The pSCT: an innovative, next-generation ground-based gamma-ray observatory

Massimo Capasso
Barnard College, Columbia University
(capasso@nevis.columbia.edu)

Summer Colloquium Series - 2020

Nevis Laboratories
Columbia University

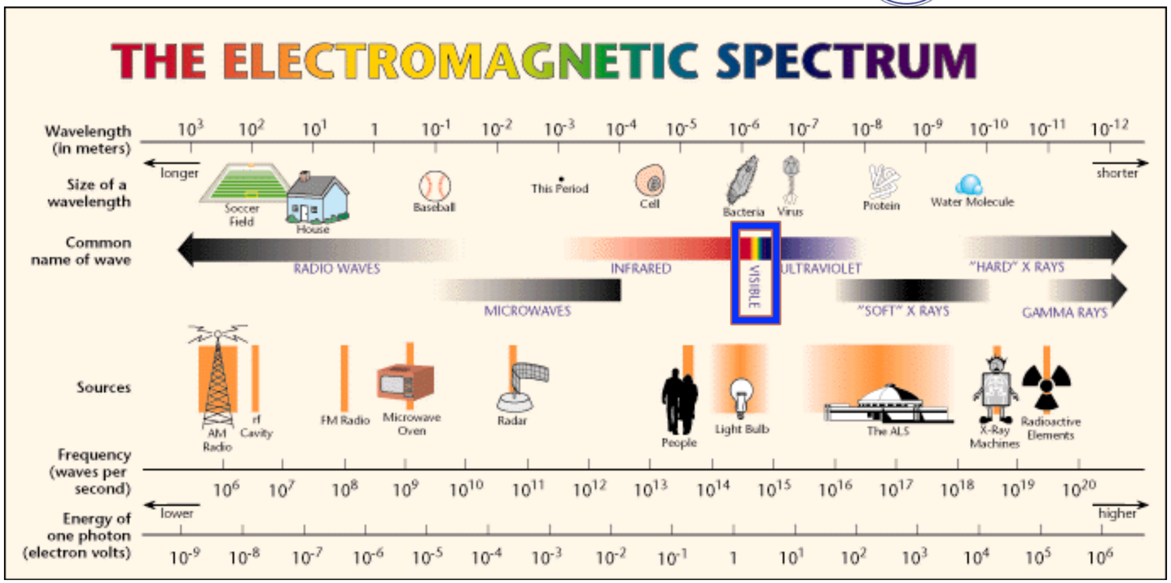
Outline

- VHE γ-ray astronomy
  - How does the sky look like in VHE γ-rays?
  - Emission mechanisms
  - γ-ray sources
  - Satellite vs. ground-based experiments
- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Current and next-generation observatories
- The prototype Schwarschild-Couder Telescope
  - Optics
  - Detectors
  - Electronics

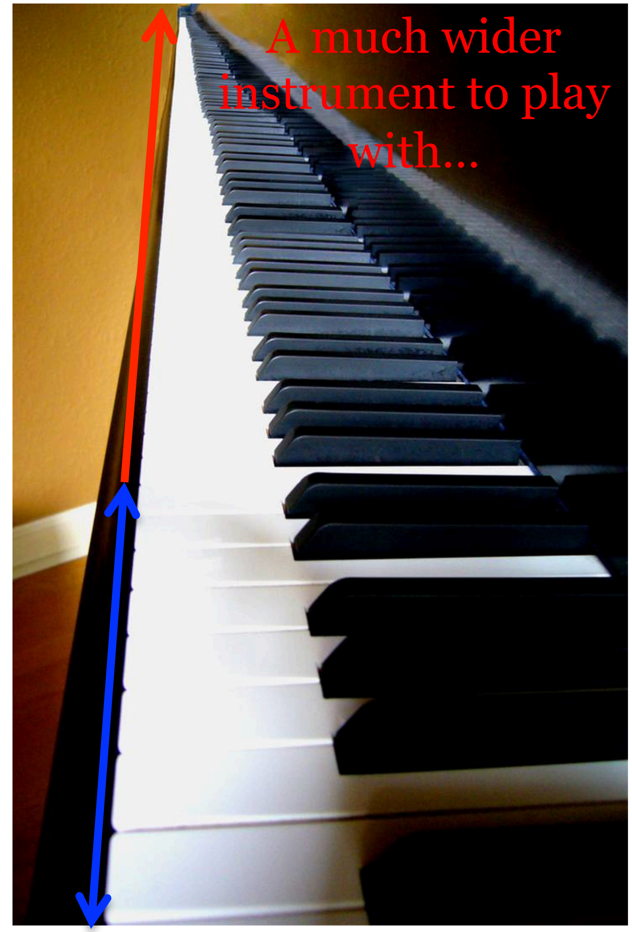
Outline

- VHE γ-ray astronomy
  - How does the sky look like in VHE γ-rays?
  - Emission mechanisms
  - γ-ray sources
  - Satellite vs. ground-based experiments
- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Current and next-generation observatories
- The prototype Schwarschild-Couder Telescope
  - Optics
  - Detectors
  - Electronics

Beyond the eyes



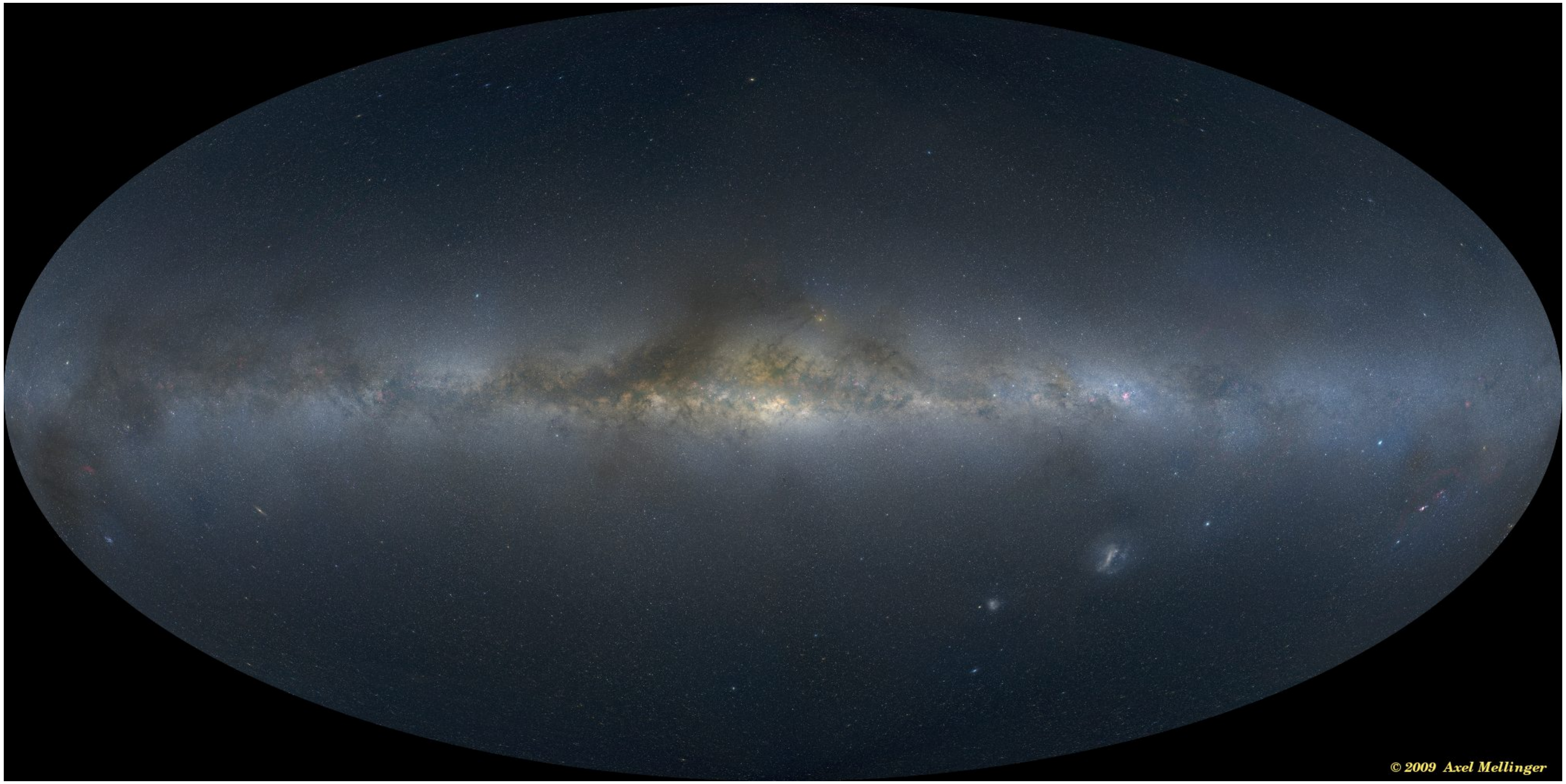
https://www2.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html



Visible

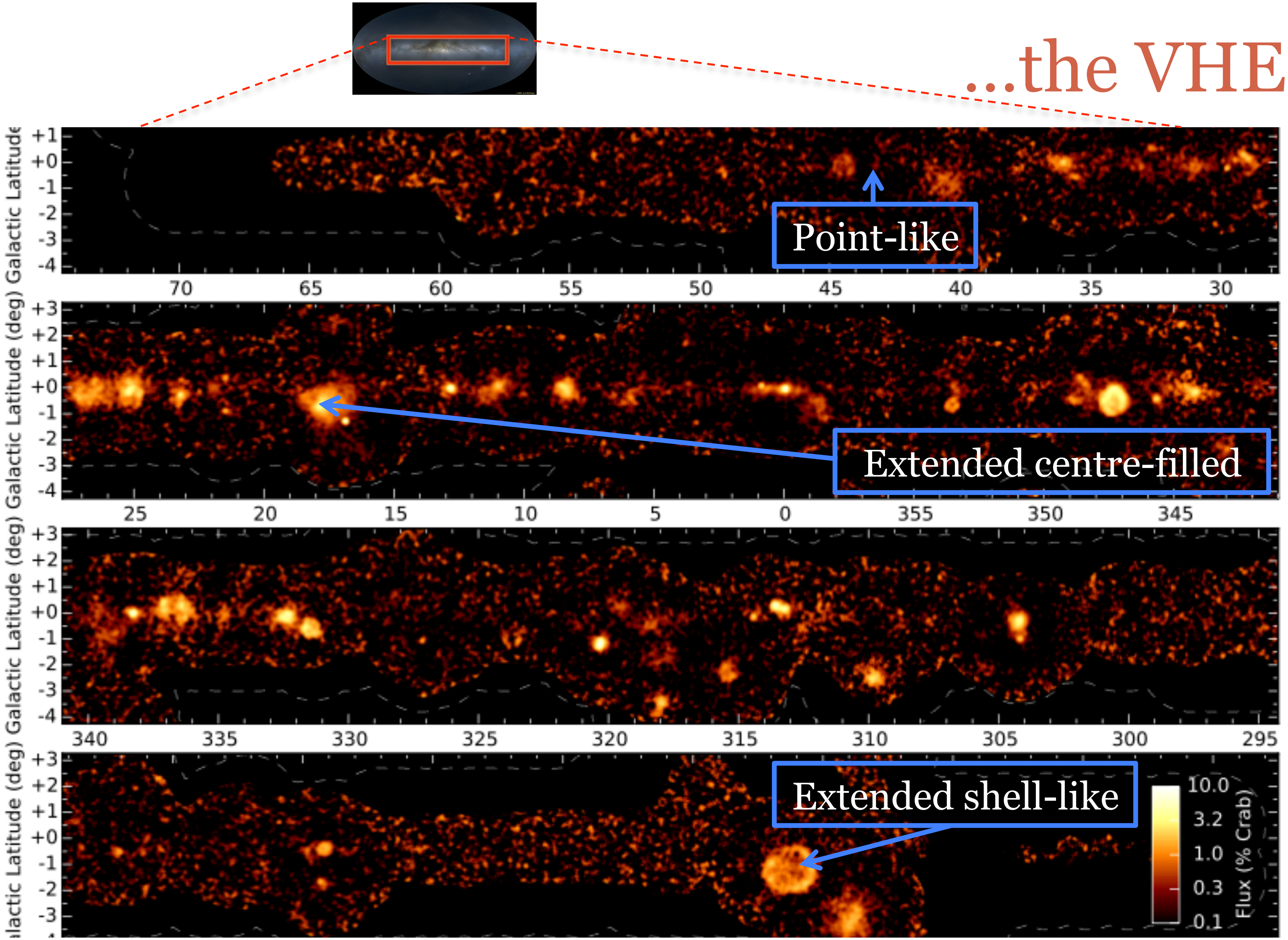
https://www.deviantart.com/vidpen/art/The-very-long-piano-56181014

The optical sky…



A. Mellinger, A color All-Sky Panorama Image of the Milky Way, Publ. **Astron. Soc. Pacific 121, 1180-1187 (2009)**

...the VHE one!



Integral flux above 1 TeV in units of % of the Crab nebula, the brightest VHE γ-ray source in the sky. Image taken from [(H.E.S.S. Collaboration et al. 2018b)]

Emission mechanisms (VHE γ-rays)

- Inverse Compton (IC) scattering:
  - Ultra-relativistic electrons scatter low-energy ambient photons to high energies → the photons gain energy at the expenses of the electrons' kinetic energy

- $\pi^0 \rightarrow \gamma\gamma$
  - Relativistic protons and nuclei interact on ambient gas through inelastic collisions, producing both charged (π^{+-}) and neutral pions (π^0)

VHE γ-ray sources

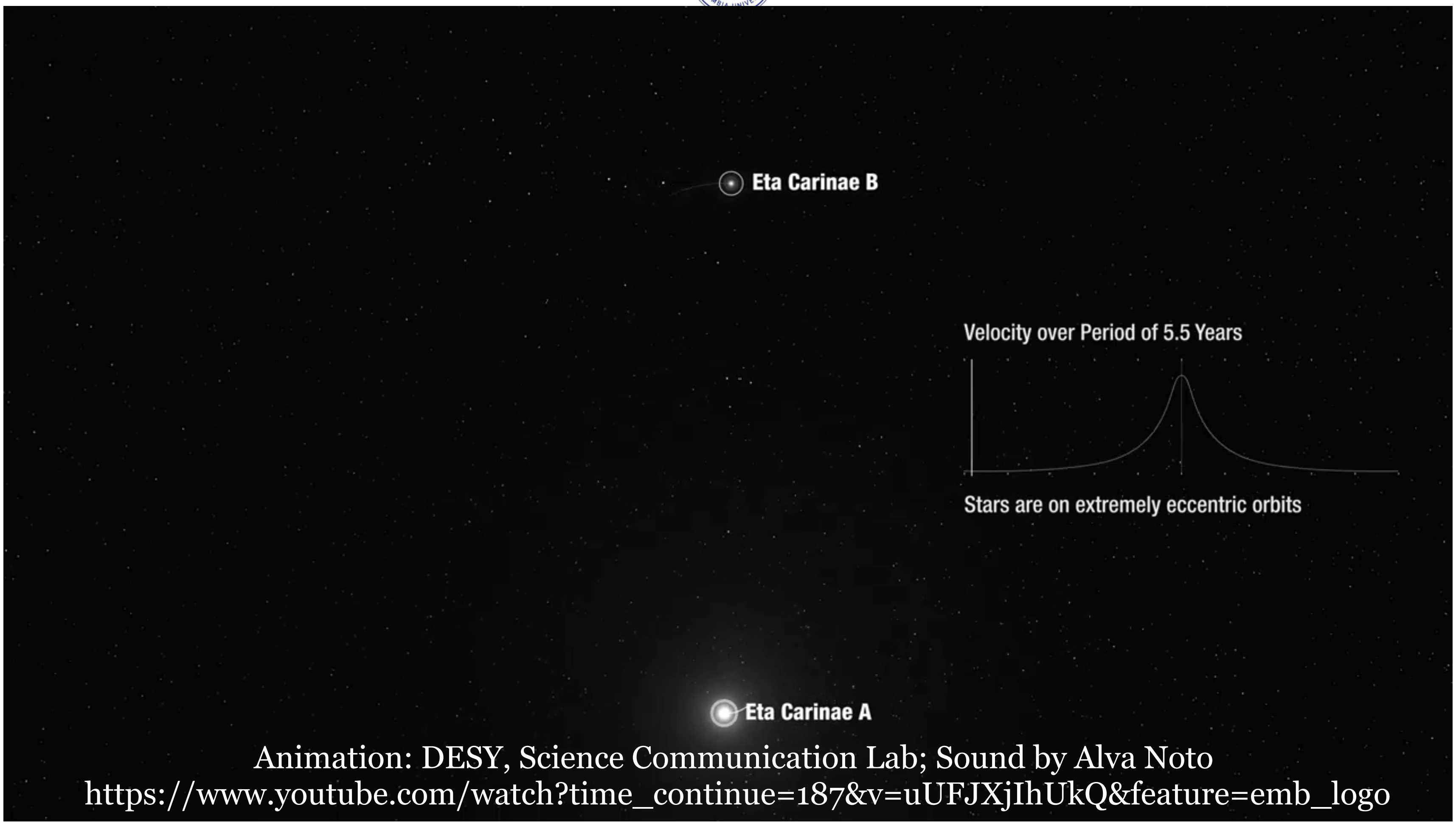
Galactic sources

- Pulsar Wind Nebulae (PWN)
  - Wind of e^+/e^- accelerated to relativistic energies by magnetic field of a rotating neutron star (pulsar)
- Supernova Remnants (SNRs)
  - Remnants of a Supernova explosion expanding into the interstellar medium (ISM) → sources of bulk (protons and heavier nuclei) of galactic Cosmic Rays (CRs)?
- Binary systems
  - Compact object (e.g. a NS) and a massive star companion. VHE γ-ray emission possibly from particles accelerated at the shock between the wind of the massive star and the one of a pulsar

Extragalactic sources

- Active Galactic Nuclei (AGN)
  - A SMBH at the center of a galaxy accretes material from the galaxy dense central region; narrow beams of energetic particles are produced and ejected outward in opposite directions away from the disk
- Gamma-Ray Bursts (GRBs)
  - *Short and sudden e.m. signals in the gamma-ray band which, for a few blinding seconds, become the brightest objects in the Universe* (see Dr. E. Bissaldi's talk from this series)

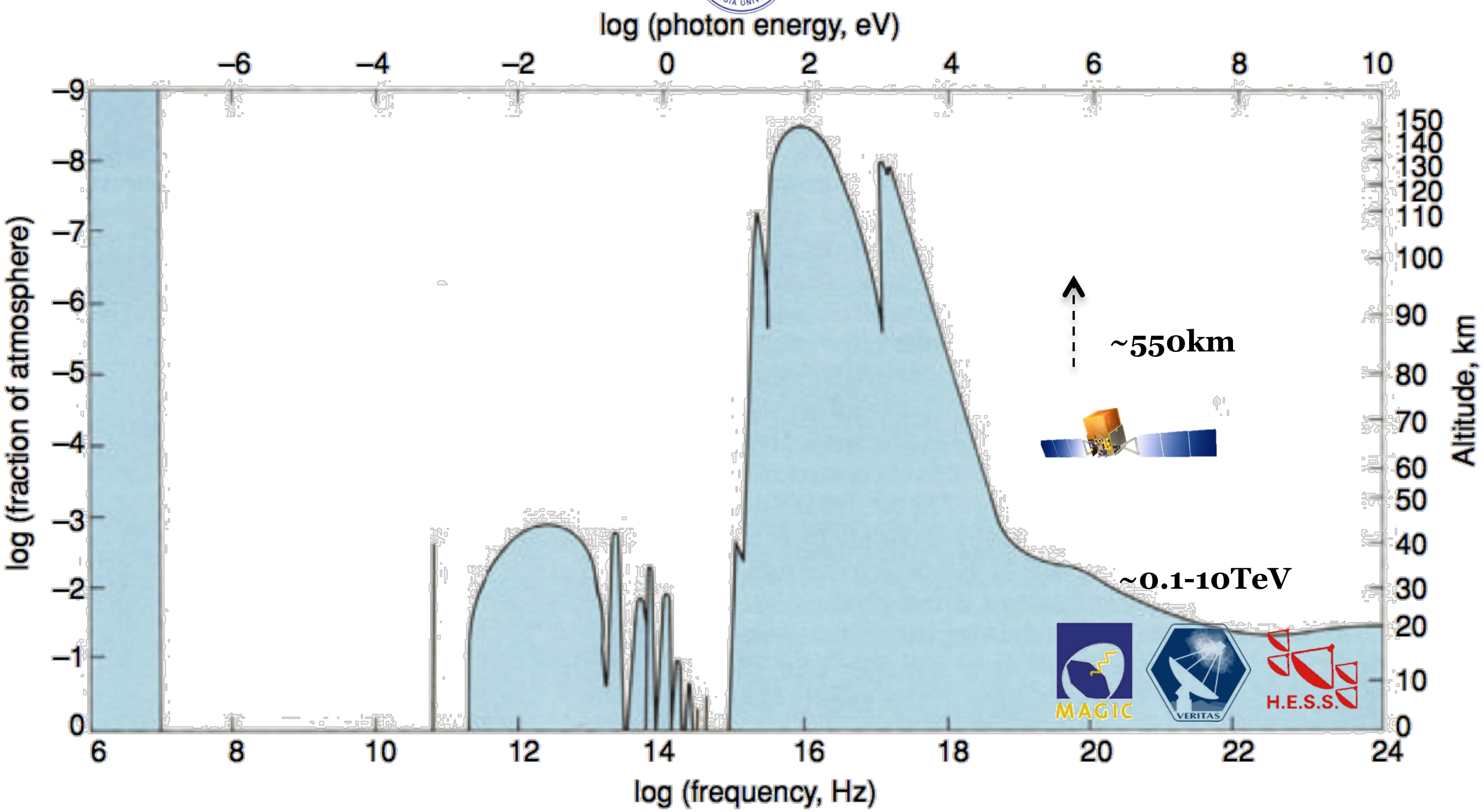
VHE γ-rays from Eta Car



Animation: DESY, Science Communication Lab; Sound by Alva Noto
https://www.youtube.com/watch?time_continue=187&v=uUFJXjIhUkQ&feature=emb_logo

Astronomy & Astrophysics, 2020; DOI: [10.1051/0004-6361/201936761](https://doi.org/10.1051/0004-6361/201936761)

Satellite vs. ground-based experiments

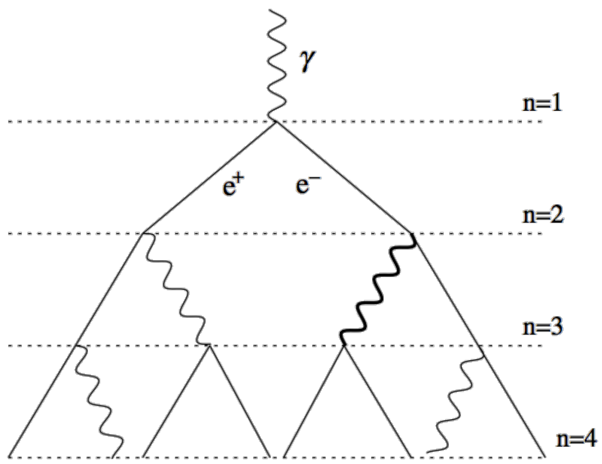


Transparency of the atmosphere for radiation of different wavelengths. The solid line shows the height above sea-level at which Earth's atmosphere is 50% transparent to incoming electromagnetic radiation, for radiation of different wavelengths. Figure taken from [Longair (2011)]

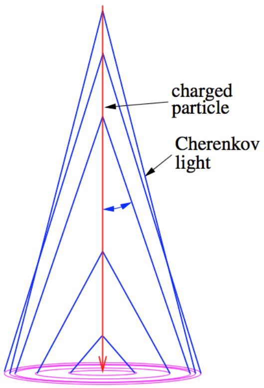
Outline

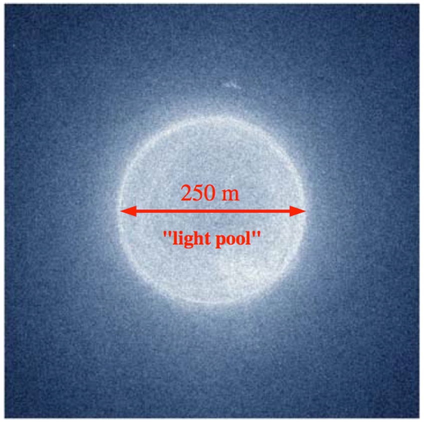
- VHE γ-ray astronomy
  - How does the sky look like in VHE γ-rays?
  - Emission mechanisms
  - γ-ray sources
  - Satellite vs. ground-based experiments
- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Current and next-generation observatories
- The prototype Schwarschild-Couder Telescope
  - Optics
  - Detectors
  - Electronics

Imaging Atmospheric Cherenkov Telescopes

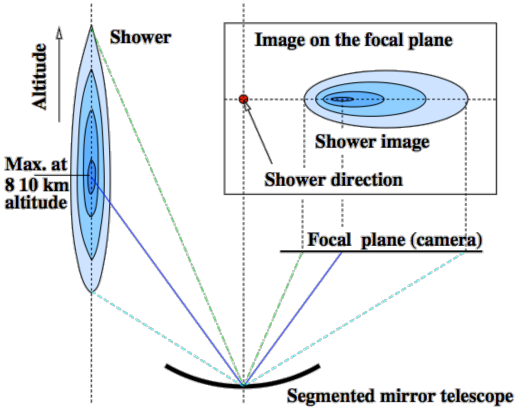


Schematic view of an e.m. shower. Figure taken from Matthews (2005)



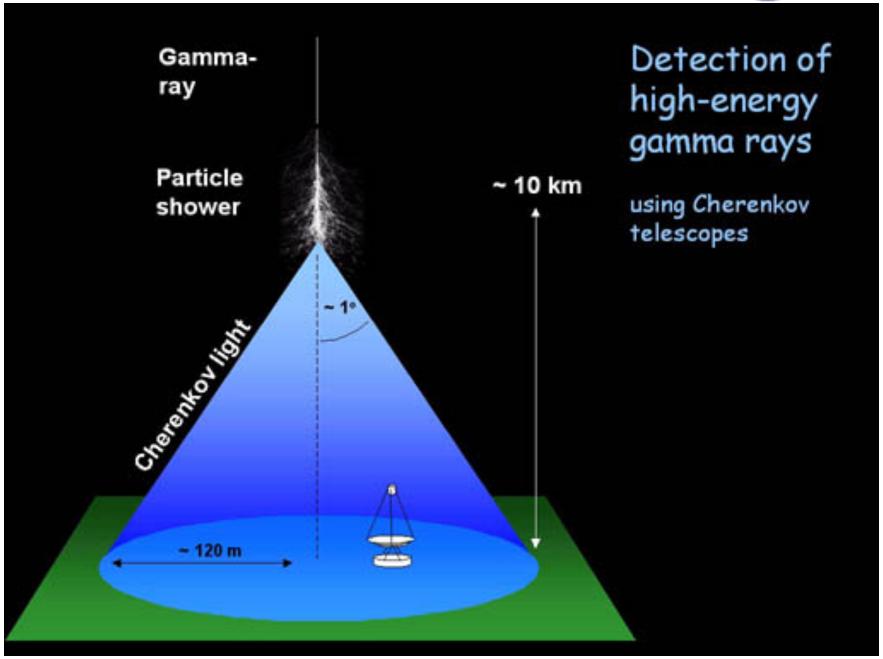


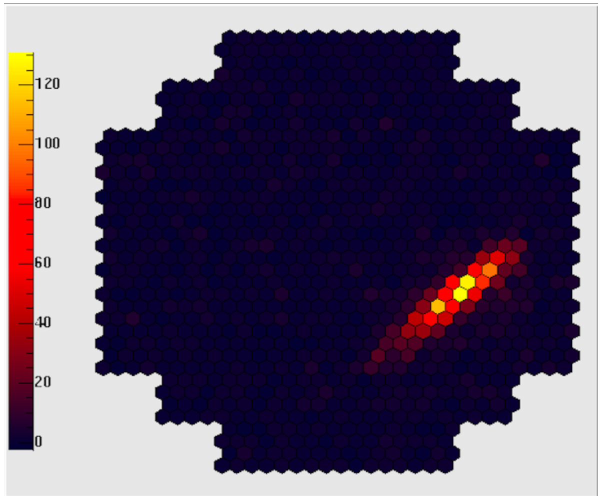
- A γ-ray photon (E_o) enters the atmosphere and generates an electromagnetic shower
- $v_{e+(e-)}>c/n$ → Cherenkov photons are emitted
- A telescope placed in the *light pool* can image the shower by means of a camera (usually photomultiplier-based) reconstructing energy and direction



Imaging of a γ-ray initiated e.m. shower by a telescope. Image taken from Völk and Bernlöhr (2009)

A picture of an e.m. shower - 1

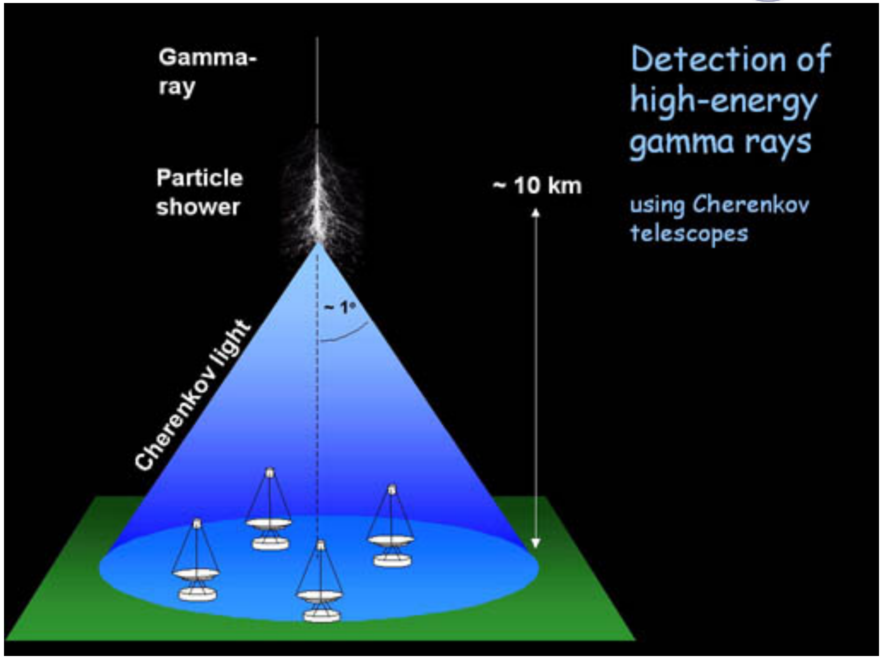


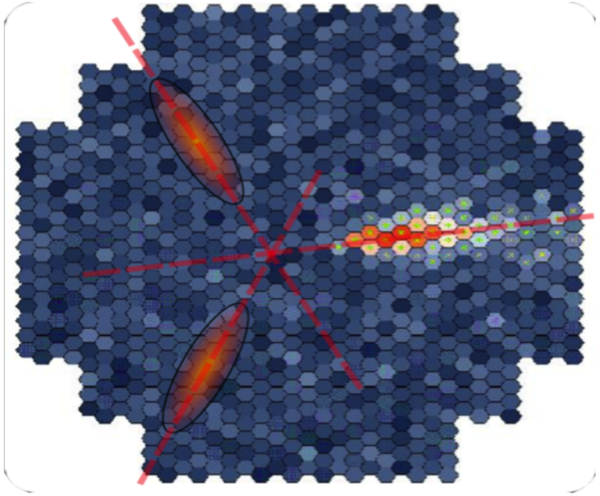


https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/

- Cherenkov light beamed around the direction of incident primary particle → illuminates on the ground an area of ~250m in diameter (Cherenkov light pool)
- Light collected by a large dish and focused on a PMT camera
- The image from a γ-ray-induced shower can be parametrized with an ellipse (Hillas, 1985) → Hillas parameters: width, length, distance of image axis to the camera center, orientation angle, size of the image (related to shower energy)

A picture of an e.m. shower - 2

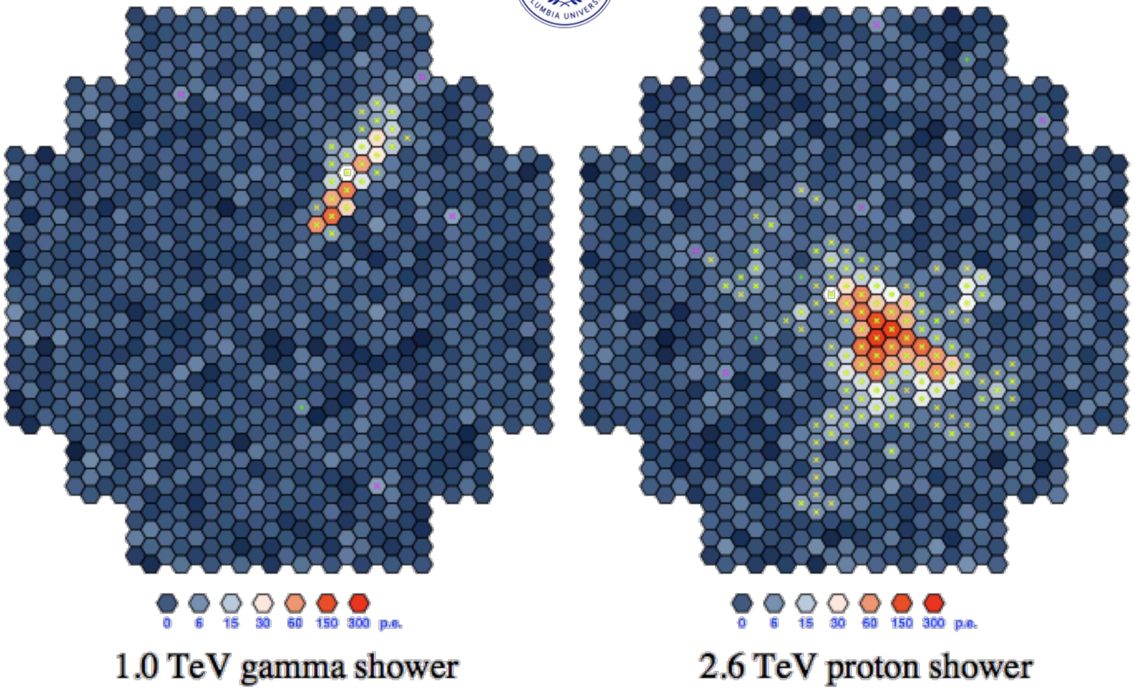




https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/

- Multiple telescopes → stereoscopic reconstruction of the shower: improved angular and energy resolution

Background contamination

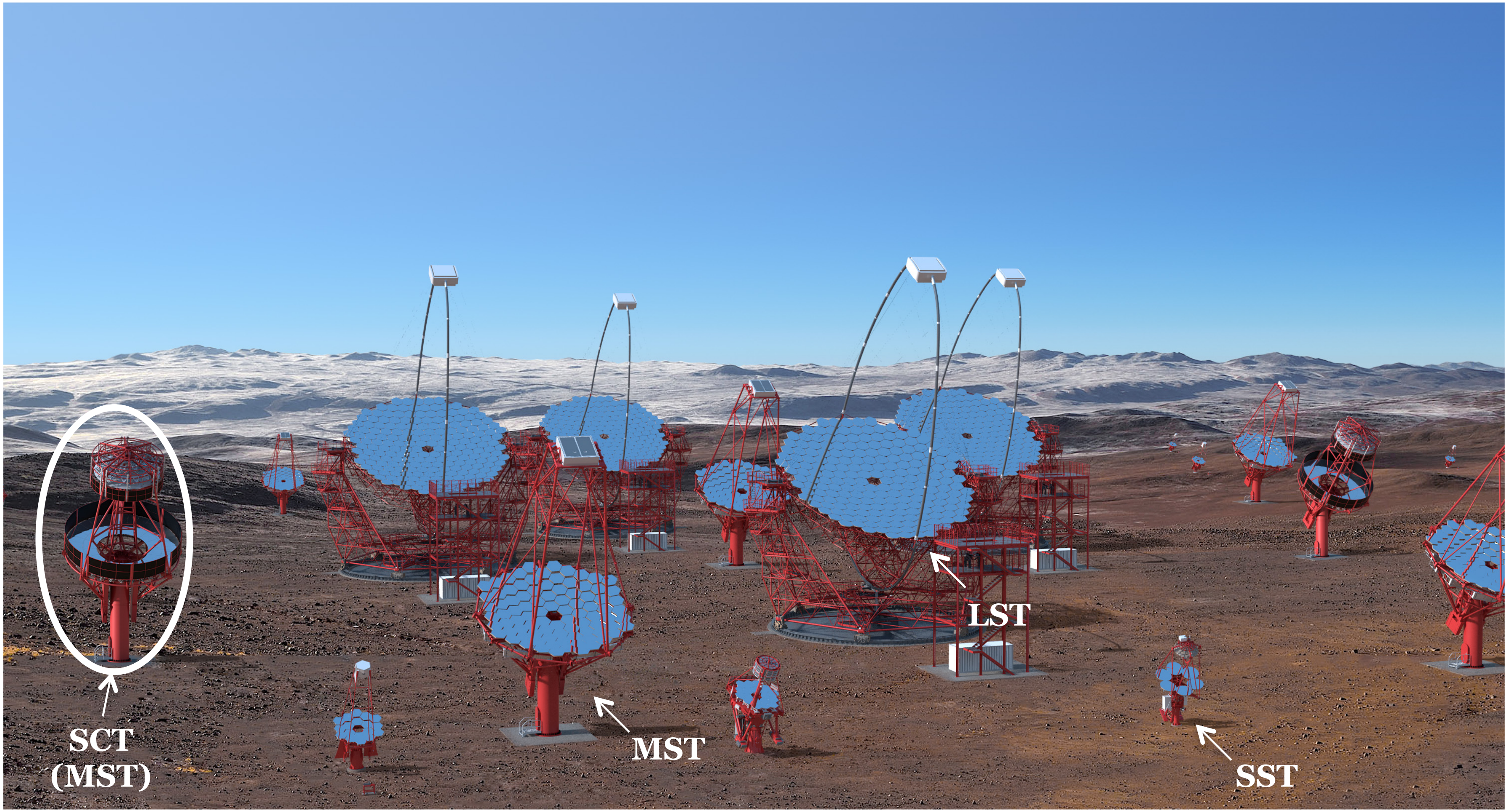


Difference between the images of gamma-induced and hadron-induced showers in the camera (from K. Bernlöhr)

- CR-induced hadronic showers can be distinguished by the different shape of their image in the camera (though some of these events can be still mis-recognized as γ)

Current-generation IACTs

Next-generation IACT

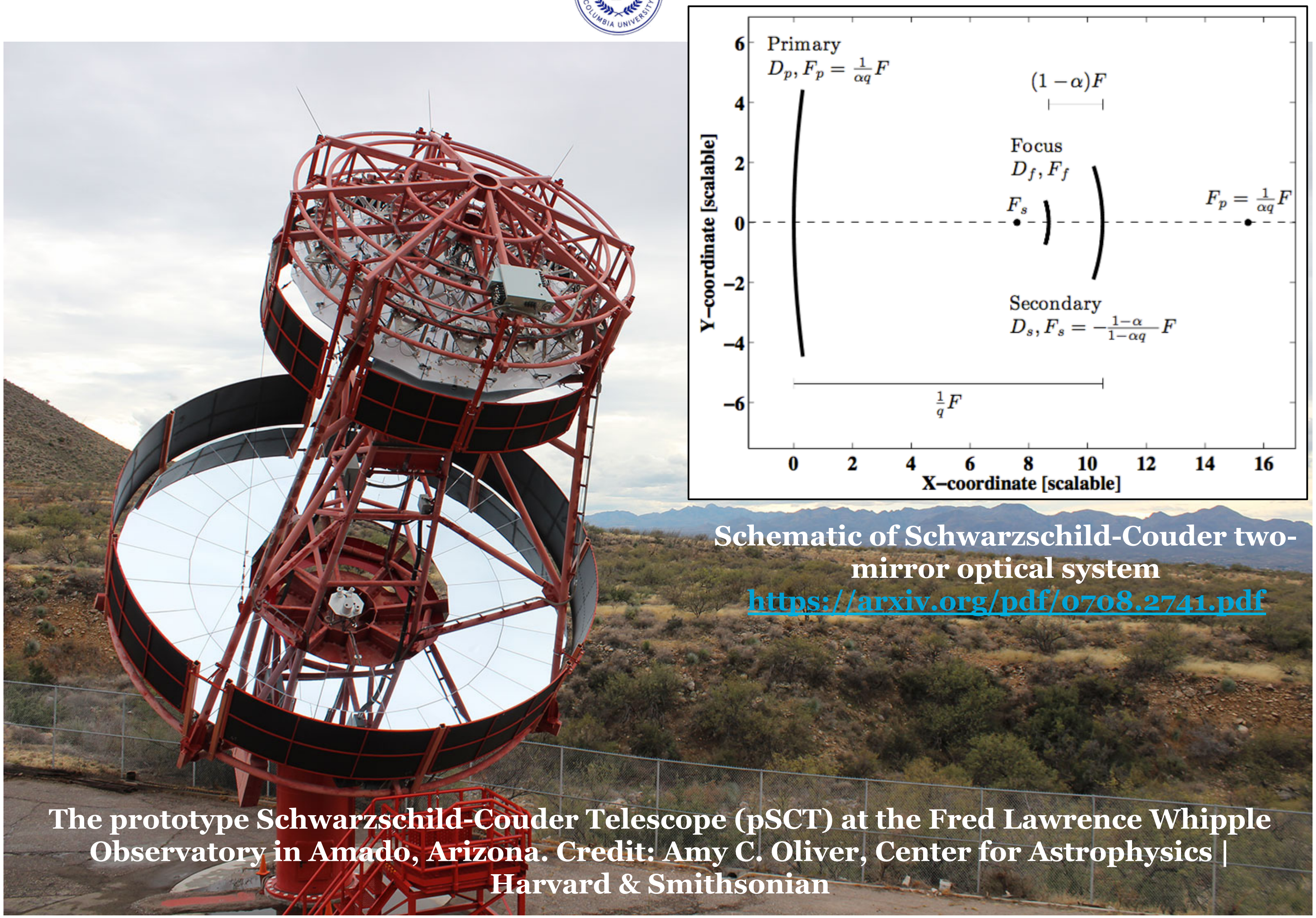


Artistic impression of the CTA South, Credit Gabriel Pérez Diaz, IAC / Marc-André Besel CTAO

Outline

- VHE γ-ray astronomy
  - How does the sky look like in VHE γ-rays?
  - Emission mechanisms
  - γ-ray sources
  - Satellite vs. ground-based experiments
- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Current and next-generation observatories
- The prototype Schwarschild-Couder Telescope
  - Optics
  - Detectors
  - Electronics

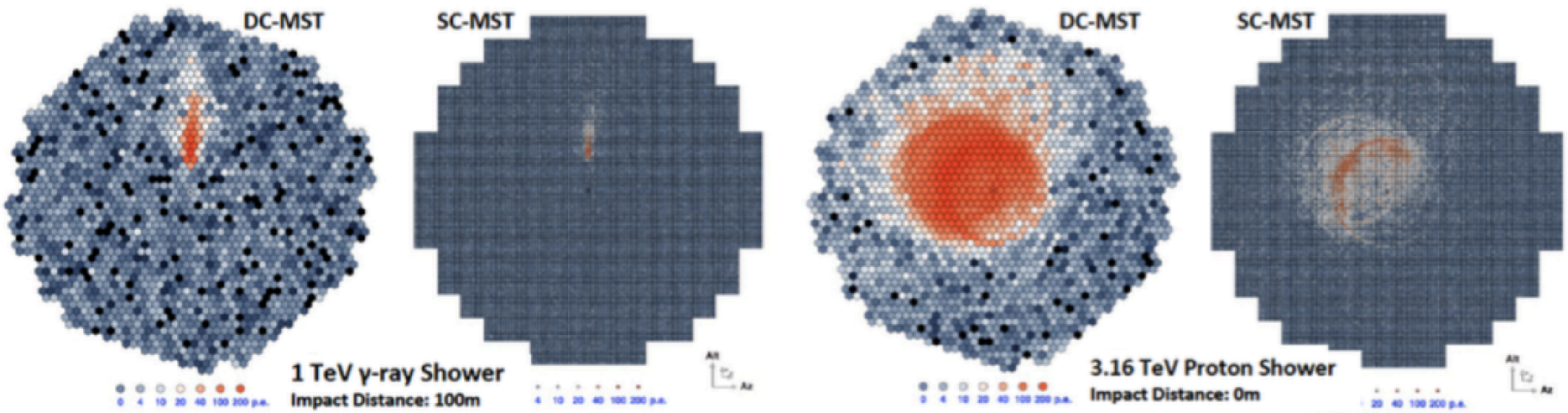
A dual-mirror system



Schematic of Schwarzschild-Couder two-mirror optical system
https://arxiv.org/pdf/0708.2741.pdf

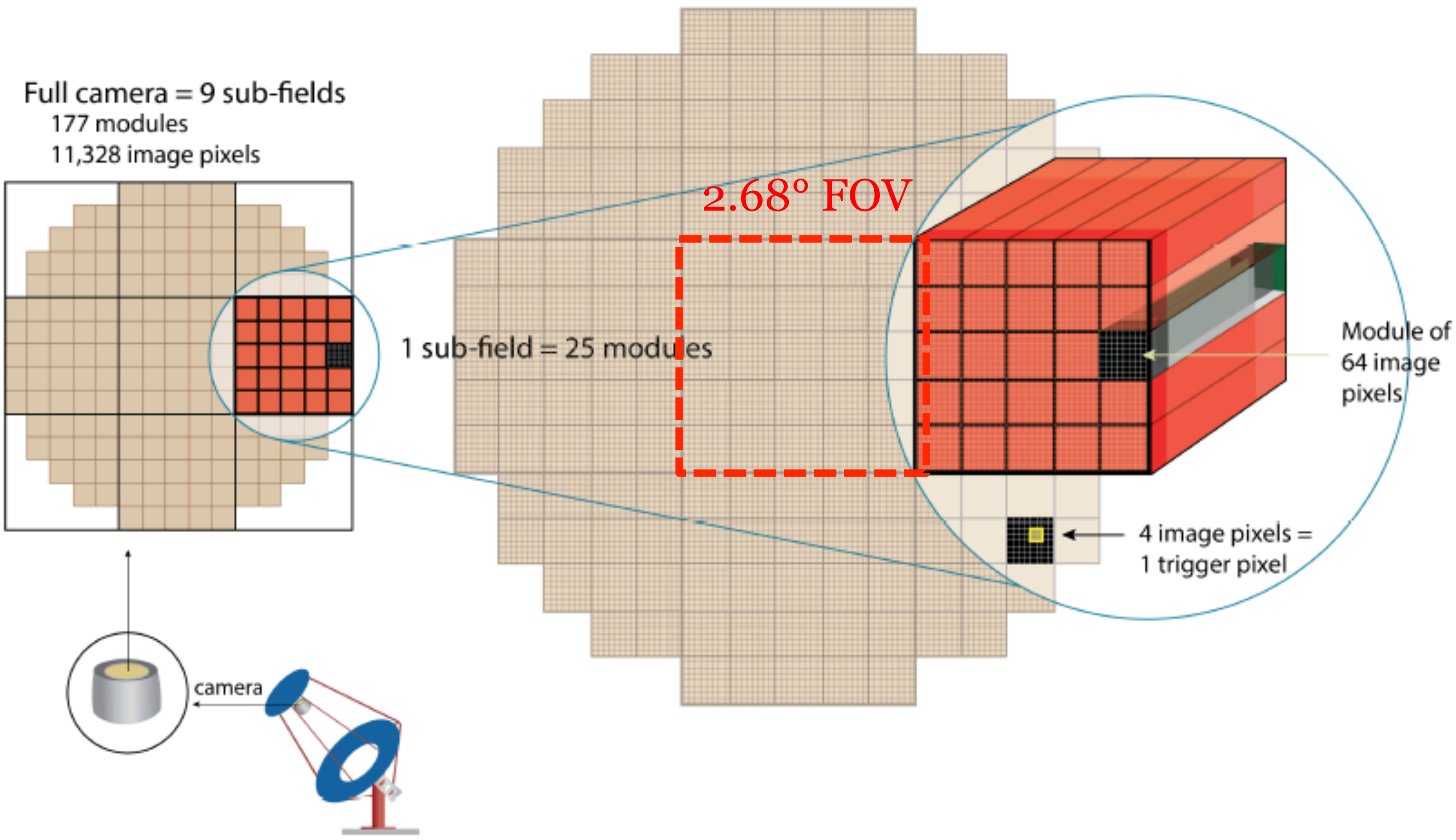
The prototype Schwarzschild-Couder Telescope (pSCT) at the Fred Lawrence Whipple Observatory in Amado, Arizona. Credit: Amy C. Oliver, Center for Astrophysics | Harvard & Smithsonian

Big eyes and a sharper view



- Superior optical angular resolution over a wide (~8°) field of view
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors (SiPMs) and electronics
- Better sensitivity and reduced observation time

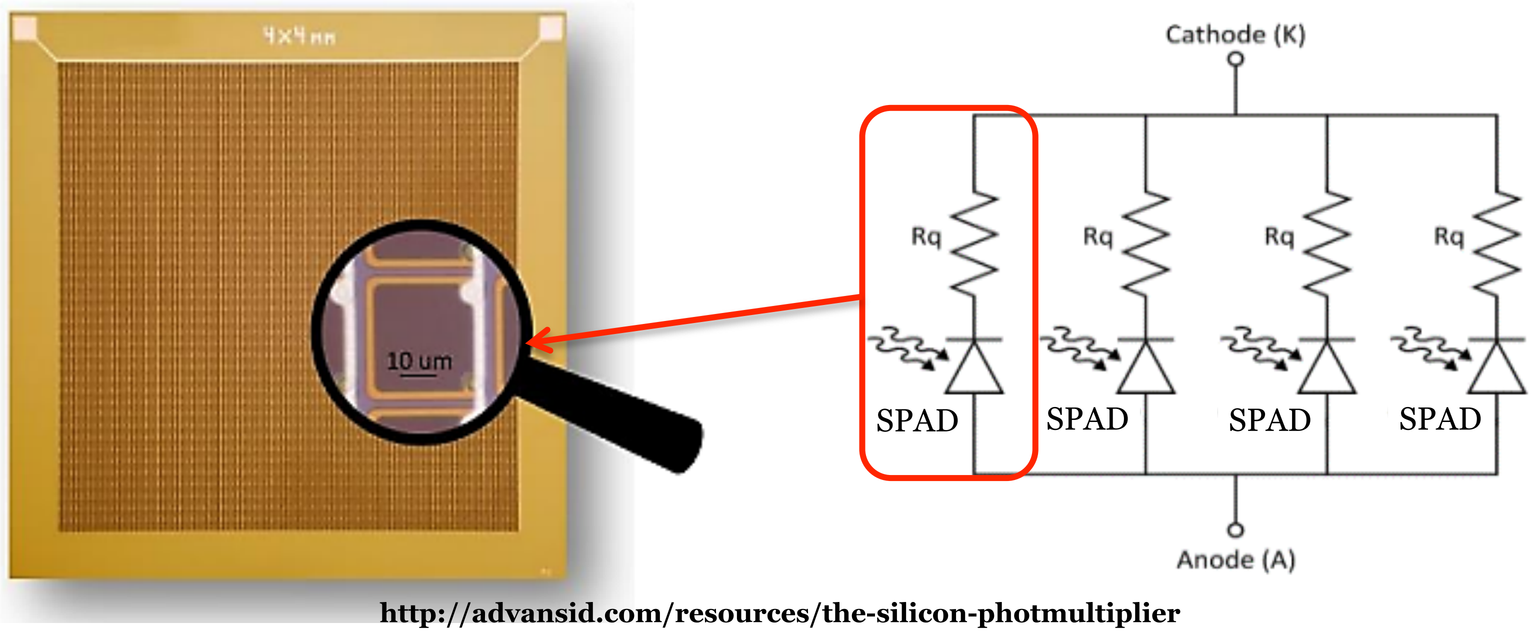
Focal plane structure



https://arxiv.org/pdf/1910.00133.pdf

The detectors: Silicon Photomultipliers

SiPMs: array of reverse-biased Single Photon avalanche Diodes (**SPADs**) connected in parallel, each with **integrated quenching resistor**



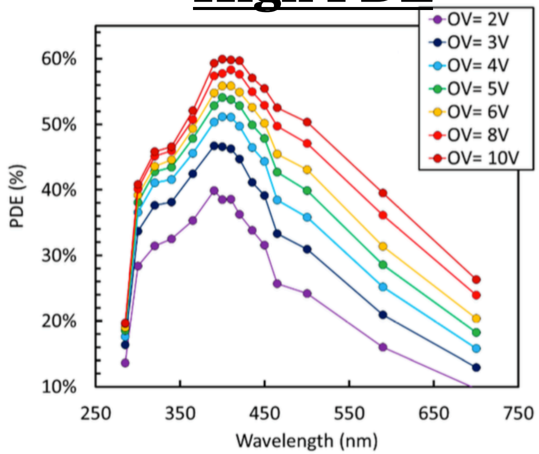
http://advansid.com/resources/the-silicon-photmultiplier

SiPM size: from $1x1mm^2$ to $10x10mm^2$

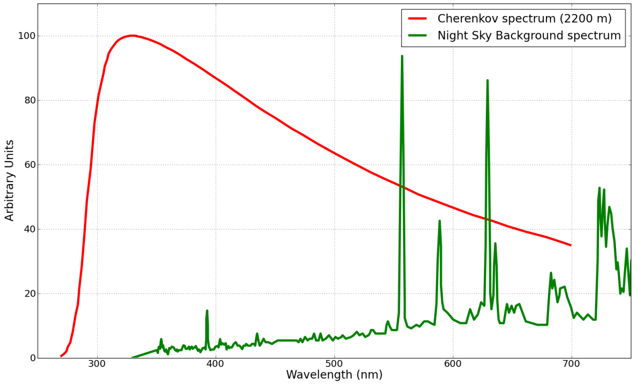
SPAD size: from 5µm to 40µm (typical)

Main SiPM characteristics

High PDE

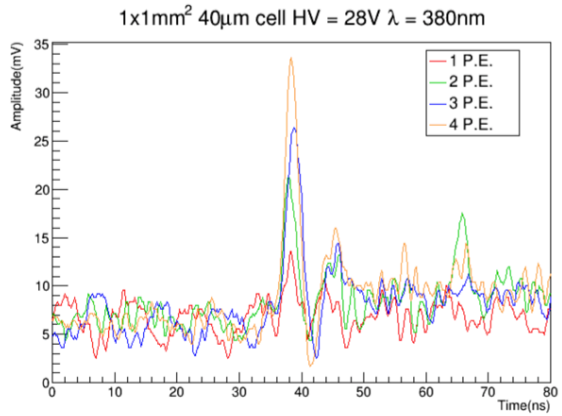


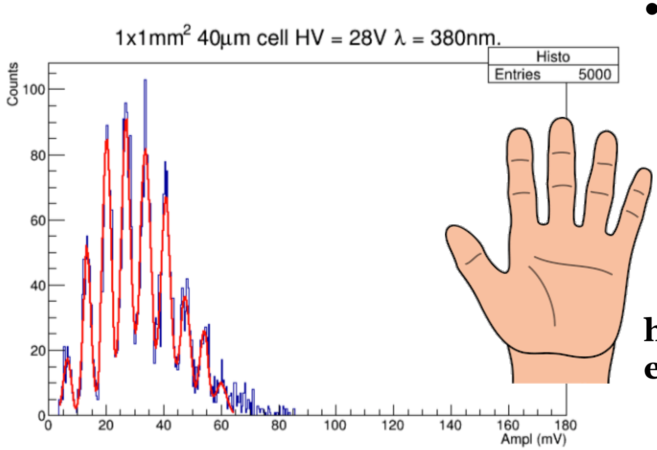
Gola et. al. https://www.mdpi.com/1424-8220/19/2/308



Bonardi et. al 2014

Single p.e. resolution

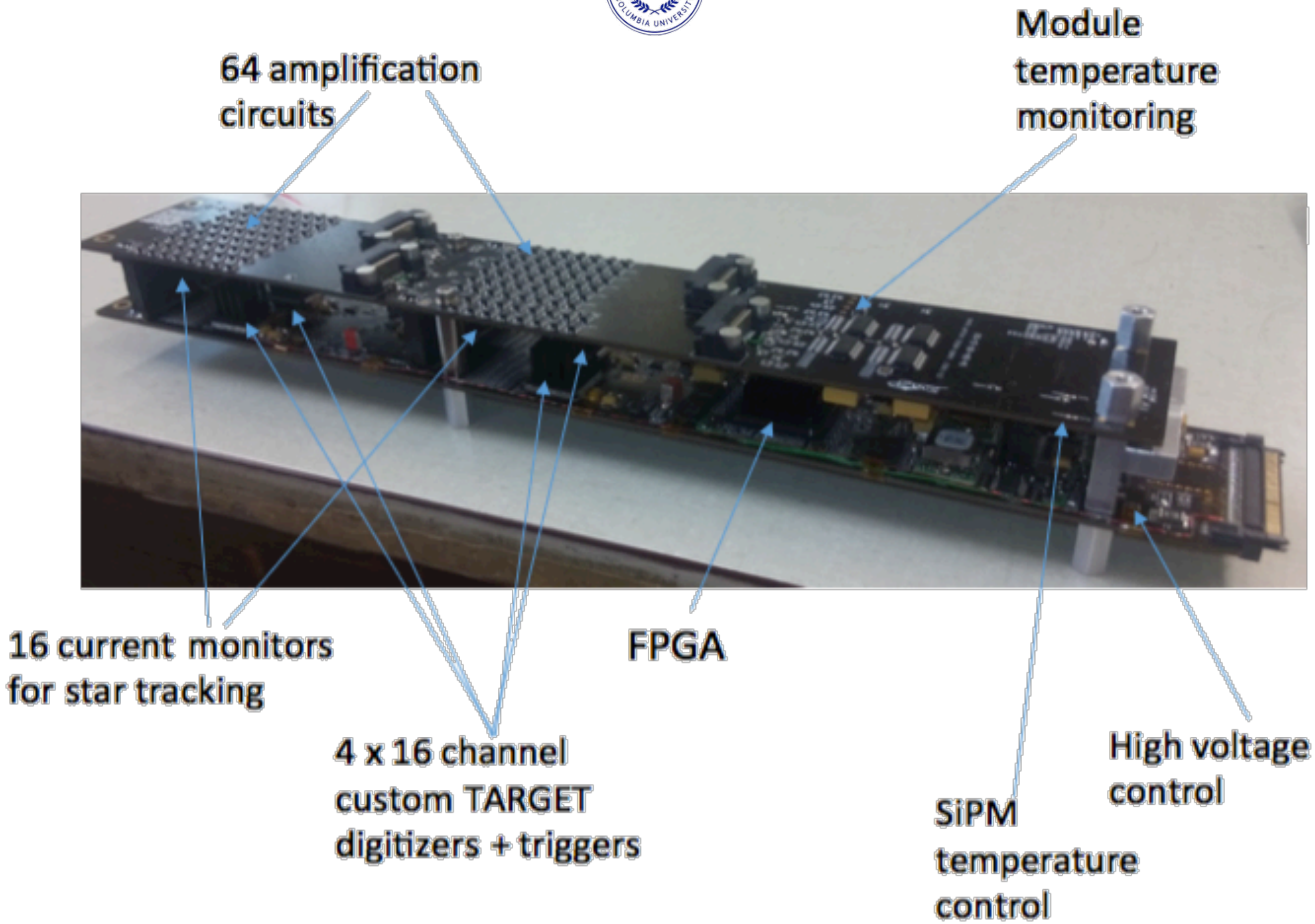




- **Ruggedness**
- **Insensitivity to magnetic fields**
- **…**

https://webstockreview.net/explore/thumb-clipart-hand/

The pSCT FEE electronics



***Design and Performance of the Prototype Schwarzschild-Couder Telescope Camera* – in preparation**

pSCT first γ-ray source!

Announcement

CTA Prototype Telescope, the Schwarzschild-Couder Telescope, Detects Crab Nebula

Read the Center for Astrophysics | Harvard & Smithsonian Press Release (https://www.cfa.harvard.edu/news/2020-11)

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Media Links:
pSCT (https://www.flickr.com/photos/cta_observatory/49947783283/in/photostream/)
pSCT Inauguration (https://www.flickr.com/photos/cta_observatory/49947782948/in/photostream/)
Event Animation (https://www.cta-observatory.org/wp-content/uploads/2020/05/image002_optimized.gif)
Sky Map (https://www.flickr.com/photos/cta_observatory/49948281611/in/dateposted/)
Histogram (https://www.flickr.com/photos/cta_observatory/49948572777/in/photostream/)
Film: How CTA Works (https://youtu.be/5gRHFQP_SjU)

Guests of the pSCT inauguration in January 2019 gather in front of the telescope. Credit: Deivid Ribeiro, Columbia University

Armado, AZ — On 1 June 2020, scientists from the Cherenkov Telescope Array (CTA) Consortium (https://www.cta-observatory.org/about/cta-consortium/) announced at the 236th meeting of the Americ Astronomical Society (AAS) that they have detected gamma rays from the Crab Nebula using a prototype telescope proposed for CTA, the prototype Schwarzschild-Couder Telescope (pSCT) (https://www.cta-observatory.org/project/technology/sct/), proving the viability of the novel telescope design for use in gamma-ray astrophysics.

“The Crab Nebula is the brightest steady source of TeV, or very-high-energy, gamma rays in the sky, so detecting it is an excellent way of proving the pSCT technology,” said Justin Vandenbroucke, Associate Professor, University of Wisconsin. “Very-high-energy gamma rays are the highest energy photons in the universe and can unveil the physics of extreme objects including black holes and possibly dark matter.”

Detecting the Crab Nebula with the pSCT is more than just proof-positive for the telescope itself. It lays th groundwork for the future of gamma-ray astrophysics. “We’ve established this new technology, which will measure gamma rays with extraordinary precision, enabling future discoveries,” said Vandenbroucke. “Gamma-ray astronomy is already at the heart of the new multi-messenger astrophysics, and the SCT technology will make it an even more important player.”

The use of secondary mirrors in gamma-ray telescopes is a leap forward in innovation for the relatively young field of very-high-energy gamma-ray astronomy, which has moved rapidly to the forefront of astrophysics. “Just over three decades ag TeV gamma rays were first detected in the universe, from the Crab Nebula, on the same mountain where the pSCT sits today,” said Vandenbroucke. “That was a real breakthrough, opening a cosmic window with light that is a trillion times more energetic than we can see wi our eyes. Today, we’re using two mirror surfaces instead of one, and state-of-the-art sensors and electronics to study these gamma rays with exquisite resolution.”

BARNARD COLLEGE COLUMBIA UNIVERSITY

COLUMBIA NEWS

Home » News Archive » Scientists Detect Crab Nebula Using Innovative Gamma-Ray Telescope

Scientists Detect Crab Nebula Using Innovative Gamma-Ray Telescope

First-of-its-kind telescope promises to shed new light on the physics of high-energy phenomena, from supernovae to dark matter.

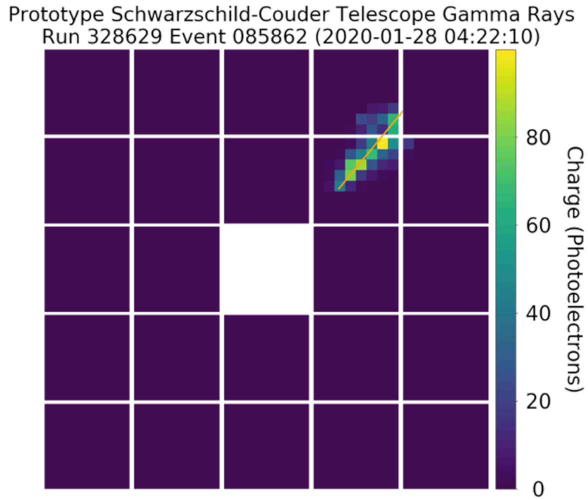
By Carla Cantor
June 01, 2020

02 GIUGNO 2020

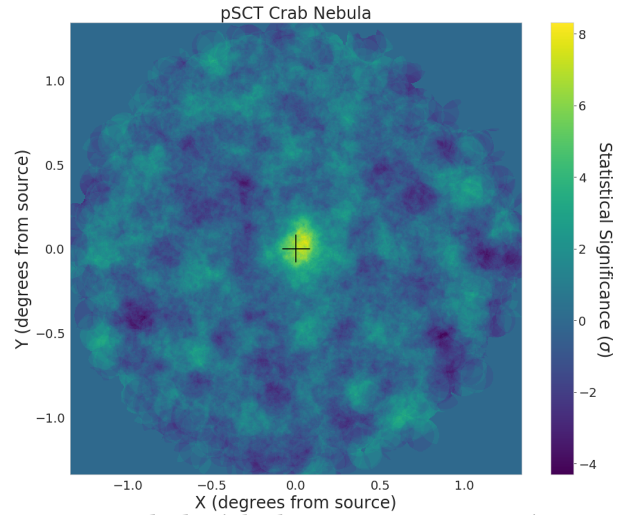
CON TECNOLOGIA MADE IN ITALY, IL PIÙ GRANDE TELESCOPIO SCHWARZSCHILD-COUDER OSSERVA LA SUA PRIMA SORGENTE DI RAGGI GAMMA

COMUNICATO CONGIUNTO INFN-INAF. Il telescopio pSCT, un prototipo di telescopio di tipo Schwarzschild-Couder dell’osservatorio di prossima generazione CTA (Cherenkov Telescope Array), ha osservato la sua prima sorgente gamma, grazie a soluzioni tecnologiche innovative sviluppate in Italia dall’INAF Istituto Nazionale di Astrofisica, e dall’INFN Istituto Nazionale di Fisica Nucleare.

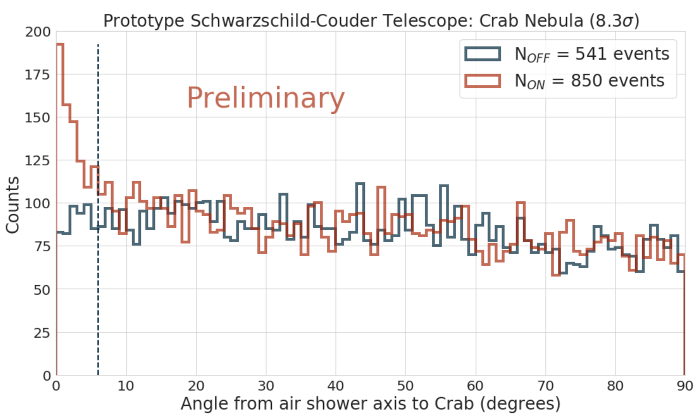
Looking at the Crab



Animation showing 18 gamma-ray events from the Crab Nebula detected with the pSCT telescope. Credit: CTA/SCT consortium



Sky map recorded with the pSCT over a region centered on the Crab Nebula, detection of the Crab Nebula marked at center. Credit: CTA/SCT consortium

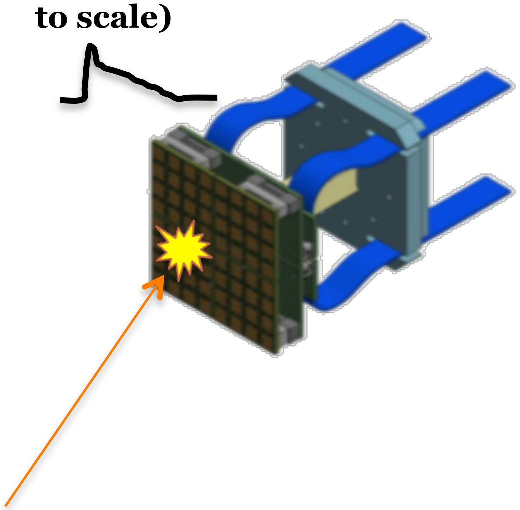


Histogram showing the detection of gamma-ray events from the Crab Nebula, with NOFF representing background and NON representing a combination of signal and background. Credit: CTA/SCT consortium

Upgrading the prototype

Preamplified and shaped signal from SMART chip (not to scale)

SiPM signal (not to scale)



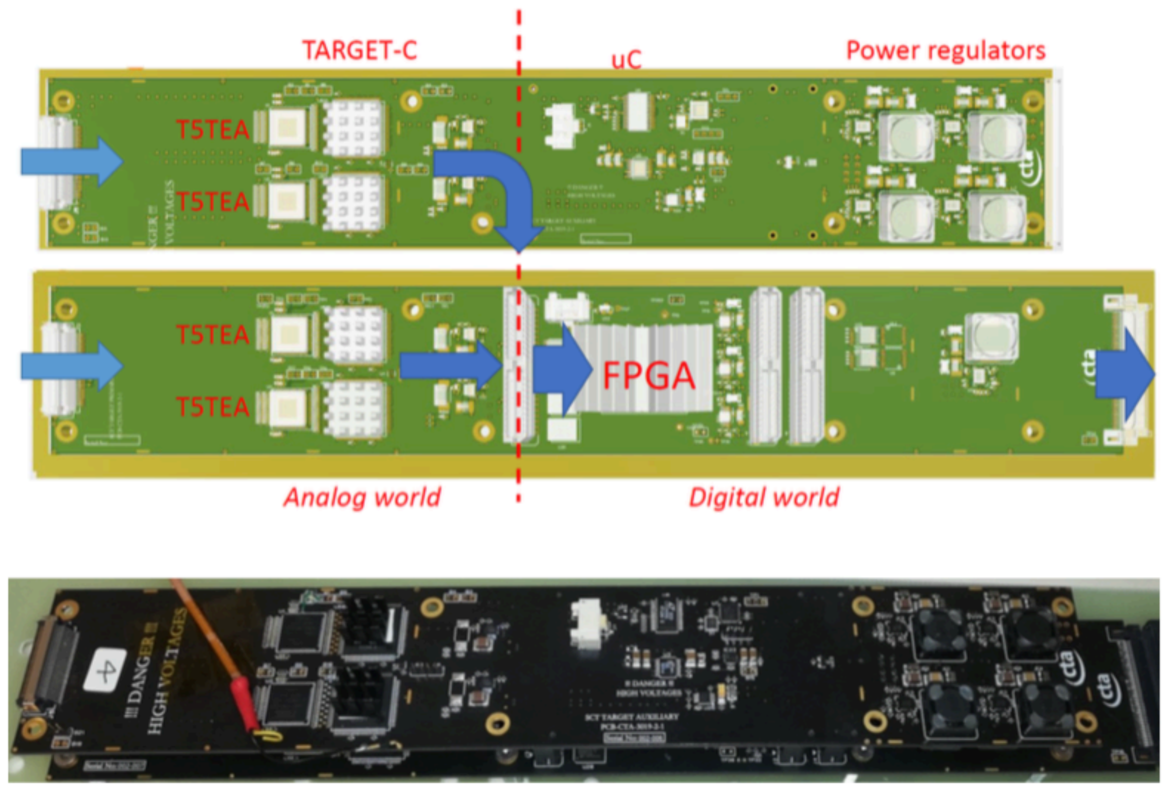


Figure 5. (top) Sketch of the upgraded camera FEE module, the Auxiliary and Primary boards are shown on top and bottom, respectively. Both boards have been logically divided into an analog and digital/power sections. (bottom) Picture of the prototype FEE module currently under test.

R. Paoletti: SPIE 2019

Summary and outlook

- VHE γ-ray astronomy is a powerful tool to explore the energetic Universe
- In the last 20+ years, IACT technology has continuously improved, opening the window to the farthest accessible γ-ray band (around 1 TeV and beyond)
- The next-generation observatory (CTA) is under construction
- Within CTA, the pSCT represents a high-potential, first-of-its-kind IACT
  - Technology validation: Crab detection
  - Towards the upgrade: lower-noise electronics + fully populated (11k+ pixels) camera

Stay tuned!

Massimo Capasso
Barnard College, Columbia University
(capasso@nevis.columbia.edu)

Summer Colloquium Series - 2020