Basics of observations and data reduction: imaging and photometry

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[1] Silva D., McLean I.S. (2013) Introduction to Telescopes. In: Oswalt T.D., McLean I.S. (eds) Planets, Stars and Stellar Systems. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-5621-2_1

[2] Robert K. Tyson Benjamin W. Frazier, *Field guide to Adaptive Optics, Second Edition*, Bellingham, WA: SPIE, The International Society for Optical Engineering, 2012.

What makes a perfect imaging system in astronomy ?

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by

or

➢ Maximize the amount of signal collected from the source

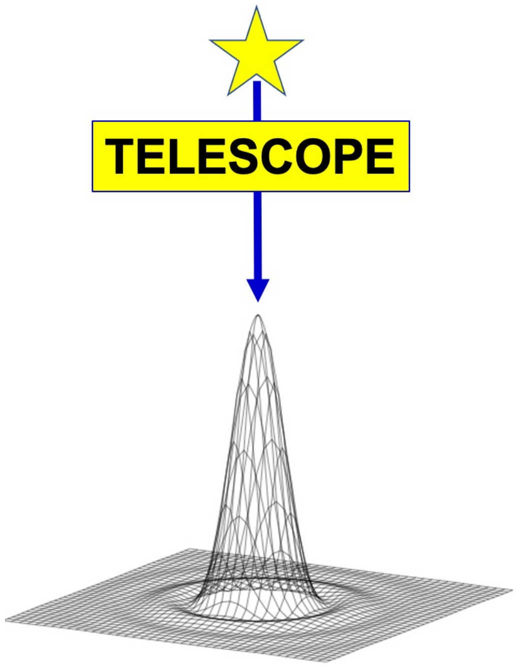
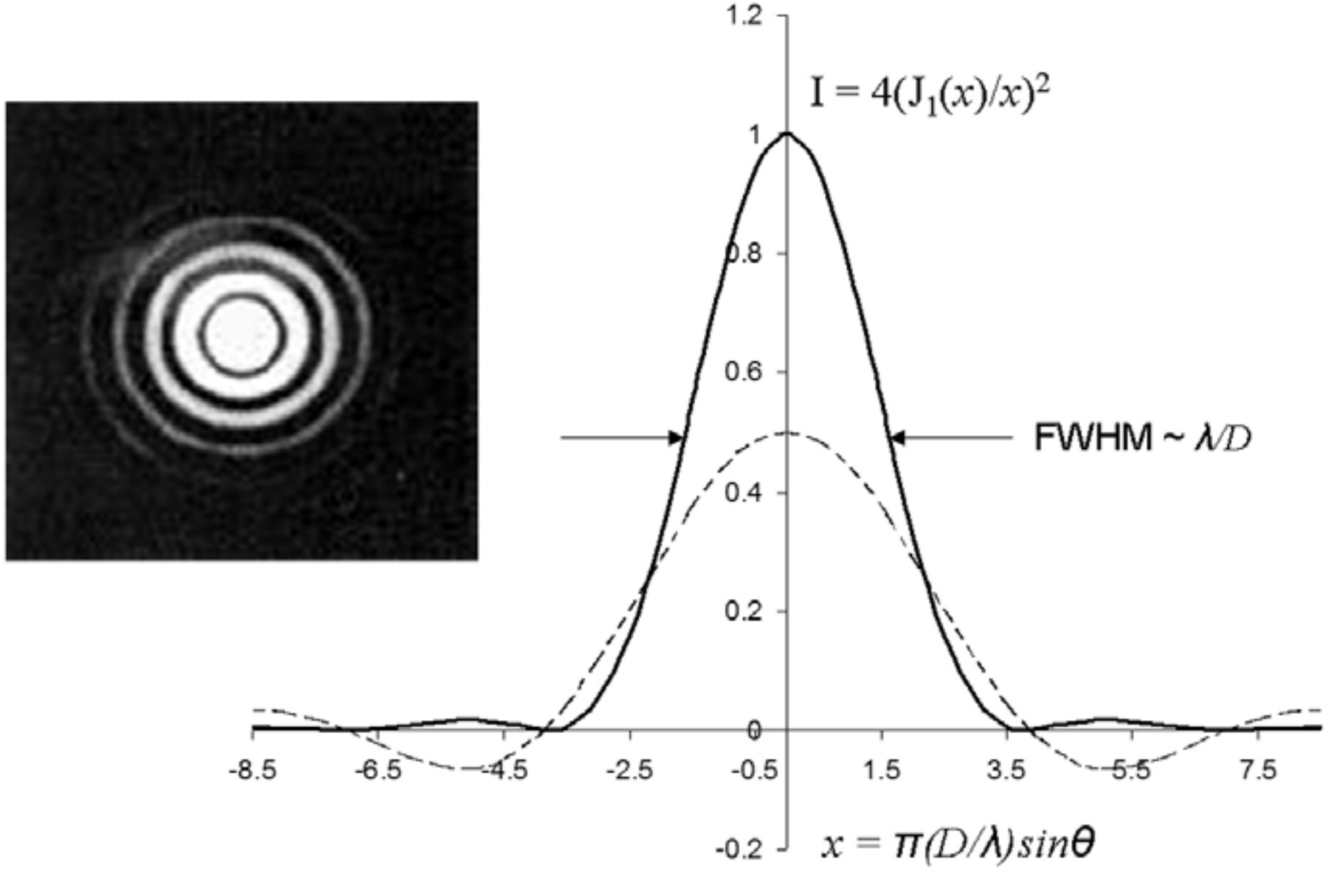
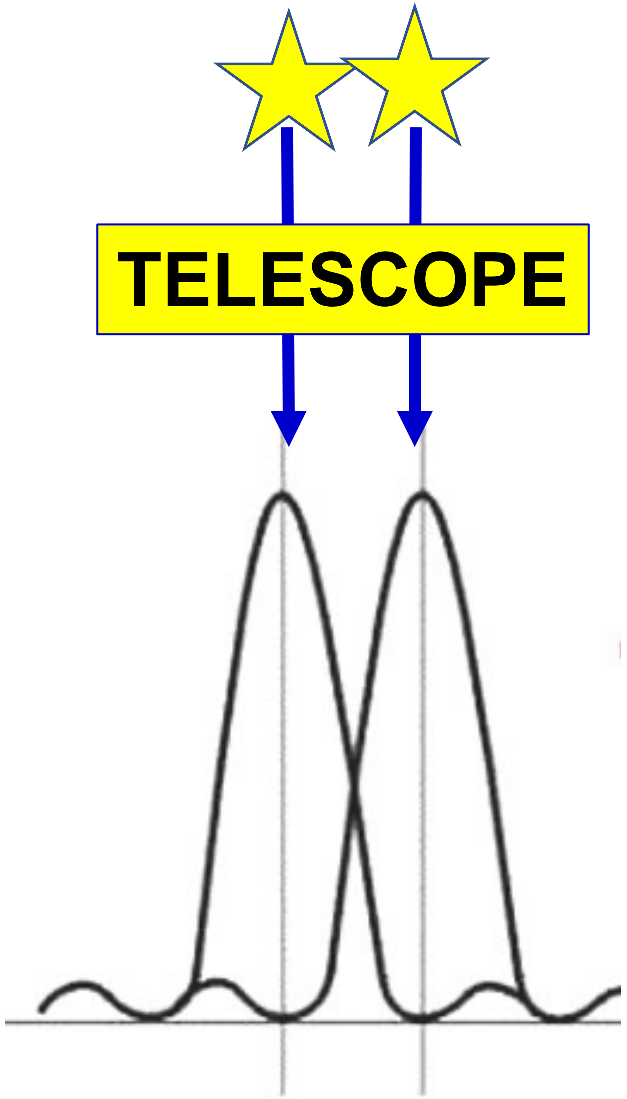


Image Formation: diffraction pattern



- The PSF is typically described with the Full Width at Half Maximum (FWHM) intensity. For the diffraction-limited case this corresponds to ~λ/D or ~1.8 λ/D (80% encircled energy).

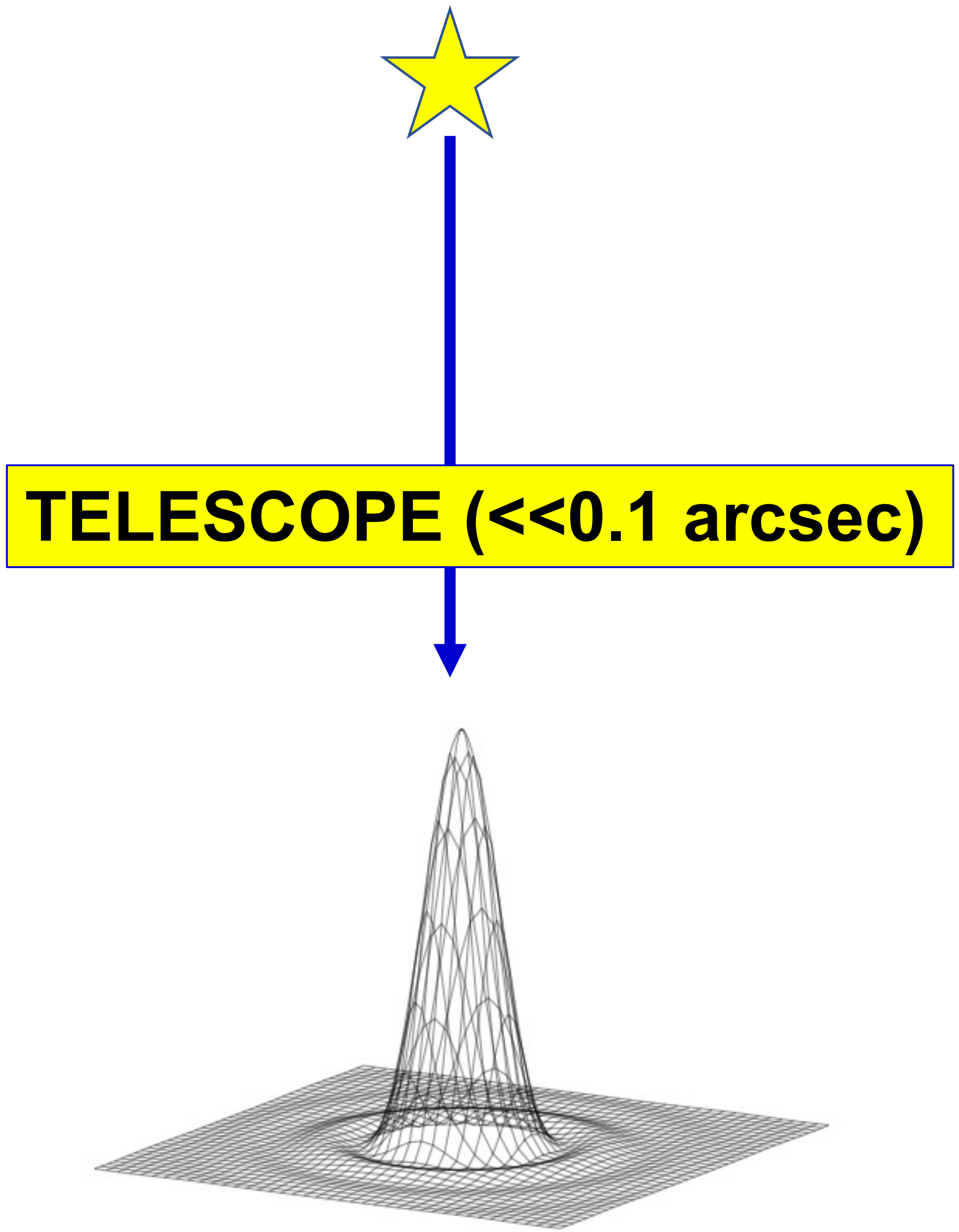
Resolution: how close 2 objects can be so that I can distinguish them?

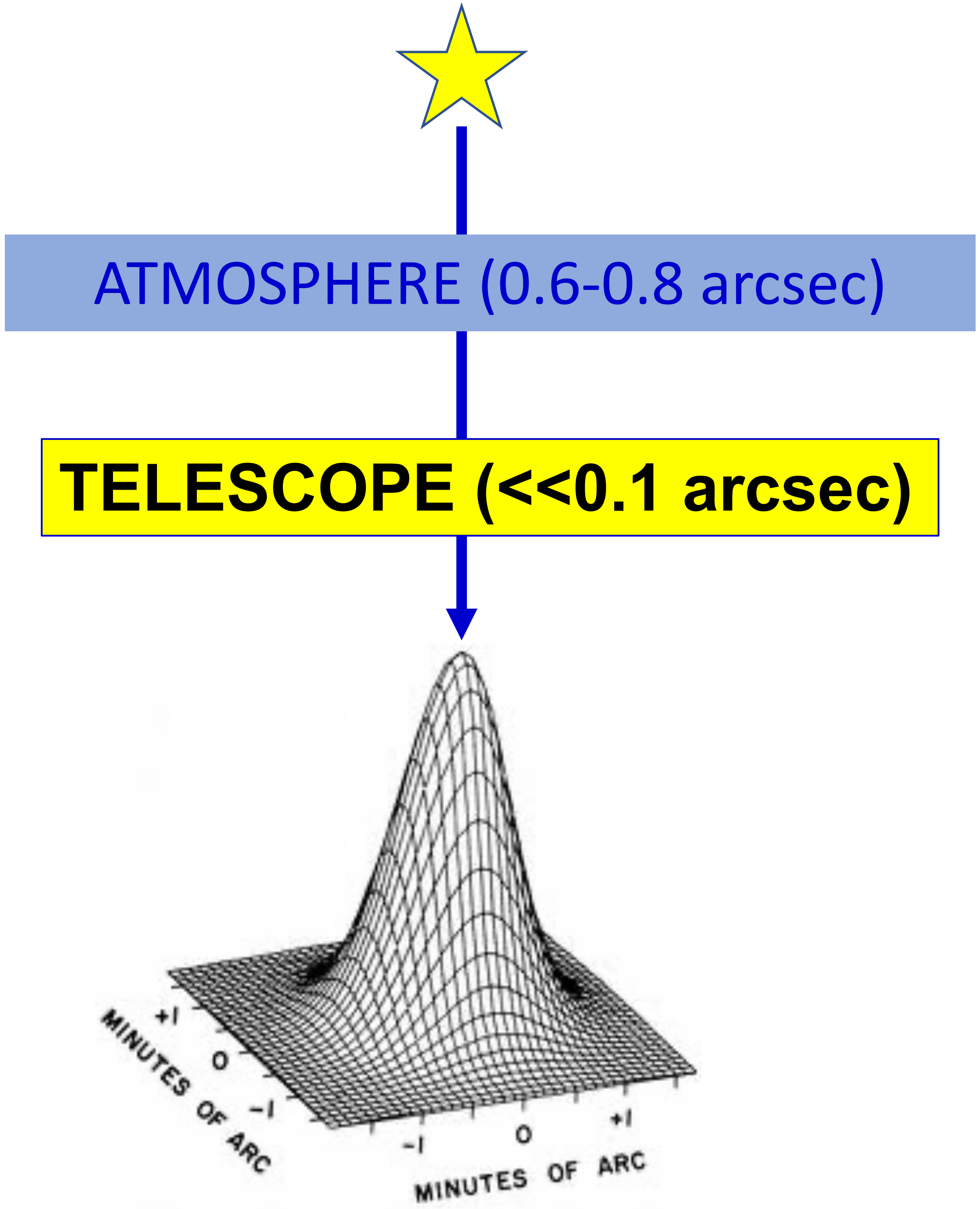


The Rayleigh Criterion: two diffraction-limited PSFs are distinguishable if the maximum of one Airy disk falls on the first minimum of the second; this is a separation of ~1.22 λ / D

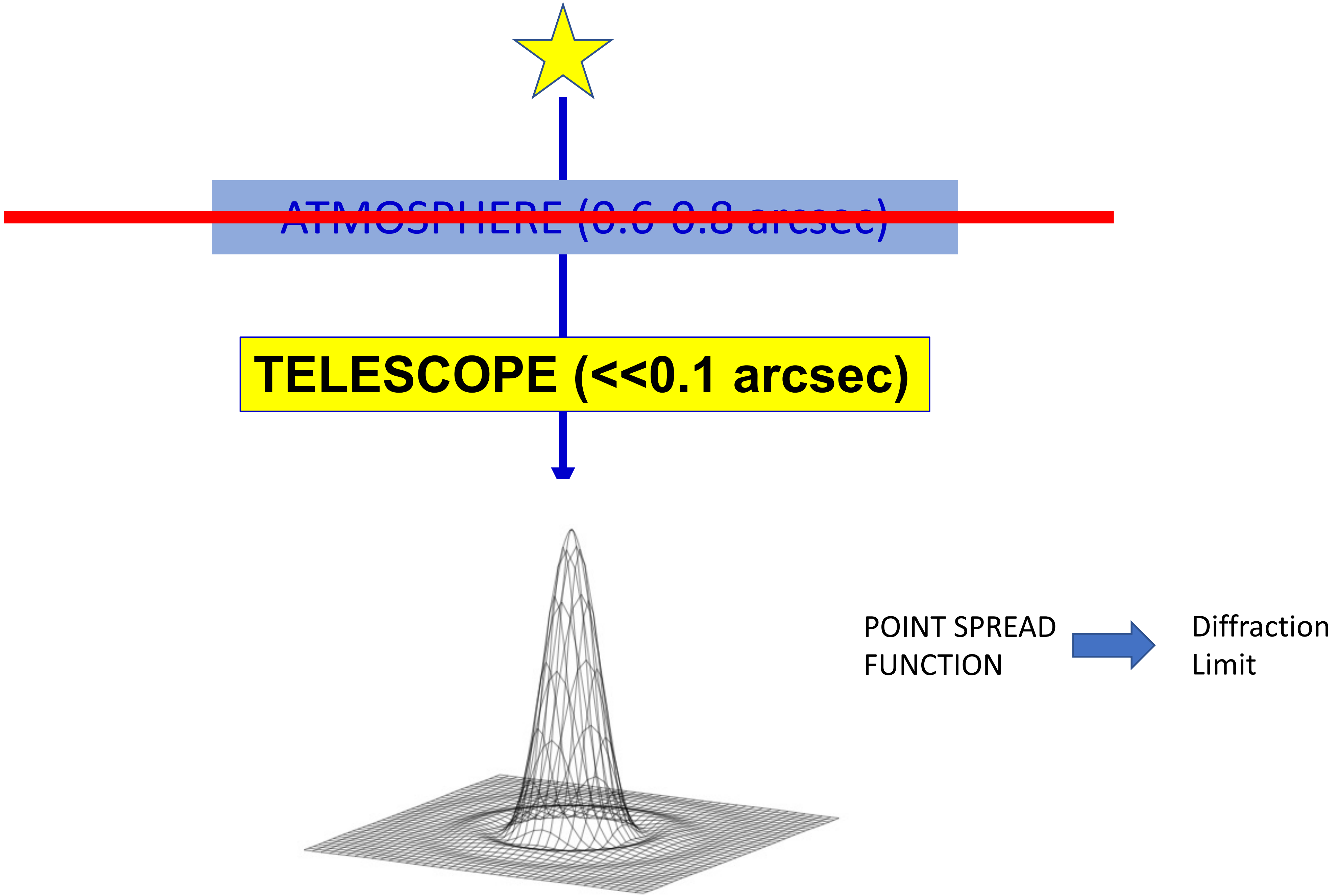
What makes a perfect imaging system in astronomy ?

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

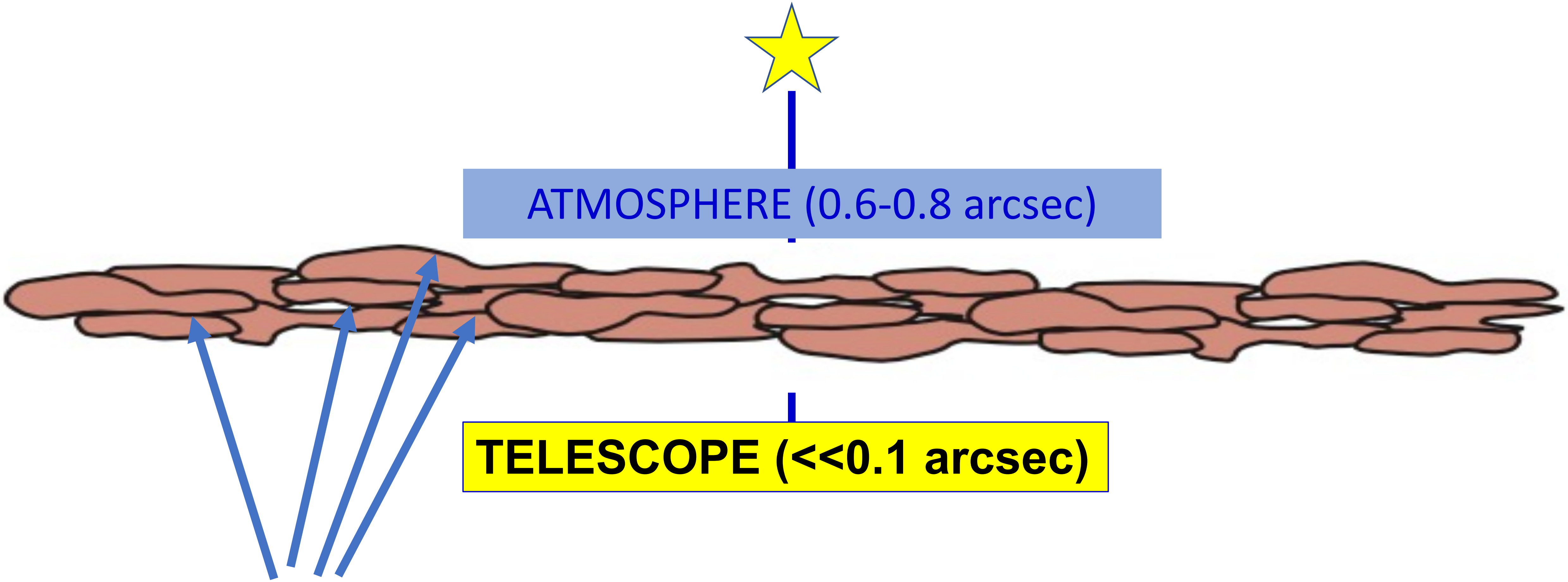

TELESCOPE (<<0.1 arcsec)



POINT SPREAD FUNCTION



~~ATMOSPHERE (0.6-0.8 arcsec)~~
TELESCOPE (<<0.1 arcsec)
POINT SPREAD FUNCTION
Diffraction Limit

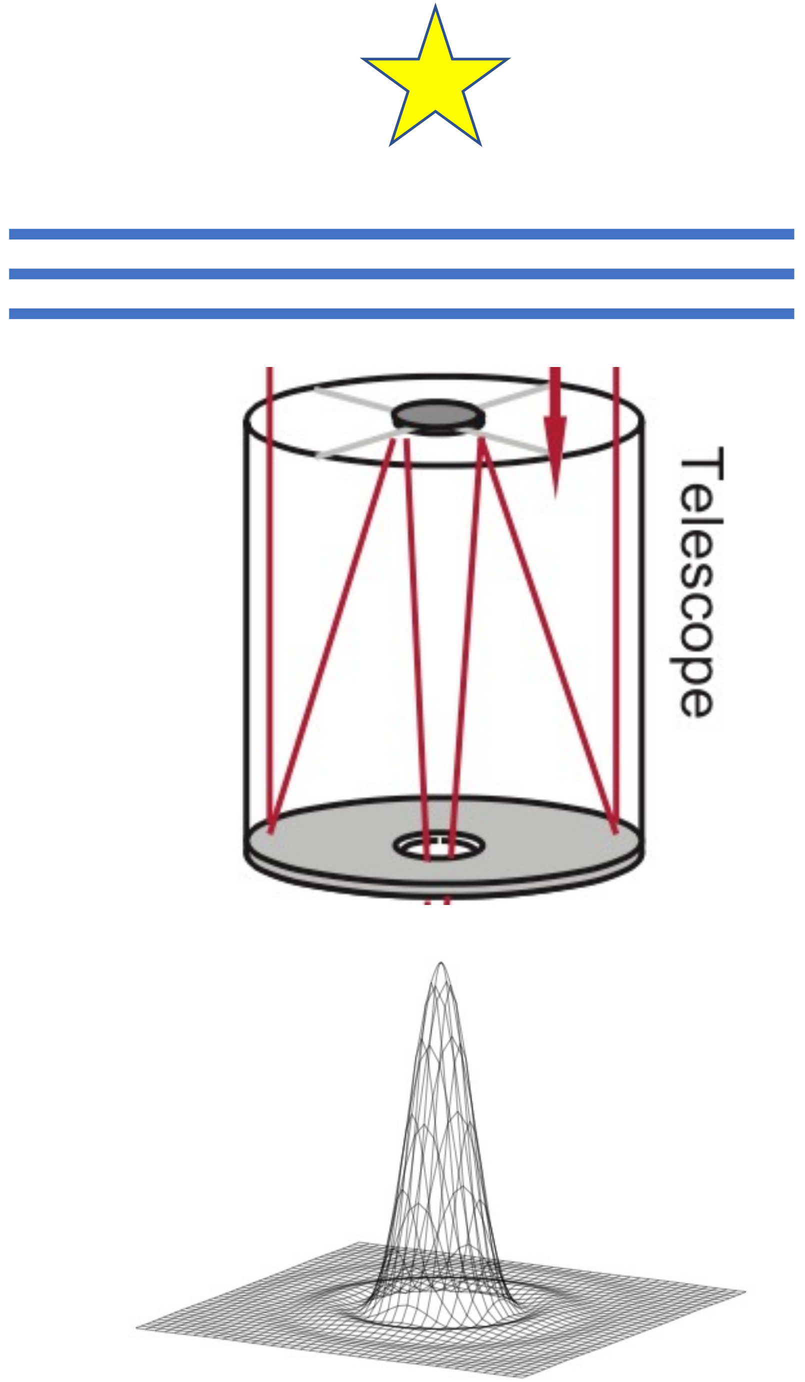


Turbulent Cells with different:

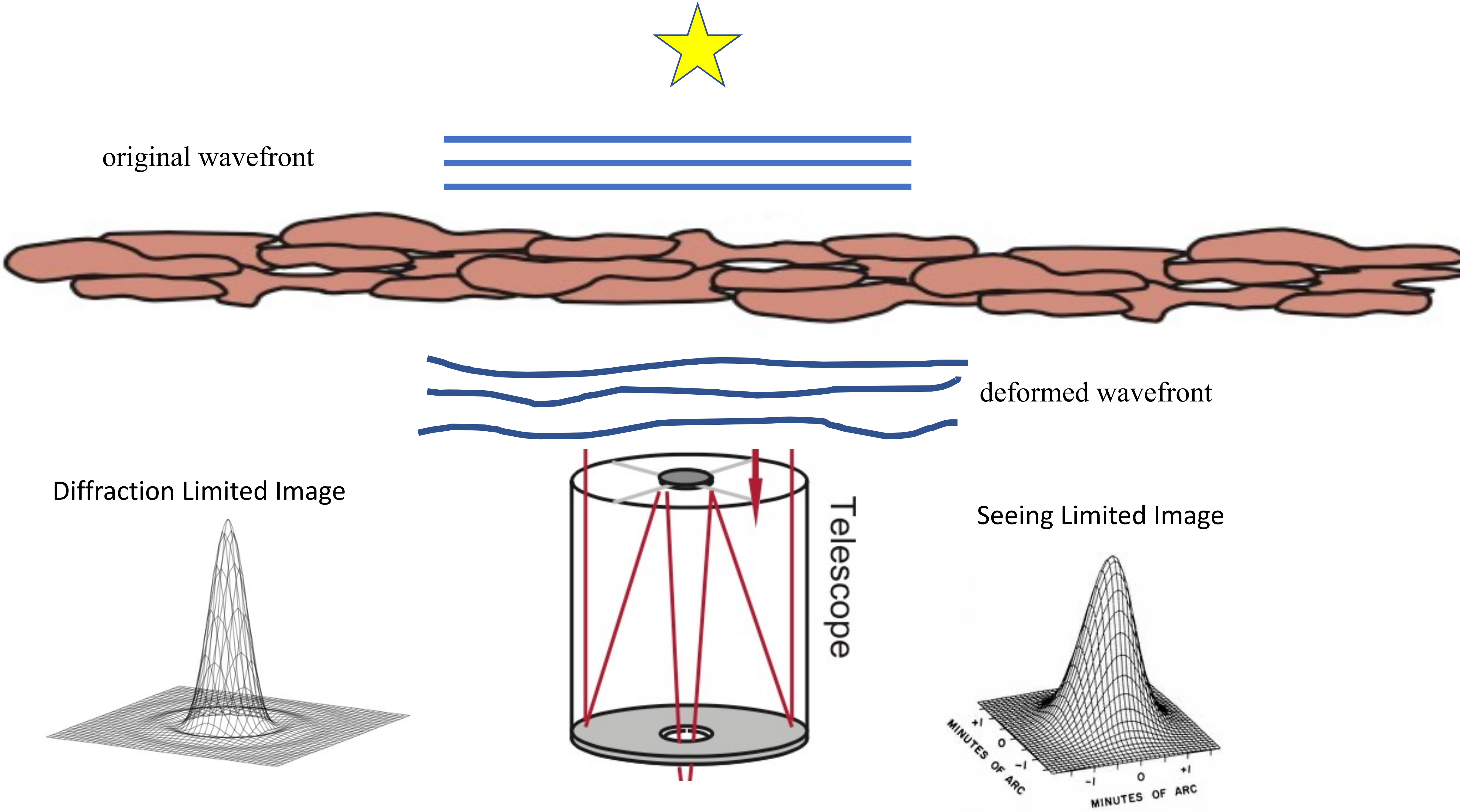
- density
- temperature
- internal wind speed

1. different indices of refraction
2. changes rapidly with time

original wavefront



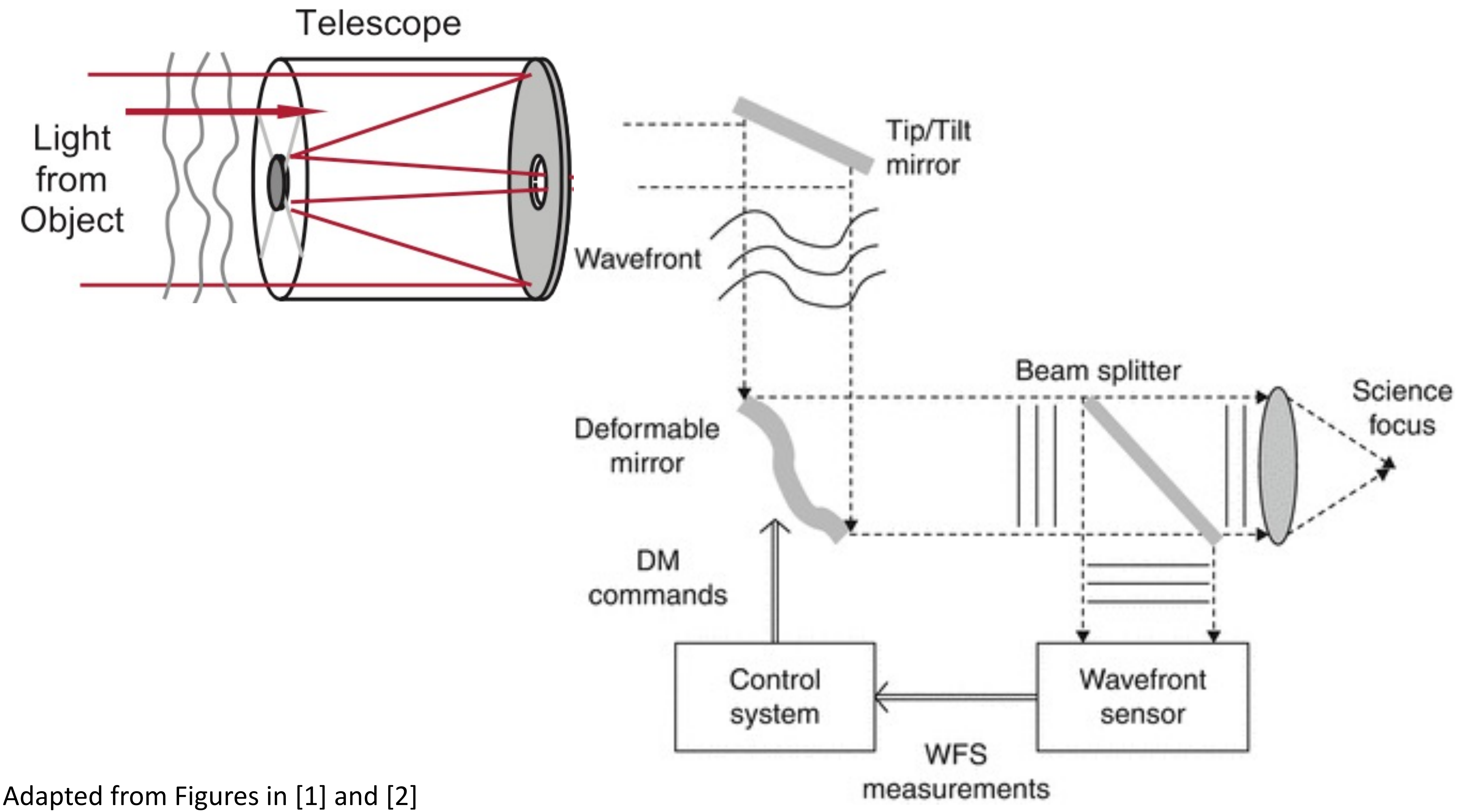
Diffraction Limited Image


original wavefront
deformed wavefront
Diffraction Limited Image
Telescope
Seeing Limited Image
MINUTES OF ARC
+1
0
-1
MINUTES OF ARC
-1
0
+1

Atmospheric Turbulence structure constant as a function of altitude is the H-V model:

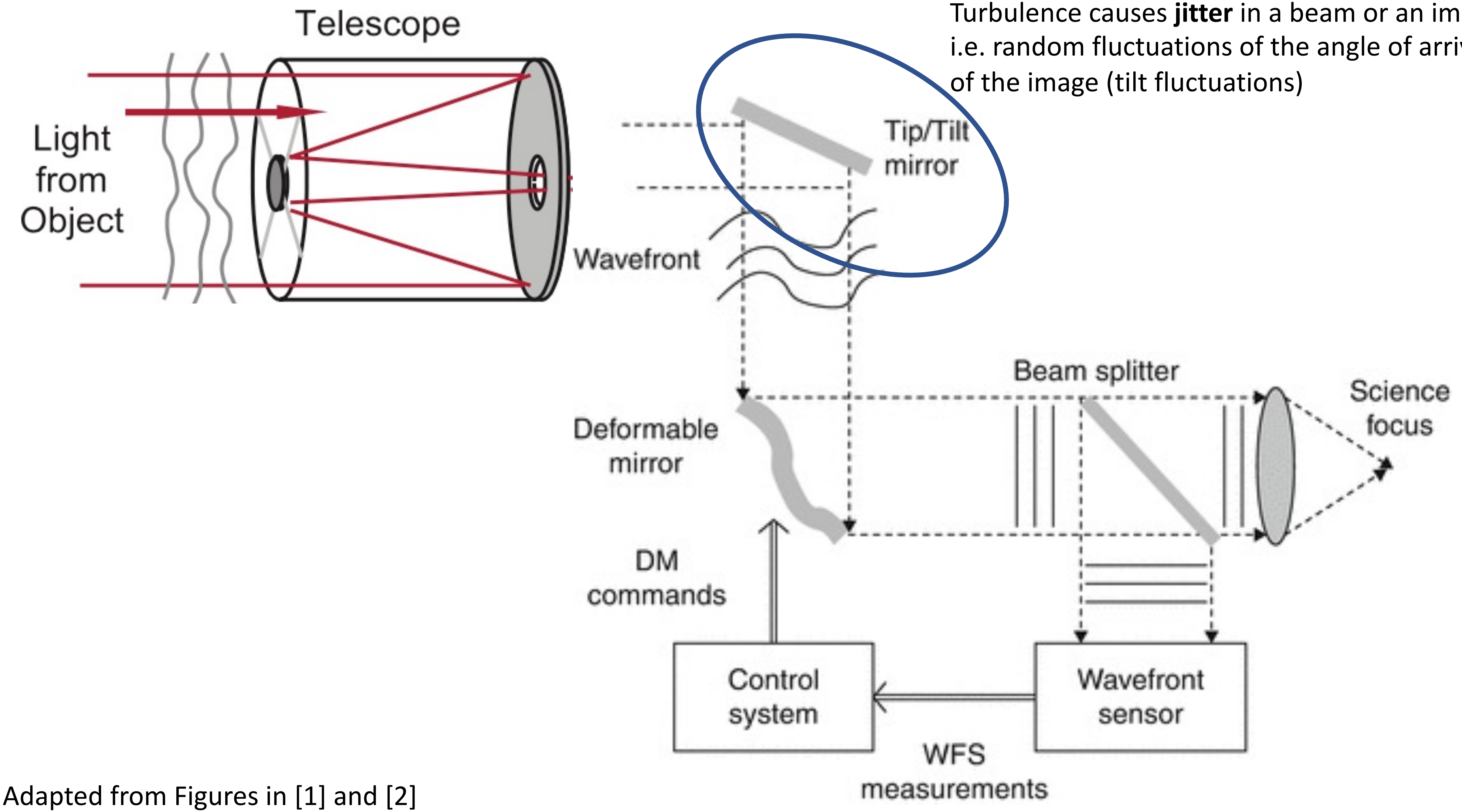
$$\boxed{\begin{aligned} C_n^2(h) &= 5.94\times10^{-23}h^{10}\left(\frac{W}{27}\right)^2\exp(-h) \\ &\quad +2.7\times10^{-16}\exp(-2h/3)+A\exp(-10h) \end{aligned}}$$

- $C_n^2(h)$ is the index of refraction structure function [$m^{-2/3}$]
- *h* is the altitude in km
- *A* and *W* are adjustable for local conditions

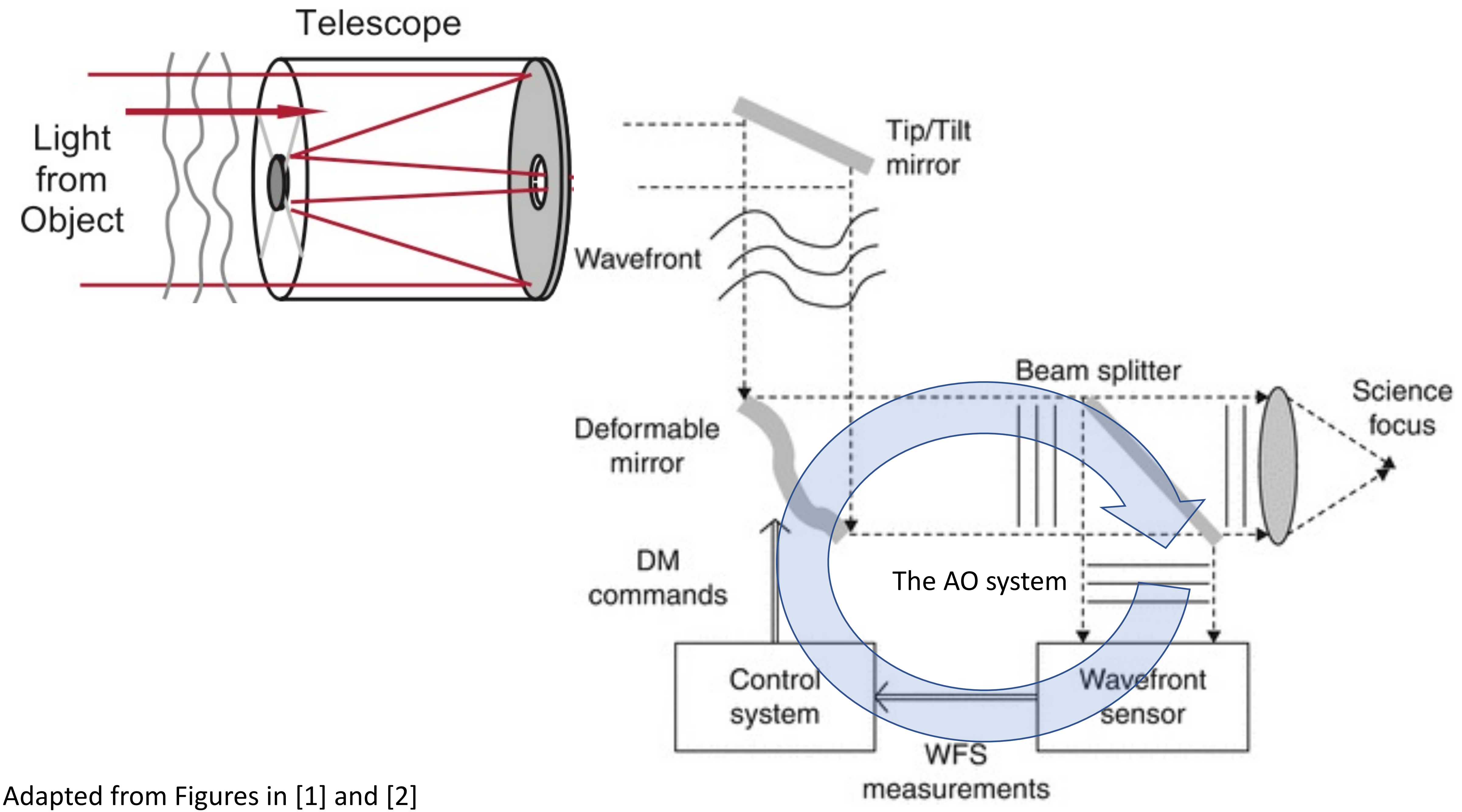


Adapted from Figures in [1] and [2]

Turbulence causes **jitter** in a beam or an image, i.e. random fluctuations of the angle of arrival of the image (tilt fluctuations)



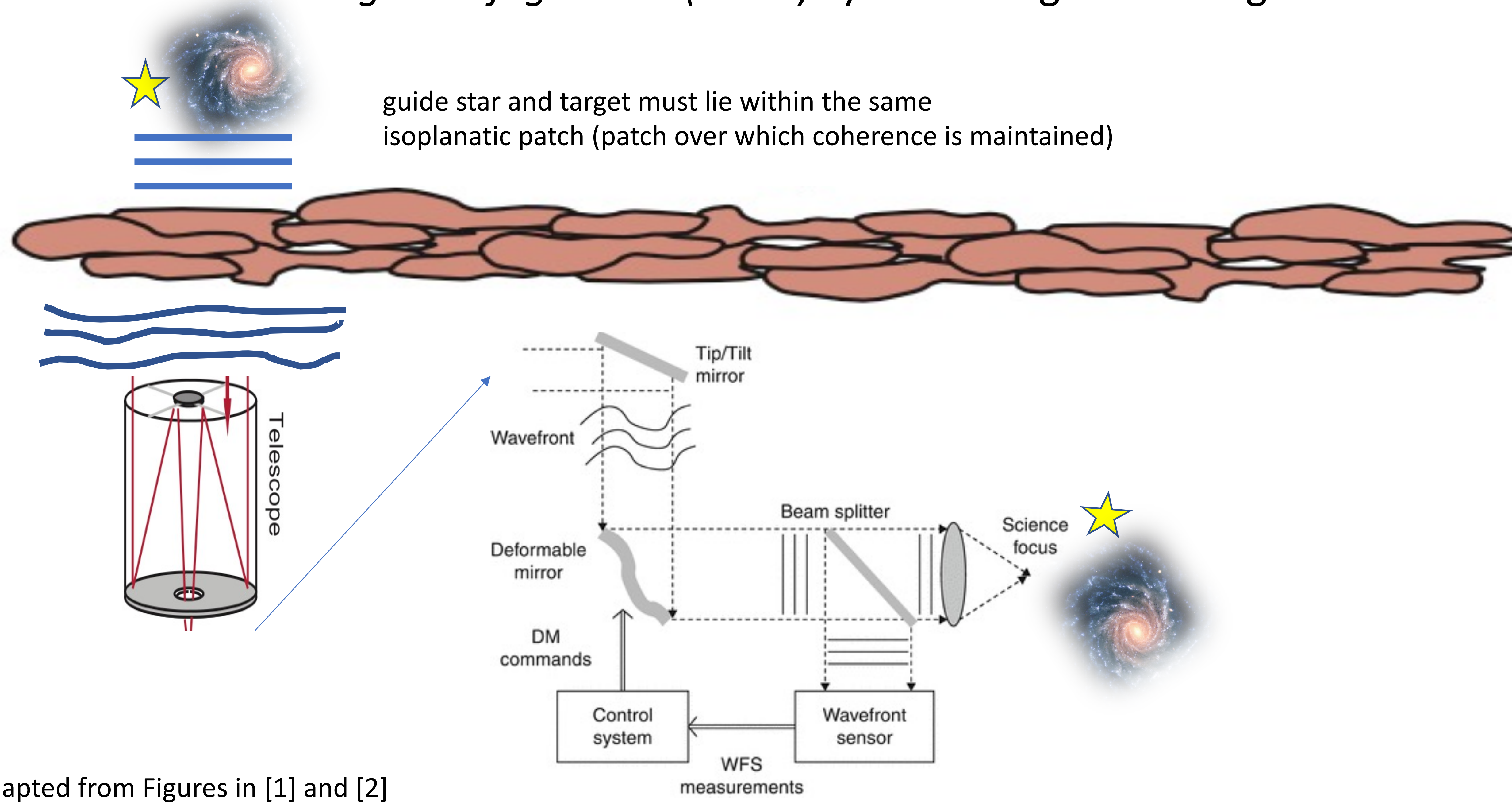
Adapted from Figures in [1] and [2]



Adapted from Figures in [1] and [2]

single conjugate AO (SCAO) system using a natural guide star

guide star and target must lie within the same
isoplanatic patch (patch over which coherence is maintained)



Adapted from Figures in [1] and [2]

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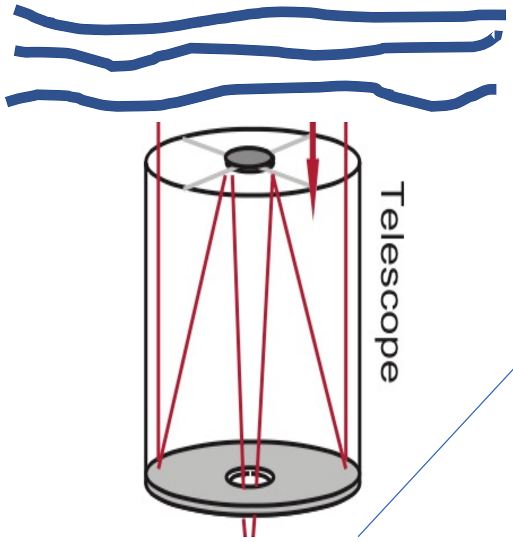
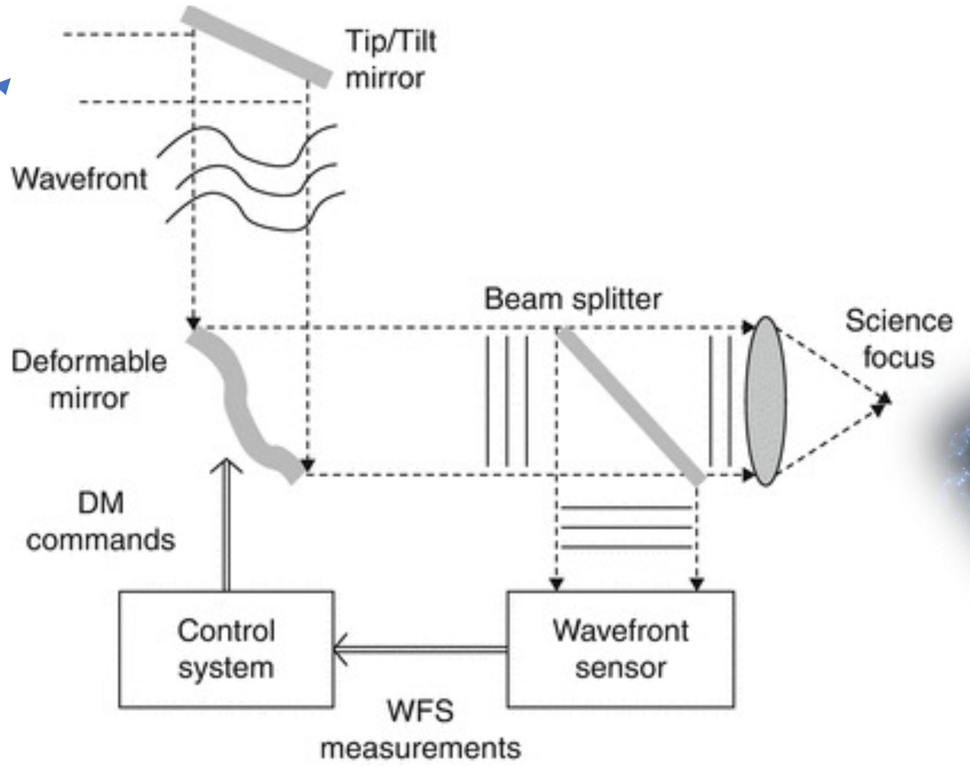
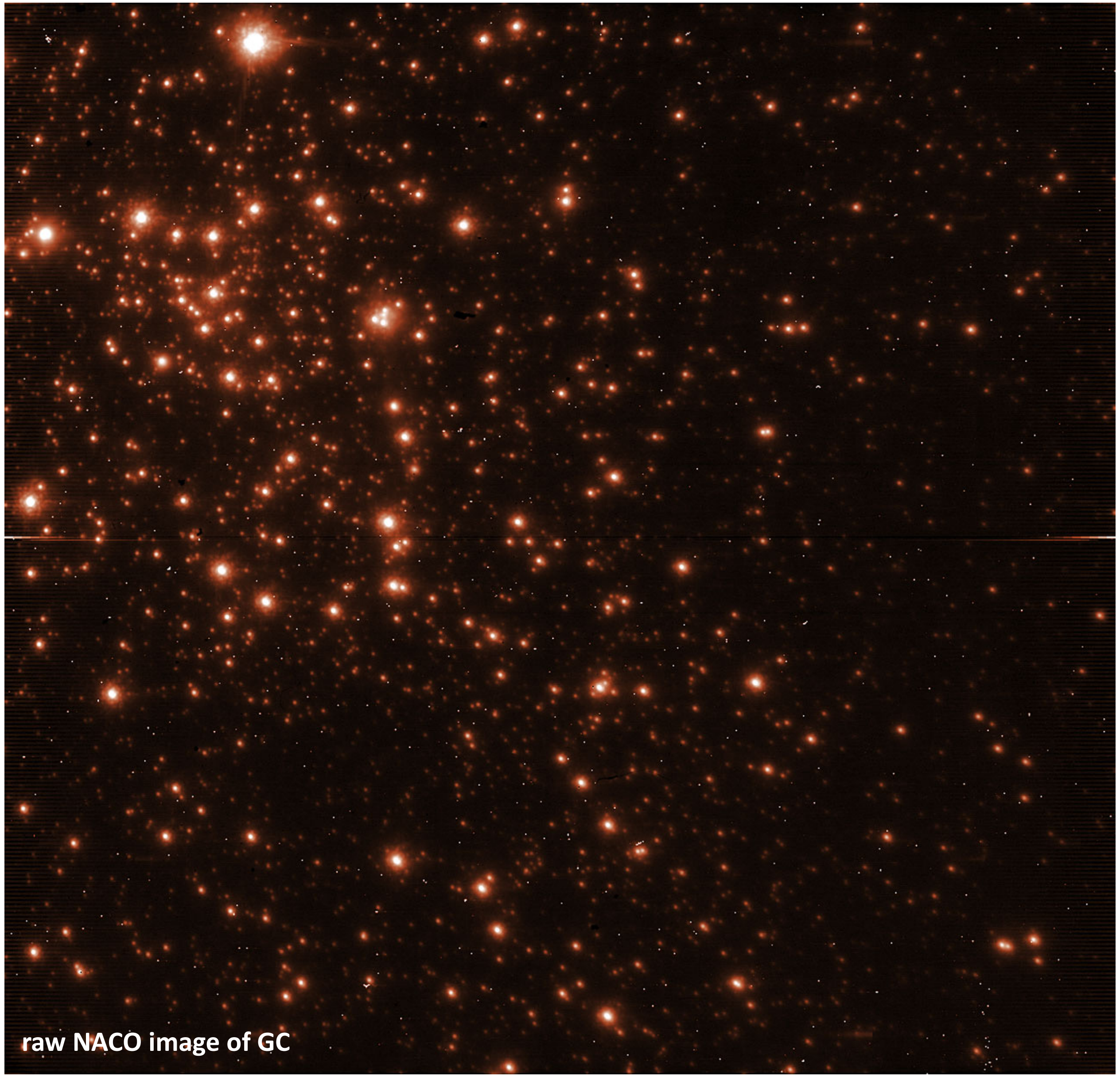
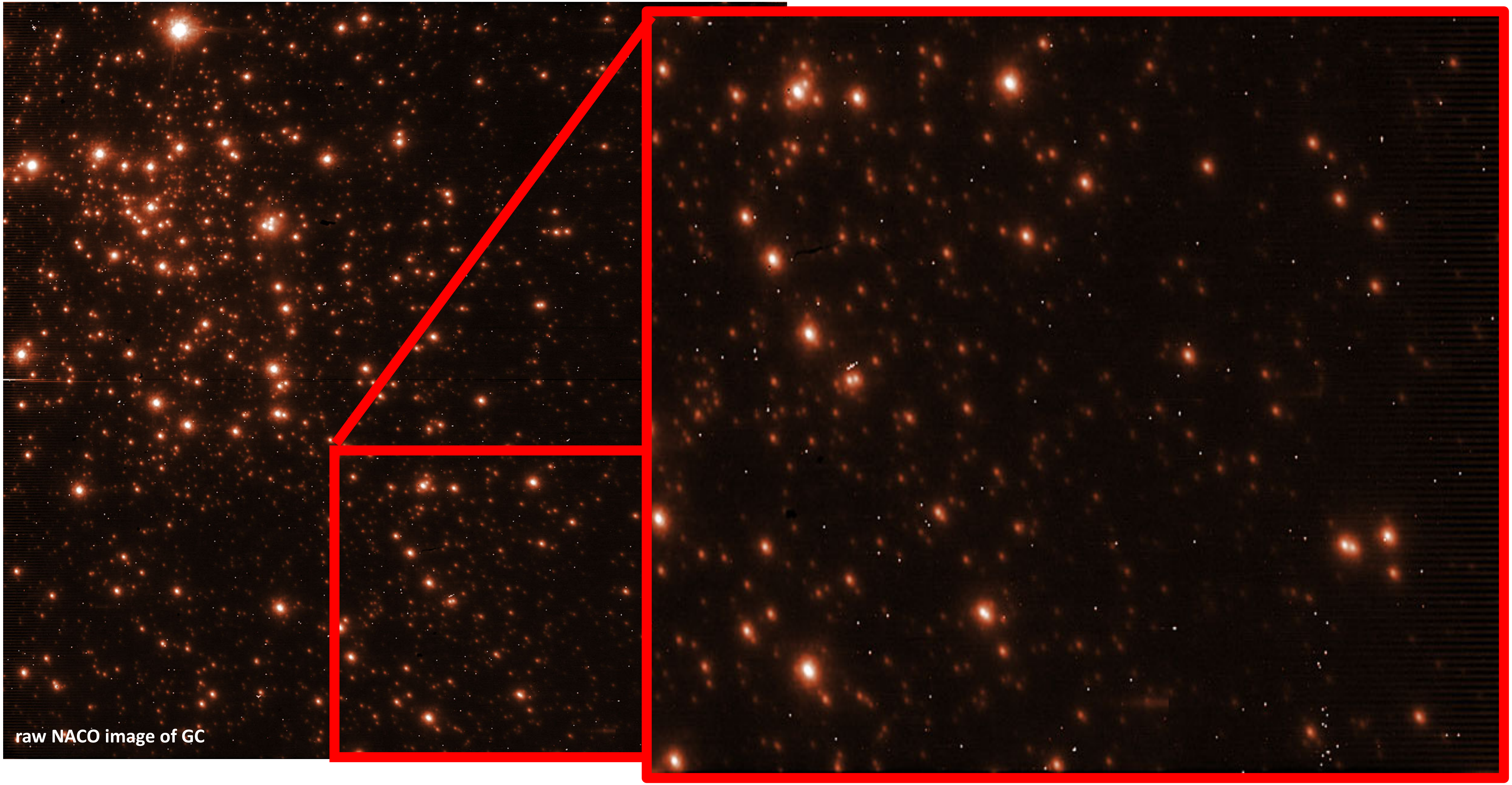




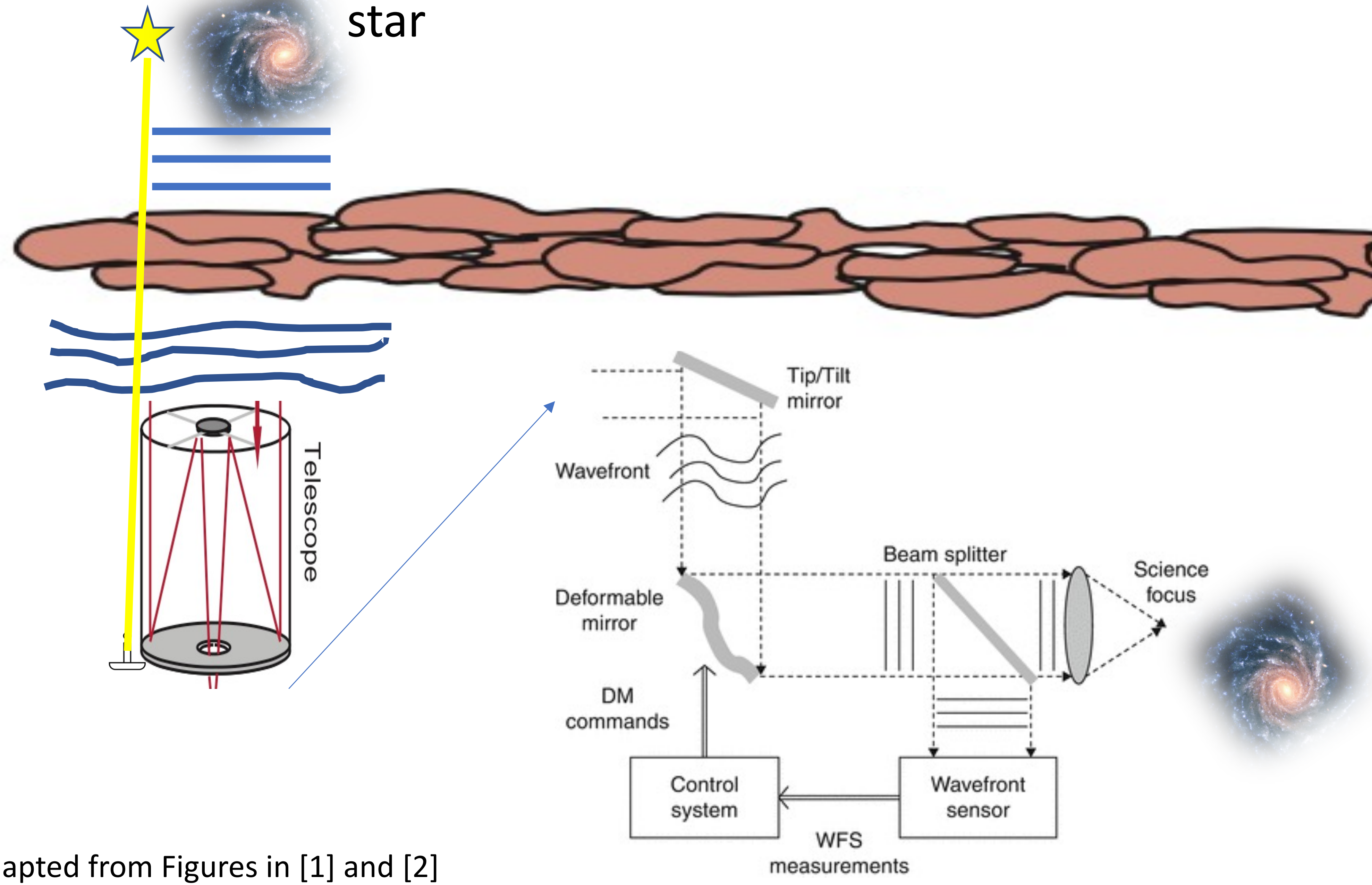
- Need a bright star next to your target
- wavelength decreases, the isoplanatic patch decreases in size and phase changes occur faster

Adapted from Figures in [1] and [2]


raw NACO image of GC


raw NACO image of GC

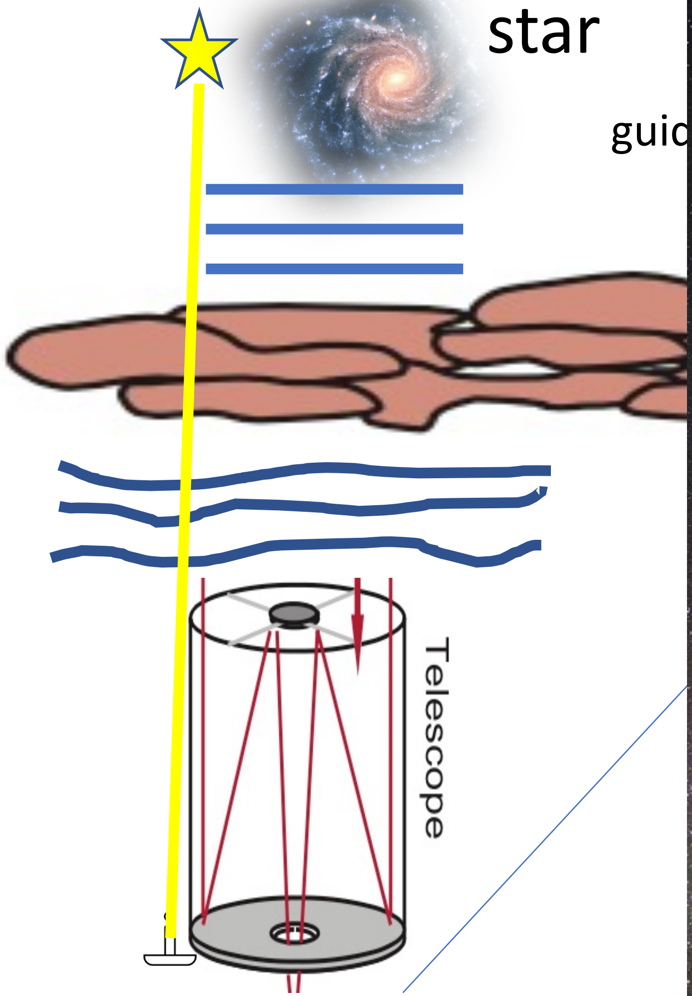
Laser guide star AO (LGS-AO) system using a laser and a guide star

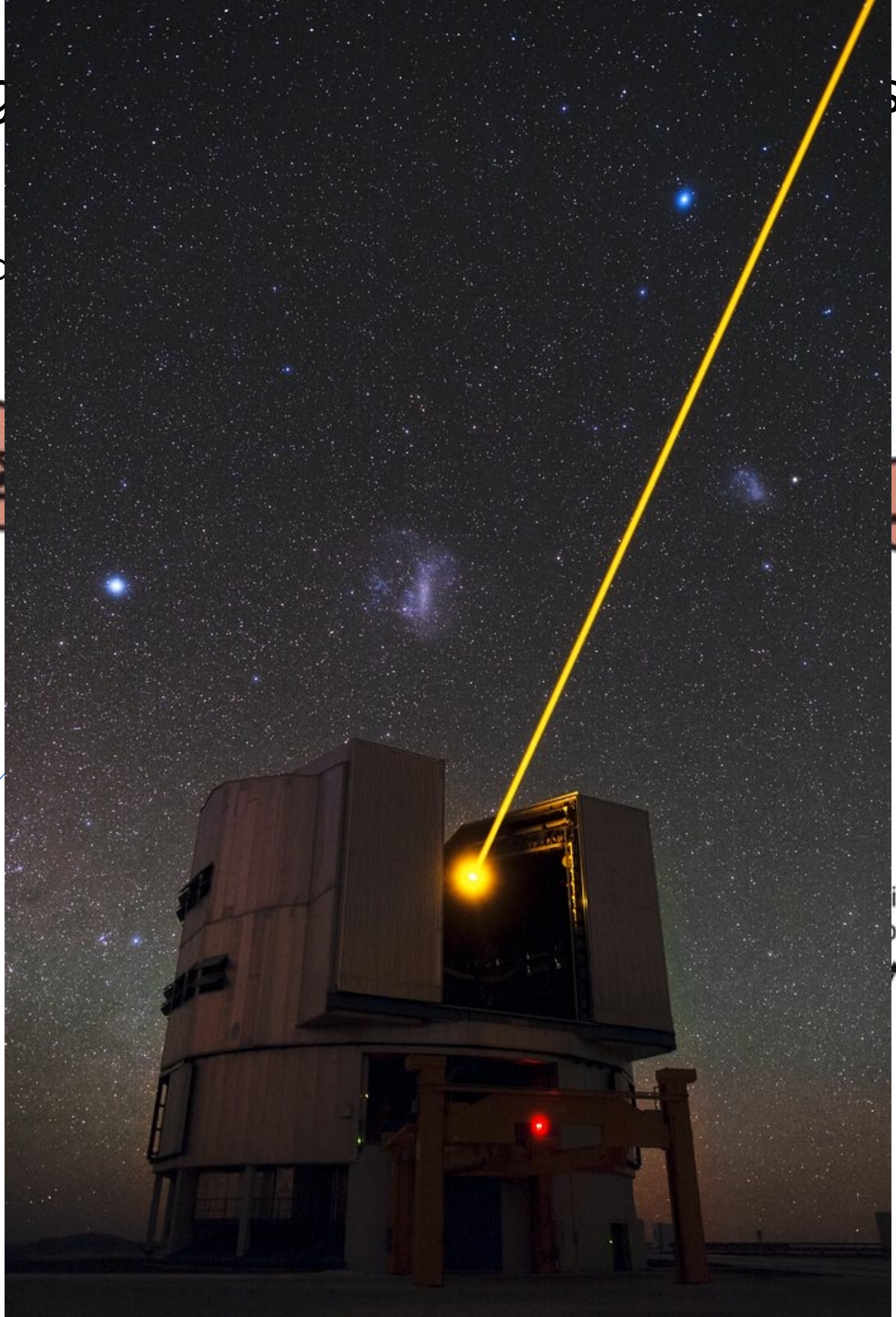


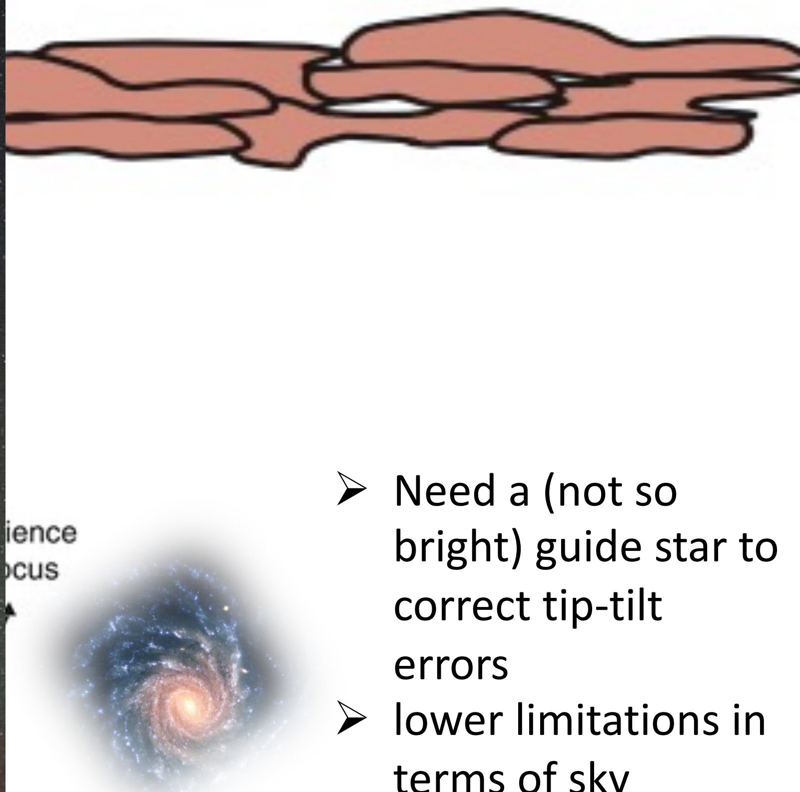
- Need a (not so bright) guide star to correct tip-tilt errors
- lower limitations in terms of sky coverage

Adapted from Figures in [1] and [2]

Laser g sing a laser and a guide star



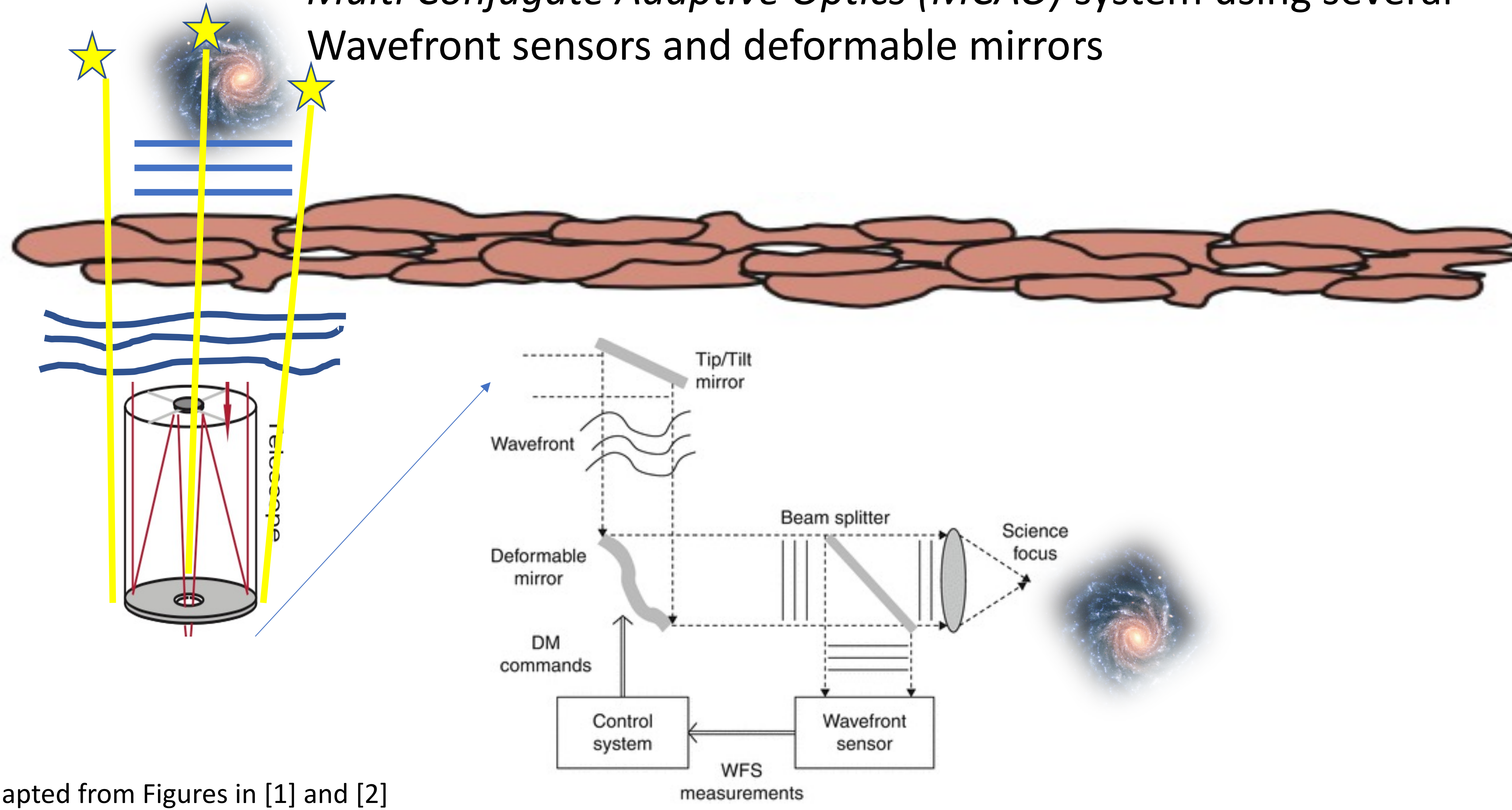




- Need a (not so bright) guide star to correct tip-tilt errors
- lower limitations in terms of sky coverage

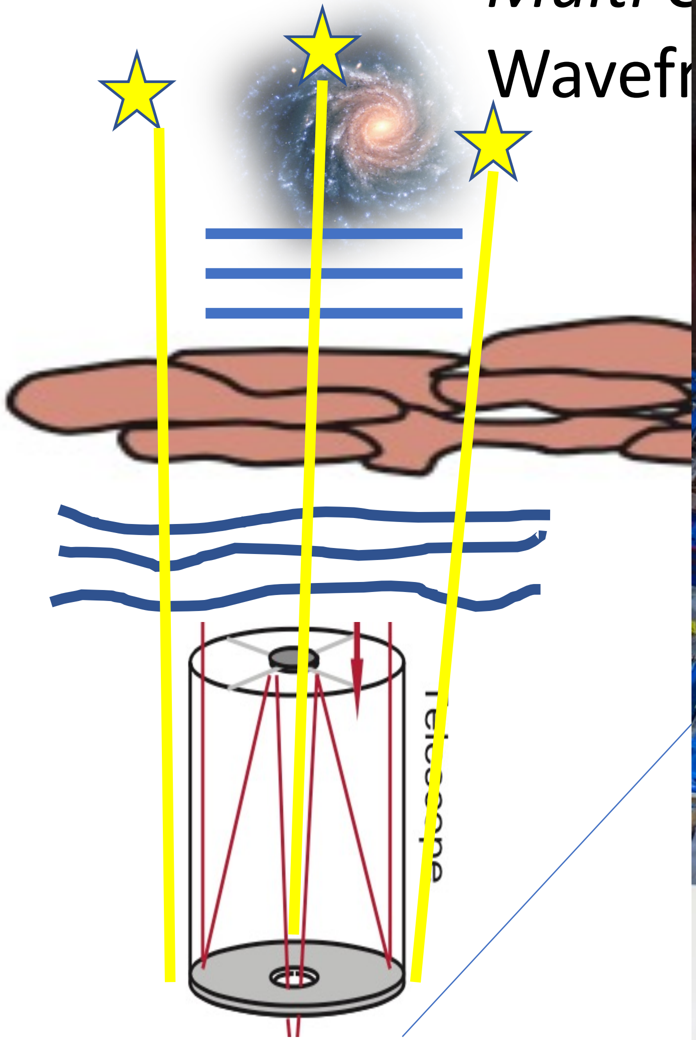
Adapted from Figures in [1] and [2]

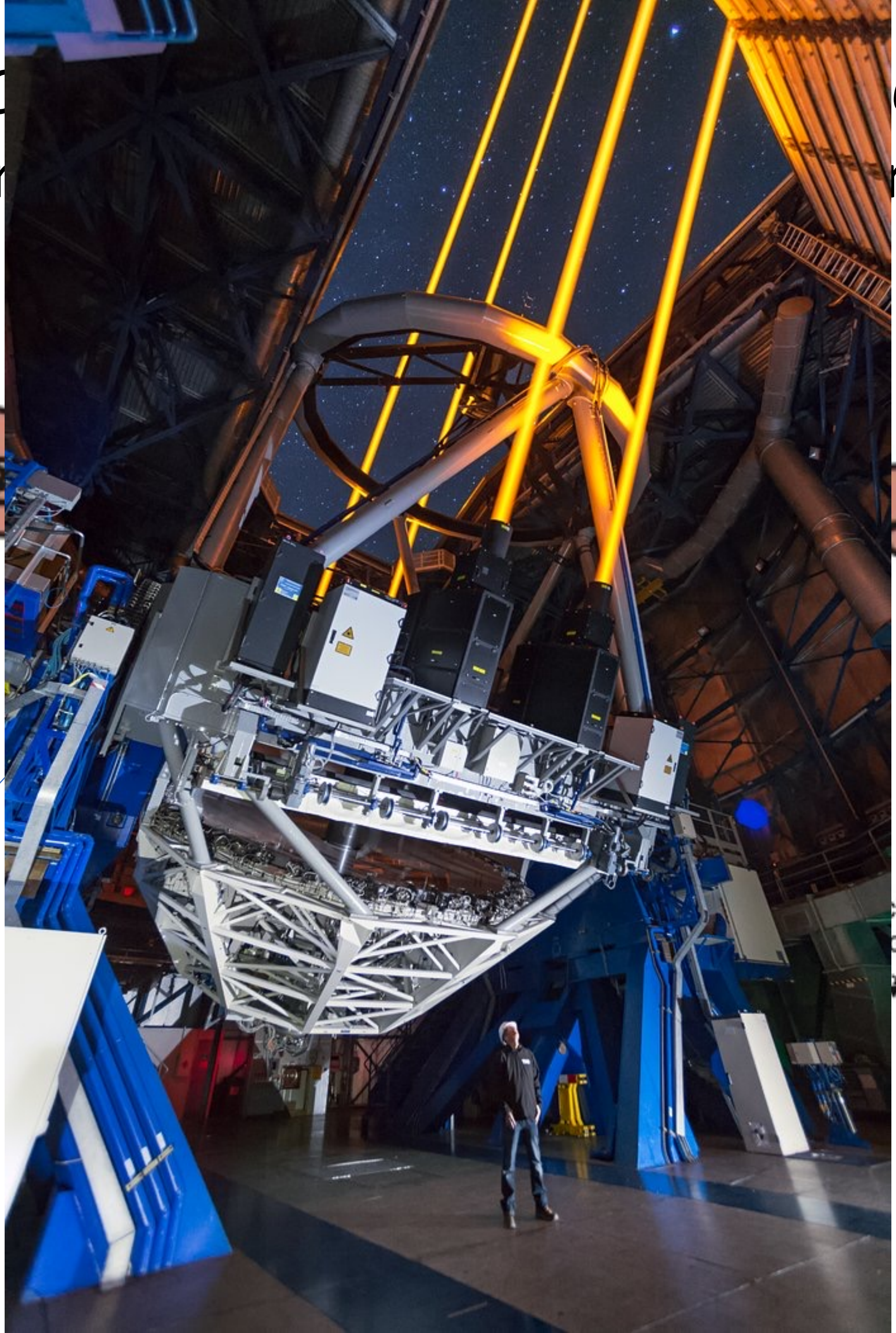
Multi Conjugate Adaptive Optics (MCAO) system using several Wavefront sensors and deformable mirrors

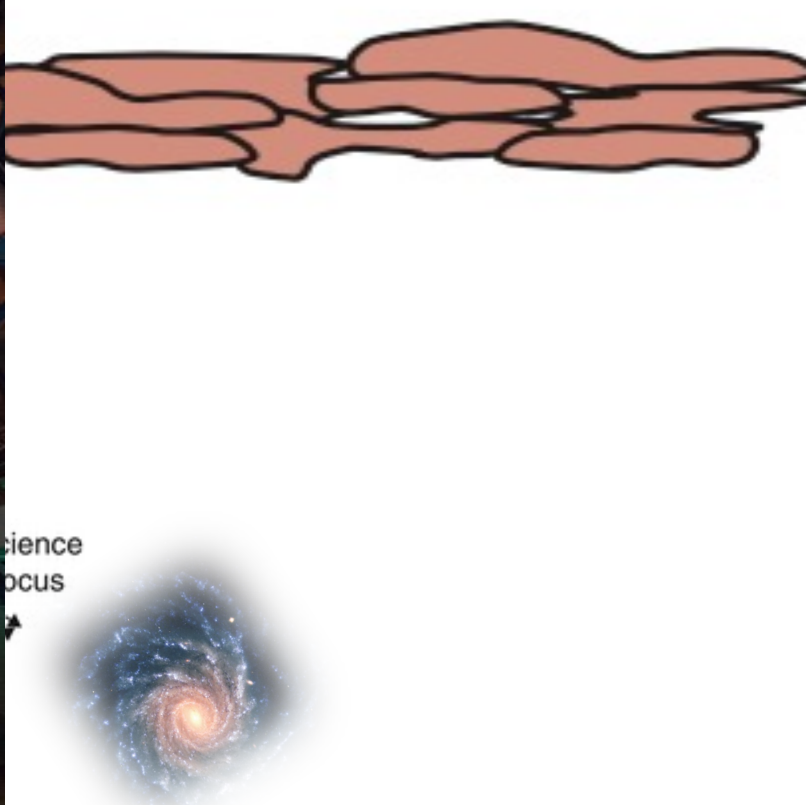


Adapted from Figures in [1] and [2]

Multi C *O)* system using several
Wavefr rrors

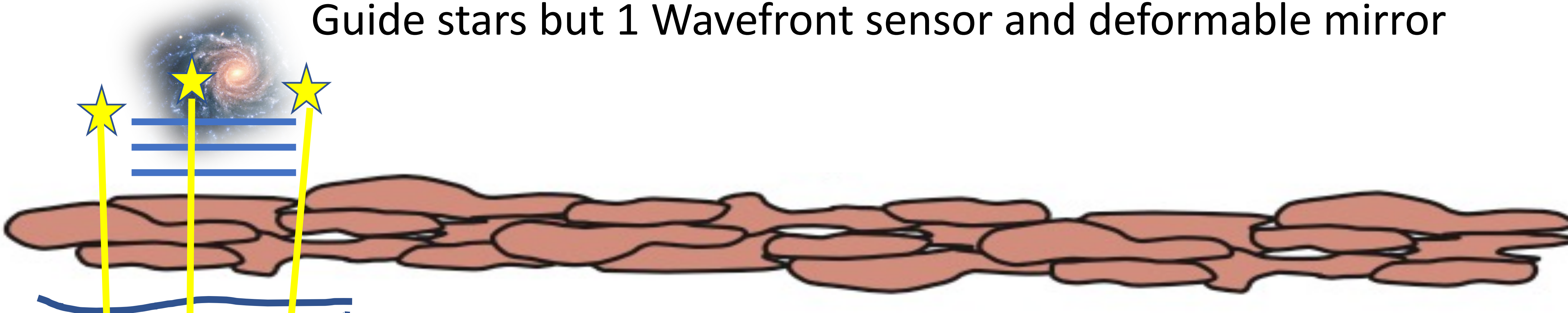


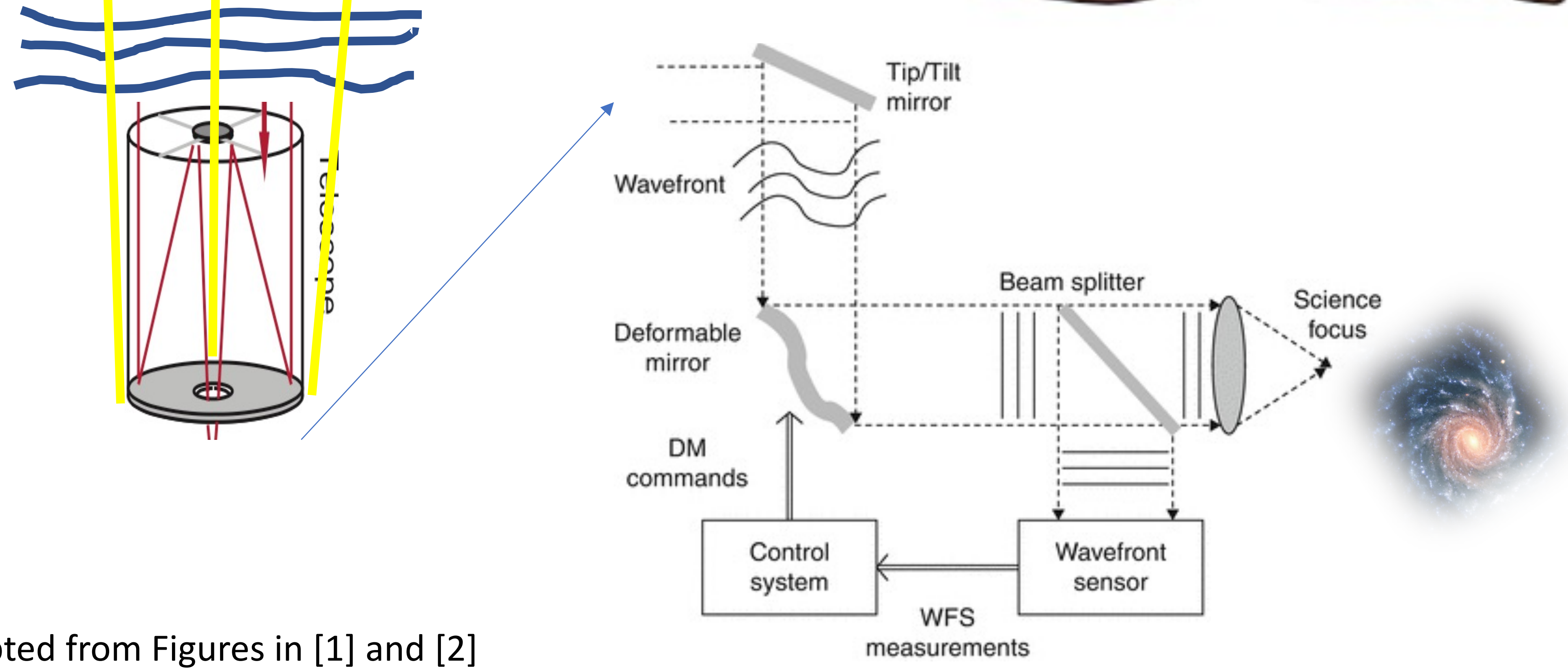




Adapted from Figures in [1] and [2]

Ground-layer AO (GLAO) system using several Guide stars but 1 Wavefront sensor and deformable mirror

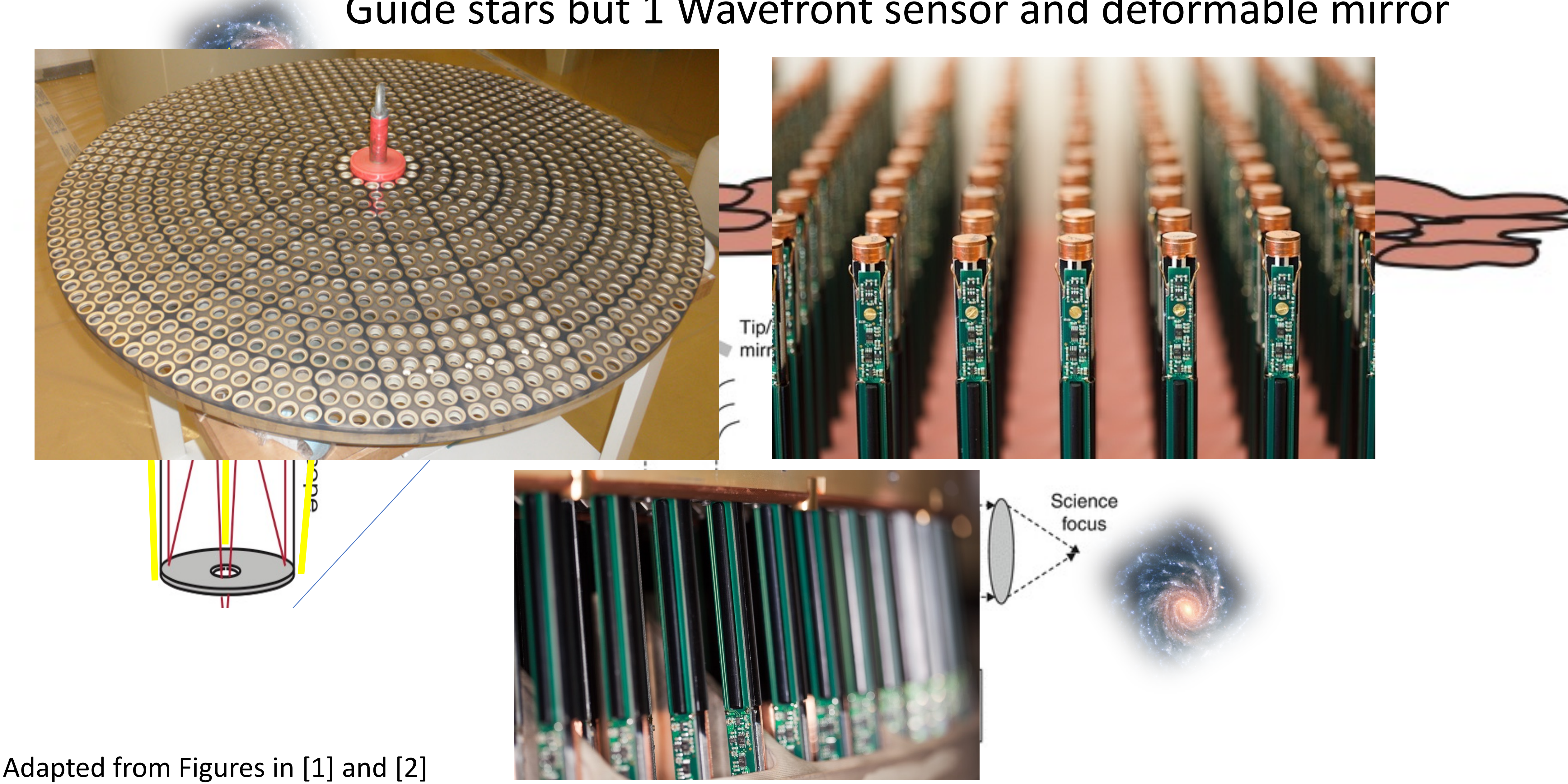




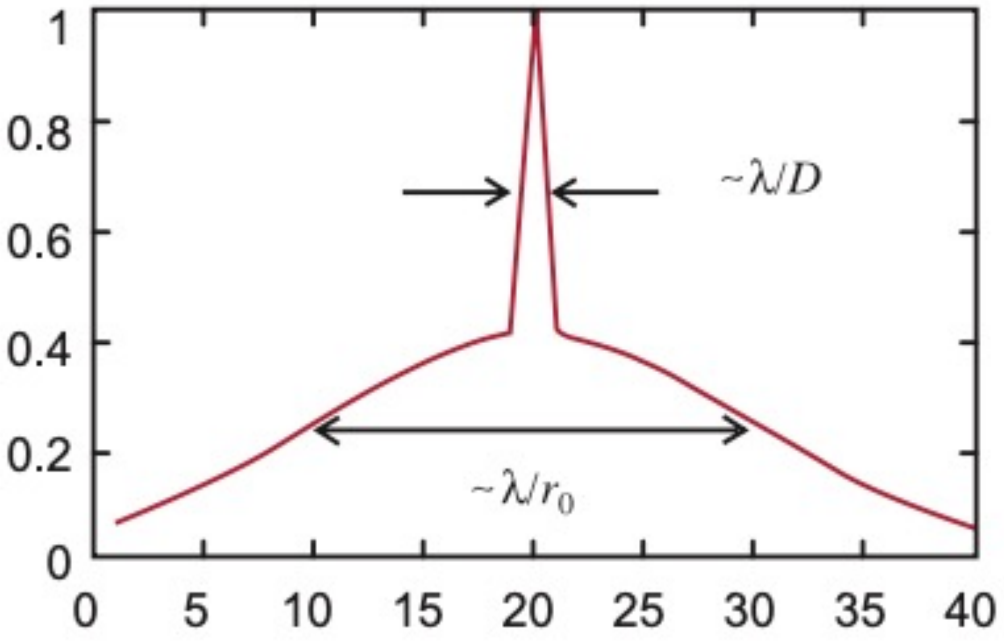
- One DM to correct for the lower layer of the atmosphere < 2km

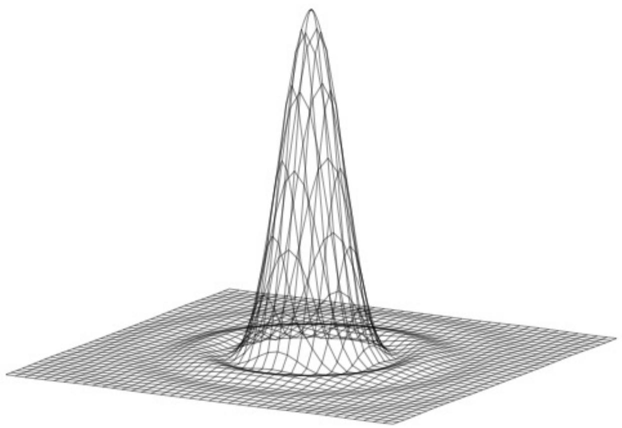
Adapted from Figures in [1] and [2]

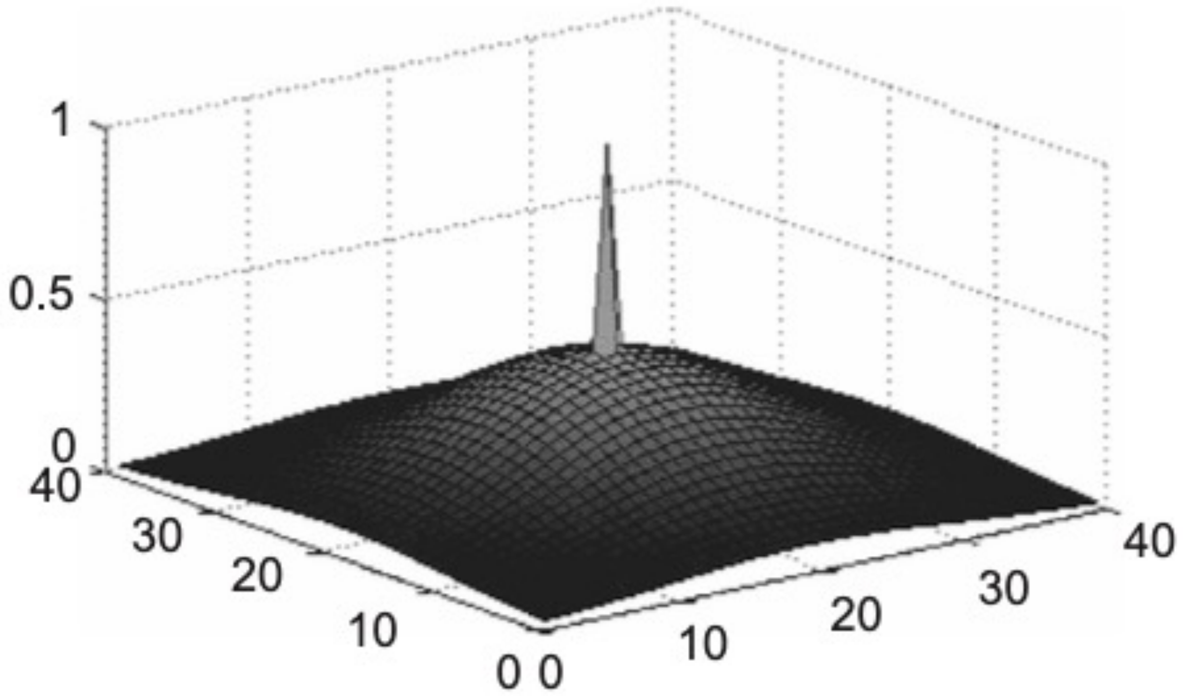
Ground-layer AO (GLAO) system using several Guide stars but 1 Wavefront sensor and deformable mirror



Adapted from Figures in [1] and [2]



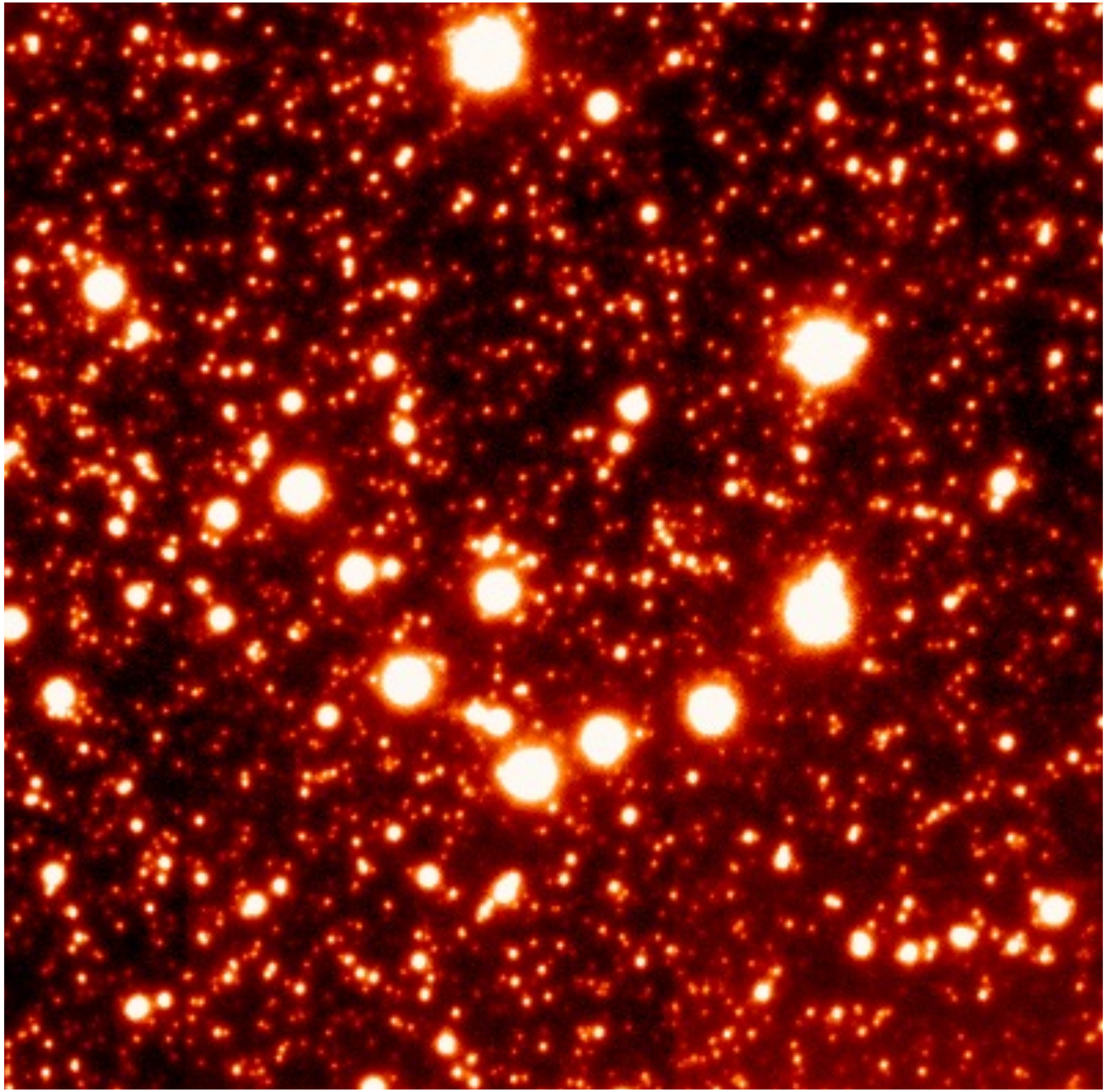




r_0=Fried's coherence length is a widely used descriptor of the level of **atmospheric turbulence** at a particular site.

Strehl ratio (S) – the ratio of aberrated (achieved) PSF peak intensity to the diffraction-limited (theoretical) PSF peak intensity. If σ is the RMS wavefront deviation:

$$S = e^{-(2\pi\sigma/\lambda)^2}$$



Phase 2:

-From RAW to REDUCED DATA-

The ingredients:

- An instrument comes with a <u>calibration plan</u> -

The instrument's calibration plan

Calibration Frames to take care of **<u>instrument's systematics</u>**:

BIAS
DARK
FLAT FIELD

Calibration for **<u>Science</u>**:

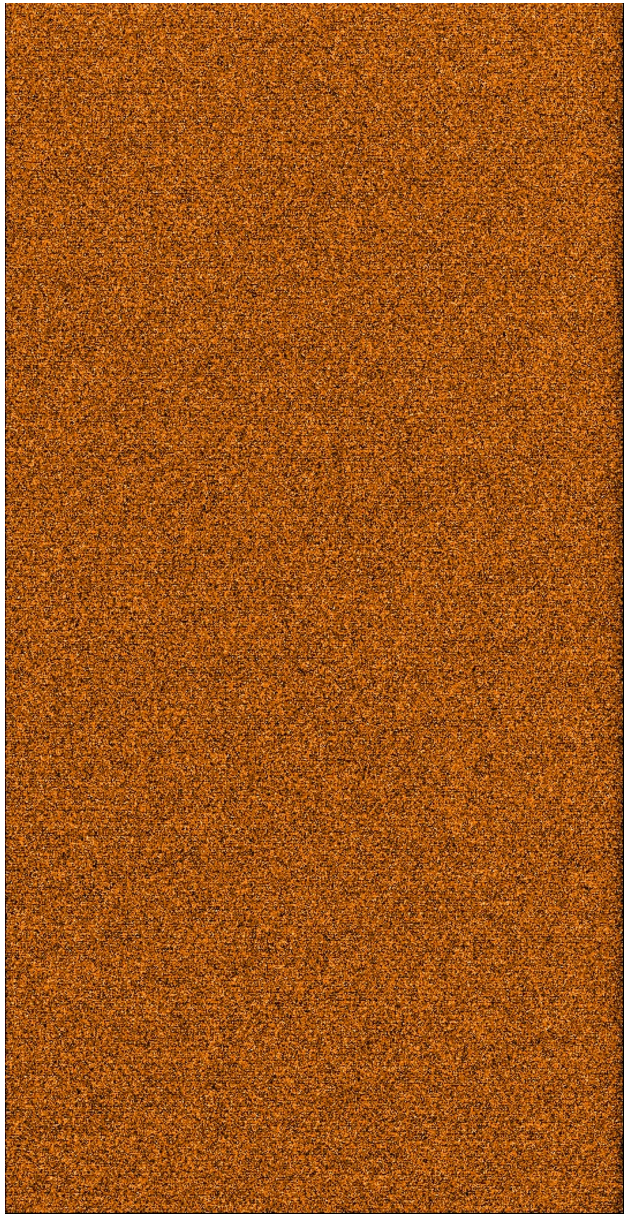
Photometric Standards

BIAS Frame

BIAS frame:

- WHAT? “measures” underlying structure in the image from the CCD or electronics
- HOW? taken with Exp Time=0s

ACTION:
To be subtracted from each image



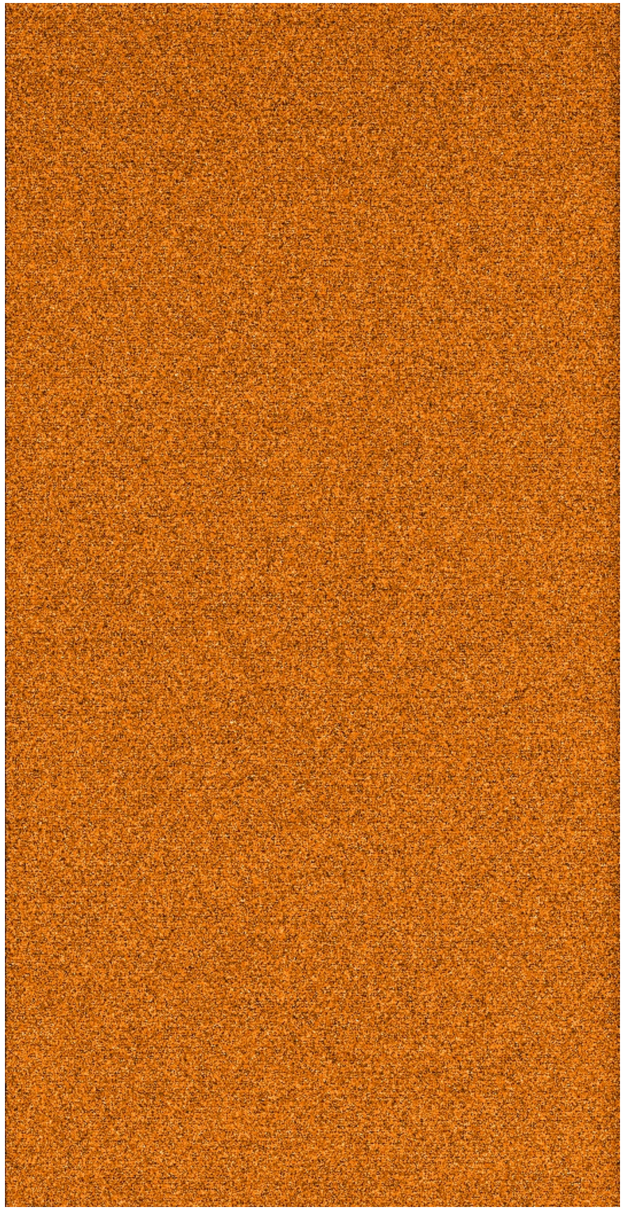
DARK Frame

<u>DARK frame</u>:

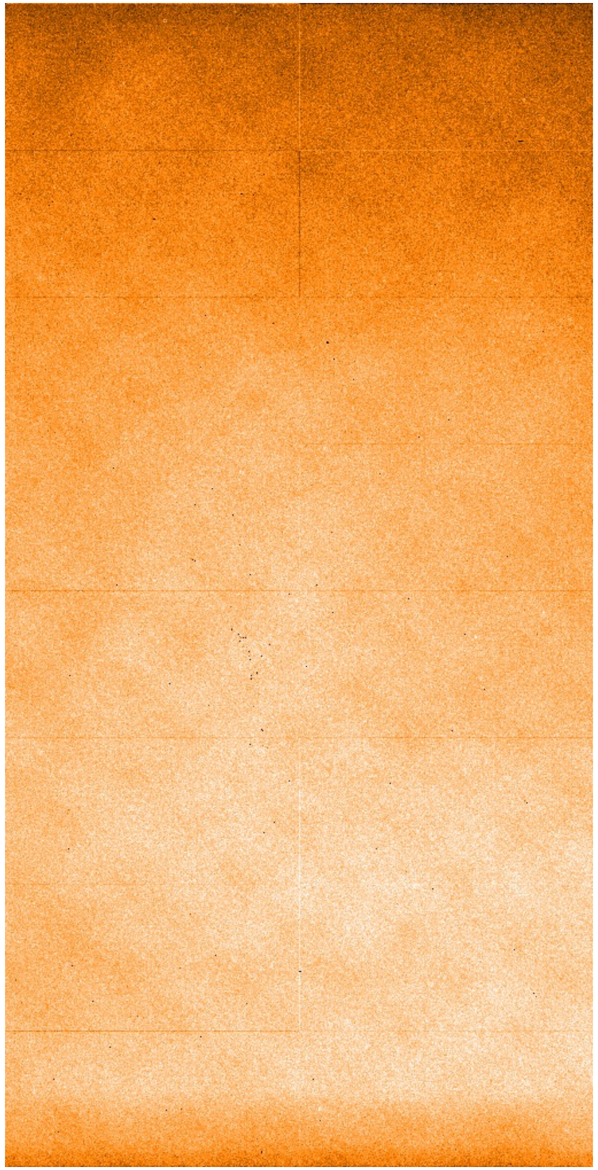
- WHAT? “measures” the noise form dark current: Dark current arises from thermal energy within the silicon lattice comprising the CCD.

- HOW? taken with Exp Time=Exp Time of Science Frame but with the shutter closed so no light falls on the CCD

ACTION:
To be subtracted from each Science image
(after also the BIAS is subtracted)



FLAT FIELD Frame

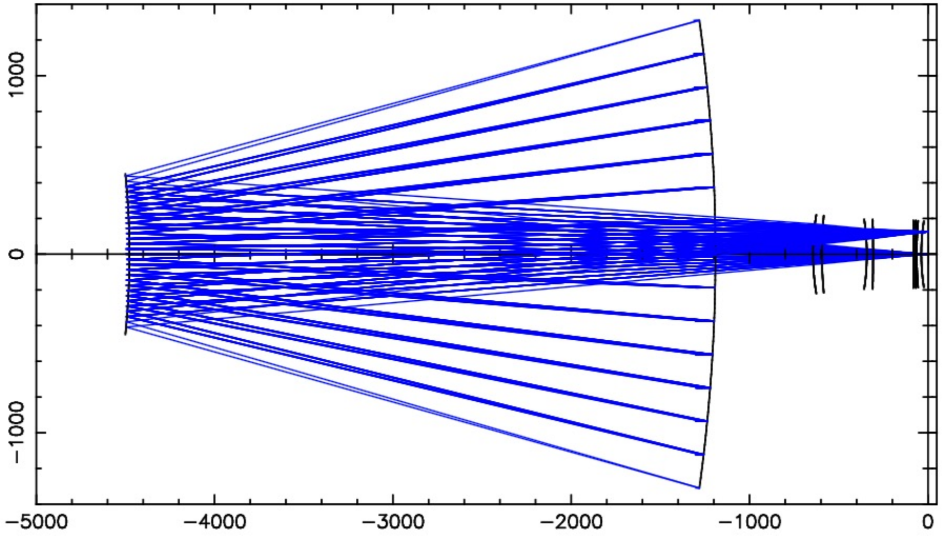


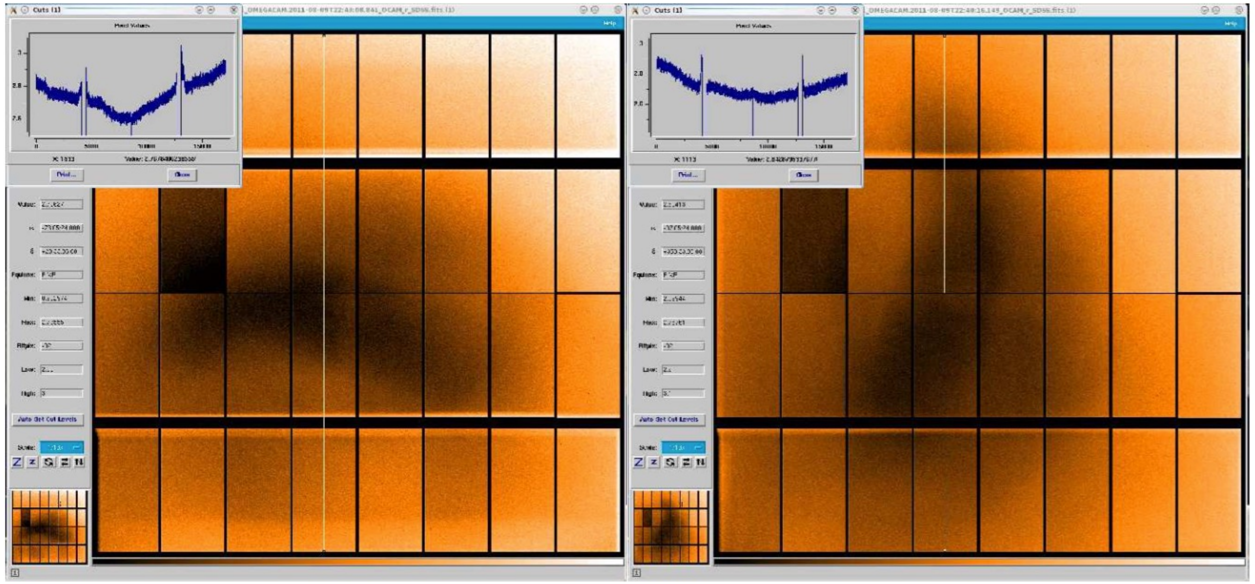
FLAT FIELD frame:

- WHAT? “measures” non-uniformities between pixels (different efficiency, vignetting)

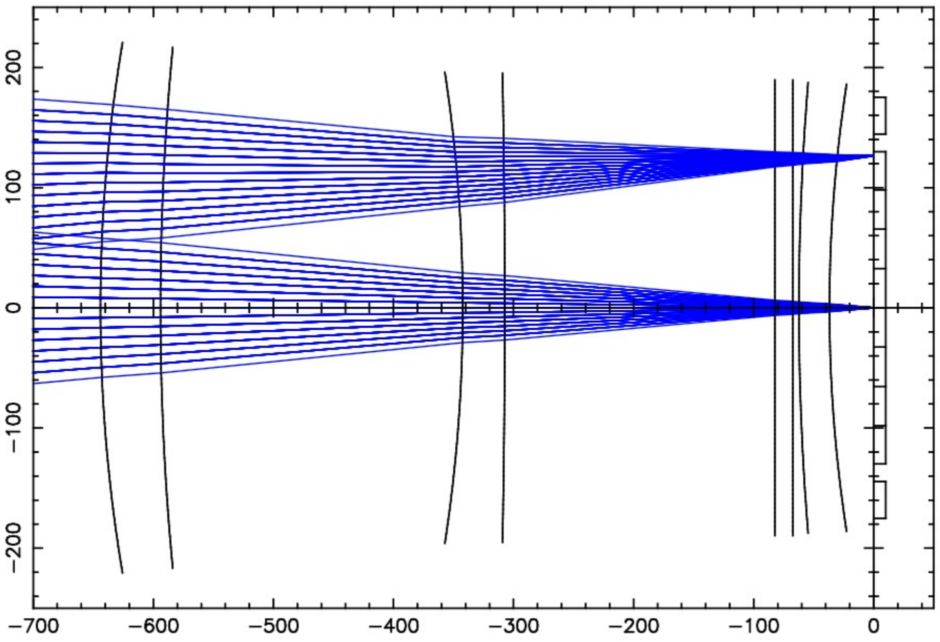
- HOW? Open Shutter image of a fetureless and uniformly illuminated source (twilight sky or a dome projector screen)

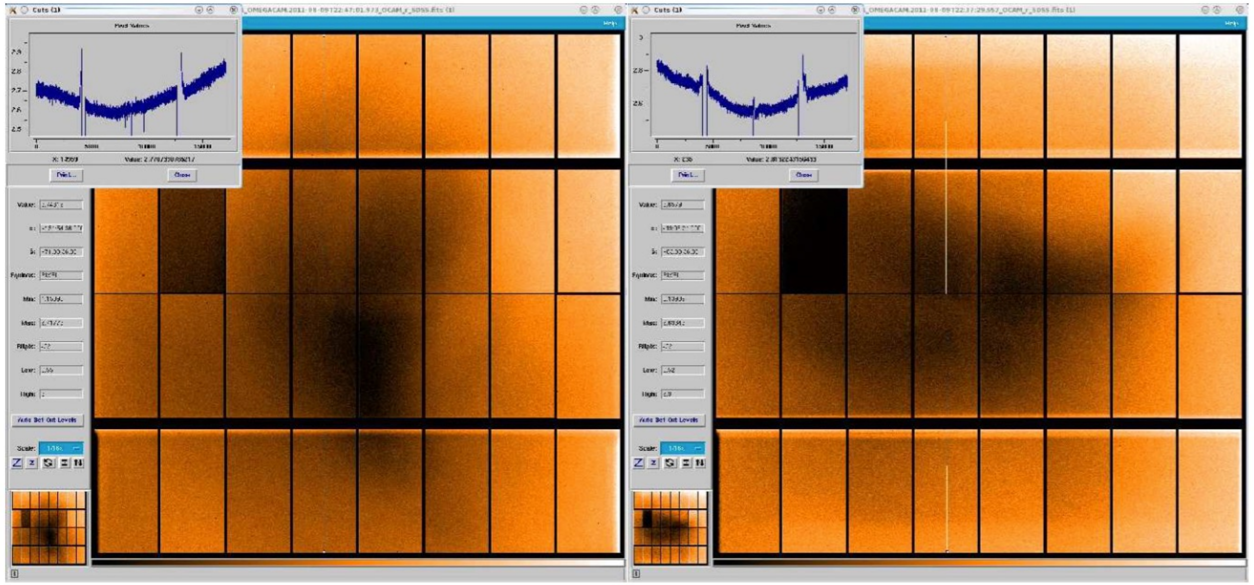
ACTION:
The Science image must be divided the FLAT FIELD (after BIAS and DARK subtraction)





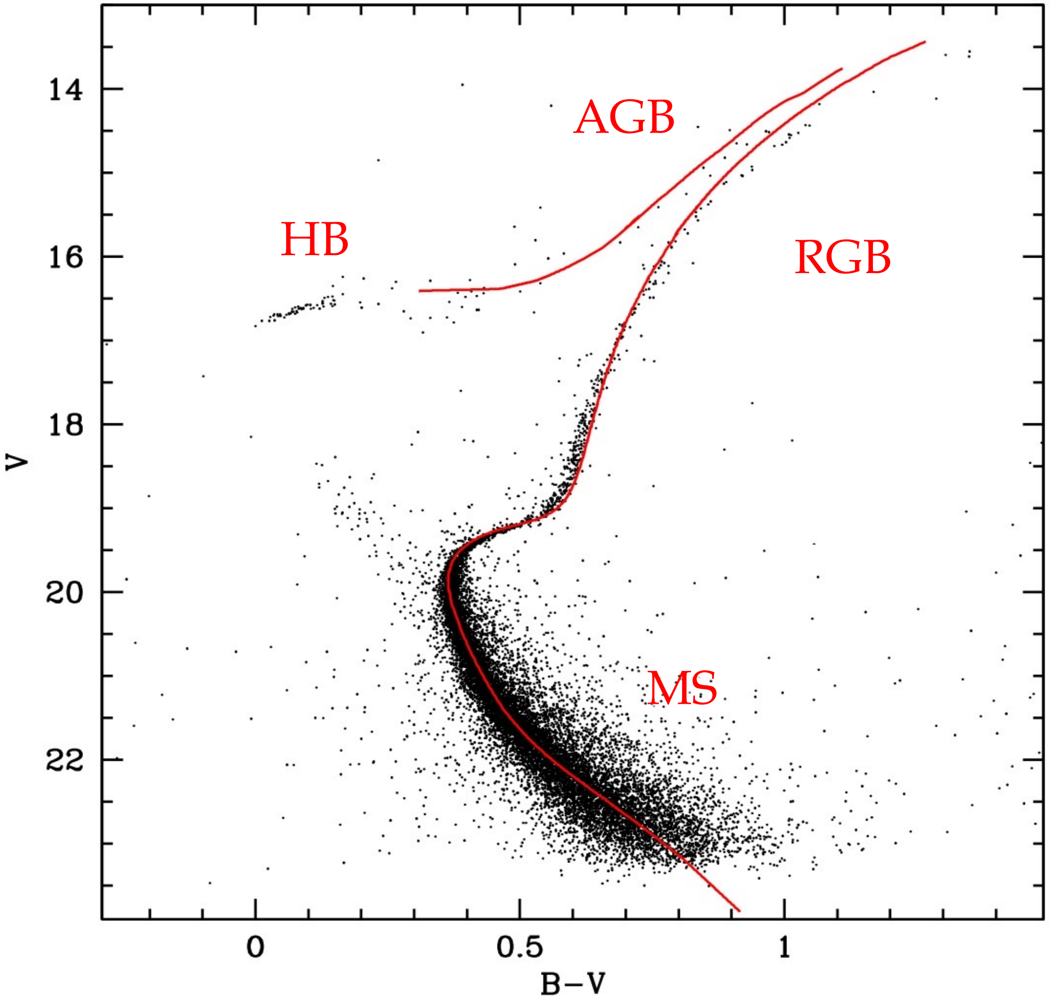
CORRECTOR ZONE





Phase 3:

-Photometry-

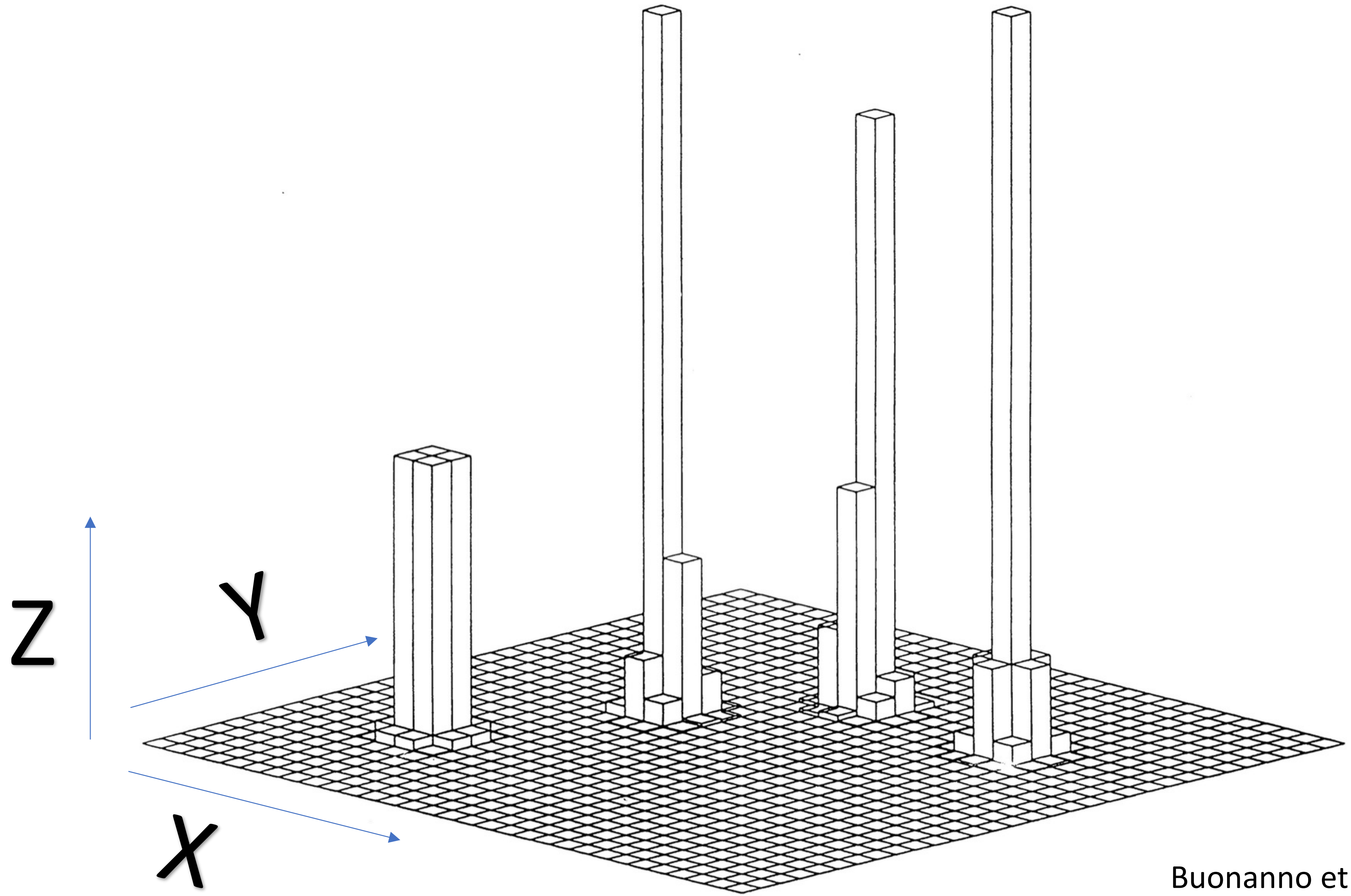


AGB
HB
RGB
MS
14
16
18
20
22
V
0
0.5
1
B−V

The ingredients:

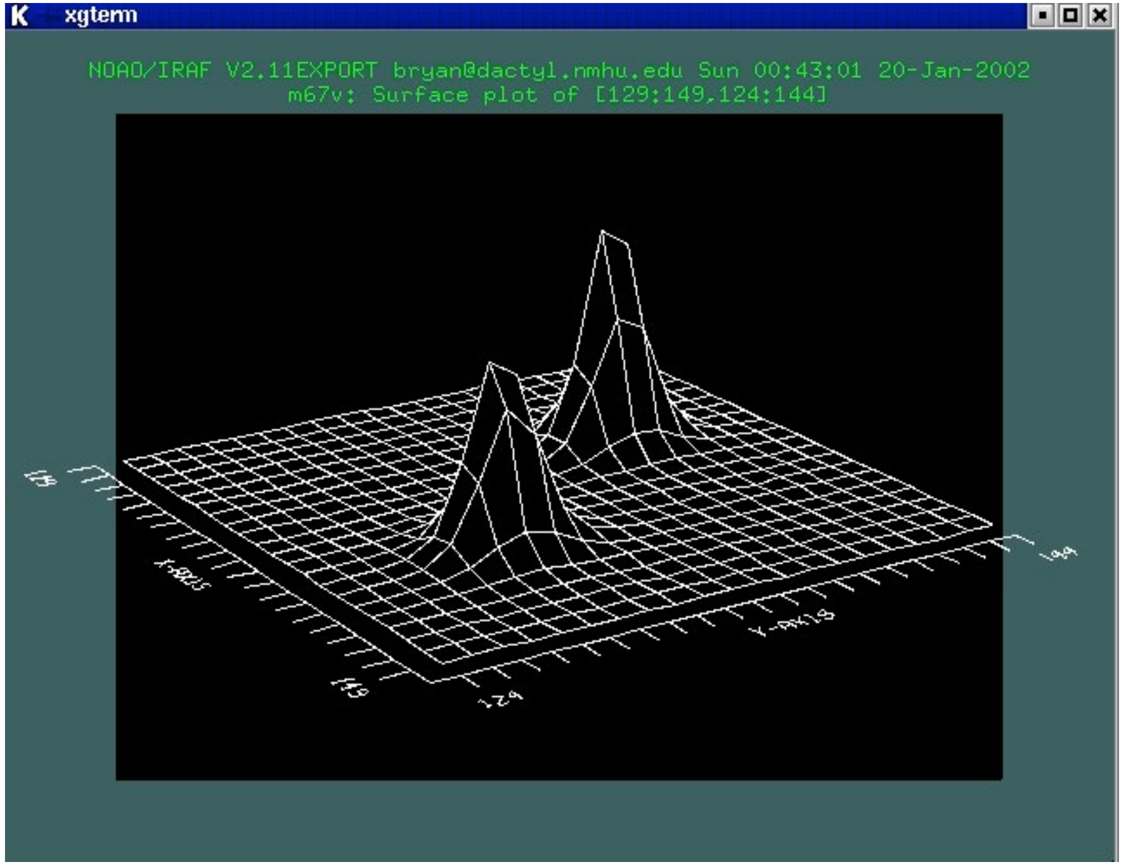
1. Calibrated (Reduced) Science Frames
2. Software

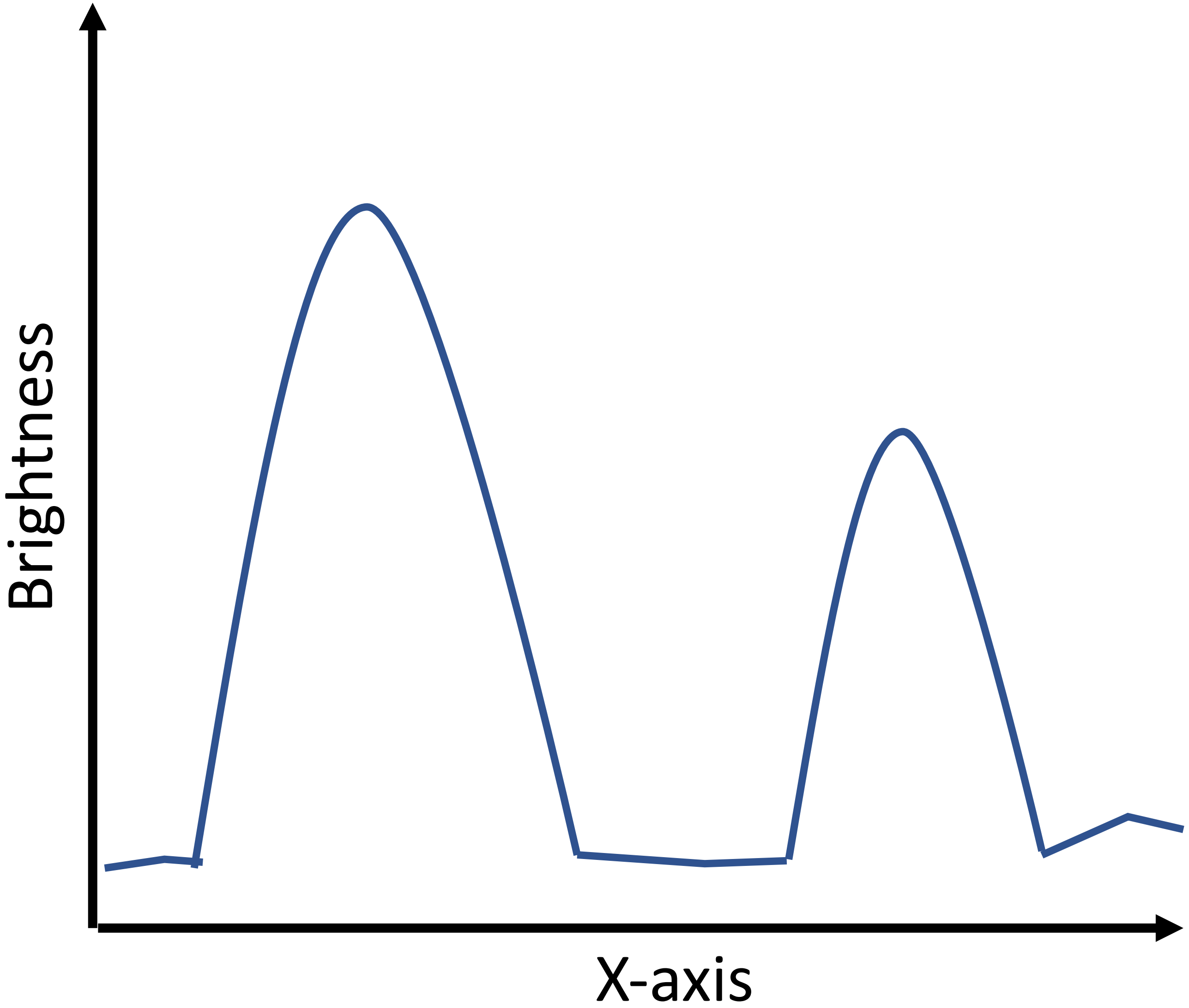
Flexible Image Transport System (**FITS**)



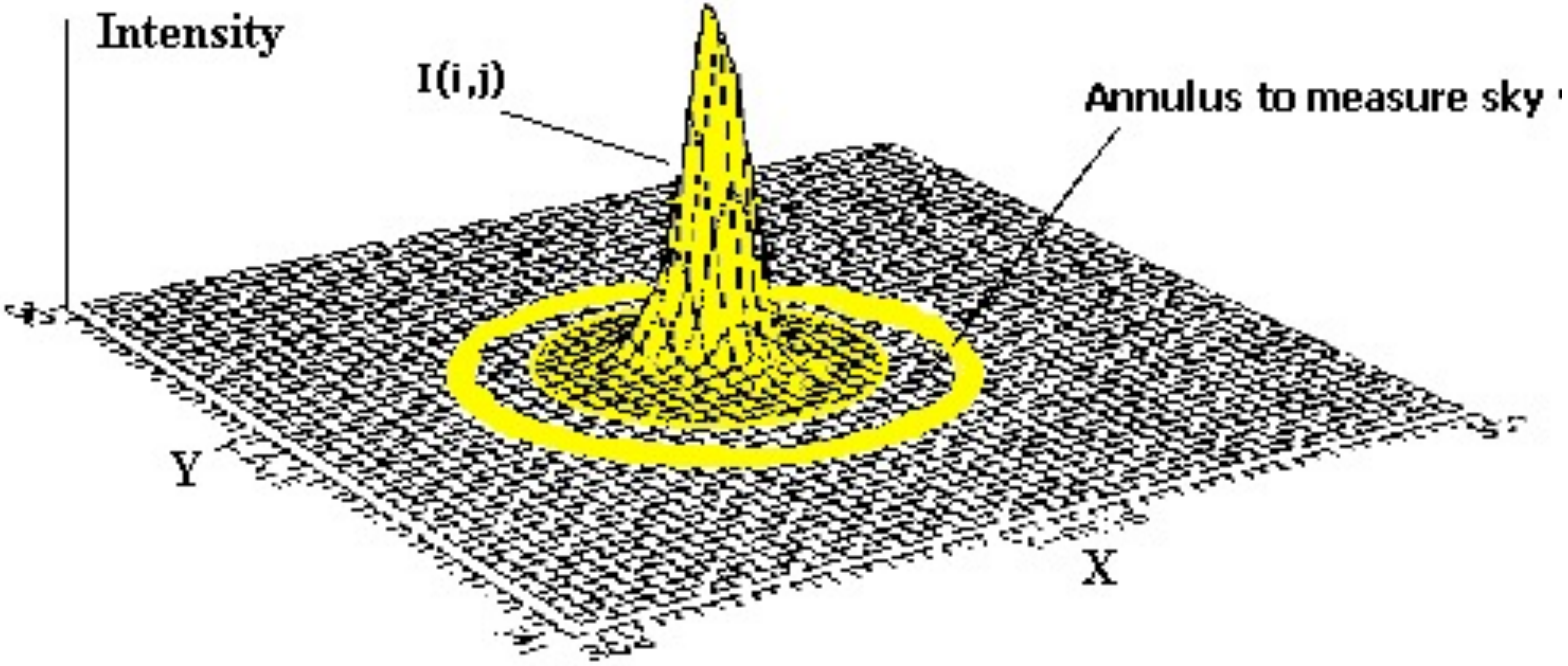
Buonanno et al. 1989, PASP, 101, 294

Low Stellar Density: Aperture Photometry



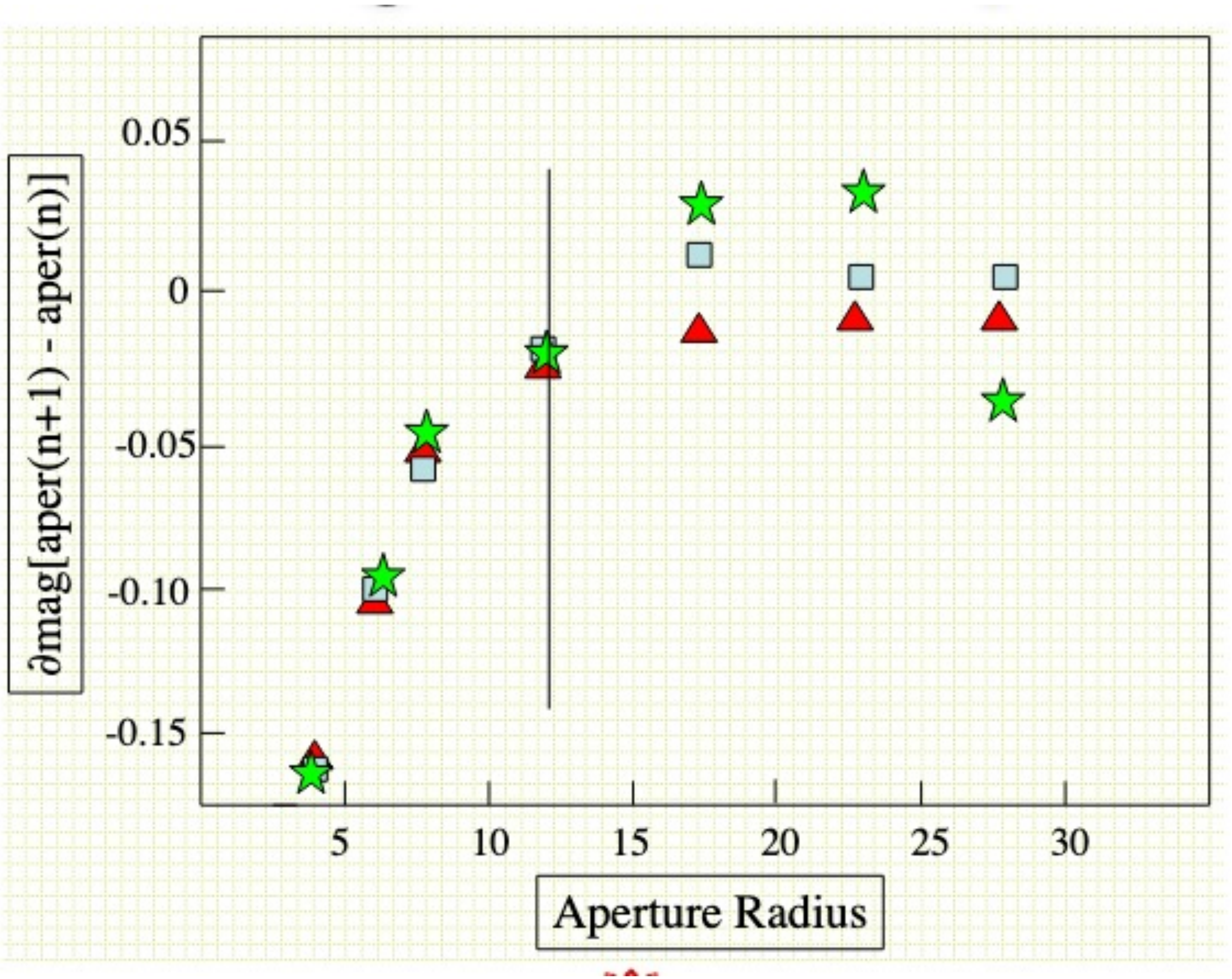


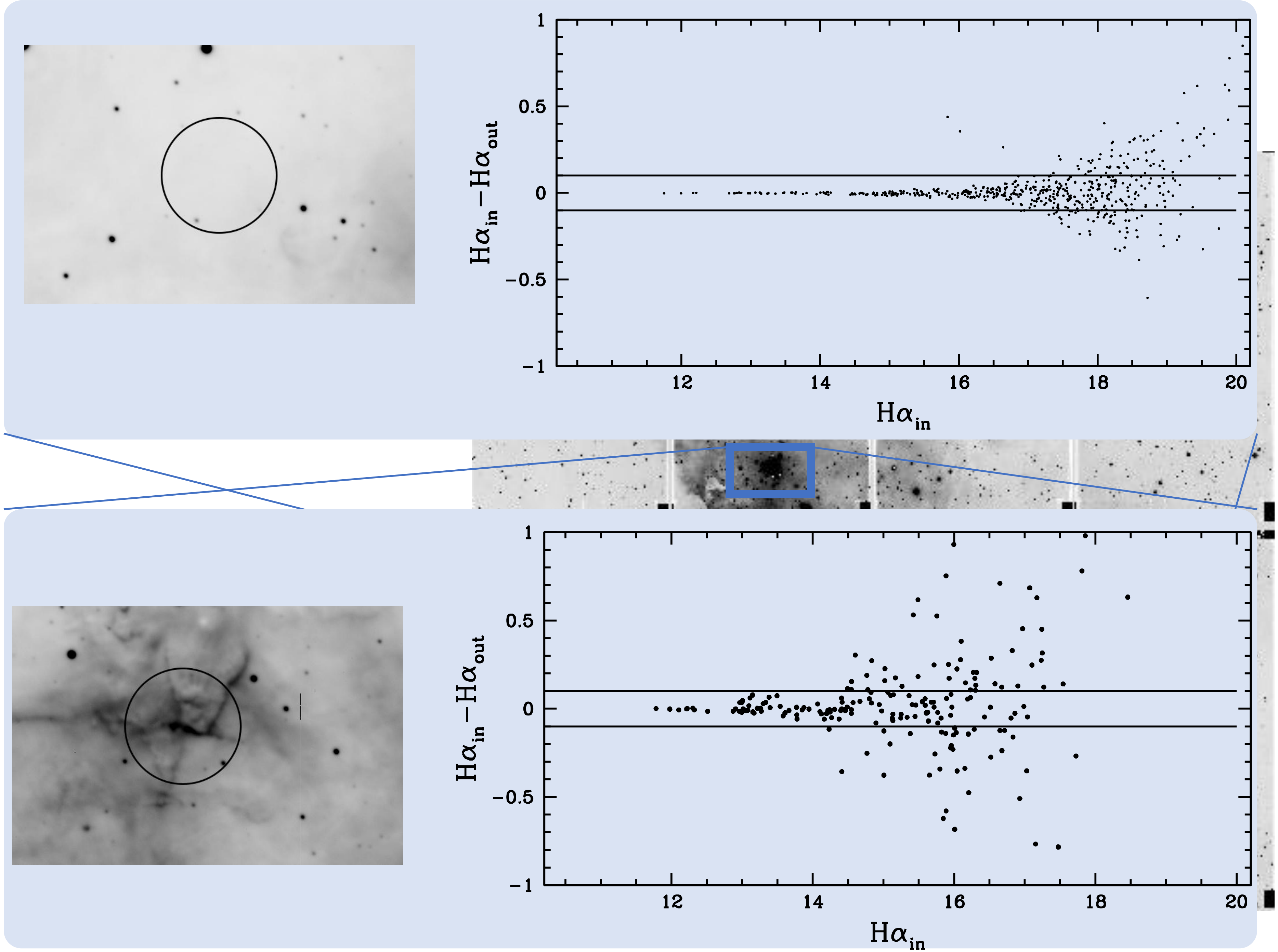
Low Stellar Density: Aperture Photometry



Mag = -[2.5 log (sum(I(i,j))) - (sky level)*(area of aperture)] + C,

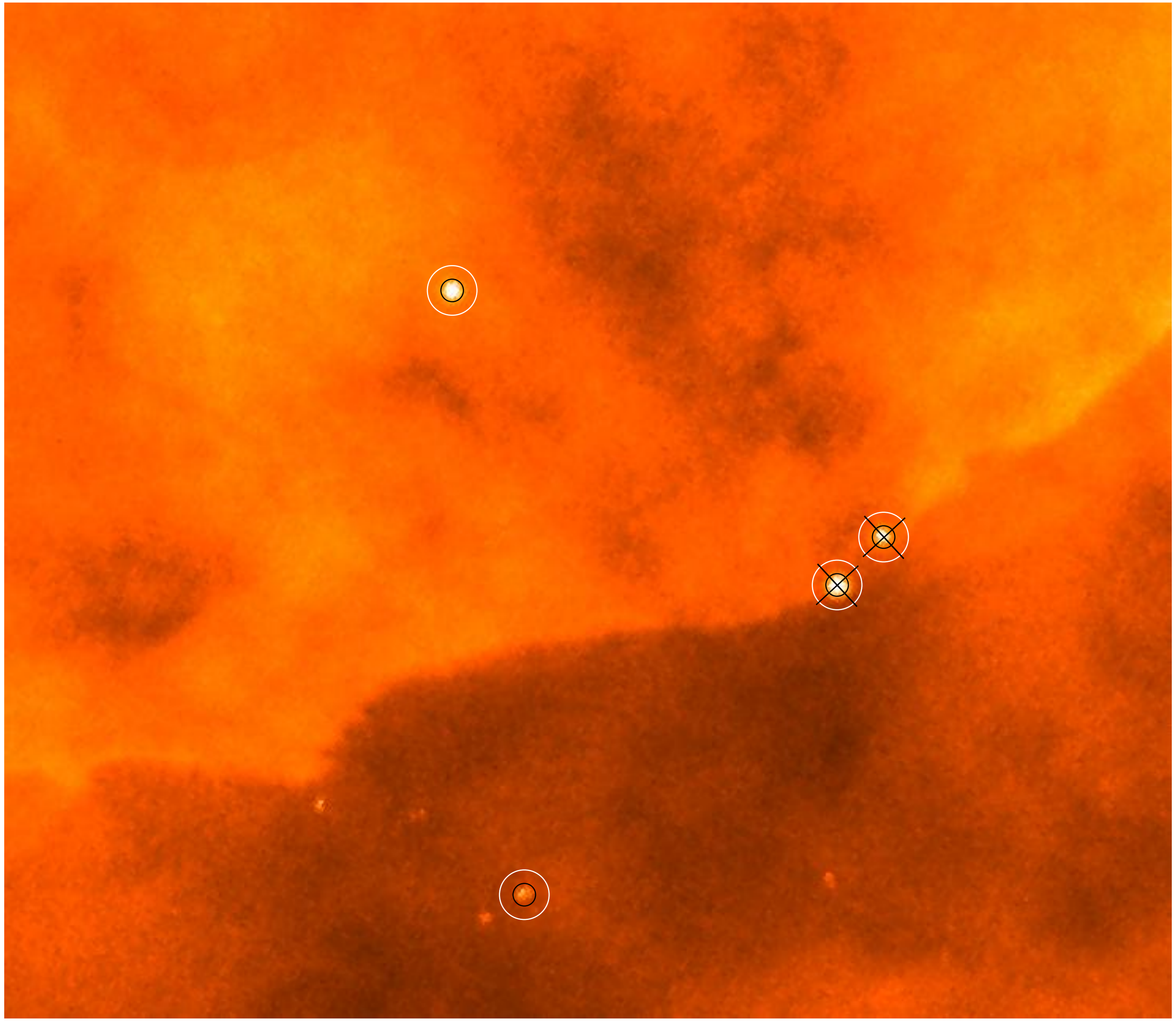
Curve-of-growth analysis: how big should the aperture be?



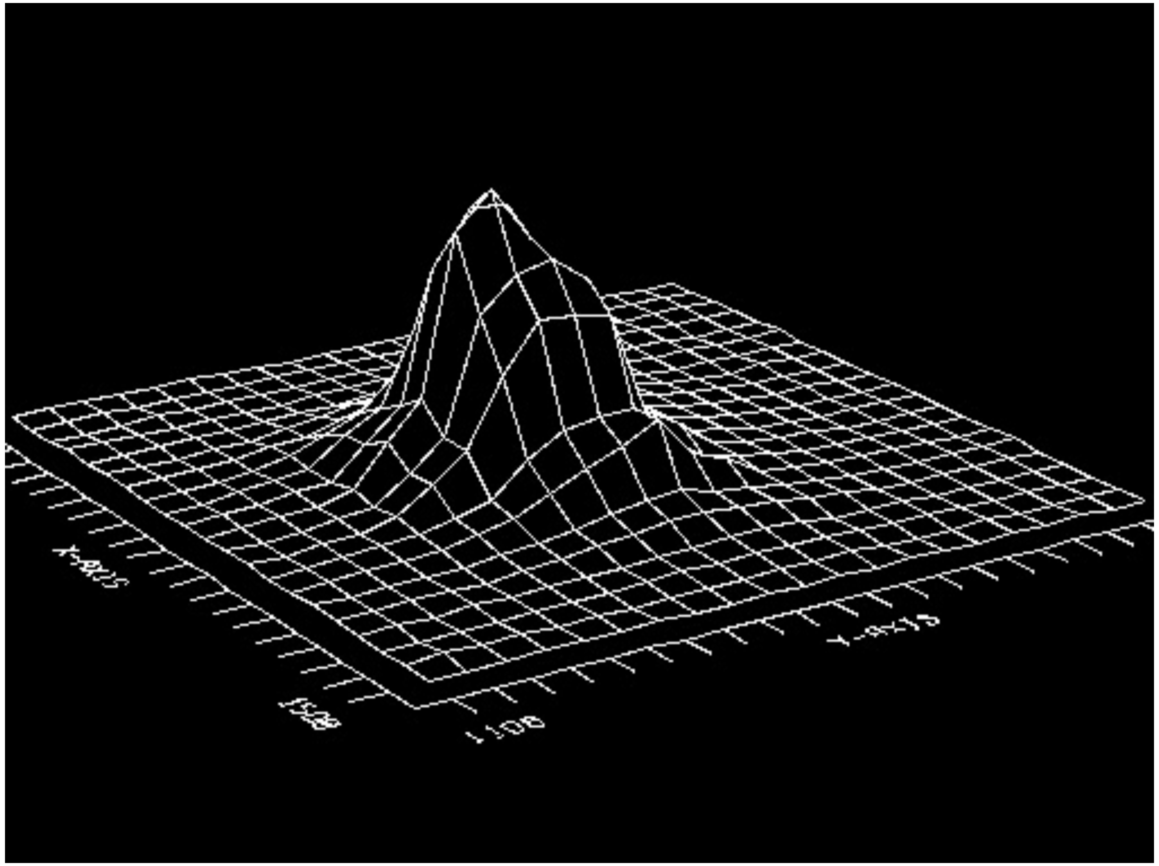


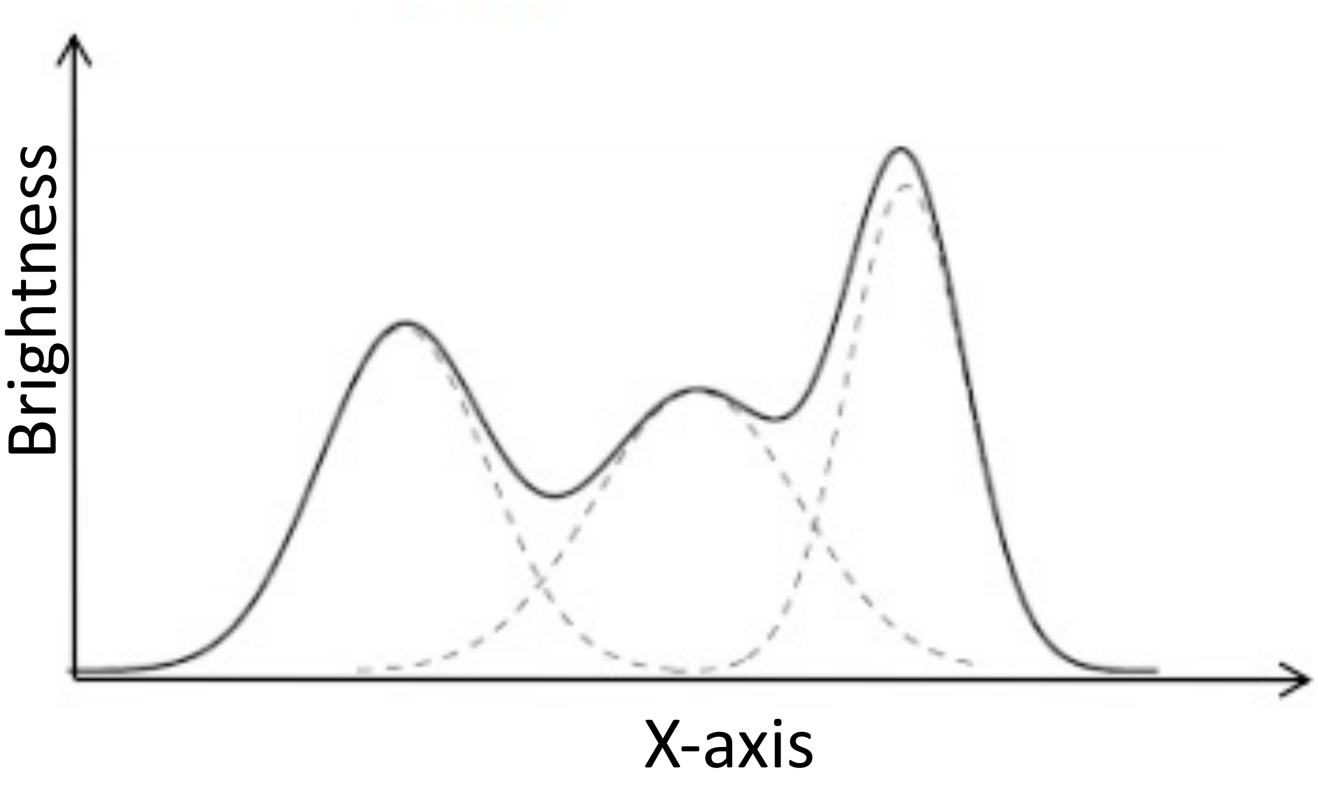
1
0.5
0
−0.5
−1
12
14
16
18
20
$H\alpha_{in} - H\alpha_{out}$
$H\alpha_{in}$

Background emission as contaminant

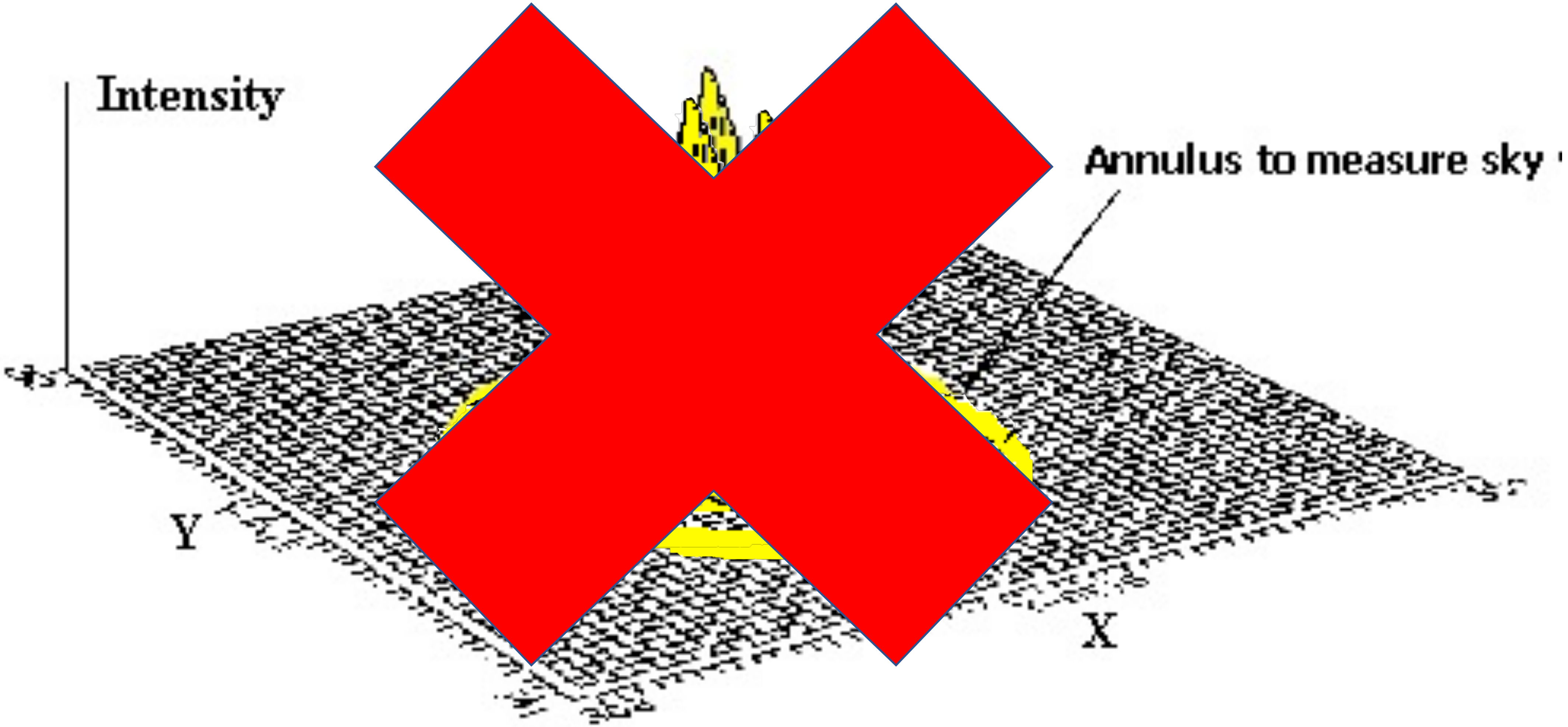


High Stellar Density: Point Spread Function (PSF) Photometry



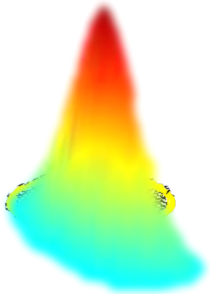
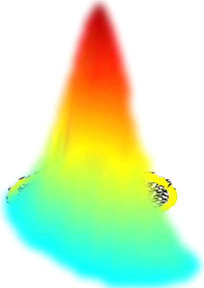


High Stellar Density: Aperture Photometry?

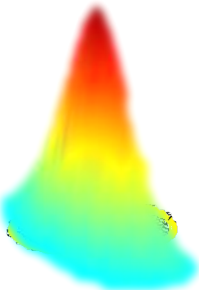
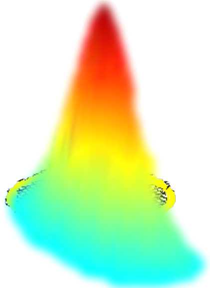


Mag = -[2.5 log (sum(I(i,j))) - (sky level)*(area of aperture)] + C,

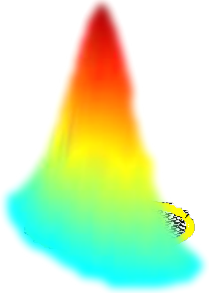
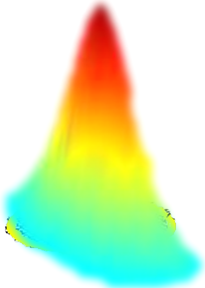

30 to 50 stars:
Isolated
Well sampled $>10\sigma_{sky}$
Not saturated

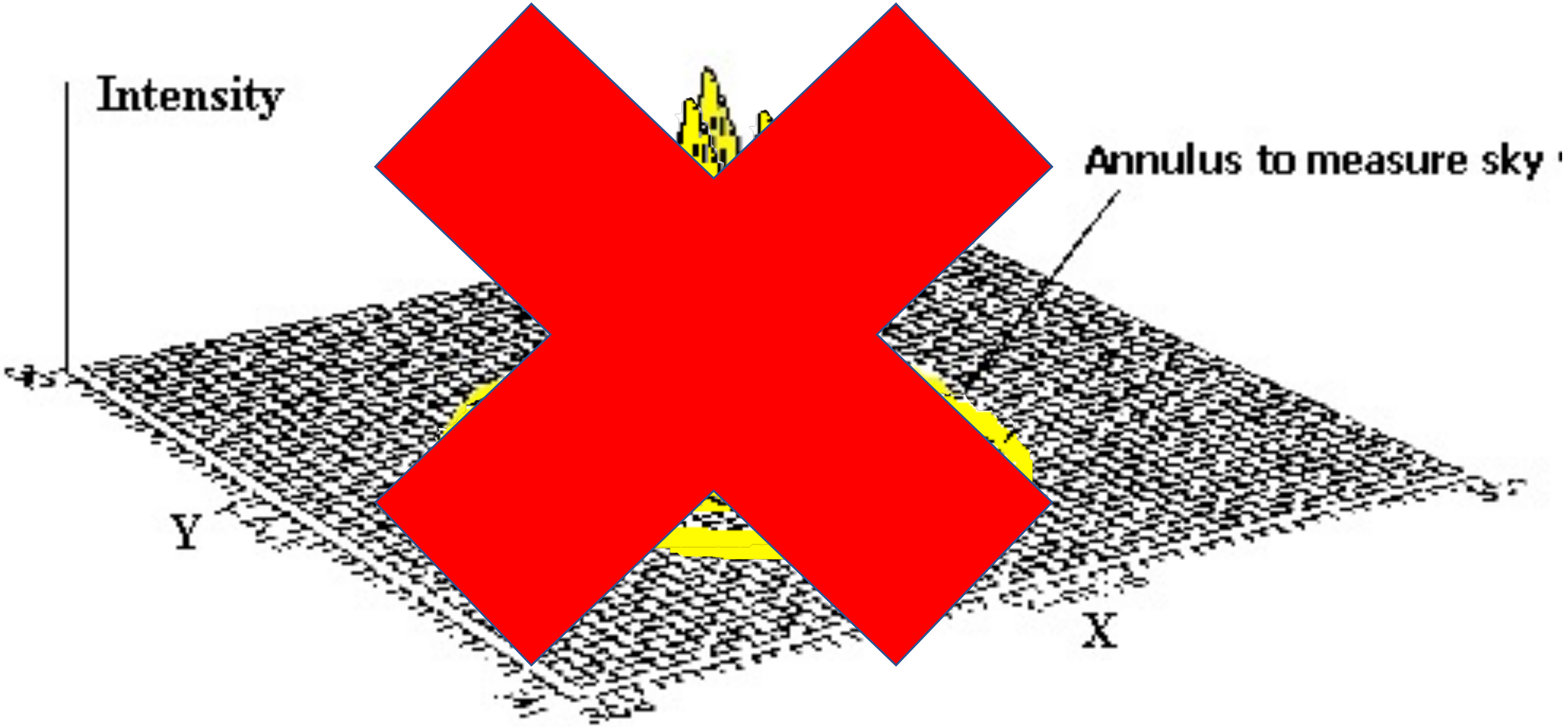
PSF Model

$$
\begin{cases}
I = p_1 \exp - \left\{ \dfrac{(x-p_2)^2 + (y-p_3)^2}{p_4^2} \right\}, & \text{Gaussian} \\
I = p_1 \left\{ 1 + \dfrac{(x-p_2)^2 + (y-p_3)^2}{p_4^2} \right\}^{-\beta}, & \text{Moffat} \ .
\end{cases}
$$

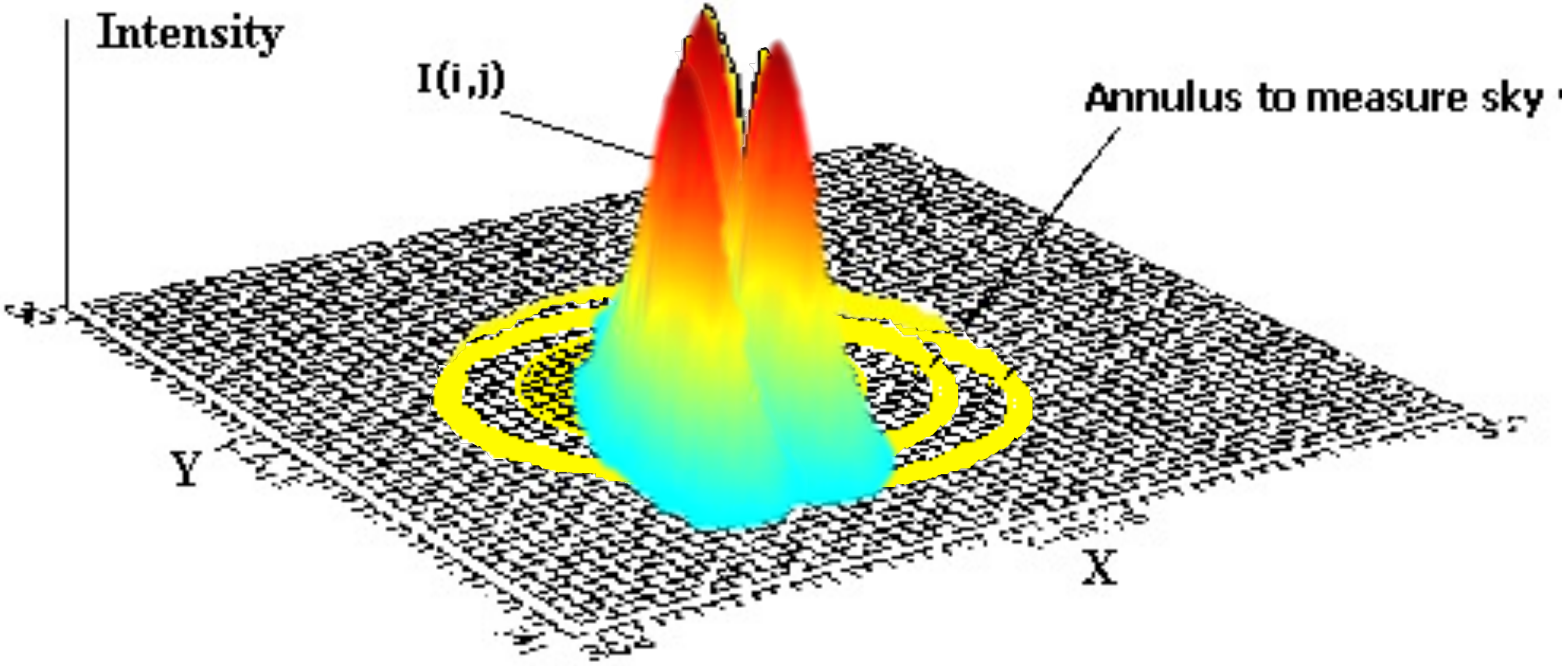



High Stellar Density: Aperture Photometry?

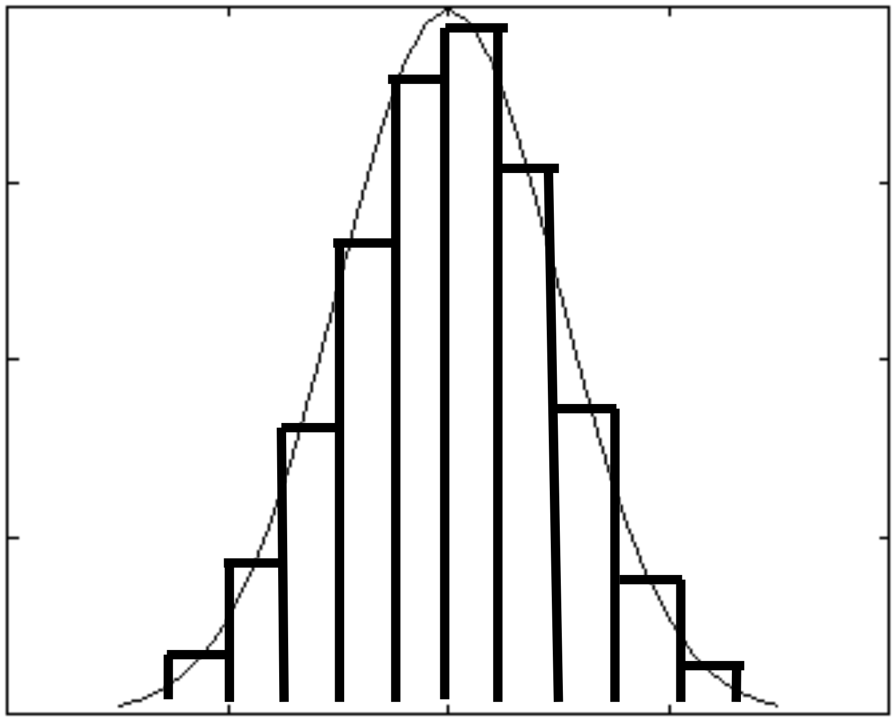


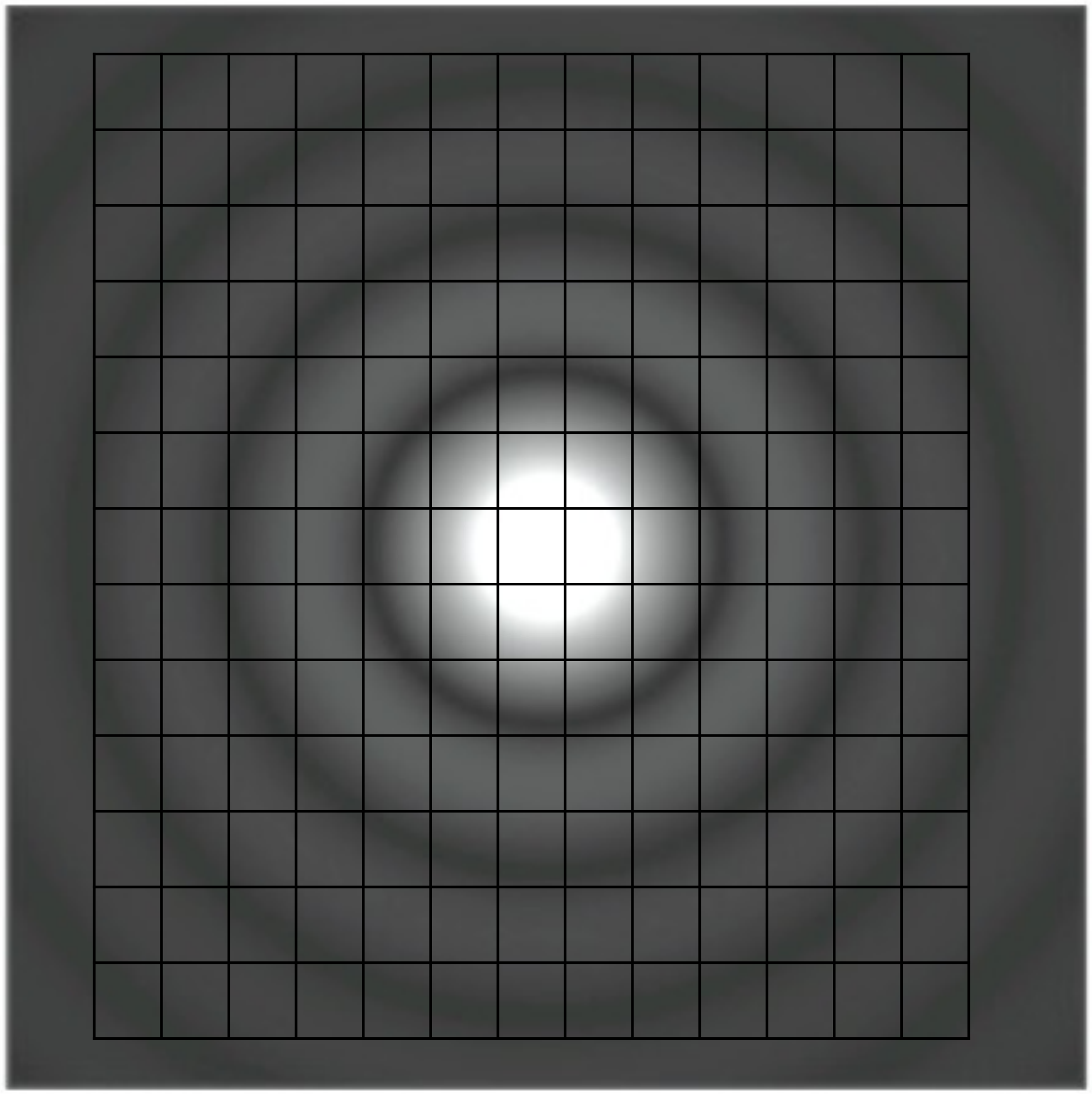
Mag = -[2.5 log (sum(I(i,j))) - (sky level)*(area of aperture)] + C,

High Stellar Density: PSF Fitting Photometry

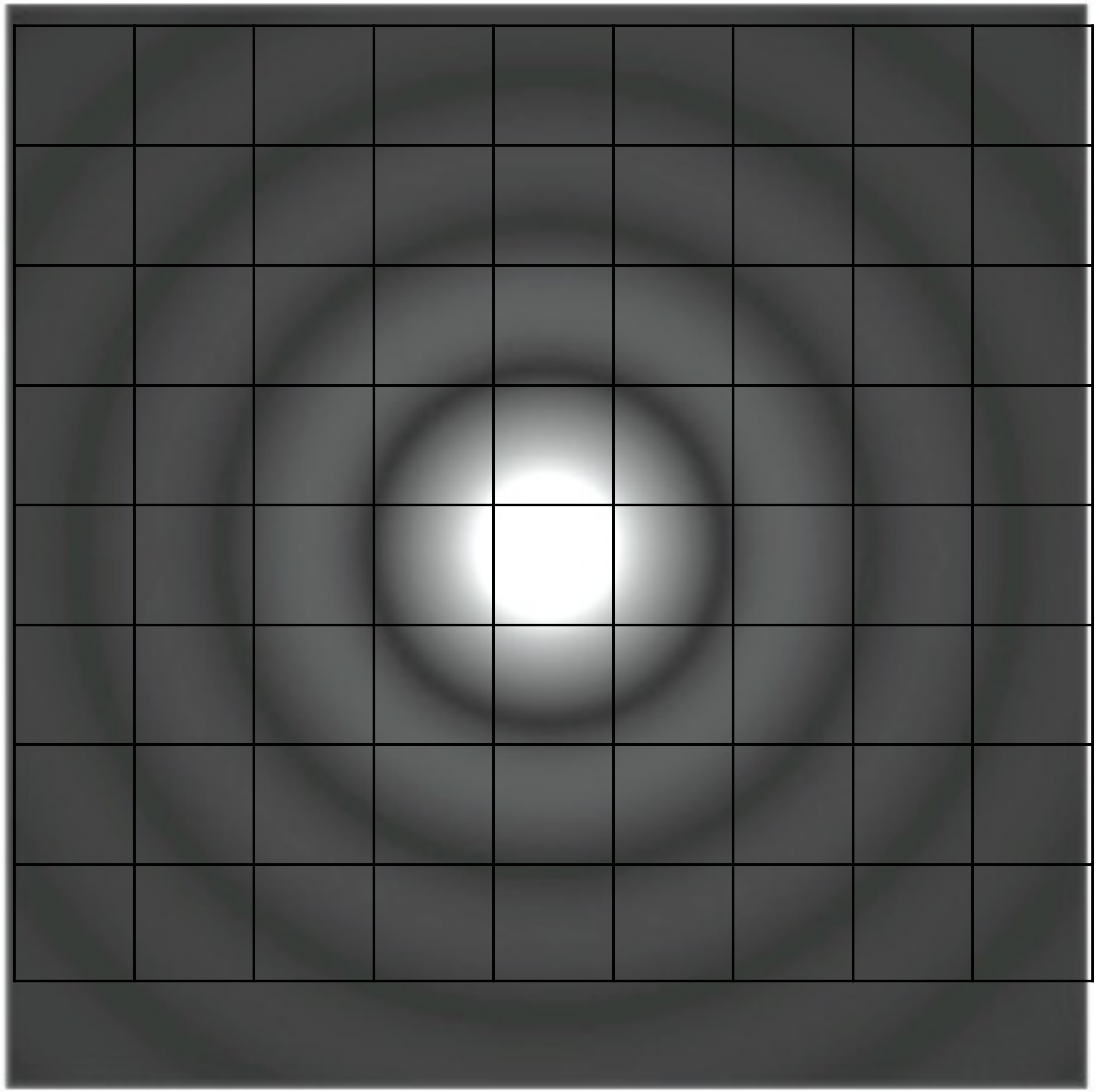


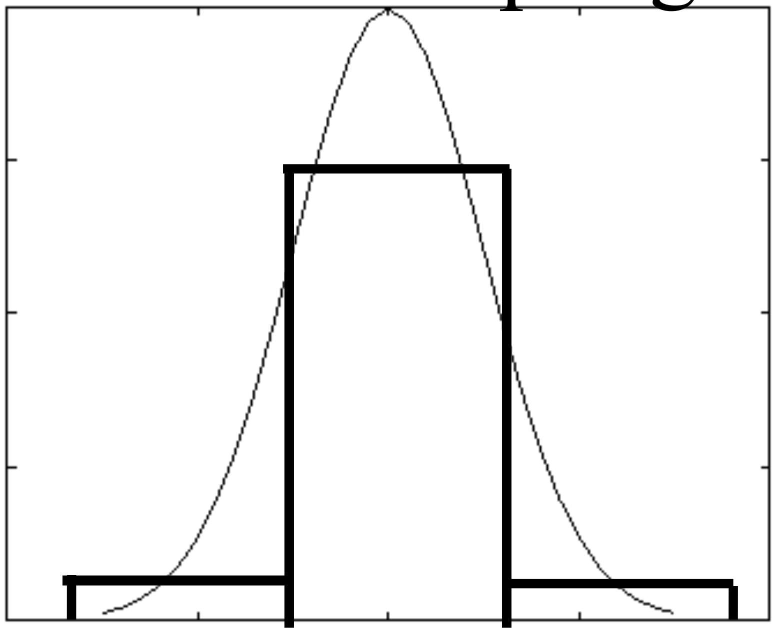
Good Sampling



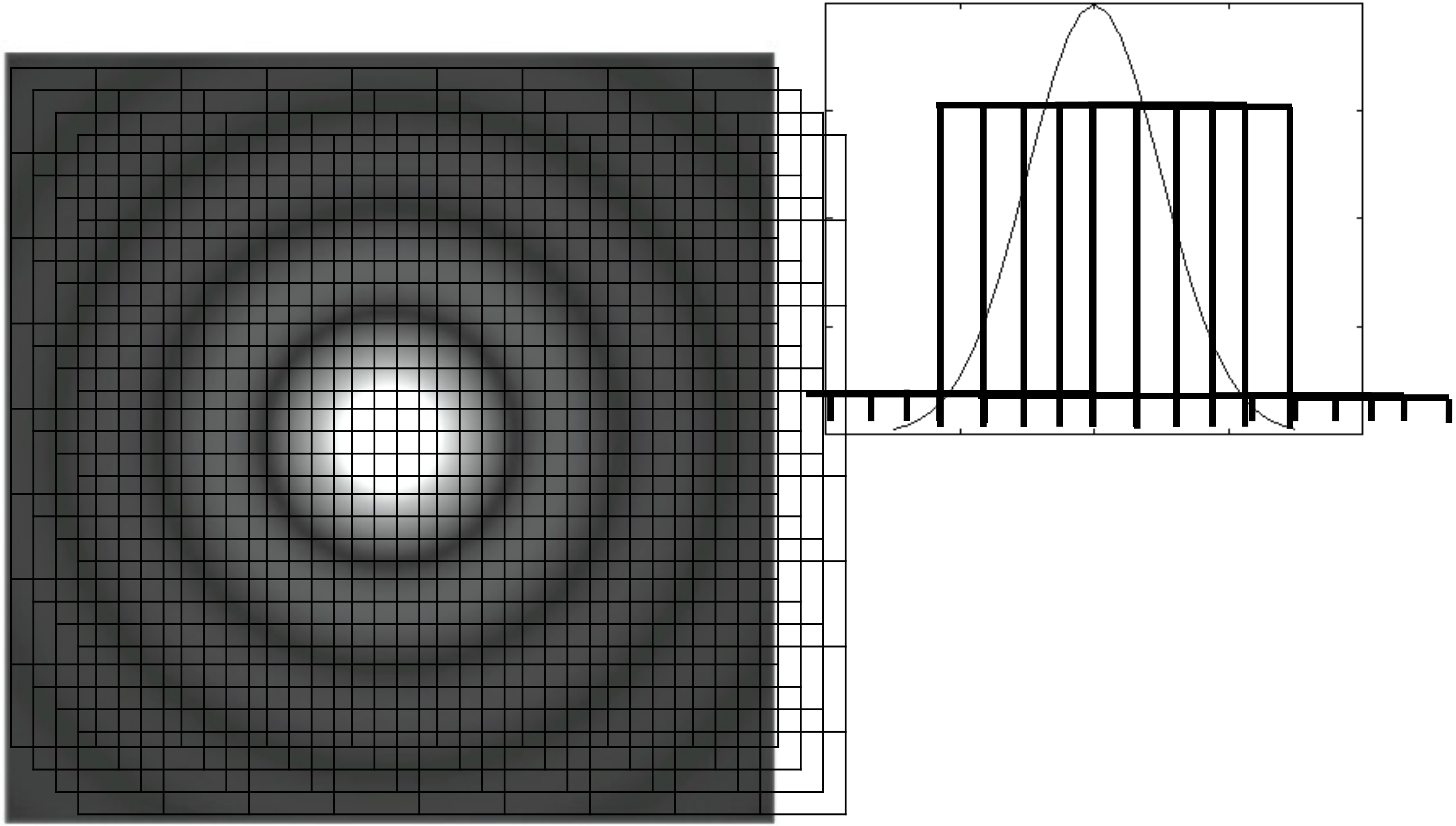


Under Sampling





Dithering



2. Software

- 2.1 Sextractor (Aperture)
- 2.2 DAOPHOT (PSF and Aperture)
- 2.3 DoPHOT (PSF and Aperture)
- 2.4 HSTPhot/Dolfphot (PSF and Aperture)
- 2.5 ROMAFOT (PSF)
- 2.6 …

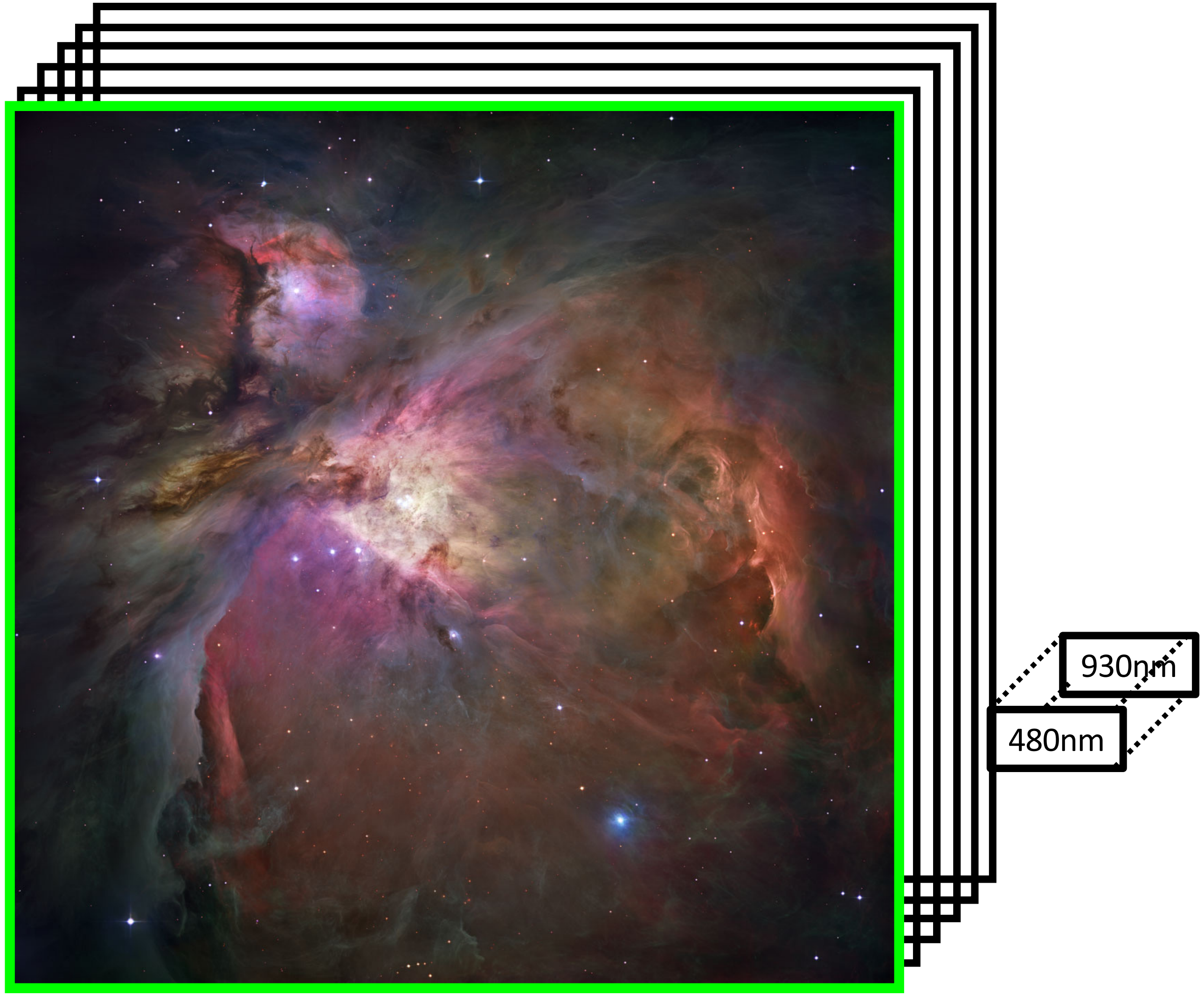
misc.

Photometry meets Spectroscopy

Multi Unit Spectroscopic Explorer

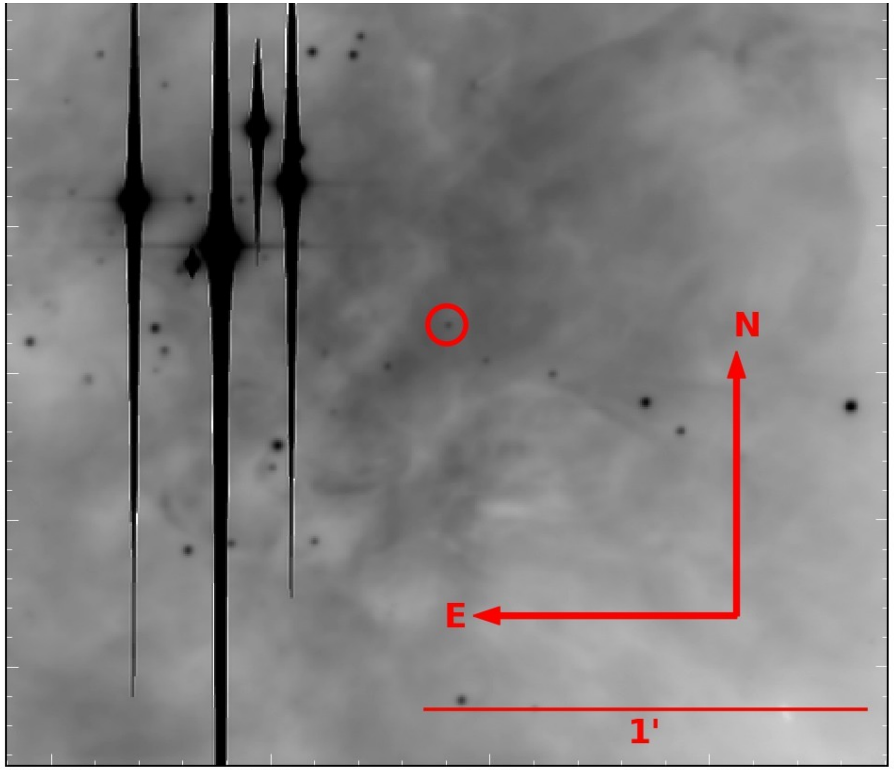
--MUSE—

Photometry meets Spectroscopy

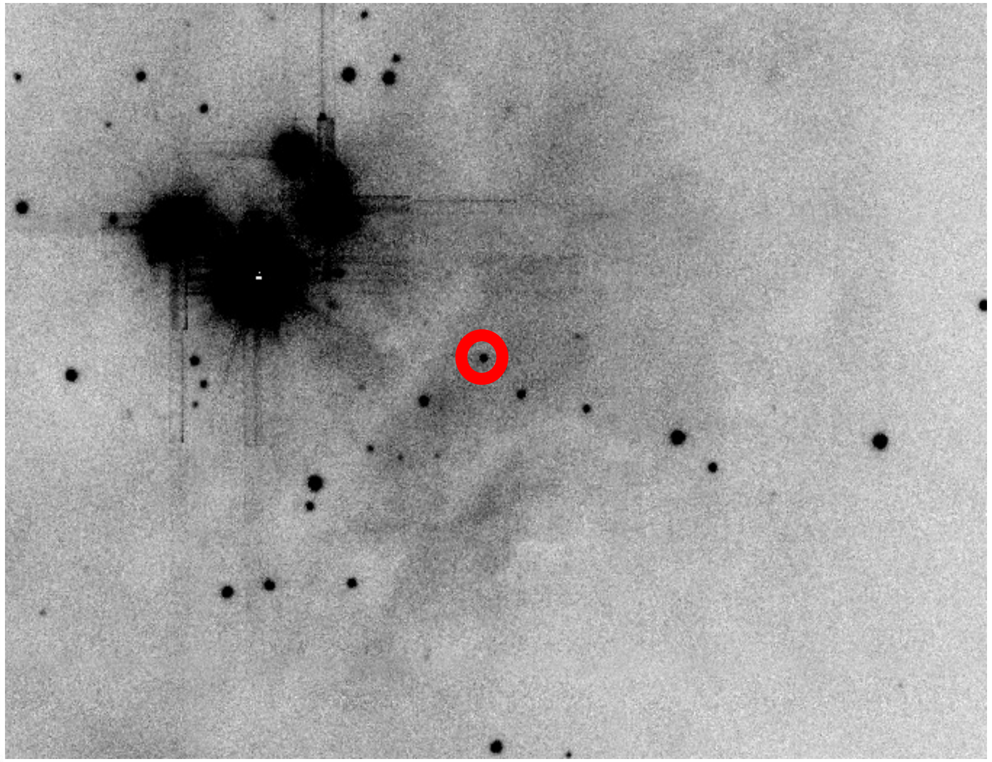


MUSE

WFI@2.2m; 30 sec; V-band

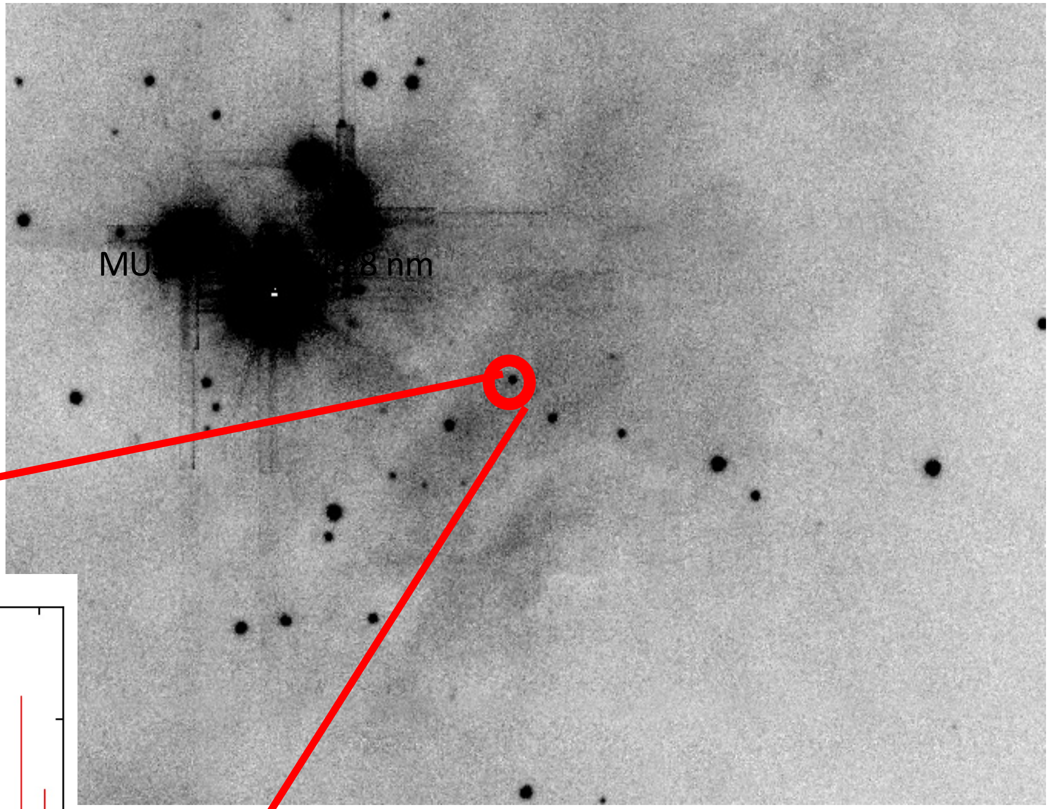


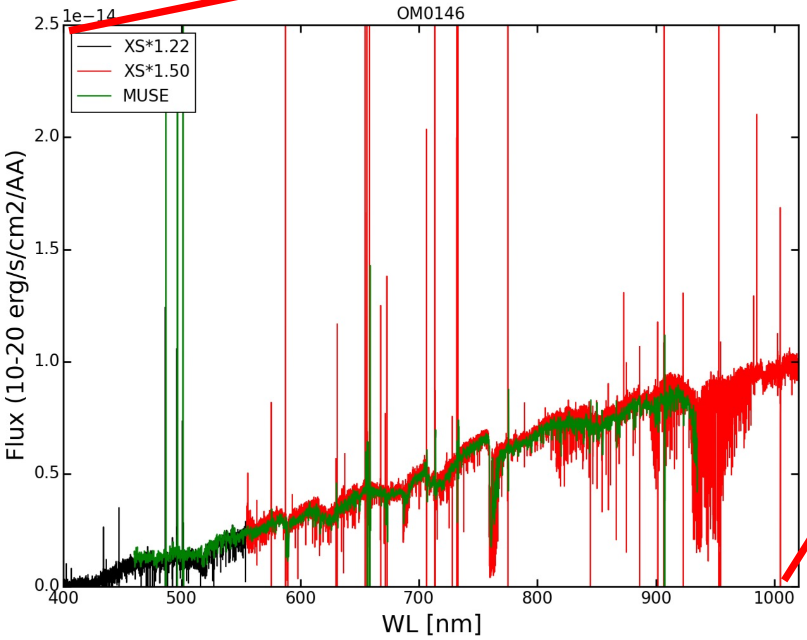
MUSE; 5 sec; 548.8 nm



Data published in Weilbacher et al. 2015

MUSE





Data published in Weilbacher et al. 2015

XSHOOTER

VIS:4x140s

UVB:4x225s

MUSE 2x5s

MUSE

WFI data
Da Rio et al 2009

MUSE data
Weilbacher et al 2015