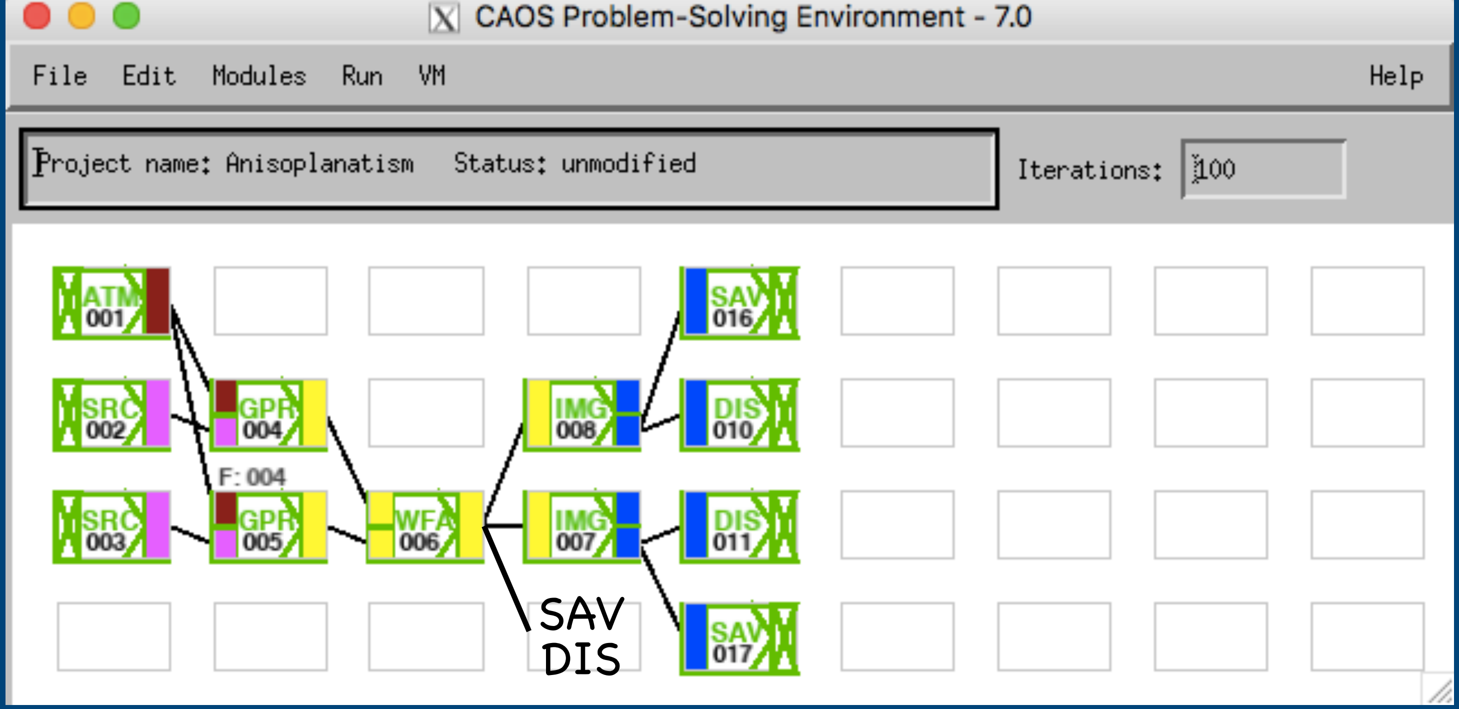
# Build project for anisoplanatism…

0- COMPLETELY FINALISE INSTALLATION OF "CAOS LITE" BEFORE GOING ON !!

Then, within the CAOS interface…



Project name: Anisoplanatism Status: unmodified

Iterations: 100

1- Reproduce the project "Anisoplanatism" here beside.

2- Click on the ATM module, its graphical user interface (GUI) opens, then change its parameters into your own ones ($r_0$, $L_0$, altitude of the layers, mainly), and finally save them with button "Save".

3- Fix the parameters of the other modules.
(Module's GUI a bit too wide => don't see the button Save ? => "Auto-hide Dock"on your PC settings !)

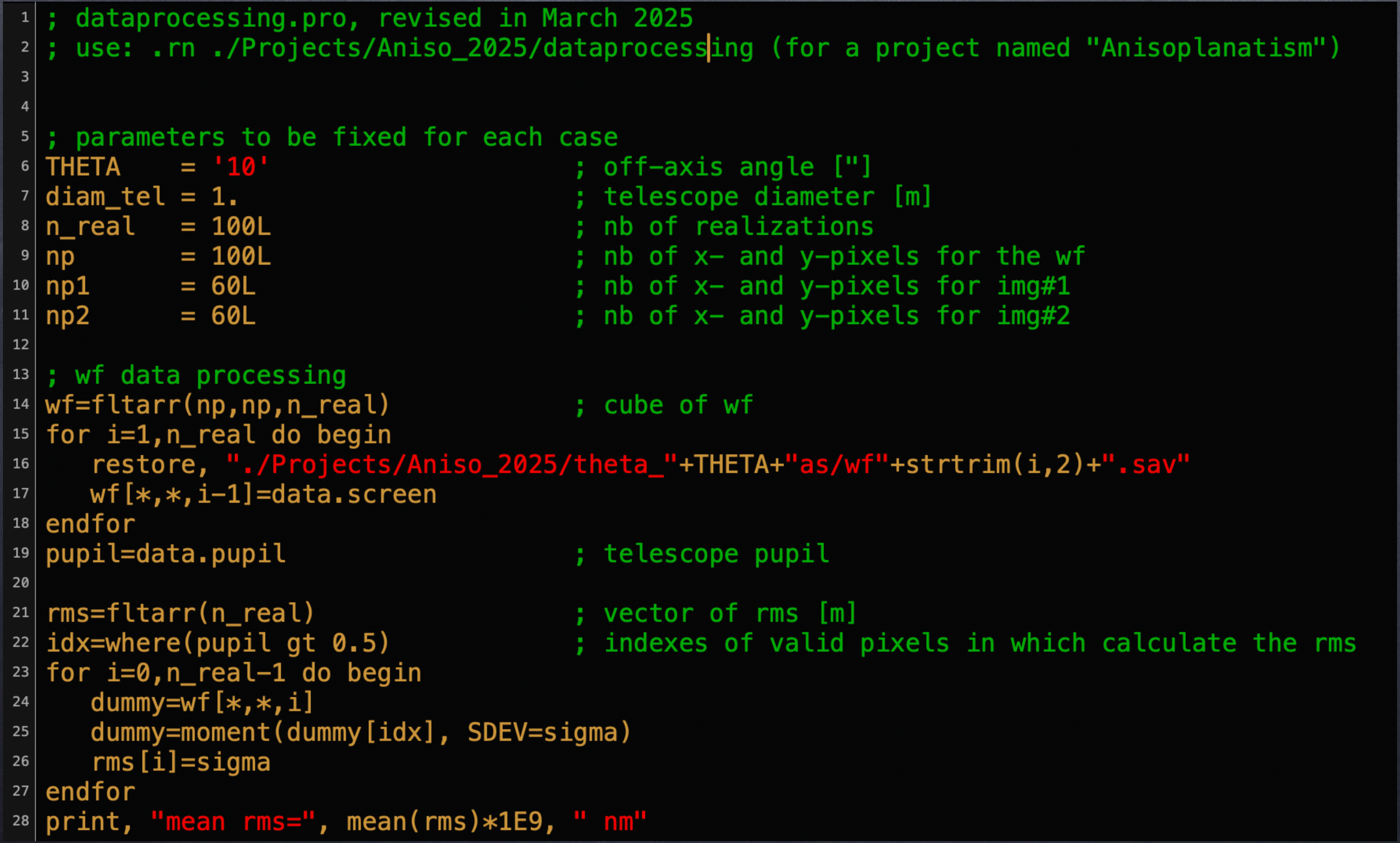
4- Choose a value for the off-axis angle (typically in between 0" and 60") within second occurence of module SRC and, as a consequence, adapt the name of the saved PSFs and wfs within the 3 modules SAV (one for each module IMG, i.e. one for each considered wavelength: for example 500nm and 1650nm).

5- Run the simulation project by using button "Run" within the CAOS interface (or with the IDL-CAOS command ".rn ./Projects/Anisoplanatism/project.pro" for a project called "Anisoplanatism").

6- Repeat steps 4 and 5 for each chosen value of the off-axis angle.

7- Compute the rms of the corrected wavefront and the FWHM for each resulting PSFs (two for each off-axis angle value) with the help of routine "dataprocessing.pro".

# (routine dataprocessing.pro — 1)



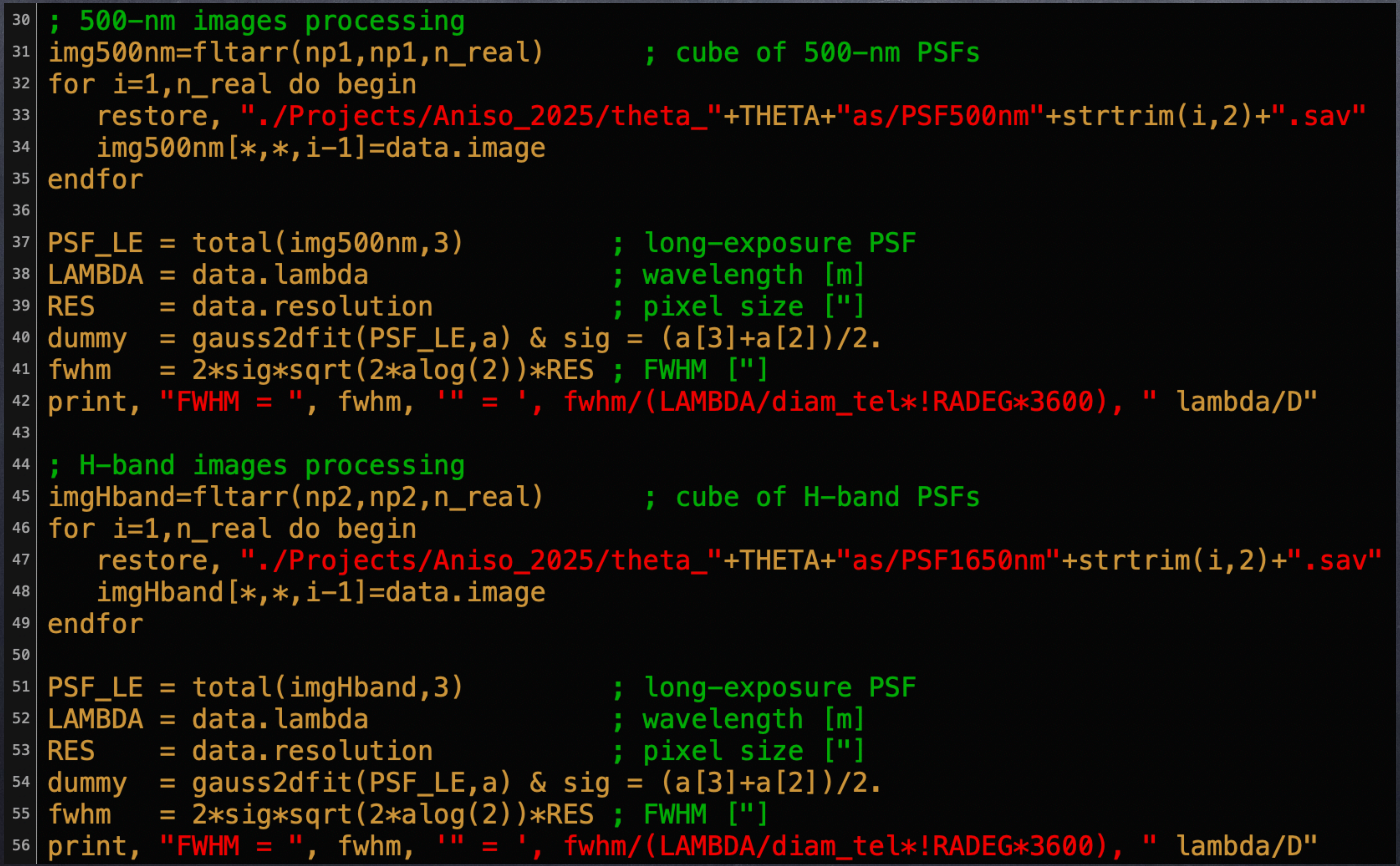
```
; dataprocessing.pro, revised in March 2025
; use: .rn ./Projects/Aniso_2025/dataprocessing (for a project named "Anisoplanatism")


; parameters to be fixed for each case
THETA    = '10'                    ; off-axis angle ["]
diam_tel = 1.                      ; telescope diameter [m]
n_real   = 100L                    ; nb of realizations
np       = 100L                    ; nb of x- and y-pixels for the wf
np1      = 60L                     ; nb of x- and y-pixels for img#1
np2      = 60L                     ; nb of x- and y-pixels for img#2

; wf data processing
wf=fltarr(np,np,n_real)            ; cube of wf
for i=1,n_real do begin
   restore, "./Projects/Aniso_2025/theta_"+THETA+"as/wf"+strtrim(i,2)+".sav"
   wf[*,*,i-1]=data.screen
endfor
pupil=data.pupil                   ; telescope pupil

rms=fltarr(n_real)                 ; vector of rms [m]
idx=where(pupil gt 0.5)            ; indexes of valid pixels in which calculate the rms
for i=0,n_real-1 do begin
   dummy=wf[*,*,i]
   dummy=moment(dummy[idx], SDEV=sigma)
   rms[i]=sigma
endfor
print, "mean rms=", mean(rms)*1E9, " nm"
```

# (routine dataprocessing.pro — 2)



```
; 500-nm images processing
img500nm=fltarr(np1,np1,n_real)      ; cube of 500-nm PSFs
for i=1,n_real do begin
   restore, "./Projects/Aniso_2025/theta_"+THETA+"as/PSF500nm"+strtrim(i,2)+".sav"
   img500nm[*,*,i-1]=data.image
endfor

PSF_LE = total(img500nm,3)         ; long-exposure PSF
LAMBDA = data.lambda               ; wavelength [m]
RES    = data.resolution           ; pixel size ["]
dummy  = gauss2dfit(PSF_LE,a) & sig = (a[3]+a[2])/2.
fwhm   = 2*sig*sqrt(2*alog(2))*RES ; FWHM ["]
print, "FWHM = ", fwhm, '" = ', fwhm/(LAMBDA/diam_tel*!RADEG*3600), " lambda/D"

; H-band images processing
imgHband=fltarr(np2,np2,n_real)      ; cube of H-band PSFs
for i=1,n_real do begin
   restore, "./Projects/Aniso_2025/theta_"+THETA+"as/PSF1650nm"+strtrim(i,2)+".sav"
   imgHband[*,*,i-1]=data.image
endfor

PSF_LE = total(imgHband,3)         ; long-exposure PSF
LAMBDA = data.lambda               ; wavelength [m]
RES    = data.resolution           ; pixel size ["]
dummy  = gauss2dfit(PSF_LE,a) & sig = (a[3]+a[2])/2.
fwhm   = 2*sig*sqrt(2*alog(2))*RES ; FWHM ["]
print, "FWHM = ", fwhm, '" = ', fwhm/(LAMBDA/diam_tel*!RADEG*3600), " lambda/D"
```

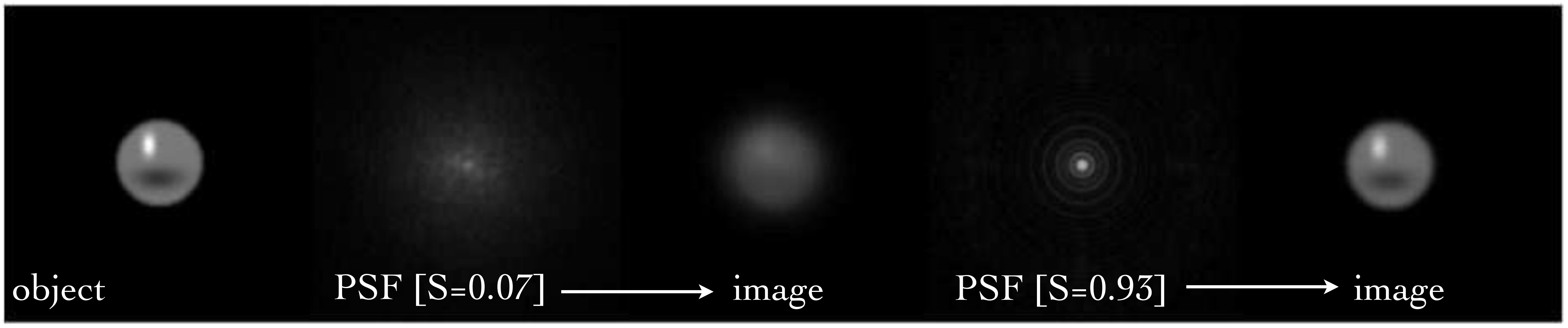
# (Another metrics: the Strehl ratio — 1)

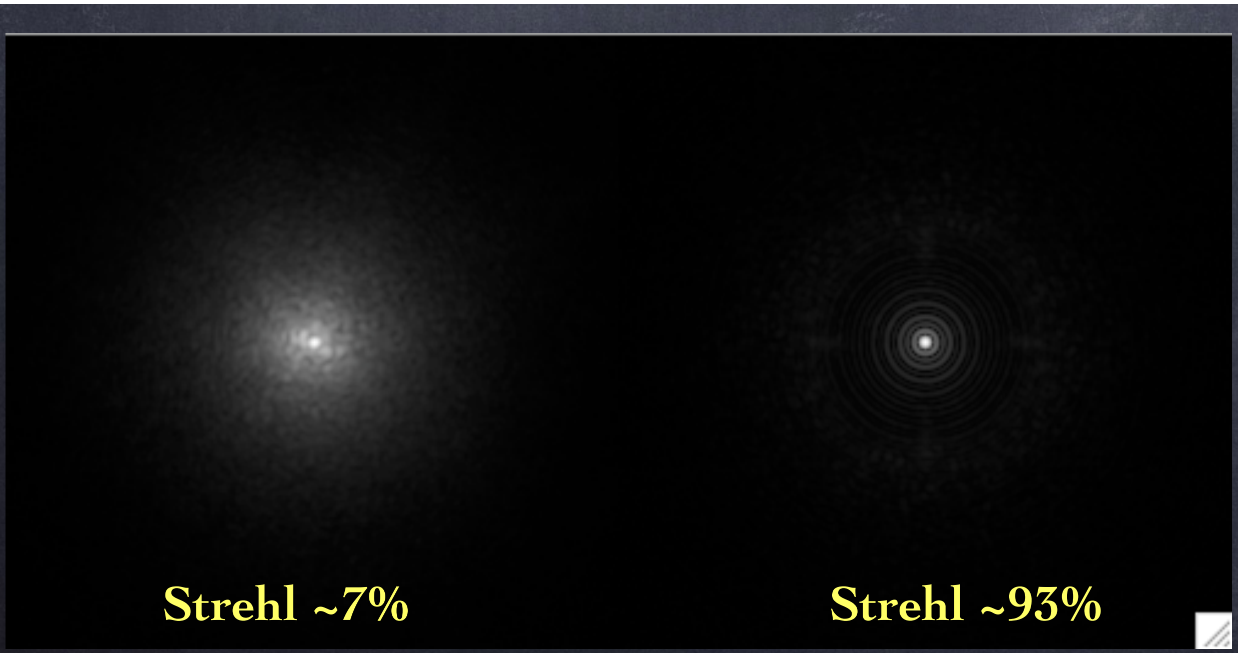
$$S = \frac{I_{\text{post AO}}[0,0]}{I_{\text{perfect}}[0,0]}$$

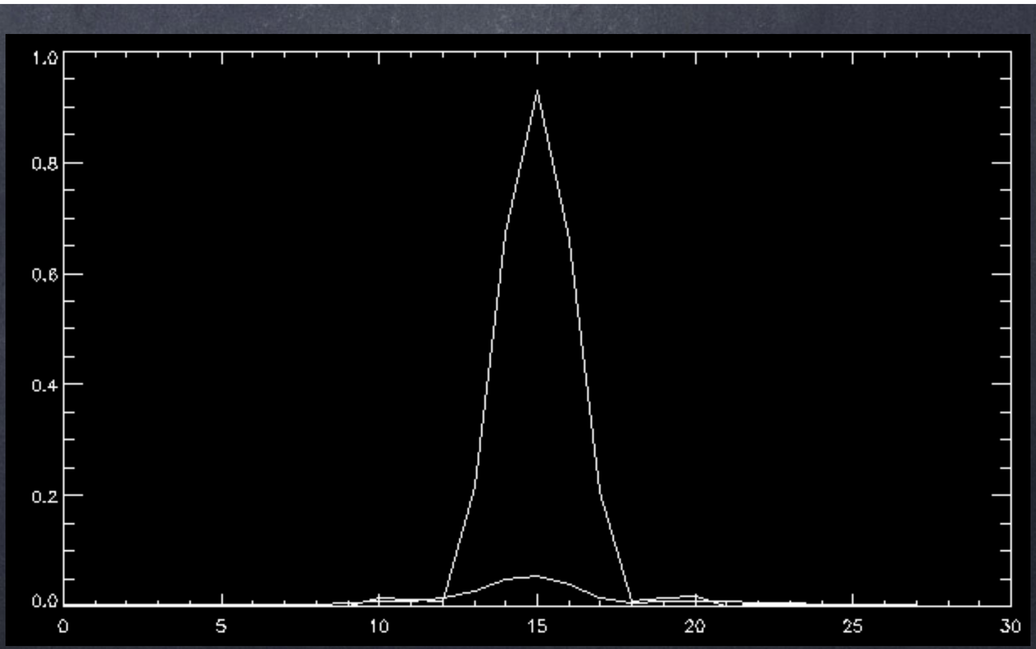
where *I[0,0]* is the intensity of the PSF at the optical center of the field (K. Strehl, Zeit. Instrumenkde 22, 213 (1902)).

$$S \simeq \exp\{-\sigma^2_{\text{post AO}}\}$$

in the framework of the Maréchal's approximation, where the variance (in radians²) is supposed to be small enough…







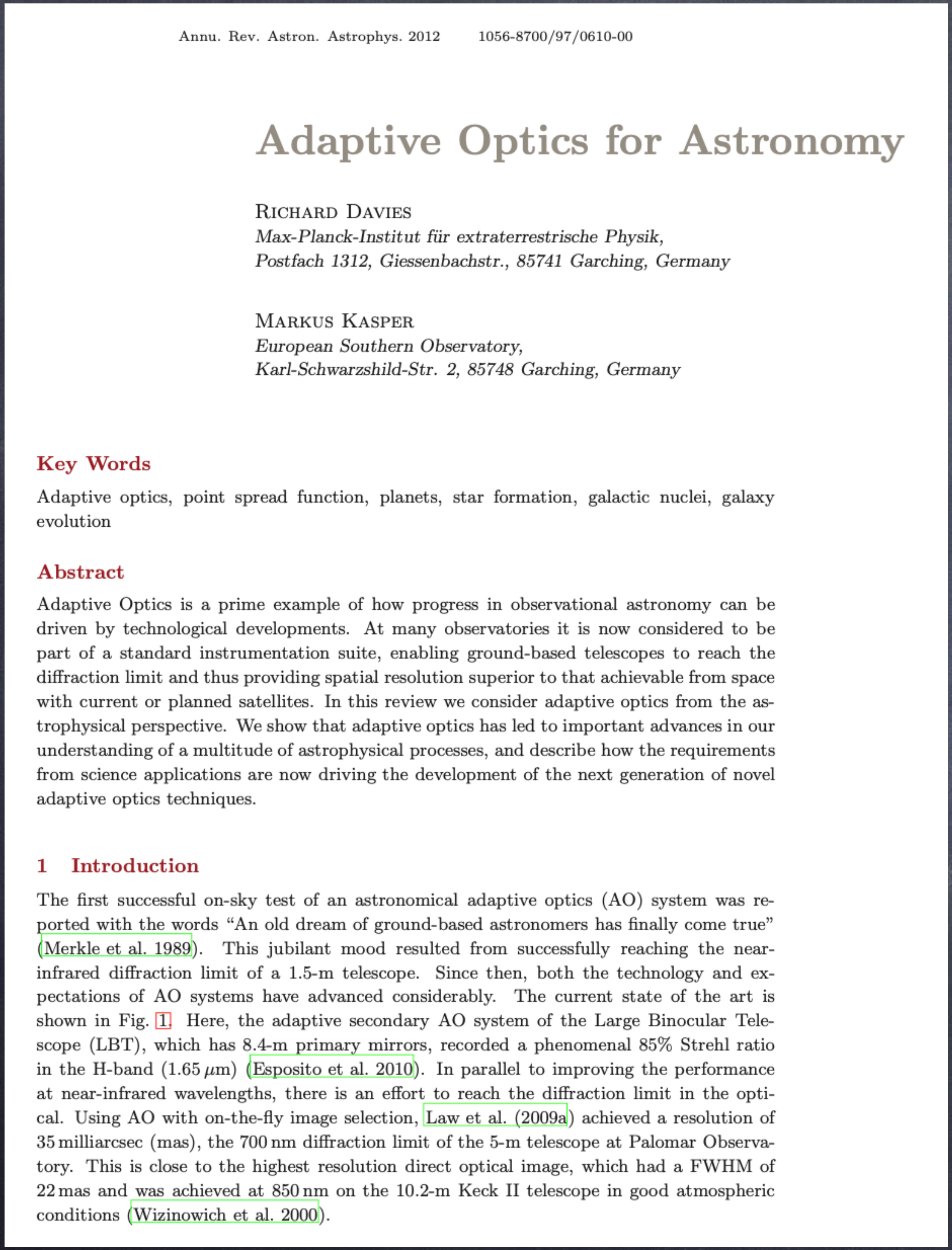
# (Another metrics: the Strehl ratio — 2)

- Approximation that neglects tip-tilt: ratio of the maxima ($S \approx \max(I)/\max(I_{ideal})$)

- Ratio of the values at the centre of the image ≈ ratio of the OTF (see for example the paper of Roberts et al.)

- From Tokovinin (PASP, 2002):

$$S = \frac{I_{max}}{I_{tot}} \frac{4}{\pi} \left( \frac{\lambda_{CCD}}{D \Delta x} \right)^2$$



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# Adaptive Optics for Astronomy

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## Key Words

Adaptive optics, point spread function, planets, star formation, galactic nuclei, galaxy evolution

## Abstract

Adaptive Optics is a prime example of how progress in observational astronomy can be driven by technological developments. At many observatories it is now considered to be part of a standard instrumentation suite, enabling ground-based telescopes to reach the diffraction limit and thus providing spatial resolution superior to that achievable from space with current or planned satellites. In this review we consider adaptive optics from the astrophysical perspective. We show that adaptive optics has led to important advances in our understanding of a multitude of astrophysical processes, and describe how the requirements from science applications are now driving the development of the next generation of novel adaptive optics techniques.

## 1 Introduction

The first successful on-sky test of an astronomical adaptive optics (AO) system was reported with the words "An old dream of ground-based astronomers has finally come true" (Merkle et al. 1989). This jubilant mood resulted from successfully reaching the near-infrared diffraction limit of a 1.5-m telescope. Since then, both the technology and expectations of AO systems have advanced considerably. The current state of the art is shown in Fig. 1. Here, the adaptive secondary AO system of the Large Binocular Telescope (LBT), which has 8.4-m primary mirrors, recorded a phenomenal 85% Strehl ratio in the H-band (1.65 $\mu$m) (Esposito et al. 2010). In parallel to improving the performance at near-infrared wavelengths, there is an effort to reach the diffraction limit in the optical. Using AO with on-the-fly image selection, Law et al. (2009a) achieved a resolution of 35 milliarcsec (mas), the 700 nm diffraction limit of the 5-m telescope at Palomar Observatory. This is close to the highest resolution direct optical image, which had a FWHM of 22 mas and was achieved at 850 nm on the 10.2-m Keck II telescope in good atmospheric conditions (Wizinowich et al. 2000).

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# Astronomical Adaptive Optics

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**ABSTRACT.** Adaptive optics is now a fully mature technique to improve the angular resolution of observations taken with ground-based astronomical telescopes. It is available at most of the major optical/IR observatories, and is planned as an integral part of the Extremely Large Telescope next generation facilities. In this mini-review aimed at non-AO specialists, we recall the history, the principle of operation, the major components, the performance, and the future of nighttime astronomical adaptive optics.

*Online material:* color figures

## 1. INTRODUCTION

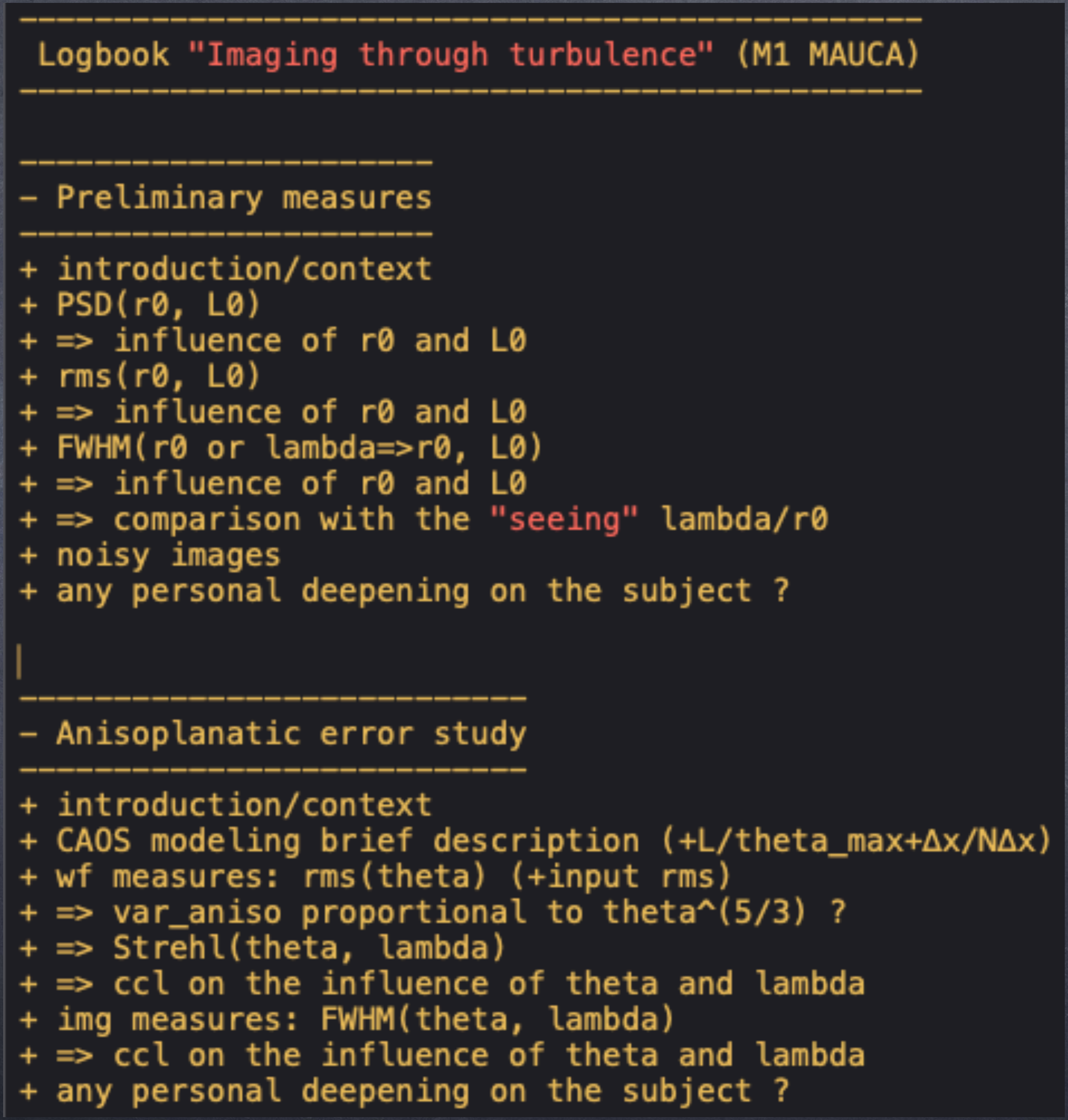
Almost as soon as telescopes were invented, astronomers realized that the quality of observations was limited by atmospheric turbulence, which distorts short exposure and blurs long exposure astronomical images. Newton was the first to be quoted as realizing that clearer observations (in the sense of being less blurred) would require observing from the top of the highest mountains. He was perfectly right of course, but even on top of Hawaii's Maunakea or the Chilean mountains, the atmospheric turbulence limits the angular resolution attainable by any arbitrarily large telescope operating in the visible to the resolution achievable by a 20-cm telescope. The *angular resolution* is the size of the smallest details that can be seen in an image. If not for the atmospheric turbulence, the angular resolution of a perfect telescope would be equal to $\lambda/D$ [rd]—for instance, 0.012″ when observing at a wavelength $\lambda = 500$ nm on a $D = 8$ m telescope. Instead, the atmospheric turbulence "seeing"—the size of the blurred image—is typically of the order of 1″, almost two orders of magnitude worse than what the telescope could achieve. Astronomers and engineers built larger telescopes because they gather more photons, but until the development of adaptive optics, the only remedy to the blurring problem was to send telescopes into space; a sometime necessary, but expensive, option.

## 2. HISTORY OF ASTRONOMICAL ADAPTIVE OPTICS

In 1953, Horace Babcock, an American astronomer, proposed the concept of adaptive optics (AO). The wavefront aberrations induced by atmospheric turbulence could be measured by a wavefront sensor and compensated for by a wavefront corrector, thereby deblurring the images in part or entirely. Babcock had already a concept in mind, and from the start had identified the limitations of the technique, including the fact that it was limited to the vicinity of stars bright enough to use as guides, in effect a very small fraction of the sky.

This remained concept until the applicable technology became mature enough. Pushed and funded by DARPA (Defense Advanced Research Projects Administration), the first defense-oriented research started in the early 1970s, and the first successful demonstration of the technology was made in 1973 in the laboratory with the Real-Time Atmospheric Compensator (RTAC), closely followed by field tests, and then by second-generation systems like CIS, installed at AMOS (Air Force Maui Optical Station) on Maui. A good description of these early endeavors can be found in Hardy (1998).

These developments advanced the state of the technology, and by the mid-1980s, AO components such as detectors, deformable mirrors, and (analog) reconstructors were available, albeit under restricted use. Having somehow heard about the DARPA AO program's success (for interesting insights, see McCray [2000]), astronomers became interested in applying this technique for astronomy. Beckers, Roddier, and Kibblewhite started a program at the National Optical Astronomical Observatories (NOAO), but the project never saw starlight and was stopped in 1987. In Europe, Léna (Paris-Meudon Observatory), Fontanella (ONERA), Merkle (ESO [European Southern Observatory]), and Gaffard (CGE) initiated an AO project named COME-ON, which was started in the wake of the VLT (Very Large Telescope) agreement when the various partners realized that AO was absolutely necessary to take full advantage of the 8 m interferometric coupling. COME-ON was a low-order system, with a 19-actuator deformable mirror (DM) and a 20-subaperture Shack–Hartmann wavefront sensor (WFS), and used a $32 \times 32$ pixel near-infrared (NIR) imager. It saw first light at the Observatoire de Haute-Provence in France in November 1989, and achieved the diffraction limit of the 1.5-m telescope in the NIR (Rousset et al. 1990). It was then moved to the ESO La Silla 3.6-m telescope where it was used



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 Logbook "Imaging through turbulence" (M1 MAUCA)
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- Preliminary measures
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+ introduction/context
+ PSD(r0, L0)
+ => influence of r0 and L0
+ rms(r0, L0)
+ => influence of r0 and L0
+ FWHM(r0 or lambda=>r0, L0)
+ => influence of r0 and L0
+ => comparison with the "seeing" lambda/r0
+ noisy images
+ any personal deepening on the subject ?


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- Anisoplanatic error study
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+ introduction/context
+ CAOS modeling brief description (+L/theta_max+Δx/NΔx)
+ wf measures: rms(theta) (+input rms)
+ => var_aniso proportional to theta^(5/3) ?
+ => Strehl(theta, lambda)
+ => ccl on the influence of theta and lambda
+ img measures: FWHM(theta, lambda)
+ => ccl on the influence of theta and lambda
+ any personal deepening on the subject ?
```