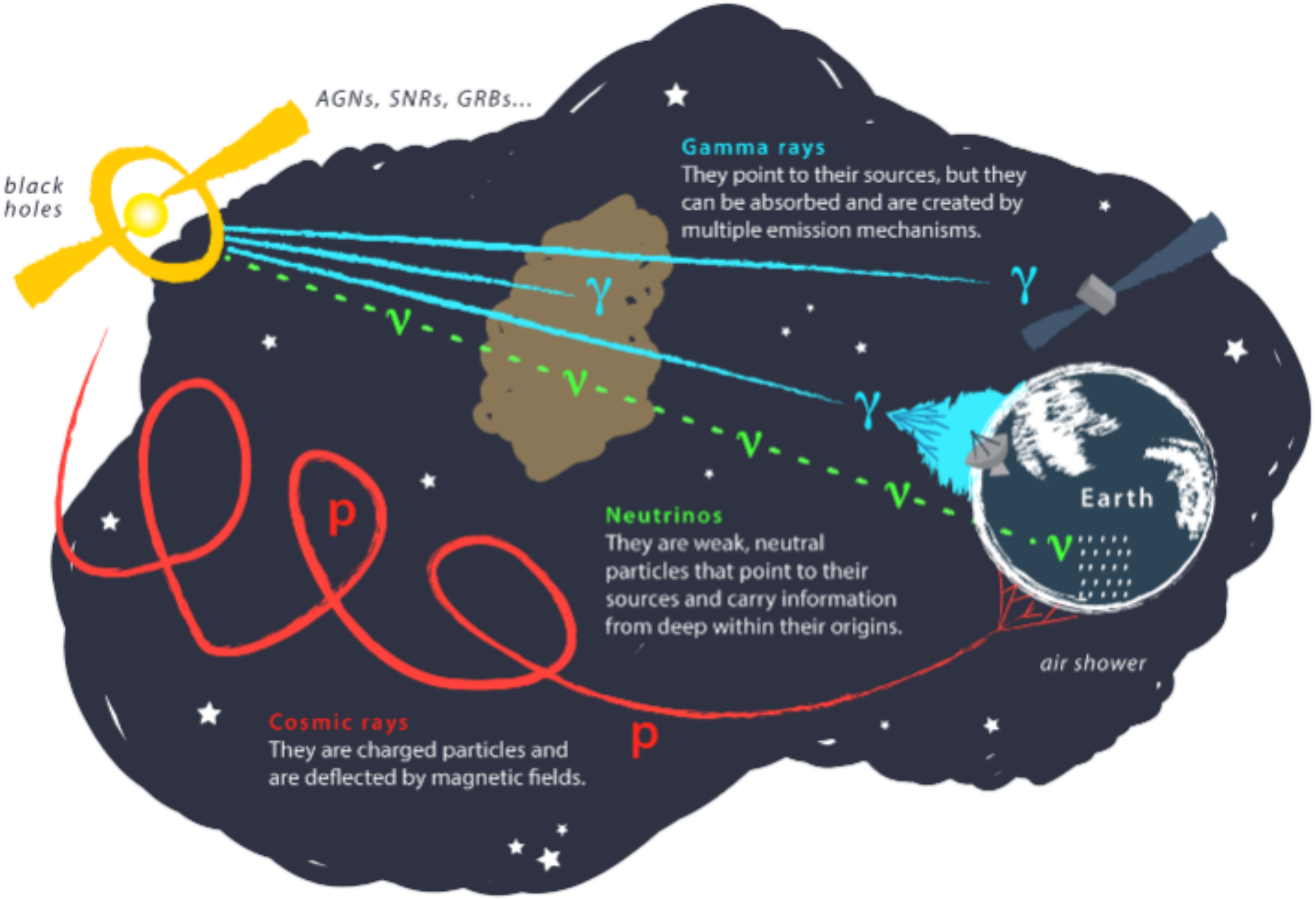

Heaps of these must
exist in the Universe

Cosmic ray spectrum

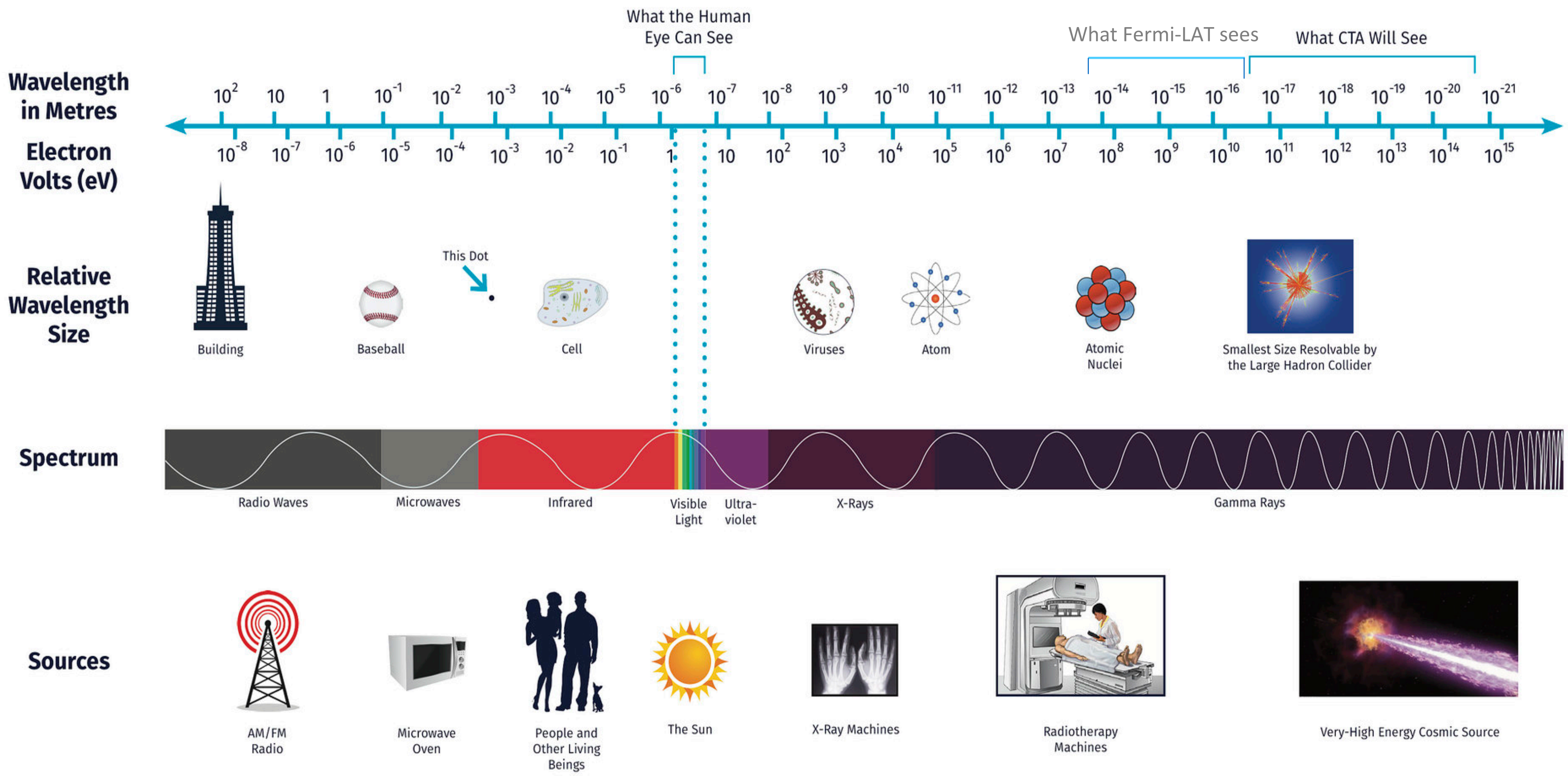




Searching for the source of CRs…



Gamma-ray astrophysics



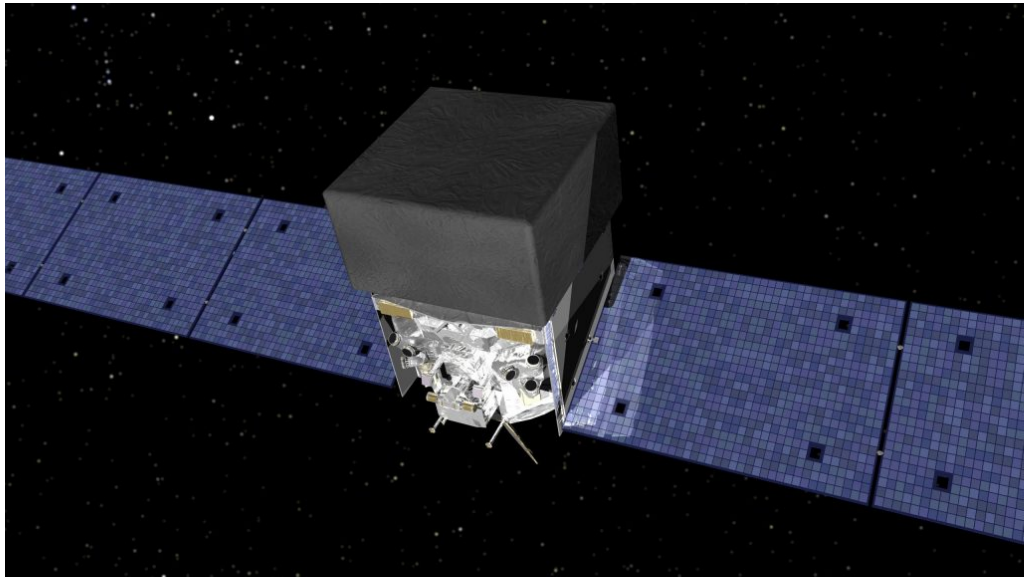
The term ‘gamma-ray’ covers an enormous energy range – at least 8 orders of magnitude and more.

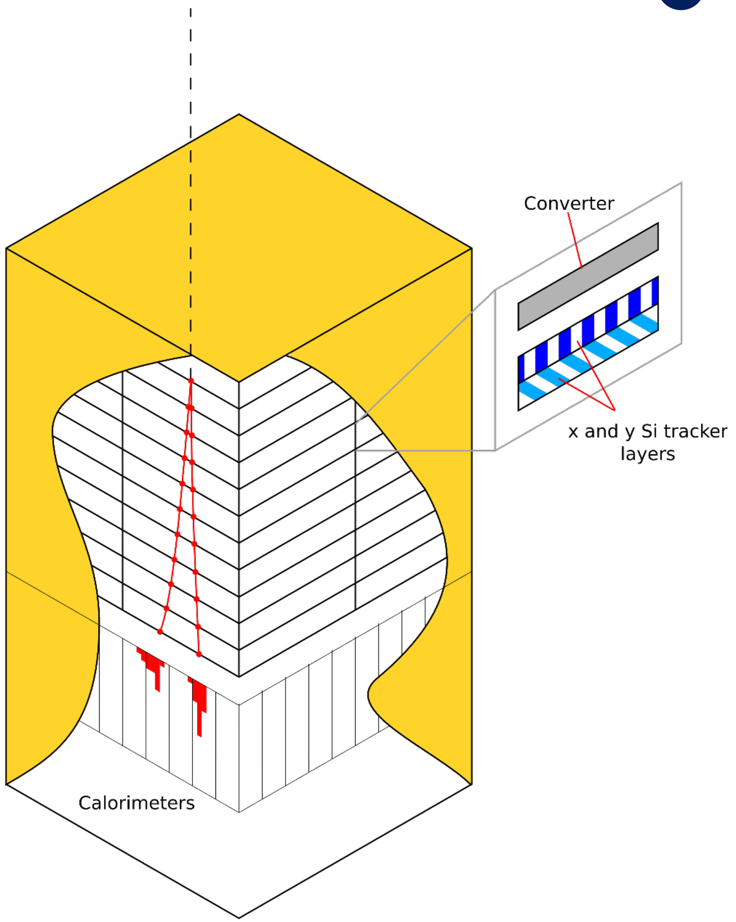
For astronomers, there are several problems:

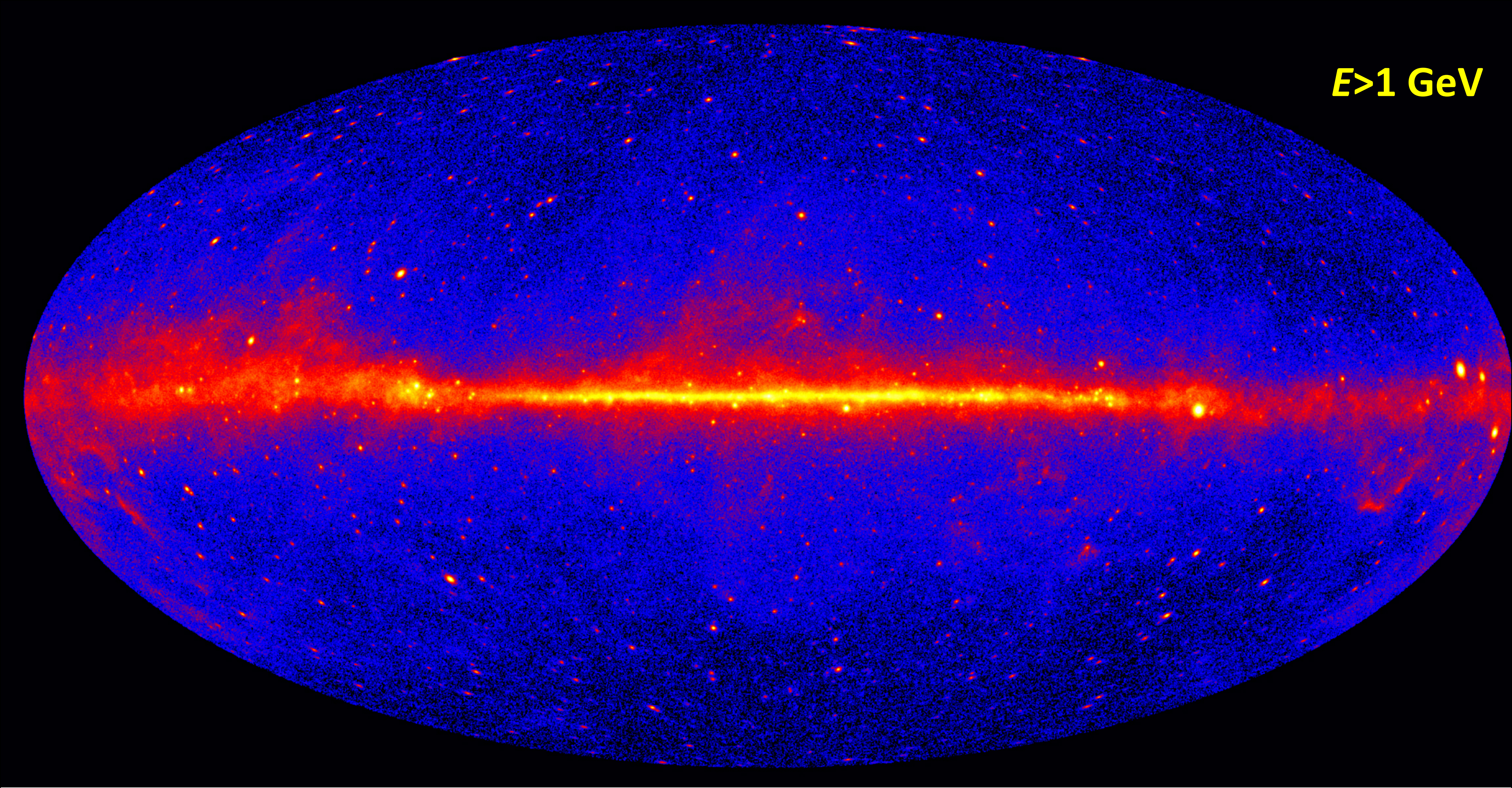
- you can’t focus gamma rays;
- gamma rays don’t penetrate the Earth’s atmosphere;
- gamma rays are rare.

Space-based telescope: *Fermi*-LAT

- Doesn't observe the gamma-rays directly, just the by-products of their absorption (essentially the LAT detector is a particle physics detector in space.)
- Observes 60 MeV - 2 TeV photons
- 0.8 degree ang. res. above 1 GeV
- LAT scans the entire sky every 3 hours (for the last ~10 years)



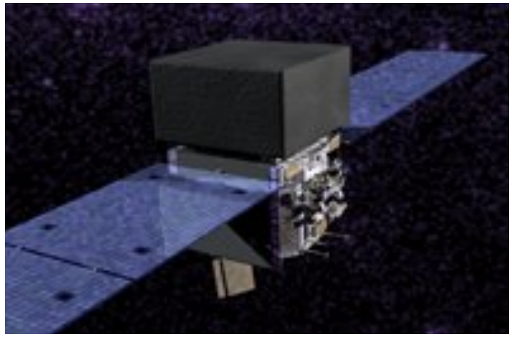



E>1 GeV

However, there are LAT limitations: Effective area

- The *Fermi*-LAT has shown us what happens when technological advances allow a step change from source discovery to source investigation…
- However, the LAT has limitations. Gamma-rays are rare and they get rarer as you go higher in gamma-ray energy.

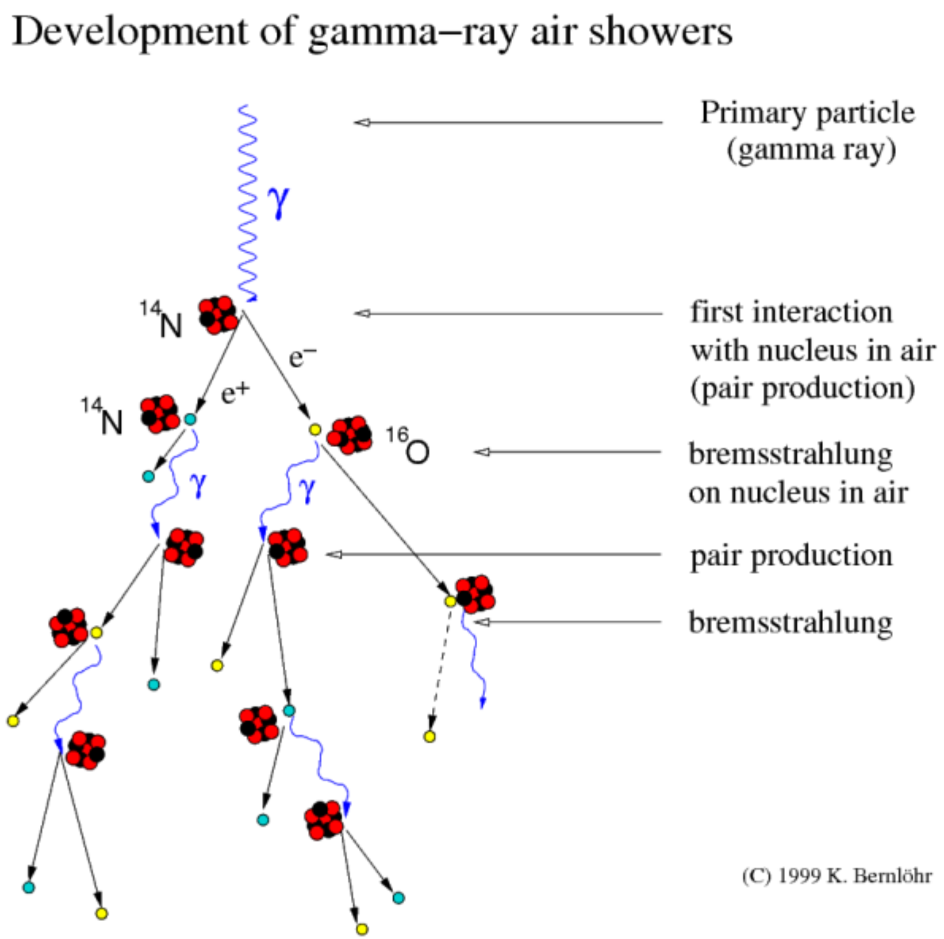
$1m^2$



$>10^4 m^2$

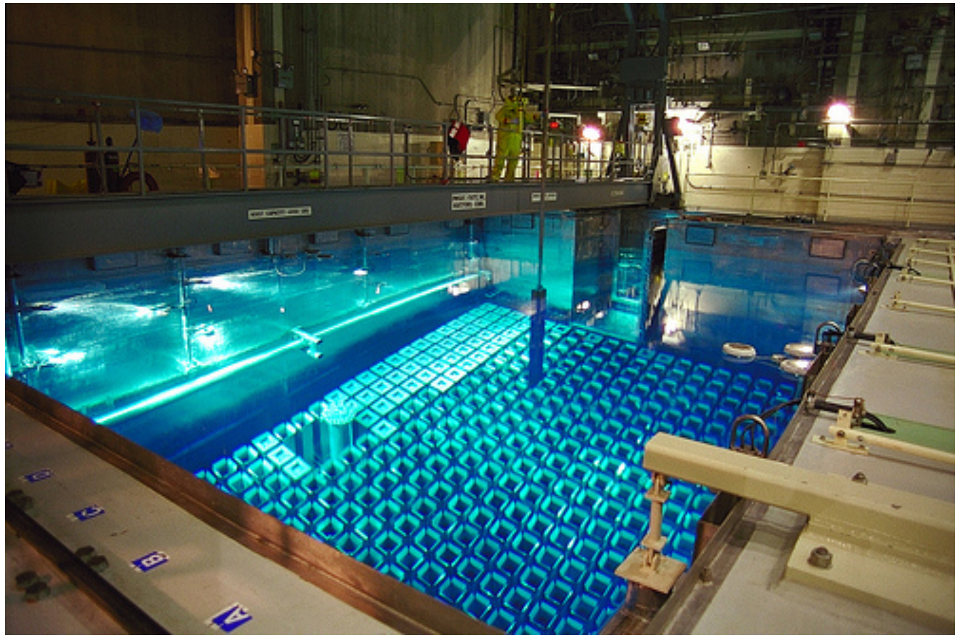
Extended air showers

- The earth's atmosphere is opaque to gamma-rays (luckily)
- The absorption of gamma-rays starts a cascade event known as an extended air shower
- Observe this air shower and we can indirectly observe the gamma-rays

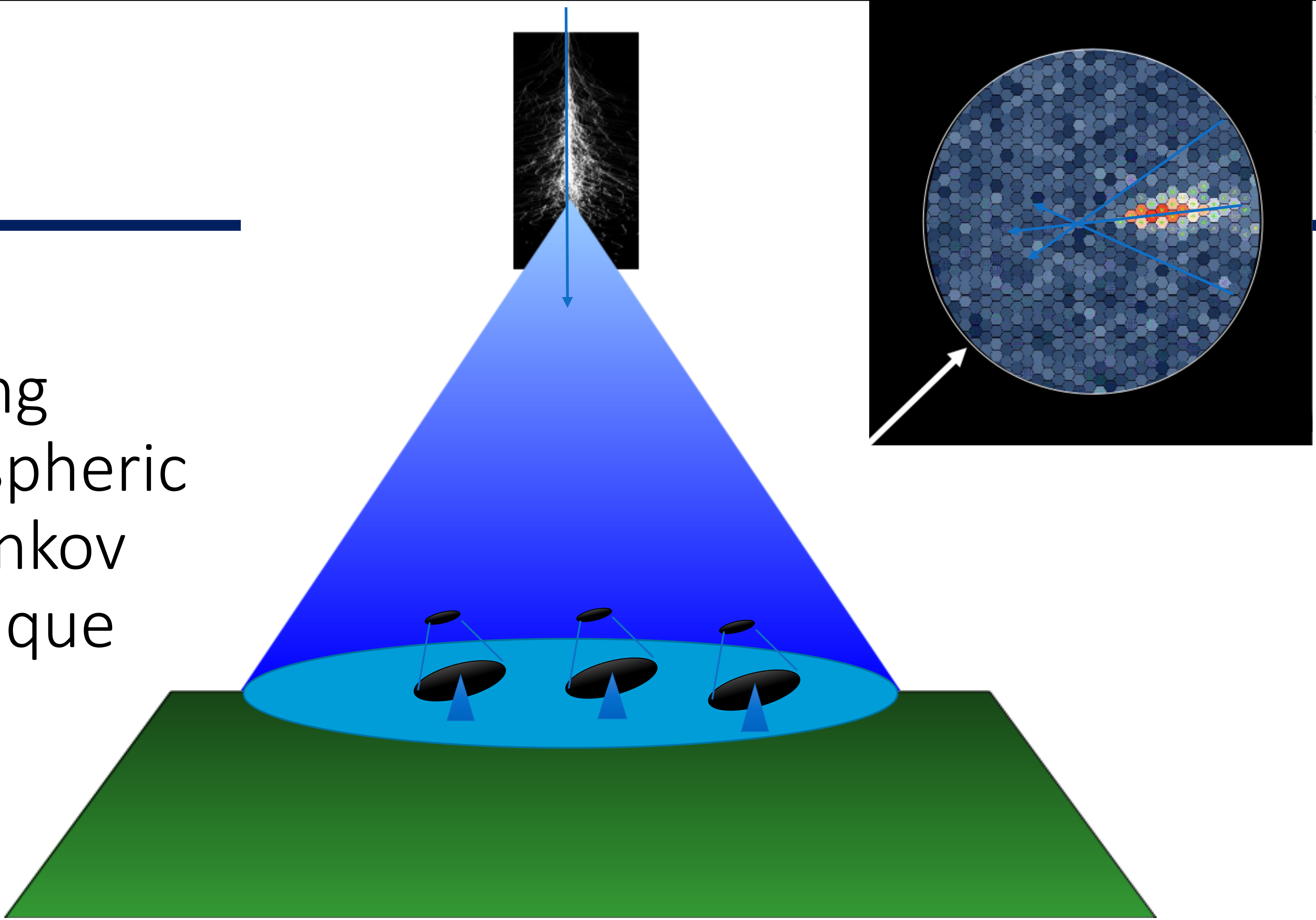


Cherenkov Radiation

- Charged particles travelling faster than the phase-velocity of light in a di-electric medium will emit light. This light is referred to Cherenkov light.
- Cherenkov light from EAS is very fast (~ns) and very faint (10^{-4} of the total star light.)

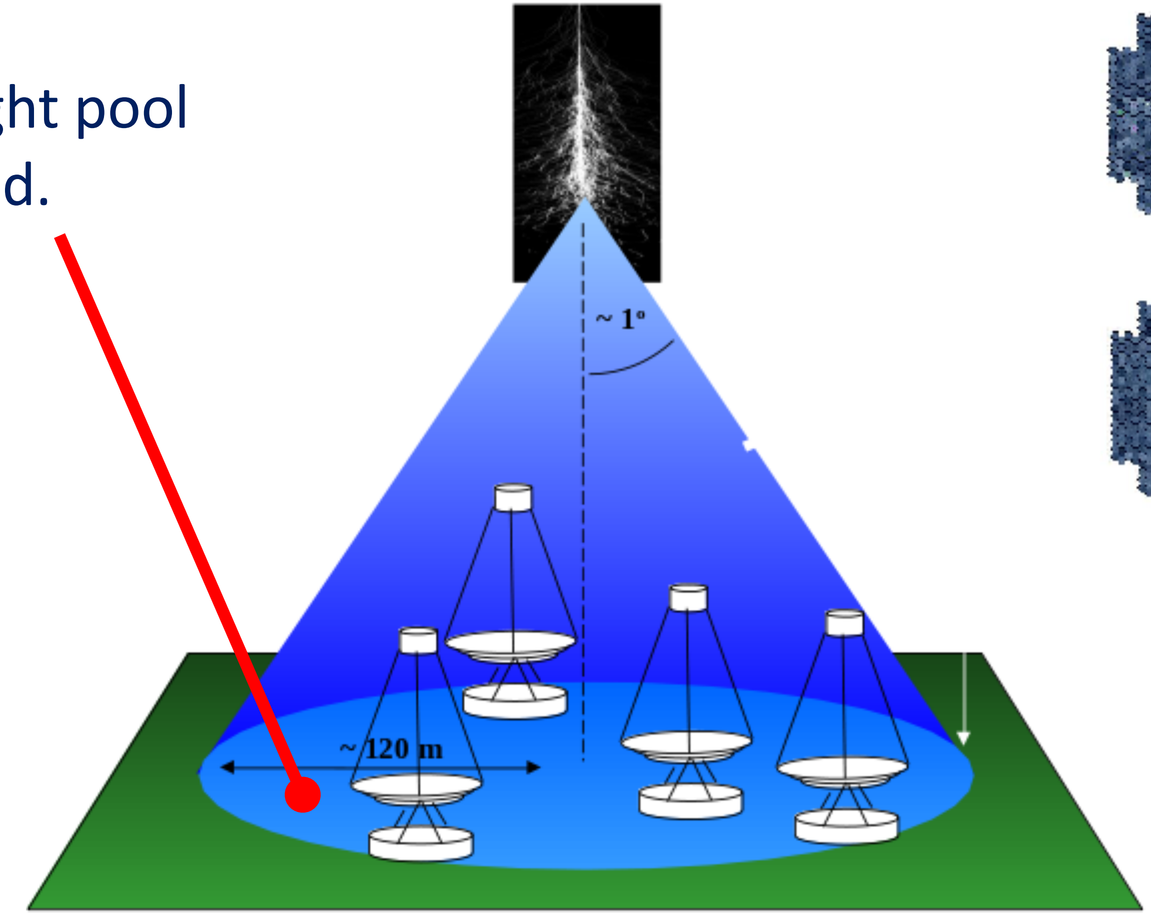


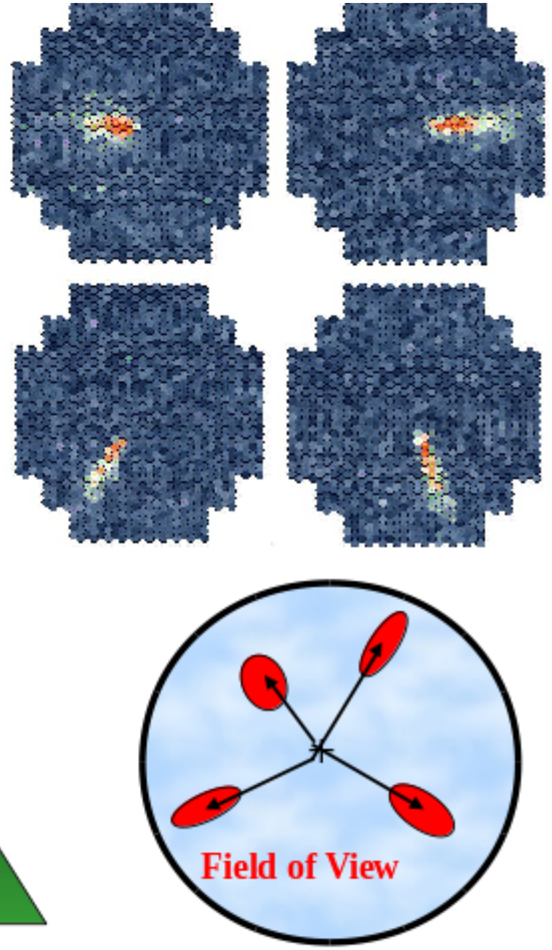
Imaging
Atmospheric
Cherenkov
Technique



Stereoscopic IACT

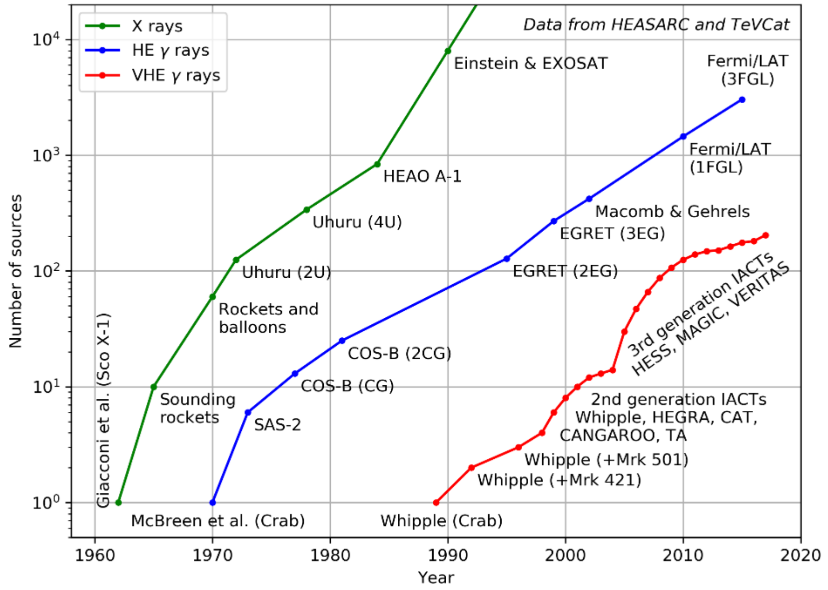
45,000 m^2 light pool on the ground.



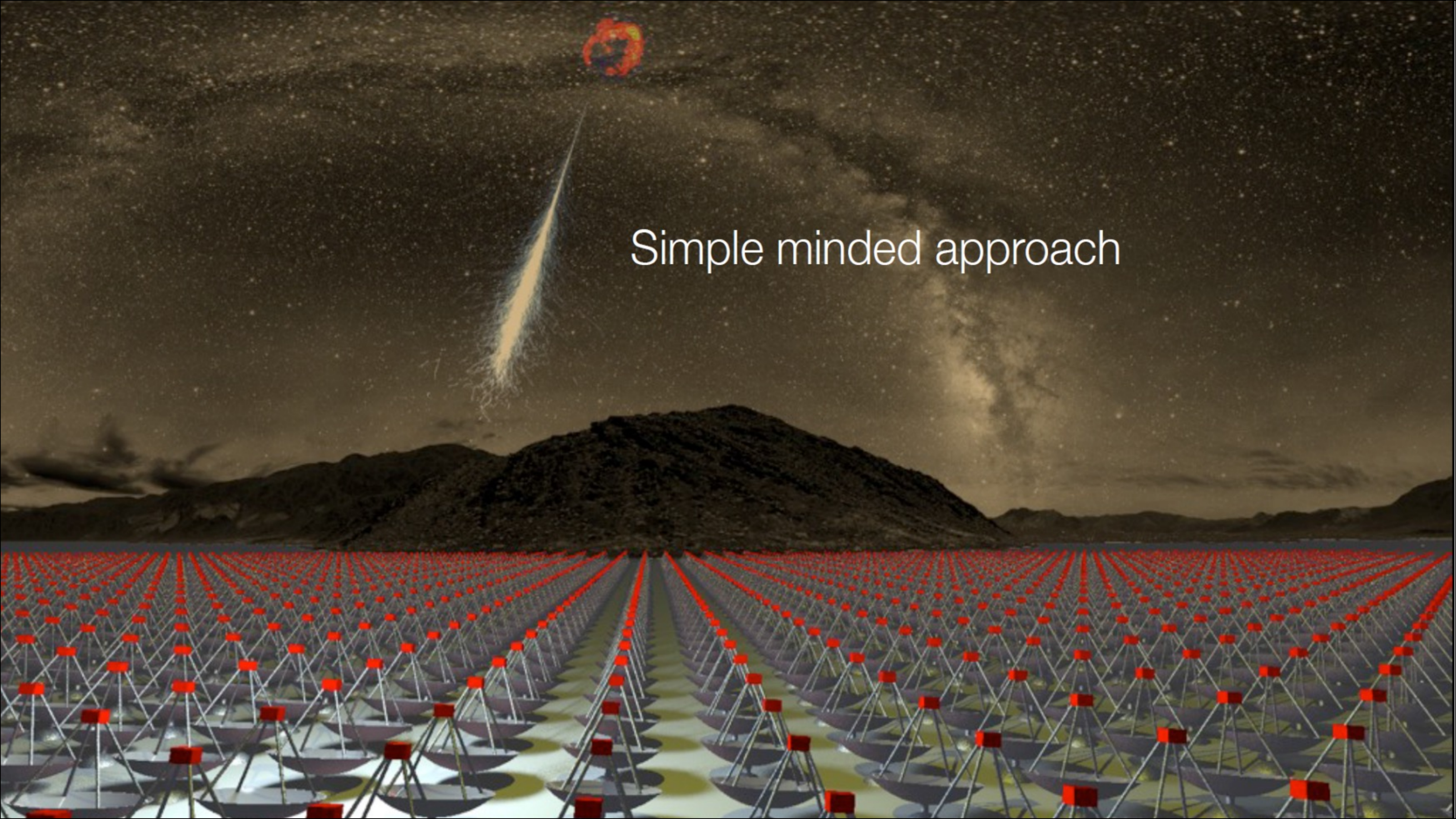


The future of IACTs

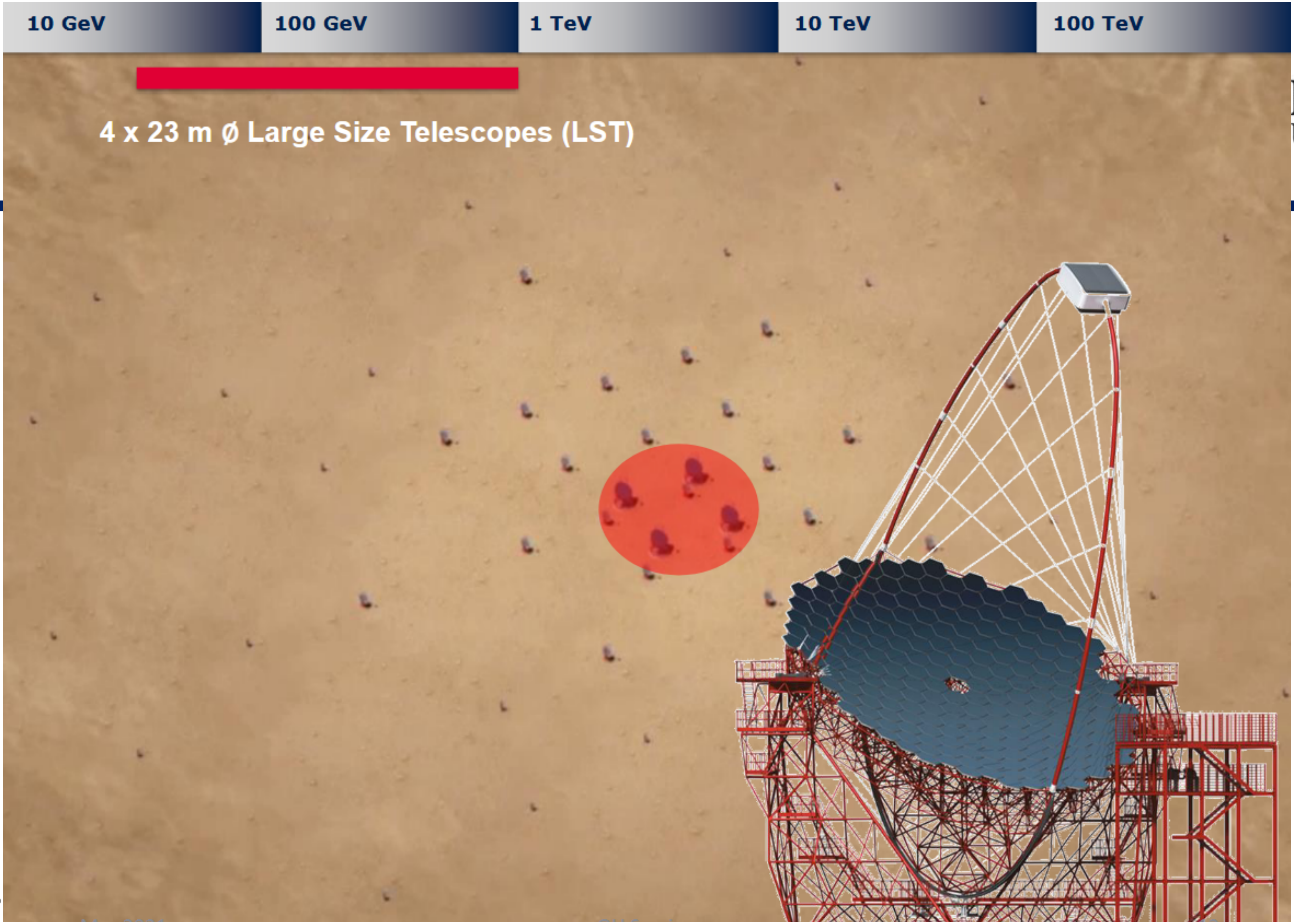
- The current generation of ground-based gamma-ray telescopes (VERITAS, H.E.S.S. & MAGIC) have been operating >15 years, during which time they have been opening up a new window through which to view the Universe by increasing the catalogue of VHE gamma-ray sources (225 sources as of this morning). Its time to think about the next step....



- Our ‘wish-list’ for the next generation of ground-based gamma-ray telescope:
  - An order of magnitude improvement in performance
  - A larger energy range (lower threshold and higher maximum)
  - All sky coverage
  - Observatory operation, ie, open to a large community of astronomers, not just those in CTA


Simple minded approach

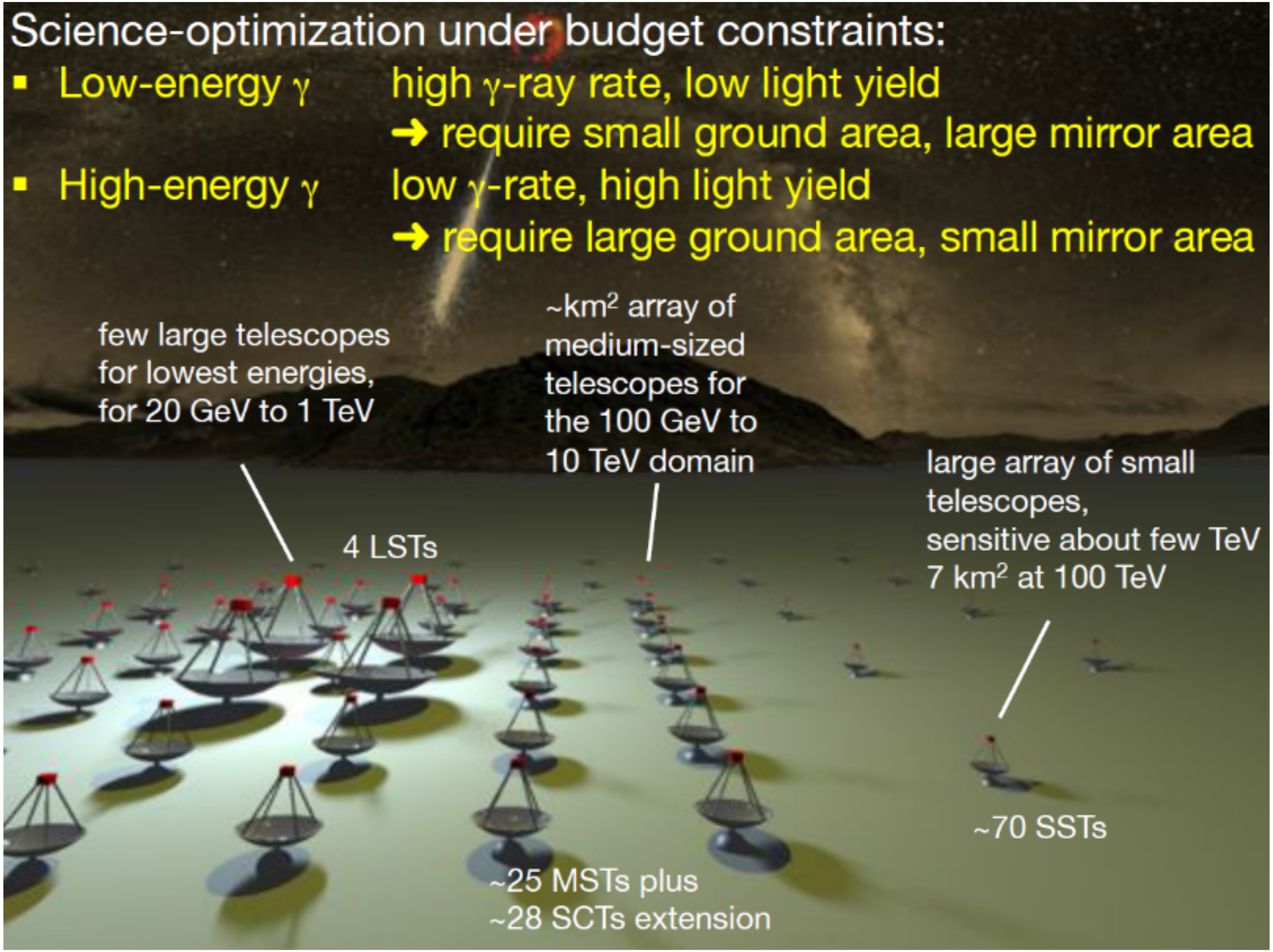

10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ / h km²
10 γ / h km²
0.1 γ / h km²
Southern array
of Cherenkov telescopes
- about 3 km across



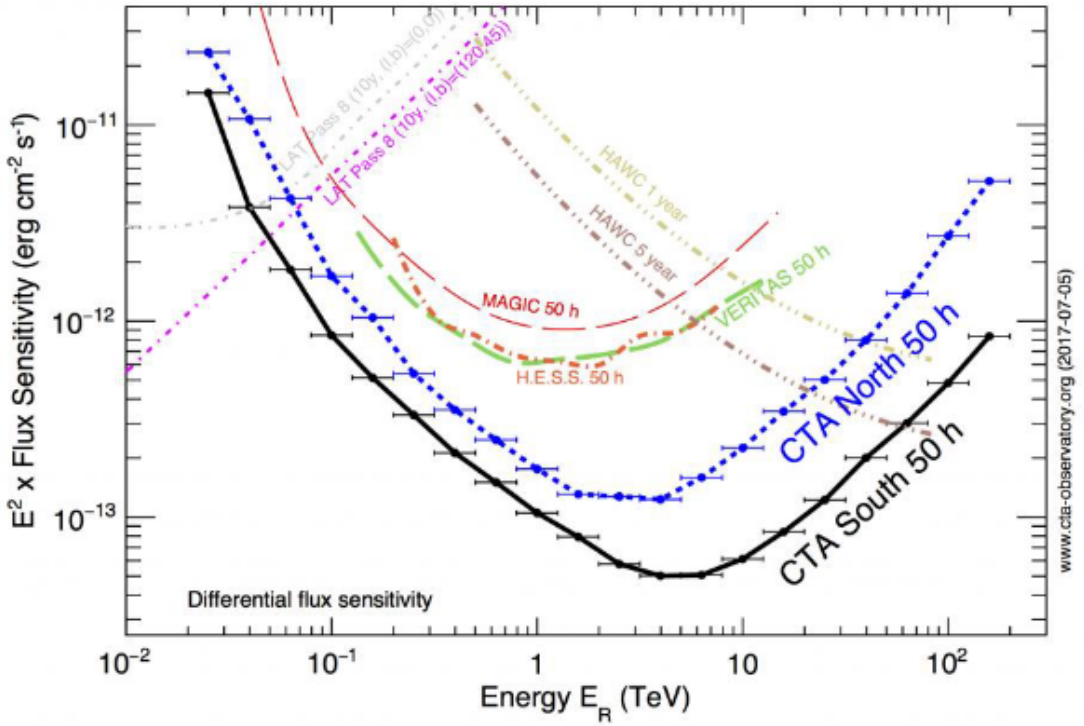
Durham
University

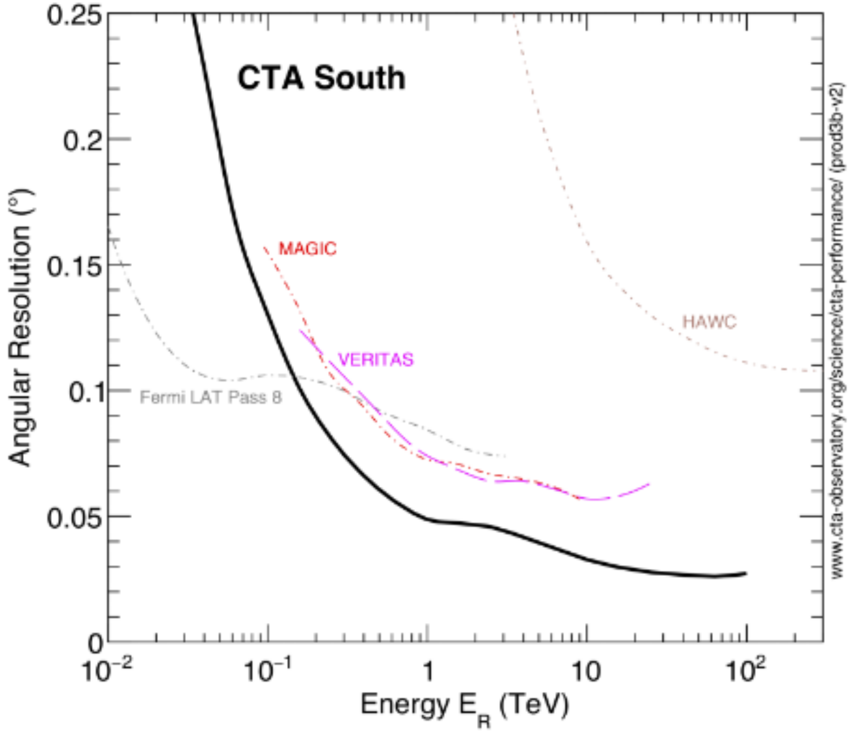

10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
25 x 12 m ø Medium Size Telescopes (MST) (North: 15)

Durham University

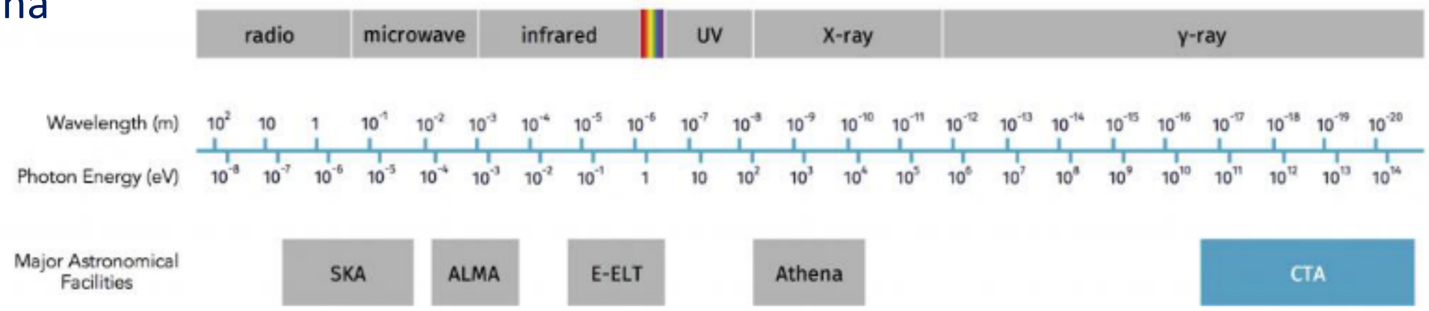

Science-optimization under budget constraints:
Low-energy γ
high γ-ray rate, low light yield
➜ require small ground area, large mirror area
High-energy γ
low γ-rate, high light yield
➜ require large ground area, small mirror area
few large telescopes for lowest energies, for 20 GeV to 1 TeV
~km² array of medium-sized telescopes for the 100 GeV to 10 TeV domain
large array of small telescopes, sensitive about few TeV
7 km² at 100 TeV
4 LSTs
~25 MSTs plus
~28 SCTs extension
~70 SSTs

Expected CTA performance

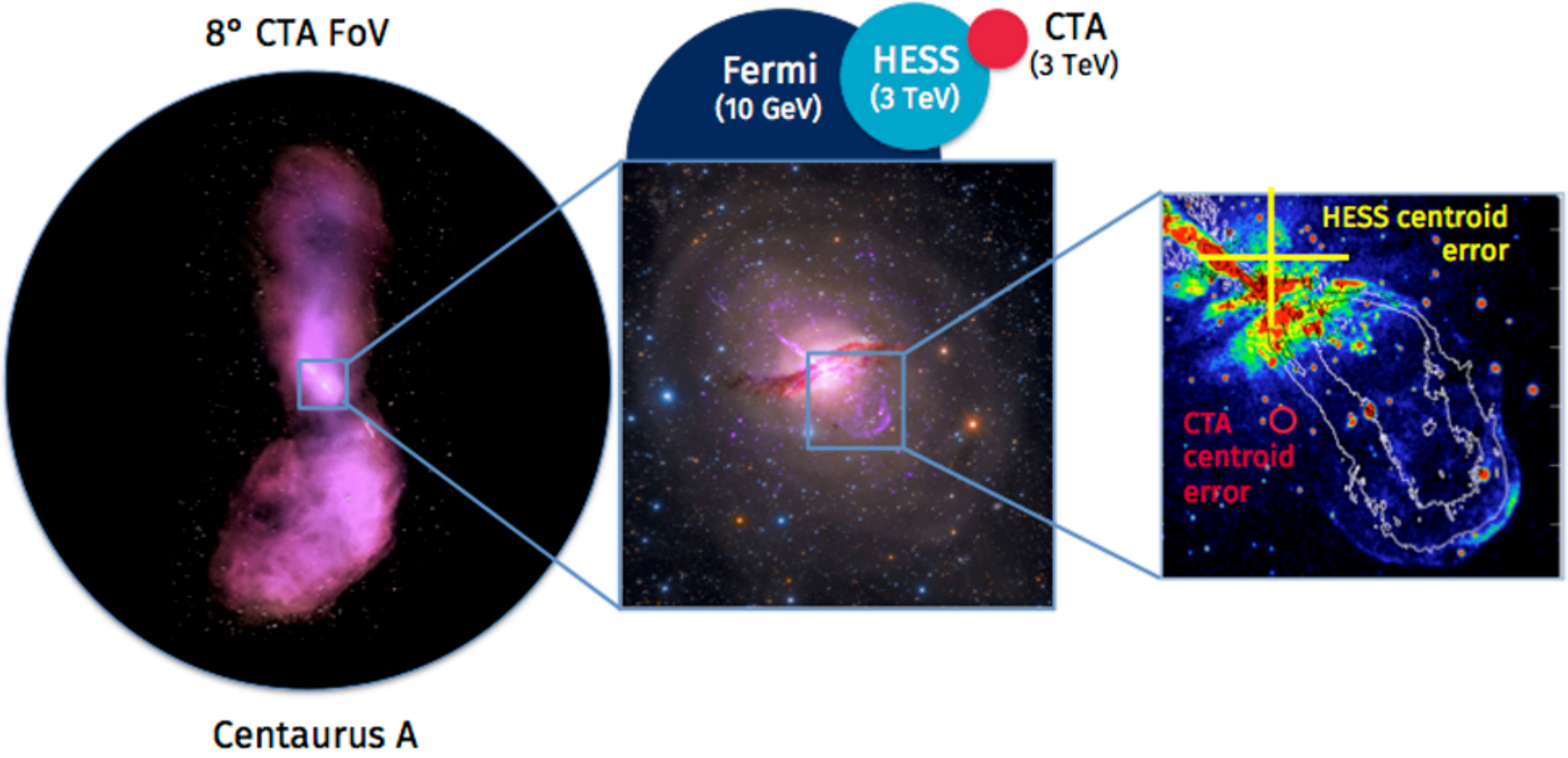




There will be an initial alpha and a final omega array.



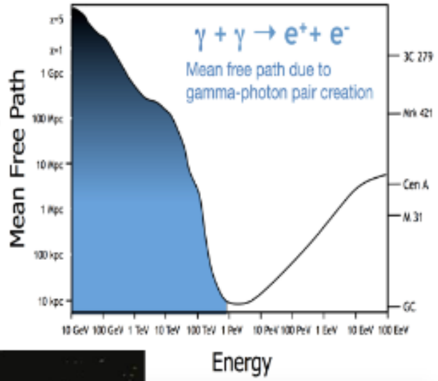
CTA angular resolution

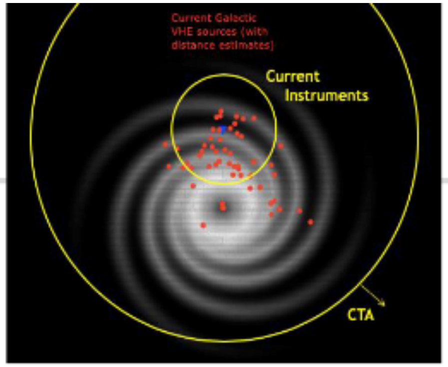


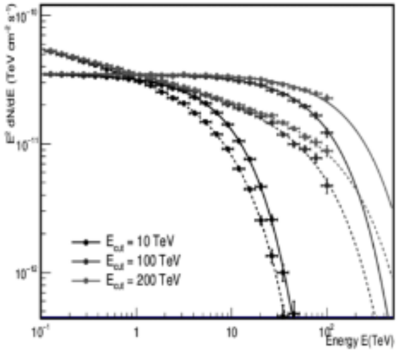
Science Cases for CTA

- Theme 1: Cosmic Particle Acceleration
  - How and where are particles accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- Theme 2: Probing Extreme Environments
  - Processes close to neutron stars and black holes?
  - Processes in relativistic jets, winds and explosions?
  - Exploring cosmic voids
- Theme 3: Physics Frontiers – beyond the SM
  - What is the nature of dark matter? How is it distributed?
  - Is the speed of light constant for high energy photons?
  - Do axion-like particles exist?

Science case online @ arxiv:1709.07997 (now also published as a hard back). Strongly encourage you to have a look at it to see what CTA can do for your favourite astronomy topic.







10 x Sensitivity, Large Collection Area

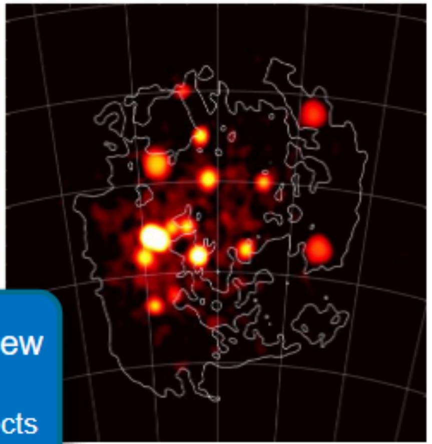
→ all topics

Energies down to 20 GeV

→ Cosmology++

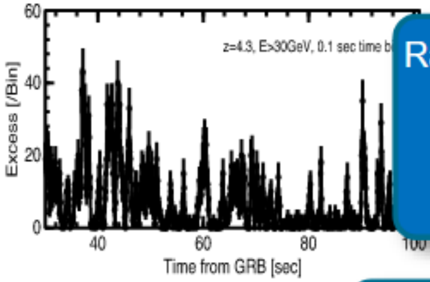
Energies up to 300 TeV

→ Pevatrons



Rapid Slewing in 20 seconds

→ transients

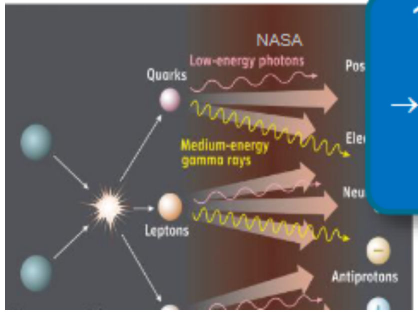


8º Field of View

→ surveys, extended objects

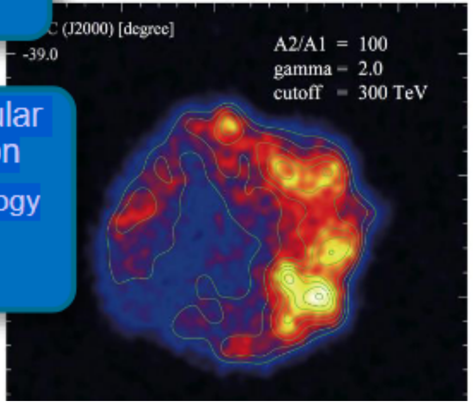
10% Energy Resolution

→ lines, features



Few ' Angular Resolution

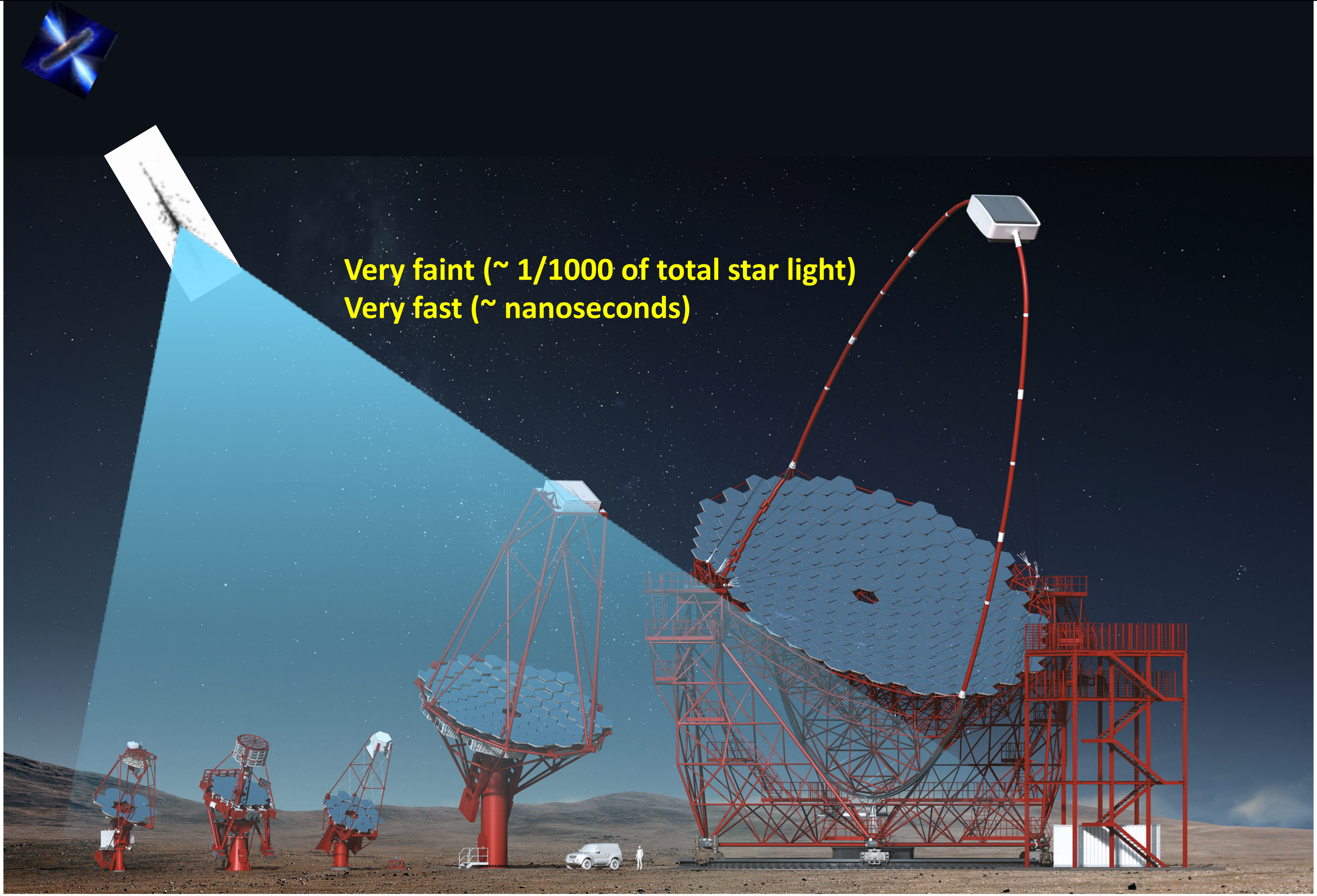
→ morphology

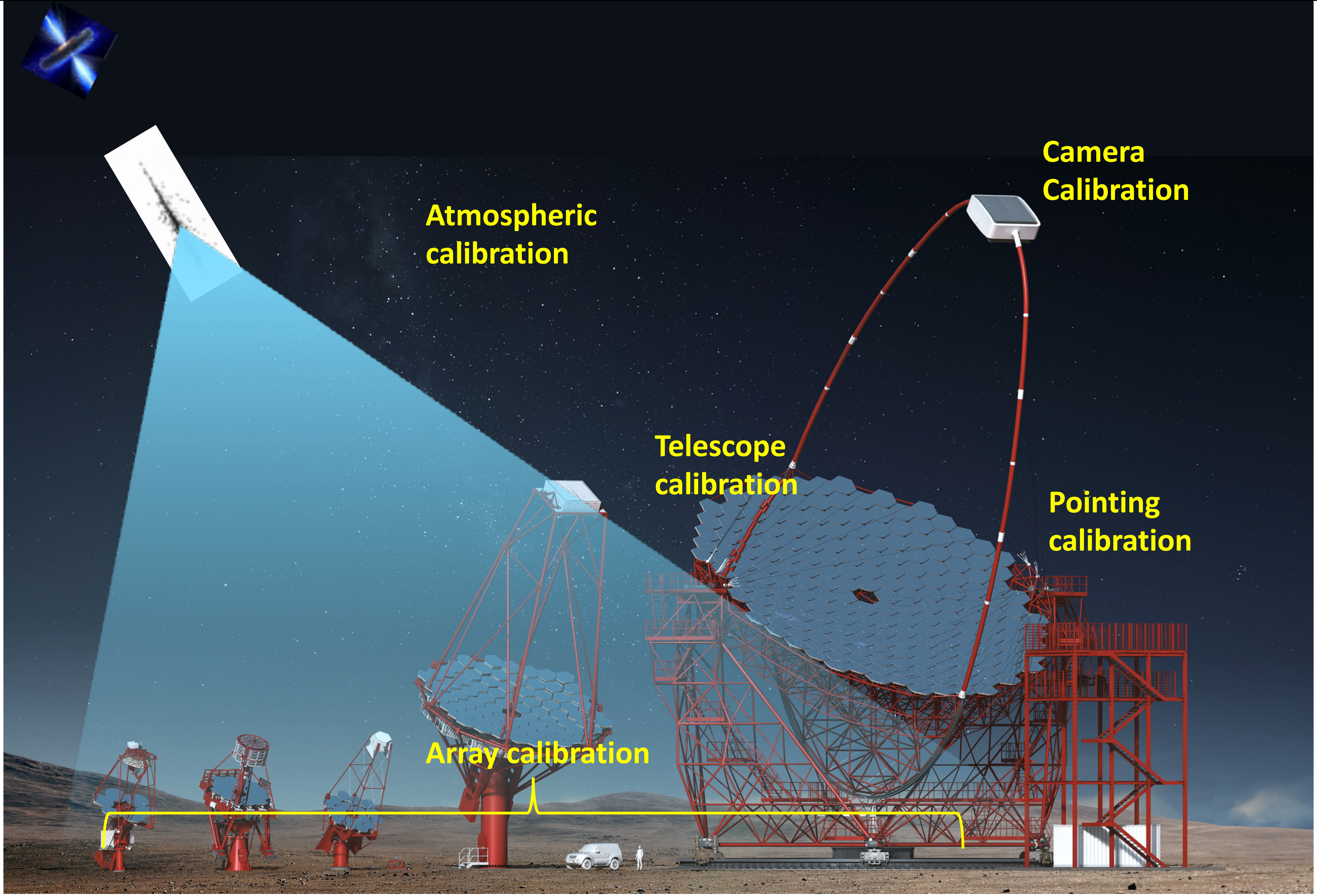


Tackling these science cases…

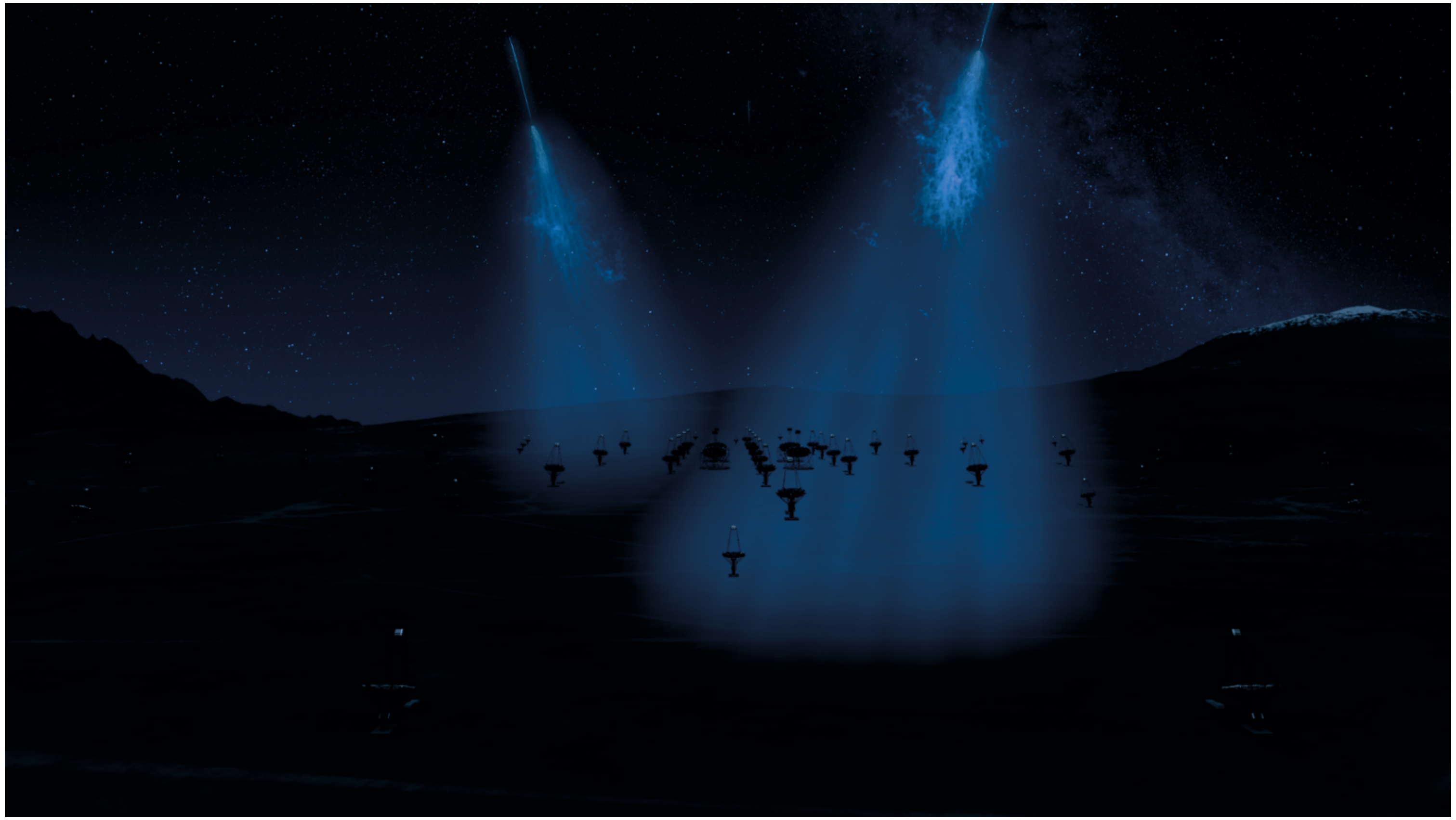
- To achieve CTA’s goals forces upon us strict requirements for the systematic uncertainties of CTA.
  - Energy res. of a photon
  - Energy scale shift (bias)
  - Angular resolution (image resolution)
  - Collection Area
  - Absolute intensity
- Quantifying these uncertainties requires multiple techniques and instruments, both at the camera level and at the array level.

  → a complex problem compounded by the shear size of CTA.


Very faint (~ 1/1000 of total star light)
Very fast (~ nanoseconds)

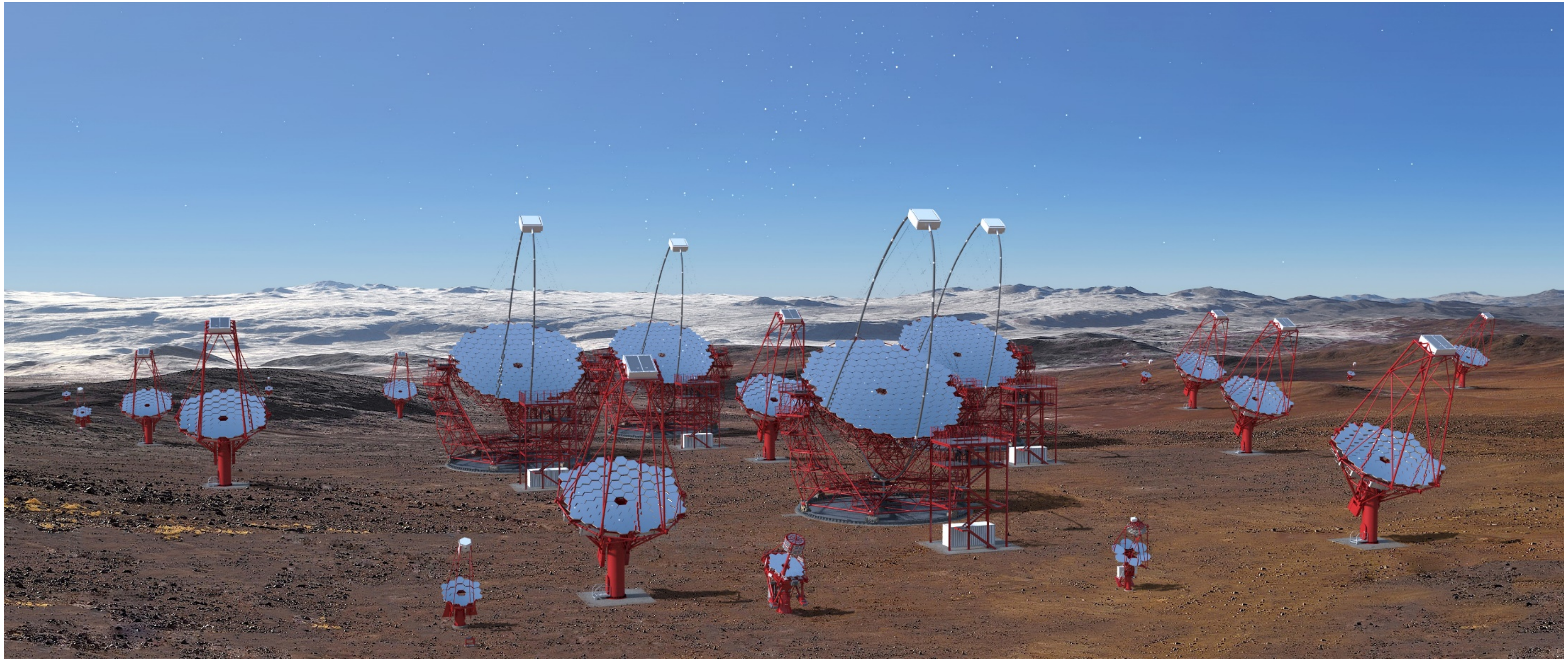

Camera
Calibration
Atmospheric
calibration
Telescope
calibration
Pointing
calibration
Array calibration

Calibration challenges:
….from the very fast & faint.



How to calibrate telescopes designed to observe faint nanosecond flashes of light?

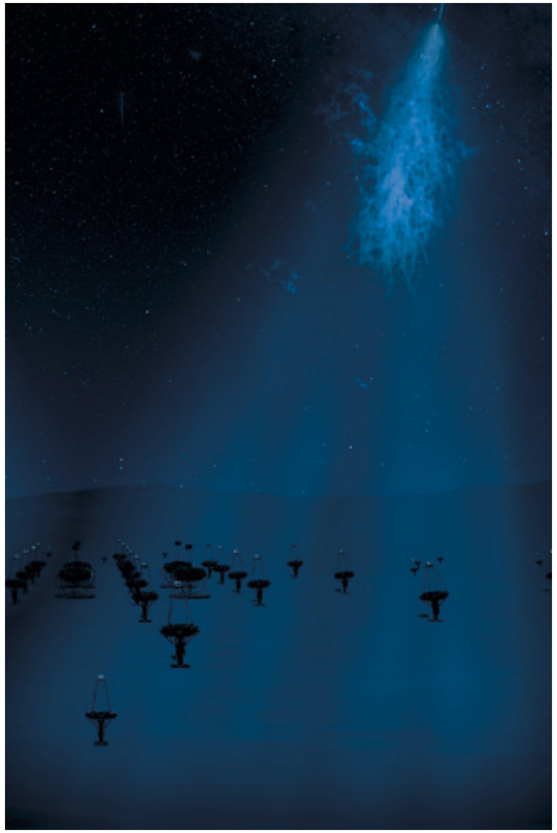
Calibration challenges:
….to the very large.



How to quickly cross-calibrate the sensitivity of 95 telescopes across 4 km^2?

Calibration challenges:
….to the very large.

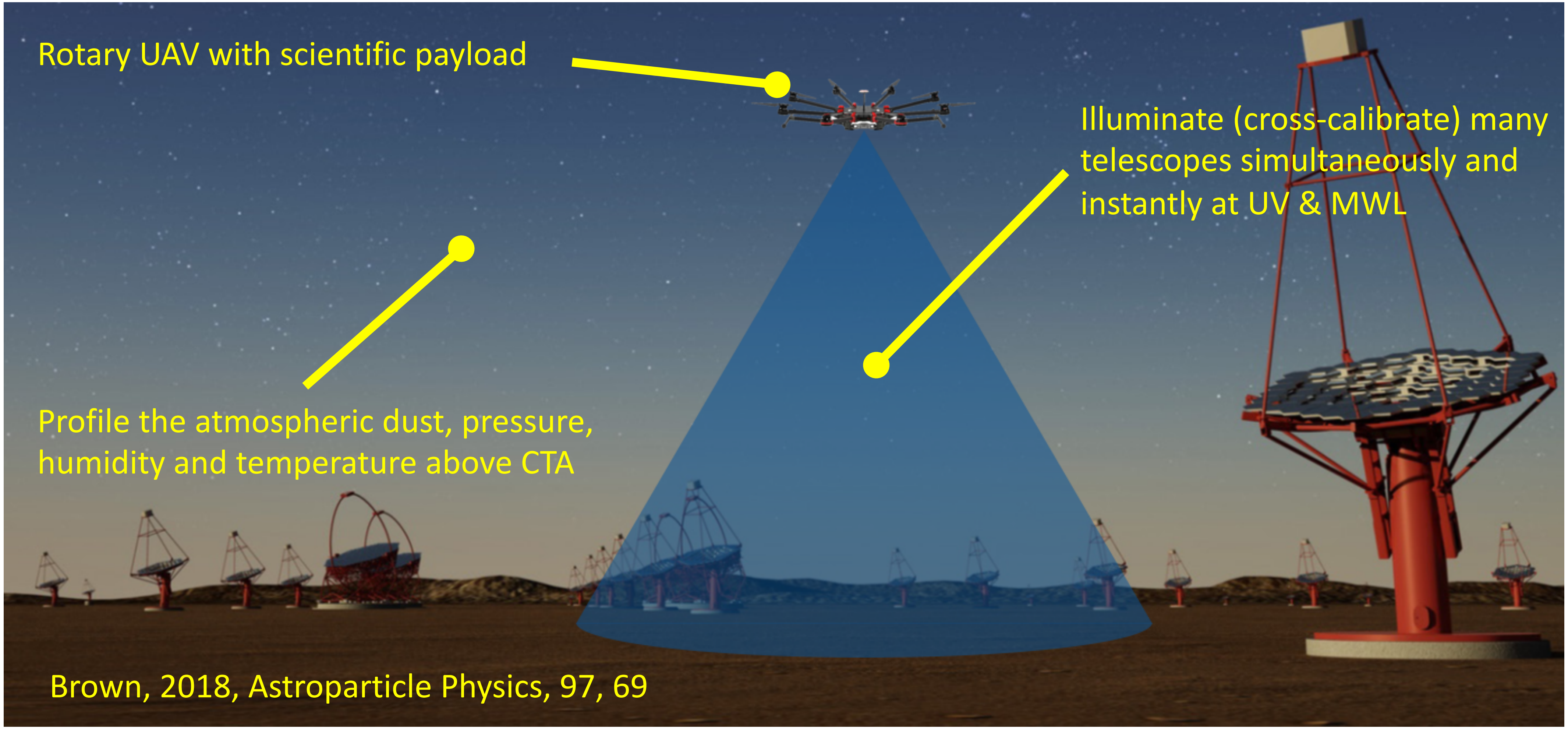
‘Central laser facility’
Pulses laser beam, viewed by
all telescopes within CTA



‘Air showers’: Compare images of the same
air shower as seen by multiple telescopes

‘Illuminator’
Well calibrated light source
driven around on a Ute

UAV-based calibration concept



Why a UAV?

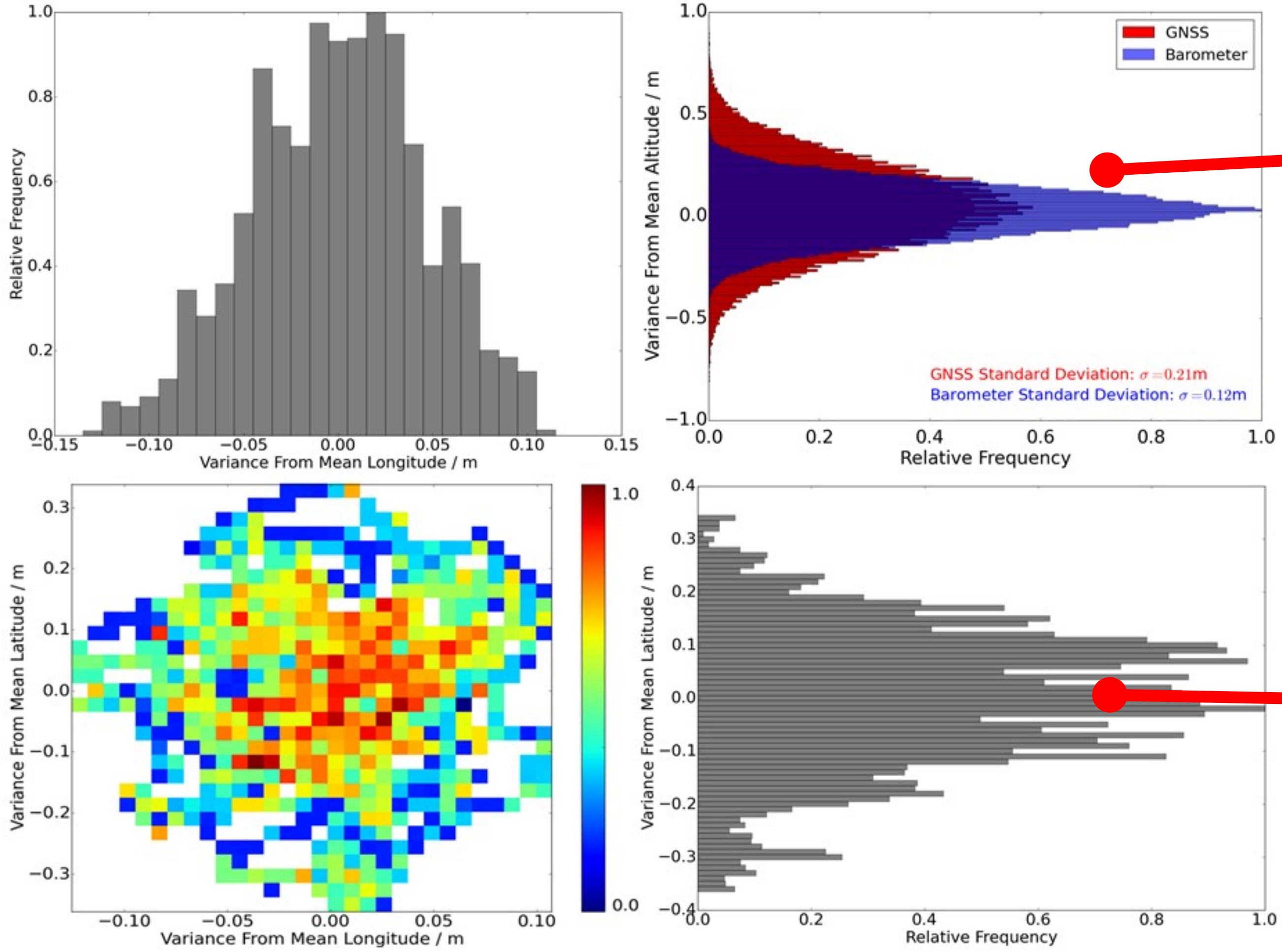
- Understanding optical throughput is critical for us to achieve our goals for the systematic uncertainties of CTA.
- Considering effort has gone into investigating telescope optical cross-calibration methods:
  - Air showers: using CR, γ-ray or muon-ring observations
    - **'For free', with no loss of observing time**
    - **No multi-wavelength (MWL) information**
  - Instrumentation: design a calibration device (CLF or illuminator)
    - **Has MWL information**
    - **Restrictive hardware requirements or large amount of time needed to perform calibration**
- The flexibility of a UAV platform allows us to fly a MWL calibration light source, with EAS timing characteristics, above CTA and simultaneously illuminate a large number of telescopes (and more!!)

But….

- These are not toys…
- To maximise the accuracy of a UAV-based approach, we need to:
  i. Understand the error budget of the technique
     Brown, A.M., 2018, Astroparticle Physics, 97, 69 (arxiv:1711.01413)
  ii. Characterise the UAV contribution to the uncertainty
  iii. Characterise the light sources contribution to the uncertainty
  iv. Then take the time to marry the scientific payload to the UAV so that each one does not negatively effect the performance of the other…

Characterising UAV stability

Positional accuracy is good…

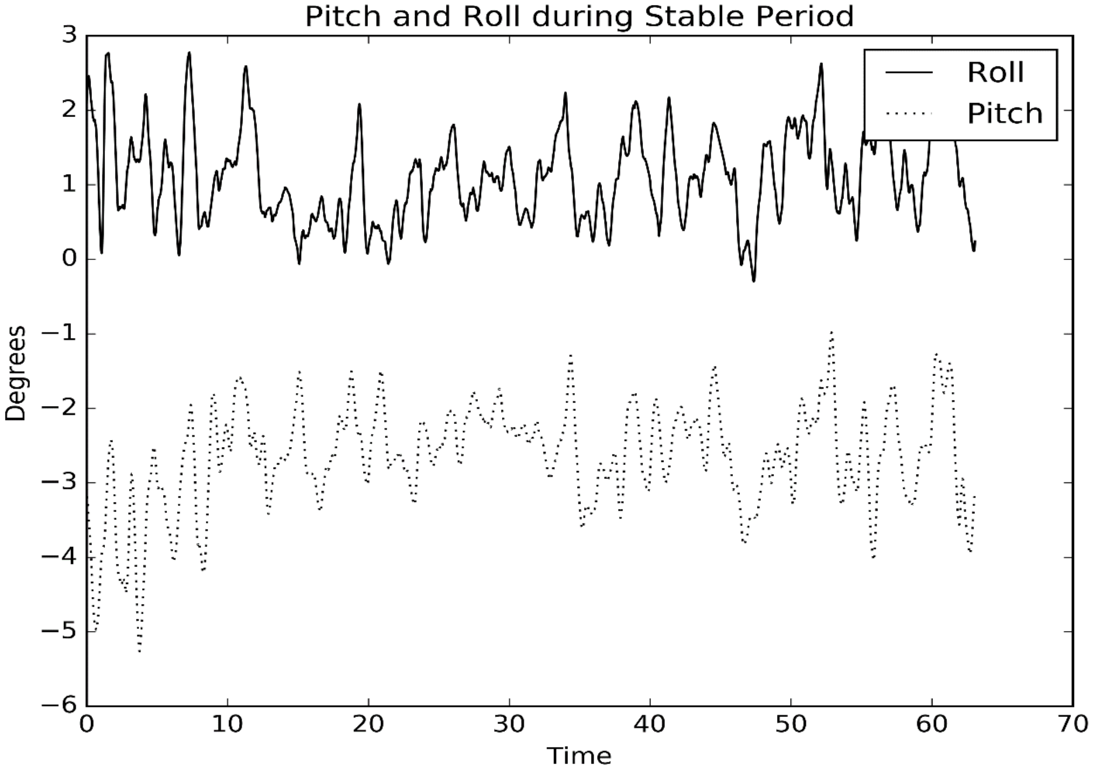


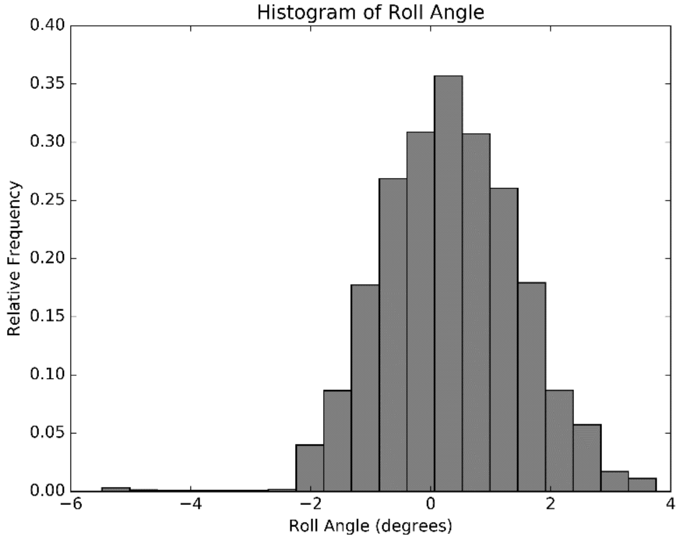
Barometer altitude determination is better than GNSS…

Tests flights of large consumer UAV

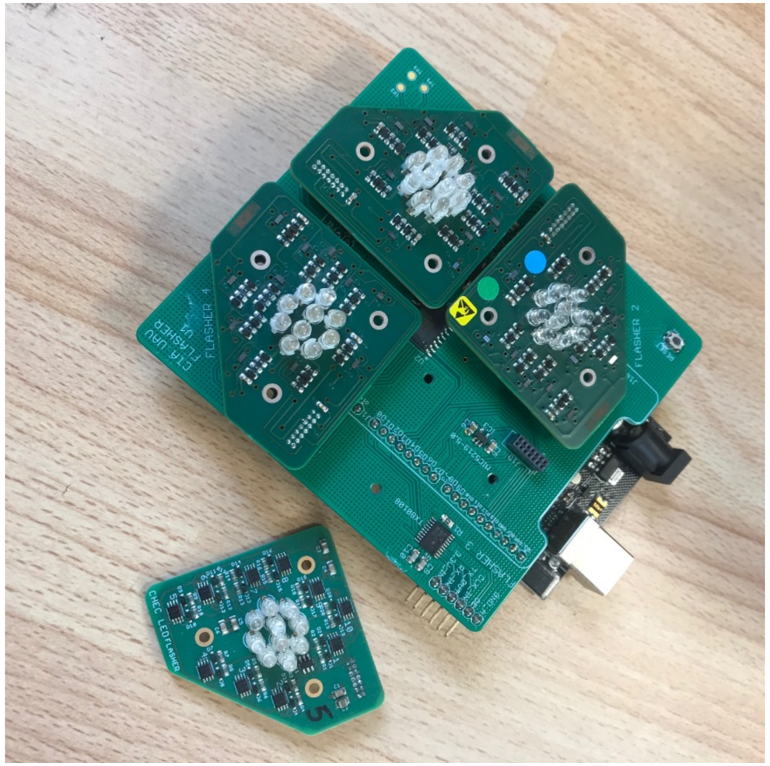
Off-the-shelf GNSS are sufficient for remaining in one pixel at ~1km from the telescope

Roll, pitch & yaw stability





Calibration payload



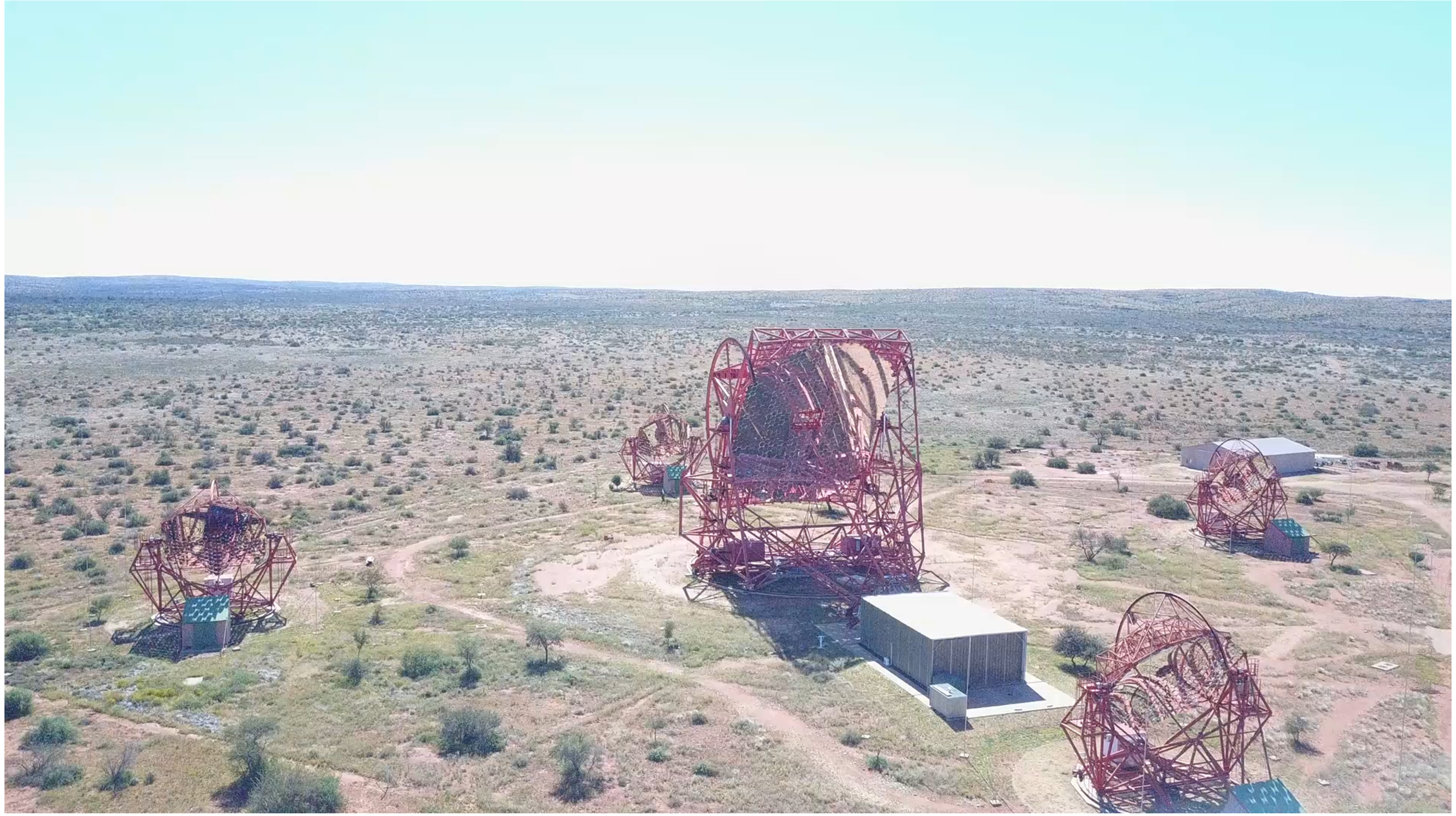
* 4 x adapted CHEC flashers
* Bespoke arduino based controller
* Dedicated GNSS system to trigger flashers

* 3D printed case
* 4 x 30° Circular top diffuser

Proof of concept…

- Item 1: characterise UAV positioning accuracy and stability ✓
- Item 2: build a lightweight (nanosecond-pulsed) UV light source that is triggered off GNSS timing signals. ✓
- Item 3: then find some telescopes to calibrate… ?

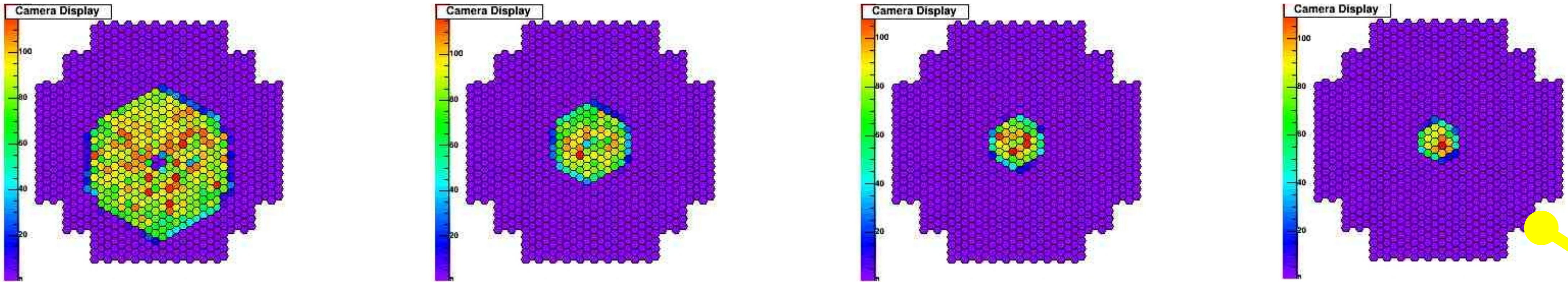
H.E.S.S. telescope array.



- H.E.S.S. telescope array in Namibia is the best proxy of the current generation to CTA.
- Namibia has strict UAV laws: I needed to engage with local air safety authorities!!
- After a review of my operational criteria and equipment by the NCAA, I had a legally granted temporary NoTAM around the H.E.S.S.
- I also had legally granted authority to fly to 1km agl and at night (ie BVLOS).

Flying at Namibia

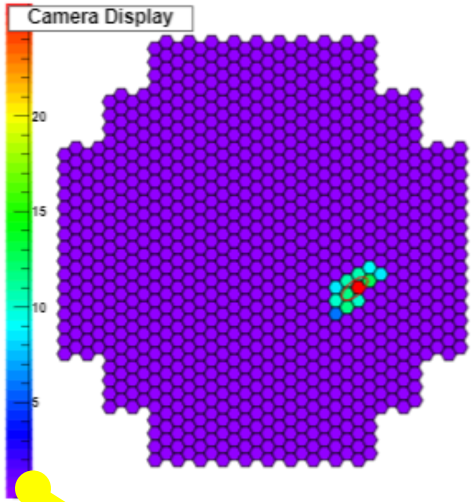
- Visited HESS telescope array in May 2018
- Due to focal length of HESS-I telescopes, UAV had to be >750m from array



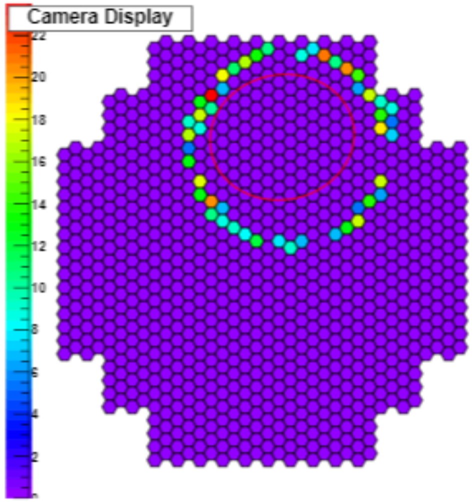
UAV simulations → Detector simulations → Image cleaning

Background discrimination

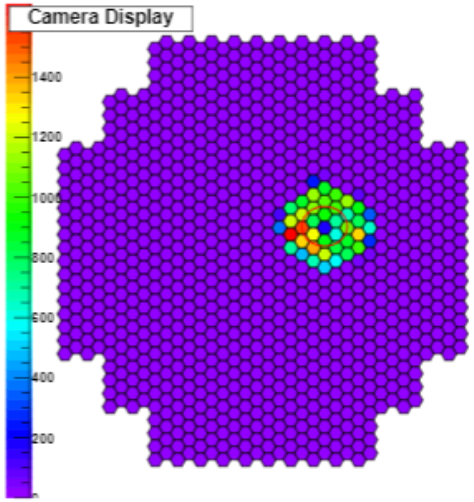
Cosmic ray

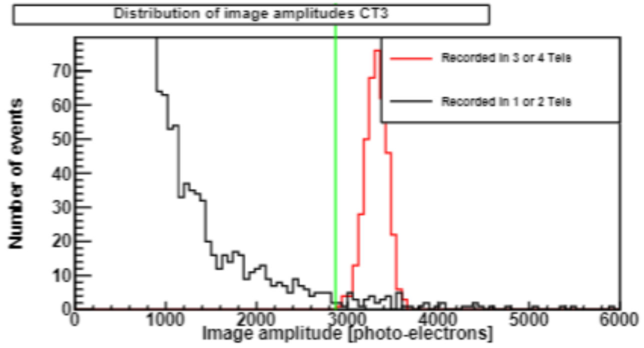


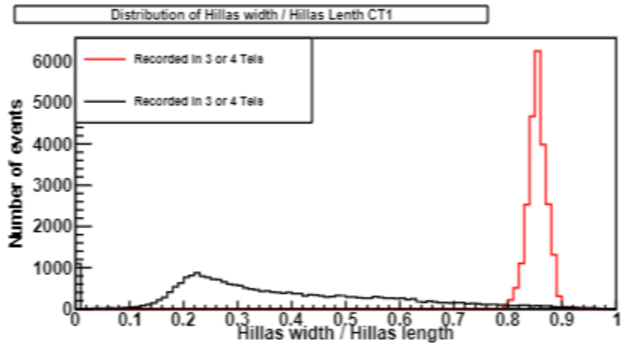
Muon ring



UAV event

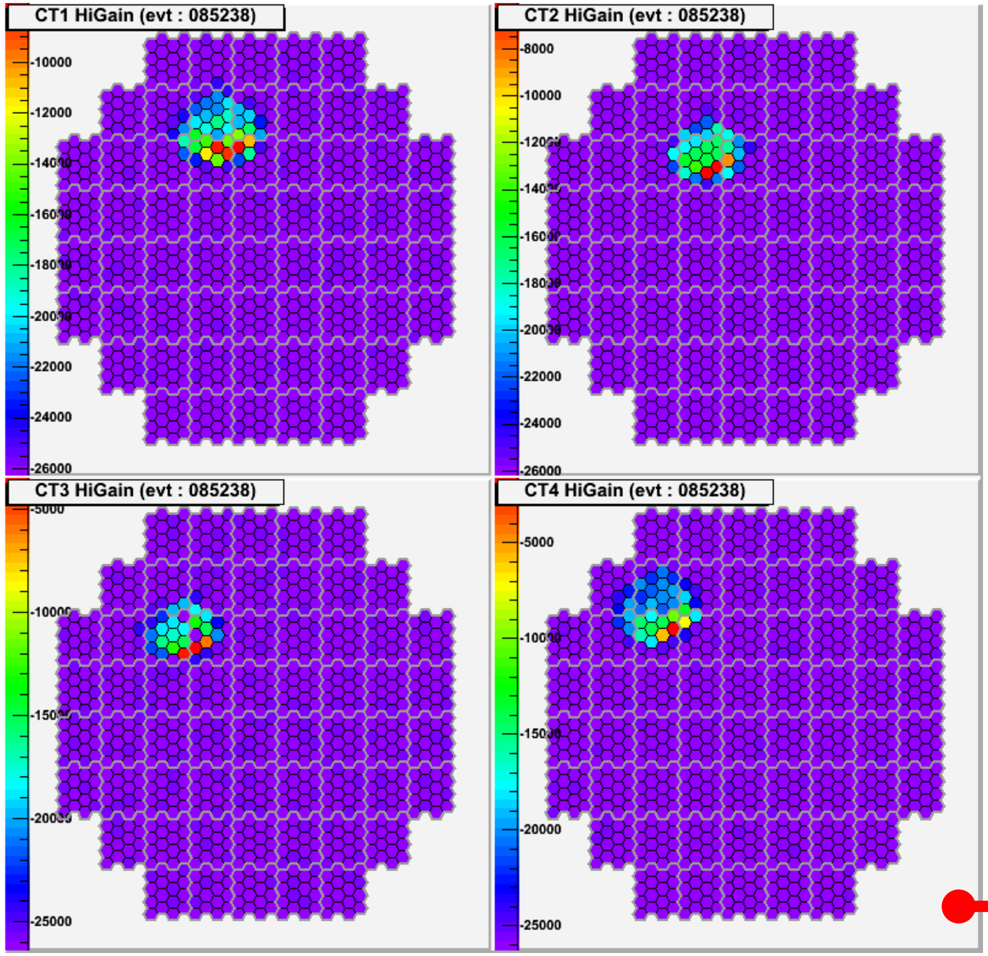






Colour-scale indicates the intensity (pe) recorded by each pixel

Airborne array calibration



- Calibration payload are a modified CHEC calibration system, controlled by a PI and triggered by GNSS signals.
- UAV (DJIS1000) was flown via full GNSS/barometer/gyro info.
- Stability of drone is sufficient for the calibration image to illuminate the same pixel
- Two successful calibration runs (A&B), resulting in ~700 UAV calibration events (@1Hz)

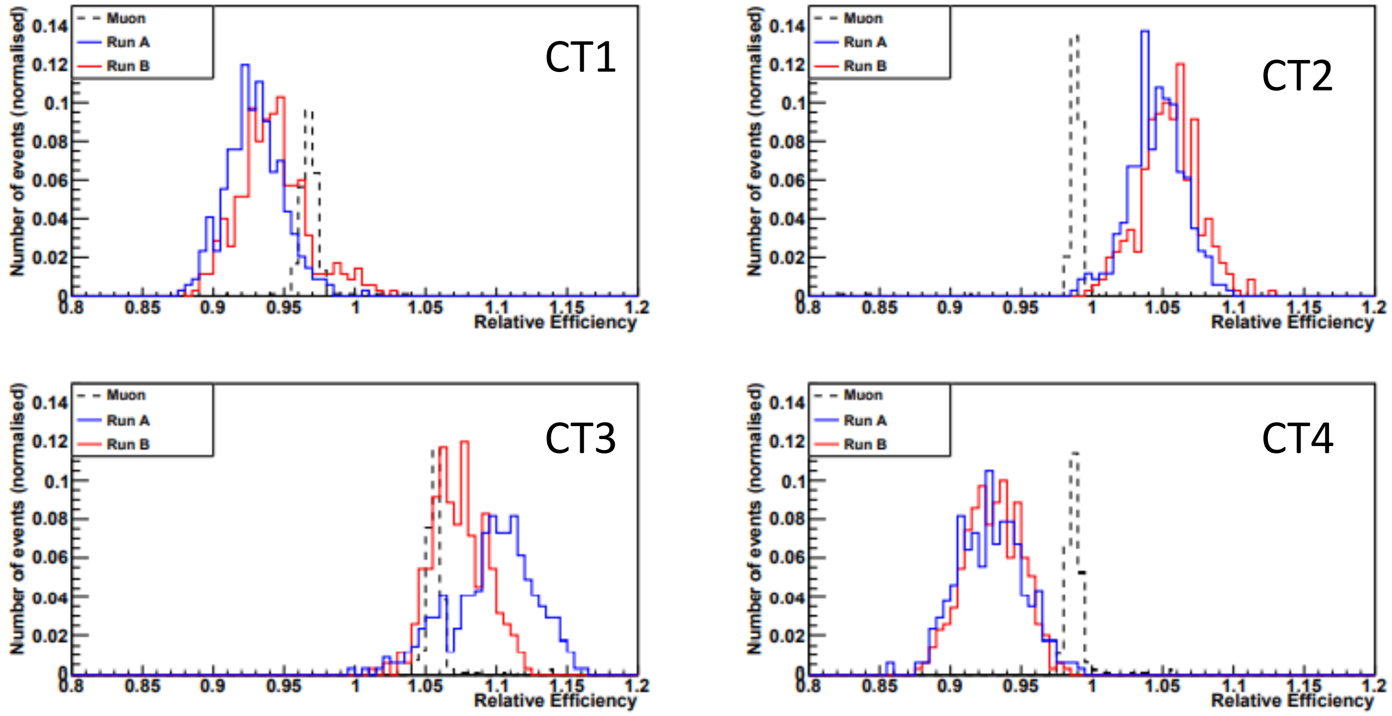
Quick look results of raw data from each UAV flash

Inter-calibration of the HESS-I telescopes

$$\epsilon_i = \frac{(I \times d^2 \times C)_i}{\langle (I \times d^2 \times C)_j \rangle}$$

For each UAV calibration event, calculated the relative efficiency for each telescope (compared to run average of muon calibration)

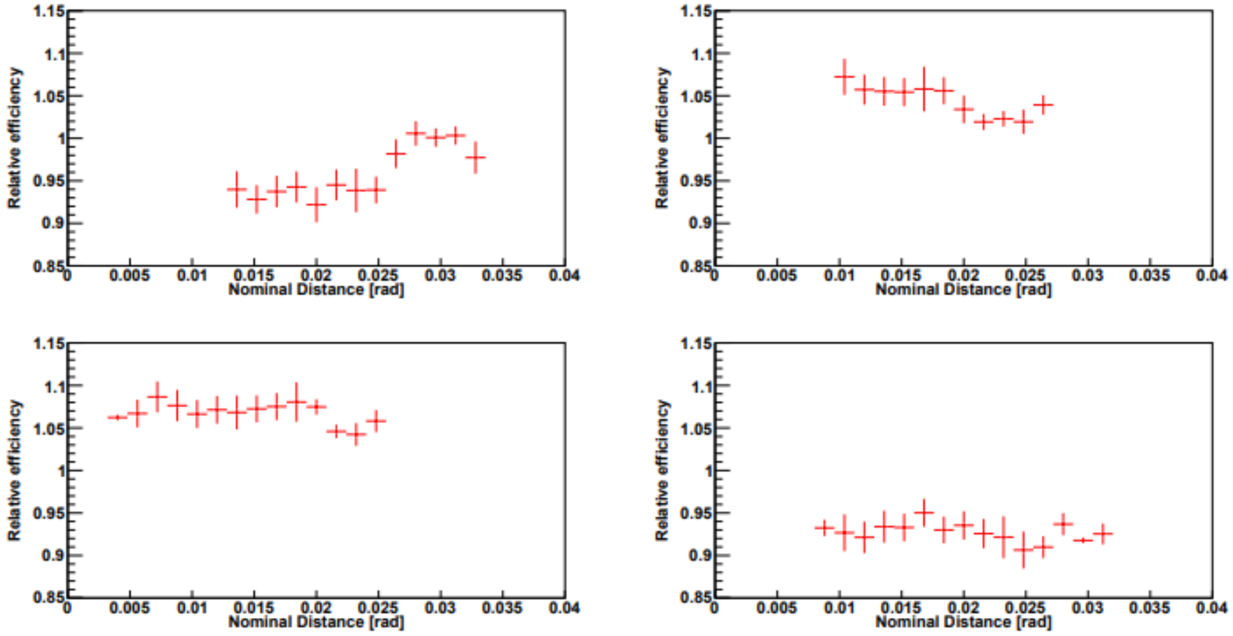
Run Identification	A		B		Muon (Observation Period Average)	
Telescope	Relative Efficiency	Statistical Uncertainty	Relative Efficiency	Statistical Uncertainty	Relative Efficiency	Statistical Uncertainty
1	0.929	0.001	0.942	0.001	0.9661	0.0002
2	1.046	0.001	1.055	0.001	0.9872	0.0002
3	1.097	0.002	1.073	0.001	1.0579	0.0002
4	0.928	0.001	0.930	0.001	0.9889	0.0002

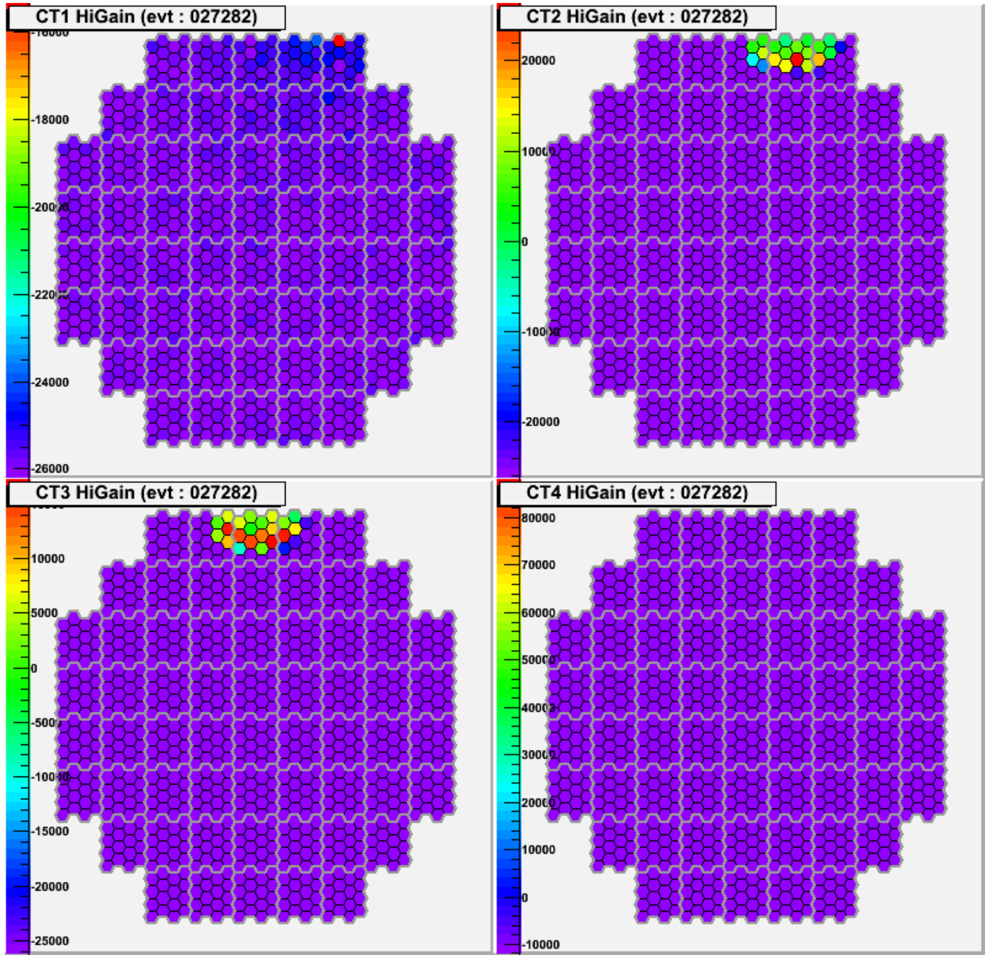


A.M.B (Durham) & J.M, MdN (LLR, Ecole Polytechnique)
Recently accepted by Astroparticle Physics

Scanning the focal plane

- You can also move the UAV to scan the camera focal plane…

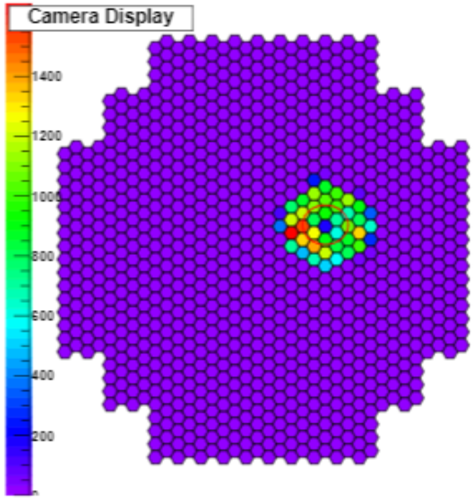


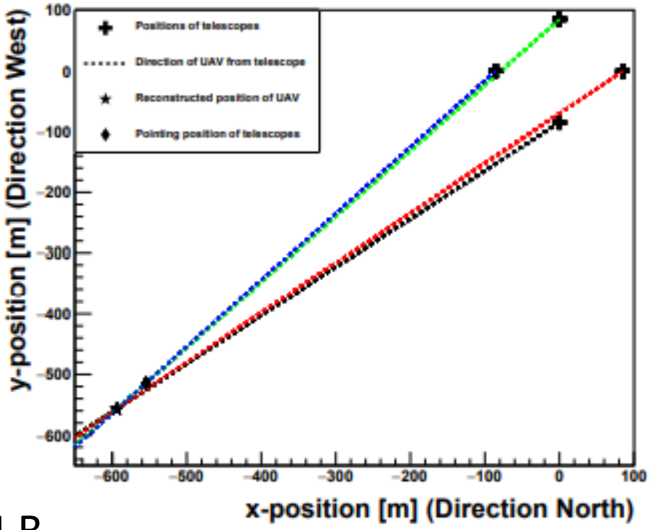


J.M, MdN & A.M.B

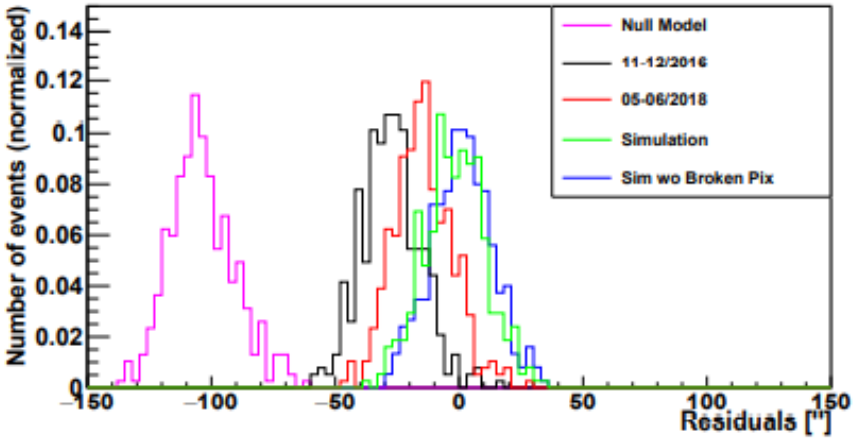
Pointing resolution

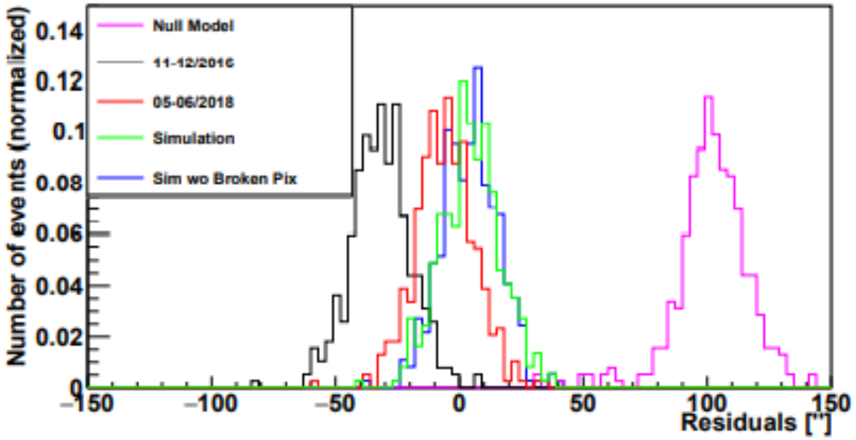
By comparing different pointing corrections, we are able to probe telescope pointing accuracy at the 10-20 arcsec level.



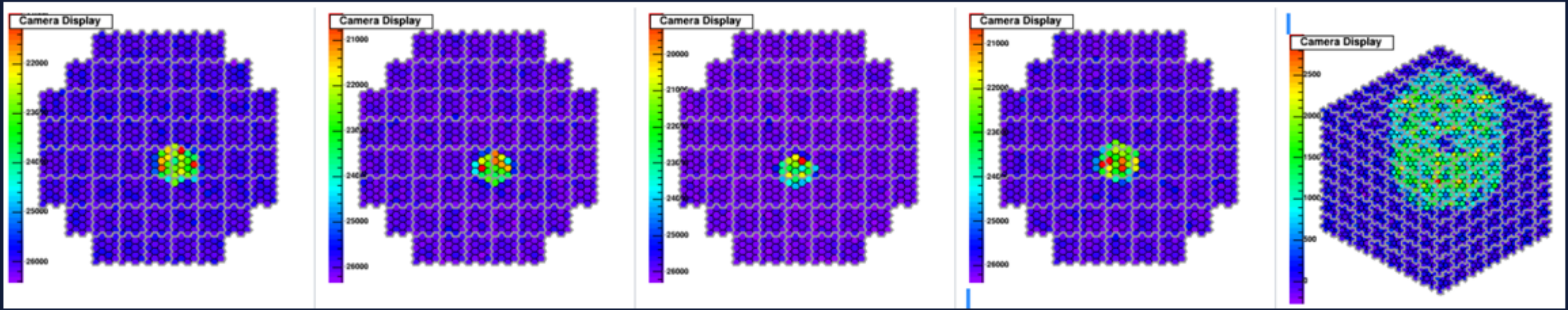


J.M, MdN & A.M.B





The next campaign…



- Nov 2019: second campaign @HESS site with bespoke UAV and new light source
- UAV flown to 1km agl above array.
- Was able to cross-calibrated HESS-I & HESS-II telescopes (10m and 28m diameter respectively).

Take home points…

- Gamma-ray astronomy allows us to probe the most extreme events in our Universe.
- We expect the Cherenkov Telescope Array to give us unparalleled views of these events at very-high-energies.
- Airborne (UAV) calibration of a telescope array is a thing and will allow CTA to attain its desired energy (pointing) resolution.

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