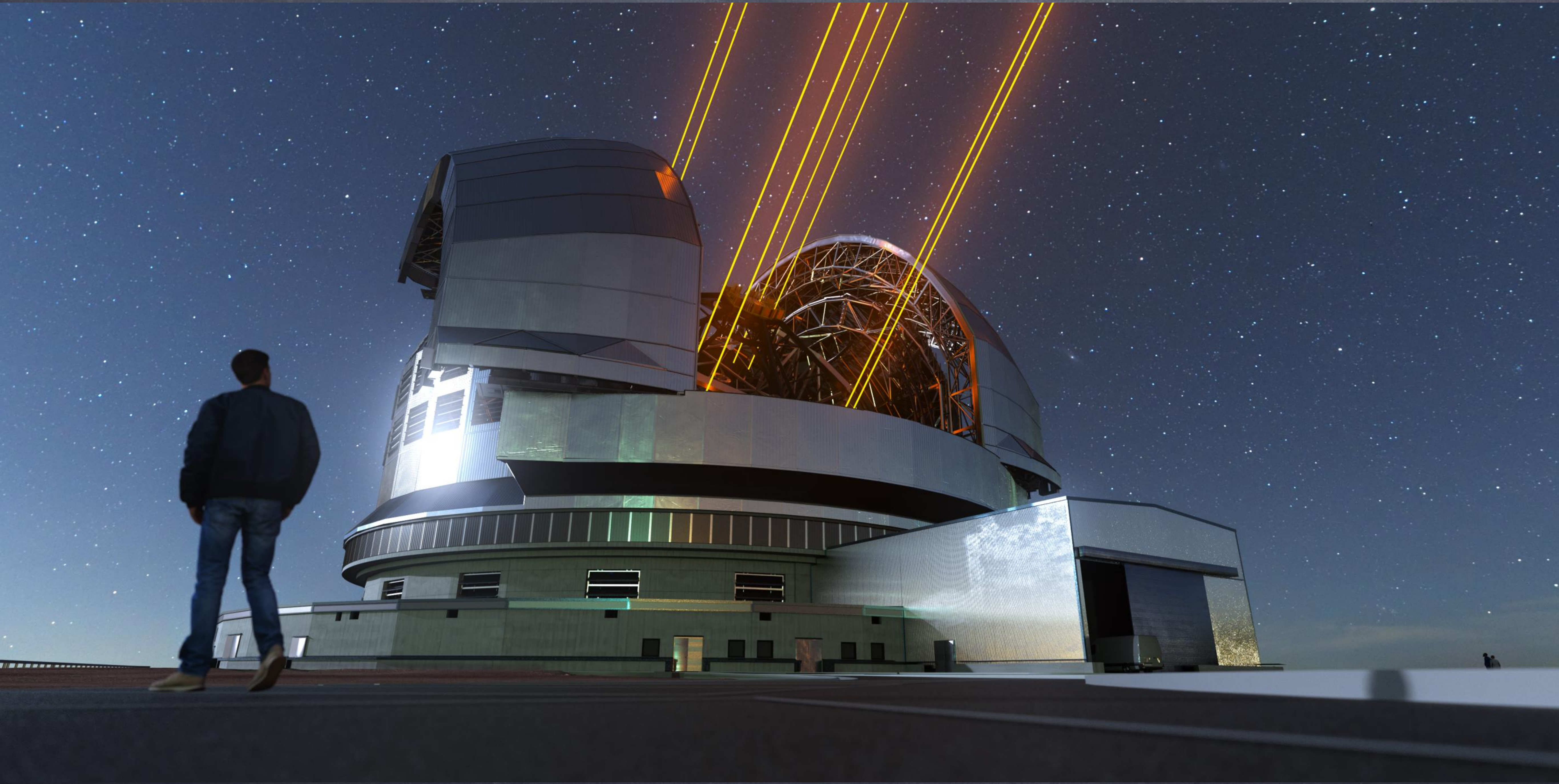
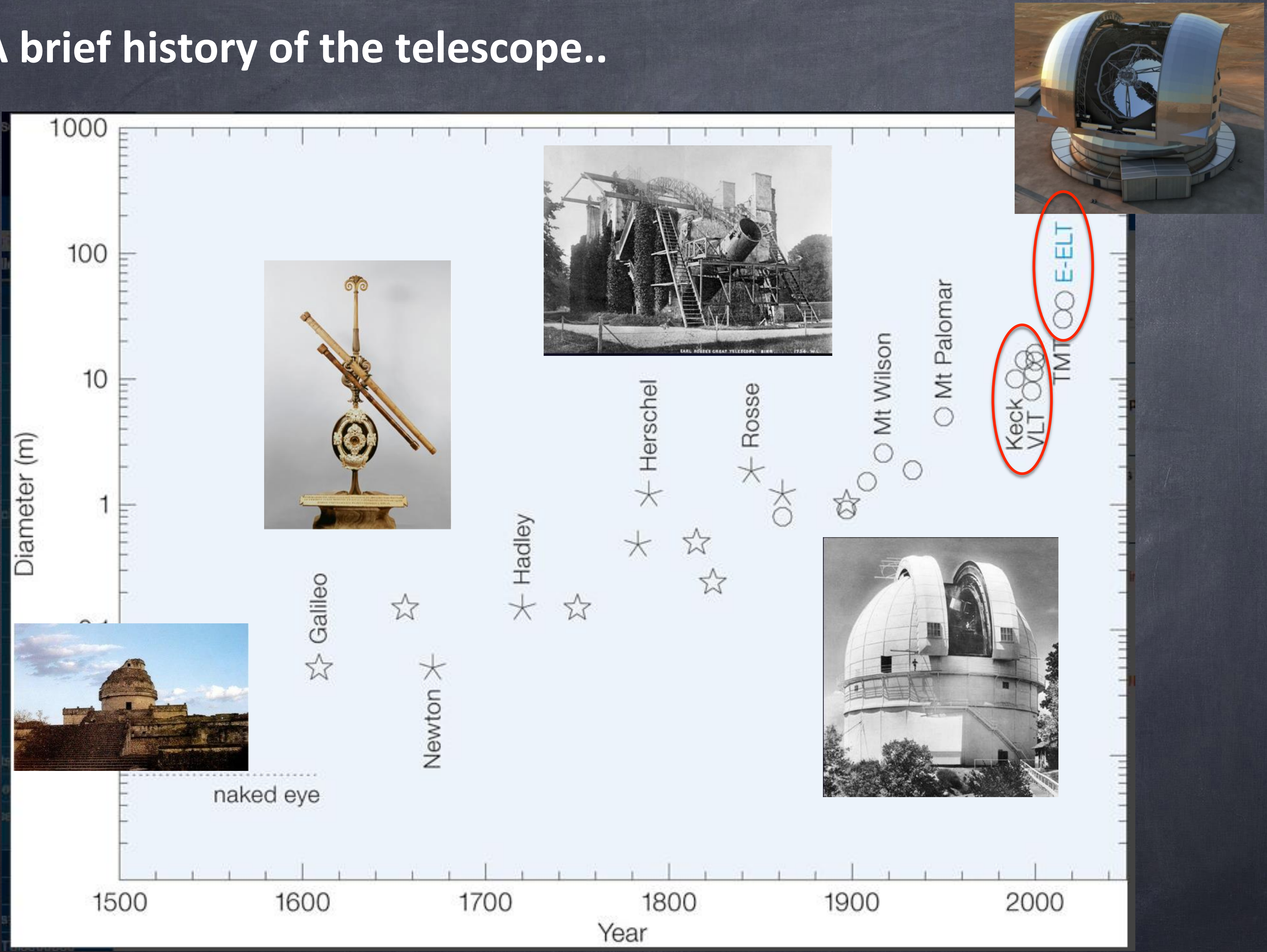
Telescopi ottici

Adriano Fontana

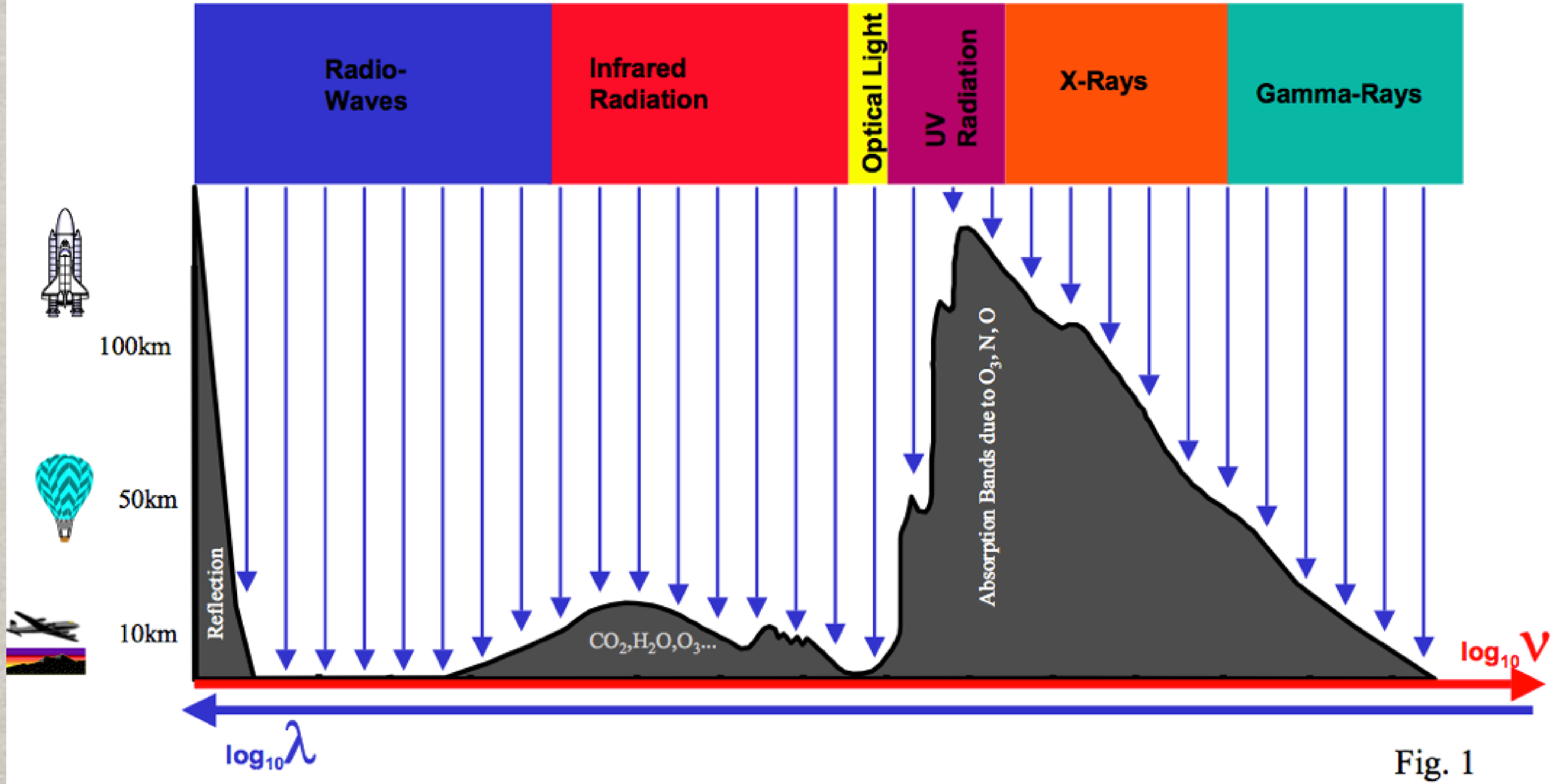
INAF Osservatorio di Roma



A brief history of the telescope..



Perchè si chiamano telescopi “ottici”?

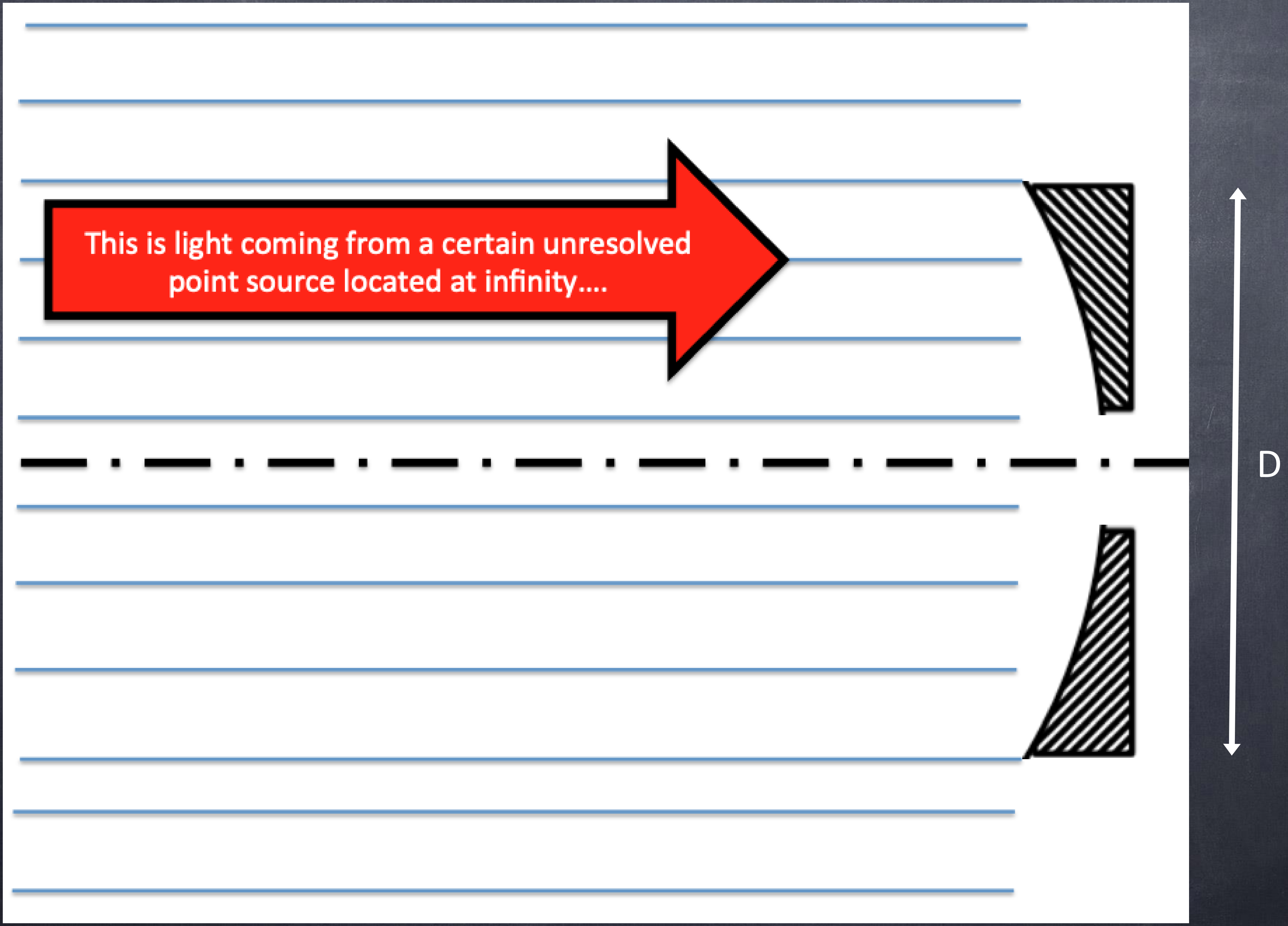


The Earth’s Atmosphere (I)

Fig. 1

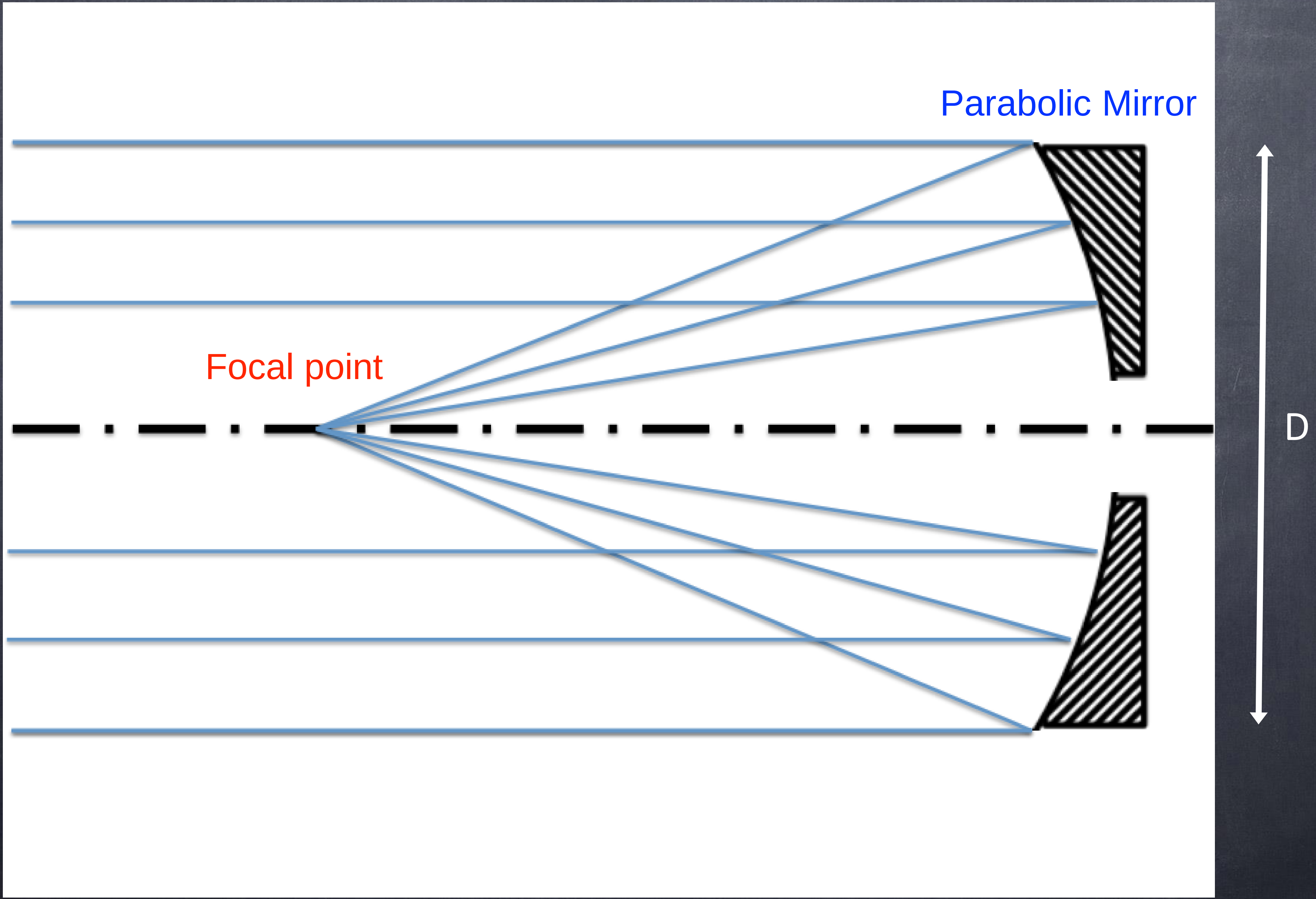
Observations from the ground are only possible in certain frequency ranges, caused by the variation of atmospheric transparency with frequency.

Come sono fatti i telescopi (ottici)?

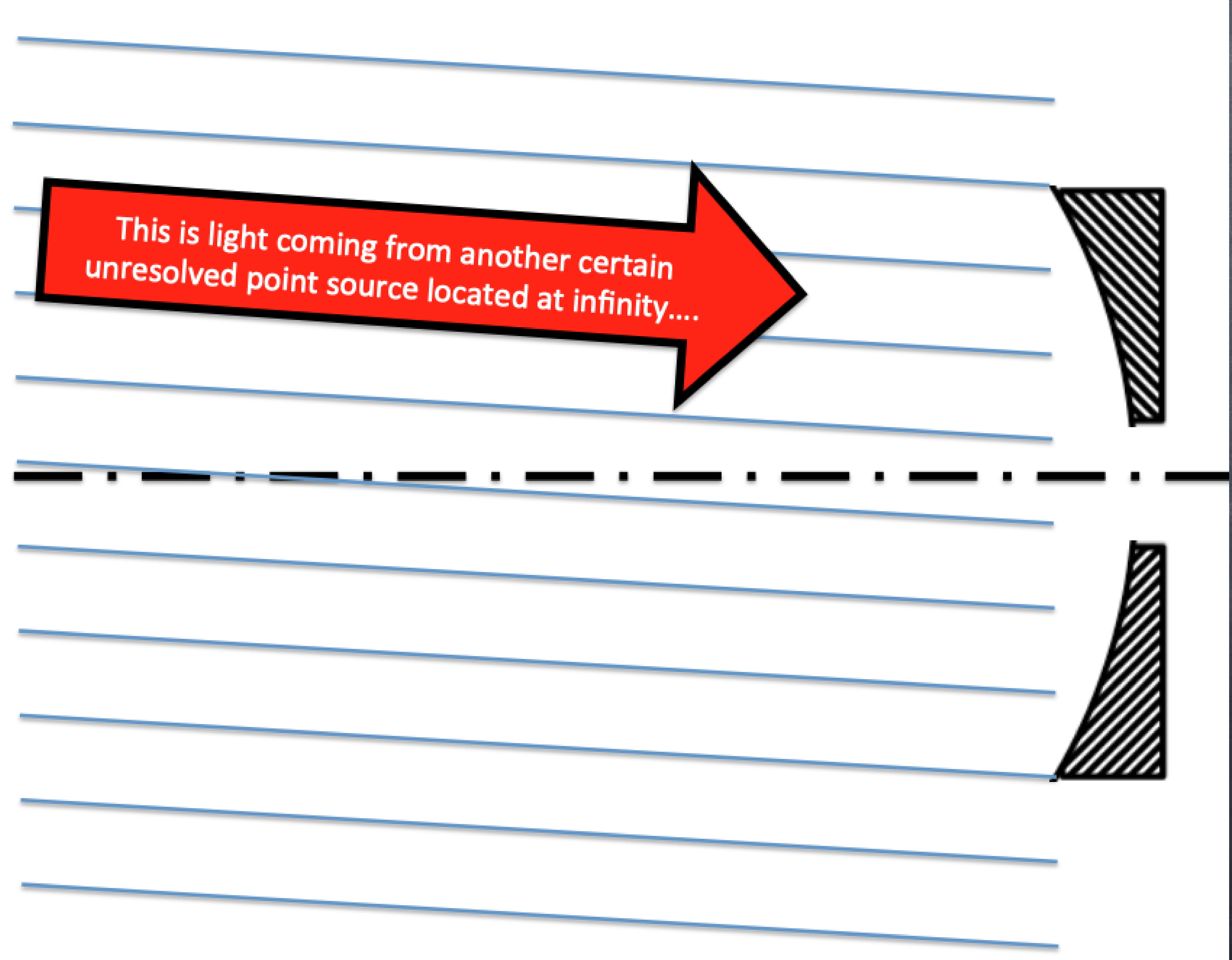


This is light coming from a certain unresolved point source located at infinity....

Come sono fatti i telescopi (ottici)?

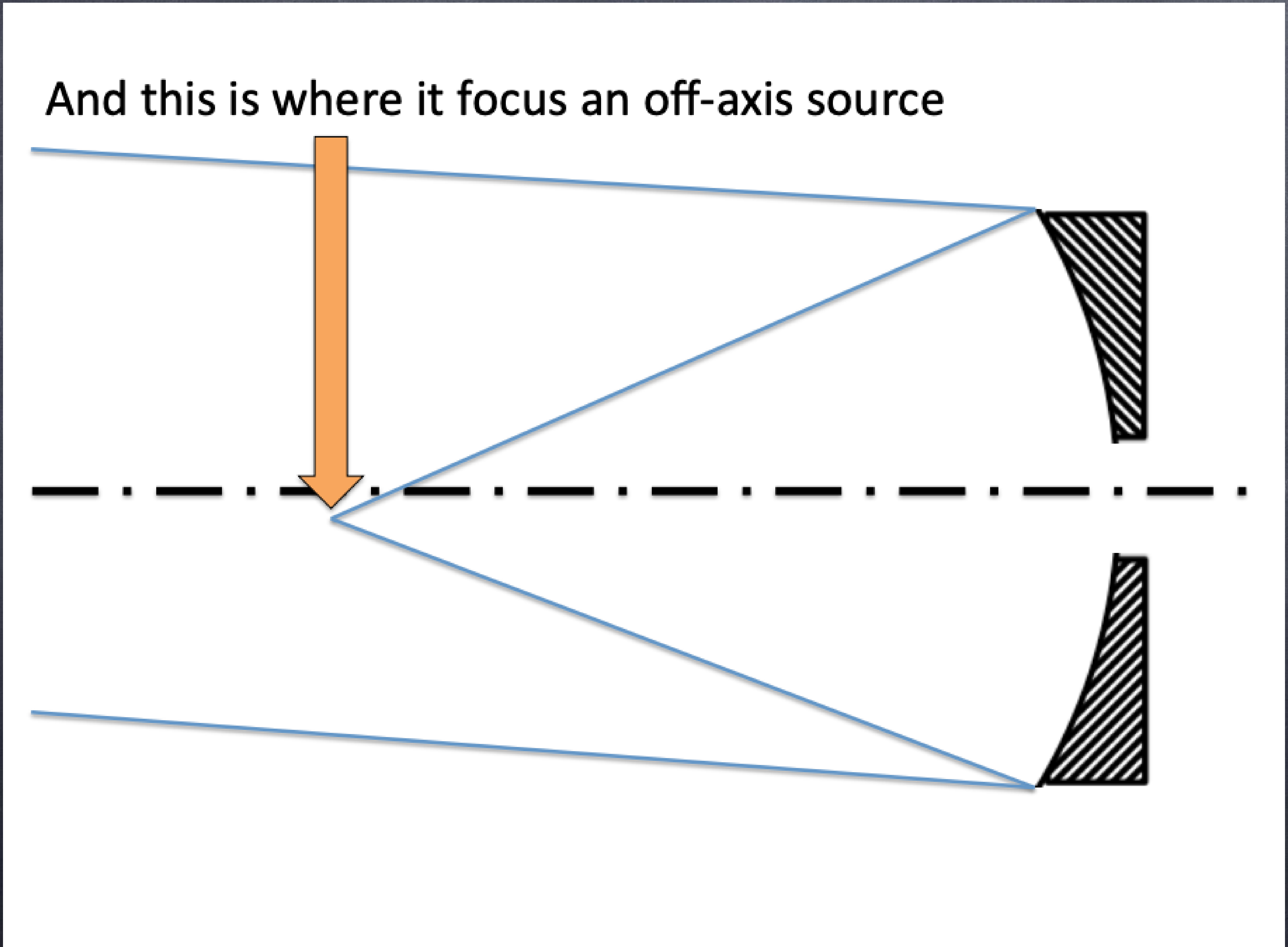


Come sono fatti i telescopi (ottici)?



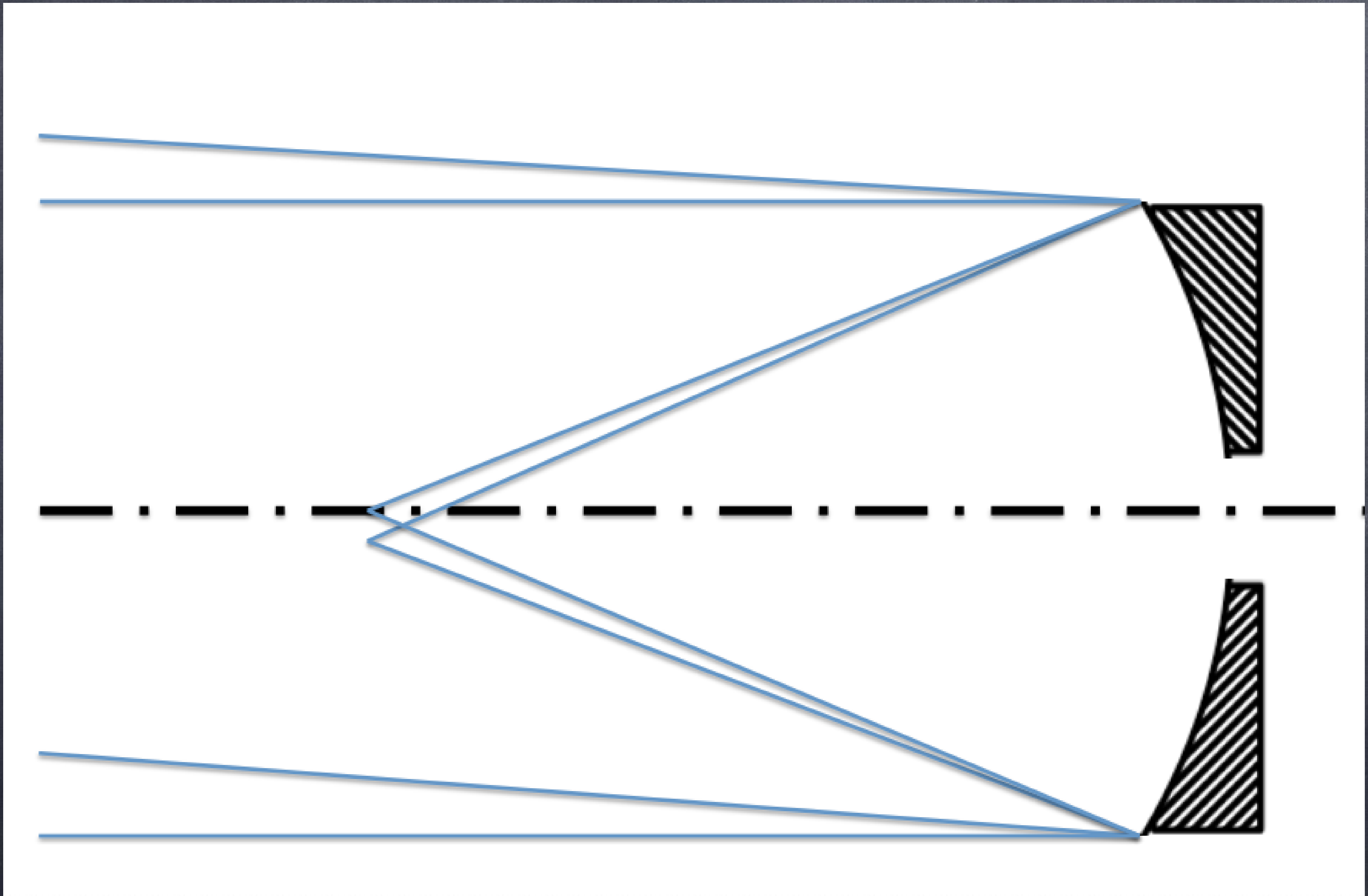
This is light coming from another certain unresolved point source located at infinity….

Come sono fatti i telescopi (ottici)?

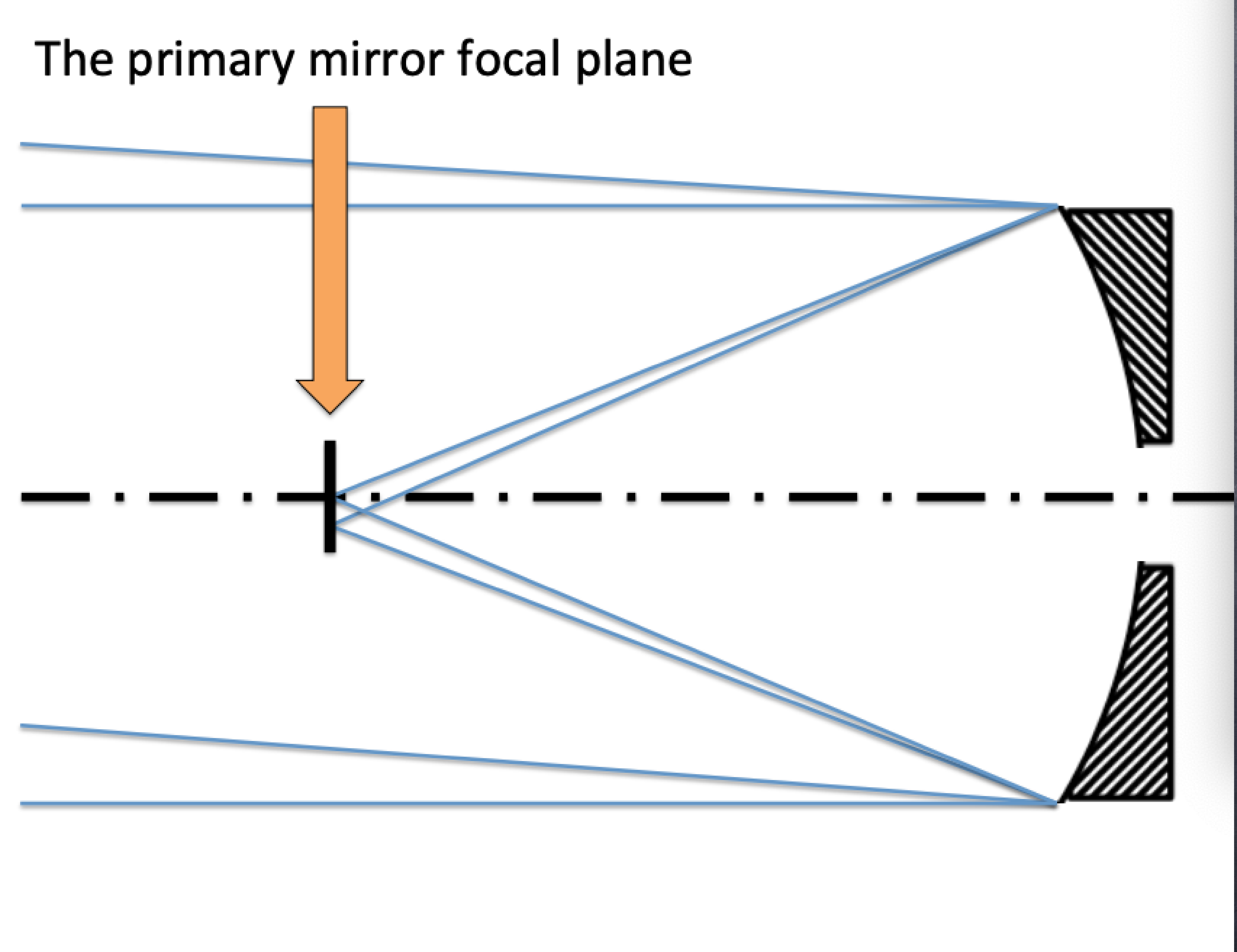


And this is where it focus an off-axis source

Come sono fatti i telescopi (ottici)?

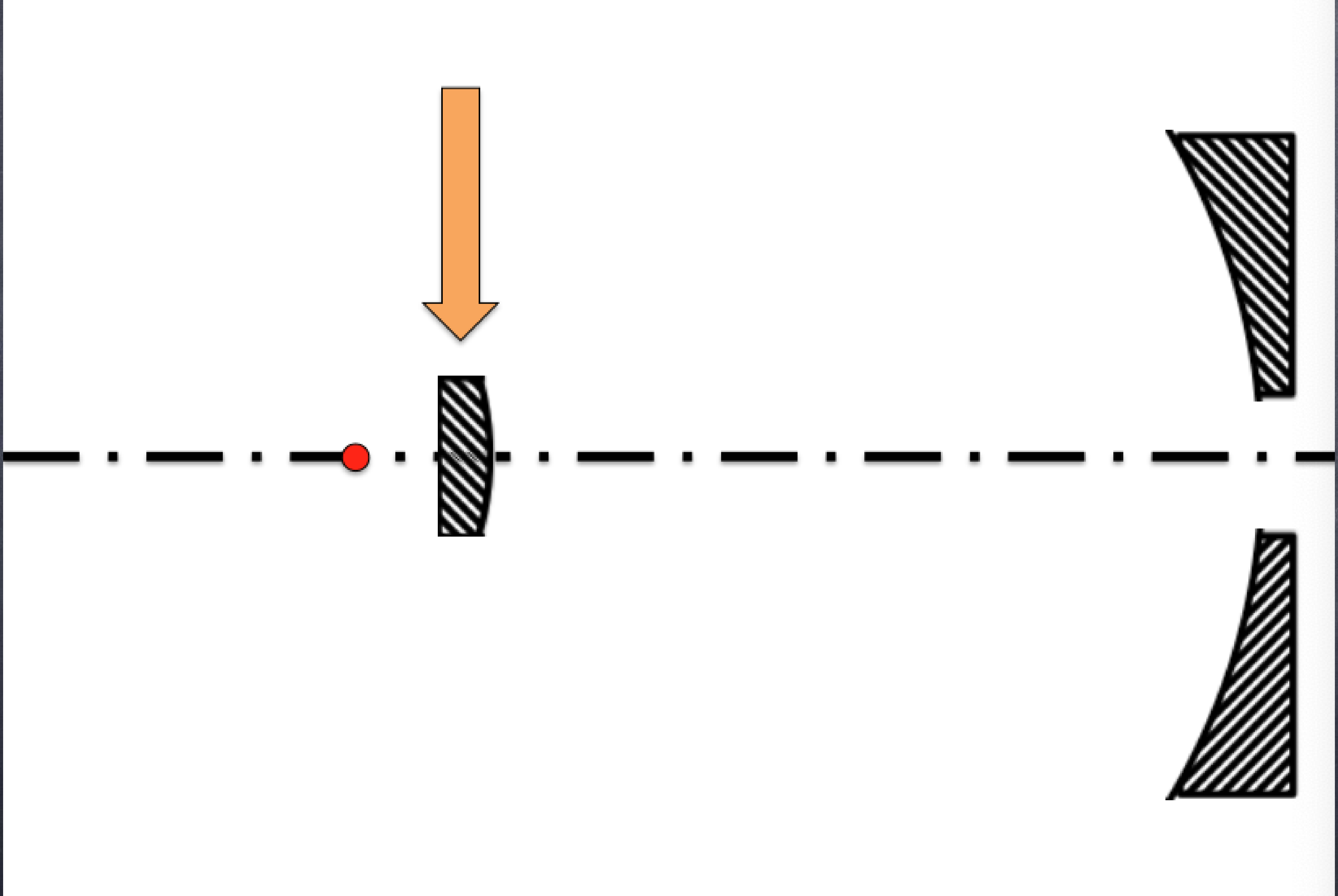


Come sono fatti i telescopi (ottici)?

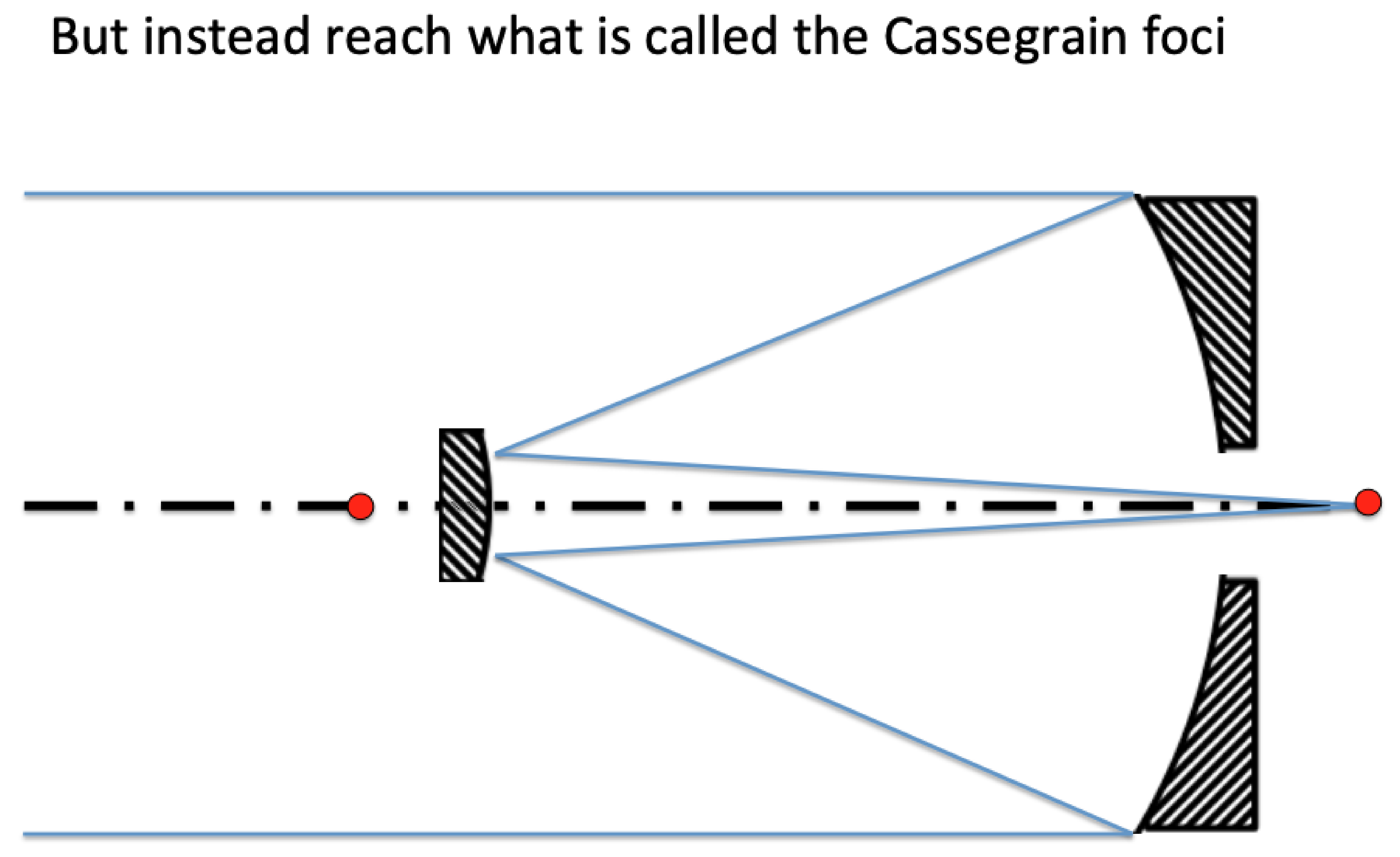


The primary mirror focal plane

Come sono fatti i telescopi (ottici)?

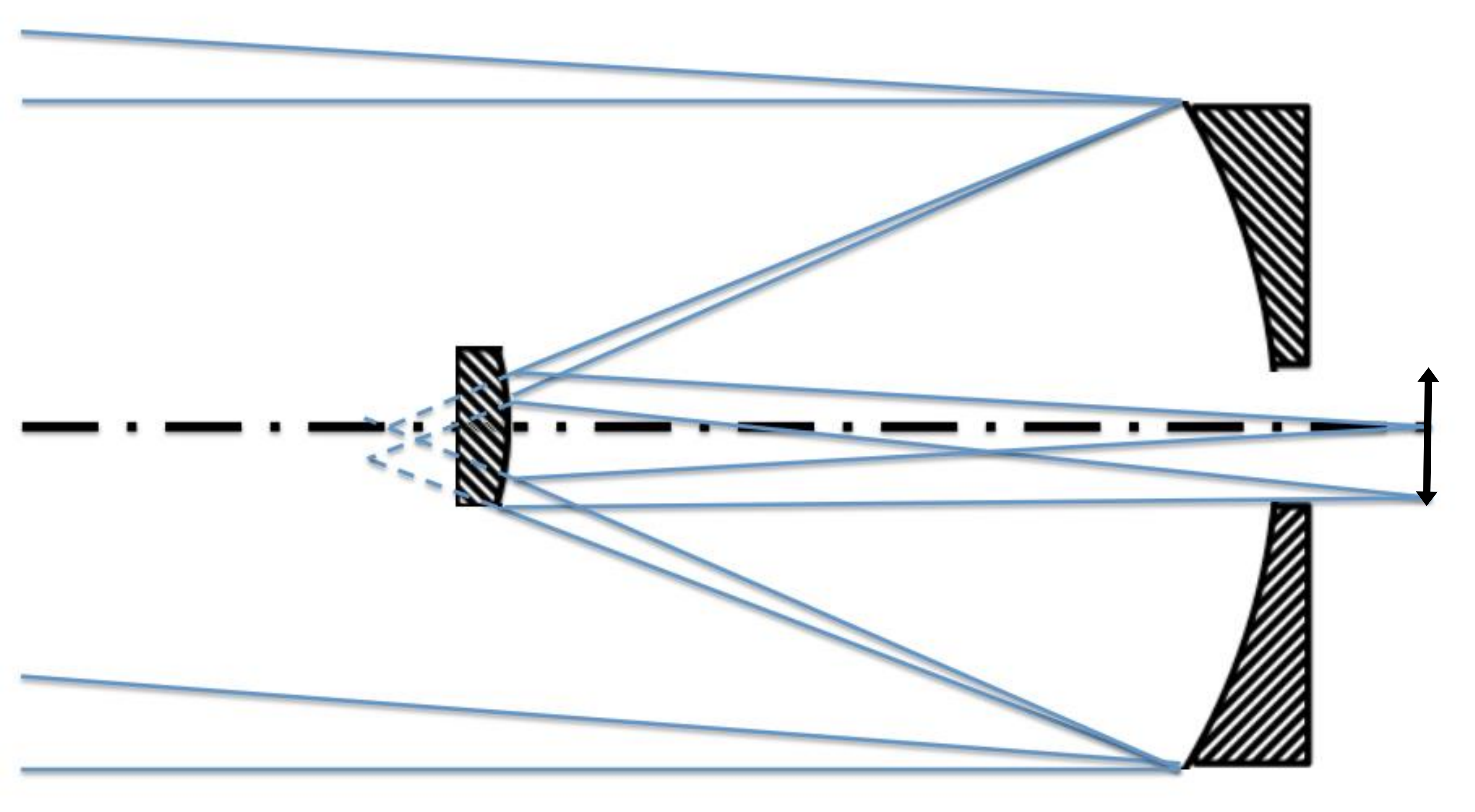


Come sono fatti i telescopi (ottici)?

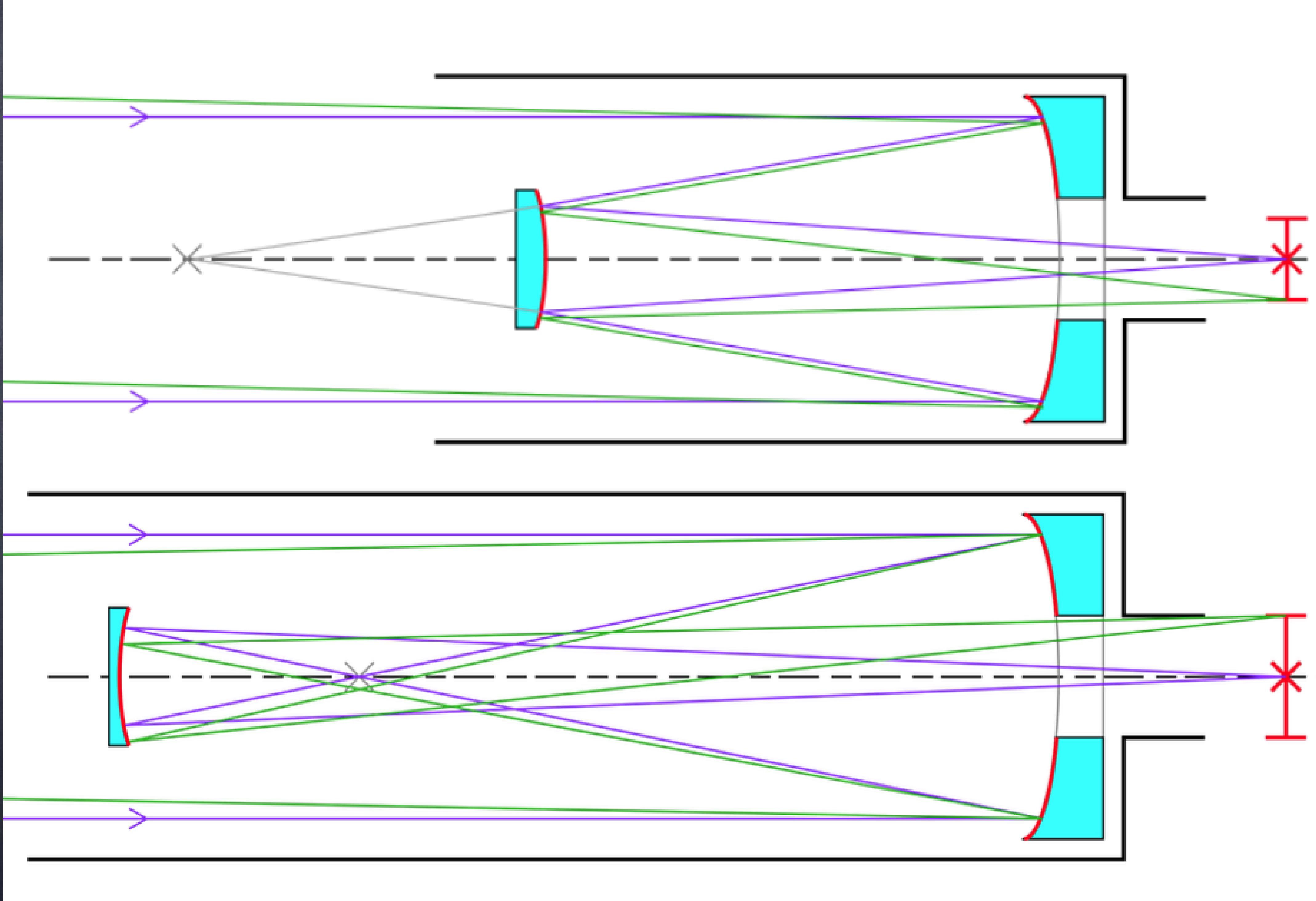


But instead reach what is called the Cassegrain foci

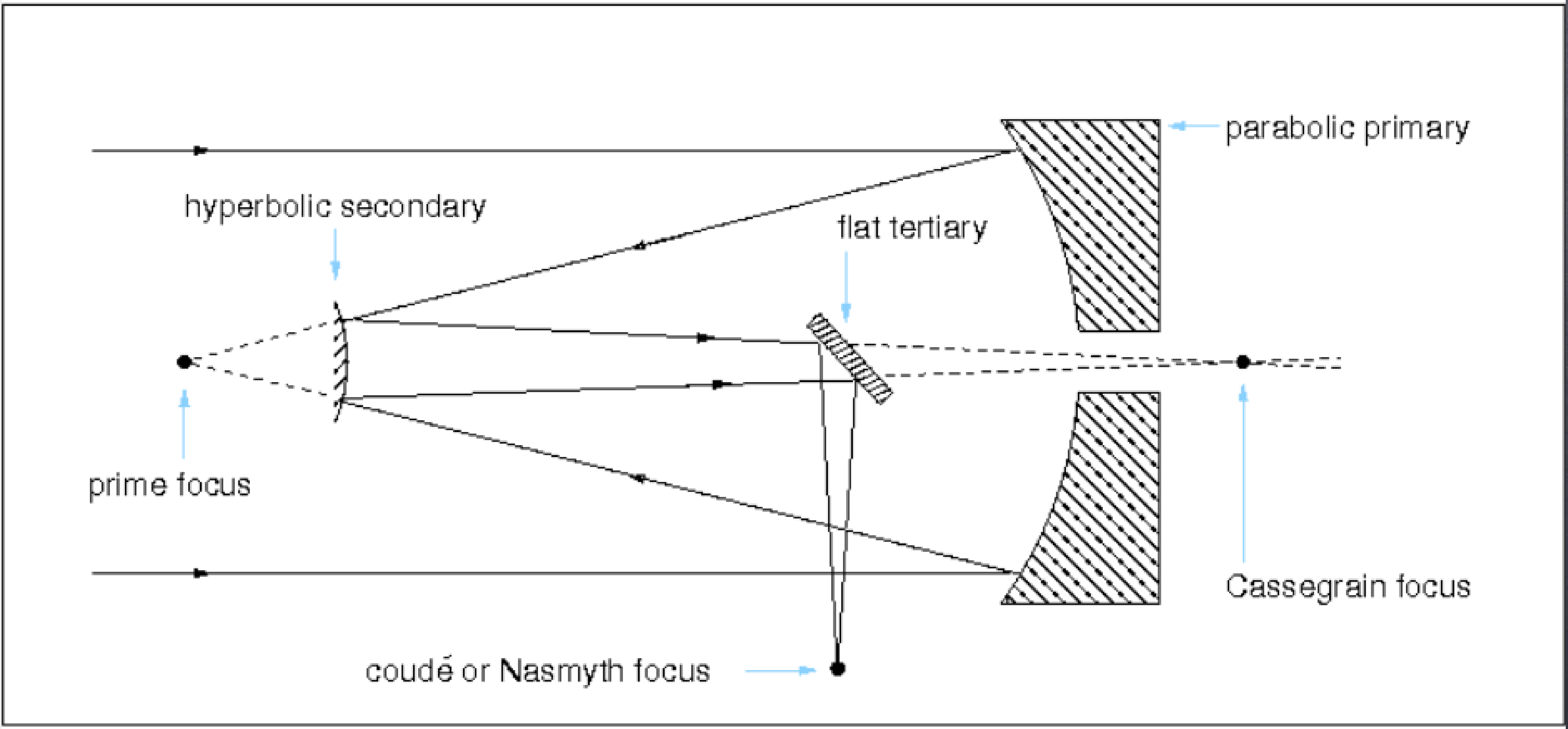
Come sono fatti i telescopi (ottici)?



Come sono fatti i telescopi (ottici)?



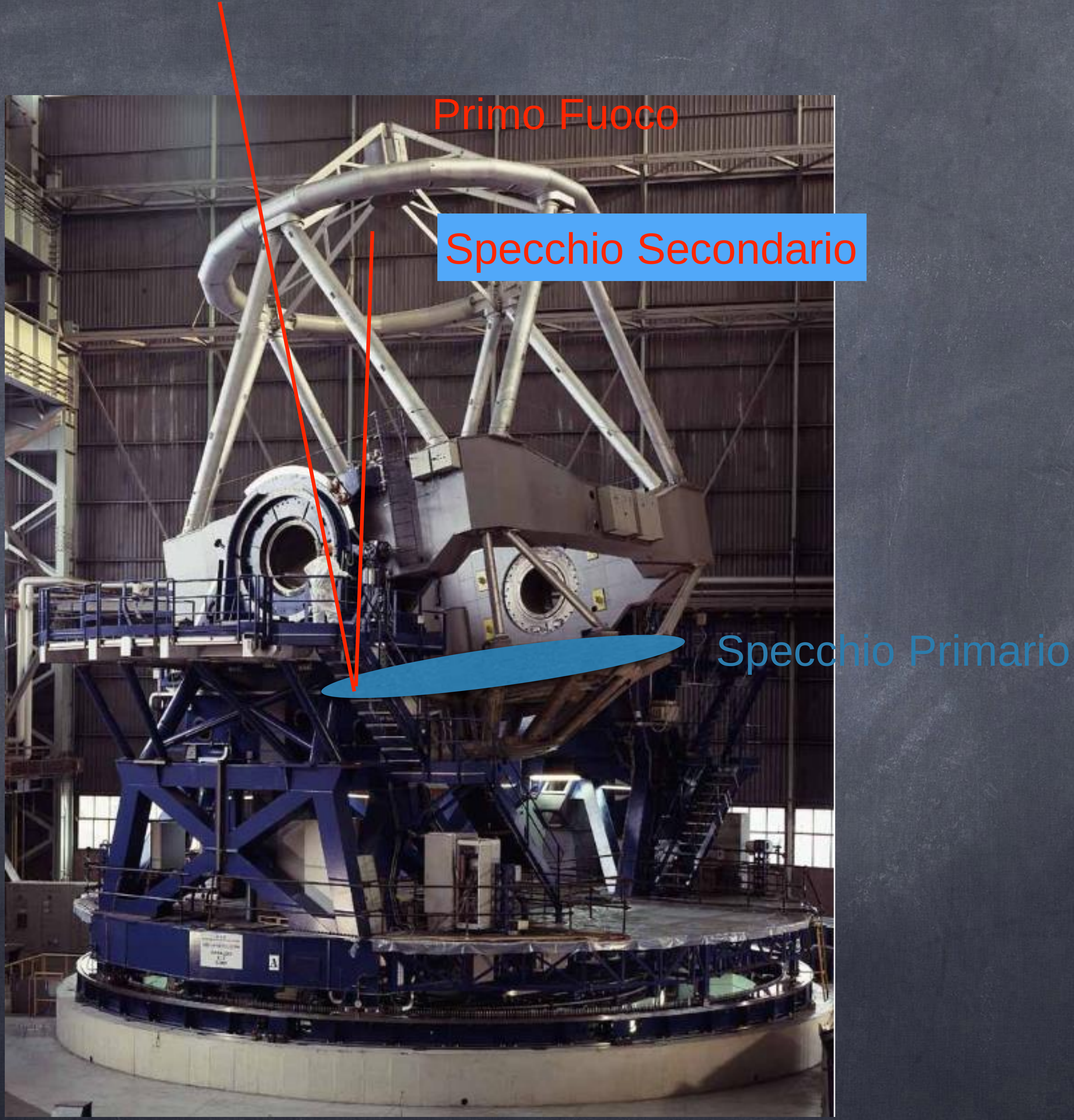
Come sono fatti i telescopi (ottici)?



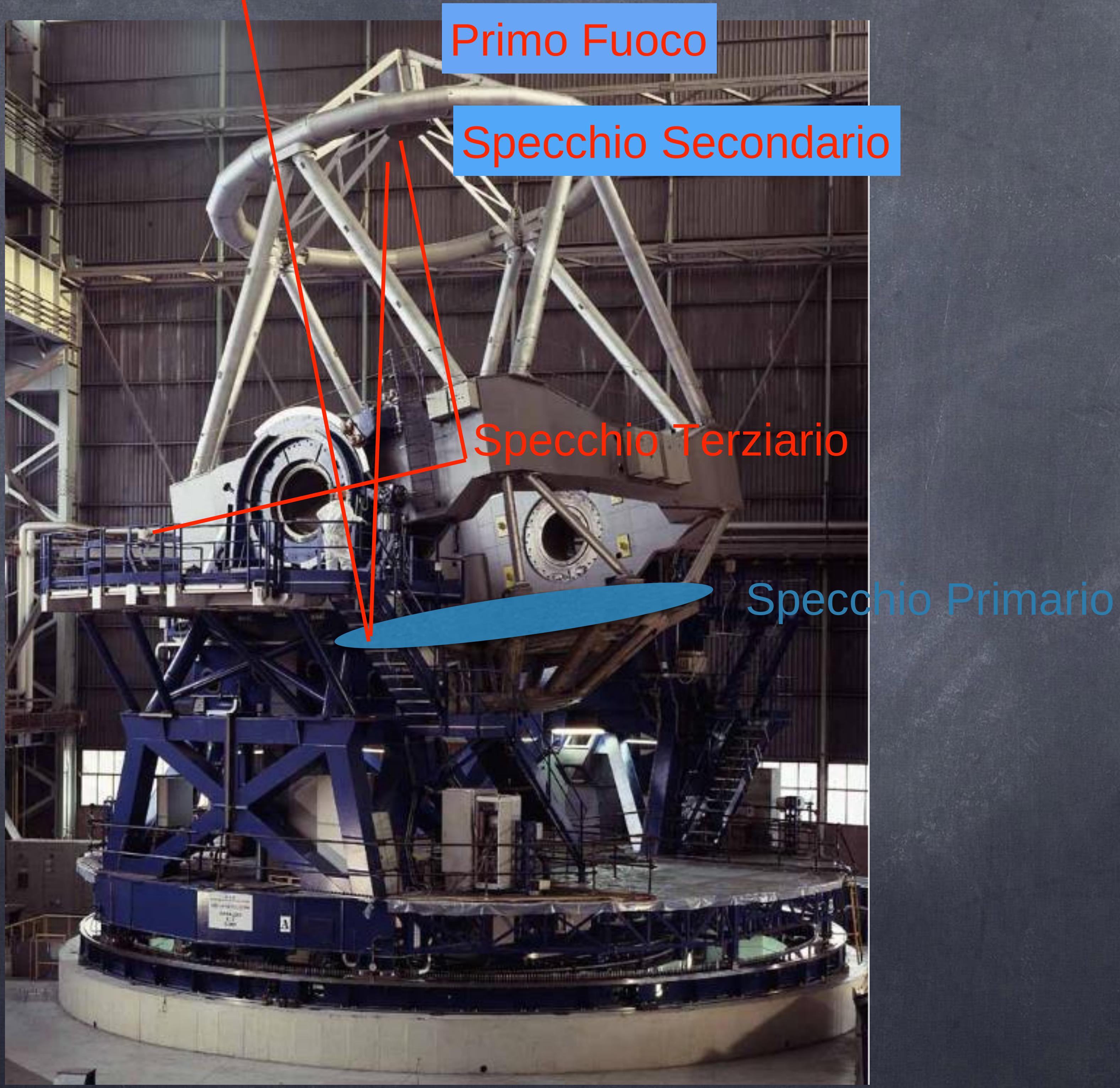
Come sono fatti i telescopi (ottici)?

Come sono fatti i telescopi (ottici)?

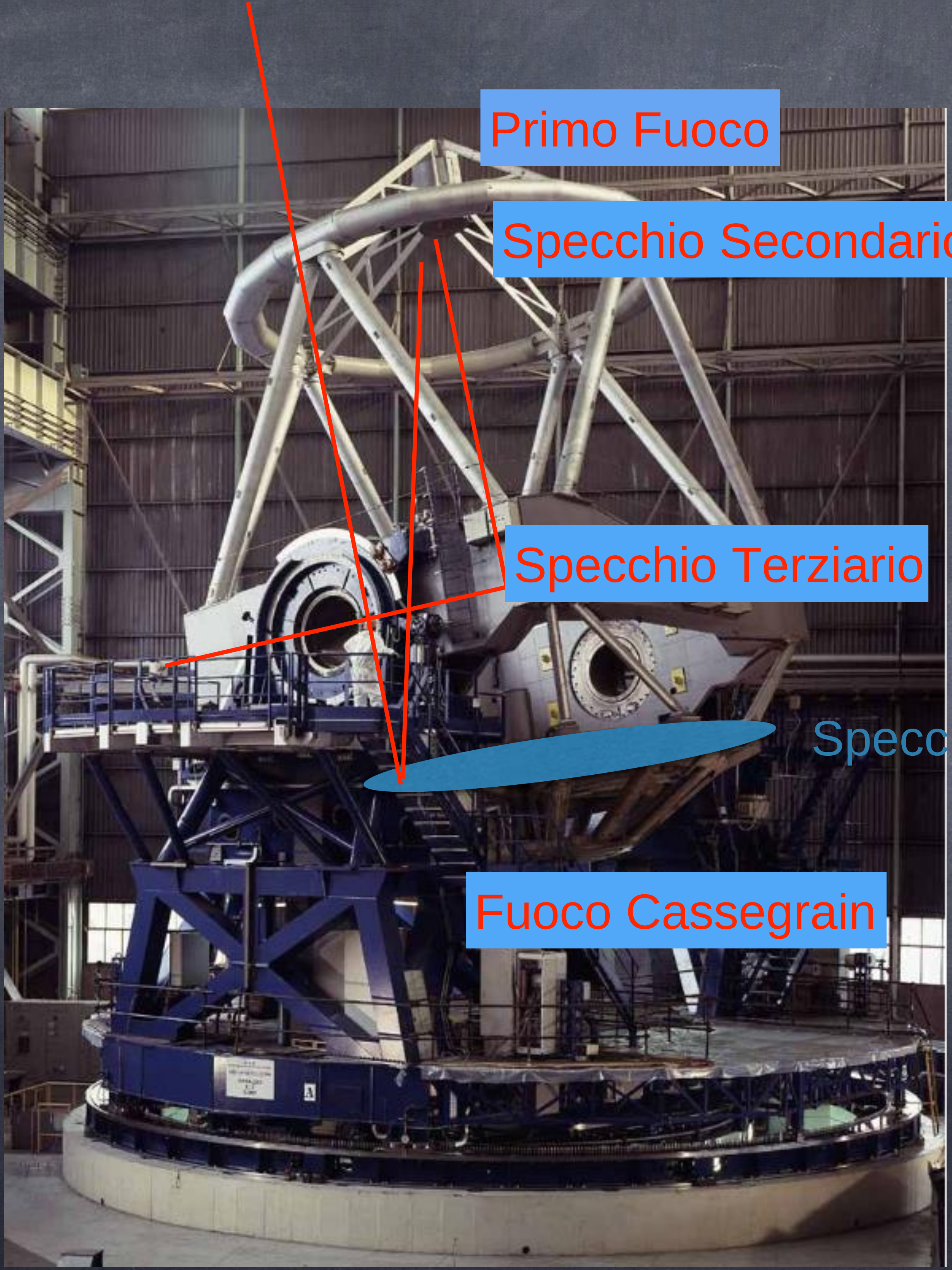
Come sono fatti i telescopi (ottici)?



Come sono fatti i telescopi (ottici)?



Come sono fatti i telescopi (ottici)?



Primo Fuoco

Specchio Secondario

Specchio Terziario

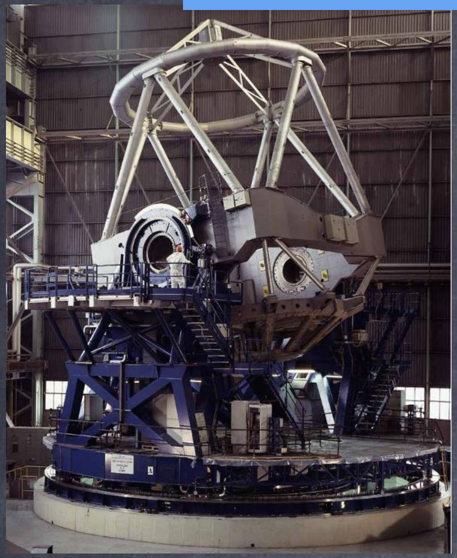
Fuoco Nasmyth

Specchio Primario

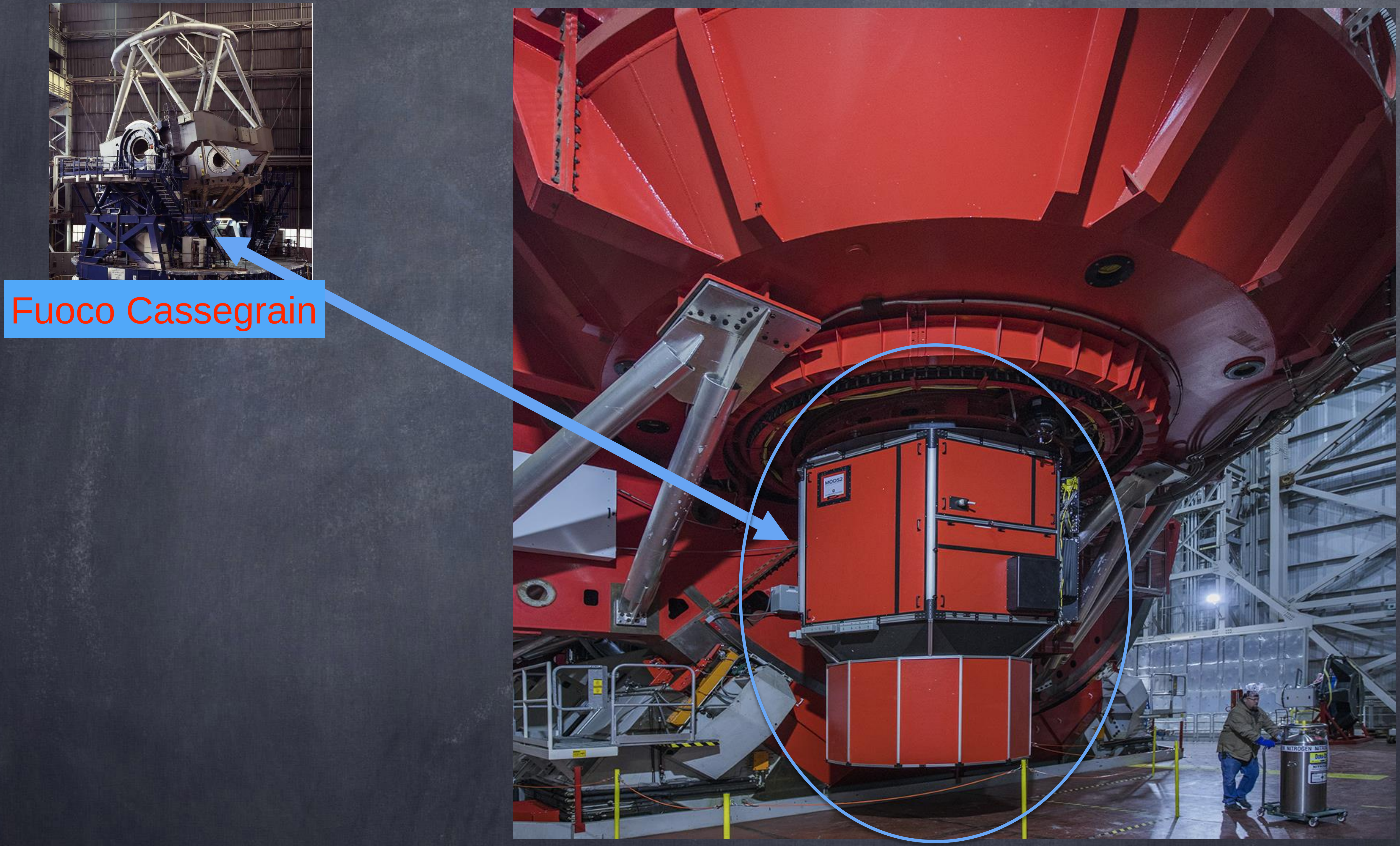
Fuoco Cassegrain

Come sono fatti i telescopi (ottici)?

Primo Fuoco

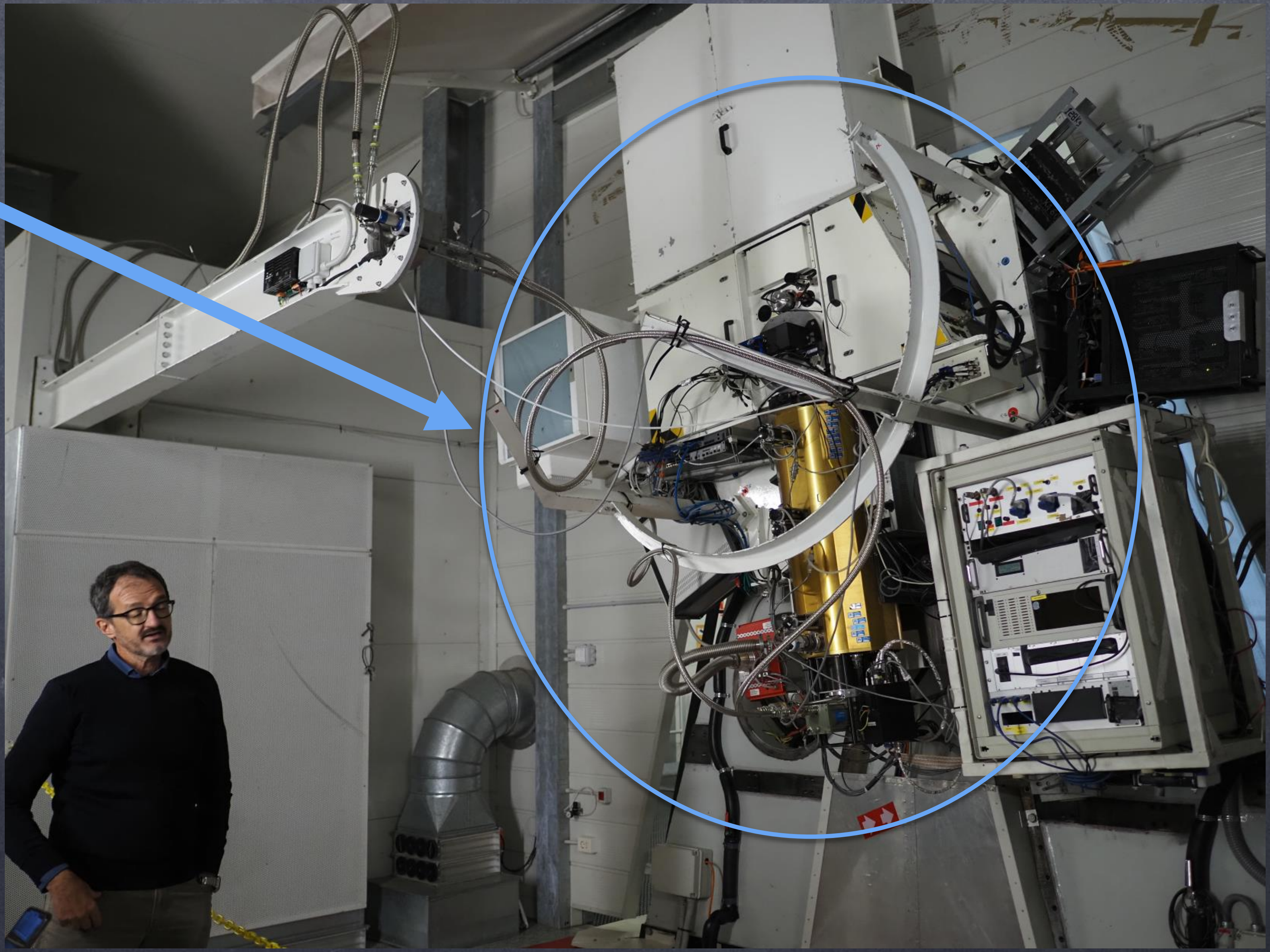


Come sono fatti i telescopi (ottici)?


Fuoco Cassegrain

Come sono fatti i telescopi (ottici)?

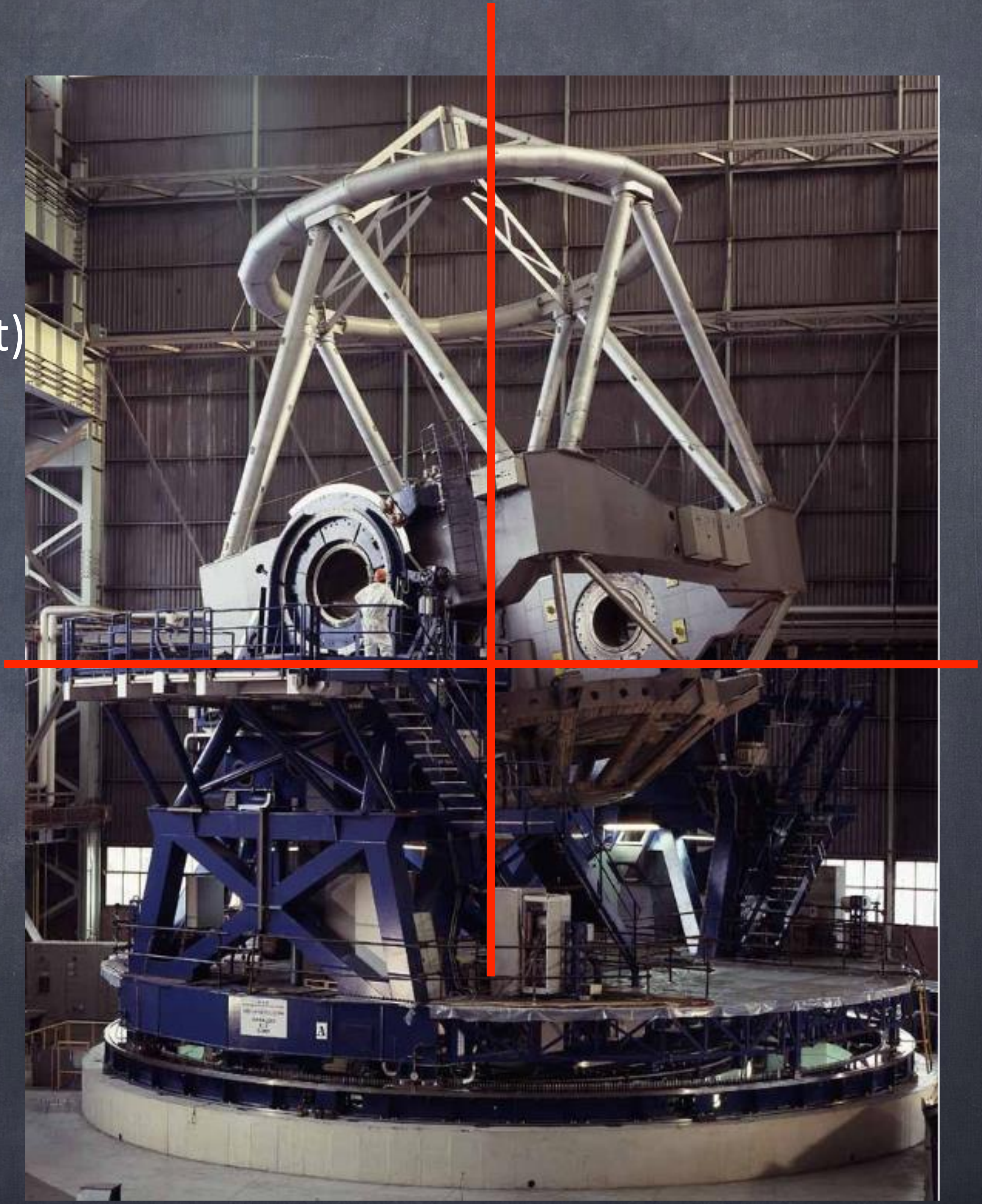
Fuoco Nasmyth



Come si muovono i telescopi (ottici)?

2 Assi tra loro perpendicolari

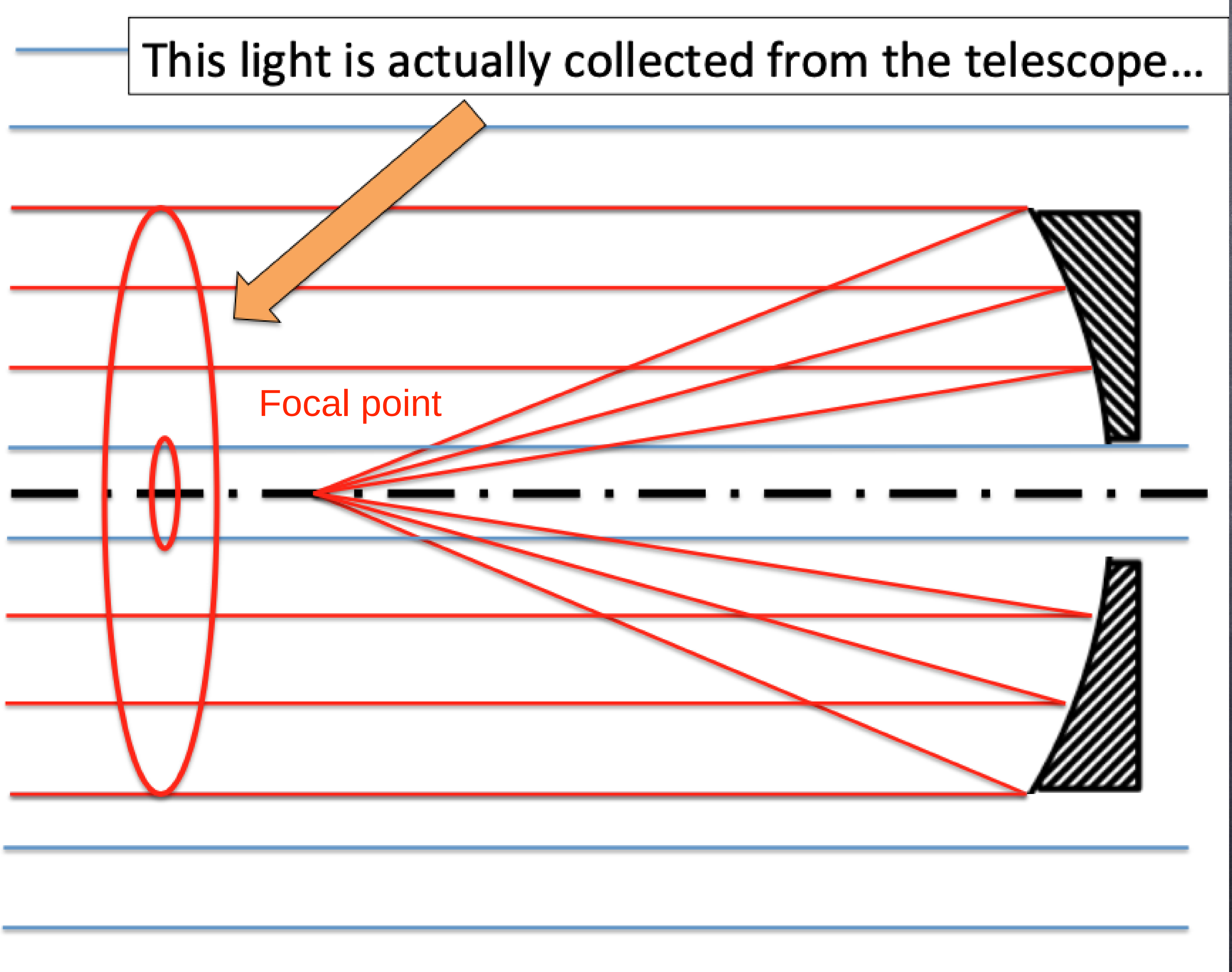
- uno perpendicolare al terreno (azimut)
- uno parallelo all’orizzonte (altezza)



Come sono fatti i telescopi (ottici)?

D=1.22m the Asiago-Pennar telescope
D=1.82m the Asiago-Ekar telescope
D=3.58m the TNG, Telescopio Nazionale Galileo
D=8.2m one of the VLT, Very Large Telescope
D=8.4m one of the mirror of the LBT, Large Binocular Telescope
D=30m the TMT, Thirty Mirror Telescope
D=39m the E-ELT, European Extremely Large Telescope

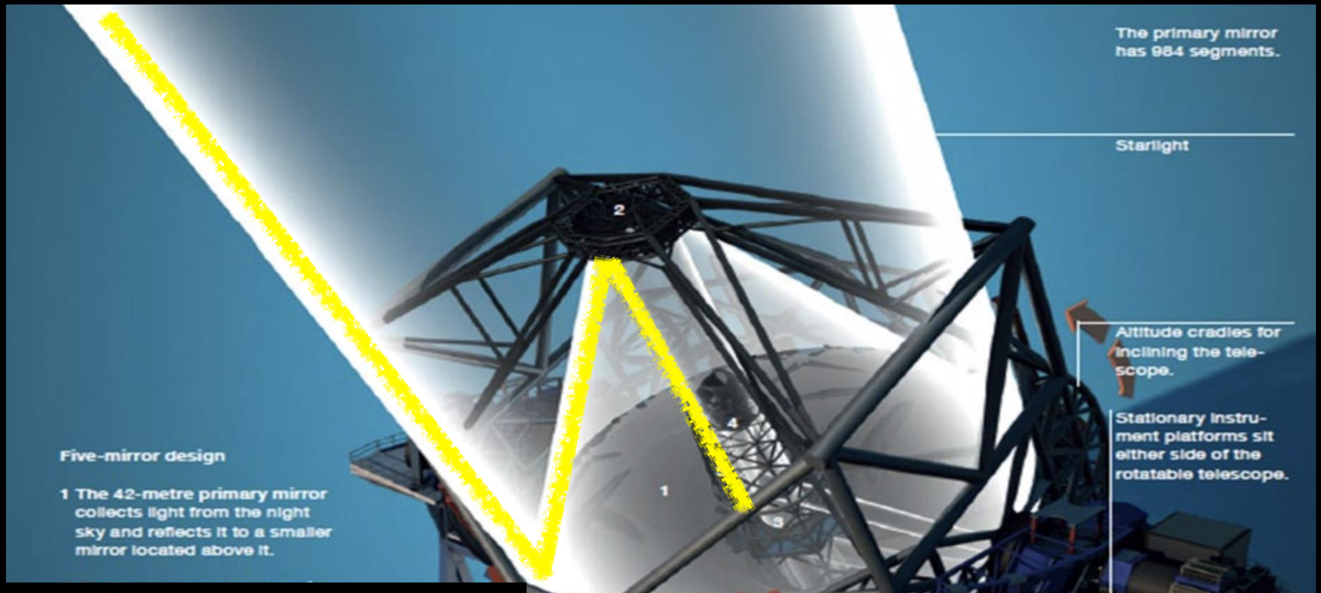
Come sono fatti i telescopi (ottici)?



This light is actually collected from the telescope…

Even for a perfect telescope, a star is not a point but a diffraction shape: Airy disk.

For a light-ray, a telescope is an aperture donut-shaped


The primary mirror has 984 segments.

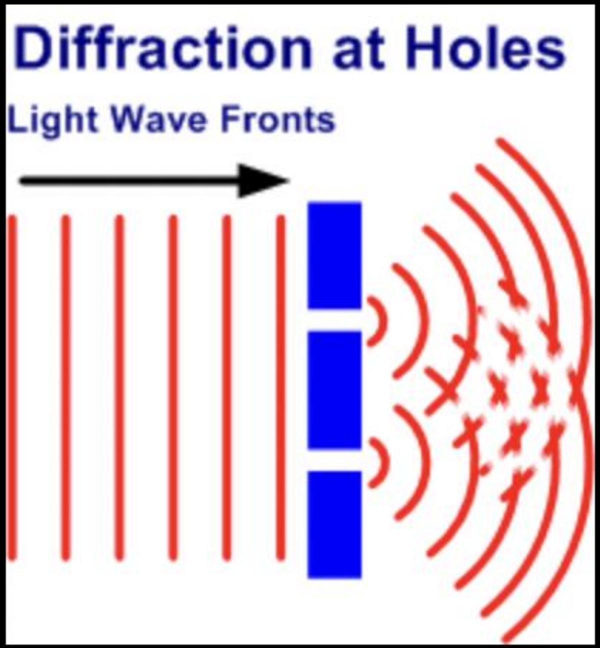
Starlight

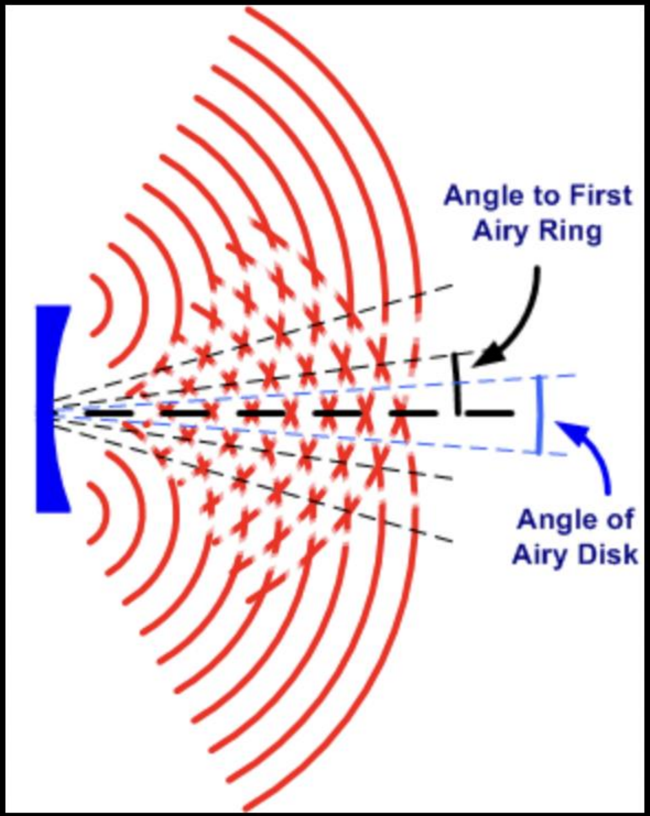
Altitude cradles for inclining the telescope.

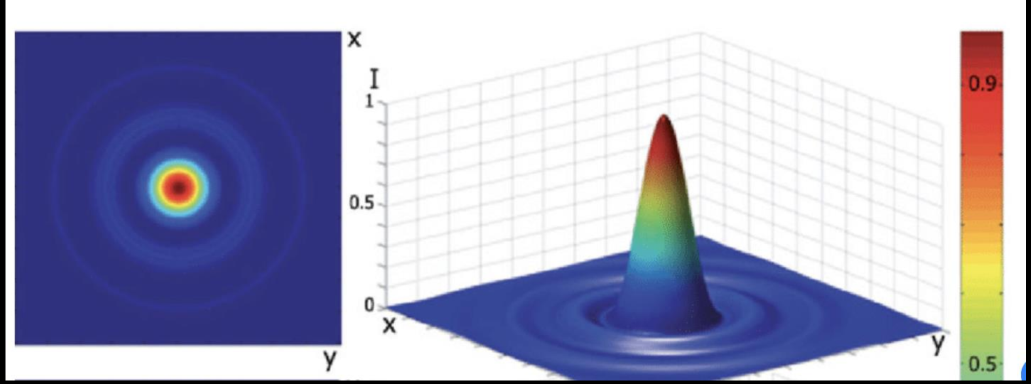
Stationary instrument platforms sit either side of the rotatable telescope.

Five-mirror design

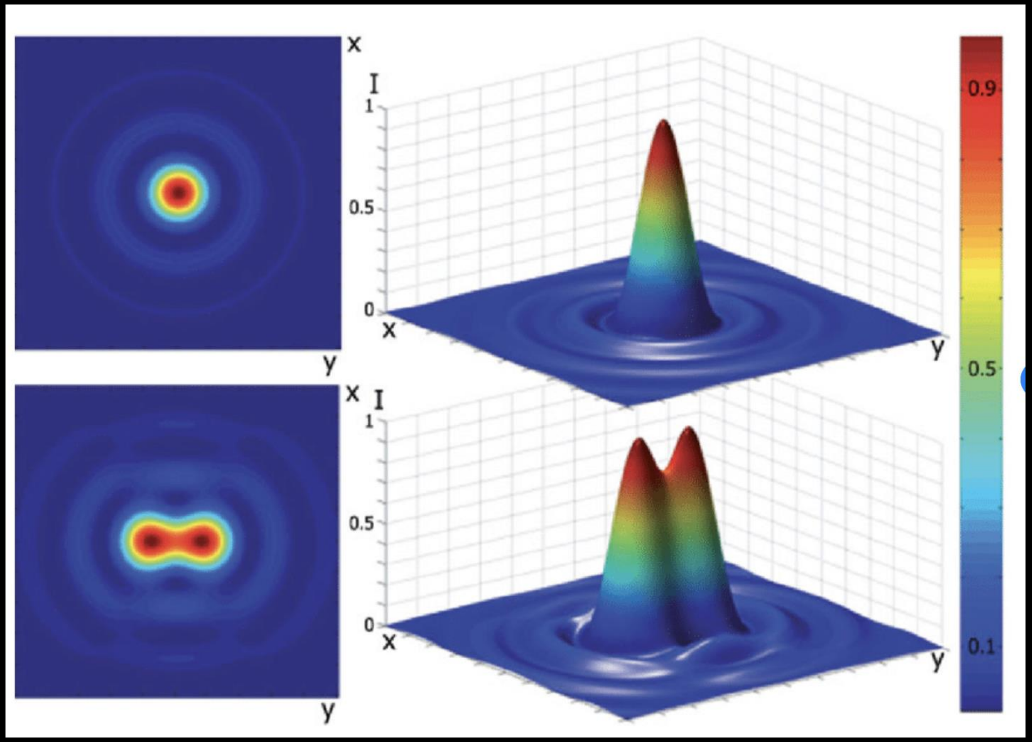
1 The 42-metre primary mirror collects light from the night sky and reflects it to a smaller mirror located above it.

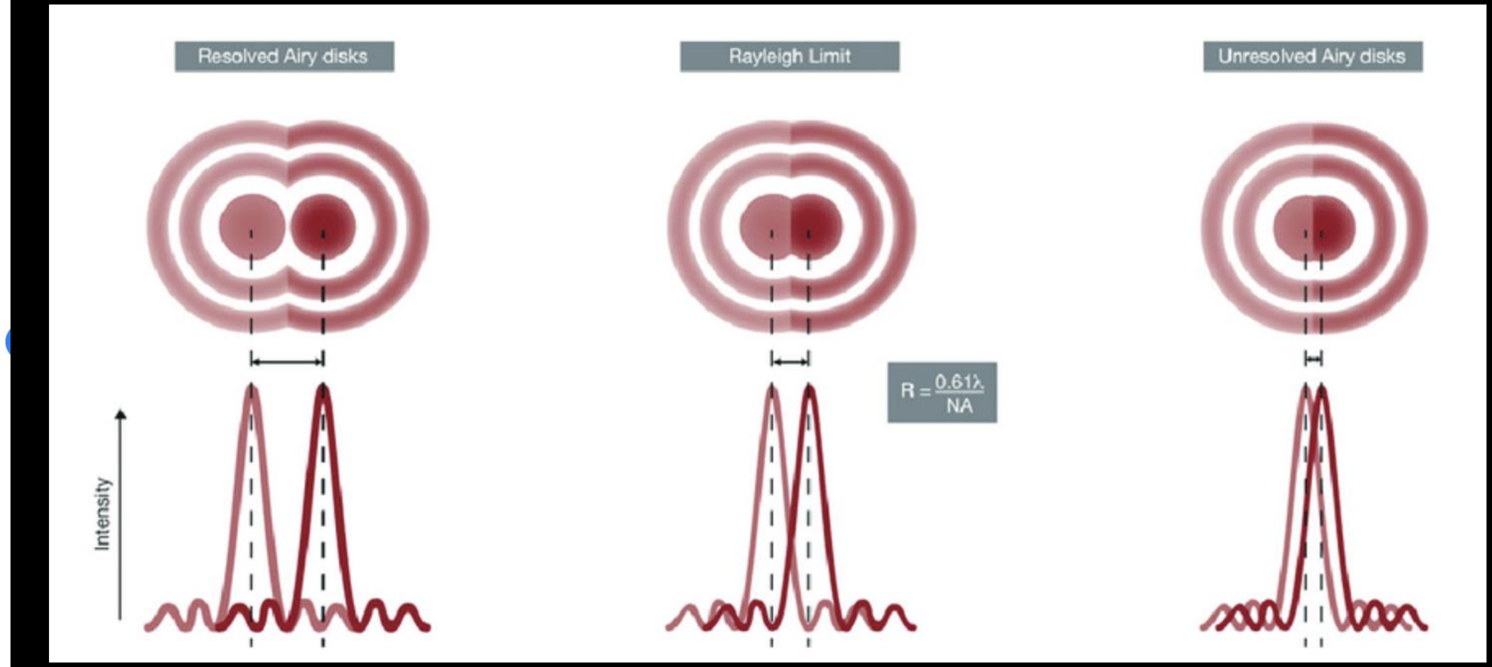


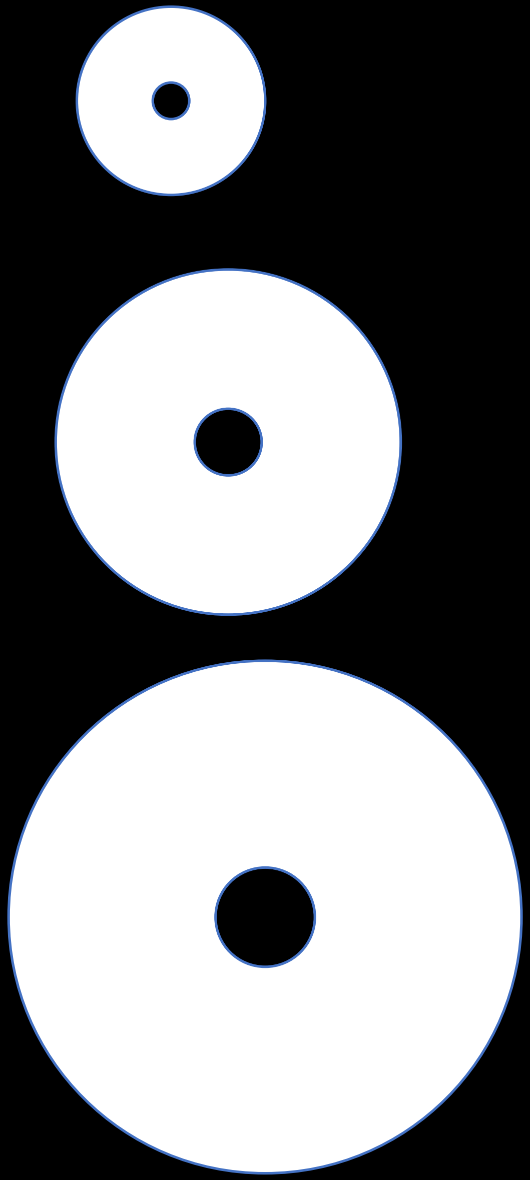


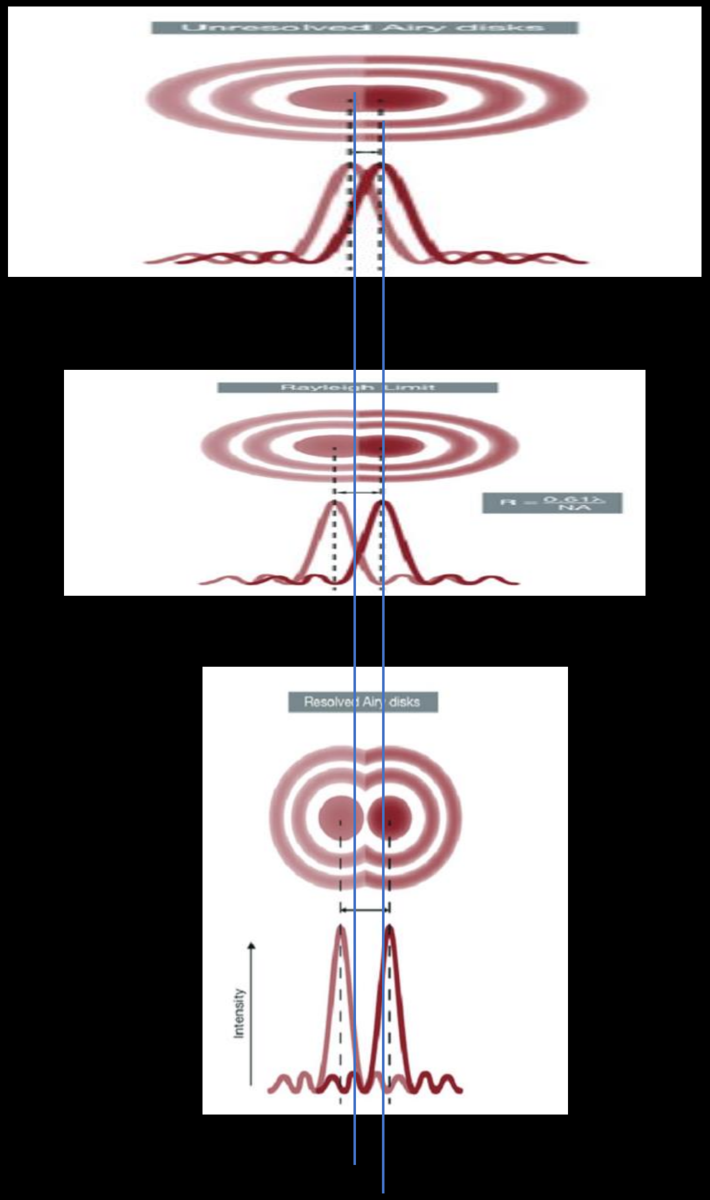


The width of the peak is the Point Spread Function (PSF).
It is the smallest distance between two point-like objects that can be detected.









$$\mathrm{FWHM} = 1.029\,\frac{\lambda}{D}$$

La PSF (Point Spread Function) tipicamente si misura in *secondi d’arco.*

$$1\text{arcsec} = \frac{\pi}{180\times60\times60} \simeq 5\times10^{-6}\ \text{rad}$$

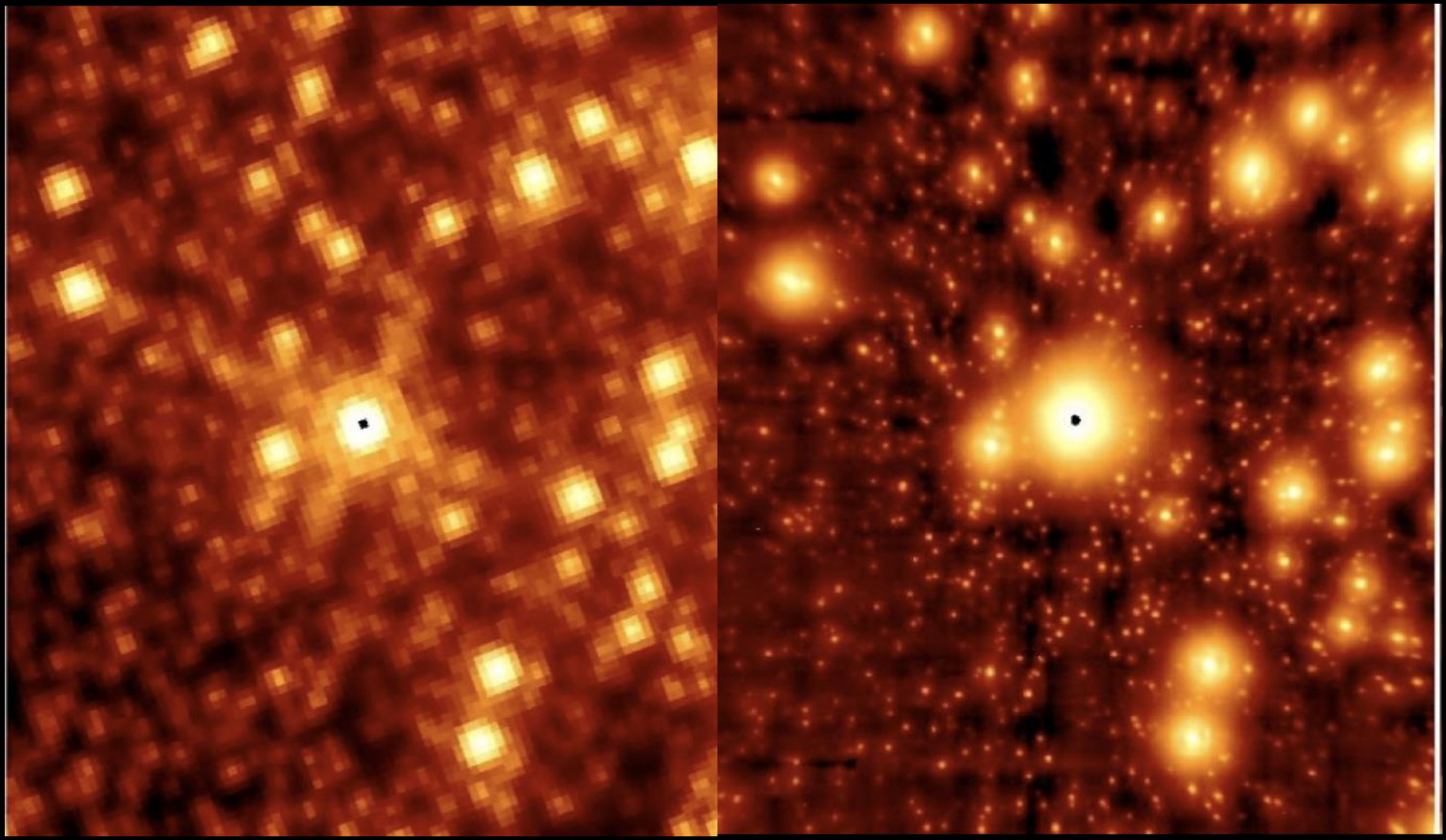
$$\text{FWHM (ideale)}^{(*)} = 1.029\,\frac{\lambda}{D} \simeq 10^{-7}\ \text{rad} = 0.02\ \text{arcsec}$$

(*) per un telescopio con D=10m e λ = 1μm

$$\text{FWHM (JWST)}^{(*)} = 1.029\,\frac{\lambda}{D} \simeq 10^{-7}\ \text{rad} = 0.06\ \text{arcsec}$$

(*) per il James Webb Space Telescope con D=6.5m e λ = 2μm

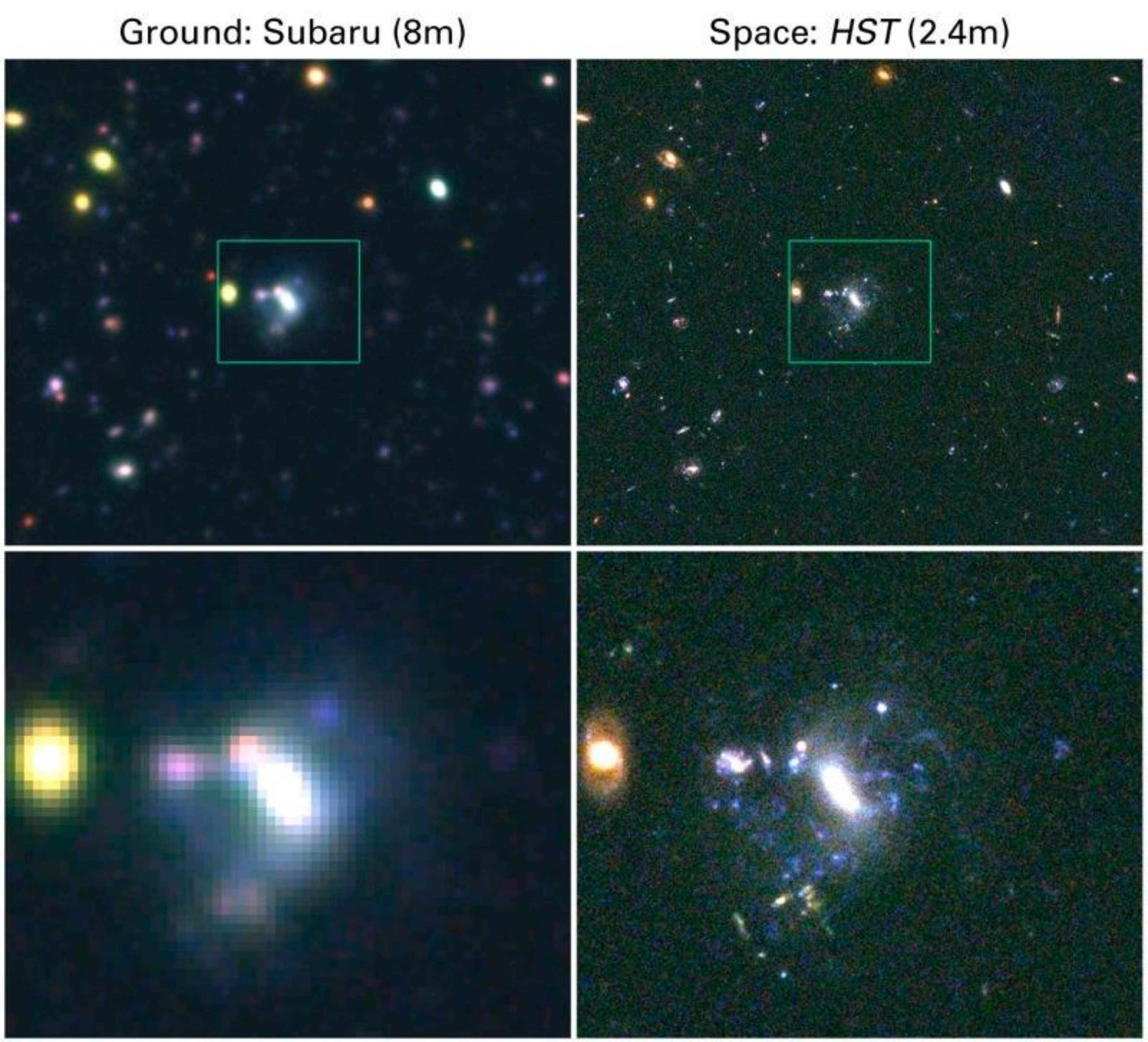
Hubble
(2.5m)



LBT
(8.4m)

Why do we need a better resolution?

1) Details matters...



Seeing

L’atmosfera non e’ omogenea ma ha una struttura di turbolenza distribuita in “bolle” al cui interno cambia l’indice di rifrazione *n.*

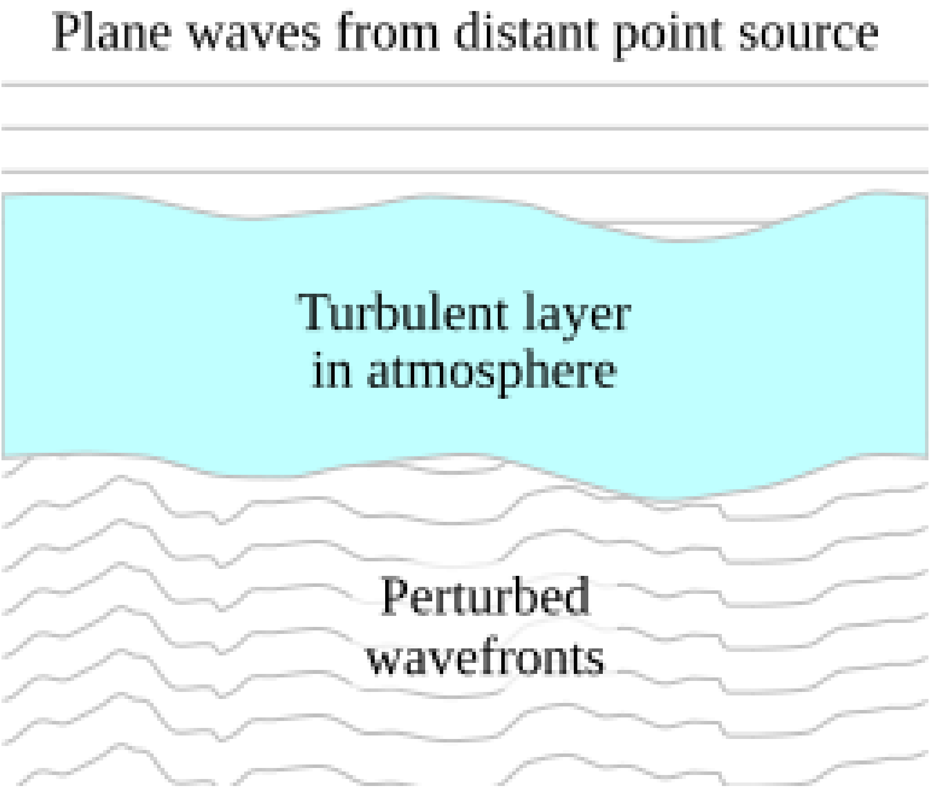
La dimensione delle bolle è in genere << della dimensione del telescopio.

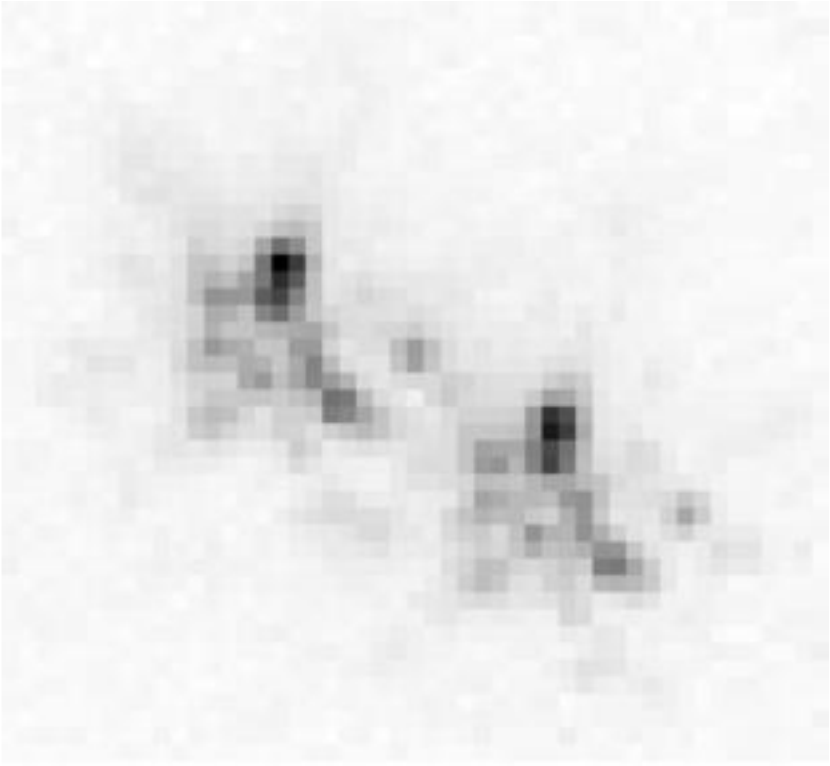
L’onda piana attraversa zone con *n* diverso in cui cambia la velocità della luce.

Il risultato è che l’onda piana viene distorta. La distorsione cambia rapidissimamente portando ad una PSF molto allargata.

L’effetto è maggiore per λ minori.

Nei migliori telescopi la PSF risultante è 0.5arcsec



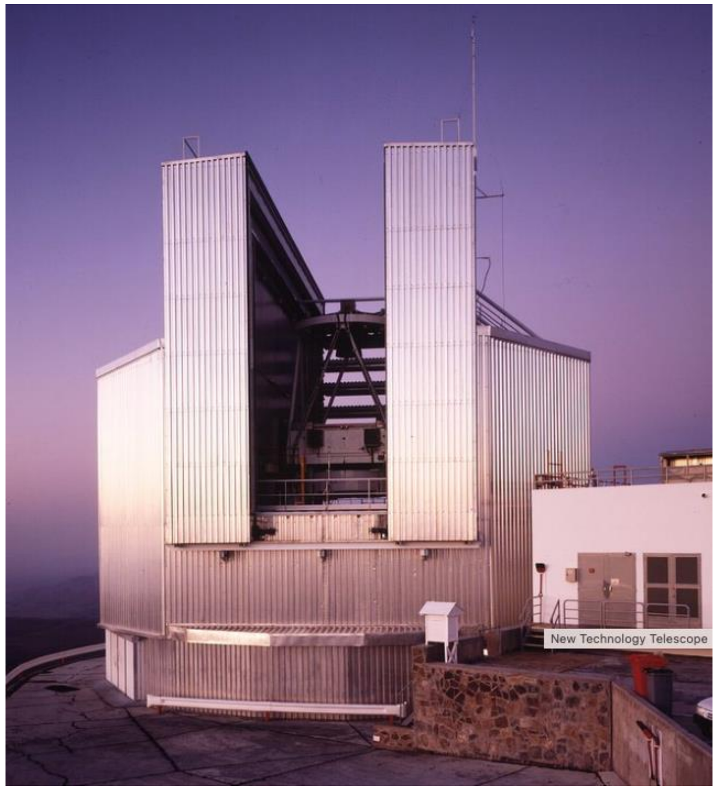


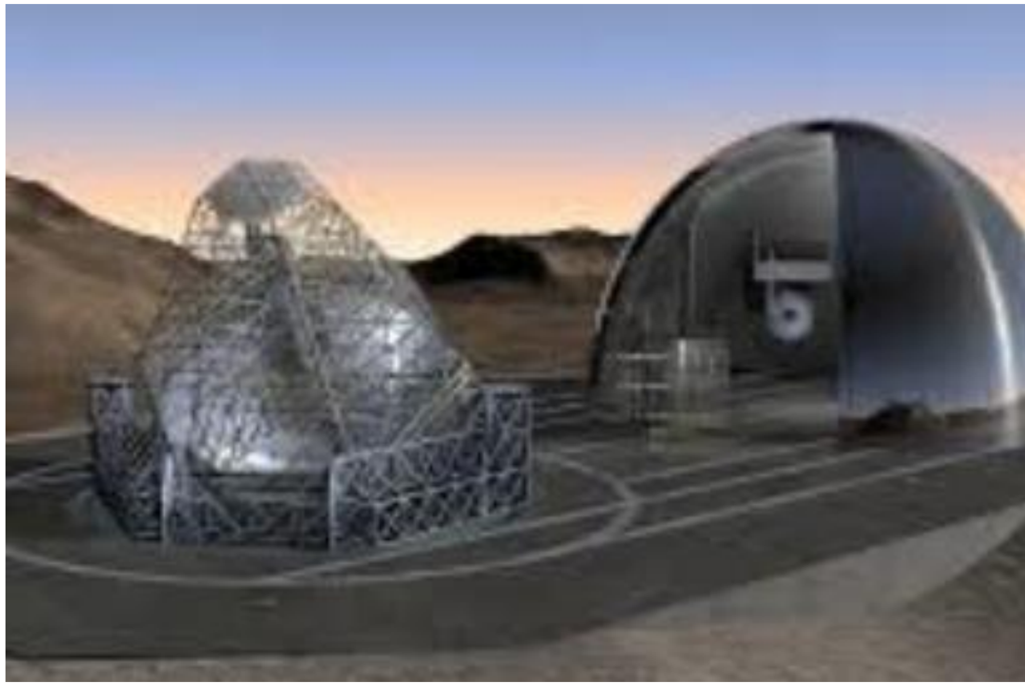
https://en.wikipedia.org/wiki/Astronomical_seeing

Il “sistema telescopio” può *peggiorare* ulteriormente il seeing

1) Gradienti di temperatura interni alla cupola

Soluzione: cupole “aperte”





Il “sistema telescopio” può *peggiorare* ulteriormente il seeing

2) Lo specchio primario si può deformare per effetto di gravità temperatura etc:

Soluzione: ***Ottica attiva***

Un sistema di “pistoni” sotto lo specchio lo mantiene nella forma giusta.

TNG: Lato inferiore dello specchio primario

Cosa misurano i telescopi (ottici)?

La luminosita’ degli oggetti.

La luminosita’ e’ un flusso di energia.

Convenzionalmente si misura in erg/cm^2/s

Di solito non si prende mai tutto lo spettro —> si misura il flusso per unita’ di frequenza o lunghezza d’onda

Flux Density:

f_λ [erg/cm^2/s/A]

f_ν [erg/cm^2/s/Hz]

Magnitudine: $m = -2.5\log(f_\nu) + C$

$0<m<6$: visibility a occhio nudo

TNG: m=18-25

VLT: m= 20-27

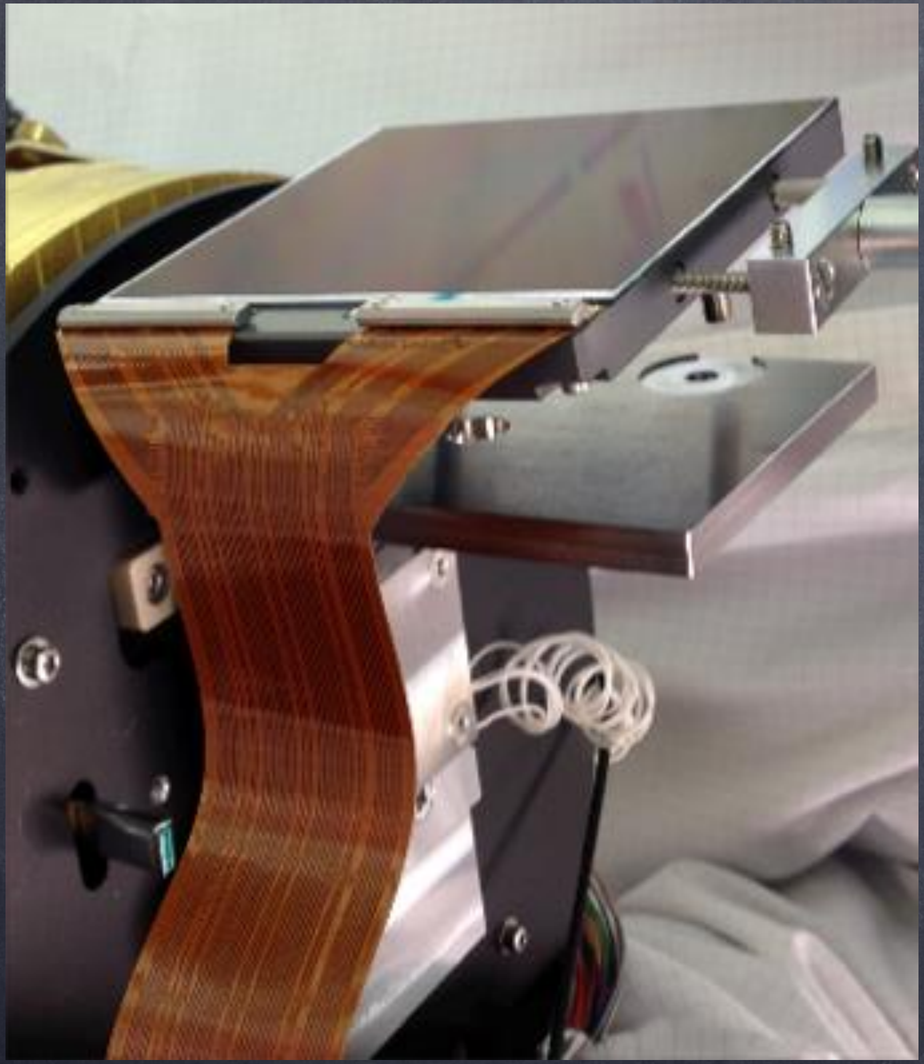
JWST: m = 24-30

Come misurano i telescopi (ottici)?

Con dei sensori (CCD / CMOS)

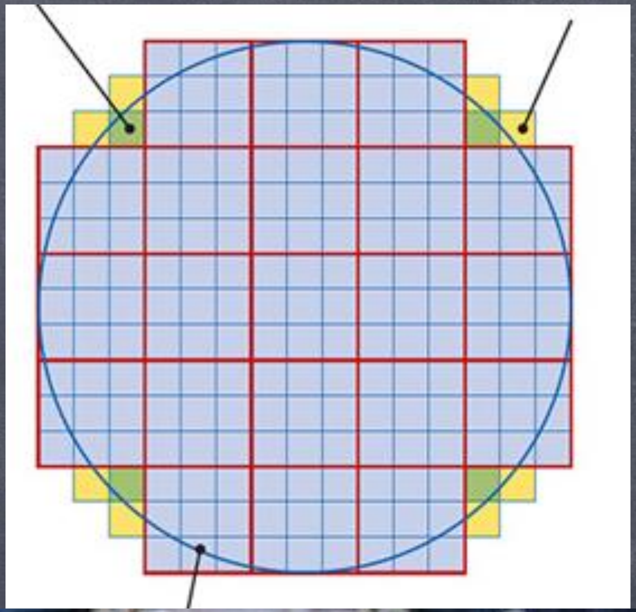
I sensori sono **matrici** di pixel

Possono essere disposti a mosaico

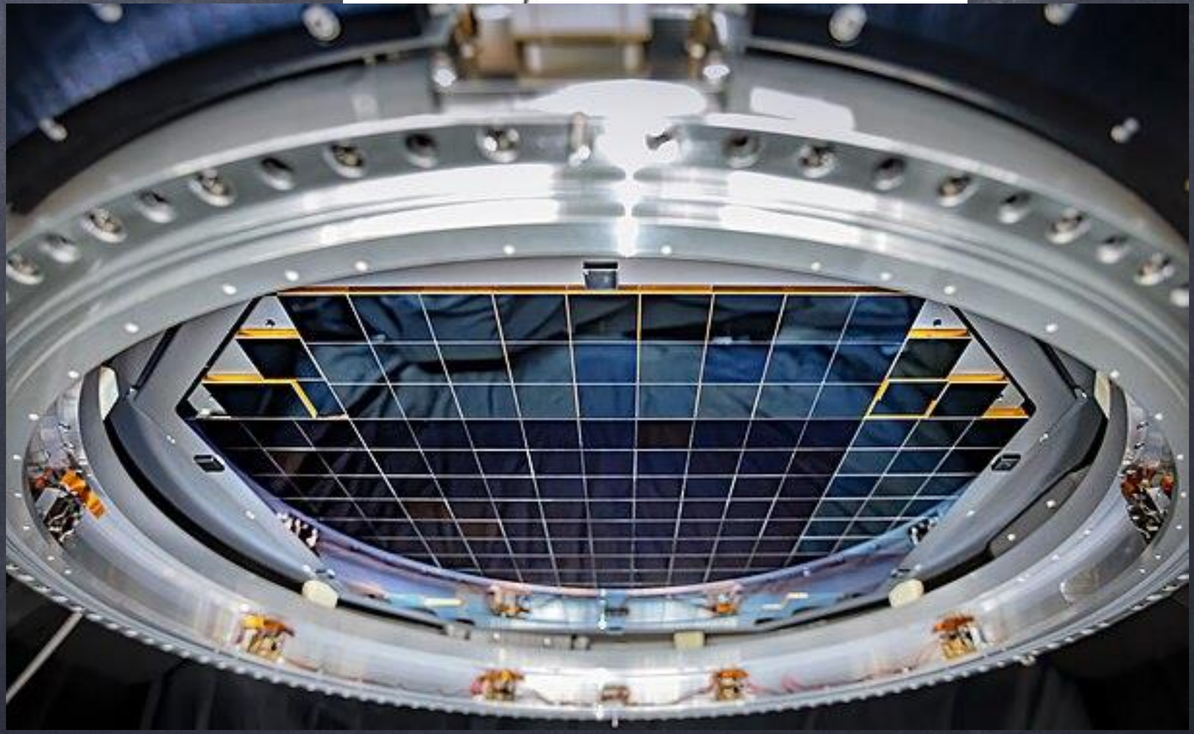


Plato
ESA space mission

Vera Rubin
Telescope

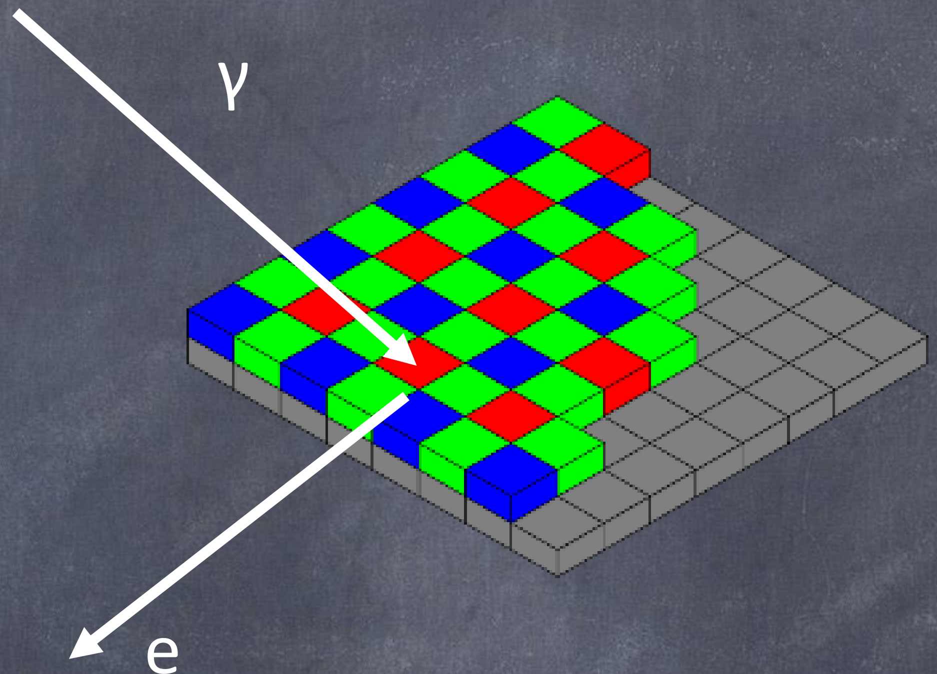


189 CCD
4096x4096



Come misurano i telescopi (ottici)?

Con dei sensori (CCD / CMOS)



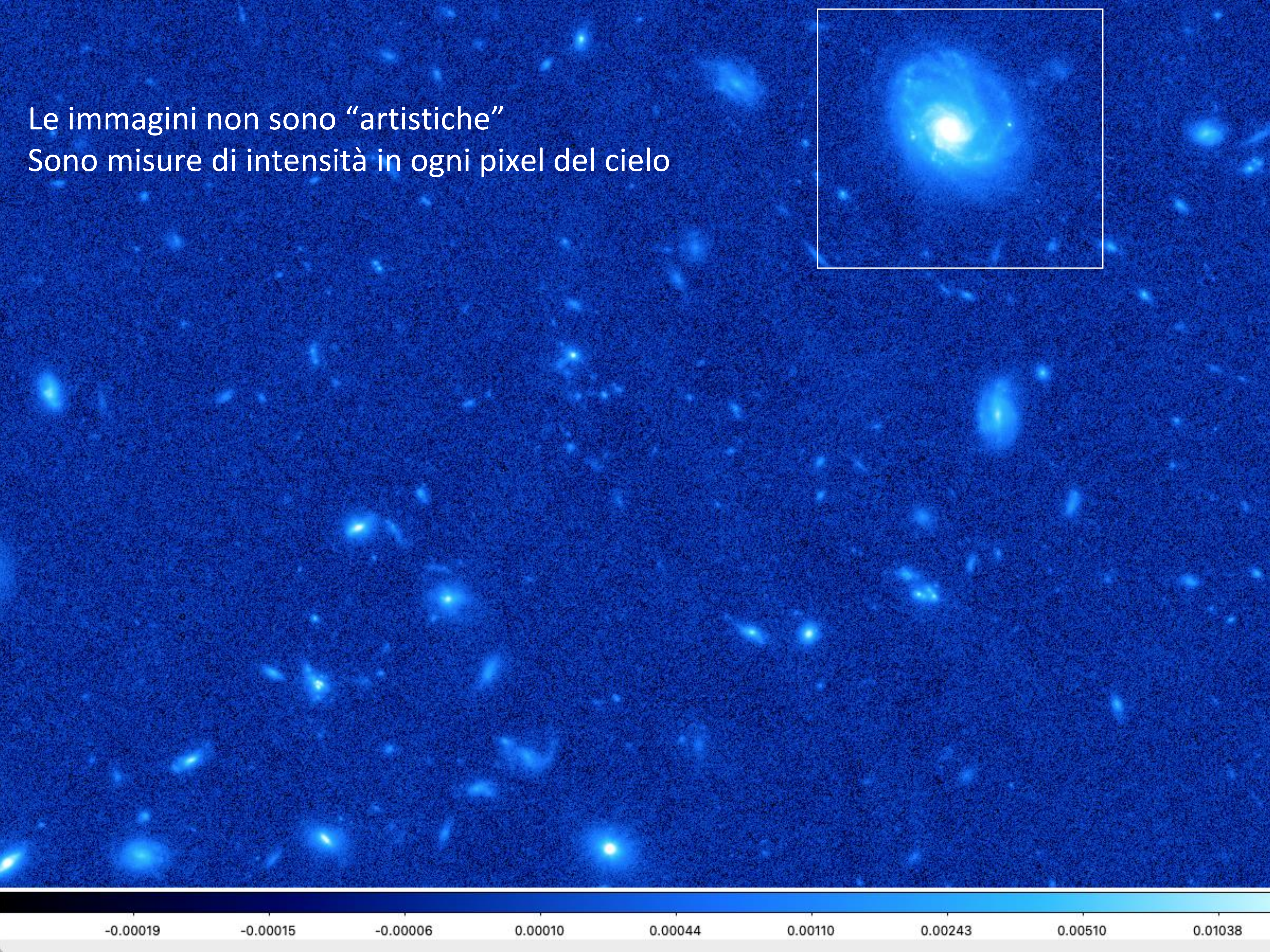
Ogni pixel:

1) converte un fotone in un elettrone
2) accumula gli elettroni finche' non vengono letti (CCD) o li legge in tempo reale (CMOS)

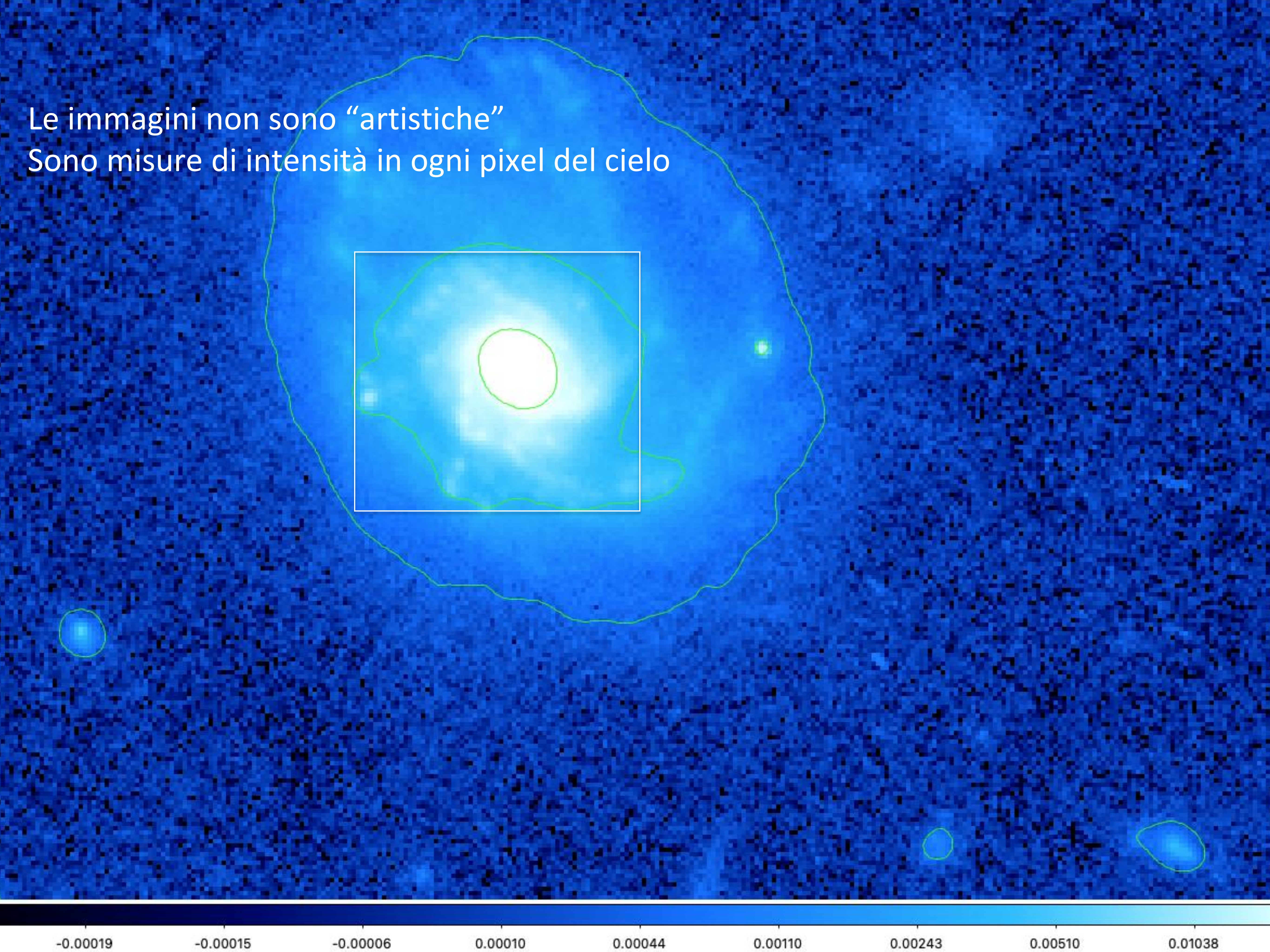
$$n_e \propto n_\gamma \propto \frac{f_\nu}{h\nu}$$

Ogni pixel misura la densità di flusso proveniente dalla zona di cielo sottesa.

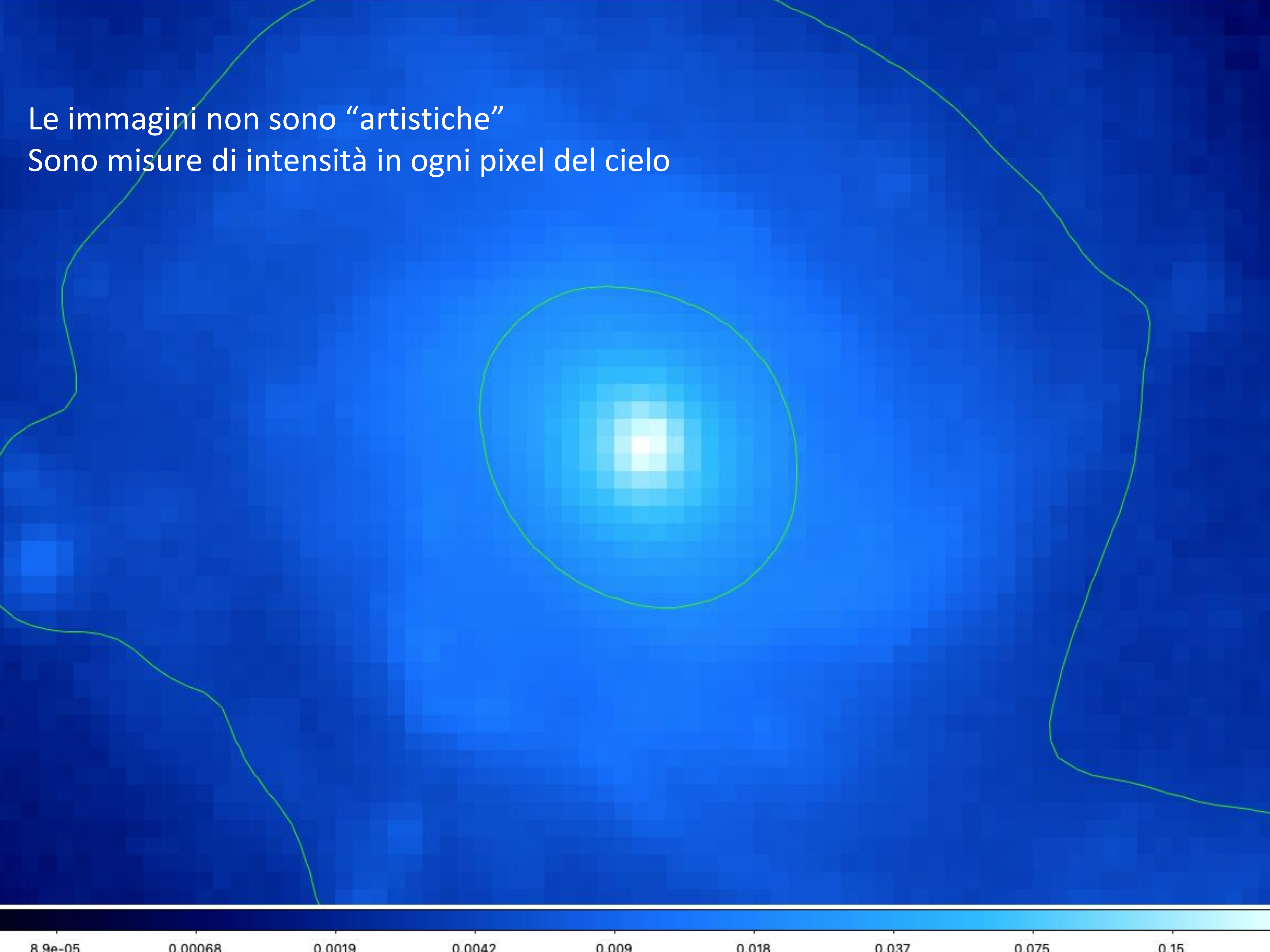
Le immagini non sono “artistiche”
Sono misure di intensità in ogni pixel del cielo



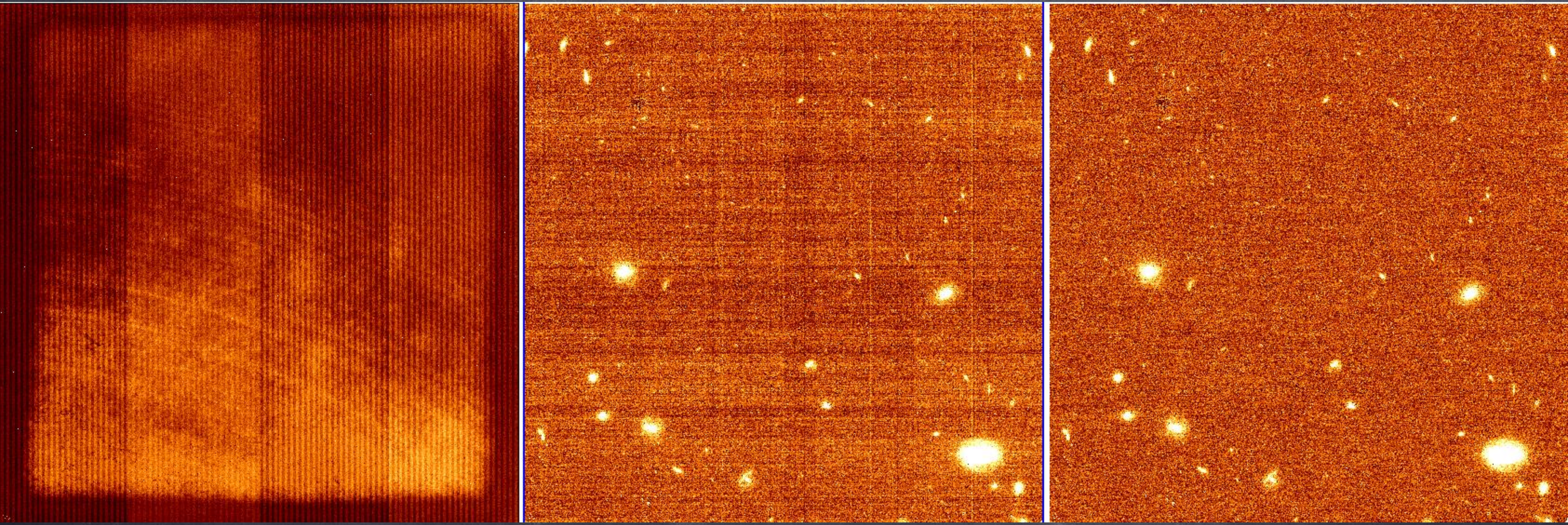
Le immagini non sono “artistiche”
Sono misure di intensità in ogni pixel del cielo



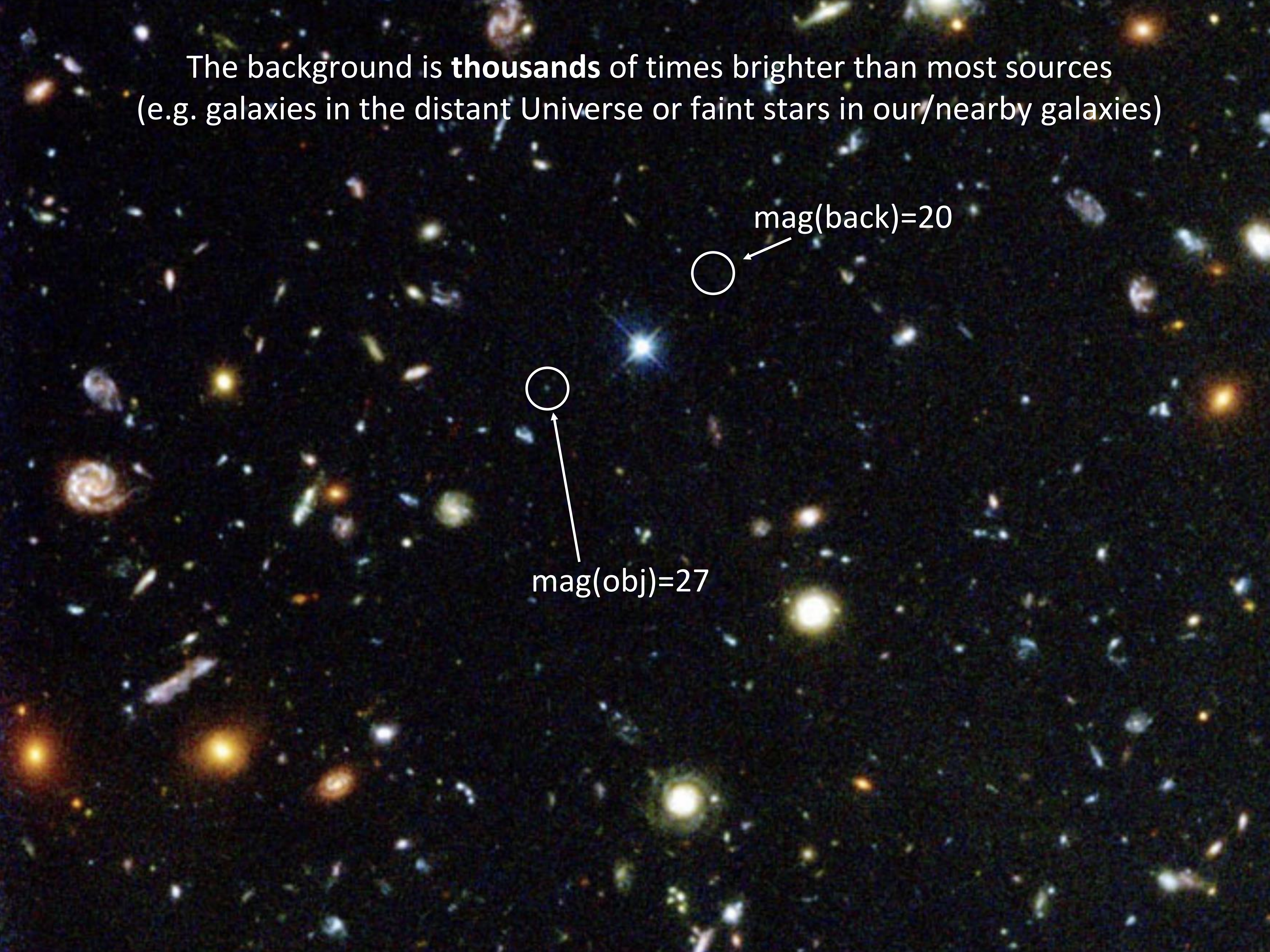
Le immagini non sono “artistiche”
Sono misure di intensità in ogni pixel del cielo



Le immagini prodotte dal sensore vanno <u>calibrate.</u>
Non è una procedura "estetica" ma una procedura "fisica" di calibrazione + rimozione se



The background is **thousands** of times brighter than most sources
(e.g. galaxies in the distant Universe or faint stars in our/nearby galaxies)



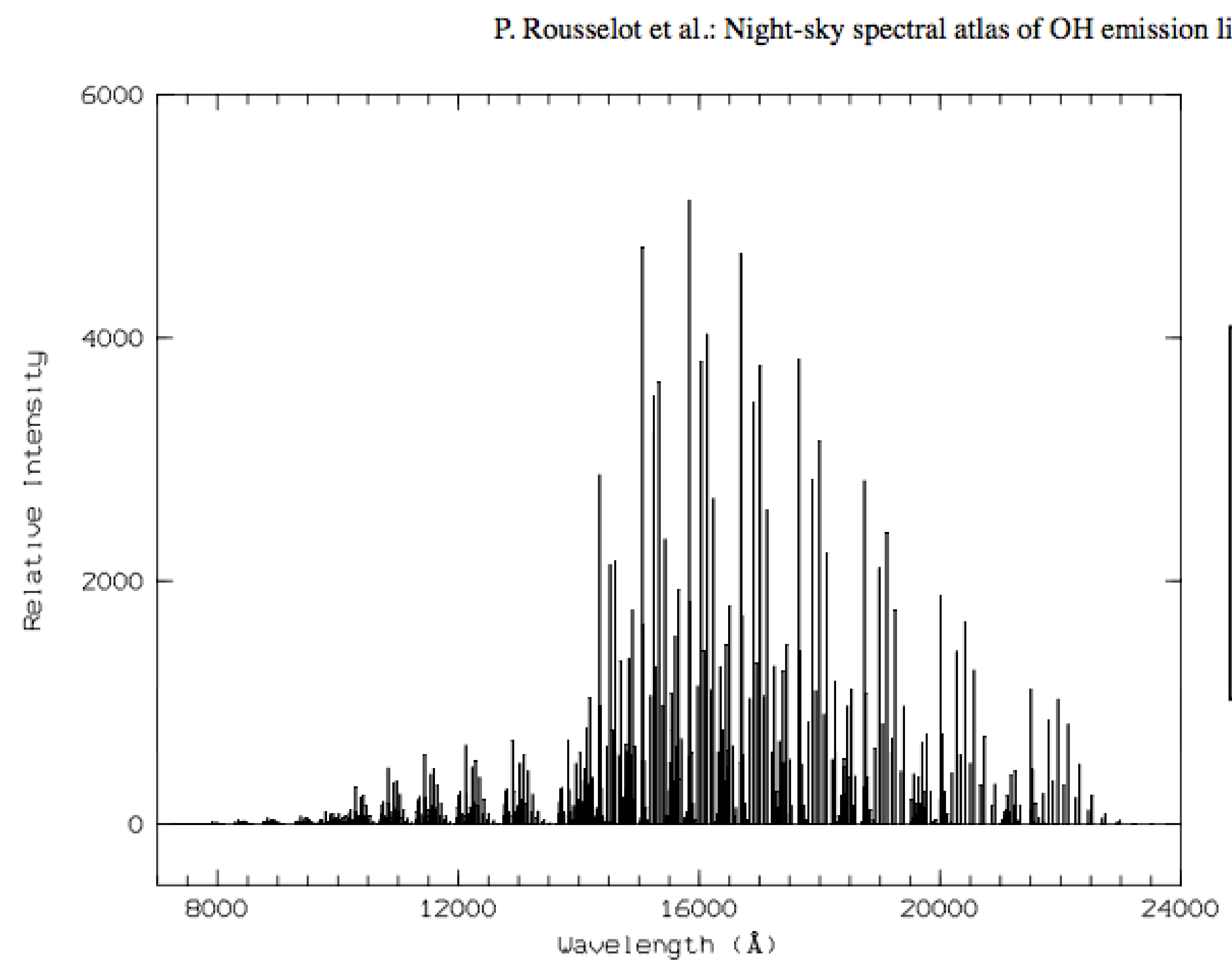
mag(back)=20

mag(obj)=27

Background sources

1) Thermal radiation from instruments & atmosphere
   Effective at λ>20000A.
2) Skylines from atmosphere (molecules)
   Increasingly important at λ>6000A
3) Sunlight reflected by Moon (UV/Visible)
   Effective 15 days/month...
4) Zodiacal Light (sunlight reflected from minor bodies of solar system) .. inevitable!
5) Dust cirrus in the Galaxy (long wavelengths)
   depend on direction; lower for high latitude
6) Cosmic rays and other high energy particles (high energy satellites)

OH Sky lines in the optical /near IR


P. Rousselot et al.: Night-sky spectral atlas of OH emission lines

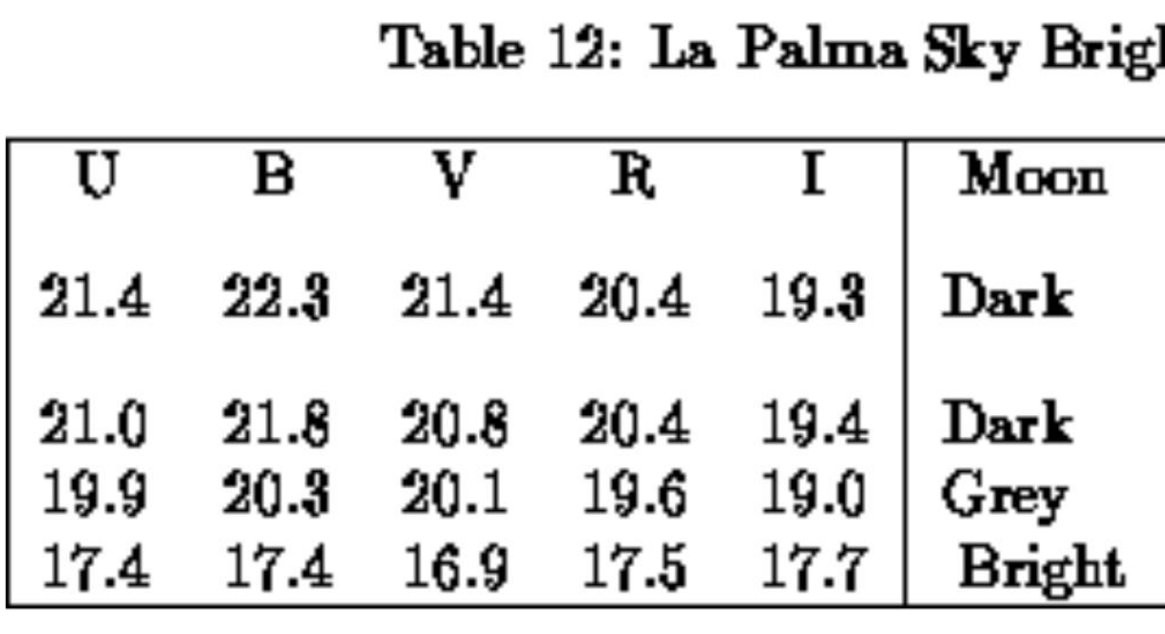
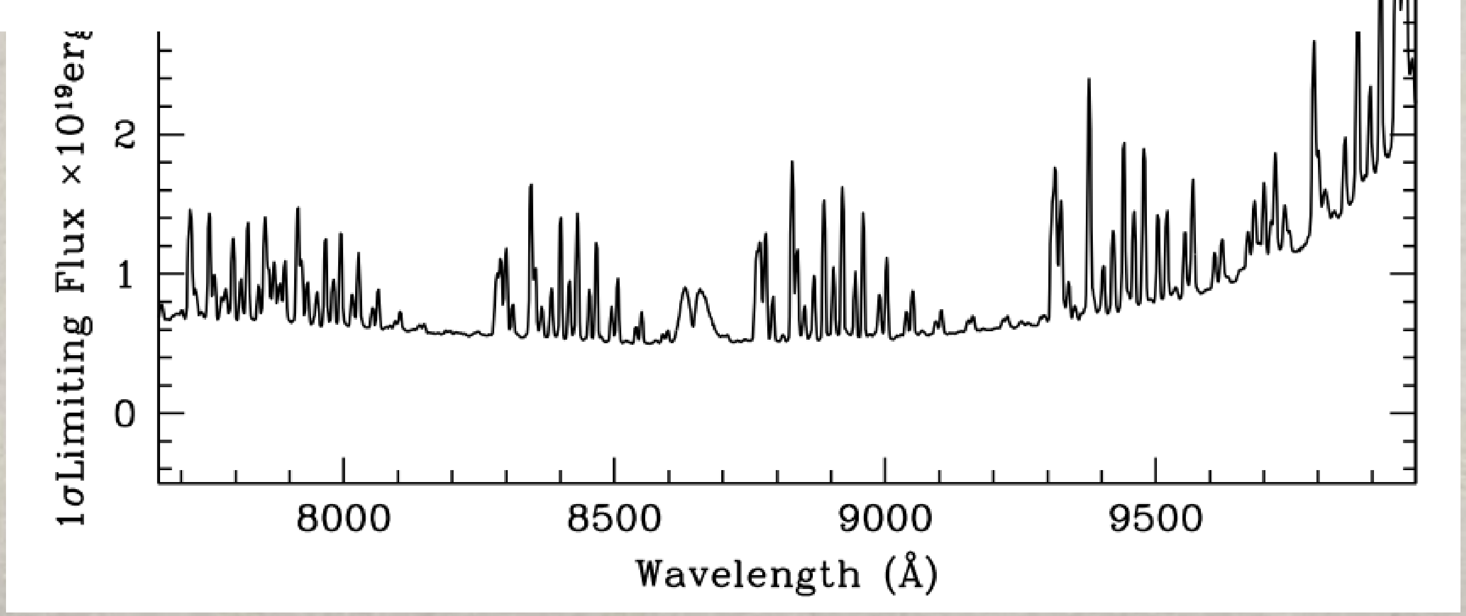


Table 12: La Palma Sky Brigl

U	B	V	R	I	Moon
21.4	22.3	21.4	20.4	19.3	Dark
21.0	21.8	20.8	20.4	19.4	Dark
19.9	20.3	20.1	19.6	19.0	Grey
17.4	17.4	16.9	17.5	17.7	Bright

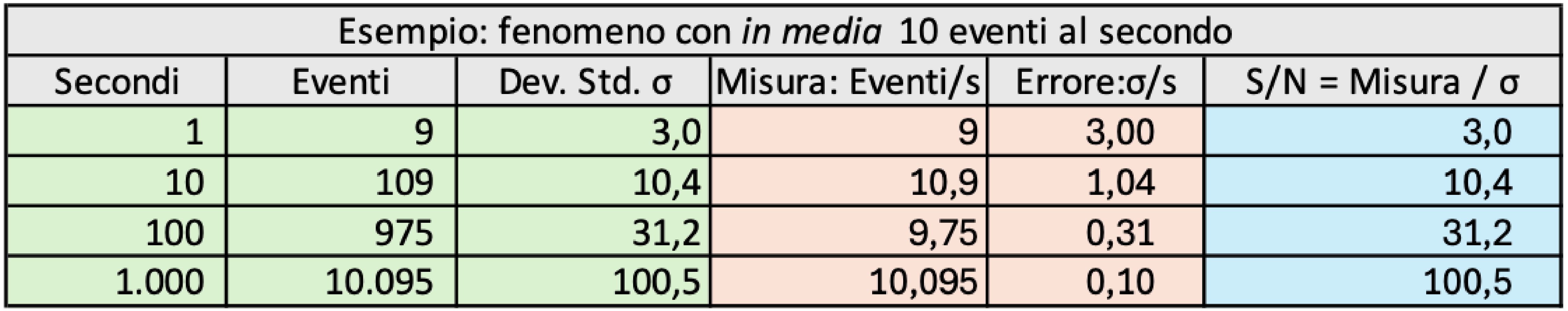


Come facciamo a osservare oggetti più deboli del fondo?

Ci aiuta la Statistica di Poisson

nti che accadono casualmente, successivamente e individualmente con probabilità costant
Per es.: decadimento radioattivo, arrivo di fotoni da una stella..

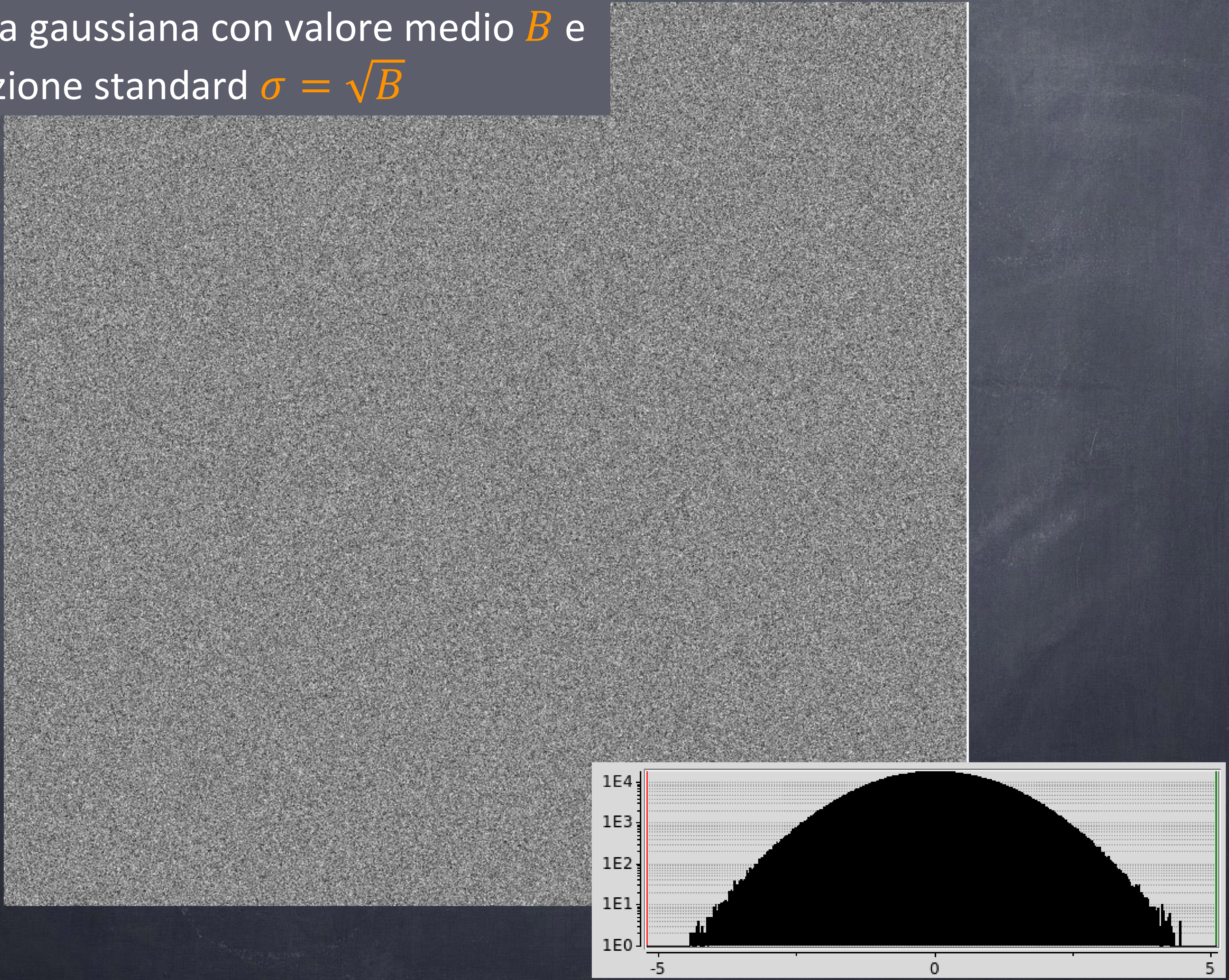
Per un processo che in un tempo T genera in media N eventi,
il valore aspettato degli eventi misurati sarà N
distribuito con una distribuzione gaussiana(*) con $\sigma = \sqrt{N}$

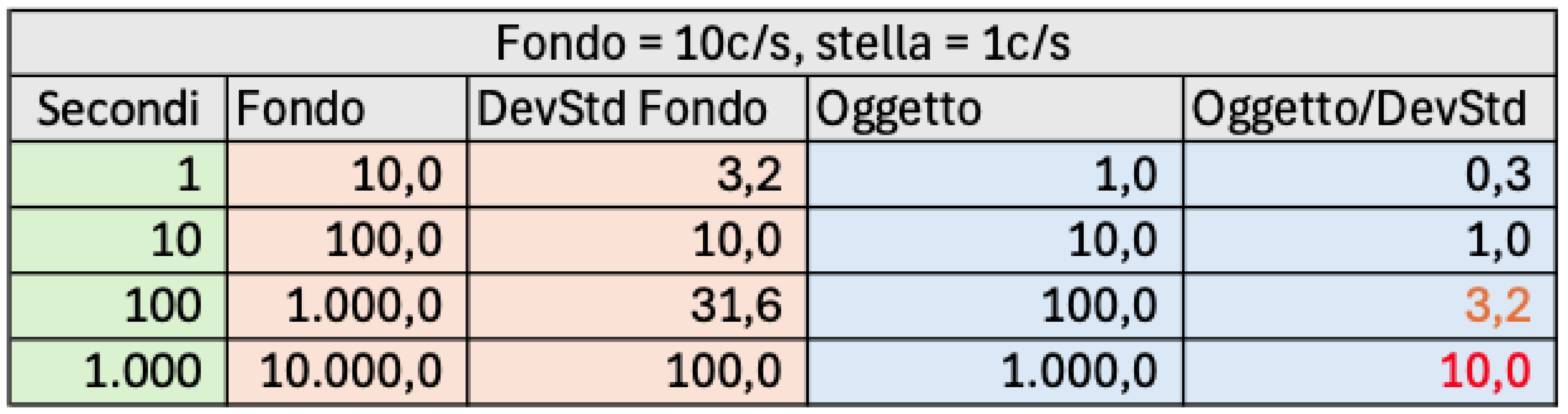


Esempio: fenomeno con *in media* 10 eventi al secondo					
Secondi	Eventi	Dev. Std. σ	Misura: Eventi/s	Errore:σ/s	S/N = Misura / σ
1	9	3,0	9	3,00	3,0
10	109	10,4	10,9	1,04	10,4
100	975	31,2	9,75	0,31	31,2
1.000	10.095	100,5	10,095	0,10	100,5

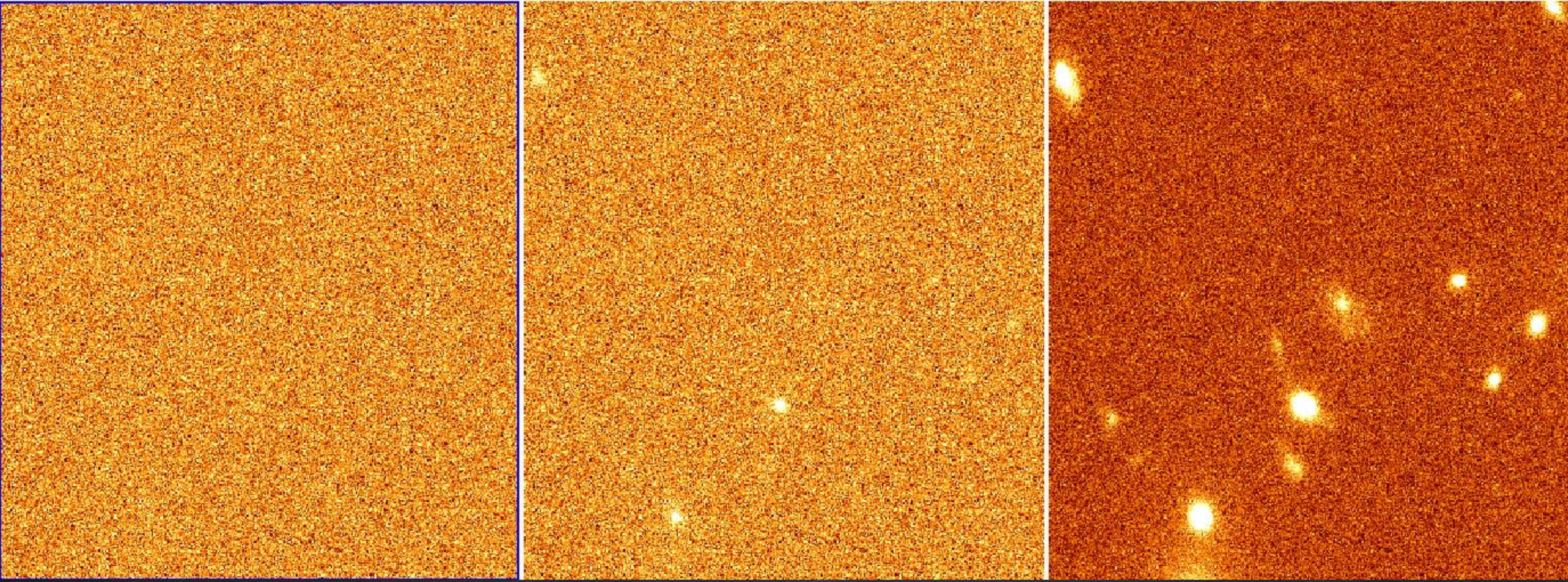
(*) Approssimazione valida per $N > 10$

Il “fondo cielo” genera nei pixel di un rivelatore un segnale B distribuito secondo statistica di Poisson, ovvero come una gaussiana con valore medio B e deviazione standard $\sigma = \sqrt{B}$





Fondo = 10c/s, stella = 1c/s				
Secondi	Fondo	DevStd Fondo	Oggetto	Oggetto/DevStd
1	10,0	3,2	1,0	0,3
10	100,0	10,0	10,0	1,0
100	1.000,0	31,6	100,0	3,2
1.000	10.000,0	100,0	1.000,0	10,0



Segnale prodotto da un oggetto osservato ad un telescopio di diametro D in un tempo di posa T

$$S_\nu = \frac{f_\nu}{h\nu} \times \frac{\pi}{4} D^2 \times T \times \epsilon_\nu$$

Numero fotoni

Area Telescopio

Tempo posa

Efficienza

Rumore di misura sullo stesso oggetto osservato ad un telescopio di diametro D in un tempo di posa T

1) Rumore “di lettura” (read-out noise): fattore costante σ_{ron}

2) Rumore Poisson sul segnale misurato: Oggetto + Fondo Cielo σ_B

$$\sigma_B = \sqrt{\frac{f_\nu + B_\nu}{h\nu} \times \frac{\pi}{4} D^2 \times T \times \epsilon_\nu}$$

Numero fotoni oggetto + cielo

Area Telescopio

Tempo posa

Efficienza

Rumore di misura sullo stesso oggetto osservato ad un telescopio di diametro D in un tempo di posa T

Gli errori si sommano quadraticamente

$$\sigma_{TOT}^2 = \sigma_{ron}^2 + \sigma_B^2$$

$$\sigma_{TOT} = \sqrt{\sigma_{ron}^2 + \frac{f_\nu + B_\nu}{h\nu} \times \frac{\pi}{4} D^2 \times T \times \epsilon_\nu}$$

Rapporto Segnale / Rumore per un oggetto osservato ad un telescopio di diametro D in un tempo di posa T

$$\boxed{\frac{S}{N} = \frac{\dfrac{f_\nu}{h\nu}\dfrac{\pi}{4}D^2 T \epsilon_\nu}{\sqrt{\sigma_{ron}^2 + \dfrac{(f_\nu + B_\nu)}{h\nu}\dfrac{\pi}{4}D^2 T \epsilon_\nu}}}$$

Rapporto Segnale / Rumore per un oggetto osservato ad un telescopio di diametro D in un tempo di posa T

Caso 1: $\sigma_{ron}^2 \gg \frac{(f_\nu + B_\nu)}{h\nu}\frac{\pi}{4}D^2 T\epsilon_\nu$

$$\boxed{\frac{S}{N} = \frac{\frac{f_\nu}{h\nu}\frac{\pi}{4}D^2 T\epsilon_\nu}{\sqrt{\sigma_{ron}^2 + \cancel{\frac{(f_\nu + B_\nu)}{h\nu}\frac{\pi}{4}D^2 T\epsilon_\nu}}}}$$

Dominati dal rumore di lettura

(T è molto piccolo

o

$(f_\nu + B_\nu)$ è molto piccolo)

$$\frac{S}{N} \propto f_\nu \times D^2\epsilon \times T$$

Il S/N cresce rapidamente con tempo di posa (T) e molto rapidamente con le dimensioni del telescopio (D^2)

f_{limit}: Oggetto più debole che potete osservare con un dato S/N

$$f_{limit} \propto \frac{S}{N} D^{-2} T^{-1}$$

Rapporto Segnale / Rumore per un oggetto osservato ad un telescopio di diametro D in un tempo di posa T

$$\boxed{\frac{S}{N} = \frac{\frac{f_\nu}{h\nu}\frac{\pi}{4}D^2 T\epsilon_\nu}{\sqrt{\xcancel{\sigma_{ron}^2} + \frac{(\xcancel{f_\nu} + B_\nu)}{h\nu}\frac{\pi}{4}D^2 T\epsilon_\nu}}}$$

Caso 2: $B_\nu \gg f_\nu, \sigma_{ron}^2$

Dominati dal Fondo Cielo

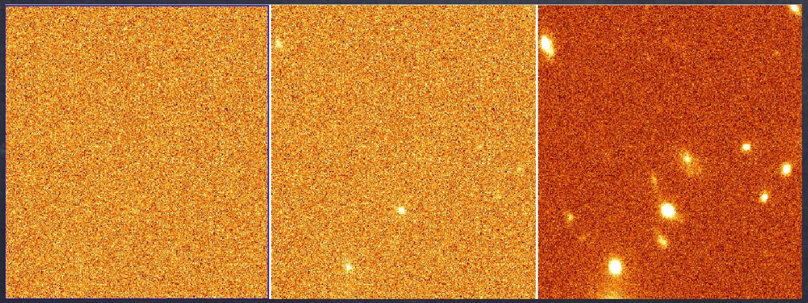
e/o T è grande

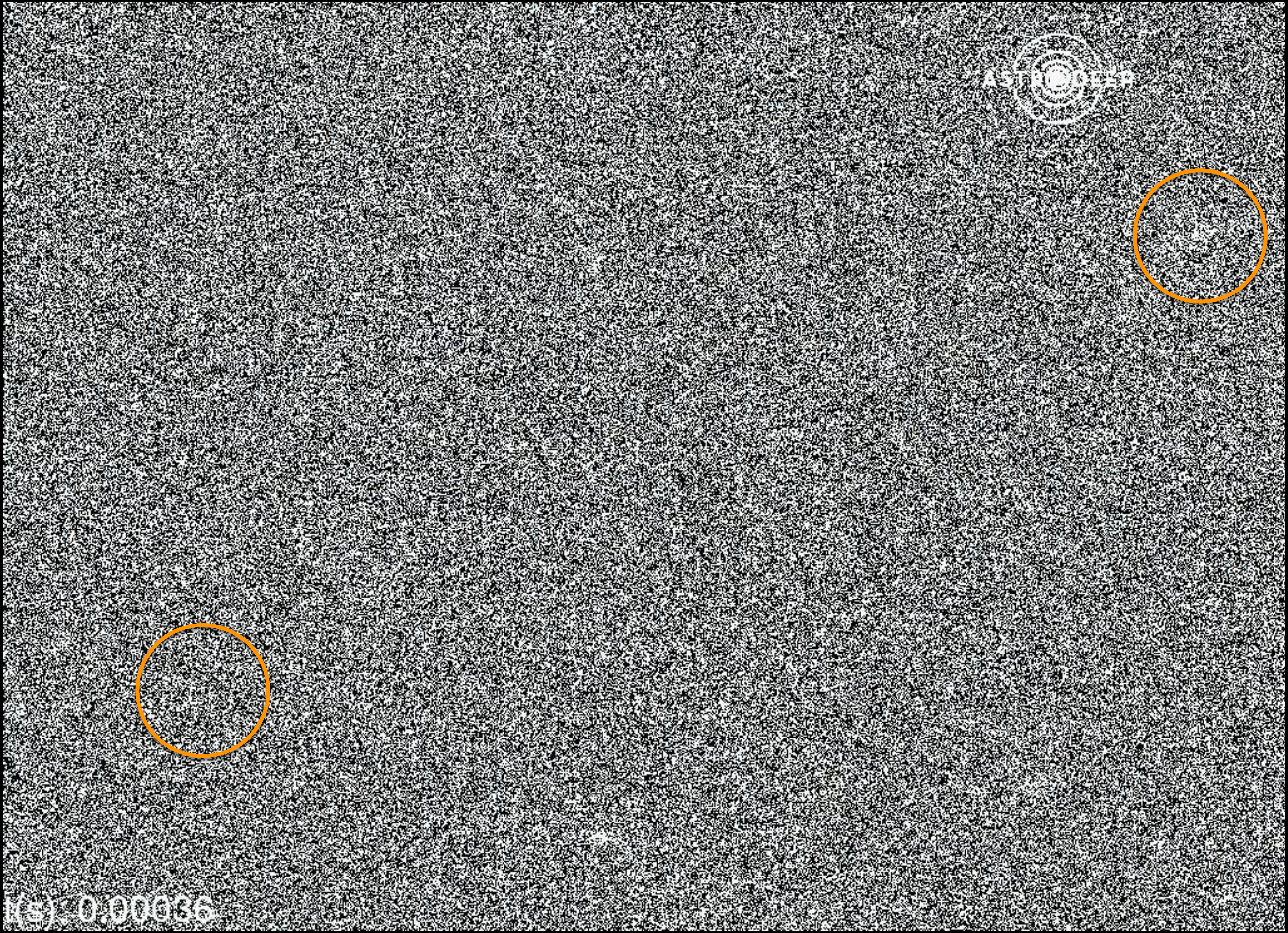
$$\frac{S}{N} \propto f_\nu \times D\epsilon^{1/2} \times T^{1/2} B^{-1/2}$$

Il S/N cresce lentamente con tempo di posa ($T^{1/2}$) e linearmente con le dimensioni del telescopio (D)

f_{limit}: Oggetto più debole che potete osservare con un dato S/N

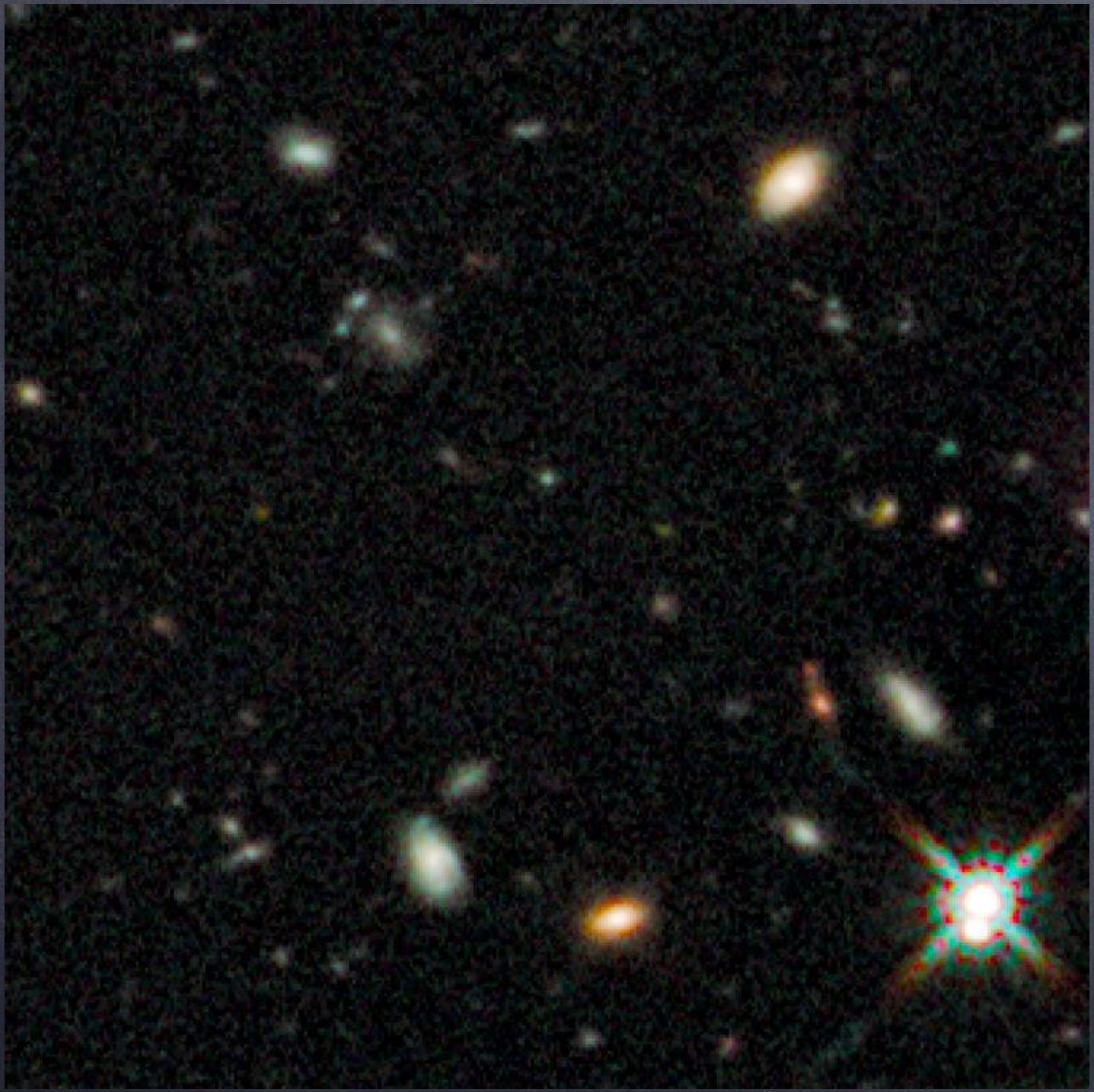
$$f_{limit} \propto \frac{S}{N} D^{-1} T^{-1/2}$$



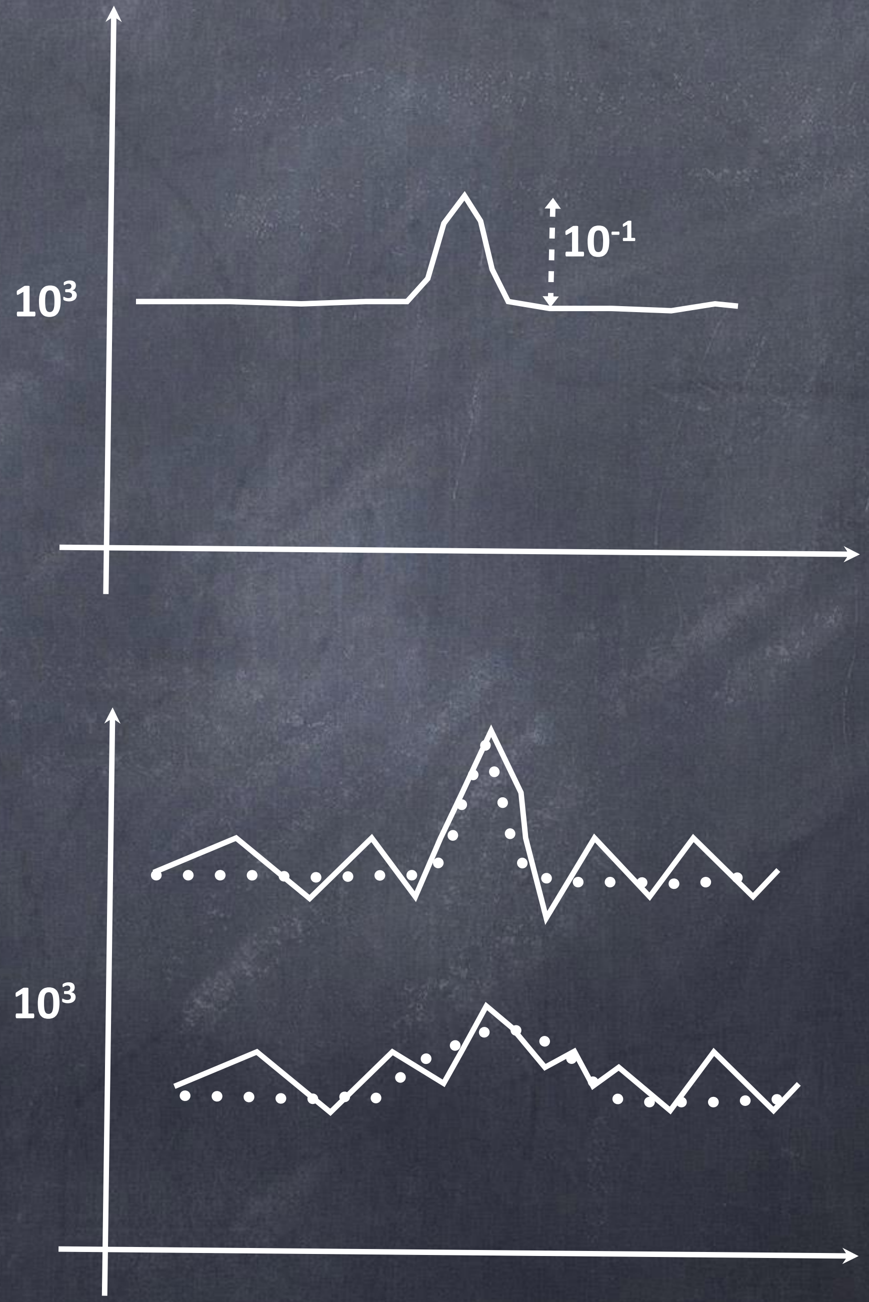

ASTRODEEP
(s): 0.00036

Why do we need a better resolution?

2) Reduce the background --> improve S/N

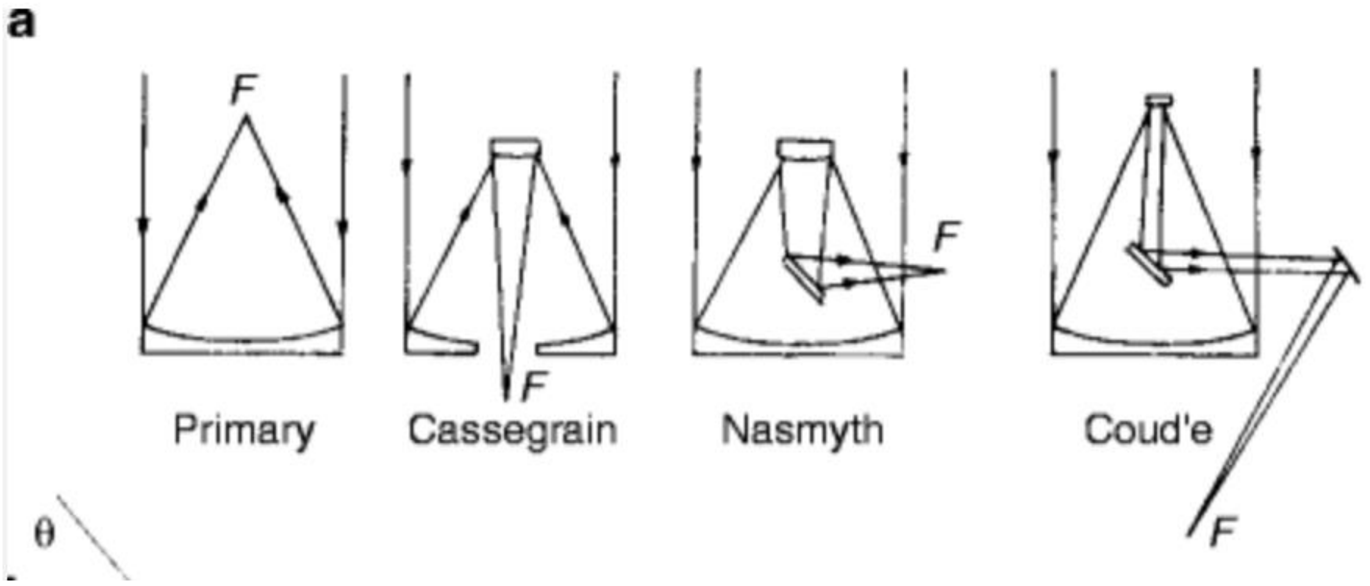


The sky is not dark: background is 10^2-10^4 times brighter than objects.
Shot-noise (Poisson) dominates the S/N



Instruments for optical/IR telescopes

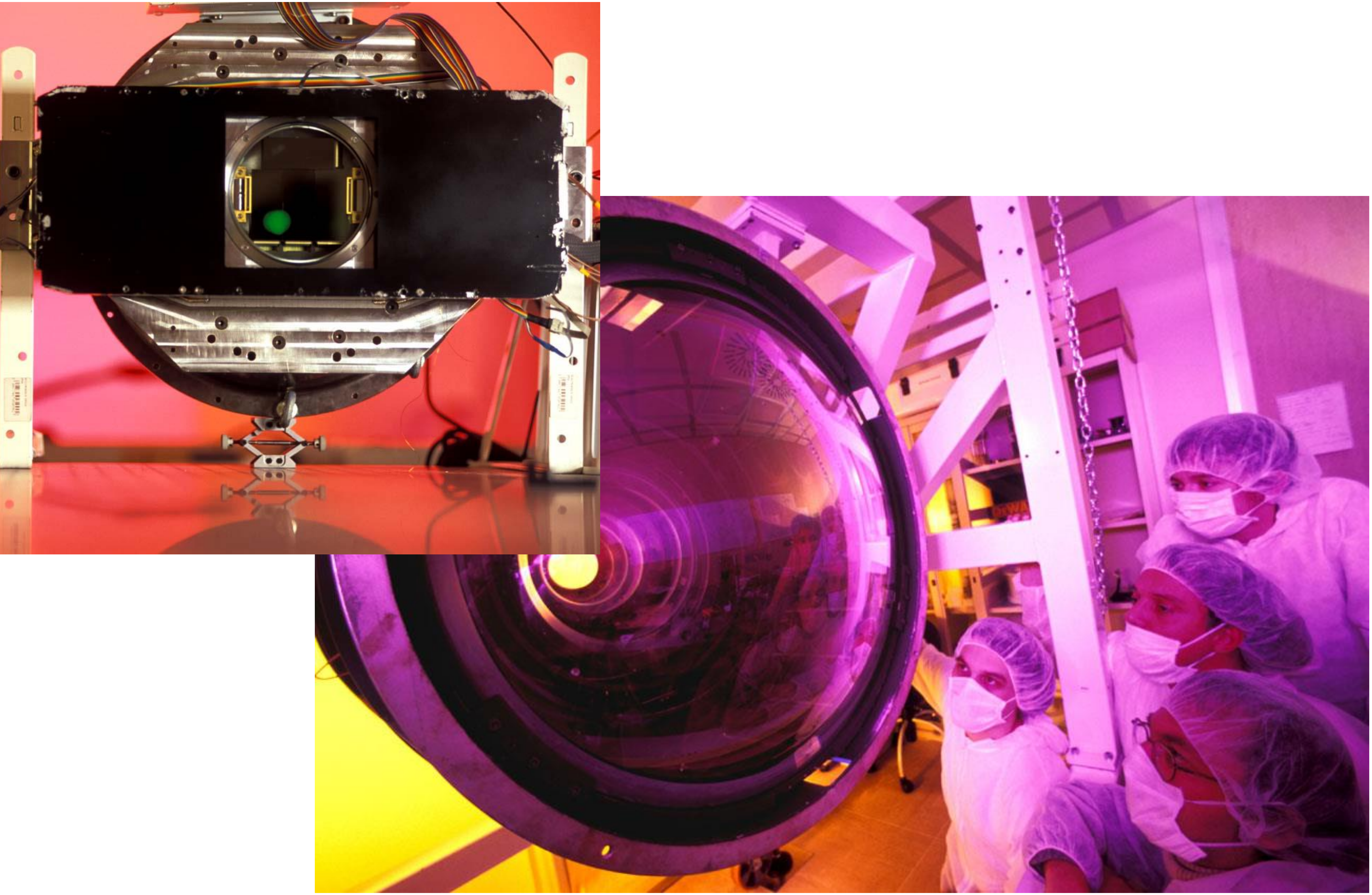
Common focal stations



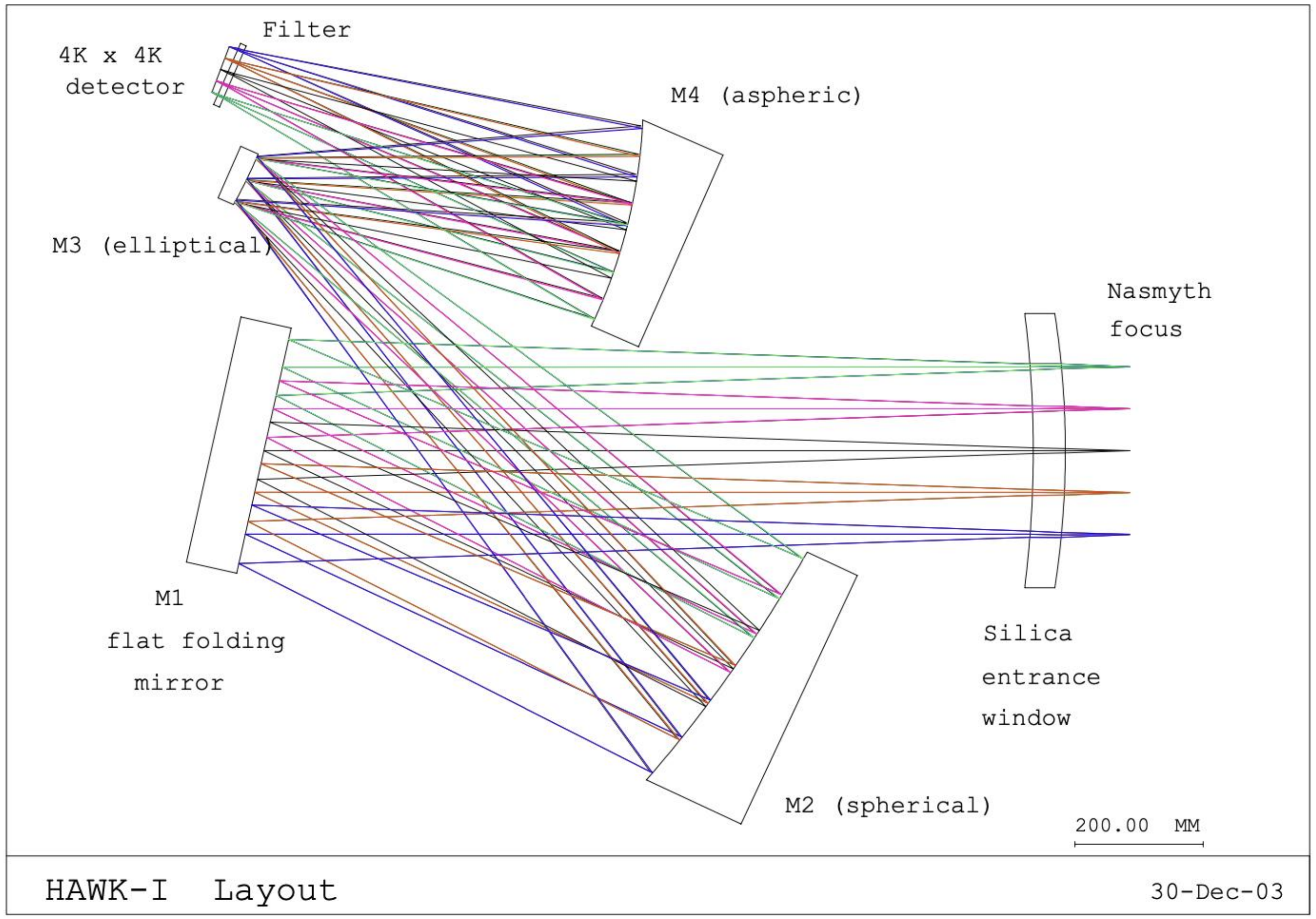
Instrument types

1) Imagers
2) Long/Multi Slit Spectrographs
3) Fiber-fed spectrograph
4) Integral Field Units (IFU)

1) Imagers



Imagers at Cassegrain or Nasmyth foci are usually more compact.

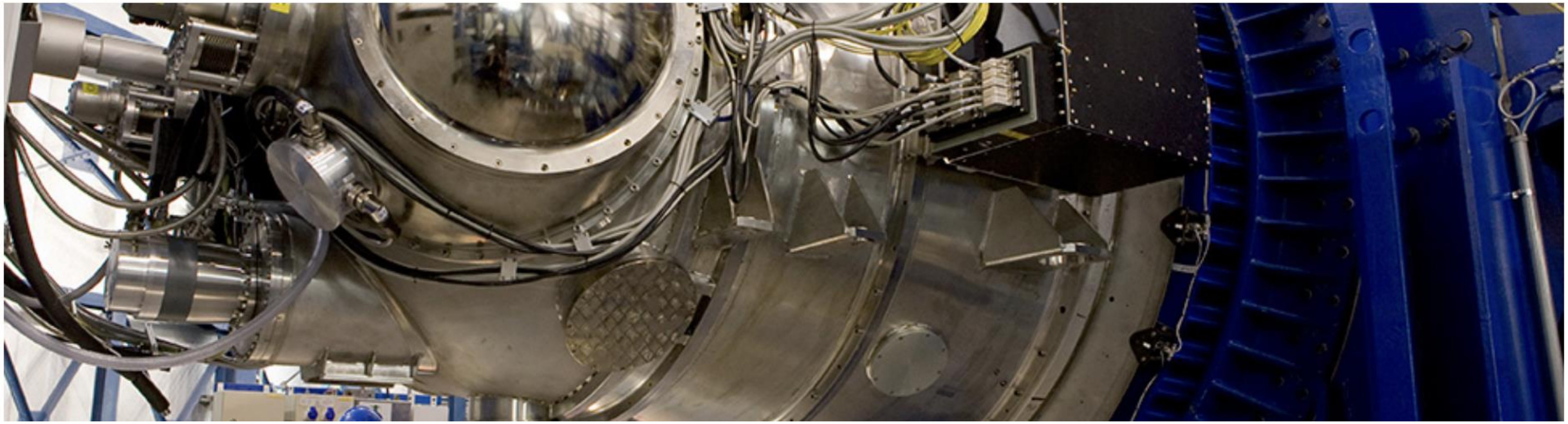


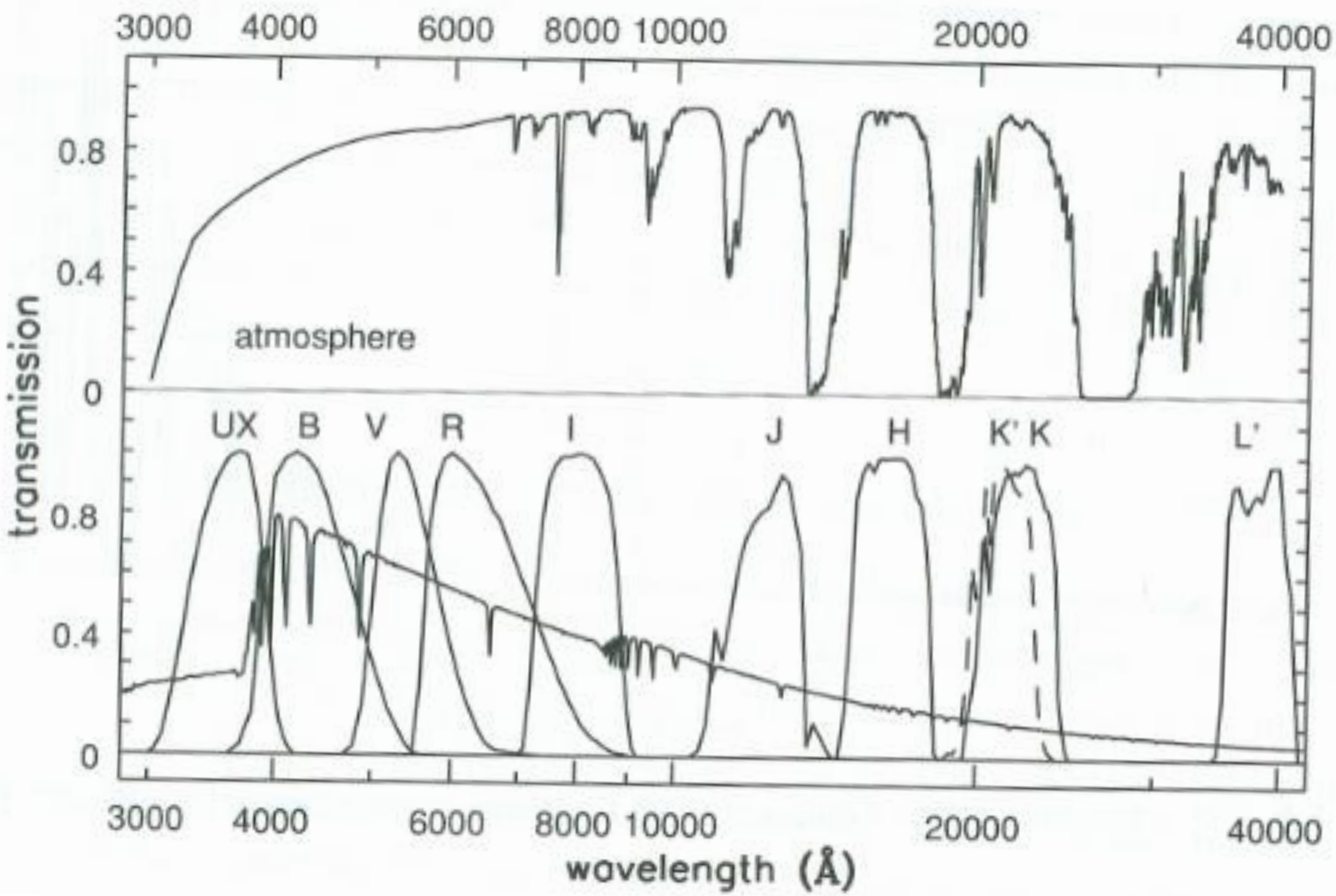
NICS@TNG

European Southern Observatory

HAWK-I

High Acuity Wide-field *K*-band Imager

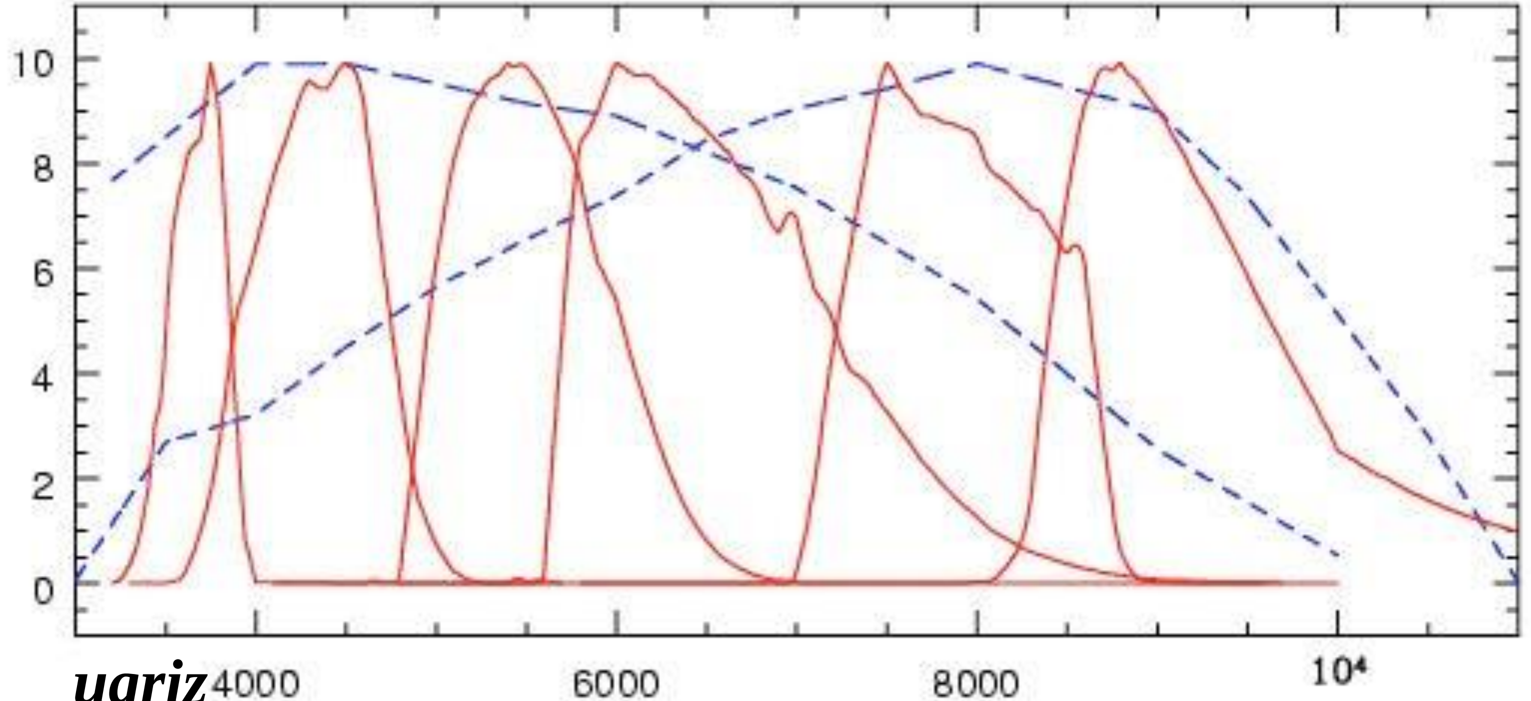


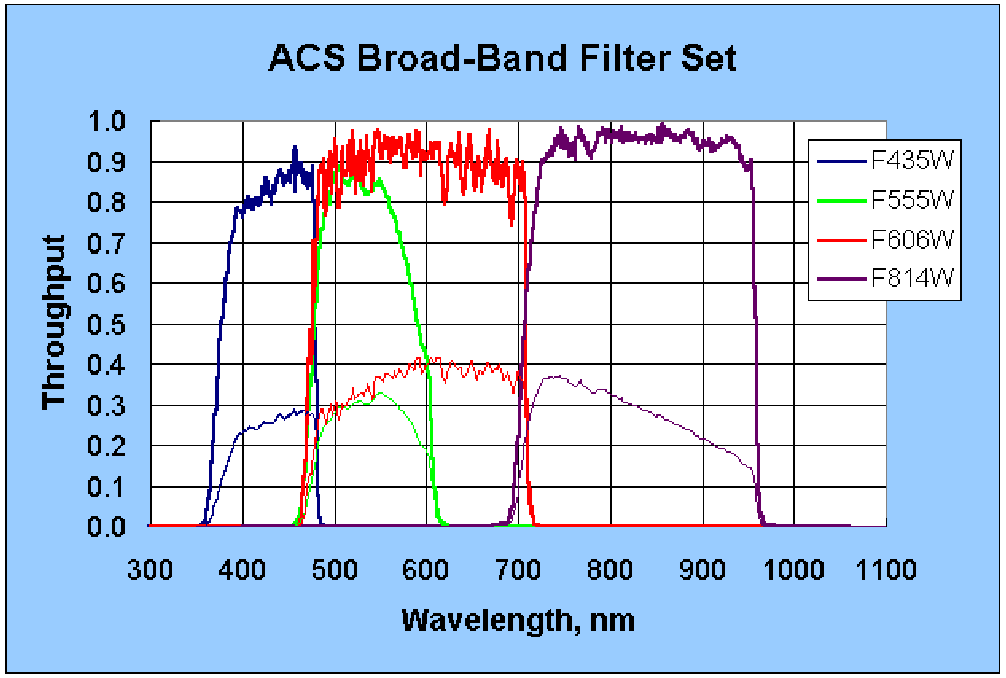

3000
4000
6000
8000
10000
20000
40000
transmission
0.8
0.4
0
atmosphere
UX
B
V
R
I
J
H
K'
K
L'
wavelength (Å)

Filtri astronomici

UBVRIz BESSEL

(FORS-VLT)

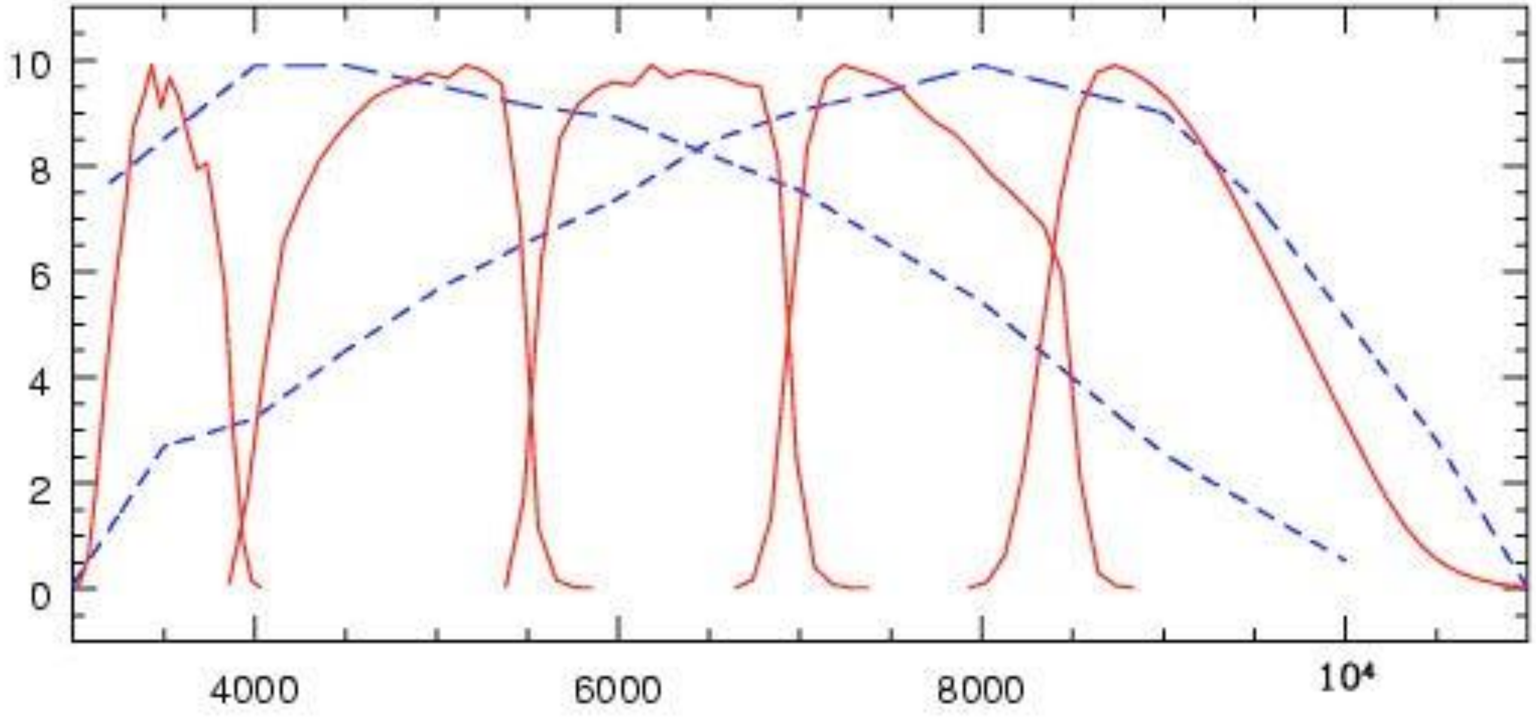


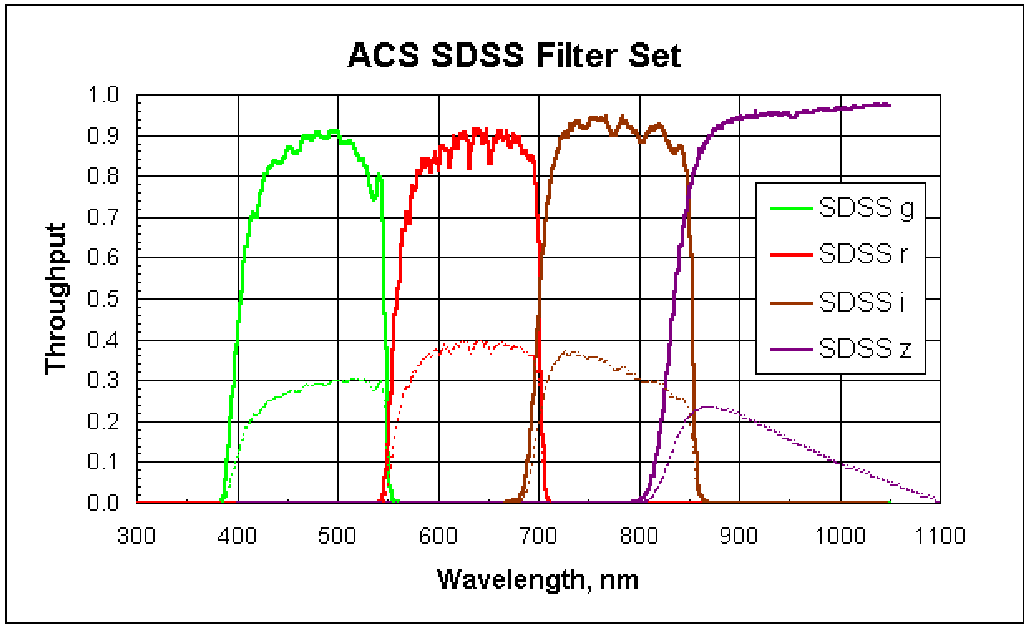


ugriz

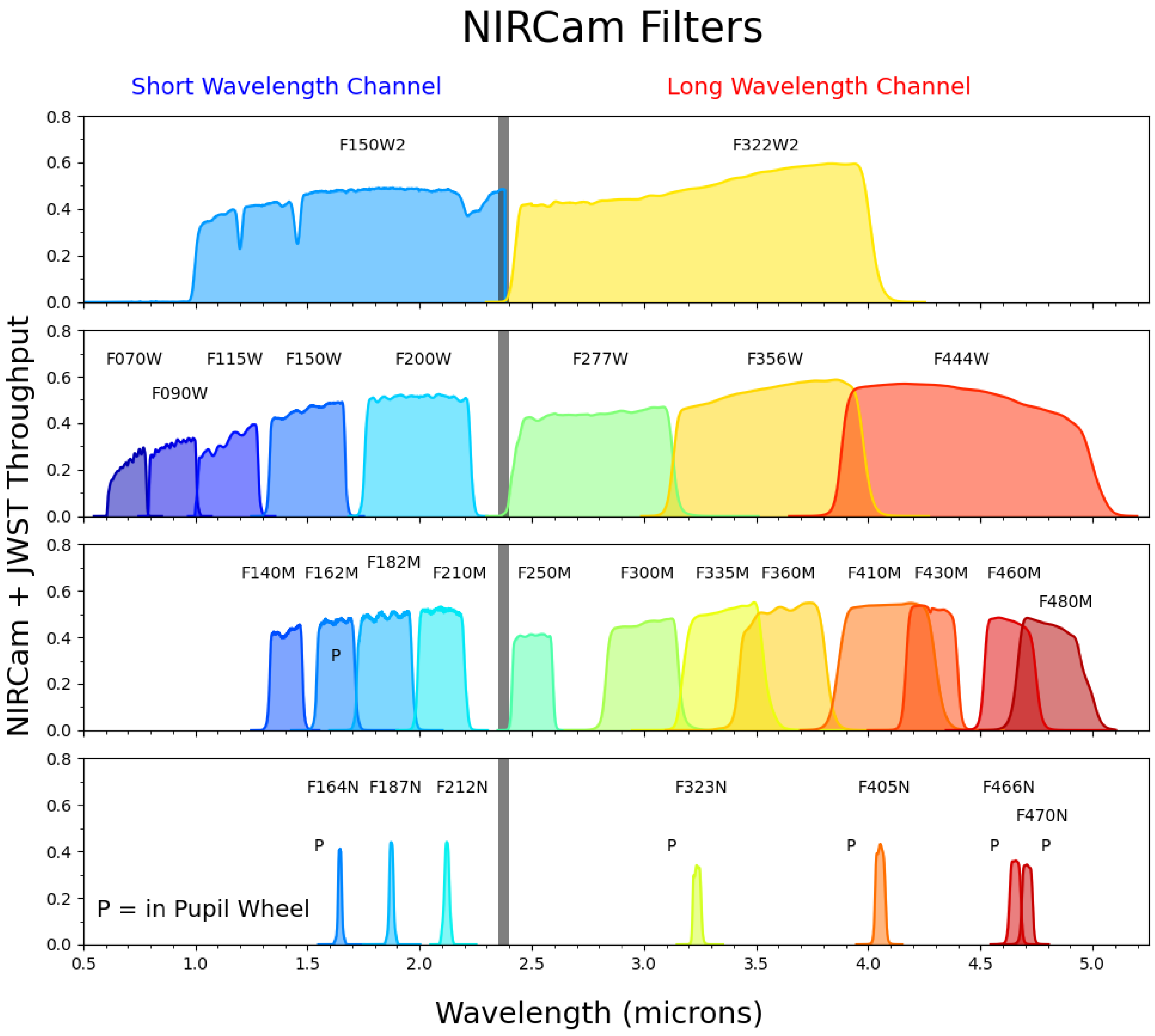
Sloan Survey

CFHT Legacy Survey

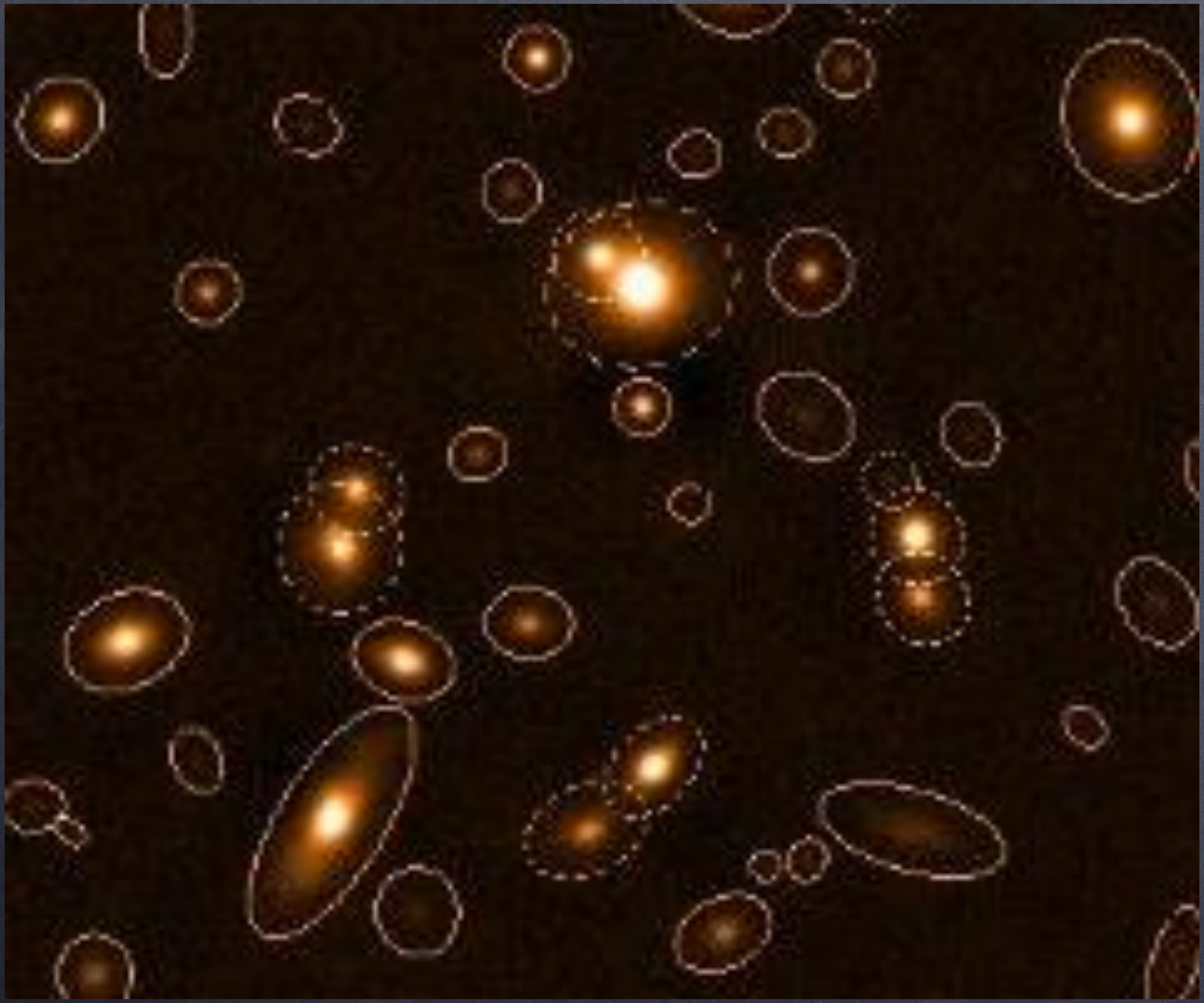




Filtri astronomici



Come si analizzano le immagini?

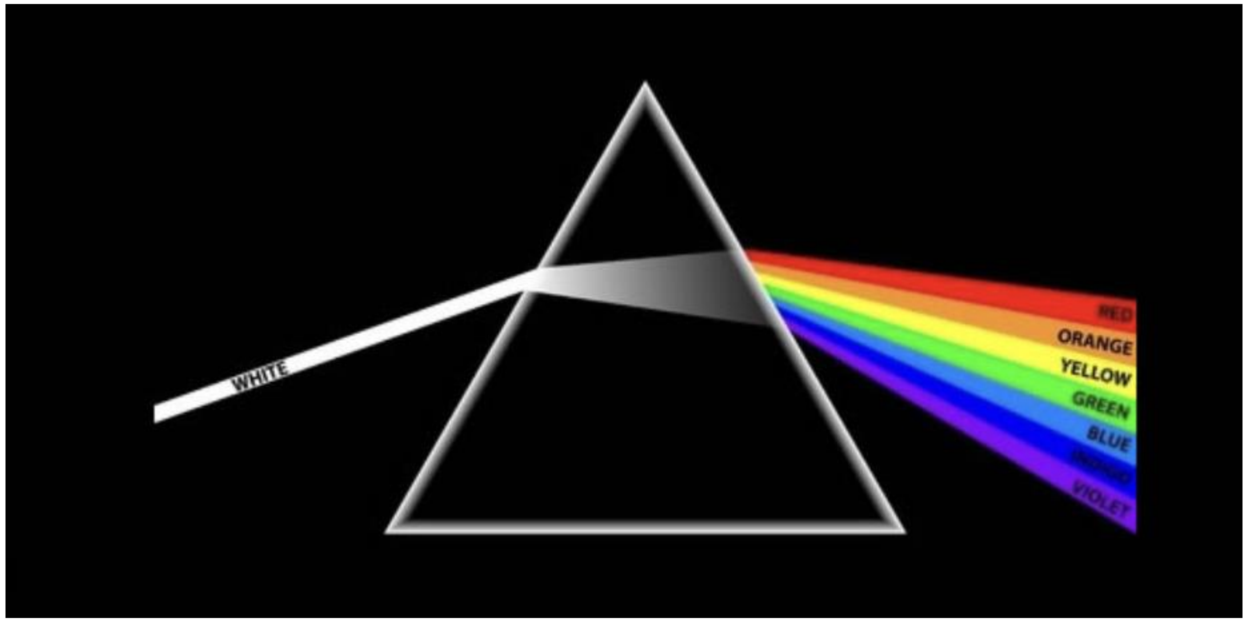


Le immagini vengono analizzate con software specifici che individuano gli oggetti e ne misurano:

1) il flusso nelle varie bande
2) parametri che descrivono la forma ("morfologia")

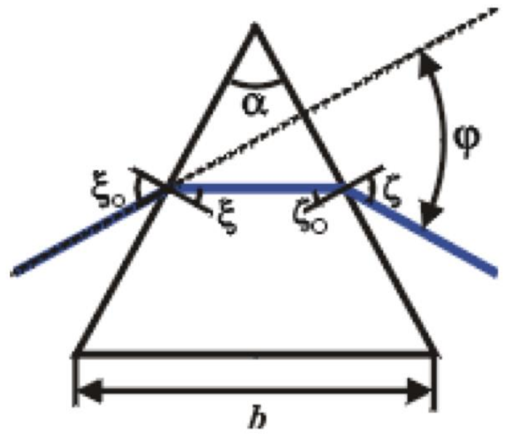
Sebbene concettualmente semplice, è difficile ottenere accuratezze superiori a qualche %, e rimangono effetti sistematici difficili da trattare, specie nel caso di galassie.

2) Spettrografi

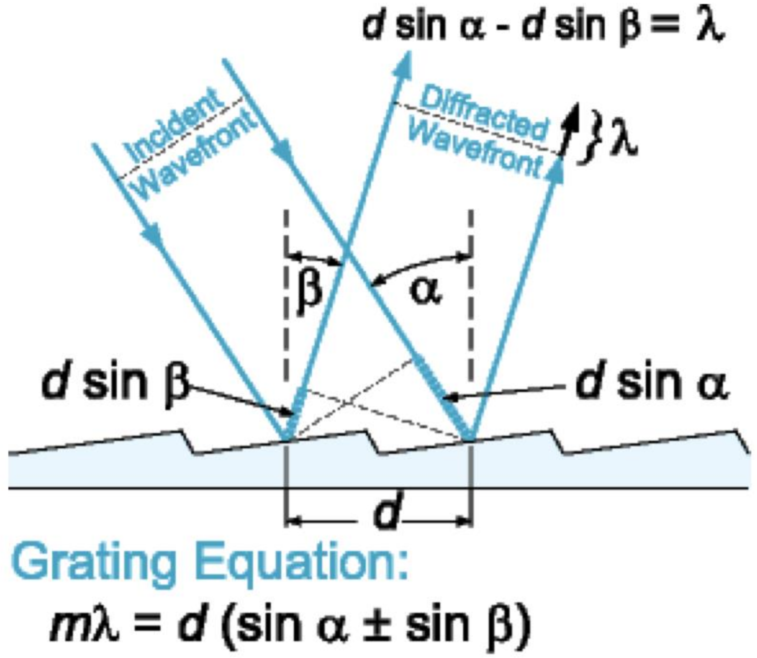


Spectrographs use a “dispersing element” to split wavelengths

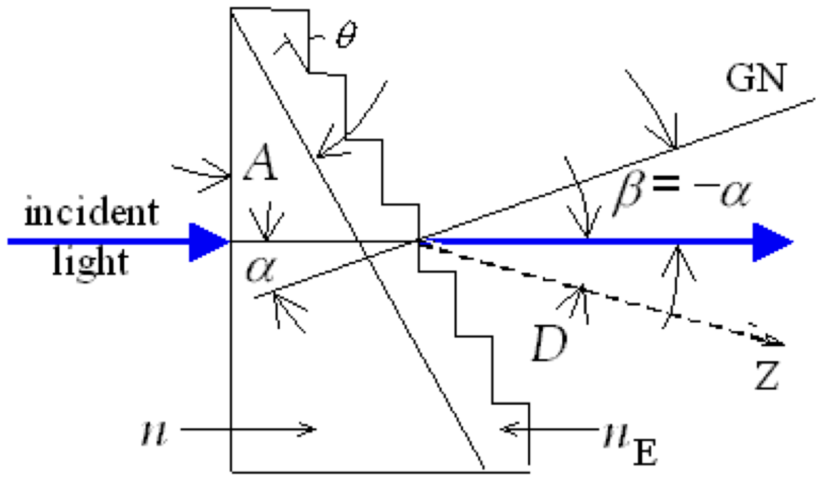
Prism
(refractive element)



Grating
(diffractive element)

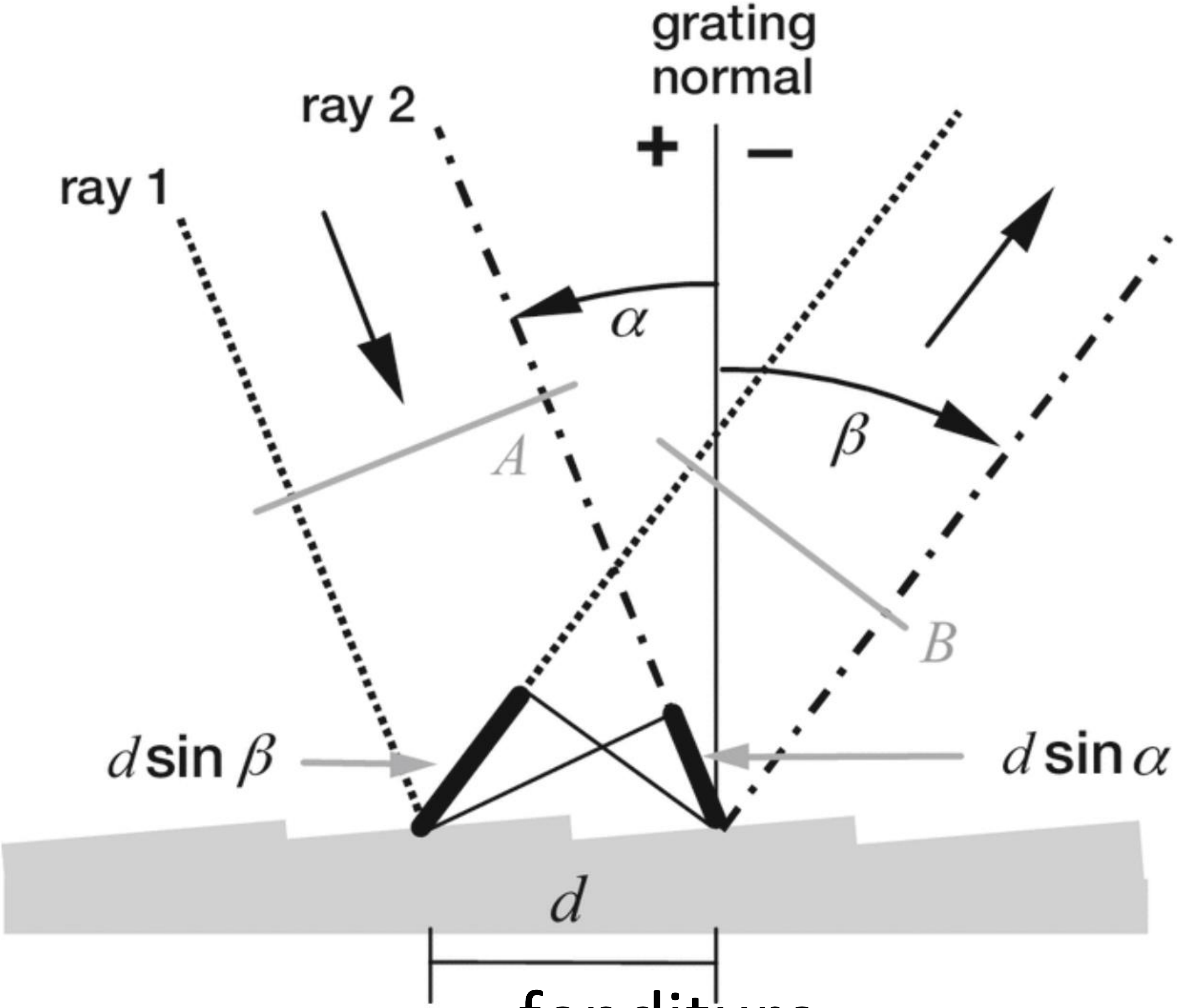


Grism
(prism+grating)



$$m\lambda = d(\sin\alpha + \sin\beta)$$

Grating



N fenditure

https://www.newport.com/n/the-grating-equation?srsltid=AfmBOoprffOj7XhwygauHBYjS8zKoVUEnJ68ZIQn0sMmlUBUW0GPWgSc

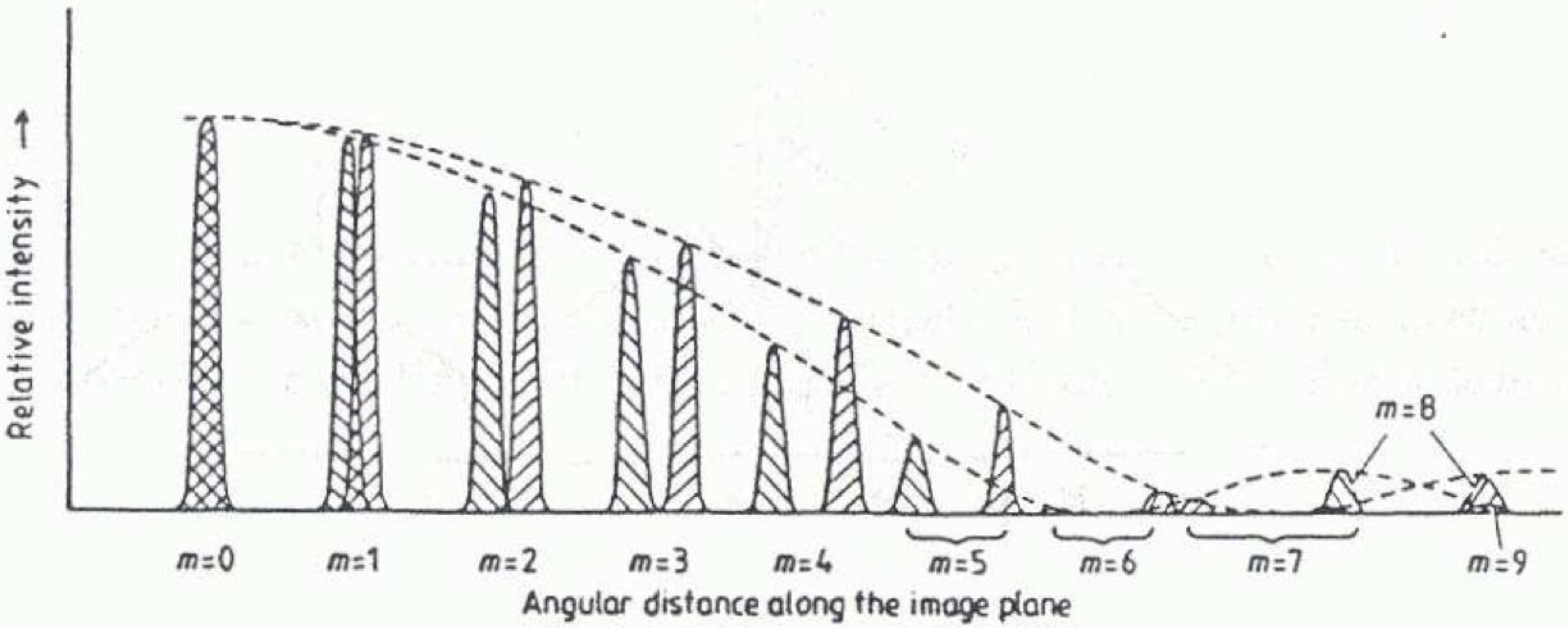
4.3.1 Grating dispersion

Given the grating equation:

$$m\,\lambda \;=\; d(sin\ \alpha \;\pm\; sin\ \beta)$$

and the fact that the angle of incidence, α, is constant, then differentiating the grating equation gives the **angular dispersion** of the grating:

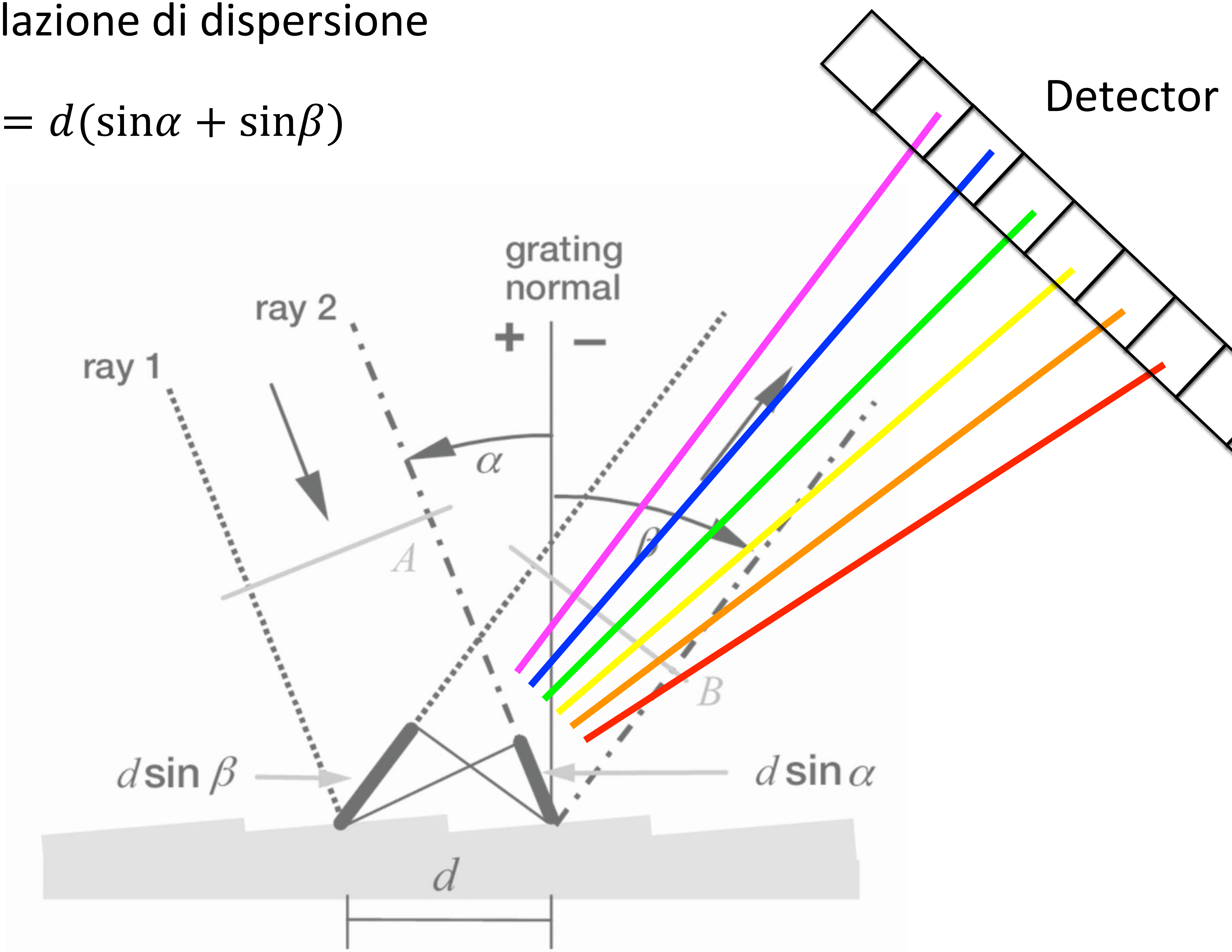
$$\frac{\Delta\beta}{\Delta\lambda} = \frac{m}{d\ cos\ \beta}$$



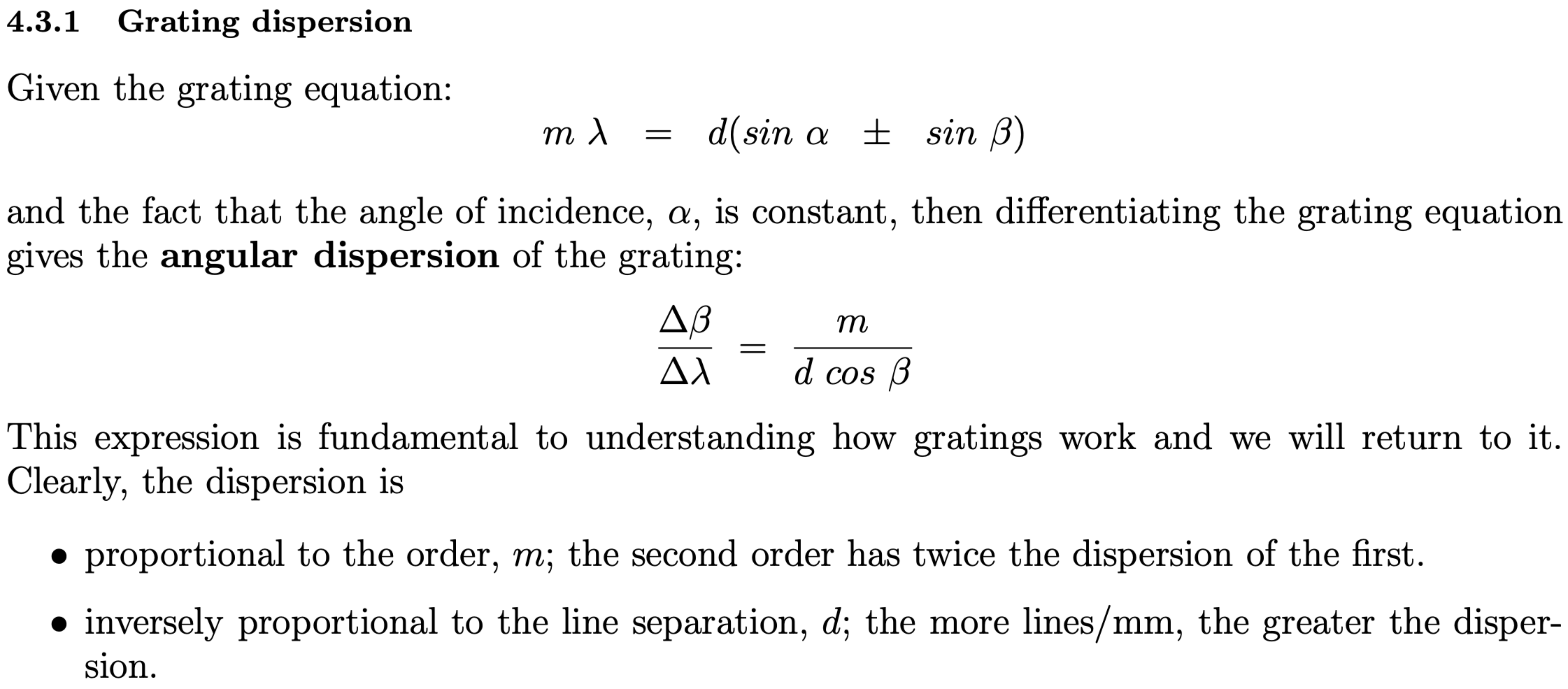
https://science.uct.ac.za/sites/default/files/content_migration/science_uct_ac_za/1471/files/spec1.pdf

Relazione di dispersione

$$m\lambda = d(\sin\alpha + \sin\beta)$$



https://www.newport.com/n/the-grating-equation?srsltid=AfmBOoprffOj7XhwygauHBYjS8zKoVUEnJ68ZIQn0sMmlUBUW0GPWgSc



4.3.1 Grating dispersion

Given the grating equation:

$$m\,\lambda \;=\; d(sin\ \alpha \;\pm\; sin\ \beta)$$

and the fact that the angle of incidence, α, is constant, then differentiating the grating equation gives the **angular dispersion** of the grating:

$$\frac{\Delta\beta}{\Delta\lambda} \;=\; \frac{m}{d\ cos\ \beta}$$

This expression is fundamental to understanding how gratings work and we will return to it. Clearly, the dispersion is

- proportional to the order, m; the second order has twice the dispersion of the first.
- inversely proportional to the line separation, d; the more lines/mm, the greater the dispersion.

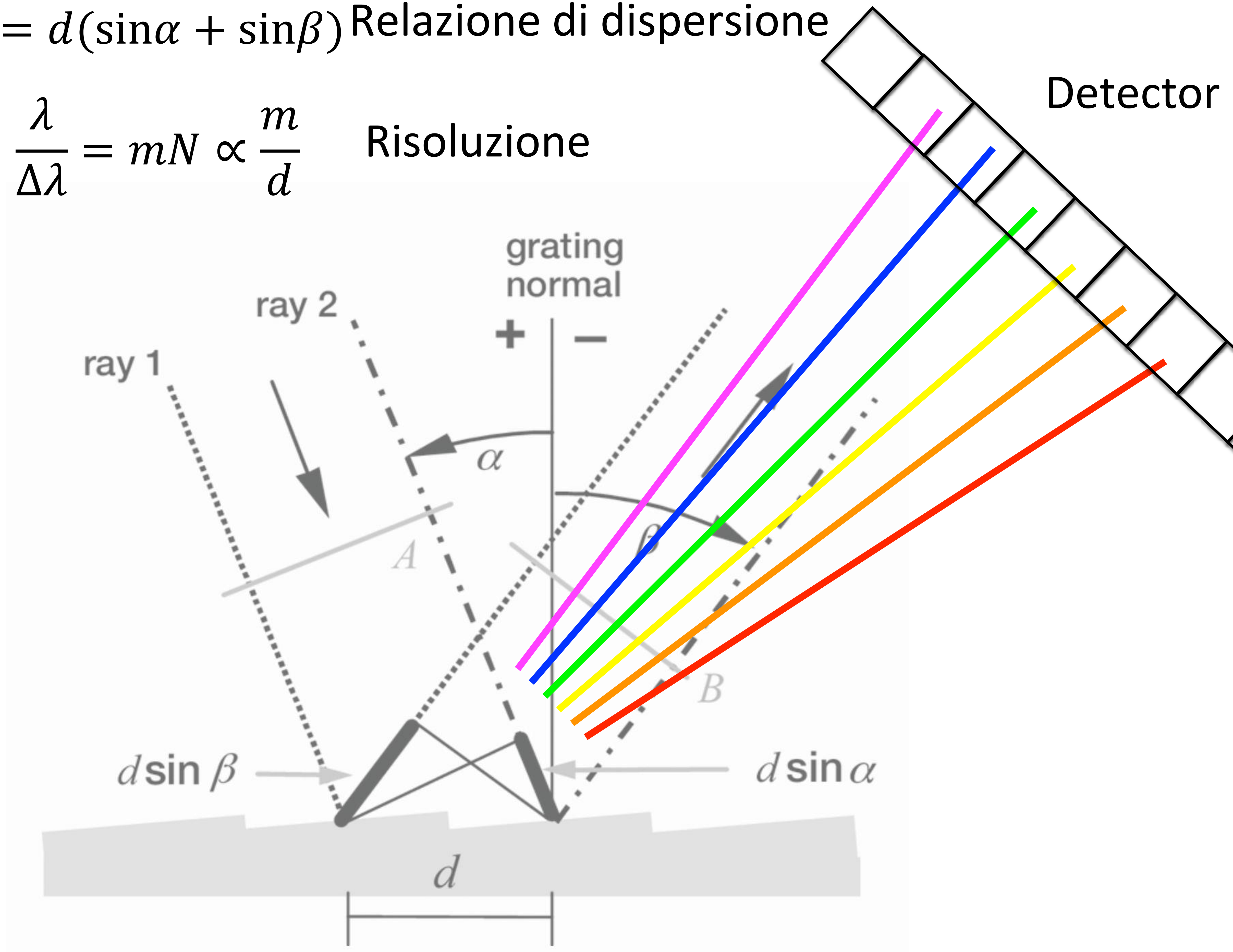
$$R = \frac{\lambda}{\Delta\lambda} = mN \propto \frac{m}{d}$$

Risoluzione

https://science.uct.ac.za/sites/default/files/content_migration/science_uct_ac_za/1471/files/spec1.pdf

$$m\lambda = d(\sin\alpha + \sin\beta)$$ Relazione di dispersione

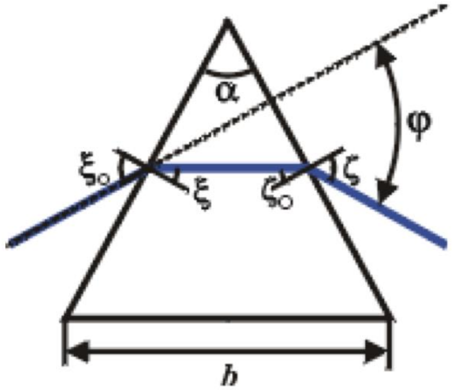
$$R = \frac{\lambda}{\Delta\lambda} = mN \propto \frac{m}{d}$$ Risoluzione



https://www.newport.com/n/the-grating-equation?srsltid=AfmBOoprffOj7XhwygauHBYjS8zKoVUEnJ68ZIQn0sMmlUBUW0GPWgSc

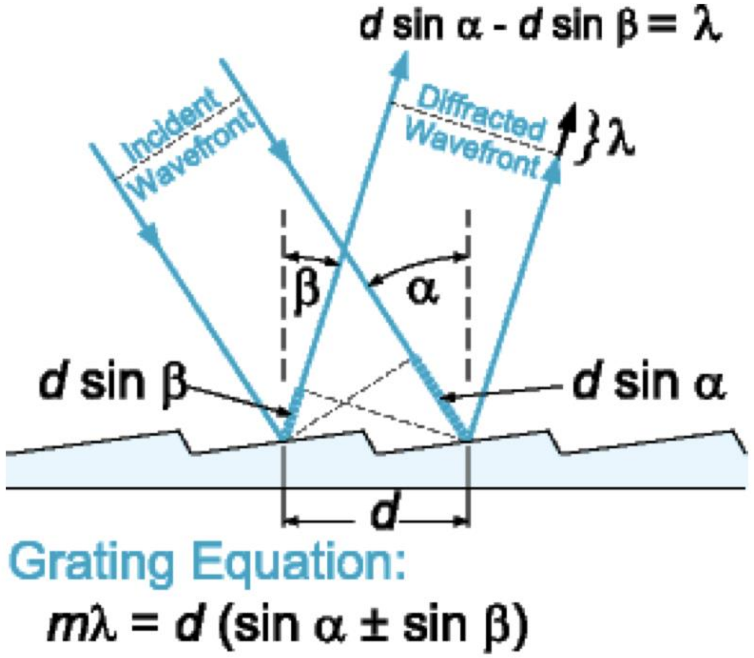
Resolution R = λ / Δ λ

Prism
(refractive element)



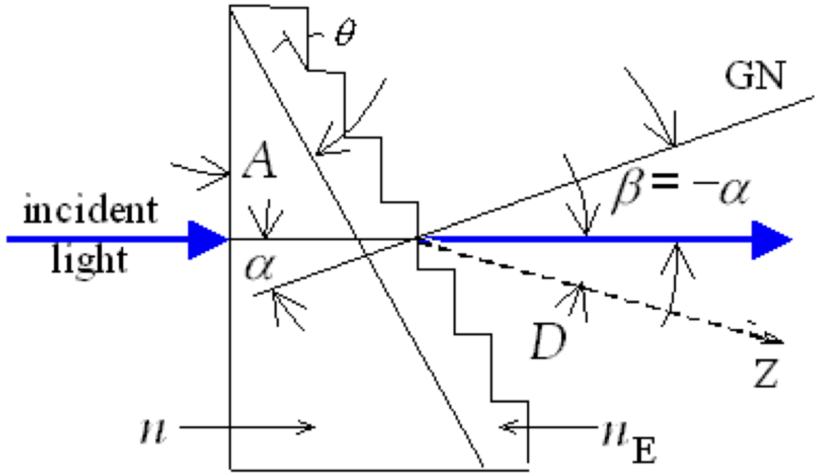
R ~ 100-200

Grating
(diffractive element)



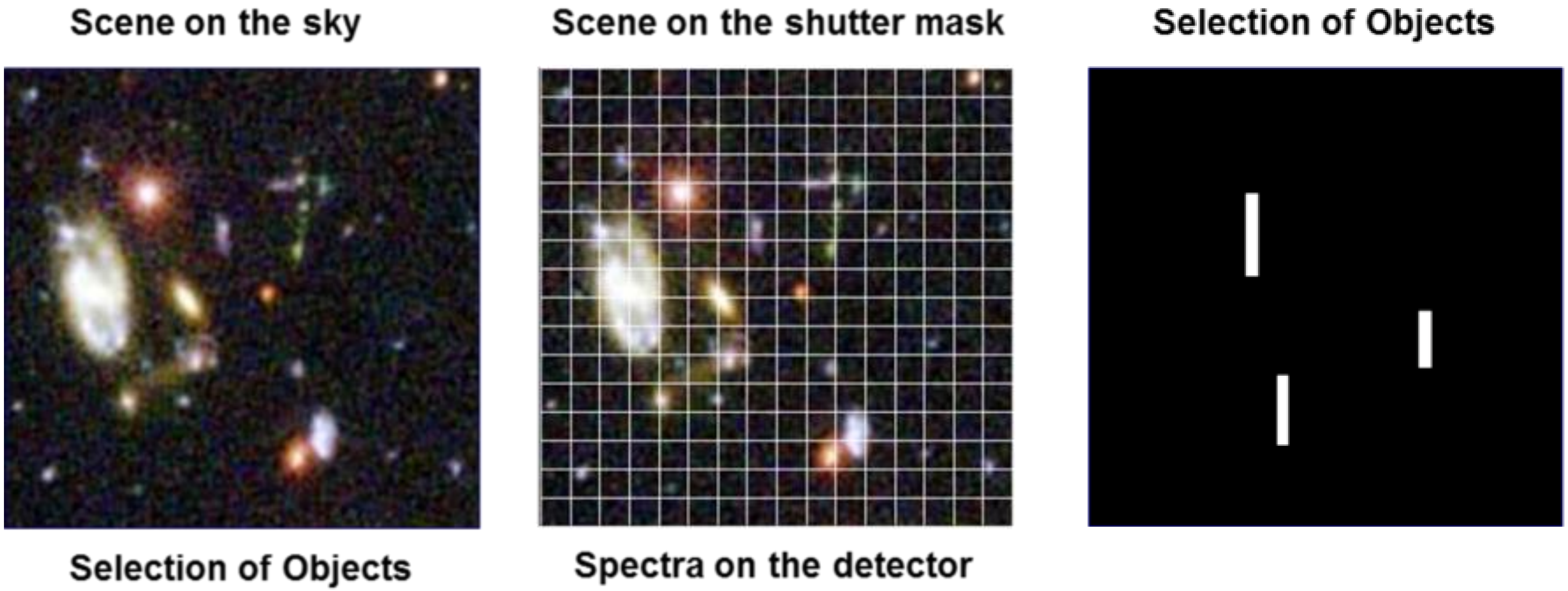
R ~ 1.000-20.000
R~200.000

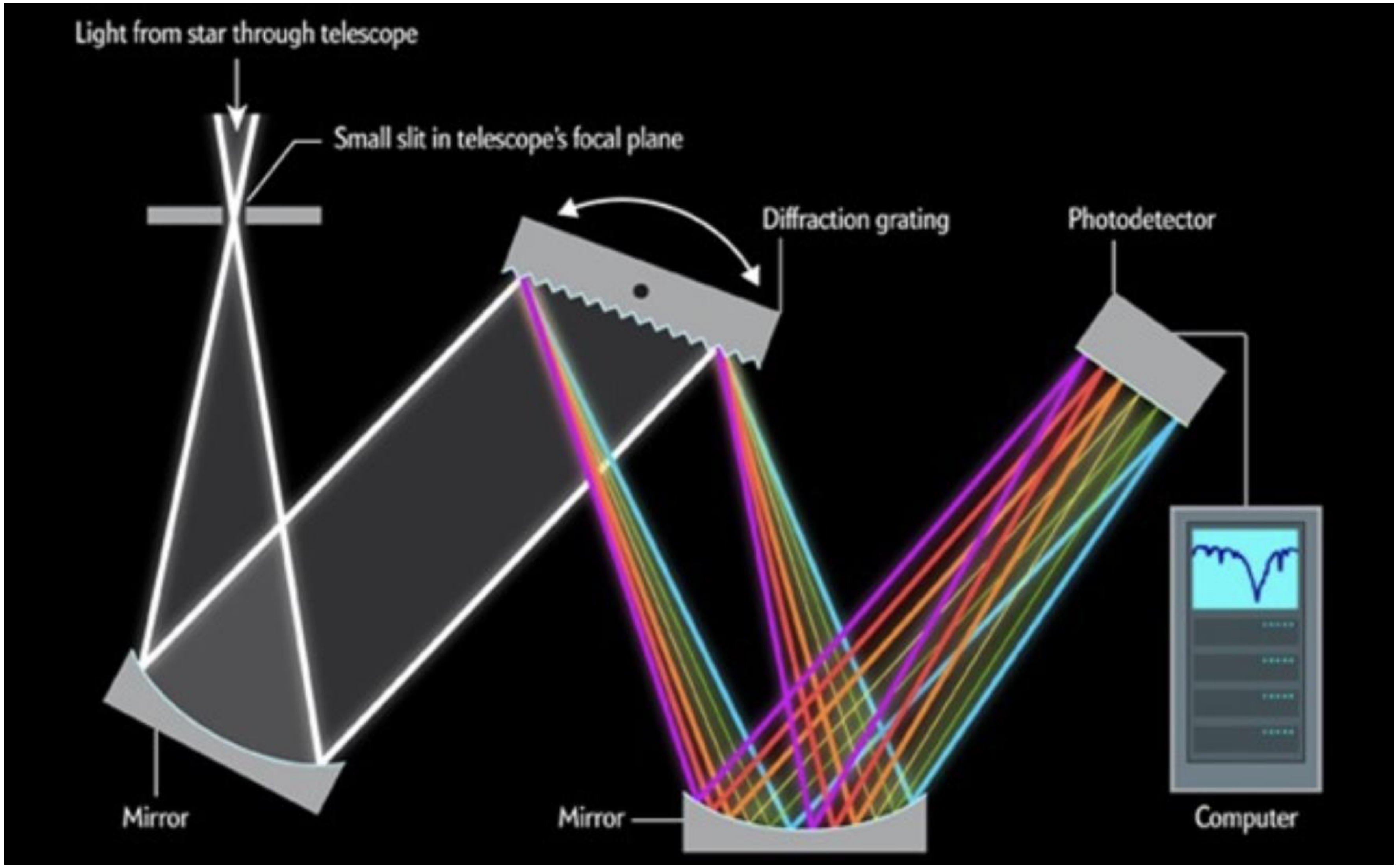
Grism
(prism+grating)



R ~ 1.000-5.000

Multi-object spectroscopy.
“Slits” are inserted to take the spectra only of selected targets

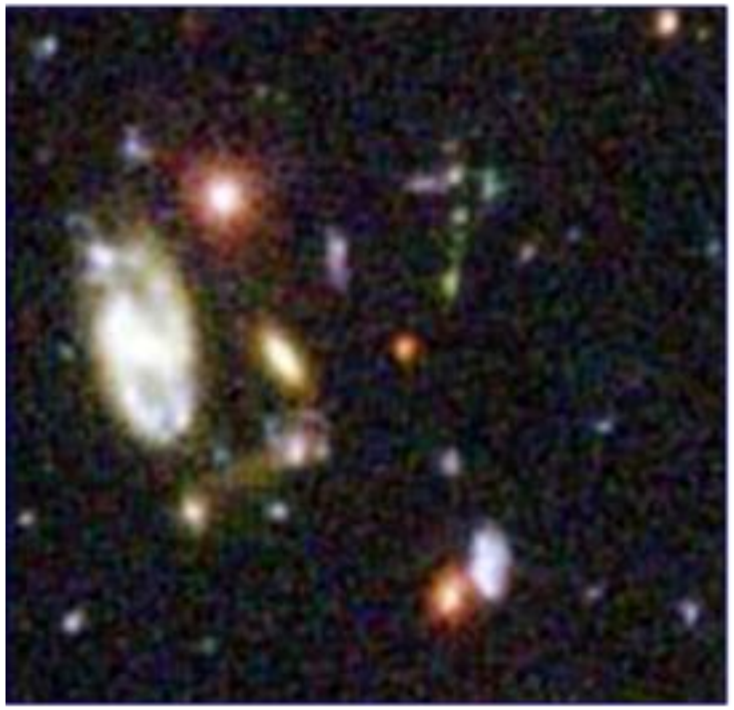



Light from star through telescope
Small slit in telescope's focal plane
Diffraction grating
Photodetector
Mirror
Mirror
Computer

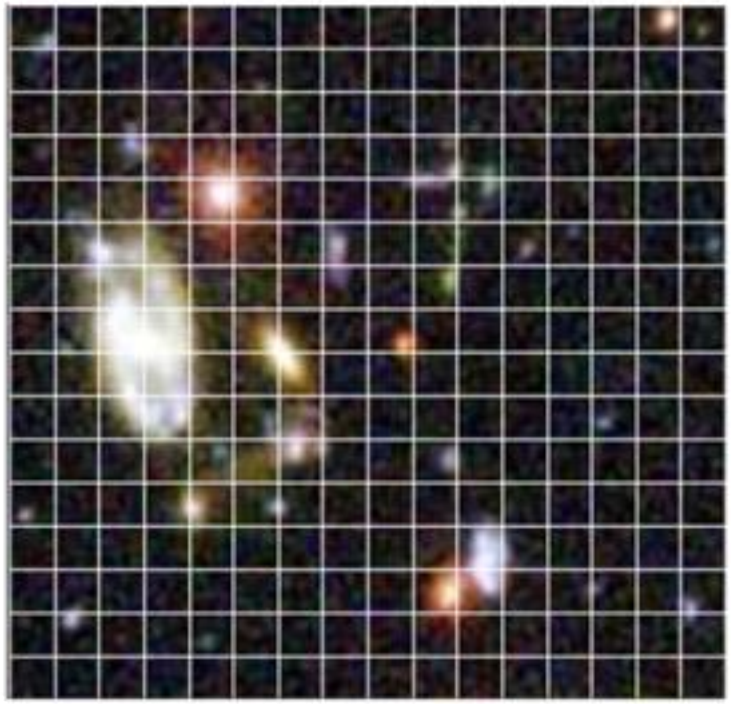
Multi-object spectroscopy.
“Slits” are inserted to take the spectra only of selected targets

DOLORES@TNG

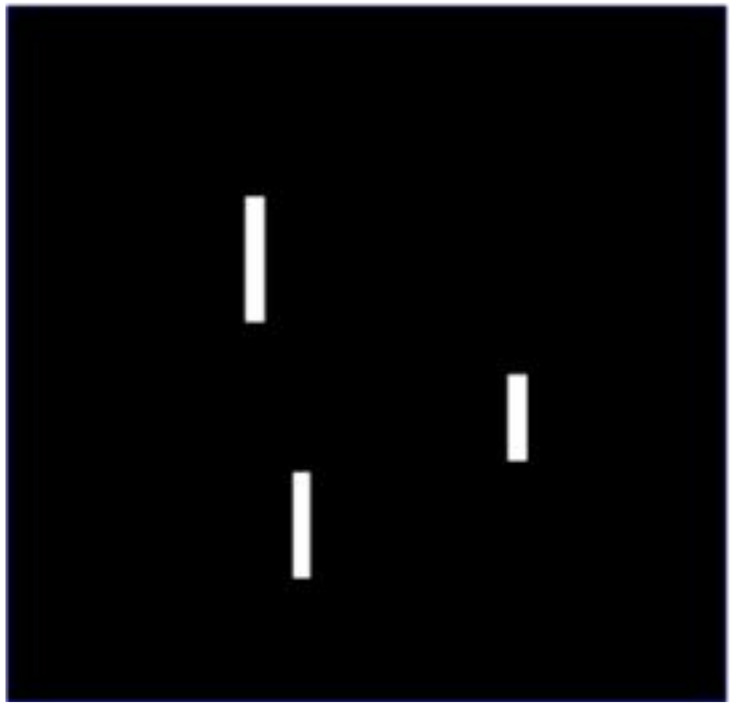
Scene on the sky



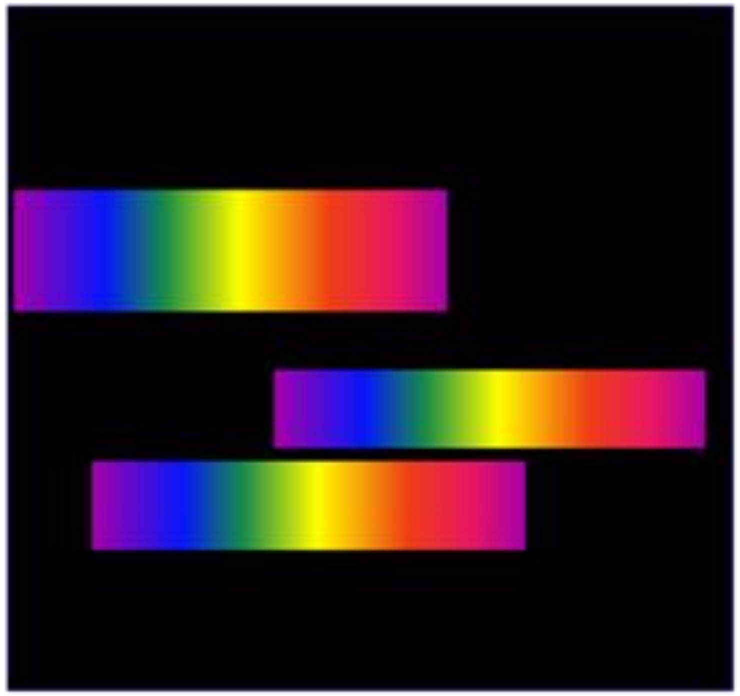
Scene on the shutter mask



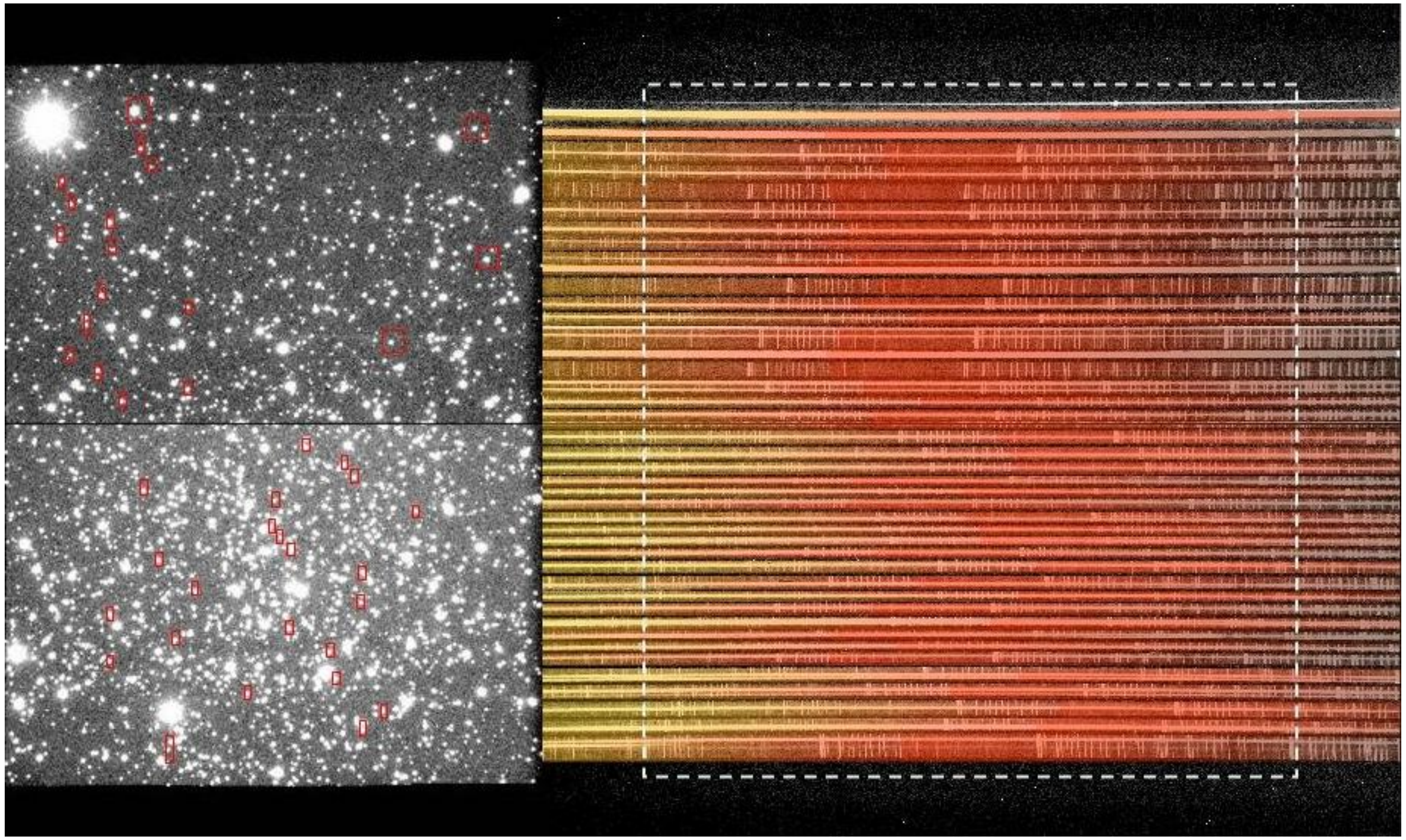
Selection of Objects



Spectra on the detector



Multi-object spectroscopy (MOS).
“Slits” are inserted to take the spectra only of selected targets



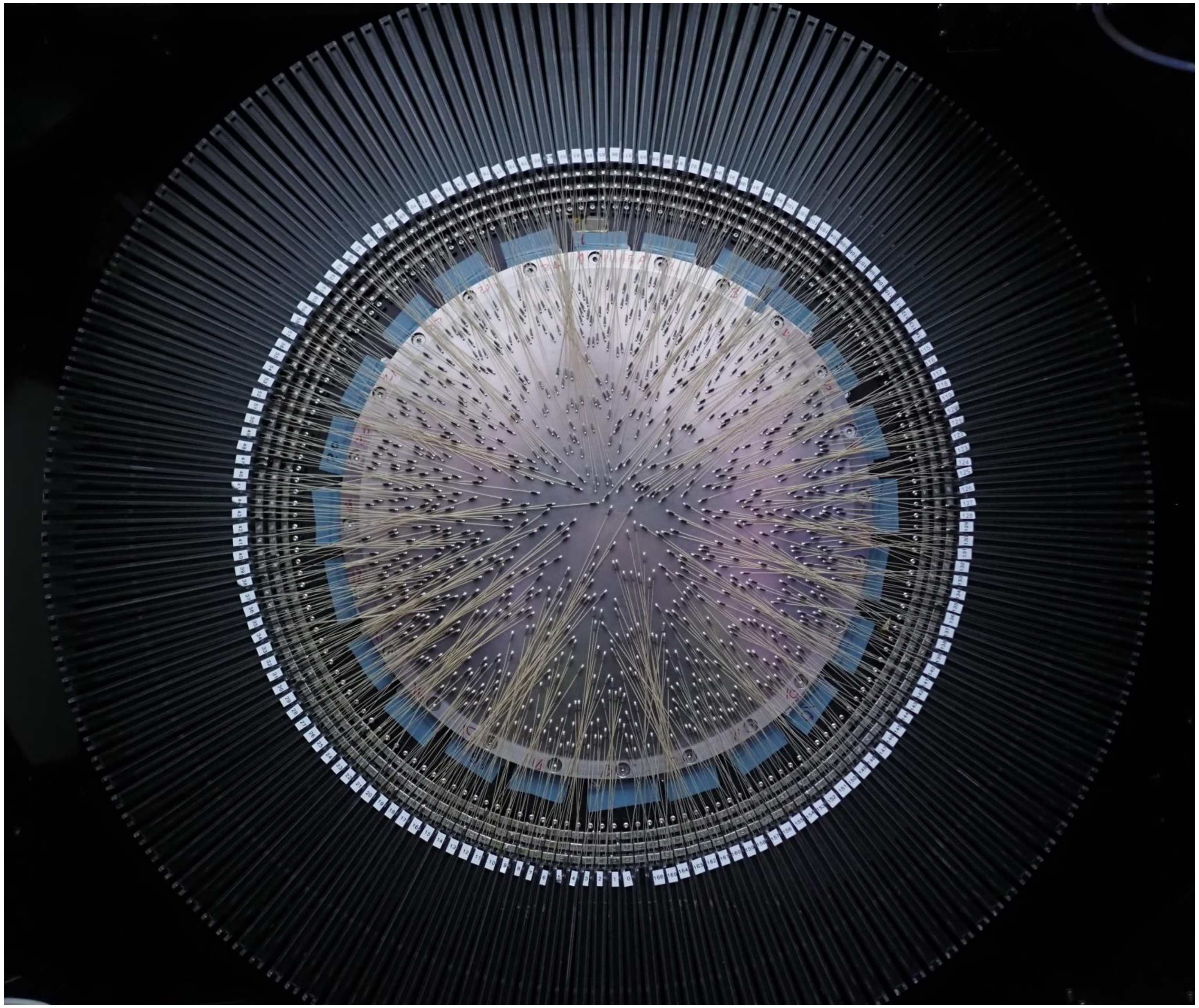
Advantages:

- Strongly reduces the background
- Observes only objects you are interested to.
- 1D spatial info is preserved

Disadvantages:

- relatively few objects (~50)
- may miss part of the light if the object is larger than the slit
- spectrograph may be unstable (rotation)

Fiber-fed spectroscopy.
Head of optical fibres are placed (by robots) on selected targets



WEAVE@WHT

Advantages:

- Strongly reduces the background
- Observes only objects you are interested to.
- Many more objects than MOS (~1000).
- Fibers allow you to build a large spectrograph in a stable environment

Disadvantages:

- more difficult than MOS to measure the bckg
- may miss part of the light if the object is larger than the fibre head
- spatial info is lost

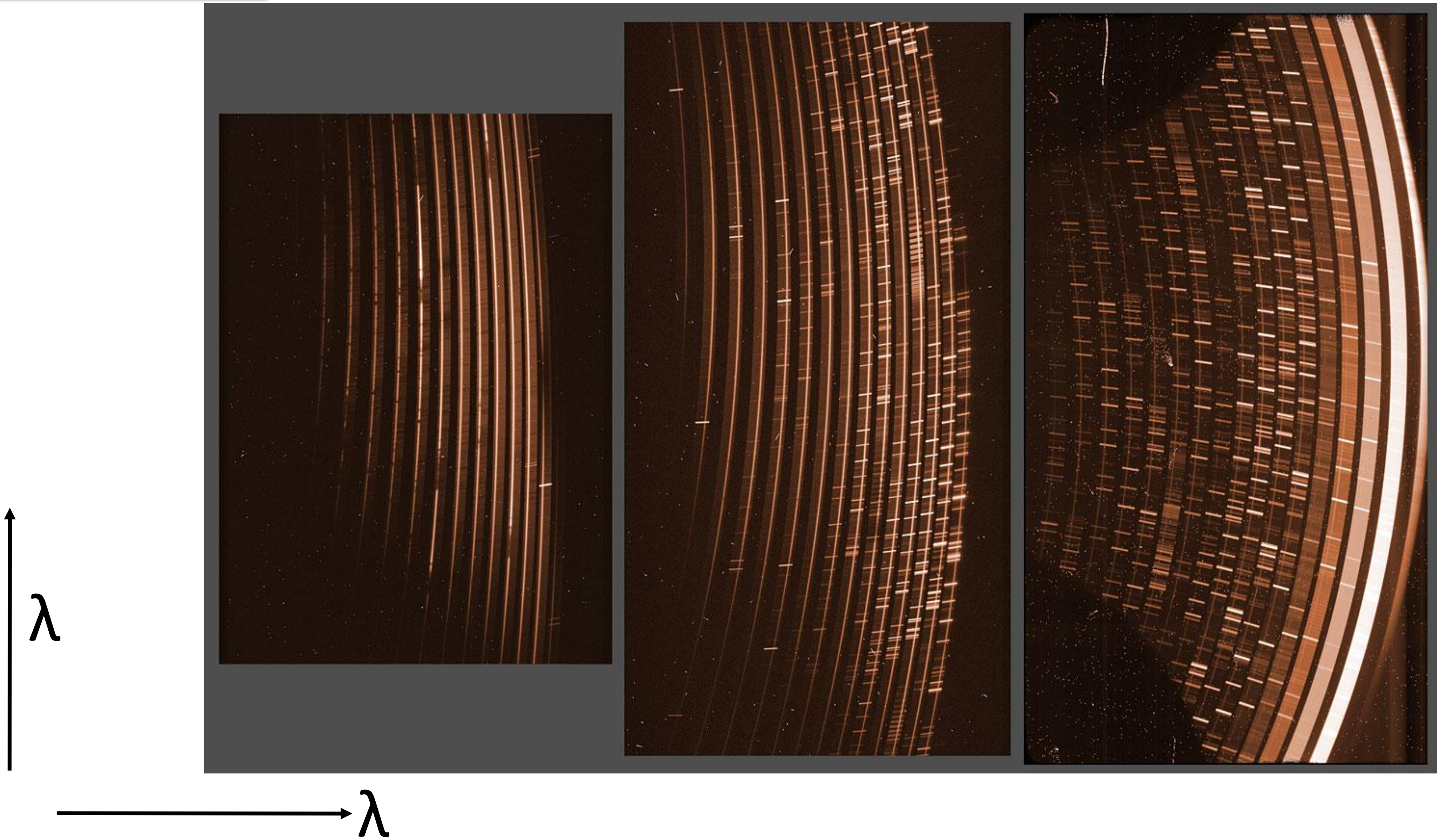
Problem: you may want both high resolution R and wide wavelength coverage.

The resulting spectrum will be very long.

Solution: double dispersion.

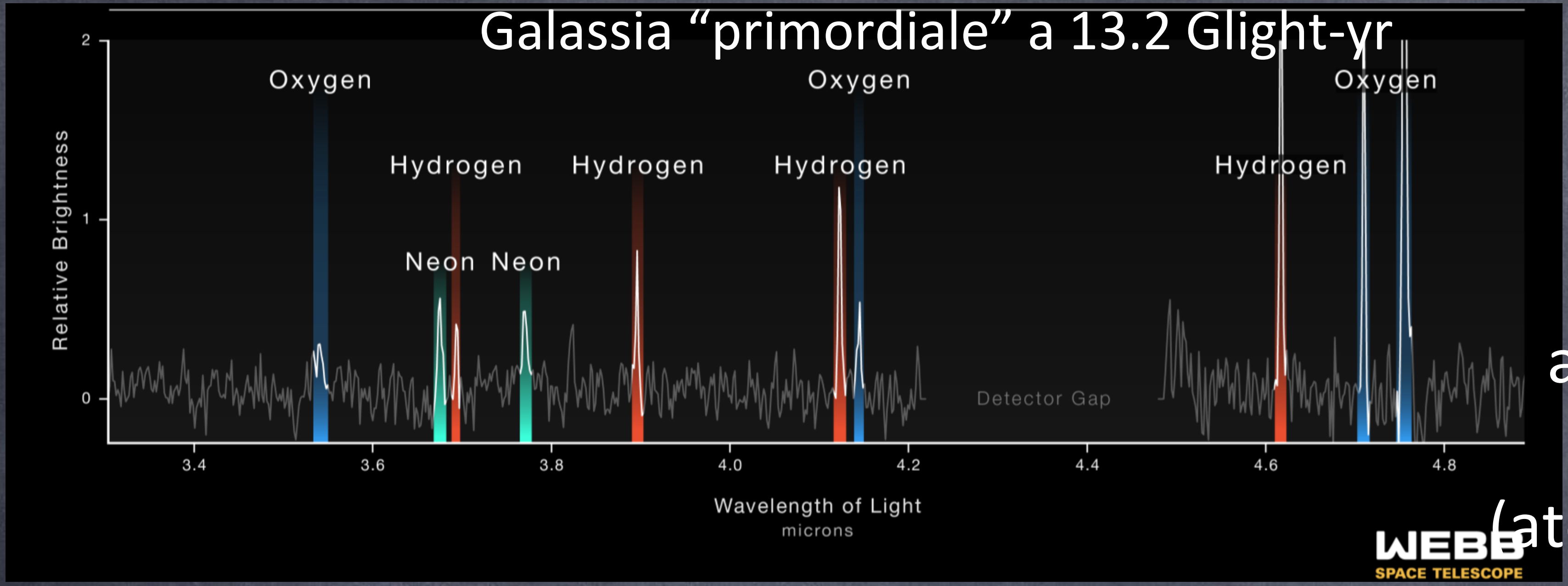
HARPS@TNG
GIANO@TNG

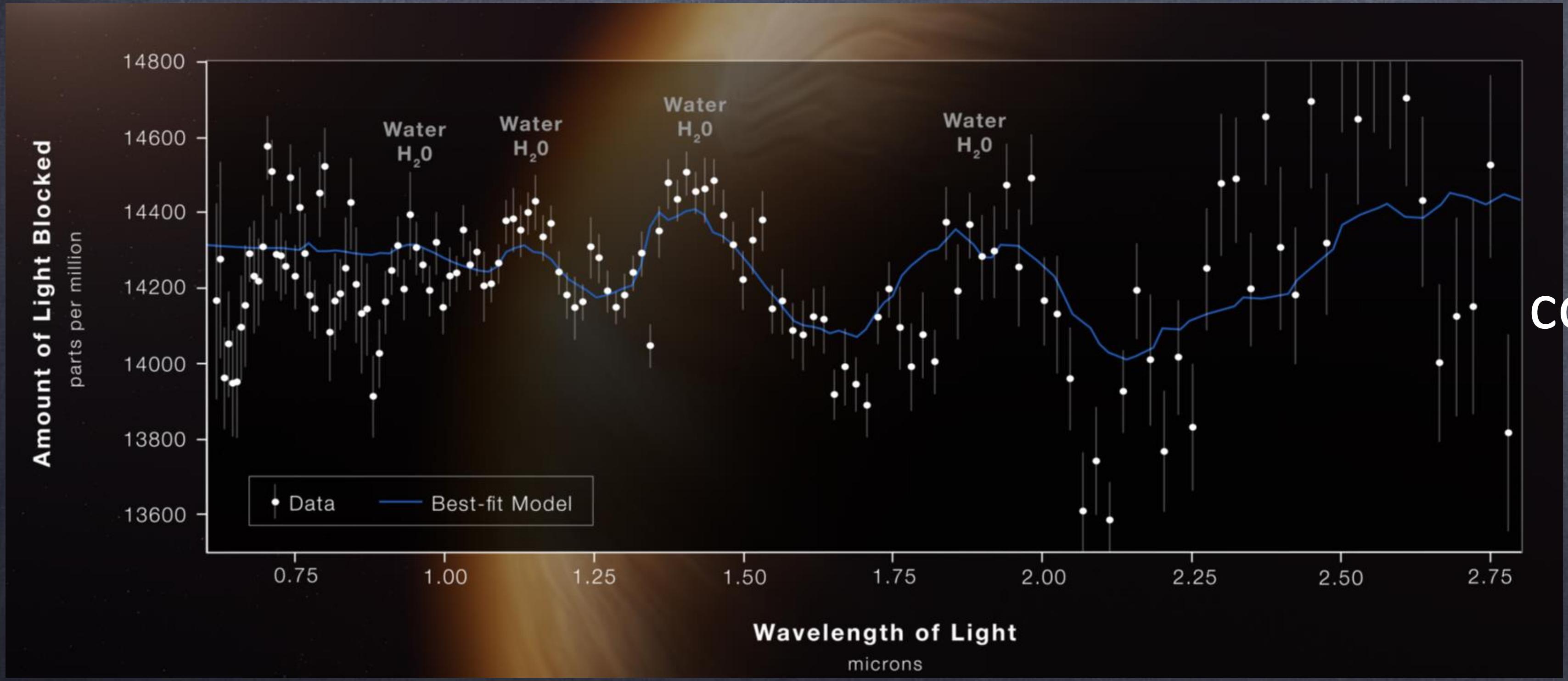
X-shooter



Cosa imparìamo dagli spettri?

Galassia “primordiale” a 13.2 Glight-yr





Eso-pianeta intorno ad una stella nella Via Lattea

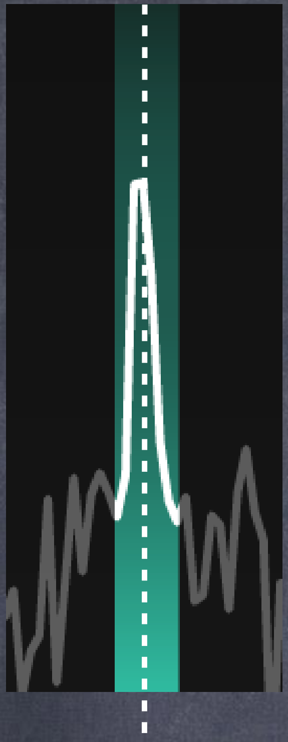
1) CHIMICA

Le righe/bande in emissione o assorbimento sono dovute alla presenza di elementi chimici (atomi o molecole) in vari stati di ionizzazione.

La loro analisi ci può dare la composizione chimica, densità , temperatura del mezzo che stiamo studiando.

Cosa impariamo dagli spettri?

2) VELOCITA’



λ_{oss}

$$\boxed{\frac{\lambda_{oss}-\lambda_{lab}}{\lambda_{lab}}} = \frac{v}{c}$$

Il centro della riga misura la velocità rispetto alla Terra (effetto Doppler).

$\frac{v}{c} \ll 1$

“Moti propri”
(e.g. stelle nella MW)

$z = \frac{v}{c} \gg 1$

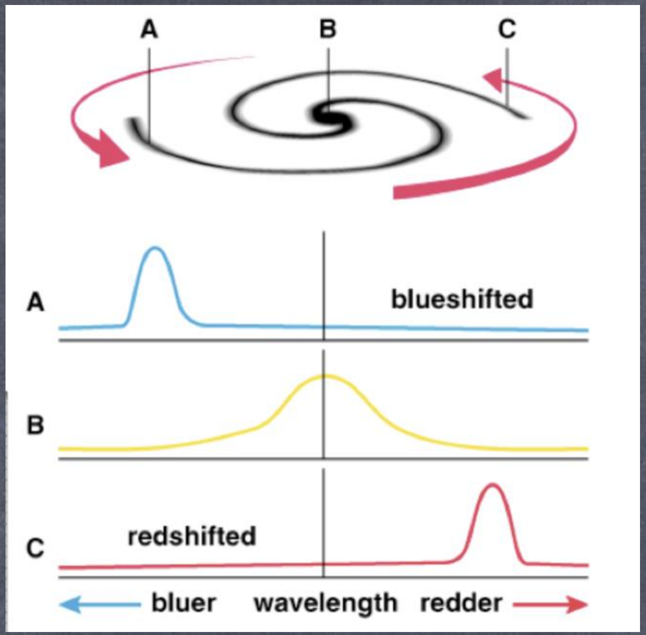
“Redshift” z dovuto all’espansione cosmologica dell’Universo

$$\frac{\lambda_{oss}-\lambda_{lab}}{\lambda_{lab}} = \frac{v}{c} \rightarrow \lambda_{oss} = \lambda_{lab}(1+z)$$

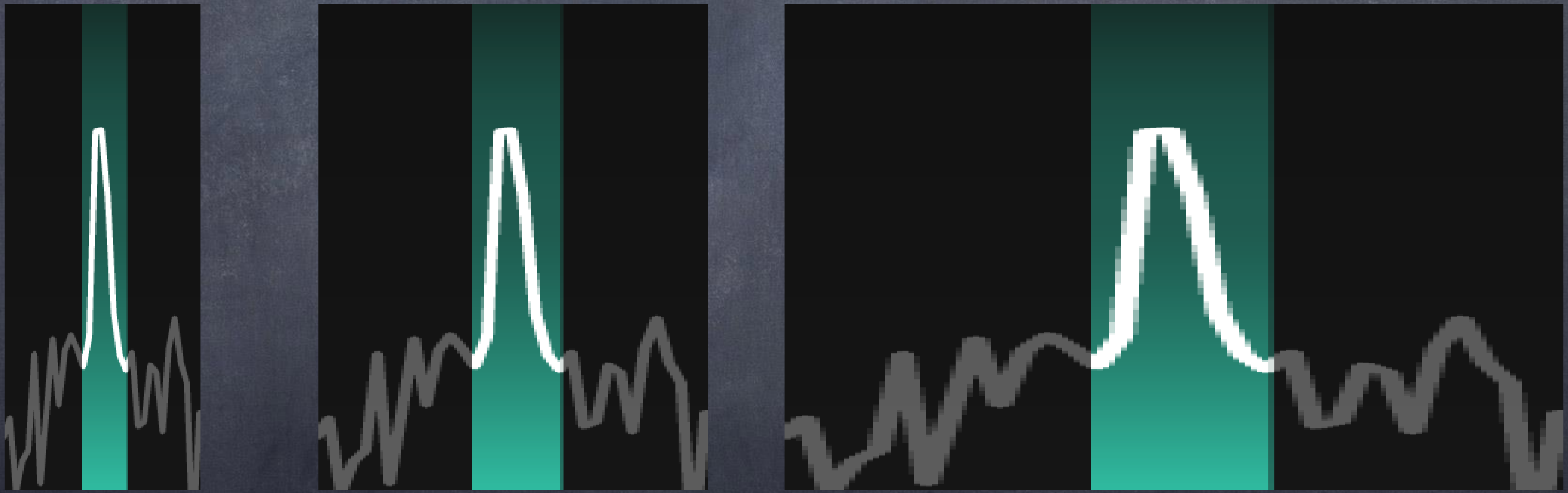
Cosa impariamo dagli spettri?

2) VELOCITA’

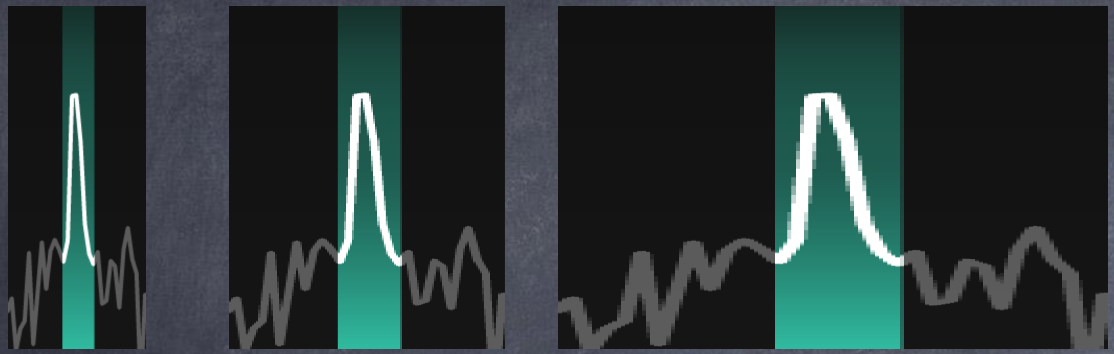
$$\sigma^2_{\frac{\lambda_{oss}-\lambda_{lab}}{\lambda_{lab}}} = \sigma^2_{\frac{v}{c}}$$



La larghezza della riga misura la dispersione di velocità all’interno dell’oggetto (effetto Doppler).



Che risoluzione serve?



$$\boxed{\frac{1}{R} = \frac{\lambda_{oss} - \lambda_{lab}}{\lambda_{lab}} = \frac{v}{c}}$$

La larghezza della riga misura la dispersione di velocità all'interno dell'oggetto (effetto Doppler).

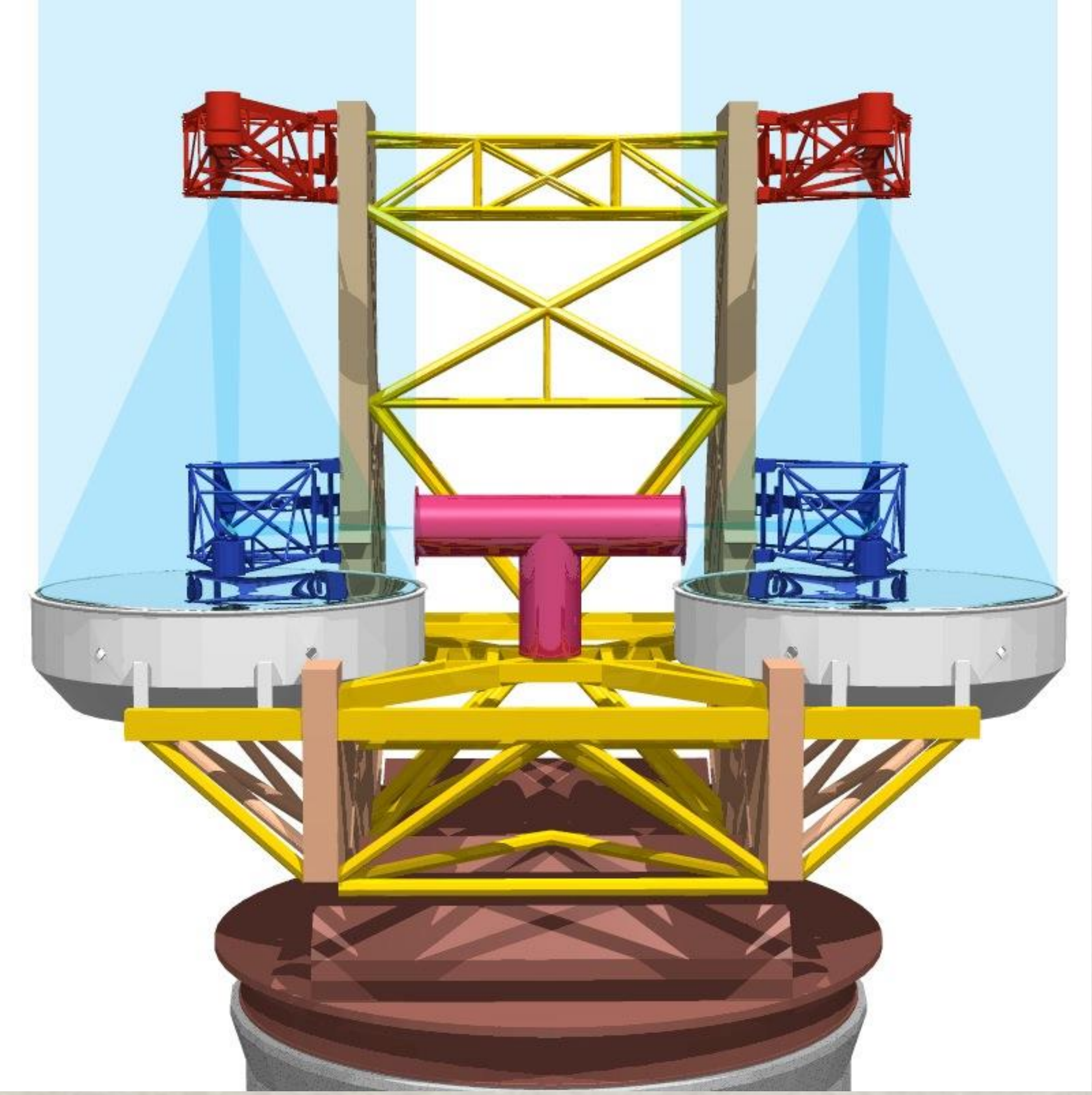
1) Moti dinamici in una galassia:

$$V_{rot}(Terra) \simeq 220 kms^{-1} \rightarrow \frac{v}{c} \simeq \frac{1}{1000} \rightarrow R = 1000 - 10000$$

2) Moto di una stella perturbata dal suo pianeta:

$$V \simeq 1 ms^{-1} \rightarrow \frac{v}{c} \simeq 10^{-8} \rightarrow R > 100.000 - 500.000$$

Come “sconfiggo” il seeing atmosferico?



Large Binocular Telescope

Secondary *deformable* mirrors at a much higher frequency (1kHz) to compensate for atmospheric turbulence:

ADAPTIVE OPTICS

(00’s technology)


NATIONAL GEOGRAPHIC HD


NATIONAL GEOGRAPHIC HD

The magic trick:
Adaptive optics

FLAO test in Arcetri

AO corrected

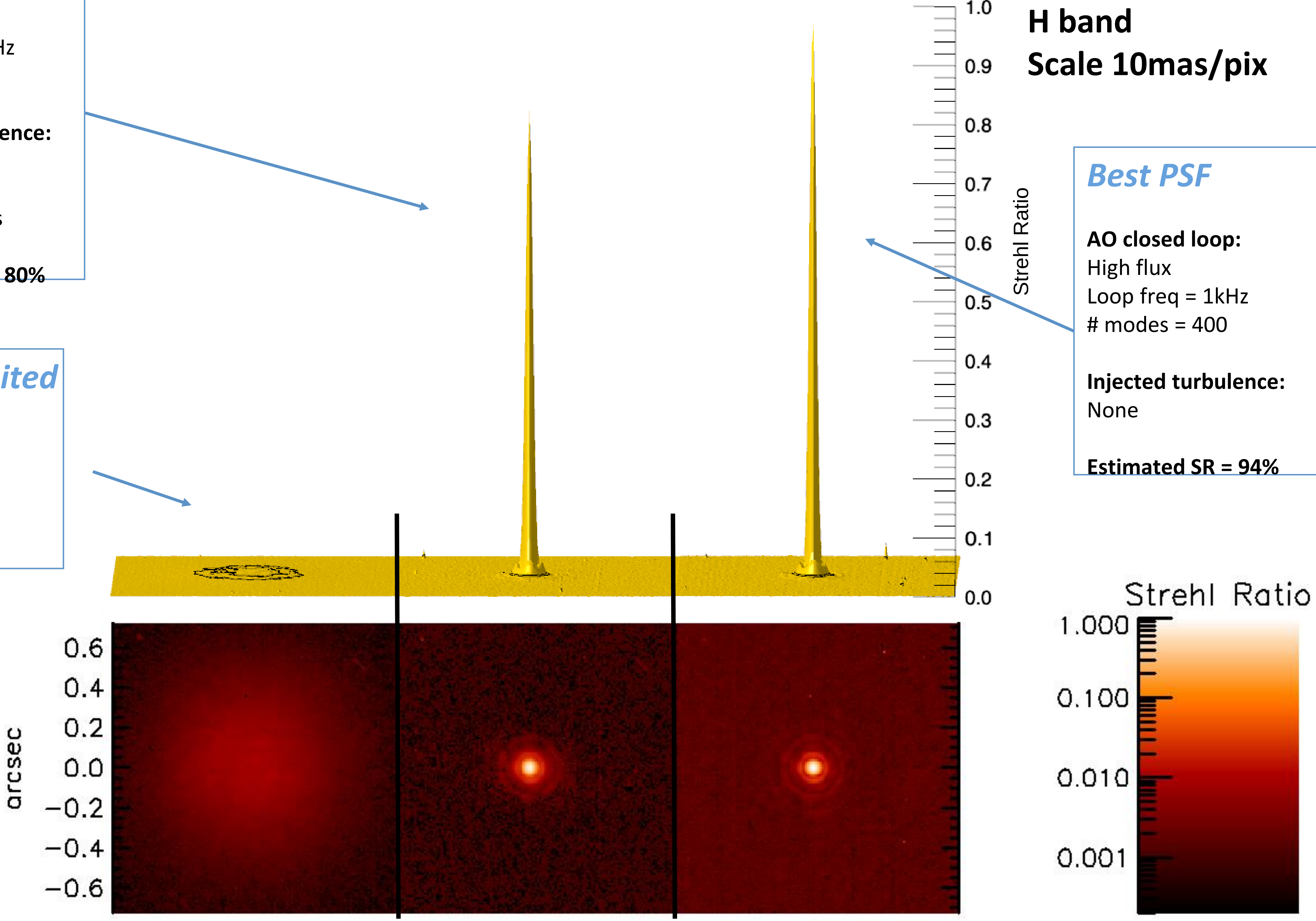
AO closed loop:
Ref mag = 8.5
Loop freq = 1kHz
modes = 400

Injected turbulence:
FWHM = 0.8”
L0 = 50m
Vwind = 15 m/s

Estimated SR = 80%

Seeing limited

Simulated turbulence:
FWHM = 0.8”
L0 = 50m
Vwind = 15 m/s



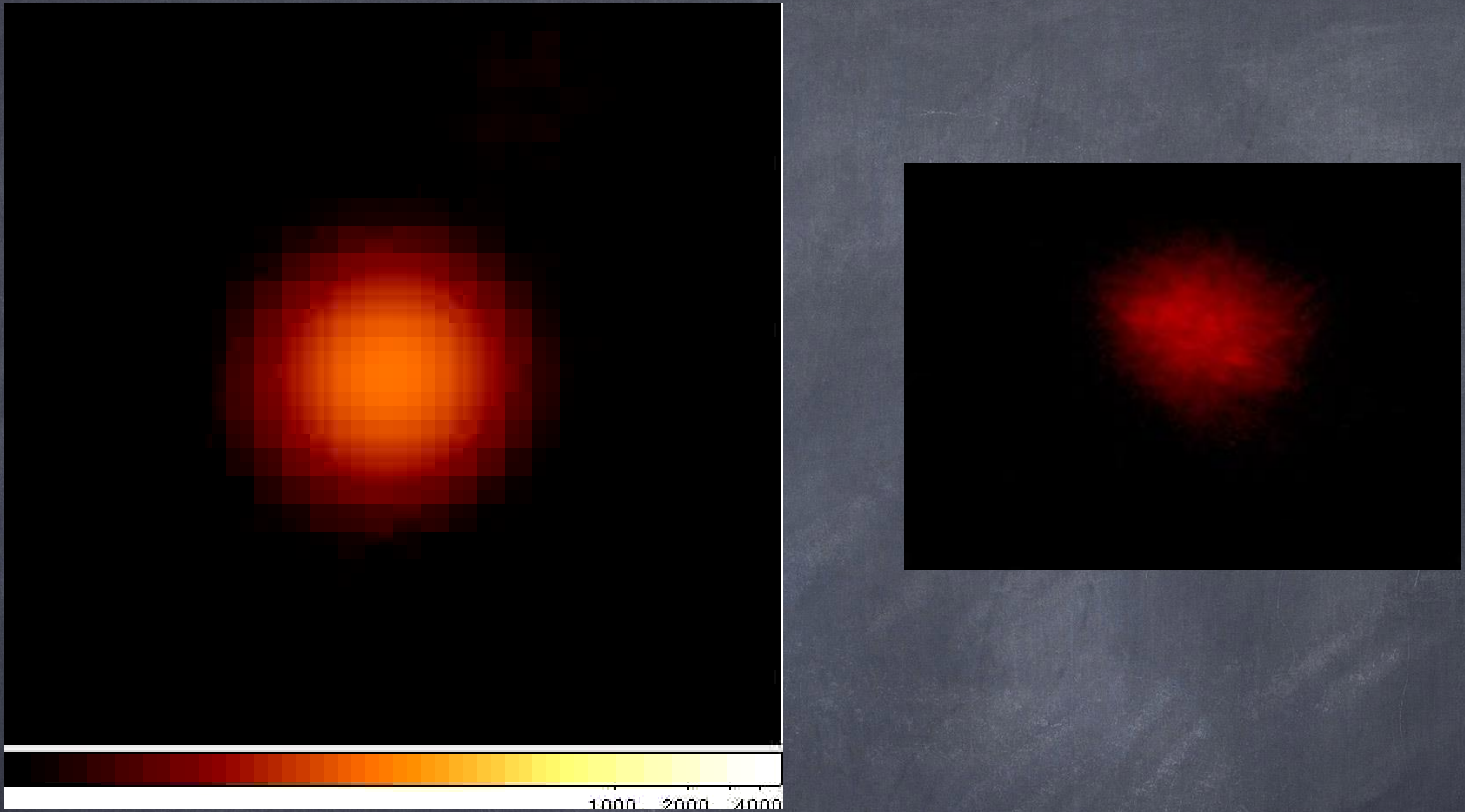
H band
Scale 10mas/pix

Best PSF

AO closed loop:
High flux
Loop freq = 1kHz
modes = 400

Injected turbulence:
None

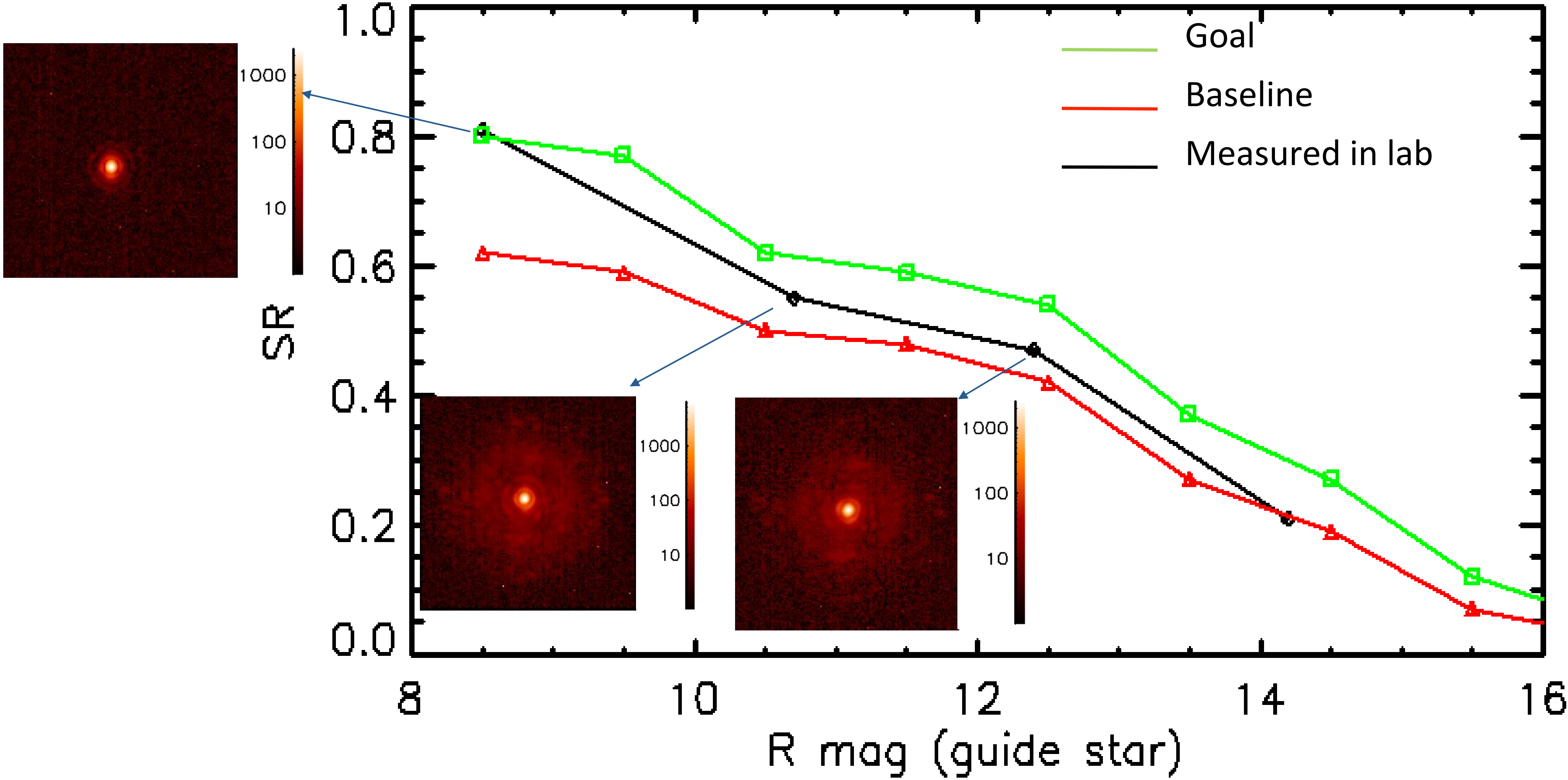
Estimated SR = 94%


1000
2000
4000

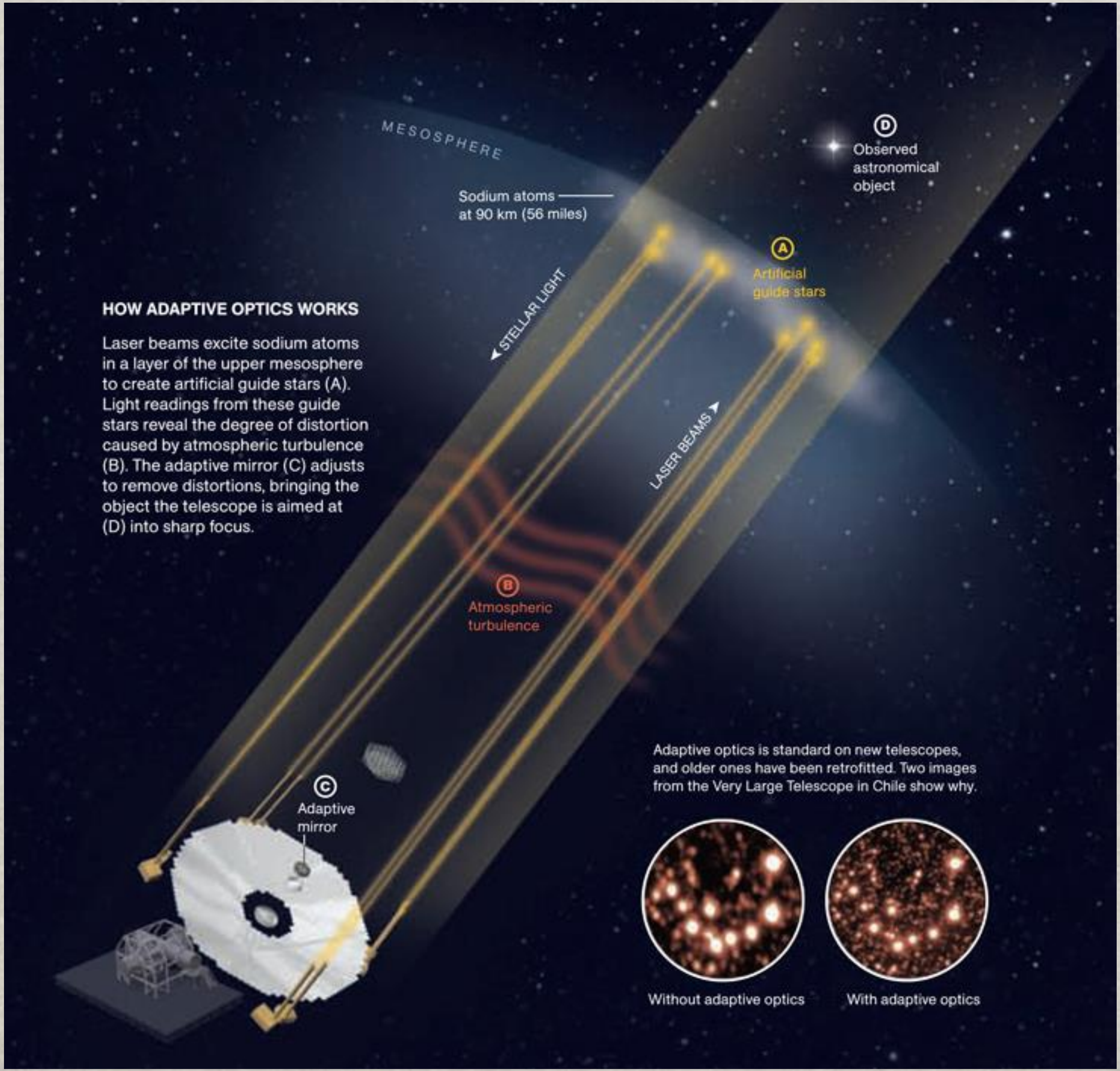
Laboratory performances

Performances measured with FLAO in the Arcetri test tower.
SR measured on the IR Test Camera (INAF-OAB) in H band with 10mas/pix
Atmospheric disturbance of 0.8” @550nm wind speed 15 m/s

Strehl Ratio in H band



Natural Guide Stars cover 10-15% of the whole sky.
For the rest, one needs to create artificial stars..
Laser Guide Star



HOW ADAPTIVE OPTICS WORKS

Laser beams excite sodium atoms in a layer of the upper mesosphere to create artificial guide stars (A). Light readings from these guide stars reveal the degree of distortion caused by atmospheric turbulence (B). The adaptive mirror (C) adjusts to remove distortions, bringing the object the telescope is aimed at (D) into sharp focus.

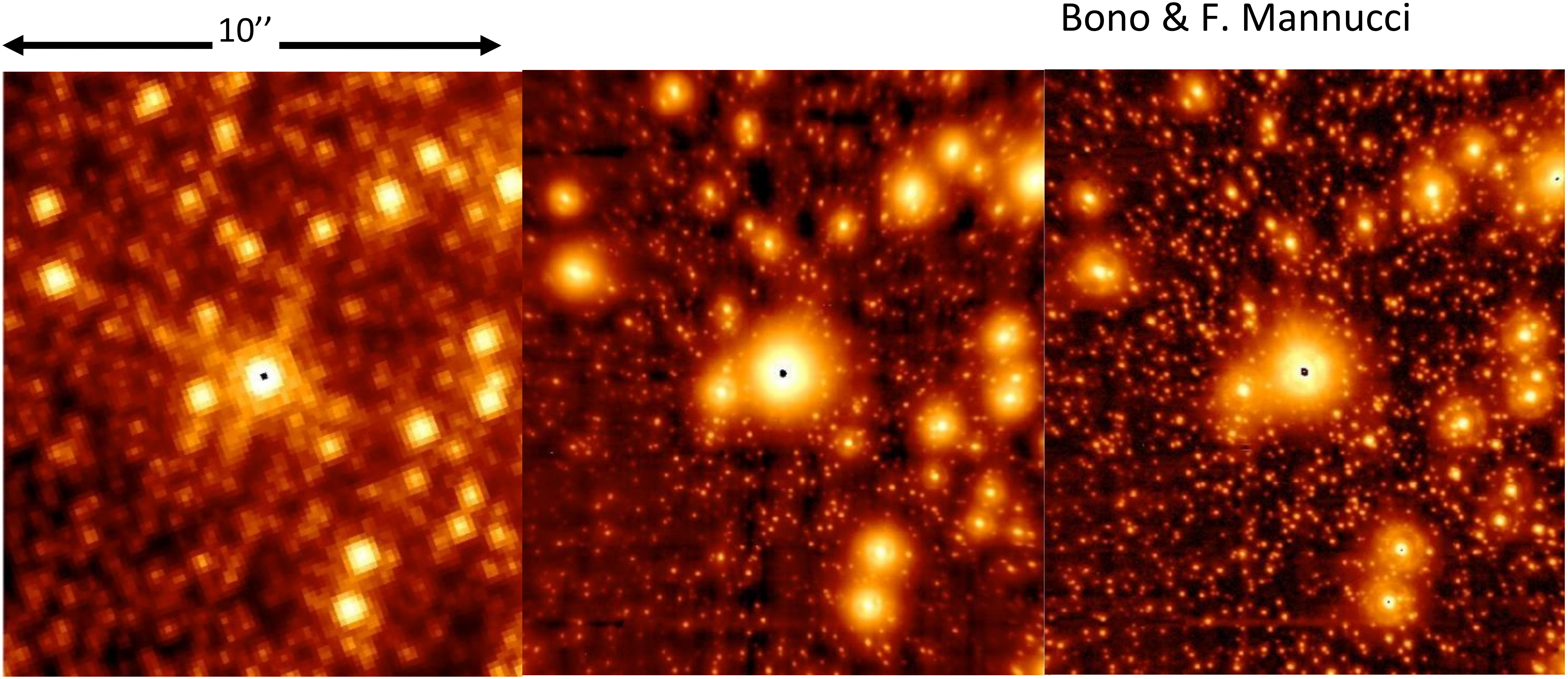
Adaptive optics is standard on new telescopes, and older ones have been retrofitted. Two images from the Very Large Telescope in Chile show why.

Na layer (90km altitude..)

Need high power Na lasers

The Globular cluster M92

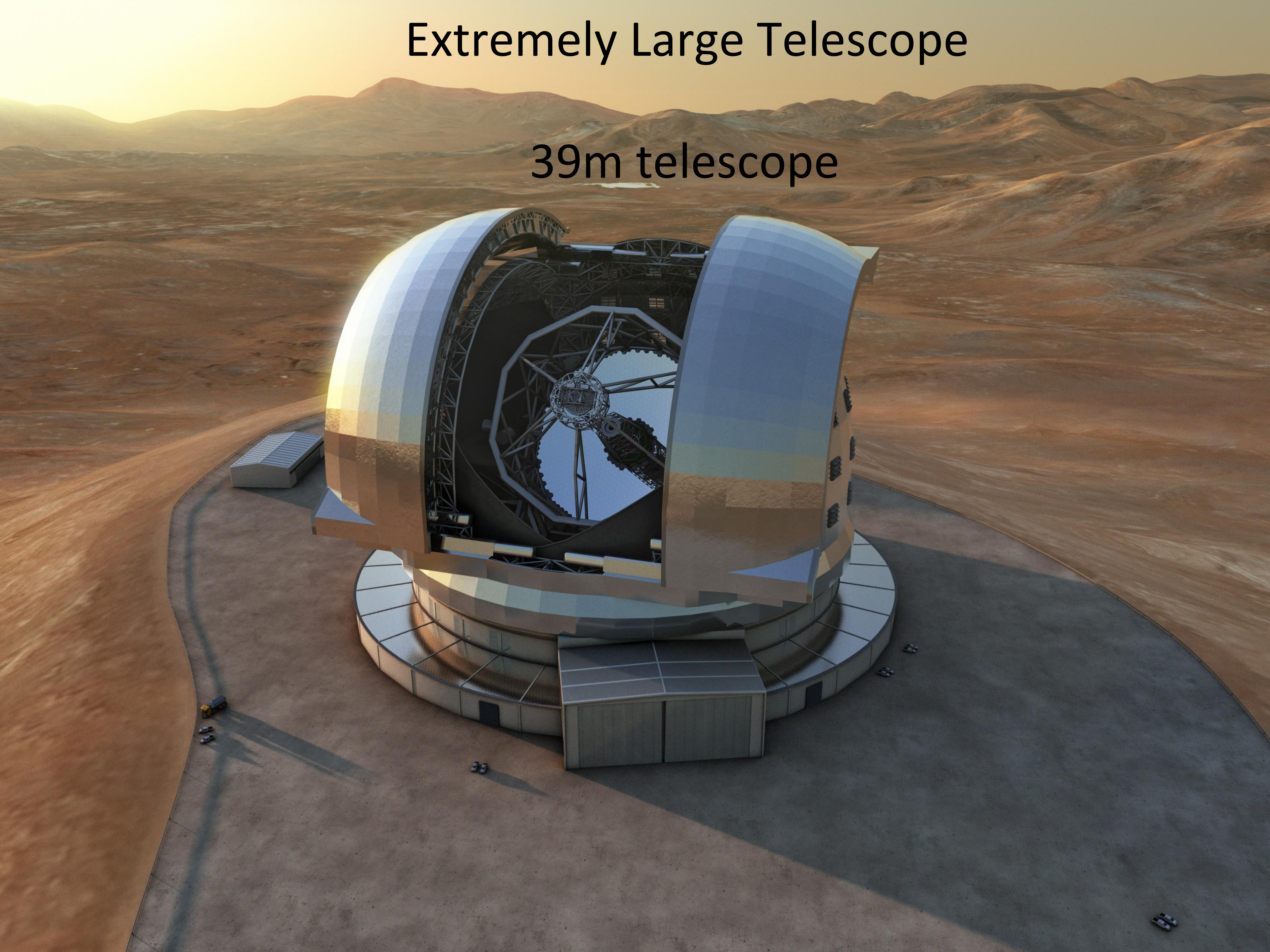
Data reduction G. Bono & F. Mannucci



HST/WFPC3, H band 21min **LBT J band, 6min** **LBT K band, 3min**

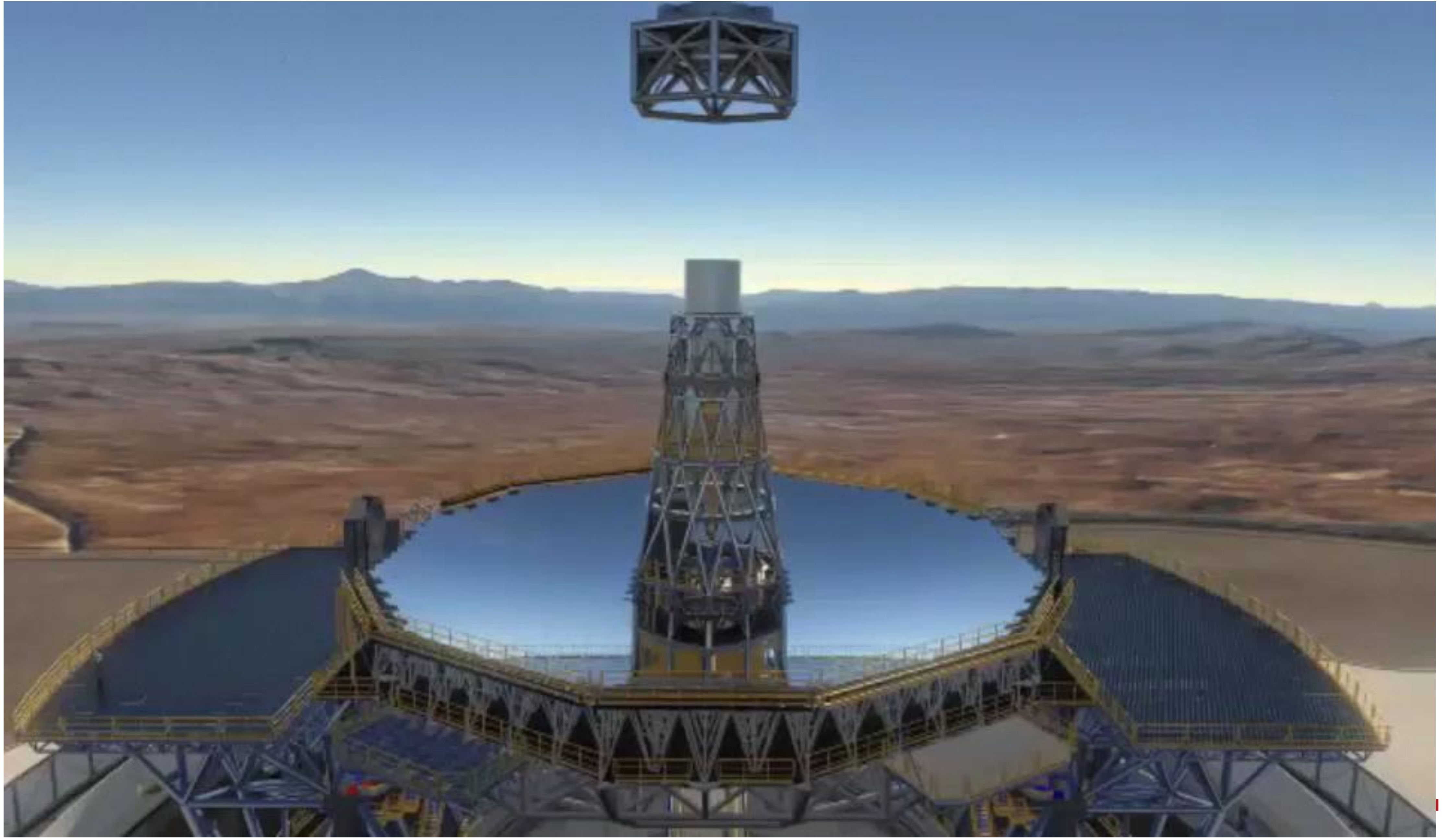
Main data: Rmag 12.0, 0.9'' seeing
AO settings: 0.5KHz, 15x15 subaps, 153 corrected modes

Extremely Large Telescope



39m telescope

ELT Optomechanics



ELT status