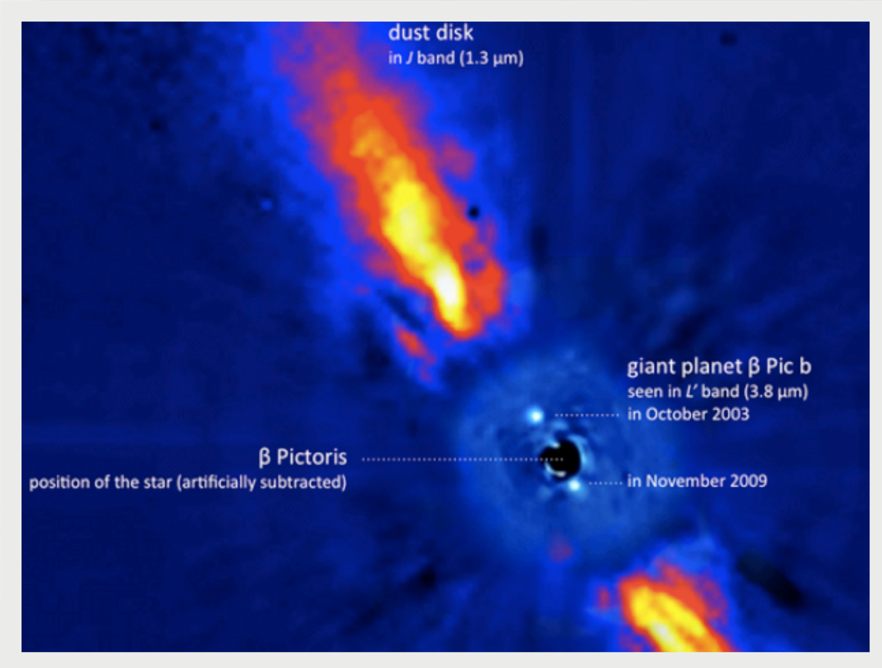
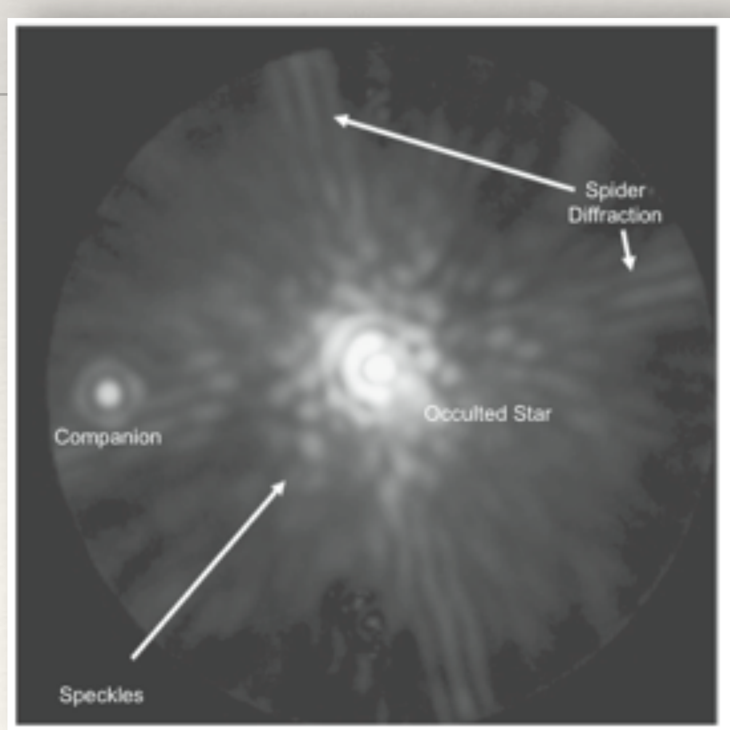



*R. Claudi - INAF - Astronomical Observatory of Padova*

# DIRECT IMAGING OF EXTRASOLAR PLANETS

## III: ADAPTIVE OPTICS




*1st ADVANCED SCHOOL OF EXOPLANETARY SCIENCE*
*METHODS OF DETECTING EXOPLANETS*
*MAY 25-29, 2015 - VIETRI SUL MARE (SA)*

# Adaptive Optics

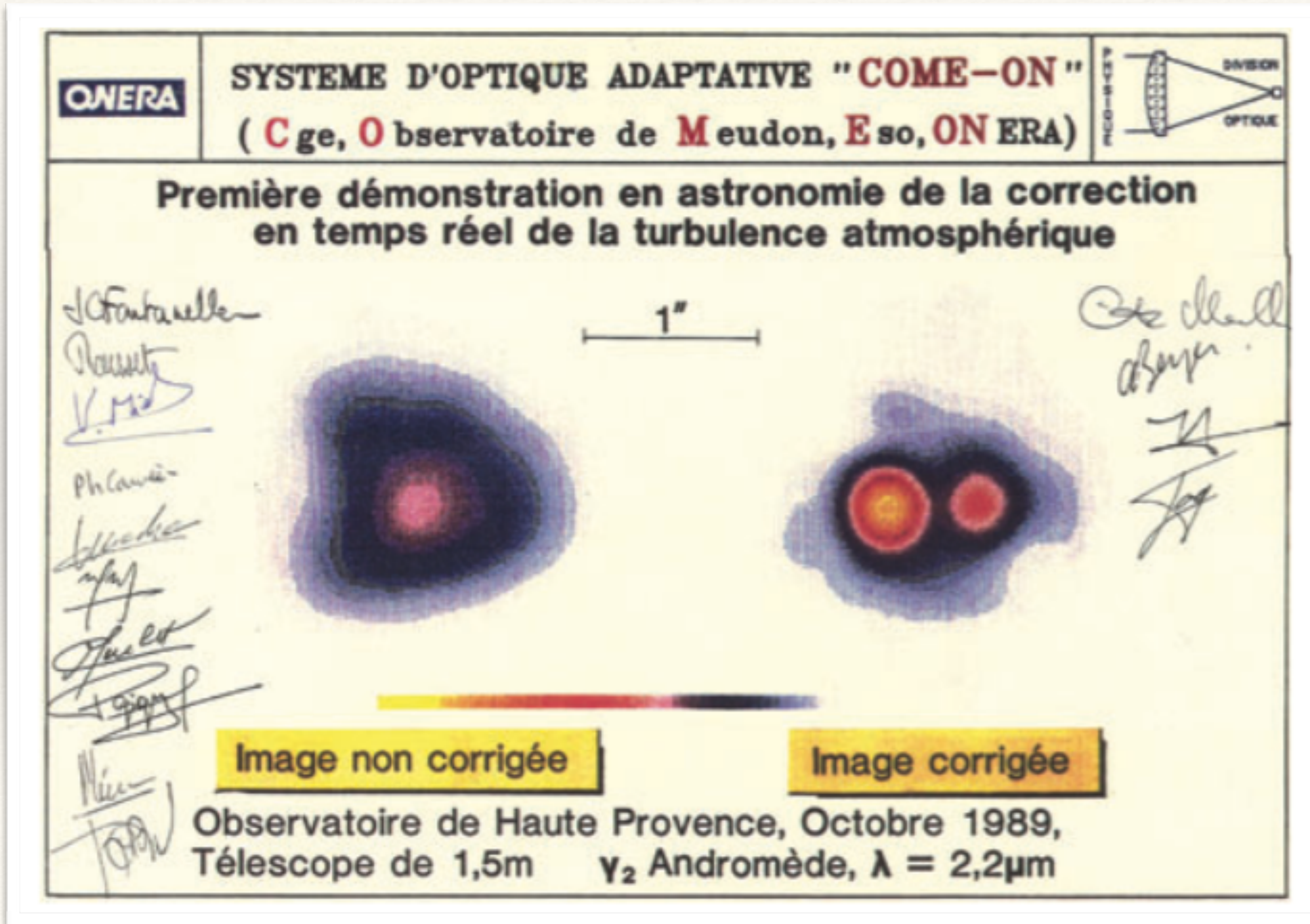
# AO: the very beginning …

Mt. Wilson

*If we had the means of continually measuring the deviation of rays from all parts of the mirror, and of amplifying and feeding back this information so as to correct locally the figure of the mirror in response to the schlieren pattern, we could expect to compensate both for the seeing and for any inherent imperfection of the optical figure*

Babcock 1953, Publ. Astron. Soc. Pac. 65:229

In the late 1980s COME-ON was tested at the 1.52-m telescope (Merkle et al. 1989, 1989. *Messenger* 58:1, Rousset et al. 1990, *Astron. Astrophys.* 230:L29) of the Observatoire de Haute-Provence and later installed at ESO's 3.6-m telescope on La Silla in Chile (Rigaut et al. 1991, *Astron. Astrophys.* 250:280).



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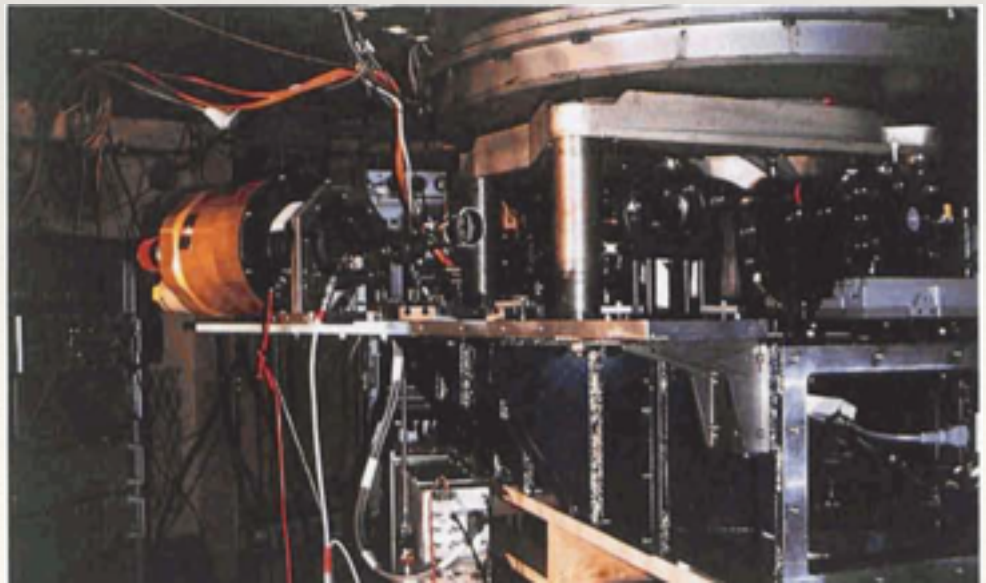
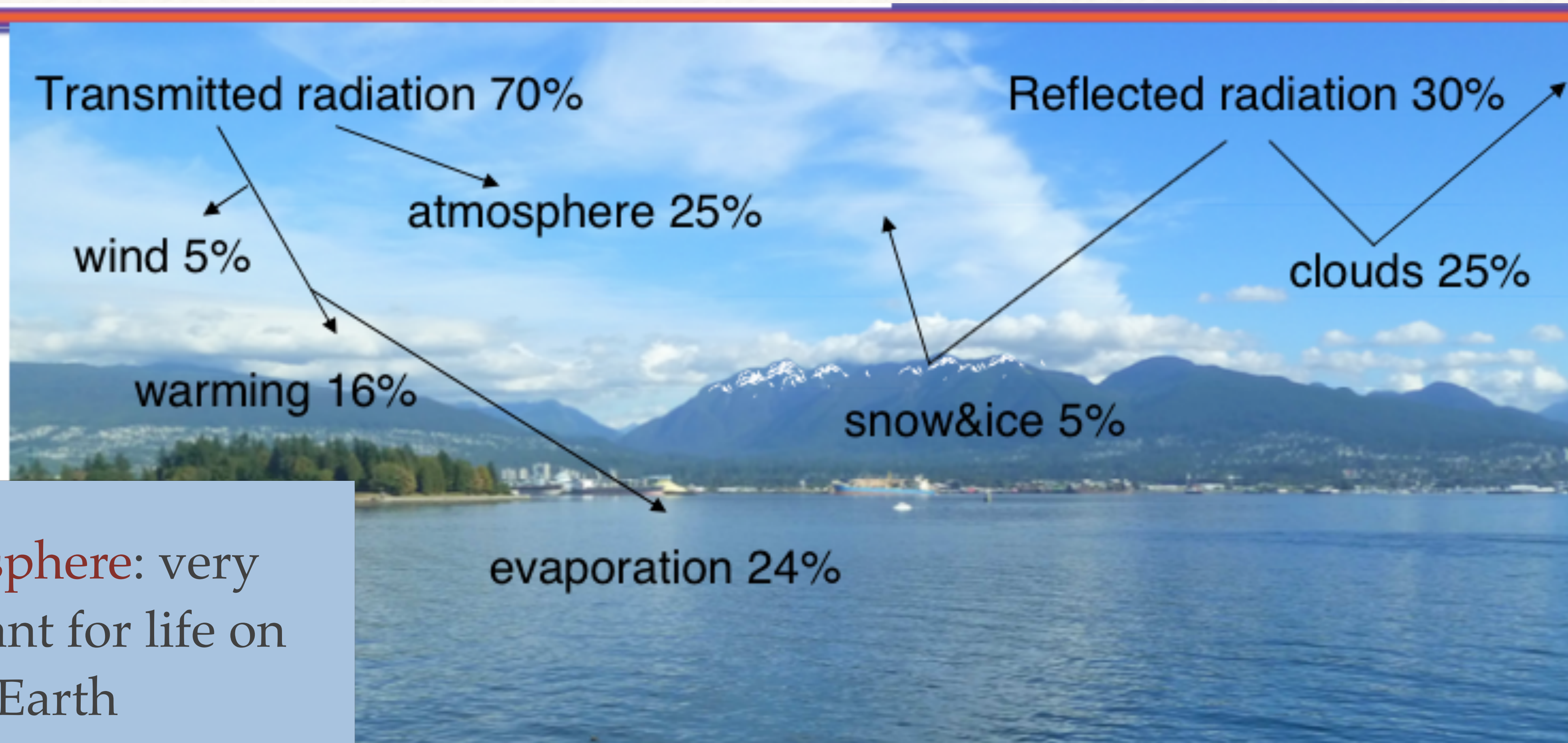


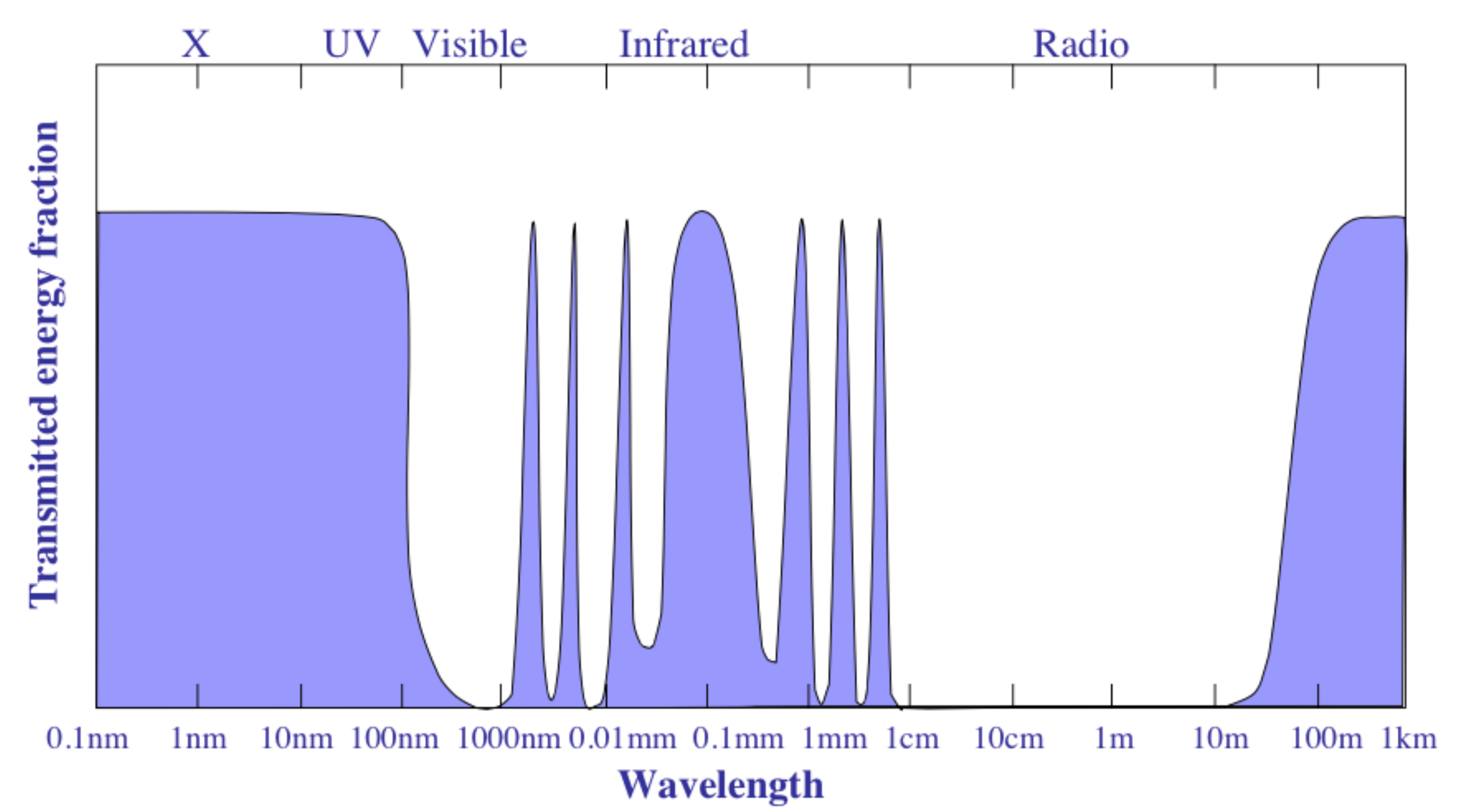
# Earth's Atmosphere



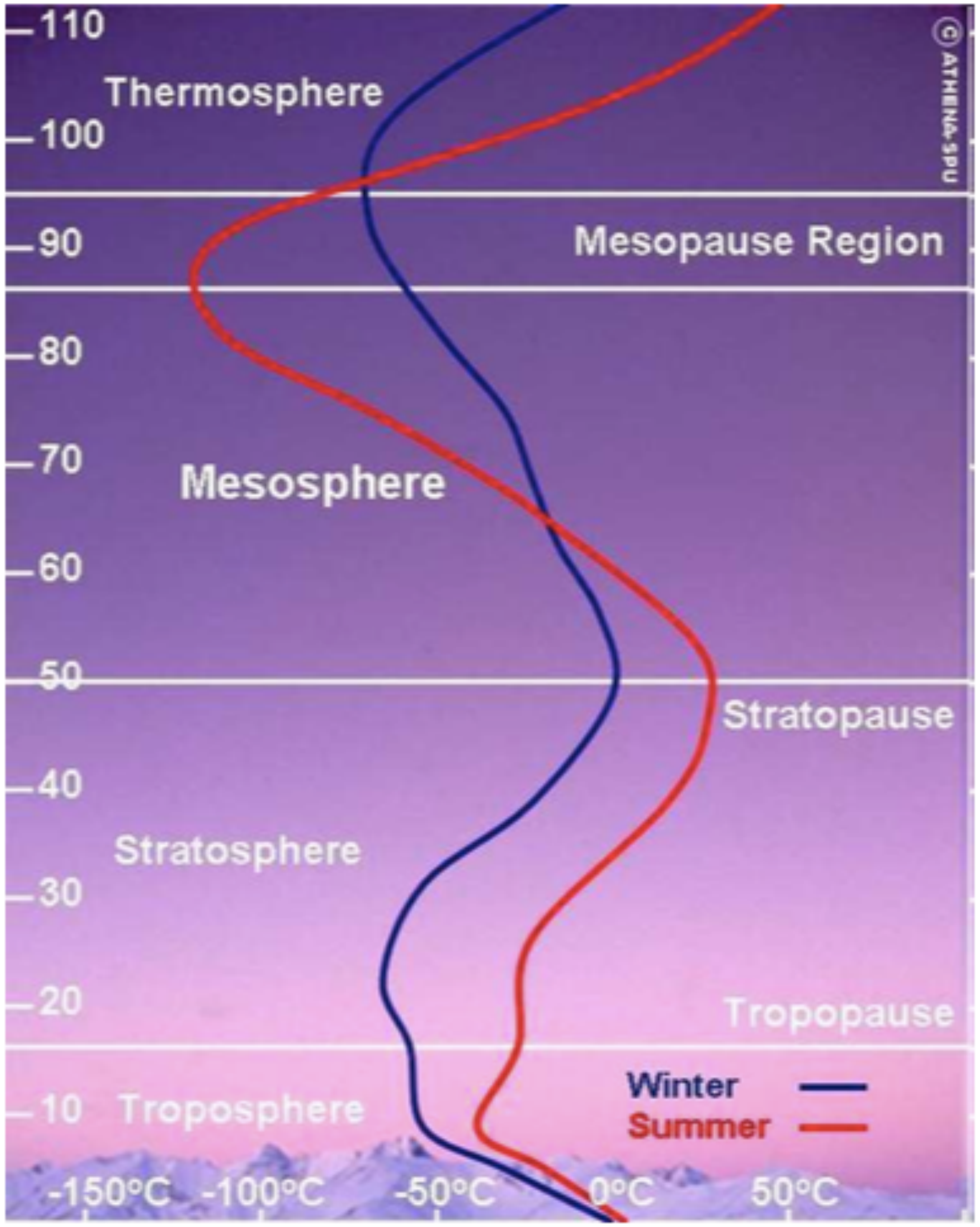

Atmosphere: very important for life on Earth

**Day-time: Sun shield (UV radiation)**
**Night-time: low thermal excursion**
**Absorbes part of the radiation** → **Absorption**, **Scattering**
**Deformation of the light coming from astronomical objects**

# Atmospheric Absorption



# Atmospheric Structure




**Troposphere**

Lower part: ~10 km

Contains about 80% of the total atmospheric mass

**Tropopause**

Thermal inversion zone

Height ~10 km (16 km @ equator and 9 km @ poles)

**Stratosphere**

~10 to 50 km height

$O_3$ molecules ⟶ The temperature increases

**Mesosphere**

Extends up to about 90 km

Negative thermal gradient

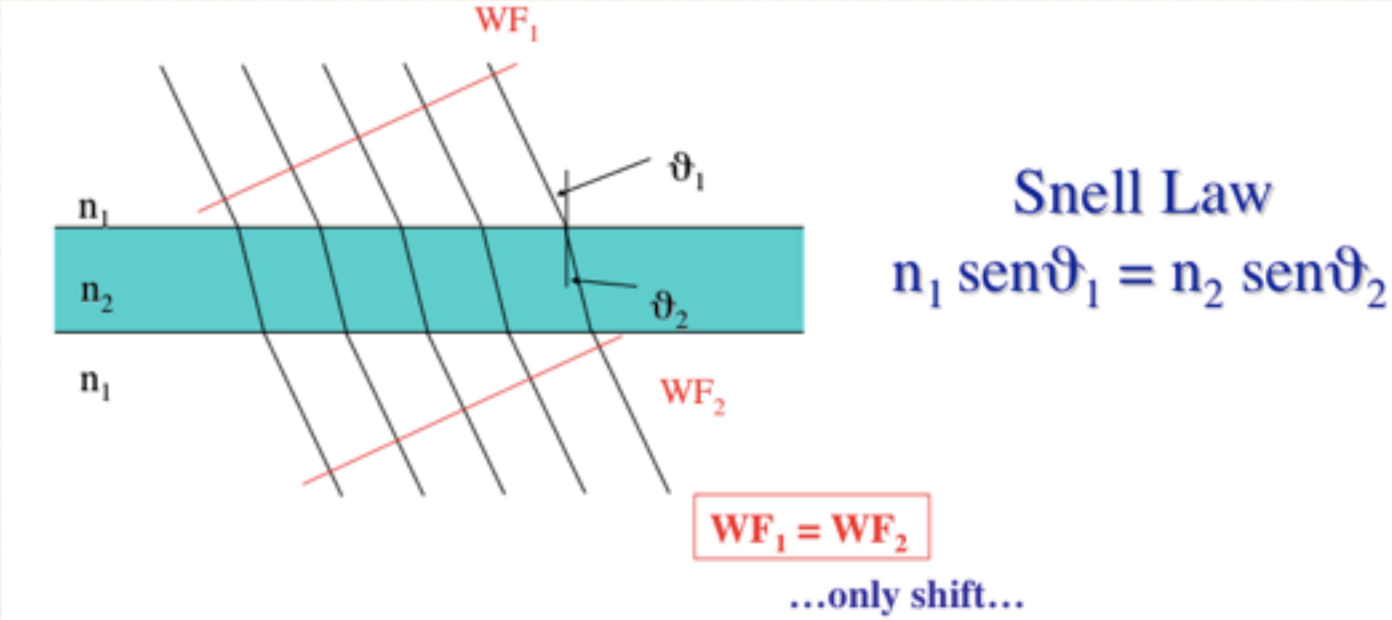
**Mesopause**

Coldest layer of the atmosphere (no solar heating, $CO_2$ radiative cooling)

Sodium Layer

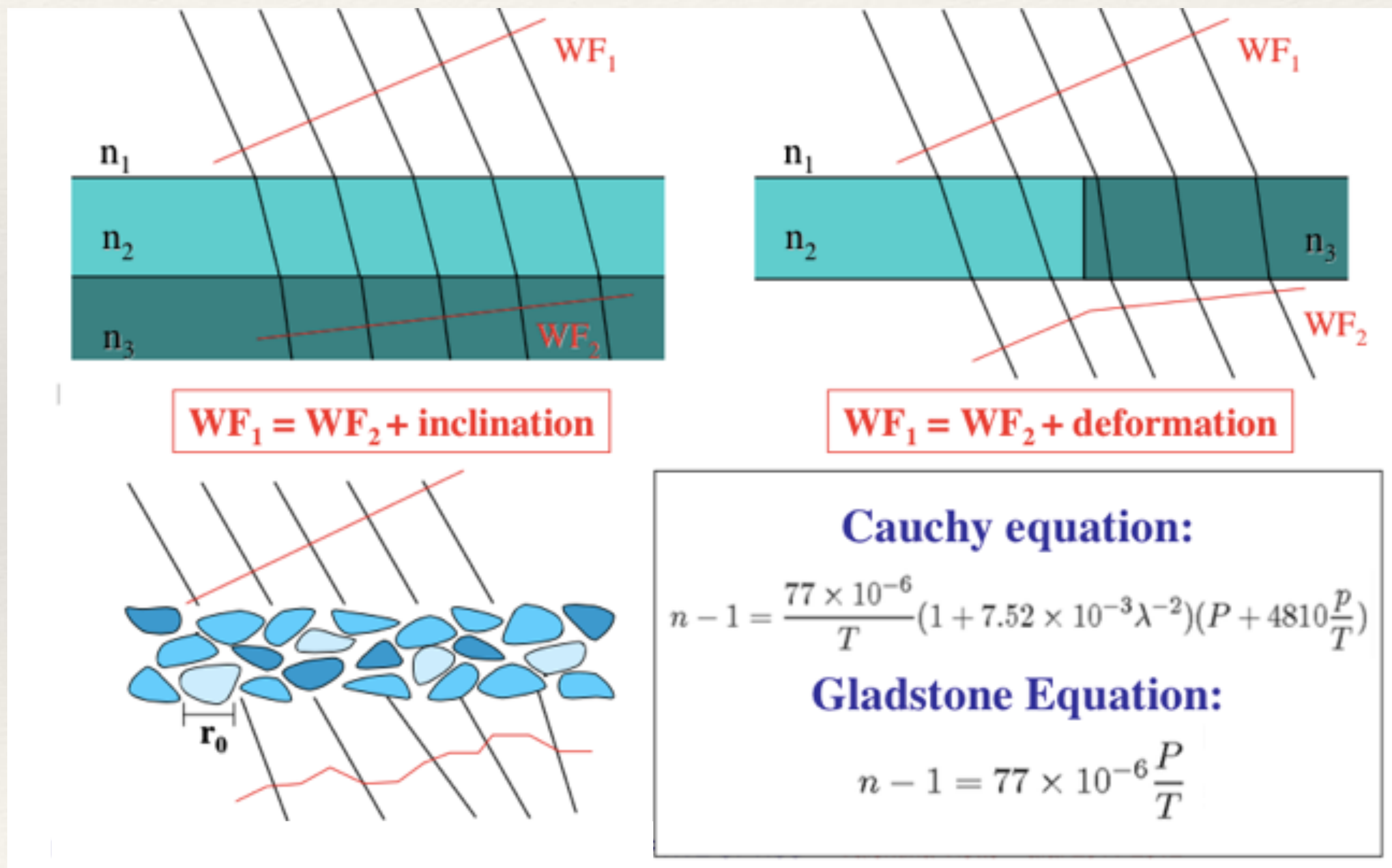
**Thermosphere**

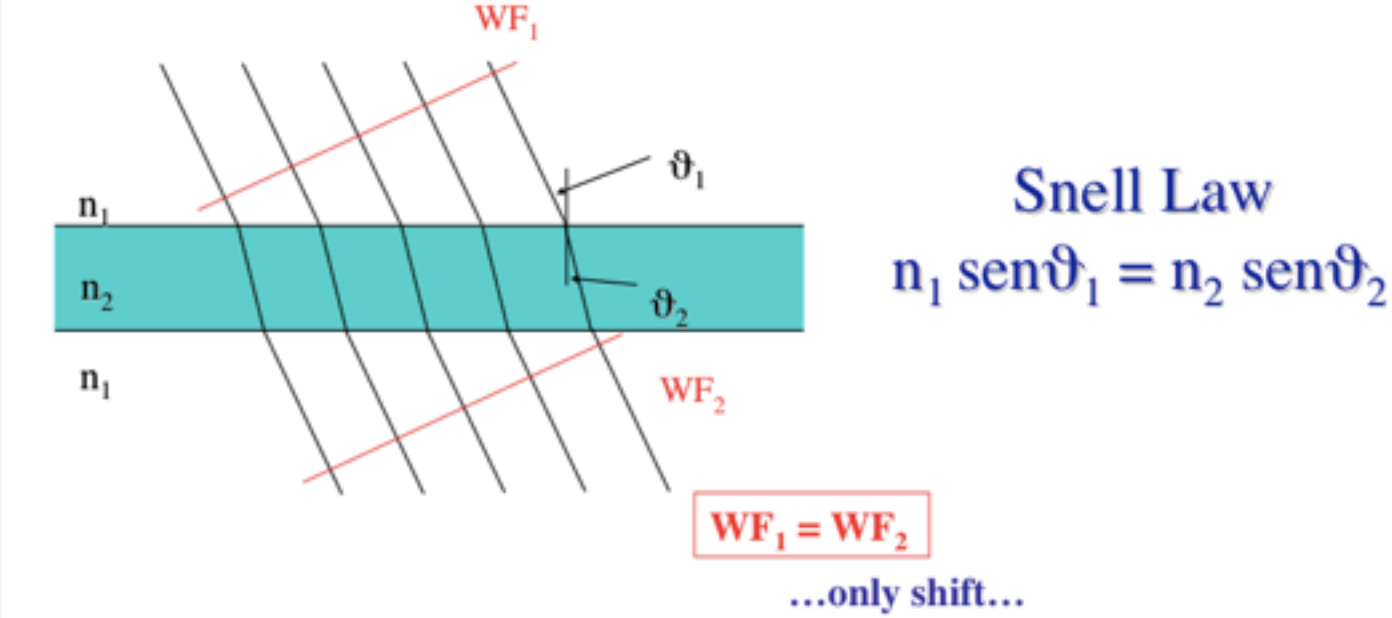
…rarified air




## Ideal Atmosphere!

## Real Atmosphere!

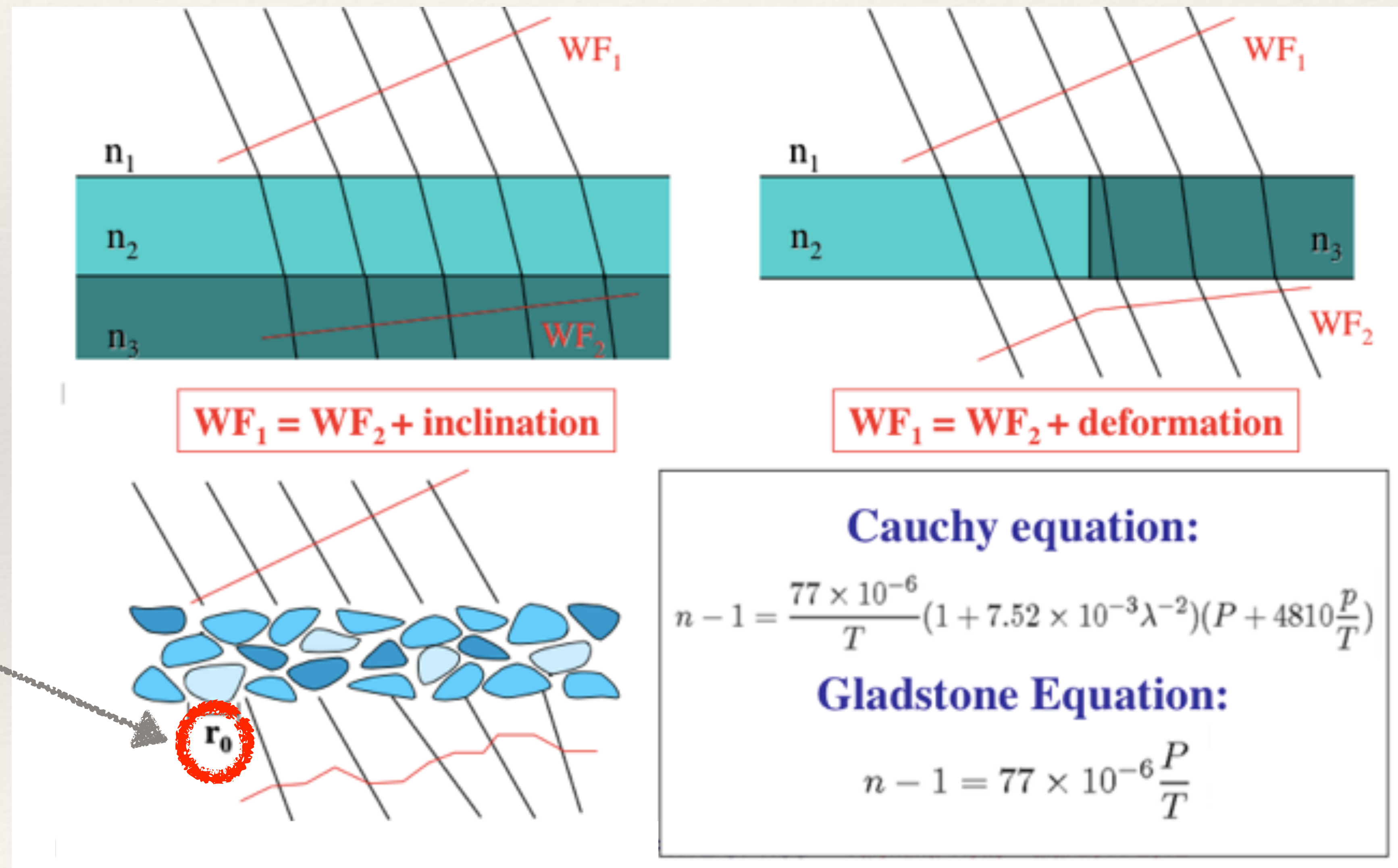




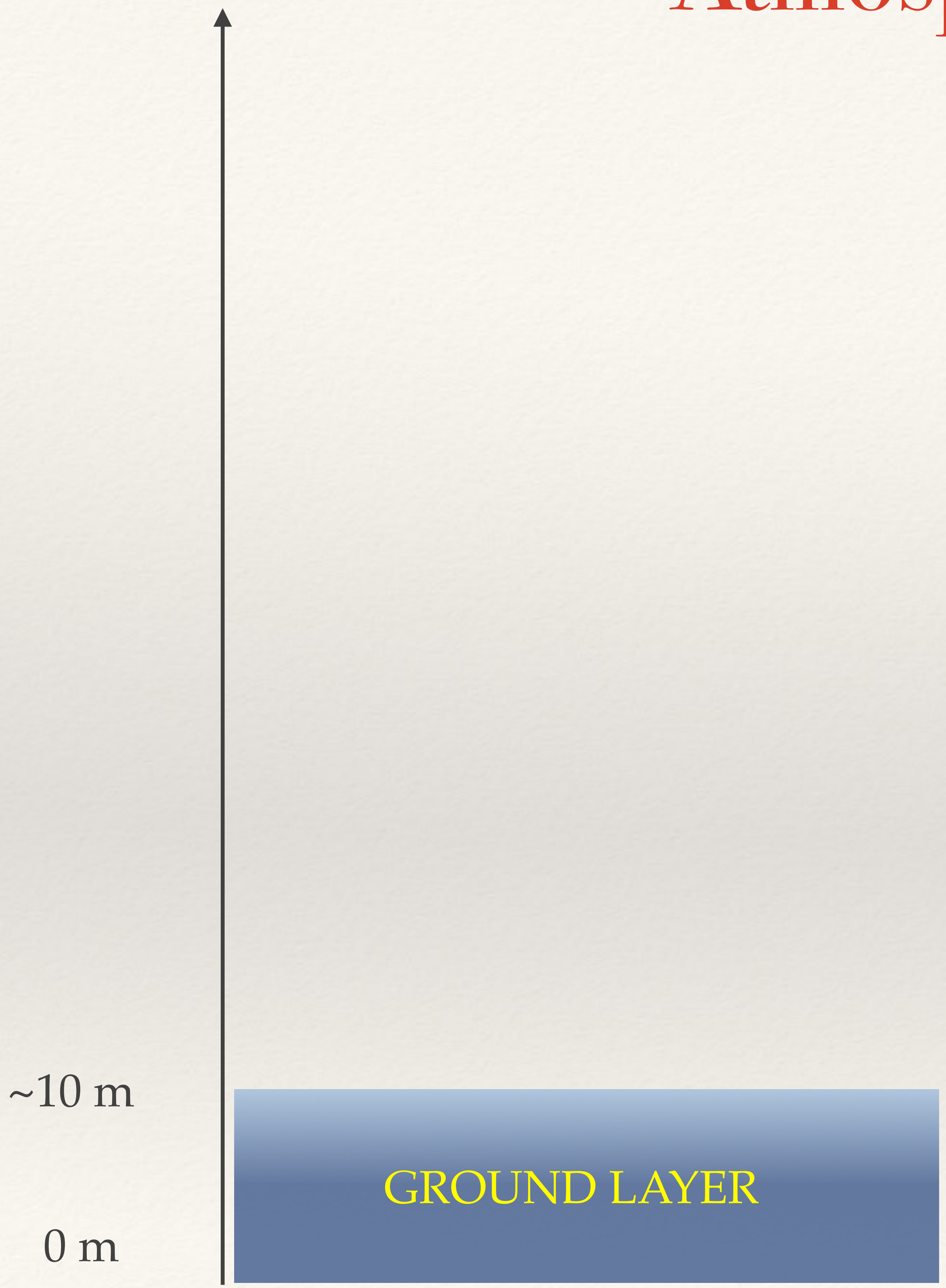

# Ideal Atmosphere!

# Real Atmosphere!

# Fried Parameter

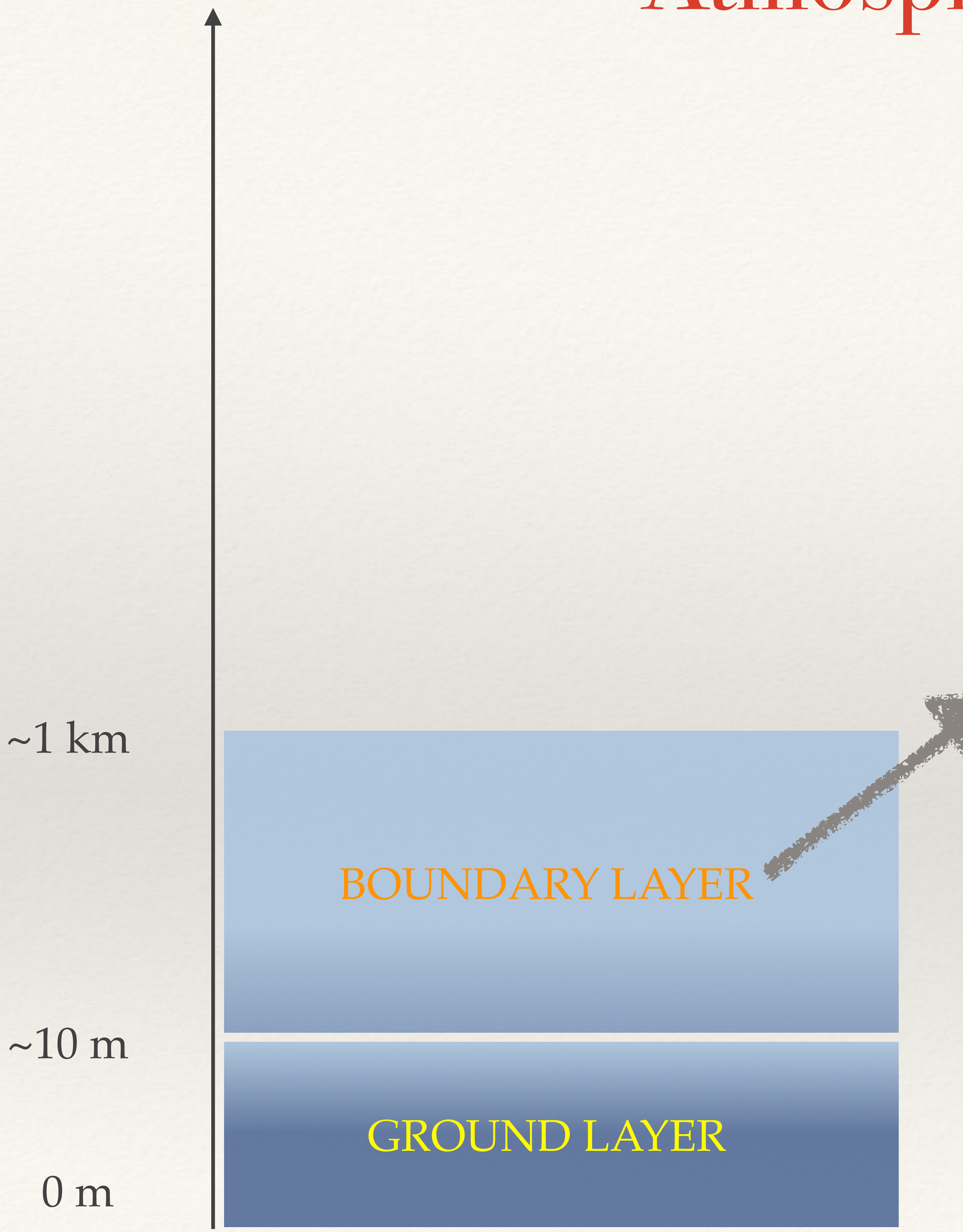


# Atmospheric Layers




Thermal exchange between the ground surface and the air (humidity and air streams => turbulent layer)

# Atmospheric Layers

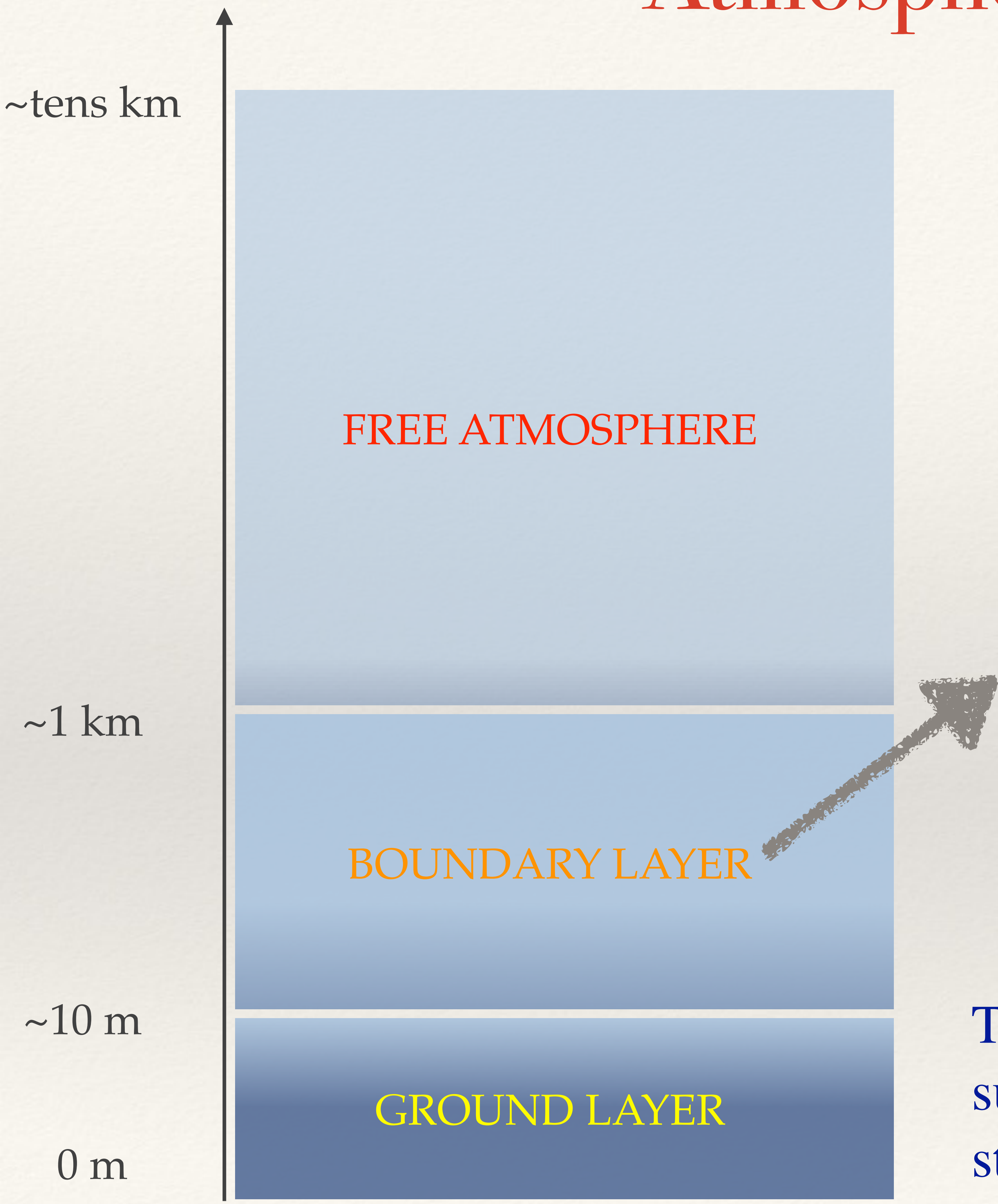



-Ascending streams due to difference of T which move turbulent air bubbles

-Sites with thermal background constant (oceans, deserts)

Thermal exchange between the ground surface and the air (humidity and air streams => turbulent layer)

# Atmospheric Layers

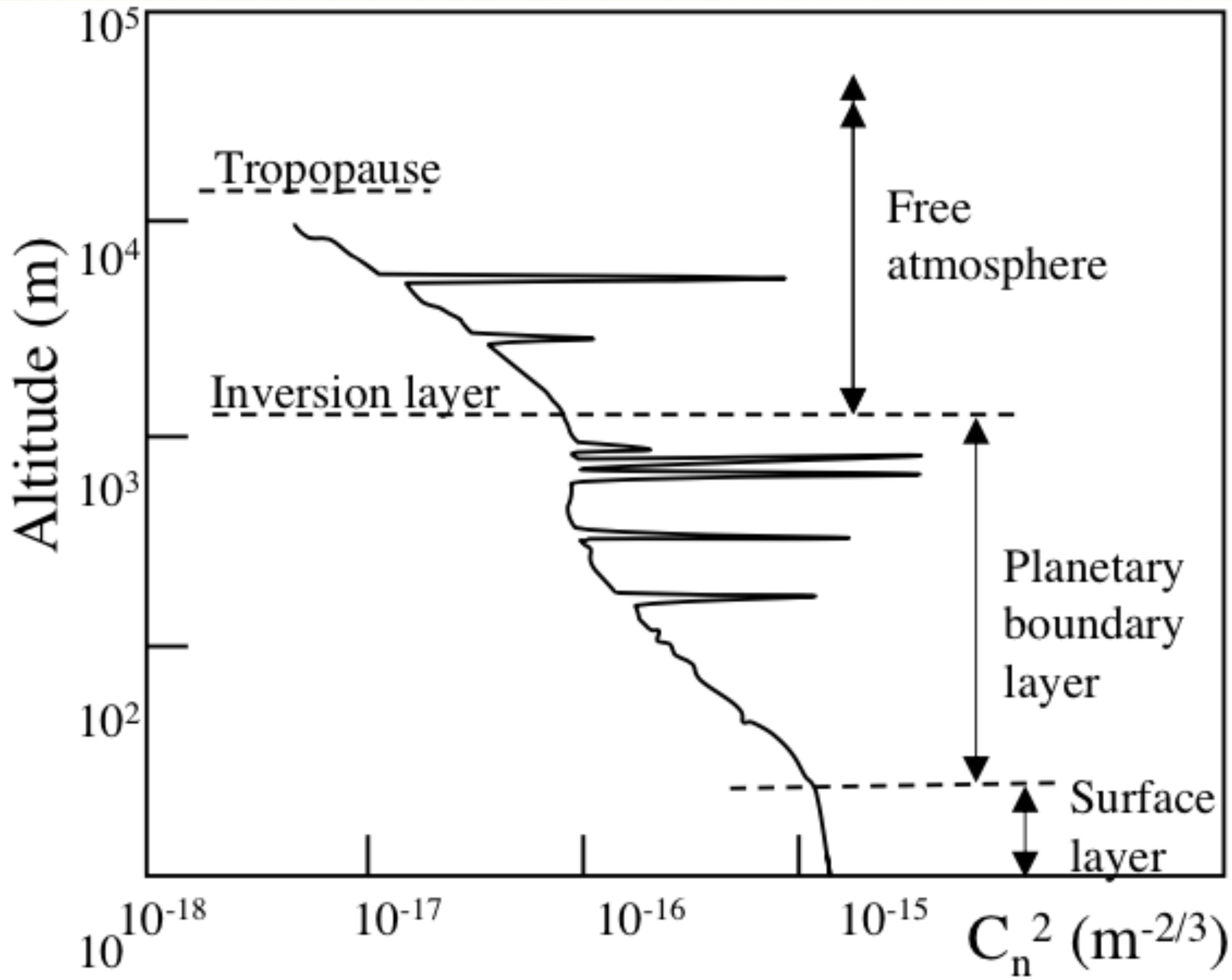



Turbulent motion of air bubbles (T, n, wind)

-Ascending streams due to difference of T which move turbulent air bubbles
-Sites with thermal background constant (oceans, deserts)

Thermal exchange between the ground surface and the air (humidity and air streams => turbulent layer)

# Atmospheric Layers

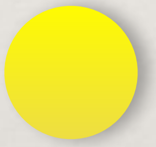



**Several models describing the most important observing sites**

$C_n^2(h)$: structural function of the refractive index n

Thus, the definition of the average $r_0$ is more complicated…

# Wavefront Deformation



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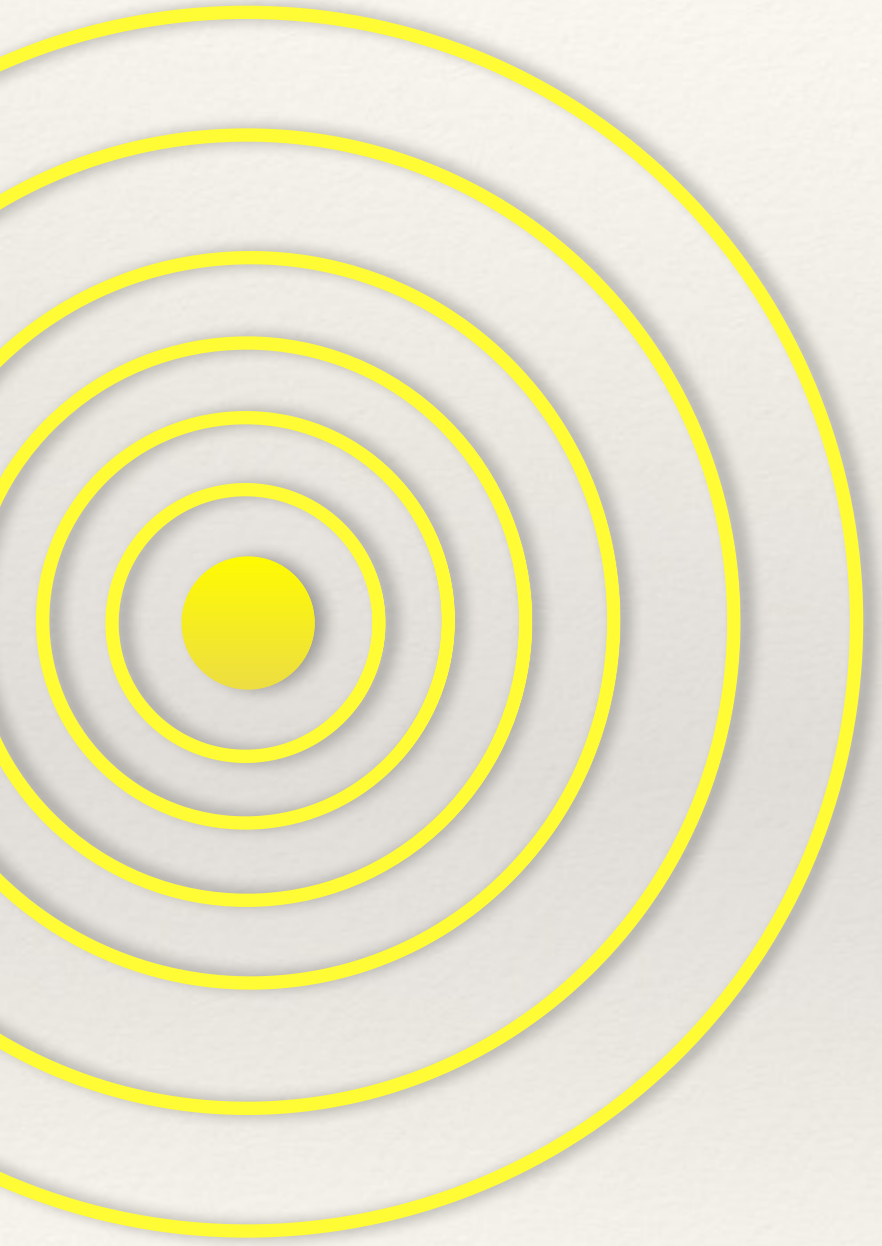

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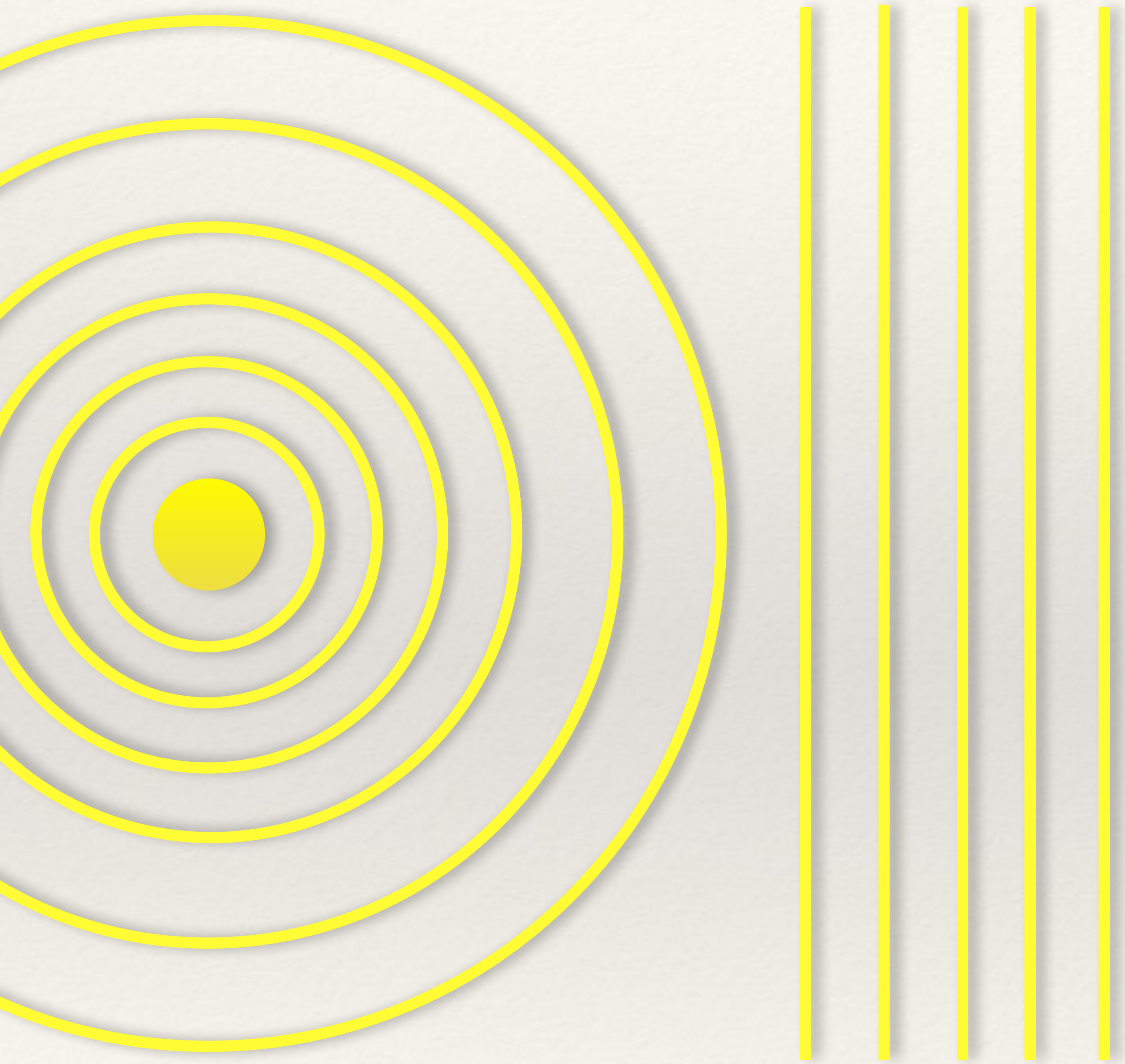

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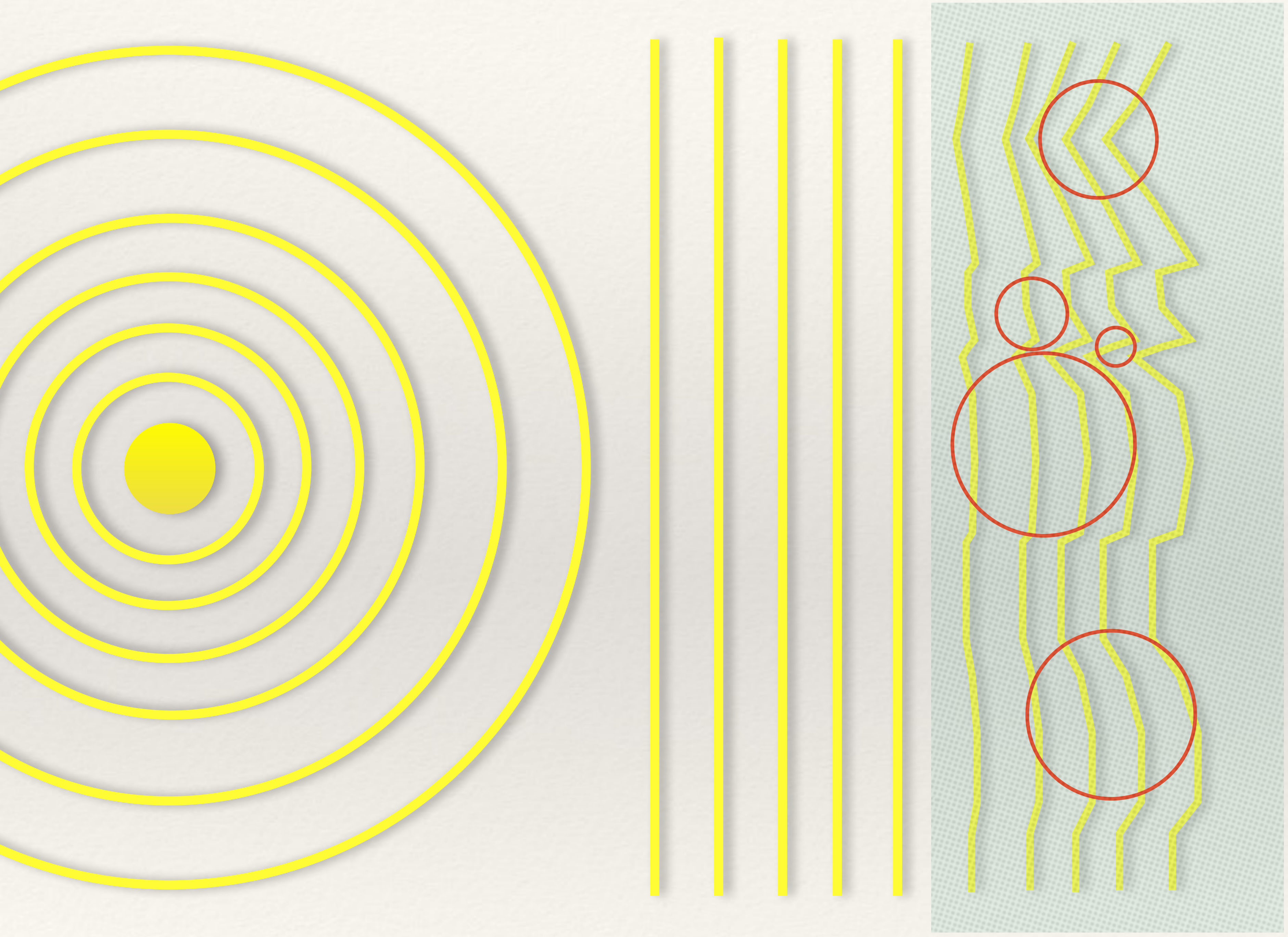

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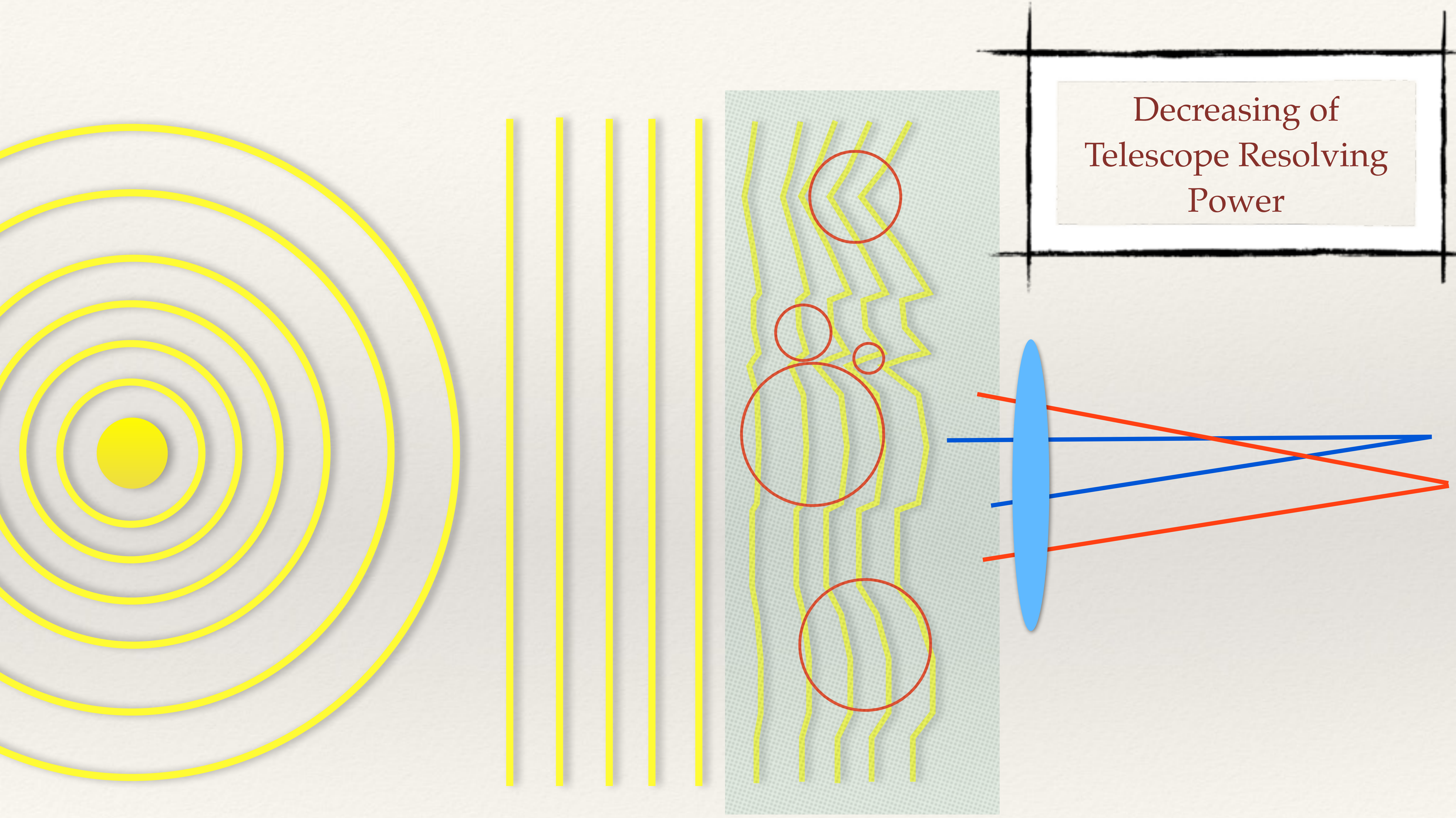
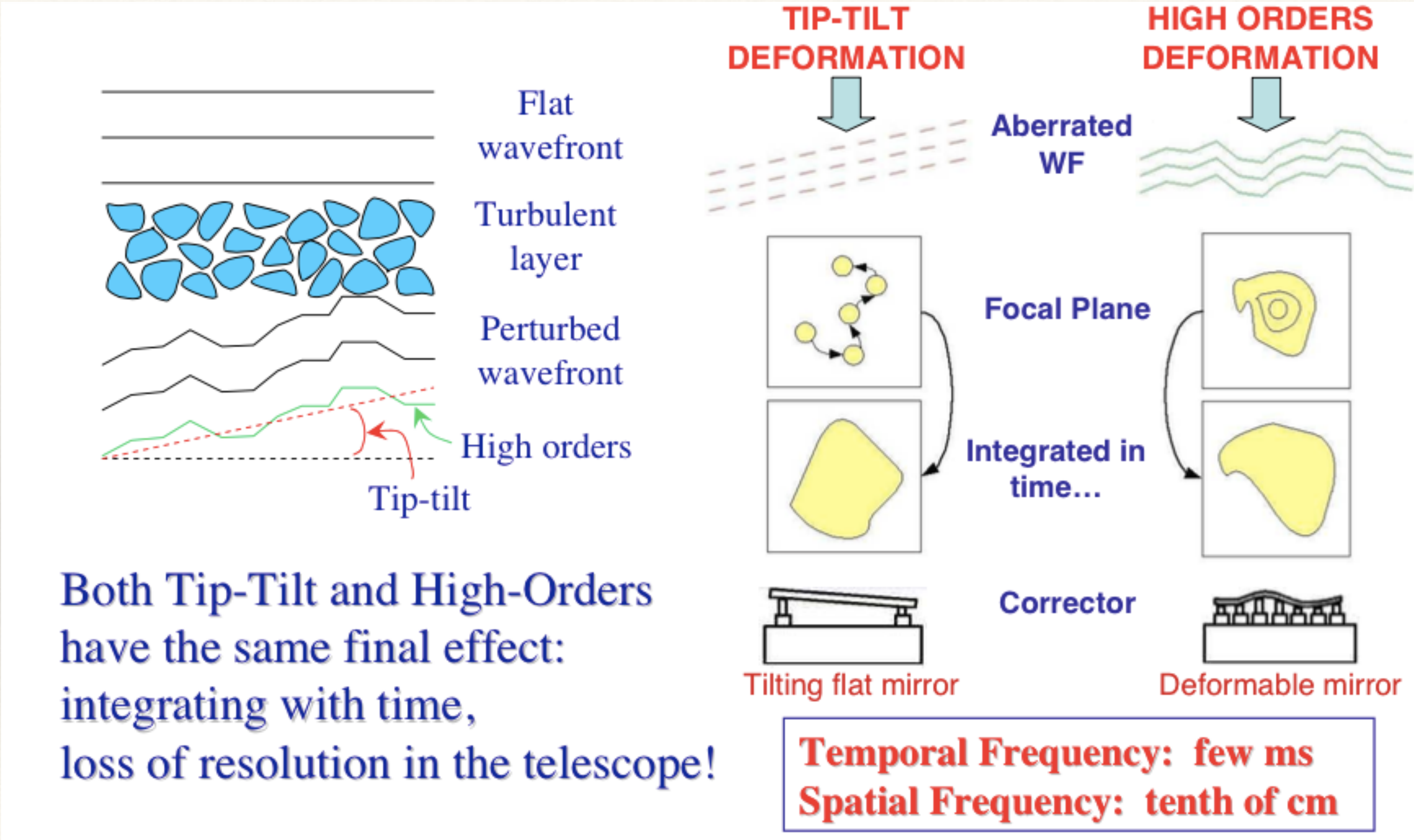


# …what happen on the focal plane of the telescope?



# Atmospheric Parameters

**FRIED parameter:**

-Spatial scale inside which the WF statistically varies less than 1 rad

-Average size of turbulent cell

-Size of an air bubble with constant **n**

$$r_0 \propto \lambda^{6/5}\left[\int_0^\infty dh C_n^2(h)\right]^{-3/5}$$

Good sites:
K band => $r_0$=30cm

**ISOPLANATIC angle:**

-Angular scale inside which the WF statistically varies less than 1 rad

$$\theta_0 \propto r_0 / \bar{h} \propto \lambda^{6/5}$$

**COHERENCE time:**

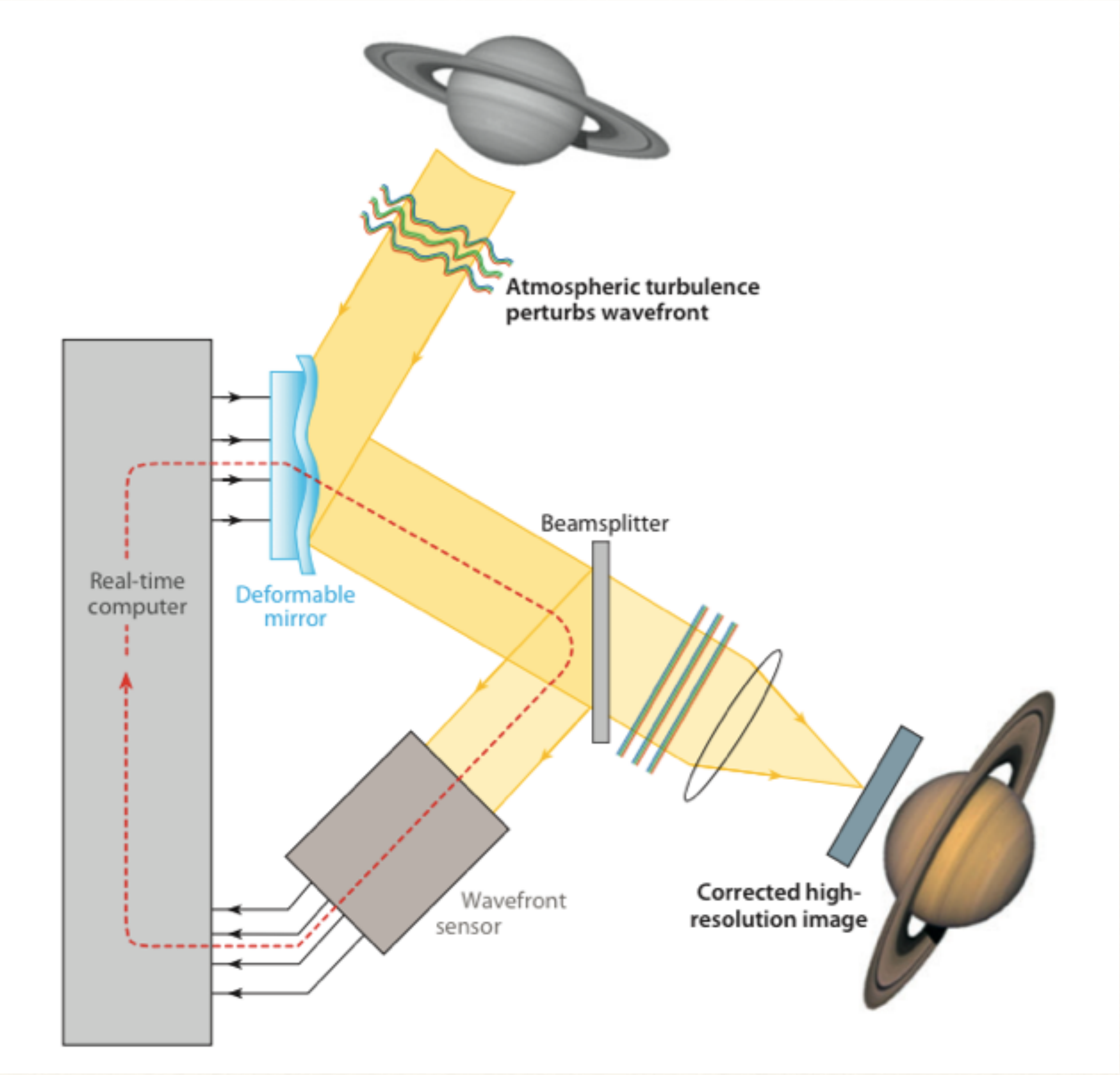
-Time scale inside which the WF statistically varies less than 1 rad

$$\tau_0 = r_0 / v \propto \lambda^{6/5}$$

$$\tau_0 \approx 1ms$$

**Strehl Ratio:** $PSF_{obs}/PSF_{teo}$

# AO Working Principles



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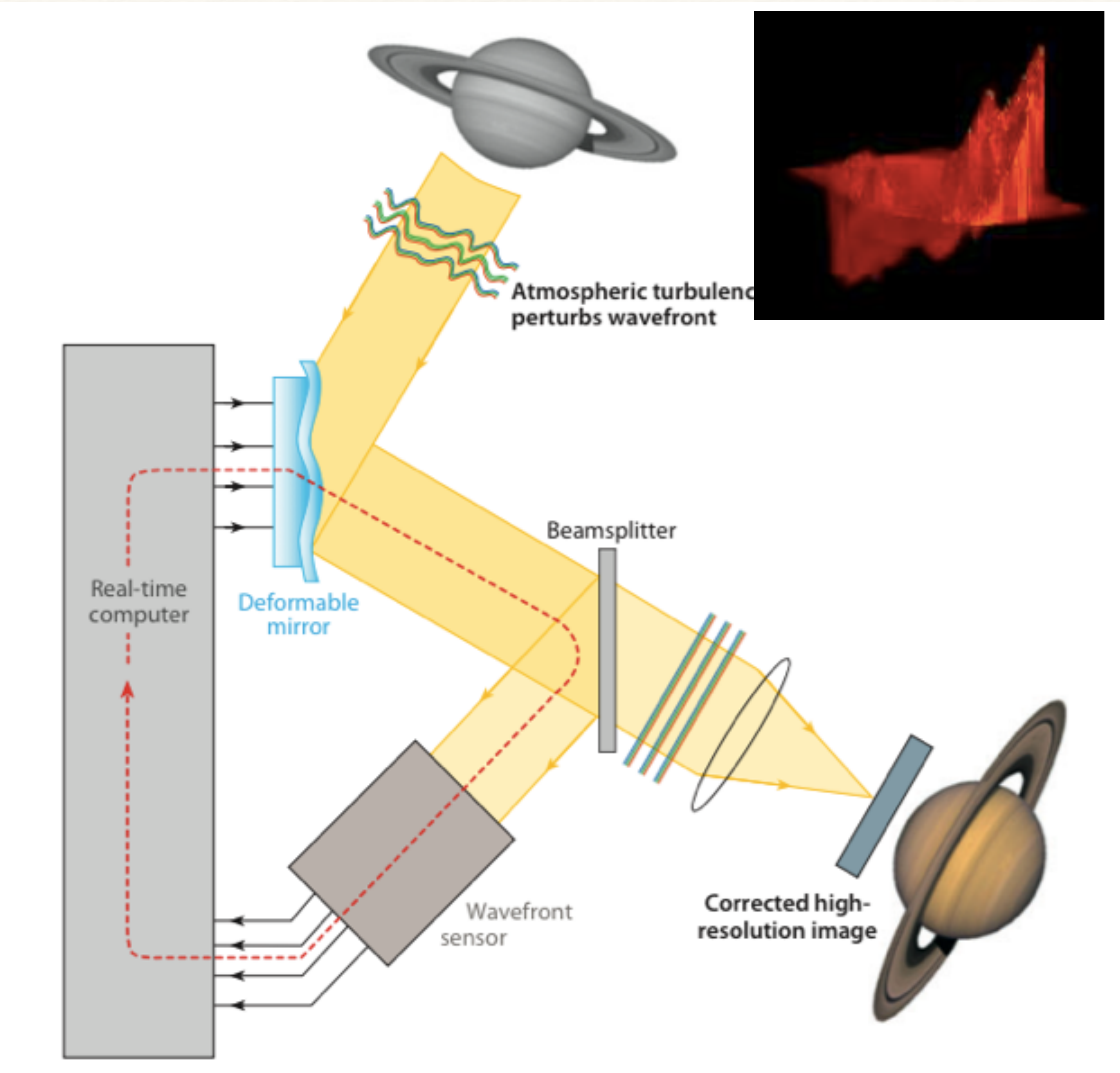

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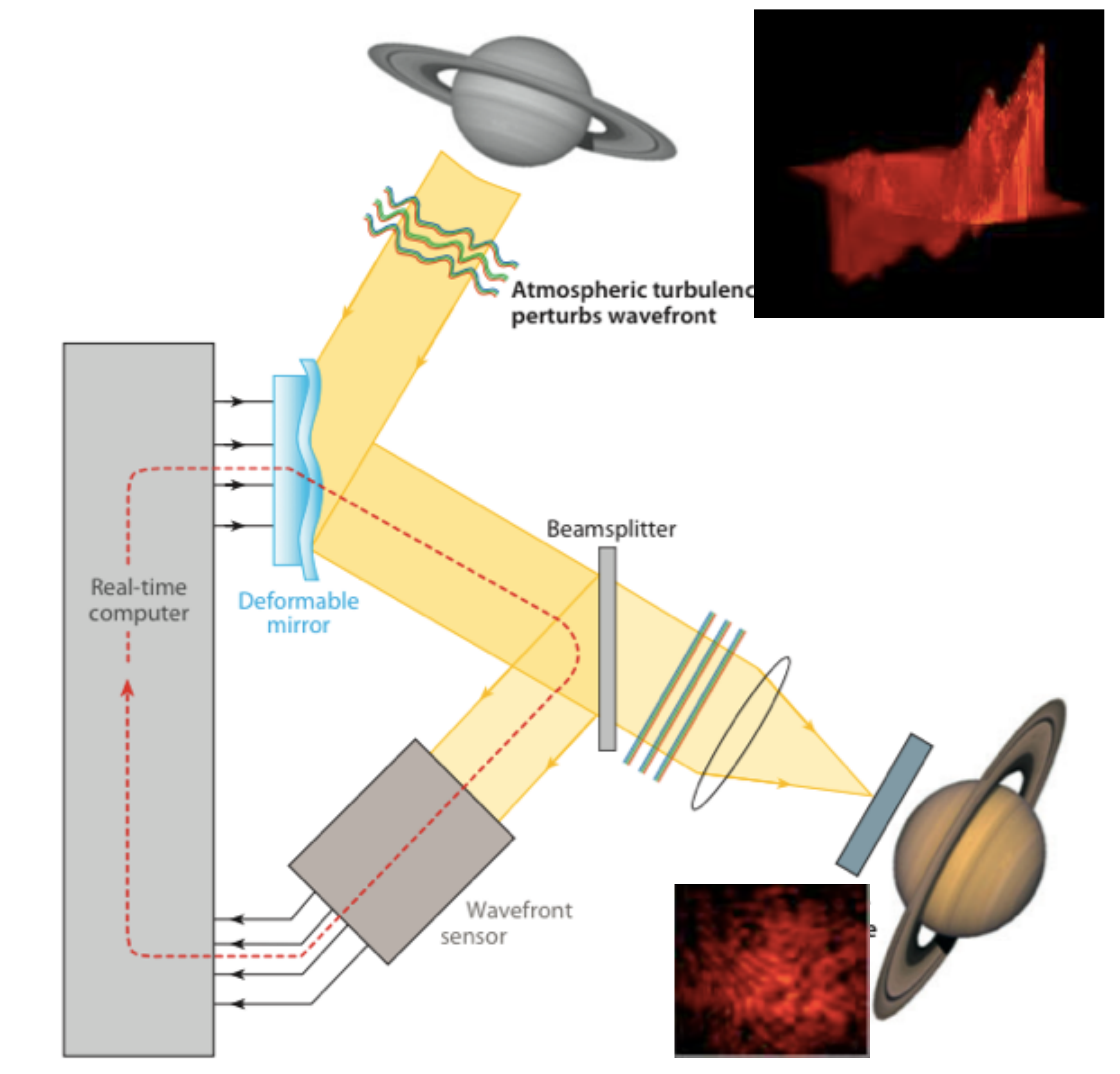
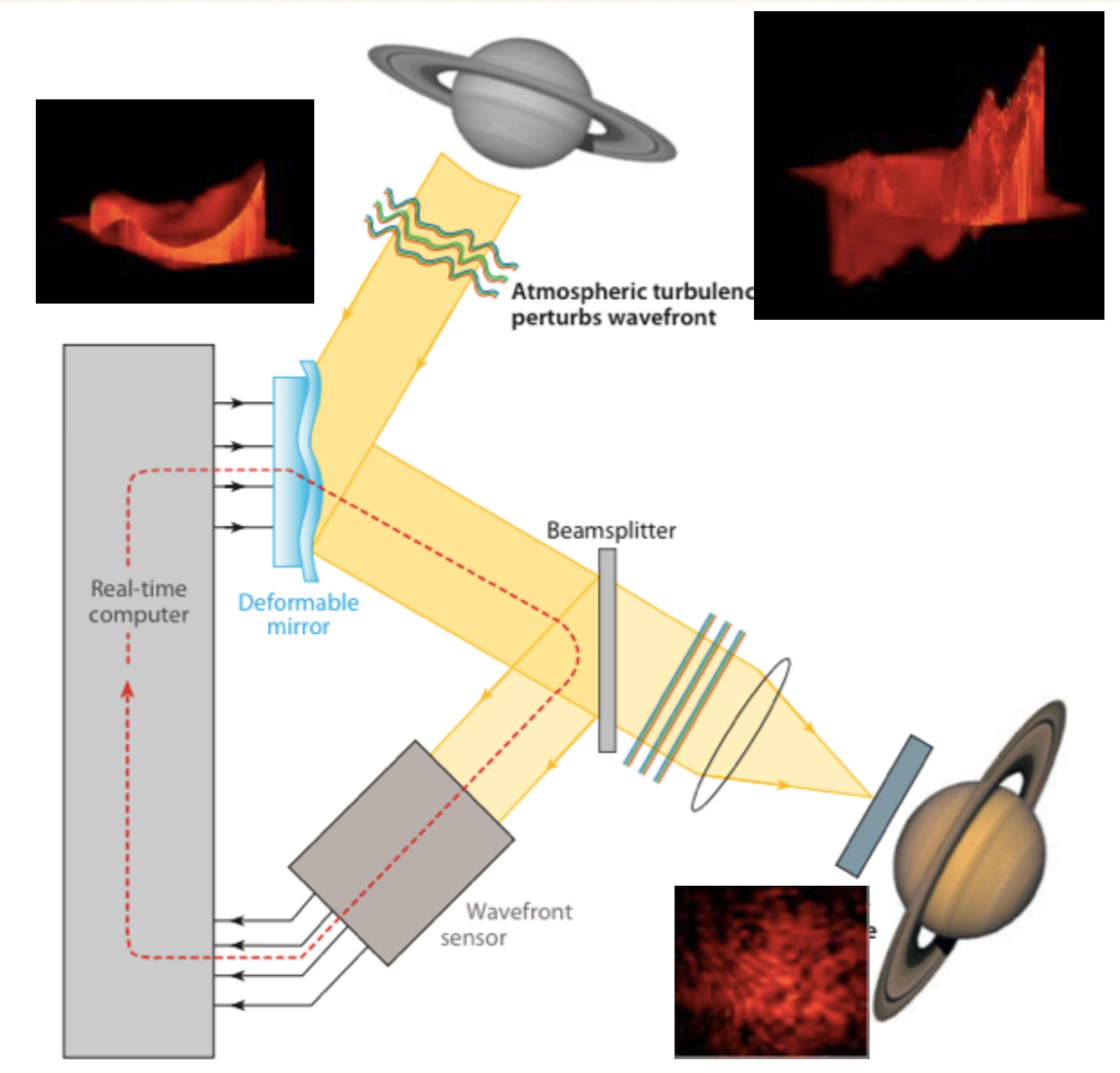
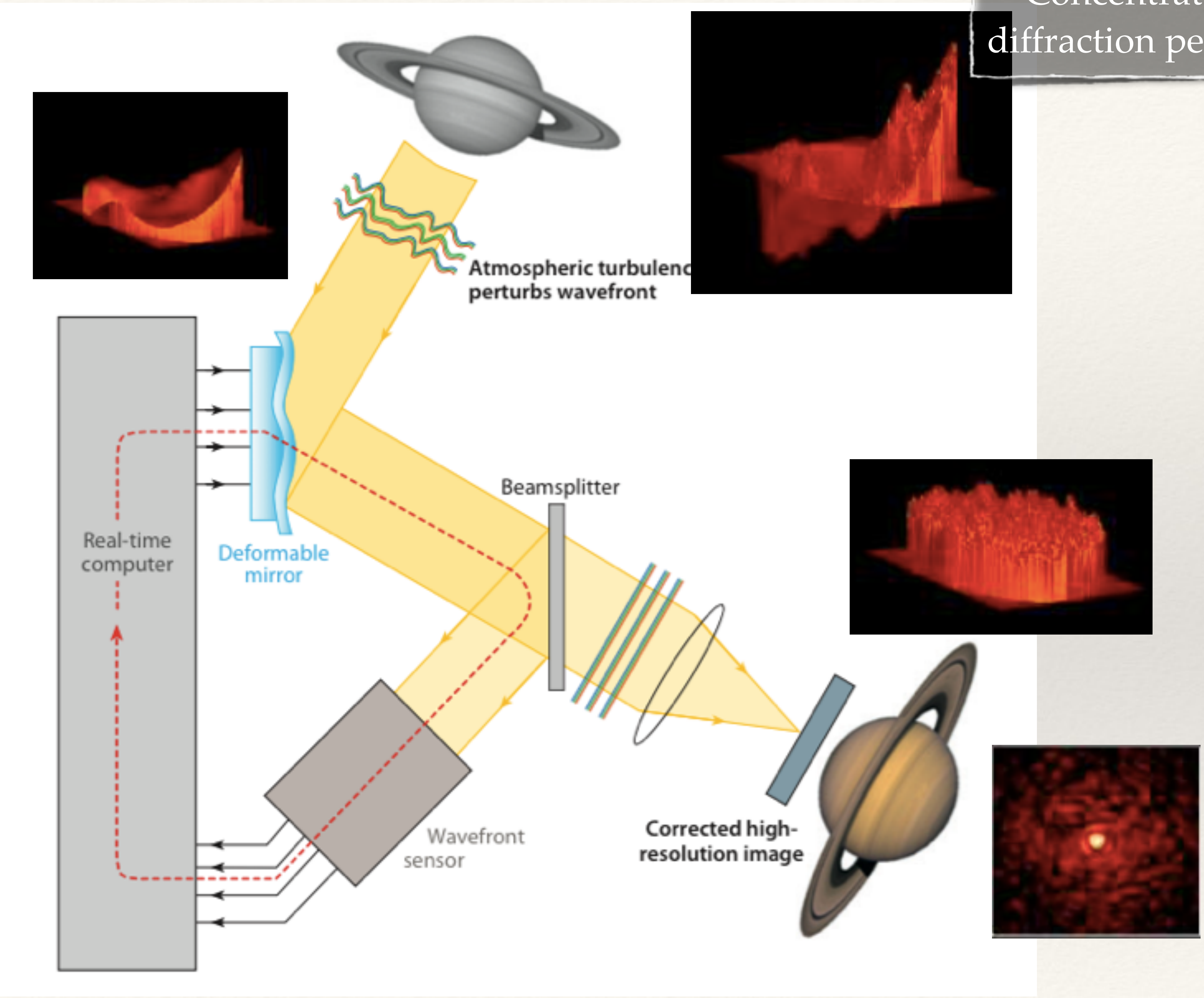


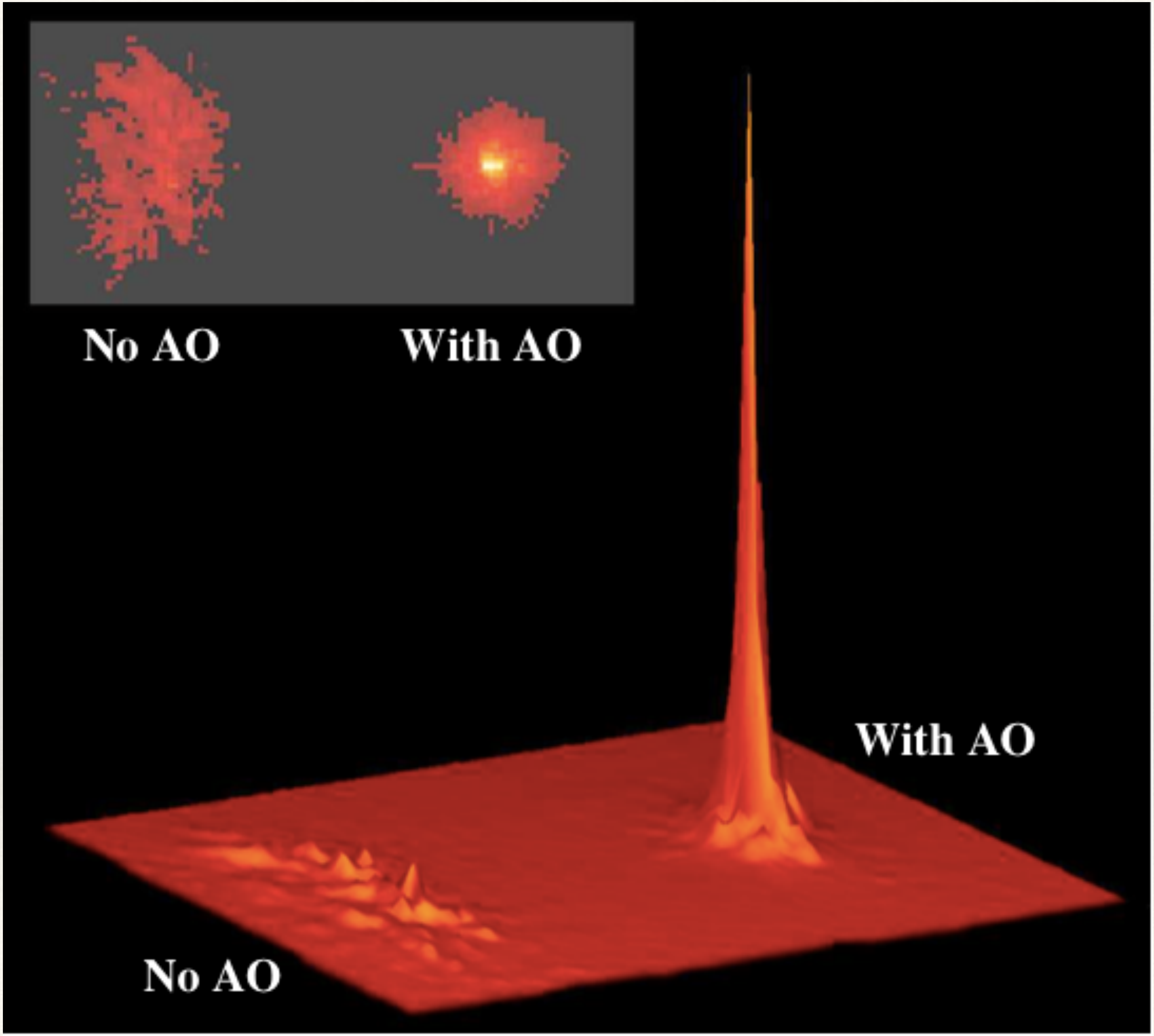
# AO Working Principles



# AO Working Principles

- ✓ Restore the theoretical angular resolution
- ✓ Concentrate the flux inside the diffraction peak




No AO
With AO
With AO
No AO

# Main Elements of an AO System

Wavefront Sensor

Real Time Computer

Deformable Mirror

# Main Elements of an AO System

## Wavefront Sensor

should allow high order correction and be very sensitive (fast response).

## Real Time Computer

## Deformable Mirror

# Main Elements of an AO System

## Wavefront Sensor

should allow high order correction and be very sensitive (fast response).

## Real Time Computer

should close the loop at >1 kHz frequency.

## Deformable Mirror

# Main Elements of an AO System

## Wavefront Sensor

should allow high order correction and be very sensitive (fast response).

## Real Time Computer

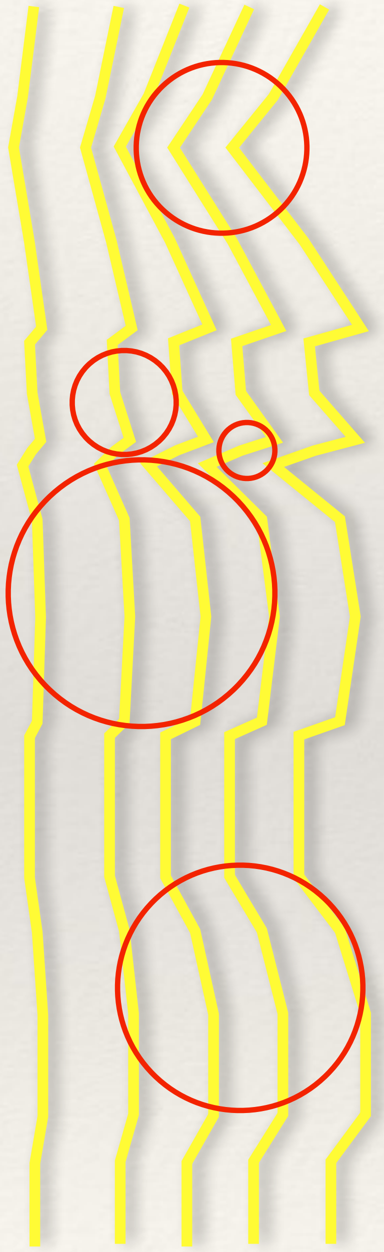
should close the loop at >1 kHz frequency.

## Deformable Mirror

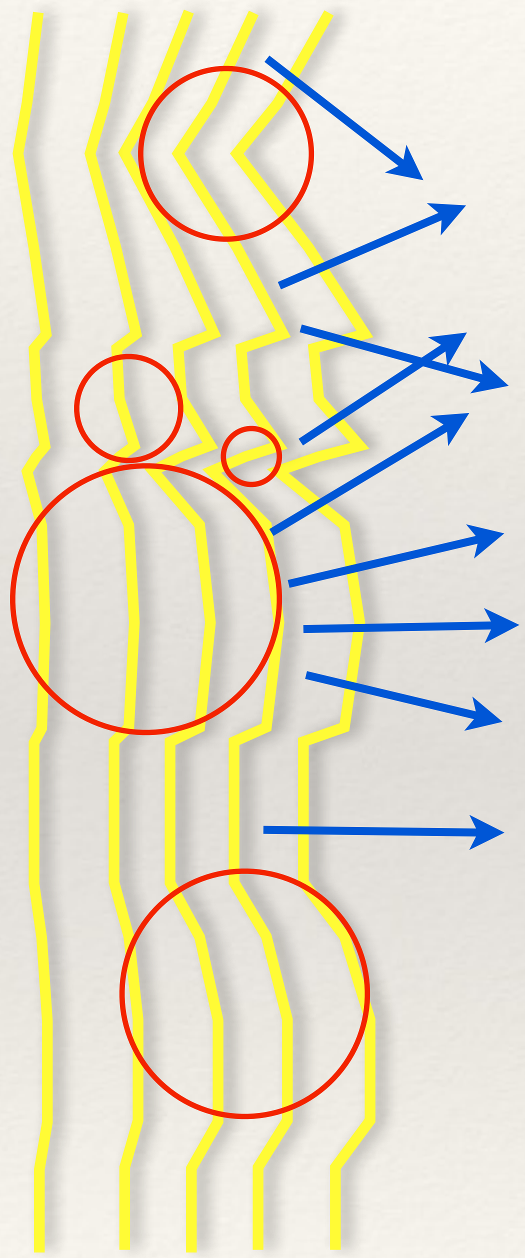
the highest the number of actuators, best correction of the wavefront error can be obtained. Other important parameters are speed, dynamic range, number of fault elements, and density of actuators (optics size)

# Wavefront Measurement

to improve … we need measurements



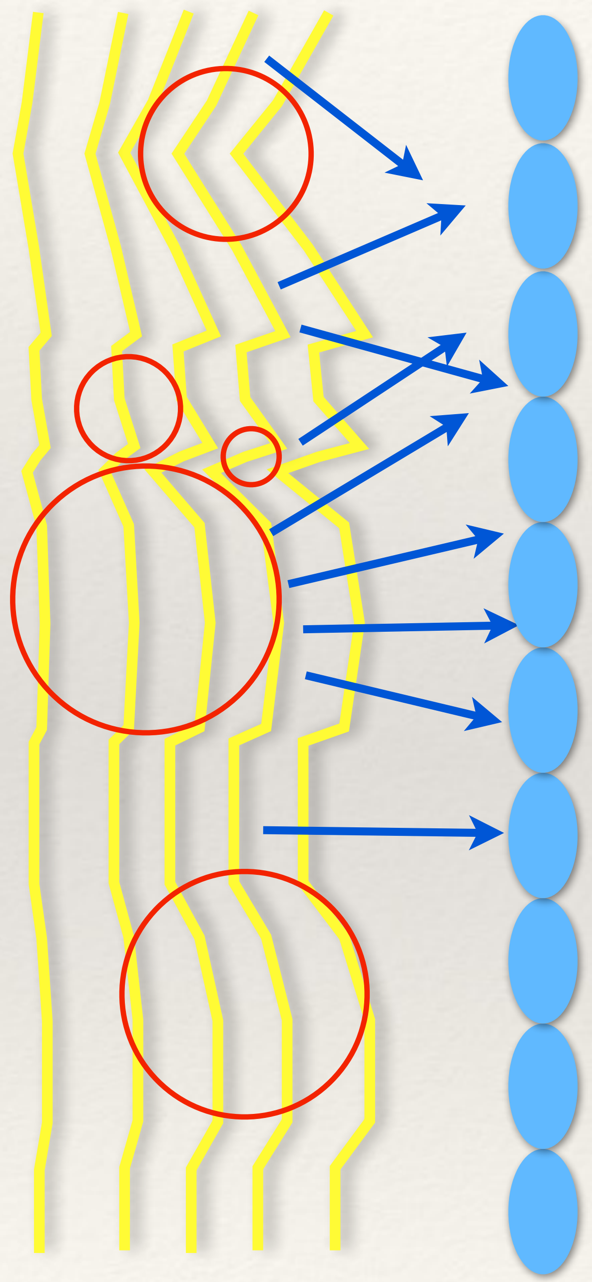
# Wavefront Measurement



to improve … we need measurements

the direction of propagation is perpendicular to the wavefront

# Wavefront Measurement

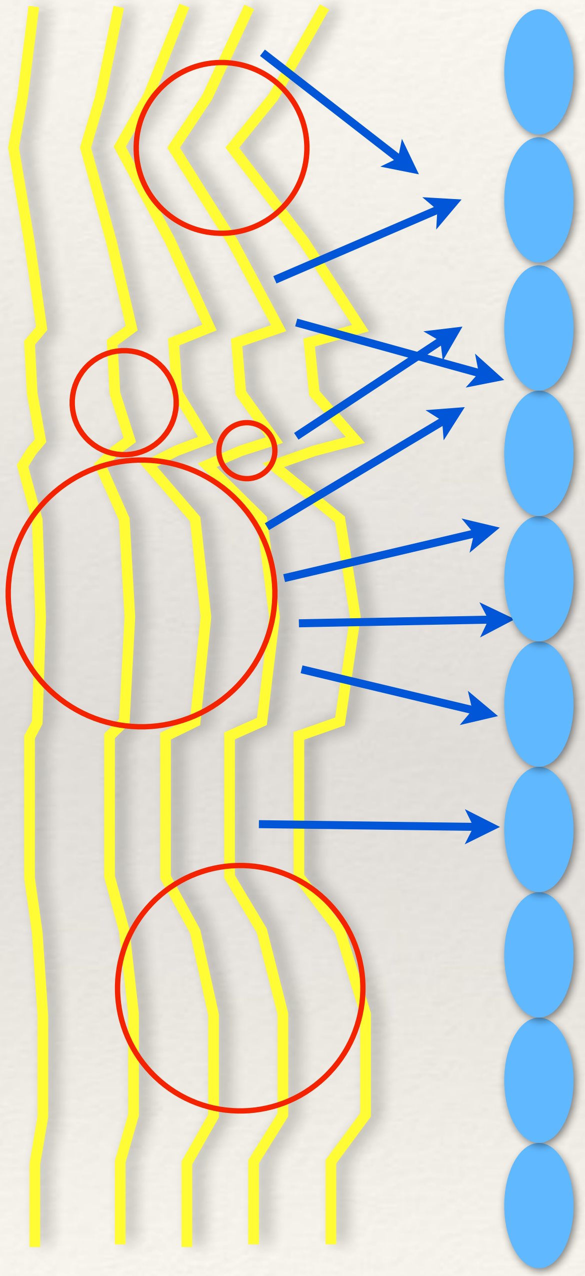


to improve … we need measurements

the direction of propagation is perpendicular to the wavefront

Using micro lenses we can have an idea on the “local” tilt of the wavefront

# Wavefront Measurement



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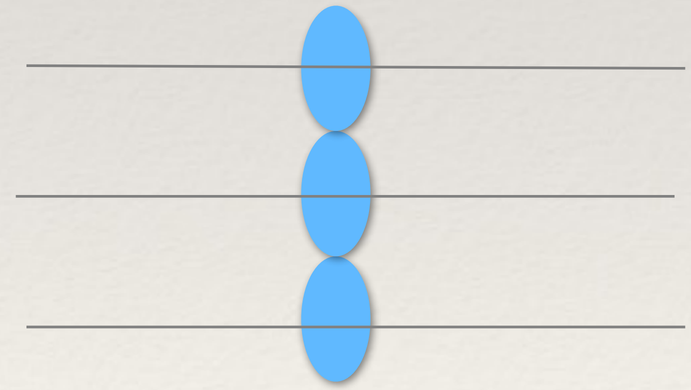
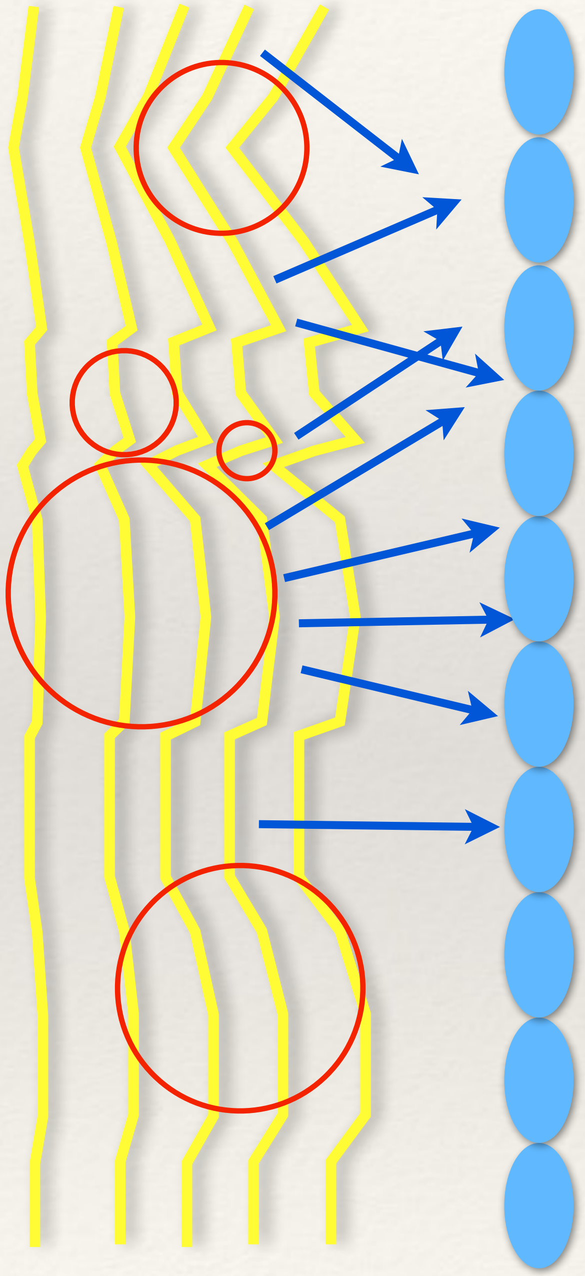


# Wavefront Measurement



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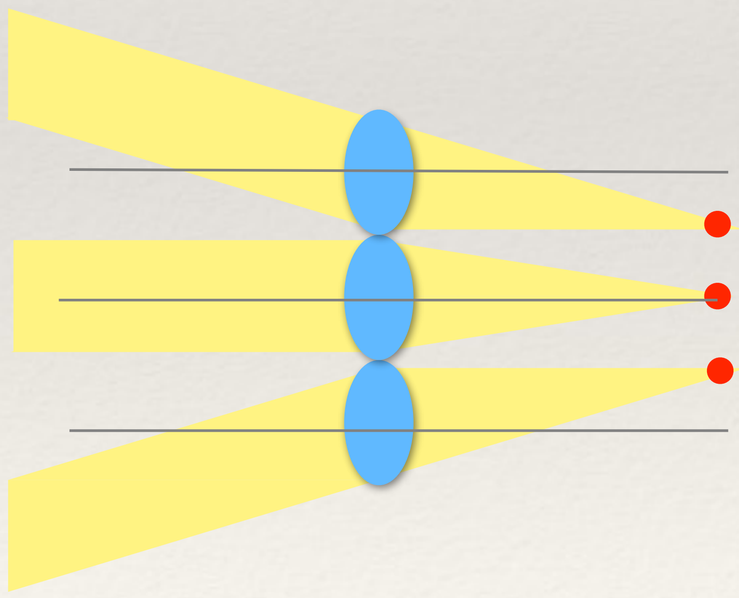
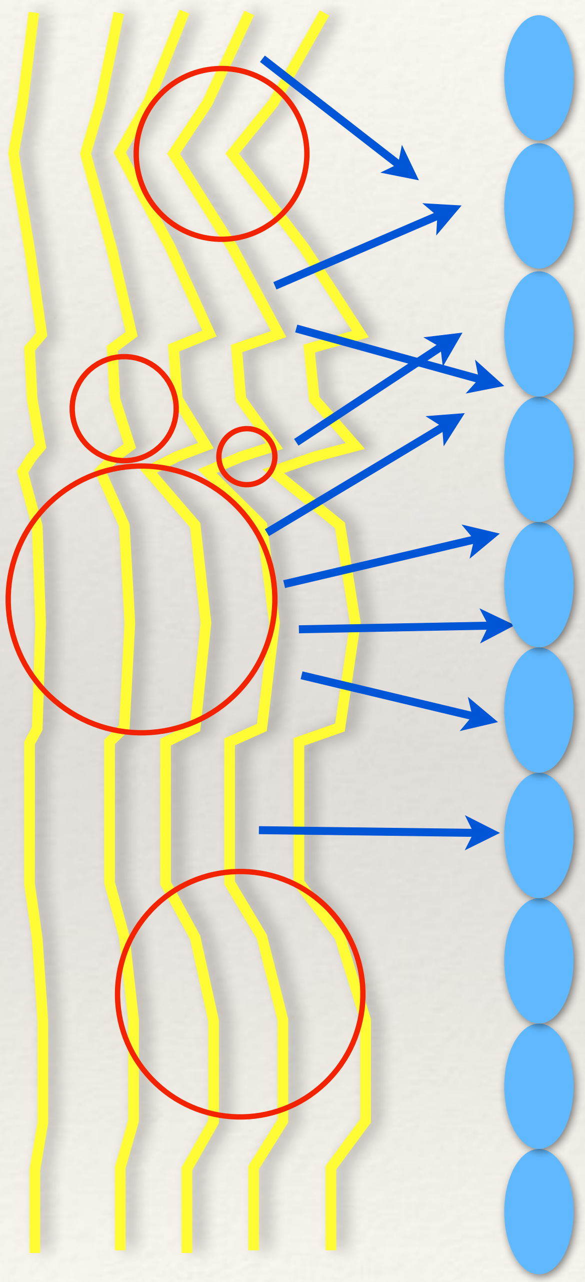


# Wavefront Measurement

to improve … we need measurements



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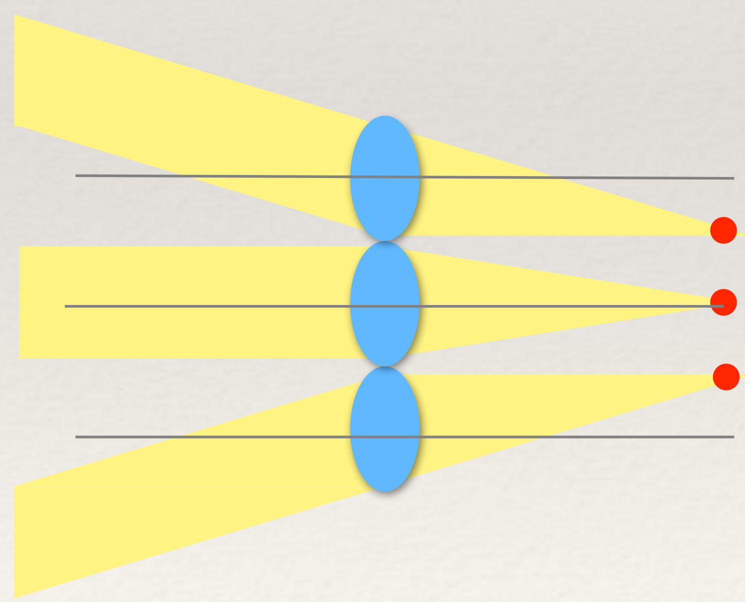
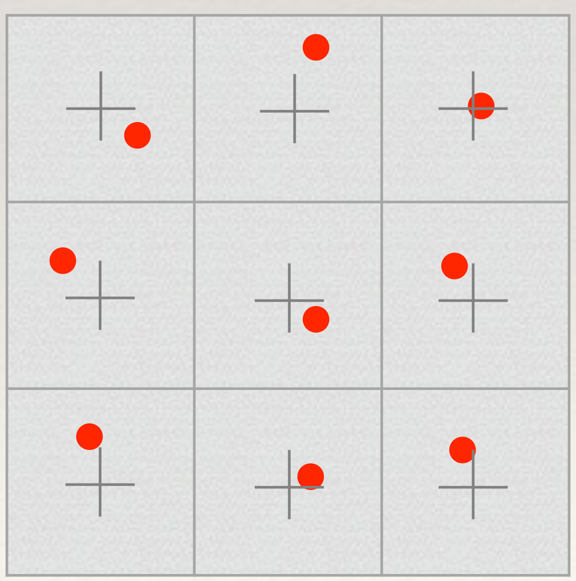
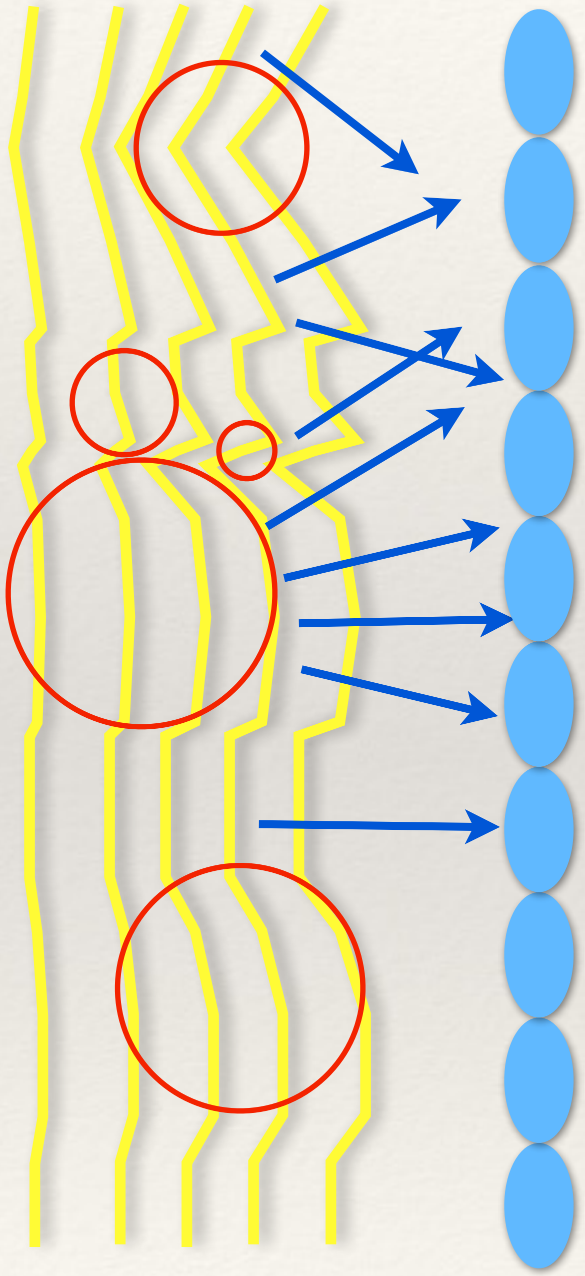




# Wavefront Measurement



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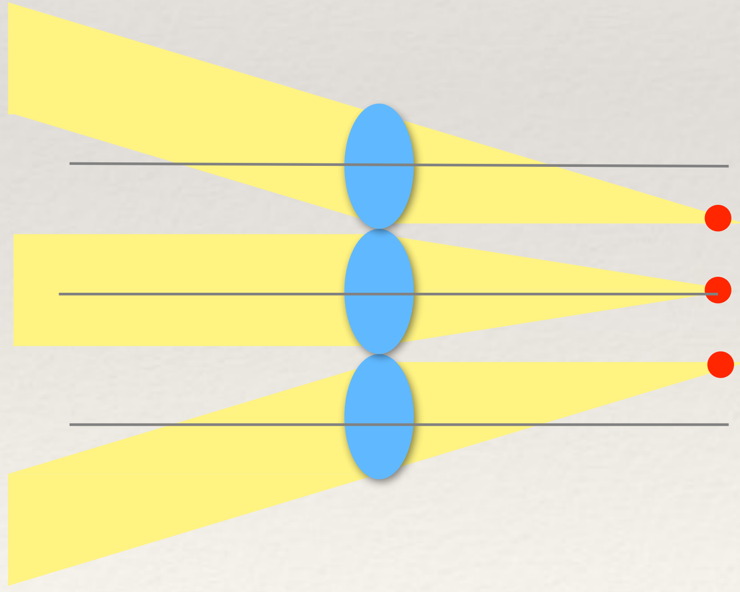
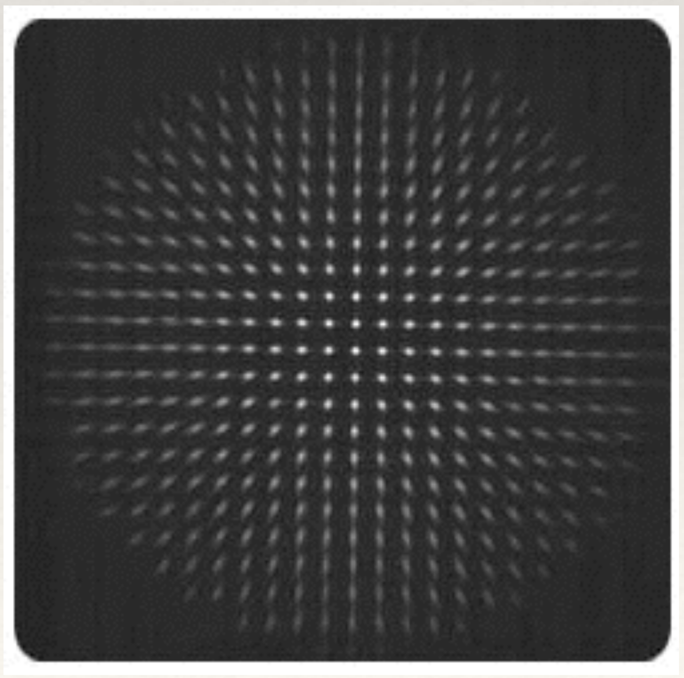


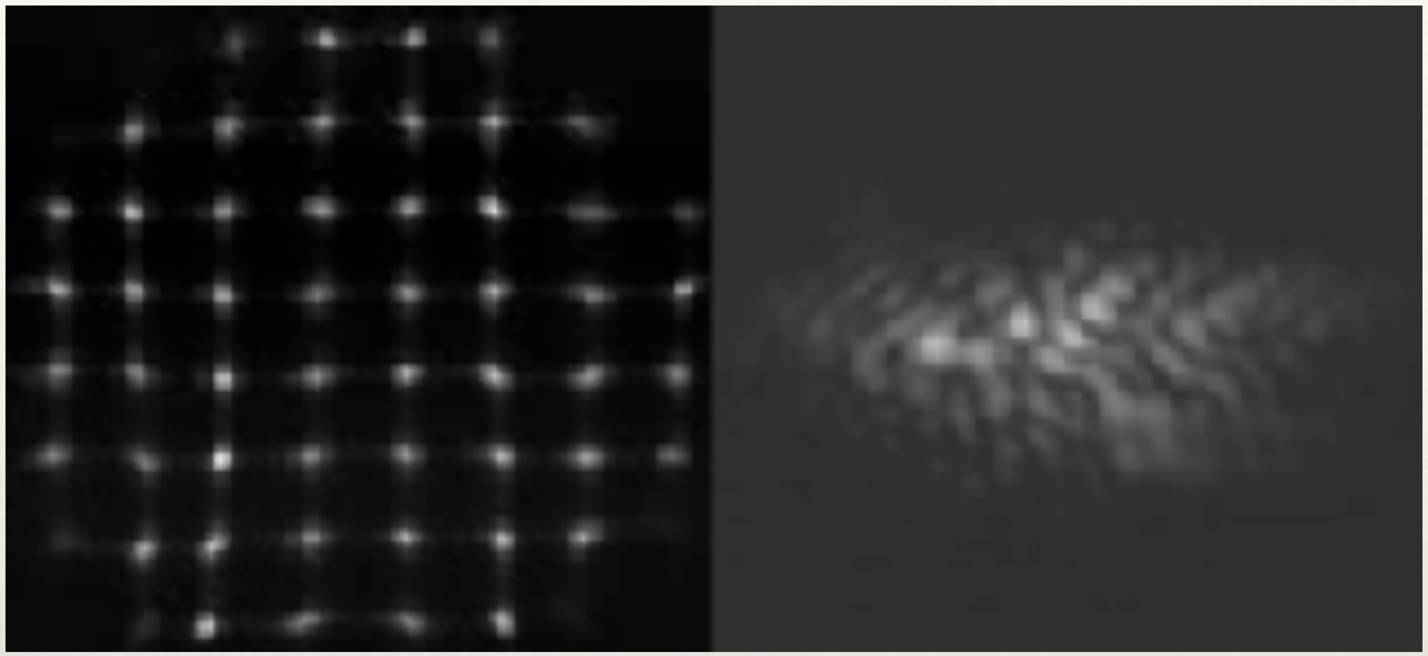


# High Order Wavefront Measurement

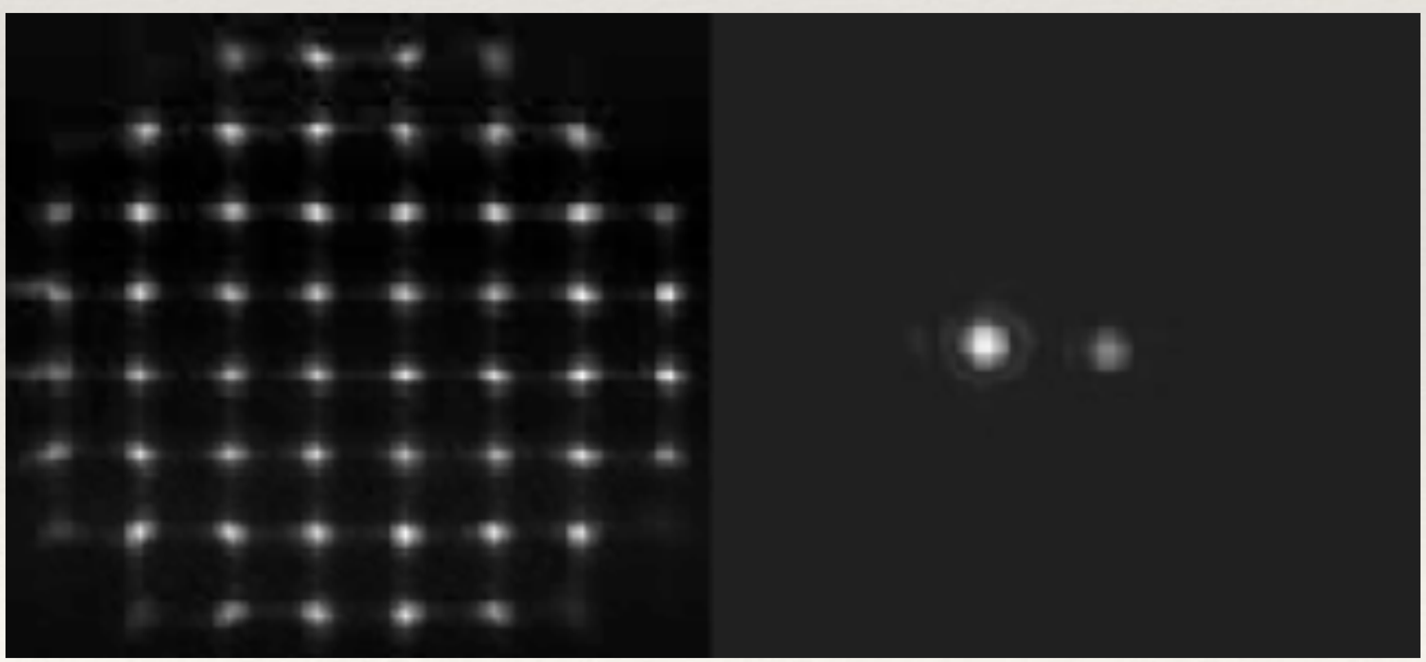
How to perform High-Order WFSensing? The basic idea is to split the incoming wavefront in several part to check which are the aberrations in that small portion

- The higher the number of sub-apertures, the better the sampling, but:
- The higher the number of sub-apertures, the lower the light for each subaperture
- A limit is imposed also from the number of actuators of the DM
- Of course the scientific wavelength is important to select the n of sub-apertures being $r_0$ dipendent on the wavelength

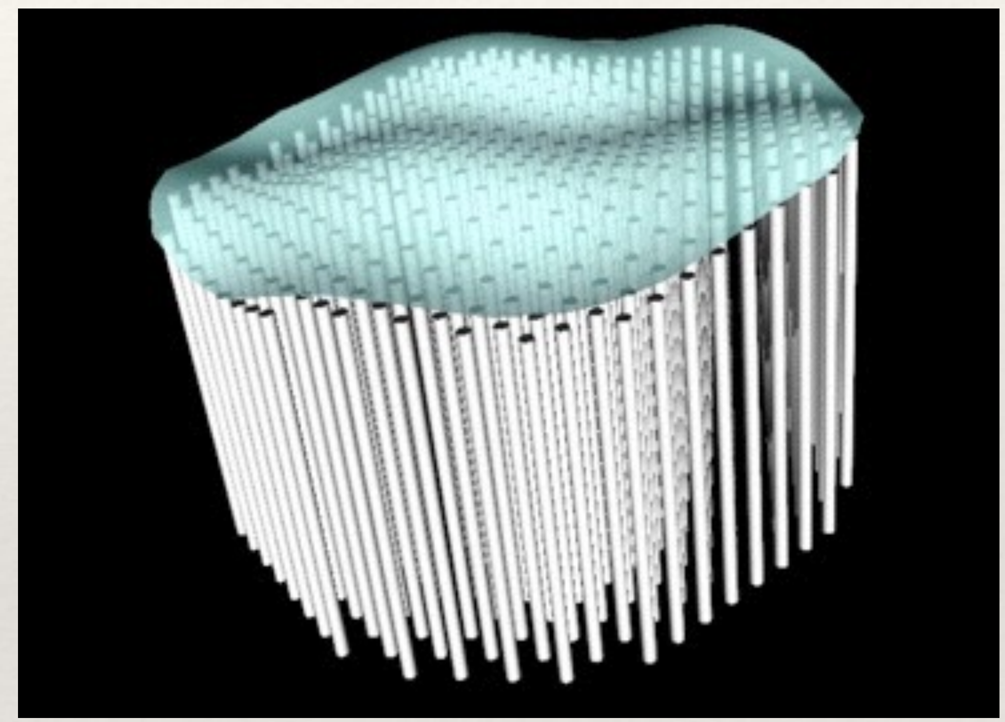
# WAVEFRONT ANALISYS



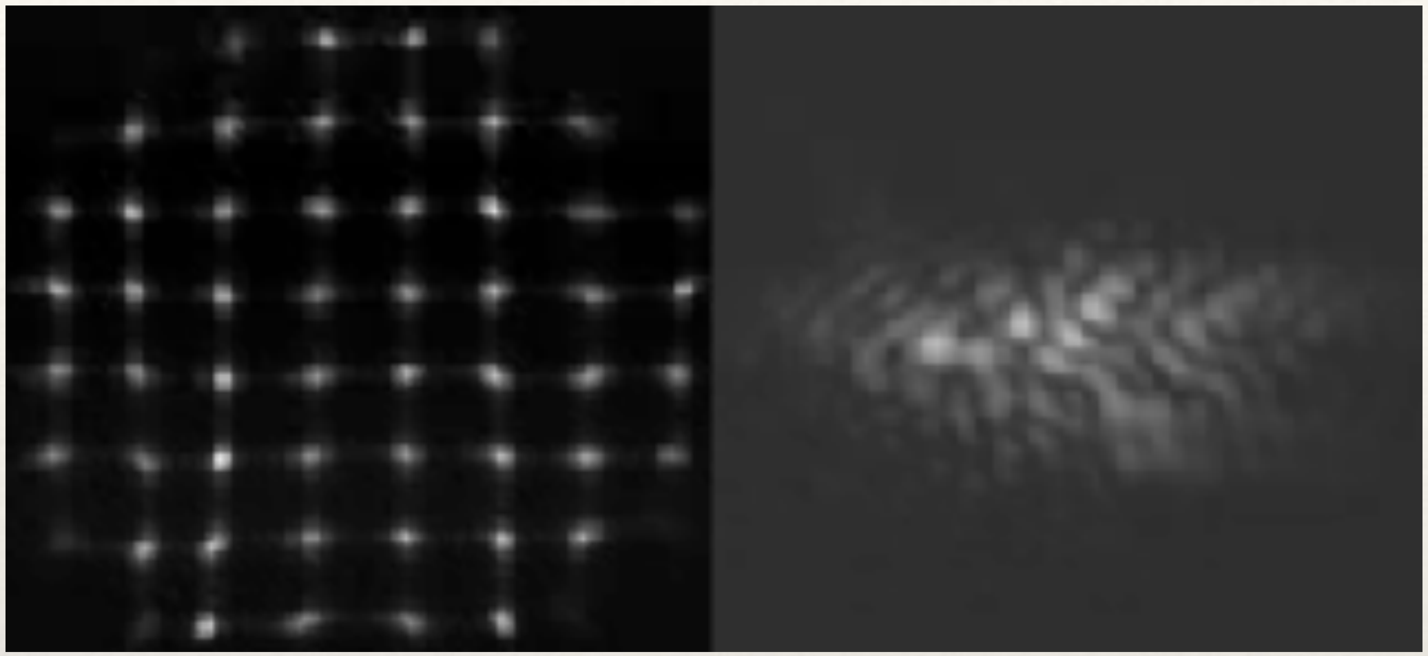
Open Loop



Close Loop



# WAVEFRONT ANALISYS



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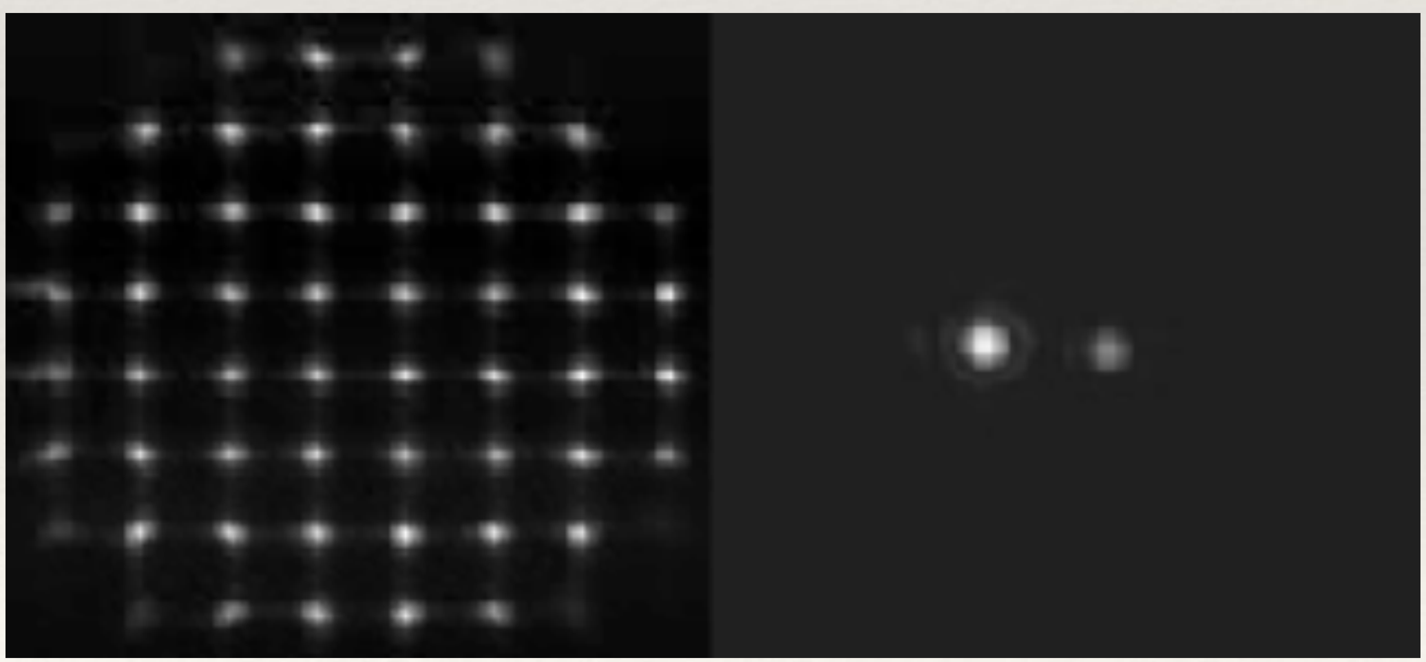

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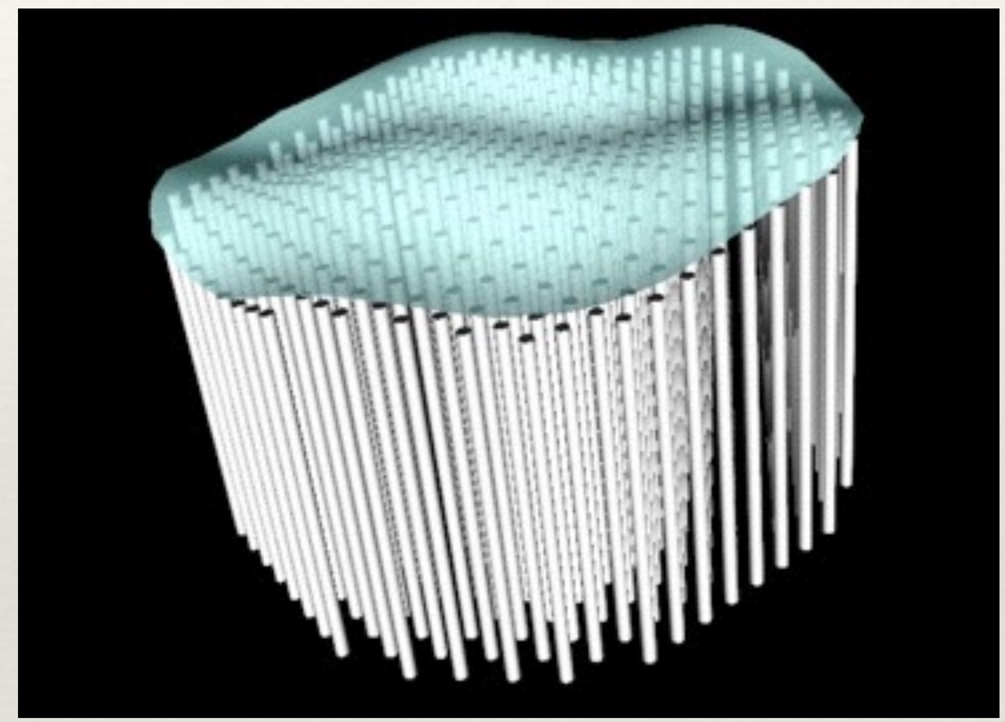
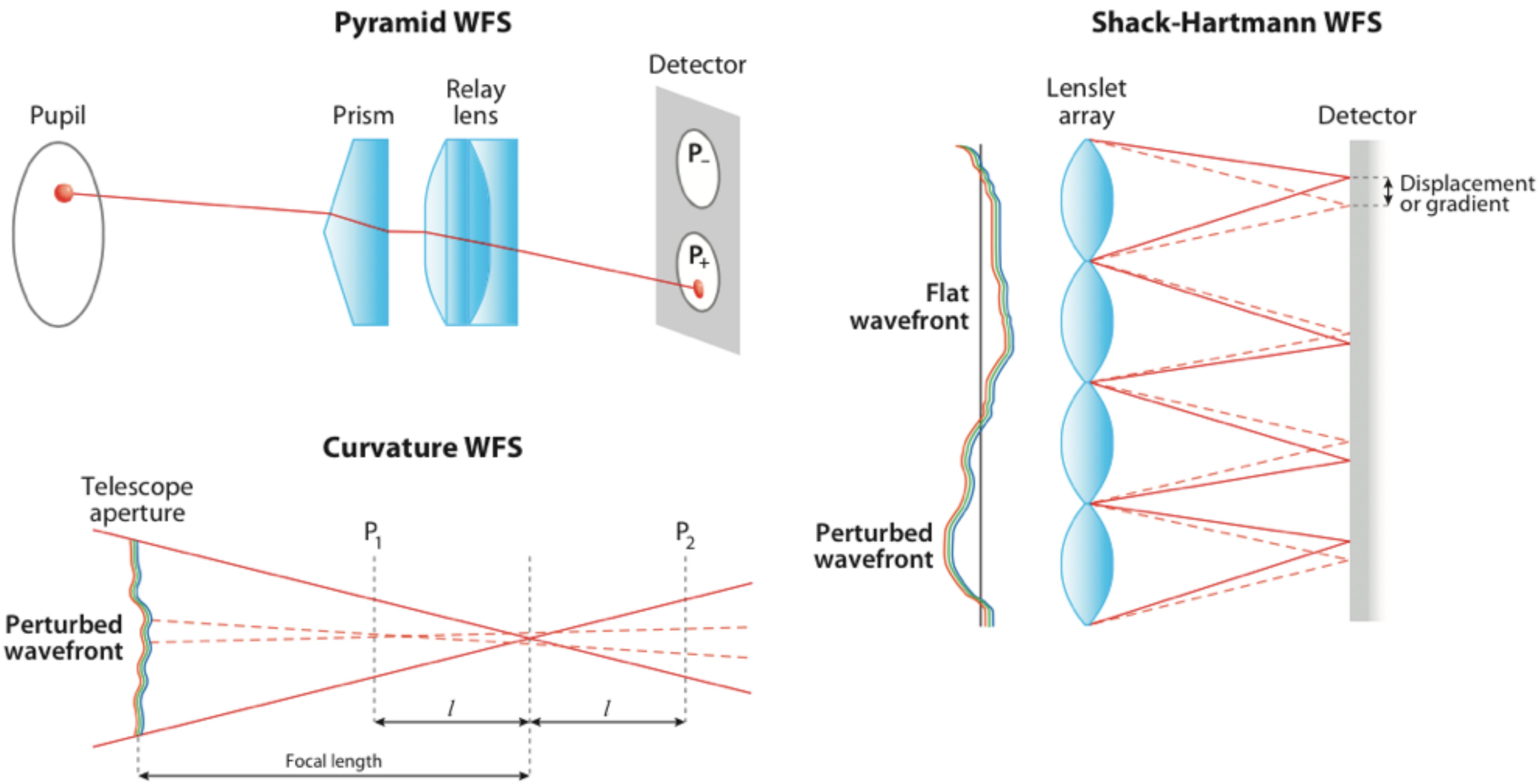
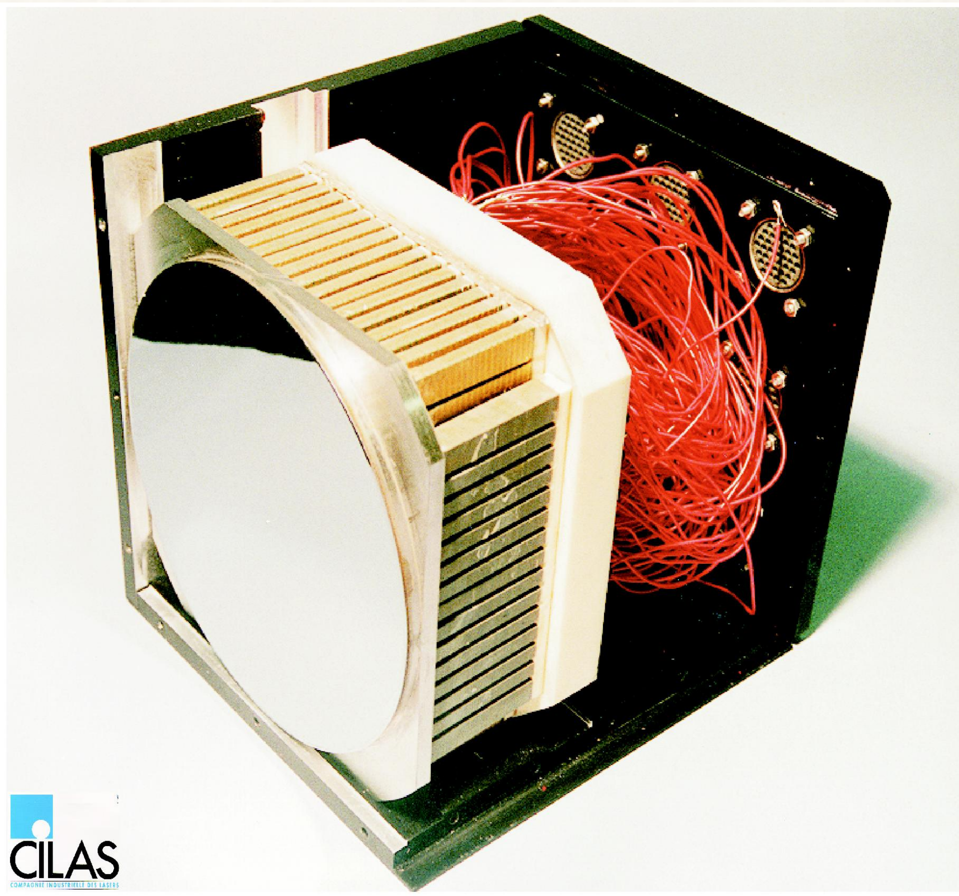


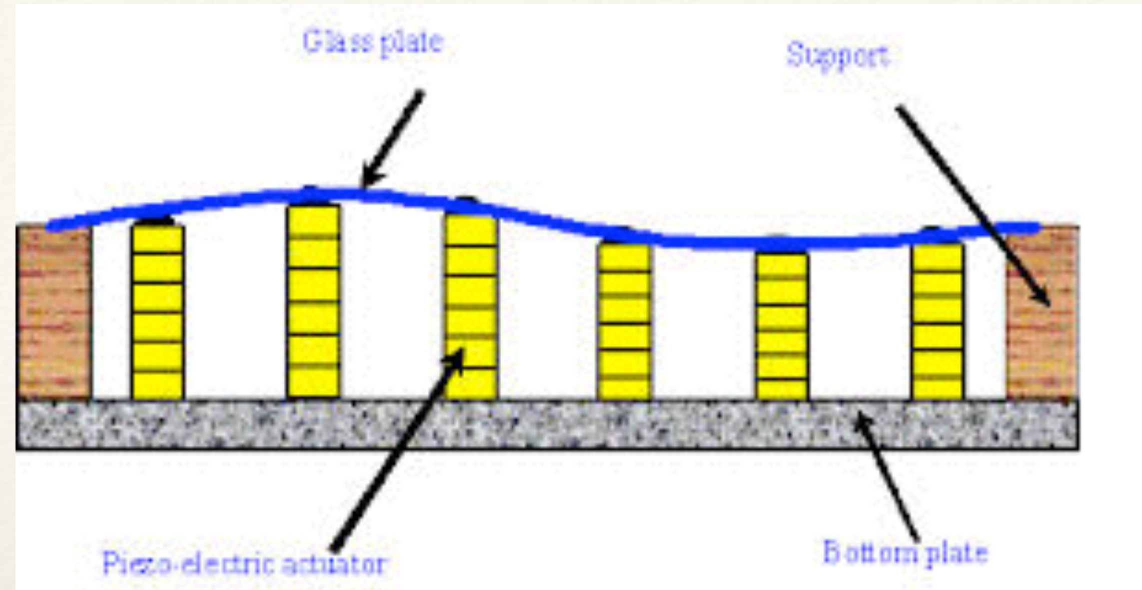
# Wave Front Sensors

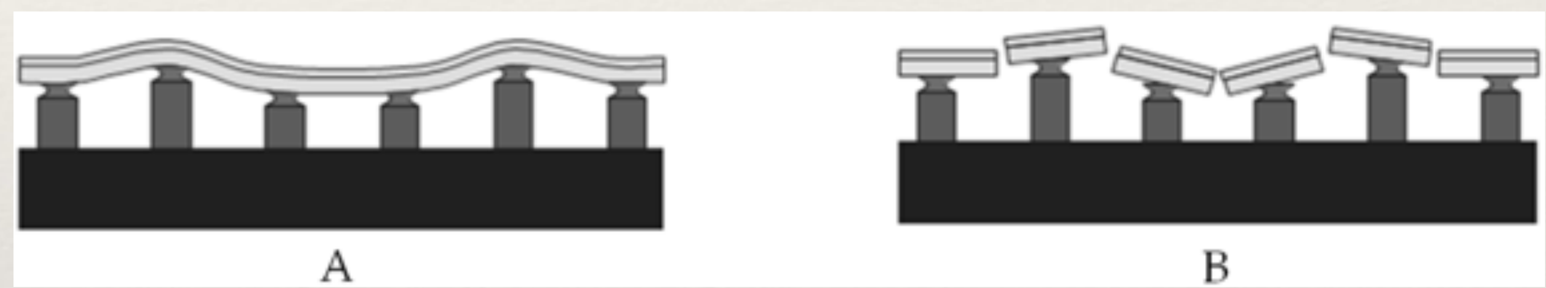


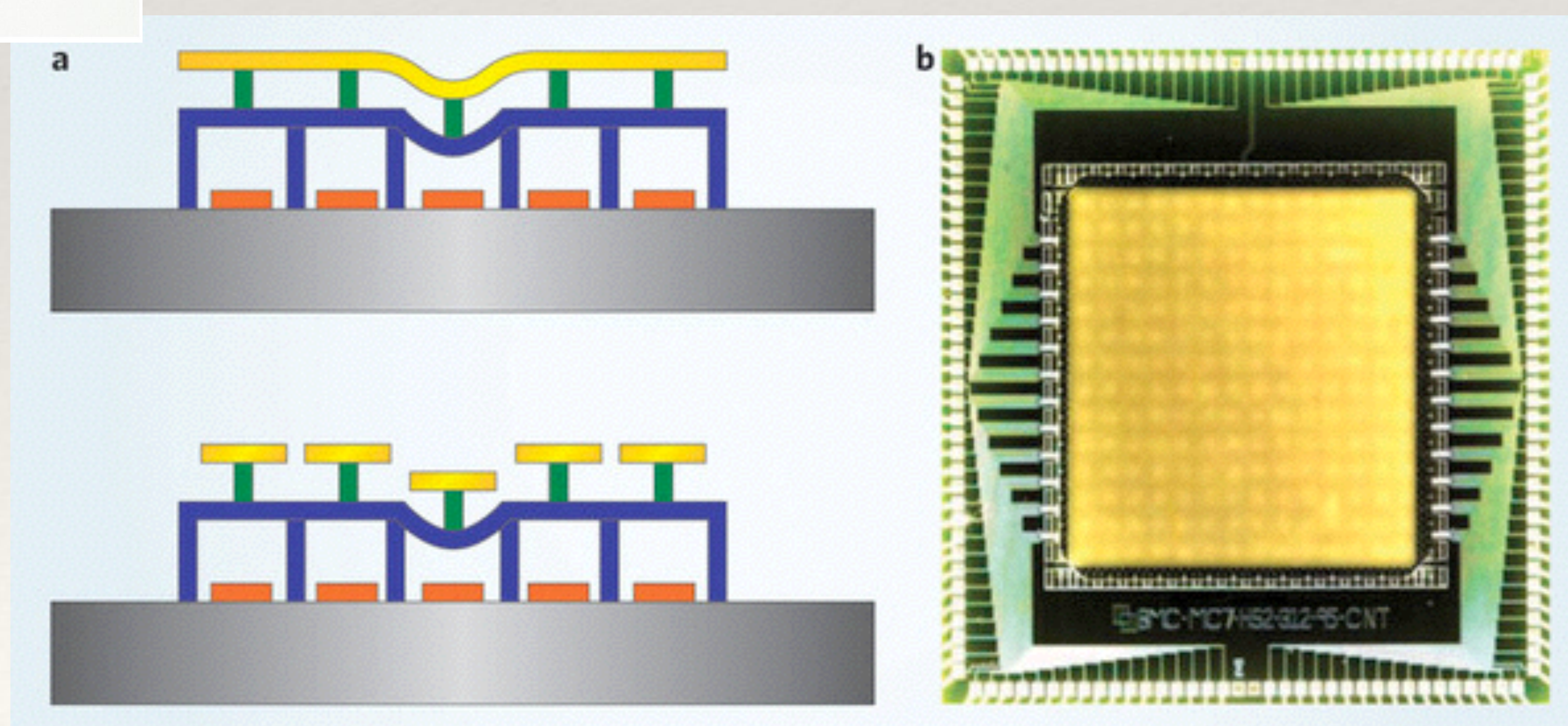
# DEFORMABLE MIRRORs



Deformable mirror by CILAS
17 x 17 actuateurs



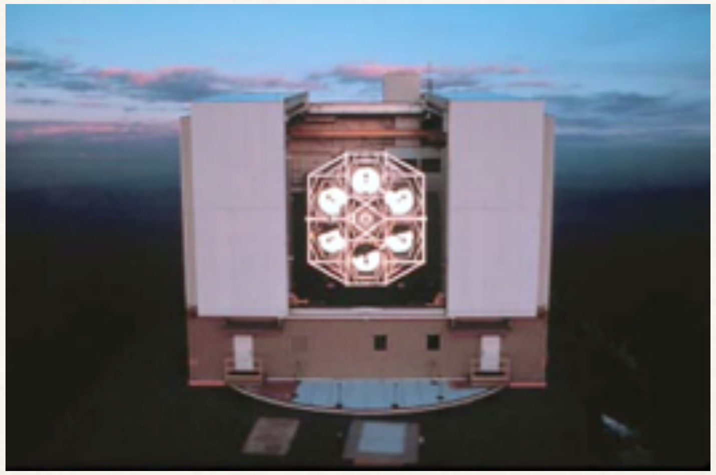




*Several technologies …*

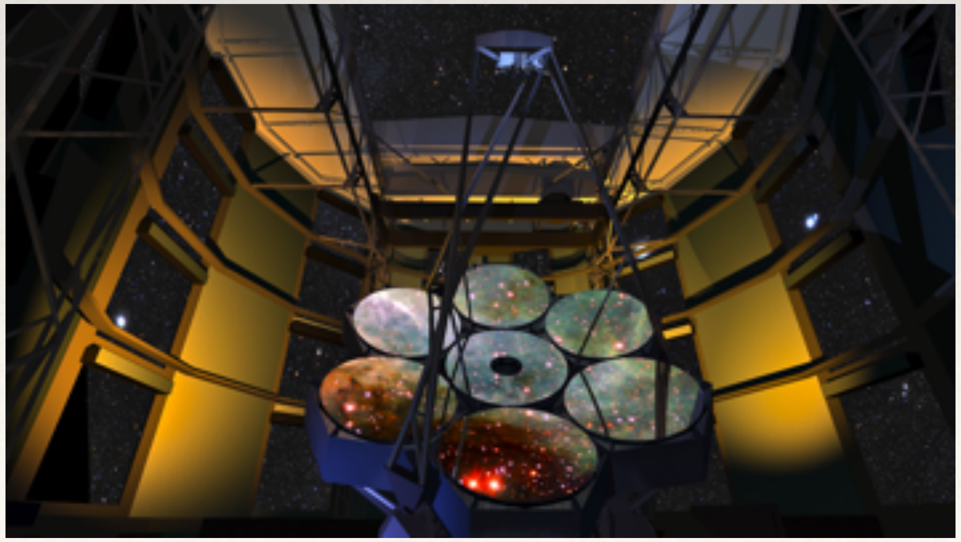
- *piezo-electric*
- *micro mirror*
- *membranes*

# DEFORMABLE MIRRORs

Three main technologies:

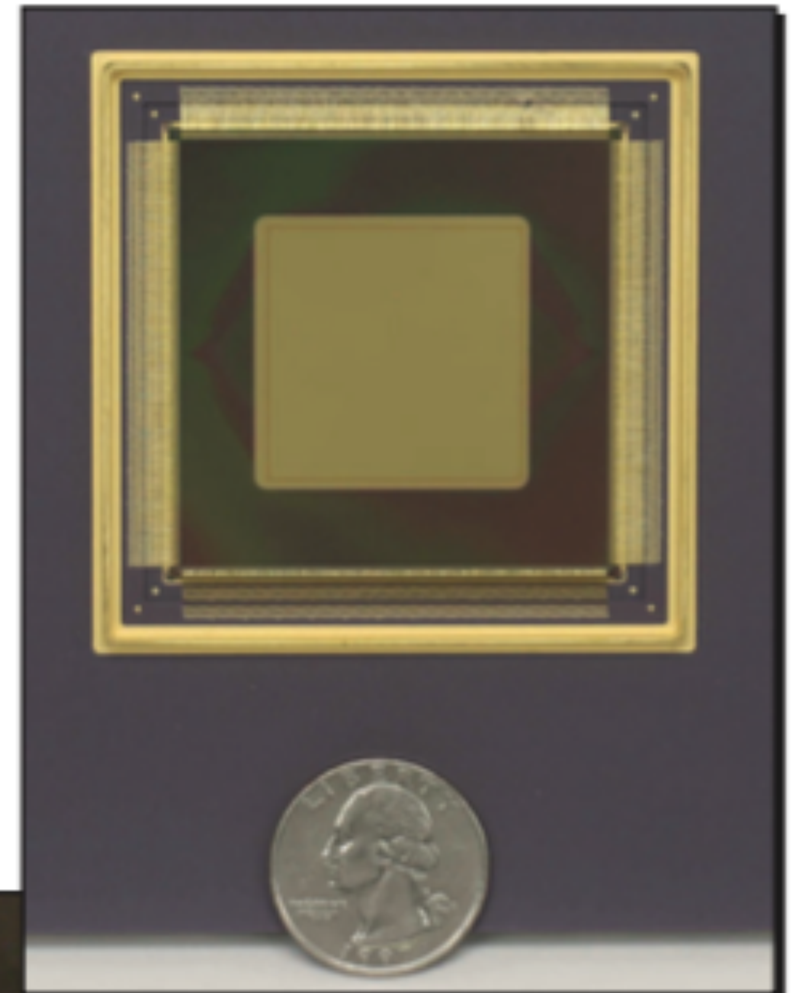


- Adaptive Secondary Mirrors (MMT; LBT; GMT;VLT)
- Piezo Deformable Mirrors (more common)
- Micro Optical Electrical Mechanical Systems (MOEMS)



Lab testing of the Large Binocular Telescope's adaptive secondary mirror system with 672 actuators

A 4,096-actuator micro-optical-electrical-mechanical system (MOEMS) DM



Piezo high-order 1,377-actuator DM for SPHERE

# DEFORMABLE MIRRORs

**DMs correct optical path difference (OPD) by advancing or retarding reflected beam:**

**- same SHAPE of the WF**

**- ½ amplitude of the WF**

**Features:**

**- # actuators: matching sub-aperture to avoid over or under-sampling**

**- update rate: accordingly to $f_G$**

$$f = 20\text{-}100\ f_G$$

**- dynamic range (mechanical stroke)**

$$s = 0.15(D/r_0)^{5/6}\,\lambda$$

# DM Classes

| | Astronomy (10m class) | Astronomy (30m class) |
|---|---|---|
| Stroke | 5 µm | 10-15 µm |
| # actuators | 350-2500 | 7000-10000 |
| Frequency response | 1-5 kHz | 1-5 kHz |
| Mirror-Surface Errors (rms) | 30 nm | 30 nm |
| Aperture Size | 1-15 cm | 2-30 cm |

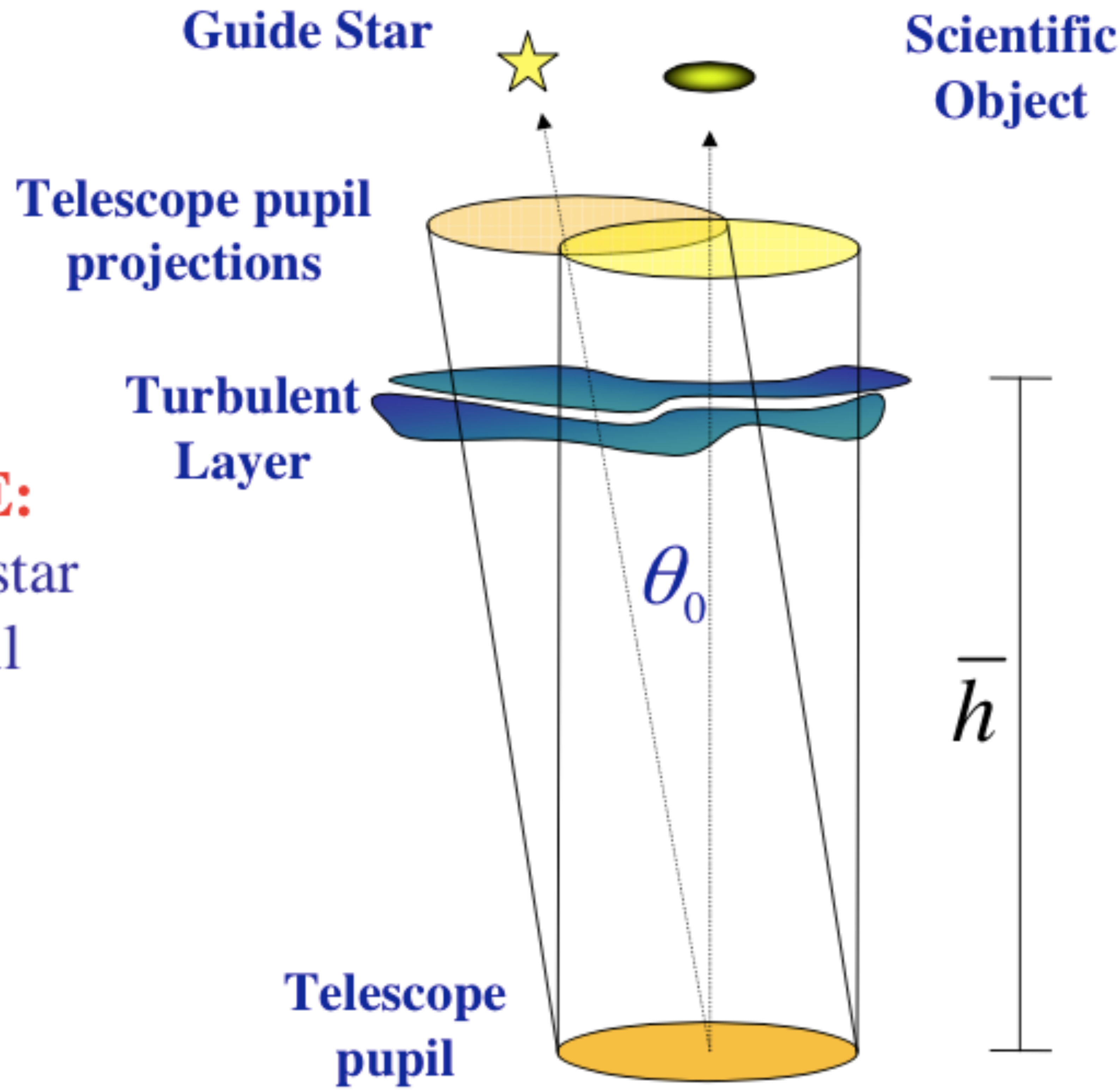
# A Reference is needed

single-conjugate adaptive optics (SCAO)

**ISOPLANATIC ANGLE:**

Angle from the reference star where the correction is still effective

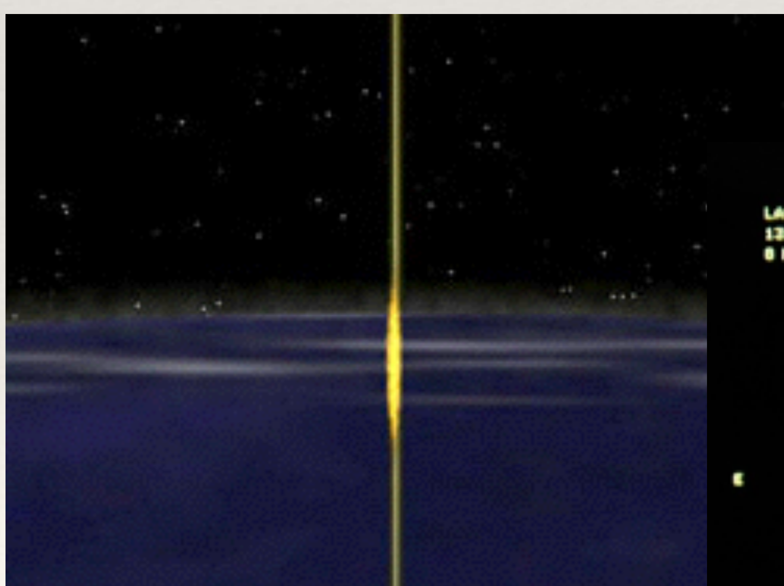
$$\theta_0 \propto r_0 / \bar{h}$$

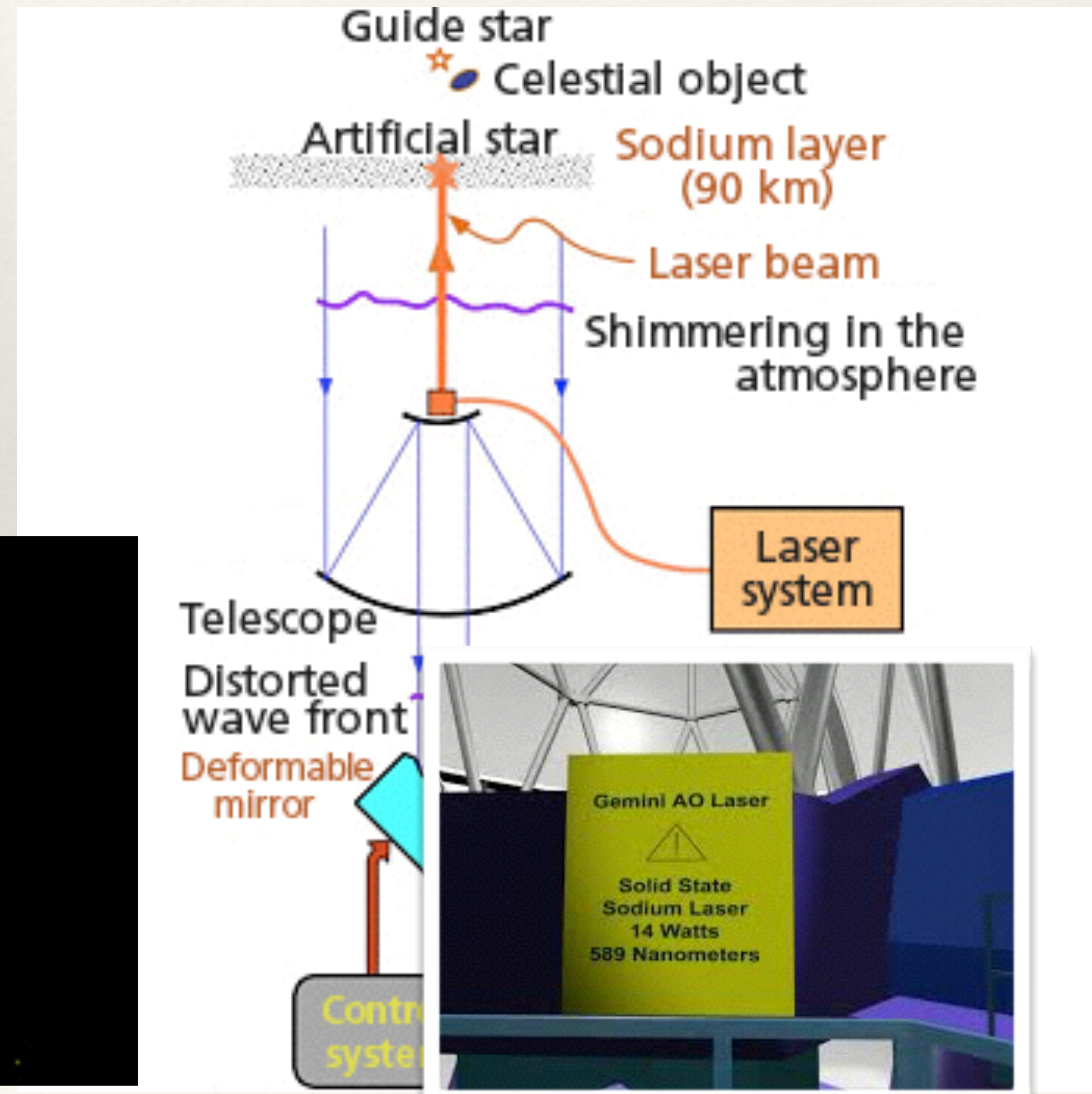


# Laser Guide Star (LGS)

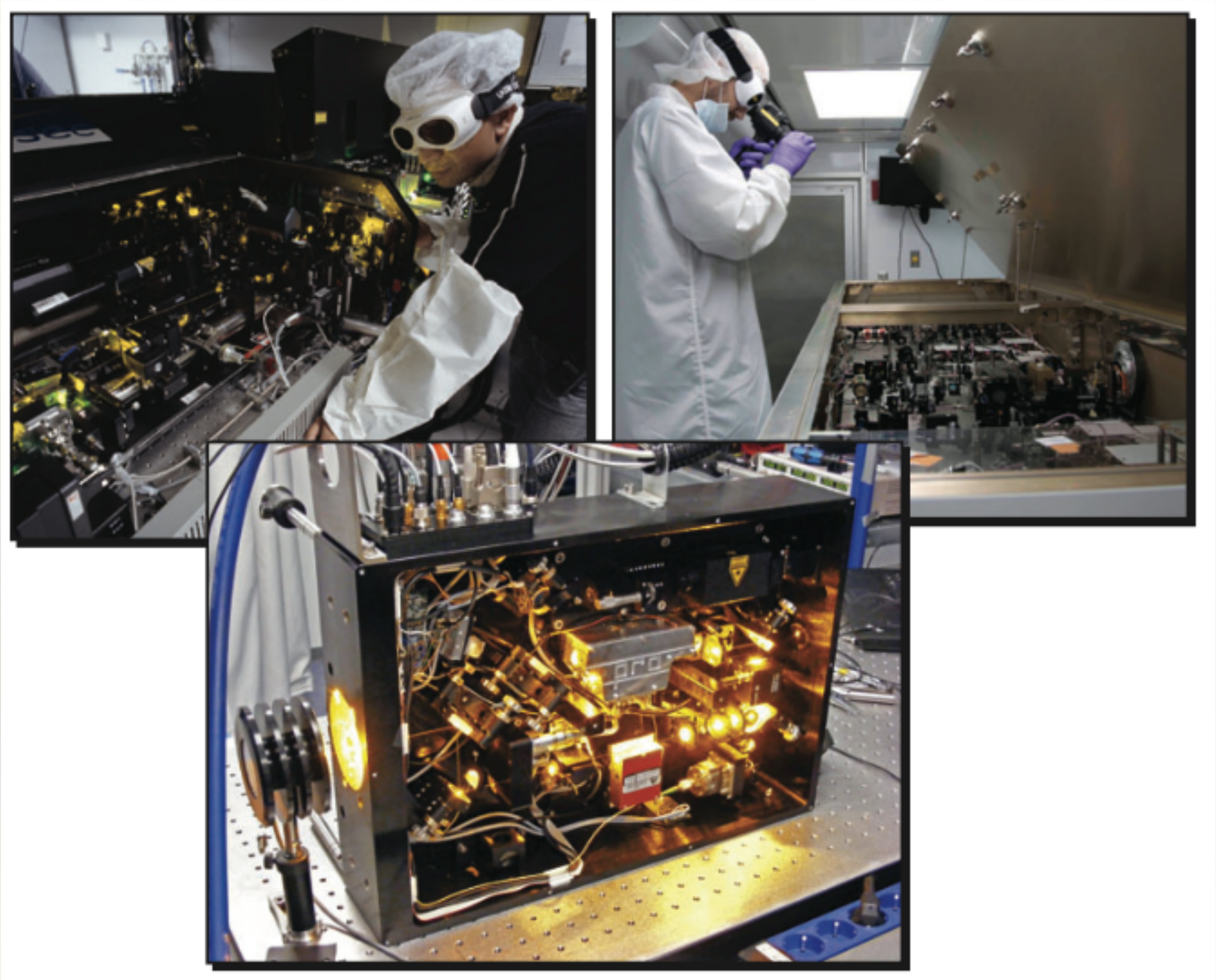
For a reasonable correction performance, AO systems need sufficiently bright (~15 mag) guide stars within $\theta_0$ of the astronomical target.

- ☑ Rayleigh Scattering (30km)
- ☑ Resonance fluorescence of sodium atoms (90km)

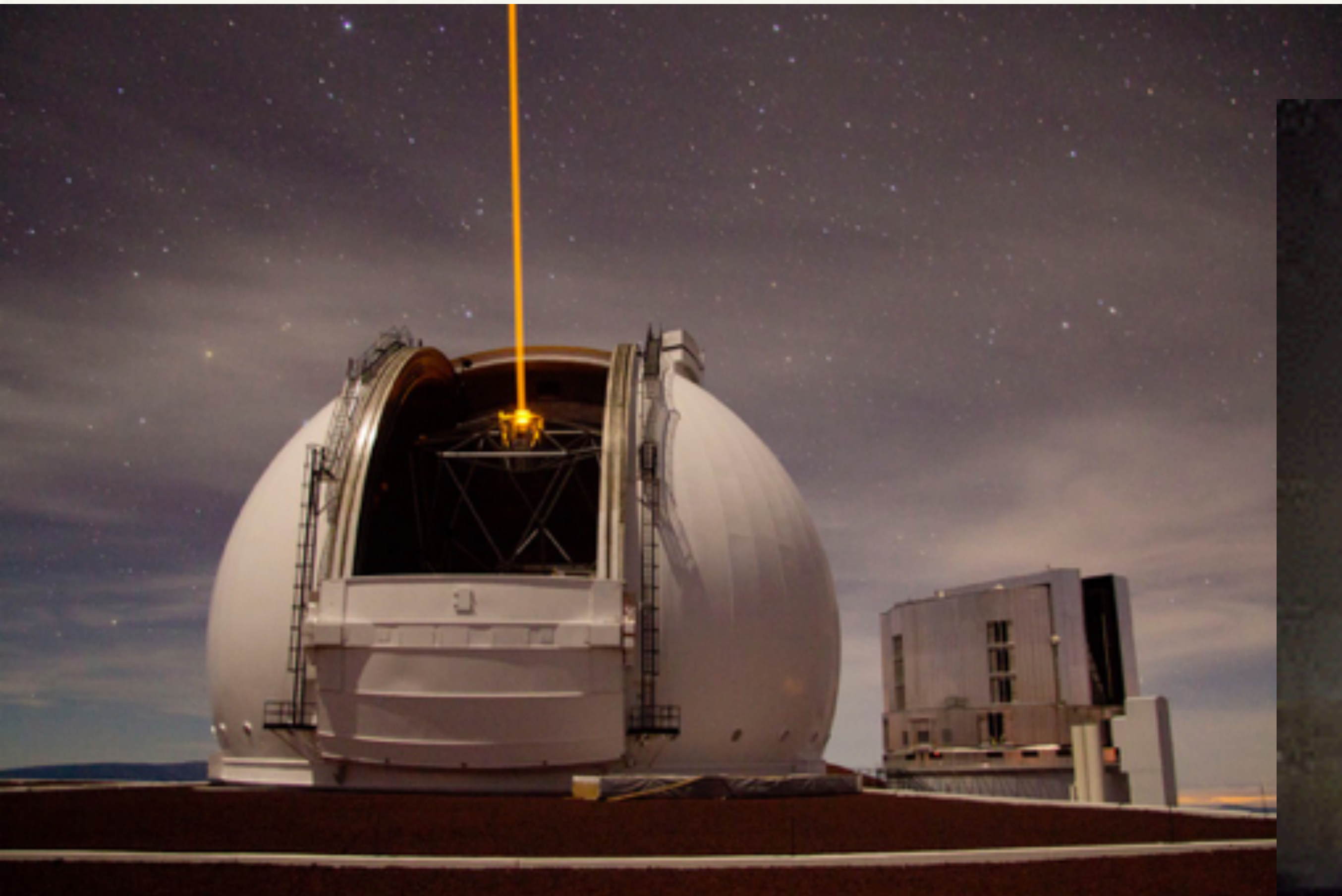


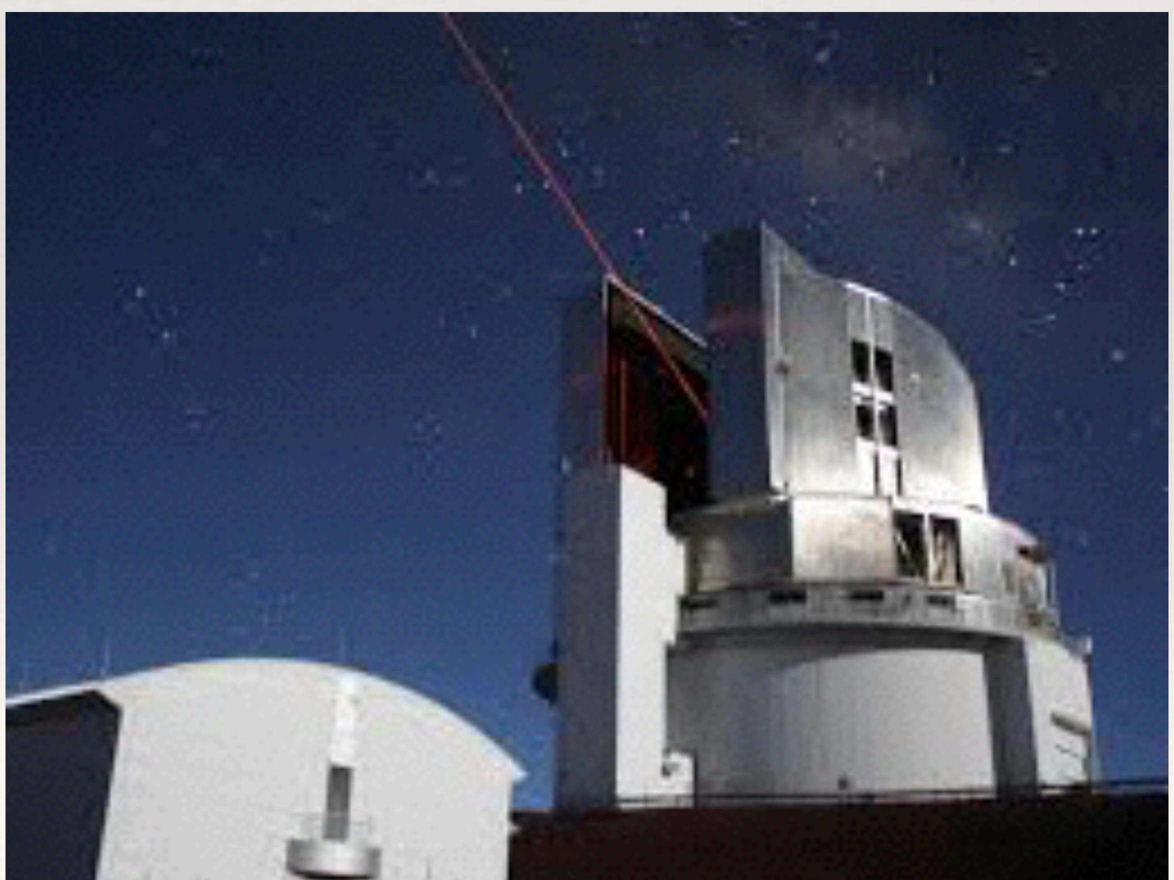



# Laser Guide Star (LGS)

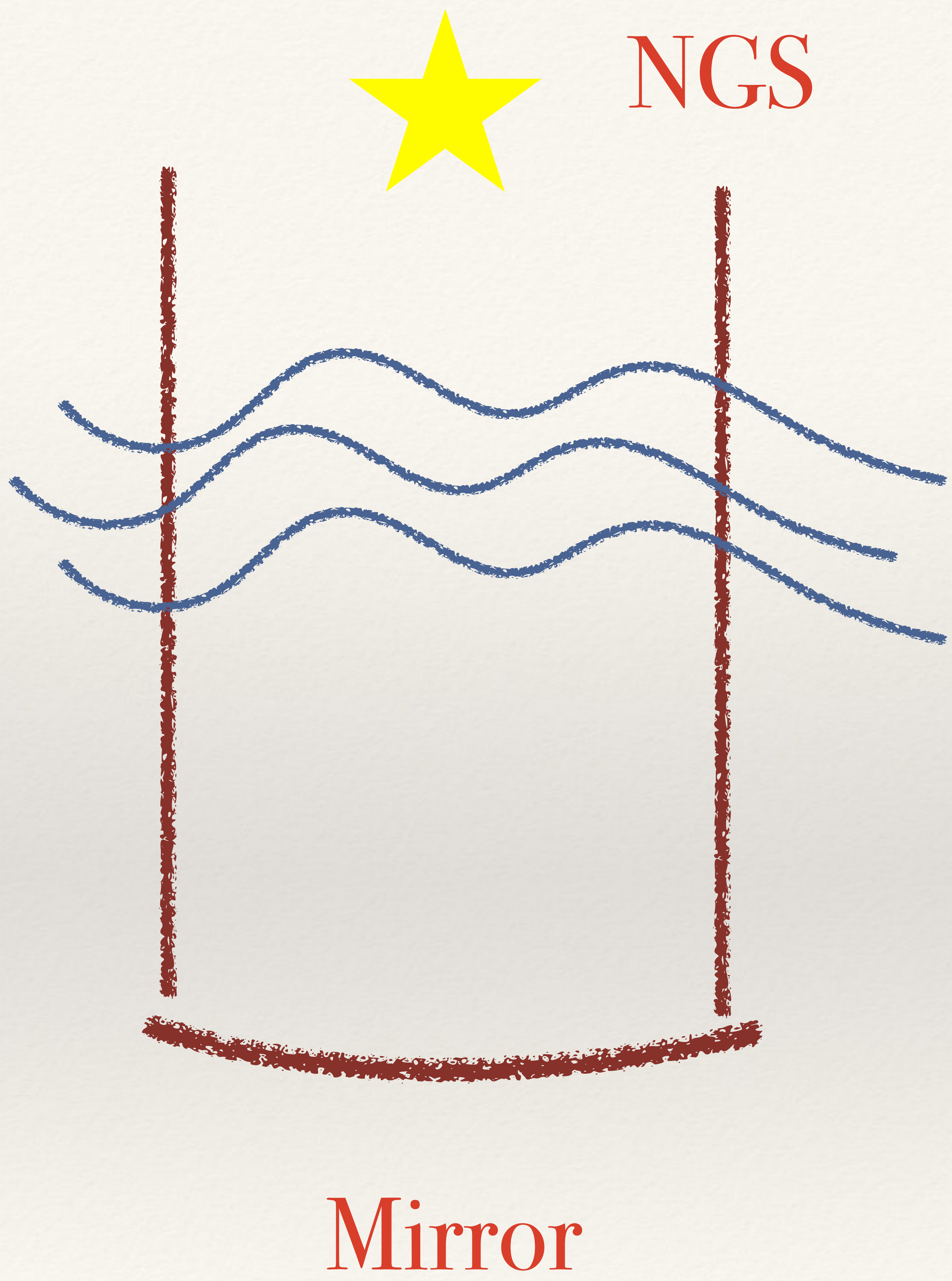


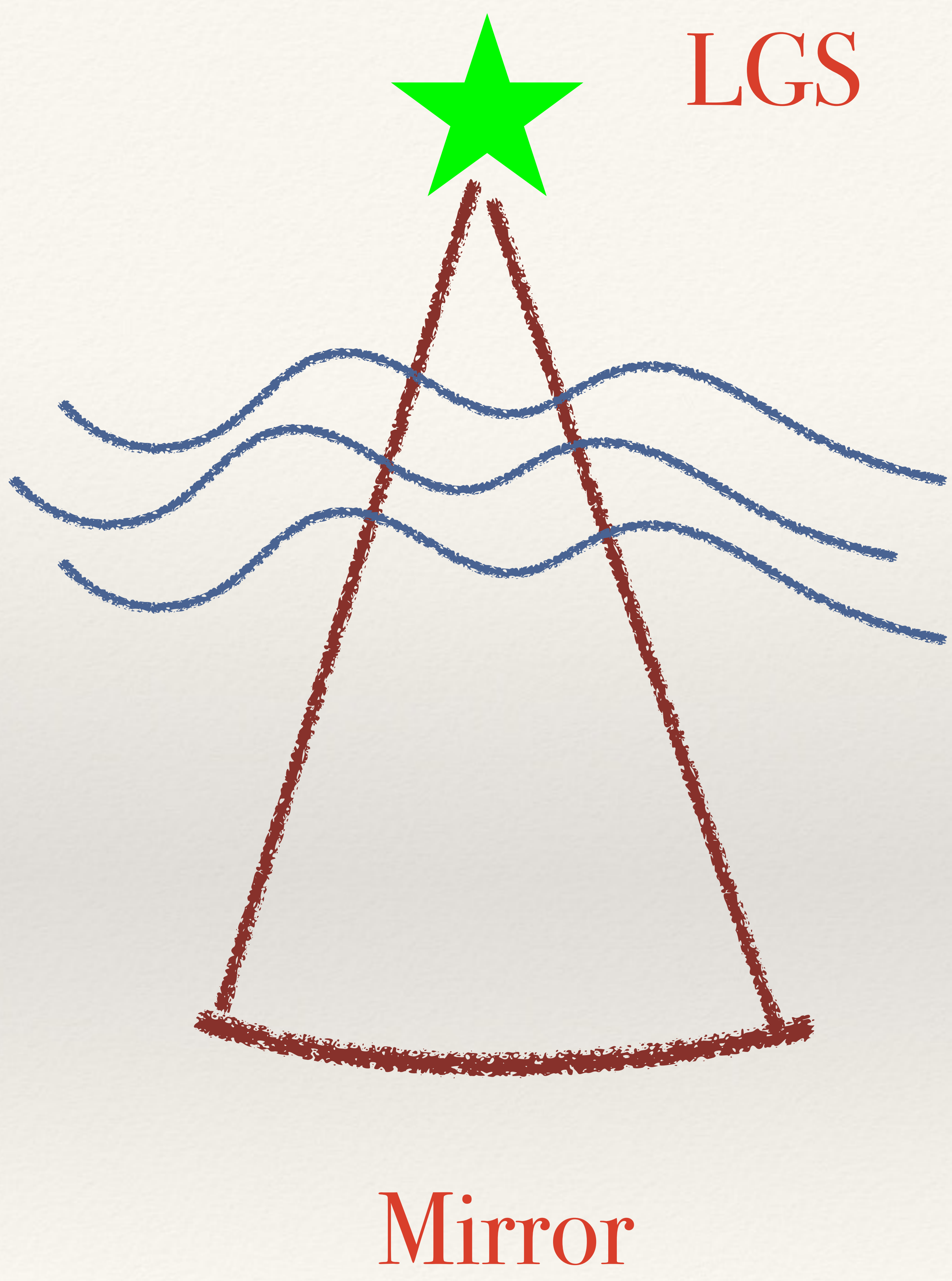
Davies & Kasper, 2012





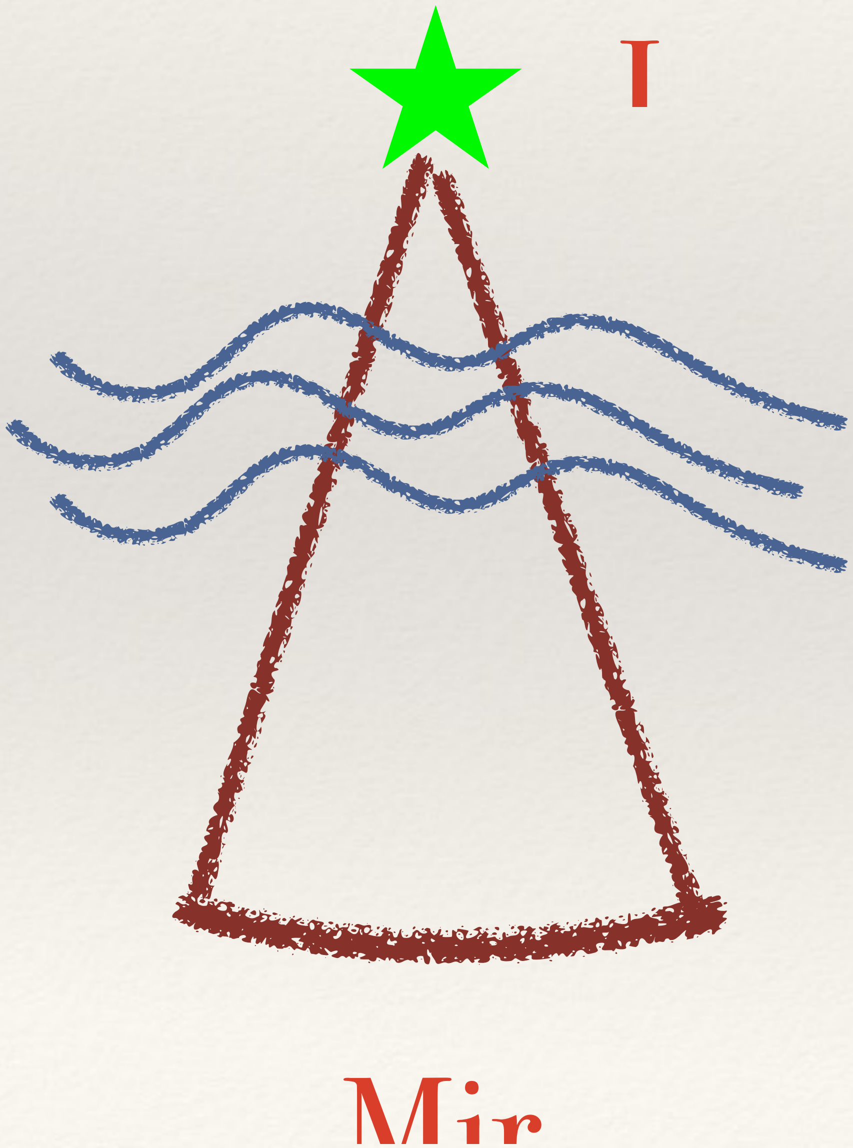

Laser Guide Star

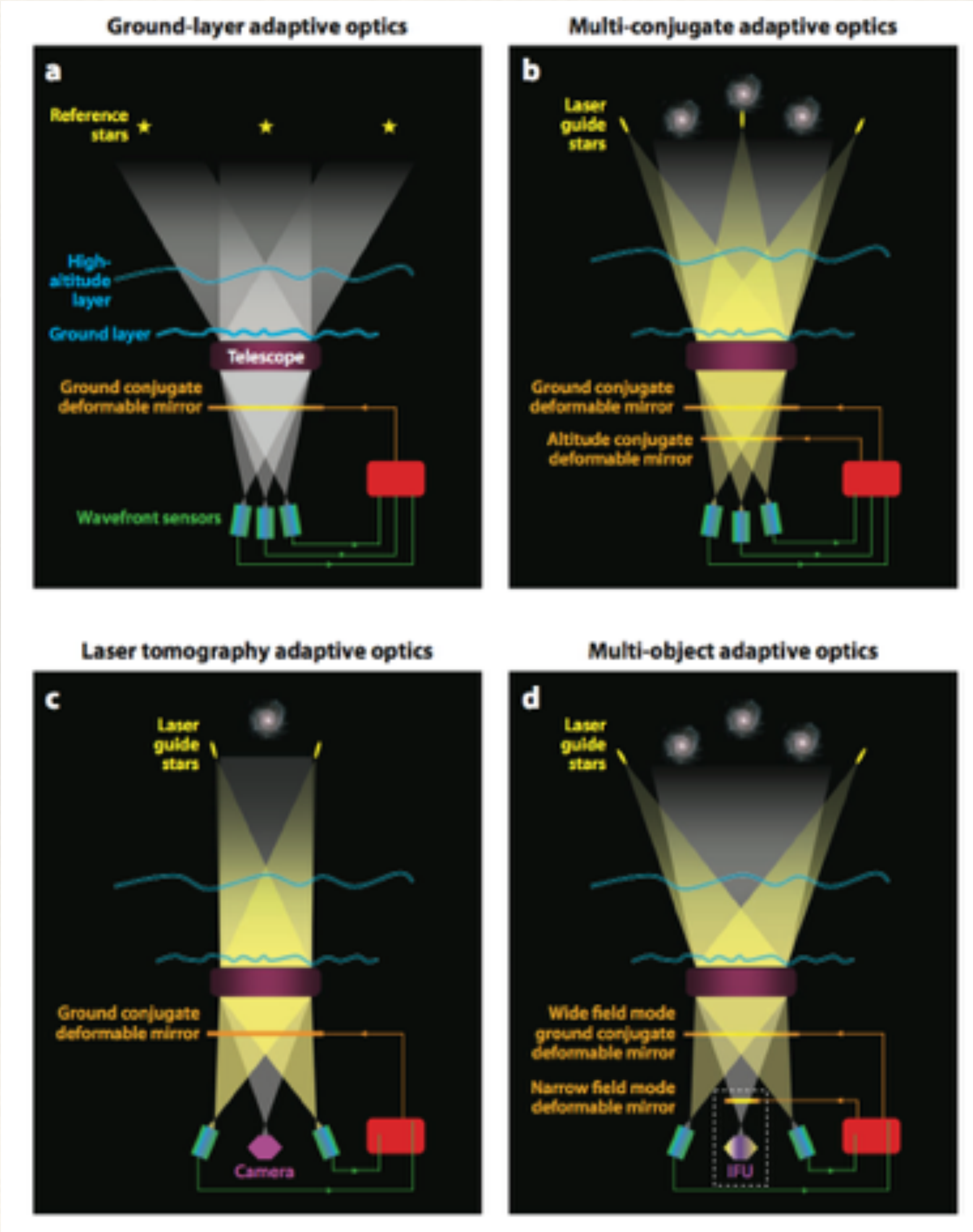

NGS
Mirror


LGS
Mirror

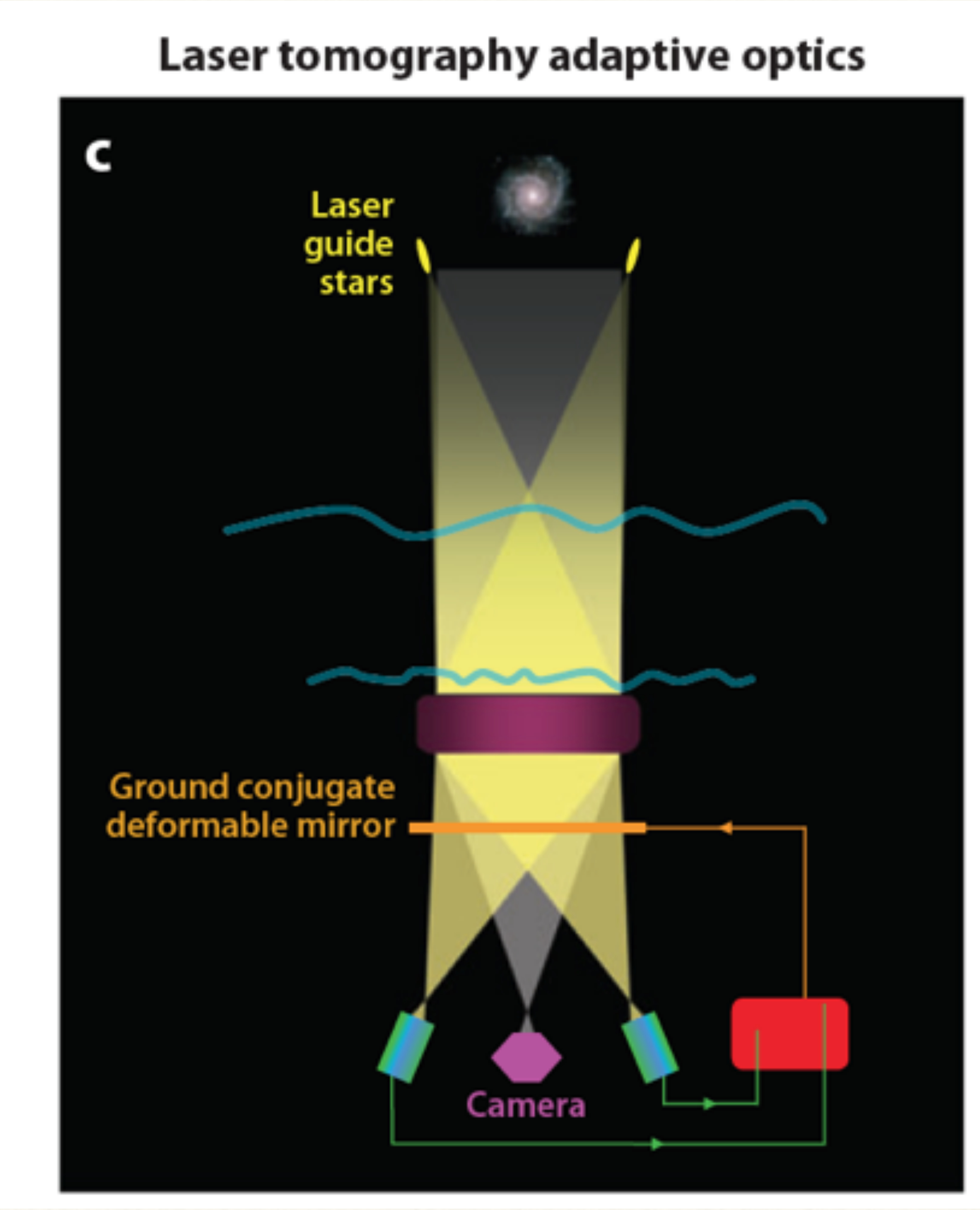
# CONE EFFECT

on telescope of 8 m could reduce the Strehl ratio of a factor of 0.6 in J and 0.85 in K



# Laser Tomography Adaptive Optics

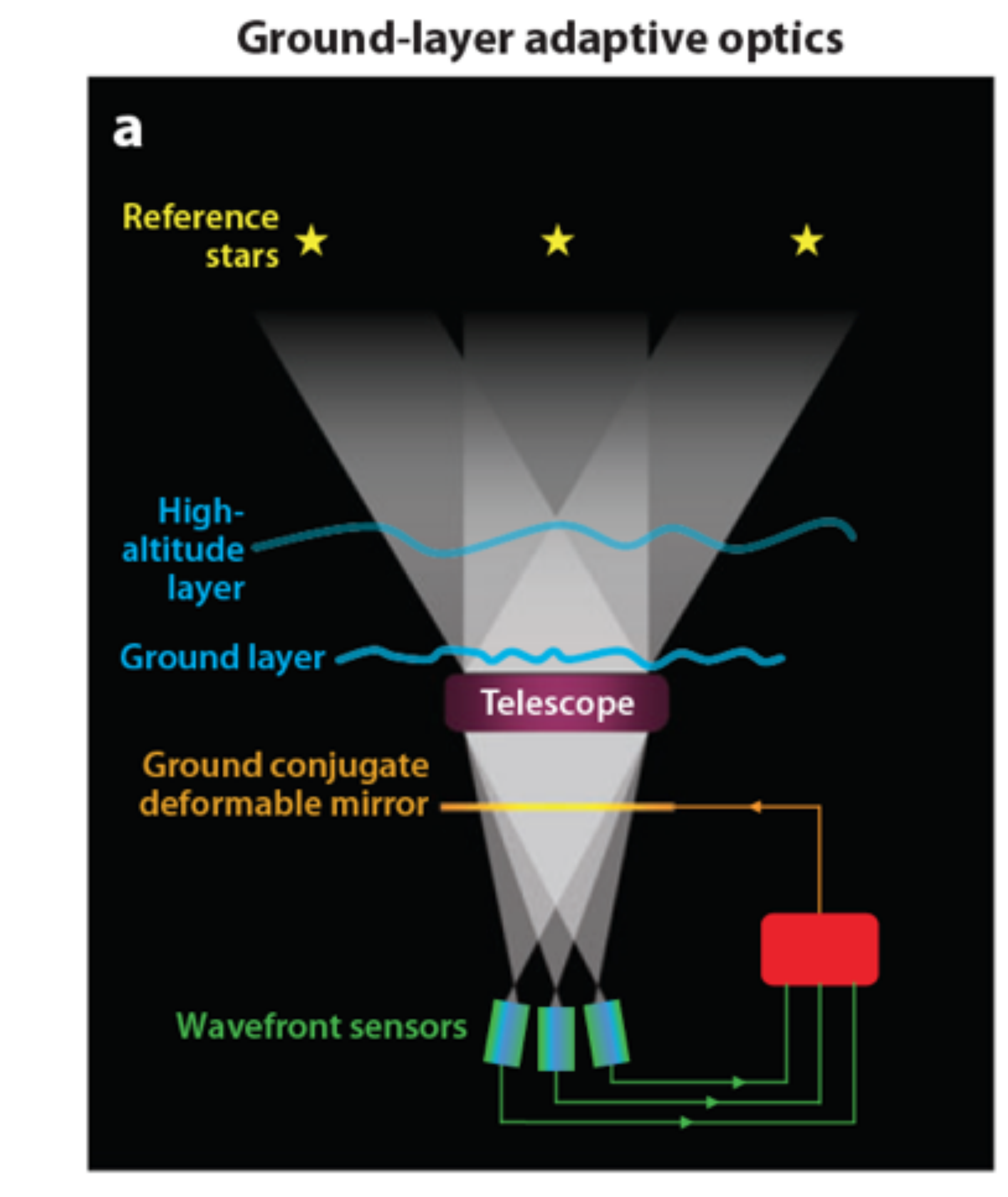



In order to contrast the Cone Effect Different LGSs are used.

Very Important:

the two cones have to superimpose on the turbulent zone

# Ground Layer Adaptive Optics



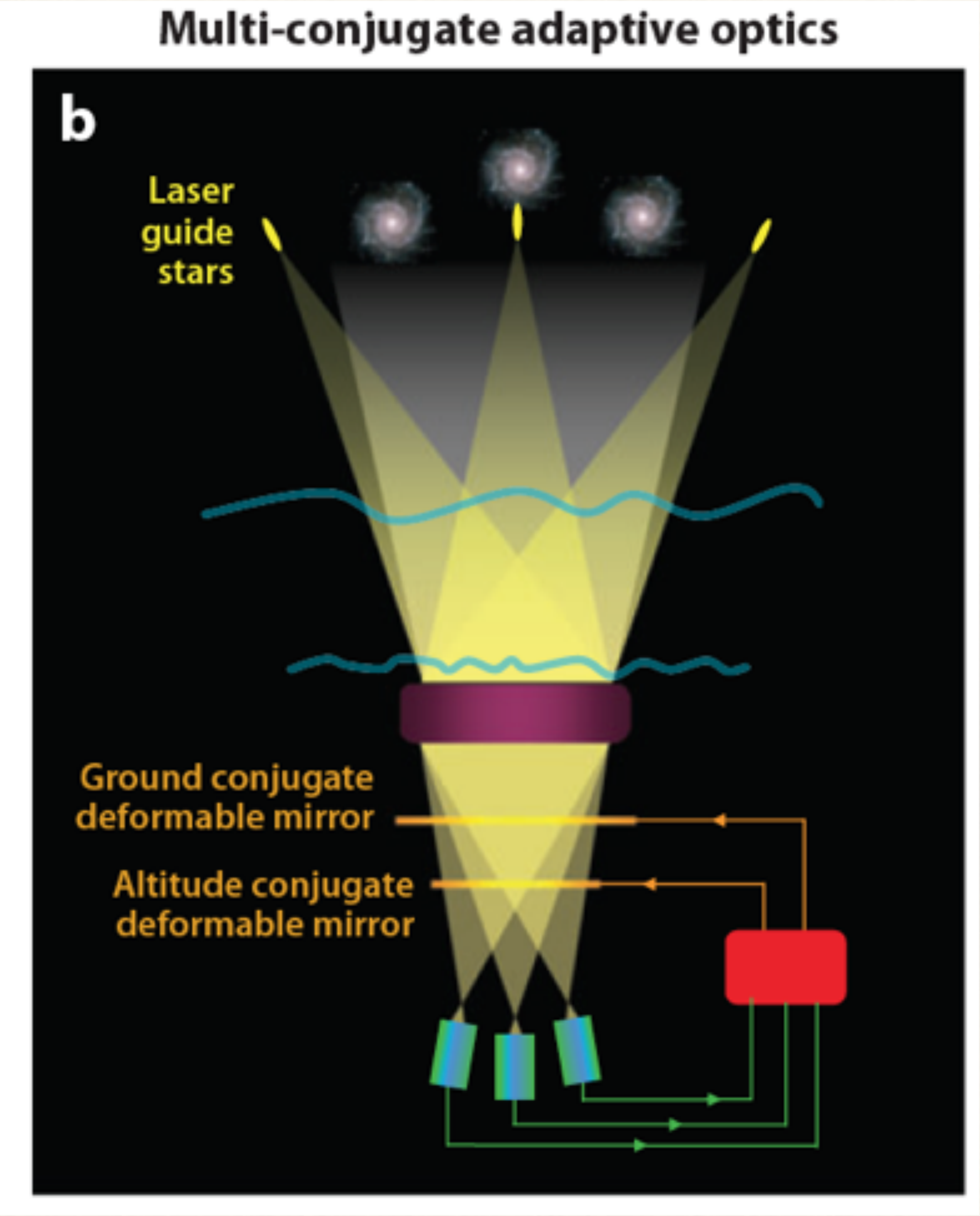

Correction only for the ground Layer. All rays (also those off axis) pass through this layer …

Advantages:

☑ Larger Field of View

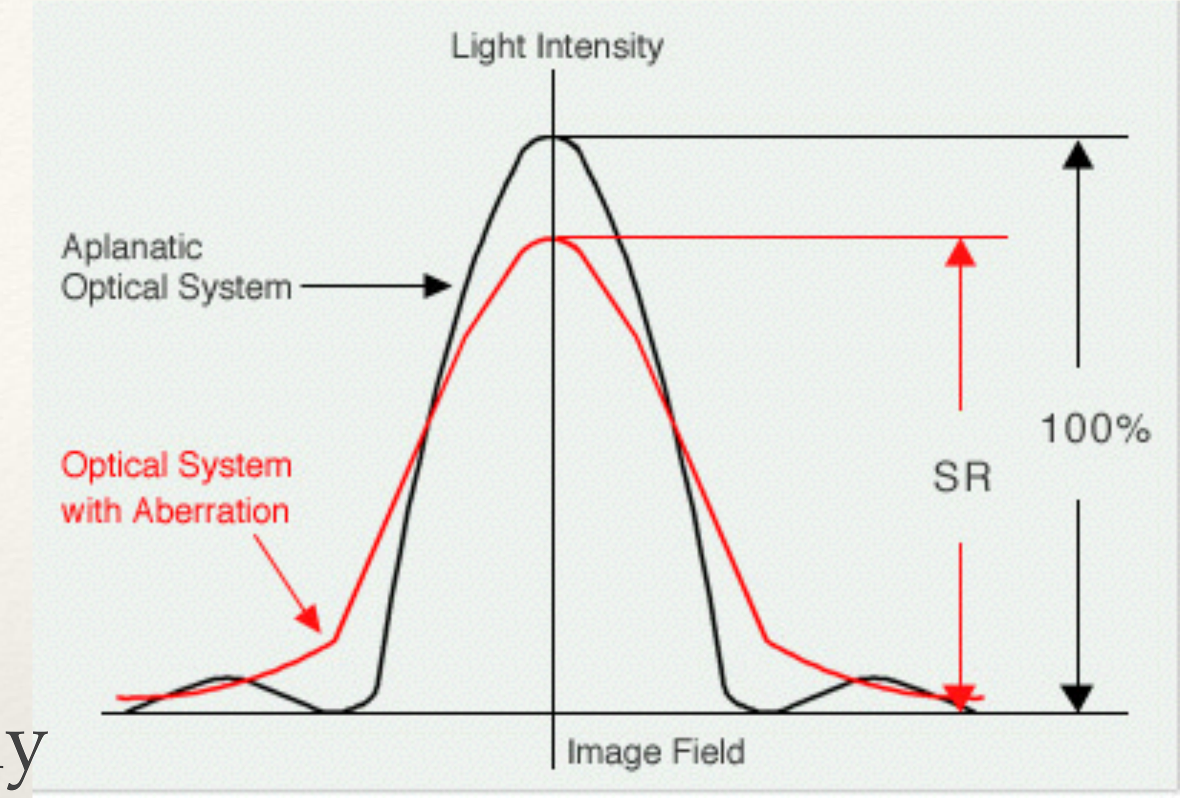
☑ correction is independent by the distance of Guide star

# Multi Conjugate Adaptive Optics




Several reference stars - Partial superimposition of cones on the turbulent layers and completely superimposed at lower height. Two or three different turbulent layers each conjugate with a deformable mirror

# Strehl Ratio




The AO Correction is never perfect

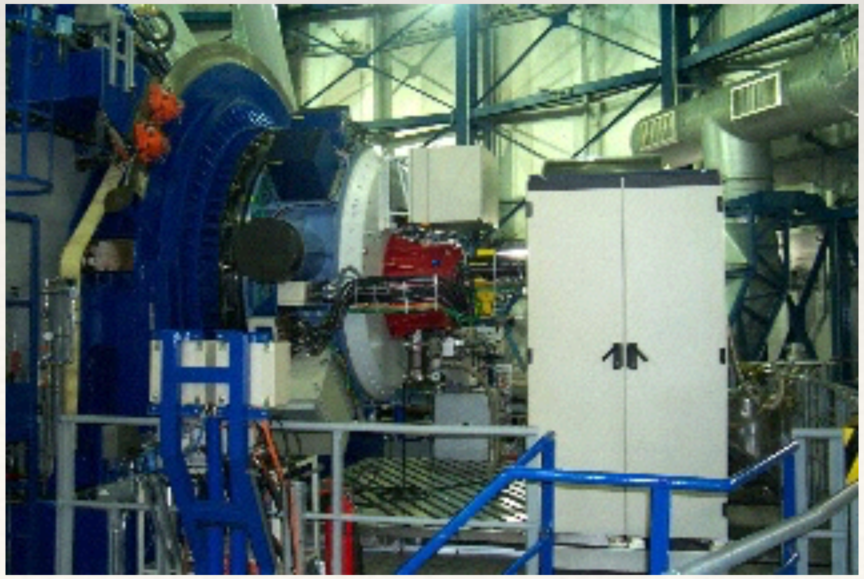
The Strehl ratio (SR) is the ratio between the intensity of the central peak as given by AO and the diffraction peak

Residual Wavefront error (and SR) mainly depends on:

- ☑ Pupil Sampling (Fried radius)
- ☑ Temporal Sampling (coherence $t_0$ ~2ms)

Marechal approximation

SR=exp[-(2πWFE/lambda)$^2$]



NACO

~ 200 Actuators (~3$r_0$) WFE~250nm

XAO (SPHERE)

~1400 Actuators ($r_0$) WFE~90nm

# Outer Working Angle

- The number of actuators limits the number of modes that are corrected
- Nyquist sampling limits the radius of the PSF region where correction is obtained (Outer working angle = OWA)
- OWA is given by the separation between actuators as projected on the telescope primary:

$$OWA \sim 1/2(\text{lambda}/D)\,(n_{actuators})^{1/2}$$

- If $n_{actuators}$~1400, OWA ~ 20 lambda/D

# Some Numbers ....

| | lambda | SR (AO) | SR (XAO) | OWA |
|---|---|---|---|---|
| | (µm) | 200 act. | 1400 act. | (arcsec) |
| | | NACO | SPHERE | |
| WFE (nm) | | 250 | 90 | |
| R | 0.64 | 0.00 | 0.46 | 0.31 |
| I | 0.79 | 0.02 | 0.60 | 0.38 |
| z | 0.95 | 0.07 | 0.70 | 0.46 |
| J | 1.25 | 0.21 | 0.82 | 0.60 |
| H | 1.65 | 0.40 | 0.89 | 0.79 |
| K | 2.20 | 0.60 | 0.94 | 1.06 |
| L' | 3.80 | 0.84 | 0.98 | 1.83 |

# Adaptive Optics Science

SOLAR SYSTEM
- SUN
- ASTEROIDS
- PLANETS

STELLAR FORMATION
- STELLAR MULTIPLICITY
- CIRCUMSTELLAR DISKS
- EXOPLANETS

RESOLVED STELLAR POPULATIONS

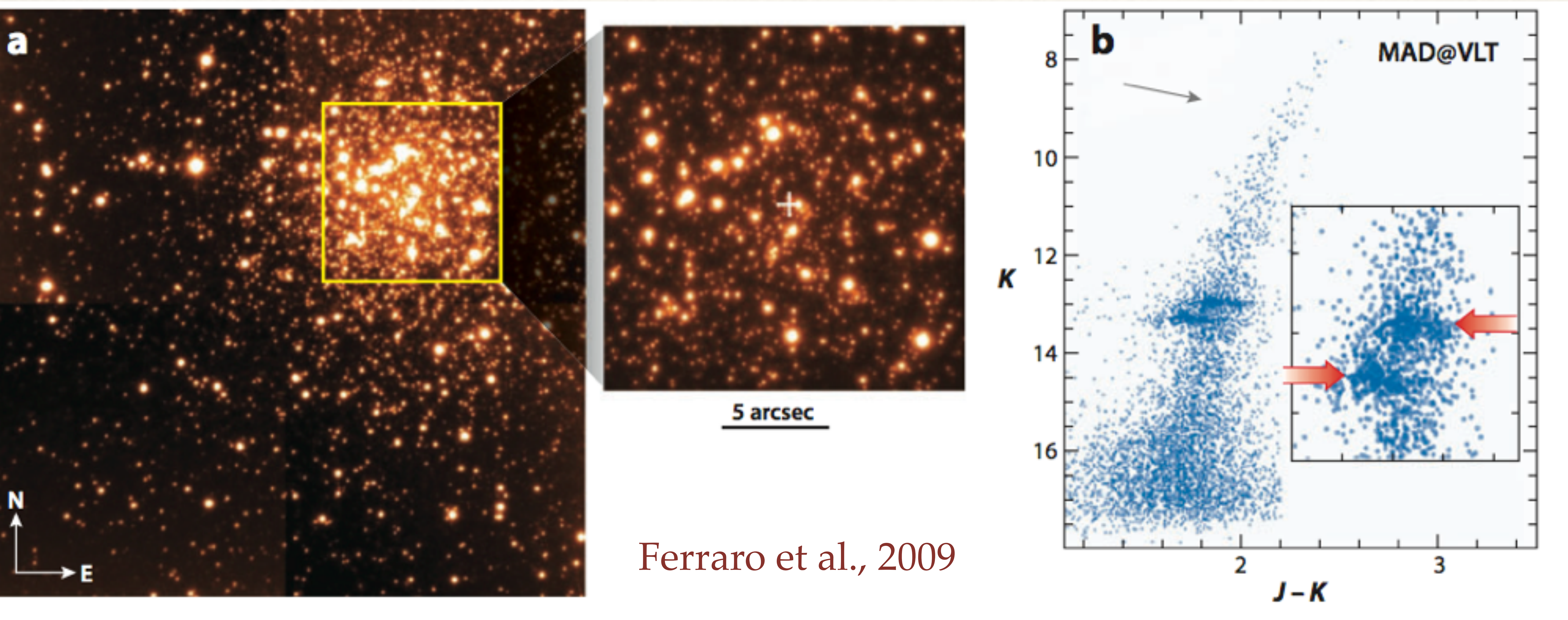
THE GALACTIC CENTER

GALAXY NUCLEII AND ACTIVE GALAXIES
- BLACK HOLE MASSES
- GAS INFLOW AND OUTFLOW
- QUASAR AND MERGER

THE HIGH REDSHIFT UNIVERSE

# Globular Cluster: Terzan 5 with MAD

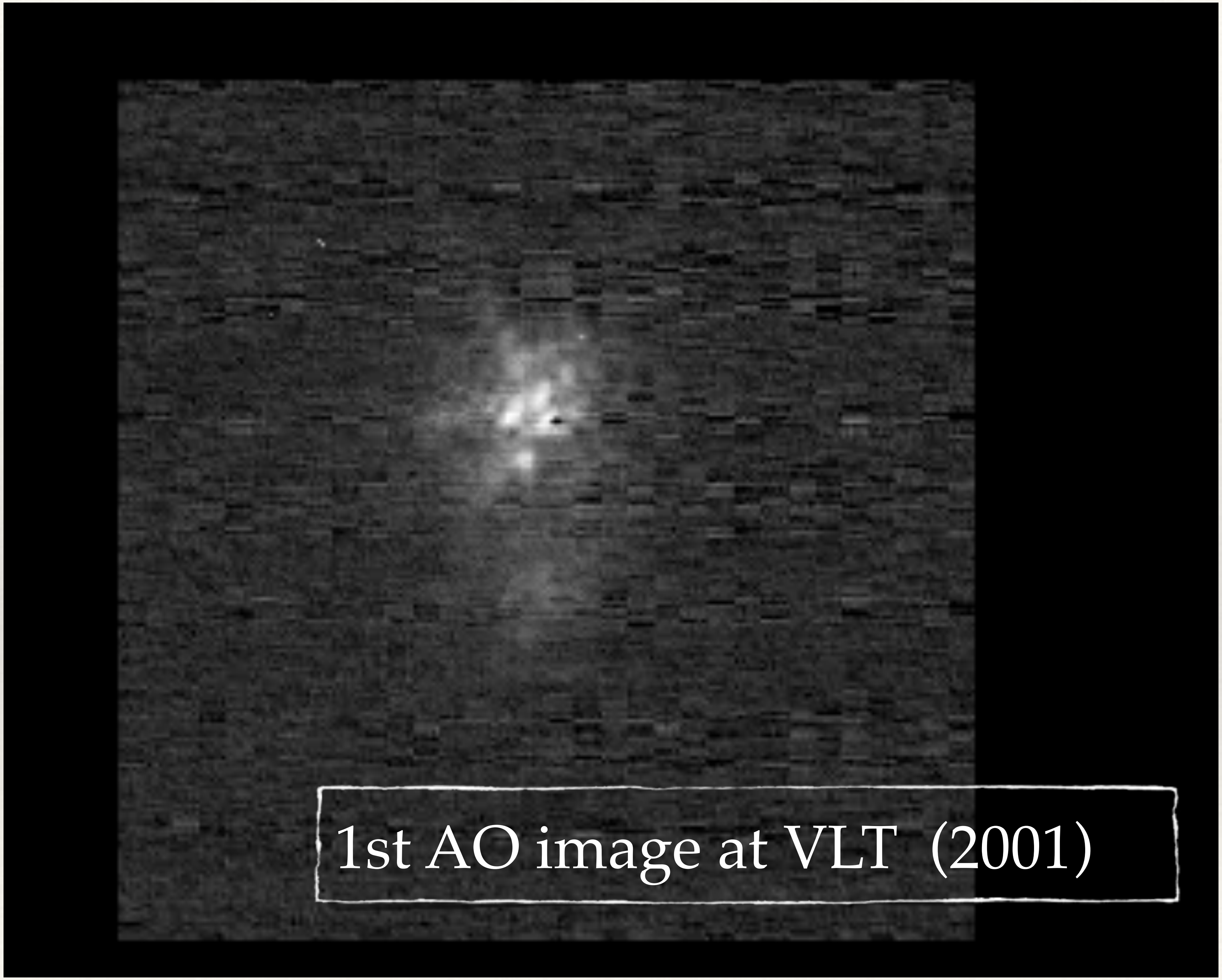
MAD (Multi conjugate AO Demonstrator) is designed to perform wide Field of View (FoV) adaptive optics correction in **K band** (2.2 μm) over **2 arcmin**on the sky by using relatively bright (mv < 14) Natural Guide Stars (NGS).



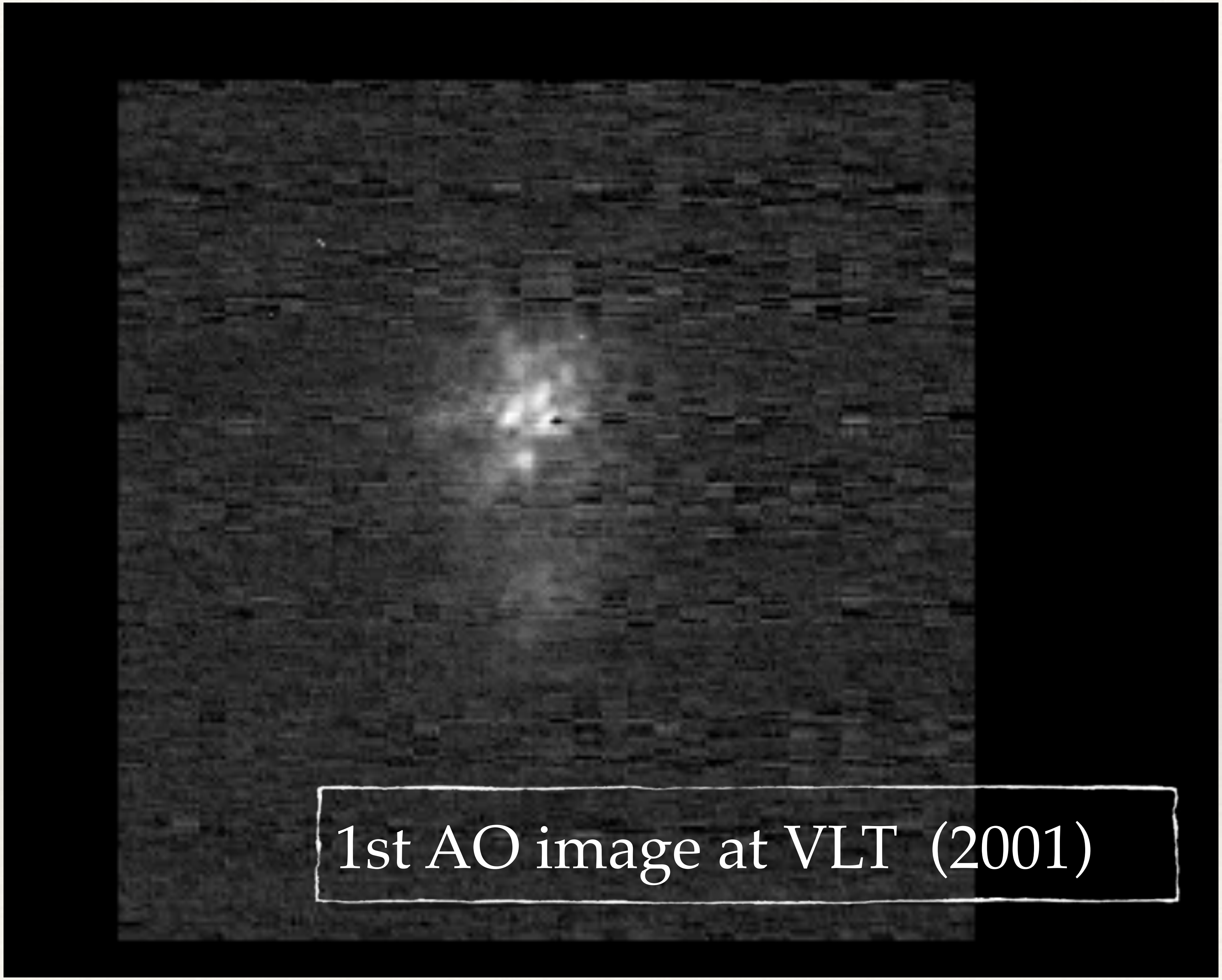

Ferraro et al., 2009

Resolution of 0.1 arcsecond on a FoV of 60 arc seconds

# Adaptive Optics



# Adaptive Optics



# Adaptive Optics