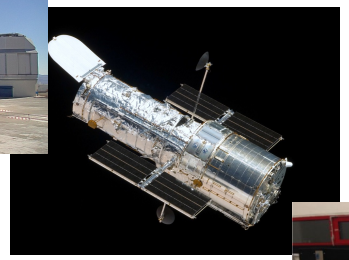
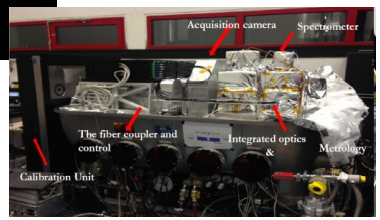
Instrumentation in Astrophysics (Why?)

- Different Approach:
  - Not what was created
    - Telescopes
    - Satellites
    - Instruments

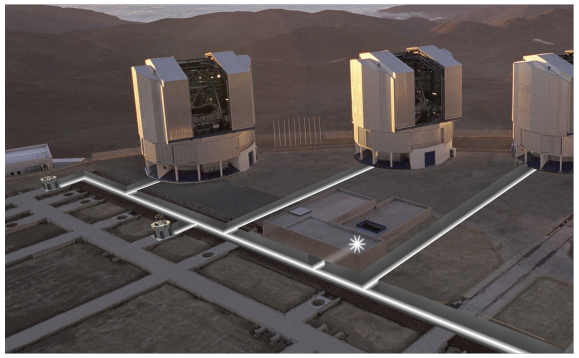


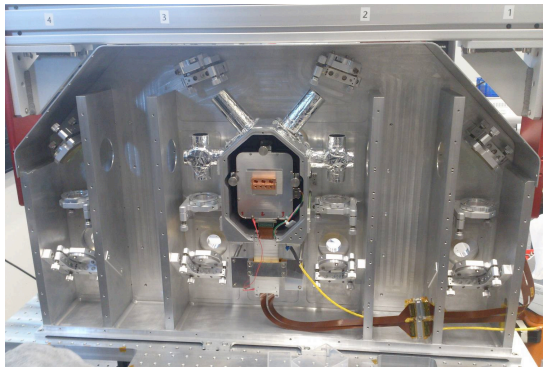


- But **why** is it there
  - Why instrumentation for astronomy?
  - What were the problems and the solutions.

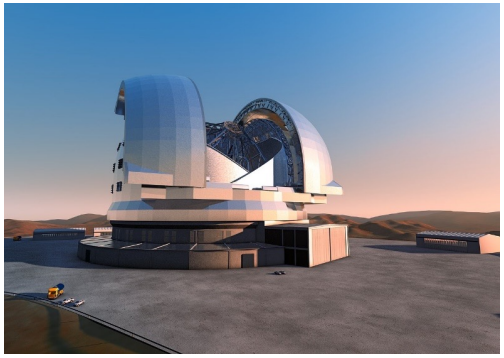
- I hope you enjoy, that is, it is “meaningful” to you.

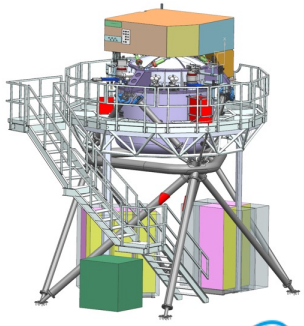
Disclaimer: LinkedIn A. Amorim





- VLT->CAMCAO – IR camera - 1st in Portugal
- VLTI->GRAVITY – IR camera – Data used in the Noble in physics 2020
- ELT-> METIS – Structure and Alignment – PT@ELT/ESO
- Physics Prof. - PhD in nuclear physics, long experience in exp-HEP





Why any human effort?

Meaning

Why are we* in the universe?

"Grave goods were oddly placed with persons who could not have used them there and then. They make sense only if meant for some later time, for an afterlife" ...

African Genesis, S. C. Reynolds, ...

100 k years ago

Power

Can we master the universe?

Agriculture in the Near East arose in the context of broad-based systematic human efforts at modifying local environments and biotic communities to encourage plant and animal resources of economic interest...

The Origins of Agriculture in the Near East, Melinda A Zedar

10 k years ago

Scientific best knowledge…

An illusion prone, resource consuming plague on the third planet of the solar system in the Milkyway, exponentially growing during the last centuries, that is causing the ever fastest mass extinction on the 4.5 billion years old planet.

Today, species extinction rates are hundreds or thousands of times faster than the "normal" or "background" rates prevailing in the last tens of millions of years

Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction
Gerardo Ceballos, Paul R. Ehrlich, and Peter H. Raven, PNAS, 2020

- To feed humans (in **Millions**) :
  25900 M chickens --- 700 M pigs --- 1000 M cows

- Wildlife (in **Millions**) :
  0.4 M elephants Africa -- 0.012 M wolves Europe -- 0.02 M polar bears artic
  0.87 M all whales --- 0.015 M wild bison

Why the effort in Astronomy?

Meaning

The meaning in sky observation?

Enūma Anu Enlil,[1]

These are the oracles when Sin (i.e., the moon) makes a decision, the great gods of heaven and earth decide the doings of mankind and their[2] . . . . ., eclipse, flood, illness, death, the great *gallû*-demons, Sebettu always block the way in front of Sin.[3]

Mesopotamian Astrology, U. Westenholtz

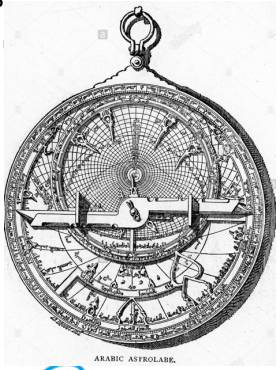
4 k years ago

Power

Can we gain power with sky obser.?

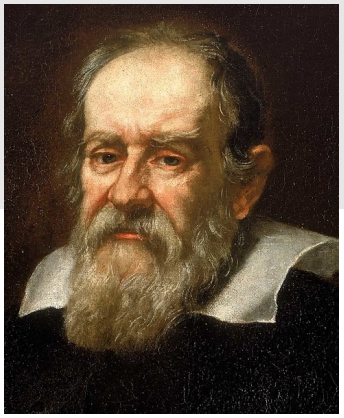
Many persons hold the opinion that the metal industries are fortuitous and ... not so much skill as labor. ... a miner must have the greatest skill in his work... a complete knowledge of the method of making all there are the various systems of assaying
...
follows Astronomy, that he may know the divisions of the heavens and from them judge the direction of the veins

- De Re Metálica, Agricola, sec. XVI.



0.4 k years ago

Why the first telescope? (1609)



Power

"Galileo was distracted from his motion experiments by rumors of a new Dutch curiosity called a spyglass, or eyeglass"

...

immediately grasped the military advantage of the new spyglass,

...

in exchange for the gift of his telescope the Venetian senate renewed Galileo's contract at the University of Padua for life

Meaning

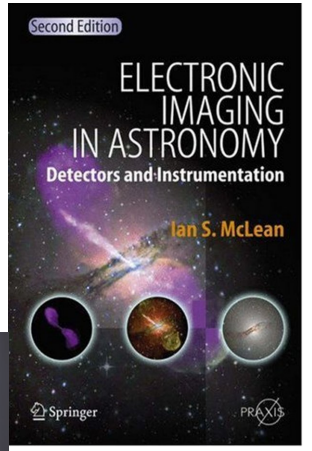
the moons of Jupiter for Cosimo I ...who… convinced the Florentine citizenry that it was Medici destiny to usurp power from the other prominent families ... Cosimo I identified with the planet Jupiter, named for the king of the Roman pantheon

Galileu's Daughter, Dava Sorbel

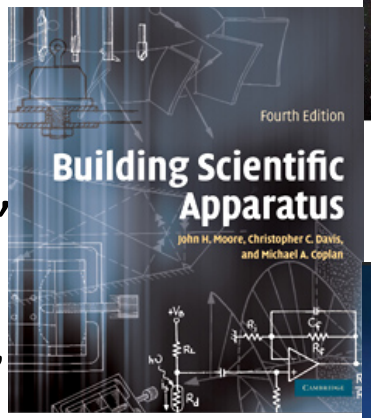
More technical (why)

To learn more for the *physics* oriented:

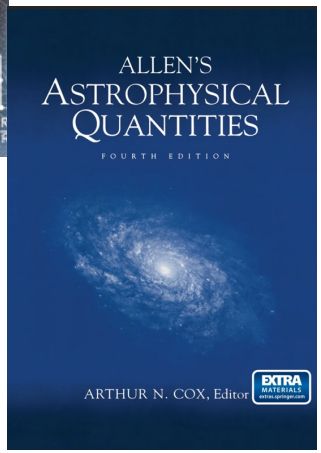
- Electronic Imaging in Astronomy, Detectors and Instrumentation, Ian S. McLean, Wiley, 1997



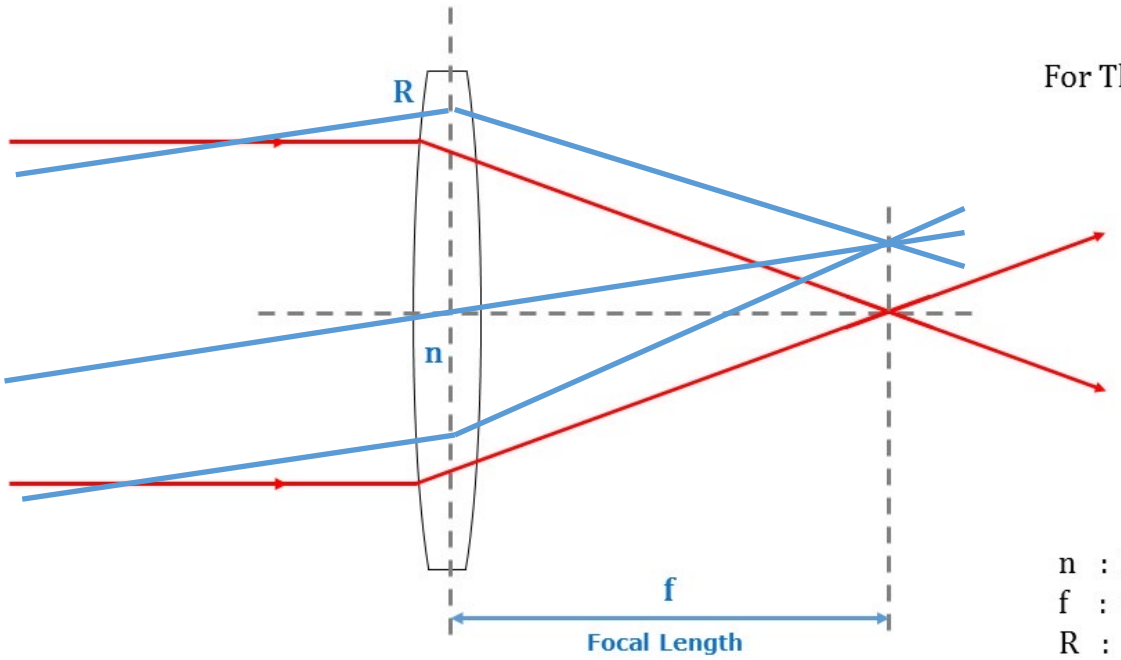
- Building Scientific Apparatus, John H. Moore, Christopher C. Davis and Michael A. Coplan, Cambridge University Press, Fourth EDITION, 2013



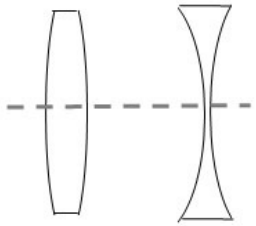
- Allen's Astrophysical Quantities. AIP Press, Arthur N. Cox. , 1999



Why the objective in a telescope?



For Thin Bi-Convex/Bi-Concave:



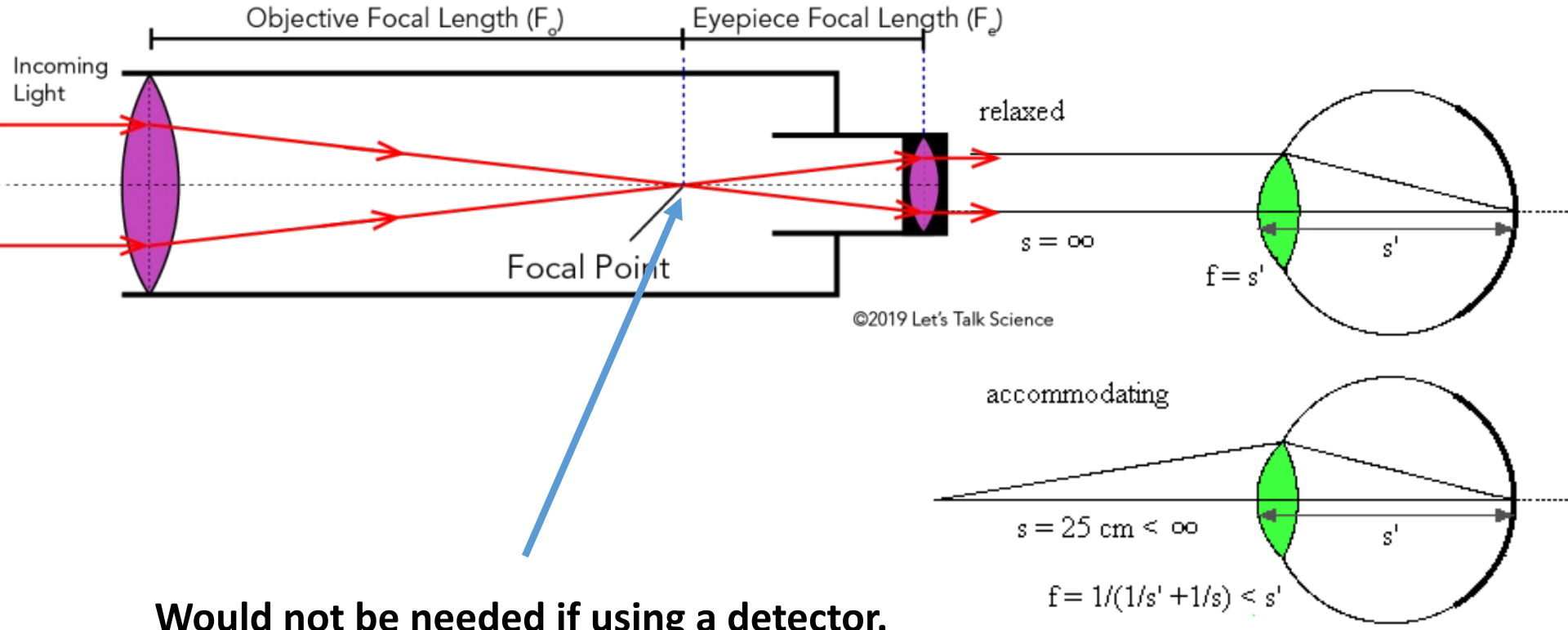
$$\mathbf{f = \frac{R}{2(n-1)}}$$

n : Refractive Index
f : Focal Length (mm)
R : Radius of Curvature (mm)

Mapping from angle to point.

$$PlateScale = \frac{1}{f} = \frac{d\theta}{dy}$$

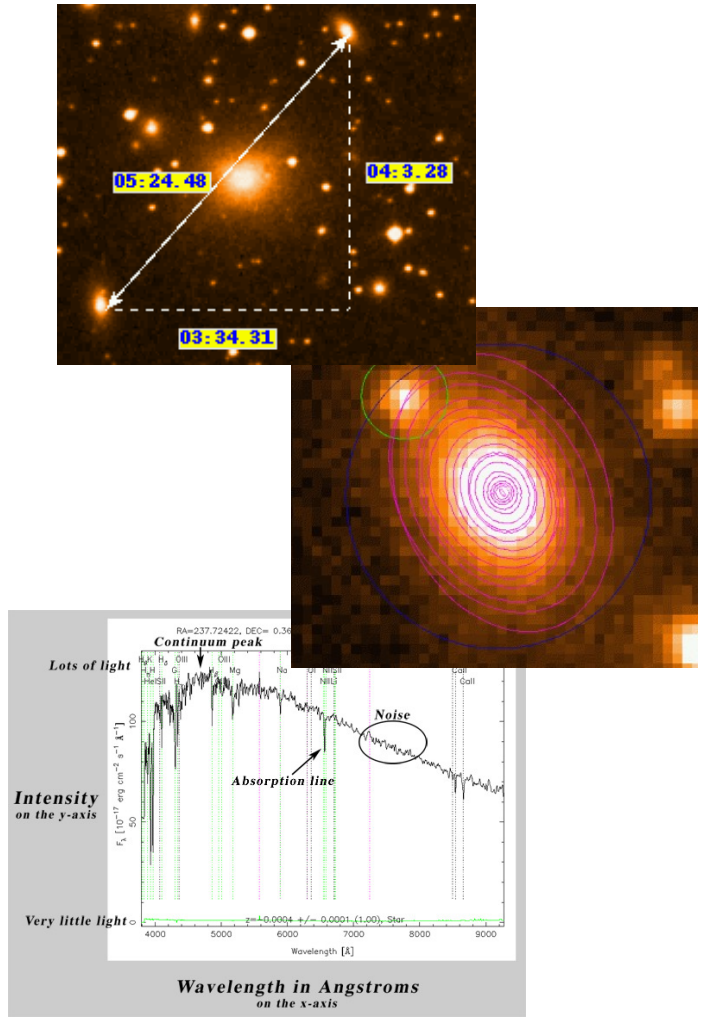
Why the ocular in a telescope?



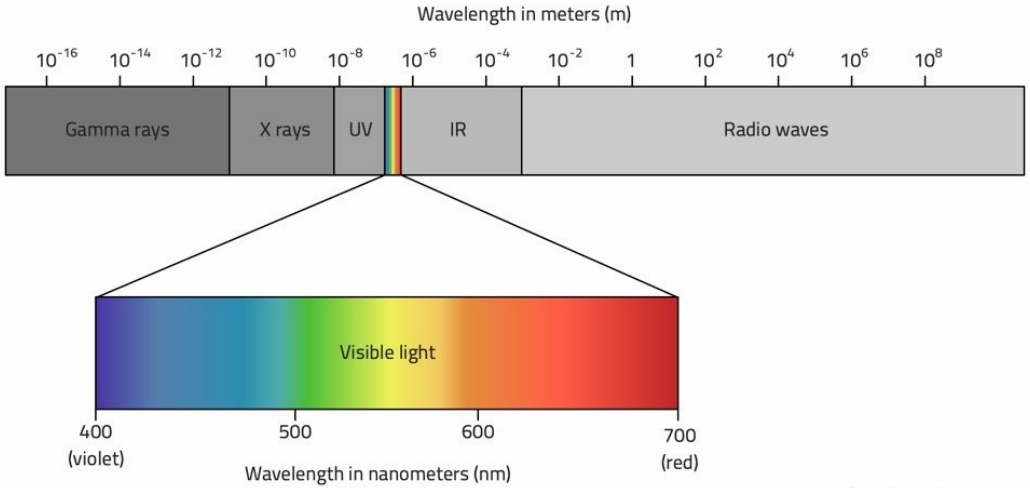
Would not be needed if using a detector.

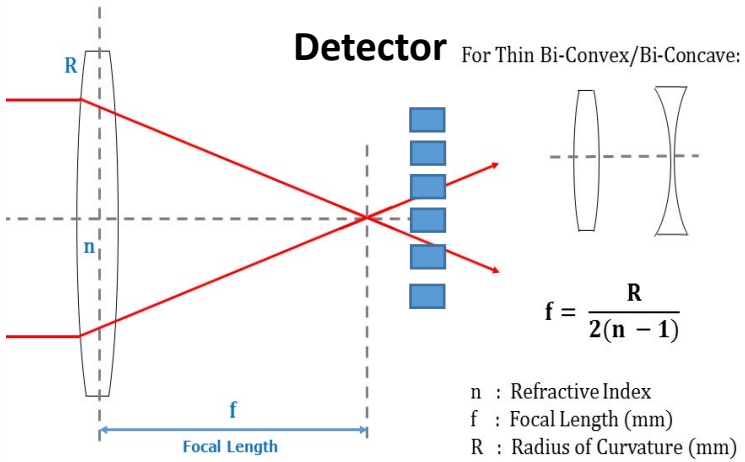
Observations in Astrophysics

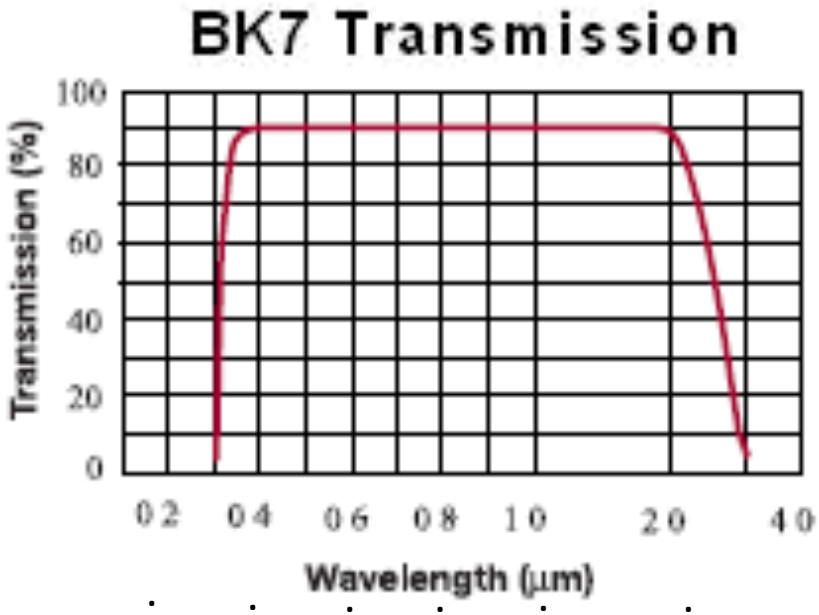
- Astrometry - RA, Dec
- Photometry - Flux
- Spectroscopy - Spectra
- Variability – f(time)



Why are lenses bad to see wide spectra?

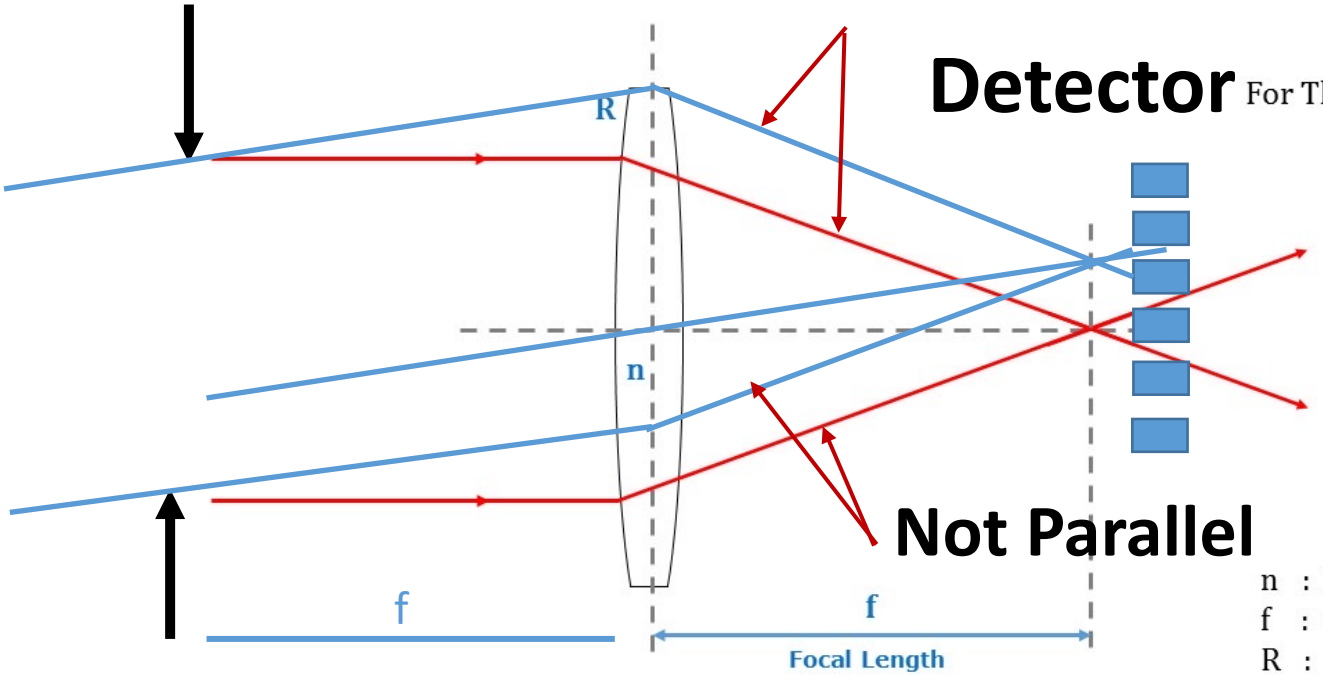






Why are they bad for photometry?

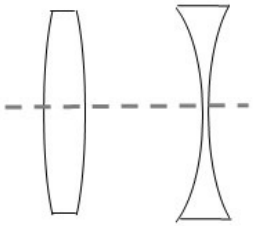
Not Parallel



Detector

Not Parallel

For Thin Bi-Convex/Bi-Concave:



$$f = \frac{R}{2(n-1)}$$

n : Refractive Index
f : Focal Length (mm)
R : Radius of Curvature (mm)

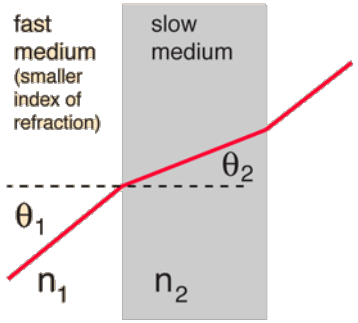
active volume of each pixel in detector needs constant cone angles over the field

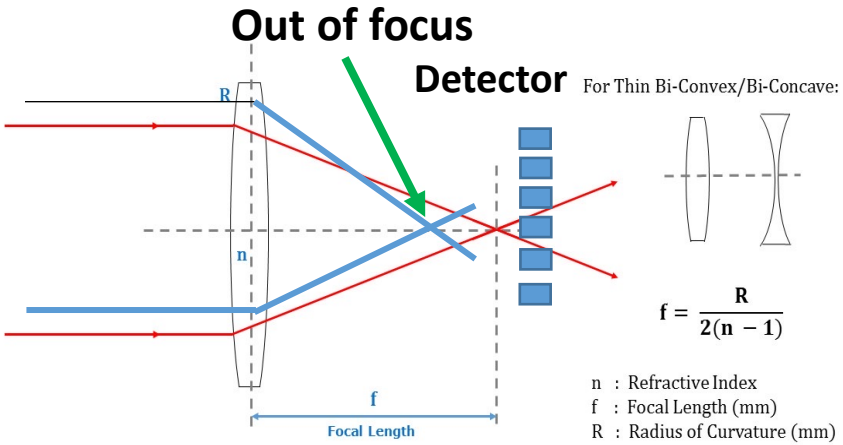
Telecentric camera / objective

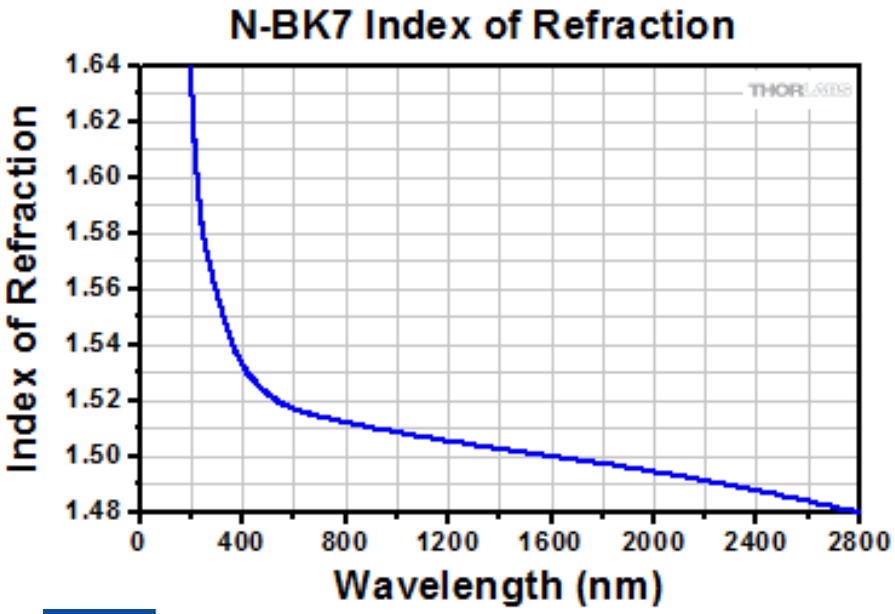
Why is it bad for spectrometry?

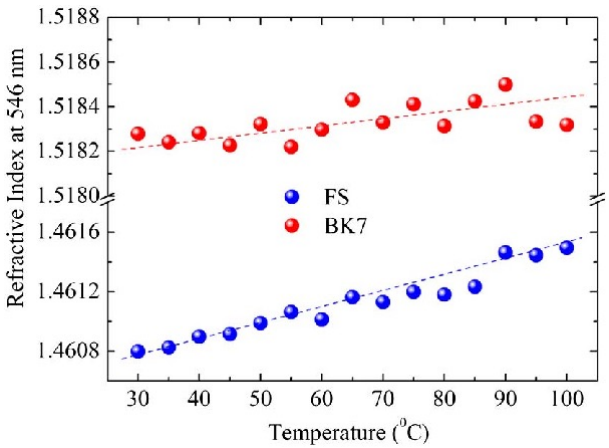
Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

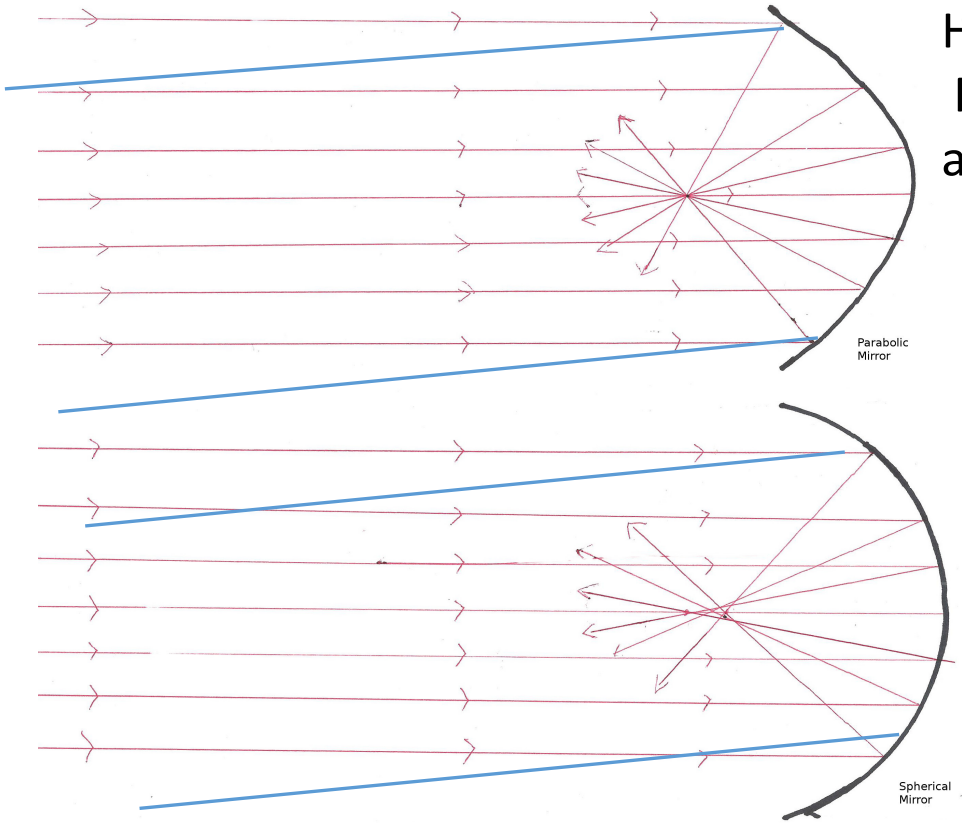






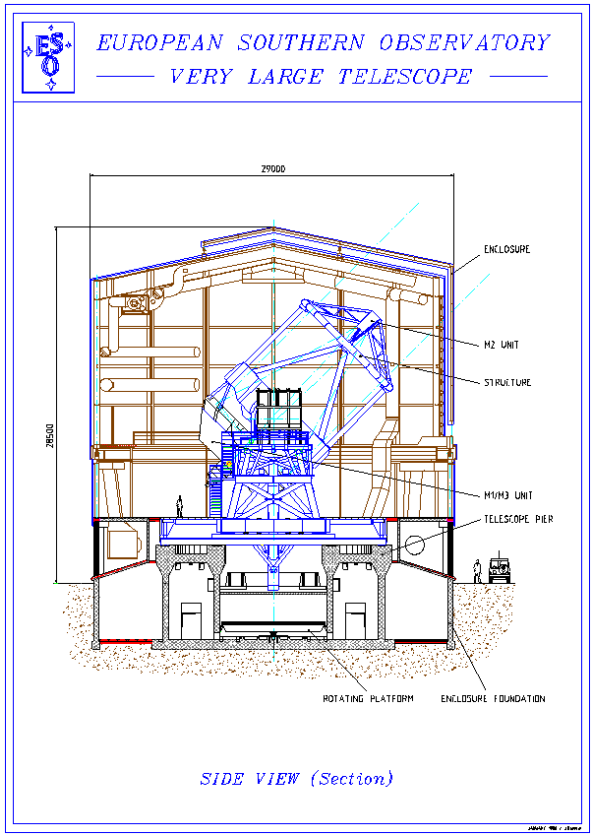


Why spherical/parabolic mirrors?



However:

For a large field of view (angle) the aberration of the parabolic is worse.



5 mirrors with aspherical shape:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}$$

Why larger collecting area (stat)?

- Larger collecting area:
  - Faint objects
  - H-res angle
  - H-res spectra
  - H-statistics

Apparent magnitude (band)

$$\frac{dN_{ph}}{d\lambda\, dA} = N_\lambda\, 10^{-0.4\, m}$$

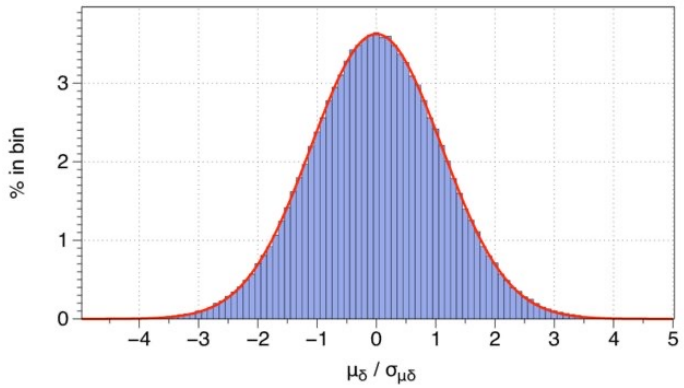
High resolution spectrometry

Telescope Area

$$\frac{dN_{ph}}{d\lambda\, d\Omega\, dA}$$

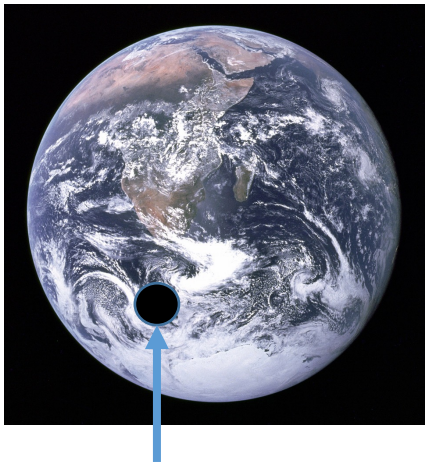
For background

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{N}}$$

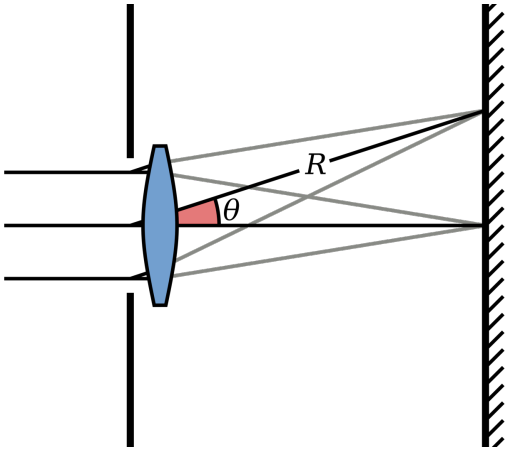


GRAVITY: ...star magnitude mH = 13 and a background efetive magnitude 13.4/arcsec^2 ...

Why larger diameter (Res.)?



Telescope Aperture



Angle of first null disk

$$\theta(rad) \approx 1.22\frac{\lambda}{D}$$

$$FWHM = \frac{\lambda}{D}$$

Small FWHM => Larger D

FWHM= 1/50 arcsec , 1 micron => D= 10 m

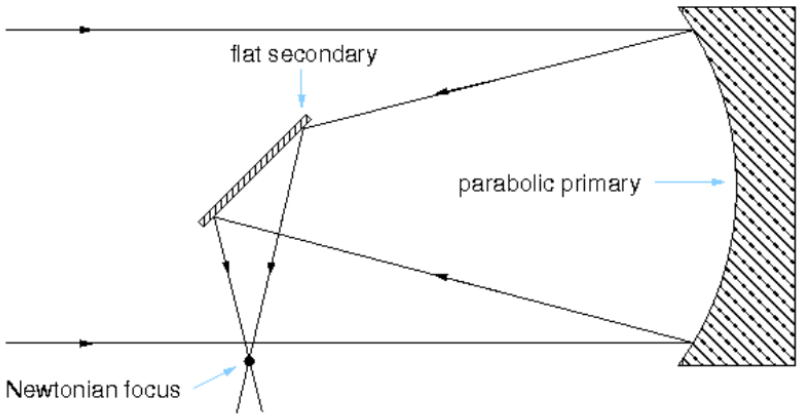
Why the secondary mirrors?

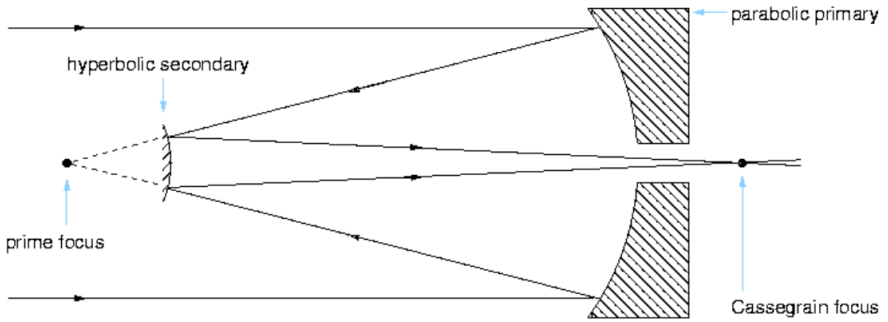
$$PlateScale = \frac{1}{f} = \frac{d\theta}{dy} \qquad PixelScale = \frac{dy(pixel)}{f}$$

High resolution means small PixelScale => large f

For ESO/VLT: f = 120 m

Secondary divides in ~ 2.

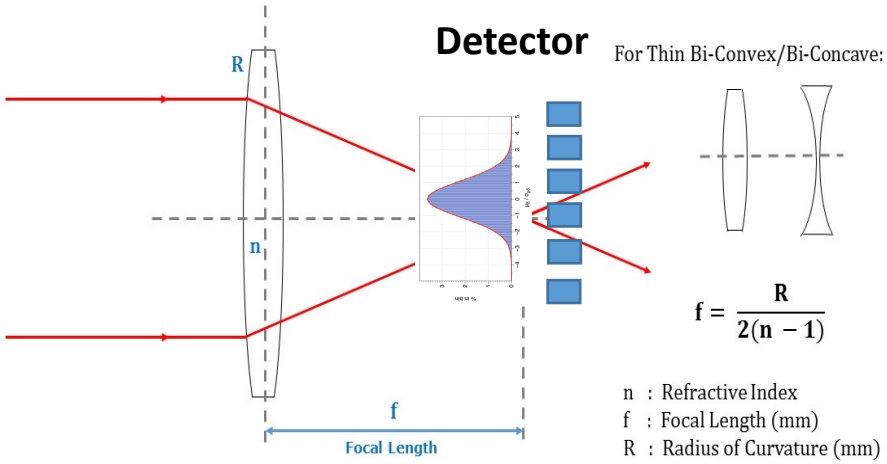




Why do you need a camera?

$$PlateScale = \frac{1}{f} = \frac{d\theta}{dy} \qquad (d\theta)PixelScale = \frac{dy(pixel)}{f}$$

Nyquist criteria = 2 pixel in FWHM



too large / too small for the detector pixel size:

- Need to reimage to magnify.
- In the Infrared, include cold stop

Why the need for “miracle” optics?

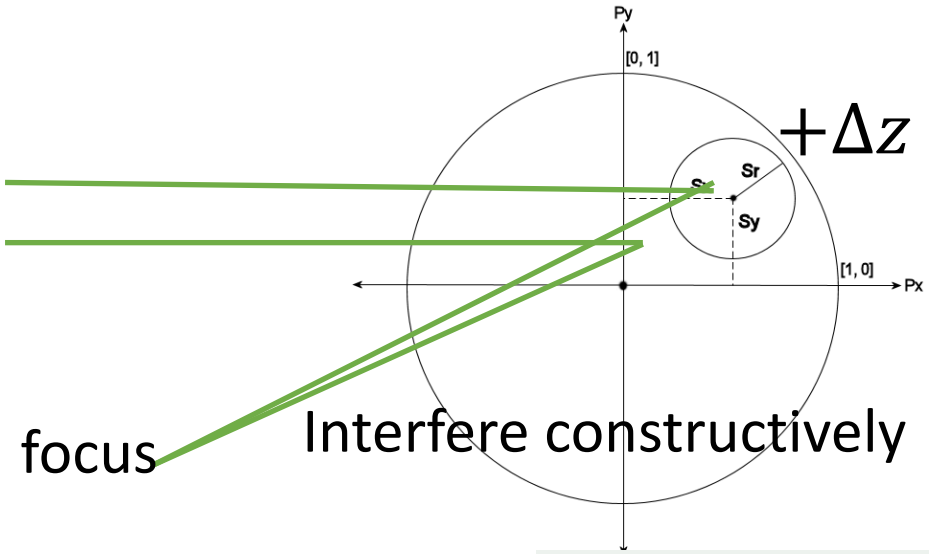
Diffraction limited $FWHM(\theta) = \frac{\lambda}{D}$

Aberration limited

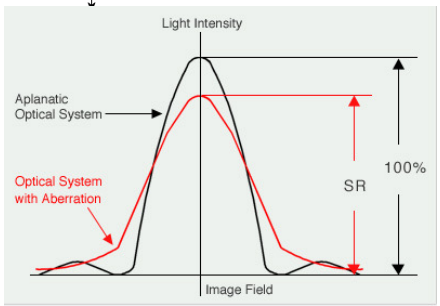
$A\, e^{-i\,k\,z} \rightarrow A e^{-i2\pi\frac{z+2\Delta z}{\lambda}}$

$\frac{\Delta z}{\lambda} < \frac{1}{20}$

$\Delta z < 50\ nm$



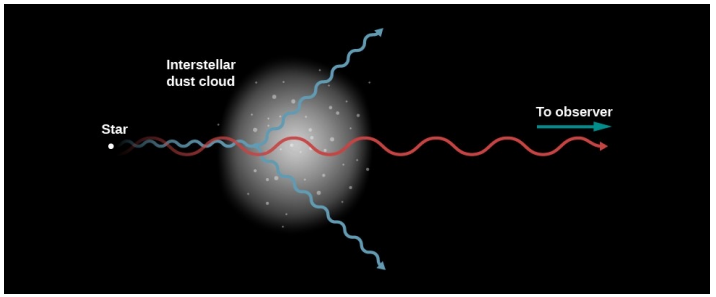
Strehl ratio > 0.7



Why the need for infrared instruments?

Interstellar dust:

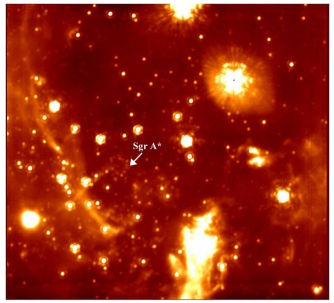
- reddening and interstellar extinction
- throughout the plane of the Milky Way



THE CORE-MANTLE INTERSTELLAR DUST MODEL

J. MAYO GREENBERG AND AIGEN LI

IR Galactic Center. Visible



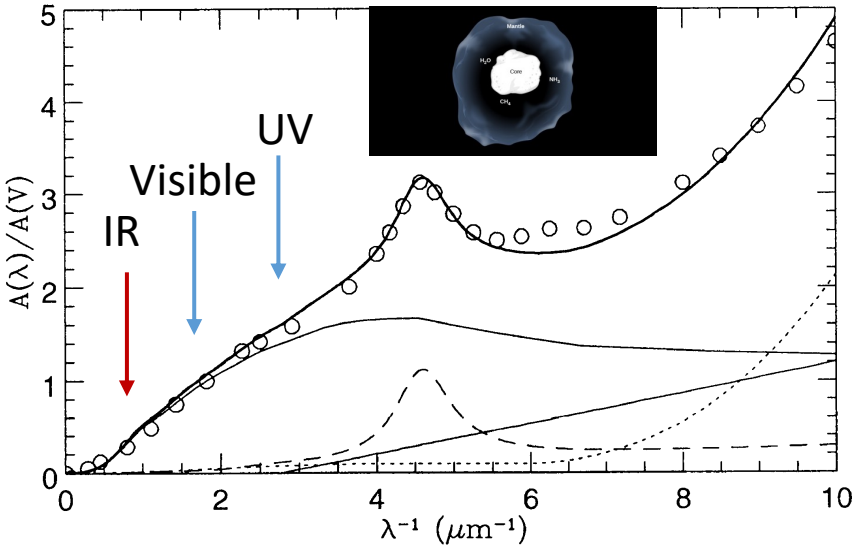


Figure 12. The observational and theoretical mean diffuse medium extinction curve. The circles are the observed average extinction curve from Savage and Mathis (1979). The thick solid line refers to our model prediction. Also shown are the individual contributions of the three dust components: large core-mantle particles (solid line + the linear part); hump particles (dashed line); and PAHs (dotted line). See Greenberg and Li (1996b).

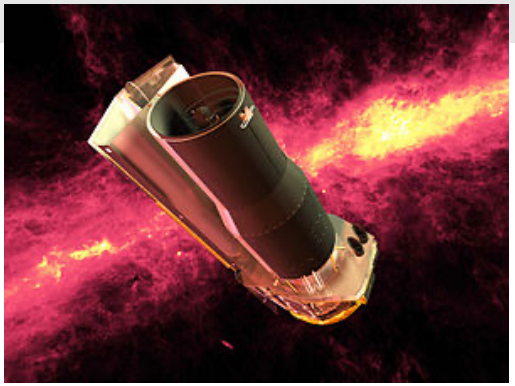
Why the need IR space instruments?

Spitzer Space Telescope (2003 – 2020)

Diameter 0.85

Focal length 10.2

Wavelength infrared, 3.6–160 µm



Infrared Radiation (transmission) Earth Atmosphere

J 1.25

H 1.65

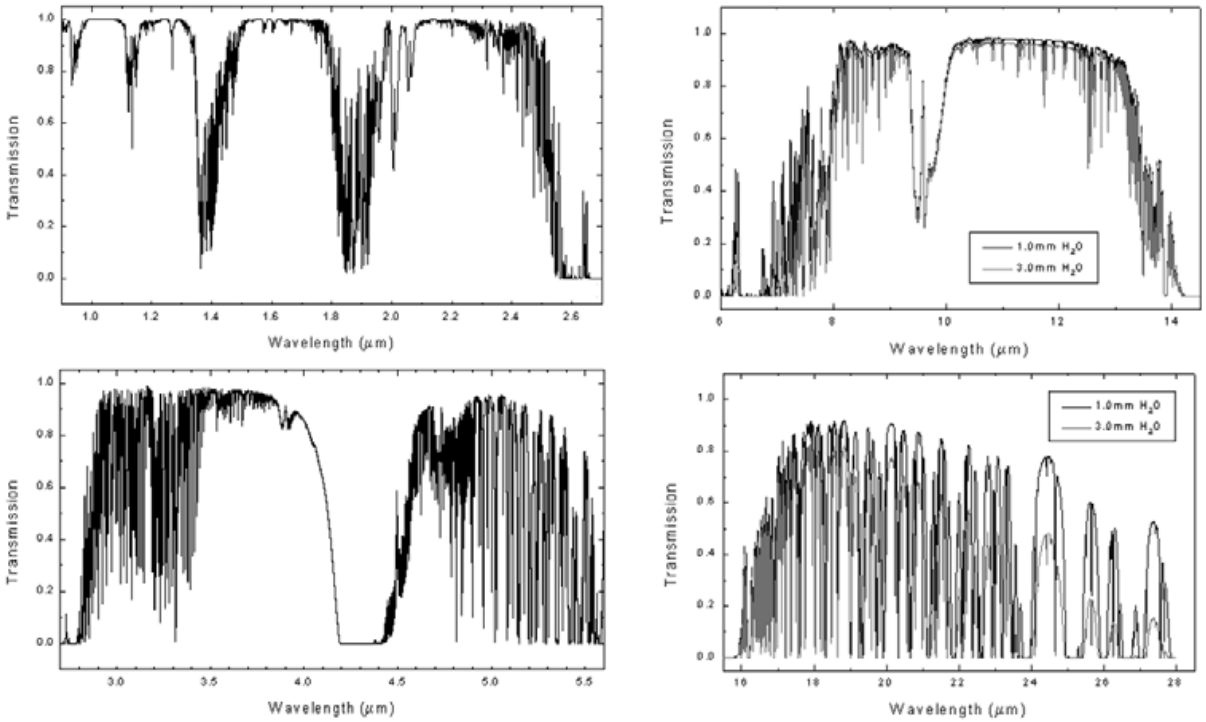
K 2.2

L 3.5

M 4.8

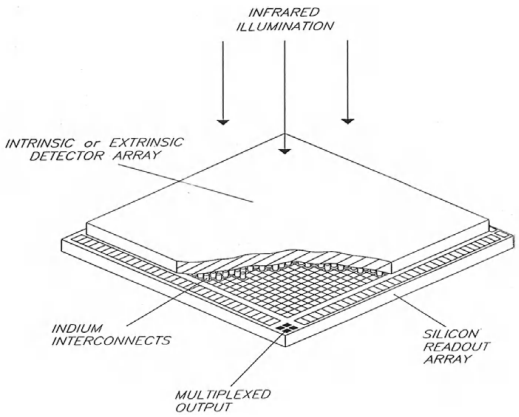
N 10.6

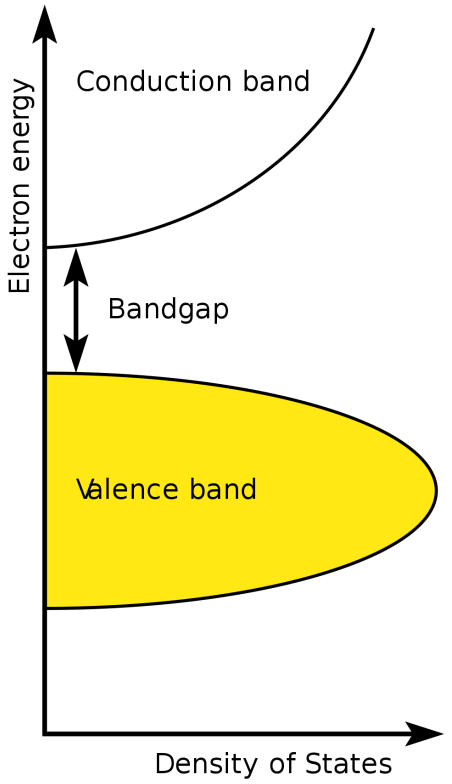
Q 21



How we deal with infrared sensors?

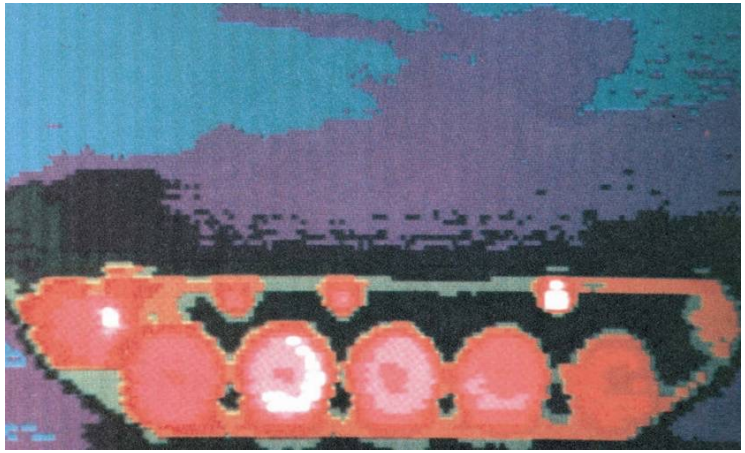
- Cooling to enable the detector
- Si Gap=1.14 EV
- $\lambda_C = \frac{hc}{E_g} = \frac{1.24\ \mu m}{E_g(eV)}$

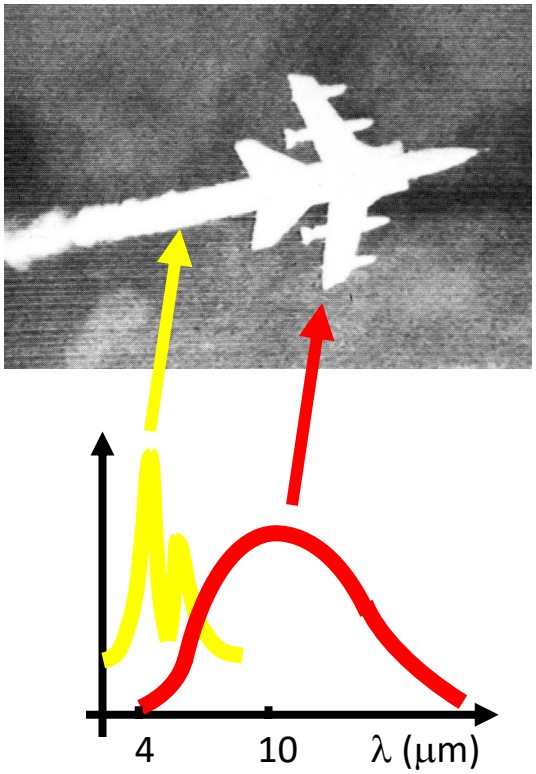




- $Hg_{(1-x)}Cd_xTe$ tune the bandgap to 0.3 EV
- Thermal excitation $T_{max} = \frac{200\ K}{\lambda_C(\mu m)}$
  - Tmax ~ 70 K
  - Use liquid Nitrogen ~ 80 K

Why we have infrared sensors?



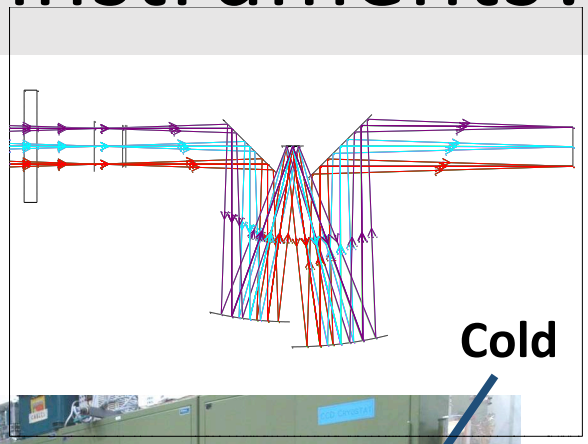


Mid-IR from heat is easily distinguished from the ambient far infrared, which peaks near 10 mm and is relatively weak in this range.

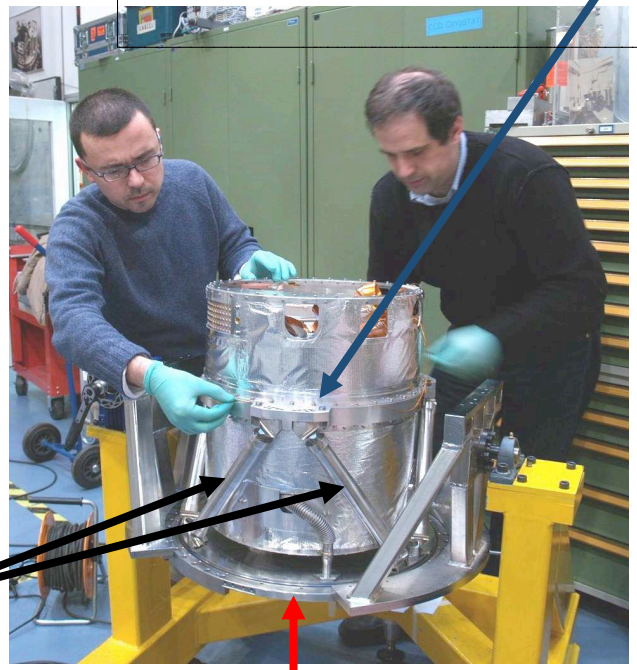
Also IR penetrates fog and smoke better than visible light.

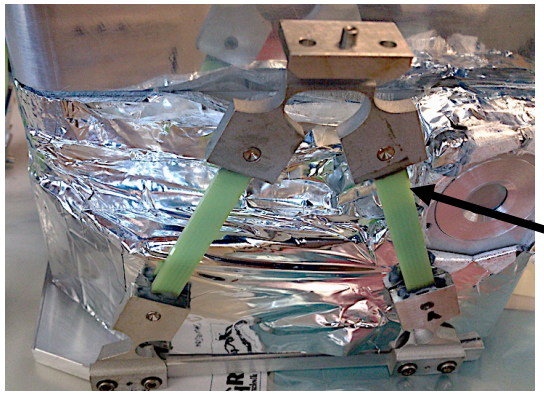
How we deal with infrared instruments?

- Cooling to avoid to thermal radiation
- Stop blocks radiation from telescope



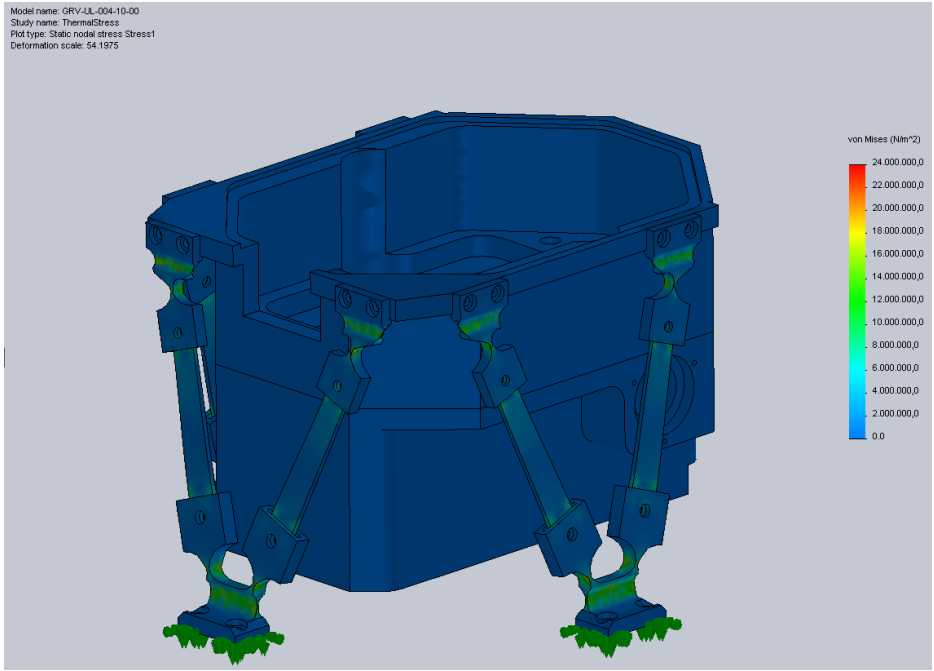
- Cooling to Liquid Nitrogen
- Minimizing thermal conductivity
- Maximizing Mechanical Stability
- Allow for thermal dilatation



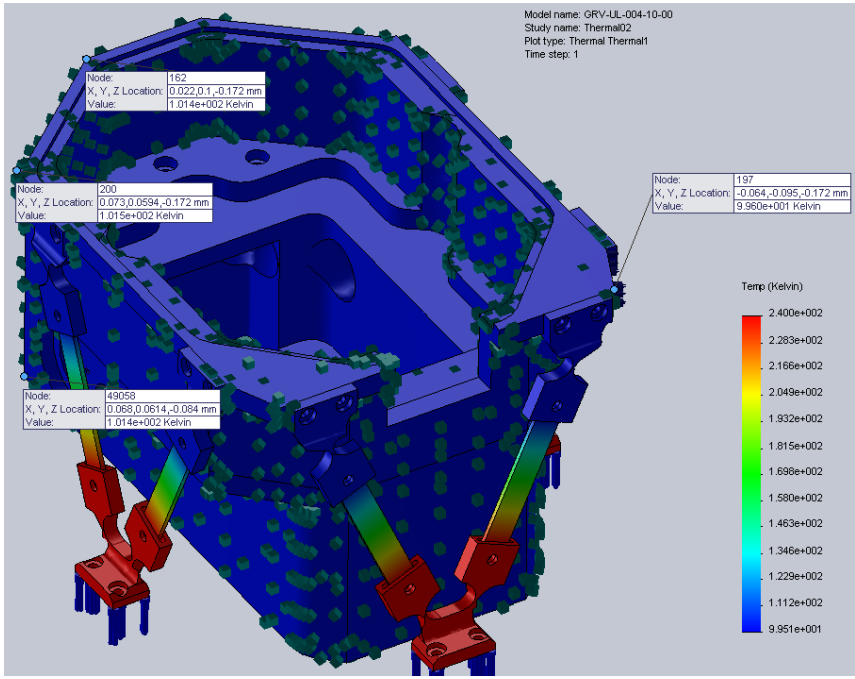


How we deal with thermal/mechanics?

- Lots of design and simulation
- Some testing



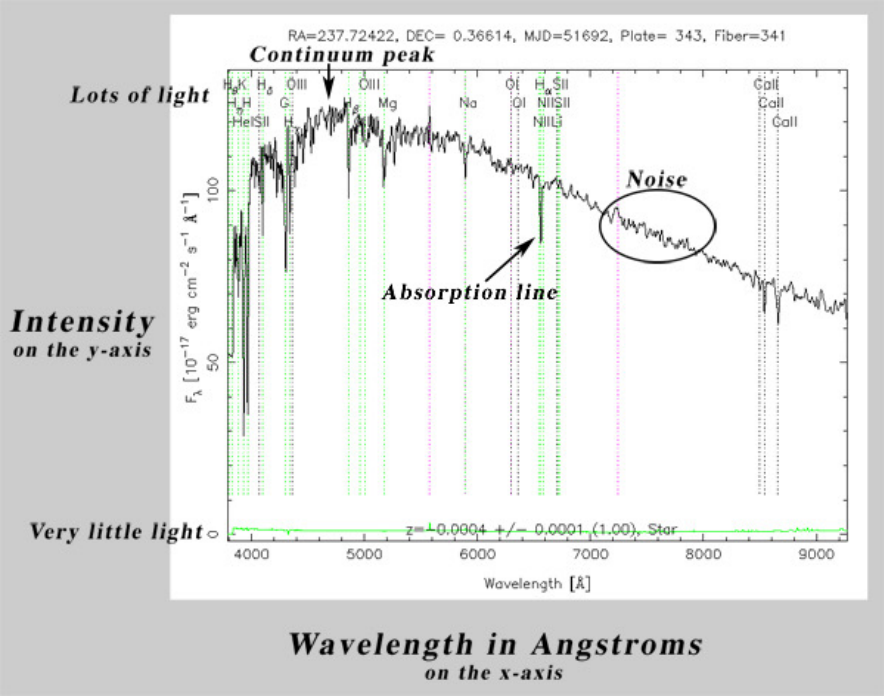
Induced Stress

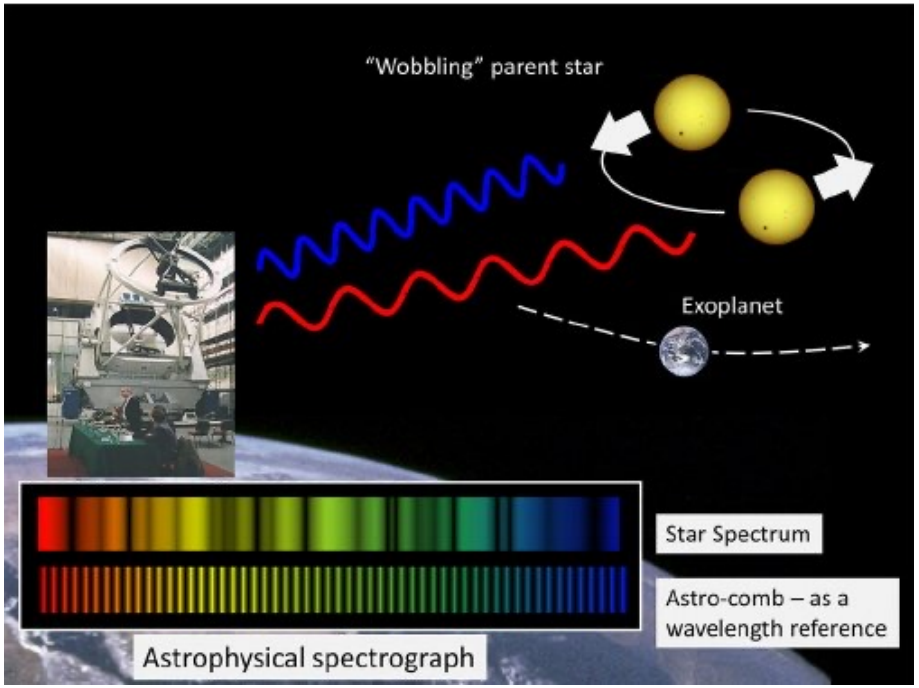


Thermal

Why the need for spectrometers?

- Composition of object - emission and absorption
- Doppler shift to measure V(radial)
- …





Why Gamma-ray?

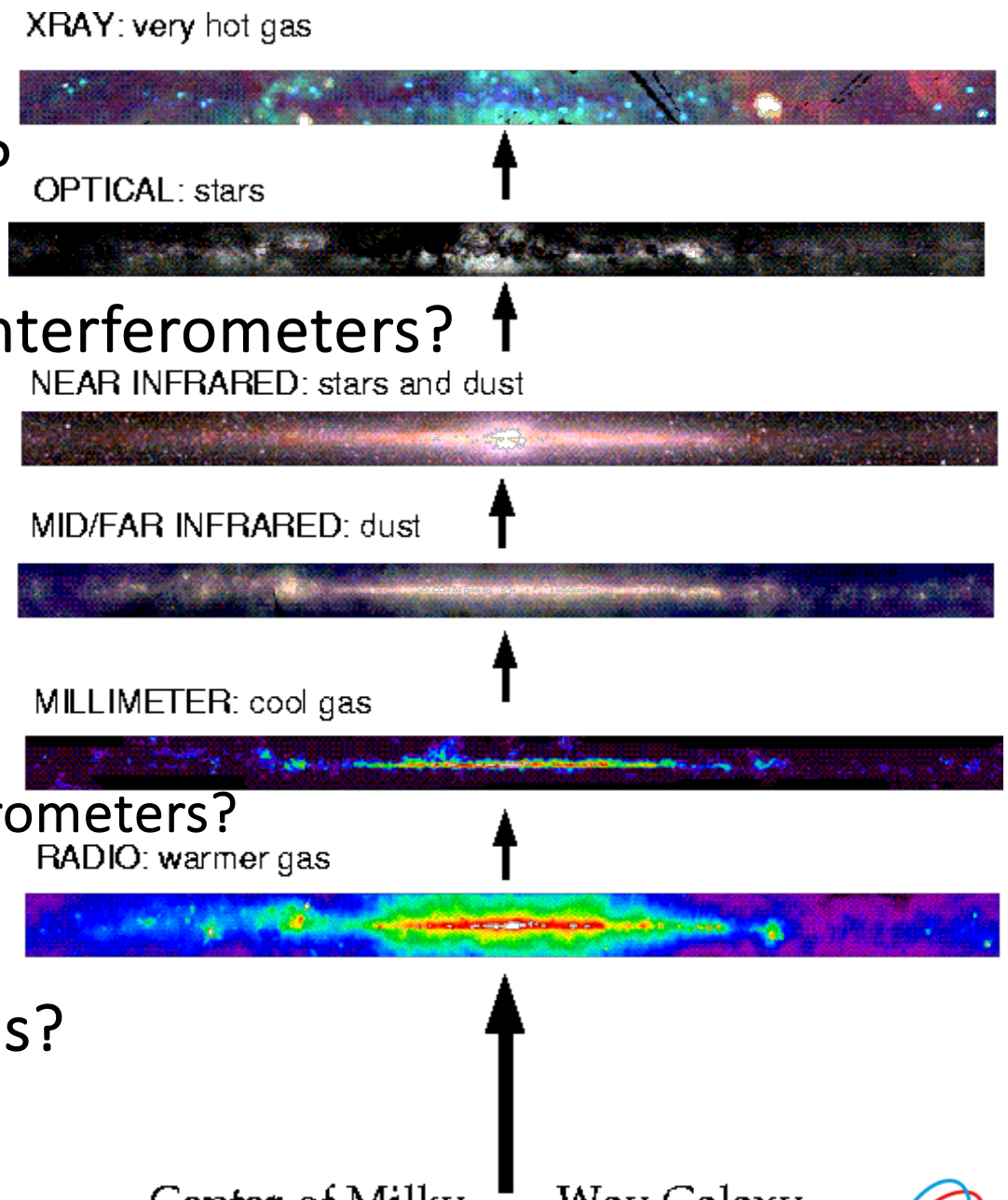
Why X-ray satellites?

Why/how Infrared interferometers?

Why/how Radio interferometers?

Why survey satellites?

...?

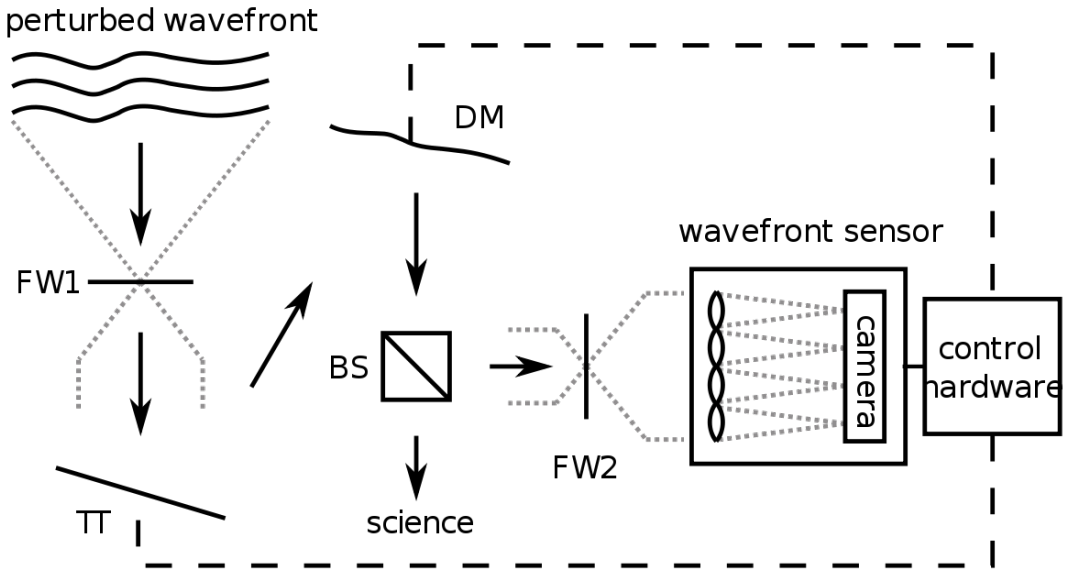


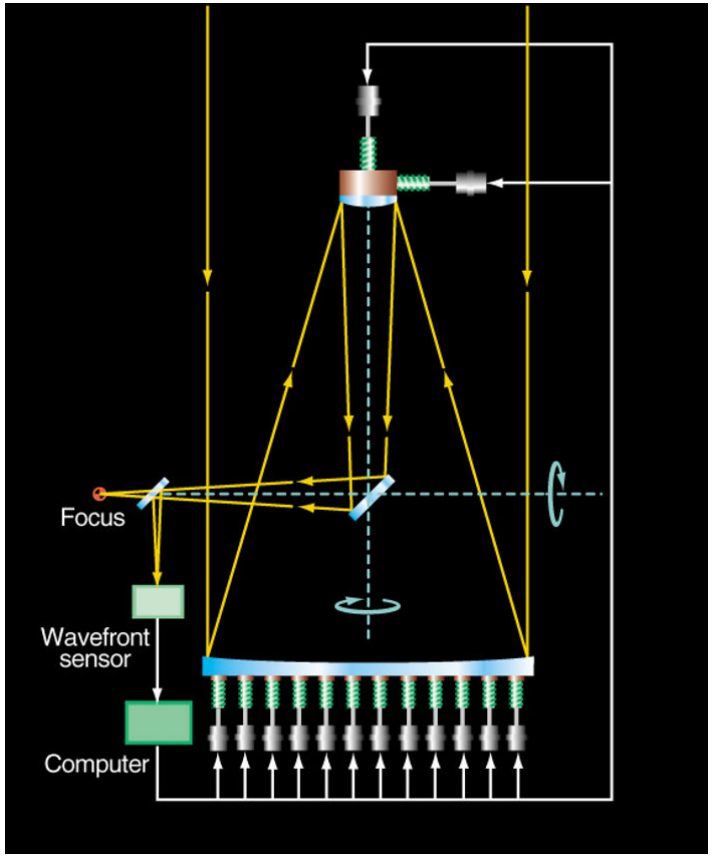
Why fix atmosphere/telescope vibrations?

ACTIVE tel. slow deformations ~ minute

Atmosphere = lens of ~

ADAPTIVE fast ~100 Hz





ADAPTIVE: fix dependent on angle -> Multiconjugate

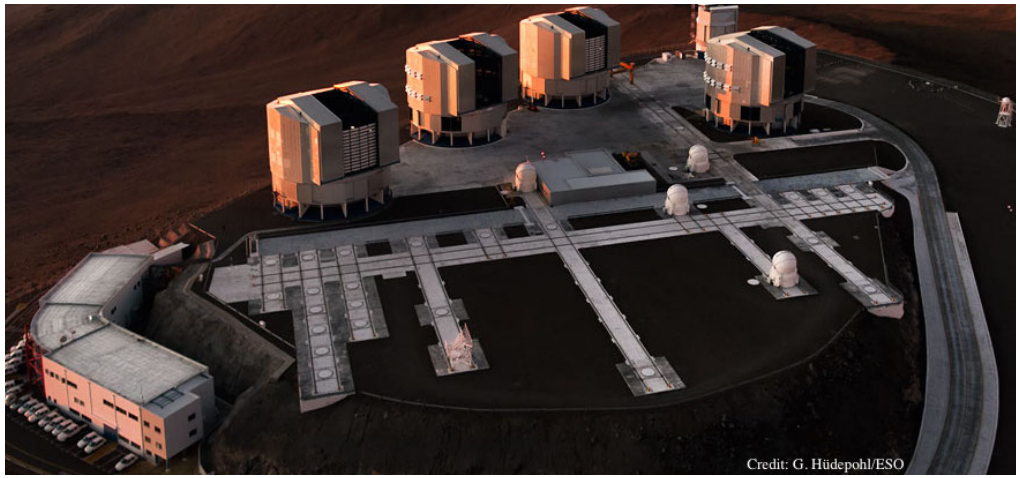
The ESO multiconjugate adaptive optics demonstrator: using CAMCAO

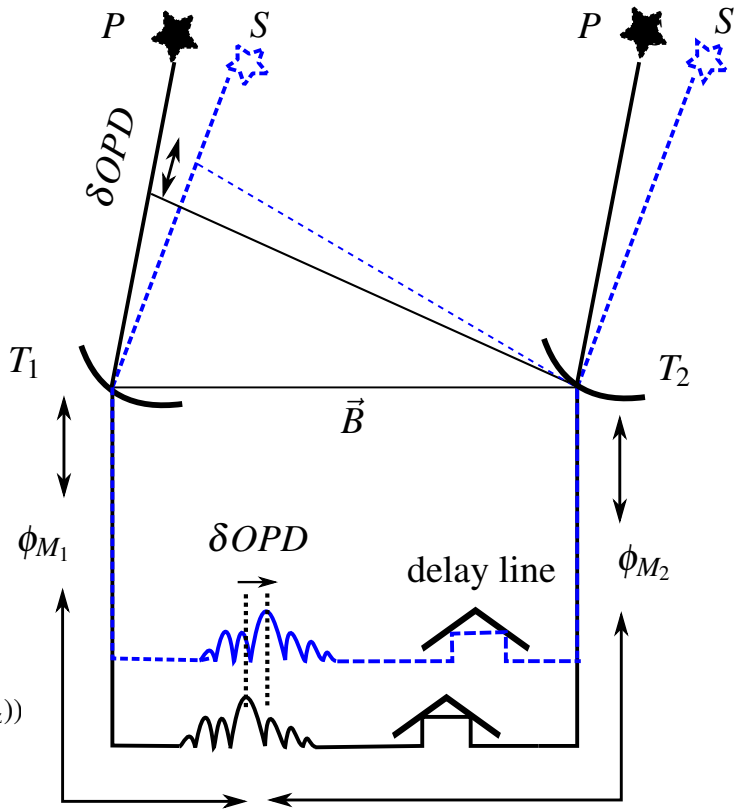
Why interferometry? (Fix vibrations!)

Phase difference measurement

~ equivalent ~

Telescope of Diameter = Baseline (B)





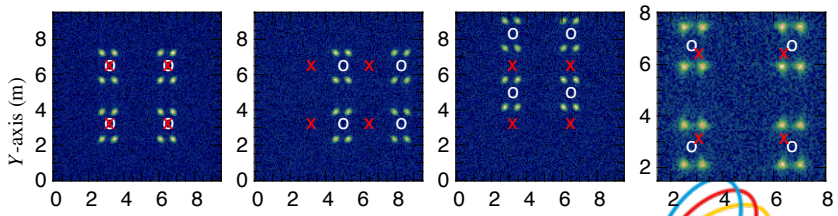
associated with the field ($\Delta\alpha$), the lateral pupil (ΔL_x) and longitudinal pupil (pupil defocus, (ΔL_z))

$$\sigma = \frac{\Delta\alpha \Delta L_x + [1 - \cos(\Delta\alpha)] L_z}{B}.$$

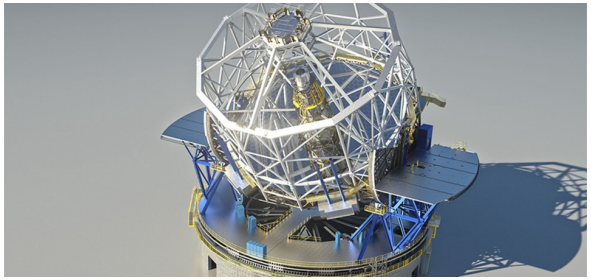
telescopes vibrate

=>

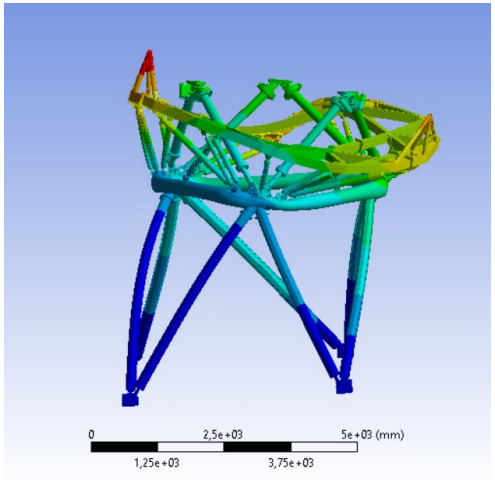
GRAVITY acquisition camera

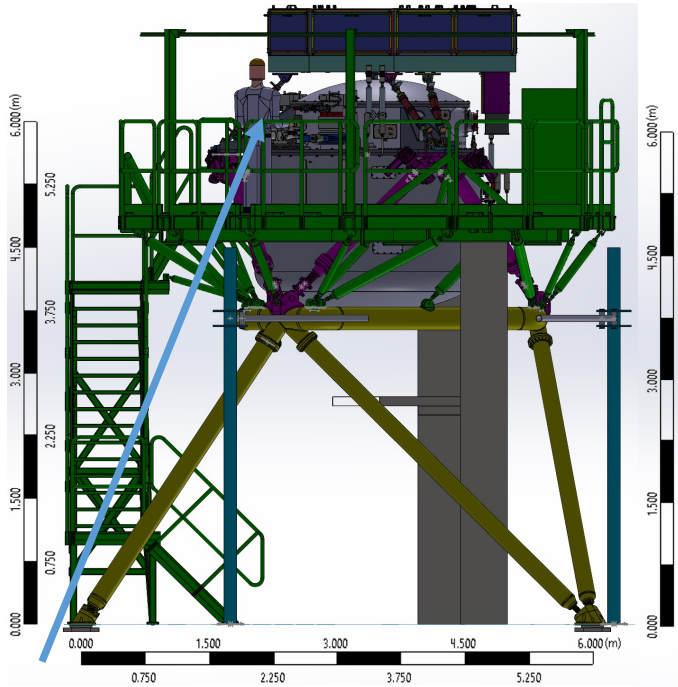


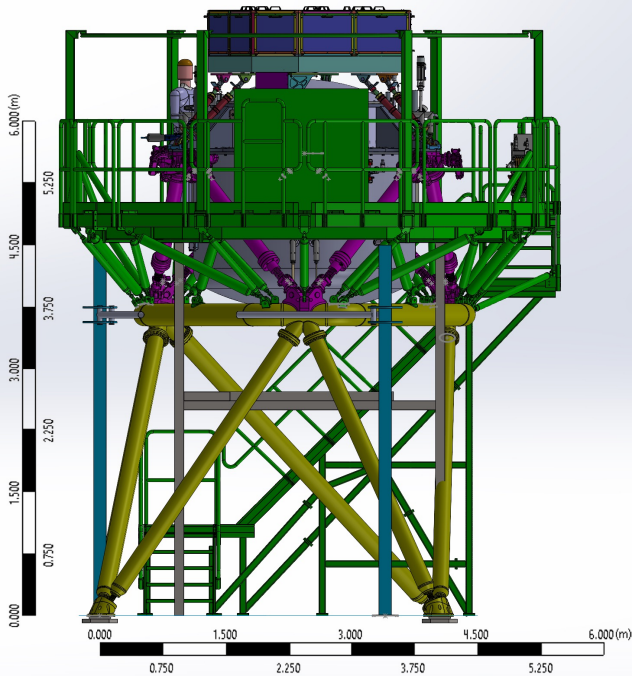
Why deal with structure vibrations E.quakes?



ESO- ELT
Infrared -> METIS
METIS support structure

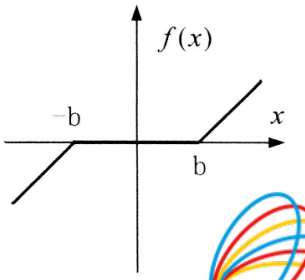






$$f(x(t)) = \begin{cases} x(t)-1 & x(t)>1 \\ 0 & -1<x(t)<1 \\ x(t)+1 & x(t)<-1 \end{cases}$$

Natural vibration at 11Hz
but
Avoid non-linear oscillator: backlash



METIS – <u>WSS support structure</u>

Why we need ESO?

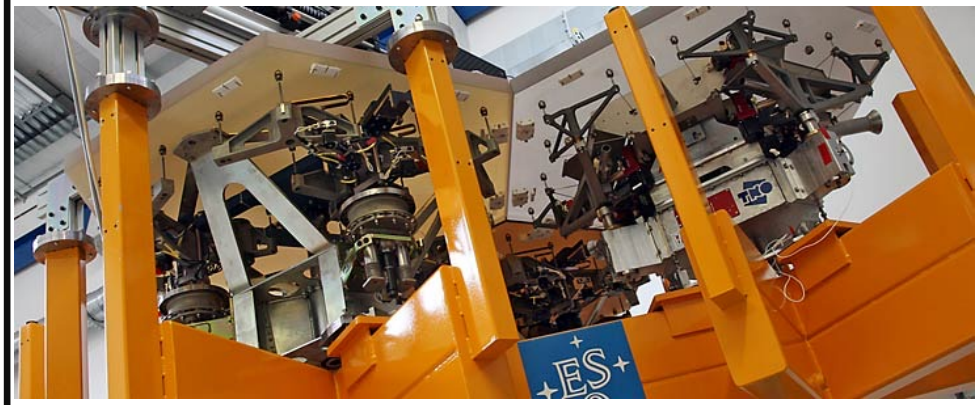
Meaning

Europe belonging/political fascination
Our team ...

Human pleasure in building something

Power

Drive the Mec./Opt/Elec./Comp. Industry?



ESO subcontracts ELT Mirrorr actuators

Many International tax-free jobs

Why the need instrument developers?

Meaning	Power
Something gets built resulting from our work	**We learn reusable technologies**
We belong to a selected group	**We publish and contribute to publishing**
Our Universities like to brag on what we do	**Decent countries allocate large amounts of resources giving a lot of power...**