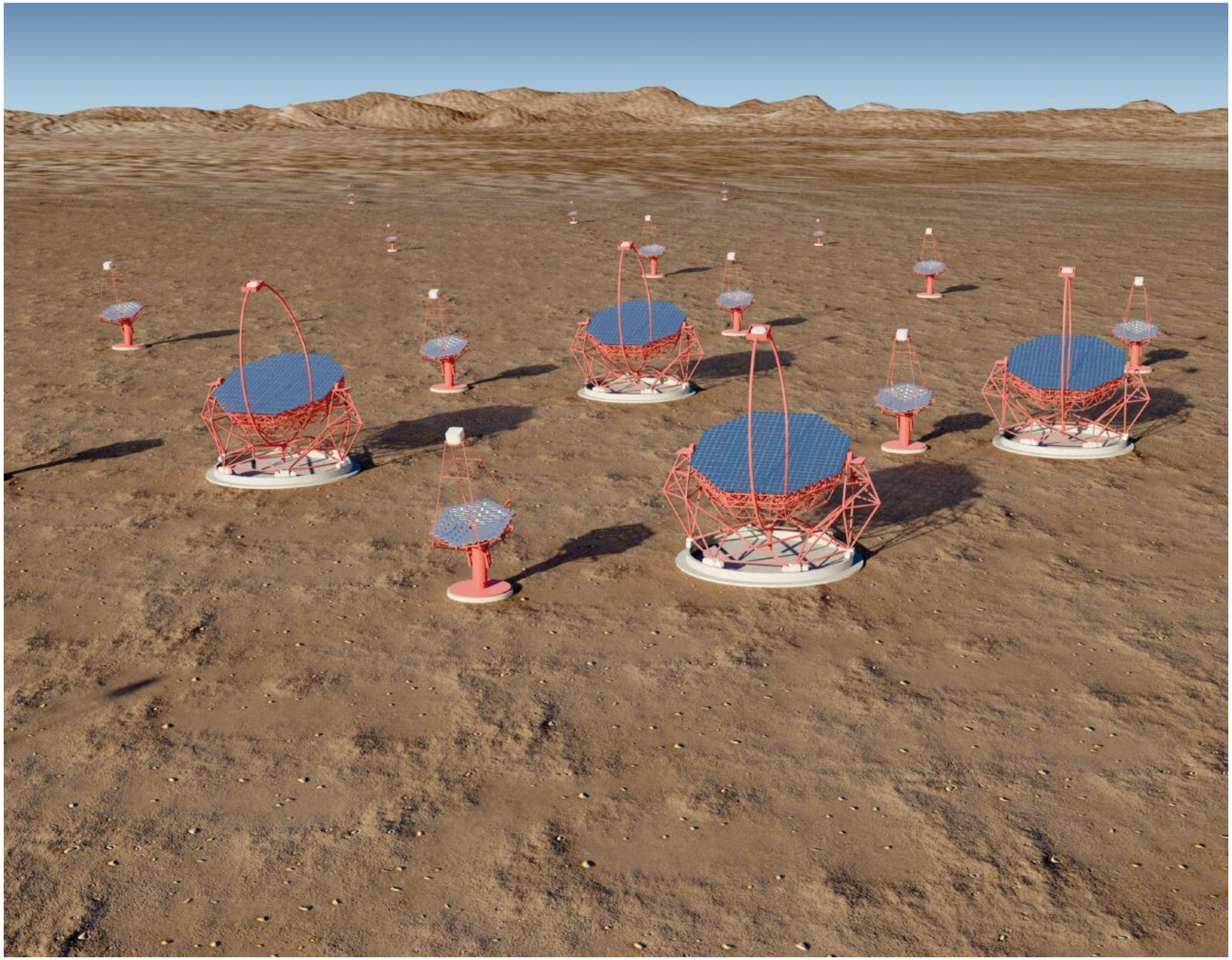
Exploring the non-thermal universe: the Cherenkov Telescope Array

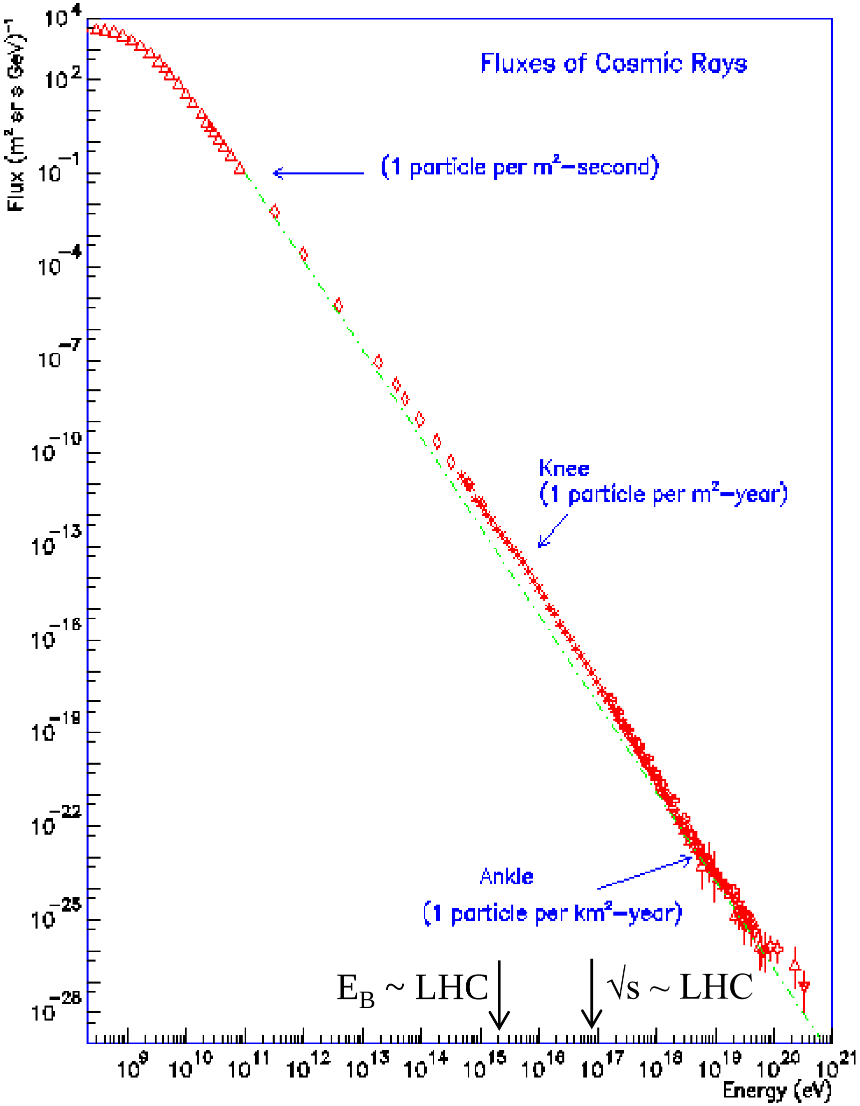
- Introduction to Cosmic Rays
- Cosmic Rays and high energy photons
- Detecting gamma rays
- The CTA concept
- CTA's telescopes and cameras
- Fundamental physics with VHE gamma rays
- Summary



Tim Greenshaw, Liverpool University

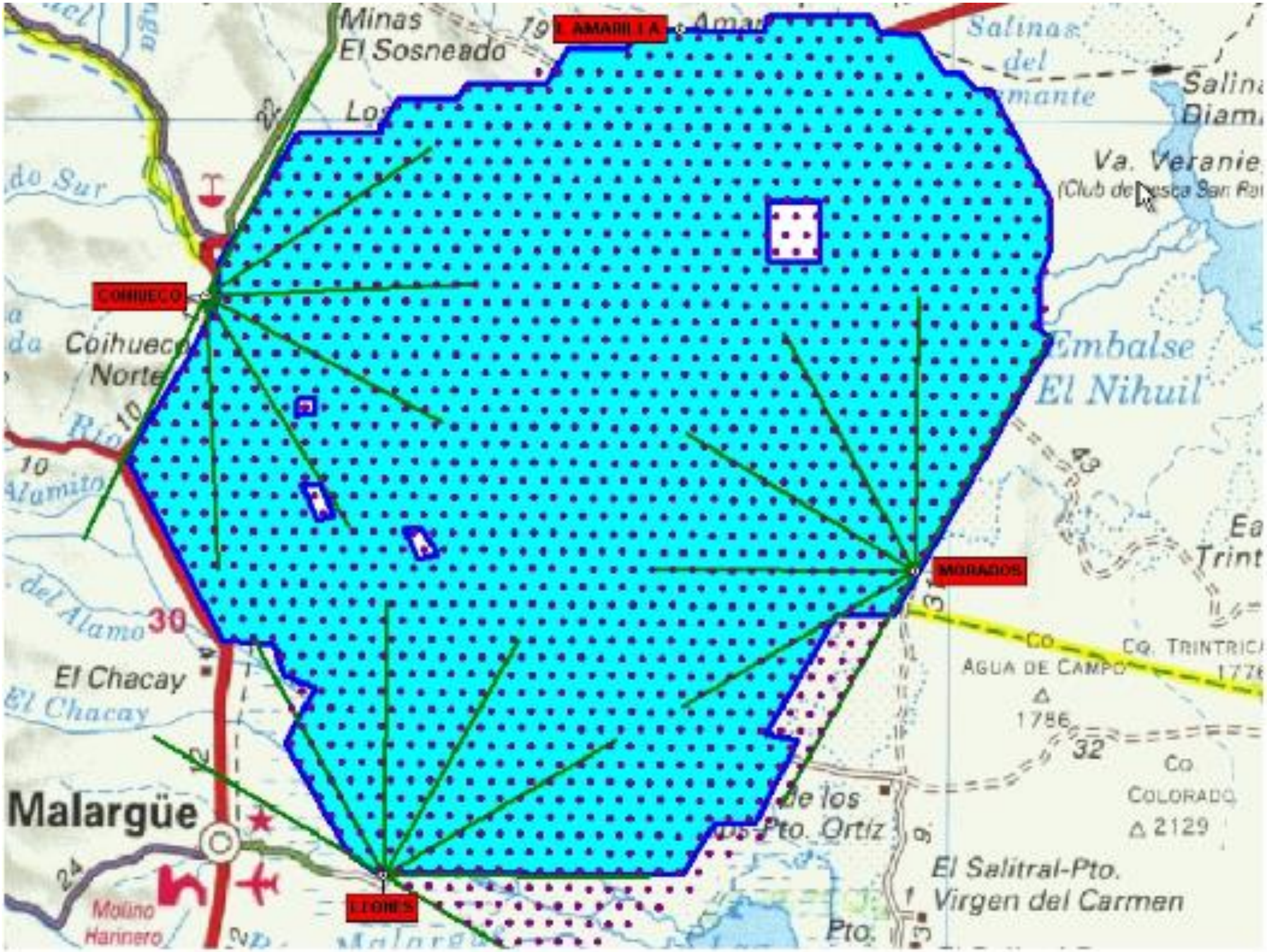
Introduction

- Cosmic Rays are high energy charged particles incident on the atmosphere from outer space.
- High energy means:
    - From about 10^9 eV = $1.6\ 10^{-10}$ J, the energy of a red blood cell moving at a few m/s…
    - …to about 3×10^{20} eV = 48 J, the energy carried by a tennis ball moving at 90 mph.
- How do we know about these particles?
- Where do they come from and how are they accelerated?
- How can we learn more about them?
- What effects do they have?



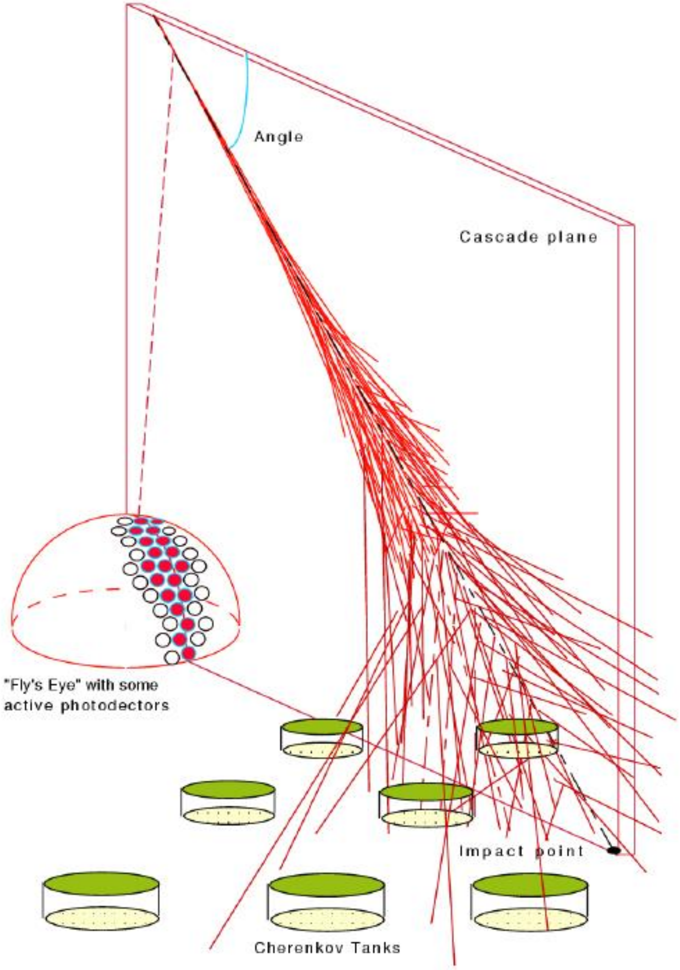
The Pierre Auger Observatory

- Located near Malargüe, Argentina.
- Proposed in 1992, completed in 2008.
- Area over 3000 km^2, twice the size of Greater London.
- Consists of 1650 Surface Detectors and four Fluorescence Detectors.
- Also Telescope Array, Utah.



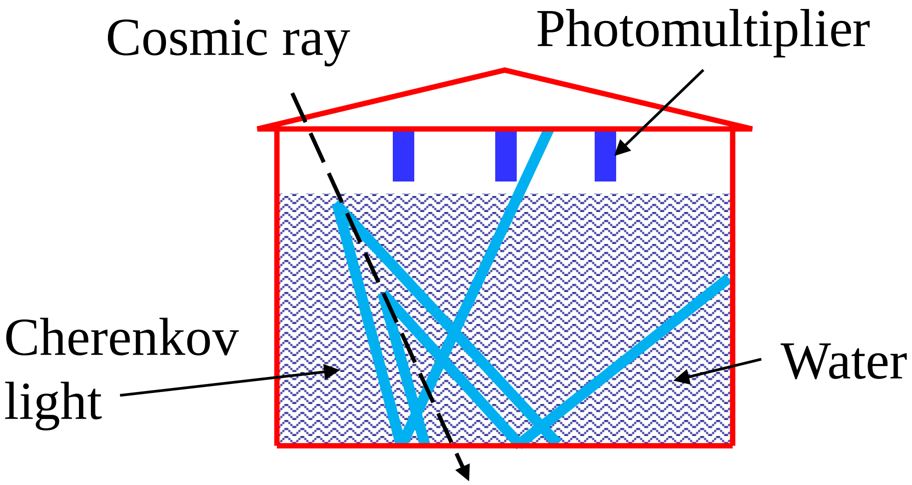
The Pierre Auger Observatory

- In principle...

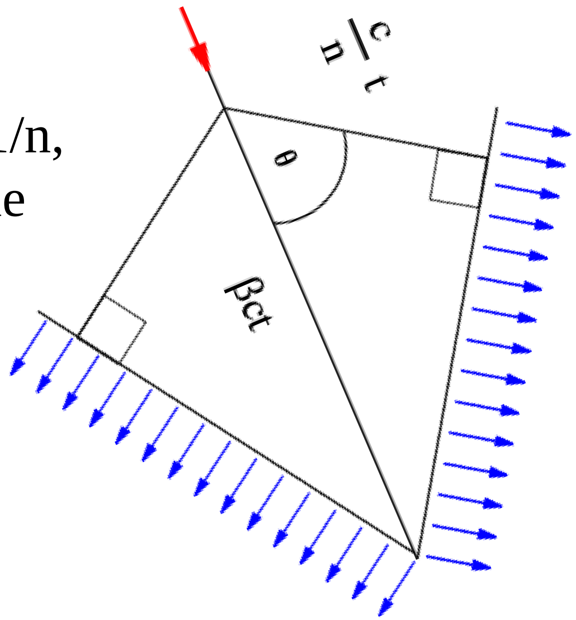


- ...and in practice

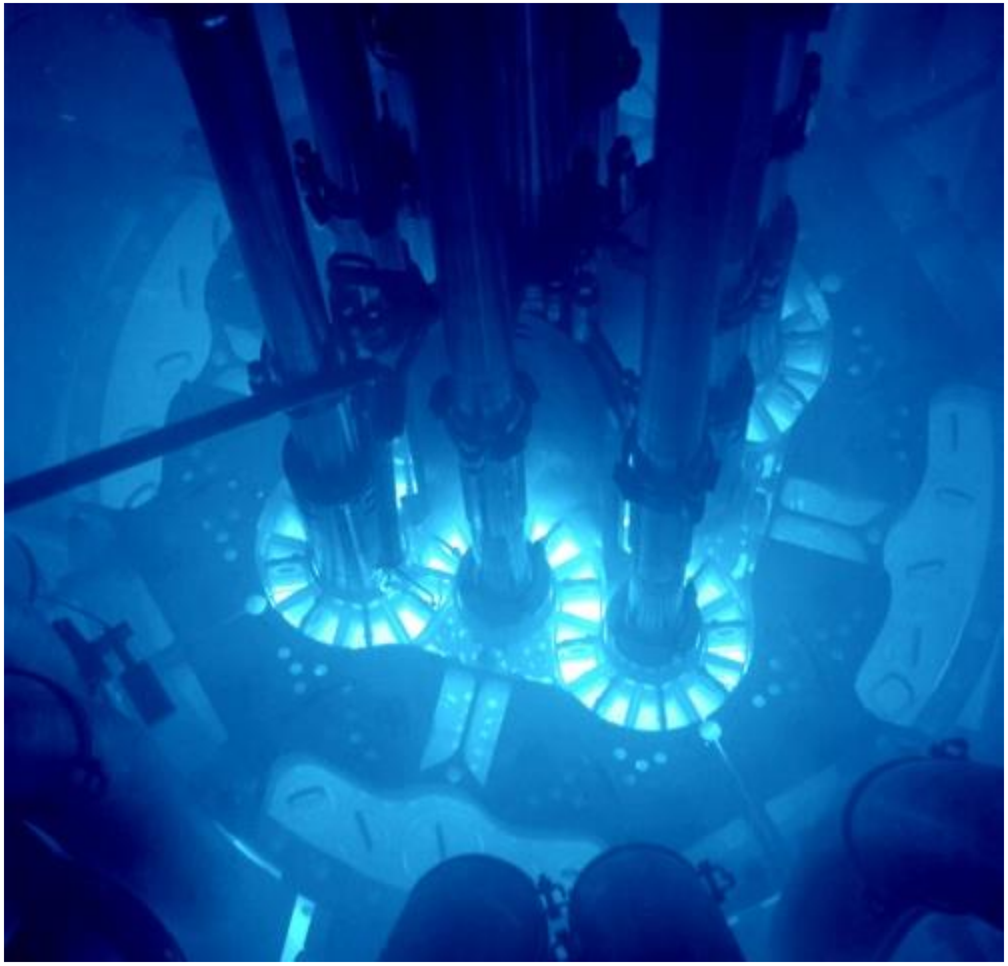
Auger surface detectors



- cos θ = 1/n, light cone angle about 40° in water.

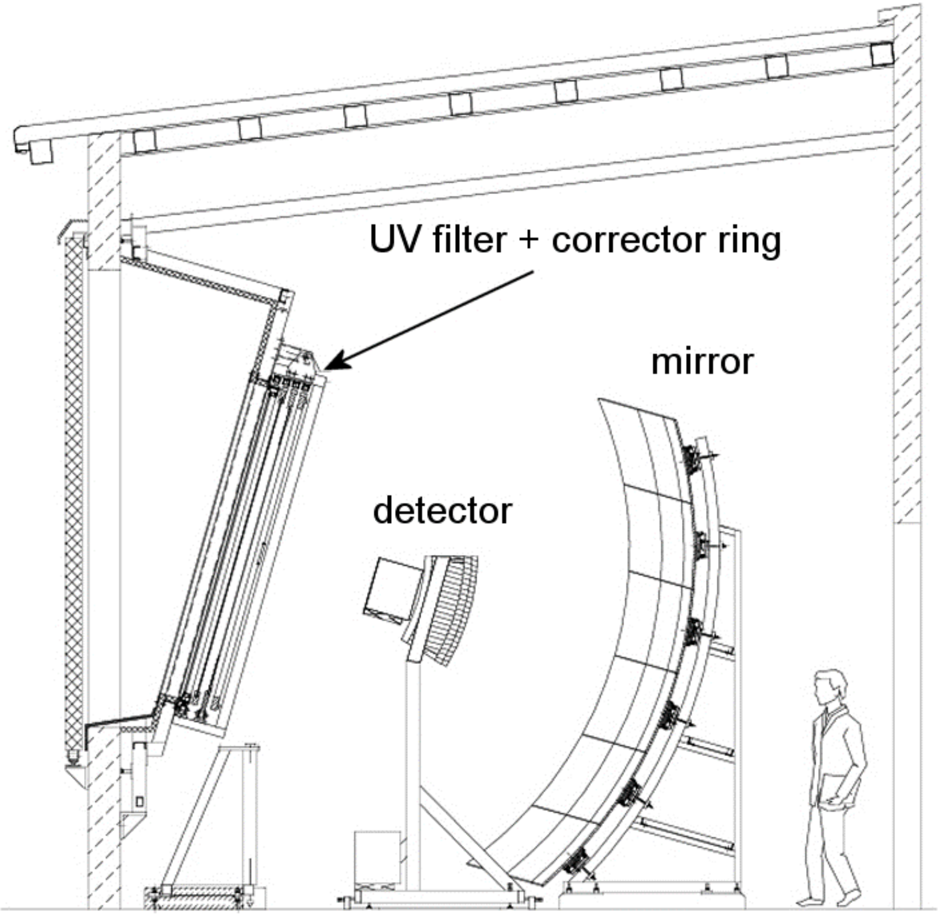


- Cherenkov light in a nuclear reactor:

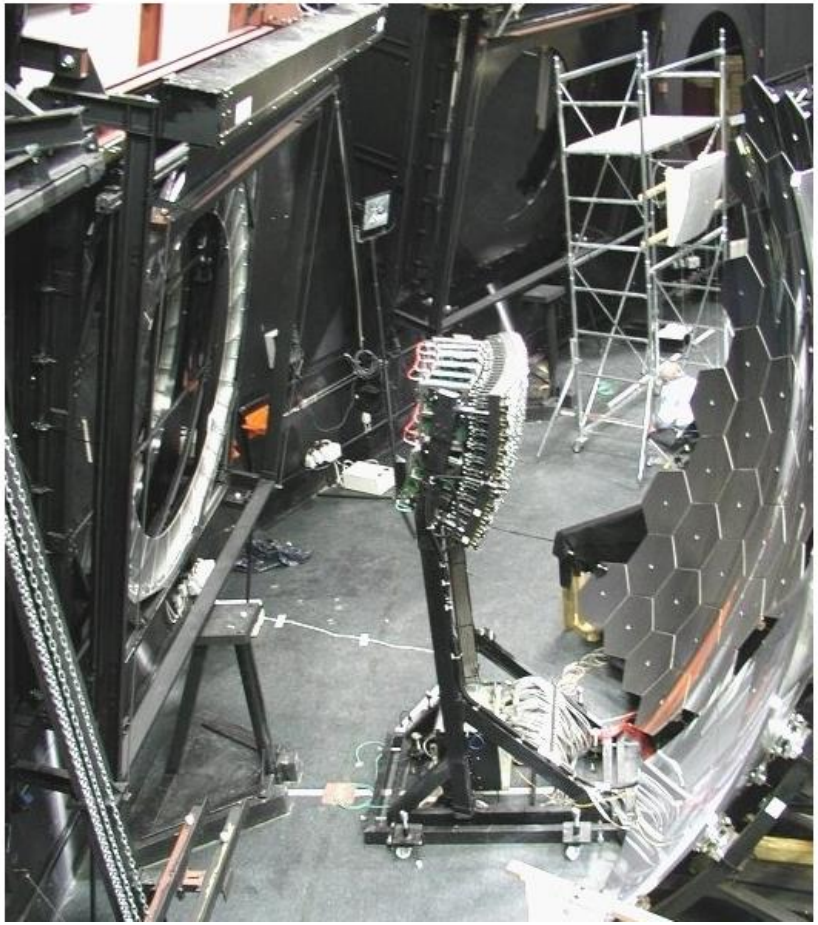


Fluorescence detectors

- What the engineers wanted:

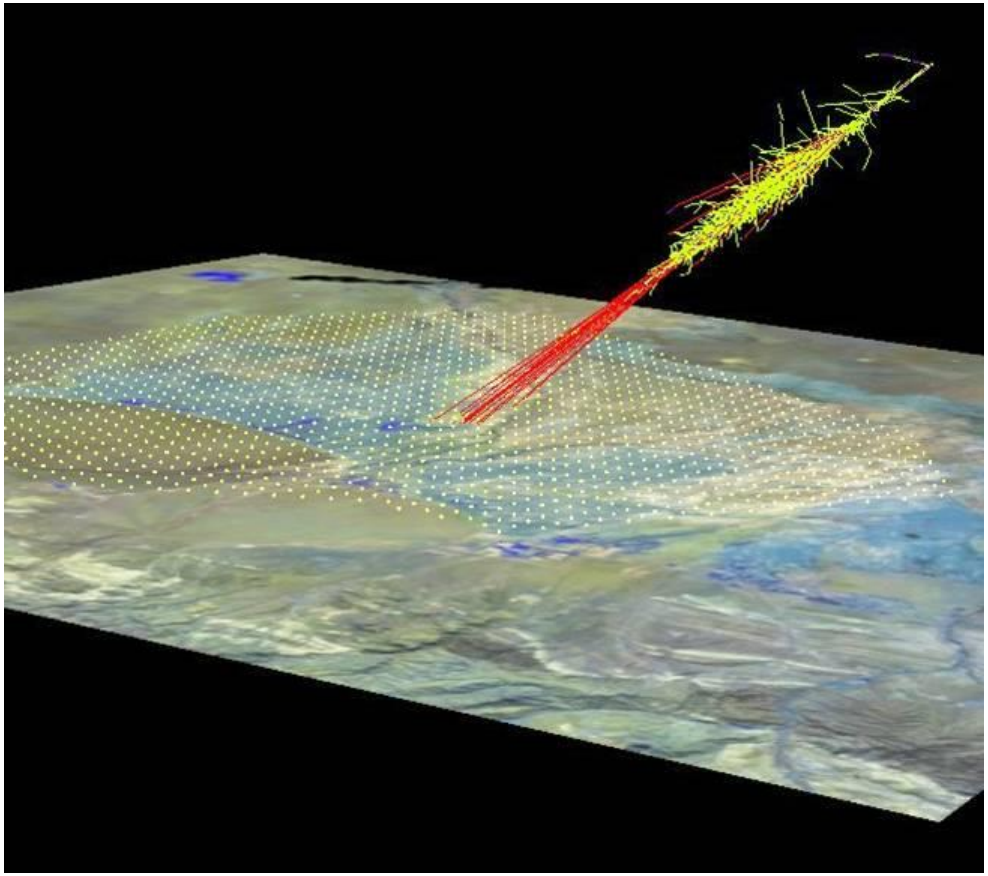


- What the physicists built:

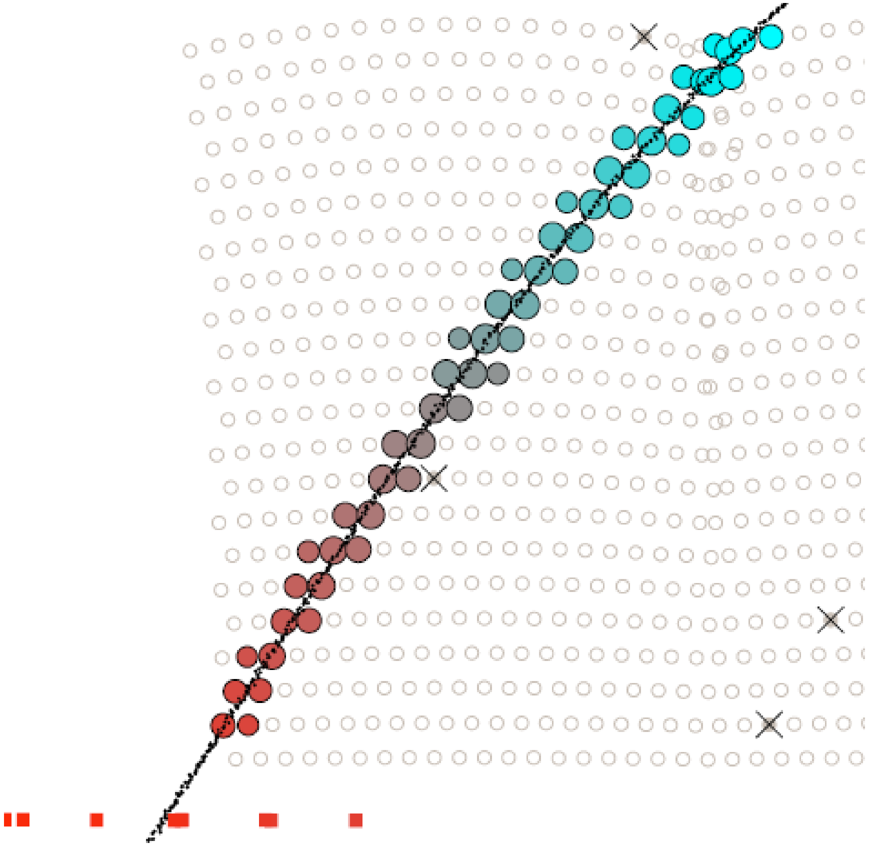


High energy event at Auger

- Computer simulation:

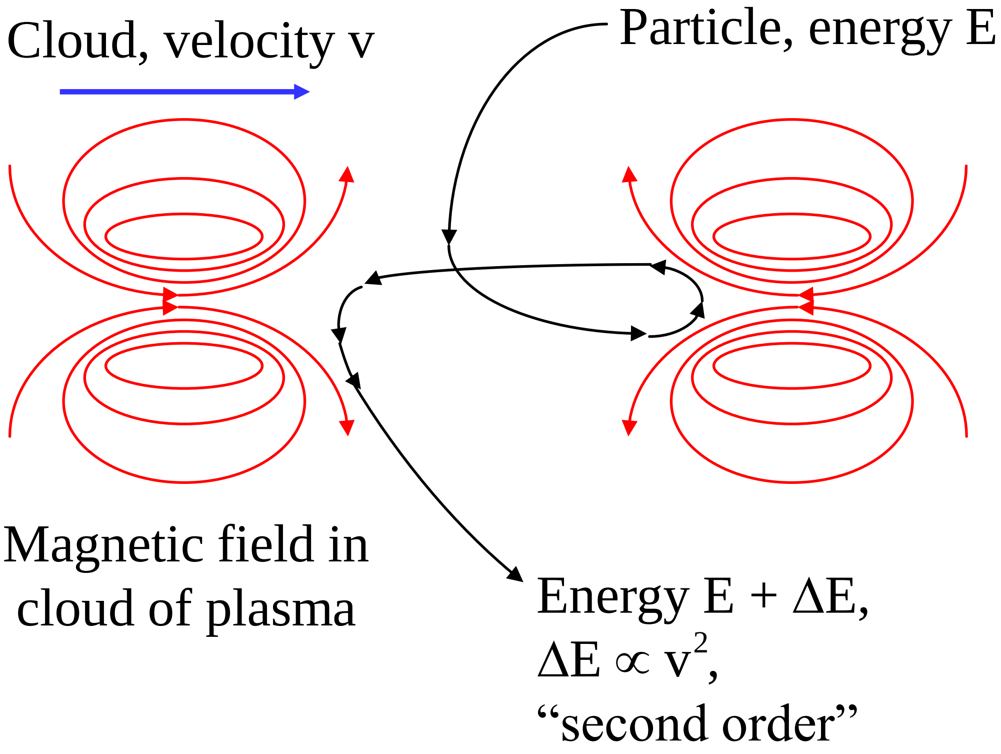


- Measurement:



Acceleration of Cosmic Rays

- Fermi mechanism:



Cloud, velocity v

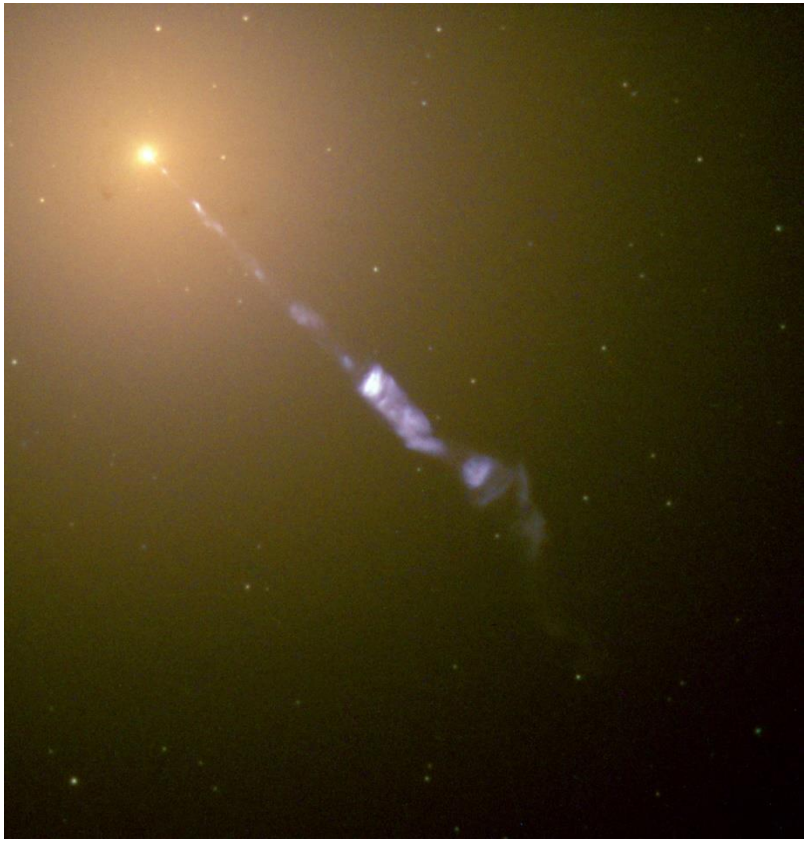
Particle, energy E

Magnetic field in cloud of plasma

Energy E + ΔE, $\Delta E \propto v^2$, “second order”

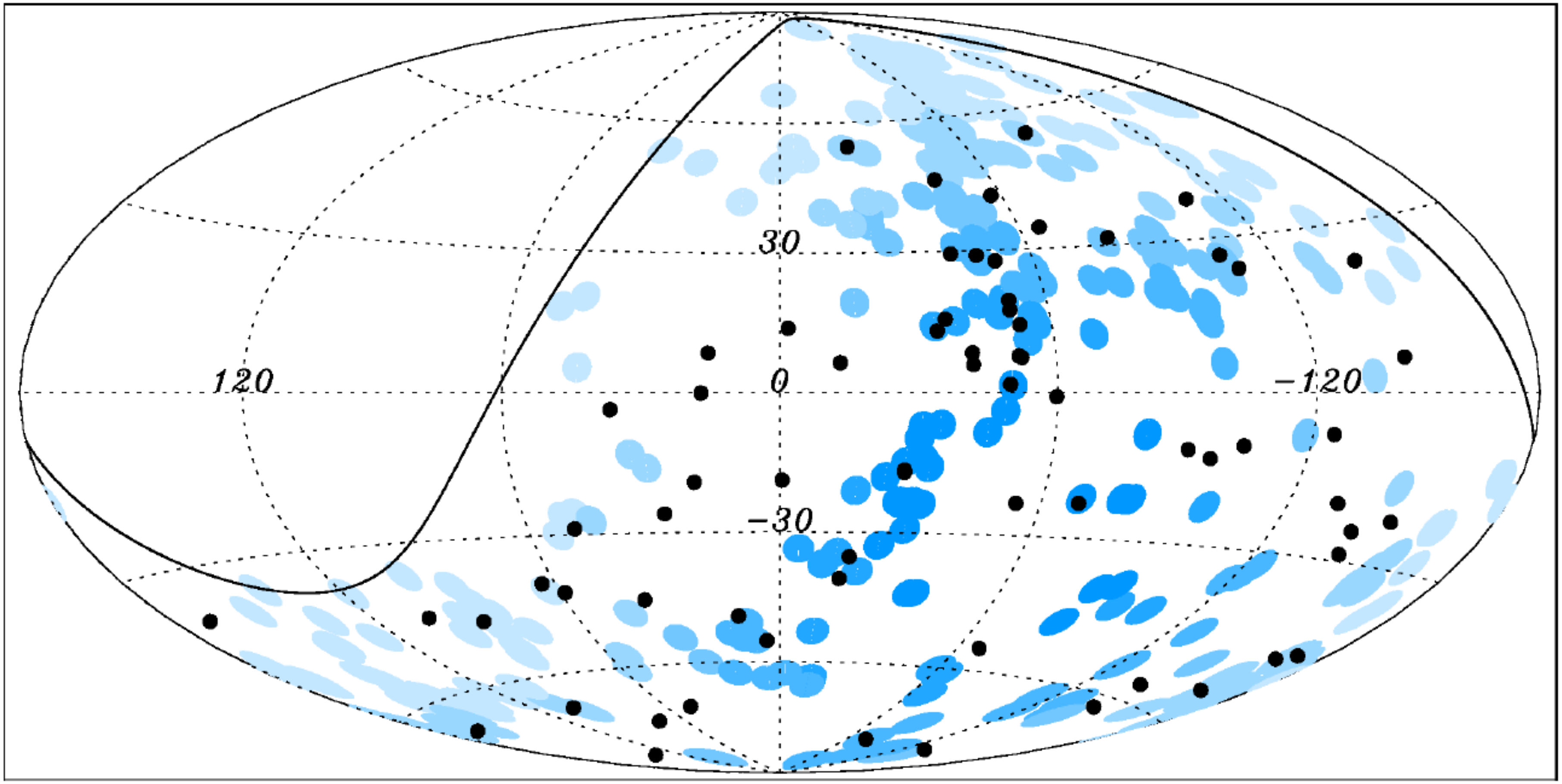
- These clouds are thought to occur around supernovae, in jets from Active Galactic Nuclei...

- Jet visible in Hubble image of M87:



- Jet is 1500 pc (4900 Ly) long!
- Seen because of synchrotron radiation.

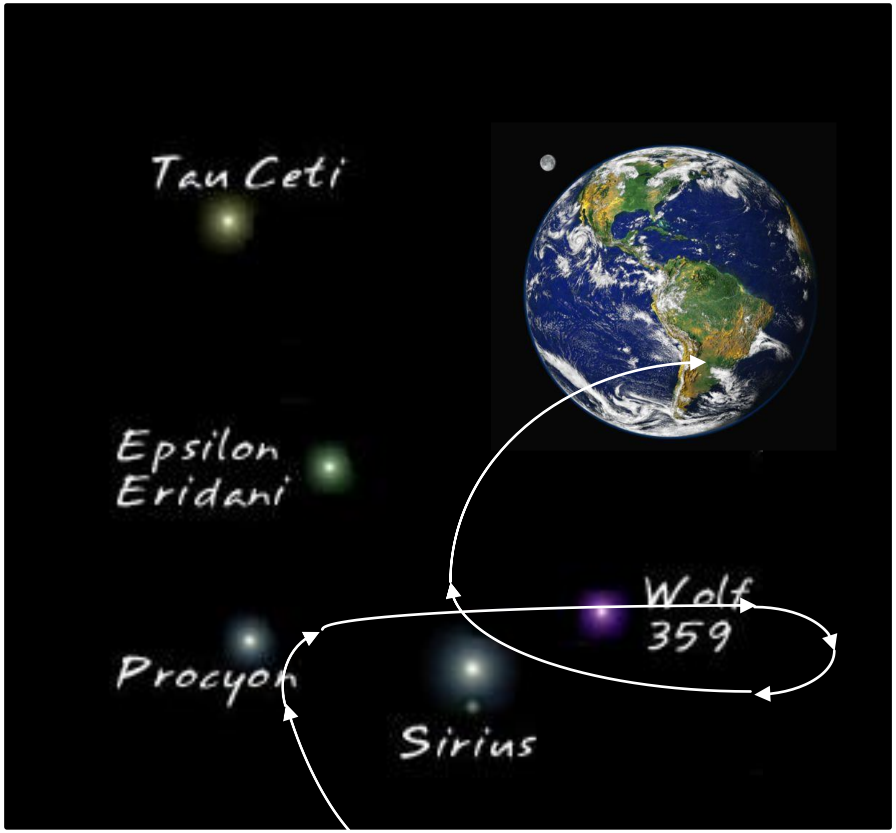
Origins of high energy Cosmic Rays



- Arrival directions of 69 CRs (black dots) with E > 55 EeV (10^{18} eV) and position of AGN within 75 Mpc (about 250 MLy) of earth – Galactic coordinates.

Origins of high energy Cosmic Rays

- Charged particle directions influenced by magnetic fields.



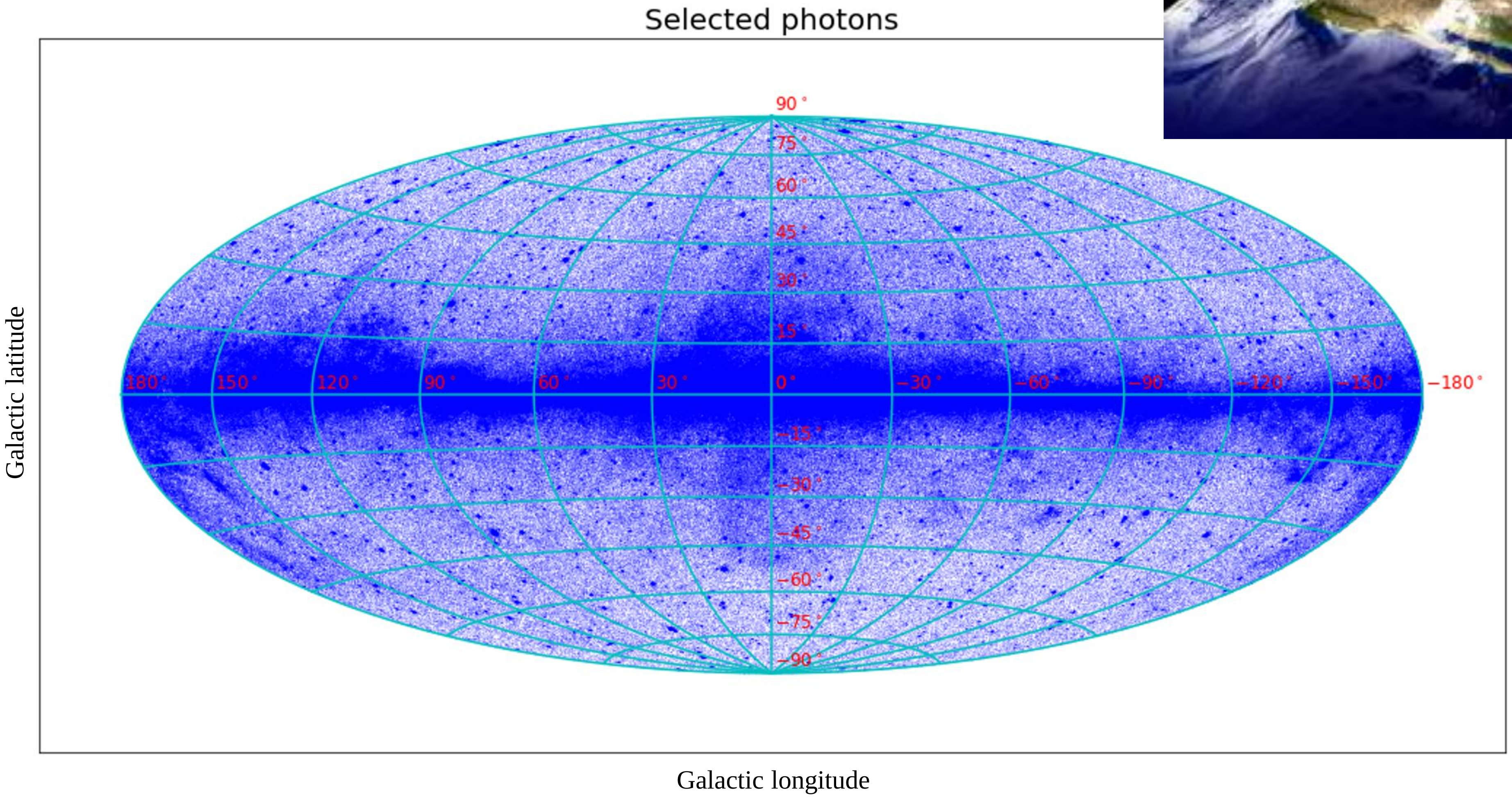
- Difficult to track Cosmic Rays back to their sources.
- Need particles that travel in straight lines through magnetic fields…photons.
- Fortunately, these are produced in association with Cosmic Rays!

$$p + N \rightarrow \pi^0 + X$$
$$\searrow \gamma\gamma$$

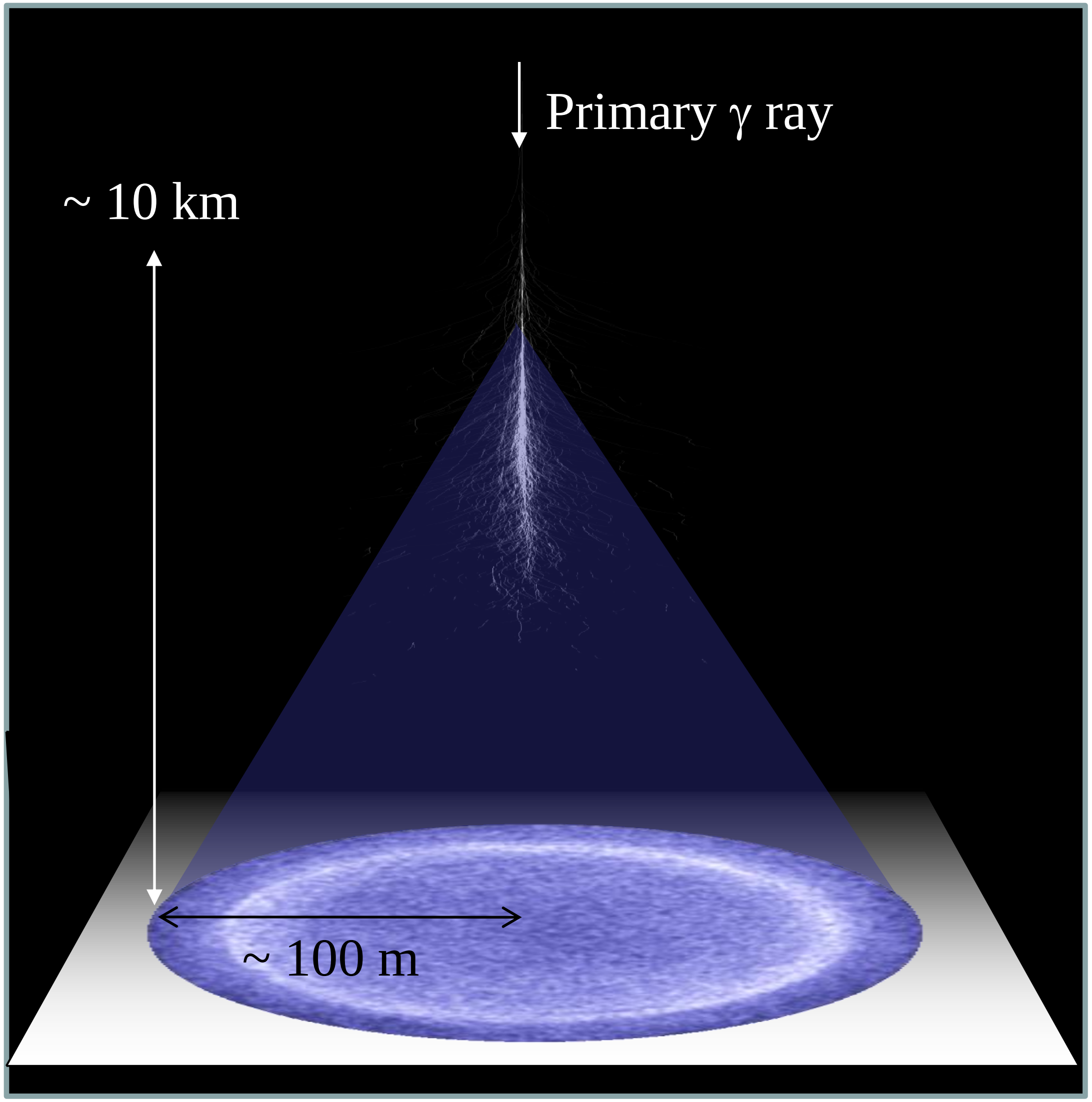
- Can we detect these very high energy photons?
- Can they show us where Cosmic Rays are being produced?

Detecting high energy γ rays – take one

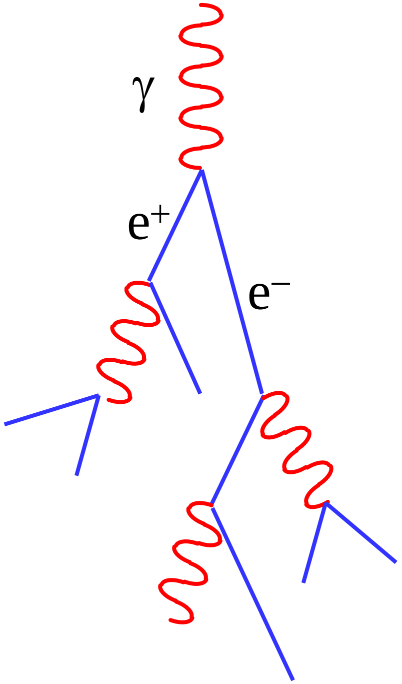
- Fermi image of universe, E_γ from 3 GeV to 300 GeV.



Detecting high energy γ rays – take two

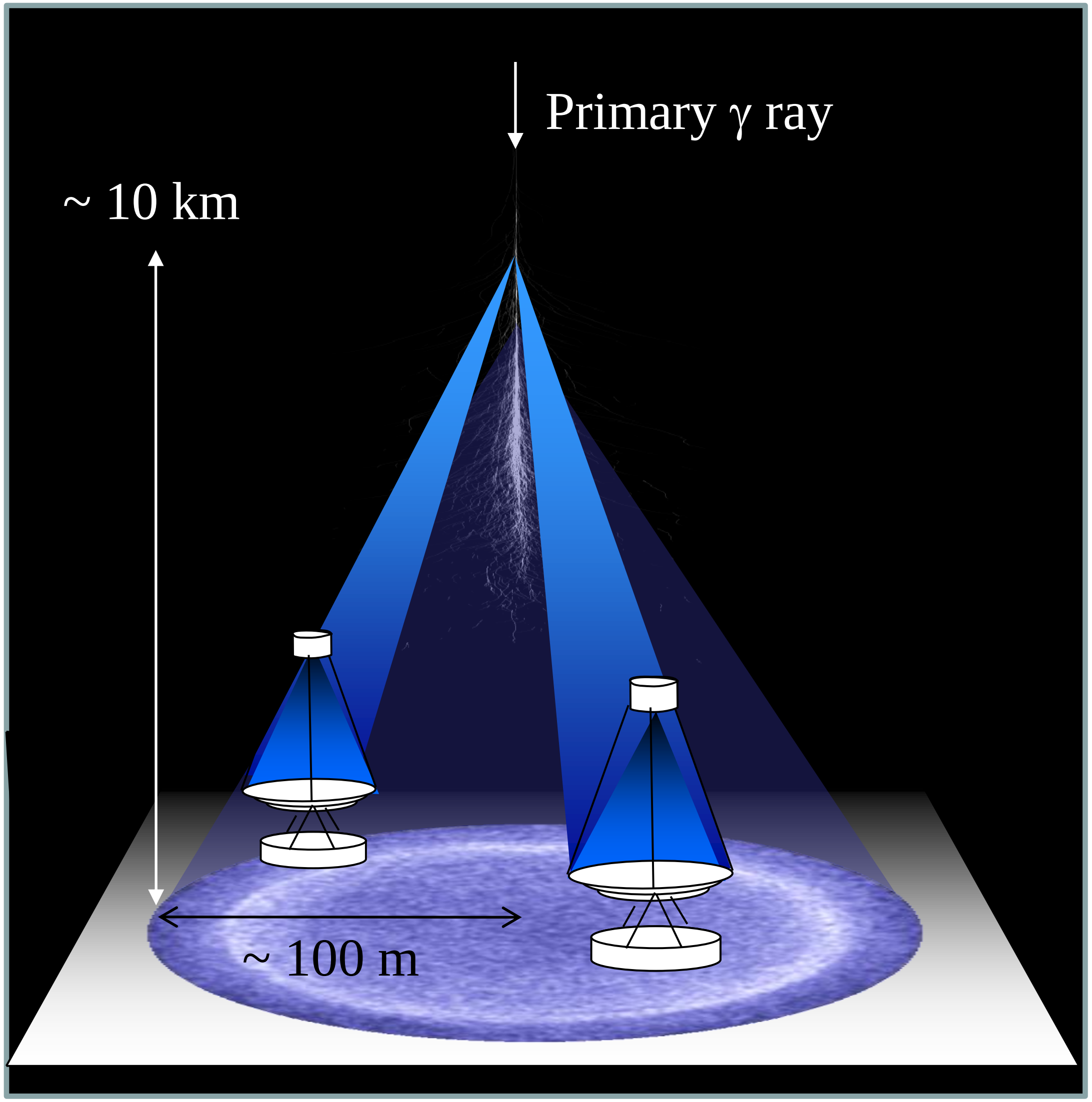


- Air shower:

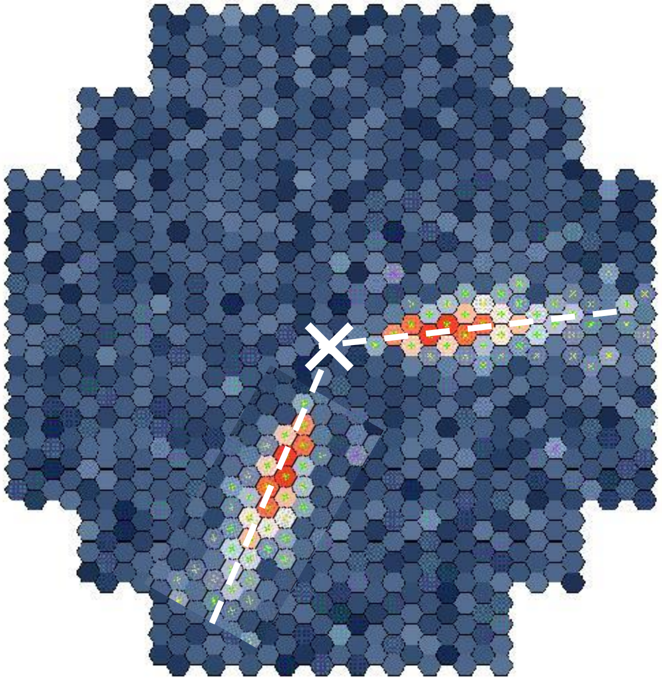


- Cherenkov light emitted from particles with v > c.
- cos θ = 1/n, light cone angle about 1° in air.

Detecting high energy γ rays

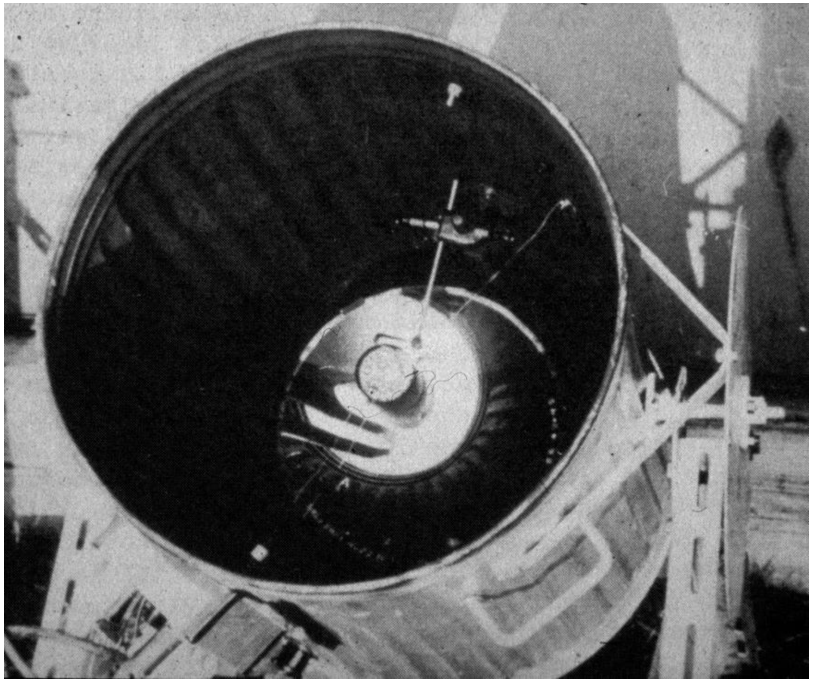


- Light flash lasts about 10 ns.
- Detect with “camera” made of photomultipliers.
- Superimpose telescope images, find γ-ray source.



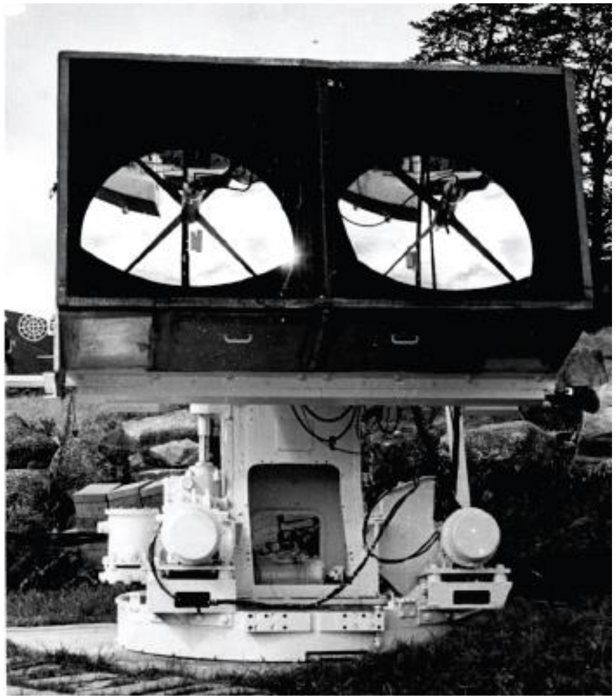
Cherenkov light from air showers

- The first detection of Cherenkov light from air showers was made in 1953:



- Seen by Galbraith and Jelley using a parabolic mirror viewed by a single phototube.

- An early “dual mirror” gamma ray telescope, Porter and Jelley, Glencullen (Ireland), 1962.

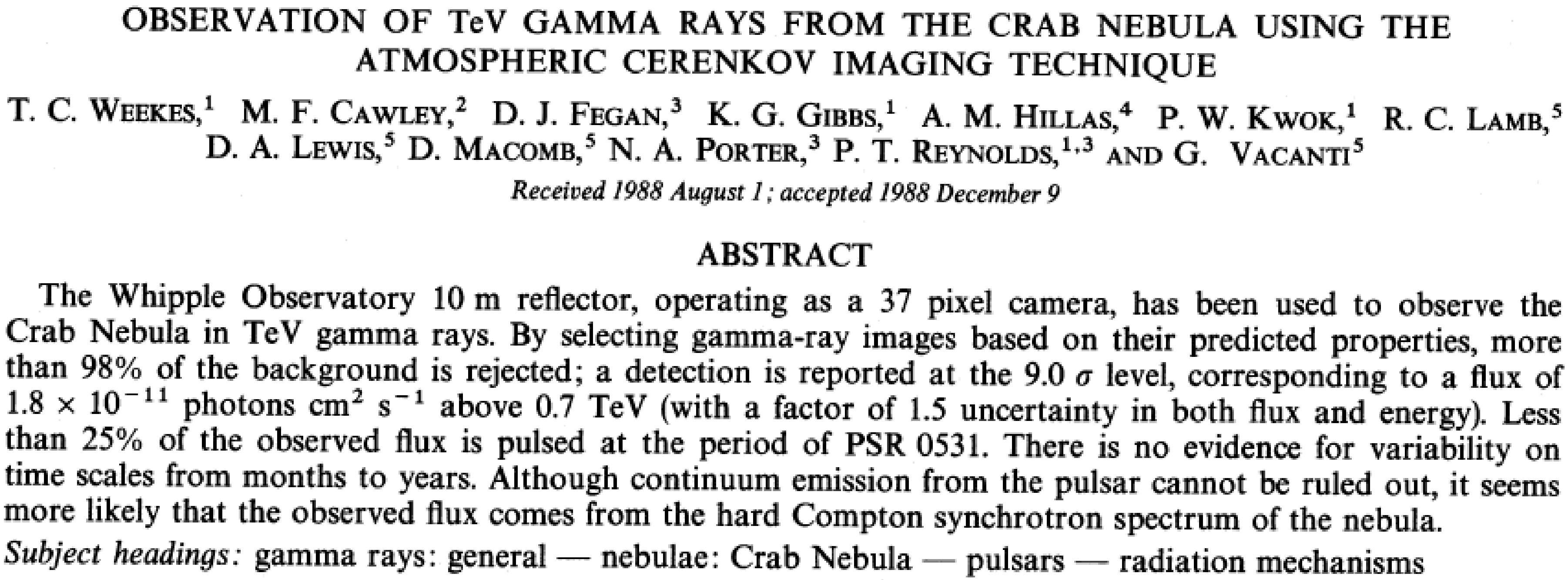


- Gun mount and searchlight mirrors from WWII.

The first TeV source…


Whipple, completed 1968


THE ASTROPHYSICAL JOURNAL, **342**: 379–395, 1989 July 1


OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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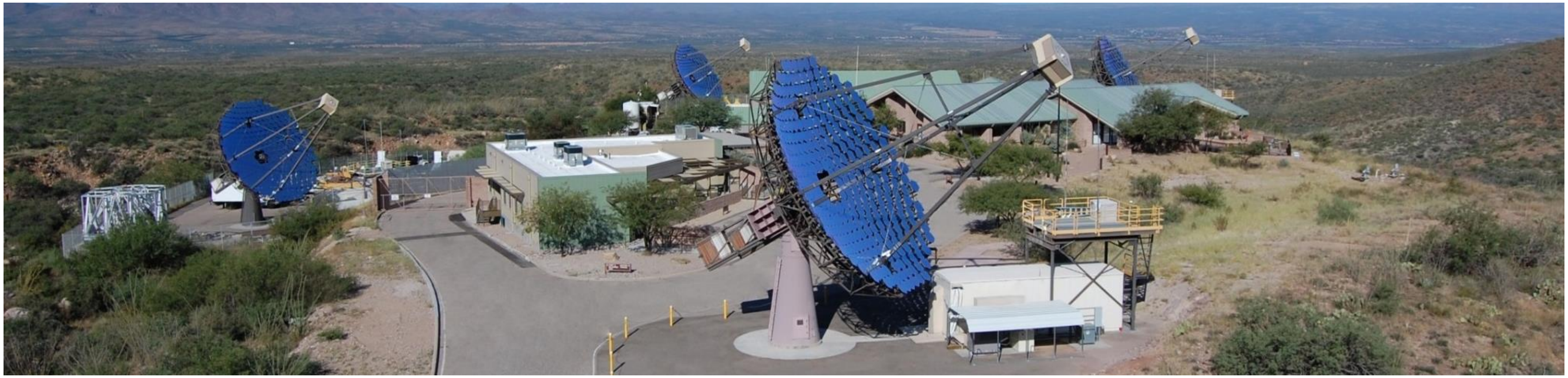
ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

Current IACT arrays

- VERITAS



- HESS

Current IACT arrays

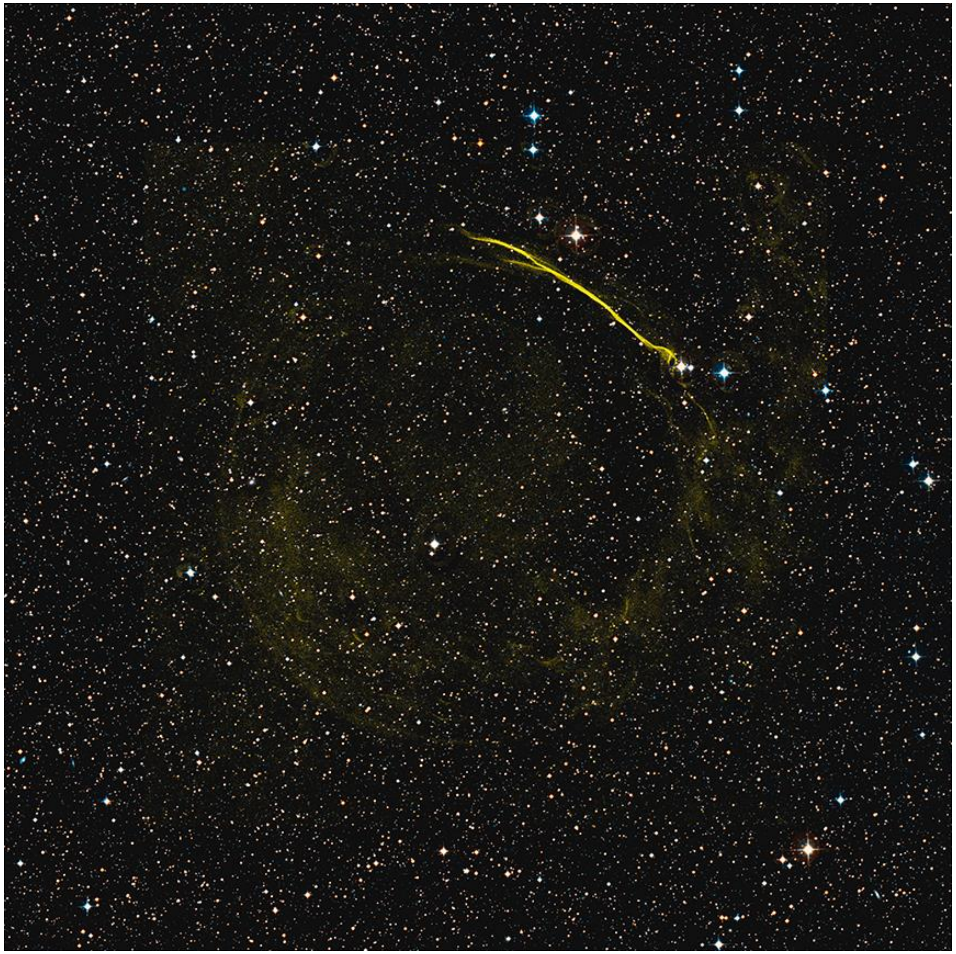
- MAGIC

A source of gamma rays – Supernova 1006

- Distance 6000 Ly.
- Diameter about 60 Ly.
- First seen 1011 years ago:

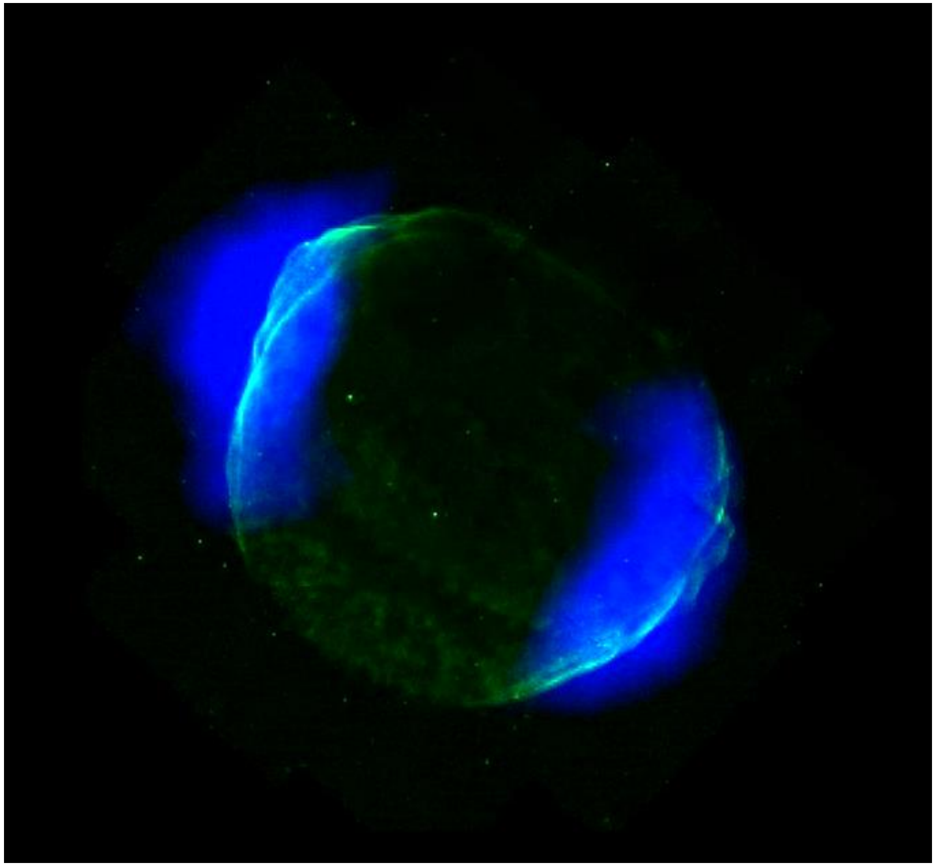
客星古現例
皇極天皇元年秋七月甲寅 客星入月
陽成院貞観十九年正月廿五日丁酉 戌時 客星
在壁 見西方
宇多天皇寛平三年三月廿九日己卯 戌時
客星在東咸星東方 相去一寸許
醍醐天皇延長八年五月 後七月八日 客星
入羽林中
一條院寛弘三年四月二日癸酉 夜以降 騎官
中 有大客星 如熒惑 光明動耀 連夜見
南方 或云 騎陣将軍星 変本体 増光
後冷泉院天喜二年四月中旬以後 丑時 客星出
觜参度 見東方 孛天関星 大如歳星
二條院永萬二年四月廿二日乙丑 戌時 客星見大
微宮 [illegible]
高倉院治承五年六月廿五日庚午 戌時 客星見
北方 近王良星 守傳舎星

- Optical

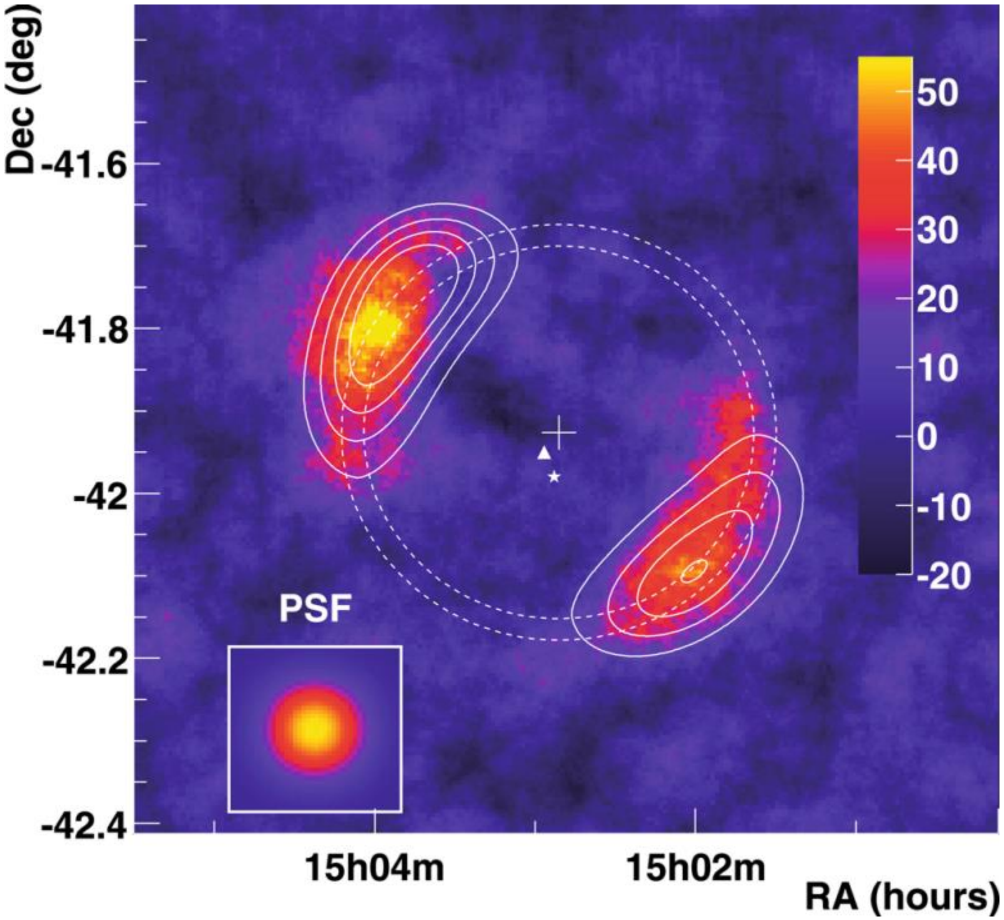


Supernova 1006

- Satellite X-ray (green) and “low energy” γ-ray images (blue):

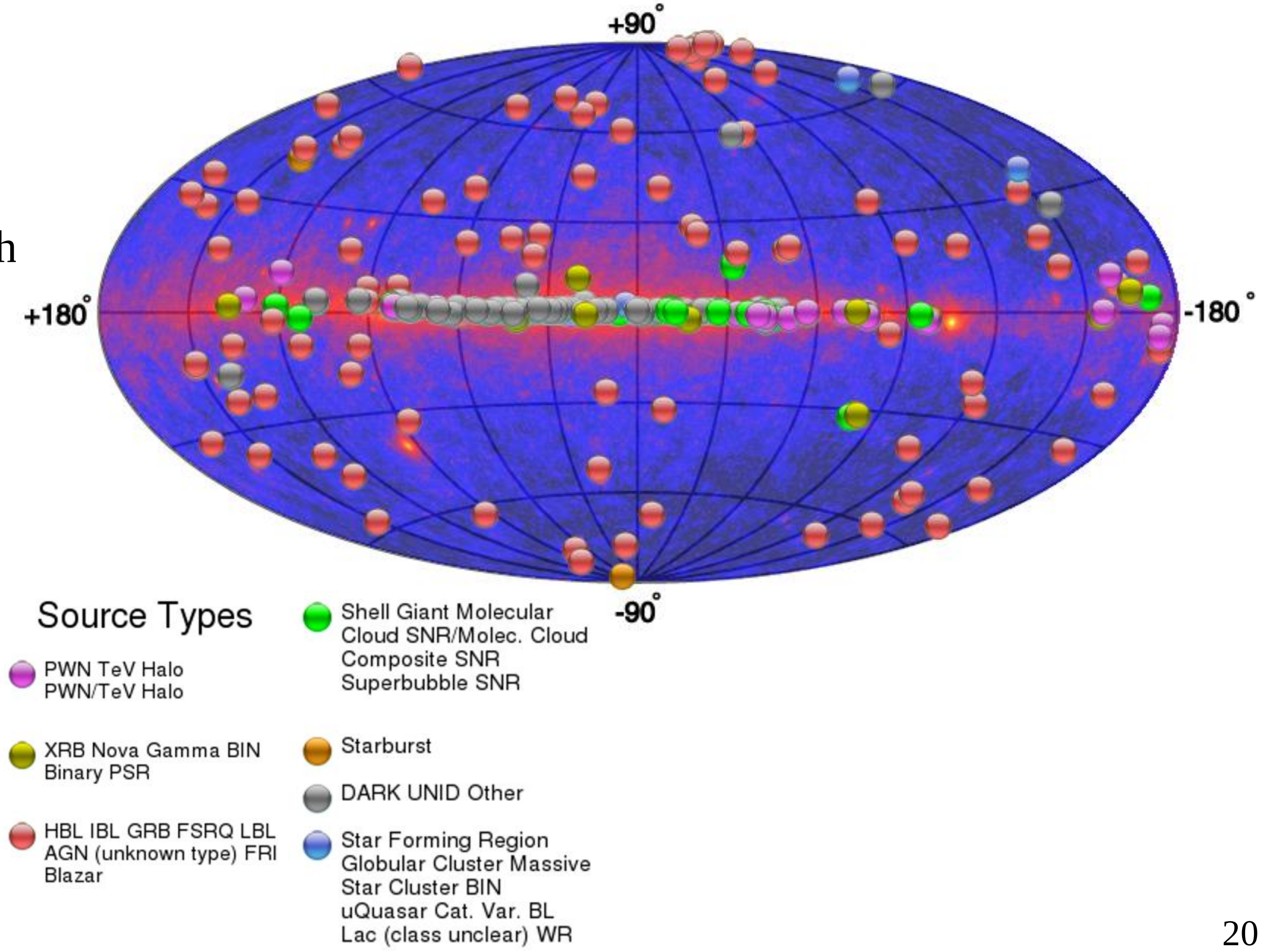


- HESS very high energy γ-ray image:



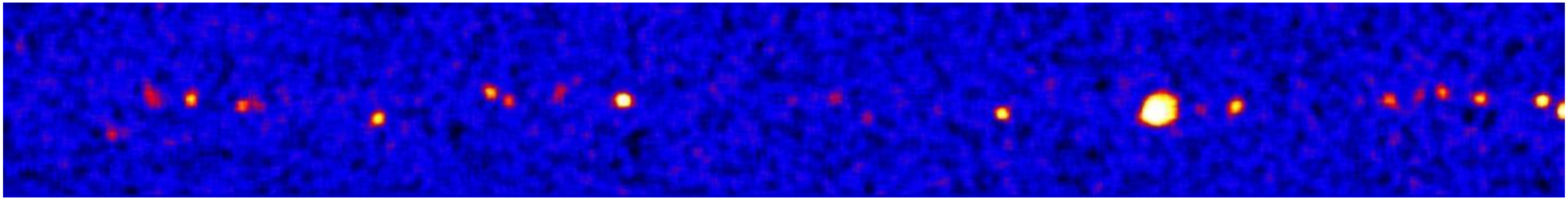
All known sources of very high energy gamma rays

- As of 8th Jan. 2022.
- 248 γ-ray sources.
  - ~ 170 Galactic.
  - ~ 200 found with IACTs.
- Further progress requires:
  - Improved sensitivity.
  - Better energy and...
  - ...angular resolution.

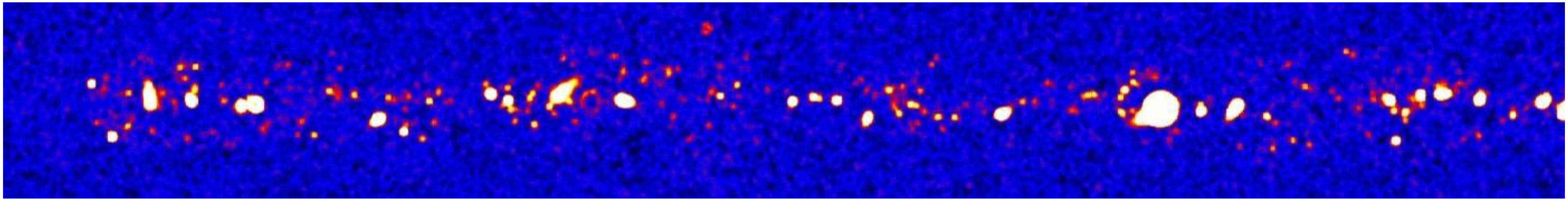


Performance goals for next-generation IACT array

- Aim for factor of 10 improvement in sensitivity.
- Compare HESS ~ 500 hour image of Galactic plane...



- ...with expectation with tenfold increased sensitivity, same exposure.



- Locate arrays in southern and northern hemispheres.
- Expect to observe around 1000 sources (Galactic and extra-Galactic).

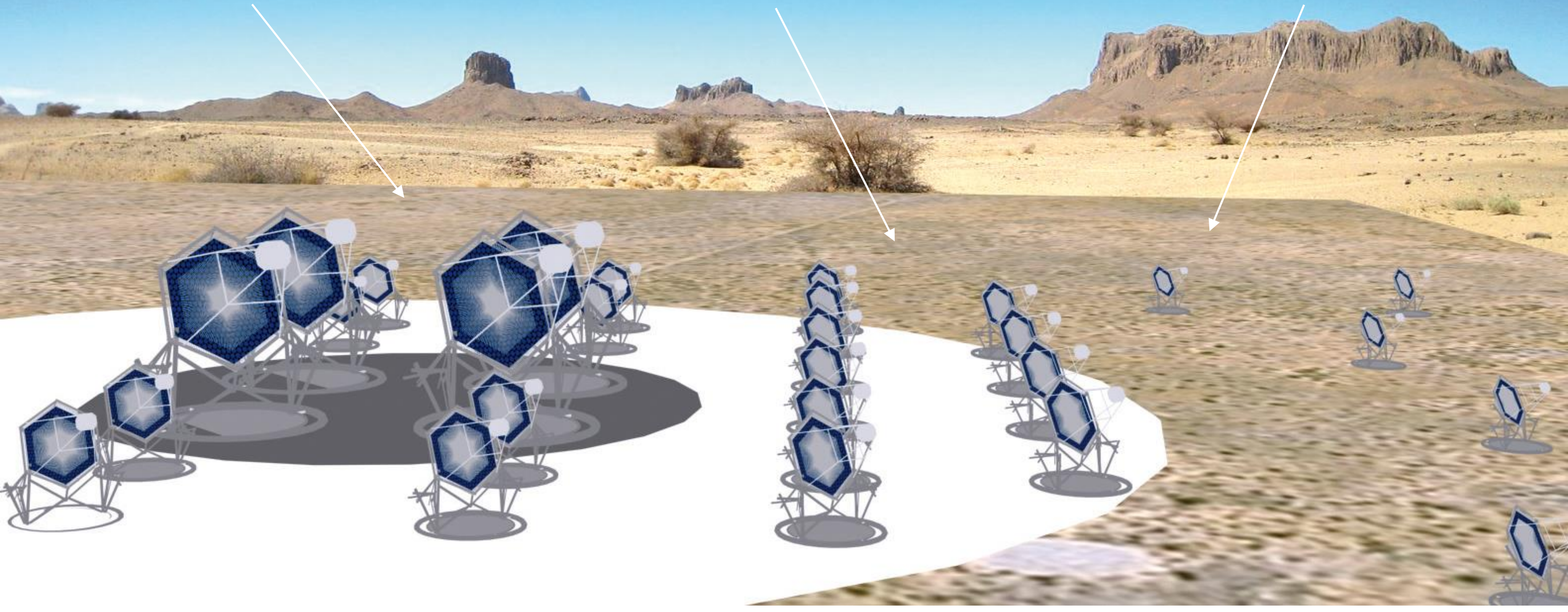
Performance goals for next-generation IACT array

- Improve angular resolution by factor ~ 5.
- Substructure of SNR shock fronts can then be resolved:

Resolution 0.1°.

Resolution 0.02°.

The Cherenkov Telescope Array concept
with southern (northern) site telescope numbers



Low energy
Four (4) 23 m telescopes
4…5^{o} FoV
~2000 pixels
~ 0.1^{o}

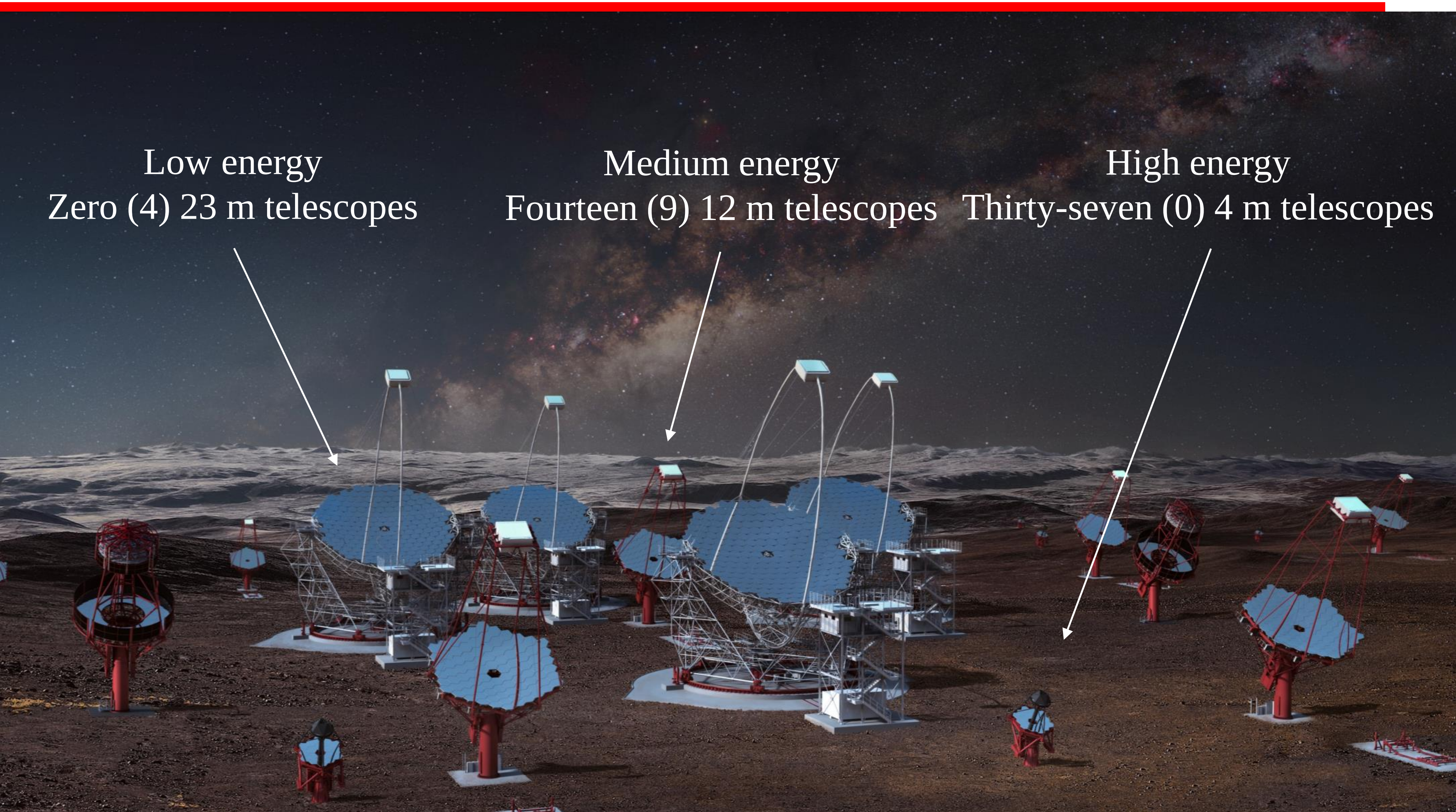
Medium energy
Twenty-five (15) 12 m telescopes
6…8^{o} FoV
~2000 pixels
~ 0.18^{o}

High energy
Seventy (0) 4 m telescopes
8…10^{o} FoV
1000…2000 pixels
~ 0.17^{o}…0.23^{o}

CTA sites

- Southern array:
  - Galactic and extra-Galactic sources.
  - 20 GeV...300 TeV.
- Northern array:
  - Mainly extra-Galactic sources.
  - 20 GeV...1 TeV.

CTA alpha phase



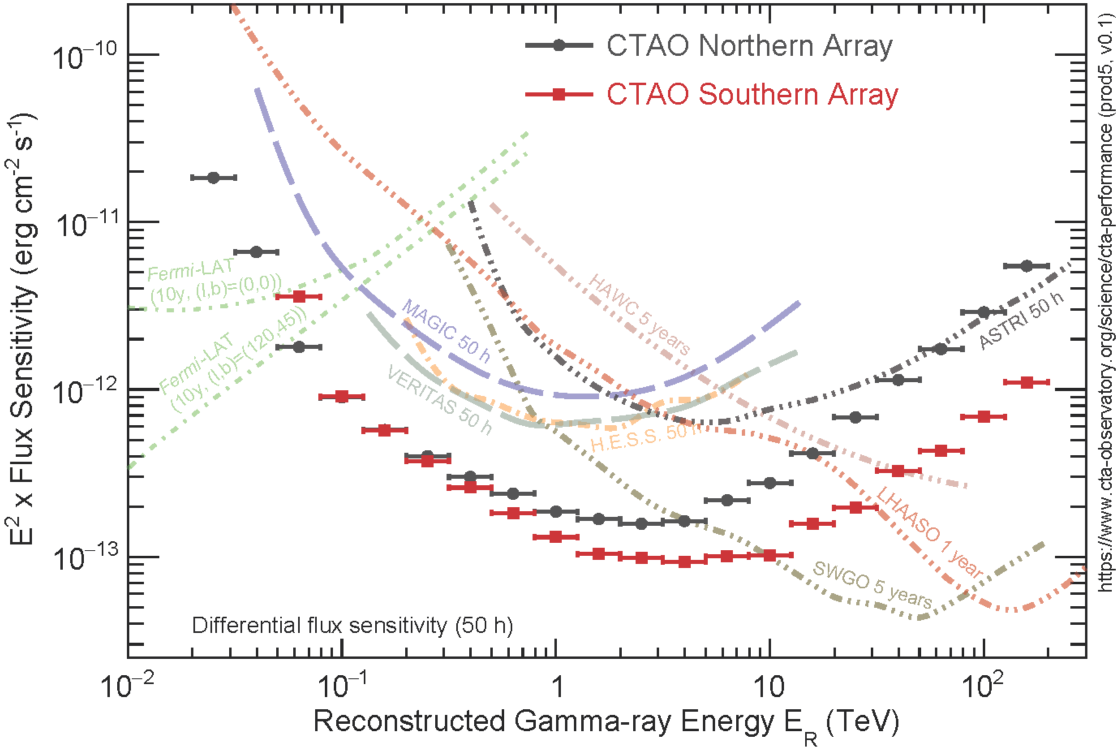
Low energy
Zero (4) 23 m telescopes

Medium energy
Fourteen (9) 12 m telescopes

High energy
Thirty-seven (0) 4 m telescopes

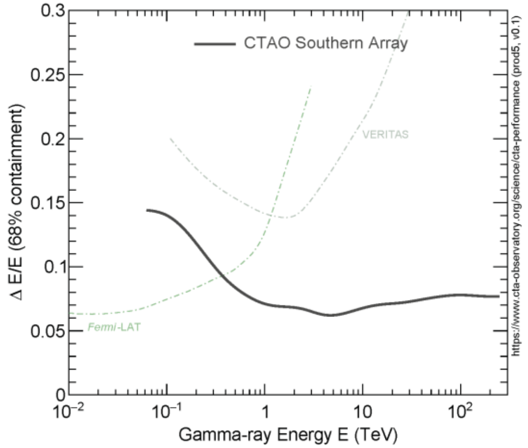
CTA performance

- CTA sensitivity:

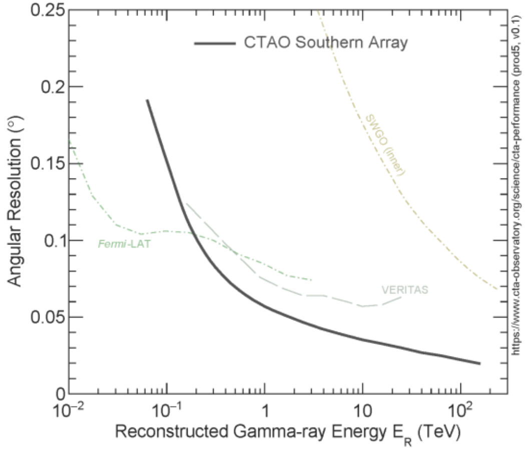


- Performance dominated by Small Size Telescopes at energies above 5 TeV.

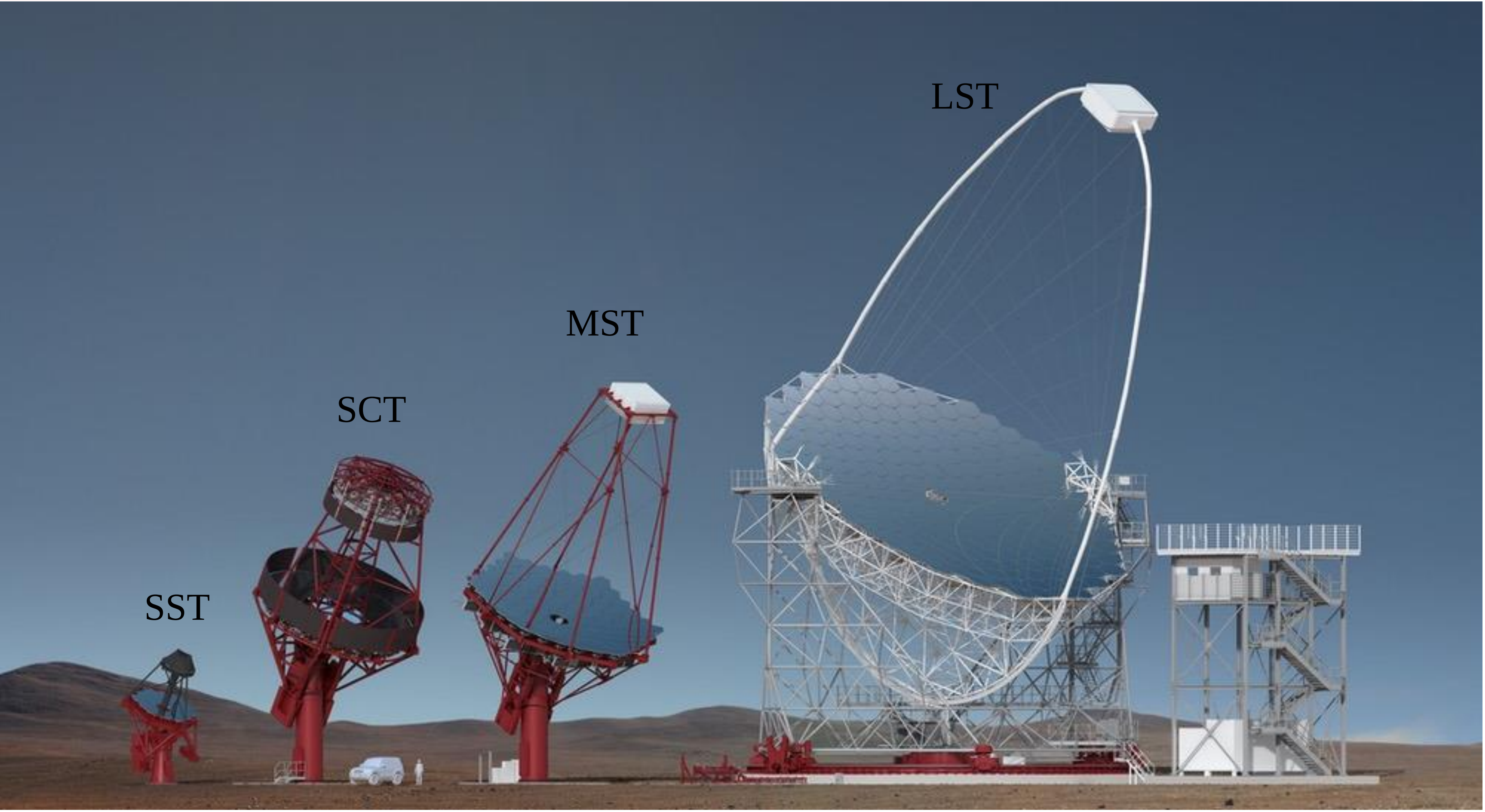
- ΔE/E < 10% for E_γ > 1 TeV.



- Ang. Res. < 0.05° for E_γ > 1 TeV.

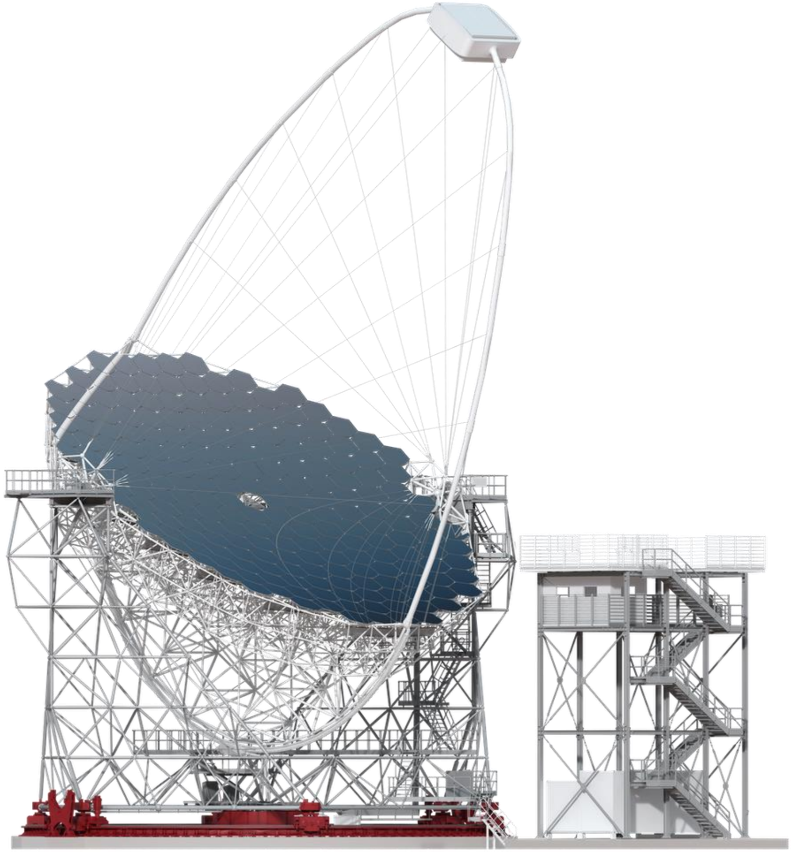


Telescope and camera development



Large Size Telescopes

- Diameter 23 m, focal length 28 m.
- (Modified) Davies-Cotton optics.
- Support structure carbon fibre.



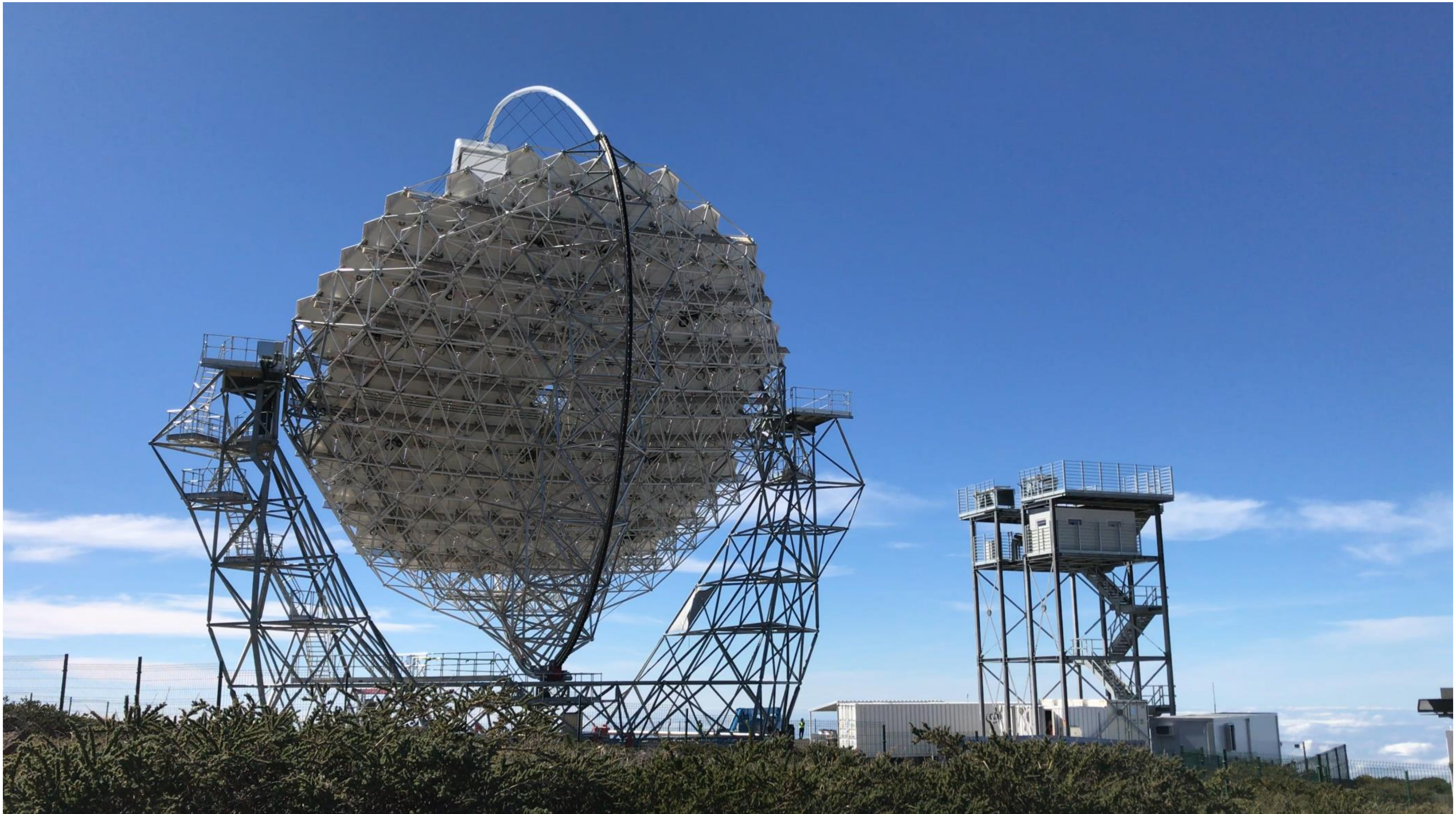
- Camera diameter ~ 2.2 m, mass ~ 2 t, uses conventional 1.5 inch (super-bialkali) photomultipliers.

LST under construction – reflection in MAGIC mirror at Roque de los Muchachos observatory

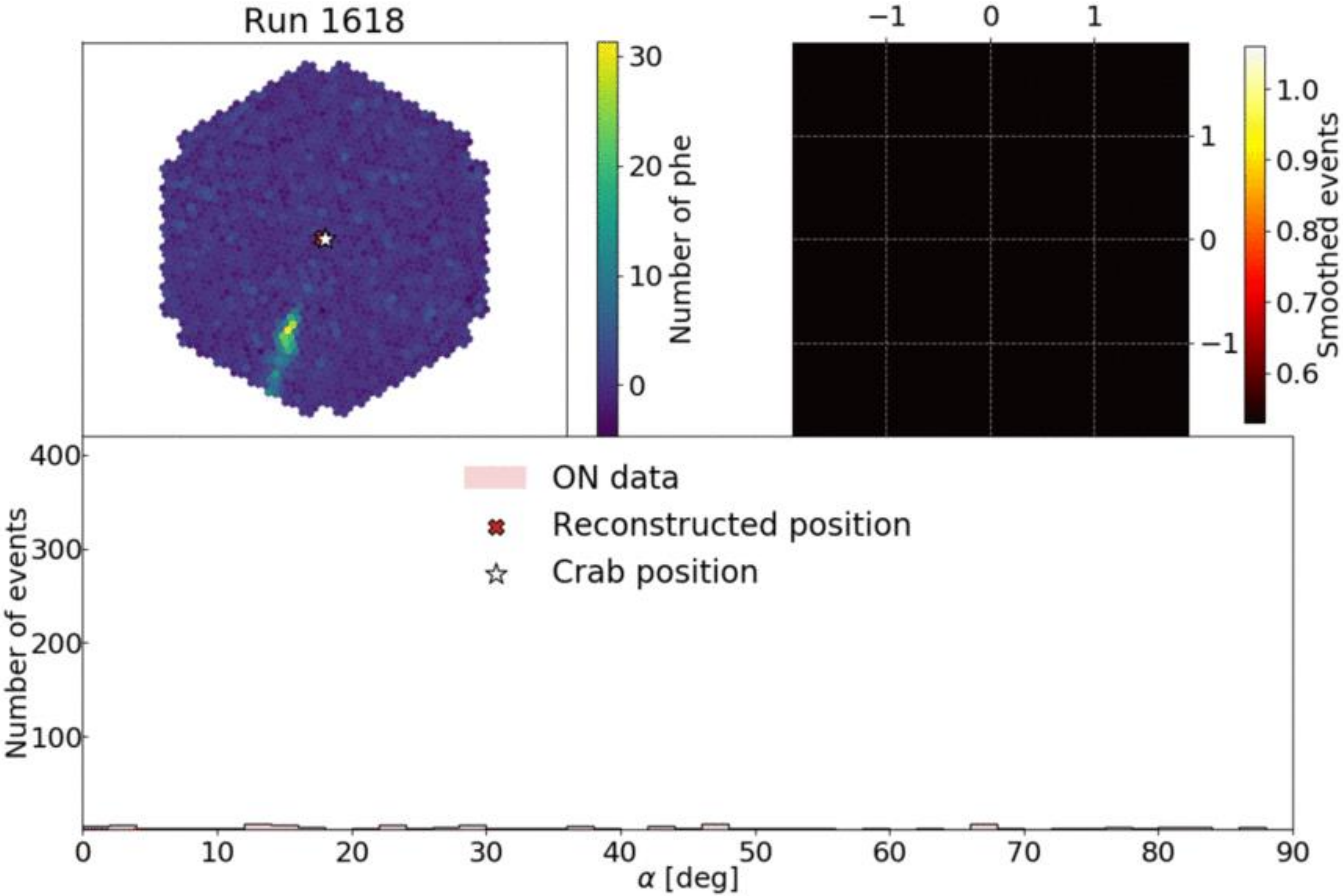
Reflection in MAGIC mirror

Residents of the Roque de los Muchachos

Large Size Telescope prototype under test



LST detection of the Crab nebula



La Palma volcano

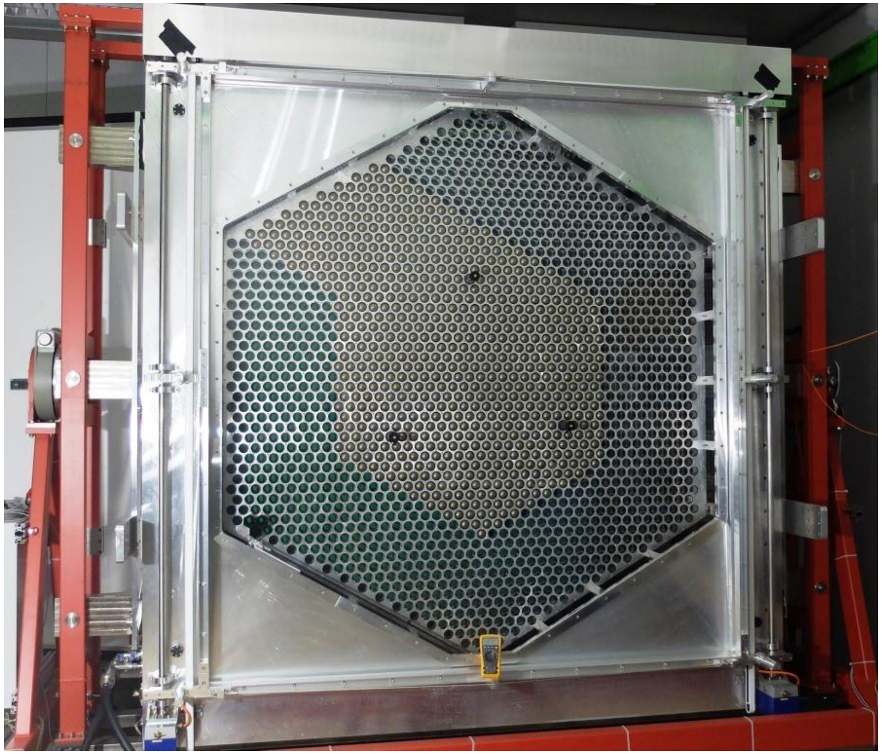
- Following seismic activity which started on 11/9/21, the Cumbre Vieja volcano erupted on 19/9/21.
- Last eruption in 1971.
- Lava flows have destroyed about 3000 buildings and 15 km of road.
- About 7000 people displaced.
- La Palma airport closed for some periods due to build-up of ash on the runway.
- No direct effects on MAGIC and CTA at the Roque de los Muchachos Observatory.
- Some concern about possible mirror damage.

La Palma volcanic eruption

- Images from Swedish Solar Telescope (SST):

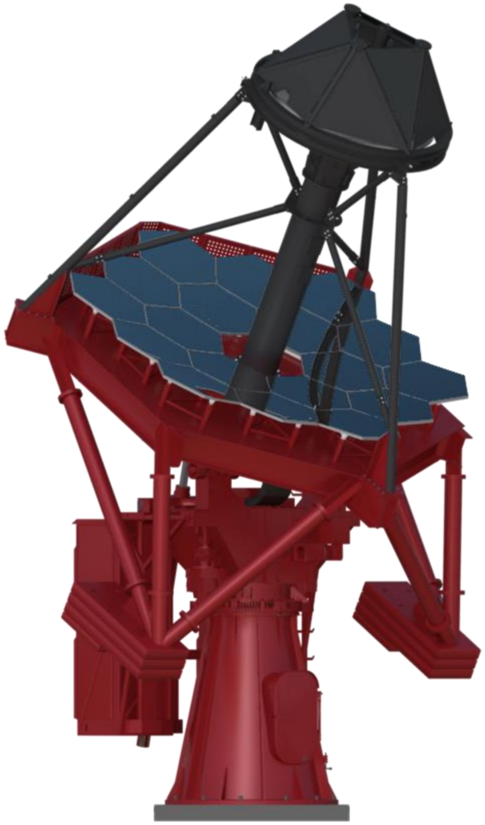
Medium Size Telescopes

- Diameter 12 m, focal length 17 m.
- Davies-Cotton optics.
- Camera support and dish structure steel.
- Camera diameter ~ 2.2 m, mass ~ 2 t.



Small Size Telescopes

- Schwarzschild-Couder optics.
- Primary diam. 4.3 m, secondary diam. 1.8 m, focal length 2.15 m.



- Schwarzschild best-known for 1916 solution to General Relativity equations.
- In 1905, described a telescope with two concave aspherical mirrors, between which is focal plane.
- No spherical aberration or coma, but significant astigmatism, partly as focal surface assumed flat.
- Couder modified design in 1926, allowed curved focal surface, curing astigmatism.
- Figured mirrors in 1930s, but telescope never built. (Perhaps because 6 m long?)
- UK groups realised design ideal for SSTs as allows use of compact camera and SiPMs, produced optical design.

Inauguration of GCT prototype – candidate SST

- 1st Dec. 2015.

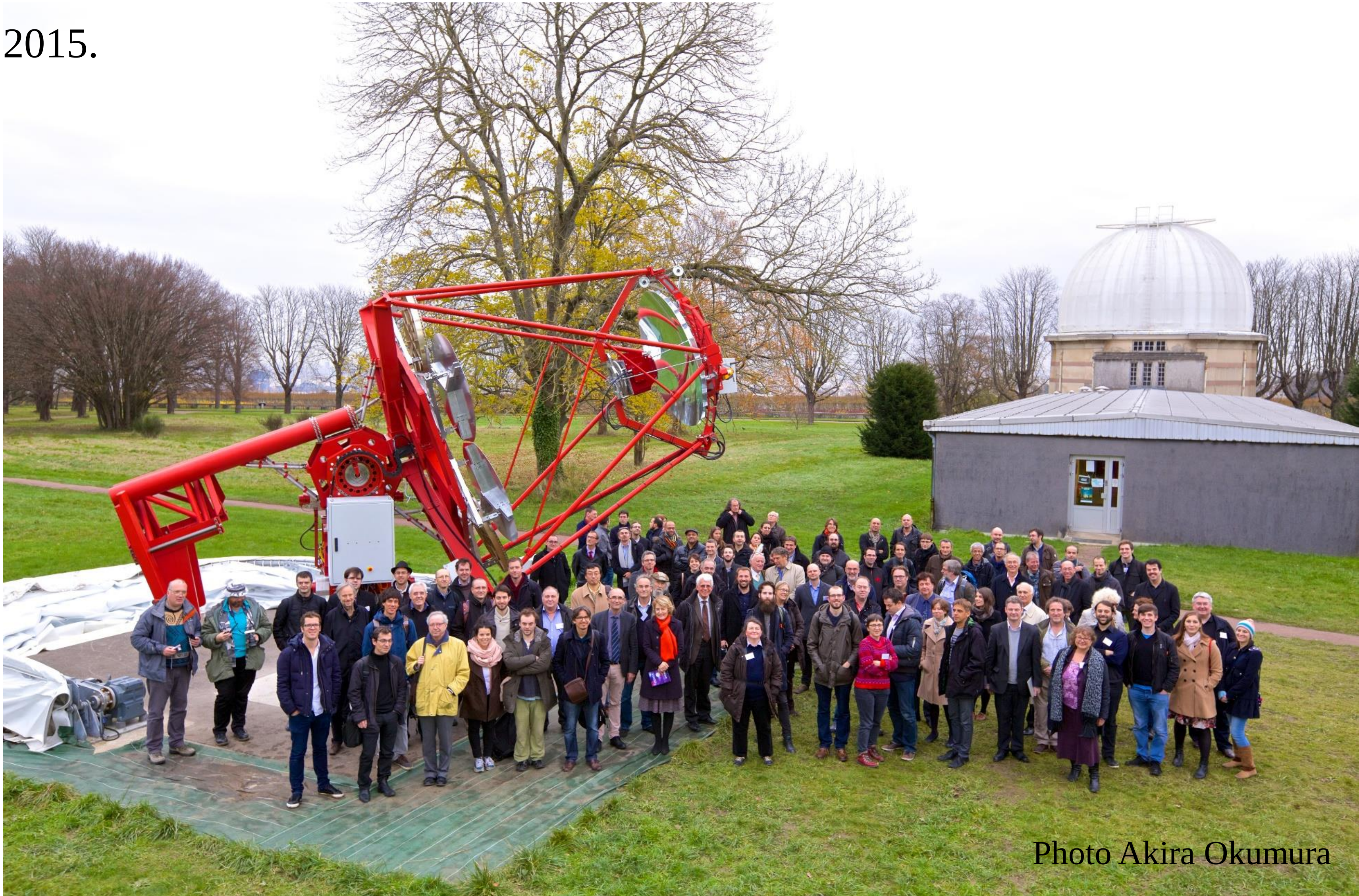


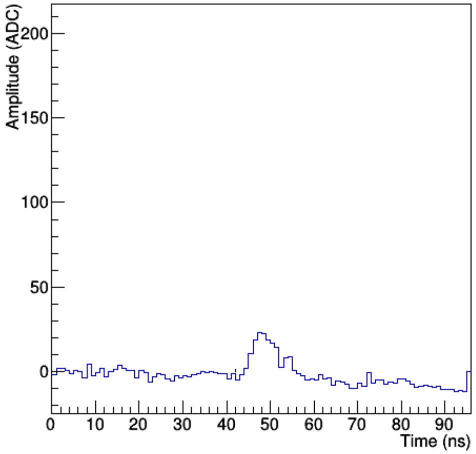
Photo Akira Okumura

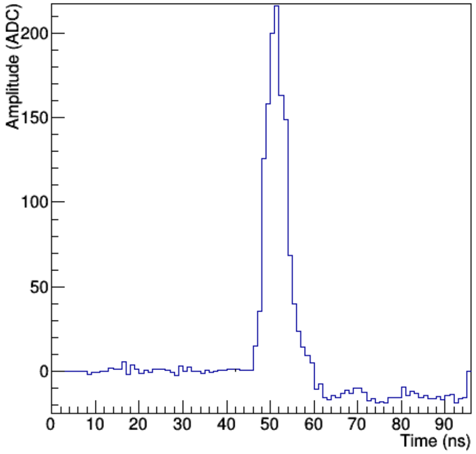
First Cherenkov light with GCT prototype

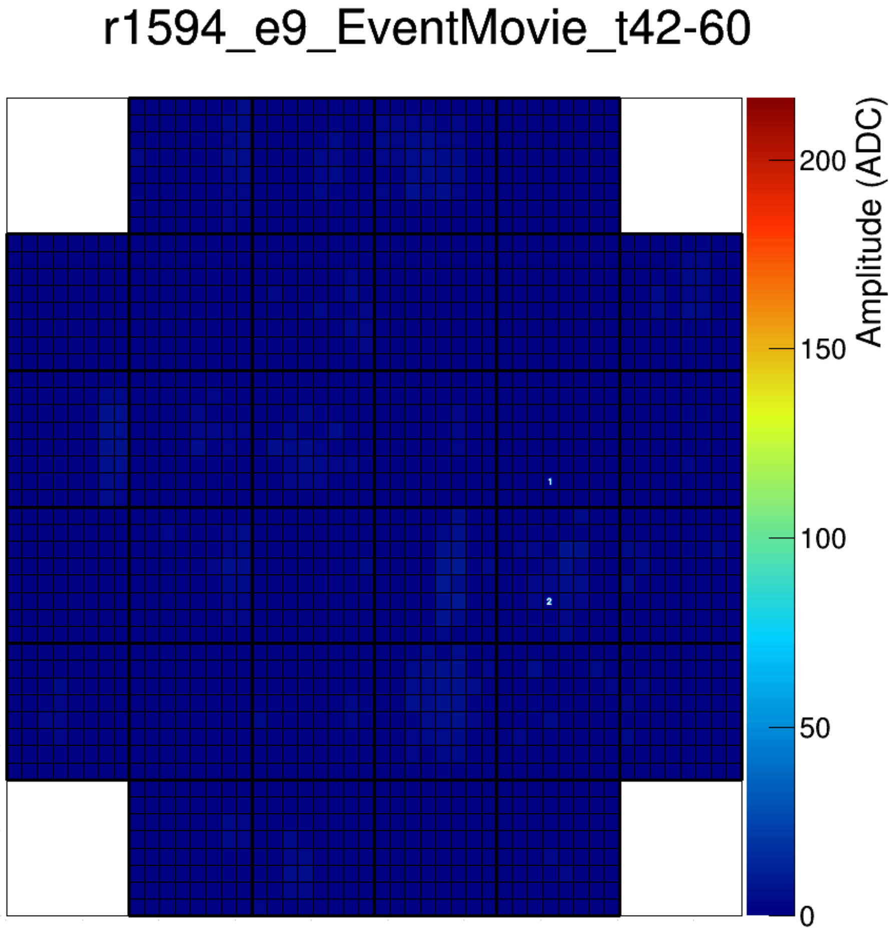
- Thursday 26th Nov 2015, NSB 20 to 100 times higher than CTA site…

First Cherenkov light with GCT prototype

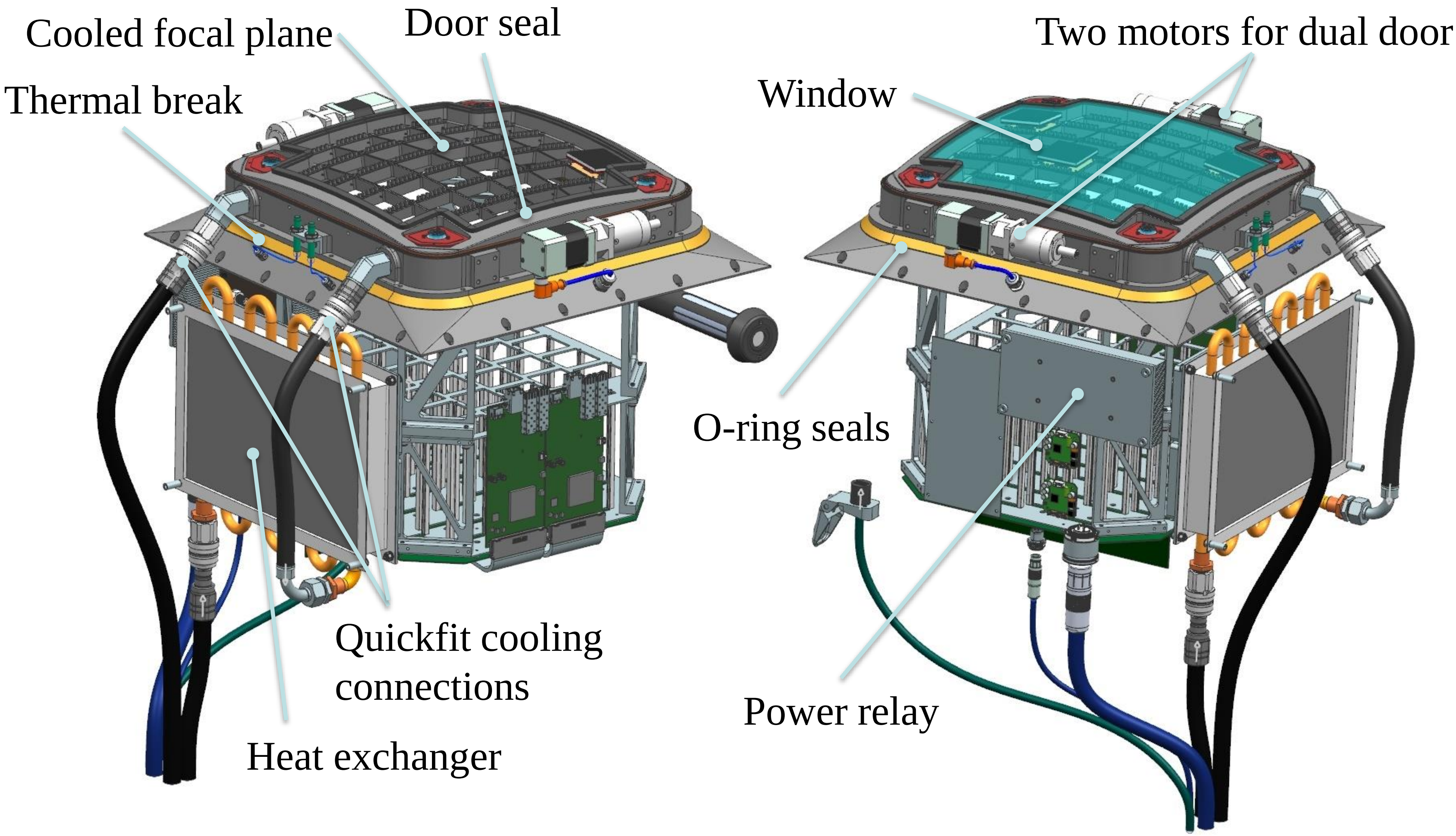
- Cosmic ray events observed with CHEC-M.



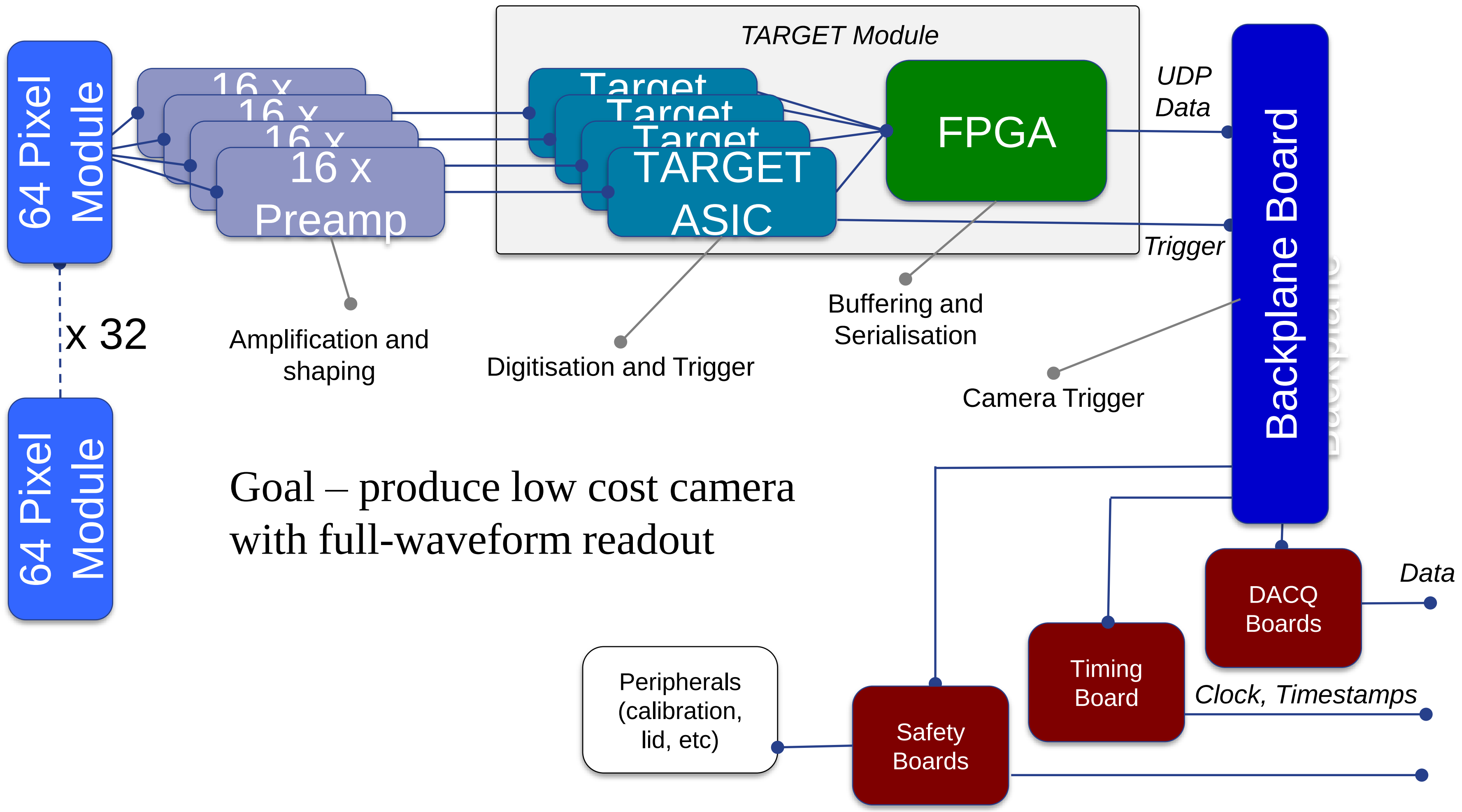




SiPM based camera – CHEC-S

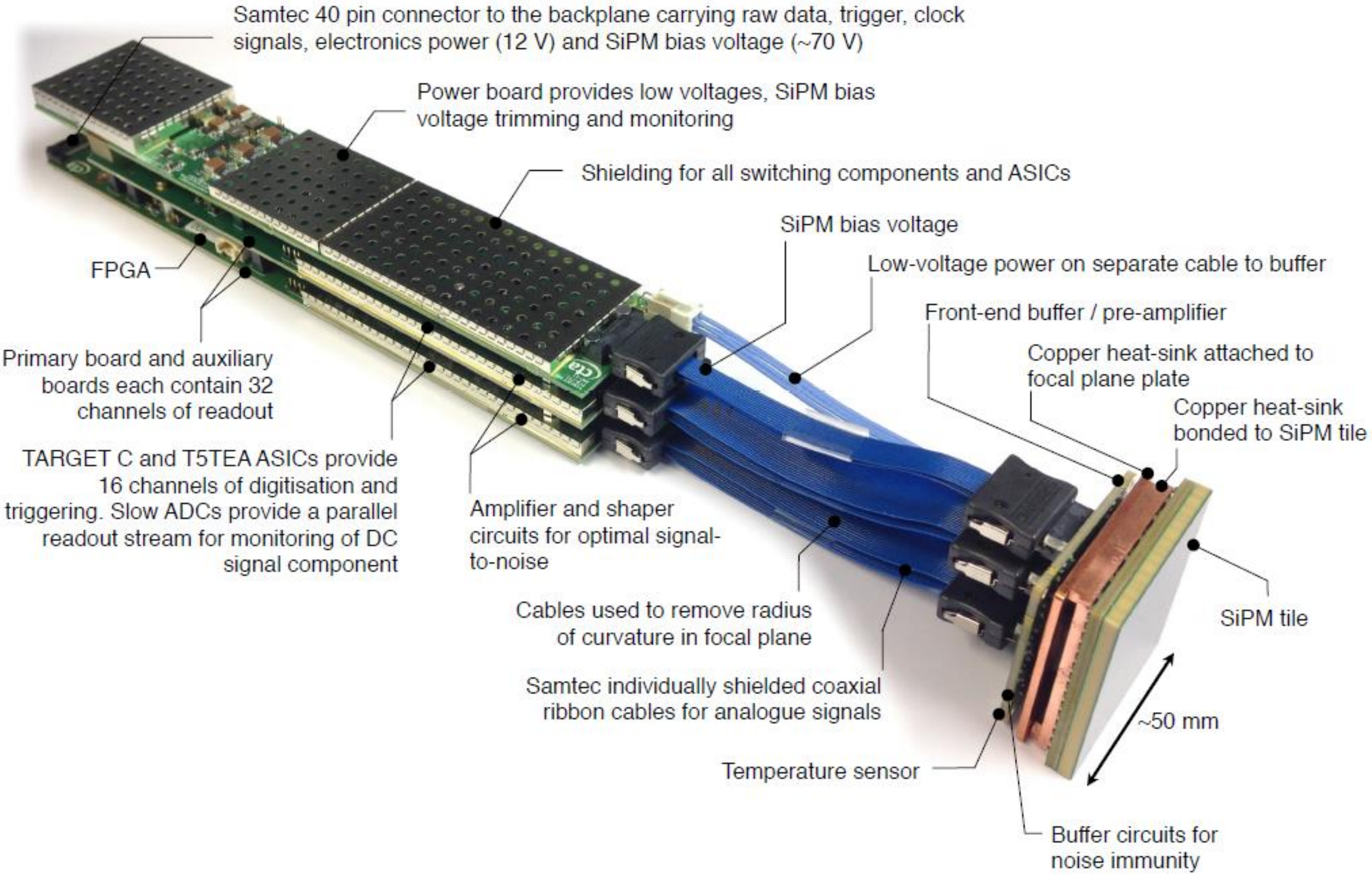


Camera architecture



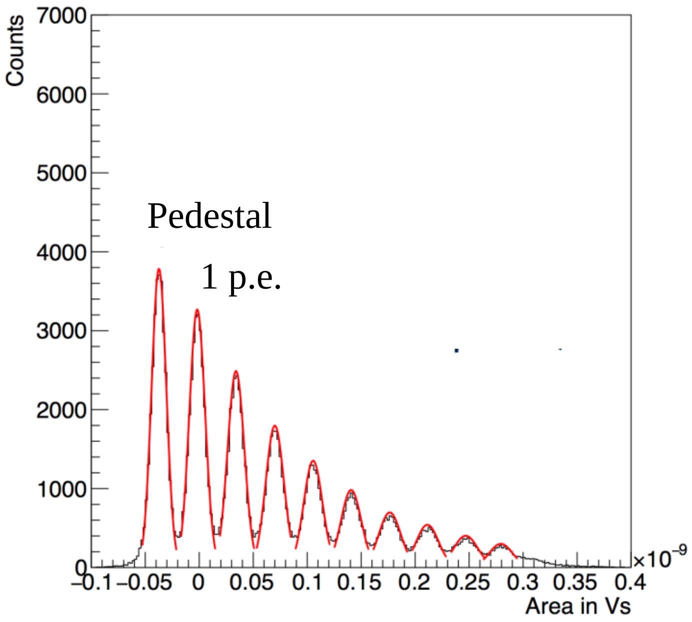
Goal – produce low cost camera with full-waveform readout

CHEC-S: TARGET modules

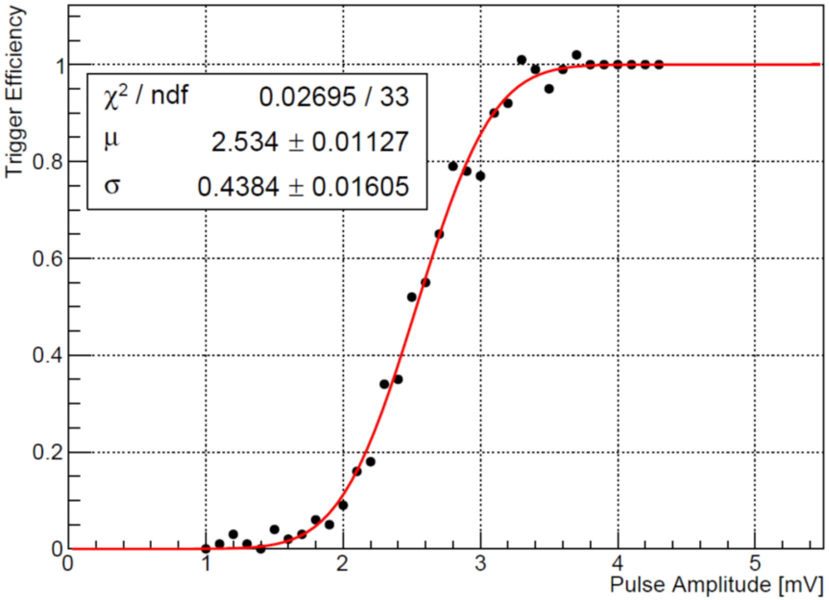


TARGET module performance

- Pulse FWHM < 10 ns, $\delta t_{peak} < 150$ ps.
- Gain spread TARGET module < 4%.
- Max. cross talk < 0.7%.
- Noise in module ~ 0.4 ADC counts.
- CHEC-S SiPM + TARGET pulse-area spectrum:



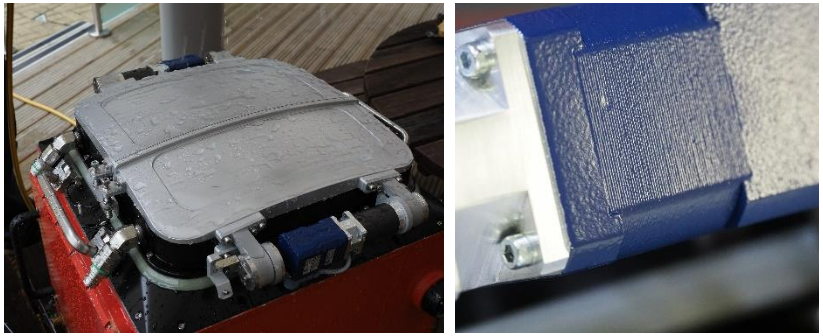
- Triggering:



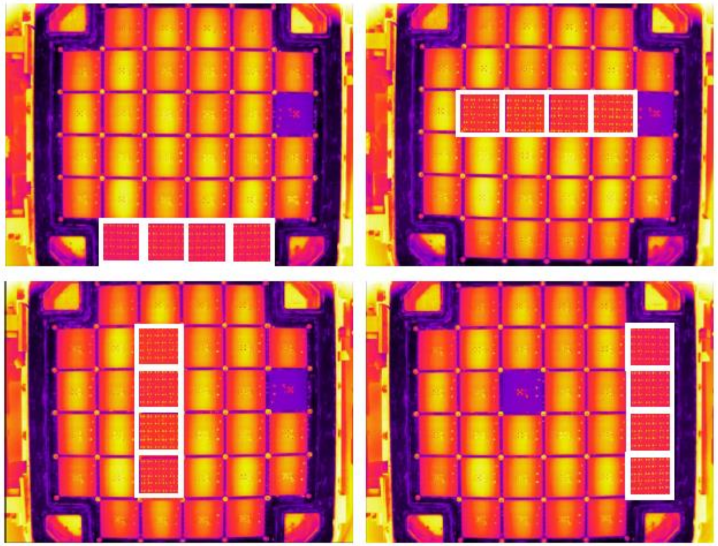
- Operation regime 3…4 mV/p.e.
- Threshold 2.5 mV (0.6…0.8 p.e.),
- Noise 0.44 mV (0.1…0.15 p.e.).
- Threshold stable over large T range (1 mV change for 5 < T < 45 C).

CHEC-S: mechanical design

- Rain and hail tests performed.



- Focal plane cooling tested:



- In Durham wind tunnel, opening and closing of doors functioned to 15 m/s.
- Here at 12.5 m/s (CTA requirement):

- With doors closed, survived max. wind speed of 30.7 m/s.

CTA southern site

- Paranal, Chile.

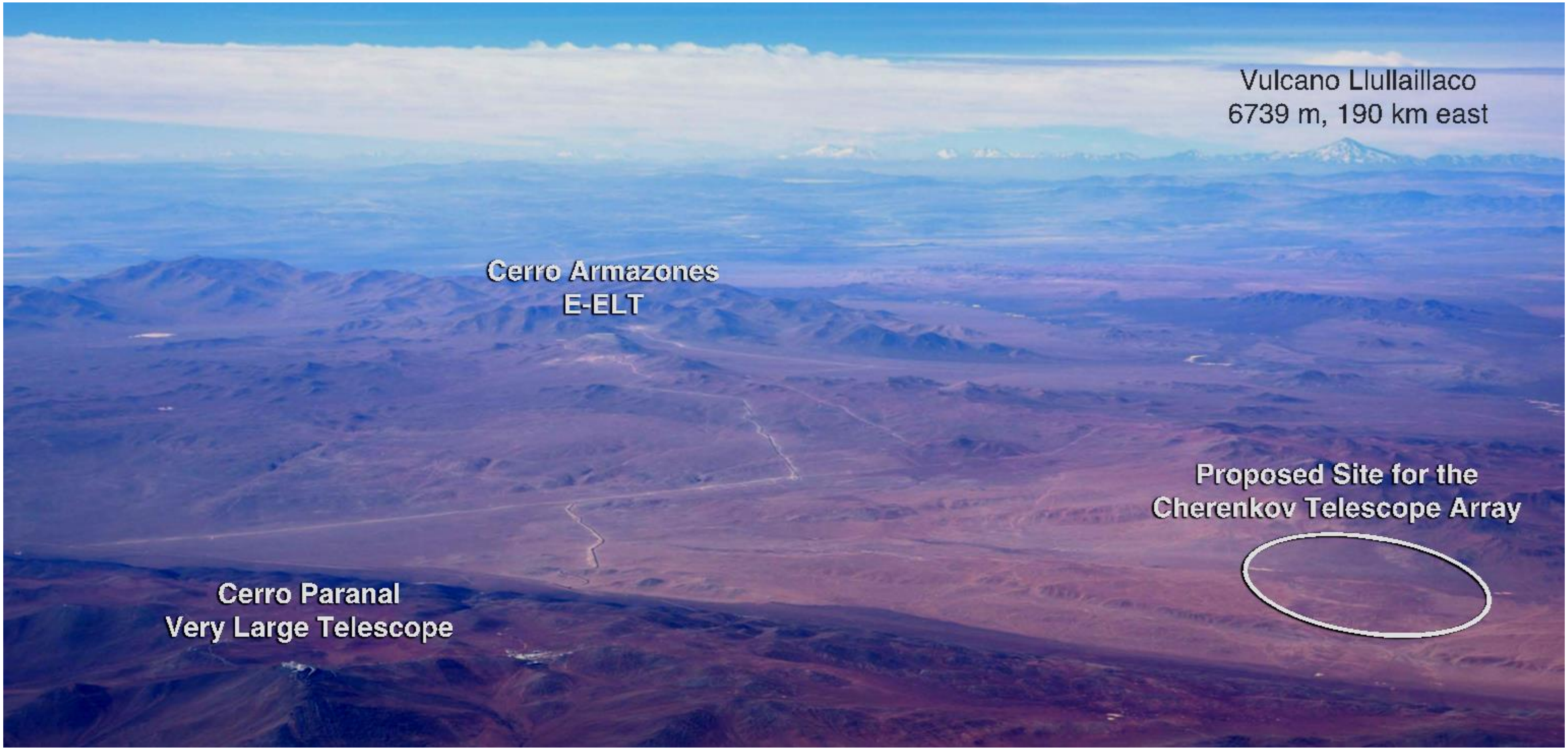


Photo: Marc-Andre Besel

CTA site in Chile

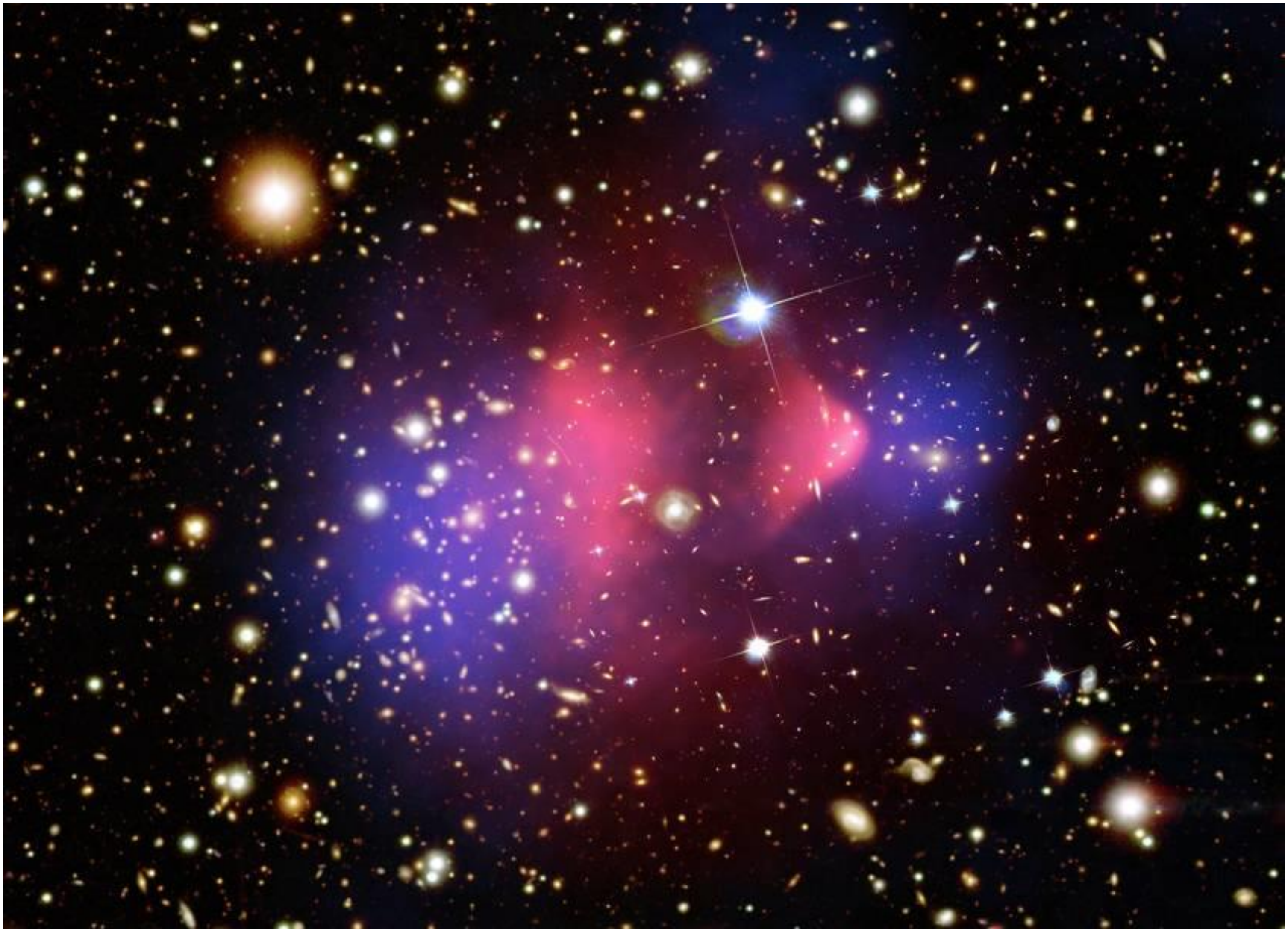
ESO Paranal site in Chile

Fundamental physics with CTA – Dark Matter

- Why do we think there is Dark Matter?
- Look at the stars orbiting around the centre of a galaxy…
- Need non-luminous matter to ensure their gravitational confinement.

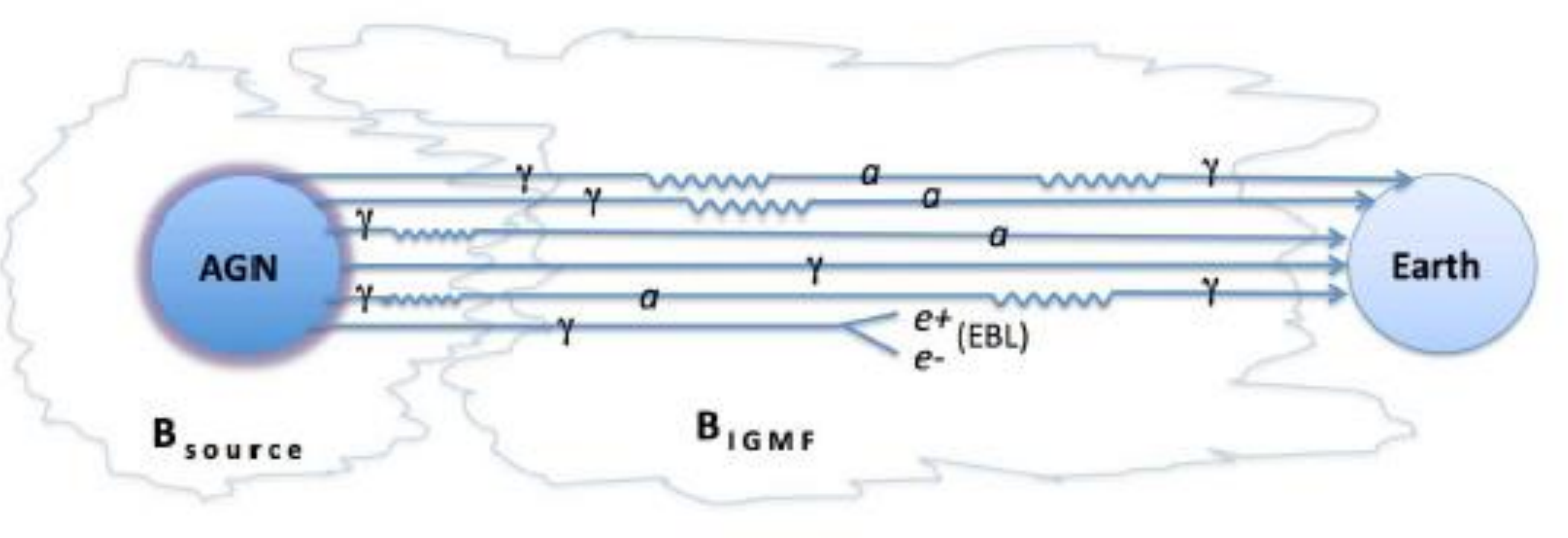
Detecting Dark Matter with CTA

- More evidence for DM – the Bullet Cluster
- Dark Matter forms most of material of Universe.
- Annihilation of WIMP Dark Matter particles could produce high energy photons that CTA could measure.



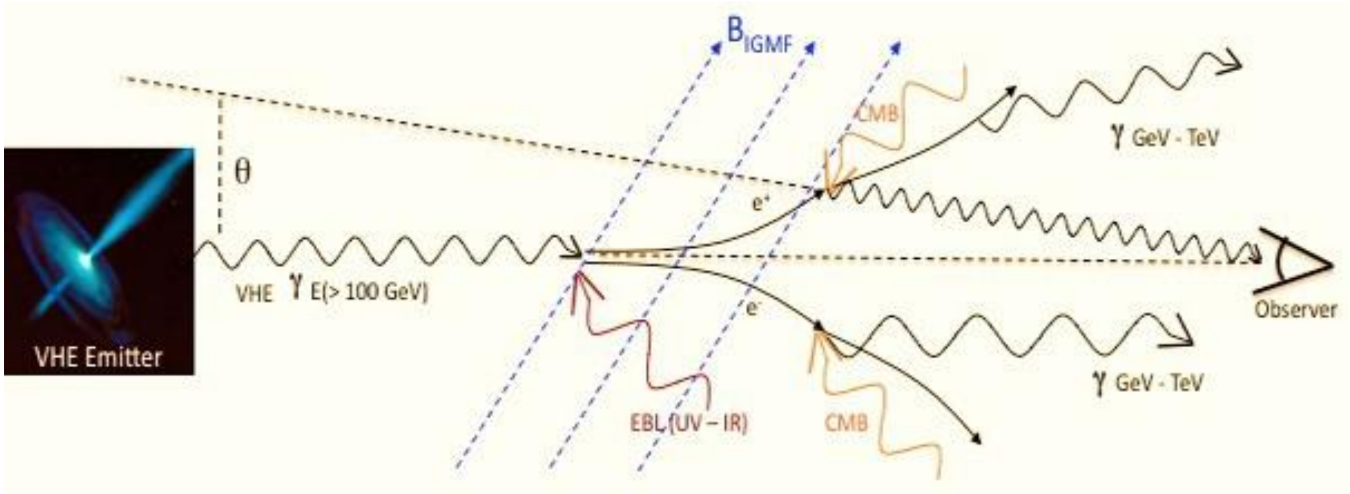
Detecting Dark Matter with CTA

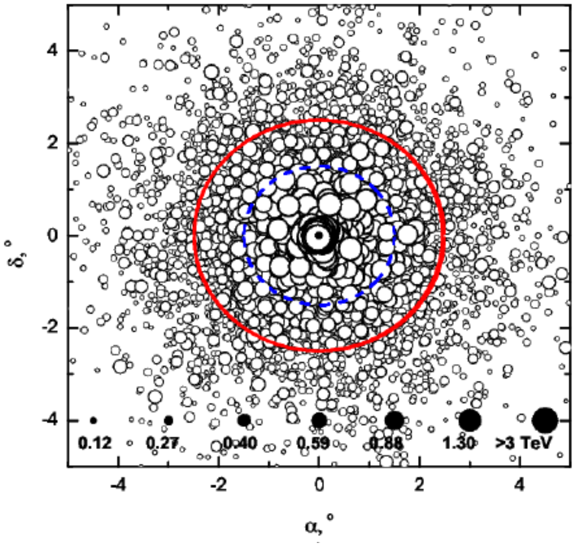
- Opacity of universe to VHE γs changes if DM is formed of axion-like particles.



- Allows searches for ALPs in mass, coupling regions not otherwise accessible.
- These studies also provide a measurement of the EBL density.
- Will allow inferences about the first “population III” stars and the stellar formation rate, but perhaps also about decays of exotic particles to photons in the early universe.

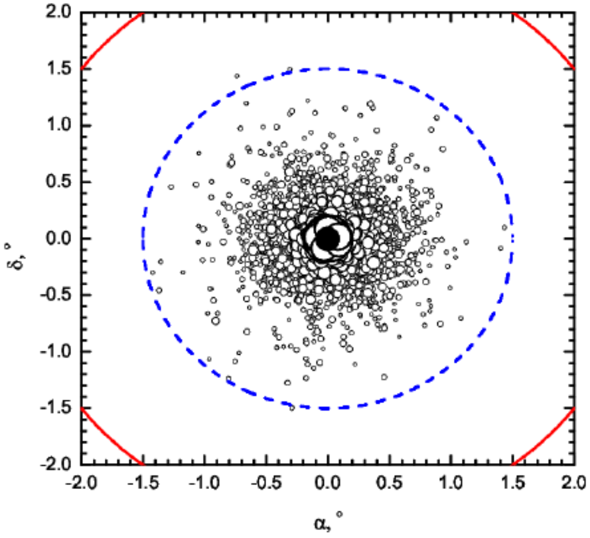
Probing intergalactic magnetic fields with CTA





- Explore origin of magnetic fields in galaxies.
- Look for extended γ-ray emission, pair haloes and pair echoes.

- Primary and secondary γ-rays from source at 120 Mpc.
- Top Fig. IGMF 10^{-14} G, bottom IGMF 10^{-15} G.
- For lower fields, can look for "pair echoes".



Summary

- Cosmic Rays continually bombard the Earth, some with astonishing energies.
- The best way of studying these particles is to measure the photons they produce.
- Studying these gamma rays with CTA will help us to understand the most violent events occurring in the Universe...
- ...and also to learn more about fundamentally new physics, such as Dark Matter.