

# Optics & Mechanics

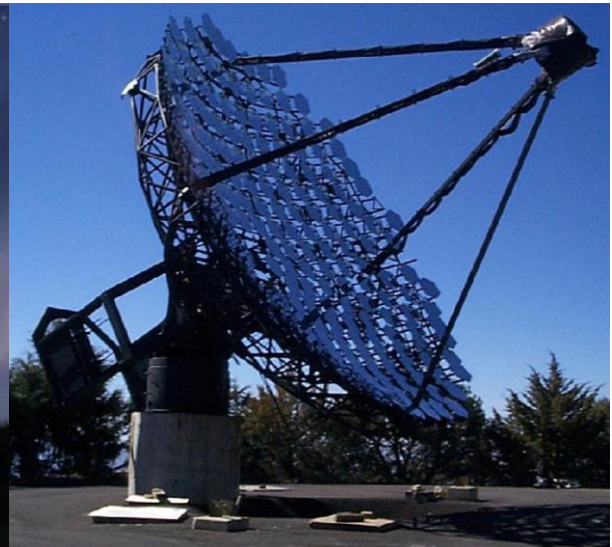


3rd CTAO School - La Palma

Martin Will

Bonus points for the first person who can tell me what's wrong in this image!

# Imaging Air Cherenkov Telescopes



# Imaging Air Cherenkov Telescopes

- In terms of hardware instrumentation, IACTs can be divided in three parts
  - Structure
  - Reflective Surface
  - Camera
- This does not contain all that is needed to have them operative, some other elements are
  - Auxiliary Systems
  - Control Software
  - Readout and Storage



# Imaging Air Cherenkov Telescopes

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# CTAO Sites & Requirements



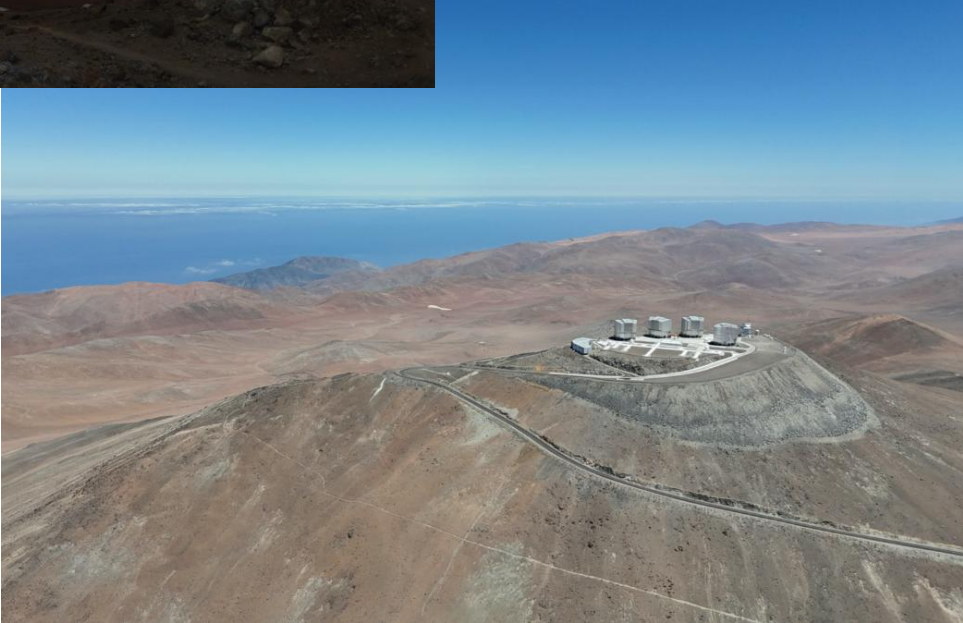
Of course we mostly care about the quality of the sky, the latitude and altitude of the site.

# CTAO Sites & Requirements



Observatorio Roque de los Muchachos, La Palma

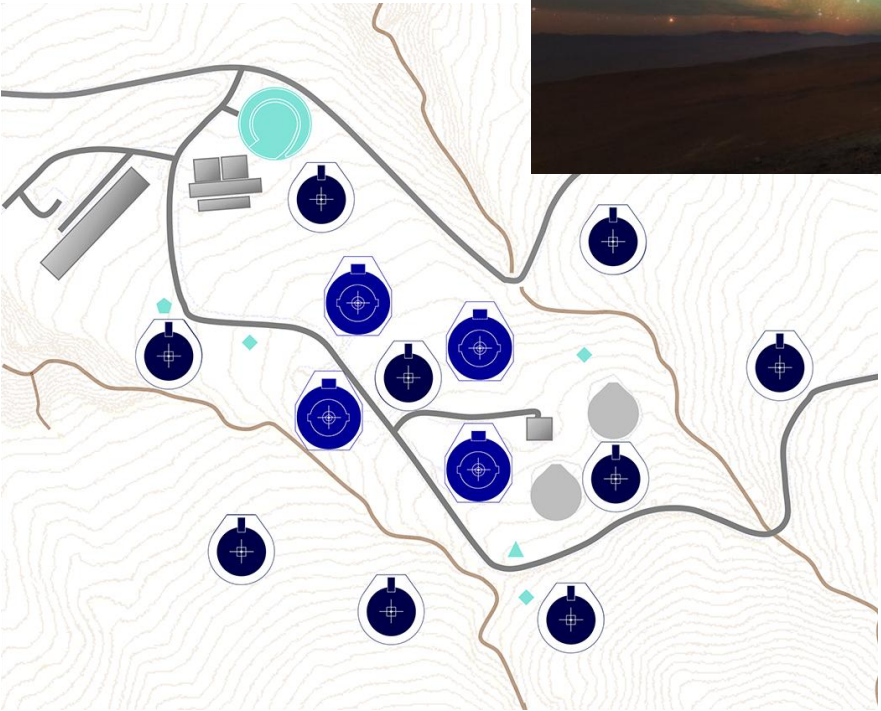
Paranal Observatory, Atacama Desert, Chile



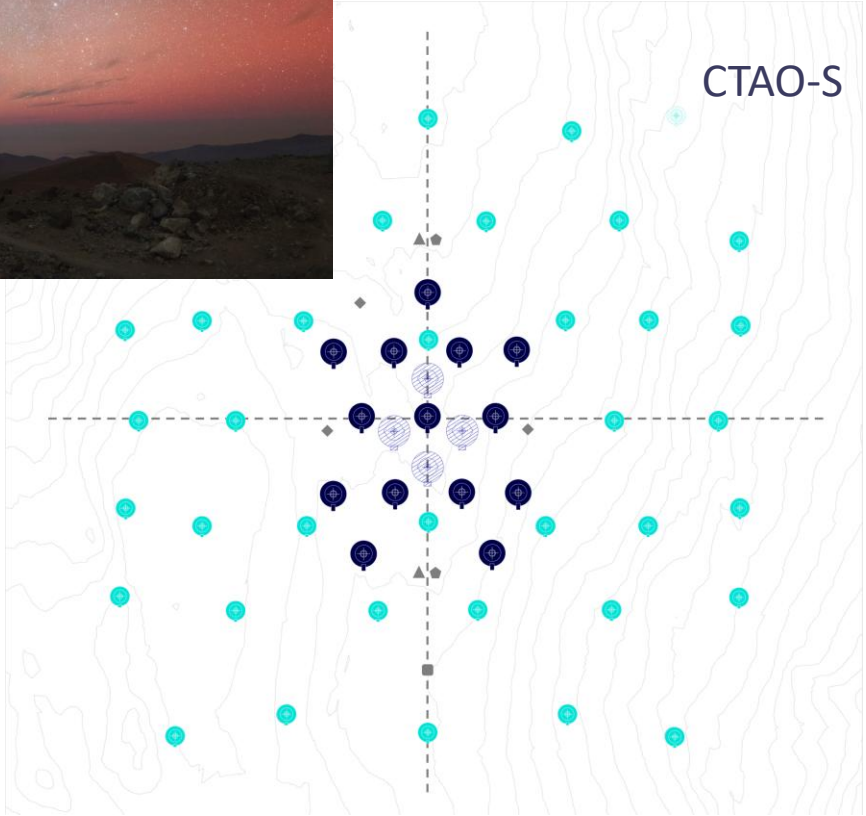
# CTAO Sites & Requirements



CTAO-N



CTAO-S



Ideally we design telescopes that can be used on either site

# Questions

- What type of light are we measuring?
- How sensitive do we need to be to faint light?
- How many events are arriving?
- What size are some of the objects?
- How short-lived are some of the objects?
- How far away are the sources of the light we are resolving?
- Where are we building the telescopes?
- How much money do we have?

# Questions → Requirements

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- How sensitive do we need to be to faint light?

just covering structure and optics here...

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- How much money do we have?

just covering structure and optics here...

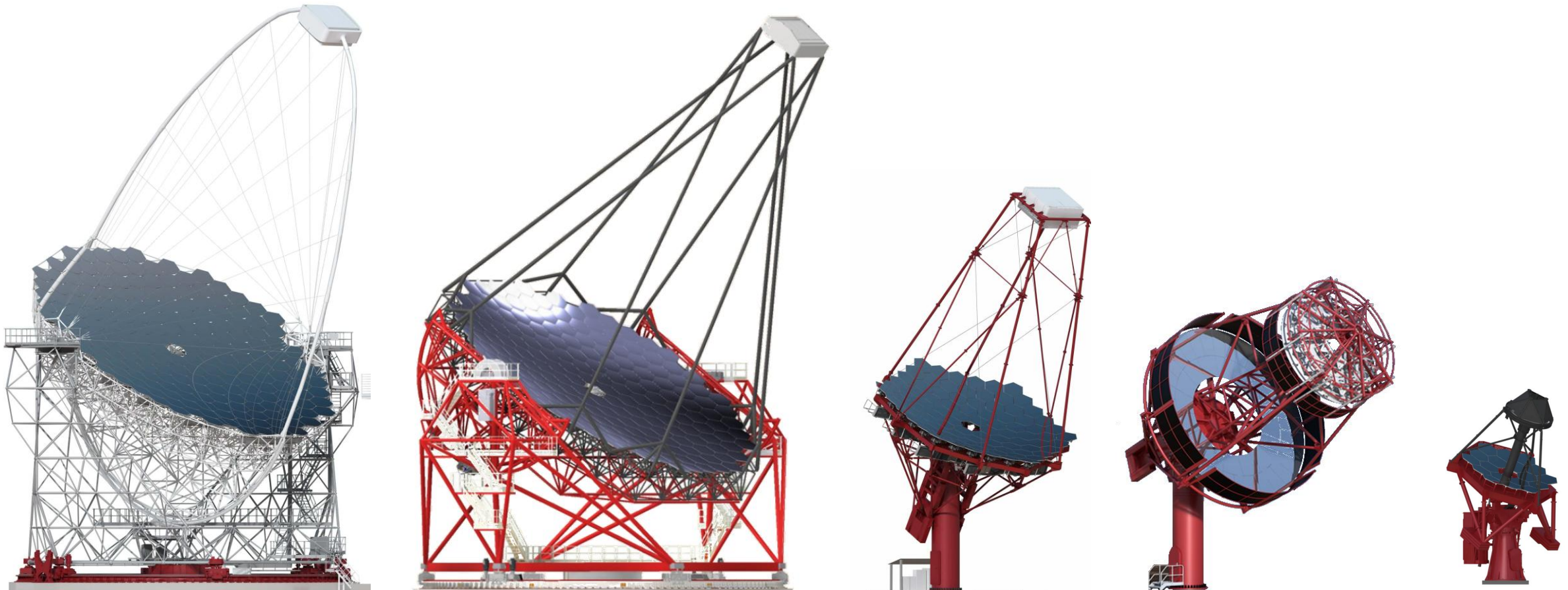
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- Where are we building the telescopes? → Temperature and Humidity Range
- How much money do we have? → Telescope Color (and of course everything else!)

just covering structure and optics here...

# CTAO Telescopes

At the end of this lecture, I hope you will understand why our telescopes look like this!



- 1 Basic Concepts
- 2 Structure
- 3 Optics
- 4 Calibration
- 5 CTAO Telescopes



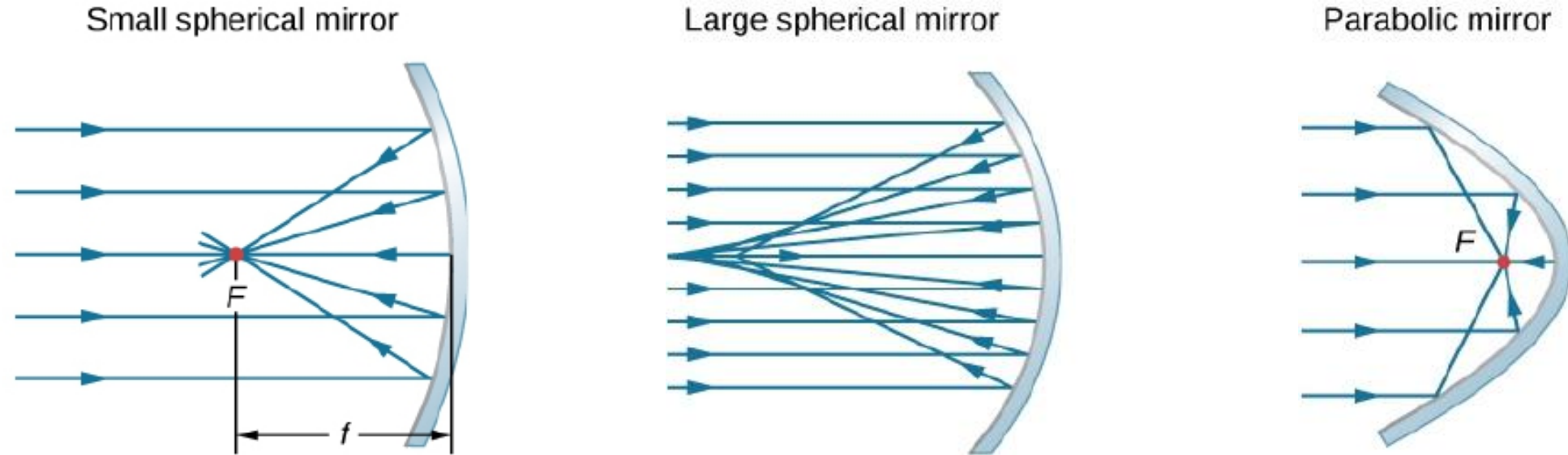
# 1 Basic Concepts

# Angular resolution

- Several concepts in this section are more relevant for optical telescopes but still good to understand.
- Angular resolution is the ability to resolve two nearby objects
- Related to the ability to image large, complex objects
- Influenced by several factors
  - Aberrations
  - Atmospheric turbulence
  - etc...



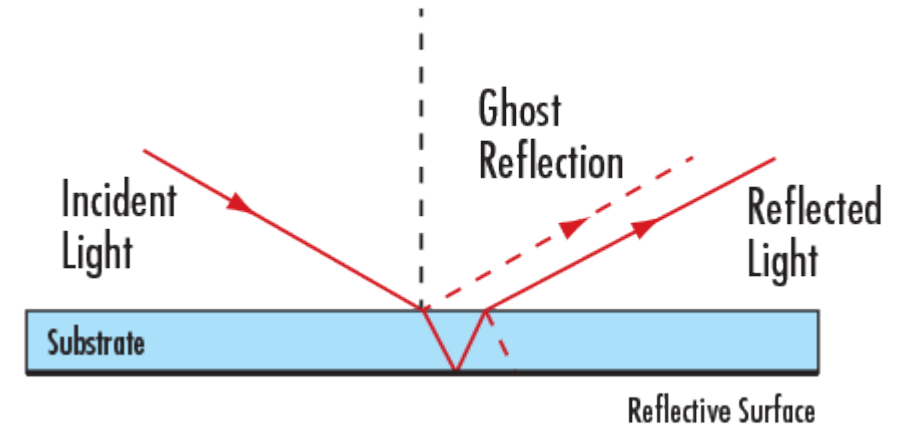
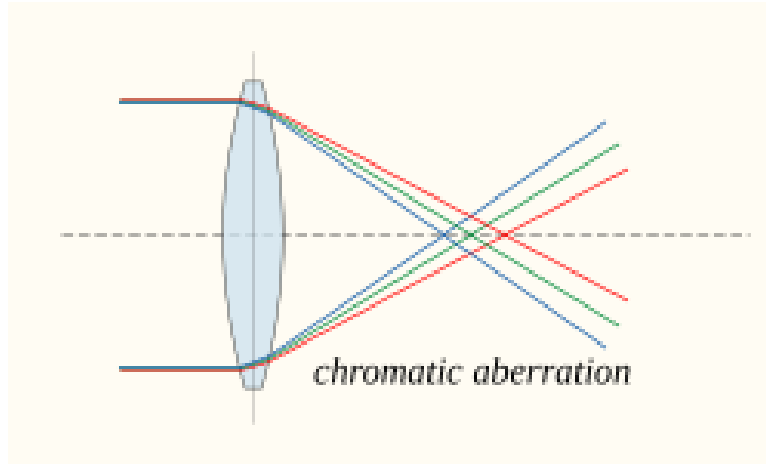
# Spherical Aberration



- In theory, all parallel rays go to the same point (focal point).  
In reality, rays cross at different points depending on radial distance.  
This is called spherical aberration: the image of parallel rays is a finite spot.
- Can be avoided by using a parabolic mirrors instead of a spherical mirrors.

# Chromatic aberration

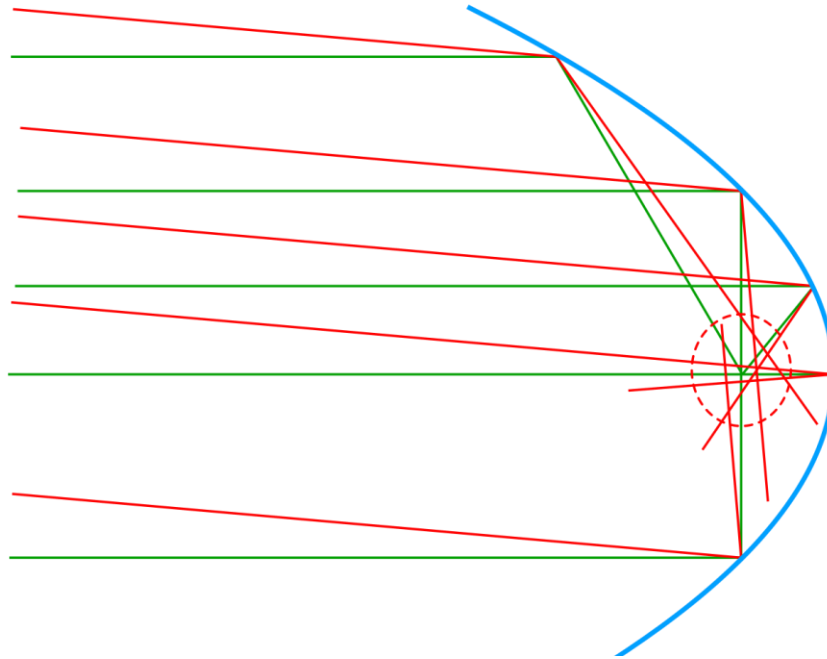
- Refractive index and therefore the focal length depends on the wavelength



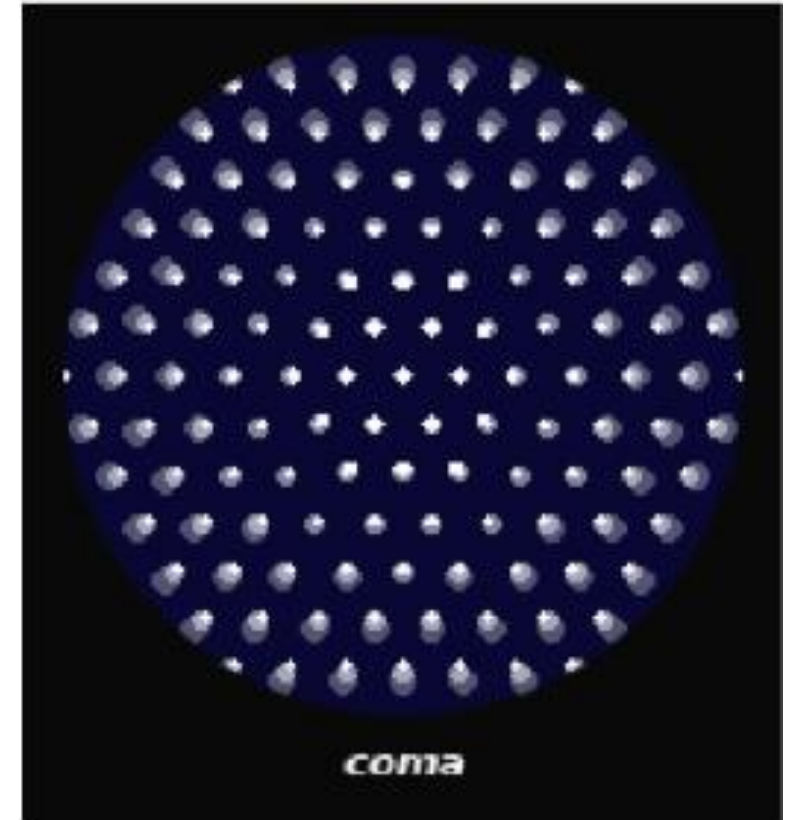
- “Reflectors typically don’t suffer from chromatic aberration”
  - The reflection will be wavelength dependent, but the reflected light of the different wavelengths will be centered on the same position.
  - It can become an issue at higher incidence angles, and it depends on the construction of the mirror.

# Coma Aberration

- Aberrations at larger angles with respect to the optical axis, increases with the angle.



Green rays parallel to optical axis converge at a focus.  
Red rays (parallel to each other but at an angle to the axis)  
intersect over a larger area (if at all)

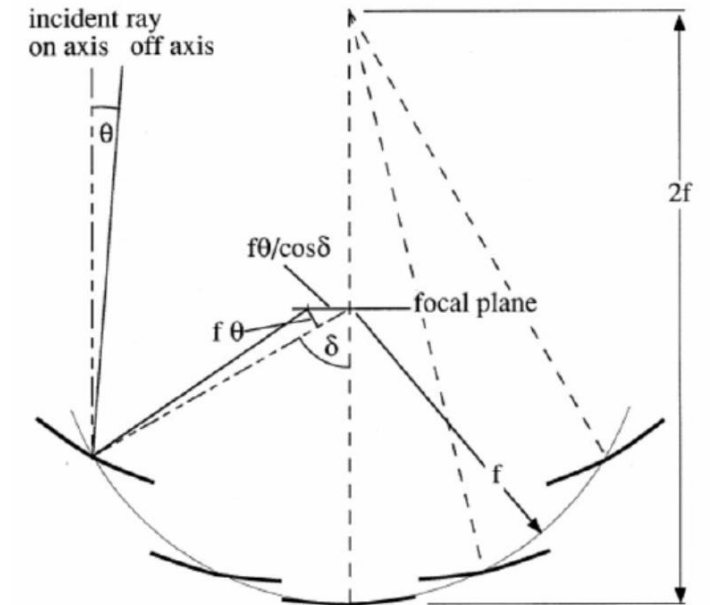


# Angular Resolution

- Other aberrations
  - Diffraction
  - Astigmatism
  - Field curvature
  - Distortion
- Telescope designers reduce the effect of aberrations by optimizing the optical parameters of the optical elements (lenses and mirrors). This can be achieved either using analytical formulas or simulations (“ray tracing”).
- **Take-home message:** due to aberrations, a point source generates a blurred spot at the image space. This limits the angular resolution of the telescope.

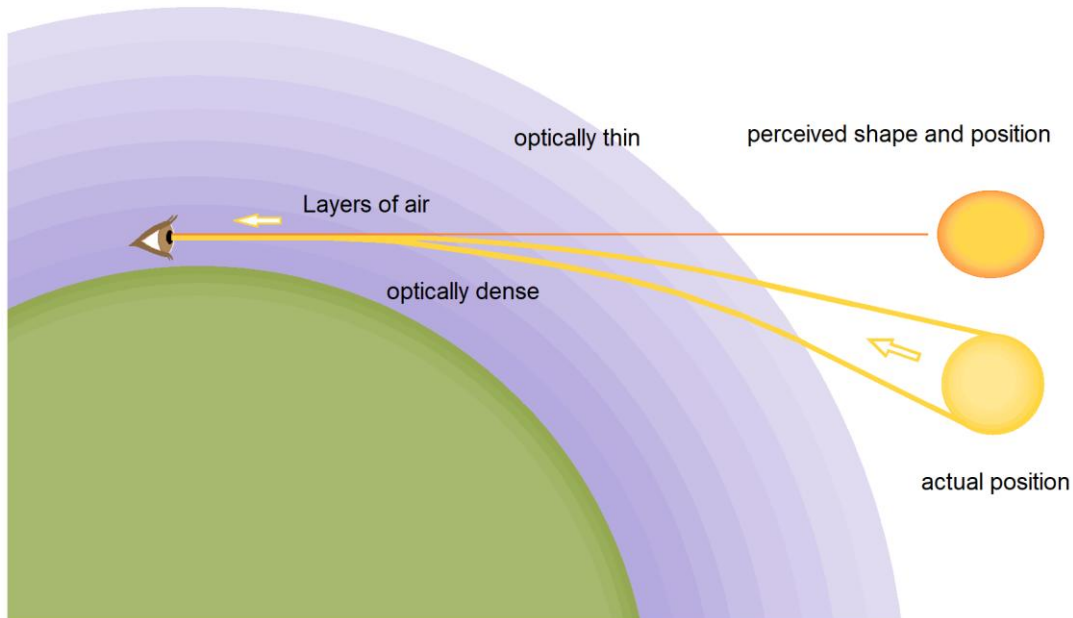
# Which Mirror Shape?

- Manufacturing parabolic mirrors is not easy, spherical mirrors are simpler to make.
- Davies-Cotton design
  - Specialized reflector layout with small, identical, spherical mirror facets that are arranged on a spherical structure.
  - Provides smaller aberrations over a large field of view compared to parabolic designs
  - It introduces a slight time delay (dispersion) in light reaching the camera plane. The dish shape is slightly distorted to improve the isochronicity of the reflector while keeping the aberrations of the PSF at a reasonable level.



# Atmosphere

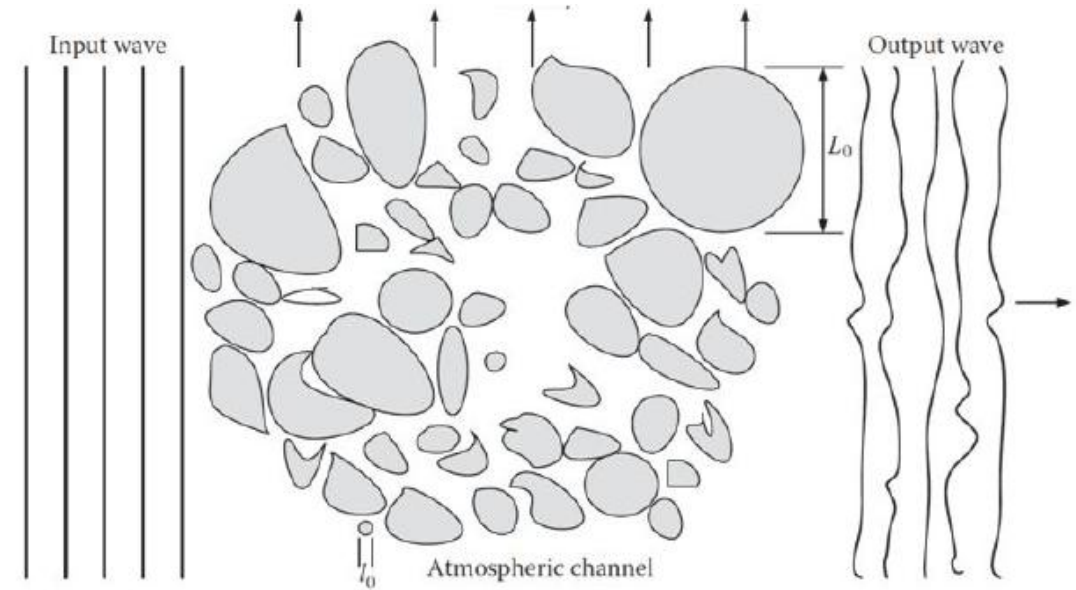
Sunset and Sunrise: Shift in the perceived position of the sun due to atmospheric refraction



- Light from astronomical objects must cross the atmosphere
- Refractive index depends on temperature (and pressure and humidity), which generally depends on altitude
- As light goes through the layers at different temperatures, it refracts
- As a result, stars change apparent position

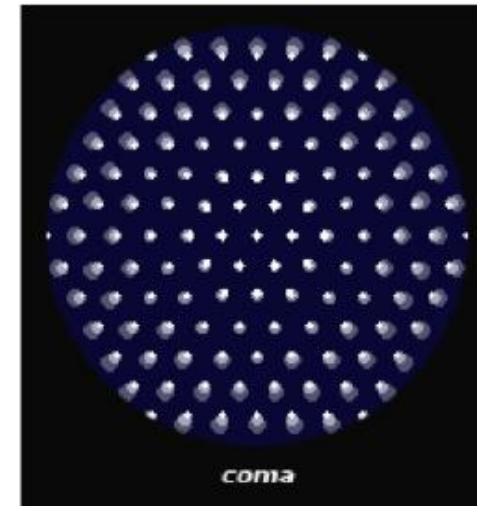
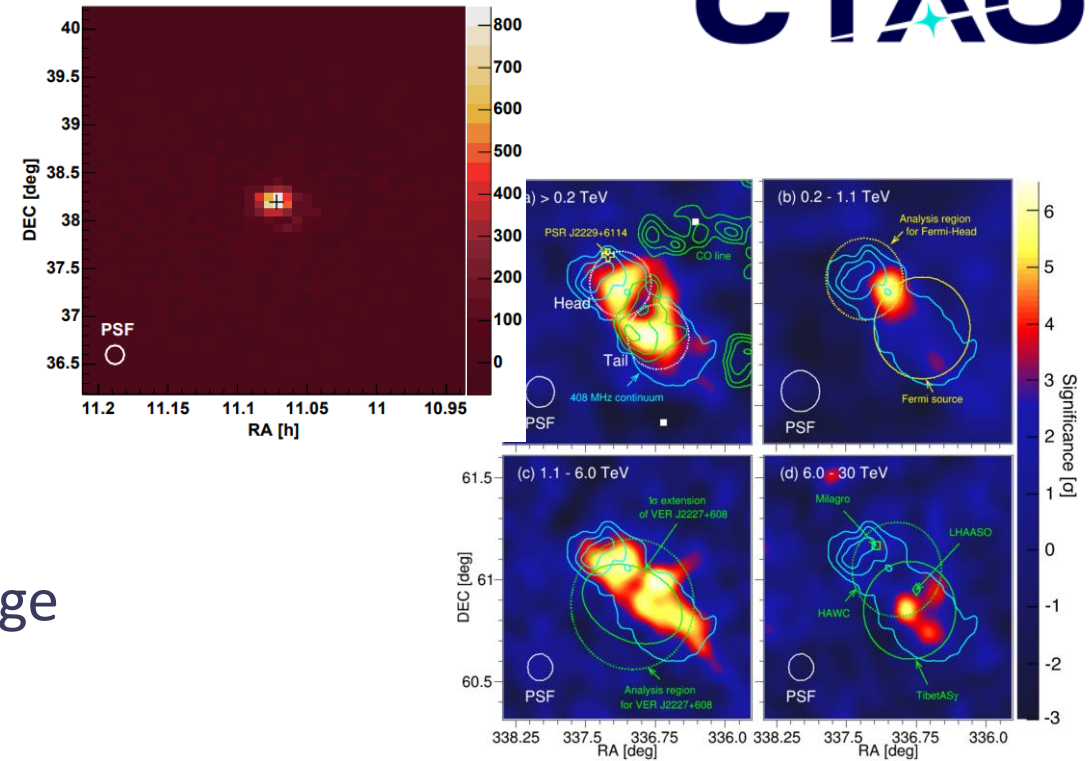
# Atmosphere

- The atmosphere is very complicated. Wind generates turbulence at different scales and generates random refractive indices.
- This has two effects
  - Light spot can get wider, angular resolution gets worse
  - Spot can change brightness with time (scintillation)
- For IACTs we care mostly about two aspects
  - Clouds
  - Atmospheric Transmission



# Field of View (FoV)

- FoV is the solid angle of the sky that is imaged (typically measured in angular diameter)
- FoV is relevant for large size objects or when covering many small size objects in a single image
- Spot blur size limits the FoV: coma aberrations get worse when going off-axis



# Light Collecting Power / Sensitivity

- The ability of a telescope to detect faint objects
- The signal collected by a telescope depends on (**Which one can we influence?**)
  - Photon detection efficiency
  - Aperture area of telescope
  - Integration time
  - Wavelength detection range
  - Photon flux per unit time, area and wavelength
- For reflectors, reflection loss is key (see Optics section later)

# Light Collecting Power / Sensitivity

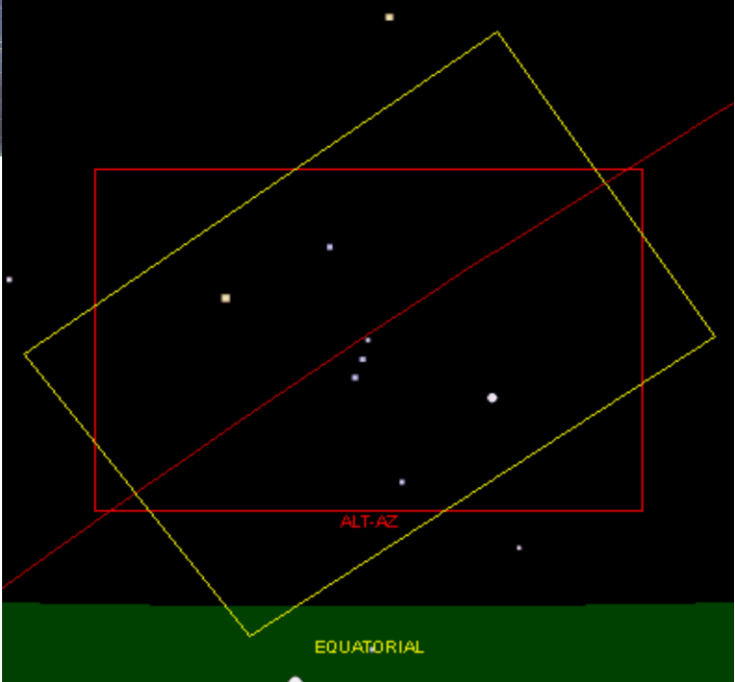
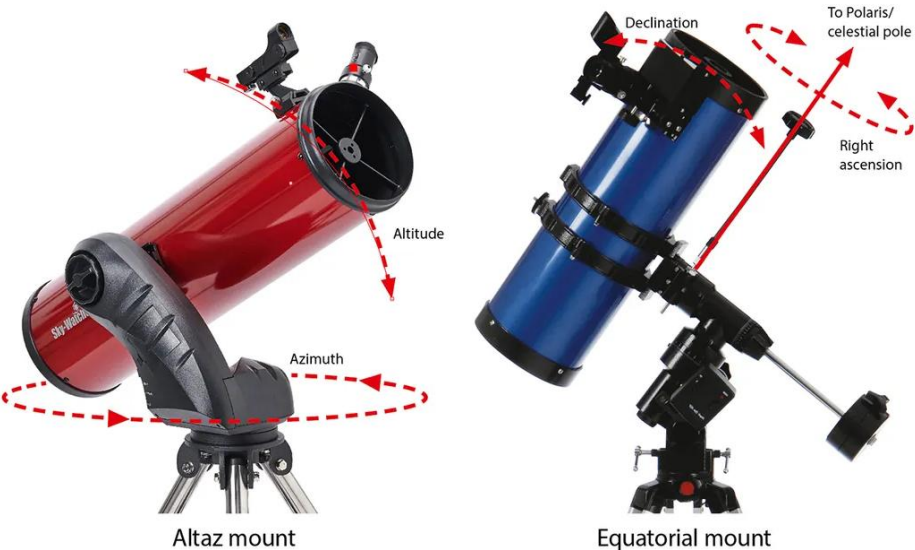
- The ability of a telescope to detect faint objects
- The signal collected by a telescope depends on
  - Photon detection efficiency (mirror reflectivity, quantum efficiency of sensors, etc.)
  - Aperture area of telescope, bigger is better
  - Integration time (usually limited to  $\sim 2000$  h / year,  $\sim 1000$  h / year with no or low moon)
  - Wavelength detection range
  - Photon flux per unit time, area and wavelength
- For reflectors, reflection loss is key (see Optics section later)



# 2 Structure

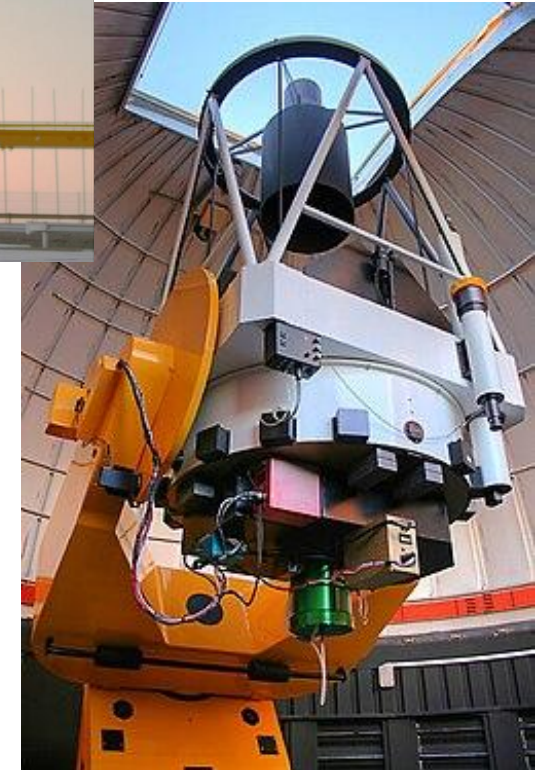
# Mount Types

- Stars “rotate” on the sky
- Two major mount types:
  - Altitude-Azimuth (AltAz) tracks in two axes, field of view rotates
  - Equatorial is aligned with rotational axis, tracks in one axis, field does not rotate



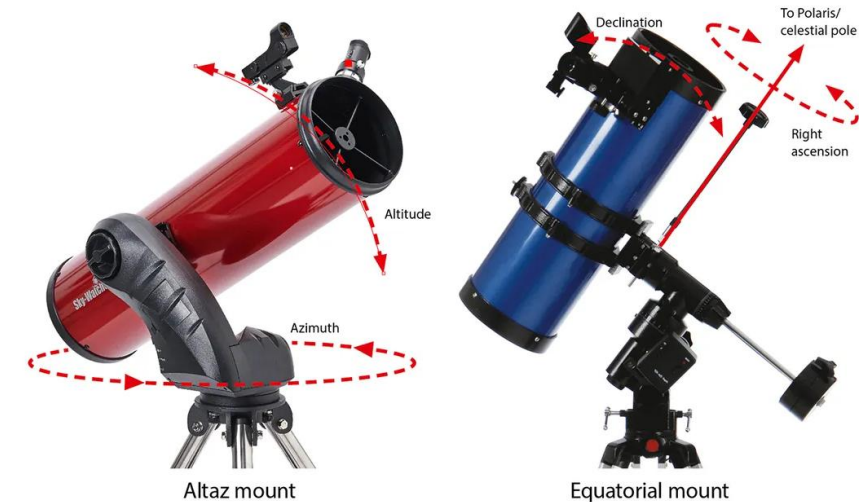
# Mount Types

- Alt-Az
  - Moves in altitude and azimuth
  - Requires two motors to track
  - Field of View rotates
  - Blind spot at zenith
- Equatorial
  - Aligned with Earth's rotational axis
  - Moves East-West, North-South
  - Requires one motor to track
  - Fork Mounts or German Equatorial Mounts with counterweights



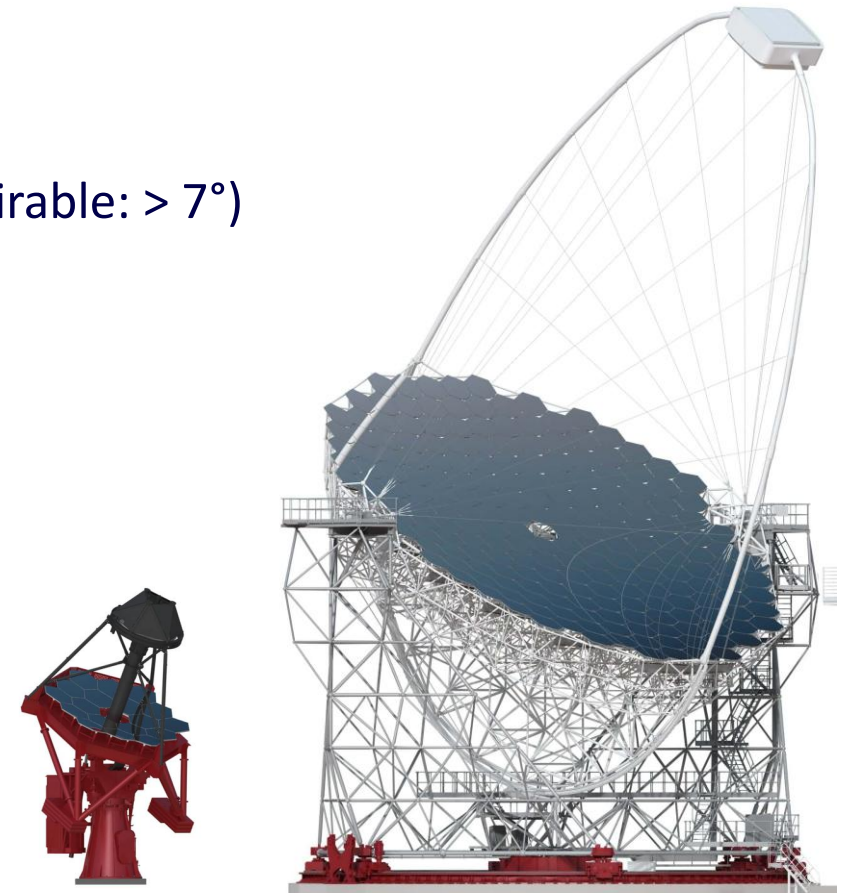
# Mount Types

- Key Reasons for Alt-Az Mounts on Large Telescopes
  - On Alt-Az mounts, the telescope sits directly on a horizontal axle, ensuring the weight is directed downward, which allows for a stiffer, more stable structure.
  - On equatorial mounts, the structural stress on a single, slanted polar axis would be unmanageable, and possibly a massive counterweight to balance the telescope would be necessary.
  - Alt-Az mounts require a smaller and less complex dome, saving a lot of money. Not an issue for IACTs.
- Trade-offs of Alt-Az Mounts
  - Field Rotation: As the mount moves in altitude and azimuth, the image rotates in the camera. Not an issue for IACTs.
  - Complex Tracking: They require more computing to move both axes at variable speeds to track stars. No challenge anymore.



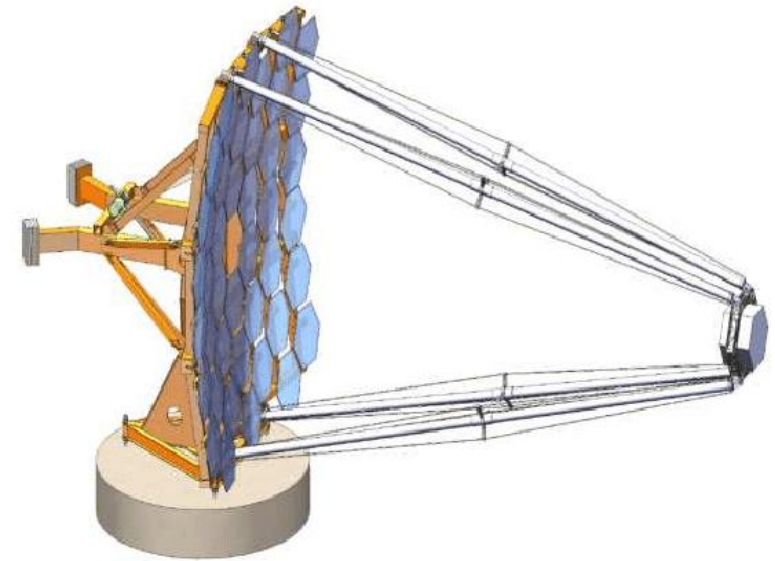
# Telescope Design Requirements

- Cherenkov flashes are extremely short ( $\sim 6$  ns) so the telescopes need ultra-fast optics
- Large primary mirrors ( $> 20$  m) required to collect enough light for low energy events
- Large field of view
  - Detection at high-energy ( $> 10$  TeV)
  - Observation of extended sources (minimum:  $\sim 3.5$ - $4.5^\circ$ , desirable:  $> 7^\circ$ )
  - Simultaneous background estimation
  - But: Aberrations increase
- Also need to think about
  - Complexity
  - Calibration
  - Deterioration
  - Maintenance
  - Safety



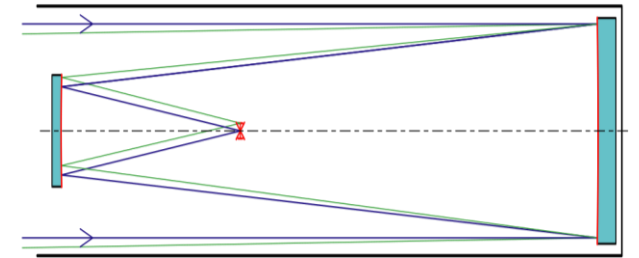
# Single-Mirror Designs

- Advantages
  - Simple optical layout
  - Minimal optical elements means reduced light loss
  - Modified Davies-Cotton design has been proven by existing IACTs
- Limitations
  - Aberrations increase rapidly for large apertures and wide FoV: coma becomes dominant limitation
  - To achieve improved resolution: required f-ratio increases to  $\sim 2.5-3$ , leads to very large focal lengths
  - Challenging with compact modern detectors (SiPMs, multi-anode PMTs, etc.)
  - **Scaling to wider FoV, finer pixels, and larger apertures becomes expensive and difficult**



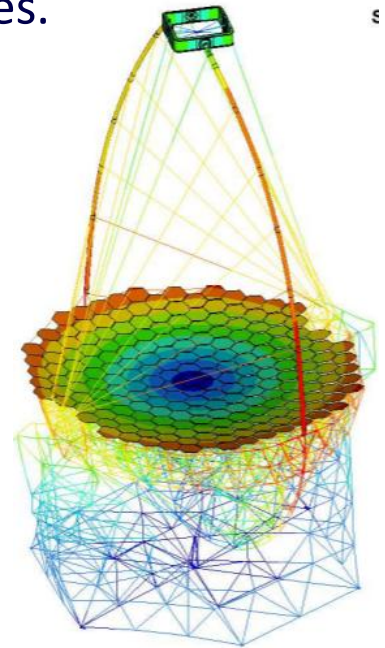
# Two-Mirror Design

- Key Idea
  - Secondary mirror reduces image size
  - Enables compact cameras with small modern sensors
- Optical Benefits
  - Corrects both spherical aberration and coma (Schwarzschild theorem)
  - Better image quality across larger field of view
  - Improved point spread function (PSF)
  - Exploited more effectively by implementing compact SiPM pixels
- Limitations
  - Curved image field
  - Complexity of mirror alignment and telescope design
  - Increased loss of reflectivity due to deterioration of two mirror surfaces
  - Safety concerns due to park position in the sun without dome



# Choice of Materials

- The choice of material has an impact on some major aspects of the telescope
  - Earthquake safety: Especially in places like Chile, telescopes must survive earthquakes. The use of proven materials and construction methods, along with detailed structural analyses, is necessary to ensure the longevity of the telescope.
  - Weight and inertia of the movement: Depending on the requirements on the speed of the repositioning, a low weight and favorable weight distribution is desirable.
  - Stiffness: Optical properties of the telescope depend on flexibility of the structure. The more flexible, the more care must be taken to keep the optics aligned.
- High weight and inertia can be counteracted by powerful motors. Low stiffness can require a complex system of optical alignment. Both increasing the complexity and cost.



# Choice of Materials

- Steel
  - Improved stiffness
  - Mirror facets of the telescope may not need refocusing for a long time
  - Weight of steel is quite high, and care must be taken against corrosion
- Light-weight / composite materials
  - Carbon Fiber Reinforced Plastics (CFRP) or similar, as well as Aluminum
  - Can significantly reduce weight and inertia, allowing higher rotation speed
  - Drawbacks are lower stiffness, potential issues with different thermal expansion, and probably increased cost.



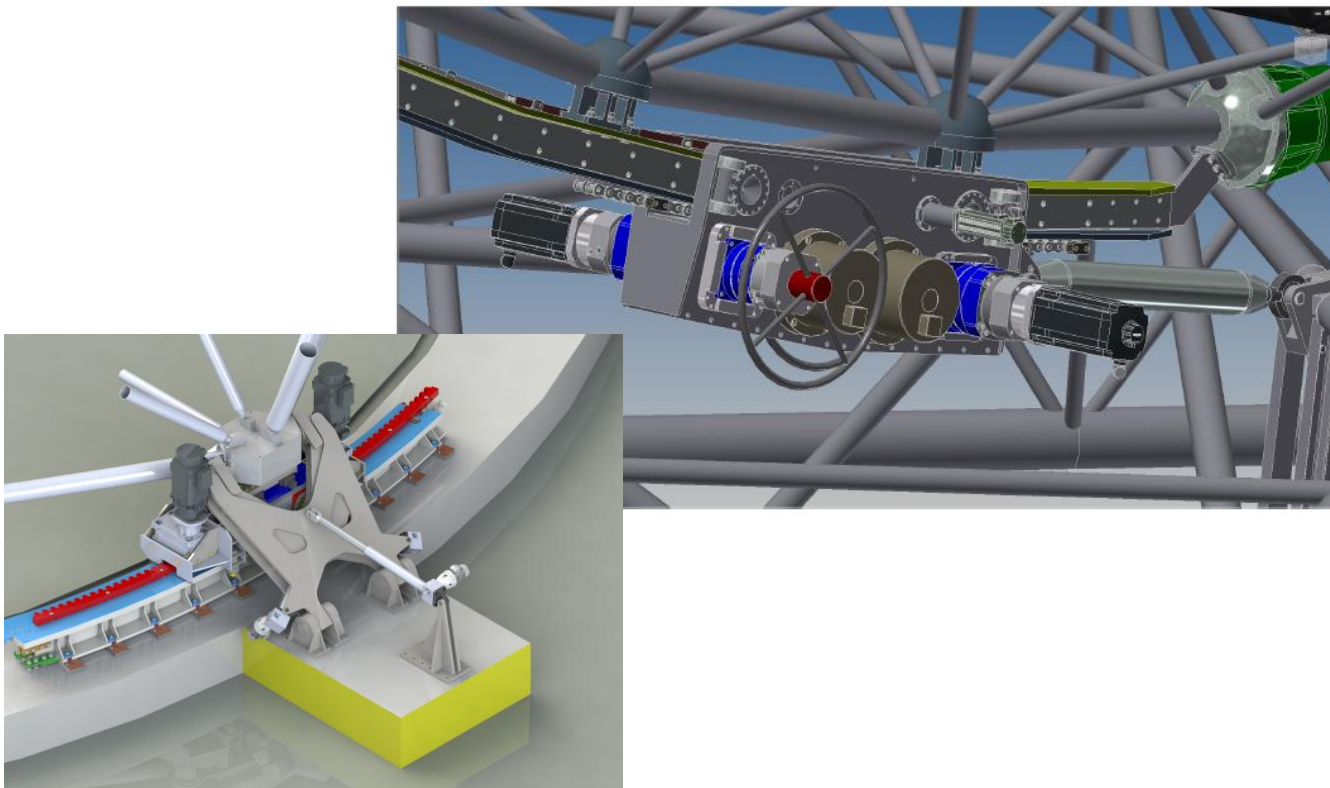
# Locking System / Maintenance

- Azimuth/Elevation Locking: For safety during wind, earthquake, etc.
- Camera Locking
  - Camera Tower: Easy access for maintenance but separate structure with different thermal expansion and behavior during wind and earthquakes
  - “In the air”: Stress for the structure, separate maintenance position needed.

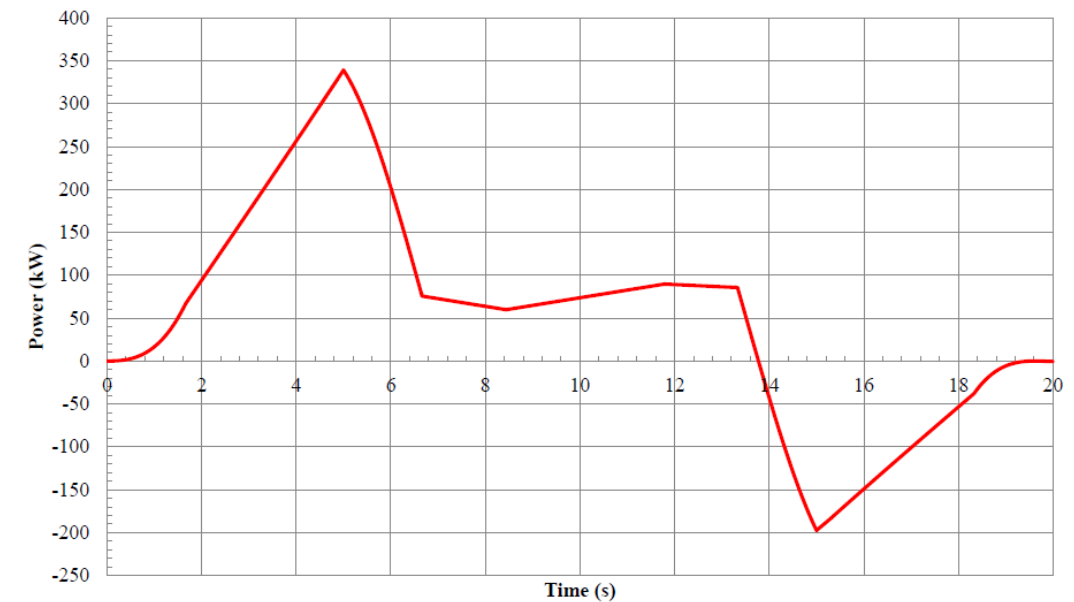


# Drive System

- Telescopes are powered by electrical motors, their design and output varies with size/weight, inertia, required speed.
- In case of a power cut, the telescope always needs to be able to go back to a safe state.



LST total Power during GRB alert with 60 km/h wind  
(Azimuth + Elevation Systems)



# Power System

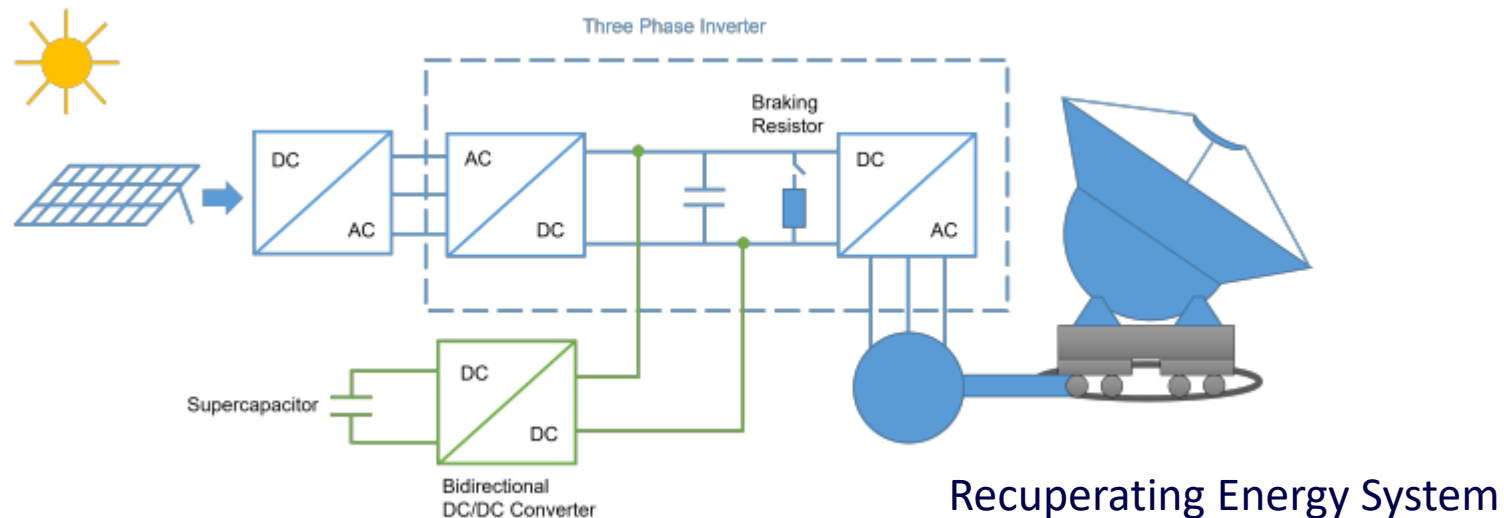
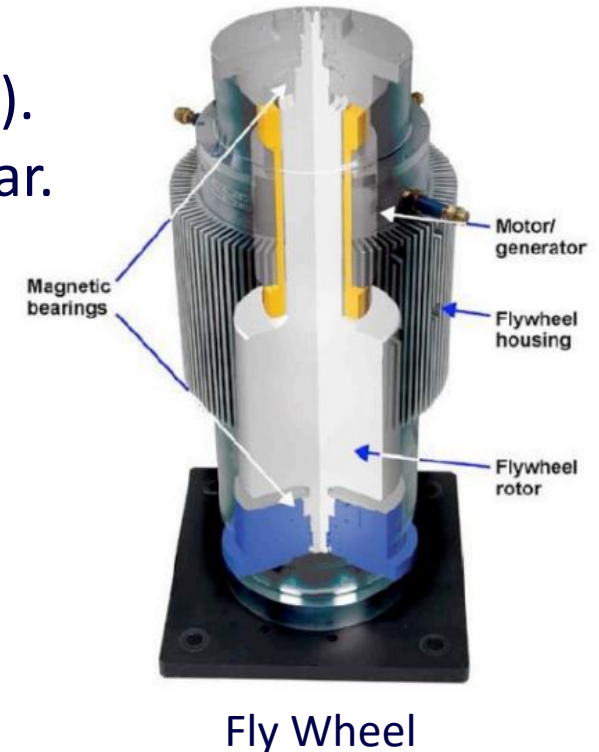
- Stability of mains power: Observatories usually in remote places with harsh environmental conditions, so frequent power cuts can be expected.
- Uninterruptable Power Supply (UPS): Fast replacement power to avoid shutdown of vital systems (control systems, safety systems, etc.), basically a large battery that is always charged.
- Backup/Emergency power: UPS is fast but does not last long, alternative power is needed, typically in the form of a Diesel generator. Consider also a portable unit for emergencies.



Diesel Generators

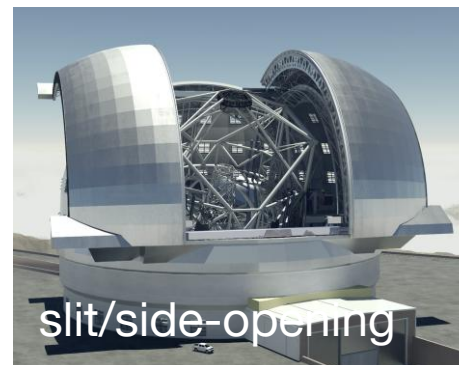
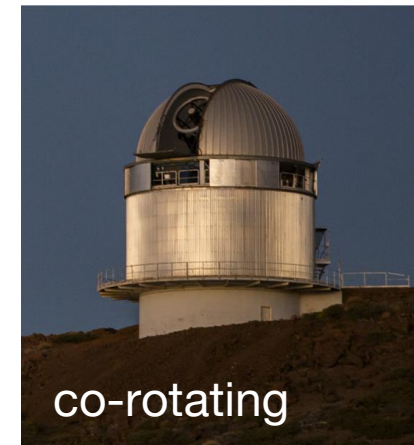
# Power System

- Additional power may be necessary to compensate high loads for power intensive actions (e.g., fast movements with high inertia). Can be provided by fly wheels (rotating mass in a vacuum) or similar.
- Can serve as emergency power
- Using renewable power and recuperating kinetic energy systems is desirable but comes with additional costs and complexity.



# Protective Dome

- Protects telescope from the environment and controls climate during the day to limit temperature expansion.
- Several aspects determine the dome design:
  - The dome can co-rotate with the telescope, rotate independently of the telescope, or not at all.
  - The size of the slit opening and other vents determine how quickly the telescope can acclimatize and impacts the seeing and the quality of the observations.
  - The size and weight of the dome can make a complex system necessary to open and rotate the dome.
- If no dome is used, the telescope systems need to be designed to withstand strong wind, rain/ice/hail, UV radiation, dust intrusion, temperature changes, etc.



# Safety Systems

- Risk Assessment / Hazard Analysis: Like every “machine”, a telescope must be safe for humans and the environment. Safety systems are necessary to mitigate the hazards associated with constructing, installing, and operating a telescope:
  - Fences: Not only to control unauthorized access but also to make authorized access safer.
  - Interlocks: System of sensors and Programmable Logic Controllers (PLCs) to inhibit dangerous motions. Must be robust and fail safe.
  - Procedures: Who is allowed to do what and when, what material do they need and how are they performing their tasks. Manuals and procedures need to be clear.
  - PPE: If technical or procedural measures are not enough, personnel needs to have the right safety equipment (helmet, harness, gloves, sun protection).
  - Cyber Security: To avoid unauthorized access to telescope systems, avoid data loss or corruption, avoid ransomware attacks or similar.



# 3 Optics

# Mirror Manufacturing

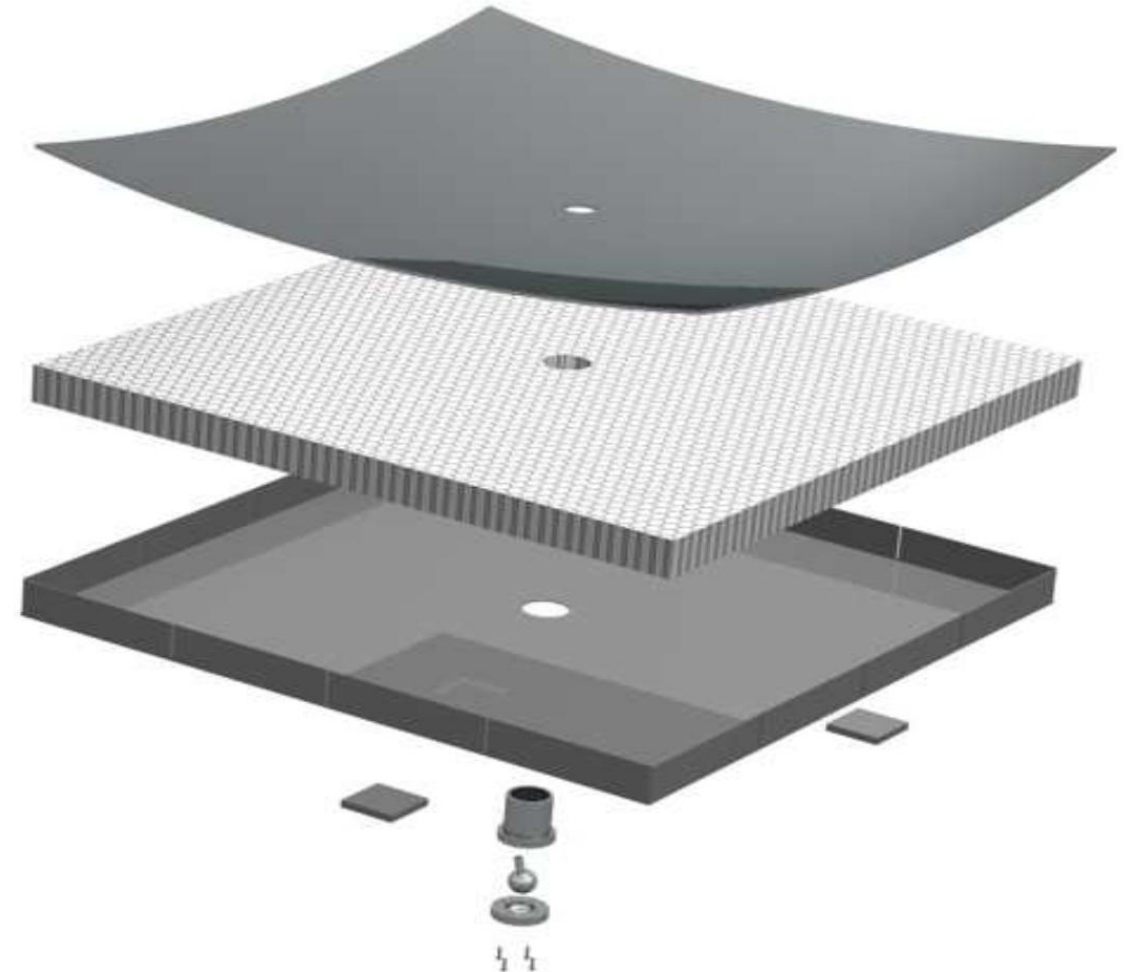
- Mirrors are used in many applications implying different requirements. Relevant aspects for telescopes are:
  - What?

# Mirror Manufacturing

- Mirrors are used in many applications implying different requirements. Relevant aspects for telescopes are:
  - Reflectivity (one of the main aspects)
  - Size and weight (impact on telescope design)
  - Coating (to prevent damage due to environment)
  - Cost (we need many...)
  - Manufacturing technologies (influences previous aspects)
- Some typical materials
  - Copper alloys: 45% (some of the oldest reflectors)
  - Aluminum coating: > 90% (can oxidize in the air)
  - Silver coating: > 95% (SO<sub>2</sub> in the air degrades them quickly and they are more expensive)

# Manufacturing Technologies

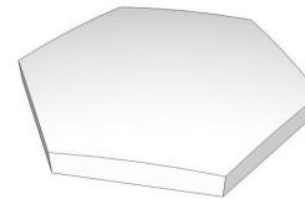
- All-aluminum mirrors
  - Center is an Aluminum honeycomb structure, provides needed rigidity but is light weight
  - Reflective surface generated by precision diamond milling
  - Quartz protection layer to prevent oxidization



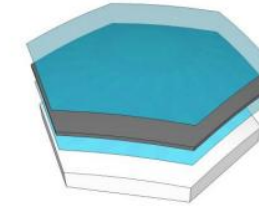
# Manufacturing Technologies

- Glass-aluminum mirrors
  - Center is an Aluminum honeycomb structure, provides needed rigidity but is light weight
  - On both sides, a glass sheet is glued with epoxy
  - The sandwich is bonded and deformed to the right shape by a mold with convex profile using heat and vacuum suction. Some spring back must be expected.
  - On the concave side, a reflecting coating (Aluminum) is applied
  - Quartz protection layer to prevent oxidization

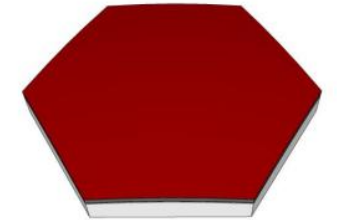
Preparation of the integration mold



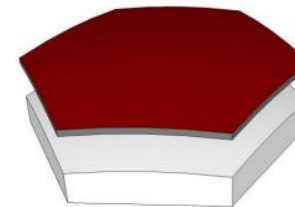
Assembly of the sandwich



Curing of the glue



Release of the sandwich



Coating of the sandwich

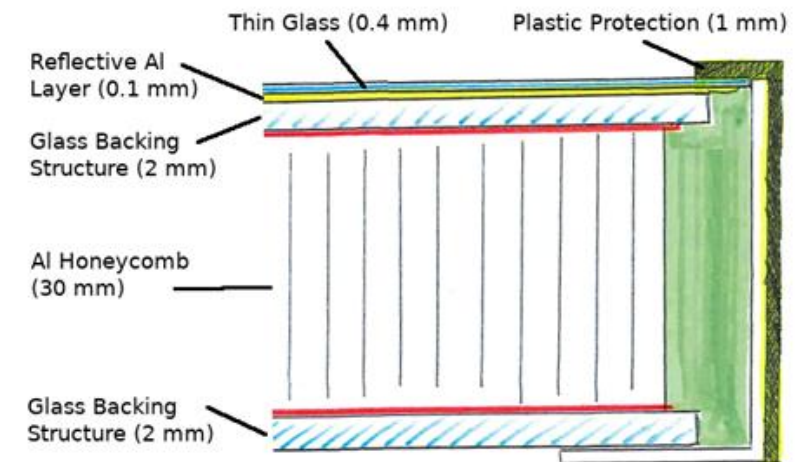


Finishing of the mirror

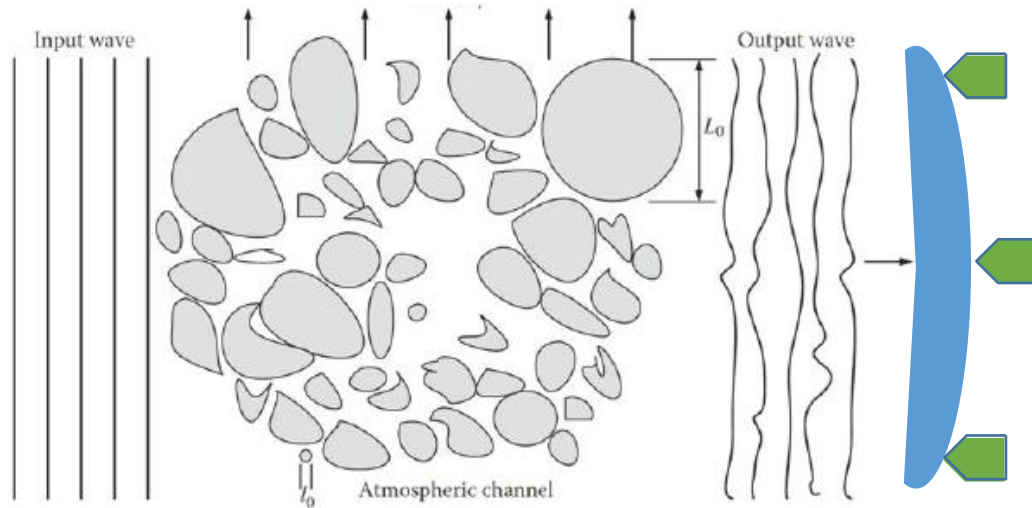


# Coating

- Relevant both for optimal reflection and protection
- Reflectance depends on the wavelength. The choice of the coating material depends on the light wavelength that needs to be reflected.
- Mirror degradation reduces performance of the telescope and needs to be minimized. A possibility to counteract degradation is to re-new reflective surface.
- Protective coating options
  - Vacuum deposited SiO<sub>2</sub>
  - Al<sub>2</sub>O<sub>3</sub> obtained by anodizing the reflective Al layer
  - Multilayer dielectric coatings of alternating layers of materials with low and high refractive index
  - Purely dielectric coatings without any metallic layer
  - Ultra-thin glass sheet (Gorilla glass)



# Adaptive Optics

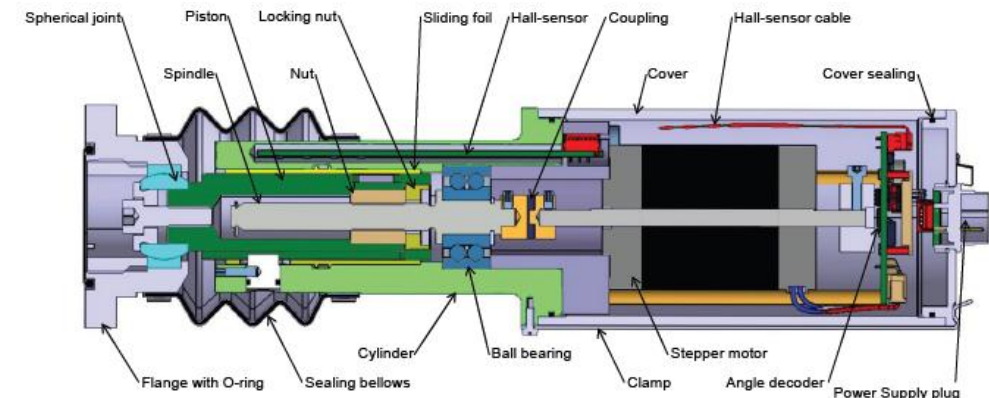
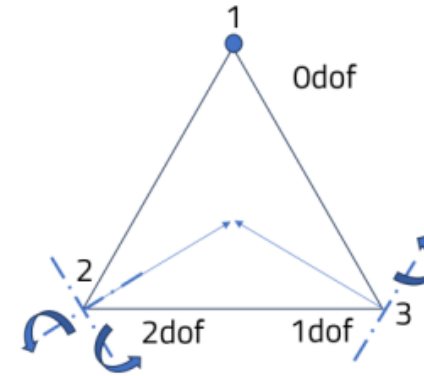


- To adapt for atmospheric distortions and other effects, a possible solution is to deform the telescope mirrors
- Small actuators apply pressure on the mirror to correct its shape slightly at a very fast rate (several times a sec)
- A bright star or “fake” guide star projected to the sky using powerful lasers are used as a reference to deform the mirror



# Active Mirror Control

- IACTs typically use a system of 2 actuators and a fixed joint per mirror to align the mirror.
- Depending on the stiffness of the structure and the requirement on precision pointing, the procedure needs to be done a few times per year, per night, per hour, or even more frequent.
- The LST actuators have a stroke of 34 mm and Hall sensors to measure position.
- With a laser beam along the optical axis projected close to the main camera, and CMOS cameras attached to each mirror, a near instantaneous alignment with high precision should be possible.



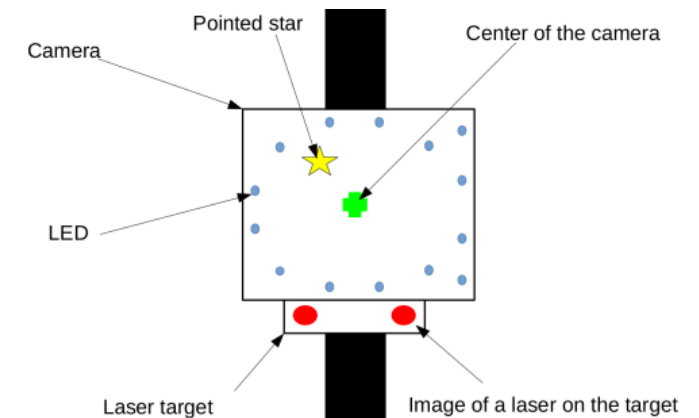
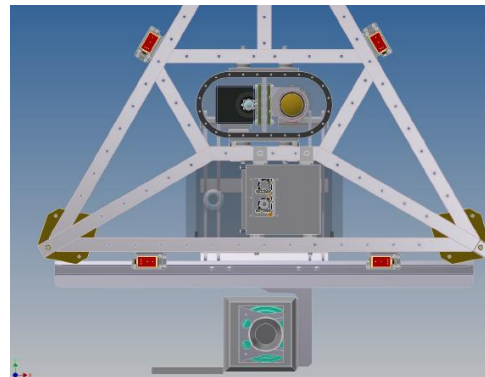
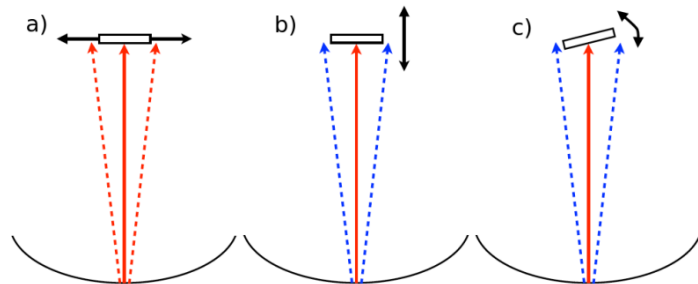


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# Calibration

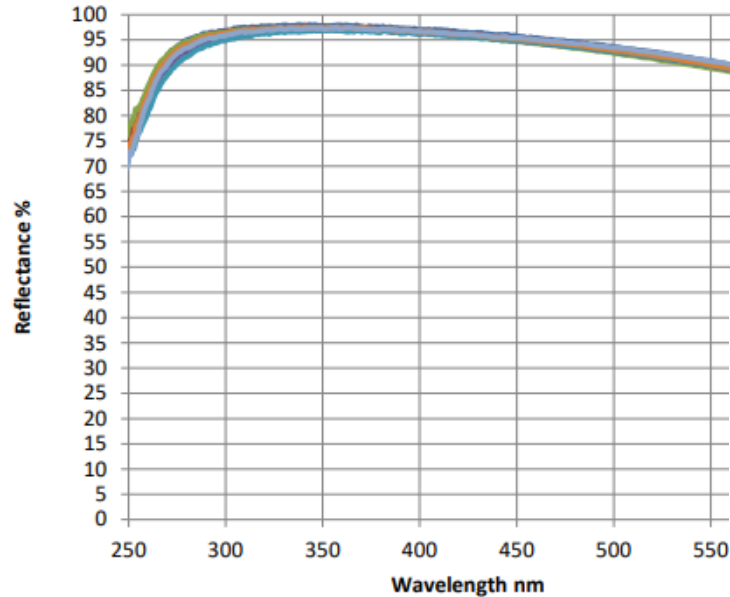
# Structure Calibration / Pointing

- More relevant for light structures like LST: pointing of the telescope is less than 1 arcmin with online correction and less than 14 arcsec after offline correction.
- Structure Calibration: Bending Model is used to align drive control and pointing direction. Depending on mount type and stiffness this can be very complicated. Hysteresis effects and oscillations may have to be considered.
- Pointing: Uncertainties or unpredictable disturbances (e.g., due to wind) affecting the pointing can be corrected by distance meters, laser guidance, or cameras to observe deformations or deviations in position (StarGuider).

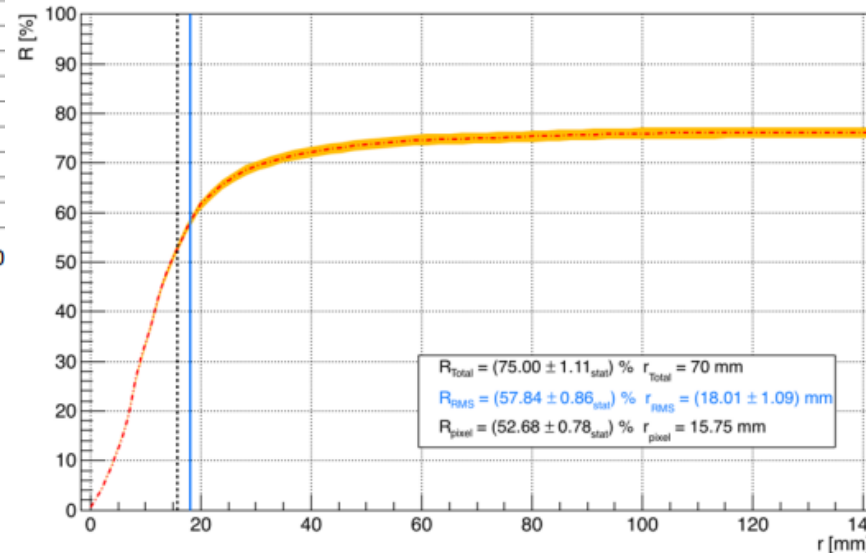


# Reflectivity and PSF

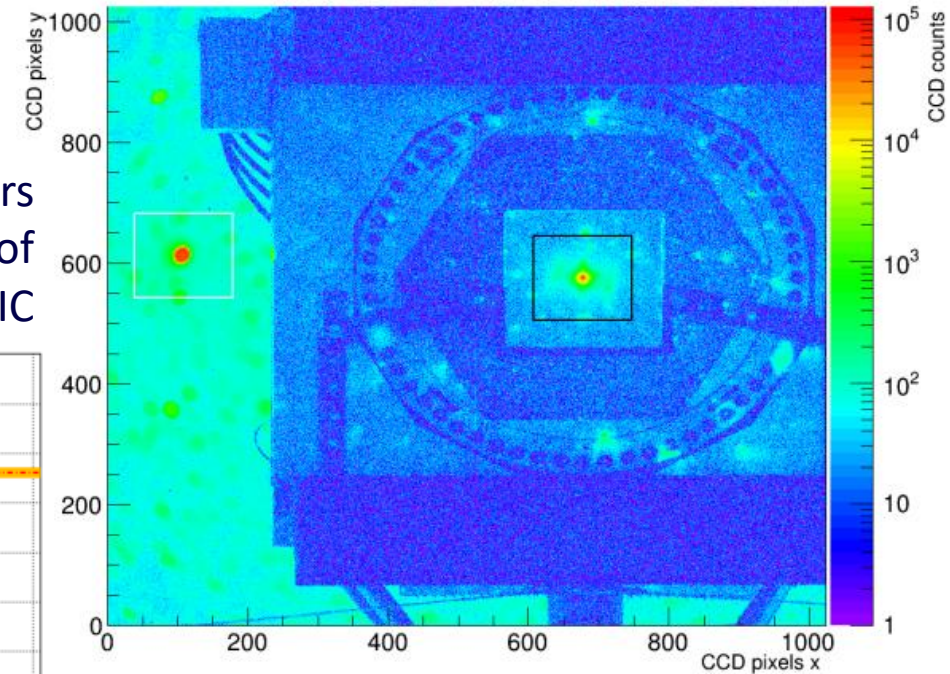
- Point Spread Function (PSF) is typically monitored by a dedicated camera and observations of stars.
- Reflectivity of the mirror is important, but in the end the “pointed” reflectivity is relevant: How big is the light spot on the camera?



Reflectivity measured on a new LST mirror at the factory



Reflectivity after 10 years integrated along the spot of 200+ mirrors at MAGIC



# Atmospheric Monitoring

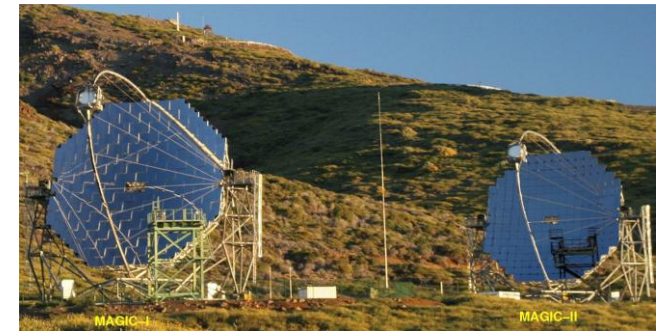
- Knowledge of basic conditions and trends is important for the telescope site. This characterization takes years and is done with many instruments (weather stations, weather balloons, numerical weather models, and many more).
- During the operations, several parameters are monitored to characterize the atmosphere (i.e., the detector volume):
  - Current Weather: Basic weather stations are important for safety (avoid damaging equipment) and data quality (avoid taking useless or corrupted data).
  - Molecular Scattering: Typically very predictable with models, does not vary a lot.
  - Aerosol Scattering: Can be very variable, profiles can be measured by LIDAR systems. Dust counters can be used to measure the concentration close to the ground.
  - Cloud Detection: Also done with LIDAR systems or specialized ceilometers.
  - Sun photometers and other photometric systems can measure integral transmission.



# 5 CTAO Telescopes

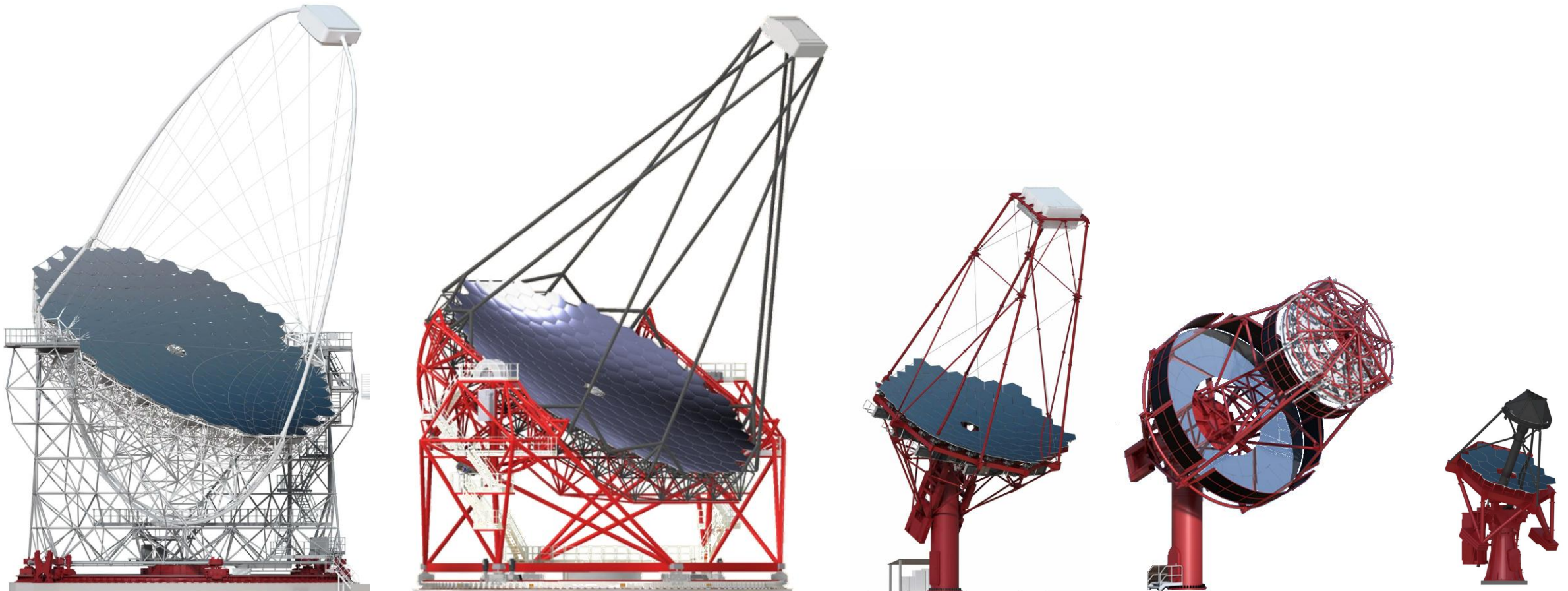
# Previous Generation

- H.E.S.S.
  - Four 12m telescopes on a square with 120 m side length, one 28m telescope in the center
  - Steel structures with high rigidity but low rotation speeds
  - Aluminized glass mirrors with quartz coating
- MAGIC
  - Two 17m telescopes at 85m distance
  - Light-weight carbon fiber frame with low rigidity but high speed
  - Aluminized glass and full aluminum mirrors with quartz coating
- VERITAS
  - Four 12m telescopes with about 100 m distance
  - Steel structures with high rigidity but low rotation speeds
  - Aluminized glass mirrors with anodization

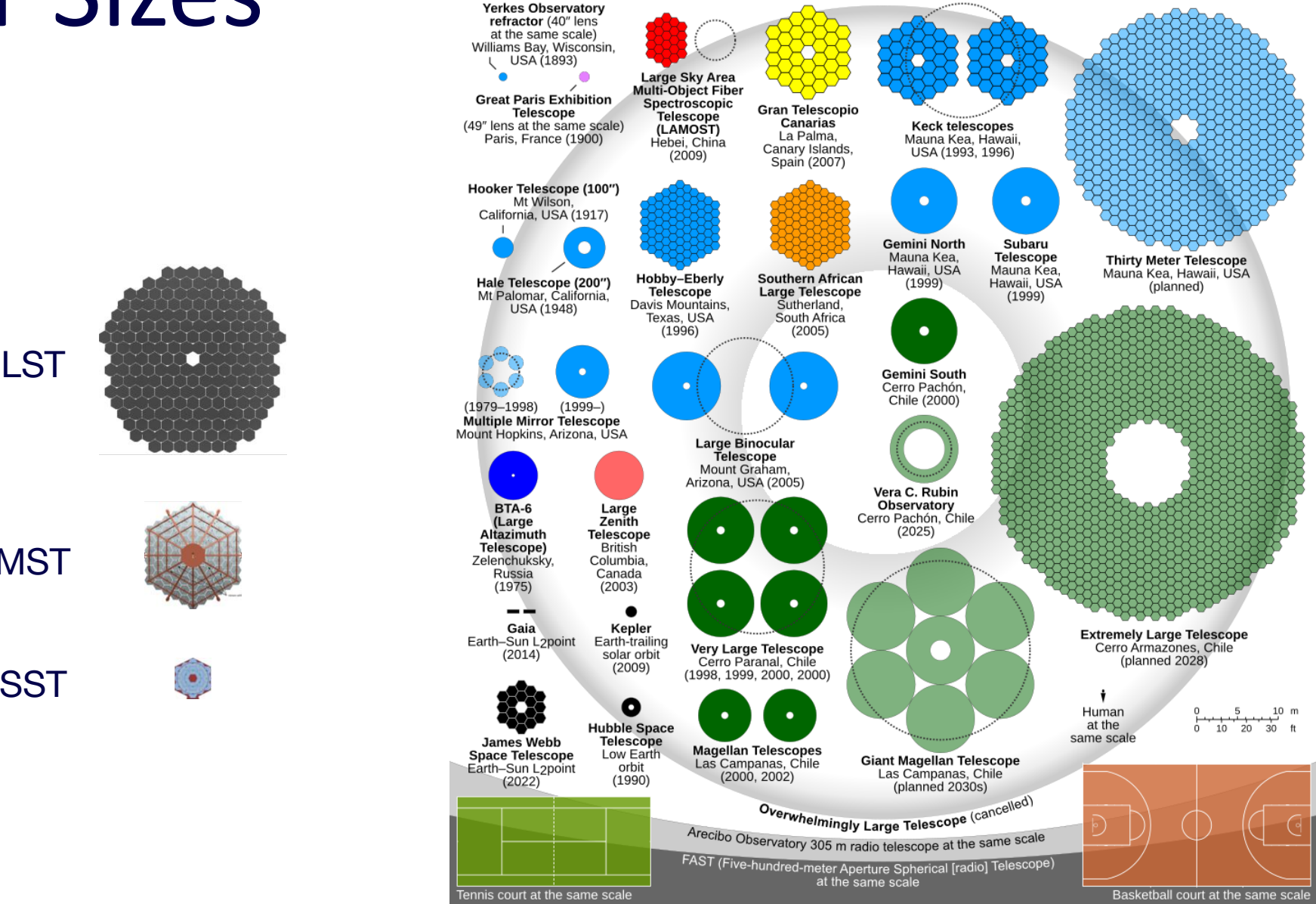


# CTAO Telescopes

Let's look again at the CTAO telescopes

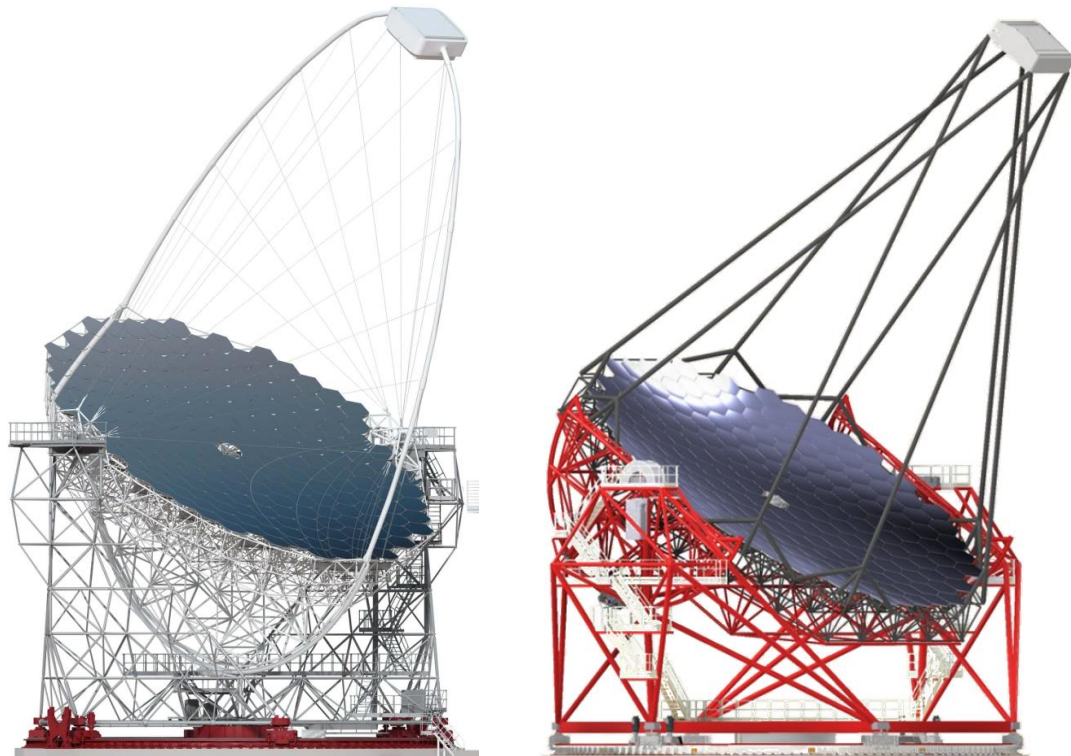


# Mirror Sizes



# CTAO-LST Telescopes

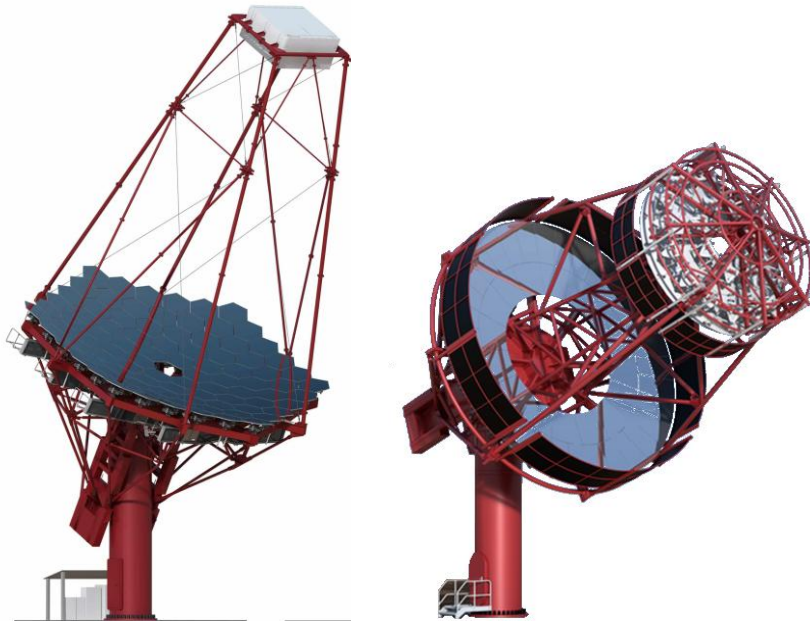
- Low energy threshold
- High speed through low weight
- Decent but still challenging pointing precision



	Large-Sized Telescope (LST)
Energy range (in which sensitivity is optimized)	20 GeV – 3 TeV
Number of LST telescopes	4 (North)
Optical design	Parabolic
Primary reflector diameter	23.0 m
Effective mirror area (including shadowing)	370 m <sup>2</sup>
Focal length	28 m
Total weight	103 t
Field of view	4.3 deg
Number of pixels	1855
Pixel size (imaging)	0.1 deg
Photodetector type	PMT
Telescope readout event rate after array trigger	>7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s
Pointing precision	<14 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

# CTAO-MST Telescopes

- Large field of view
- Good pointing precision
- Medium energy range
- Can do a little bit of everything!



	Medium-Sized Telescope (MST)
Energy range (in which sensitivity is optimized)	80 GeV – 50 TeV
Number of MST telescopes	14 (South) 9 (North)
Optical design	Modified Davies-Cotton
Reflector diameter	11.5 m
Effective mirror area (including shadowing)	88 m <sup>2</sup>
Focal length	16 m
Total weight	89 t
Field of view (FlashCam / NectarCAM)	7.5 deg / 7.7 deg
Number of pixels (FlashCam / NectarCAM)	1764 / 1855
Pixel size (imaging)	0.17 deg
Photodetector type	PMT
Telescope readout event rate before array trigger (FlashCam / NectarCAM)	>6 kHz / >7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	12 Gb/s
Positioning time to any point in the sky (>30° elevation)	90 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 20 degrees

# CTAO-SST Telescopes

- Large field of view
- Good pointing precision
- High energy threshold
- Good to cover a large area in the South



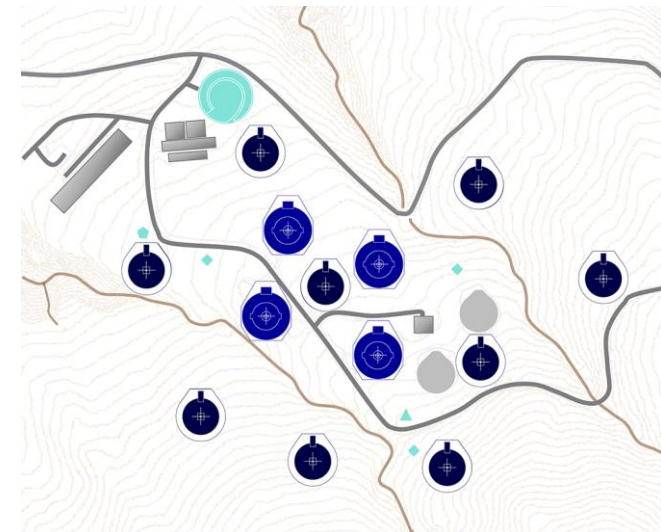
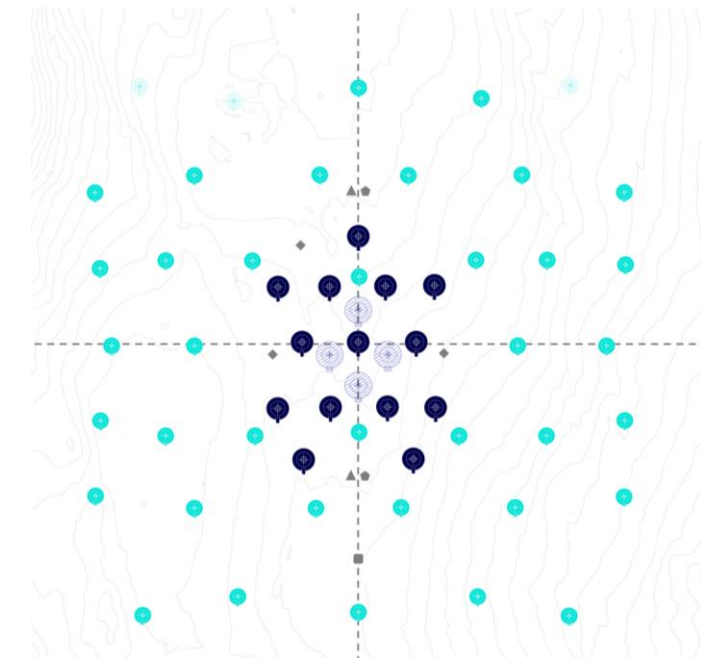
	Small-Sized Telescope (SST)
Energy range (in which sensitivity is optimized)	2 TeV – 300 TeV
Number of SST telescopes	37 (South)
Optical design	Modified Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8 m
Effective mirror area (including shadowing)	>5 m <sup>2</sup>
Focal length	2.15 m
Total weight	17.5 t
Field of view	8.8 deg
Number of pixels	2048
Pixel size (imaging)	0.16 deg
Photodetector type	SiPM
Telescope readout event rate (before array trigger)	600 Hz
Telescope data rates (readout of all pixels; before array trigger)	2.55 Gb/s
Positioning time to any point in the sky (>30° elevation)	70 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

# Which telescopes go where?

- South
  - Galactic science: high energy (80 GeV to 300 TeV), extended sources, high background
  
- North
  - Extragalactic science: low energy (20 GeV to 50 TeV), point sources, GRB, low background

# Which telescopes go where?

- South
  - Galactic science: high energy (80 GeV to 300 TeV), extended sources, high background
  - Many small-sized telescopes to cover a large area to capture rare high-energy events
  - A couple of medium and some large-sized telescopes to extend the energy range and sensitivity
- North
  - Extragalactic science: low energy (20 GeV to 50 TeV), point sources, GRB, low background
  - A few large-sized telescopes to capture a lot of light from faint showers with good pointing accuracy and high speed
  - A couple of medium-sized telescopes to extend the energy range and sensitivity



The End



The End

