Unraveling the very-high-energy Universe with ground-based Cherenkov telescopes

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2021 Nevis Labs REU Lectures

07/06/2021

Outline

- γ-rays and VHE γ-ray astronomy
  - What are γ-rays?
  - Sources of γ-rays
  - How does the sky look like in VHE γ-rays?
  - Satellite vs. ground-based experiments
- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Past, current and next-generation observatories
    - The prototype Schwarzschild-Couder Telescope (pSCT)
- Live tour!!!

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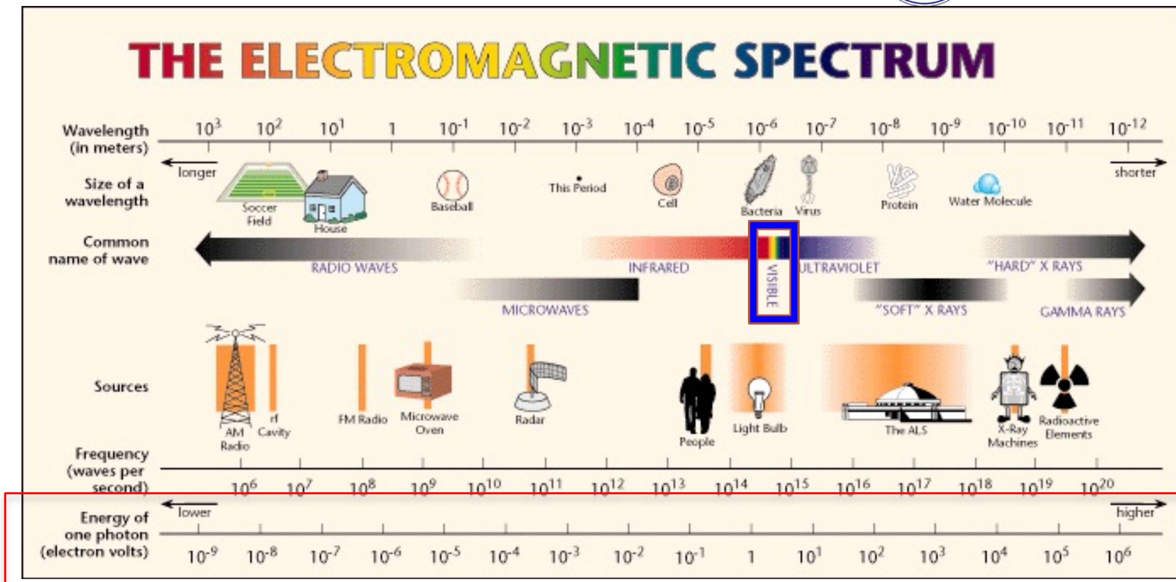
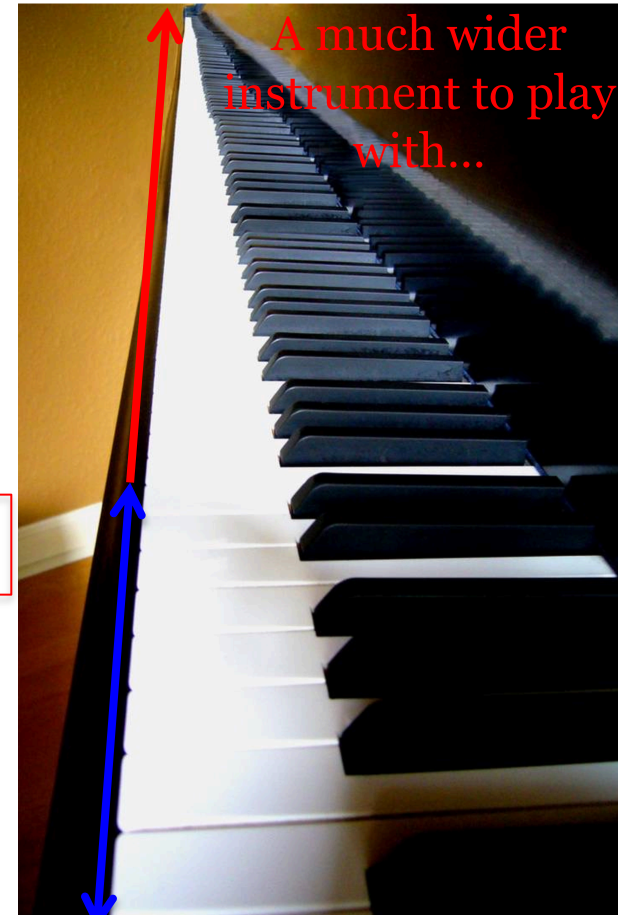
Beyond the eyes



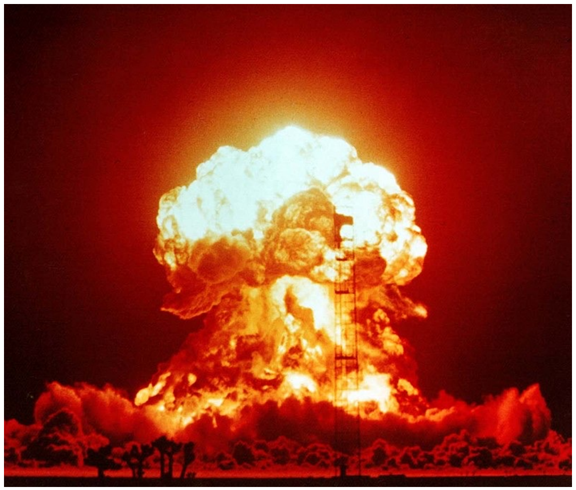
https://www2.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

Visible



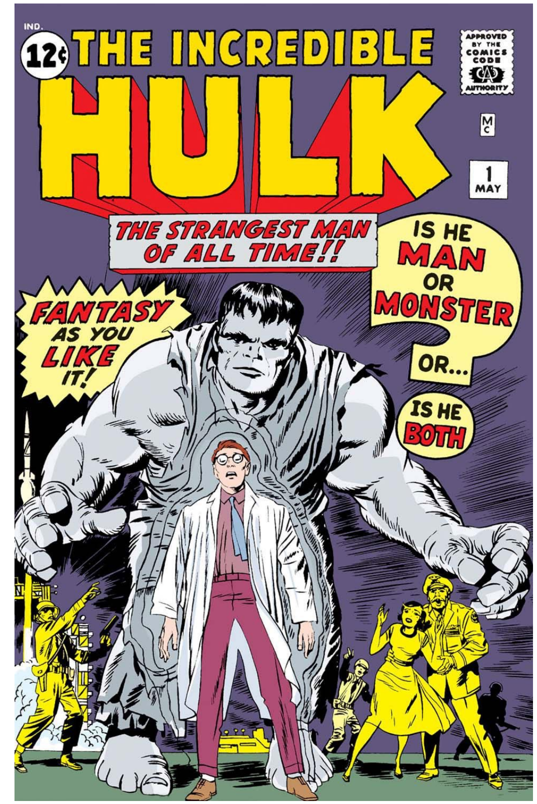
https://www.deviantart.com/vidpen/art/The-very-long-piano-56181014

Sources of γ-rays



https://en.wikipedia.org/wiki/Gamma_ray

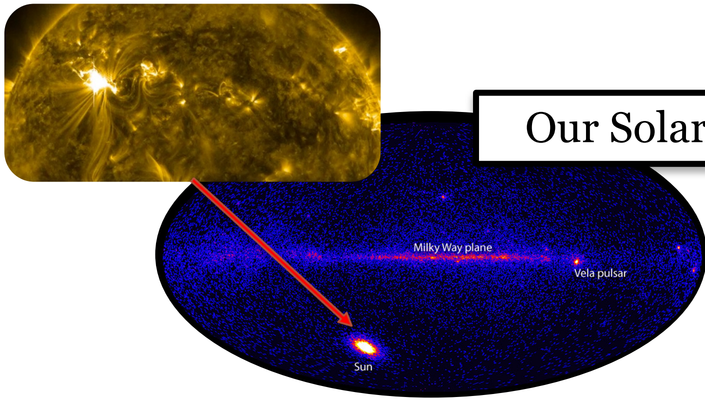
https://en.wikipedia.org/wiki/List_of_civilian_radiation_accidents



https://www.marvel.com/comics/issue/8906/incredible_hulk_1962_1

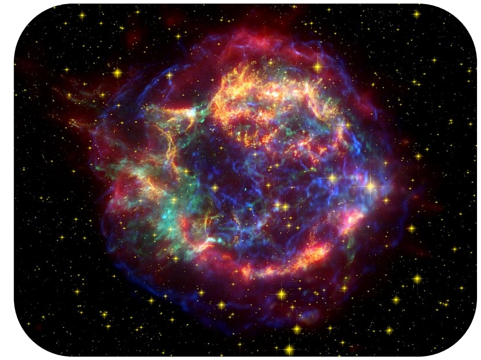
But there is more…

γ-rays are everywhere!



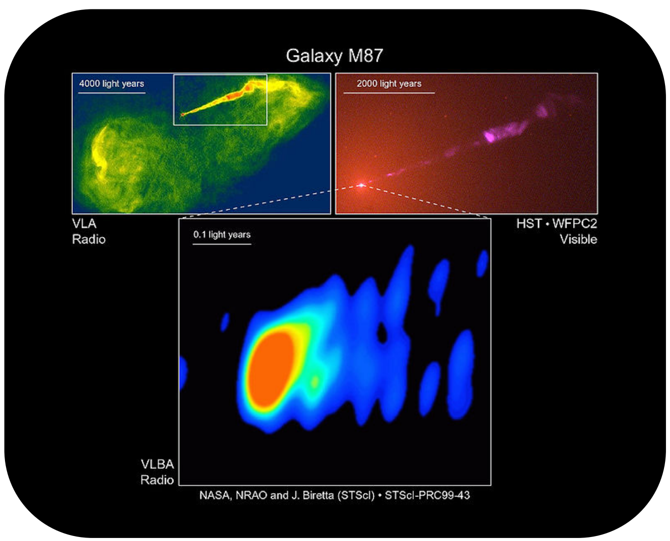
Our Solar «backyard»

https://svs.gsfc.nasa.gov/11000



https://commons.wikimedia.org/wiki/File:Cassiopeia_A_Spitzer_Crop.jpg

Our Galactic «backyard»



https://en.wikipedia.org/wiki/Active_galactic_nucleus#/media/File:M87_jet.jpg

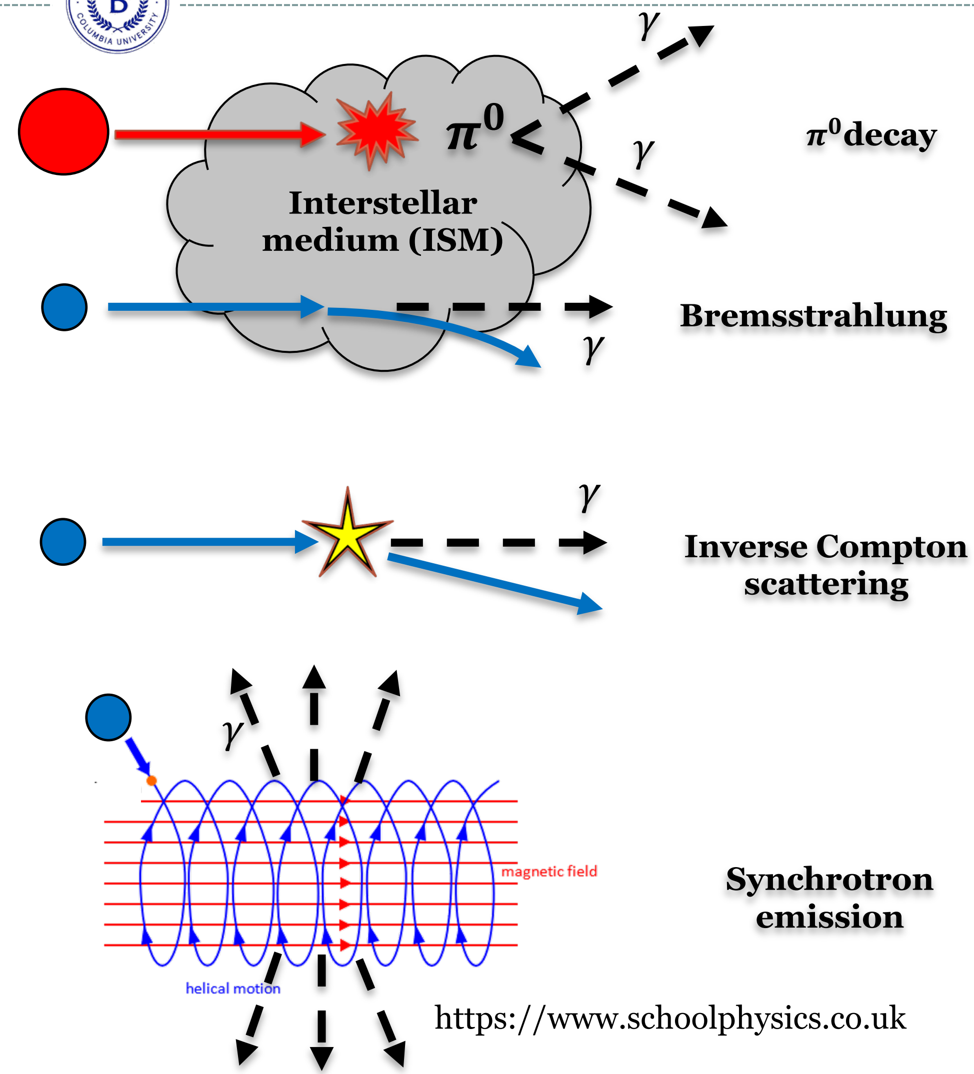
Outside our Galaxy

γ-rays emission mechanisms

Accelerated particles + matter

Accelerated particles + radiation field

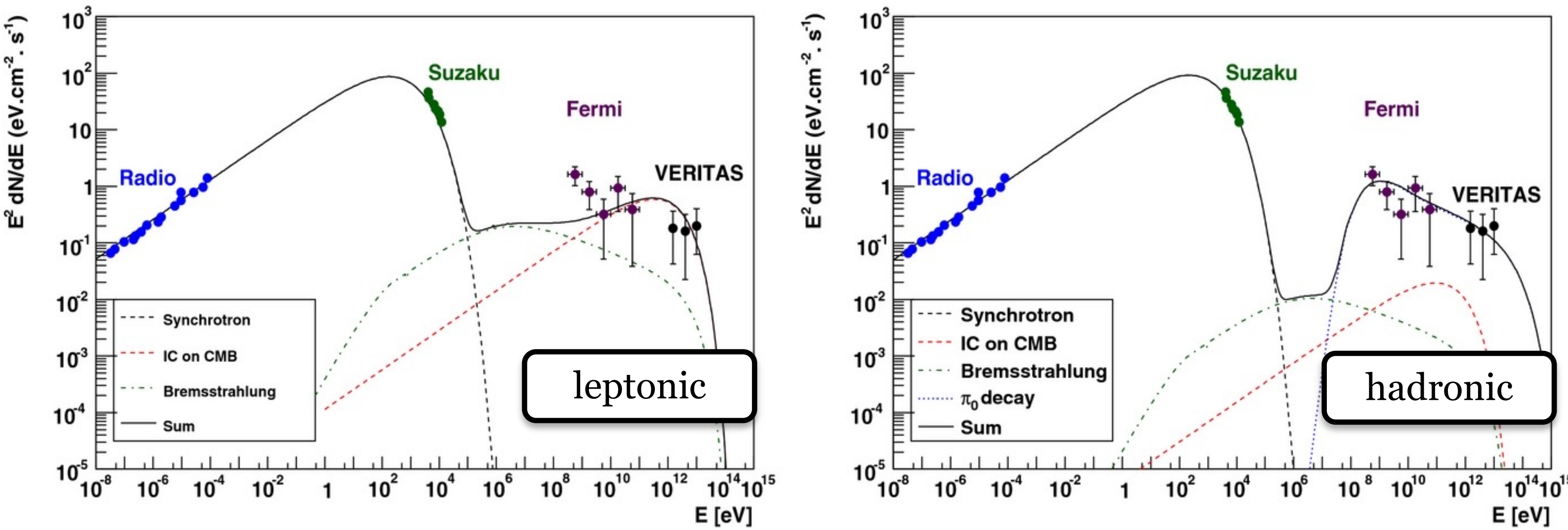
Accelerated particles + magnetic field



https://www.schoolphysics.co.uk

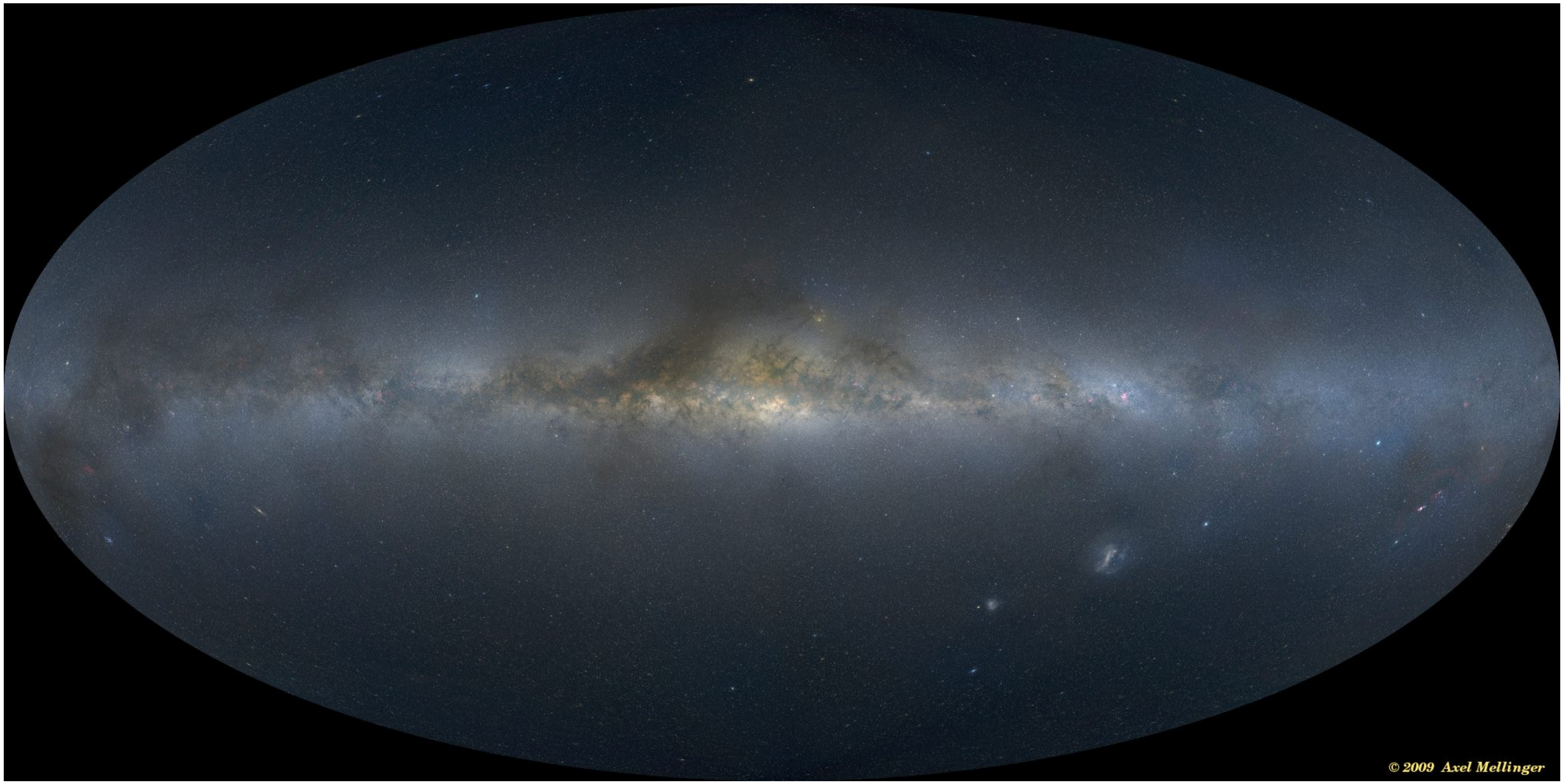
Fingerprinting the particle population

https://www.thecomicstrips.com/comic-strip/Frank+and+Ernest/2010-04-02/45896



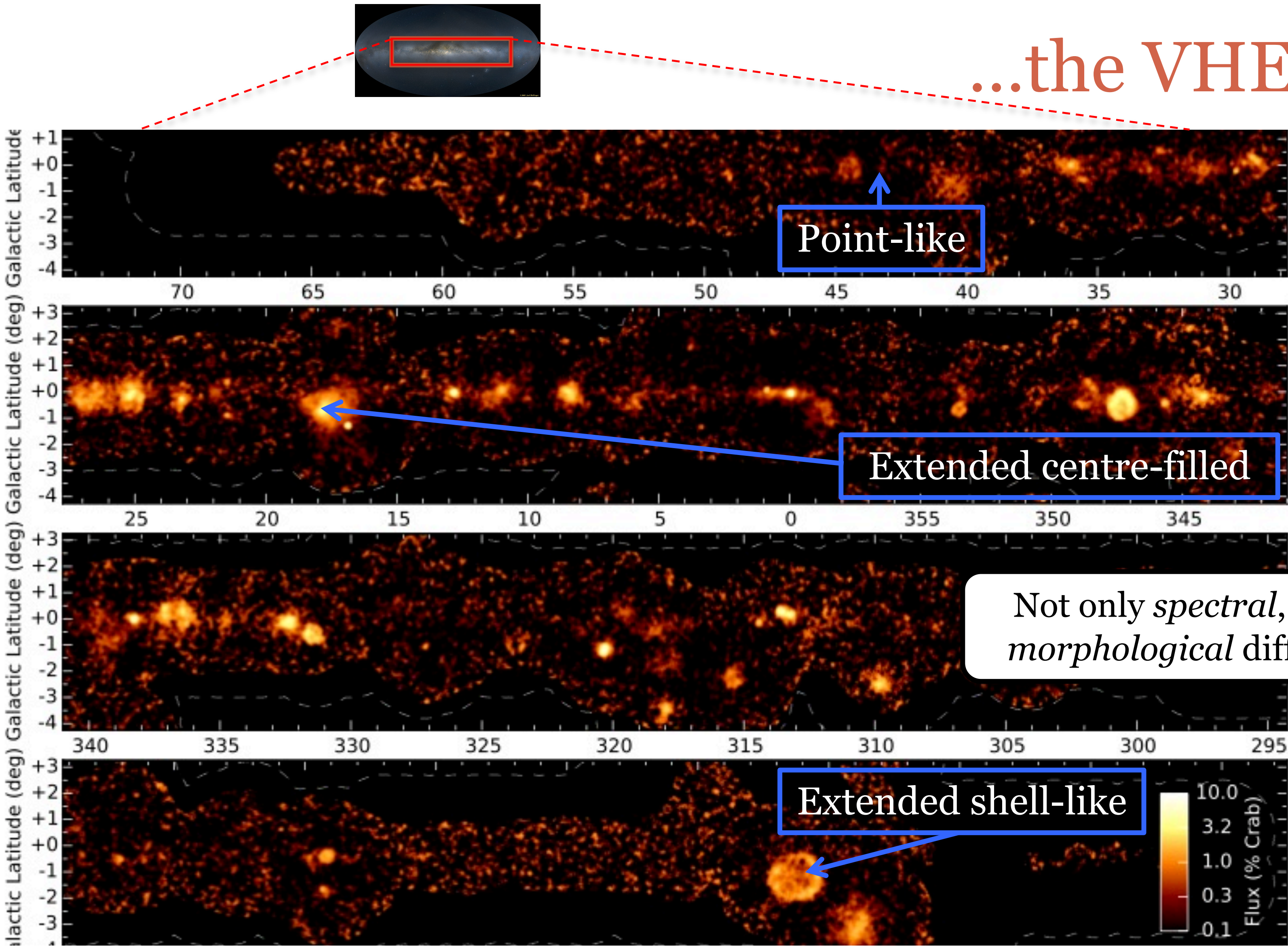
Broadband *spectral energy distribution* (SED) model of Tycho's SNR. Image taken from Giordano et al.(2012).

The optical sky…



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

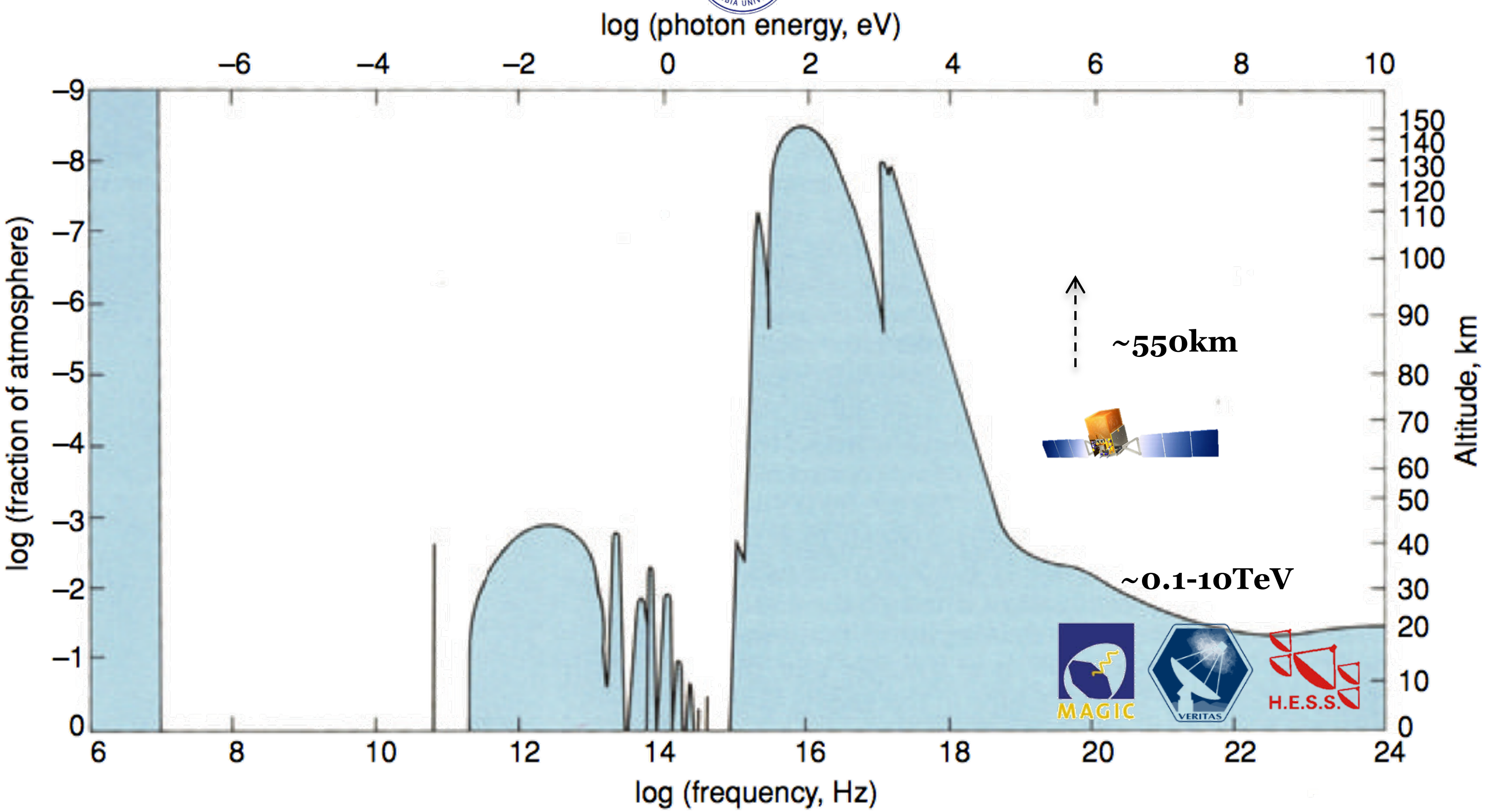
...the VHE one!



Not only *spectral*, but also *morphological* differences!

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)

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)

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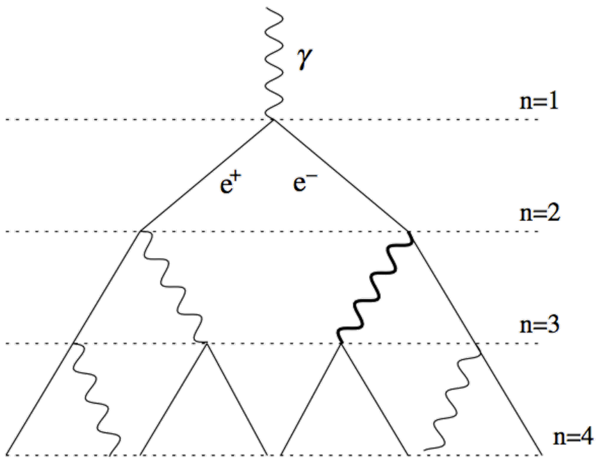
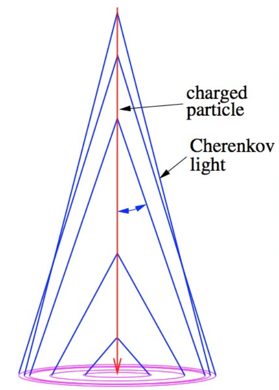
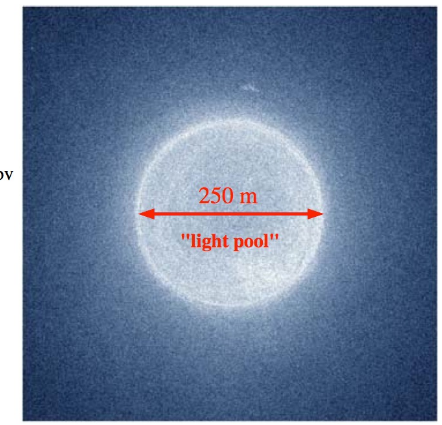
Imaging Atmospheric Cherenkov Telescopes

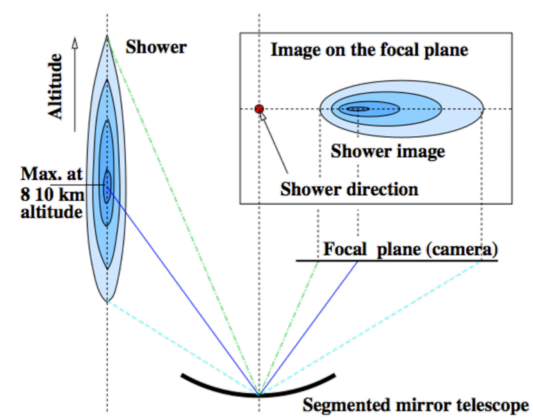


Schematic view of an e.m. shower. Figure taken from Matthews (2005)



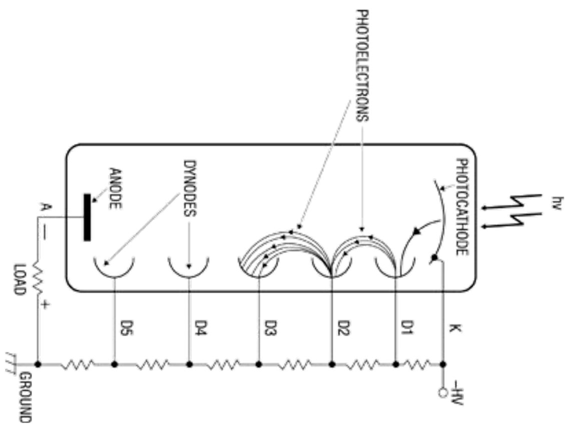


- A γ-ray photon (E_0) enters the atmosphere and generates an electromagnetic shower
- $v_{e+(e-)} > c/n$ → Cherenkov photons are emitted
- A telescope placed in the *light pool* can image the shower by means of a camera (usually photomultiplier-based) reconstructing energy and direction



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

A closer look at the components of an IACT

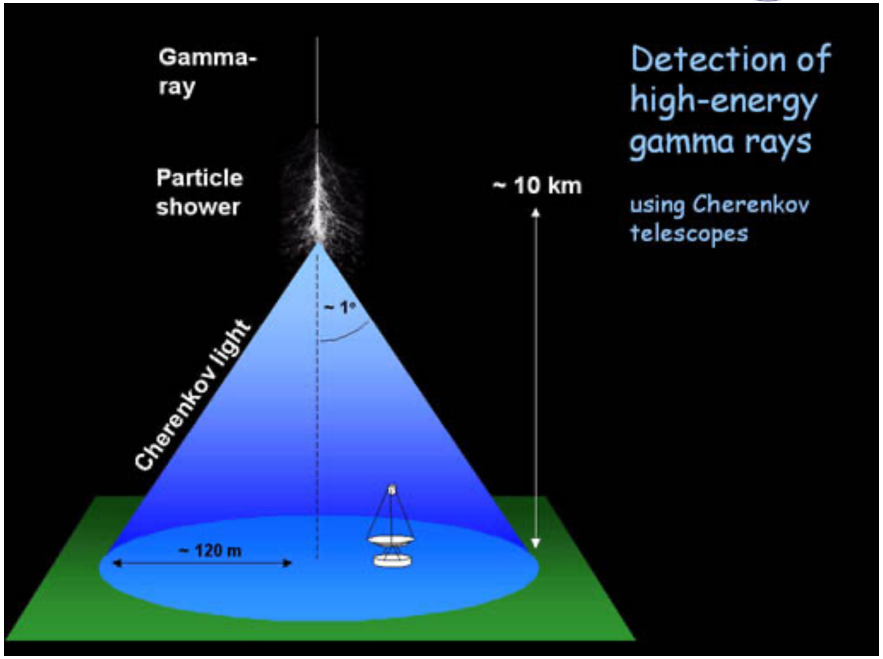


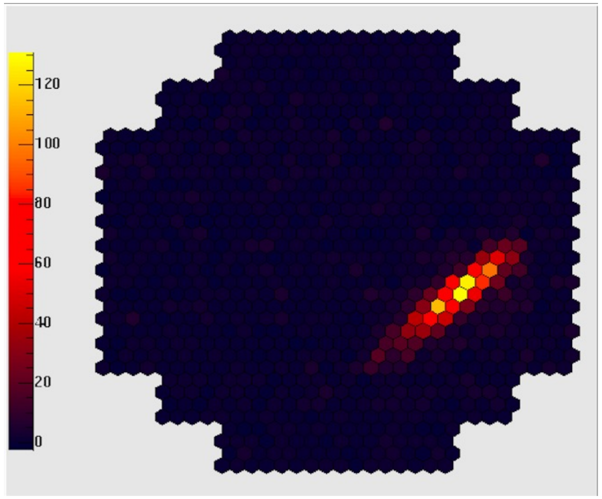
Detectors

Camera

Optics

A picture of an e.m. shower - 1

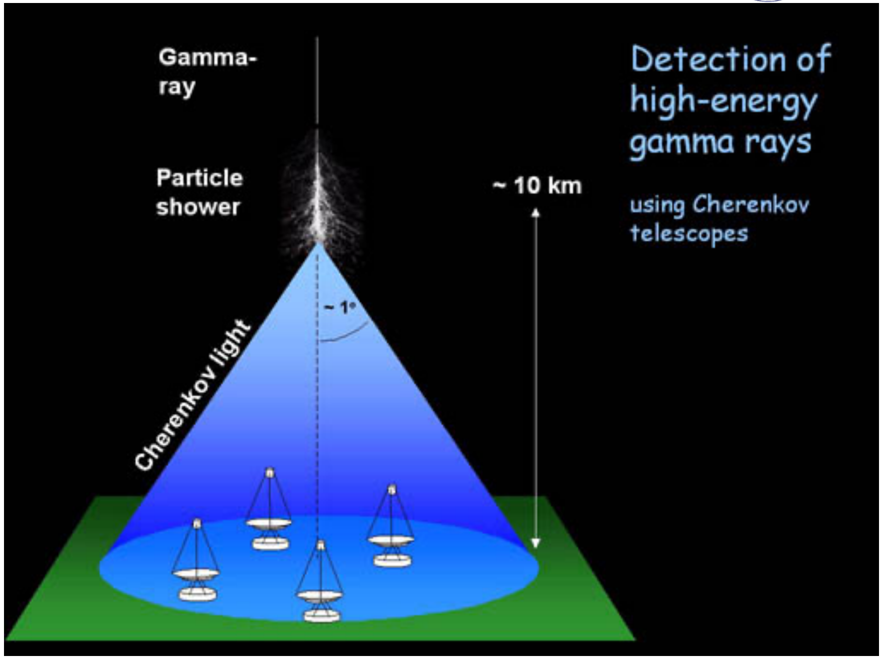


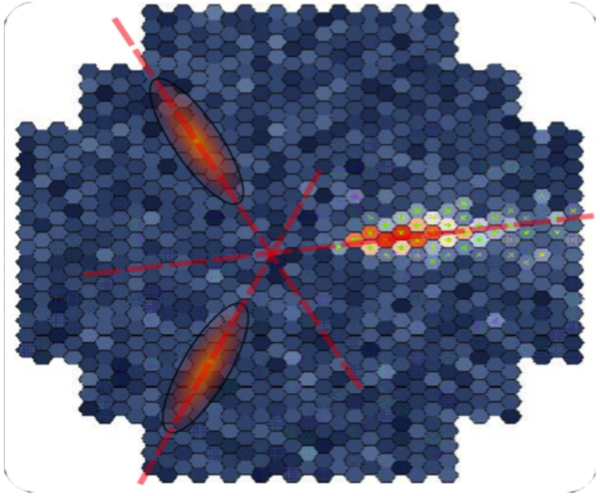


https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/

- 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

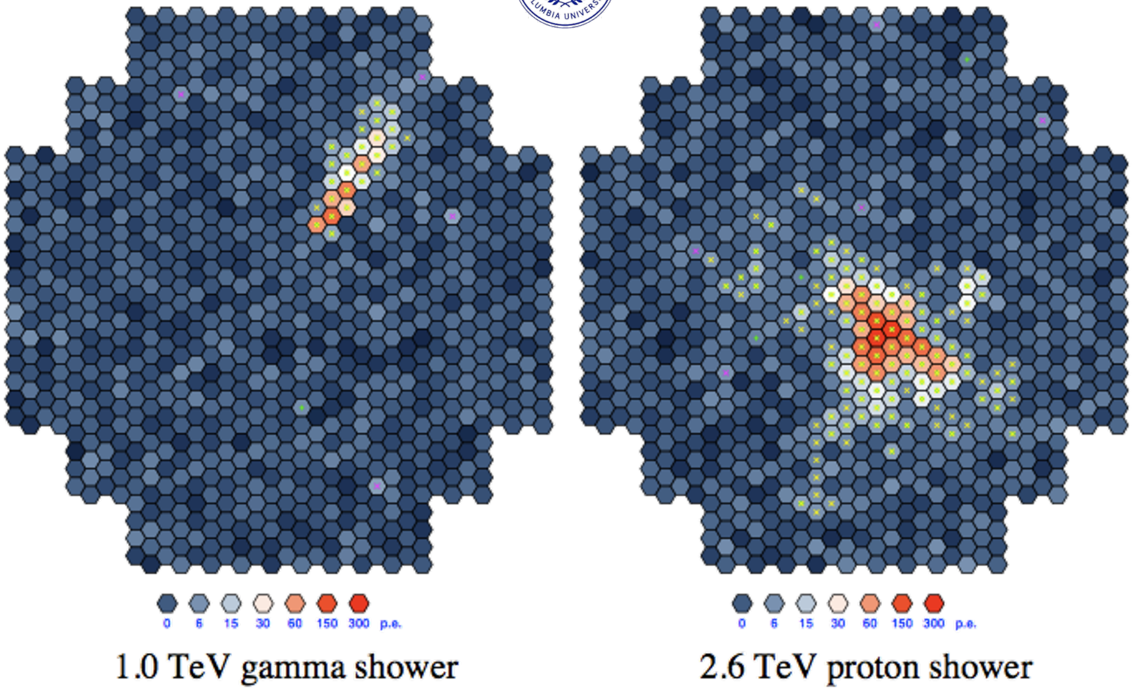




https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/

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

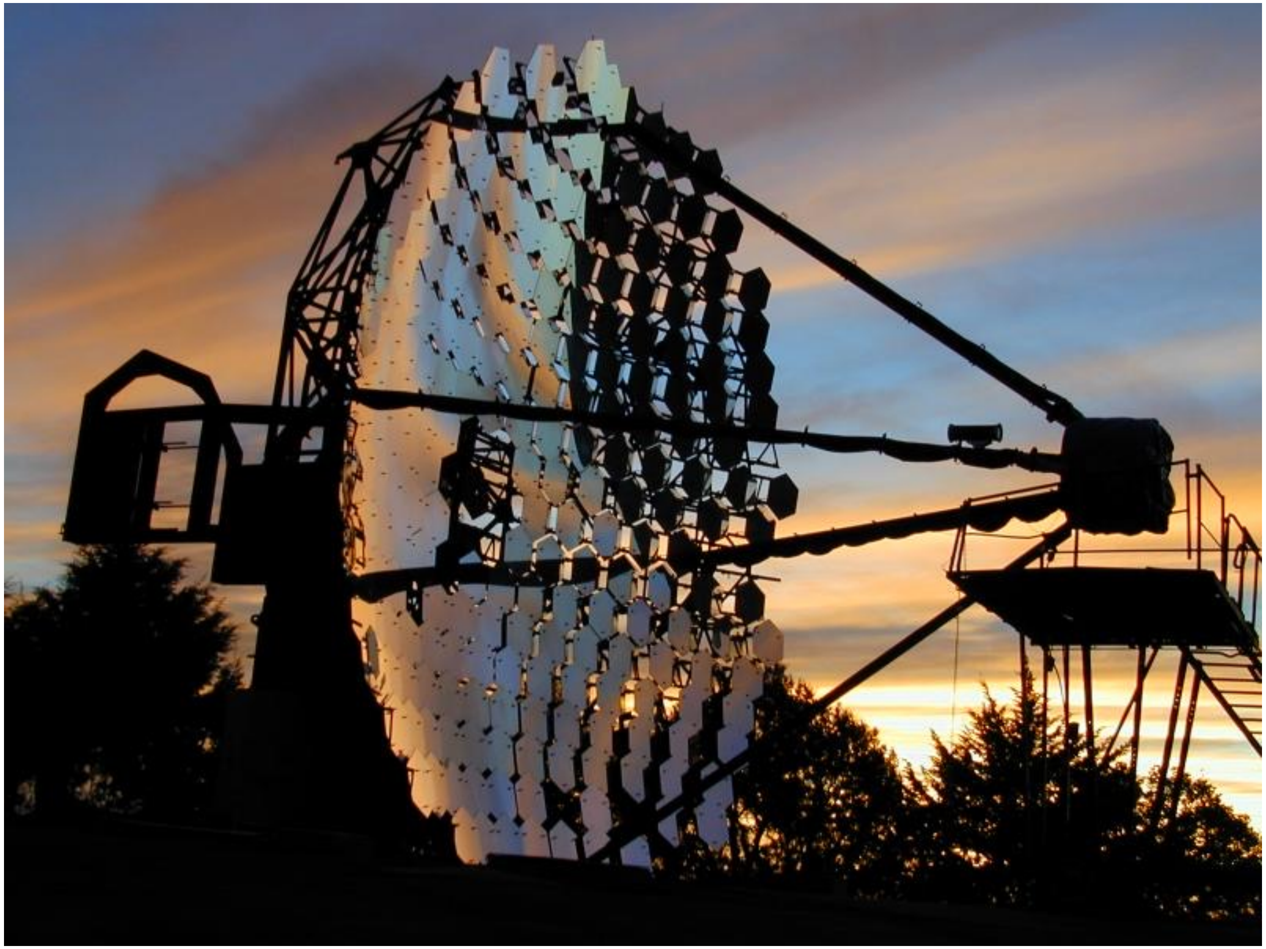
Background contamination



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)

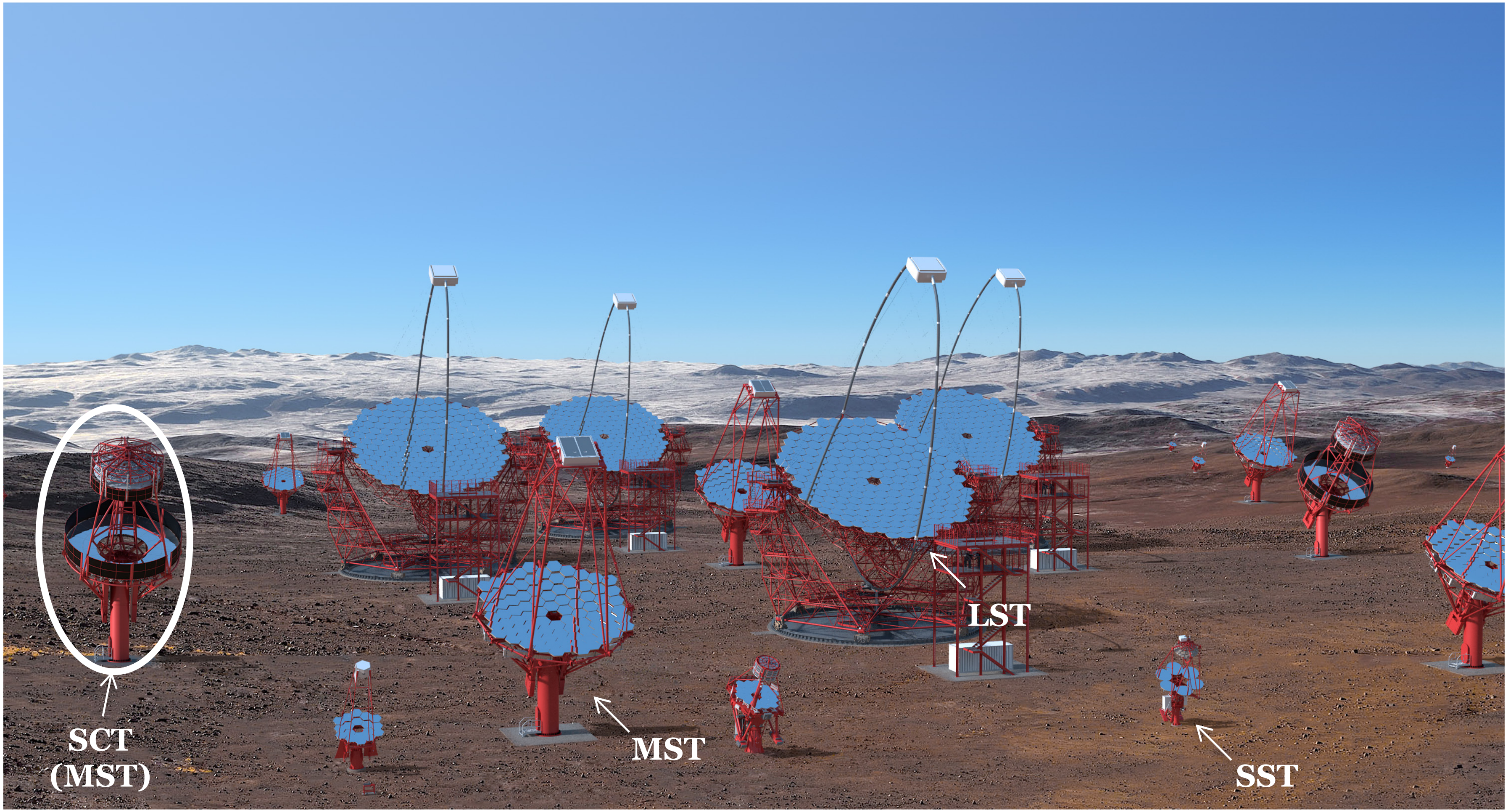
IACT pioneers: the Whipple 10 m γ-ray telescope at FLWO



https://veritas.sao.arizona.edu/whipple

Current-generation IACTs

Next-generation IACT

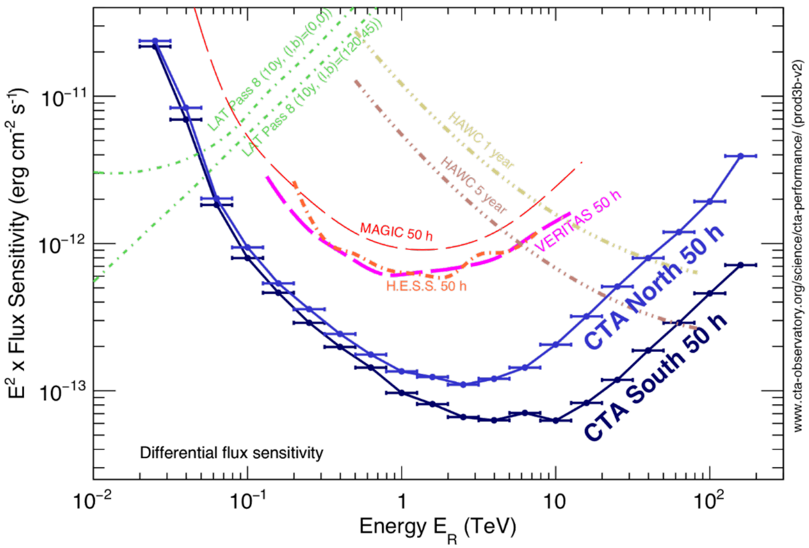


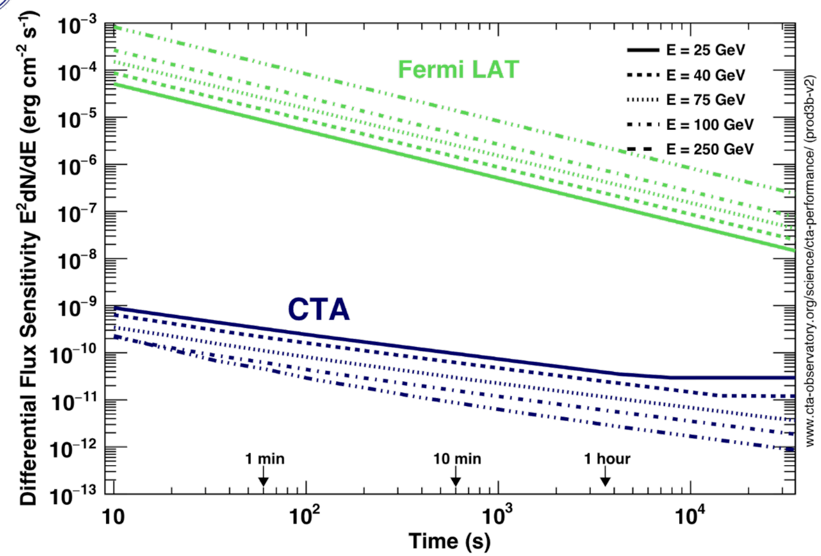
Artistic impression of the CTA South, Credit Gabriel Pérez Diaz, IAC / Marc-André Besel CTAO

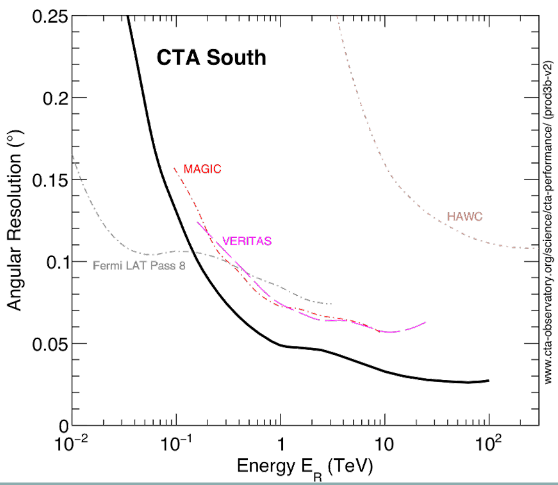
Where is CTA?

Heidelberg
MPIK
Zeuthen
DESY
Spain
La Palma
Bologna
INAF
northern hemisphere
southern hemisphere
Chile
Paranal
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google
Array Sites
CTAO Offices
Science Data Management Centre

Why CTA?

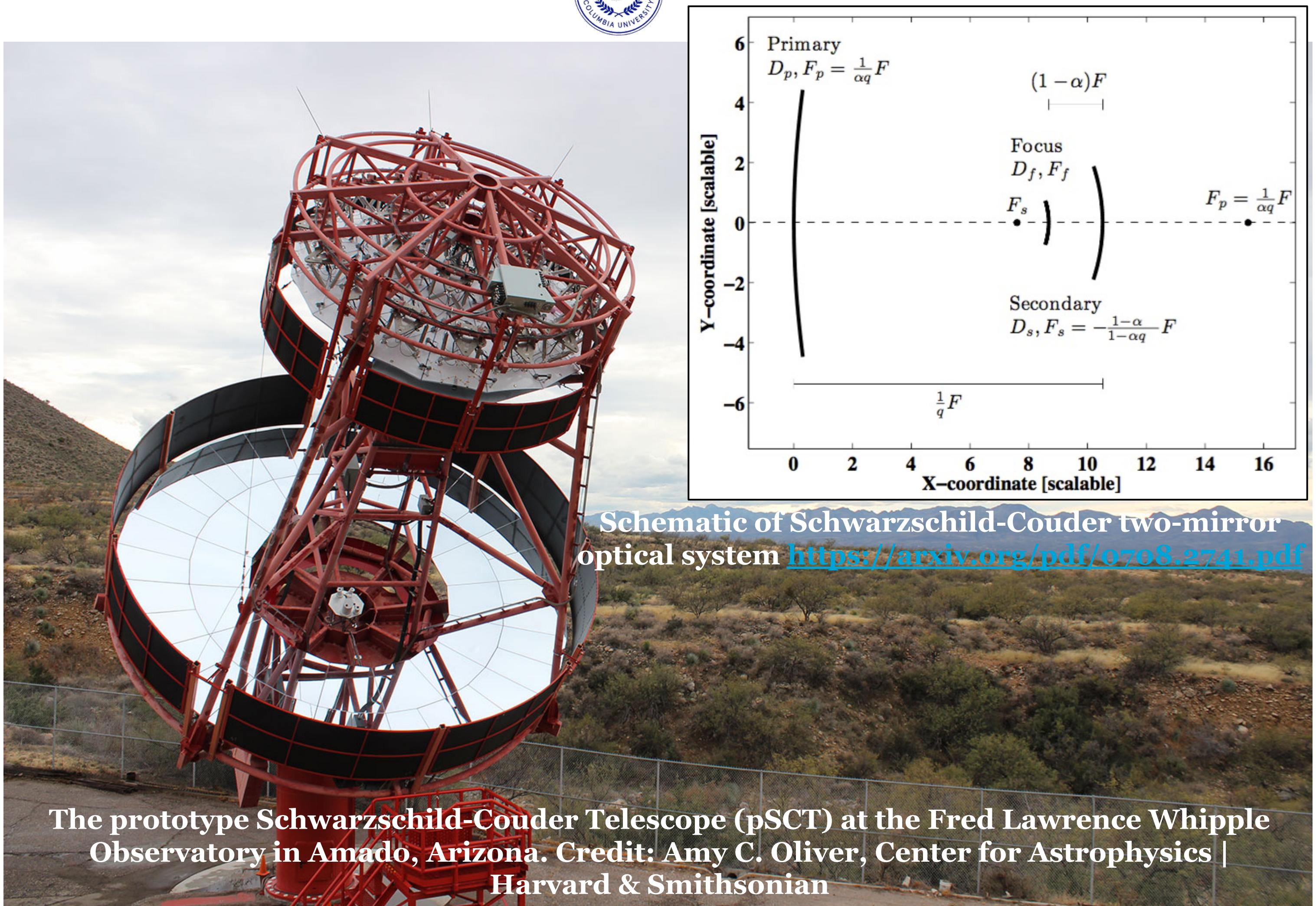






- Wider energy range
- Better sensitivity
- Better angular resolution

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

Pop quiz!!!

?

When did Karl Shwarzschild published his paper?

a) 1905
b) 1965
c) 1990

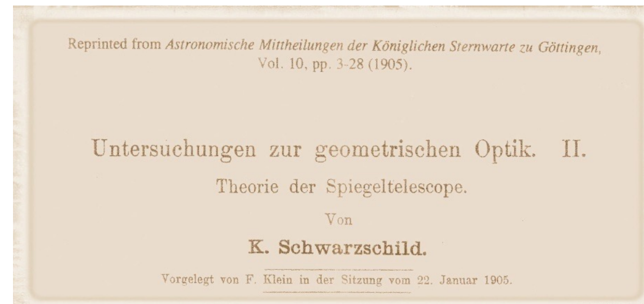
Pop quiz!!!

When did Karl Shwarzschild published his paper?

a) **1905**

b) 1965

c) 1990



Reprinted from *Astronomische Mittheilungen der Königlichen Sternwarte zu Göttingen*, Vol. 10, pp. 3-28 (1905).

Untersuchungen zur geometrischen Optik. II.

Theorie der Spiegeltelescope.

Von

K. Schwarzschild.

Vorgelegt von F. Klein in der Sitzung vom 22. Januar 1905.

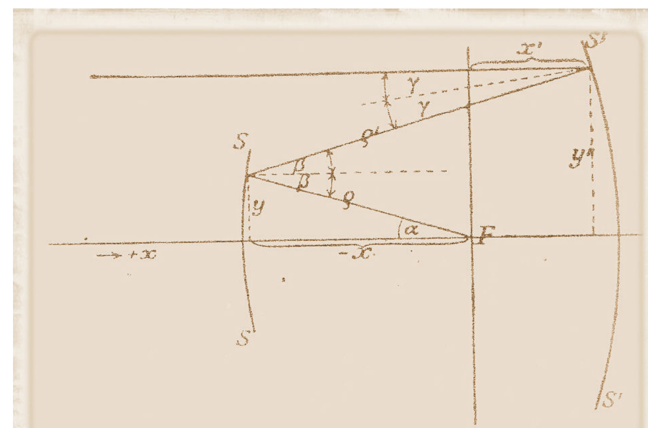
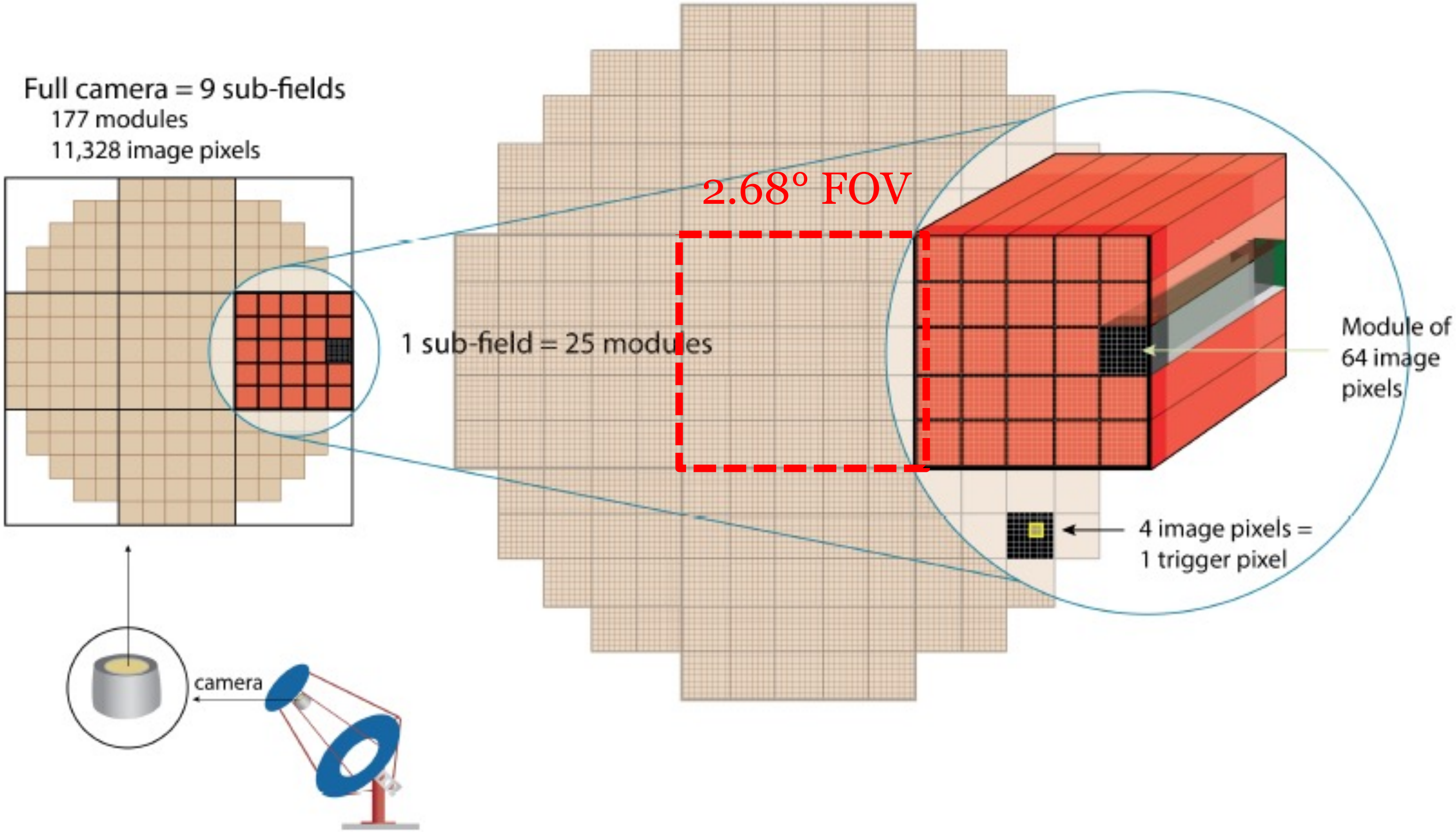


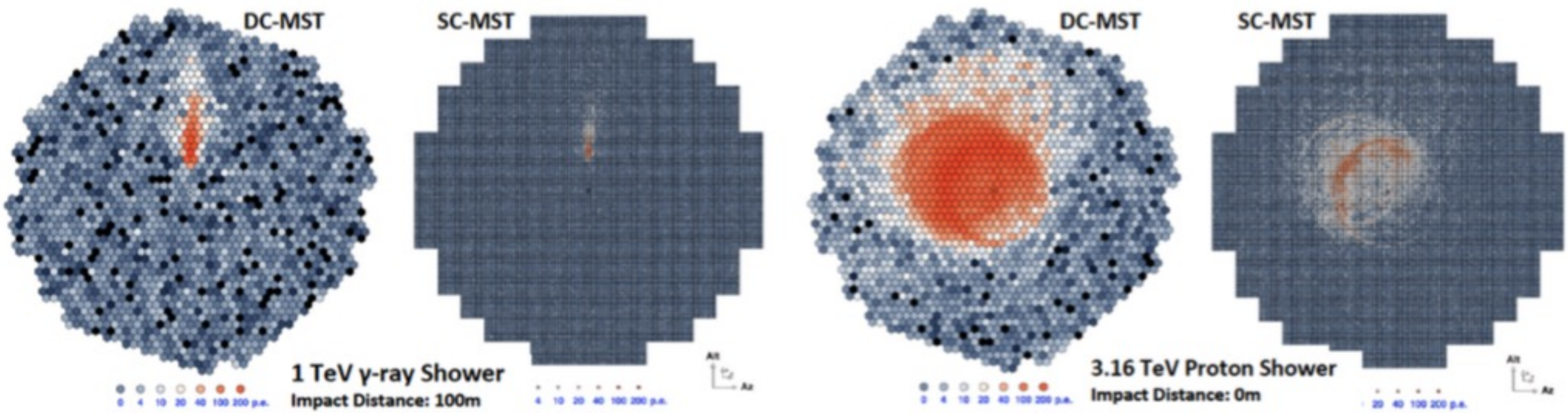
Fig. 8.

Focal plane structure



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

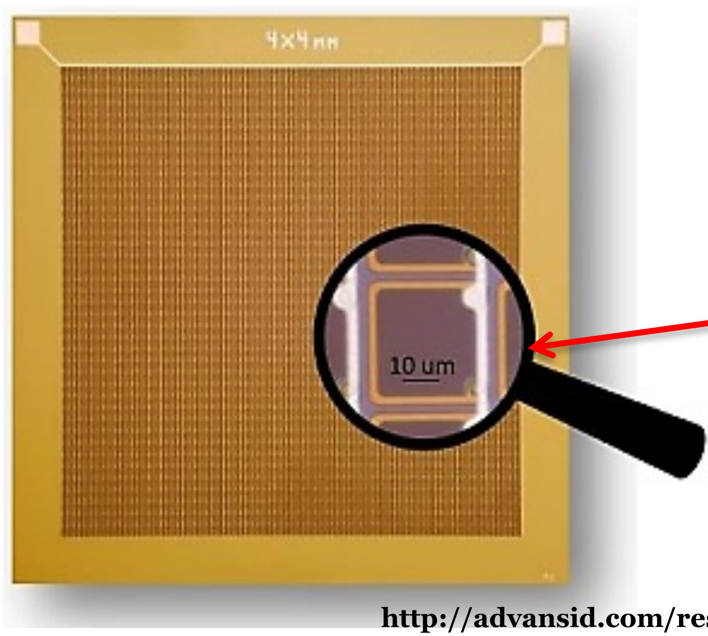
Big eyes and a sharper view

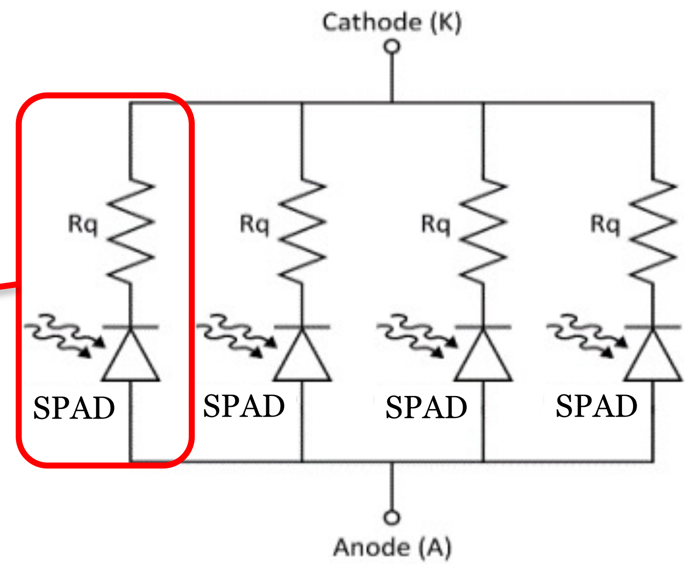


- Superior optical angular resolution over a wide (~8°) field of view (the largest IACT FOV is currently less than 5°)
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors (Silicon-photomultipliers, SiPMs) and electronics
- Better sensitivity and reduced observation time

The detectors: Silicon Photomultipliers

SiPMs: array of reverse-biased Single Photon avalanche Diodes (**SPADs**) connected in parallel





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

SiPM size: from 1x1mm² to 10x10mm²

SPAD size: from 5µm to 40µm (typical)

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)

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)

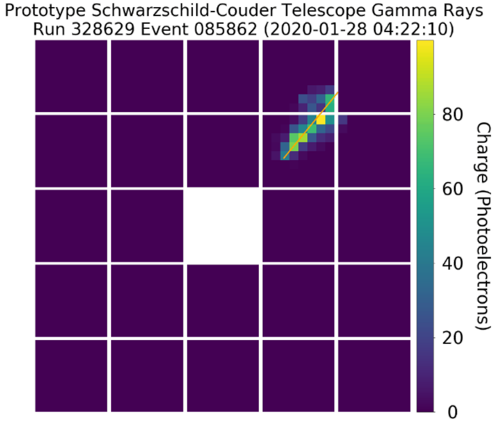
Guests of the pSCT inauguration in January 2019 gather in front of the telescope. Credit: Deivid Ribeiro, Columbia University

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 Amer 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 groundwork for the future of gamma-ray astrophysics. "We've established this new technology, which wi 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 a 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 v 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 wit exquisite resolution."



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

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.

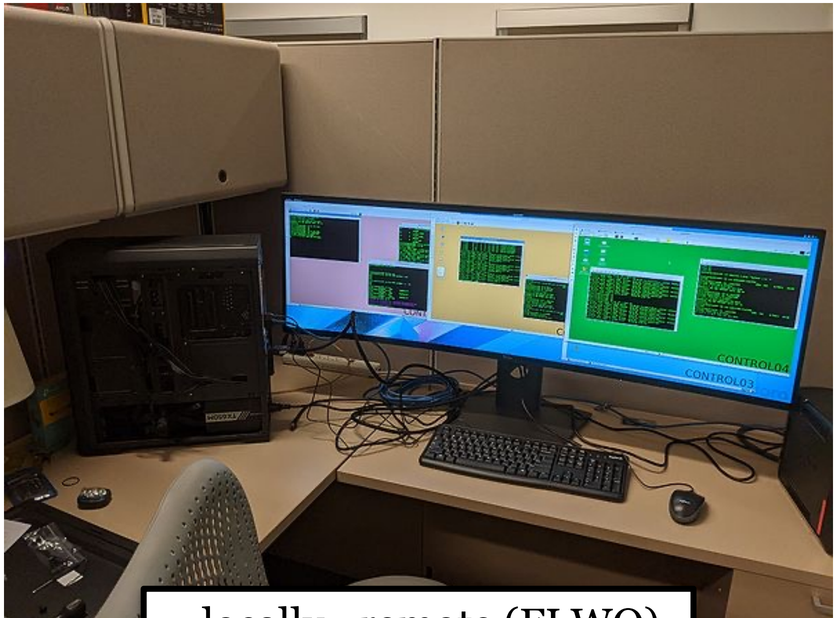
An extraordinary inter-continental effort…

...still ongoing!

Italian postdoc carefully opening the back of the pSCT camera for technical inspection (FWLO)
Photo credit: William Hanlon

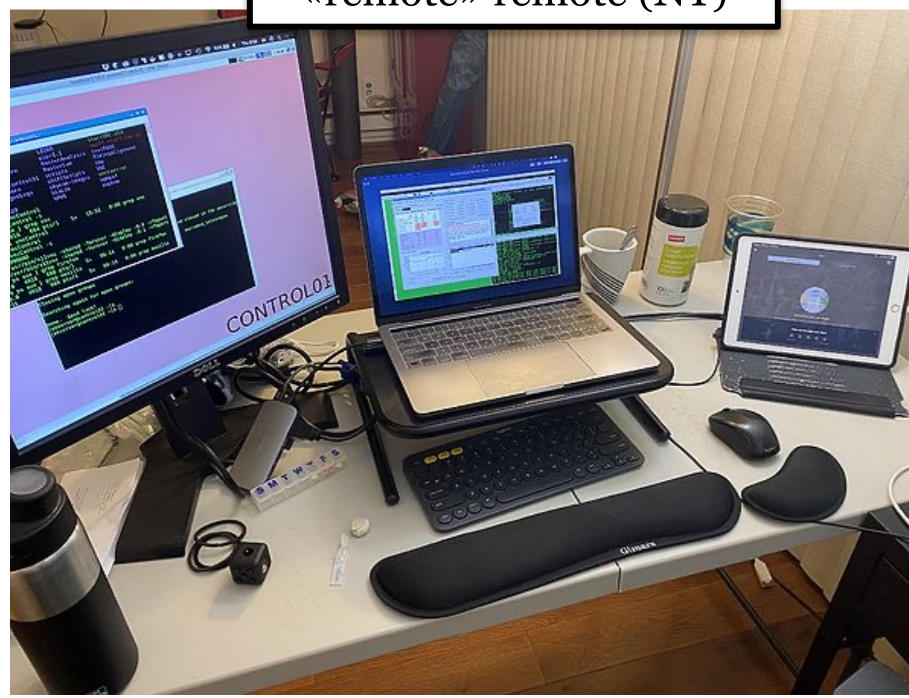
- Software and data acquisition optimization for the pSCT
- Optical alignment improvement
- Camera upgrade, towards a fully populated SCT
  - 1600 pixels → 11328 pixels (~2.67° → ~8°)
  - Upgraded photosensors
  - Upgraded preampifiers
  - Upgraded electronics

Remote observing

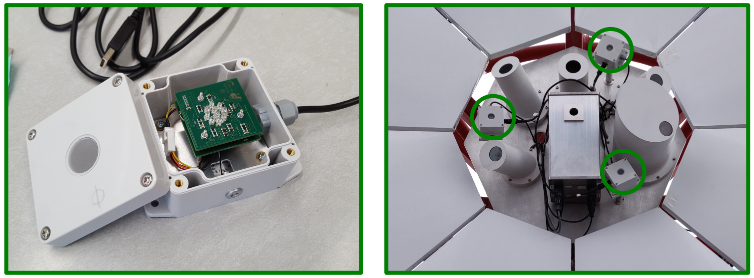


«locally» remote (FLWO)

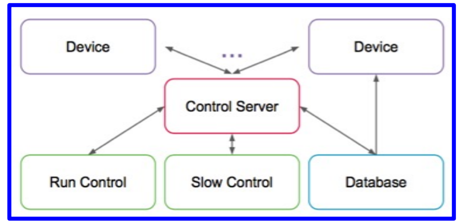
«remote» remote (NY)



Barnard and Columbia Contribution

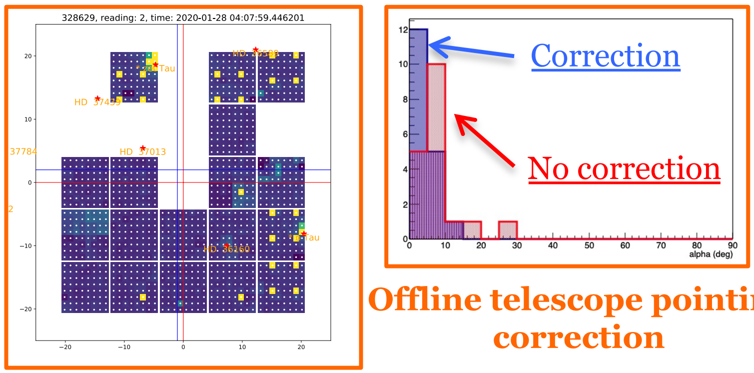


Flasher calibration units

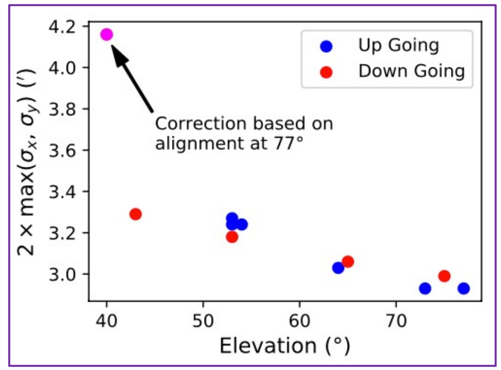


Camera slow control

On-site work



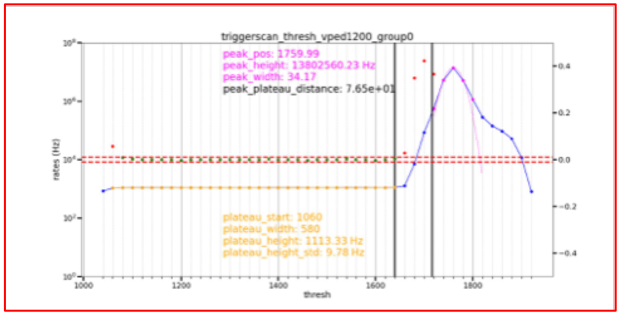
Offline telescope pointing correction



Optics

Camera upgrade PI: Prof. Reshmi Mukherjee

Camera upgrade



Some thoughts on VHE γ-ray astronomy

- 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 and will dramatically enhance IACT performance
- 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

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Stay tuned!

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Barnard College, Columbia University
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Science On Hudson, Nevis Labs
LIVE from the VERITAS site at FLWO

03/13/2021