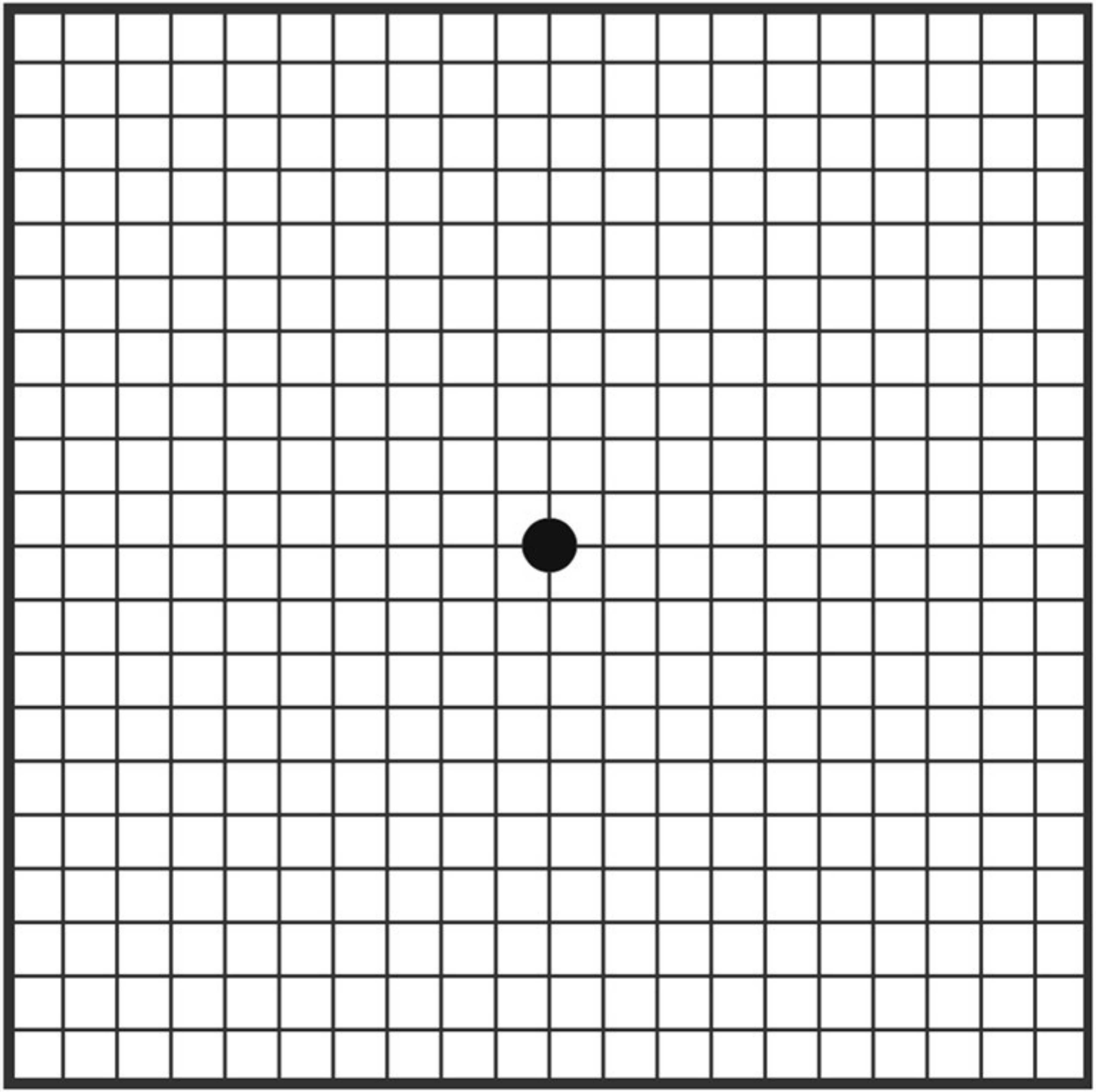


# Night sky at Paranal Observatory, Chile
# [ 25 deg south, 70 deg west, 2635m alt ]

Credit: Stephane Guisard

# Adaptive Optics for VLT und E-ELT

Stefan Hippler

Astro Tech Talk

MPIA

November 4, 2016

Photo: Yuri Beletsky

# Outline

- What is  Adaptive Optics (AO) good for?
- VLT AO systems:
  *NACO*, MACAO, PARSEC, MAD, SPHERE, *CIAO*, *AOF*, ….
- E-ELT AO systems:
  SCAO, MCAO, LTAO
- Summary

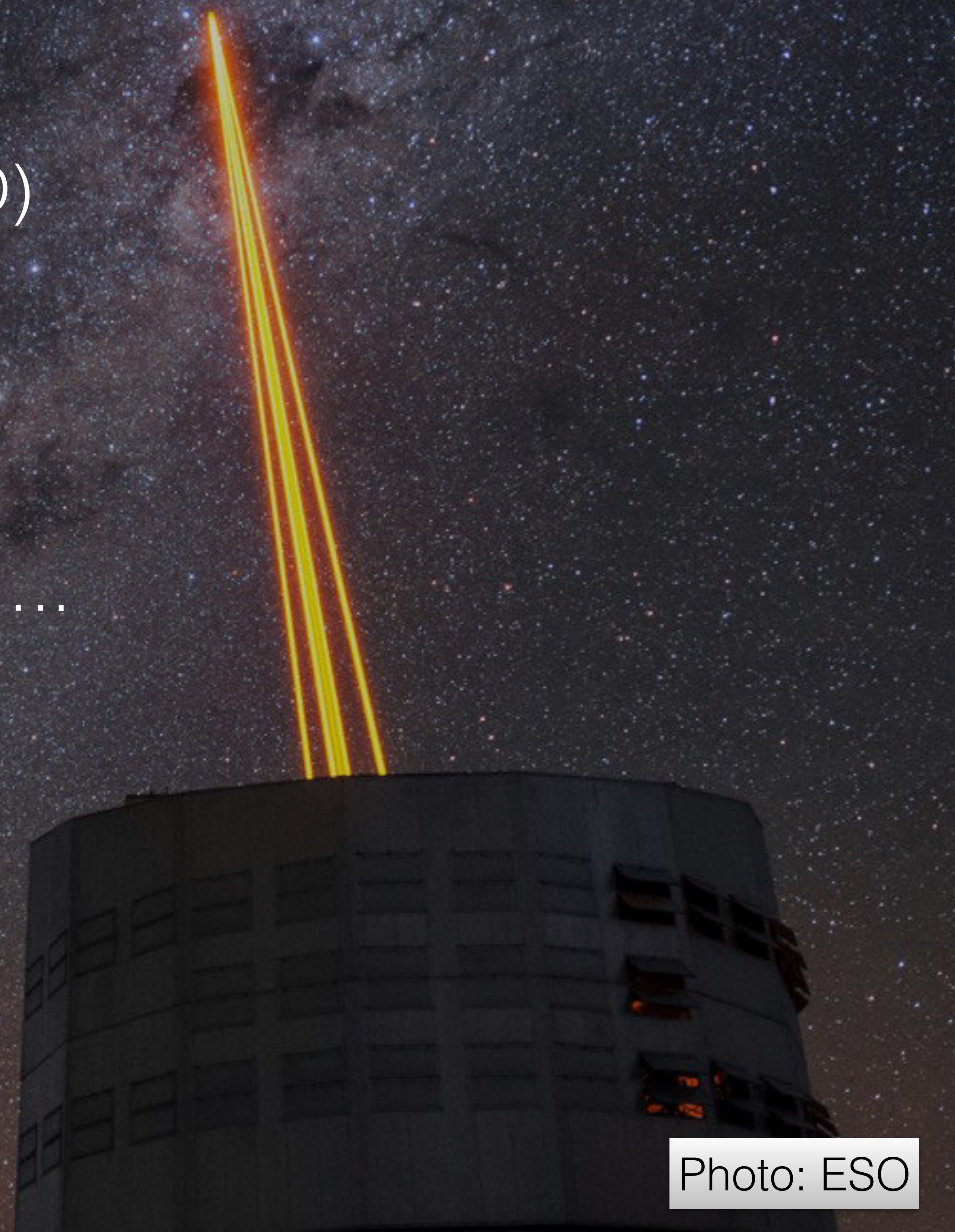


Photo: ESO

# Motivation

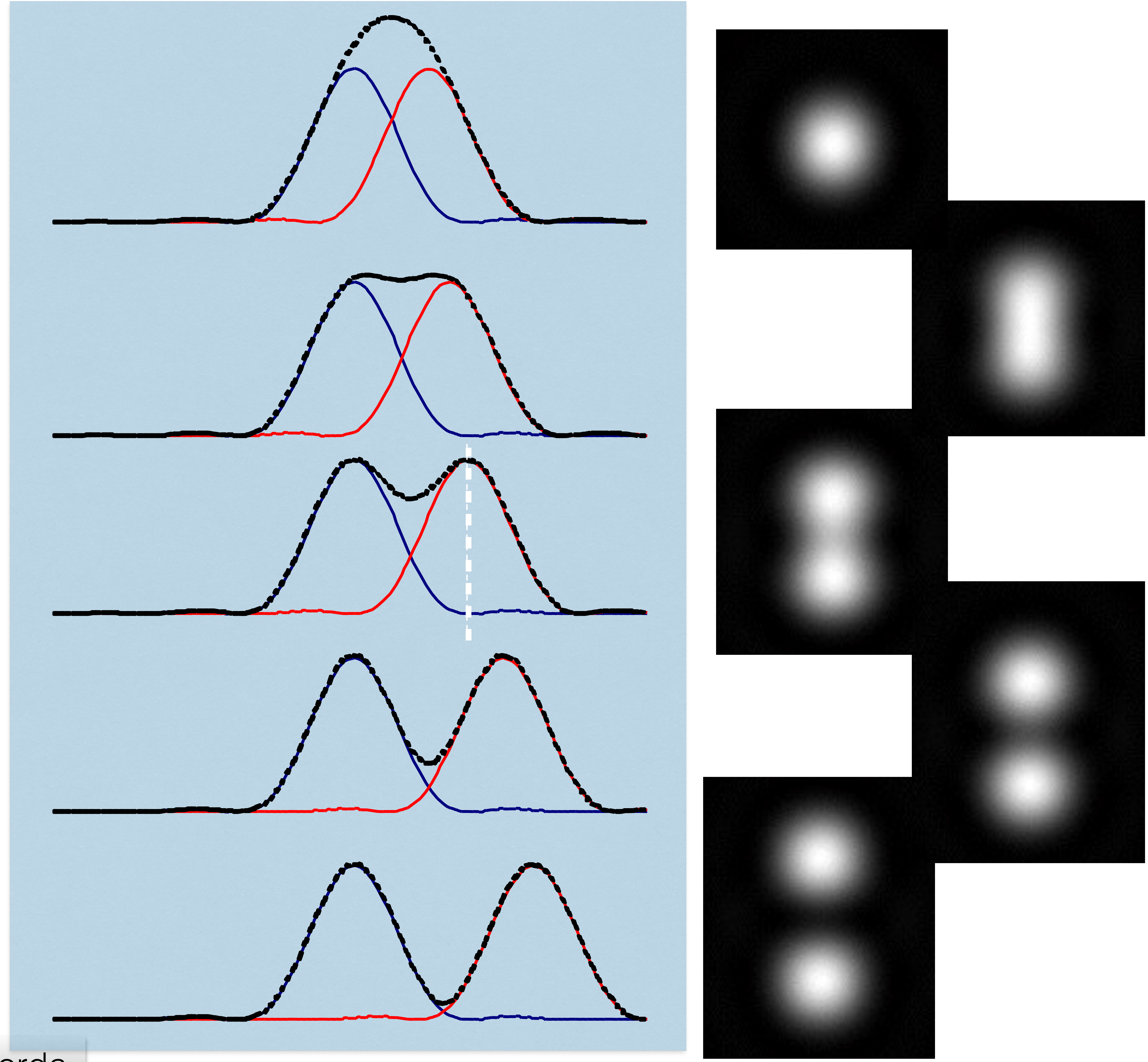
- There are essentially two parameters that determine the performance of astronomical observations: sensitivity und angular resolution.
- Sensitivity increases with the size of the telescope, larger mirrors simply collect more photons.
- The angular resolution gets better with increasing telescope size but only if the telescope delivers diffraction limited images.

## Optical resolution

2 unresolved point sources

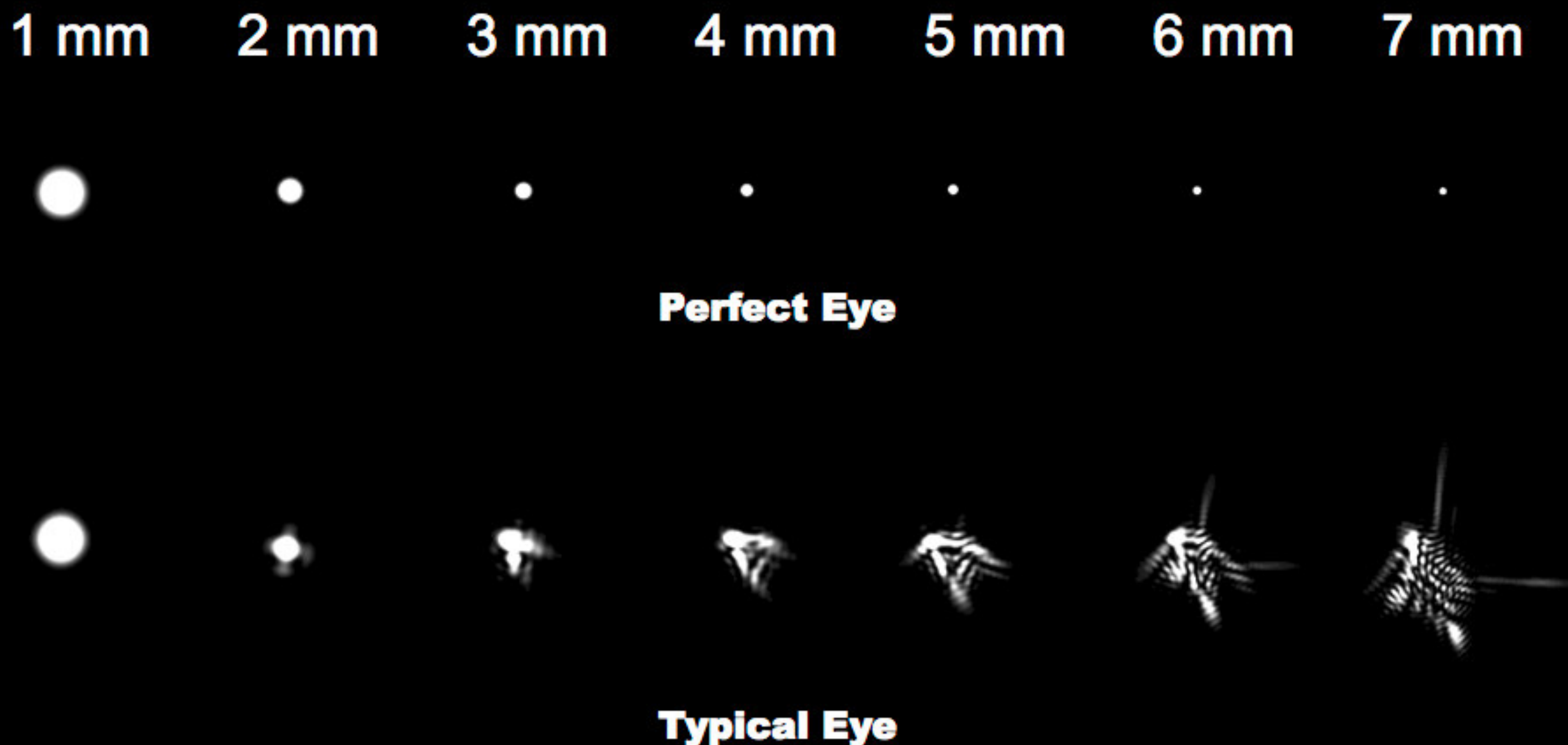
Rayleigh resolution limit:
$\Theta = 1.22\ \lambda/D$
*8m VLT: 0.015”*

Resolved:
$\Theta = 2.44\ \lambda/D$
[4mm eye: ~60”]



Credit: Austin Roorda

# Point Spread Function vs. Pupil Size

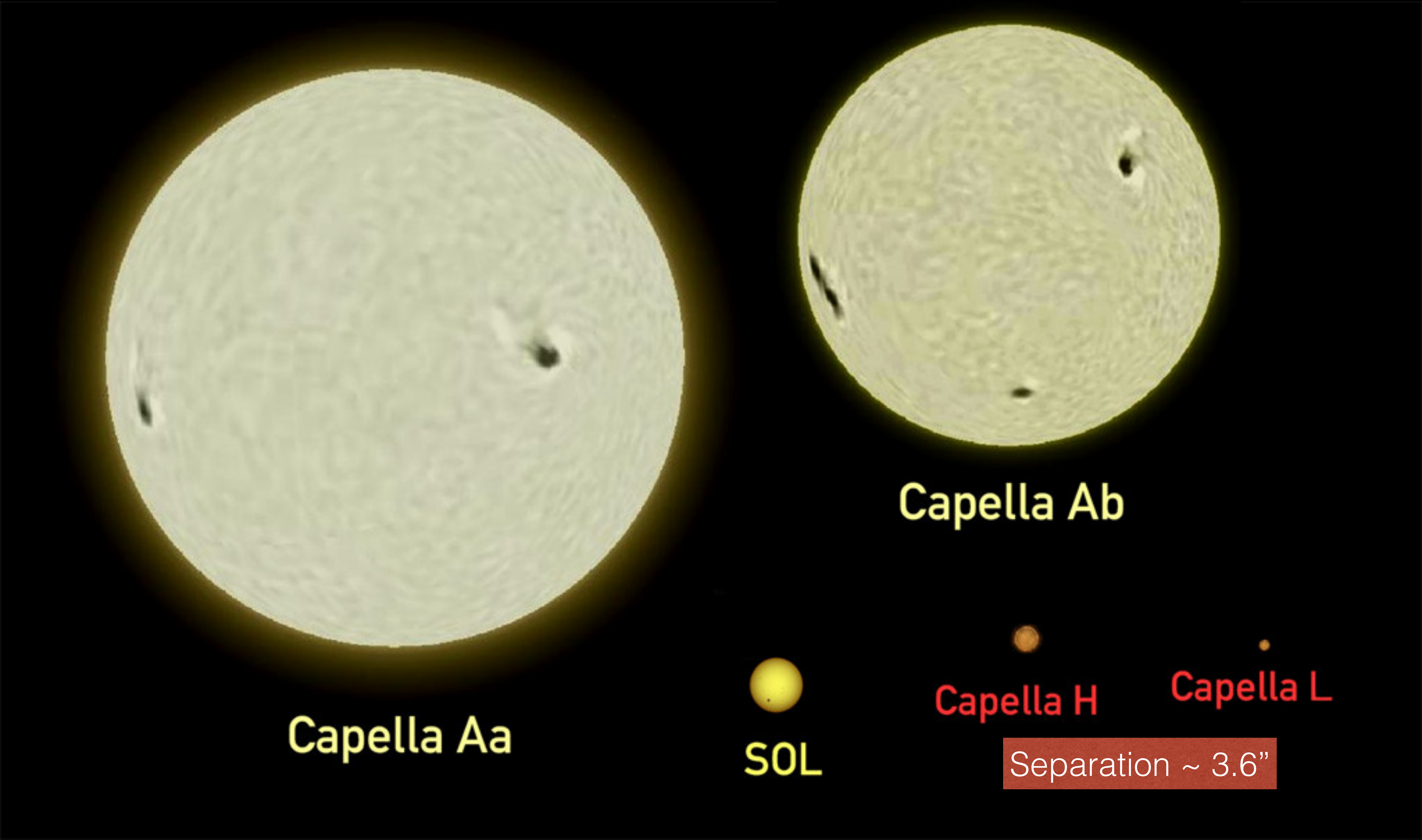



Credit: Austin Roorda


~ 45 arcsec
Night sky next Satur
19:00 hours
Earth, MPIA, 550m
FOV 2.79°
59.7 FPS
2016-11-12 19:00:00 UTC+01:00


N
W
S
Capella
Earth, MPIA, 550m
FOV 196°
25.8 FPS
2016-11-04 19:00:00 UTC+01:00

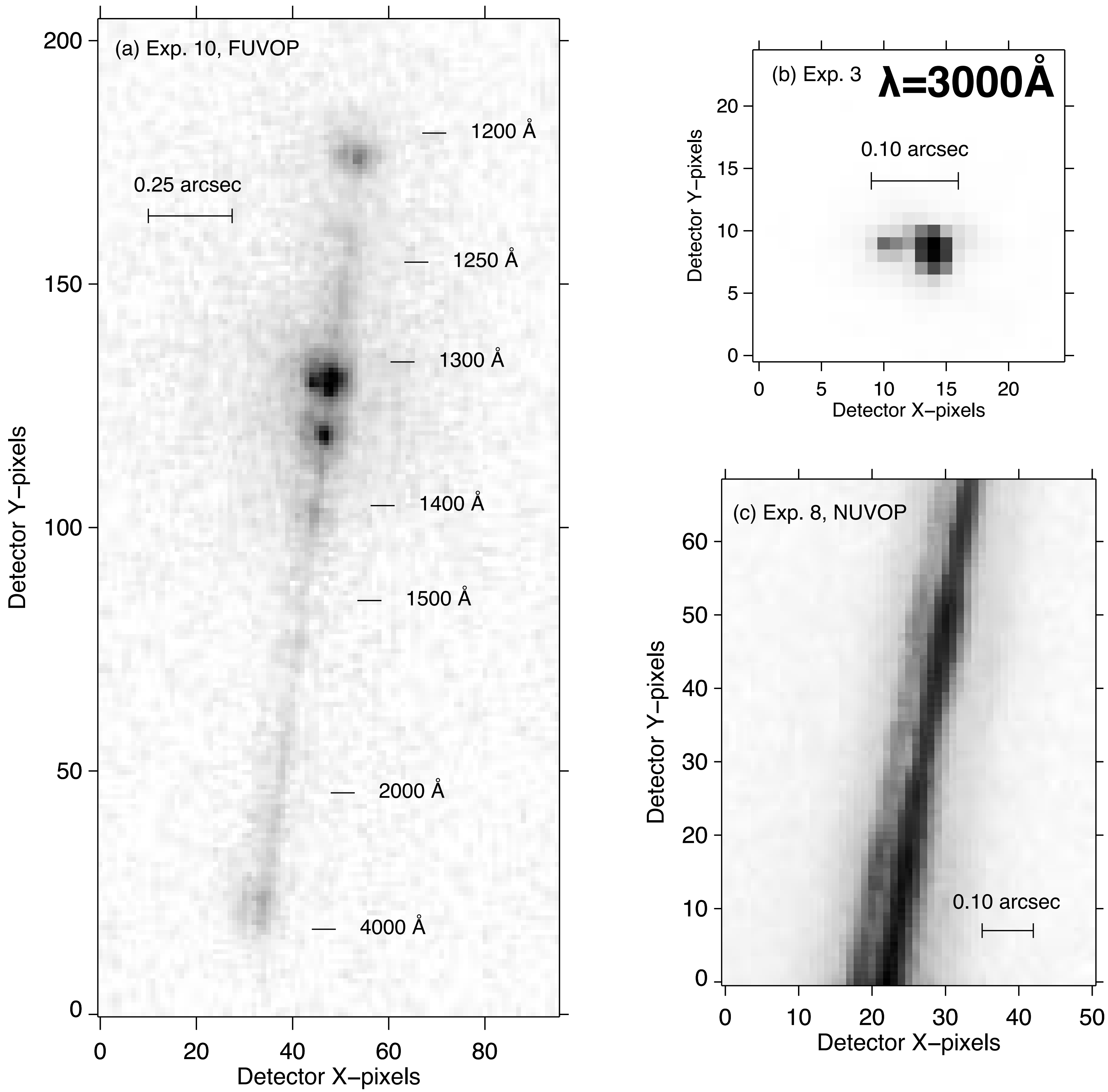
Separation ~ 56 mas (0.74 AU, 111 Mio. km)




Separation ~ 3.6”

Separation A - H/L ~ 12 arcmin (9500 AU)

Young & Dupree 2002
Hubble Faint Object Camera




$R = \lambda/D$
$= 0.3\mu m / 2.4m$
$= 0.026$ arcsec

Pixelgröße:
0.014 arcsec

Fig. 1.—Examples from the FOC exposures showing the two Capella giants to be clearly resolved. The cool G8 giant is to the left of the hot G1 giant in these images and has weaker emission at all wavelengths. The pixels in each image have the same size, corresponding to $14.35 \times 14.35$ mas$^2$. The gray-scale images are such that dark represents strong emission, and light denotes weak emission. A scaling has been applied to each image to enhance the cool giant. (*a*) FUVOP image from exposure 10 showing the spectrum from 1200 to 6000 Å. (*b*) Image from exposure 3 obtained with a broadband filter sensitive to wavelengths 2500–3000 Å. (*c*) Section of the NUVOP spectral image from exposure 8 showing a wavelength region around 3000 Å. Spectral images (*a*) and (*c*) show that the objective prisms produce spectra with a dispersion direction inclined at angles 7°–10° to the detector *Y* direction.

## The observed twinkling of stars occurs because their light passes through various layers of the Earth's atmosphere

Time scale: 0.01 - 0.001 seconds

Pattern: random, non periodic

Naming: Scintillation

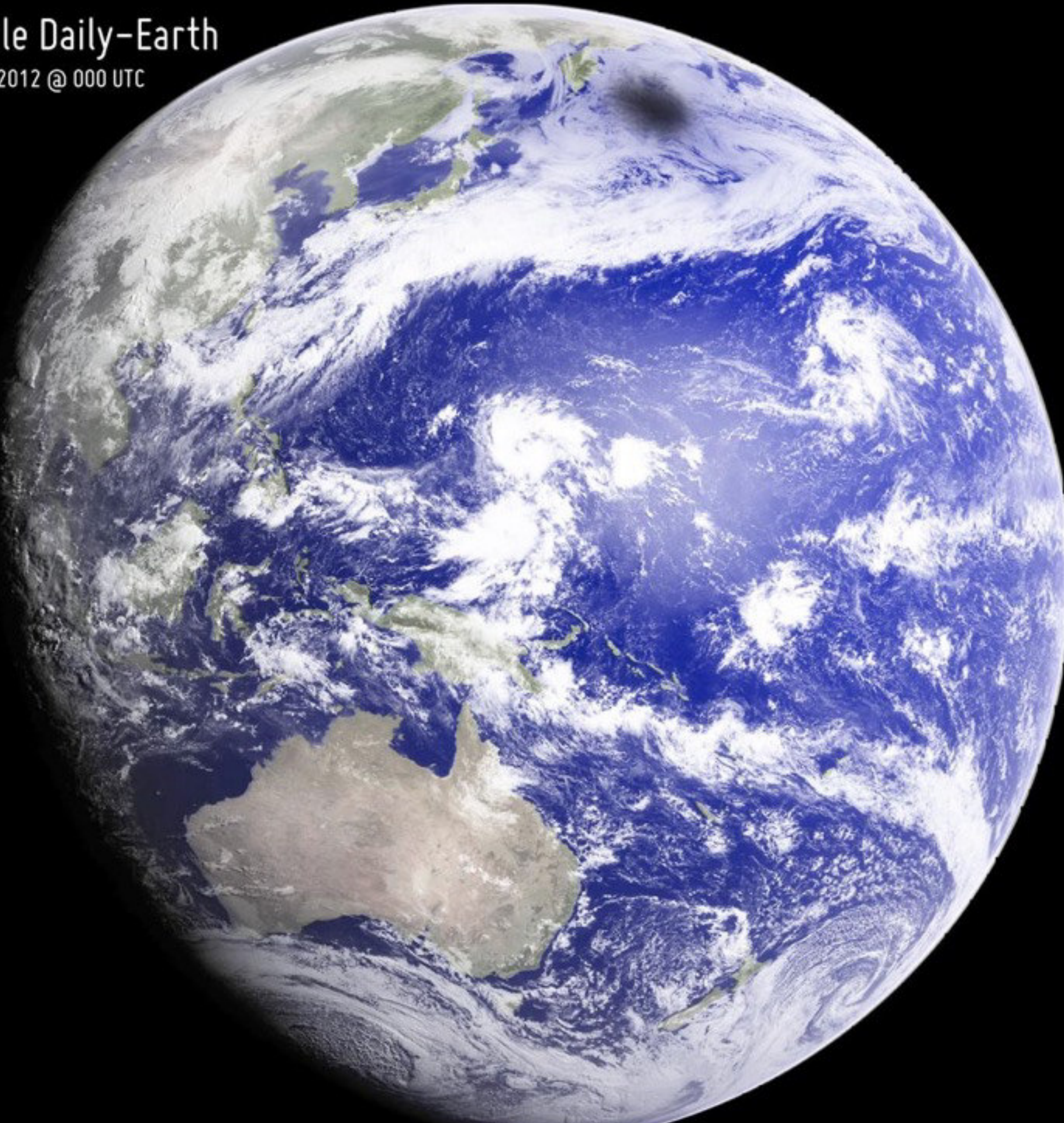
Twinkling is stronger towards horizon, less strong towards zenith

Simplified explanation: random focusing and defocusing of star light

Reason: optical turbulence of the Earth's atmosphere

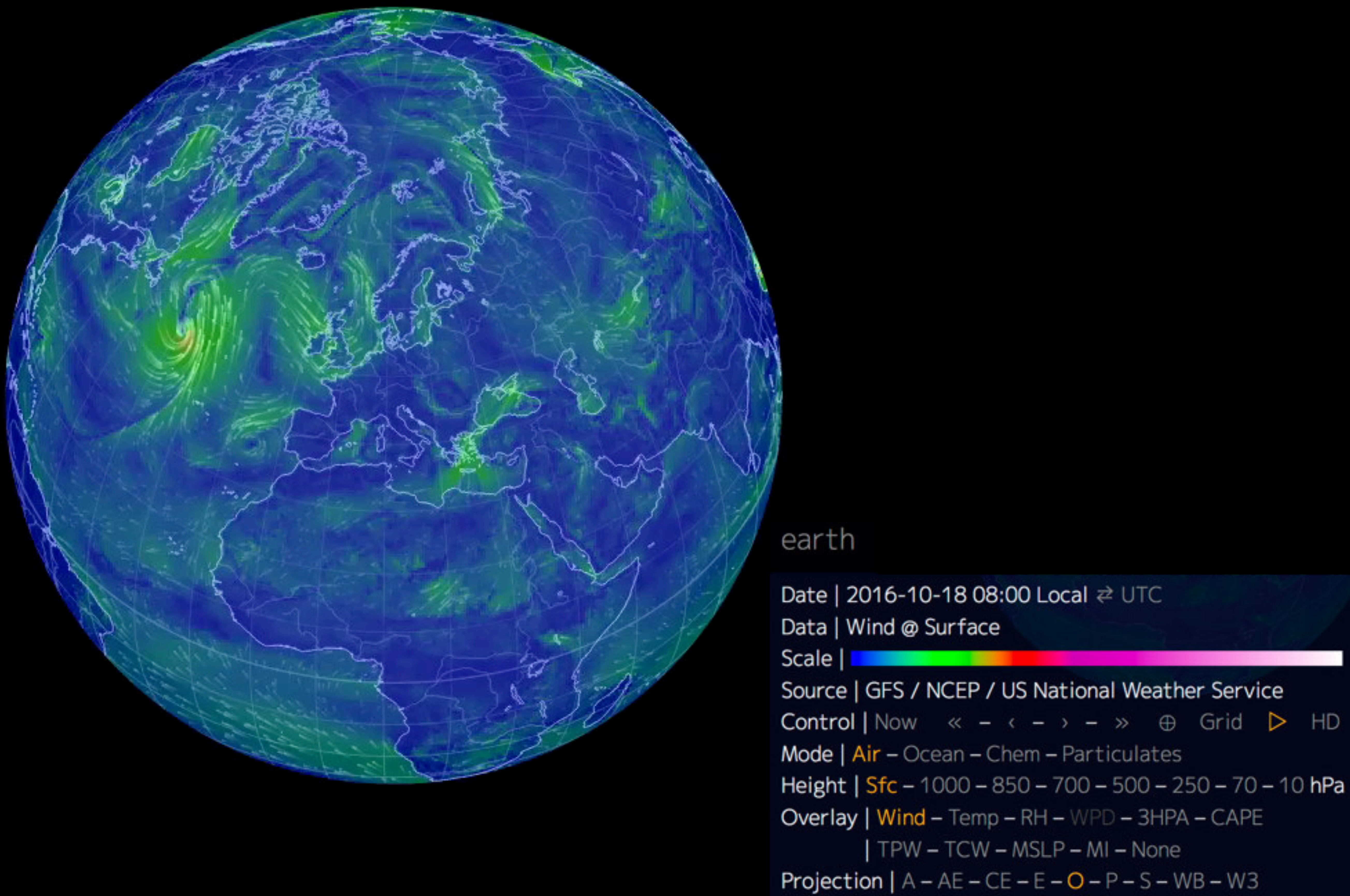
# Visible Daily–Earth

May 21, 2012 @ 000 UTC

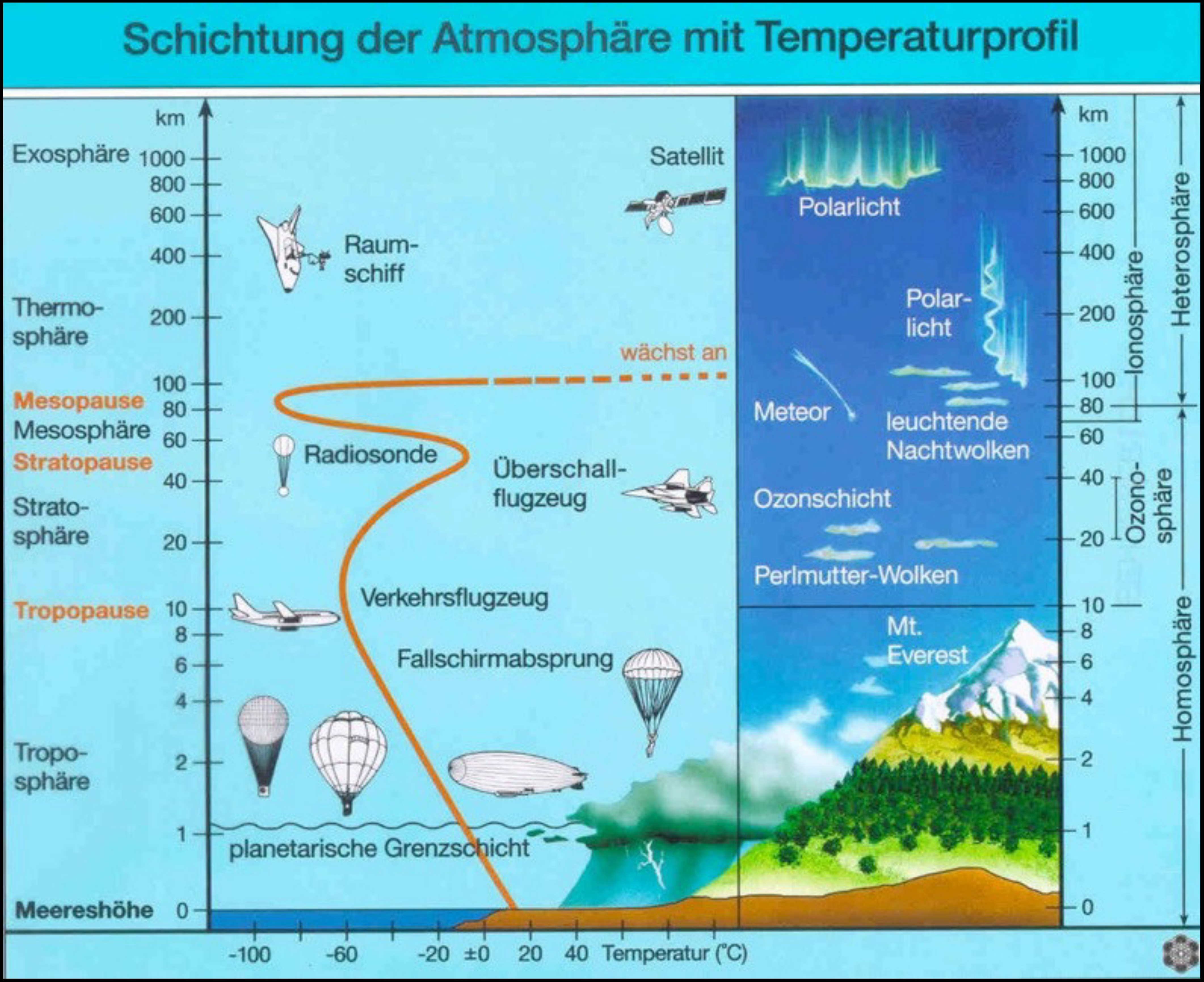


CREDIT: PHL @ UPR Arecibo (phl.upr.edu)

Credit: https://earth.nullschool.net/



# Atmospheric optical turbulence is a result of variations of air temperature and humidity




Quelle: Fonds der Chemischen Industrie, Folienserie "Umweltbereich Luft" - Folie 4, 1995

# Temperatur- und Feuchtigkeitsunterschiede in der Atmosphäre führen zu Änderungen der Brechkraft

- ⇨ **Variationen des Brechnungsindex n(r)**
- ⇨ **Differenzen in der optischen Weglänge L:**

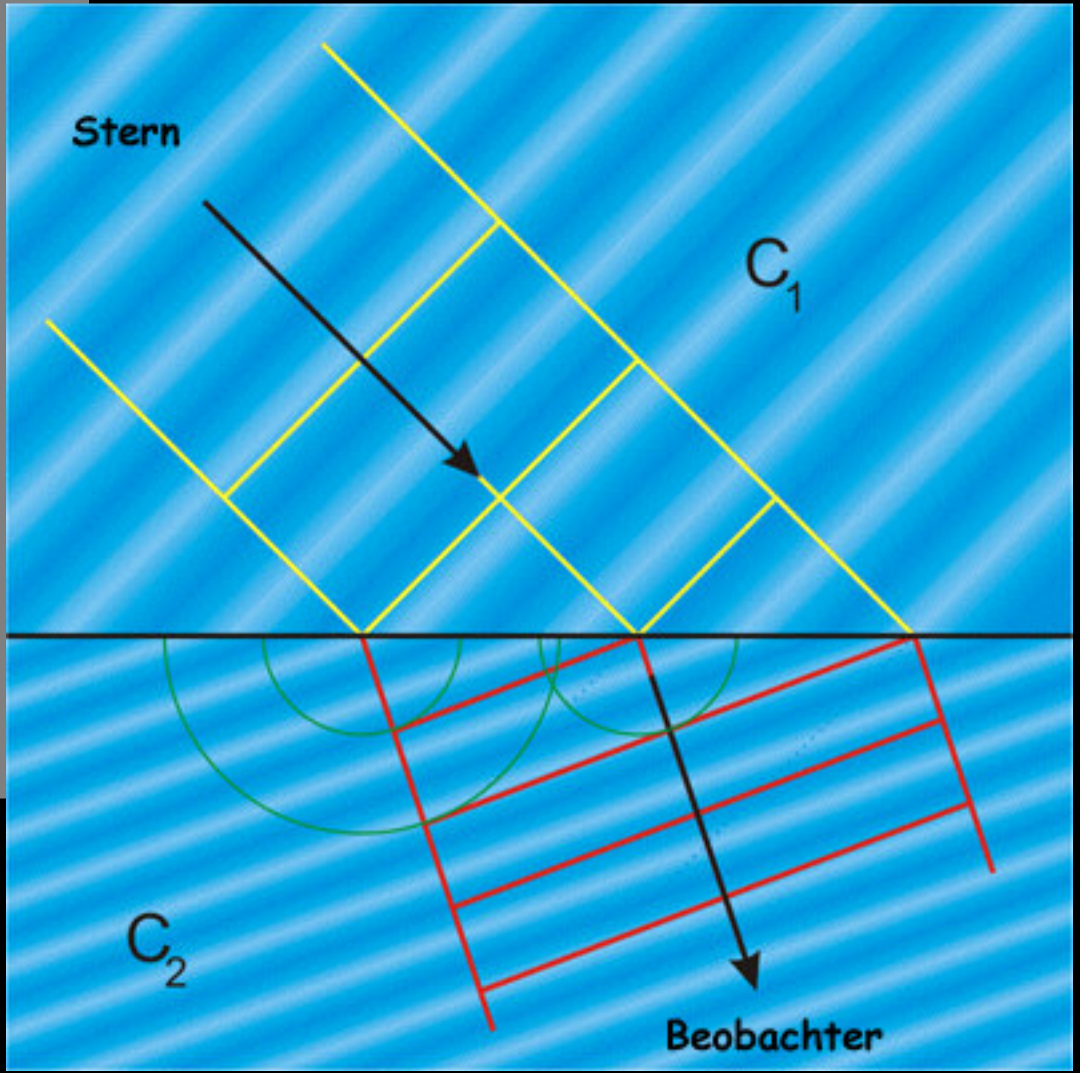
$$OPL(r) = n(r) \cdot L$$

- ⇨ **Wellenfront wird deformiert**
  (Ebene mit der gleichen Phase des Lichts)

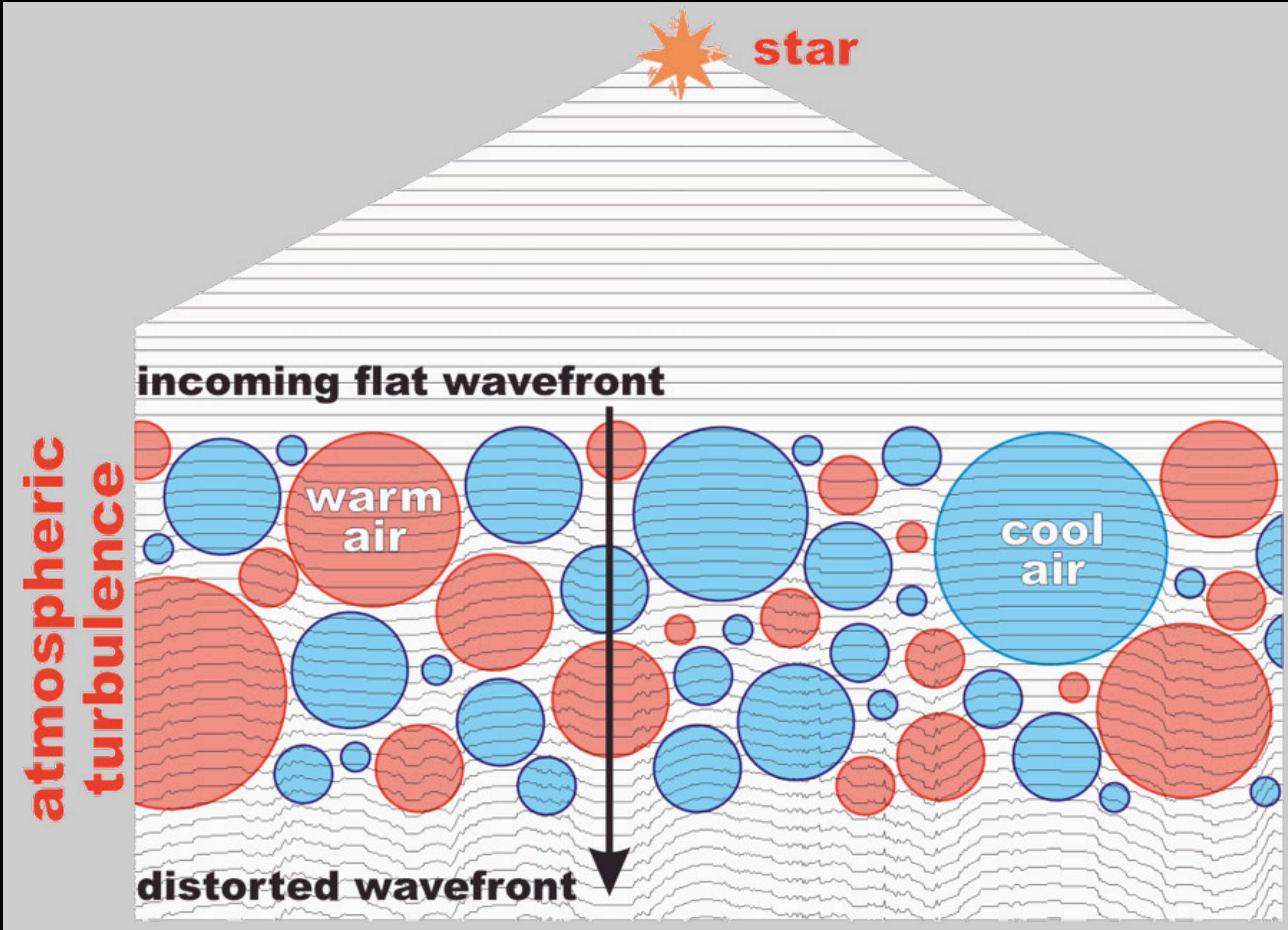
$$OPD = OPL(r_2) - OPL(r_1) \sim 10^{-6} m$$

$$\Delta\Phi = \frac{2\pi}{\lambda_0} \cdot OPD$$

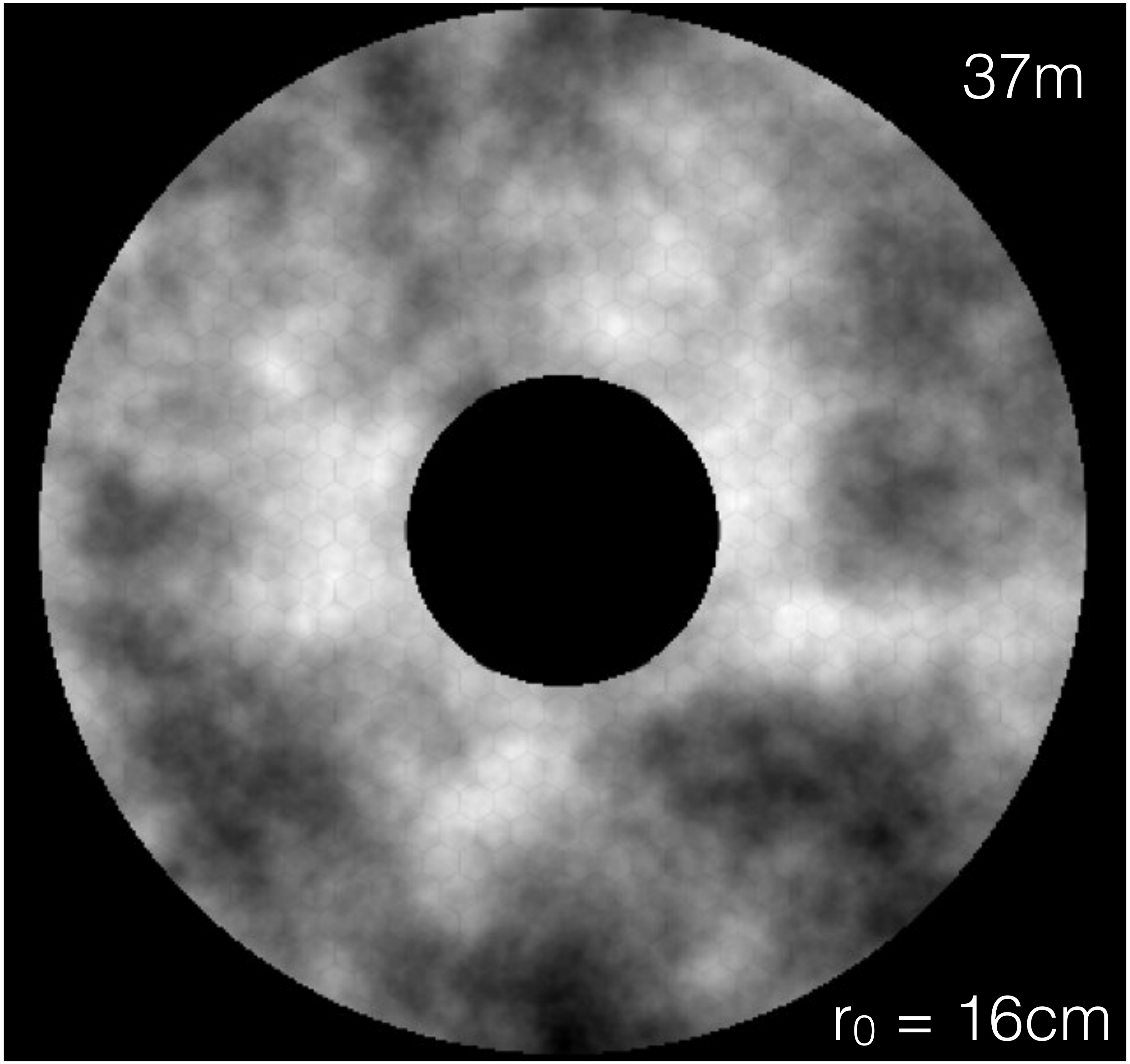
## Atmosphärische Refraktion



# Variations of refractive index lead to varying path lengths, eventually to distortions of the wavefront (phases)



# Phase screen - E-ELT Simulation

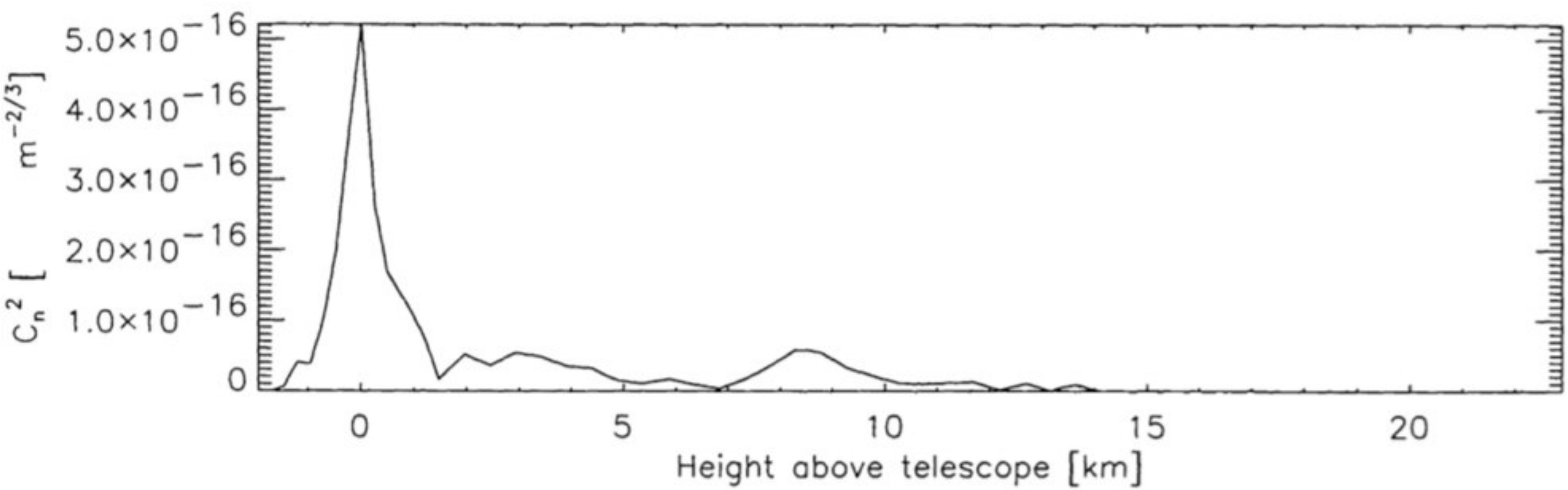



Weiss: 9 µm

Schwarz: 0 µm

# Refractive index variations strength vs altitude

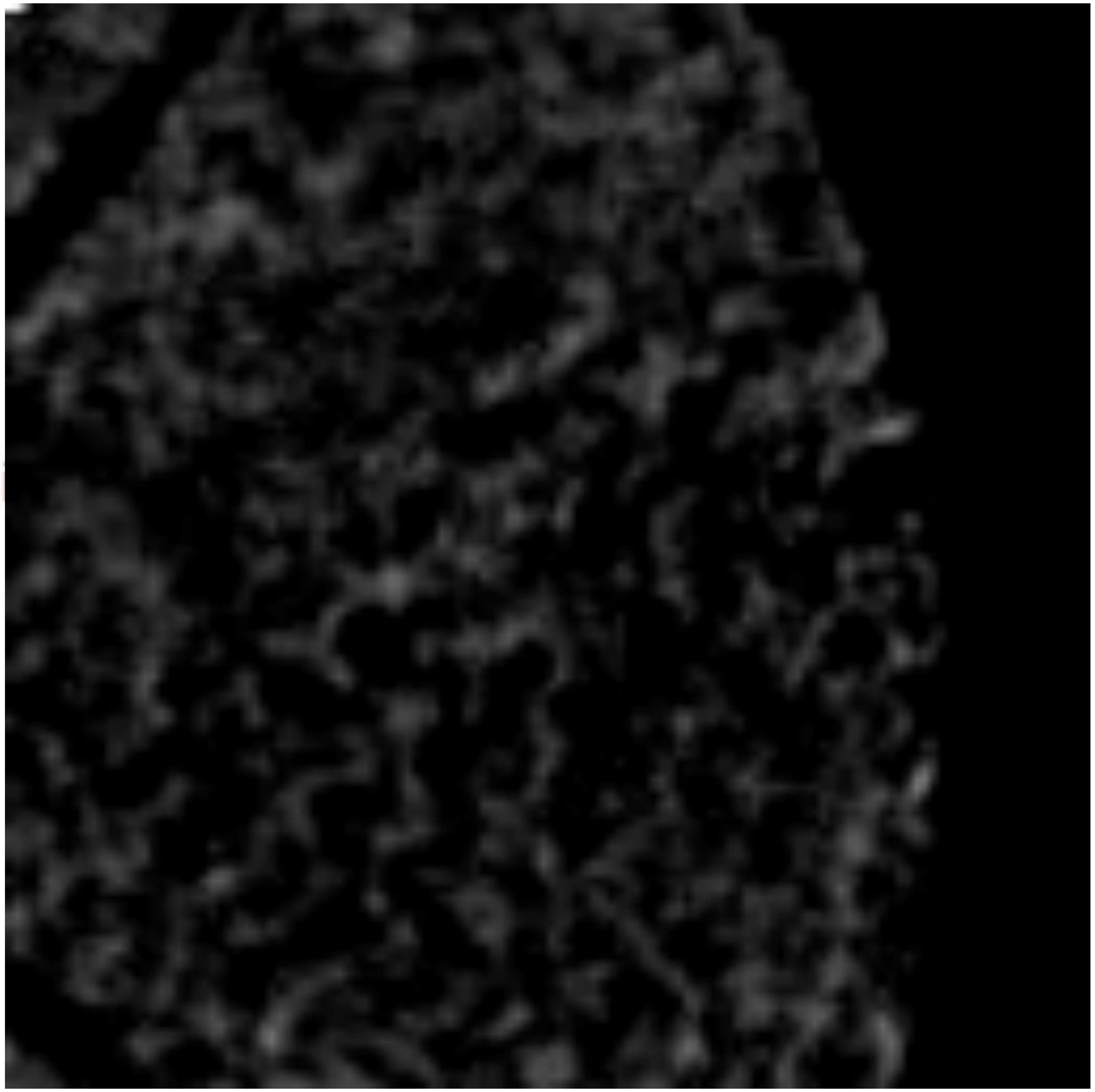
## Calar Alto $C_n^2$ Profil*, 2002




* Weiss, Hippler, Kasper (2002)

# Scintillation

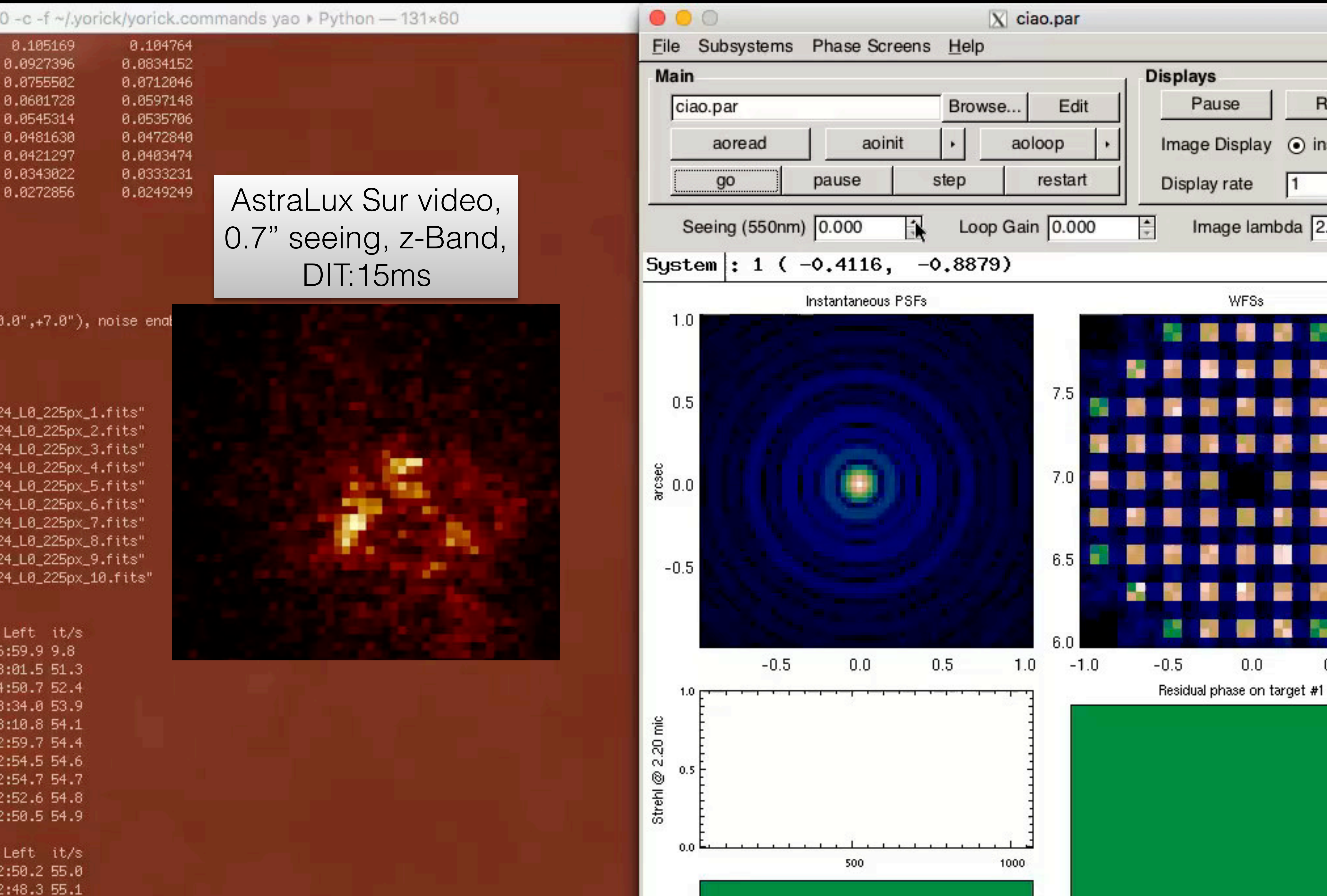
- **Propagation effect**
- Causes **brightness variations** at the ground
- Evolve with the movement of the turbulent layer (wind-speed)
- **Typical size: ~3cm** (larger than human eye ⇨ twinkling of stars)
- For large telescopes usually negligible



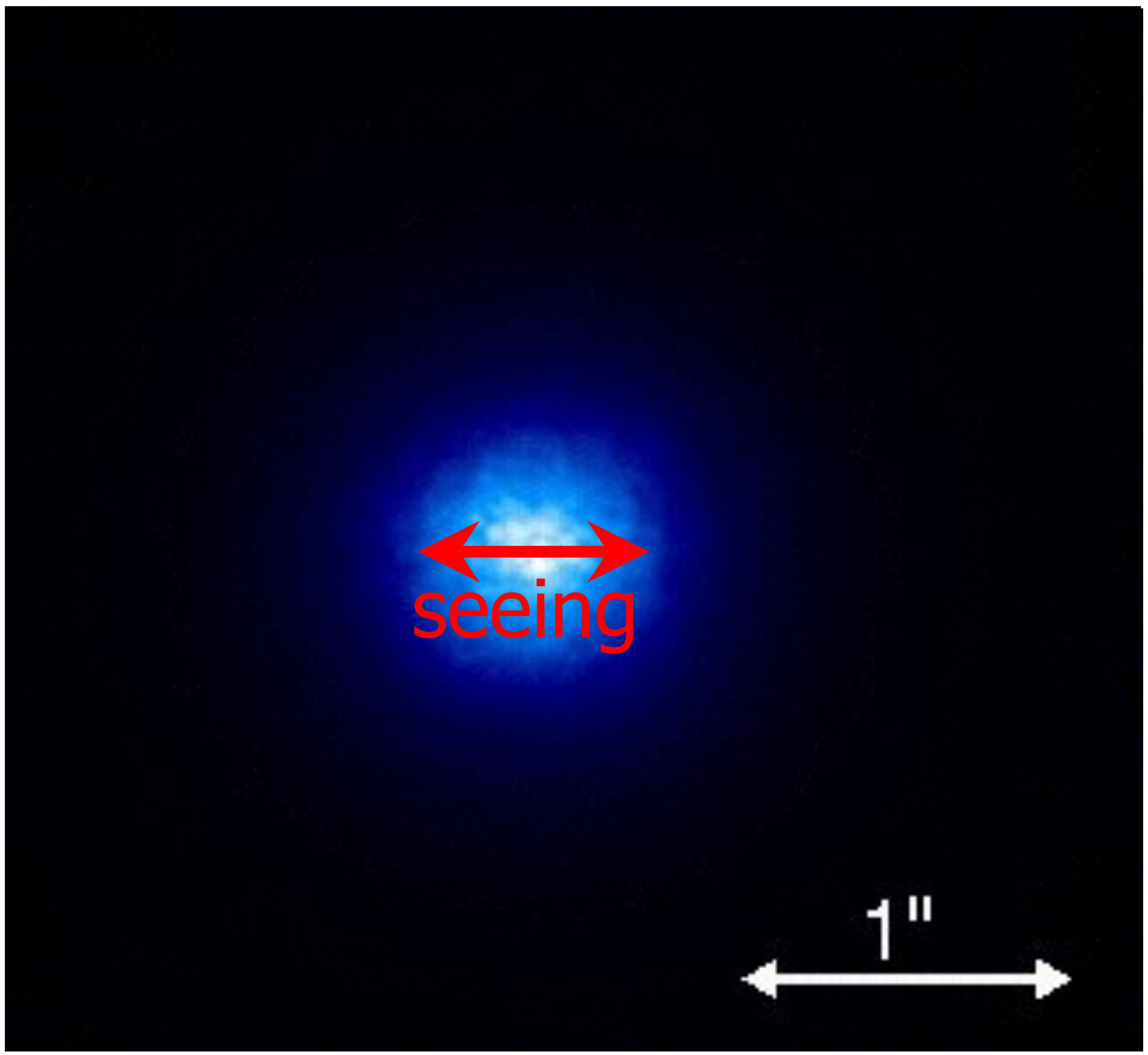
Pupil illumination

Credit: Sebastian Egner

# Speckles & Seeing: CIAO simulation with yao and AstraLux video



# Summary: speckles & seeing




Credit: Sebastian Egner

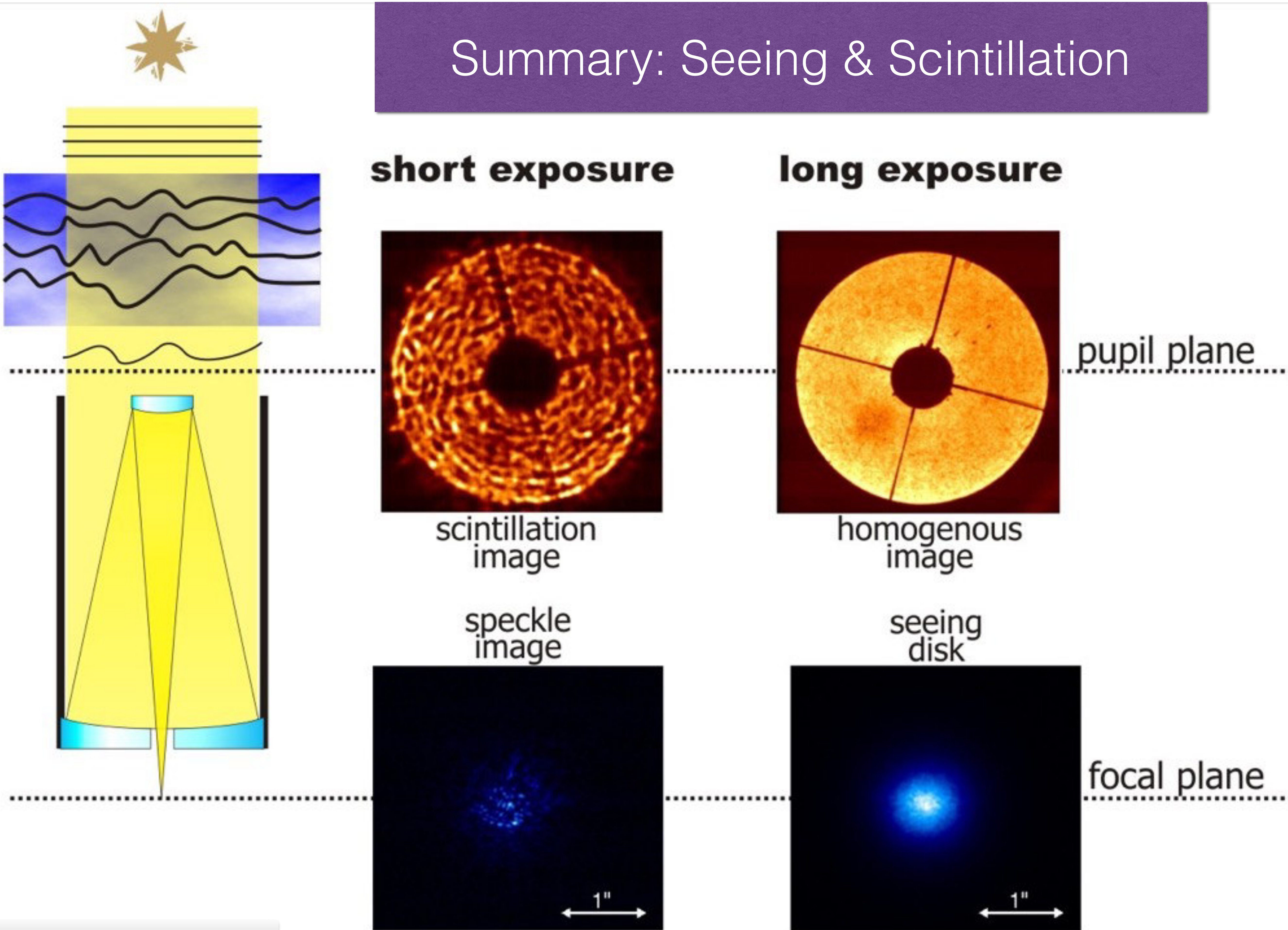
**Flat Wavefront:**

- Perfect image

**Deformation induces:**

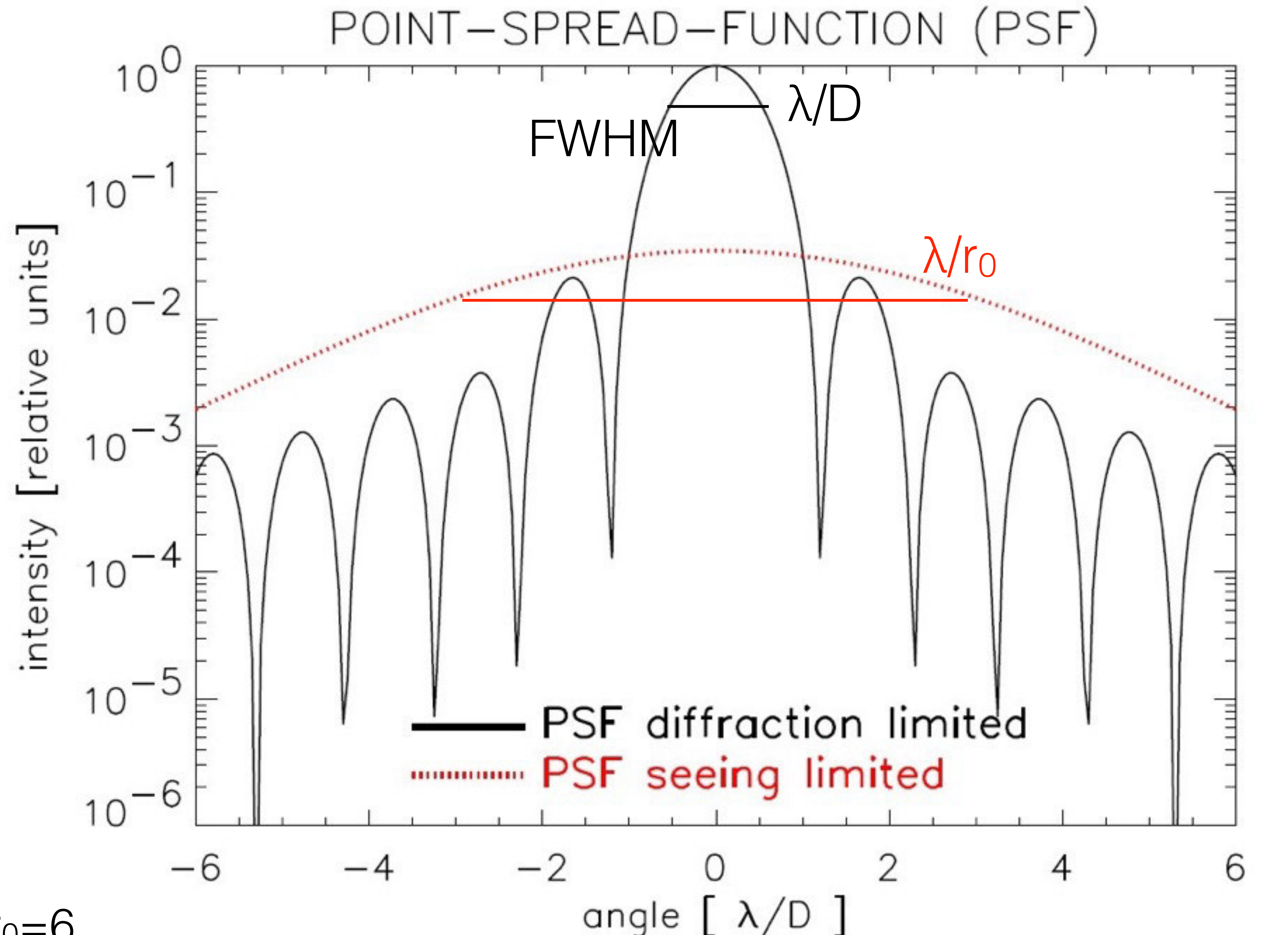
- Short integration times: „Speckles"
- Long integration times: Smearing of the speckles, Seeing-disk, FWHM: $\lambda/r_0$,
  $r_0$: Fried parameter

# Summary: Seeing & Scintillation



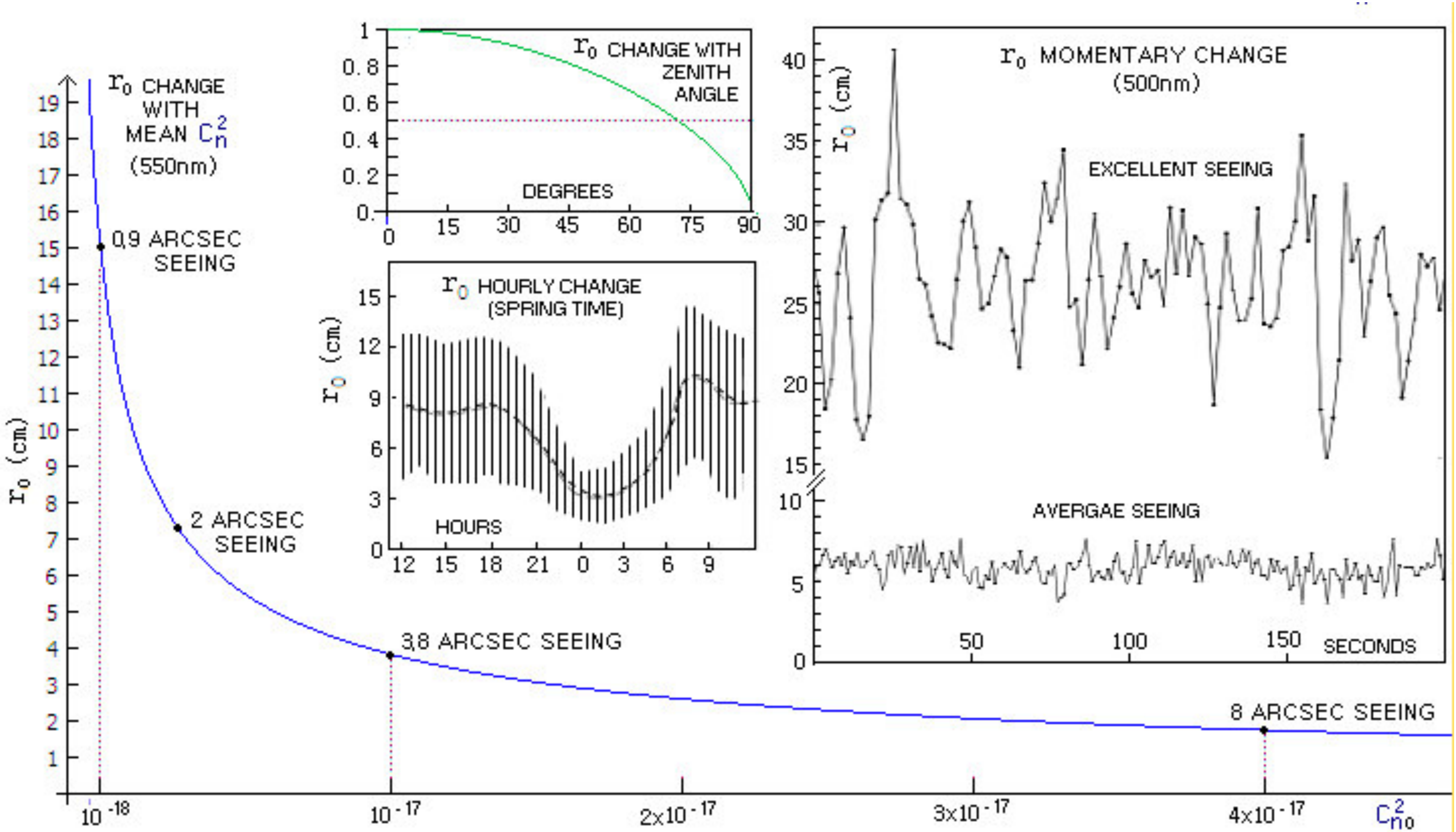

Credit: Sebastian Egner

# Quantitative description of atmospheric turbulence (3)




$D/r_0=6$

# Quantitative description of atmospheric turbulence (4)




Seeing: FWHM = $\lambda/r_0$

Credit: Vladimir Sacek

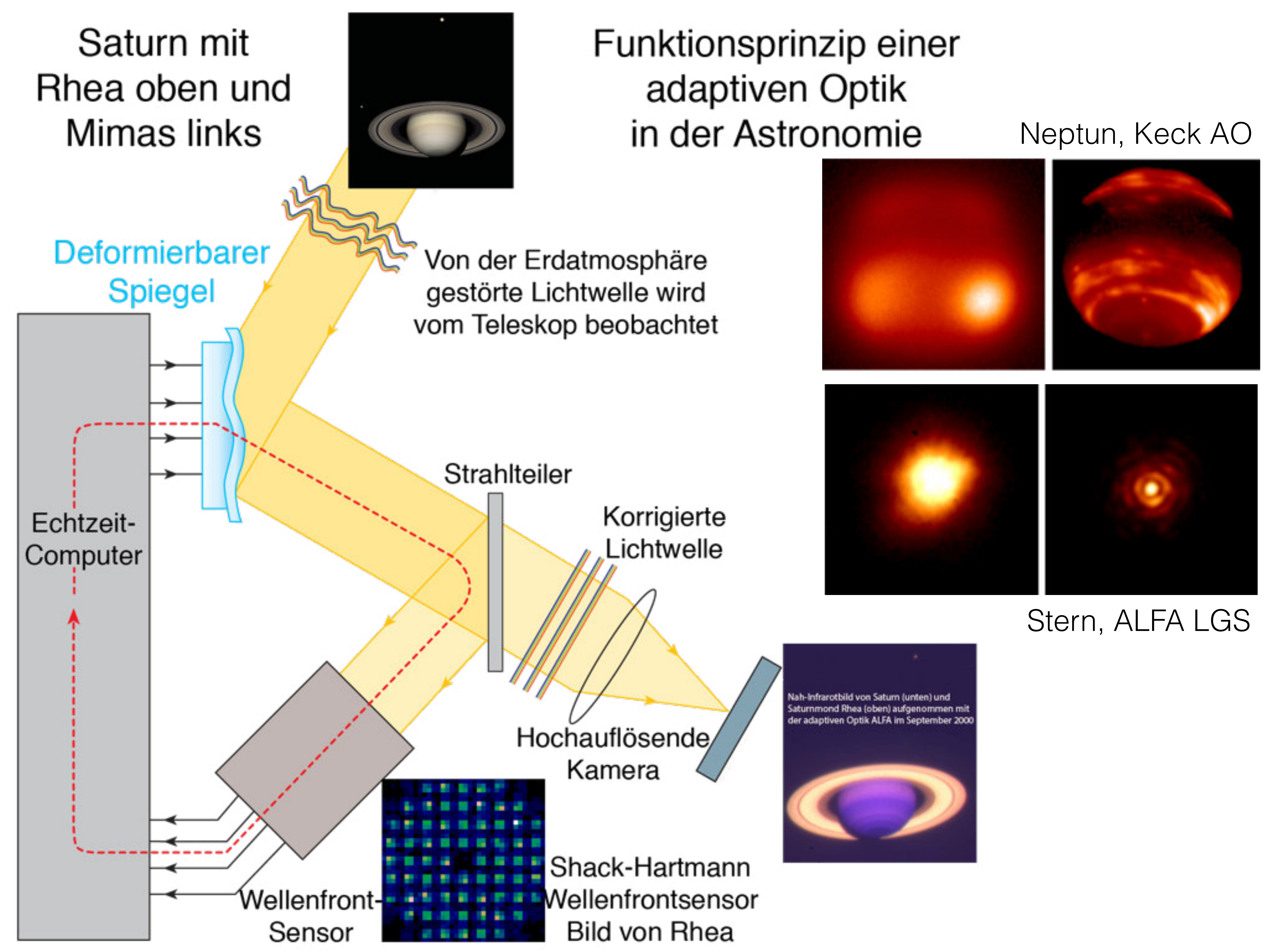
# Quantitative description of atmospheric turbulence (5)

## Definition of the Fried parameter $r_0$

$$r_0 = 0.566\,\lambda^{\frac{6}{5}} \cos^{\frac{3}{5}} \xi \left[ \int_0^\infty C_n^2(h)\,dh \right]^{-\frac{3}{5}}$$

# The goal of adaptive optics is

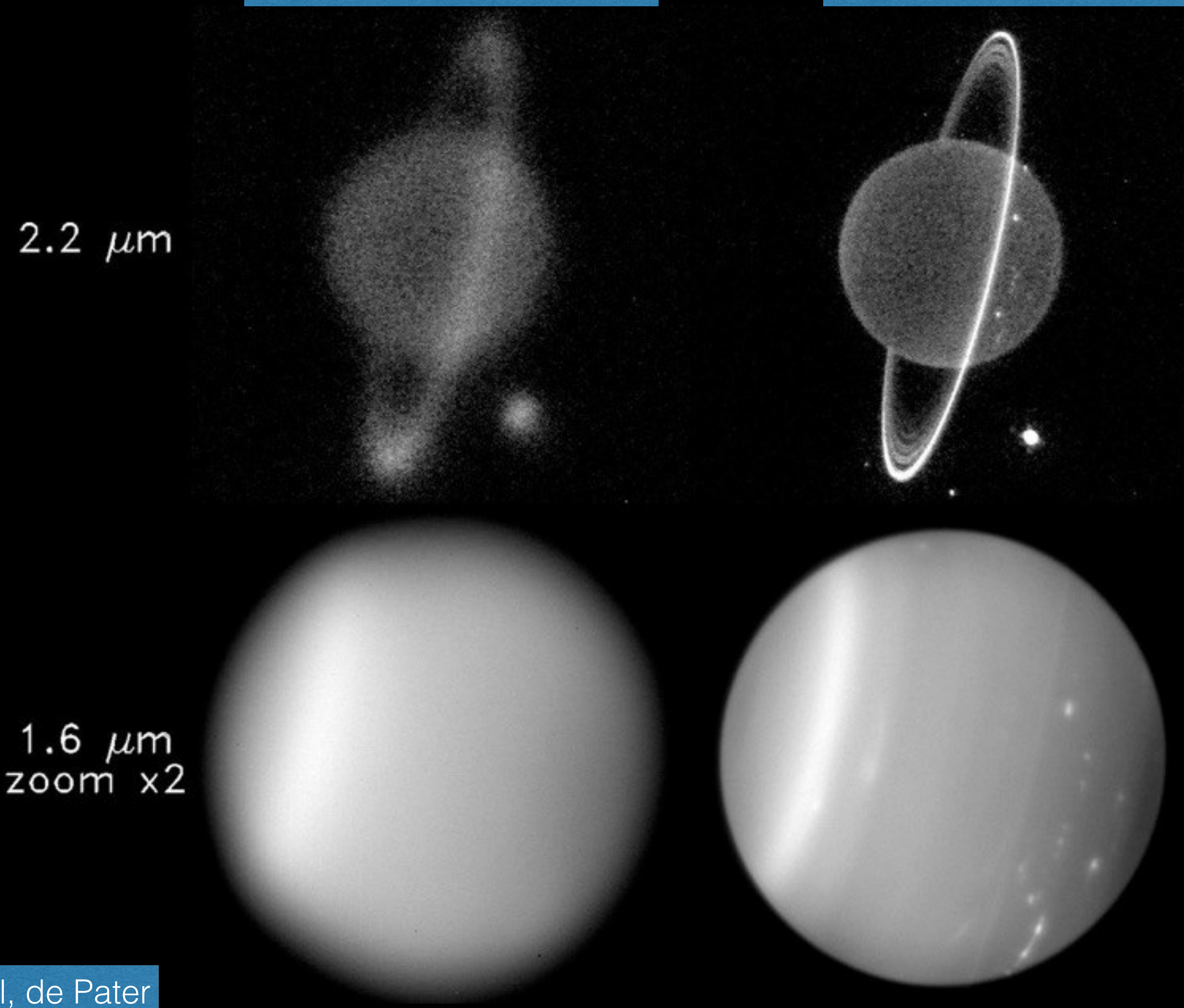
- to compensate almost all atmosphere induced optical distortions (and more…)
- under as many observing conditions (Seeing) as possible
- That means: measure and correct phase distortions induced by the atmosphere in real-time


Saturn mit Rhea oben und Mimas links
Funktionsprinzip einer adaptiven Optik in der Astronomie
Neptun, Keck AO
Deformierbarer Spiegel
Von der Erdatmosphäre gestörte Lichtwelle wird vom Teleskop beobachtet
Echtzeit-Computer
Strahlteiler
Korrigierte Lichtwelle
Stern, ALFA LGS
Nah-Infrarotbild von Saturn (unten) und Saturnmond Rhea (oben) aufgenommen mit der adaptiven Optik ALFA im September 2000
Hochauflösende Kamera
Wellenfront-Sensor
Shack-Hartmann Wellenfrontsensor Bild von Rhea

# Uranus on July 9, 2004
# observed with 10-m Keck telescope

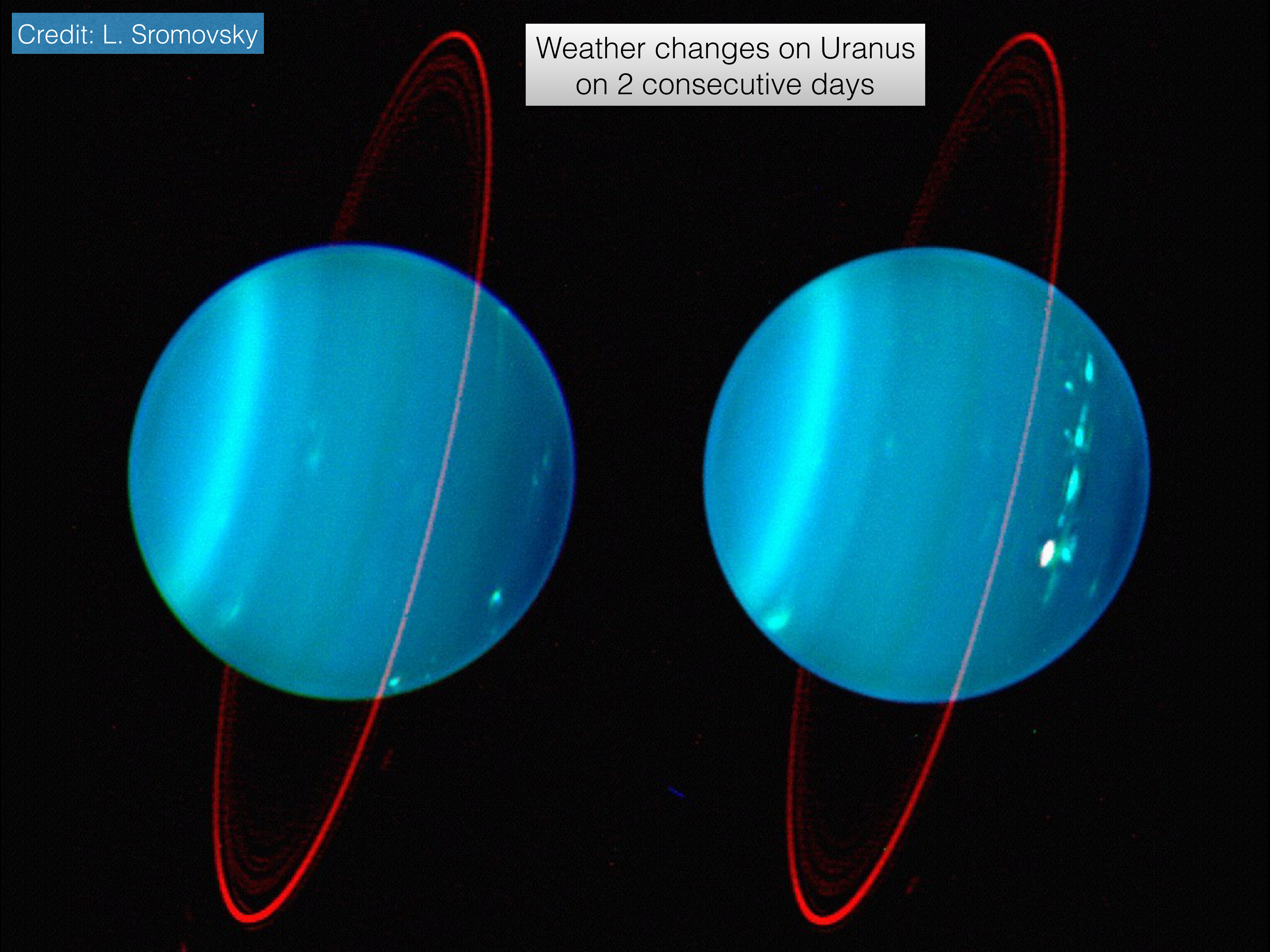
Without adaptive optics

With adaptive optics




Credit: Hammel, de Pater

Weather changes on Uranus
on 2 consecutive days



Credit: L. Sromovsky


at a distance of 0.05 AU

At a distance from Earth of 1.3 pc the maximum angular separation is about 38 mas.

Can be observed with E-ELT & AO?

$R_{E\text{-}ELT}$ ~ 5 mas at 1μm -> Planetary Camera and Spectrograph

Glance back and ahead…


**1953 -** Horace W. Babcock: The Possibility of Compensating Astronomical Seeing
**1970er/1980er Jahre -** US SDI program “Star Wars”: Militärische Projekte
**1989 -** ESO + Observatoire de Paris + ONERA et al.: Come-On
**1990er Jahre -** Adonis, ALFA, PUEO, and many more on 4m class telescopes
**1999/2000 -** 10m Keck AO

**2001/2002 -**
Paranal Observatorium
Very Large Telescope
**VLT + NACO**

**2024/2025 -**
Cerro Armazones
European Extremely
Large Telescope
**E-ELT + AO**

No. 58 – December 1989

## Successful Tests of Adaptive Optics

*F. MERKLE, ESO*
*P. KERN, P. LÉNA, F. RIGAUT, Observatoire de Paris, Meudon, France*
*J.C. FONTANELLA, G. ROUSSET, ONERA, Châtillon-Sous-Bagneux, France*
*C. BOYER, J.P. GAFFARD, P. JAGOUREL, LASERDOT, Marcoussis, France*

An old dream of ground-based astronomers has finally come true, thanks to the joint development of a new technique in astronomical imaging – called *adaptive optics* –, by ESO and Observatoire de Paris, ONERA (Office National d'Etudes et de Recherches Aérospatiales), LASERDOT (formerly CGE) in France.

It has been demonstrated that this technique effectively eliminates the adverse influence of atmospheric turbulence on images of astronomical objects, yielding images almost as sharp as if the telescope were situated in space.

### Why Adaptive Optics?

Ever since the invention of the telescope in the early 17th century; astronomers have had to accept that the quality of astronomical images obtained with ground-based instruments is severely limited by a factor which is beyond their control, that is the turbulence in the Earth's atmosphere.

For a long time it was thought impossible to avoid this natural limit. Now, for the first time, this old problem has been

### A Break-through in Optical Technology

In a major technological break-through in ground-based astronomy the VLT Adaptive Optics Prototype System (also referred to as Come-On) has now proved its ability to overcome this natural barrier during a series of successful tests in the period 12–23 October 1989. They were performed at the coudé focus of the 1.52-m telescope at the Observatoire de Haute-Provence (OHP), France.

The extensive tests showed that it was possible to effectively “neutralize” the atmospherically induced smearing of a stellar image by a closed-loop correction system. In this way stellar images were obtained at infrared wavelengths whose sharpness was only limited by the telescope aperture, i.e. diffraction limited images.

On each of the ten nights, infrared exposures were made of about 10 bright stars ranging from the visible magnitude 0.7 to 4.7 (including Capella, Deneb, Betelgeuse, $\gamma^1$ And, and others). The

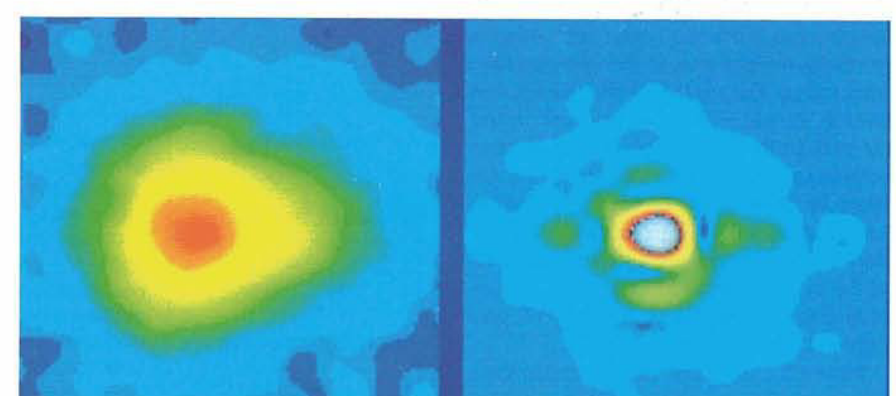


Figure 1: *Imaging of Deneb in the K-Band without and with adaptive feedback loop activated. The image diameter shrinks from 1.0 arcsec to 0.37 arcsec which is the diffraction limit in the*

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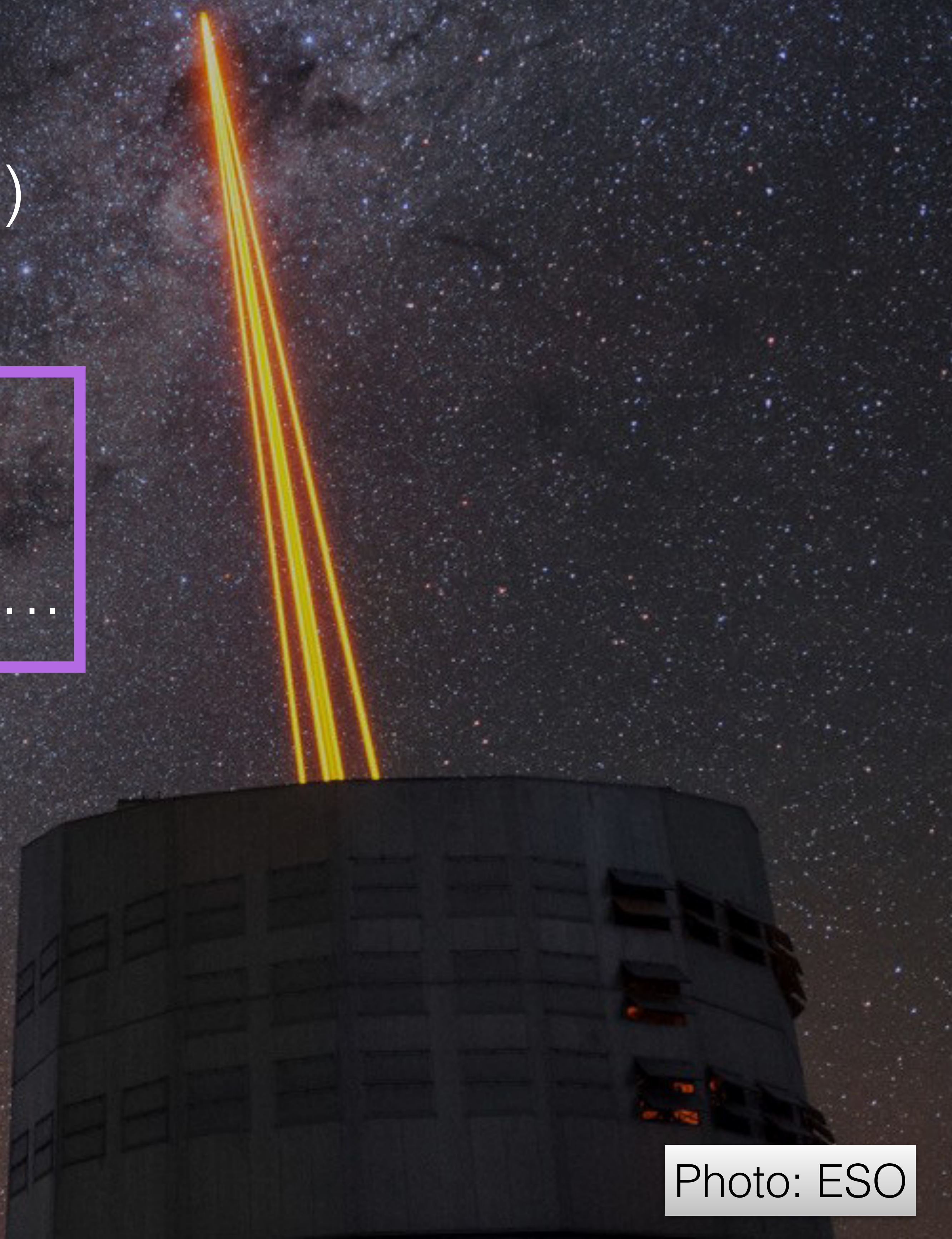

Photo: ESO


Credit: ESO

# Paranal and basecamp

Credit: ESO

# Paranal residencia

Credit: ESO