Gamma-ray Astronomy with Cherenkov Telescopes
… and beyond

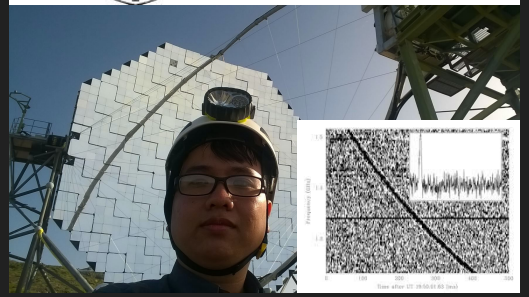
BERKELEY SETI RESEARCH CENTER

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
UC SANTA CRUZ

SAGI Summer School
ICISE QUY NHON
21st July 2023

About me

2016-2020 🇪🇸



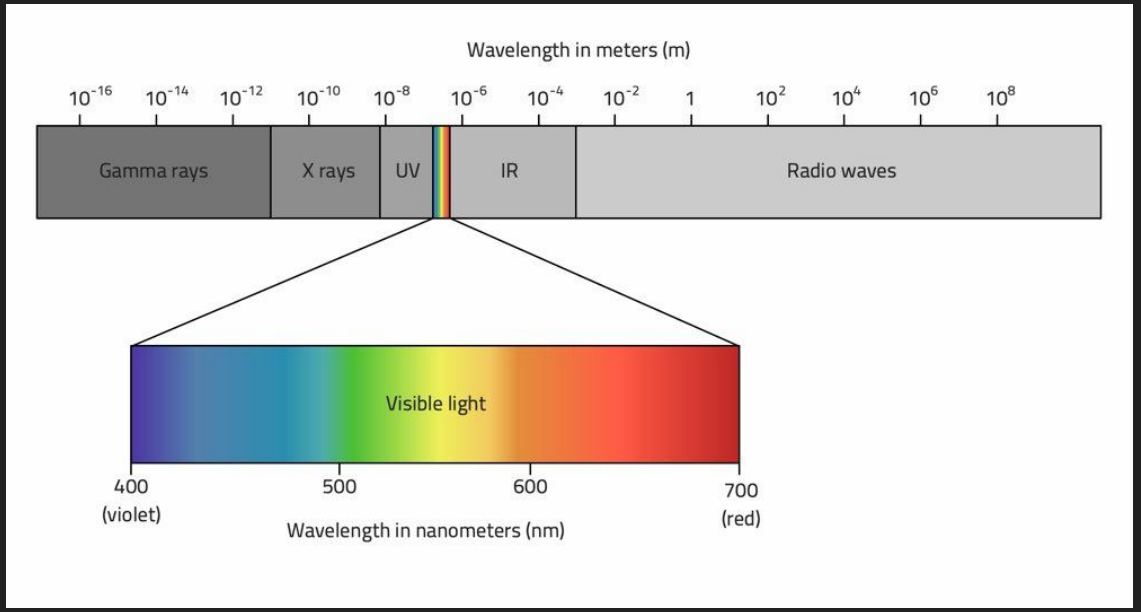
2020-now 🇺🇸

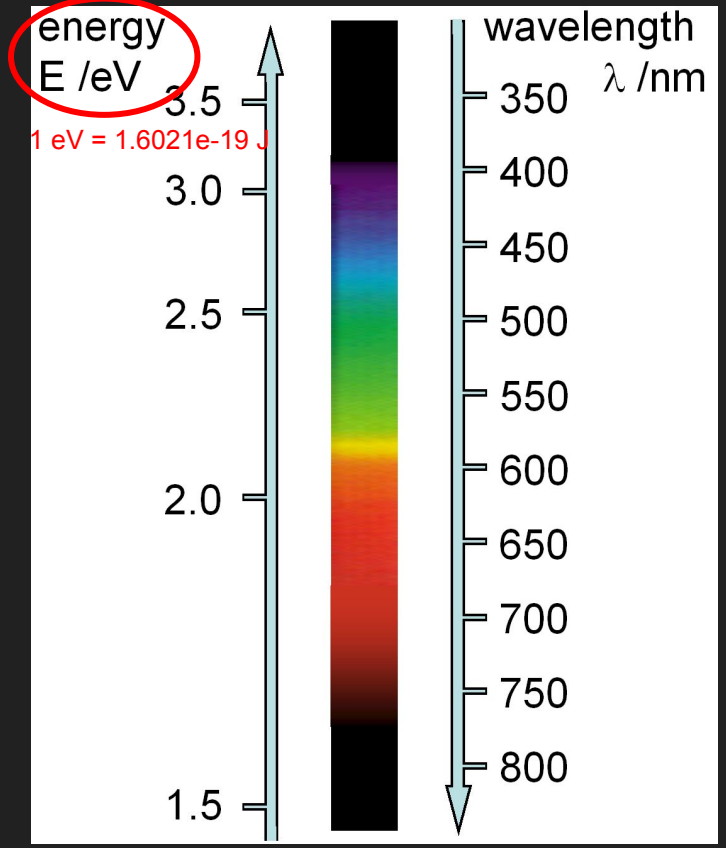
OUTLINE

1. Gamma-ray astronomy
   - Gamma-ray astronomy and gamma-ray telescope
   - The Imaging Atmospheric Cherenkov Technique
2. Q&A (1)
3. Beyond Gamma-ray: Cherenkov telescopes as optical telescopes
   - One-pixel telescope
   - Many-pixel telescope
   - Many-telescope telescope
4. Q&A (2)

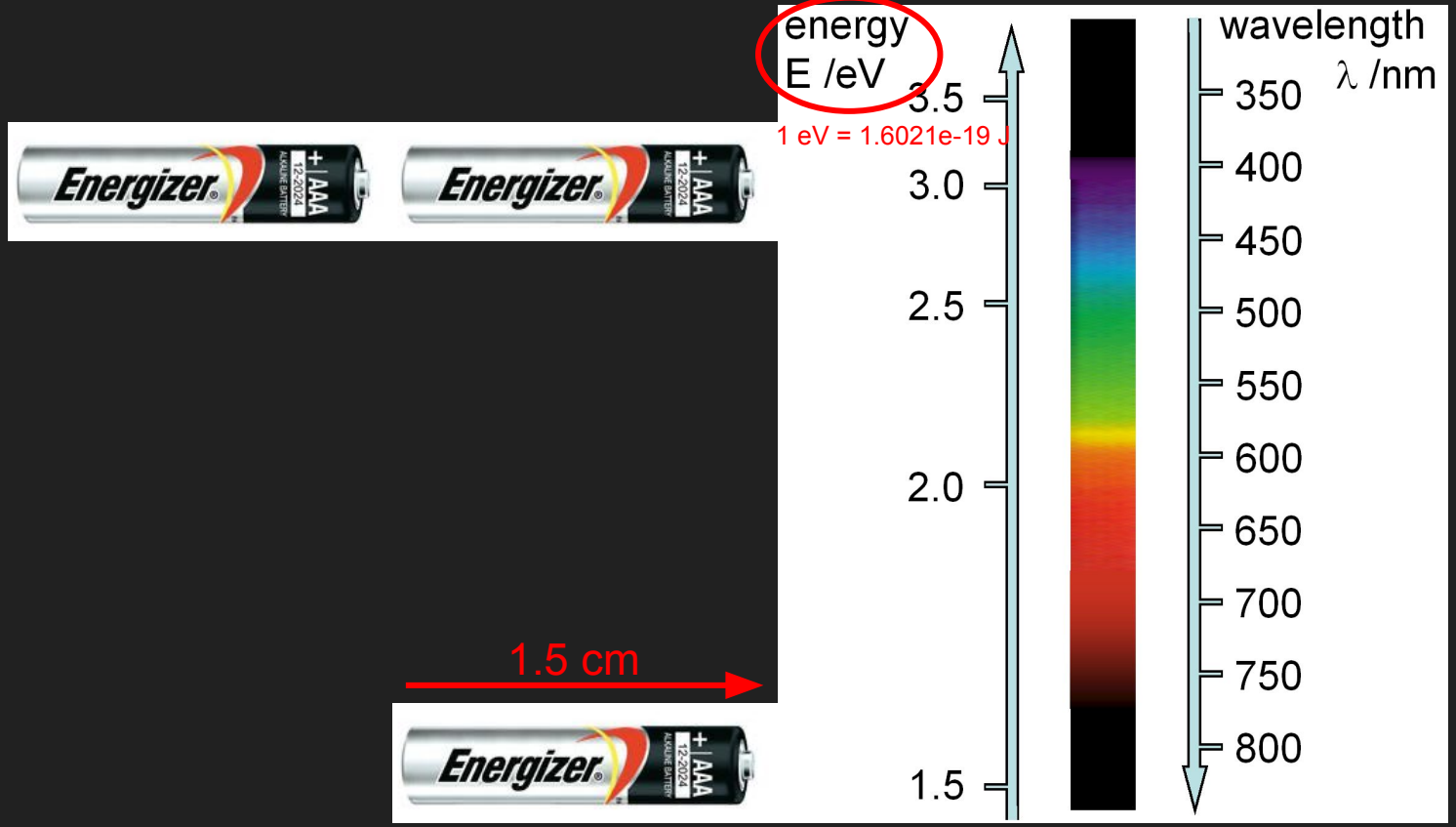
The optical sky

The optical sky

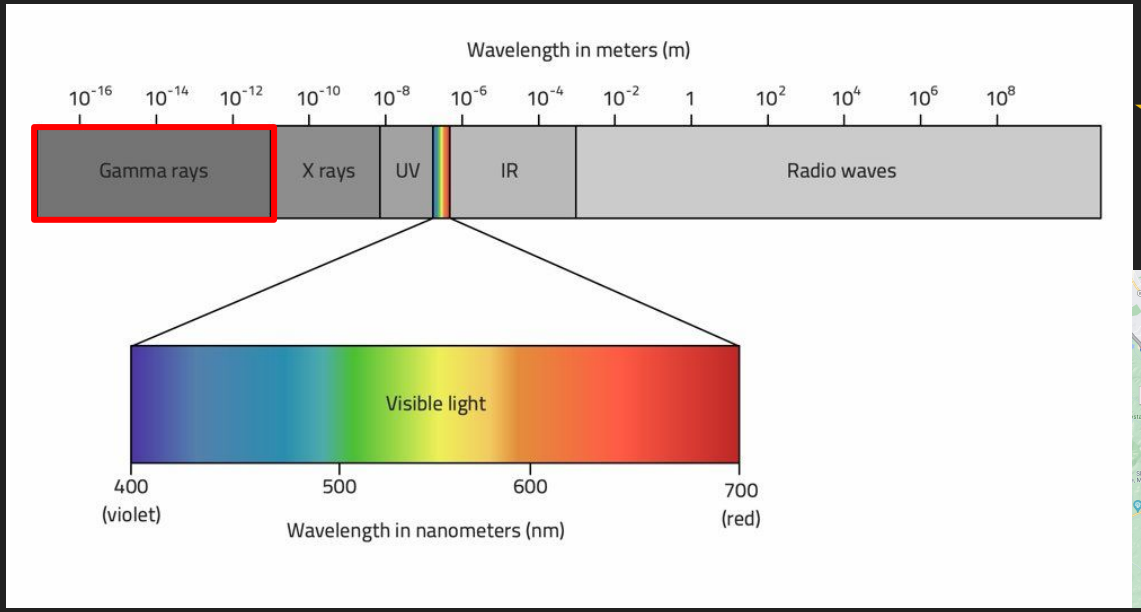




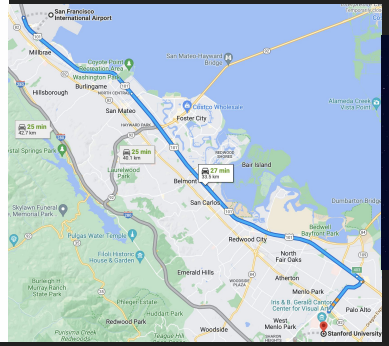
The optical sky



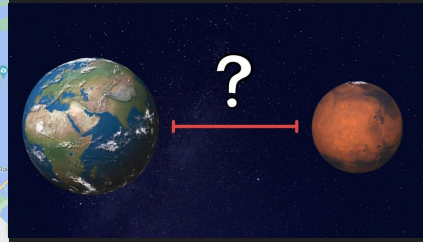
The gamma-ray sky



- ★ Gamma-ray:
  - MeV = a million eV
  - 33 km “battery train”
- ★ Very high energy gamma-ray:
  - TeV = a million MeV = a trillion eV
  - 33 million km

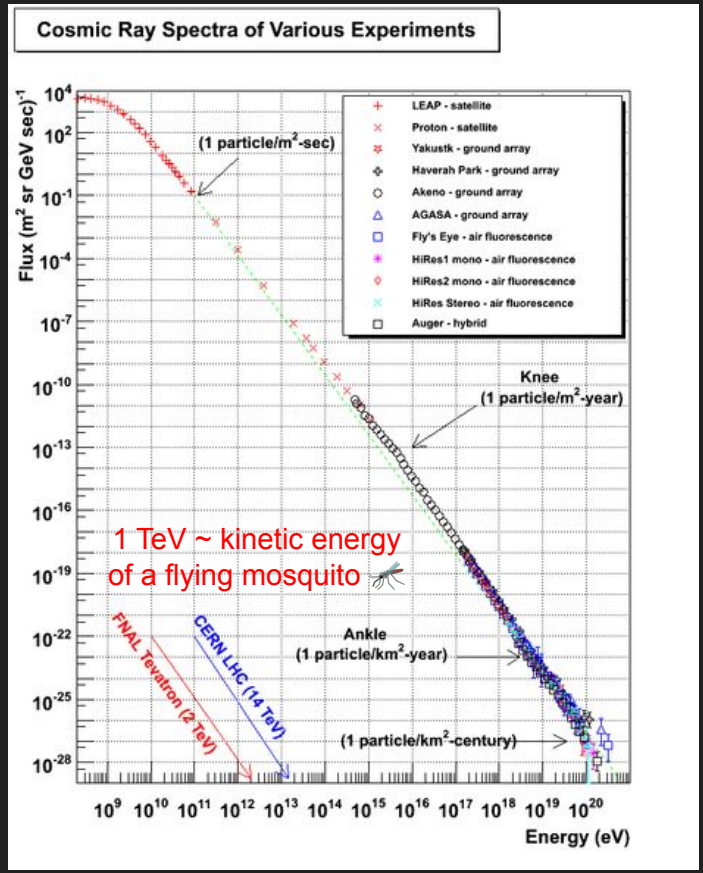


From SFO to Stanford



~ 56 million km

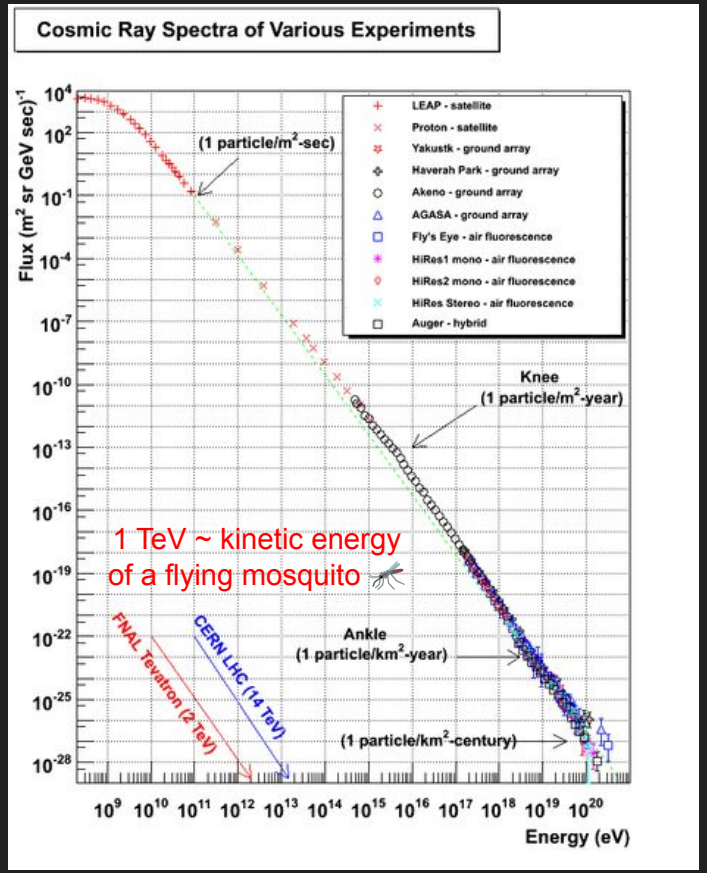
The gamma-ray sky



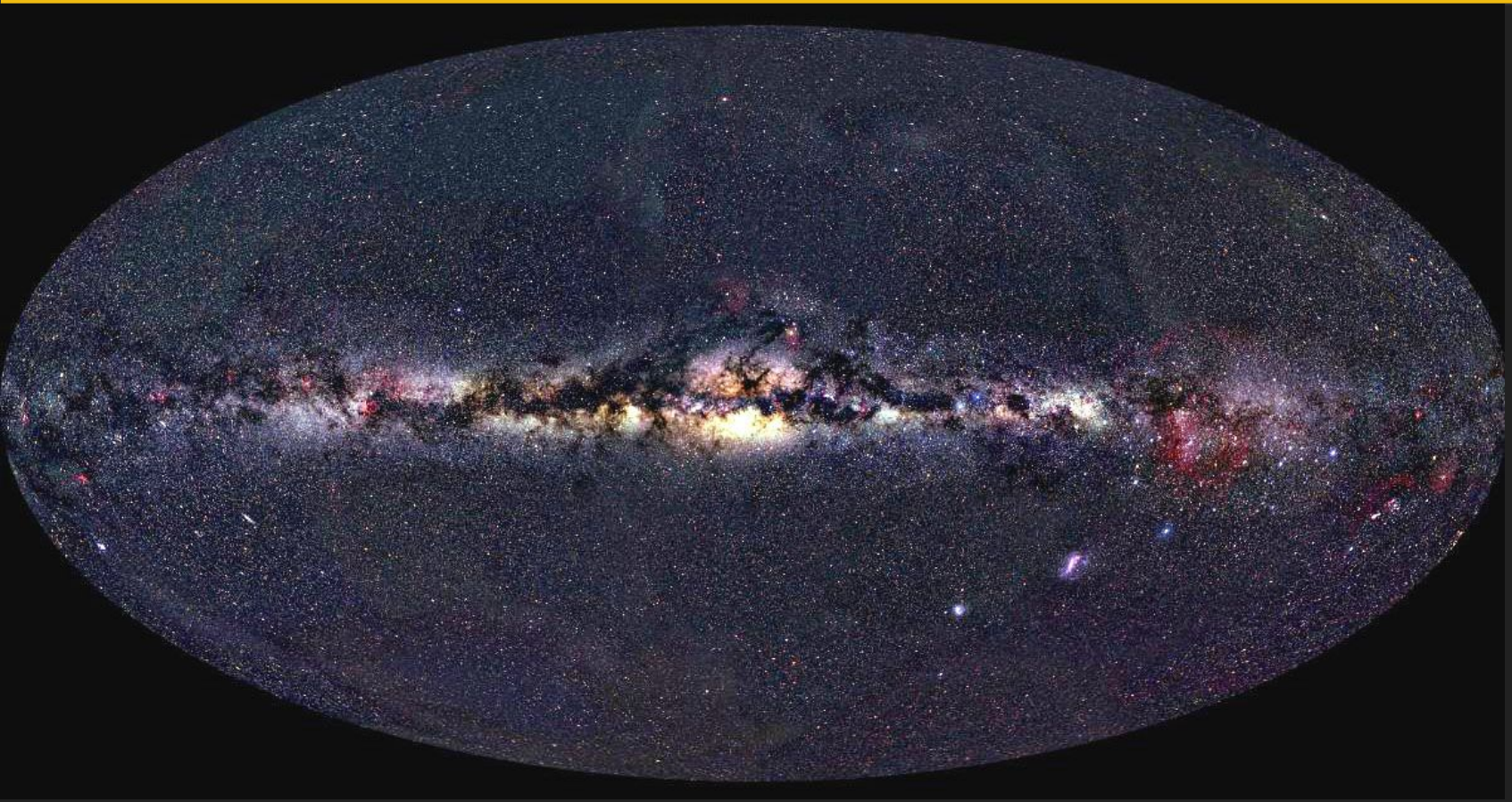
The gamma-ray sky

Balloon experiment
1911-1913

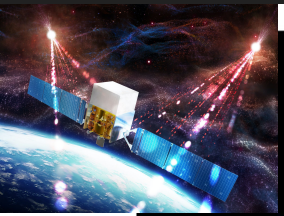
Victor Francis Hess,
Nobel Prize in Physics
1936

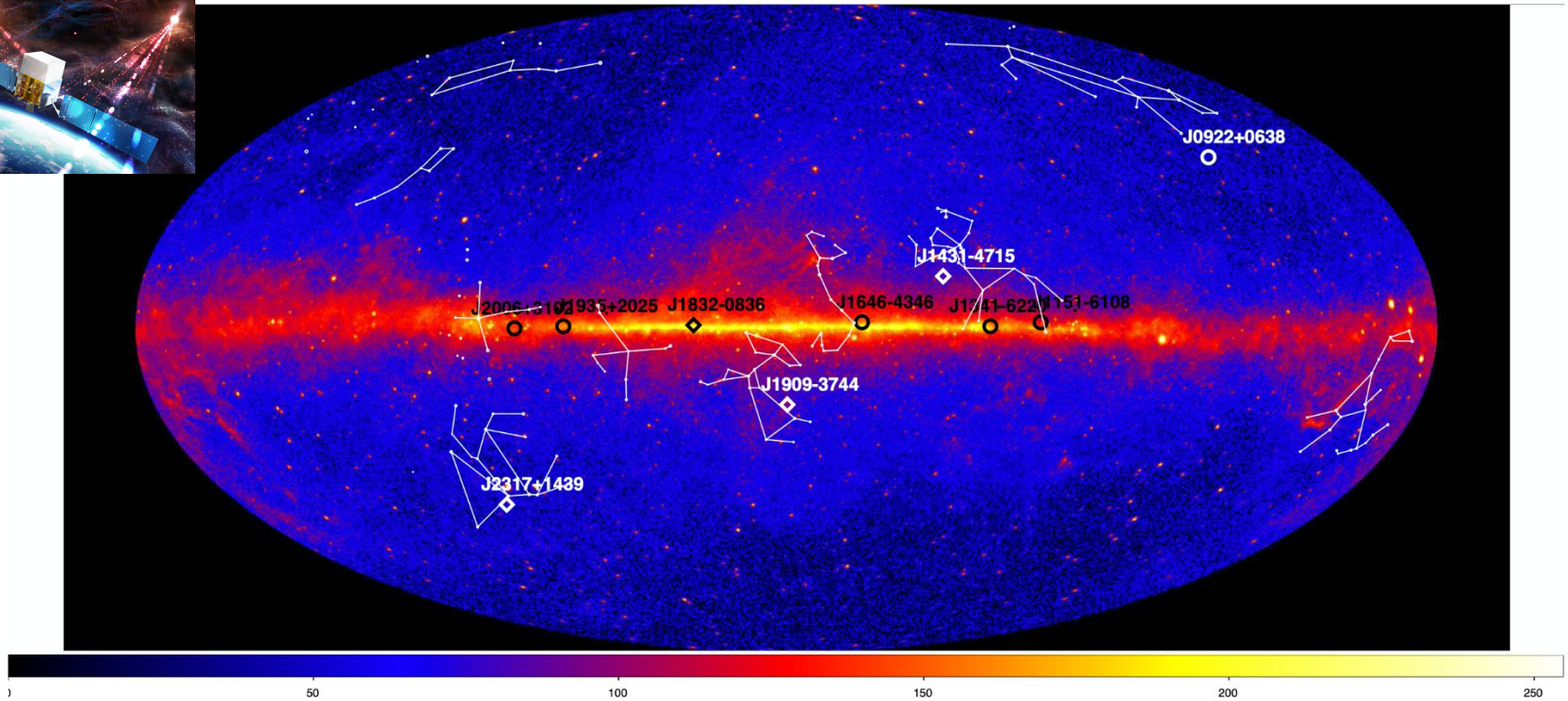


The gamma-ray sky (GeV)



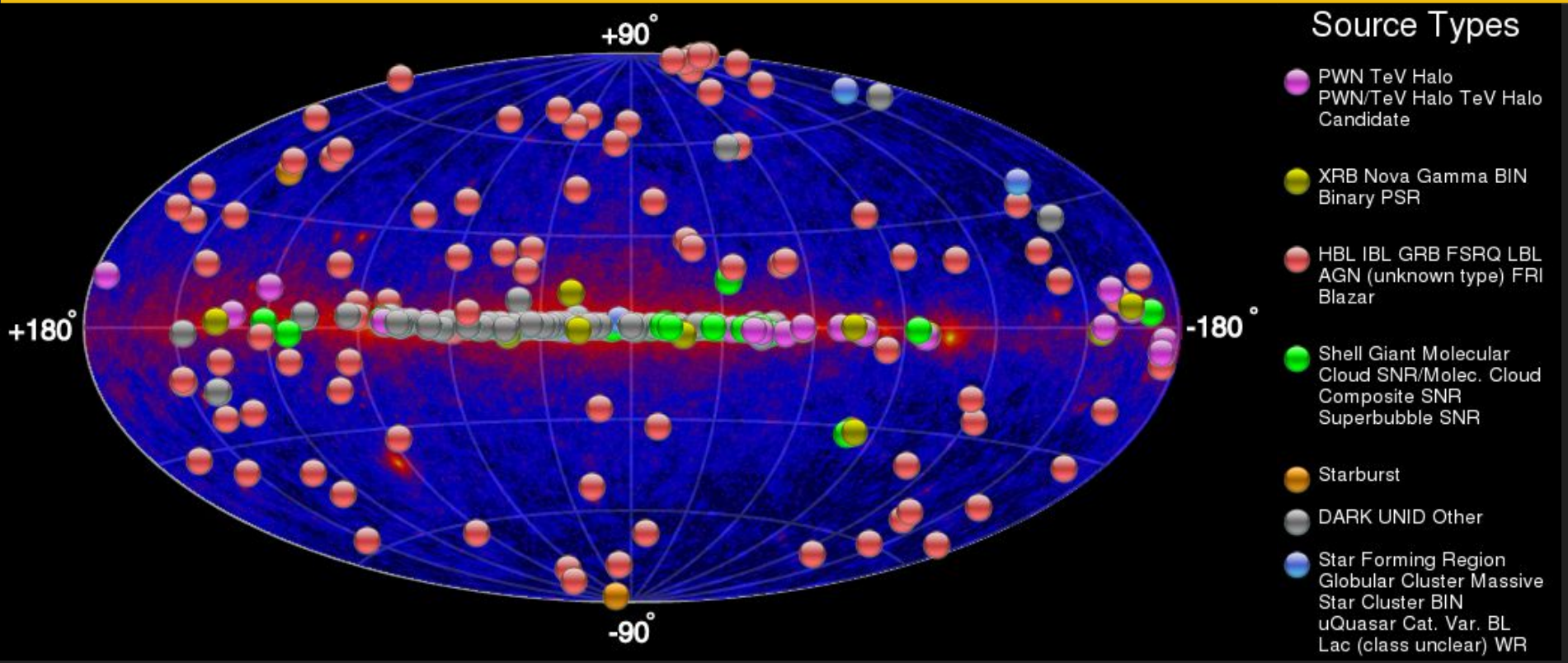
The gamma-ray sky (GeV)





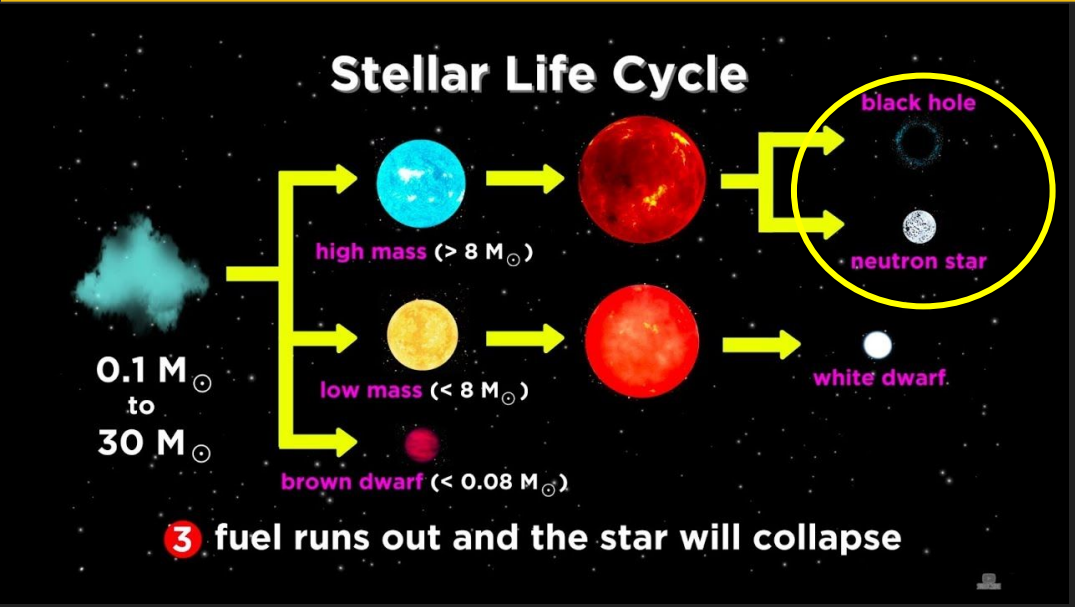
Arxiv: 1706.03592

The gamma-ray sky (TeV)



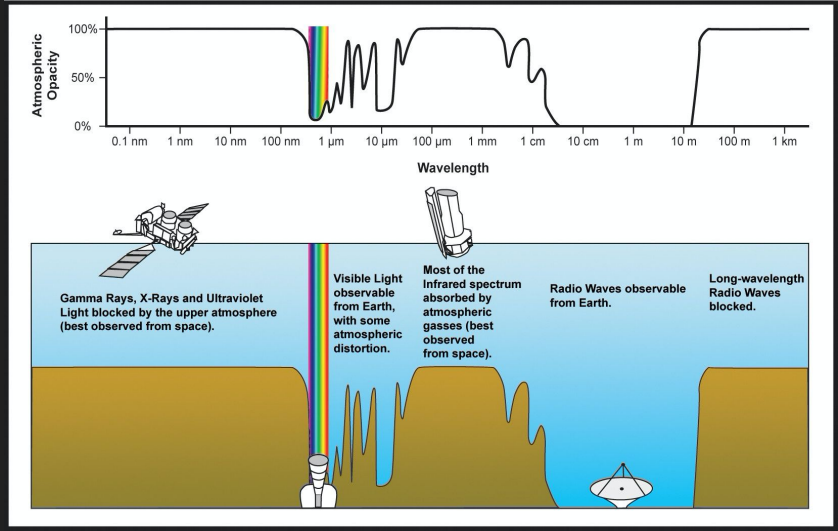
http://tevcat.uchicago.edu

The gamma-ray sky

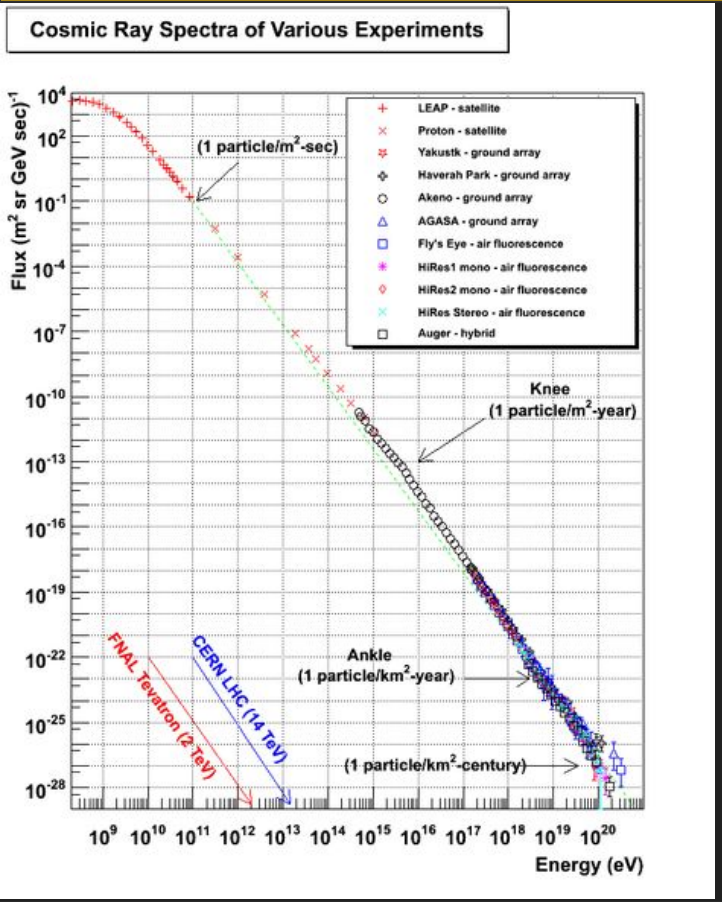


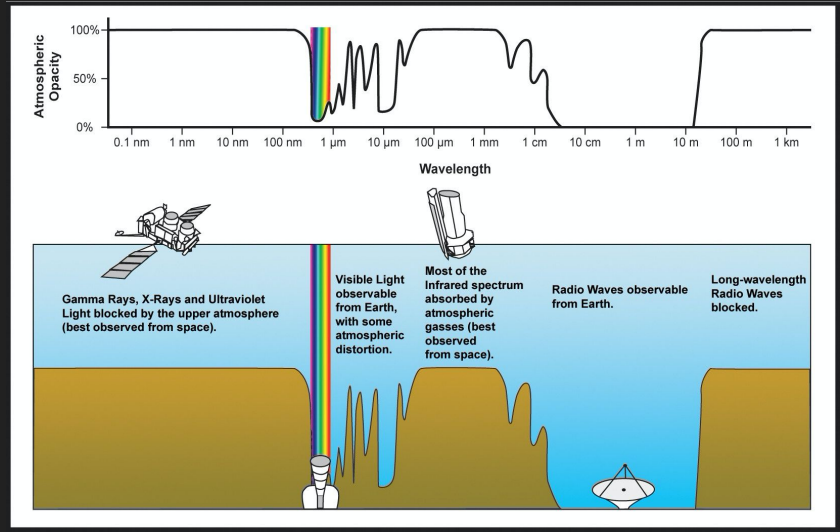
The gamma-ray sky: space or ground?

- ★ Gamma rays allow us to study the extreme universe from astrophysical sources.
- ★ To detect gamma rays:
  - Direct detection: space-borne satellite (*Fermi*)
  - Indirect detection: ground-based Cherenkov Telescopes

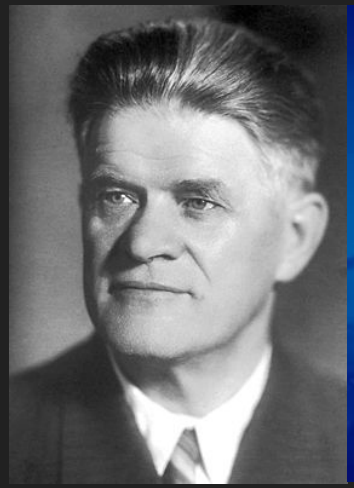


The gamma-ray sky: space or ground?

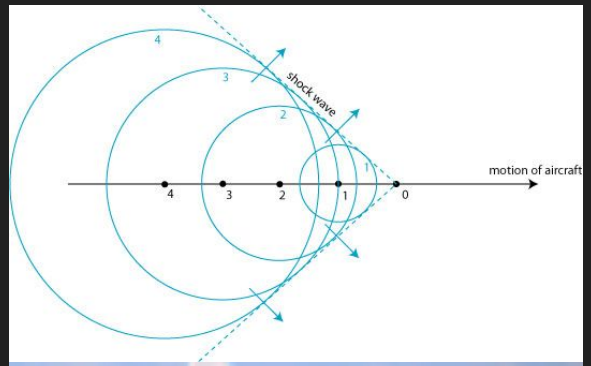




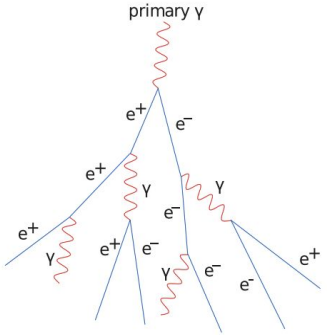
Cherenkov Technique: Cherenkov Radiation

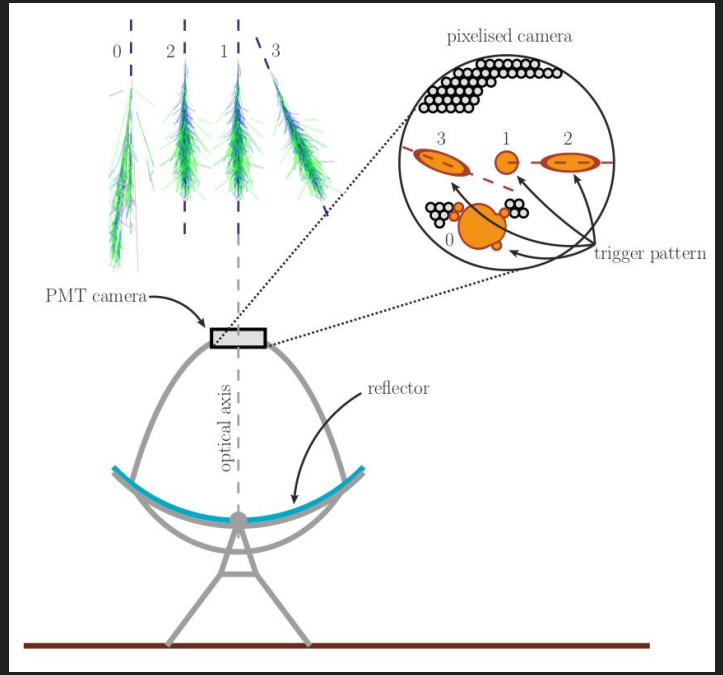


Pavel Cherenkov,
Nobel Prize in
Physics 1958

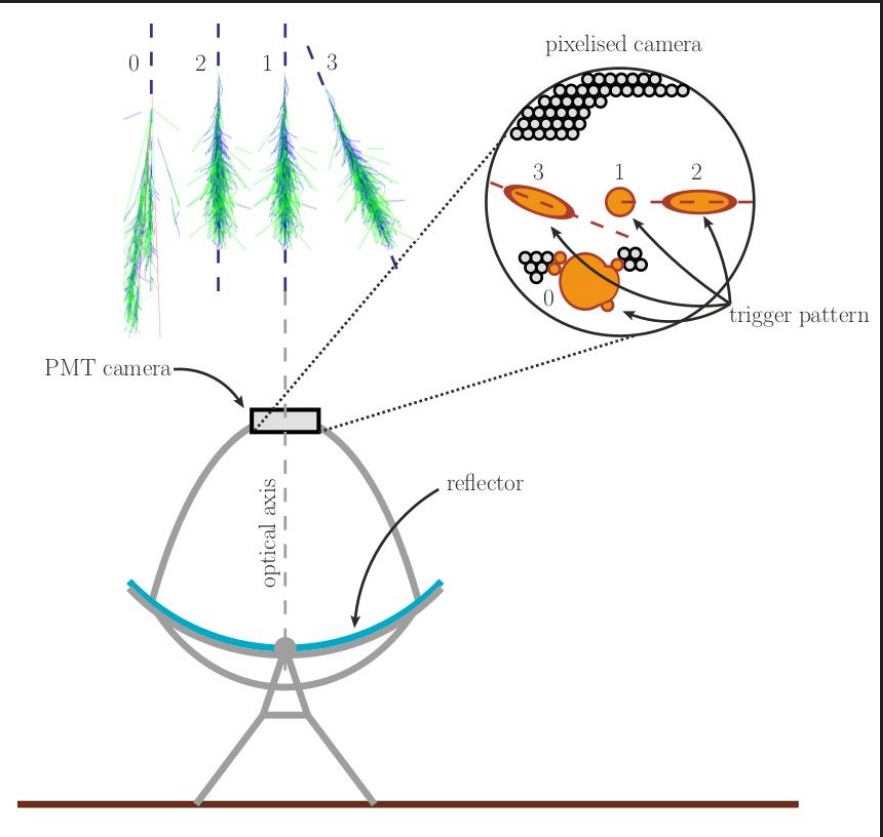


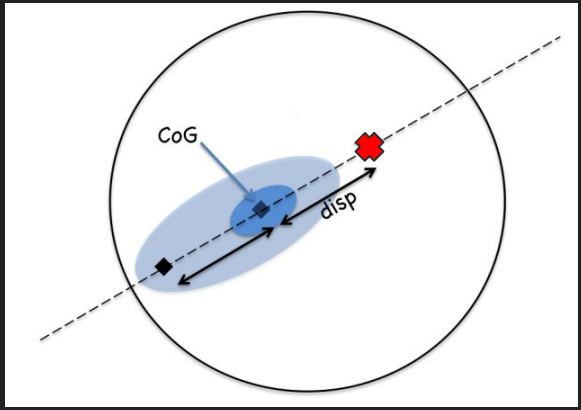
Cherenkov Technique: Air-showers





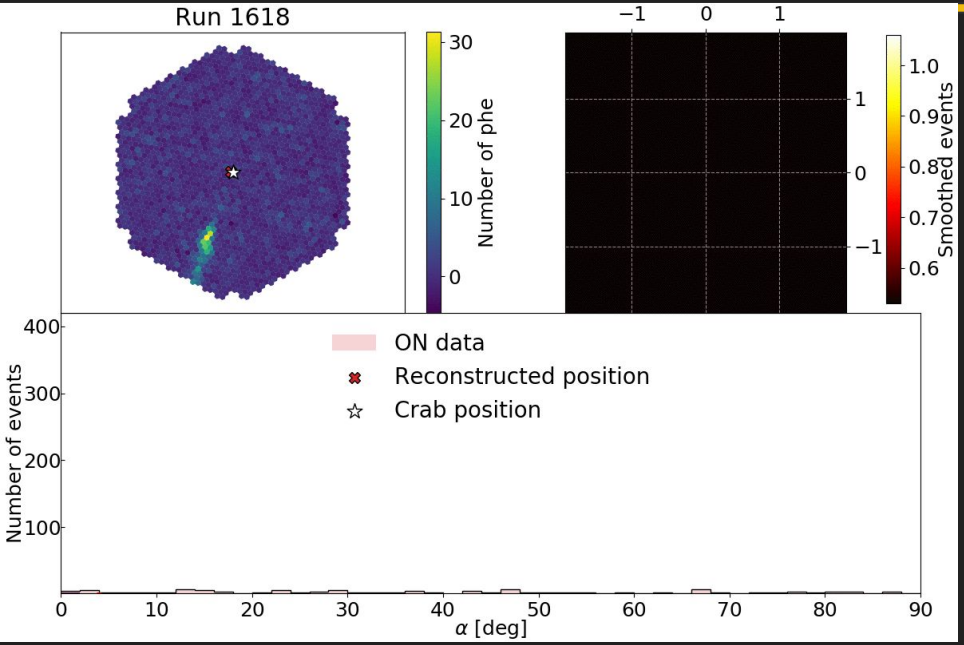
Cherenkov Technique: Hillas Parametrization

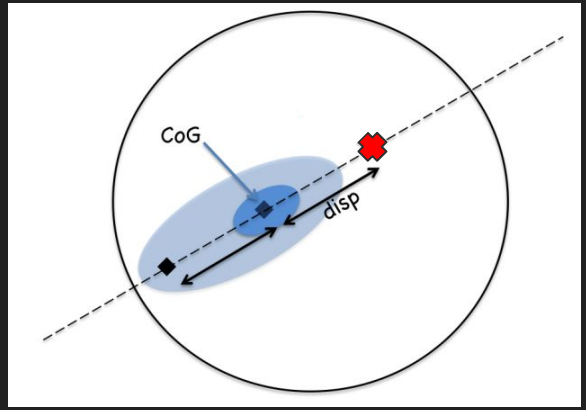




$$disp = A(size) + B(size) \cdot \frac{width}{length + \eta(size) \cdot leakage2}$$

Cherenkov Technique: Point-source Detection





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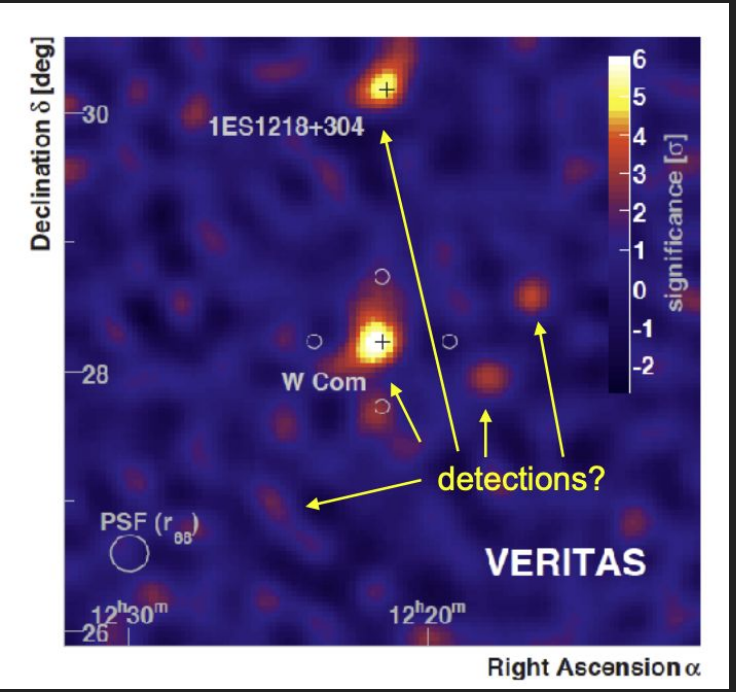
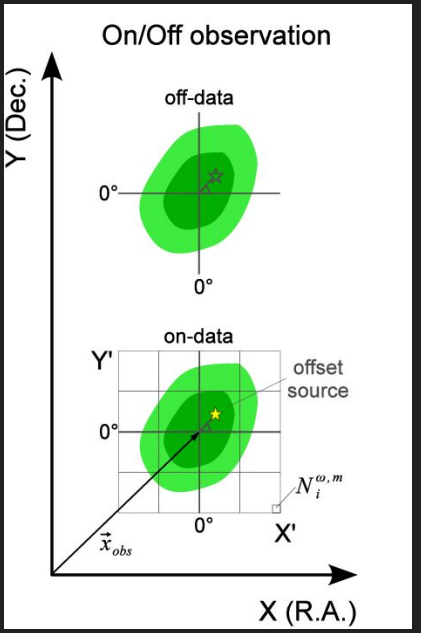
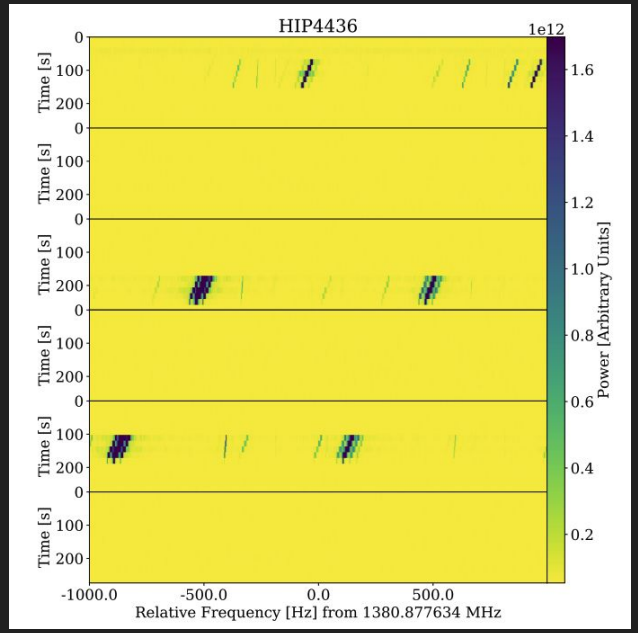
Cherenkov Technique: Point-source Detection



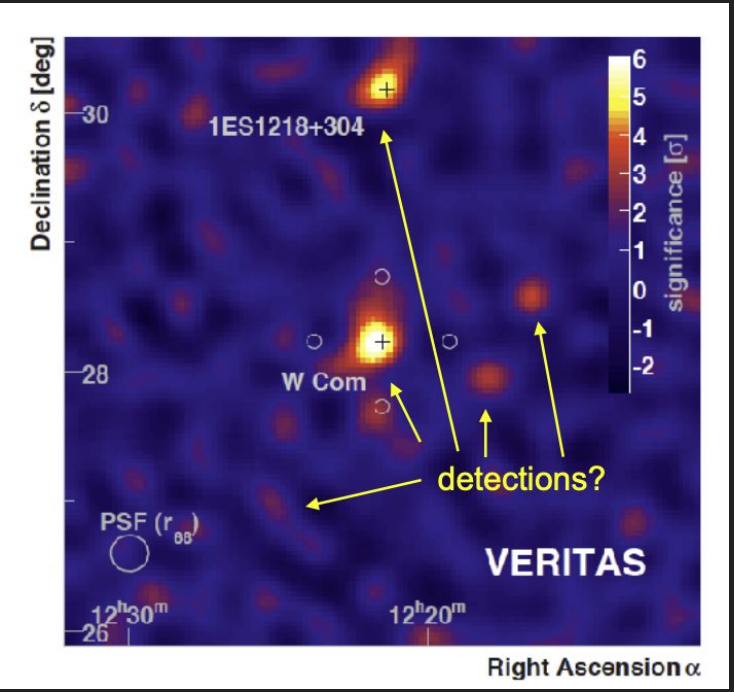
Cherenkov Technique: Point-source Detection





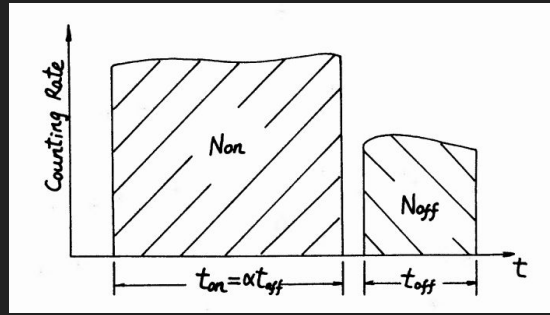
- ★ ON-OFF observation similar to radio observation
- ★ Problems:
  - More hours required for OFF observation
  - OFF is never really “off”
  - ON and OFF observations must be under similar conditions (background, zenith angle, weather)

Cherenkov Technique: Point-source Detection

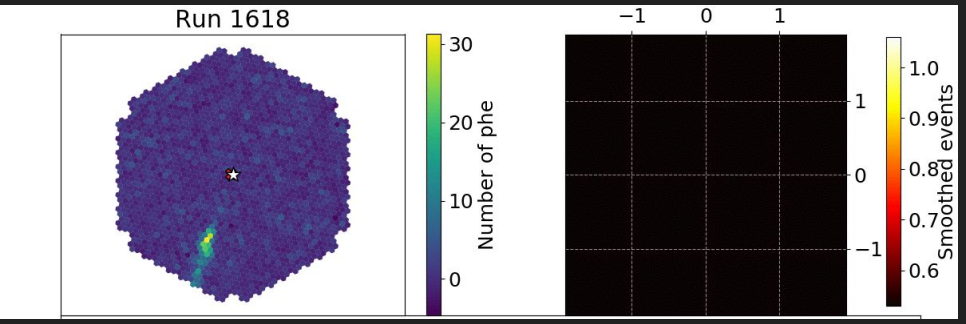


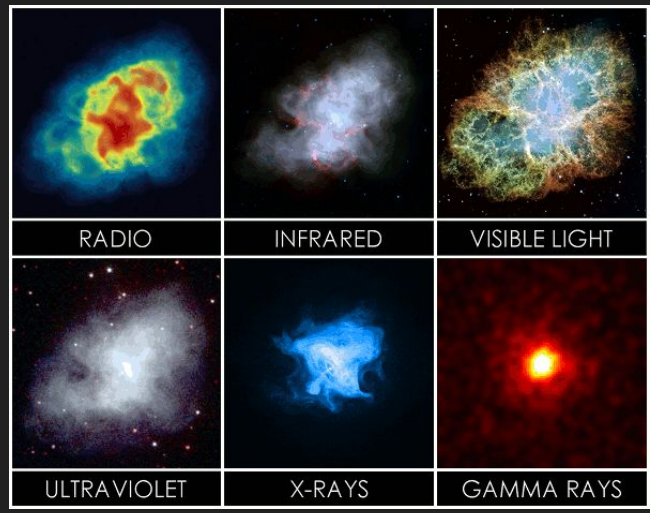
- ★ In any case, ON and OFF regions have to be defined <u>prior to the analysis</u>.
- ★ Significance will be penalized by the number of trials.
- ★ Li & Ma significance calculation:

$$S = \sqrt{-2\ln\lambda} = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}$$



Cherenkov Technique: Point-source Detection





Angular resolution comparison

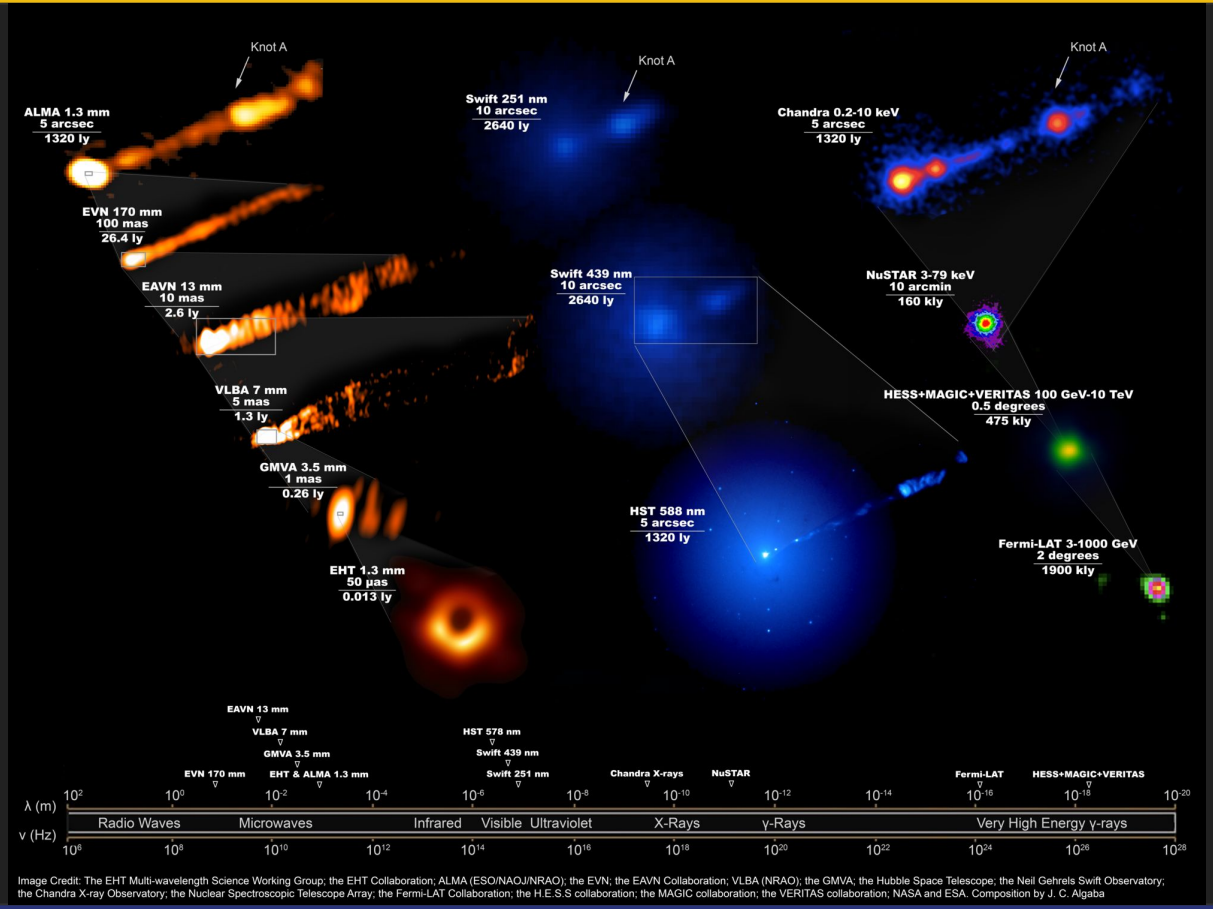
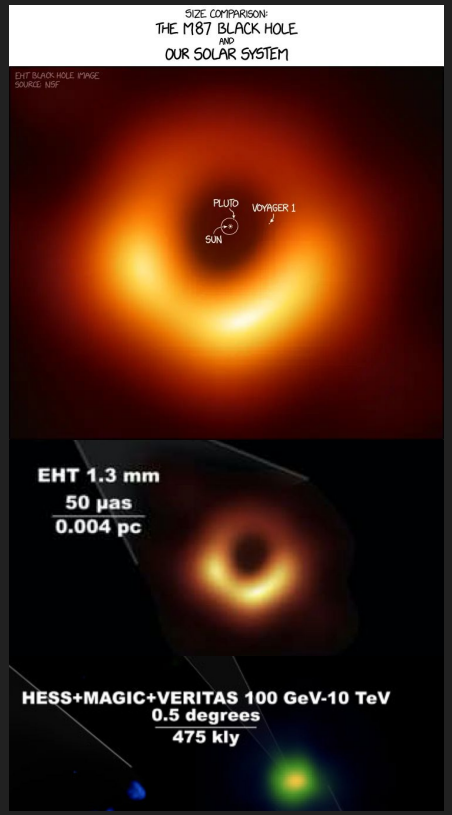


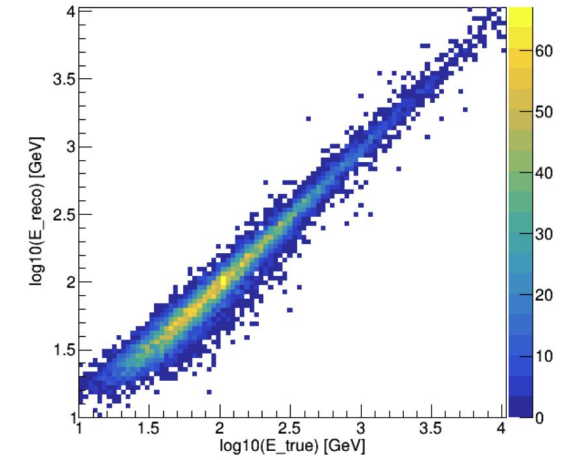
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

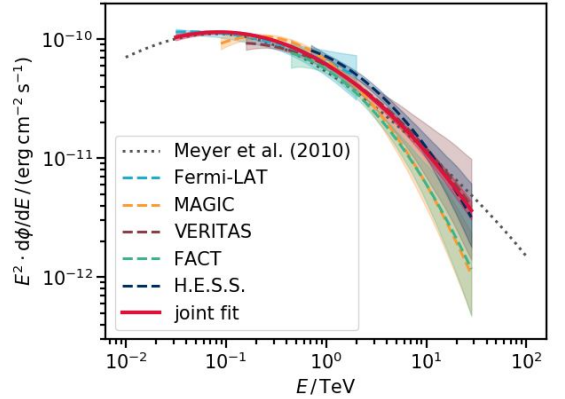


1 degree = 3,600,000,000 μas

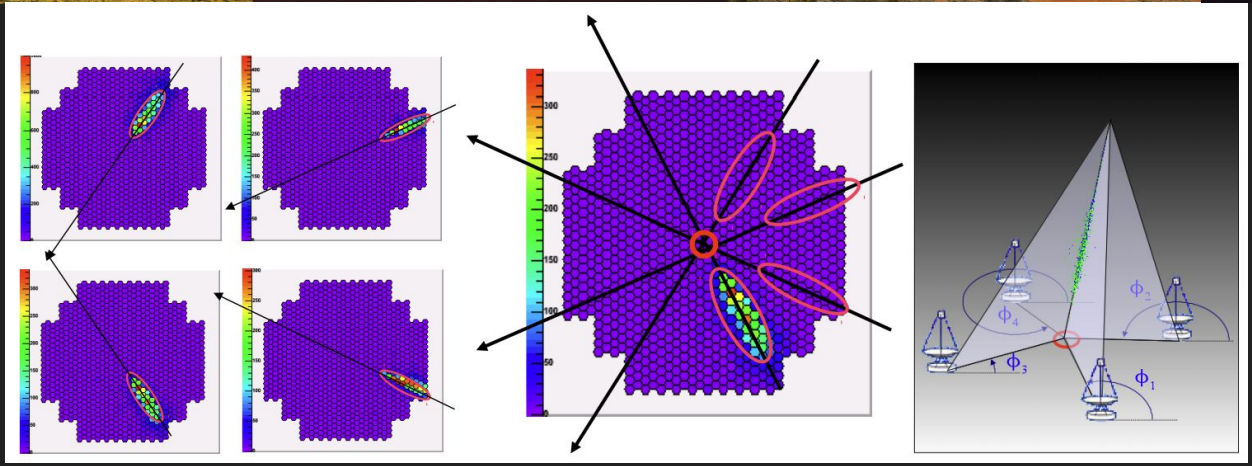
Cherenkov Technique: Energy Reconstruction

- ★ Based on simulation
- ★ Several methods:
  - Lookup table (Energy ~ number of photons)
  - Template (Energy ~ shower image)
  - Other fancy ML techniques (Random Forest, Boosted Decision Tree, CNN)
- ★ Obtain flux and spectral energy distribution as a function of energy
- ★ High systematic uncertainty (~10%)

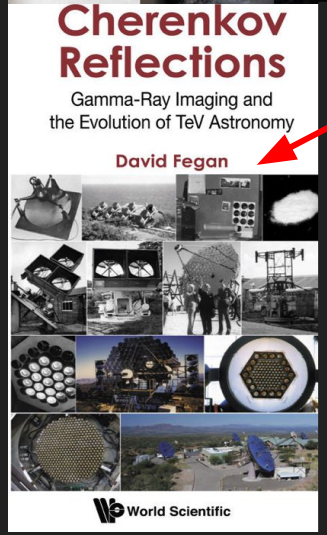




Cherenkov Technique: current-generation telescopes



Quo vadis - Whither goest thou?



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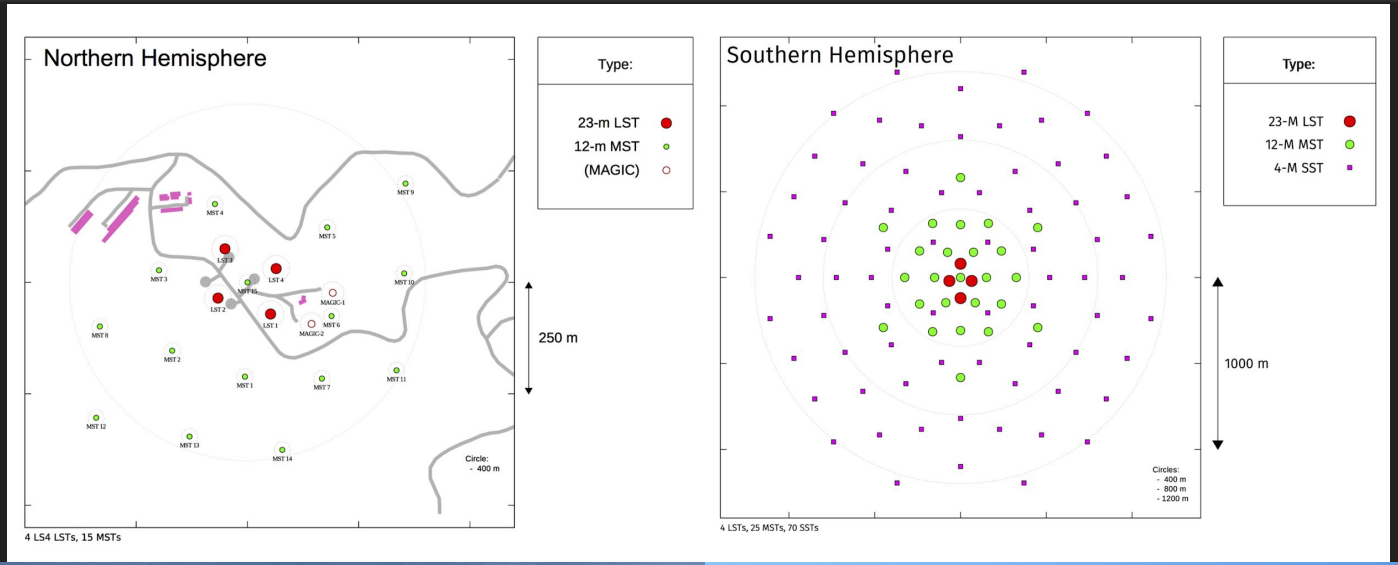
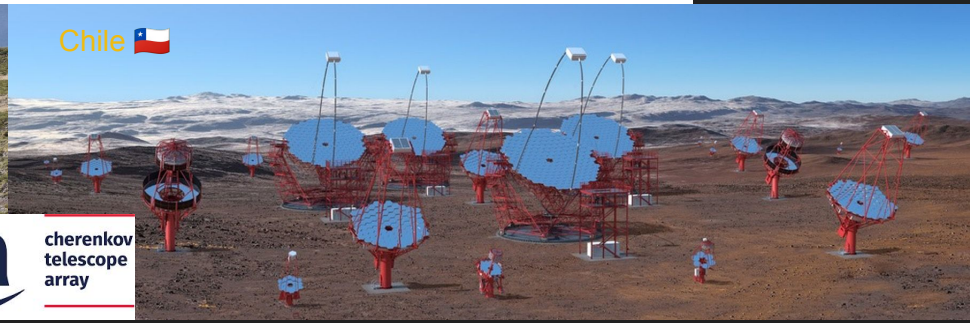
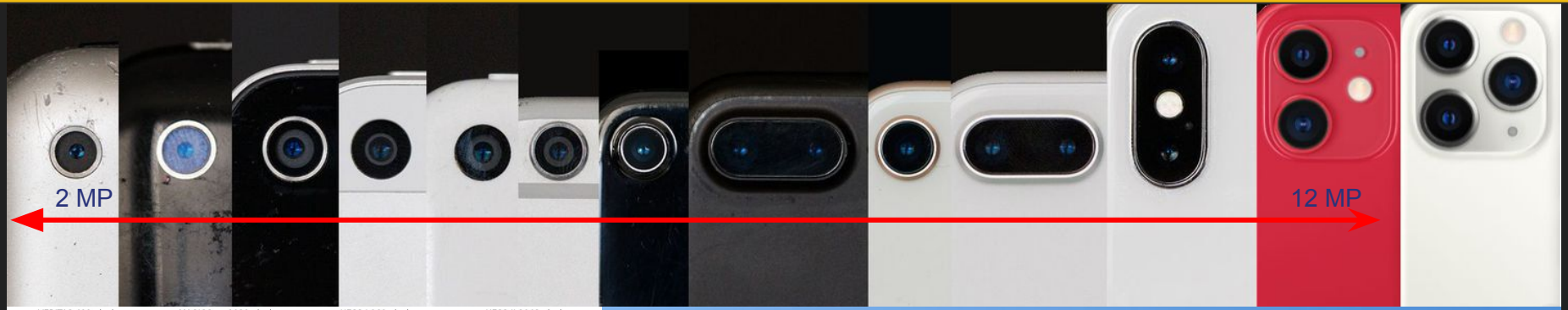
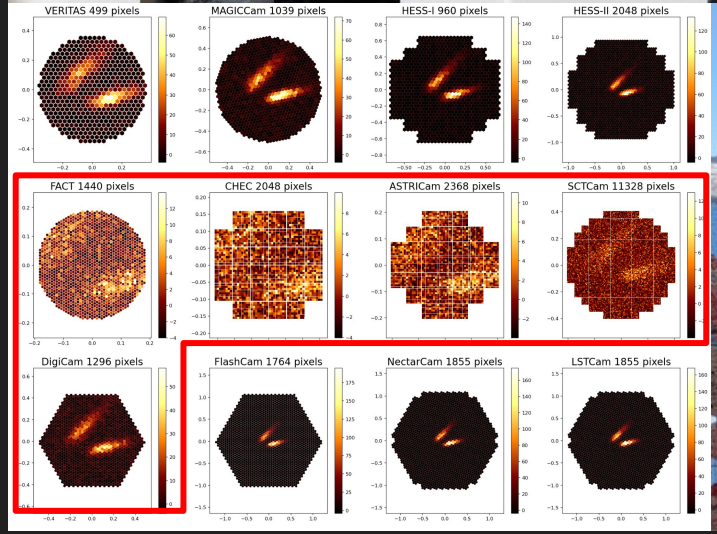


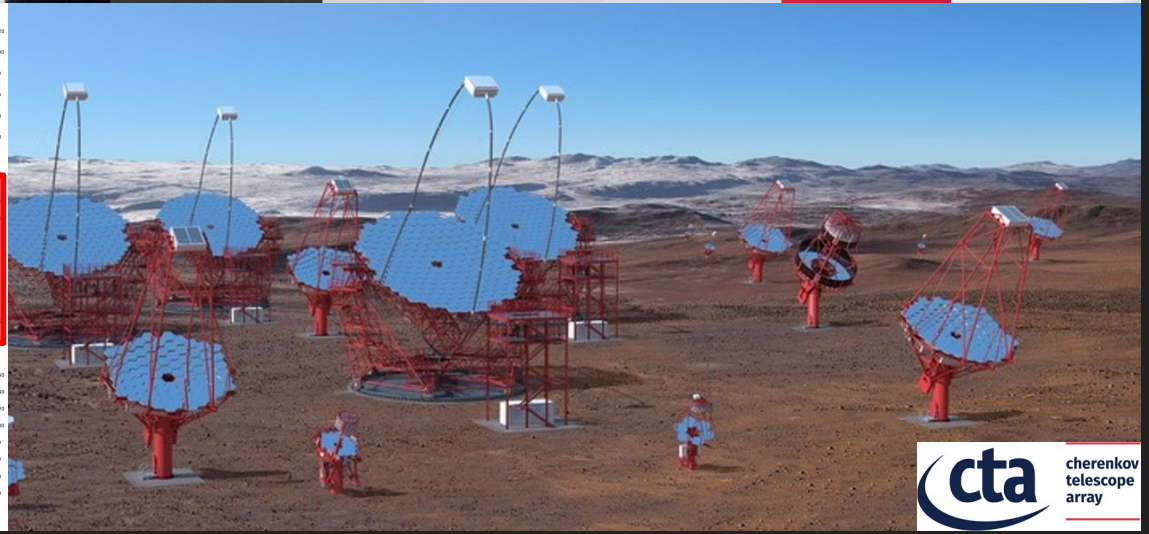


cta cherenkov telescope array

Quo vadis - Whither goest thou?

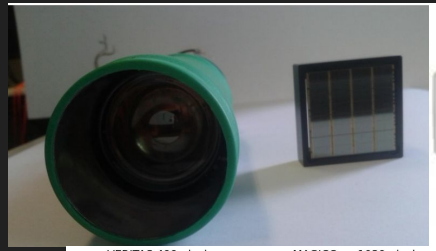




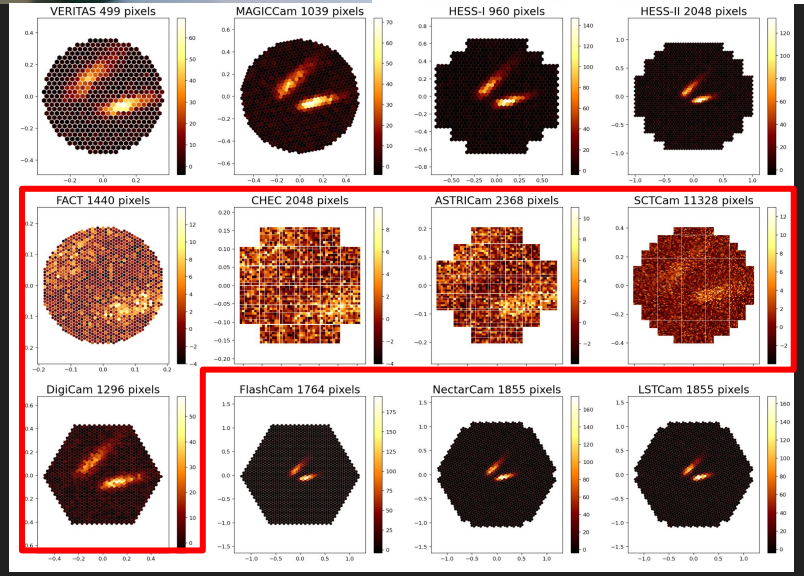


Quo vadis - Whither goest thou?

PMT vs SiPM



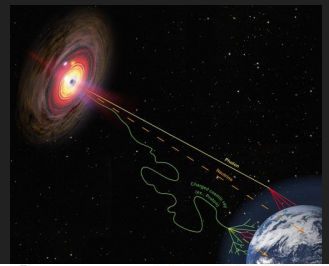
CRT vs LCD

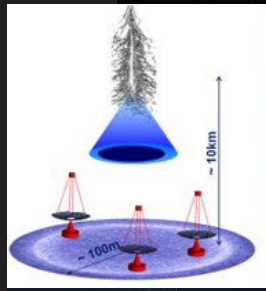


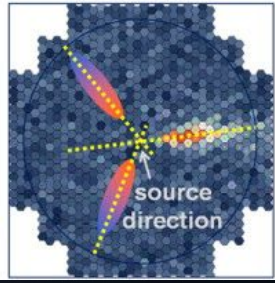
- ★ Some large cameras still use PMTs:
  - Improved detection efficiency
  - Higher pixel density
  - Plans to migrate to next-gen SiPM
- ★ Silicon PhotoMultiplier:
  - Silicon is relatively “cheap”
  - More compact and robust
  - Lower operating voltage
  - Higher pixel density
  - Comparable detection efficiency
  - Single-photon resolution

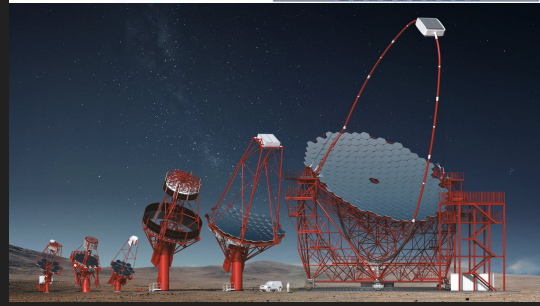
Cherenkov Telescopes are funky...

- ★ Look for energetic gamma-ray sources, indirectly:
  - Captures “images” of air-showers
  - Reconstructs source’s location based on orientation of images
  - Reconstructs energy spectra based on shape of images
- ★ Do not quite resemble conventional optical telescopes:
  - Final images are low-res, effectively point-source
  - Fast camera (PMT, ns-timescale) instead of CCD (second-timescale)
  - Large segmented mirrors, no dome, come in array



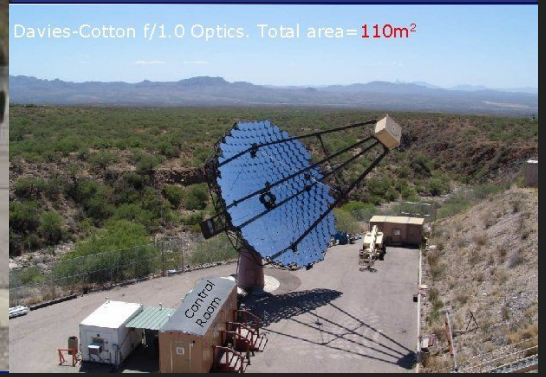






And can be a risky business (sometimes…)

How to vaporize a solid piece of steel in a few seconds



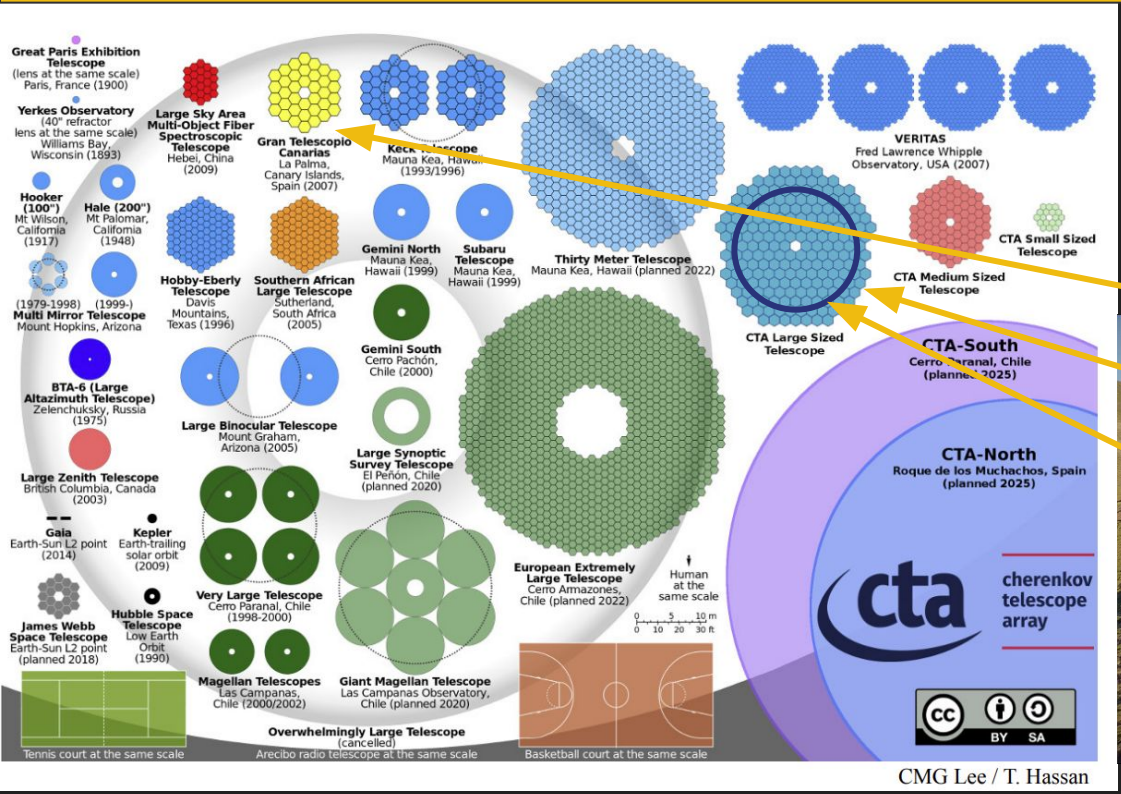
Florian Goebel

Born	18 October 1972 Cologne, Germany
Died	10 September 2008 (aged 35) La Palma, Spain

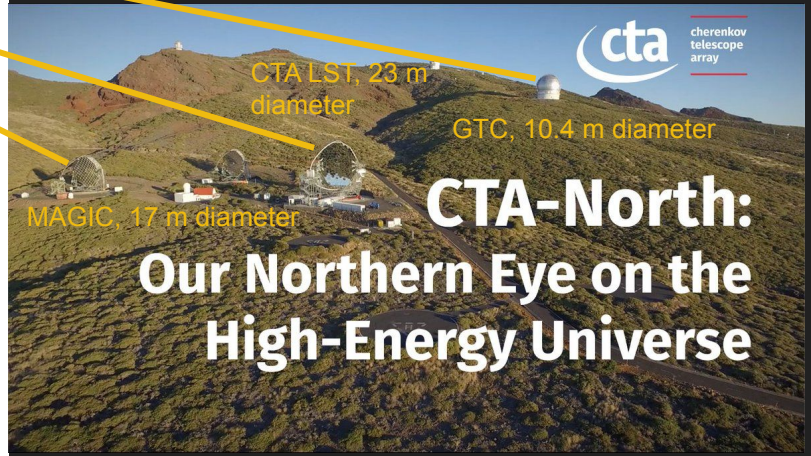
Pause for Q&A

Questions on Cherenkov Technique?

Cherenkov Telescopes are still optical telescopes



- ★ Modest mirror quality but large collecting area.
- ★ Effective "photon bucket".
- ★ Fast (ns) PMT as detector, vs. slow (ms) CCD in conventional optical telescopes.

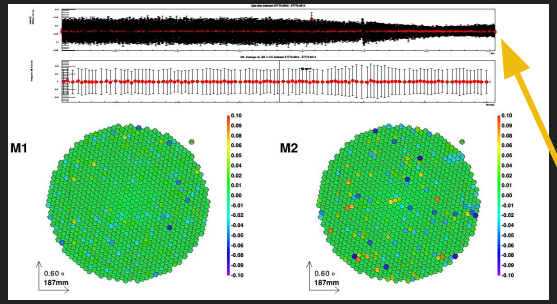


Mirror size of optical telescopes

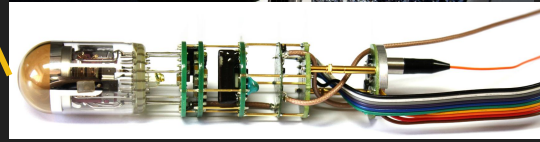
One-pixel telescope

- ★ First Cherenkov “telescope” in 1952:
  - A dustbin, a 25-cm parabolic mirror, a PMT, some simple electronics
- ★ Modified central sensors to read out <u>simultaneously</u> optical signal at 10 kHz rate (0.1º FoV):
  - Sensitive to sub-ms optical pulses (<u>continuous sampling</u> for optical observation)
- ★ PANOSETI module, with similar design:

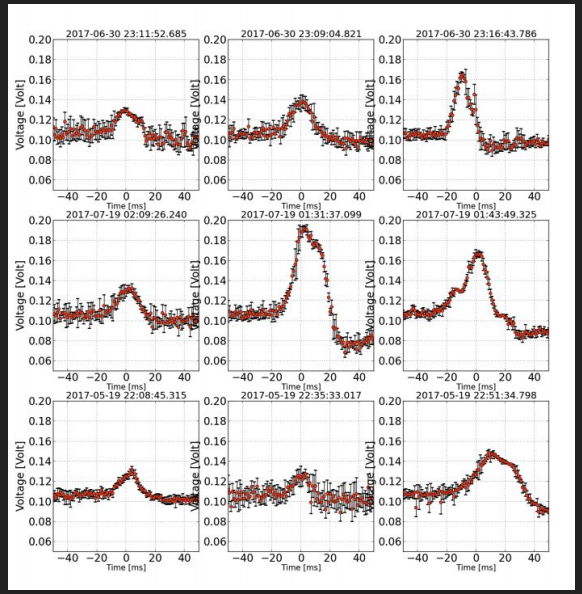
PANOSETI module



MAGIC CPix



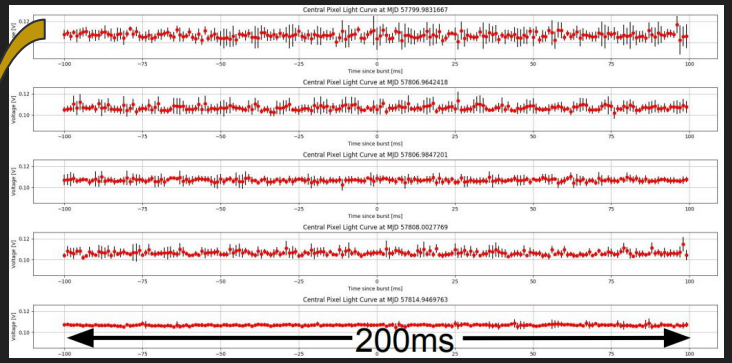
One-pixel telescope: meteors

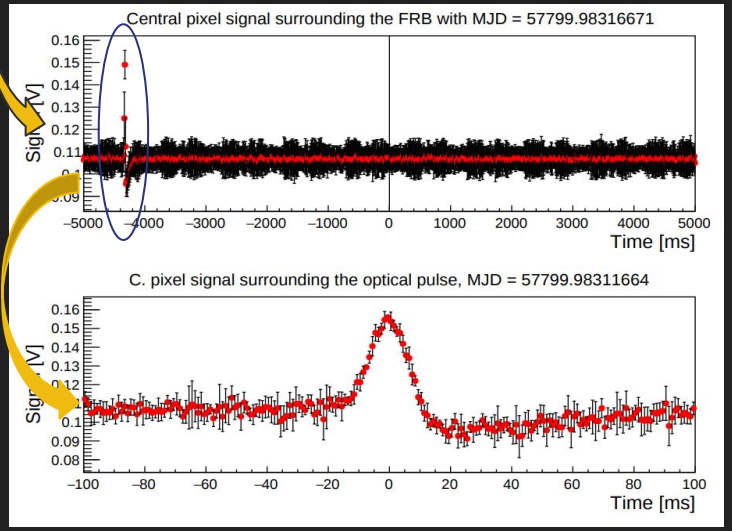


Some examples of bright isolated optical pulses due to meteors (MAGIC)

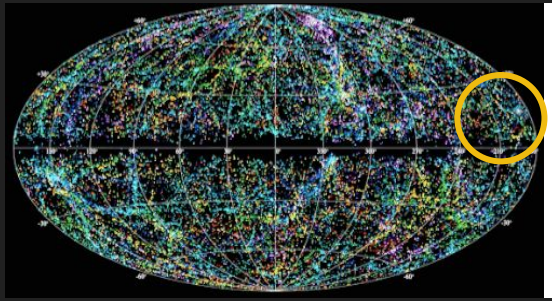
See Jim Davenport's talk

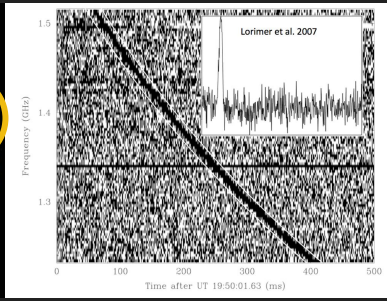
One-pixel telescope: Fast Radio Bursts



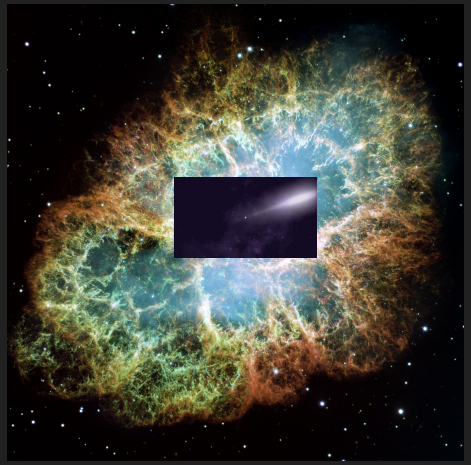


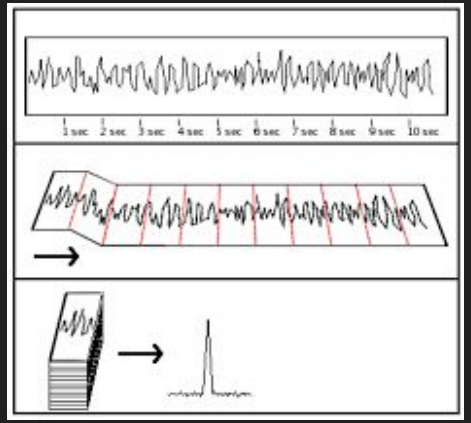
- ★ FRBs: transient radio events, bright and short
- ★ Unknown origin, tentative candidate: magnetar
- ★ FRB 121102: first repeating FRB
- ★ MAGIC observed in both optical and gamma-ray
- ★ An optical burst was detected ~4 seconds before the first radio burst, most likely a background event

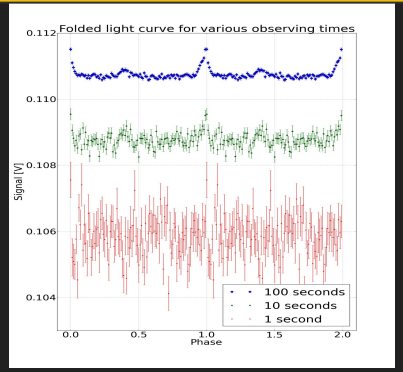


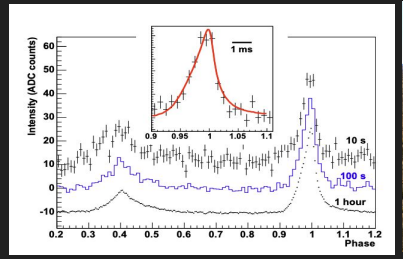


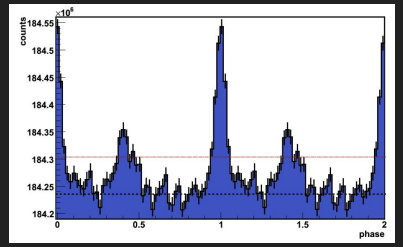
One-pixel telescope: optical pulsar



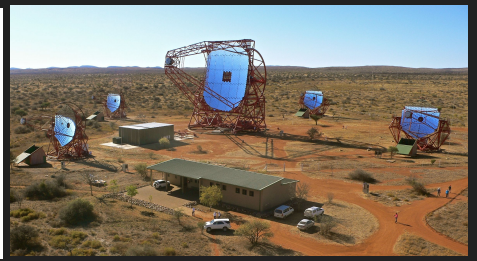








CPix on 17m MAGIC

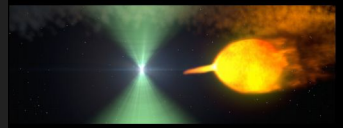
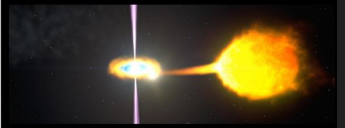


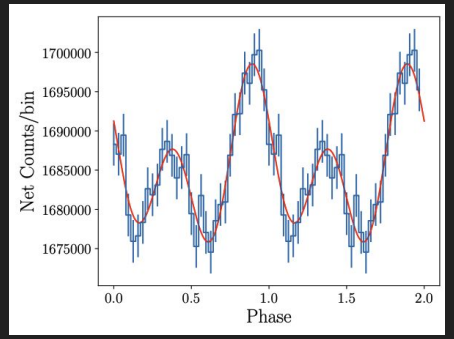
Optical pulsar camera (no longer used) on 12m H.E.S.S.-I

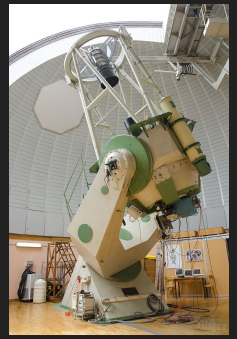
Current monitor on 12m VERITAS

One-pixel telescope: transitional millisecond pulsar

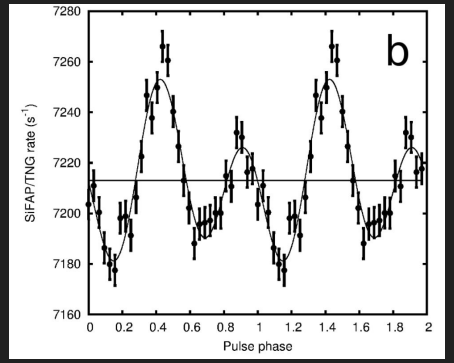
Optical pulsation from PSR J1023+0038 has been detected by several instruments

Radio Pulsar State	Intermediate Disc State
	
• Observed radio/gamma-ray pulsar. • Likely radio eclipses. • Lots of orbital timing noise. • Modulation of X-rays at orbital period (shock).	• No visible radio pulsar (off?). • Increased optical, X-ray, and gamma-ray brightness. • Double peaked optical emission lines. • Flat-spectrum radio continuum source (jet?). • No X-ray orbital modulation. • X-ray dropouts and flares.



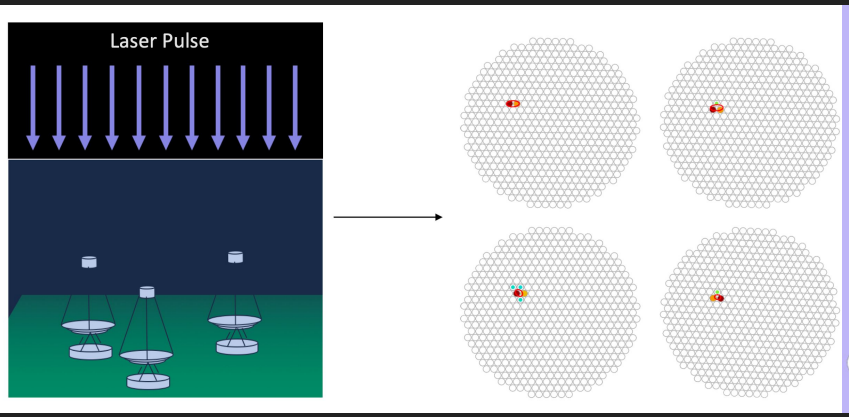


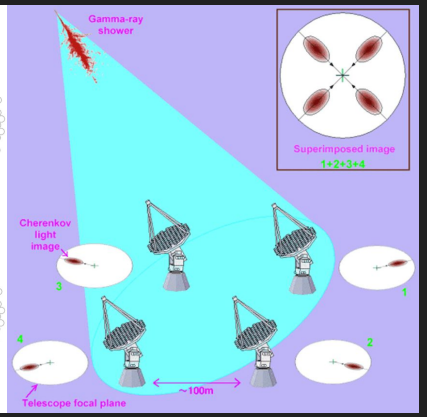
Aqueye+ on 1.8m Copernicus telescope Asiago



SiFAP2 on 3.58m TNG

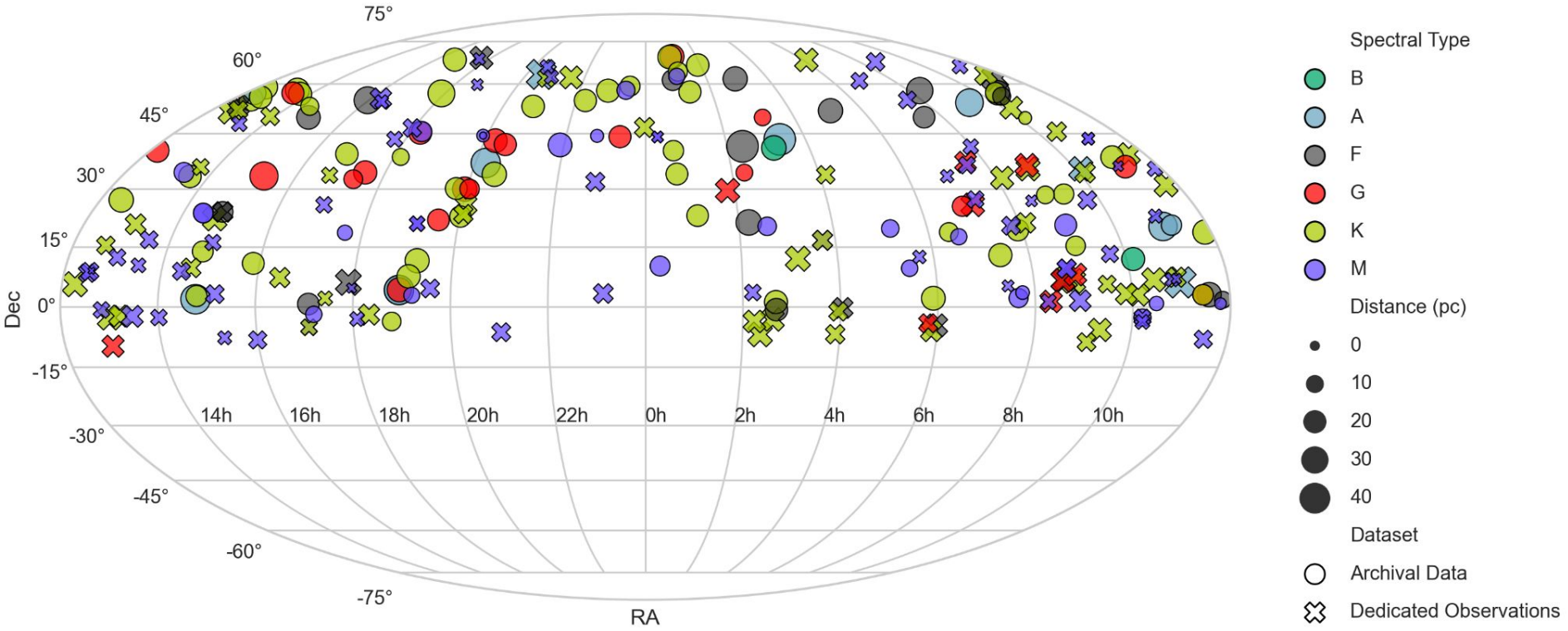
Many-pixel telescope: technosignature detection





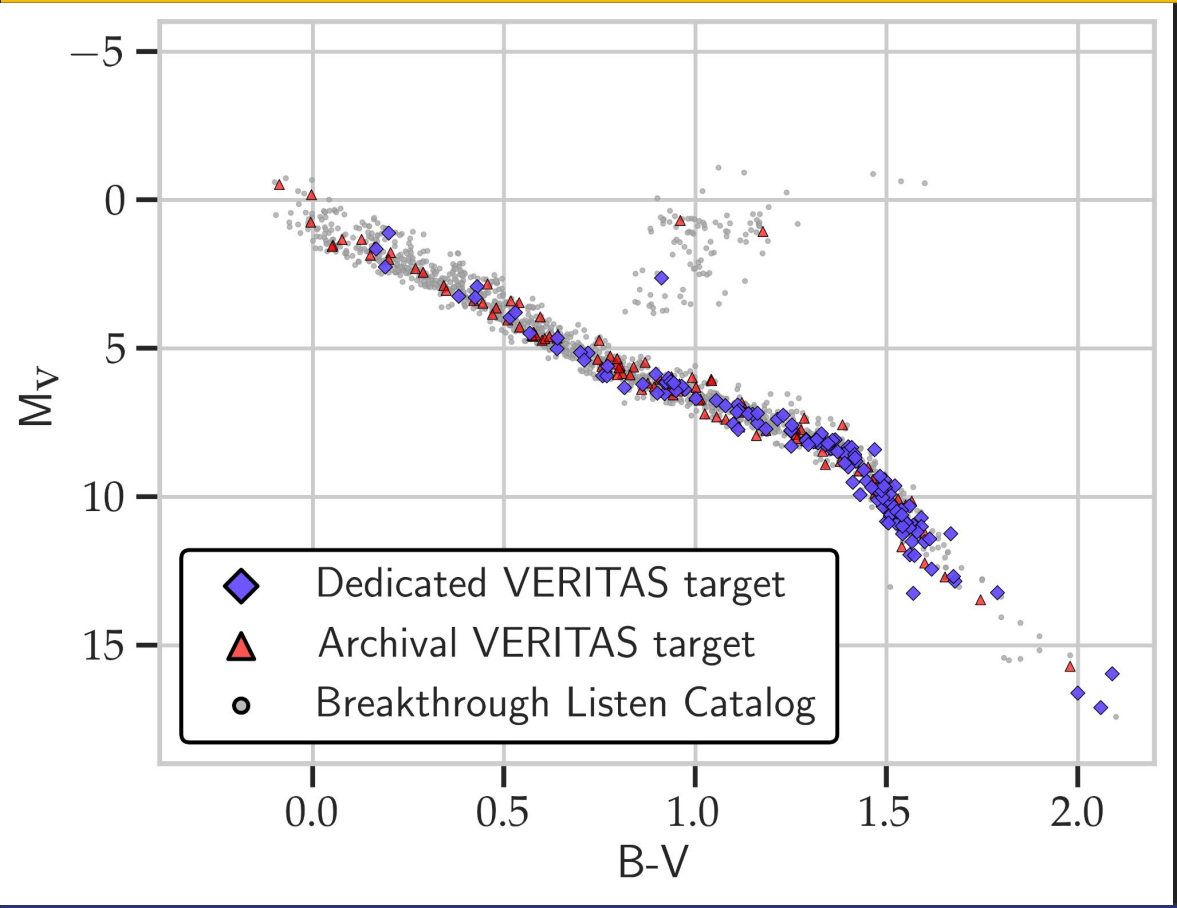
- ★ Laser pulses should appear point-like with equal intensity and in the same position in each camera.
- ★ Previous search for laser from KIC 8462852 (see arXiv: 1602.00987).

Many-pixel telescope: technosignatures search



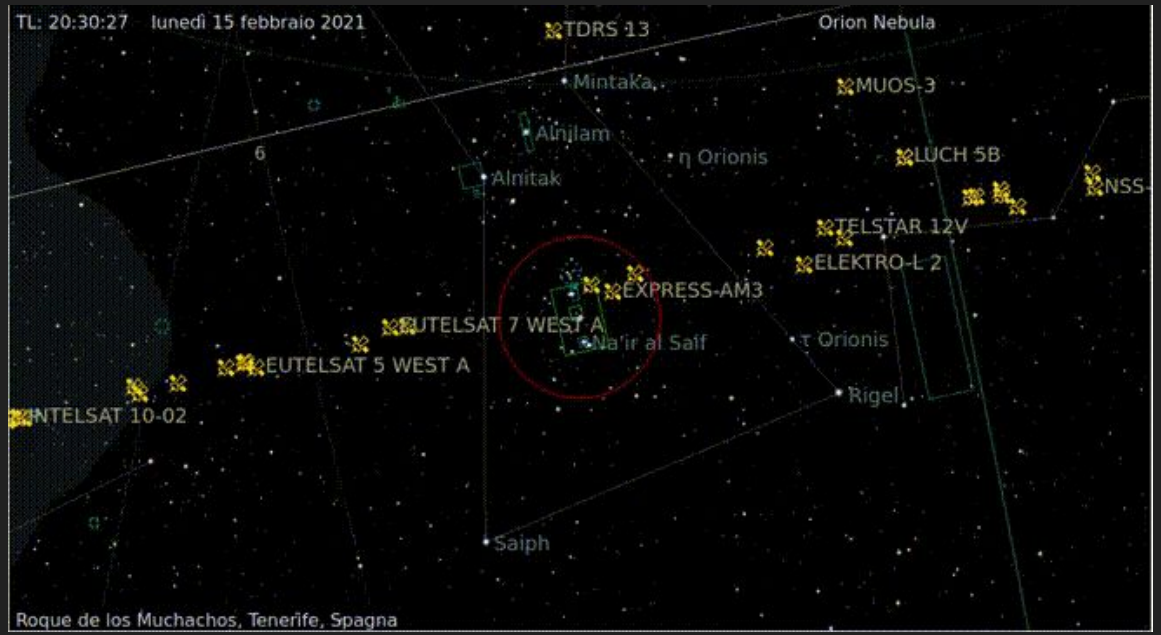
2019 - 2020 observational and archival campaign

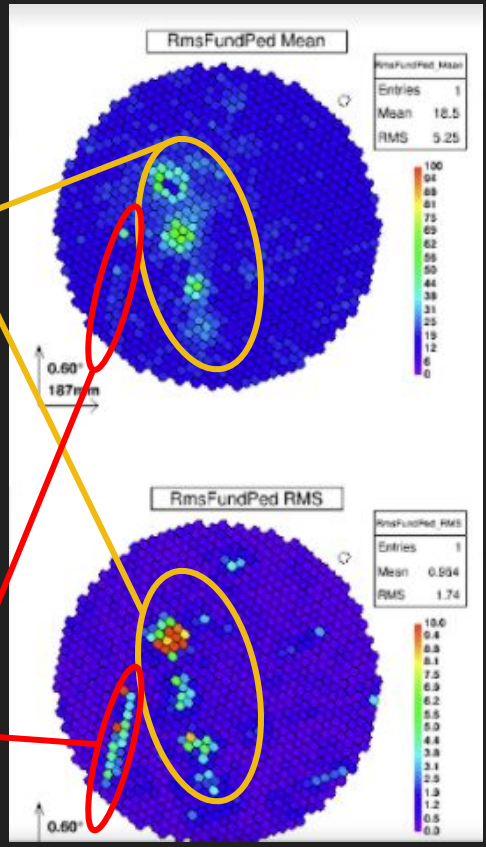
Many-pixel telescope: technosignatures search



Many-pixel telescope: technosignatures search

- ★ It's a jungle up there, really.
- ★ Sensitive enough to detect lidar laser from some satellites.
- ★ Some fantastic applications

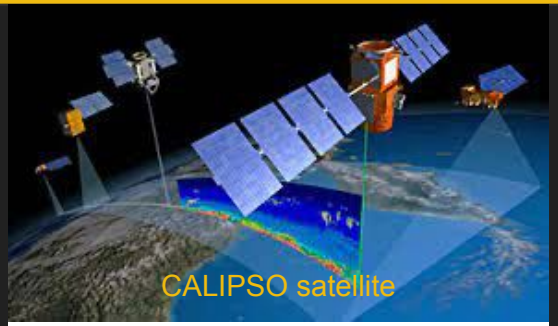


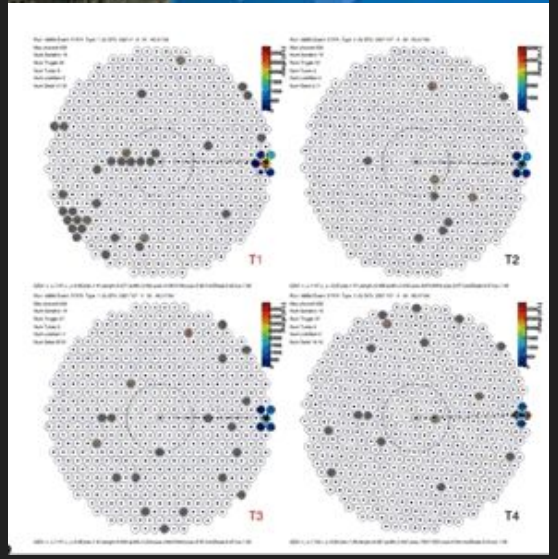


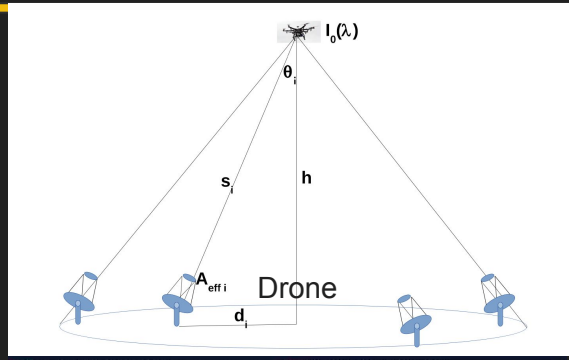
Nebulae

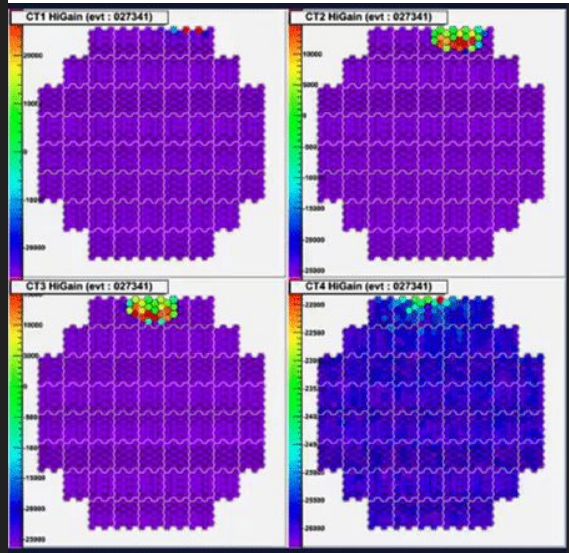
Satellite

Many-pixel telescope: technosignatures search

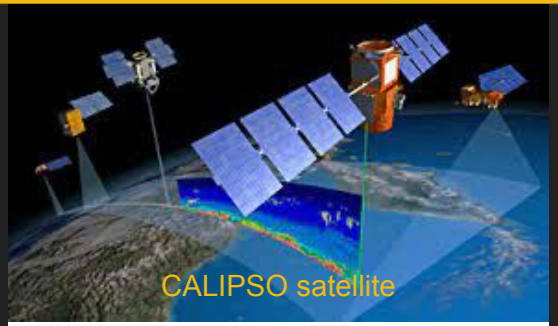


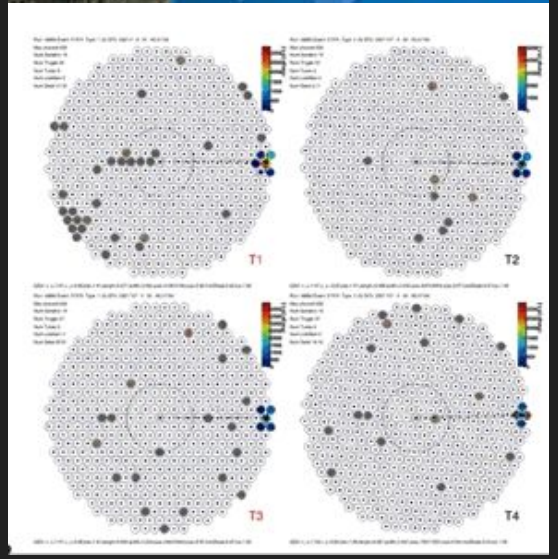


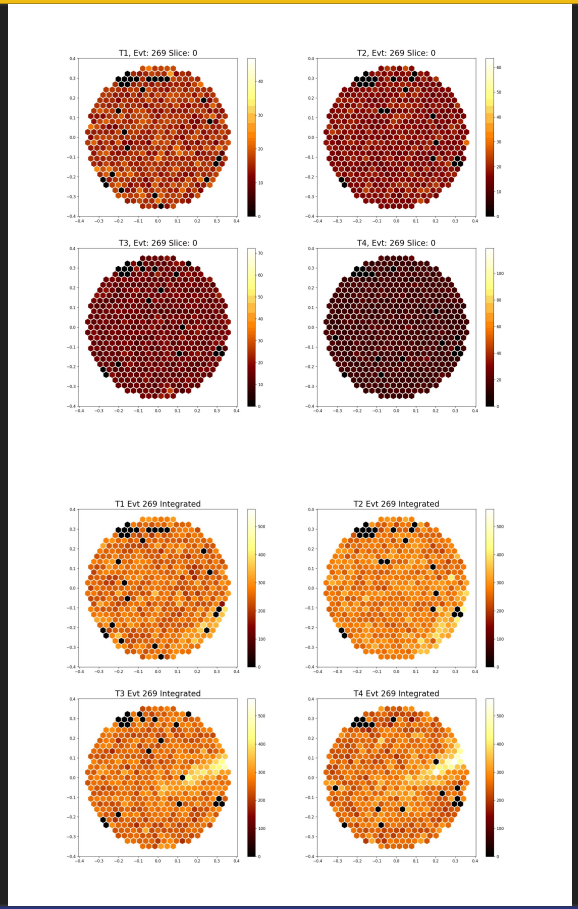




Many-pixel telescope: technosignatures search

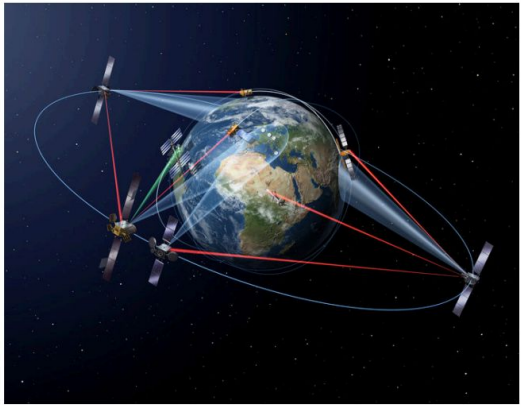


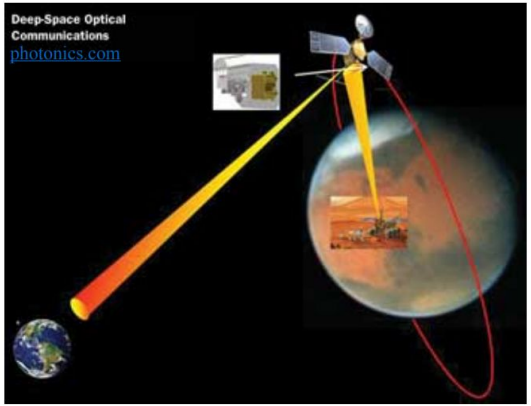




Many-pixel telescope: technosignatures detection

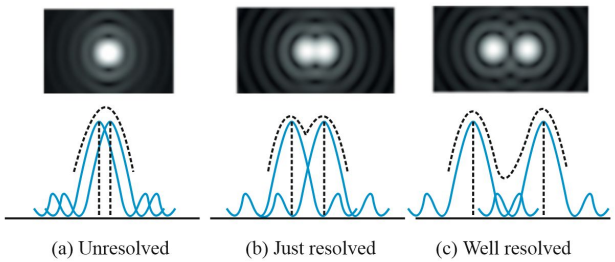
- ★ Optical tracking of orbiting objects
- ★ Optical Wireless Communication
- ★ Secure Quantum Communication





Many-telescope telescopes: angular resolution limit

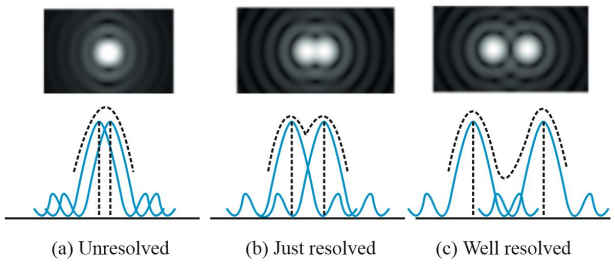
$$\theta = 1.22\frac{\lambda}{D}$$



Rayleigh's criterion for resolution of objects.

Many-telescope telescopes: angular resolution limit

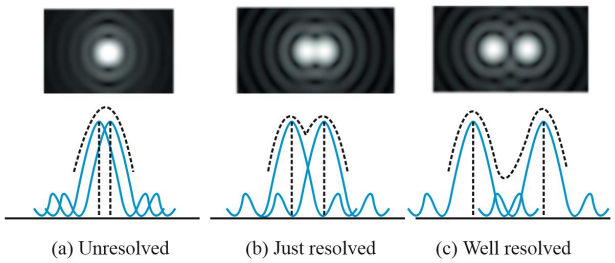
$$\theta = 1.22\frac{\lambda}{D}$$



Rayleigh's criterion for resolution of objects.

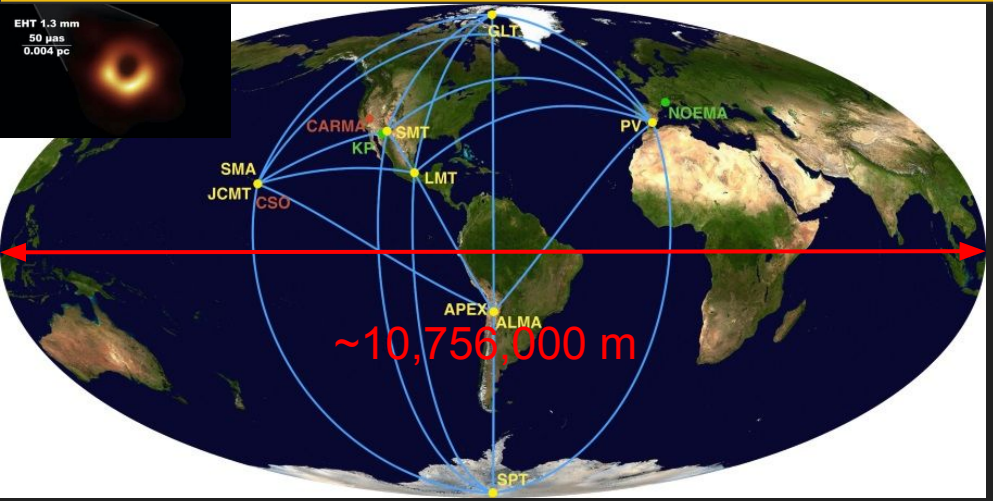
Many-telescope telescopes: optical interferometry

$$\theta = 1.22\frac{\lambda_{mm}}{D}$$

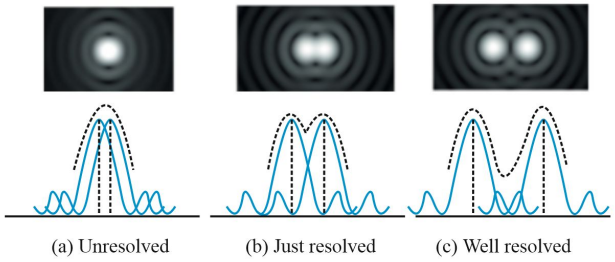


Rayleigh's criterion for resolution of objects.

Many-telescope telescopes: optical interferometry

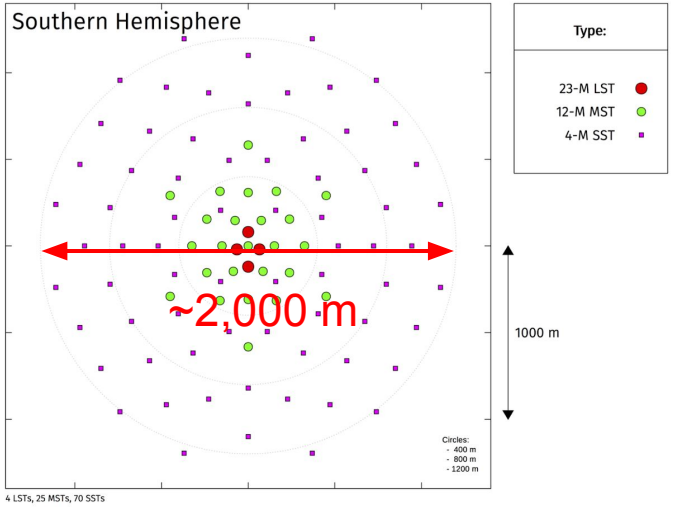


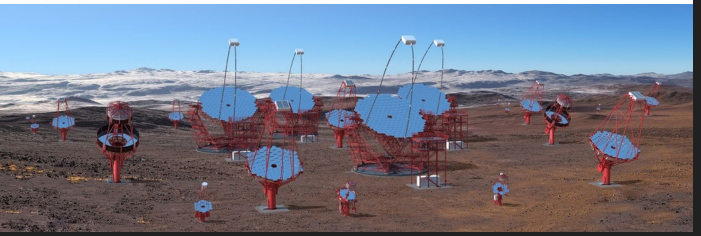
$$\theta = 1.22\frac{\lambda_{mm}}{D}$$



Rayleigh's criterion for resolution of objects.

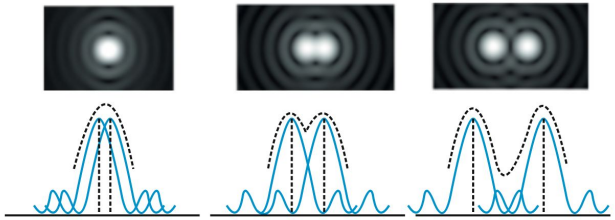
Many-telescope telescopes: optical interferometry





1mm ~ 2200 x 450 nm

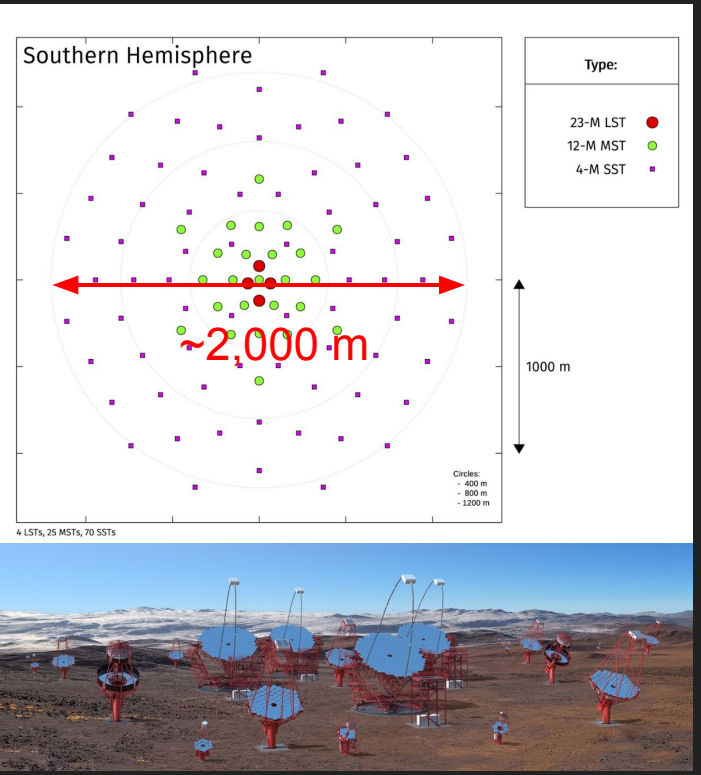
$$\theta = 1.22\frac{\lambda_{nm}}{D}$$

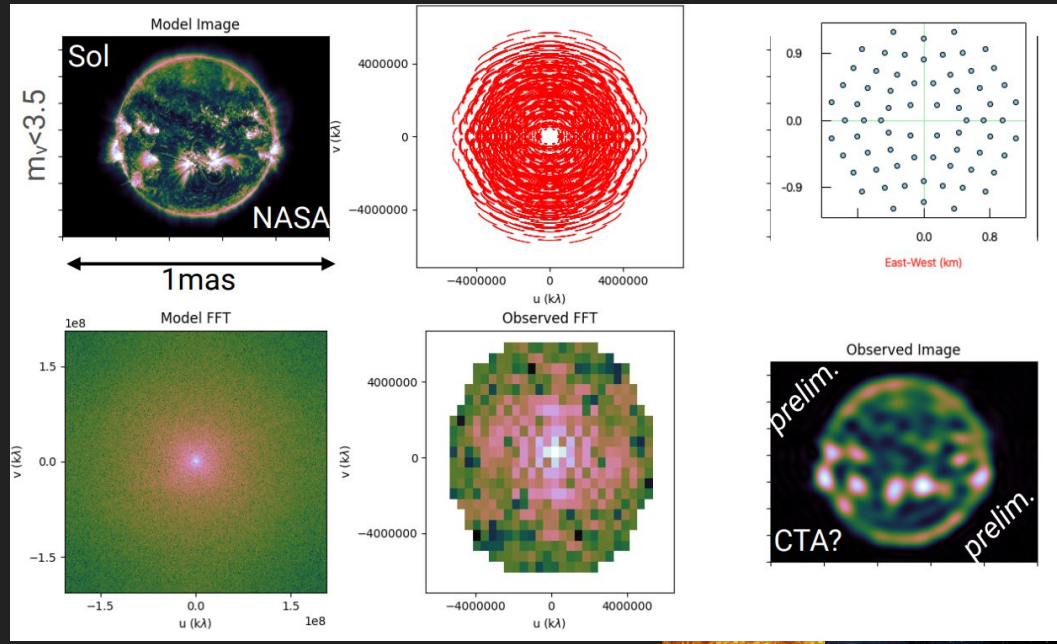


(a) Unresolved (b) Just resolved (c) Well resolved

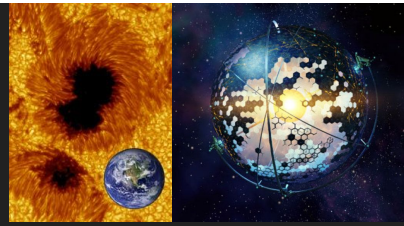
Rayleigh's criterion for resolution of objects.

Many-telescope telescopes: optical interferometry





- ★ Simulated 2h observation with CTA-South SSTs for a <1mas "solar-like" star
- ★ sub-mas resolution => New windows into SETI (exoplanet/Dyson sphere imaging)



Take-home messages

- ★ Cherenkov telescopes are unconventional:
  - Large optical dishes for gamma-ray astronomy
  - Capture airshower images to “measure” properties gamma-ray sources
  - Diverse range of targets
  - Applicable to OSETI & flying objects searches
- ★ Complementing “traditional” optical astronomy through multiple aspects:
  - Time-domain: from ns to ms and second
  - Multiwavelength: gamma and optical
  - Pixel => Telescope => Array
- ★ Large data volume, can benefit from ML techniques

Q&A

Thank you for your attention!

Cherenkov ring

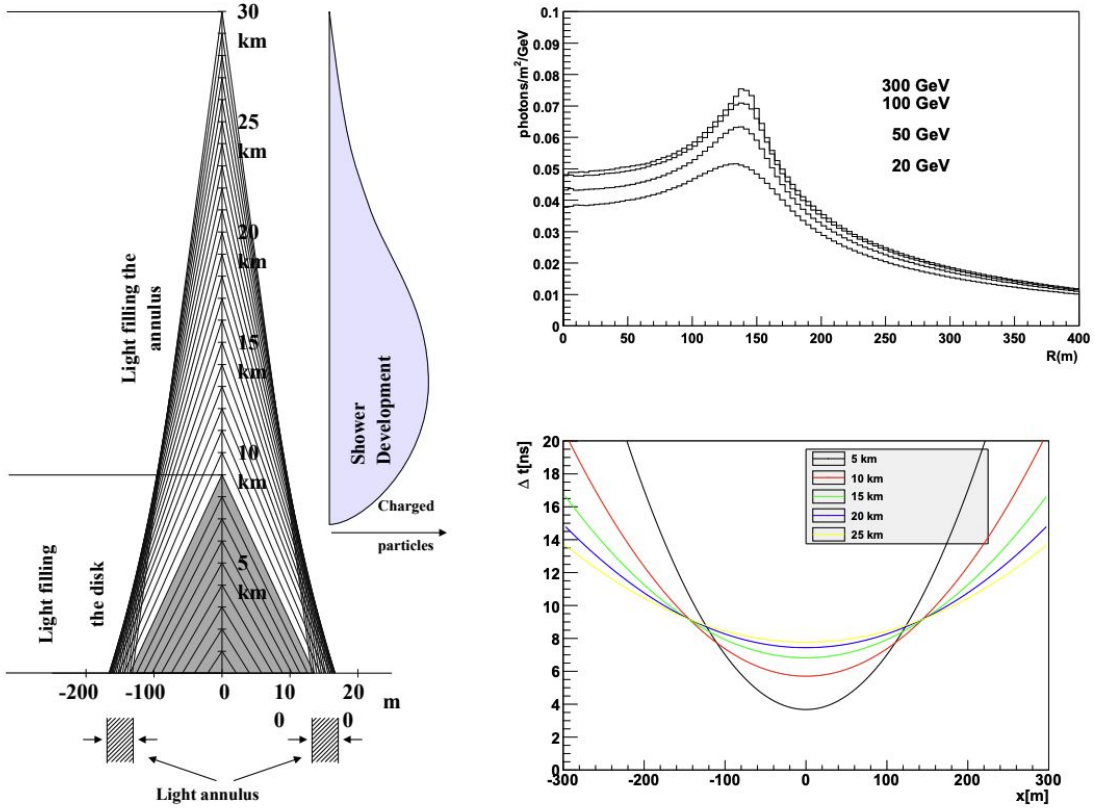
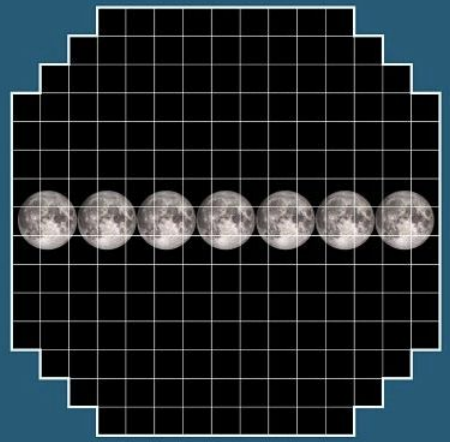
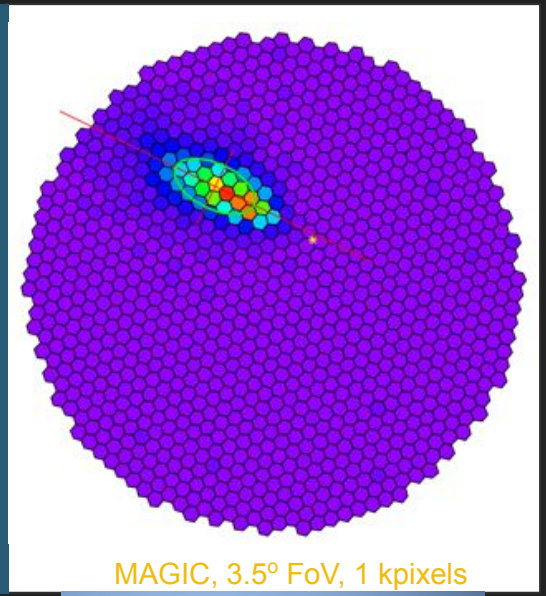


Figure 4. **Left:** Shower development. **Top Right:** Lateral profile of showers of different energies at sea level. **Bottom Right:** Time delay as function of lateral distance for various altitudes of emission.

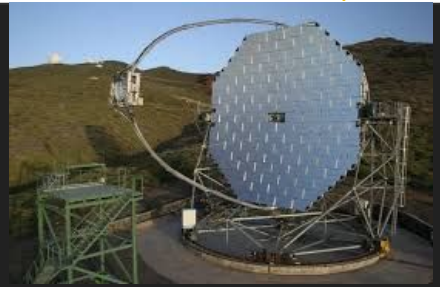
FoV comparison



LSST: 3.5° FoV, 3.2 Gpixels



MAGIC, 3.5° FoV, 1 kpixels

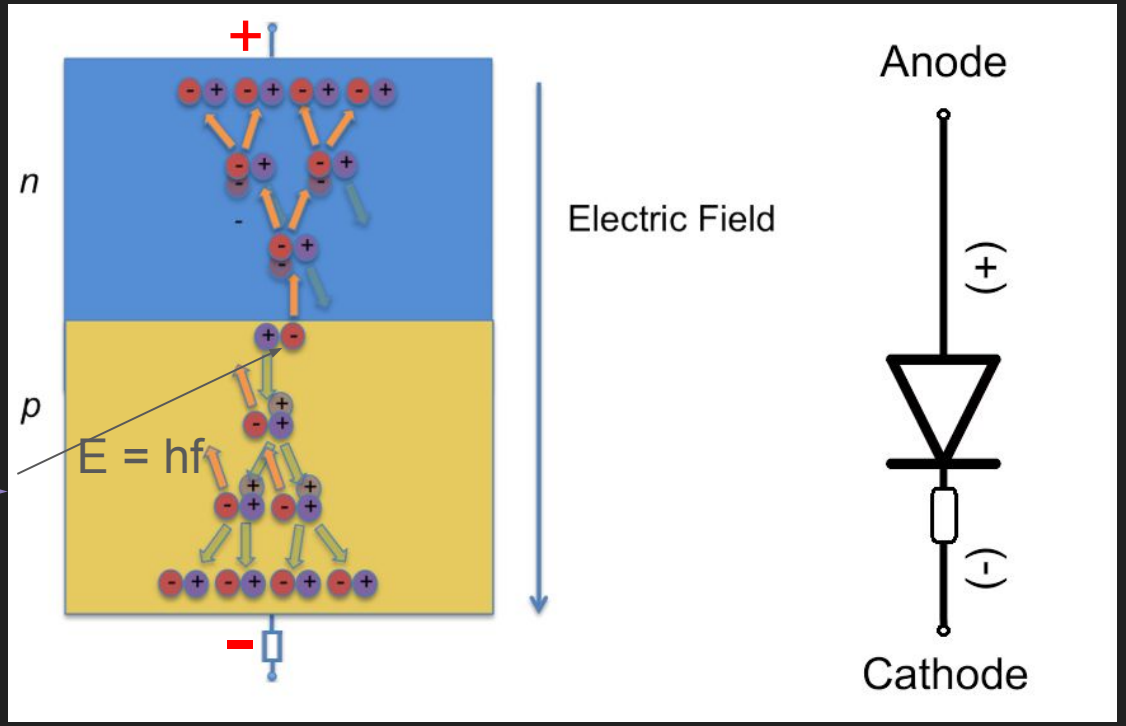


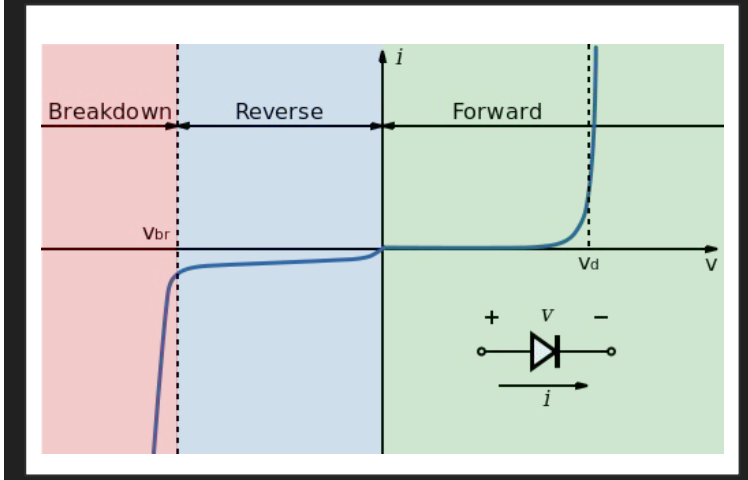
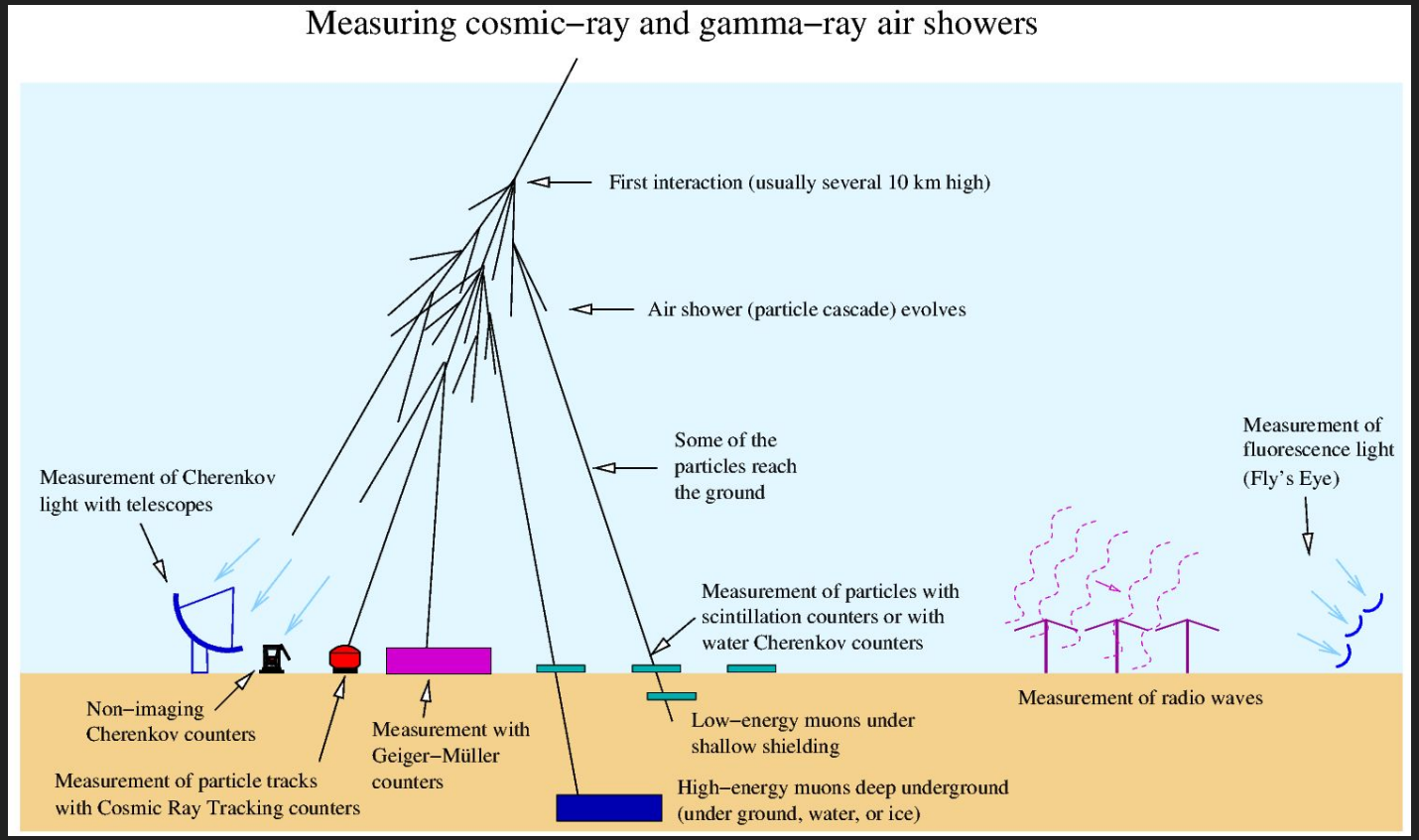
CTA Specs

	Large-Sized Telescope (LST)	Medium-Sized Telescope (MST)			Small-Sized Telescope (SST)
		FlashCam	NectarCam	SCT	
Required energy range	20 GeV – 3 TeV	80 GeV – 50 TeV			1 TeV – 300 TeV
Energy range (in which subsystem provides full system sensitivity)	20 GeV – 150 GeV	150 GeV – 5 TeV			5 TeV – 300 TeV
Number of telescopes	4 (South) 4 (North)	25 (South) 15 (North)			70 (South) 0 (North)
Optical design	Parabolic	Modified Davies-Cotton		Schwarzschild-Couder	Schwarzschild-Couder
Primary reflector diameter	23.0 m	11.5 m		9.7 m	4.3 m
Secondary reflector diameter	--	--		5.4 m	1.8 m
Effective mirror area (including shadowing)	370 m^2	88 m^2		41 m^2	8 m^2
Focal length	28 m	16 m		5.6 m	2.15 m
Total weight	103 t	82 t		80 t	19 t
Field of view	4.3 deg	7.5 deg	7.7 deg	7.6 deg	10.5 deg
Number of pixels in Cherenkov camera	1855	1764	1855	11328	2368
Pixel size (imaging)	0.1 deg	0.17 deg	0.17 deg	0.067 deg	0.19 deg
Photodetector type	PMT	PMT	PMT	SiPM	SiPM
Telescope readout event rate (before array trigger for MSTs and SSTs)	>7.0 kHz (after LST array trigger)	>6 kHz	>7.0 kHz	>3.5 kHz	>0.3 kHz
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s	12 Gb/s			2 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s	90 s			60 s
Pointing precision	<14 arcseconds	<7 arcseconds		<10 arcseconds	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees				

SiPM

$$V_{bias} = V_{breakdown} + V_{Overvoltage}$$





Backup: Other methods to detect airshowers