Introduction to Observational Astronomy

Giacomo Beccari

European Southern Observatory (ESO)

gbeccari@eso.org

What is astronomy?

- Observational science

What is astronomy?

- Observational science
  - laboratory experiment
  - observer(s)

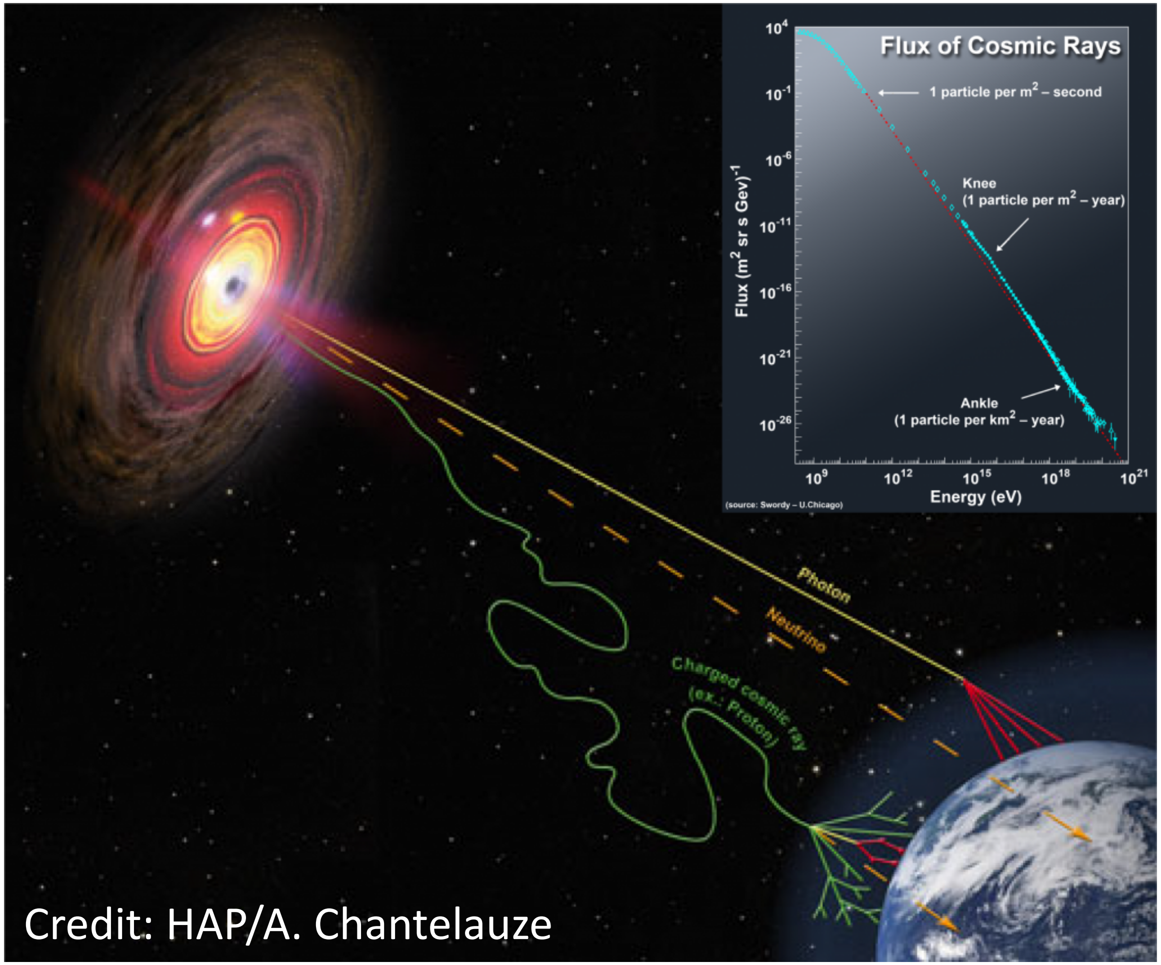
What is astronomy?

We observe energy coming from the sky

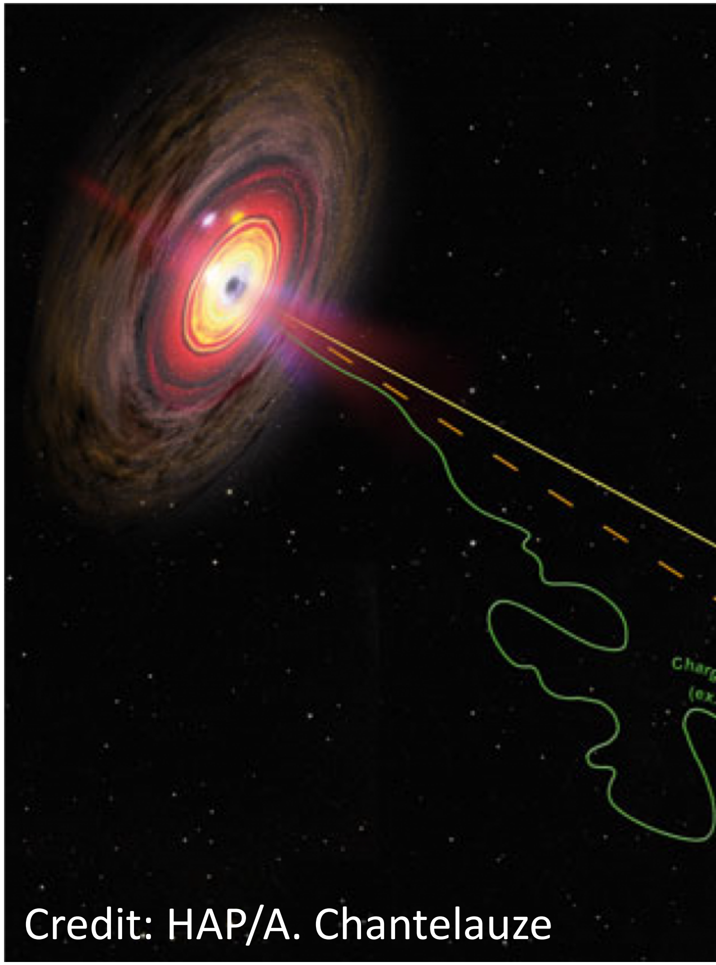
- Electromagnetic radiation
- Cosmic rays
- Neutrinos
- Gravitaional Waves

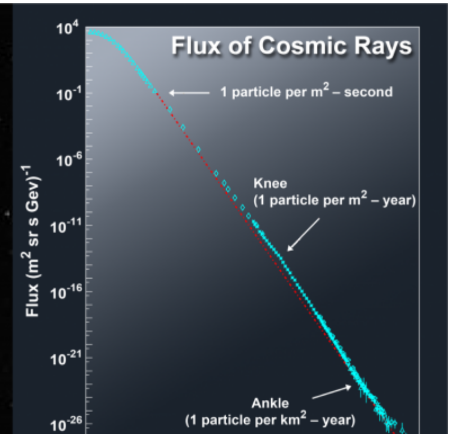
Cosmic Rays

extremely energetic sub-atomic charged particles

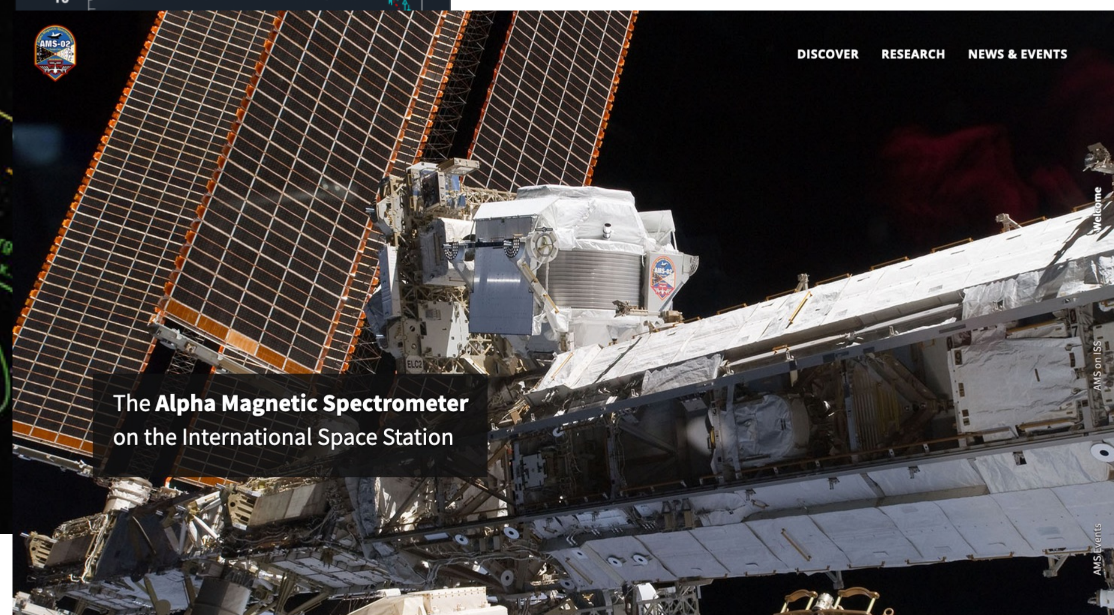


Cosmic Rays
extremely energetic sub-atomic charged particles


Credit: HAP/A. Chantelauze

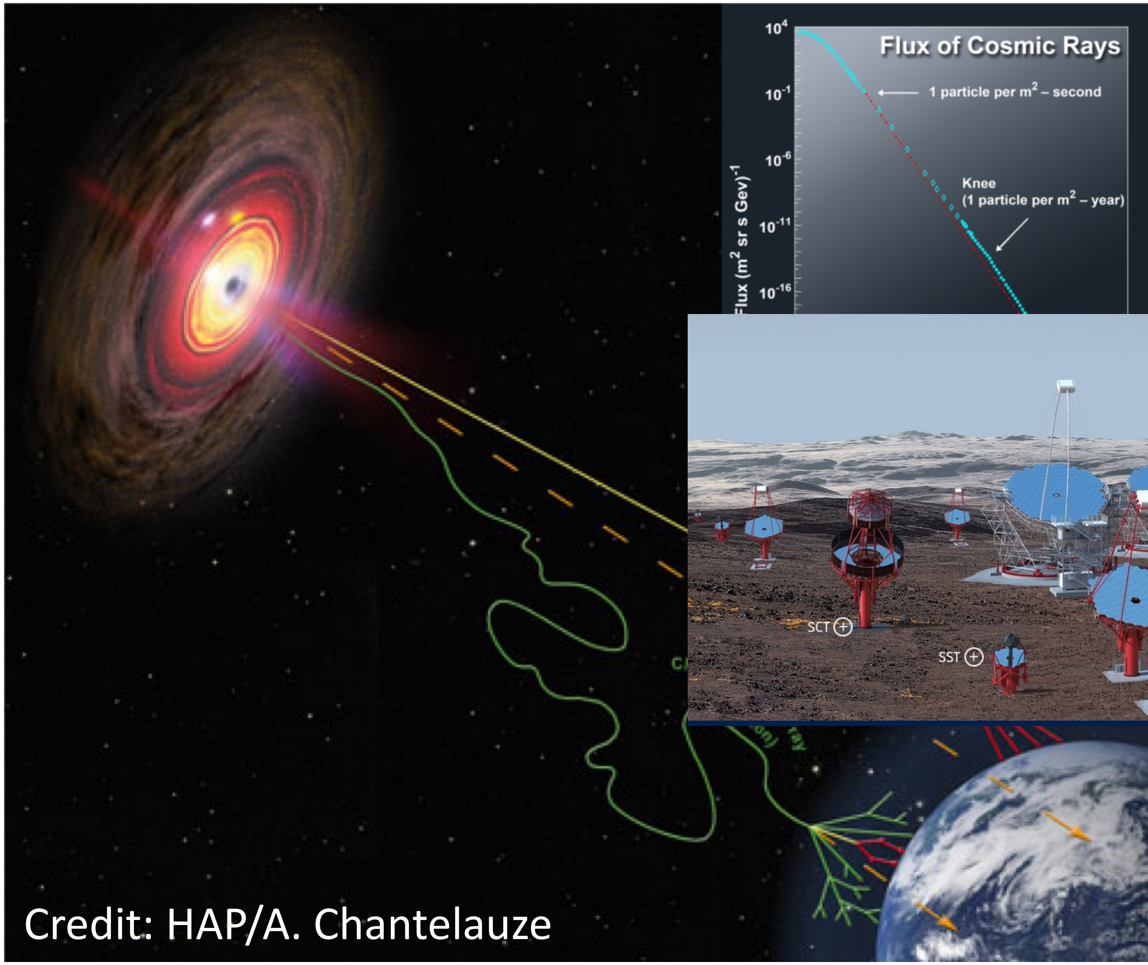


From Space:
Alpha Magnetic Spectrometer
AMS-02
http://ams02.space/

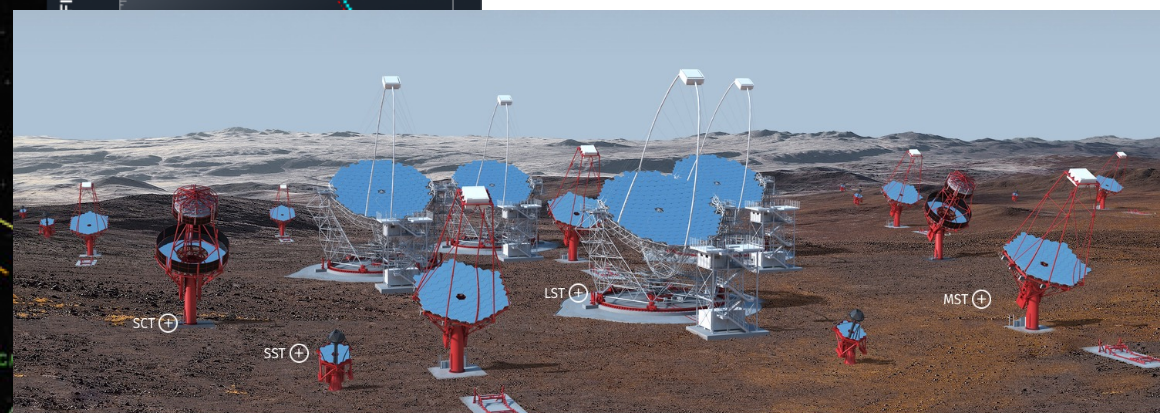


Cosmic Rays

extremely energetic sub-atomic charged particles



Credit: HAP/A. Chantelauze



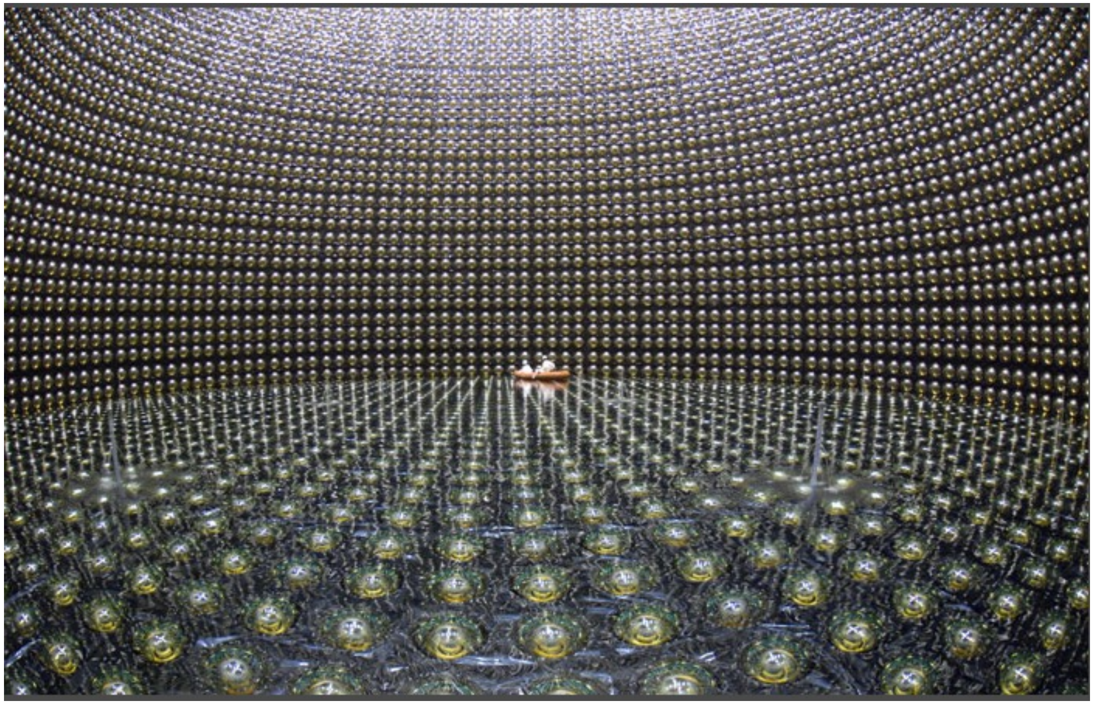
From the ground:
Cherenkov Telescope Array (CTA)
https://www.cta-observatory.org/

Neutrinos

neutral particles with almost immeasurably small mass

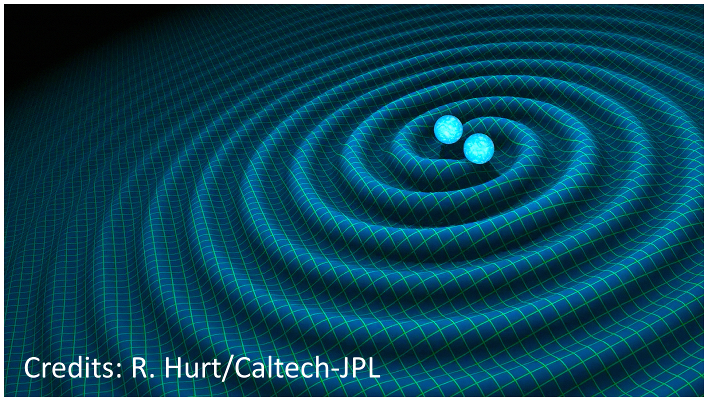
Super-Kamiokande
http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

- 39.3m diameter and 41.4m tall,
- filled with 50,000 tons of water
- ~ 13,000 photo-multipliers

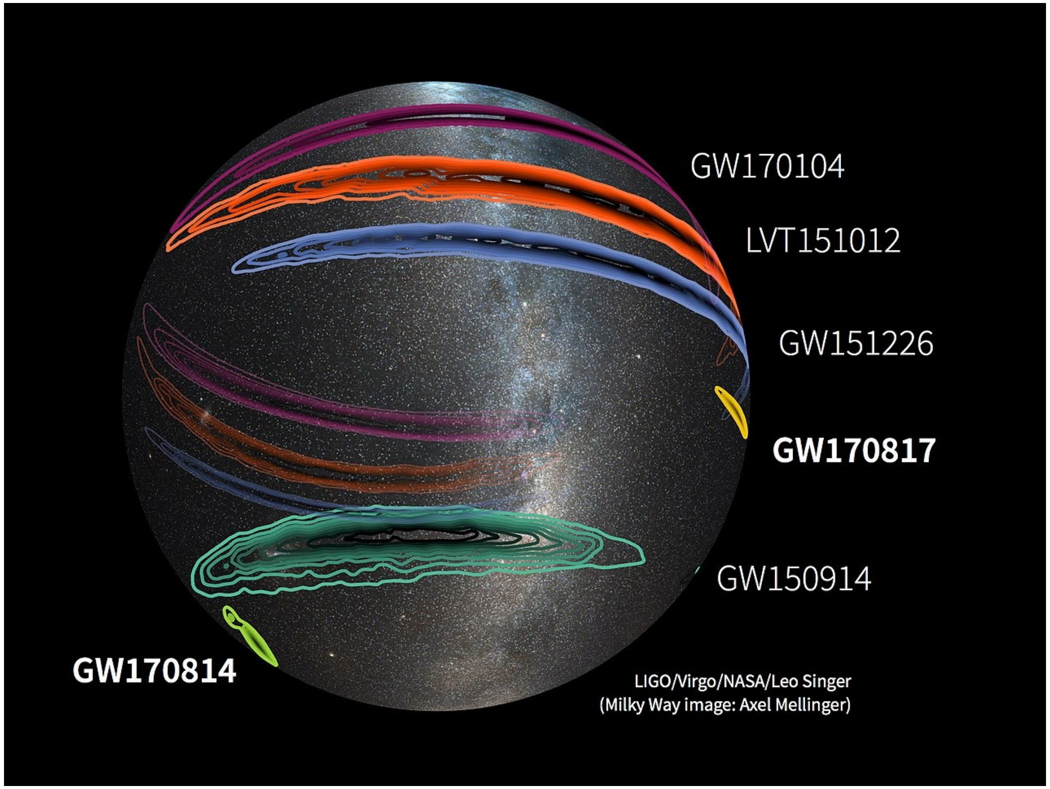


Courtesy: Kamioka Observatory, ICRR, University of Tokyo

Gravitational Waves
disturbances in a gravitational fields



Sky localisations of gravitational-wave signals detected by LIGO beginning in 2015 (GW150914, LVT151012, GW151226, GW170104), and, by the LIGO-Virgo network (GW170814, GW170817).



Credits: LIGO/Virgo/NASA/Leo Singer/Axel Mellinger

Gravitational Waves
disturbances in a gravitational fields

Munich Joint Astronomy Colloquium
https://www.eso.org/sci/meetings/garching.html

June 2021

24/06/21 (Thursday)

15:15, Webinar | ESO Garching

Munich Joint Astronomy Colloquium

Talk — The beginnings of gravitational wave astronomy: current state and future

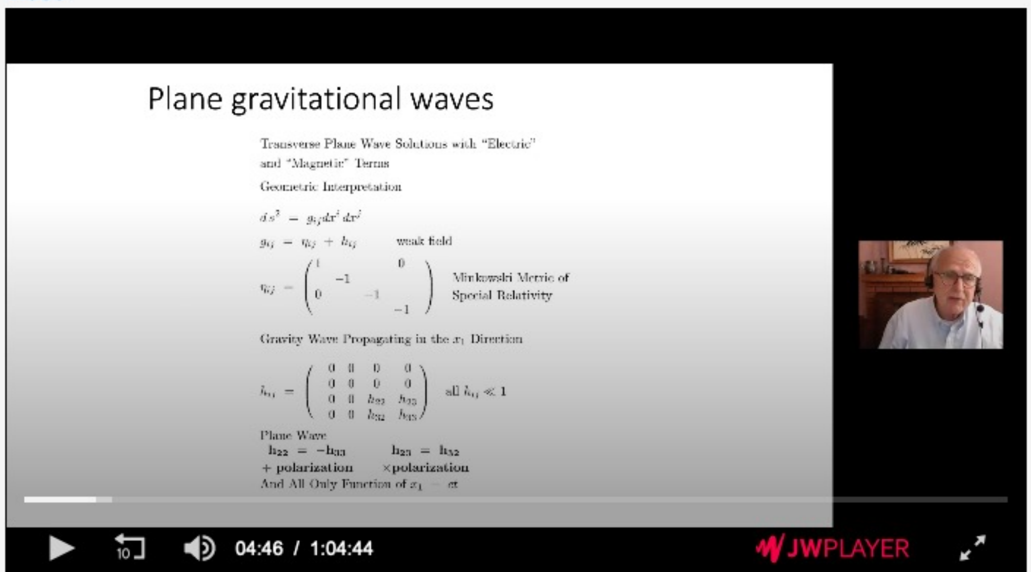
Rainer Weiss (MIT on behalf of the LIGO Scientific Collaboration)

Download video | Watch video / View Abstract

Abstract

The first detection of gravitational waves was made in September 2015 with the measurement of the coalescence of two ~30 solar mass black holes at a distance of about 1 billion light years from Earth. The talk will provide some history and description of the detector. A review will be given of more recent measurements of black hole events as well as the first detection of the coalescence of two neutron stars and the beginning of multi-messenger astronomy. The talk will end with a discussion of some prospects for the field.

Video



Electromagnetic radiation

Light

A wave and a particle

Electromagnetic radiation
Light

A wave and a particle

Maxwell's Equations of Electromagnetism

$$\nabla \cdot \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

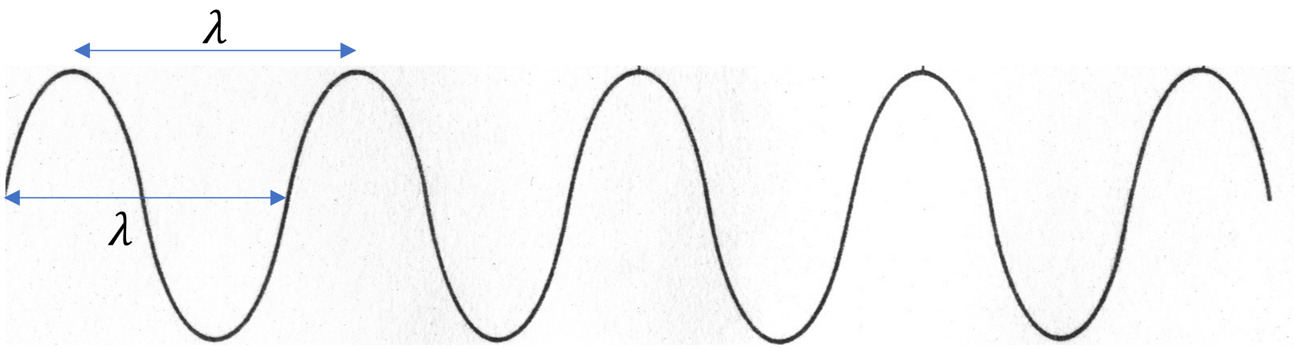
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Electromagnetic radiation

Light

A wave and a particle

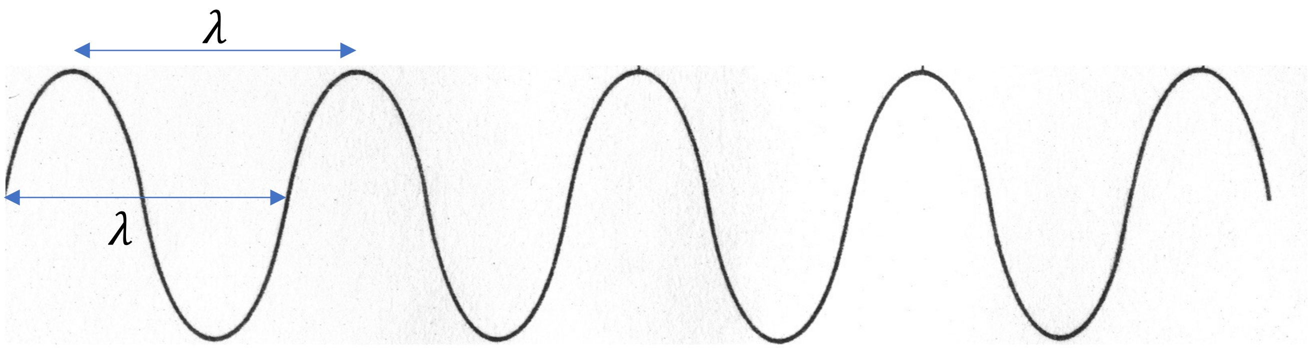


- **wavelength λ (lambda)**: distance between two corresponding positions of adjacent waves

units [meter, centimeter, micron (μm = 10^{-6}m), nanometer (nm = 10^{-9}m), and Ångstrom (Å = 10^{-10}m)]

Electromagnetic radiation
Light

A wave and a particle



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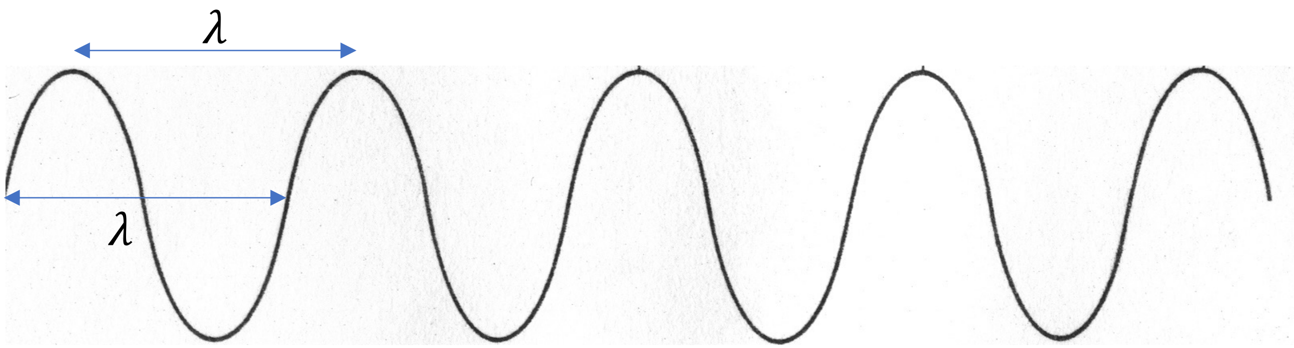
- **frequency ν (nu)**: number of waves that pass a given point per second units [s^{-1} i.e. Hertz]

Electromagnetic radiation
Light

A wave and a particle



- **wavelength λ (lambda)**: distance between two corresponding positions of adjacent waves
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- **frequency ν (nu)**: number of waves that pass a given point per second
units [s^{-1} i.e. Hertz]

- **velocity *c*** : $\lambda\,\nu = c$
units [e.g. m/*s*]
The speed of light in a vacuum is 2.99792458×10^8 m/s. ~300000 km/s

Electromagnetic radiation
Light

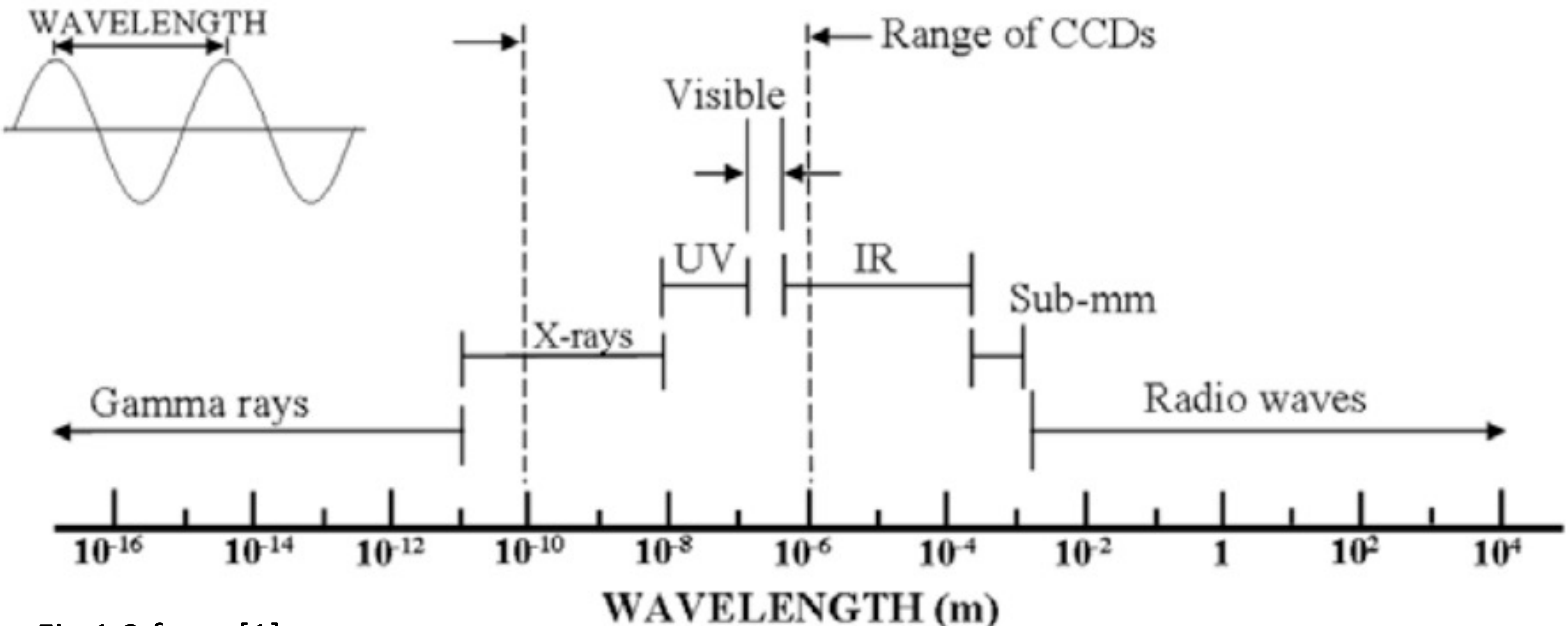


Fig 1.3 from [1]

Electromagnetic radiation

Light

A wave and a particle

$$E = h \cdot \nu$$

- *h* is **Planck's constant** (6.626 × 10^{-34} J· s)
- ν (nu): is the frequency of the light wave.

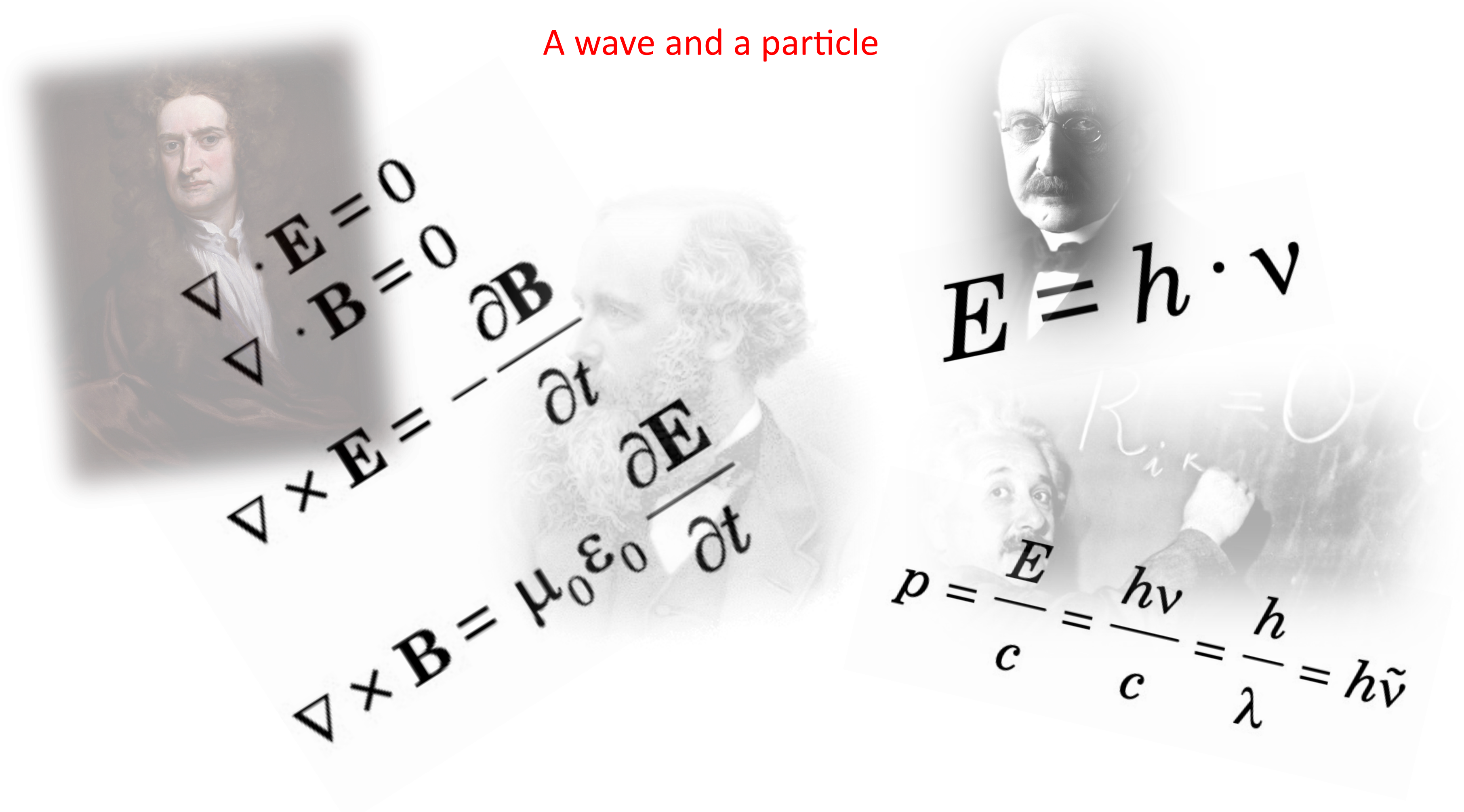
The energy of a light wave is quantized: Photons

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} = h\tilde{\nu}$$

Electromagnetic radiation

Light

A wave and a particle



Electromagnetic radiation
Light

Multi-Wavelength

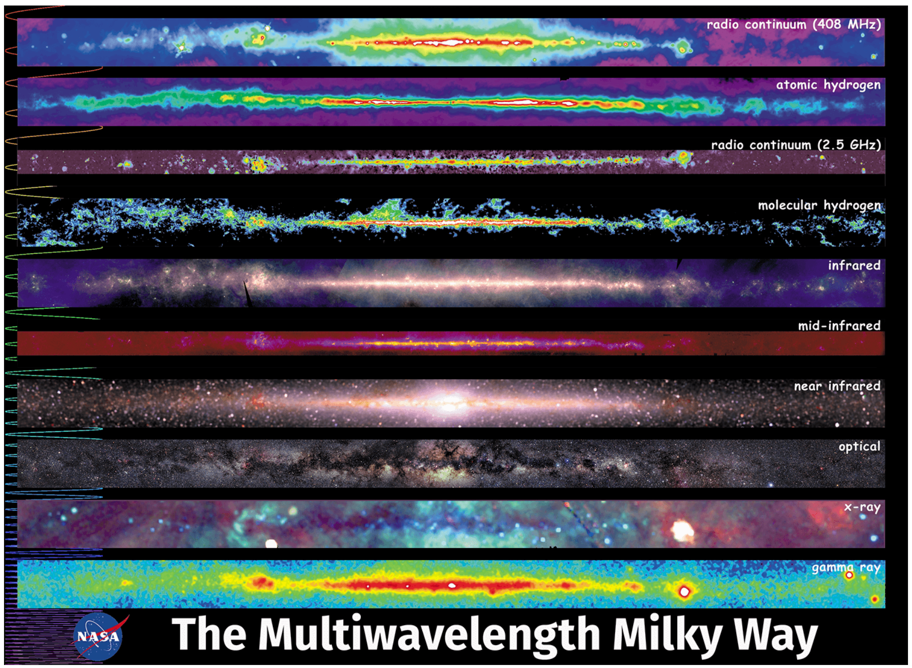
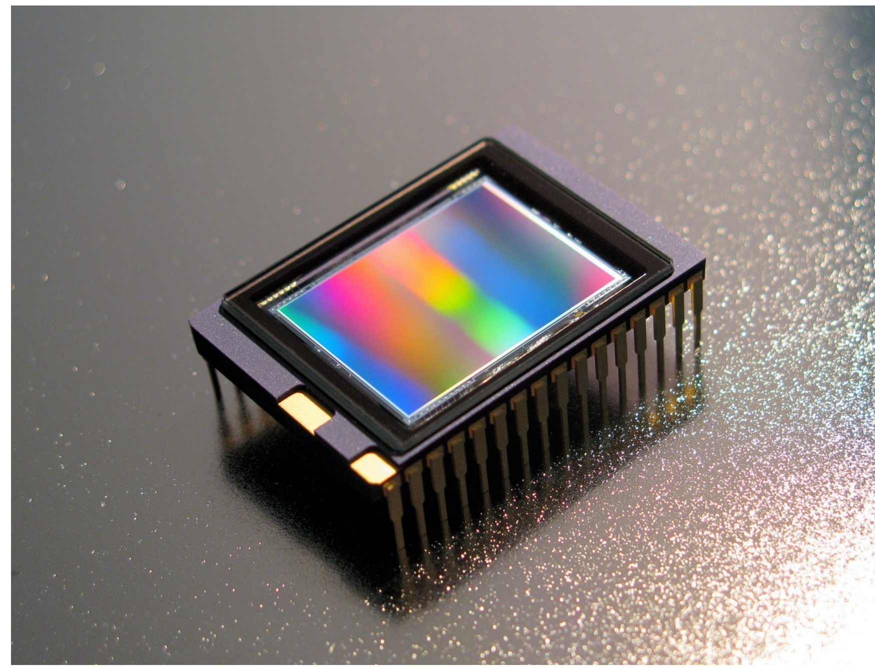


Image Credit: ESA/NASA/Felix Mirabel

Particle



Credit: Moravian Instruments

Electromagnetic radiation

Light

The history of astronomy is how human people have learn

1. to amplify and collect these waves
2. to extract (from them) fundamental informations on the structure of the universe

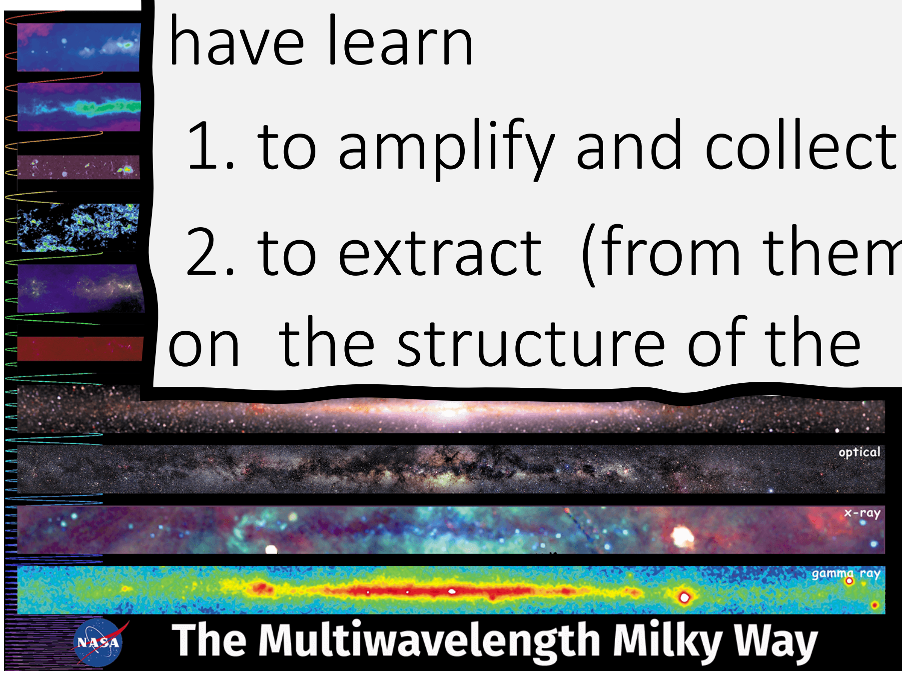
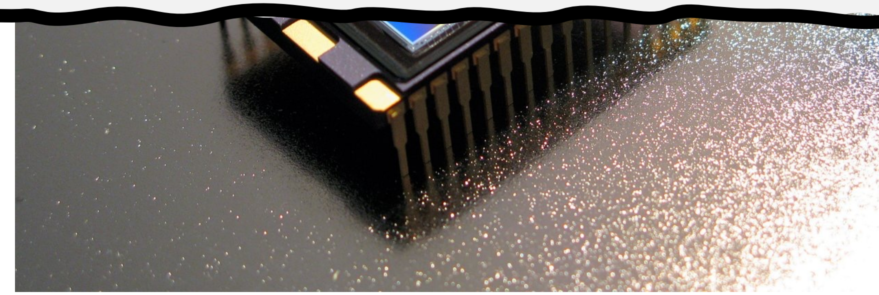
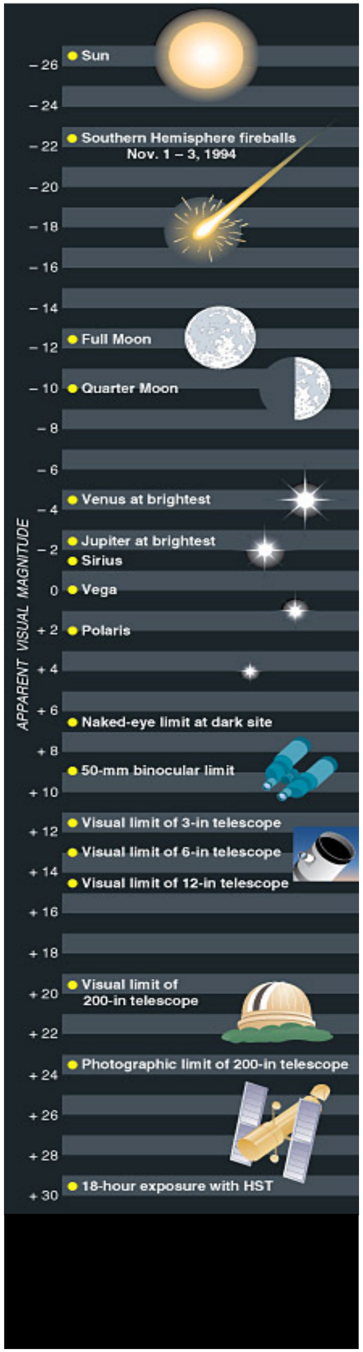


Image Credit: ESA/NASA/Felix Mirabel



Credit: Moravian Instruments



-26 Sun

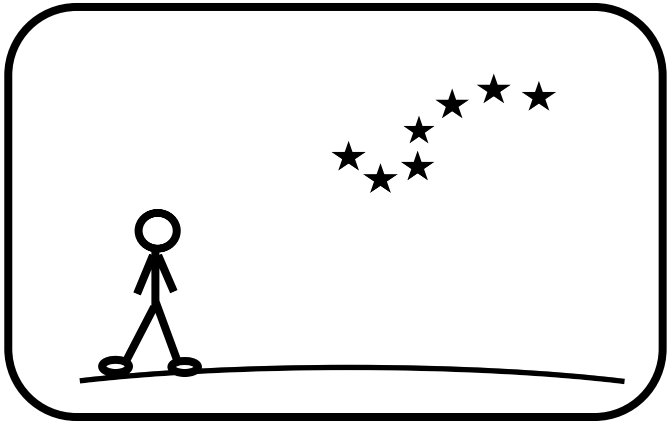
-12 Full Moon

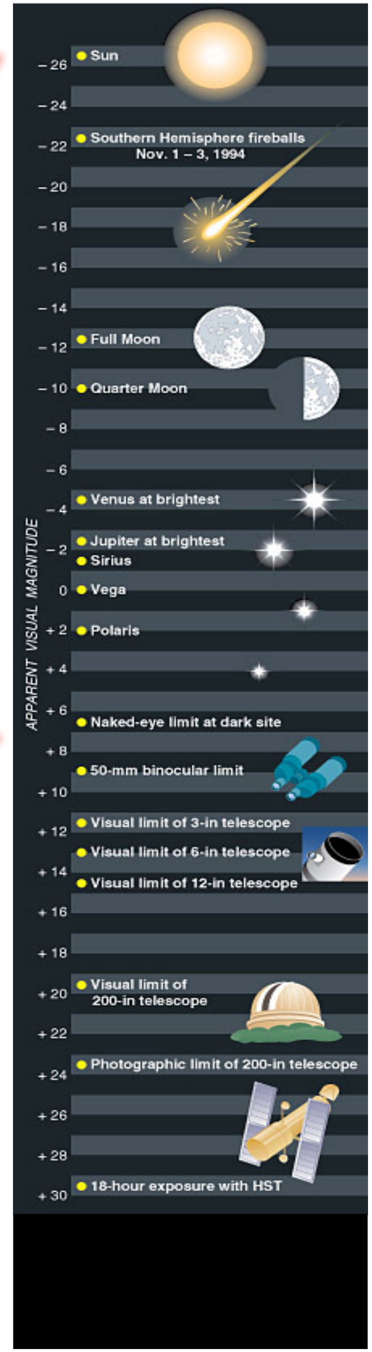
-4 Venus

0 Vega

+2 Polar

Hipparchus (120 BC)





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0 Vega
+2 Polar

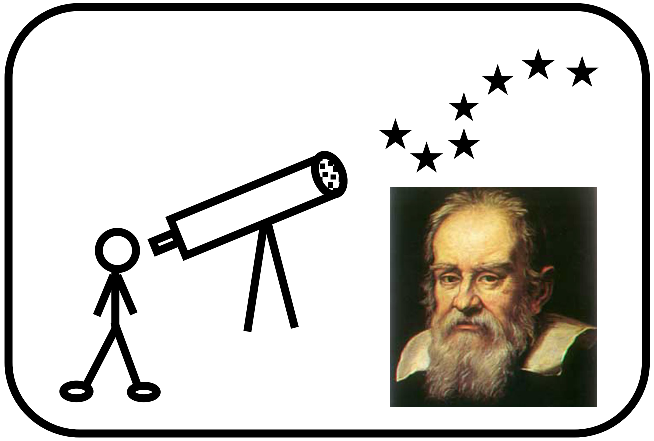
+9 Neptune
+11 Pluto

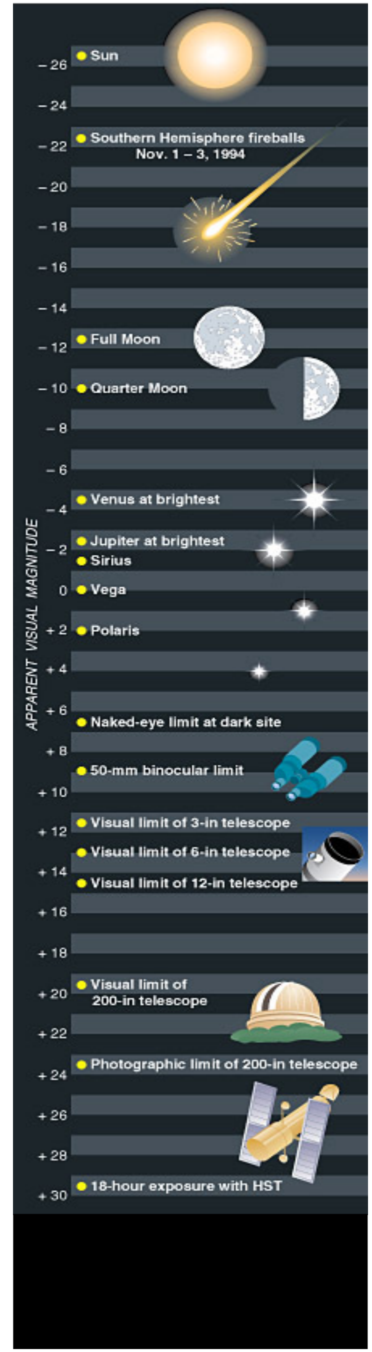
+13 LMC/SMC
+15 Globular Clusters

+23 low Z galaxies

+32 High Z galaxies

Galileo Galilei (1600 AC)





-26 Sun

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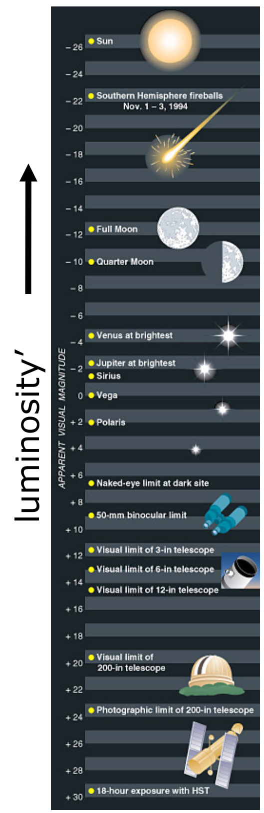
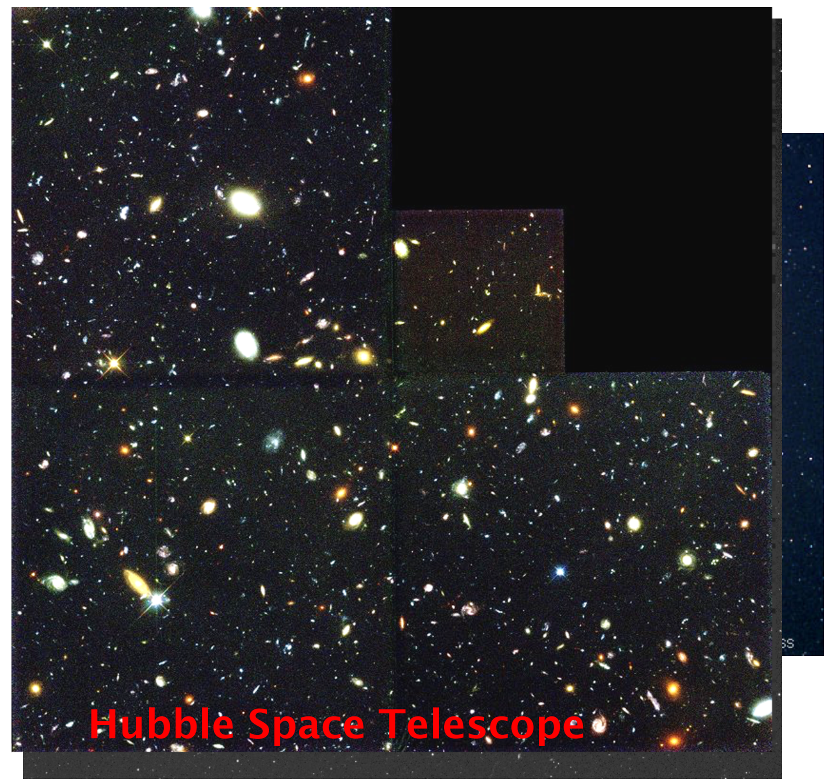
The use of Telescopes increases sensibility to light thanks to the large collecting area and use of long exposures



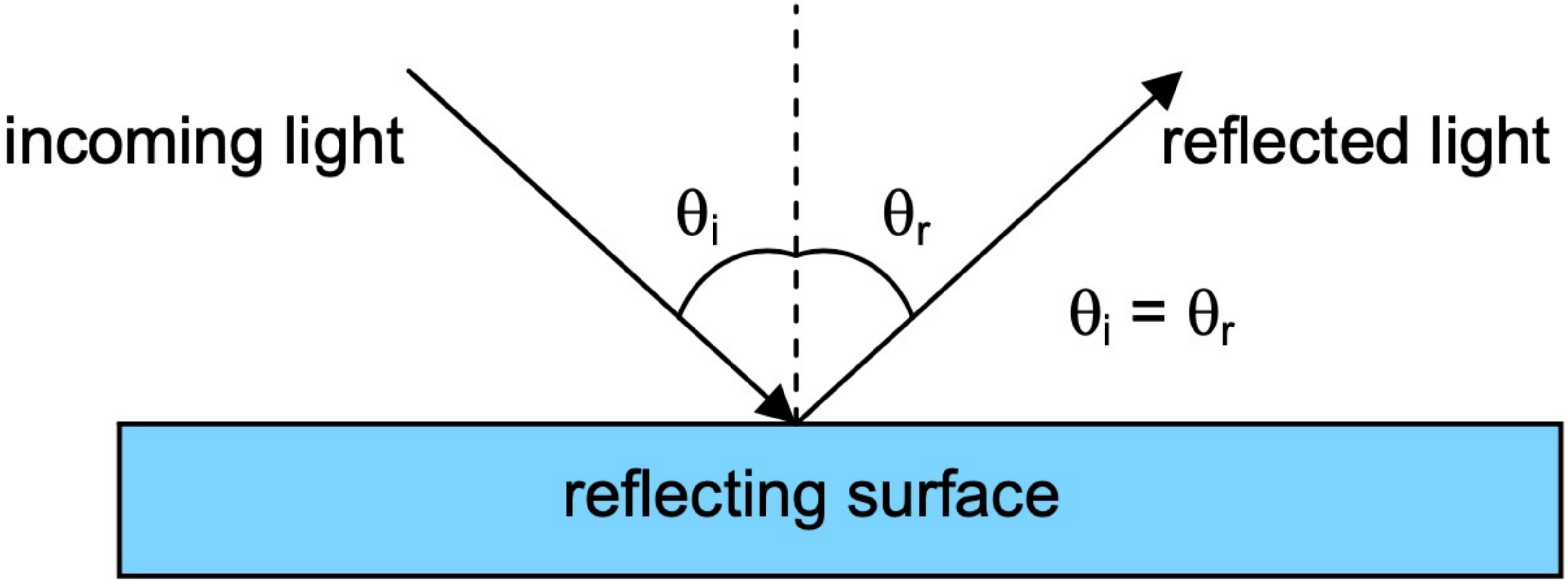


Interaction Light-matter

Reflection

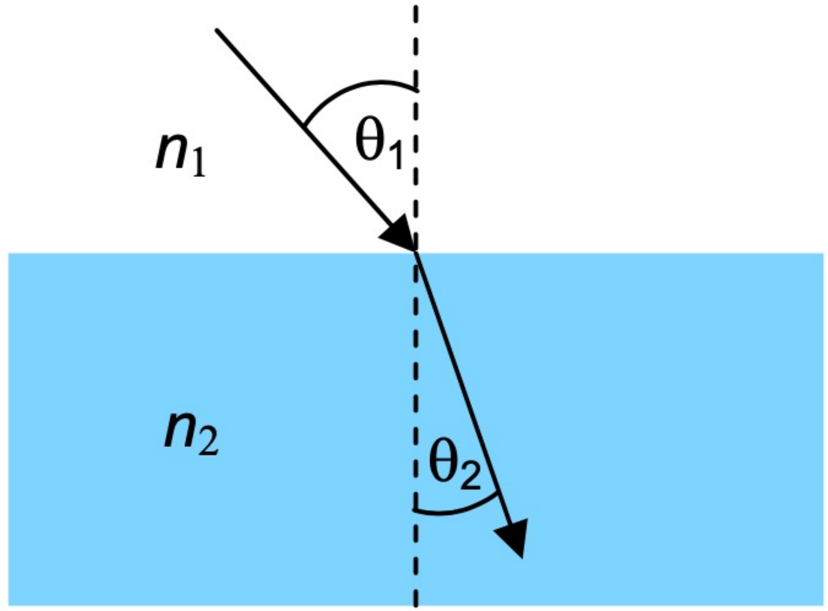
Θ_i = Angle of incidence

Θ_r = Angle of reflection



Interaction Light-matter

Refraction



$\theta_1 \neq \theta_2$

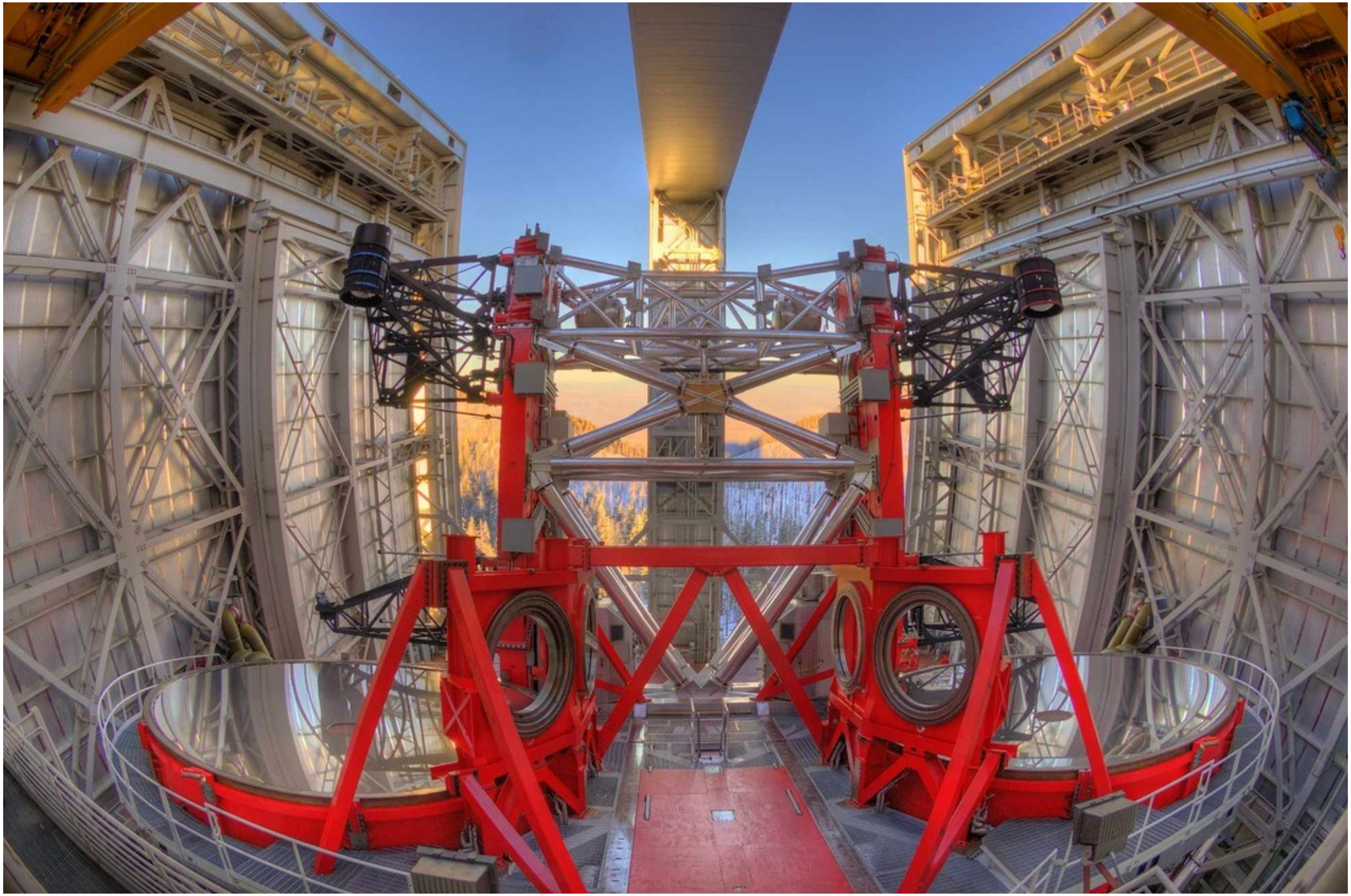
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$ (Snell's Law)

- n_1 *and* n_2= refractive index ($n=c/v$)

Indices of refraction are temperature-dependent and wavelength-dependent.

Interaction Light-matter

Refraction and Reflection



Interaction Light-matter

Refraction and Reflection

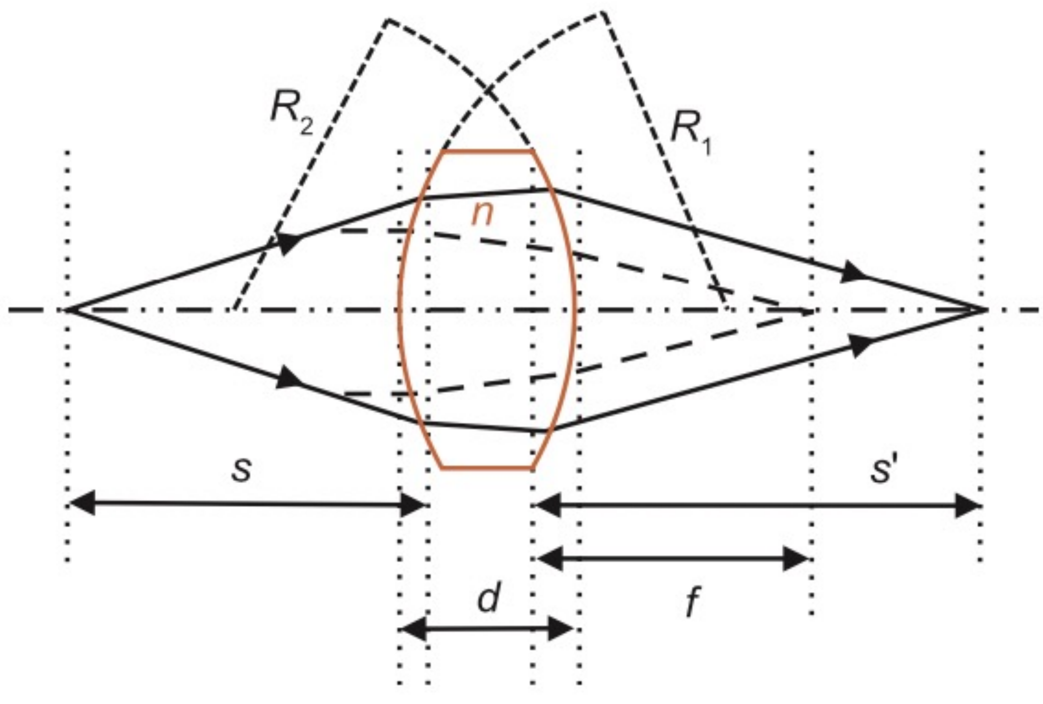
MIRROR(S)

Interaction Light-matter

Refraction and Reflection

LENS(ES)

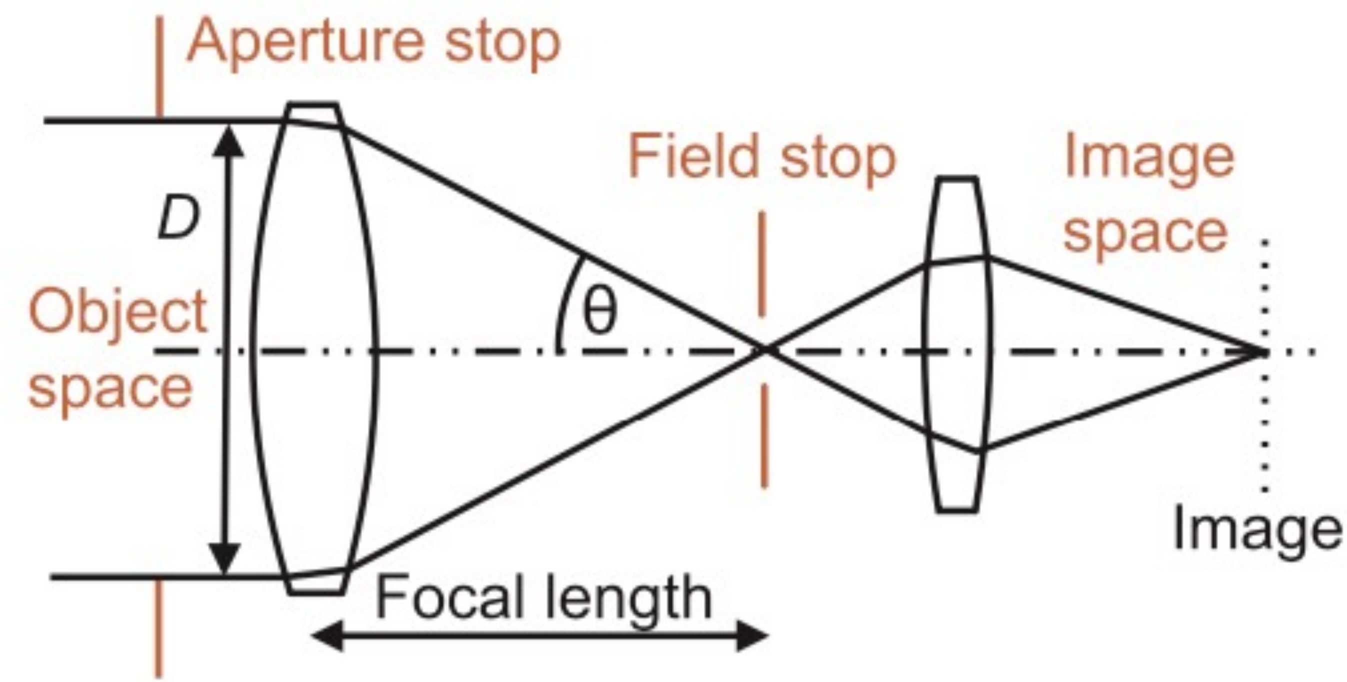
Lens: transparent refracting optical elements made of glass or crystals.



- focal length (f) ==> $\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_1}\right)$

- focal ratio=*f/D or F-number*

System of lenses



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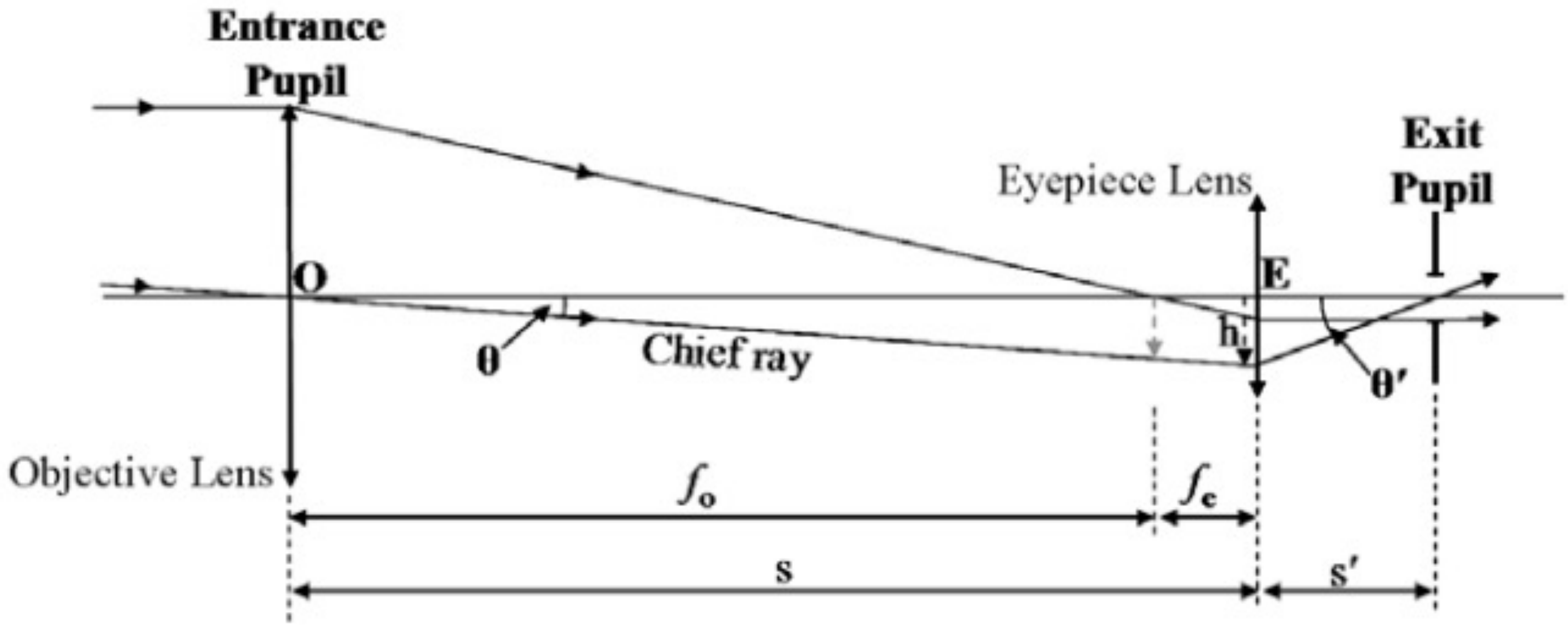


Mirrors are preferred to lenses

LENS

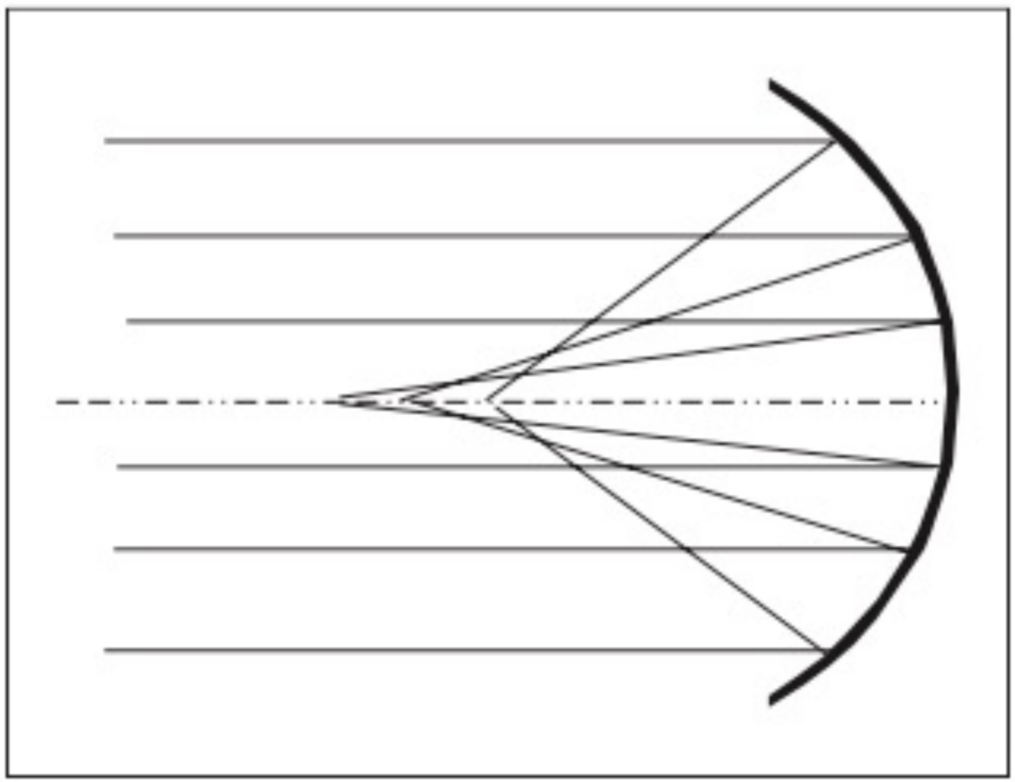
- Must be transparent and free of internal flaws that can cause scattering
- Chromatic aberration due to the wavelength dependence of its refractive index
- Must be supported around its rim

MIRROR

- Good surface
- Achromatic
- Can be fully supported across the back

Mirrors: reflective optical elements that change the direction and/or wavefront of a beam.

Spherical Mirror



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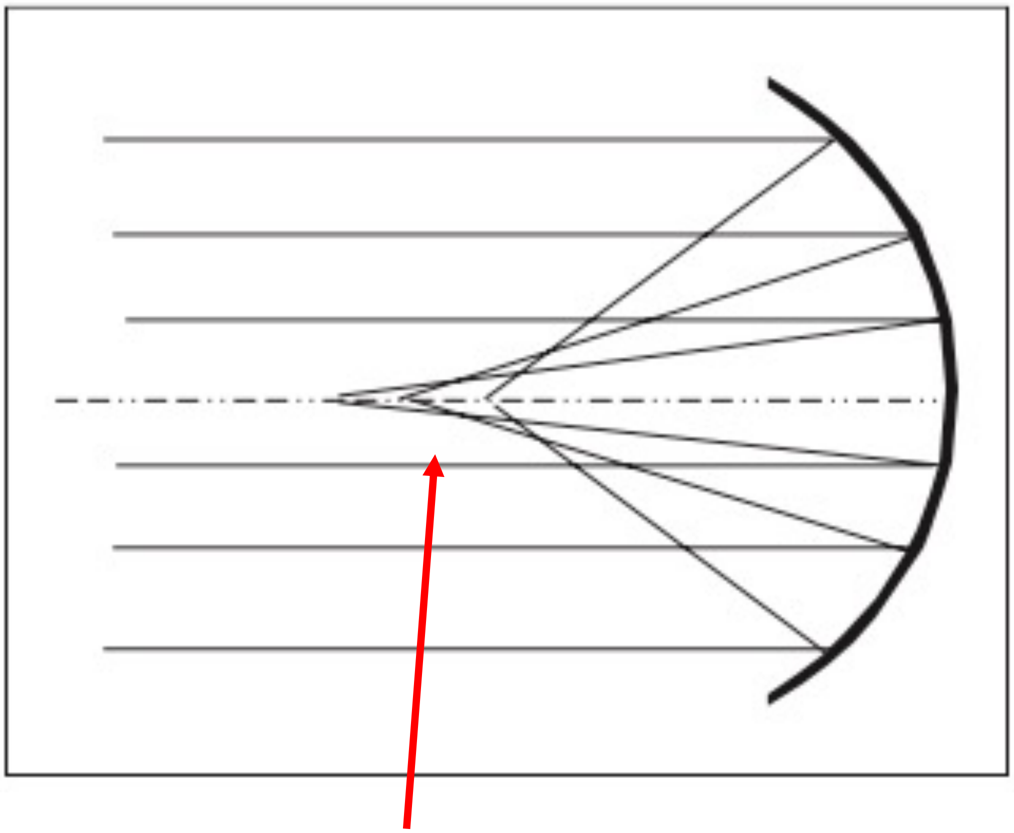
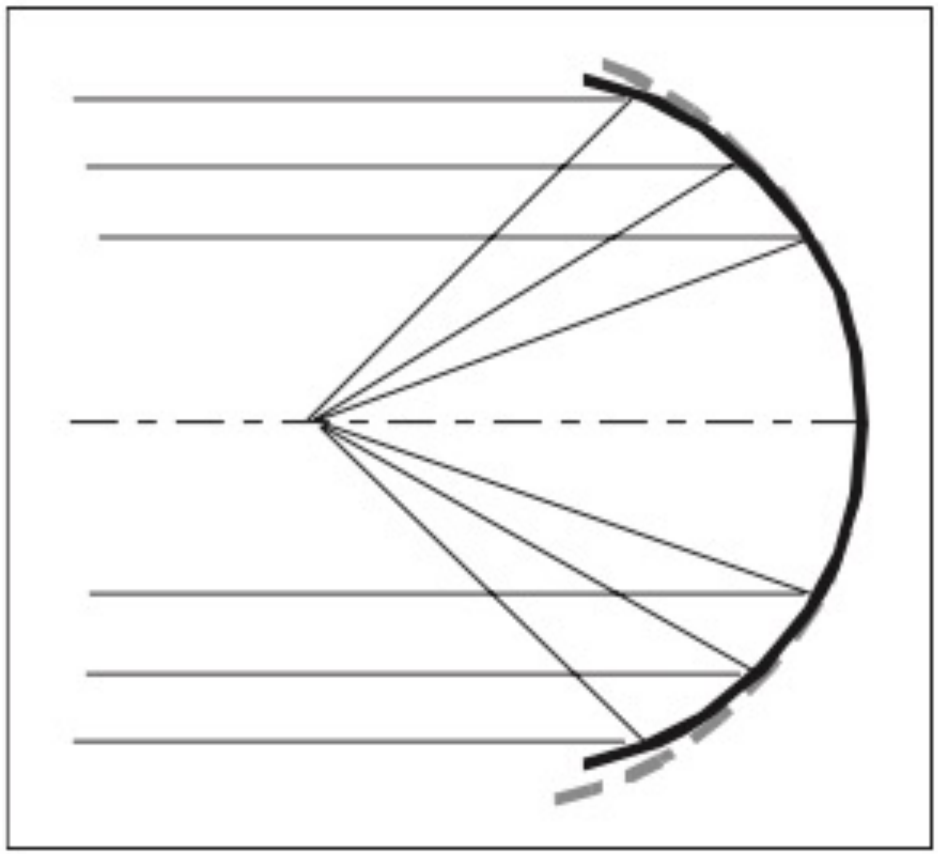
Spherical Mirror



suffers from spherical abberration

Mirrors

Best solution: use conic sections
ellipse, parabola or hyperbola



Mirrors

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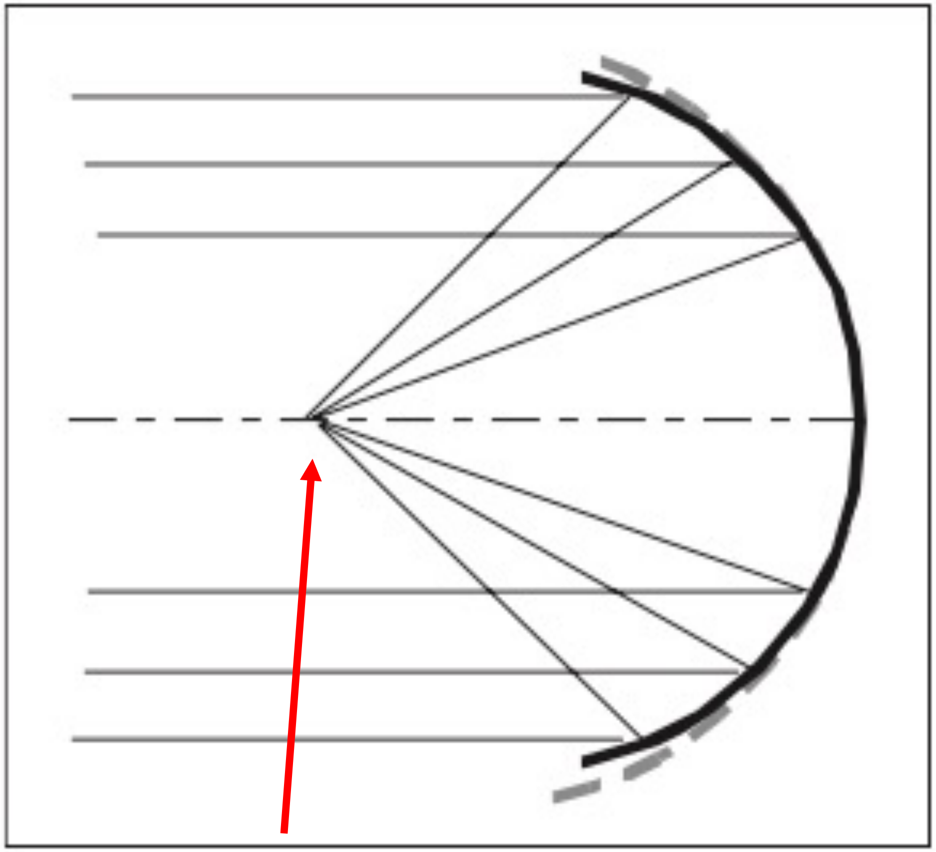
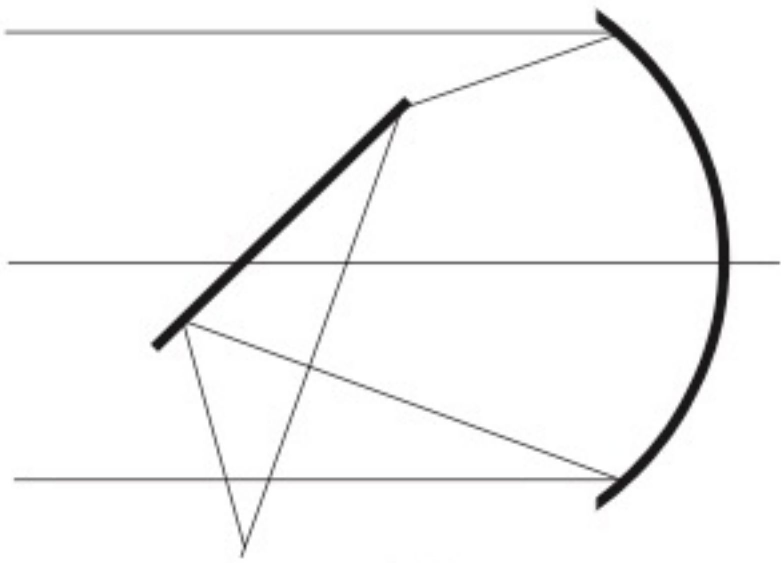
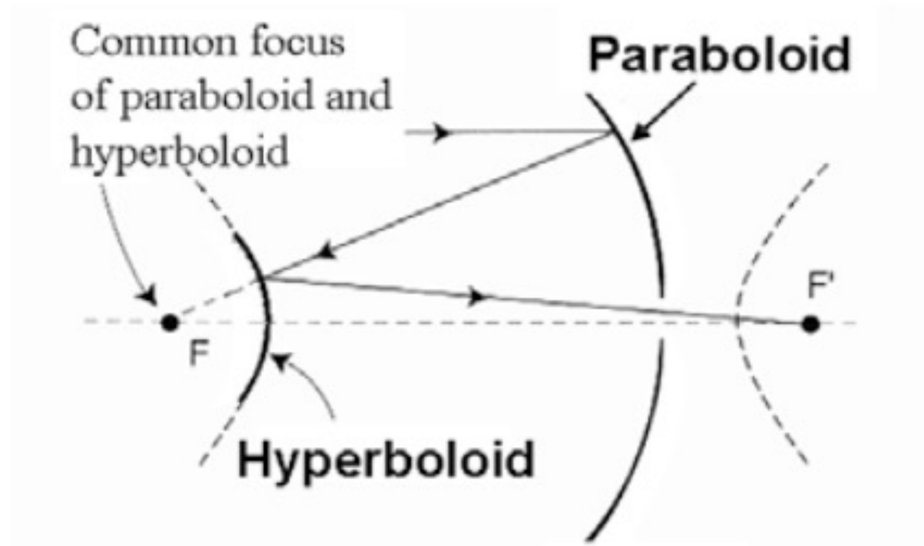


another problem:
light goes back into de incoming beam

Telscopes made of multiple mirrors!



Newtonian

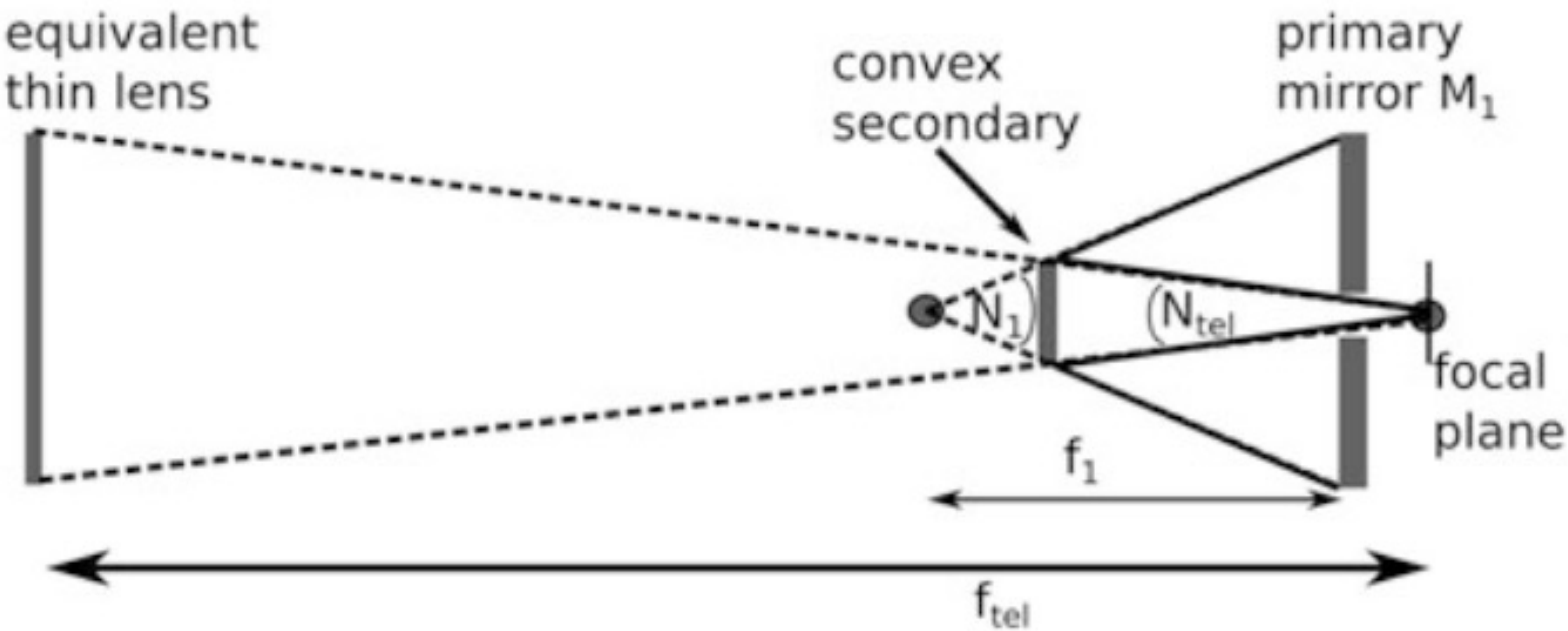


Cassegrain

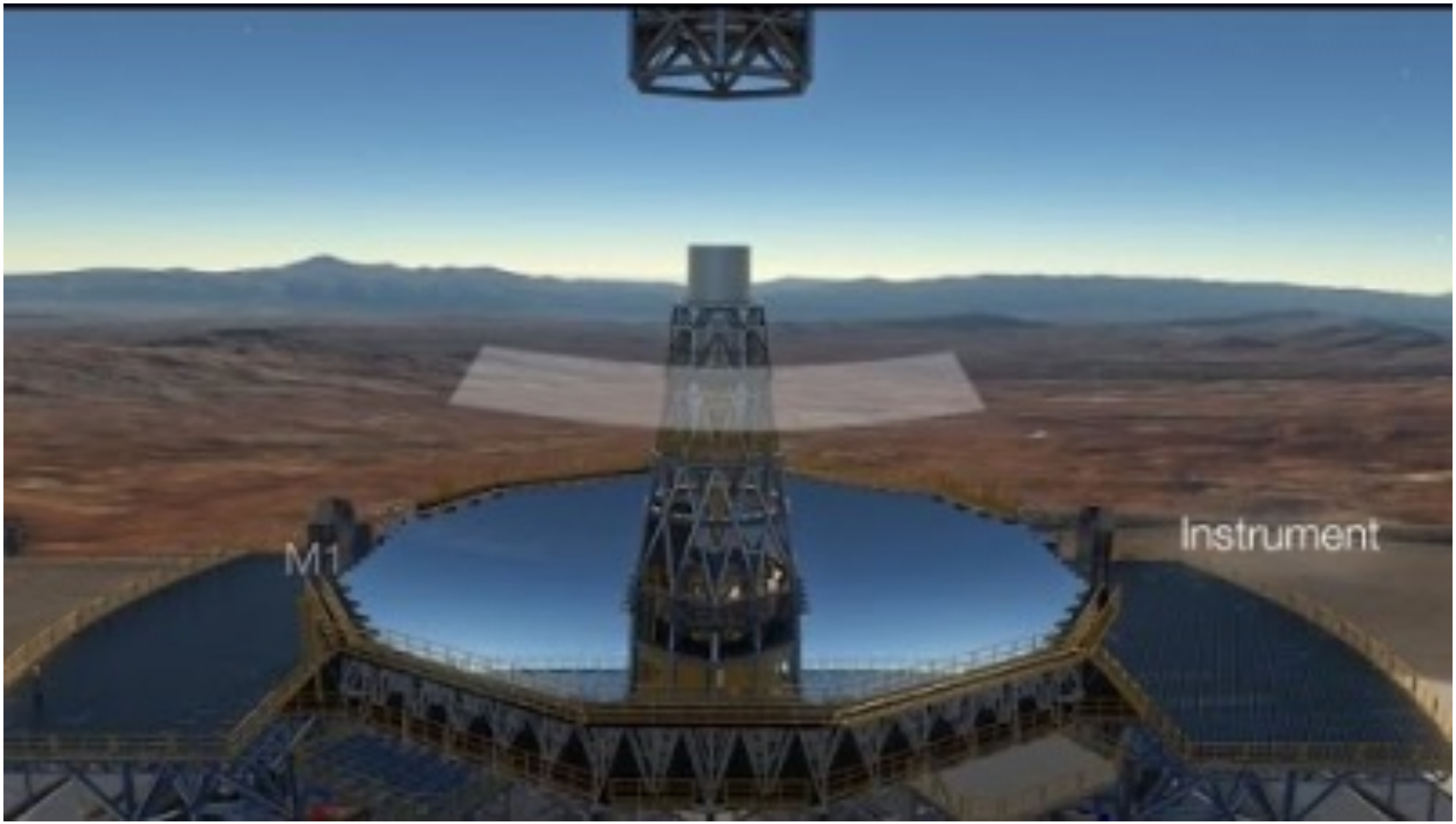
- Very successful: Ritchey-Chrétien (or RC) design in which both the primary and secondary are hyberbolic surfaces.

Final word on Lens vs Mirro Tel:

Final word on Lens vs Mirro Tel:



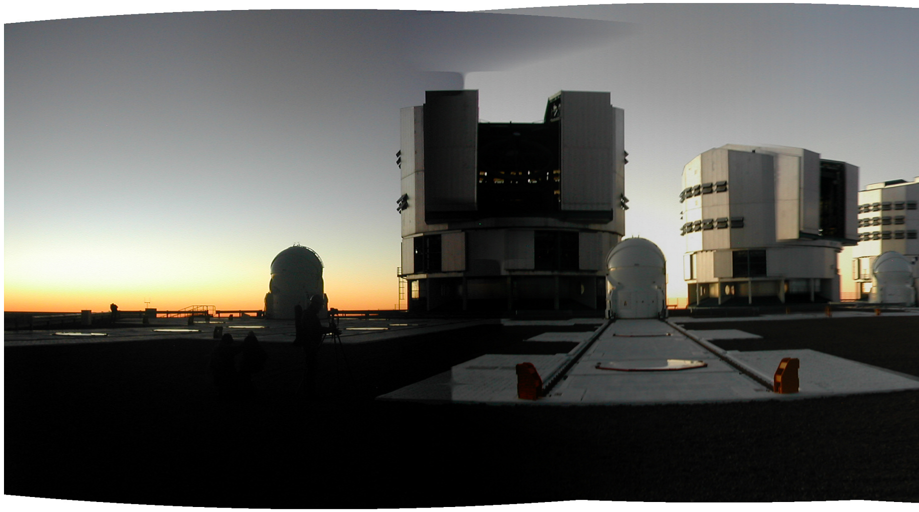
Telscopes made of multiple mirrors!



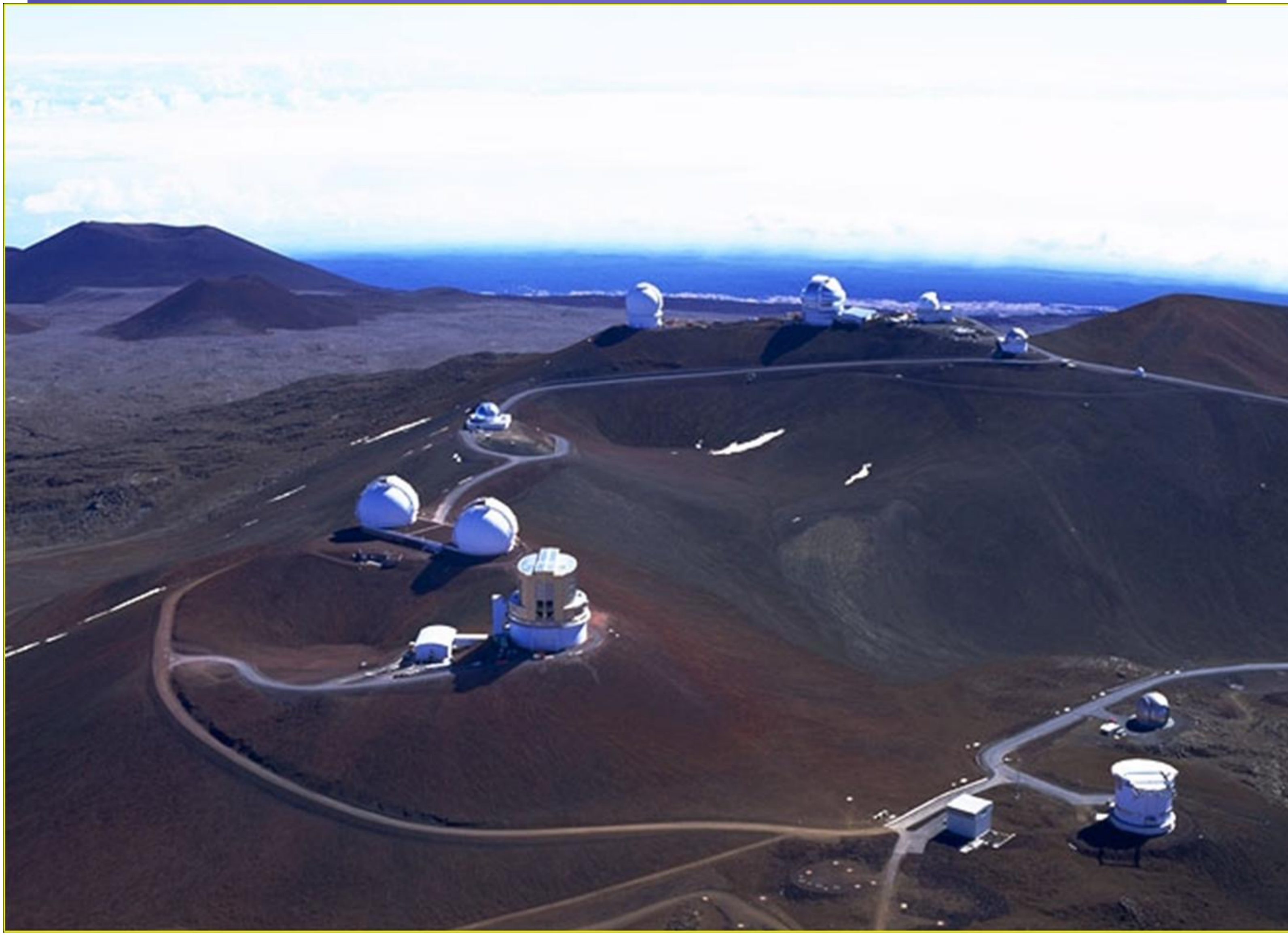
https://elt.eso.org/mirror/

Astronomical Sites

- Requirements:
  - Clear sky
  - Low umidity
  - …and dark

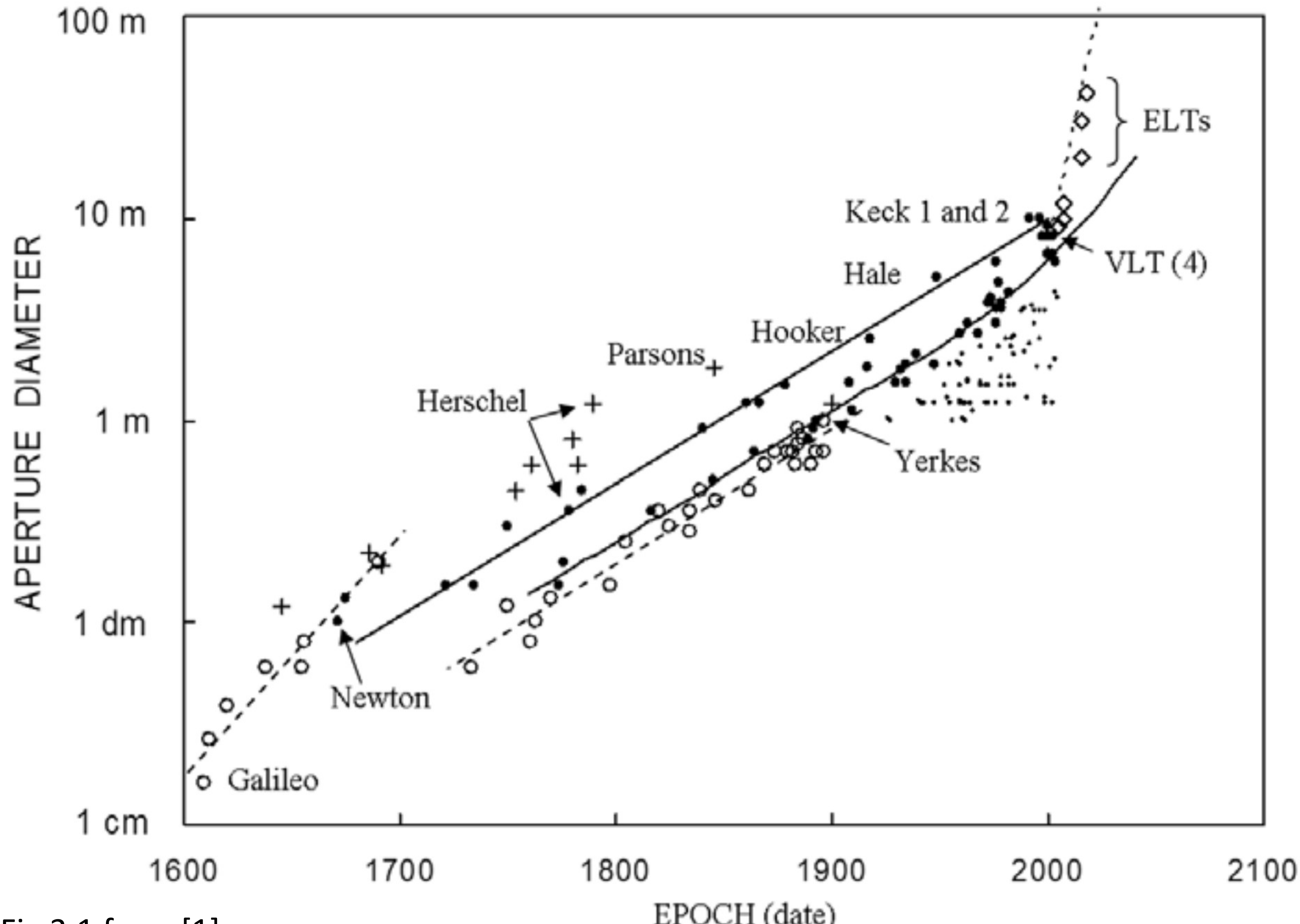


CERRO PARANAL (Cile – 2700 mt.)



- MAUNA KEA (Hawaii – 4200 mt)

- ROQUE DE LOS MUCHACHOS (Canary Islands – 2500 mt)



100 m
10 m
1 m
1 dm
1 cm
APERTURE DIAMETER
1600
1700
1800
1900
2000
2100
EPOCH (date)
ELTs
Keck 1 and 2
VLT (4)
Hale
Hooker
Parsons
Herschel
Yerkes
Newton
Galileo

Fig 3.1 from [1]

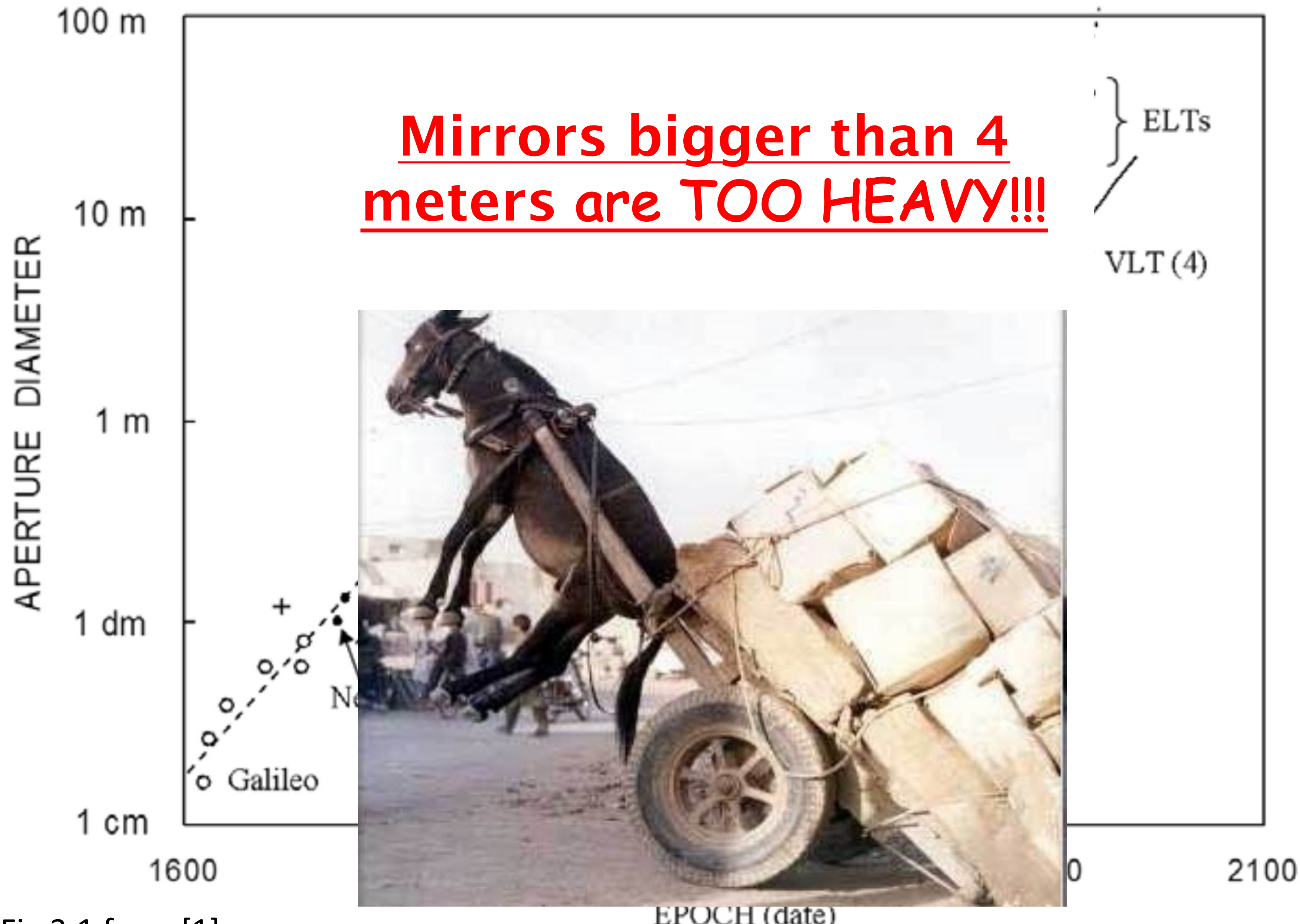
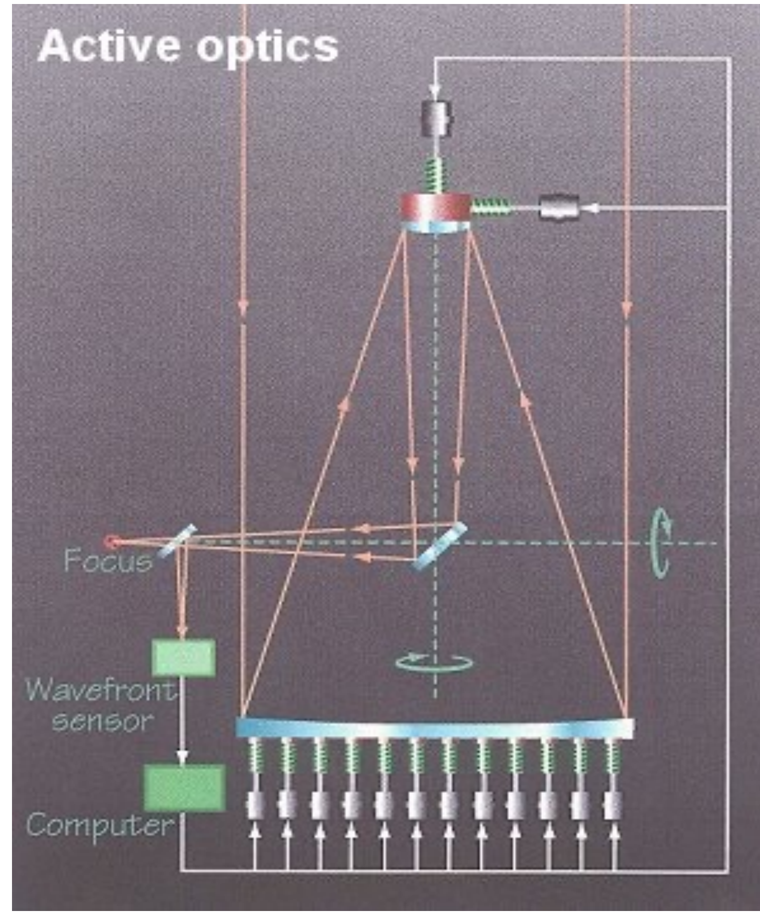
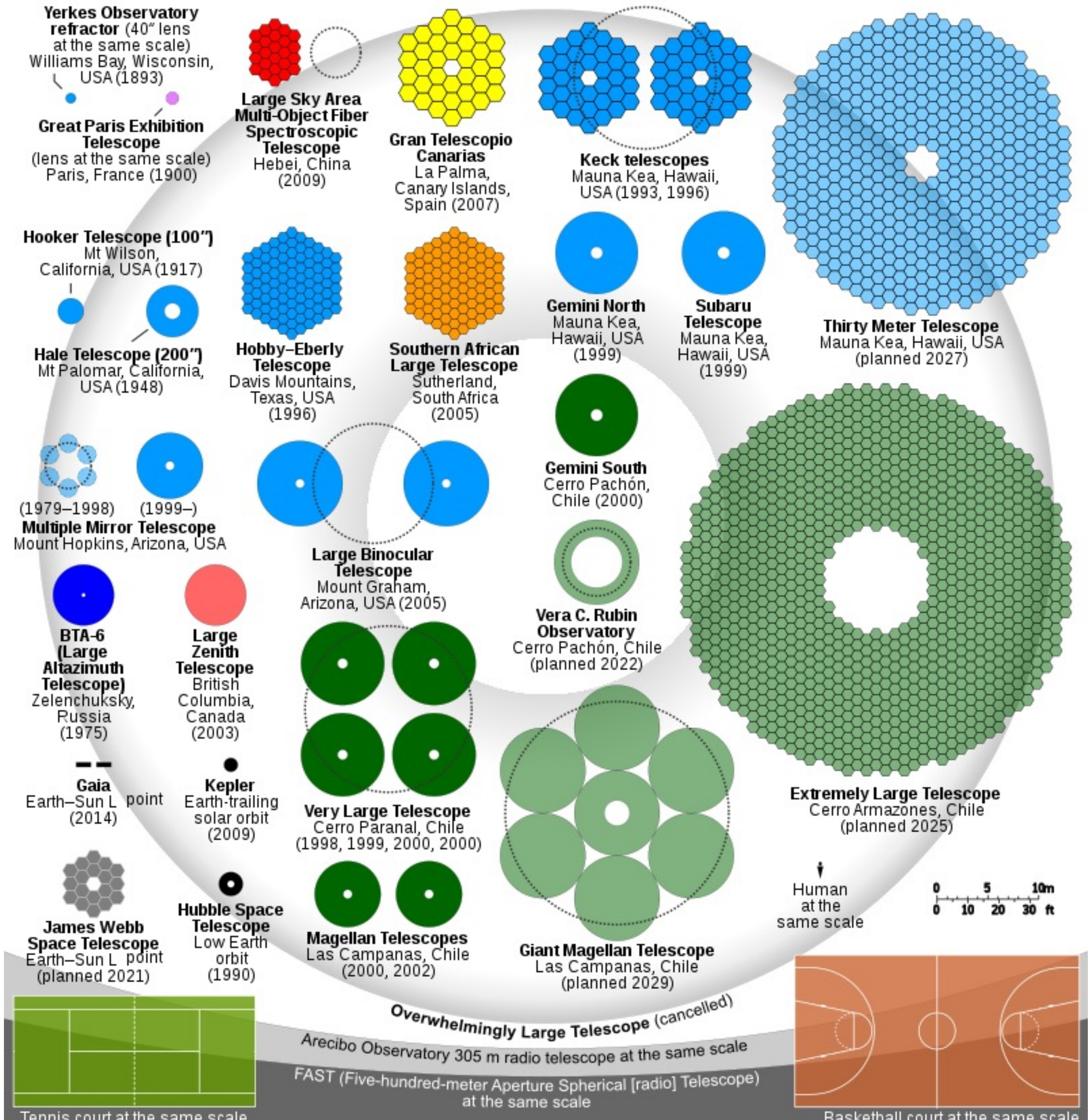

Mirrors bigger than 4 meters are TOO HEAVY!!!
100 m
10 m
1 m
1 dm
1 cm
APERTURE DIAMETER
ELTs
VLT (4)
Galileo
1600
2100
EPOCH (date)

Fig 3.1 from [1]

ESO-NTT, 3.6m, provided with an active optic



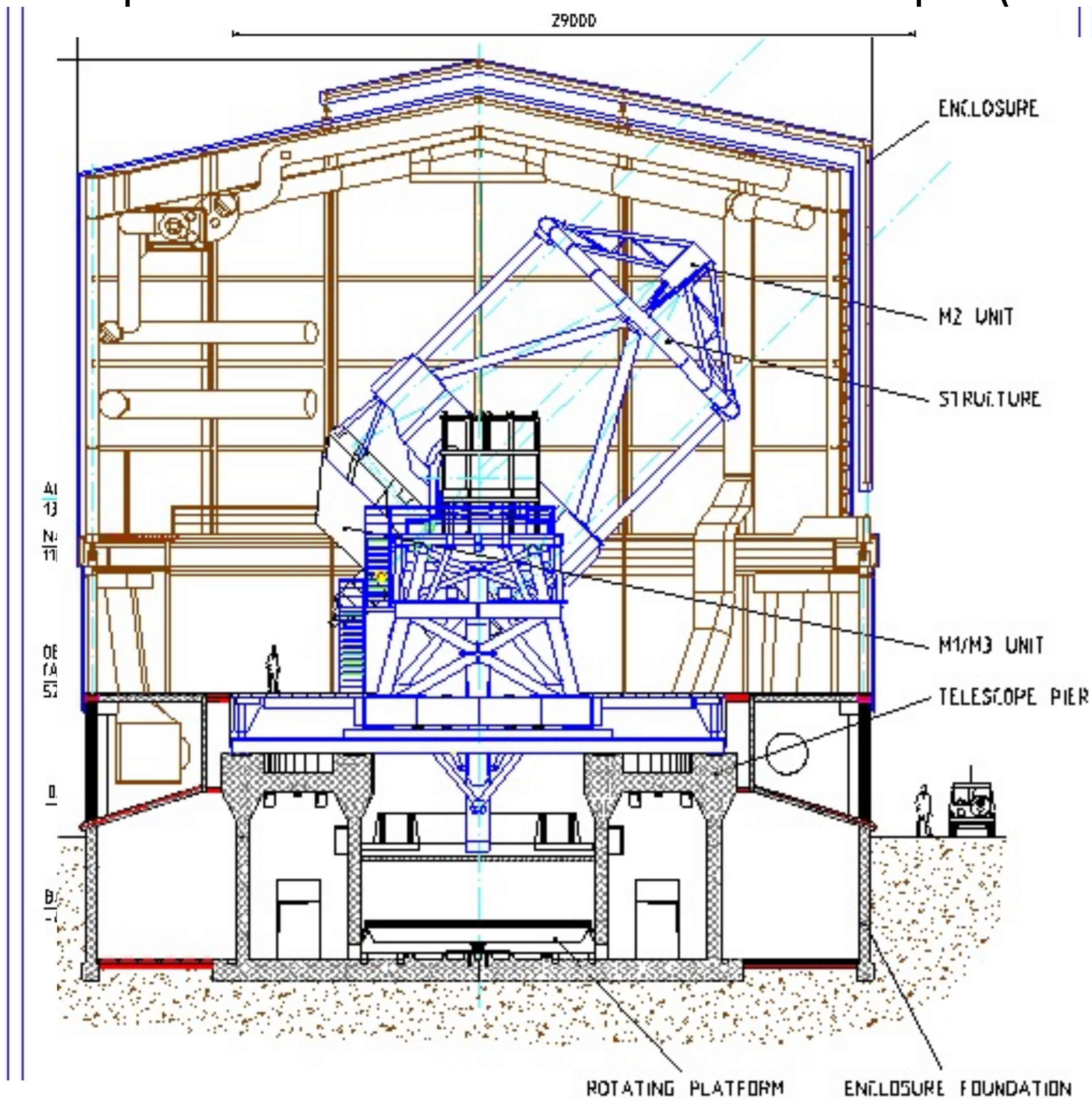


Credits: Wikipedia

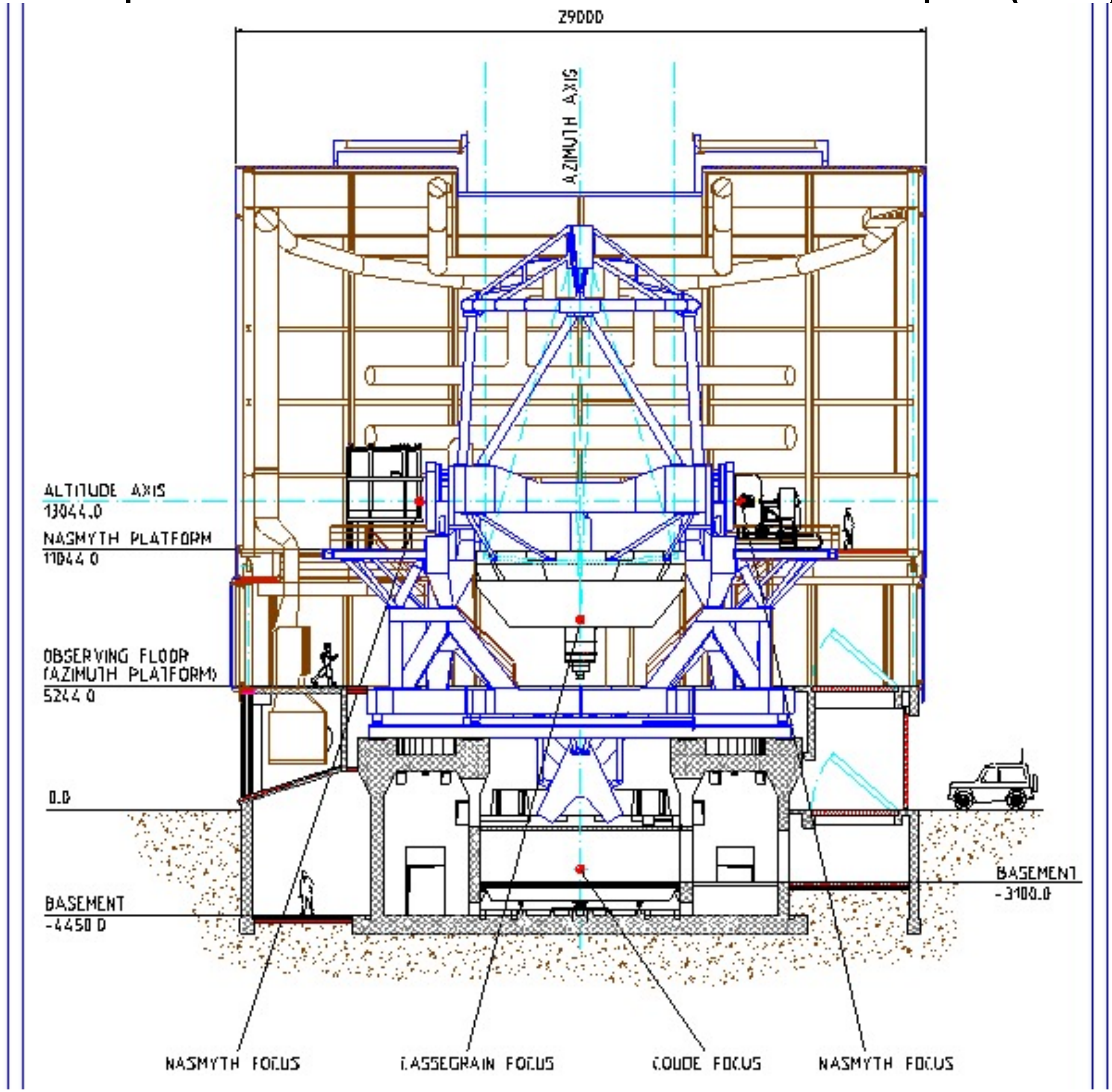
Extremely Large telescopes era!

- <u>8 meters class</u>

ESO Telescopes at Paranal: Unit Telescops (UT)



ESO Telescopes at Paranal: Unit Telescops (UT)



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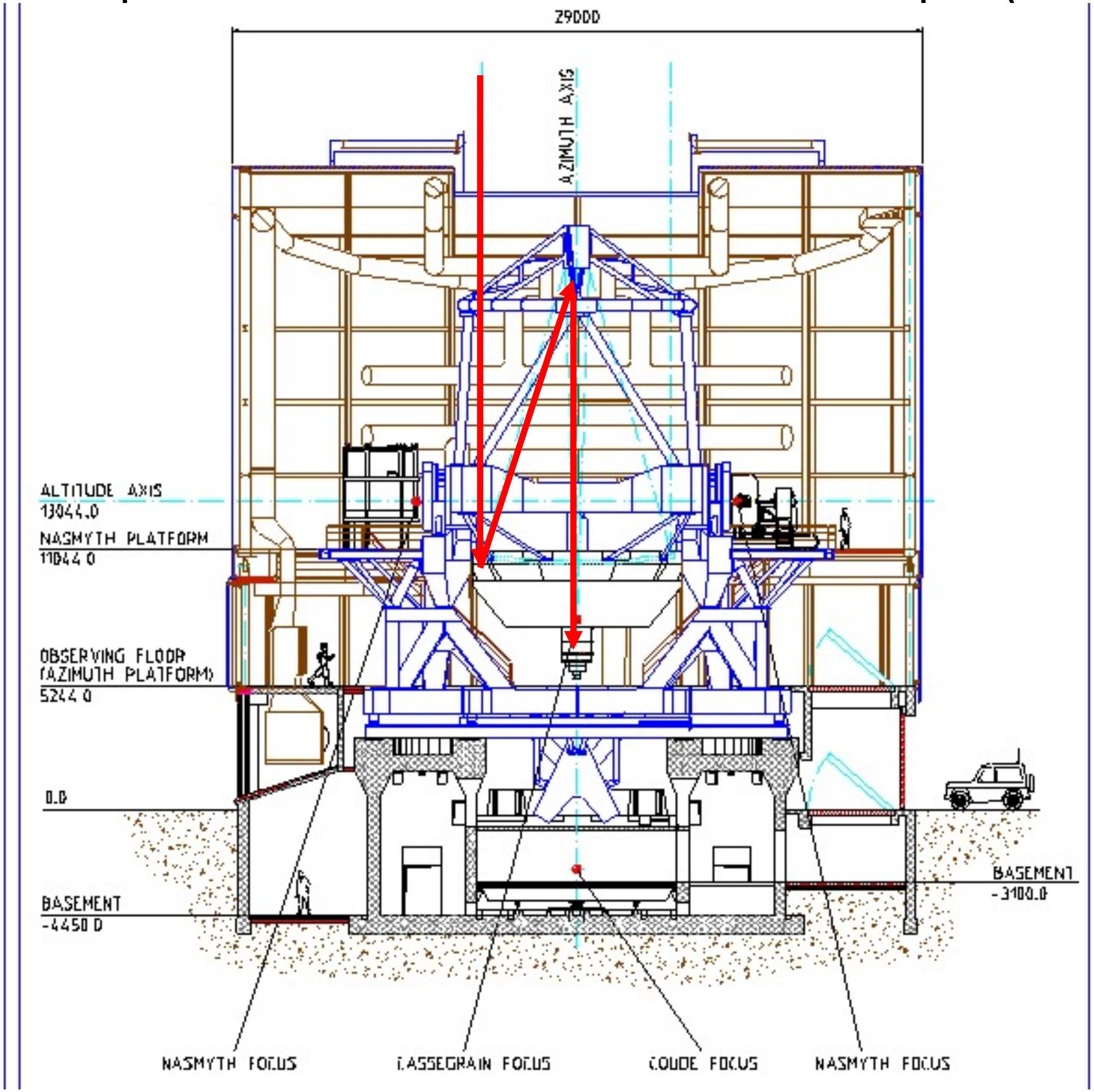
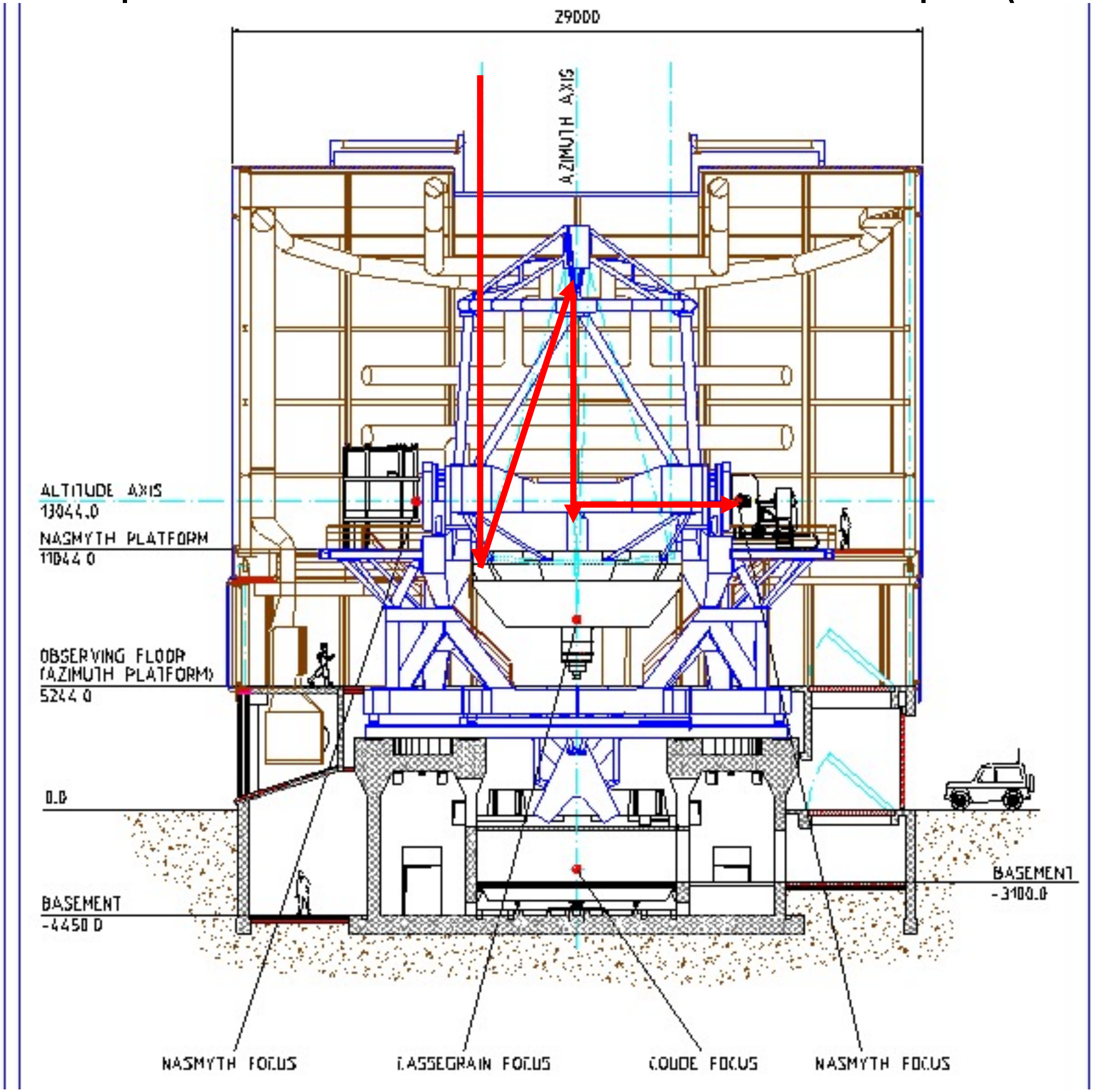


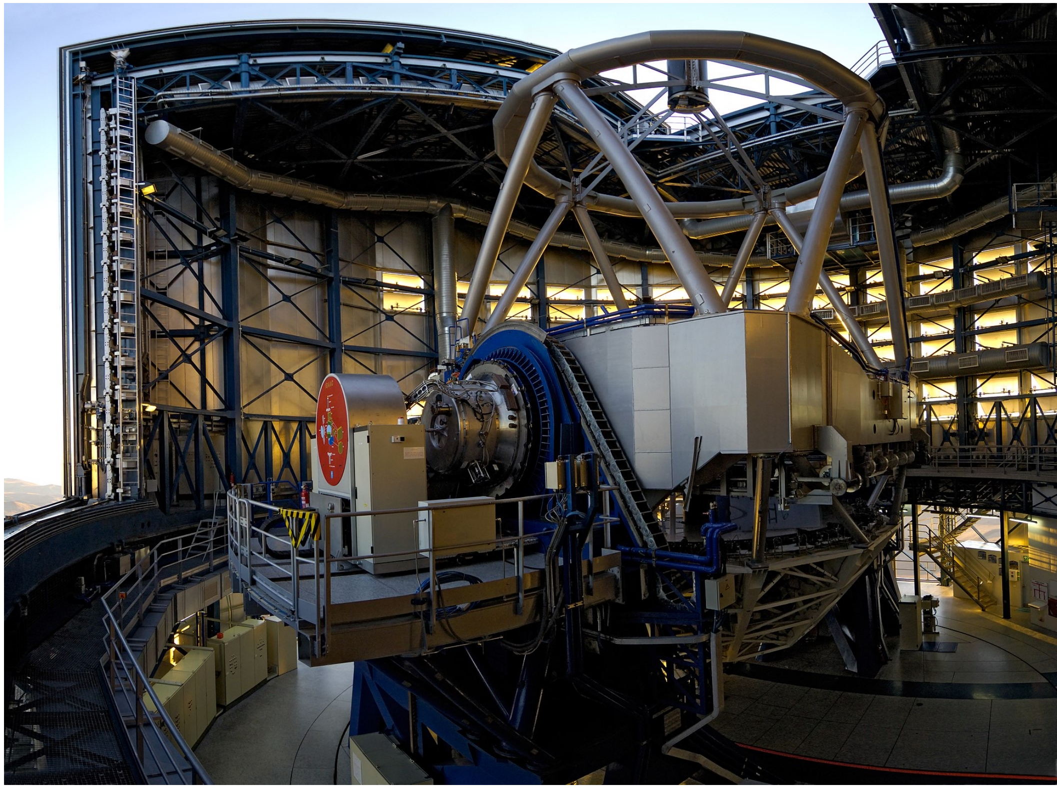
ESO Telescopes at Paranal: Unit Telescops (UT)



ESO Telescopes at Paranal: Unit Telescops (UT)

La Silla: 3.6m - Equatorial

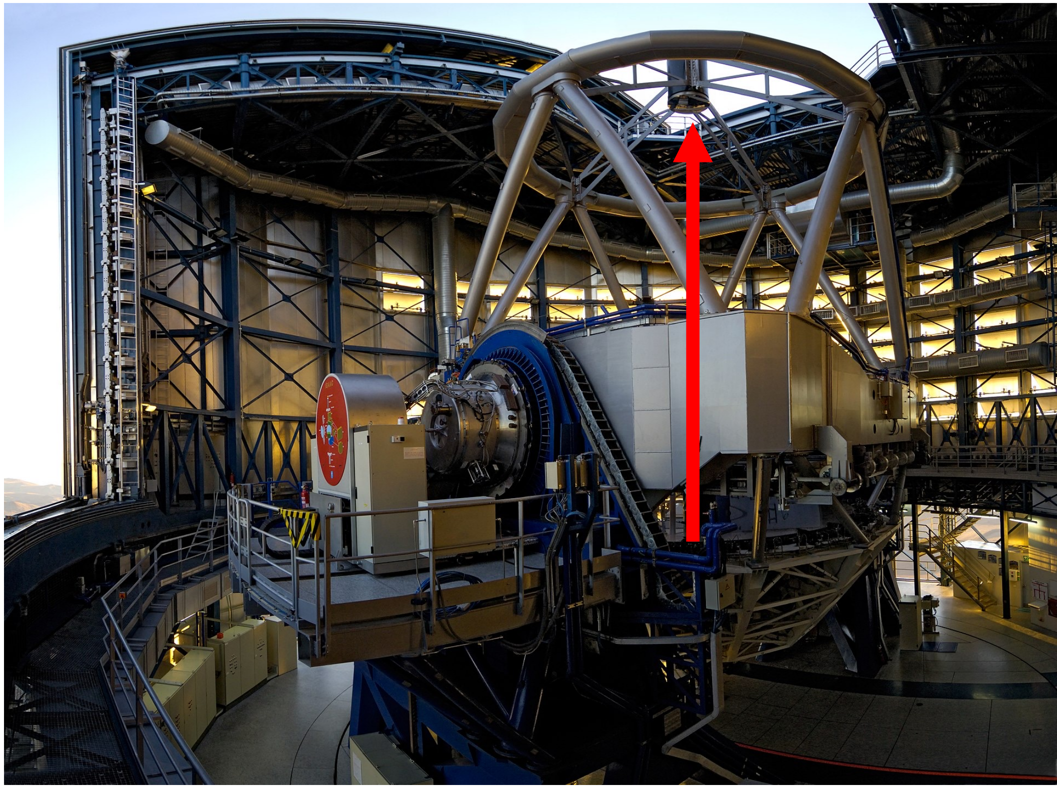
Paranal: UT – Alt-Azimuth



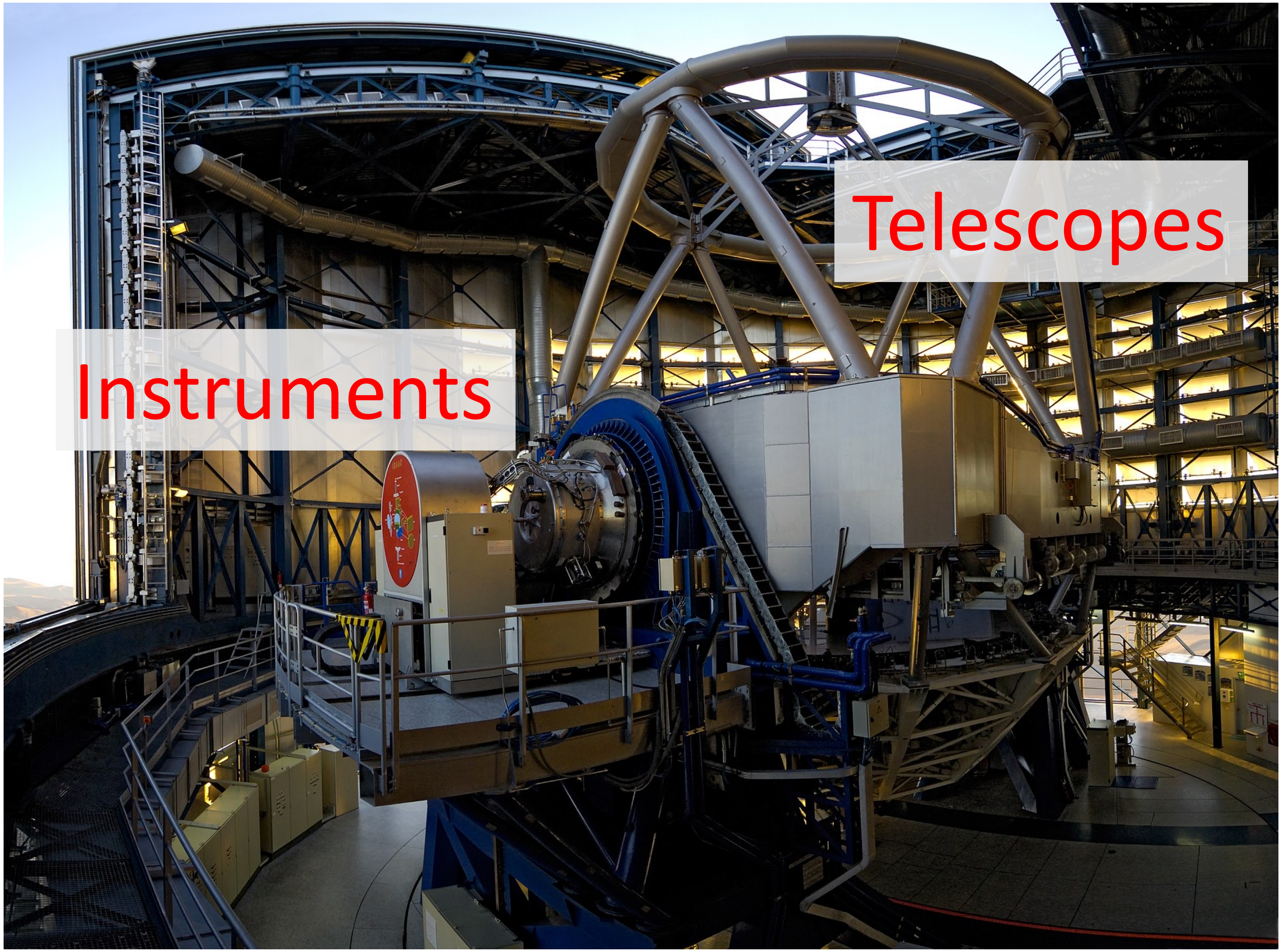
ESO Telescopes at Paranal: Unit Telescops (UT)

La Silla: 3.6m - Equatorial

Paranal: UT – Alt-Azimuth



Summary: astronomers observe the sky by using…



What makes a perfect imaging system in astronomy ?

Image of the source is driven by

fundamental diffraction of light

System of mirrors and lenses

the limit of detection for faint objects determined only by photon (Poisson) counting statistic

limit of detection is described by the signal-to-noise ratio (SNR or S/N)

What makes a perfect imaging system in astronomy ?

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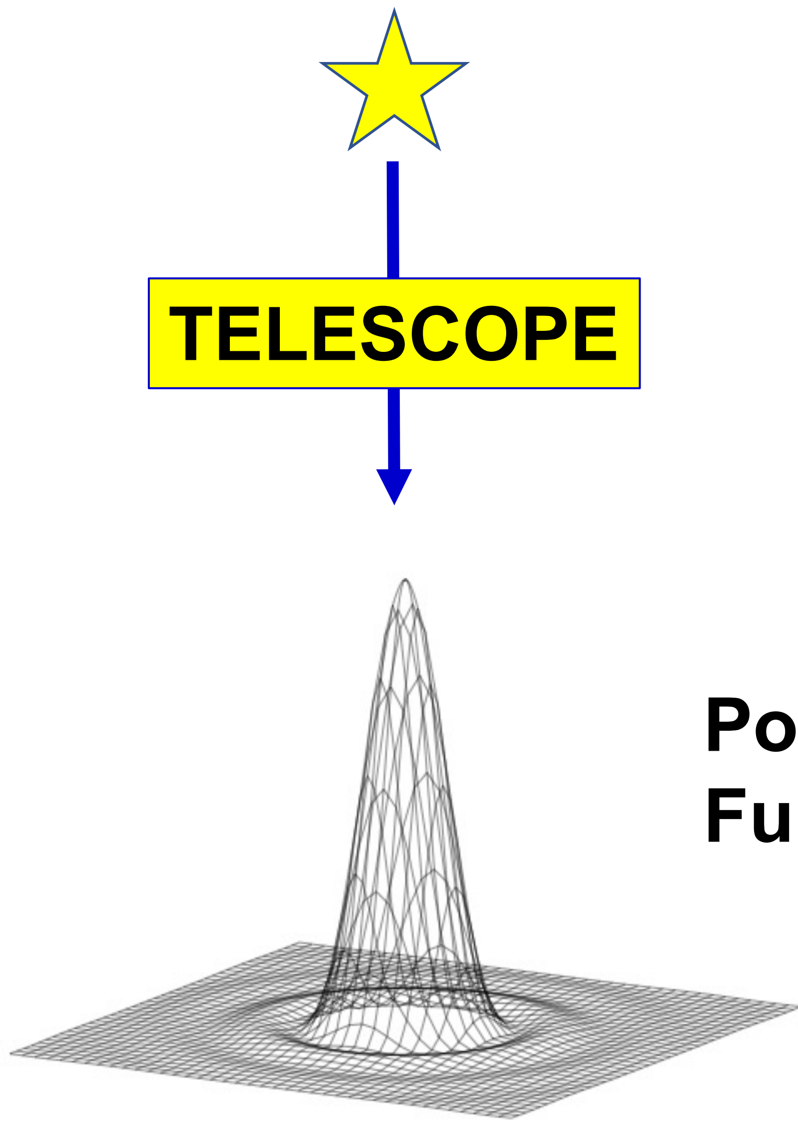
- **Maximize** the amount of **signal** collected from the source
- **Minimize** the **random errors** (the noise) to the fundamental quantum (photon) limits (electronics)

by

or

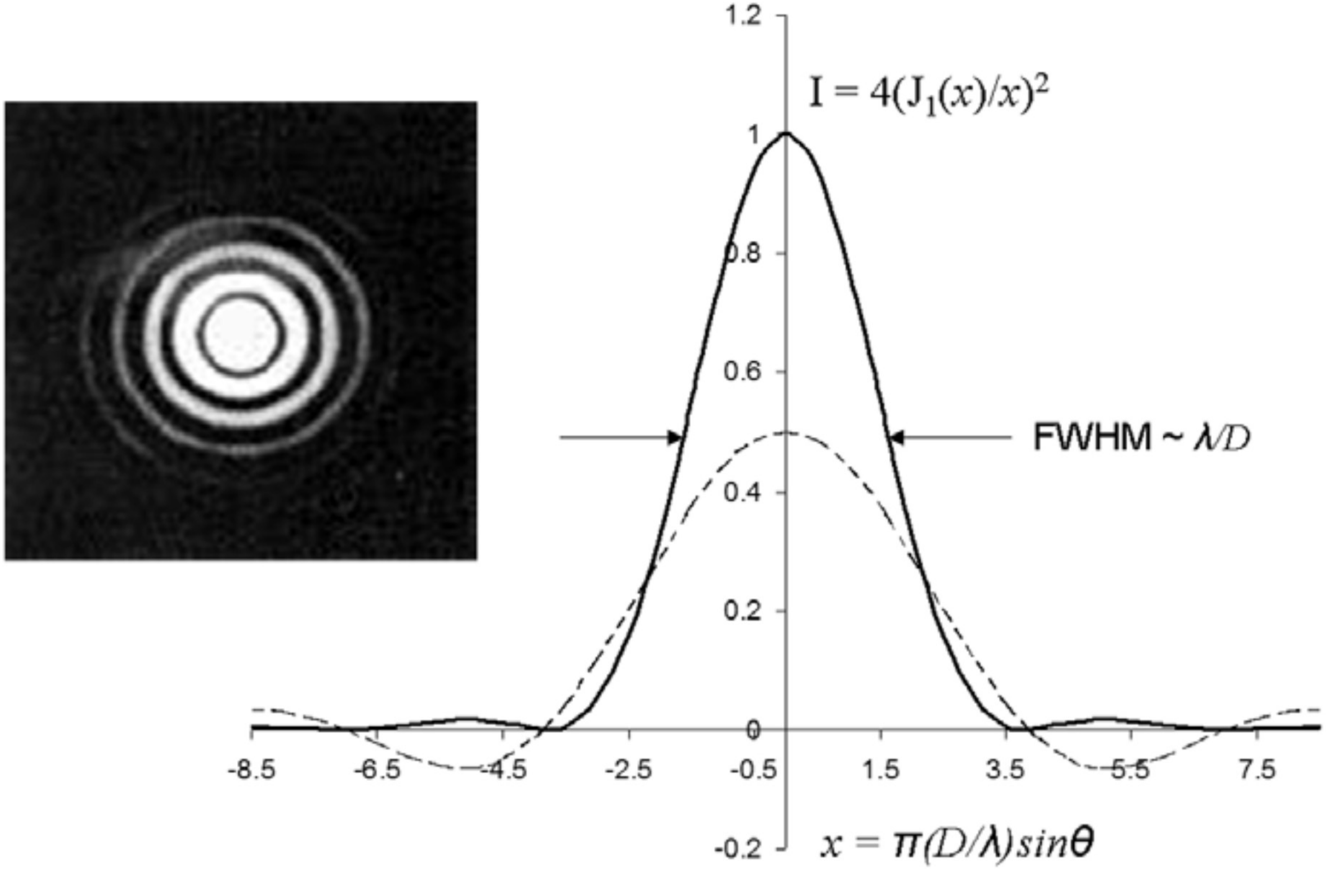
S/N)

Image Formation



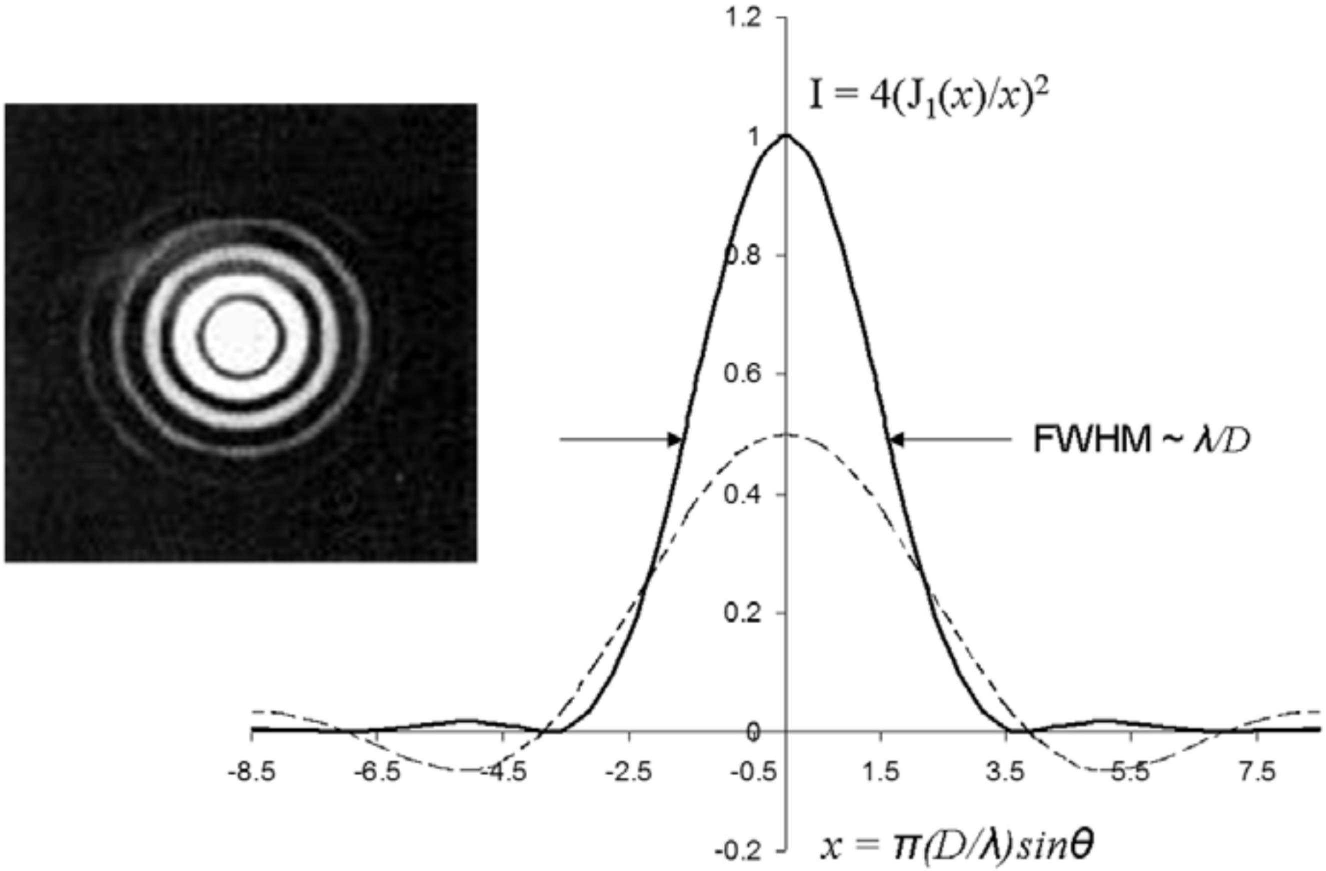
Point Spread Function (PSF)

Image Formation



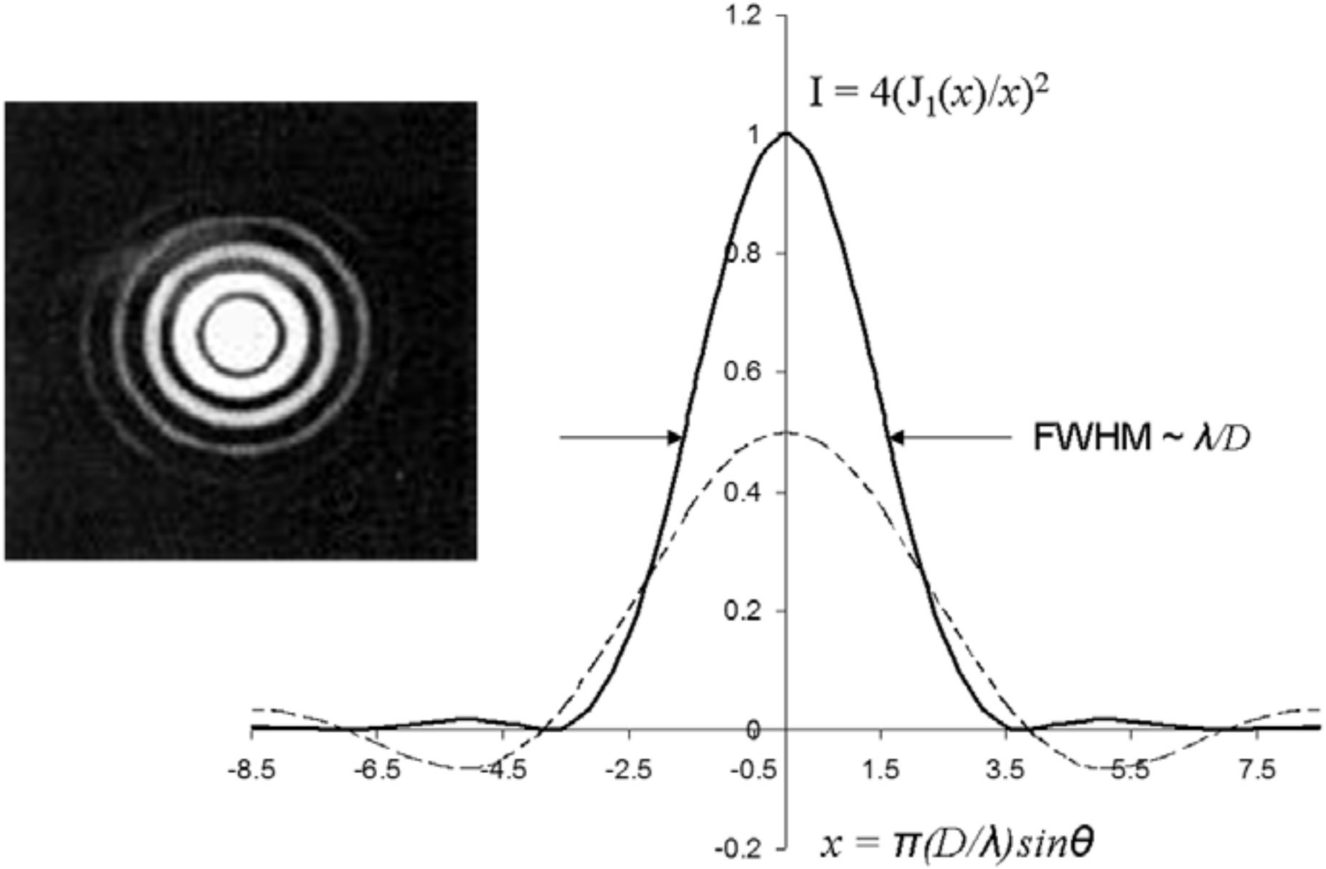
- Lens or Mirror of diameter D at a wavelength λ create and Airy diffraction disk
- Diffraction pattern introduced by the telescope optics

Image Formation



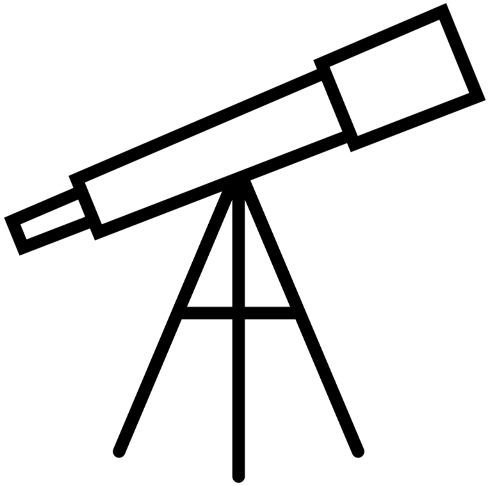
- The PSF is typically described with the Full Width at Half Maximum (FWHM) intensity. <u>For the diffraction-limited case this corresponds to ~λ/D</u>

Image Formation



- Performance is also given by the diameter that contains 80% of the energy: encircled energy. For the diffraction-limited case this corresponds to ~1.8 λ/D.

Diffraction Limited: some examples



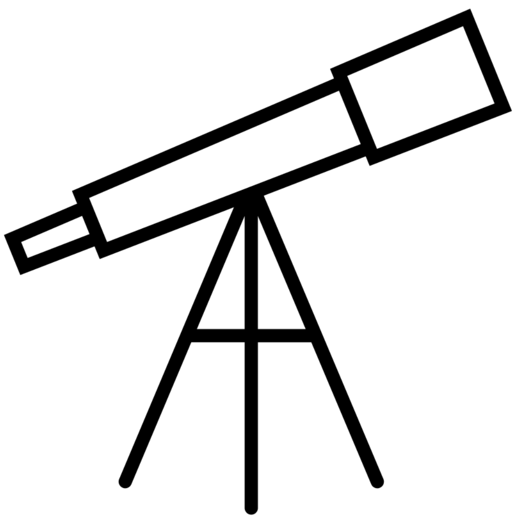
VISUAL

D=10m at 5000Å

(Å = 10^{-10}m)

Diff.Lim. FWHM = ($5000*10^{-10}$)m / 10m
= $5*10^{-8}$ radians
(1 rad = 206265 arcsec)
= 0.01 arcsec

Diff.Lim. Enc.Ener.=1.8*0.01 =~0.018arcsec



INFRARED

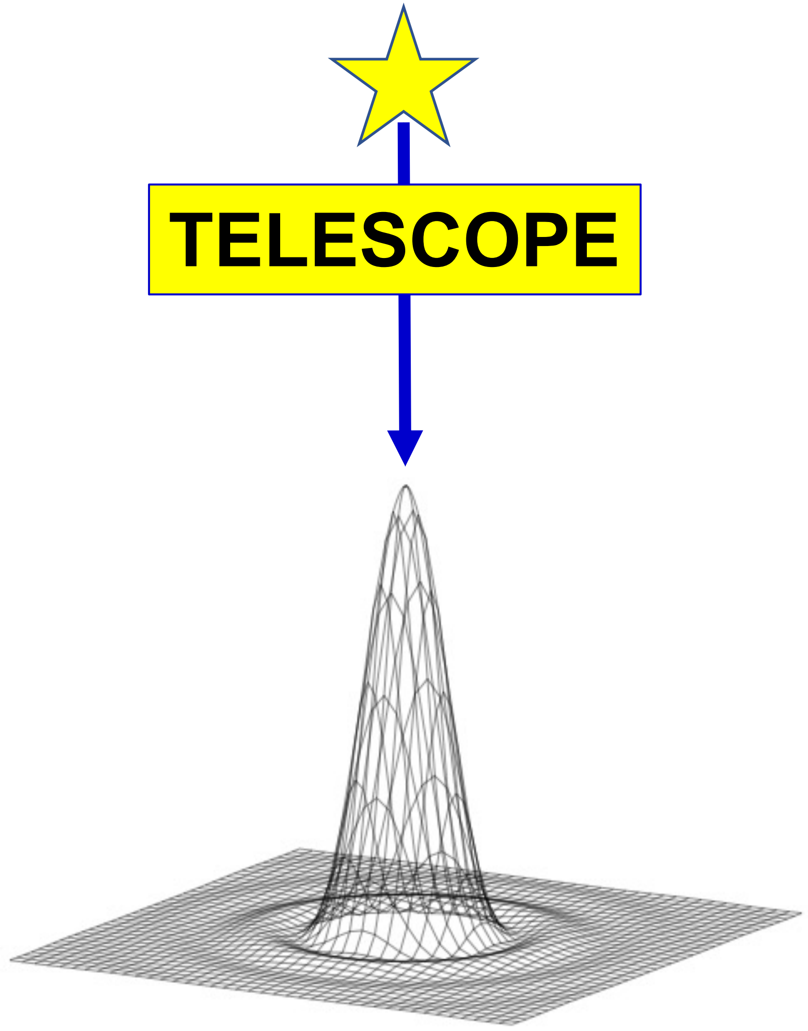
D=10m at 1 μm

(μm = 10^{-6}m),

Diff.Lim. FWHM ~= 0.02 arcsec

Diff.Lim. Enc.Ener.~=0.037 arcsec

Resolution: how close 2 objects can be so that I can distinguish them?



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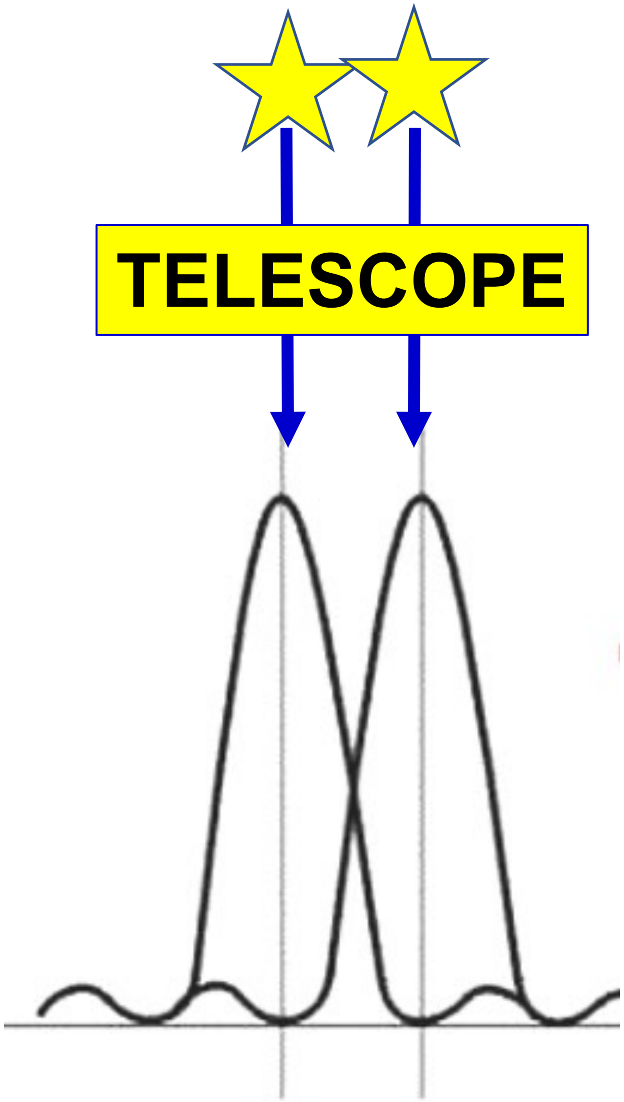
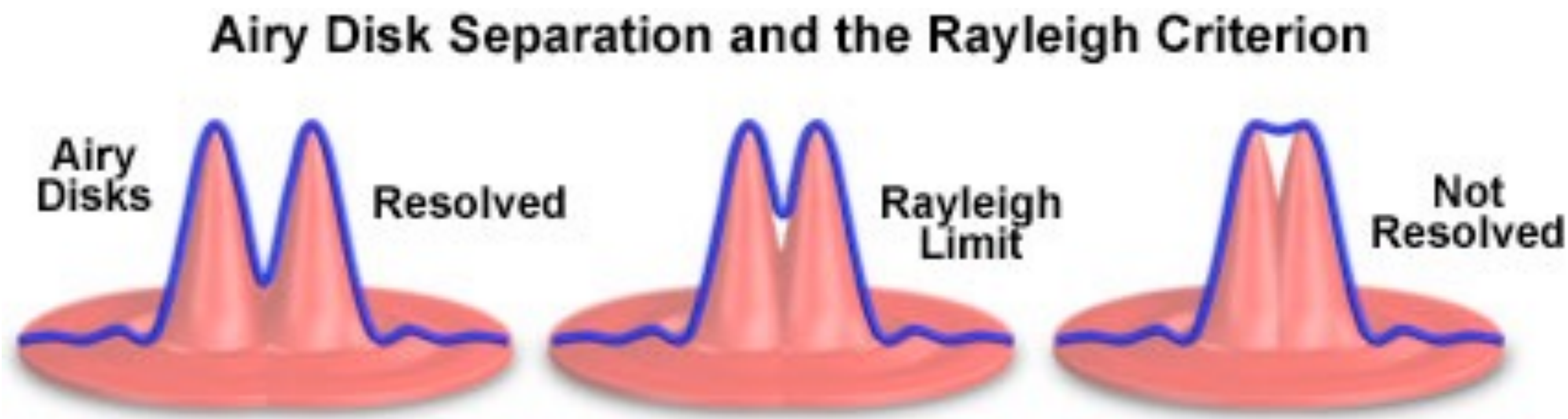
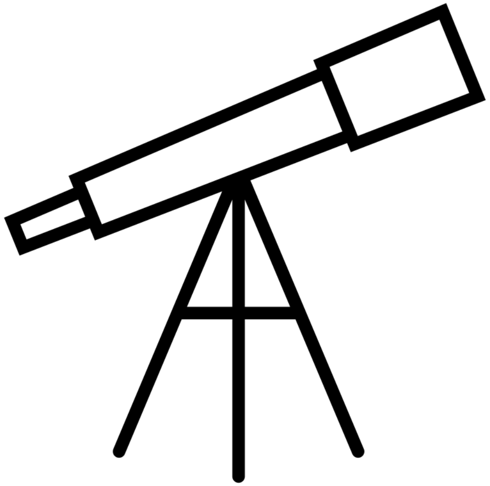


Resolution: how close 2 objects can be so that I can distinguish them?

The Rayleigh Criterion: two diffraction-limited PSFs are distinguishable if the maximum of one Airy disk falls on the first minimum of the second; this is a separation of ~1.22 λ / D



Diffraction Limited: some examples



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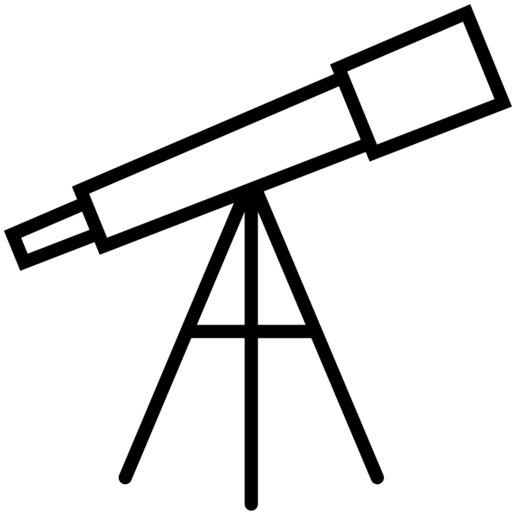

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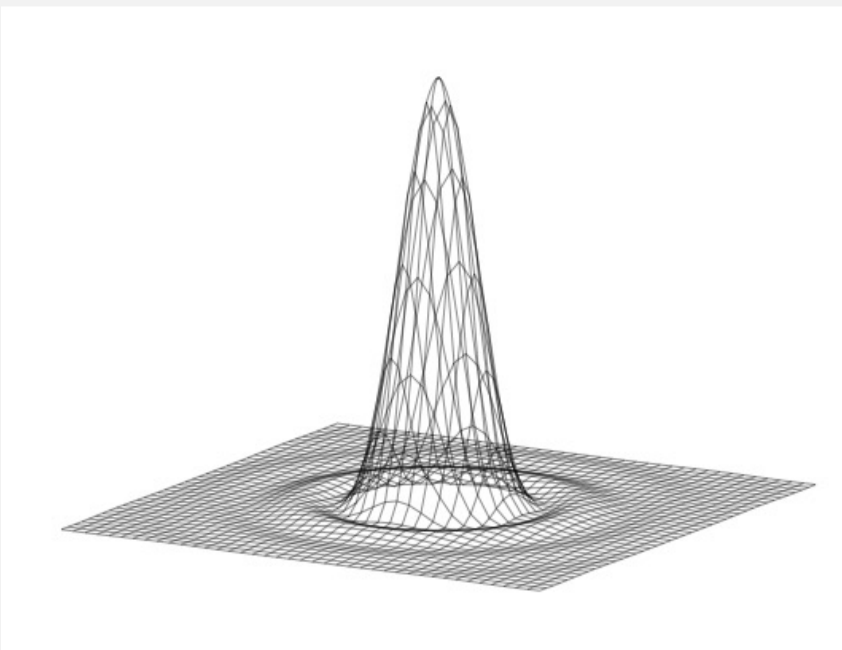
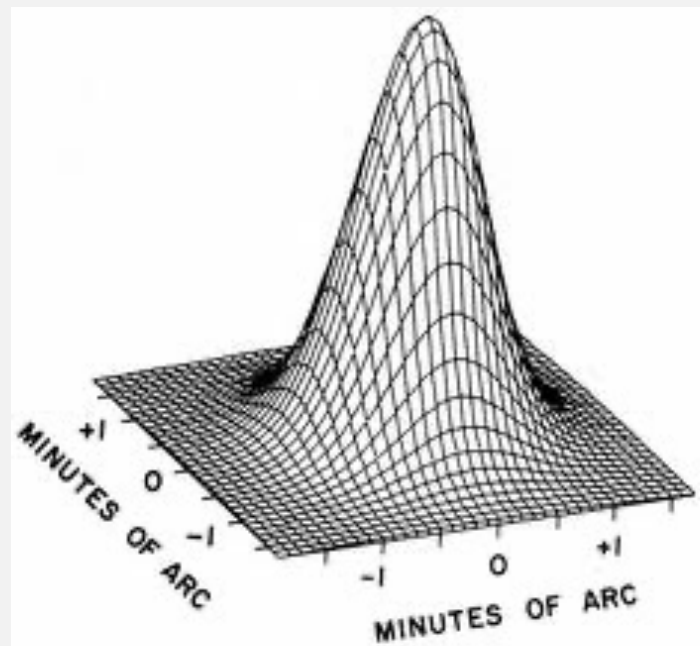
Diffraction Limited: some examples

In case of a PURELY Diffraction Limited System:

Given a mirror size → Better resolution in the Visual





What makes a perfect imaging system in astronomy ?

➢ Maximize the amount of signal collected from the source

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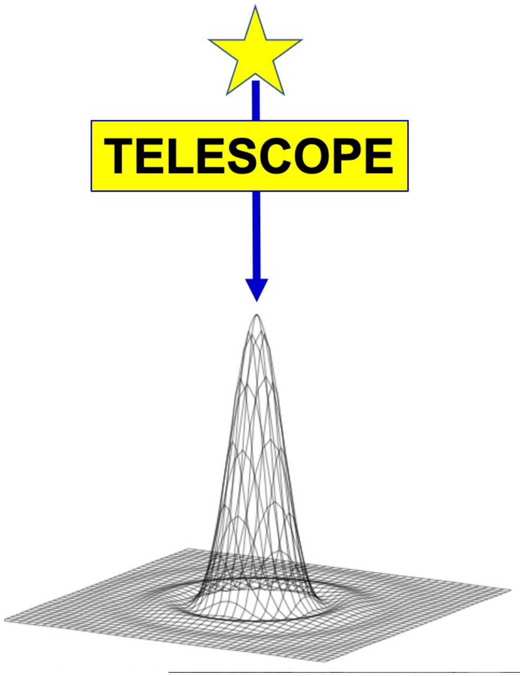

What makes a perfect imaging system in astronomy ?

In addition to diffraction, aberrations in the optical system, the Earth’s atmosphere, and scattered light contribute to the PSF.

What makes a perfect imaging system in astronomy ?

- **Minimize** the **random errors** (the noise)

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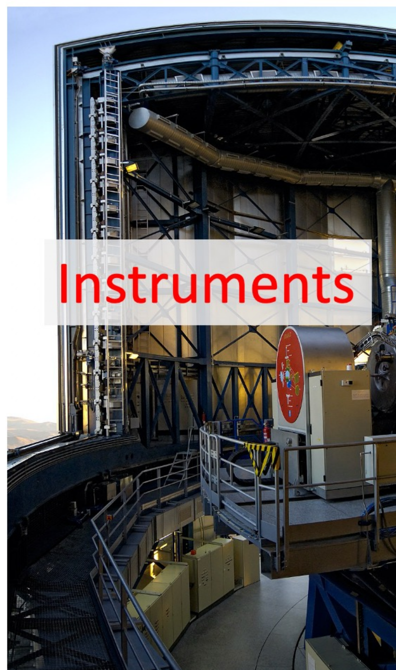

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Detectors with 100% efficiency in converting photons into electrons and later into measured counts

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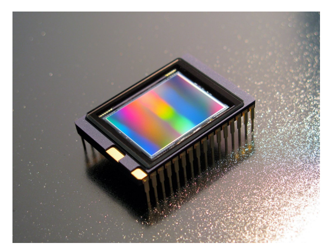

The perfect detector

- no illumination → no signal

The perfect detector

- no illumination ➔ no signal

- different measurements of the same constant light source should give the same average signal with a deviation determined only by Poisson statistics.

The perfect detector

- no illumination ➔ no signal

- different measurements of the same constant light source should give the same average signal with a deviation determined only by Poisson statistics.

- All pixels should have exactly the same characteristics.

The perfect detector

- Minimize the random errors (the noise)

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The perfect detector does not exist!

Characterise an instrument and calibrate the data is all about knowing the noise in your detector!!

References:

[1] McLean, Ian S., *Electronic Imaging in Astronomy [electronic resource] : Detectors and Instrumentation,* Berlin, Heidelberg : Springer Berlin Heidelberg : Imprint: Springer, 2008.

[2] Ball, D.W., *Field guide to spectroscopy*, Bellingham, WA: SPIE, The International Society for Optical Engineering, 2006.

[3] Keller, Christoph U; Navarro, Ramón; Brandl, Bernhard R. -- Society of Photo-optical Instrumentation Engineers, *Field guide to astronomical instrumentation*, Bellingham, Washington (1000 20th St. Bellingham WA 98225-6705 USA) : SPIE, 2014.

[4] Wolfe, William L., -- Society of Photo-optical Instrumentation Engineers, *Optics made clear : the nature of light and how we use it*, Bellingham, Washington : SPIE Press, 2007.