(Speckle interferometry - 1)

With a simple Fourier transform of the object-image relation:

$$\hat{I}(\vec{f}) = \hat{O}(\vec{f})\ \hat{S}(\vec{f})$$

Where the FT of *S* is the optical transfer function (OTF).

The instantaneous one is random and with complex non-zero values up to the telescope cutting frequency *D/λ*, and:

$$|\hat{O}(\vec{f})|^2 = \frac{< |\hat{I}(\vec{f})|^2 >}{< |\hat{S}(\vec{f})|^2 >}$$

(Speckle interferometry - 2)

$$|\hat{O}(\vec{f})|^2 = \frac{< |\hat{I}(\vec{f})|^2 >}{< |\hat{S}(\vec{f})|^2 >}$$

It is the spectral density of the object (a statistical invariant), computable from the spectral density of the observed images $I(\alpha)$ and the spectral density of an estimate of the PSF $S(\alpha)$.

It *almost* permits to deduce the object $O(\alpha)$...

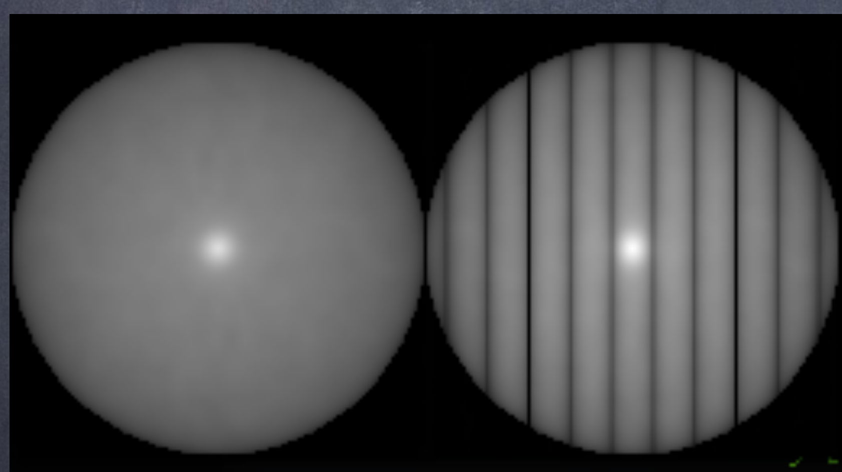
Actually, it permits to obtain its autocorrelation (the inverse FT of its spectral density), not the object itself, from which one can extract the separation and orientation of a binary star, but not the relative positions => which of the two stars is the brighter ?

This is the well-known problem of quadrant indetermination (due to the square power which turns the function even).

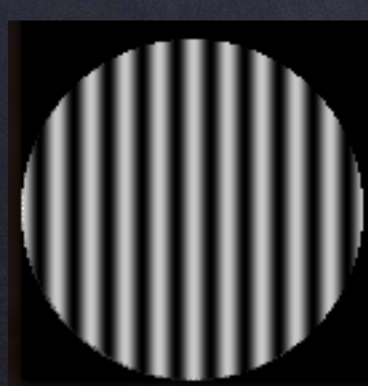
(Speckle interferometry - 3)

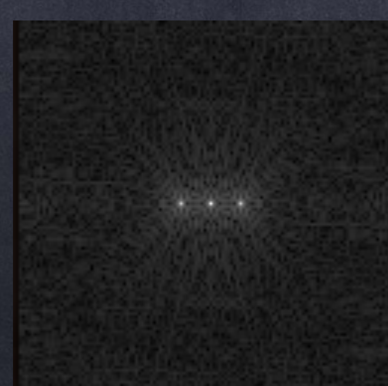
-> Computation of the spectral density of the images of an unresolved single star (hence estimates of the PSF) and a binary star (two points!), with speckles, and then speckles **and** noise(s)...

```
IDL> dsp=psd_speckle(cube, 10L)
% Compiled module: PSD_SPECKLE.
% Program caused arithmetic error: Floating underflow
IDL> help, dsp
DSP             FLOAT     = Array[256, 128]
IDL> tvscl, dsp^.1
```



Going further (visibility & autocorrelation) :





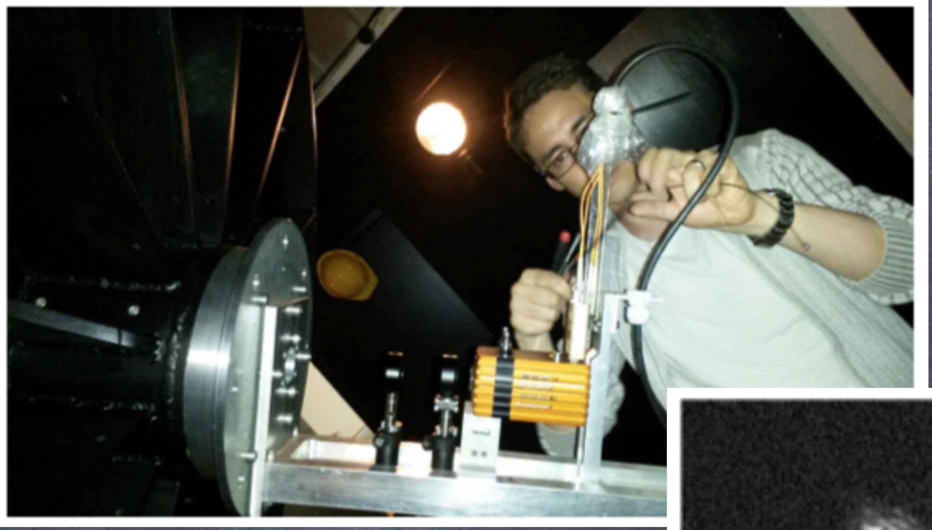
```
function psd_speckle, cube, rho
;
; Spectral density computation of speckle images from a
; reference star (PSF) and speckle images from a binary
; star of separation rho (along x)
;
; cube: reference star speckles
; rho : binary separation [px]
; use:
; rho = 10L
; dsp = psd_speckle(cube, rho)
;
; Marcel Carbillet (marcel.carbillet@unice.fr), Feb. 2018
;
dim=(size(cube))[2]
nim=(size(cube))[3]

dsp_sp=fltarr(dim,dim)
for i=0, nim-1L do dsp_sp+=(abs(fft(cube[*,*,i])))^2
dsp_sp=shift(dsp_sp, dim/2, dim/2)

double=cube+shift(cube, rho, 0, 0)
dsp_db=fltarr(dim,dim)
for i=0, nim-1L do dsp_db+=(abs(fft(double[*,*,i])))^2
dsp_db=shift(dsp_db, dim/2, dim/2)

return, [dsp_sp, dsp_db]
end
```

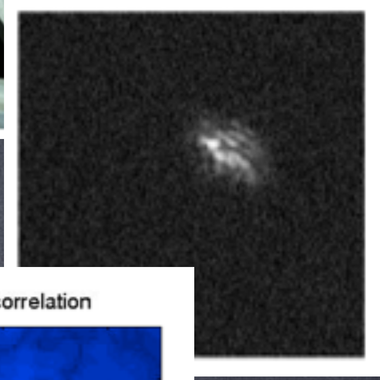
(Speckle interferometry - 4)

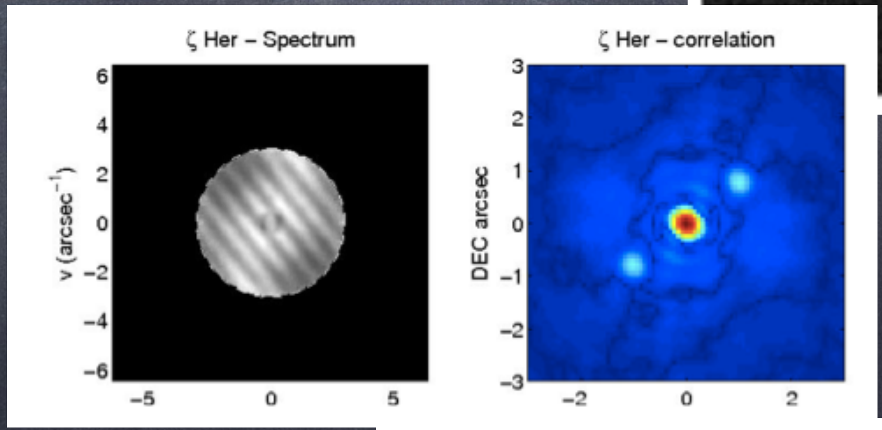
-> A simple lab' experiment speckle/binary star

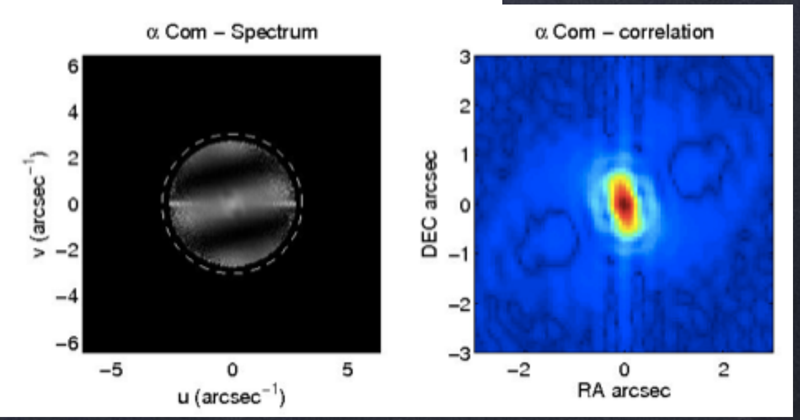
(Speckle interferometry - 5)

-> Two instruments at C2PU: PISCO (vis.) & HiPIC (nIR)









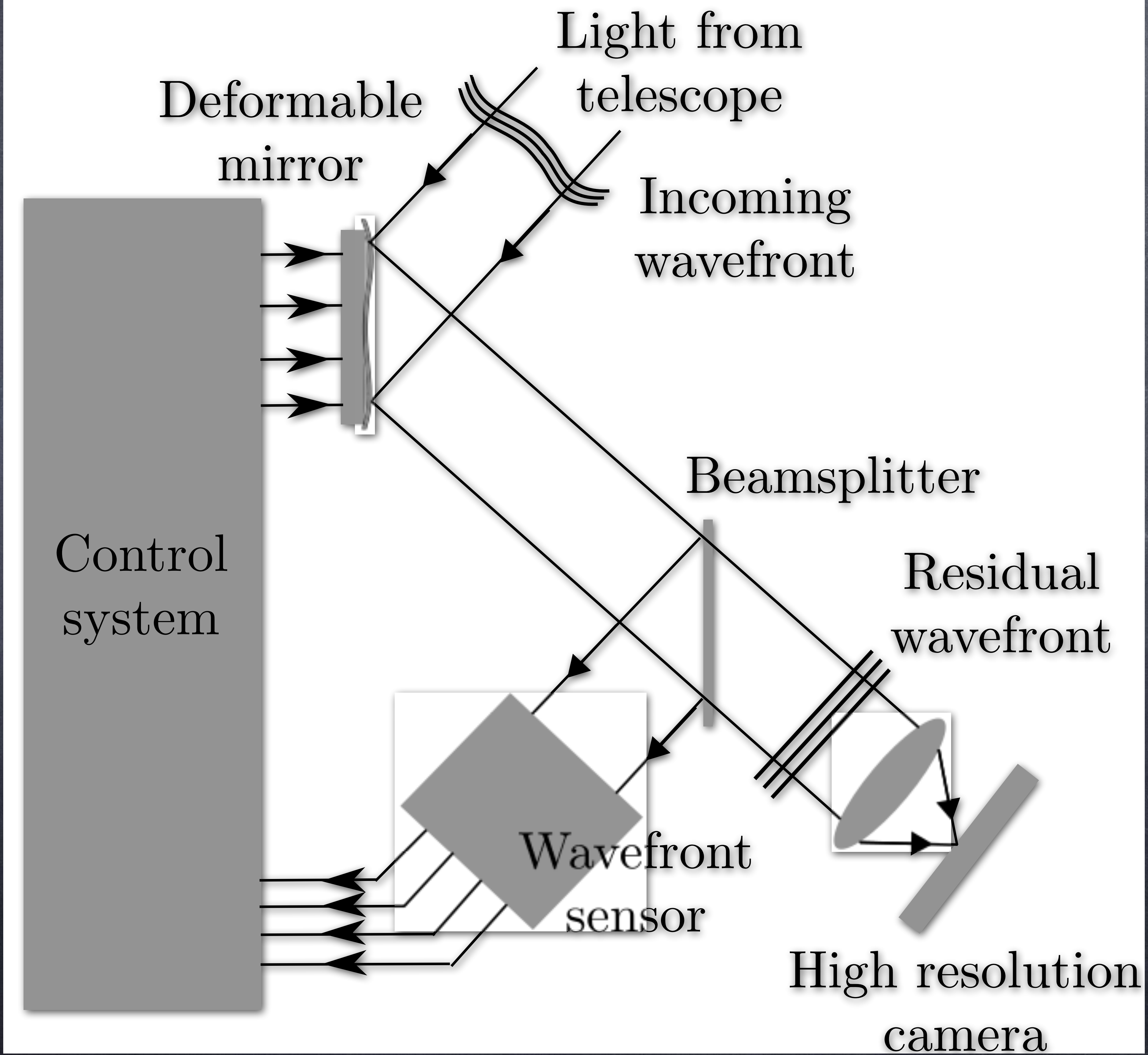
-> Also read Aime (Sec. 3)...

(Speckle interferometry - 6)

```
REPORT

- Preliminary measures
+ introduction
+ PSD(r0, L0) plot
+ => ccl on the influence of r0 and L0
+ rms(r0, L0) plot or table
+ => ccl on the influence of r0 and L0
+ image formation and FWHM(r0 or lambda, possibly L0)
+ => ccl on the influence of r0 or lambda (and poss. L0)
+ => comparison with the 'seeing' lambda/r0
+ image formation in presence of noise
+ basic speckle technique
+ (more to come...)
```

Adaptive optics - 1

Adaptive optics - 2



Adaptive optics - 3

Some orders of magnitude concerning AO systems:

	@500nm	@2.2μm
spatial sampling (WFS analysis elements size)		
→ $d \approx r_0$	≈ 10 cm	≈ 60 cm
number of WFS analysis elements (≈ number of DM actuators)		
→ $N \propto (D/d)^2$, with D=10m	≈ 7500	≈ 200
temporal sampling		
→ $f \propto 10\ v/r_0$	≈ 1 kHz	≈ 0.2 kHz

Adaptive optics - 4

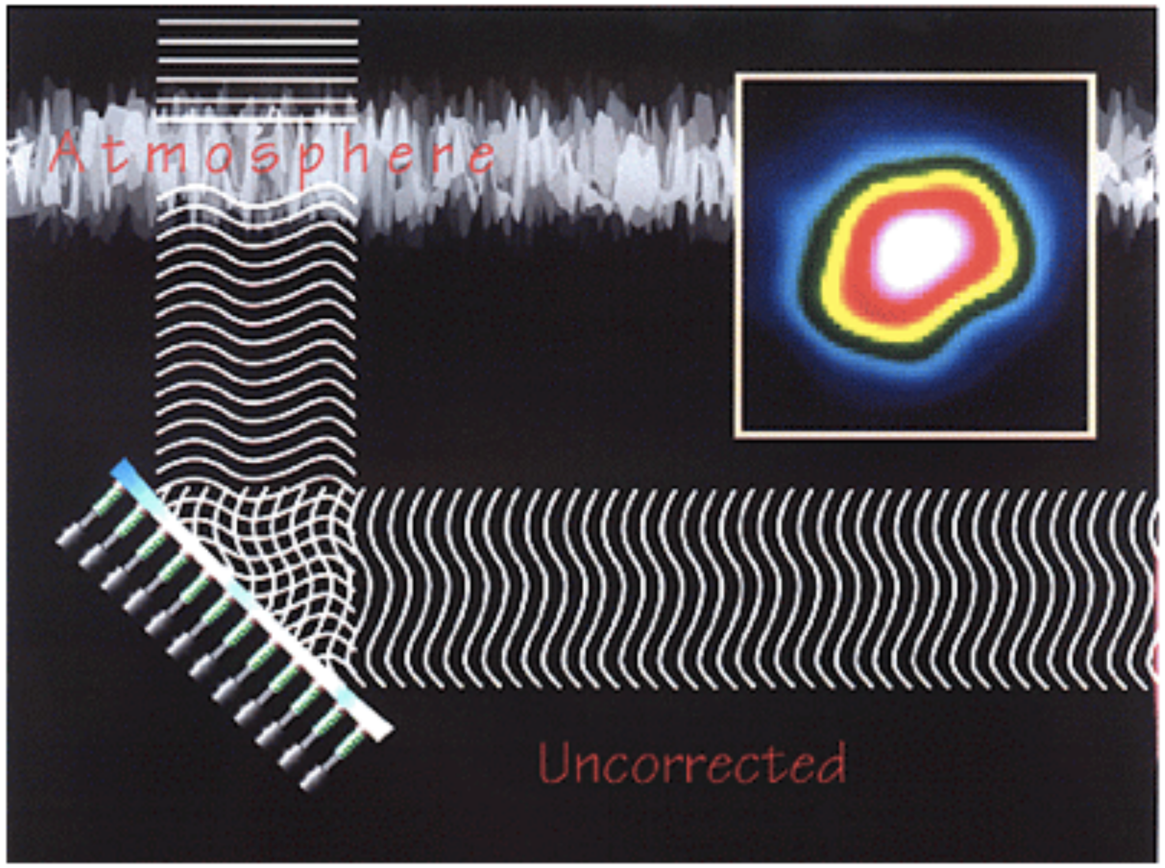
Introduction to Adaptive Optics

Credits: ESO and Jennifer Lotz

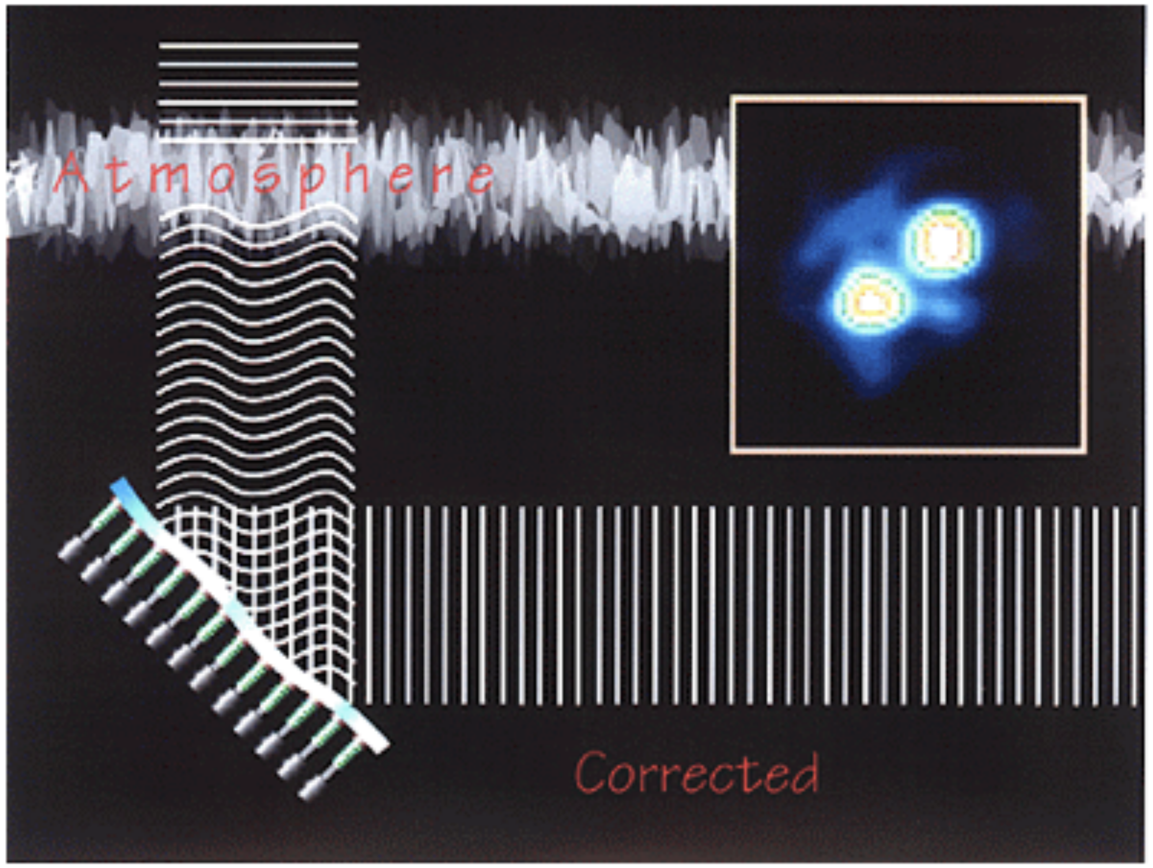
As astronomers attempt to understand the limits of the physical universe, they must look deep into the night sky with a sharp eye. Unfortunately, looking into the night sky is like looking up from the bottom of a swimming pool. Turbulence in the upper atmosphere causes spatial and temporal anomalies in atmosphere's refractive index and any planar wavefront of light passing through this turbulence will experience phase distortions by the time it reaches a ground-based telescope. These phase distortions blur the images obtained by the telescope and result in resolution an order of magnitude worse than the theoretical capabilities of the telescope. The power of ground-based telescopes to observe and resolve distant faint astronomical objects is limited by the effects of the atmosphere on the light coming from these objects.

The desire to avoid the image degradation due to the atmosphere was one of the main motivations behind the MPIA ALFA Project.

In recent years, astronomers have developed the technique of adaptive optics to actively sense and correct wavefront distortions at the telescope during observations. A telescope with adaptive optics measures the wavefront distortions with a wavefront sensor and then applies phase corrections with a deformable mirror on a time scale comparable to the temporal variations of the atmosphere's index of refraction. Adaptive optics dramatically improves image resolution as shown in the AO principle drawings below.



Blurred, uncorrected image (without Adaptive Optics)

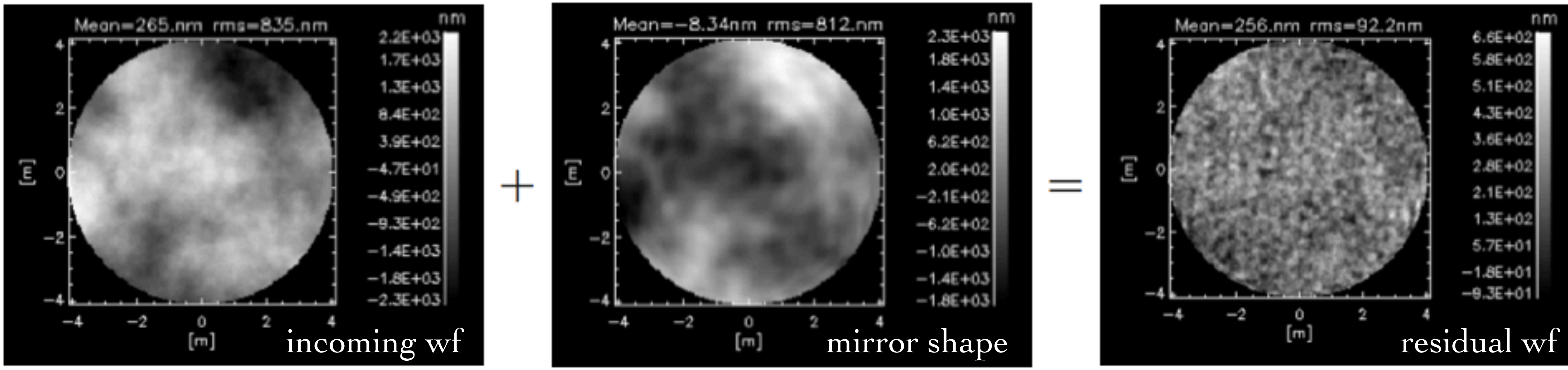


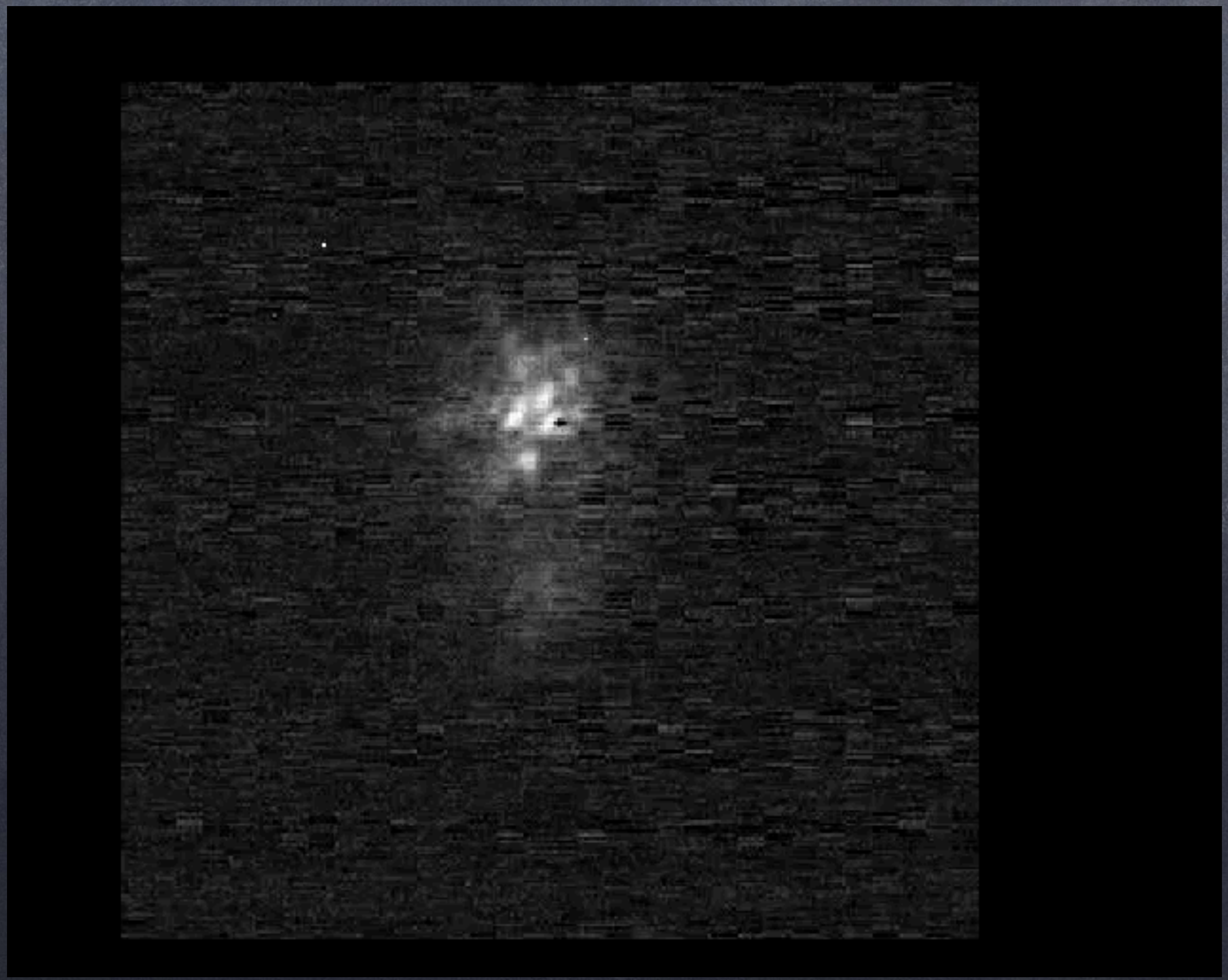
With Adaptive Optics corrected image

For more information see Adaptive Optics Tutorial in german or english by Stefan Hippler and Andrei Tokovinin.

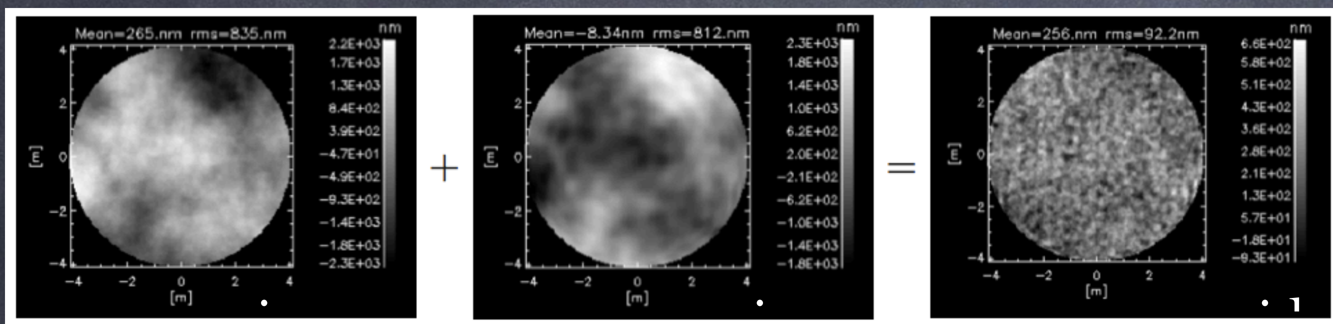
last update: 3 April 2007
editor of this page: Stefan Hippler

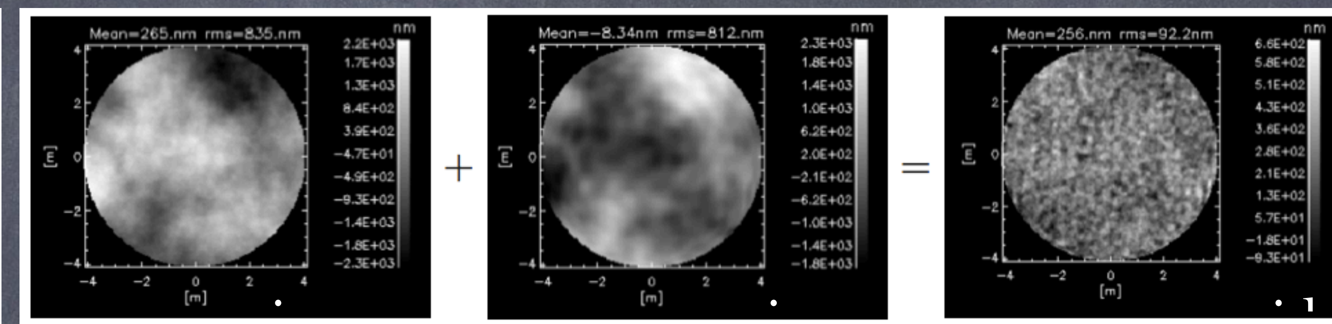
Adaptive optics - 5

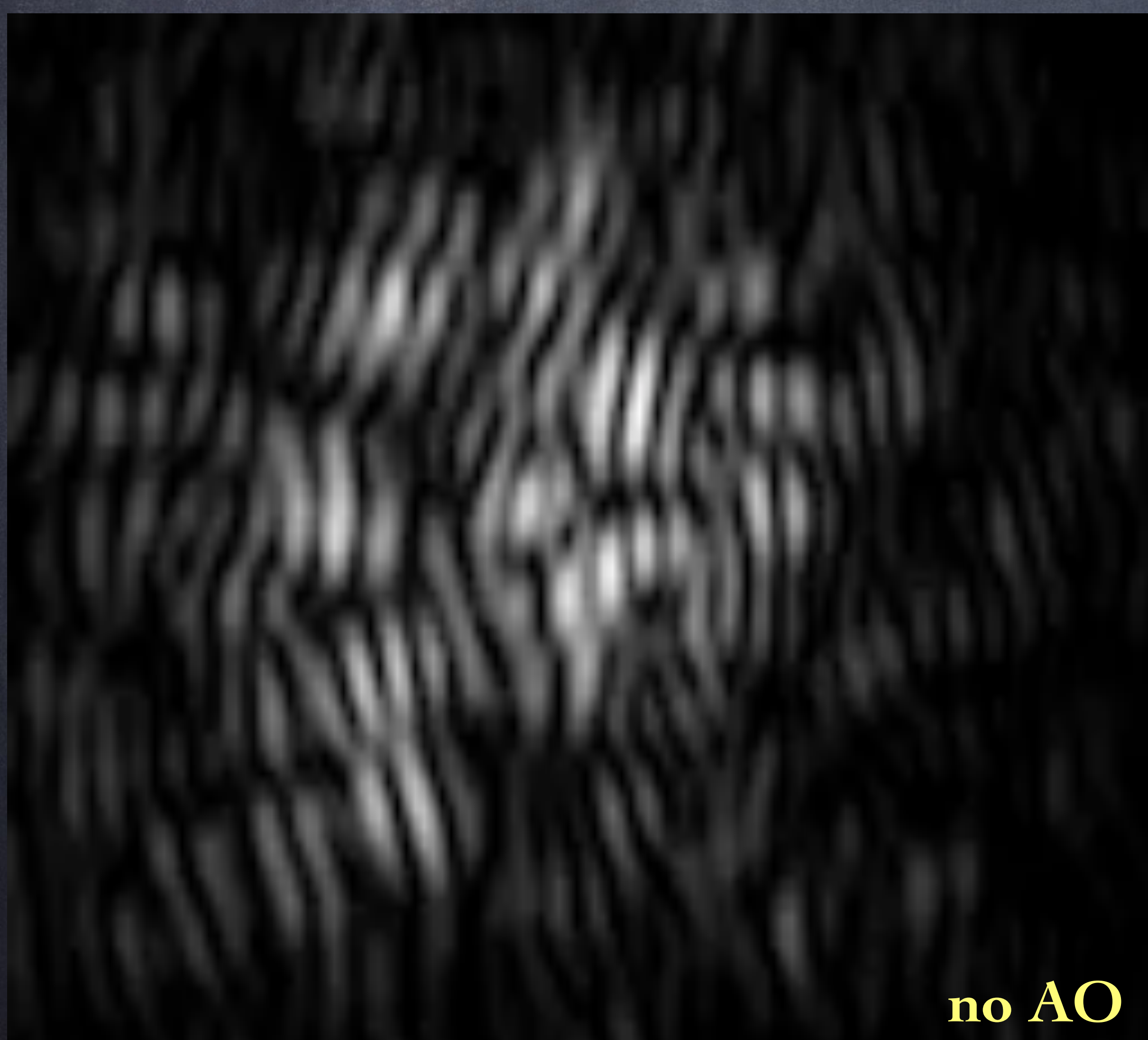


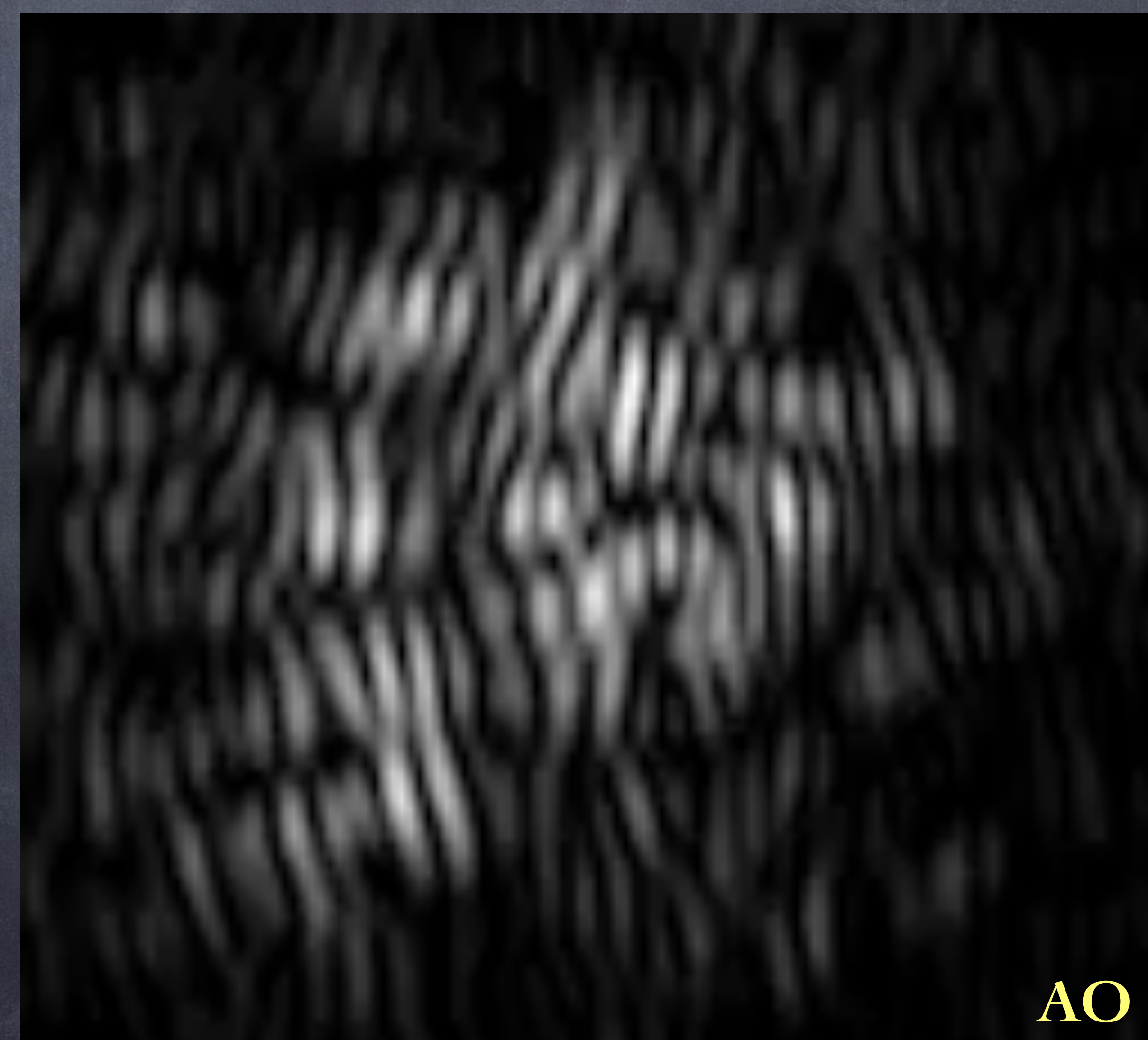


(Adaptive optics - 6)

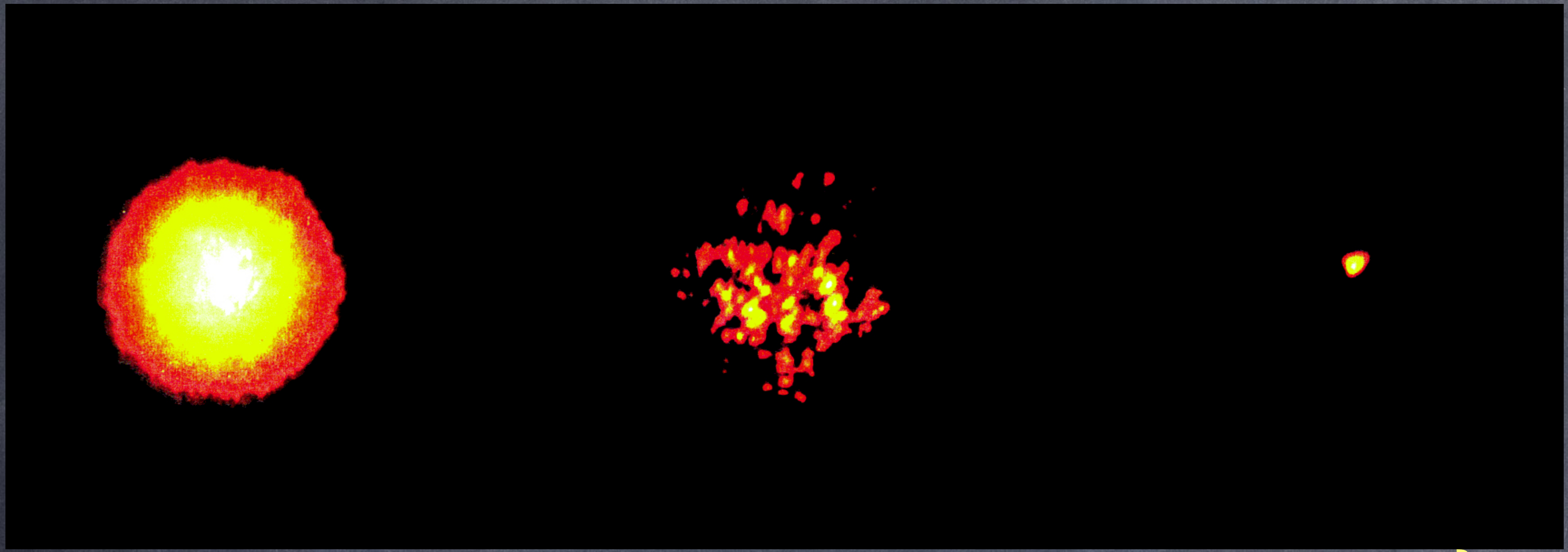




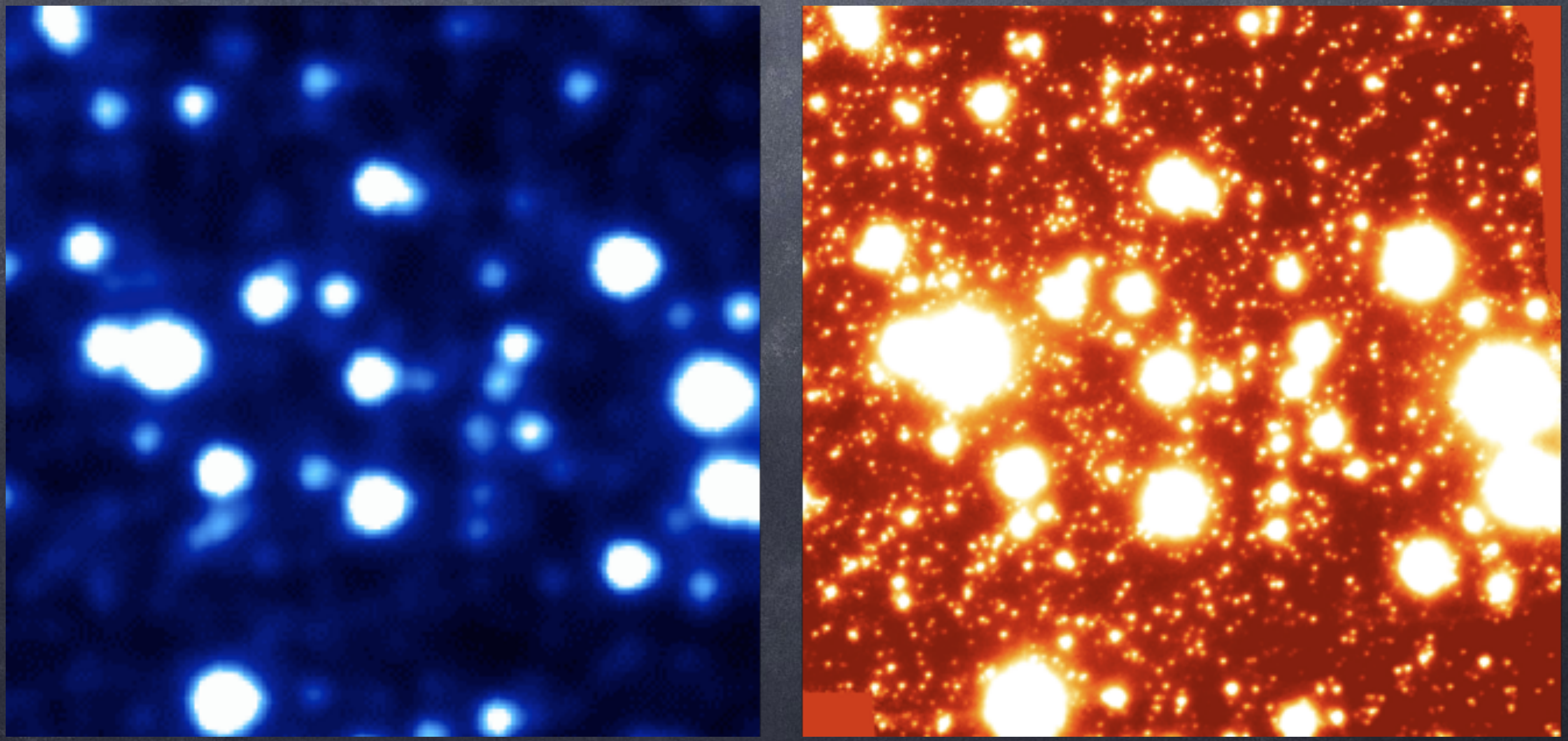




Adaptive optics - 7

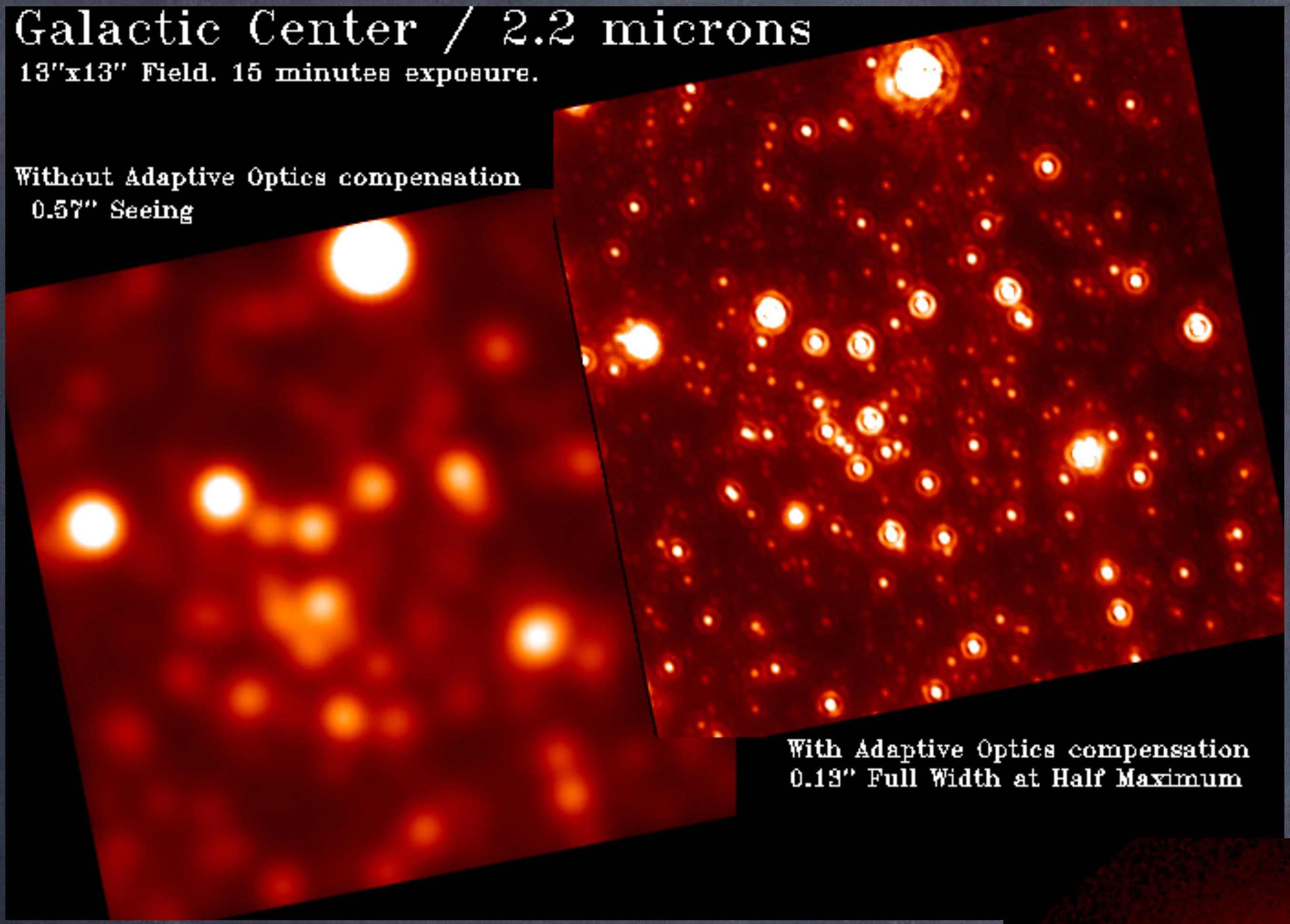


(Lick Observatory, 1-m telescope, left: FWHM≈1", right: FWHM≈λ/D)

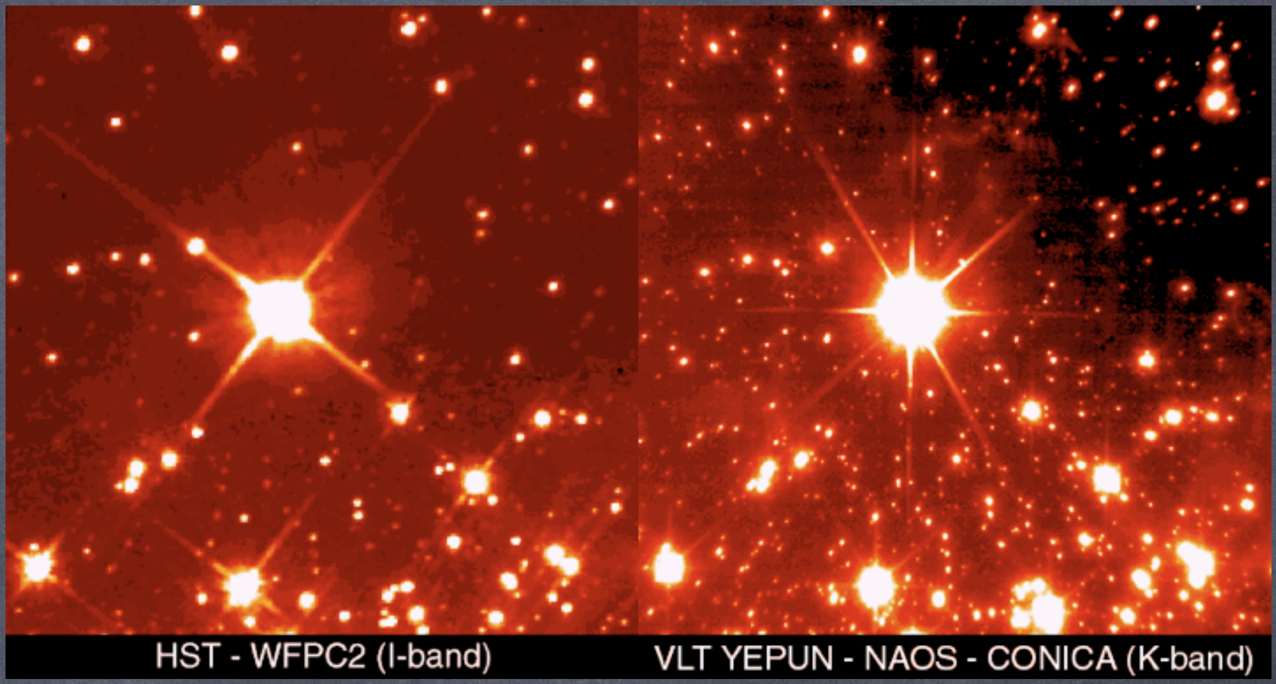


(Gemini Observatory, Hokupa'a+Quirc, left: FWHM≈0"85, right: FWHM≈0"09)

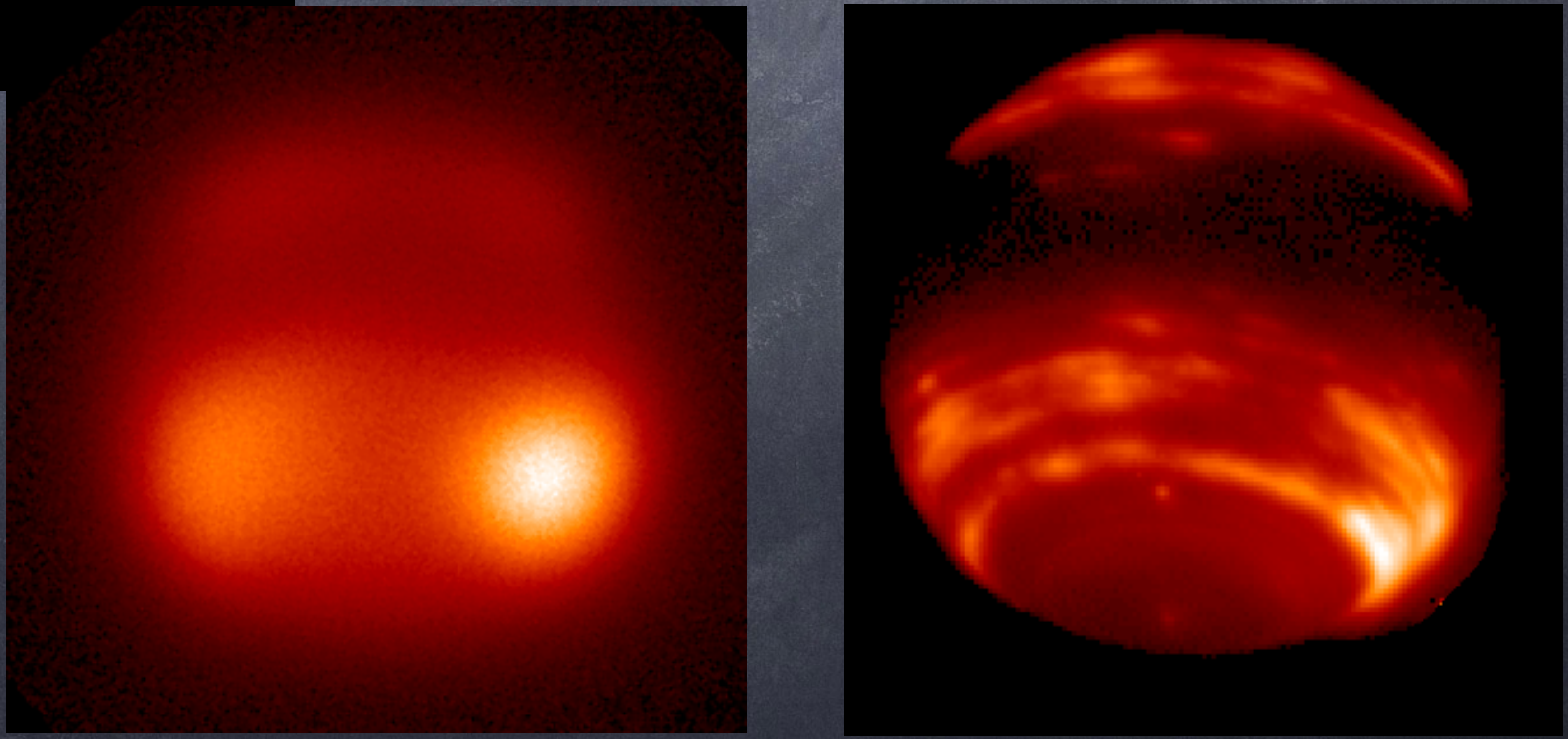
Adaptive optics - 8



(CFHT, long-exp. images (15'))

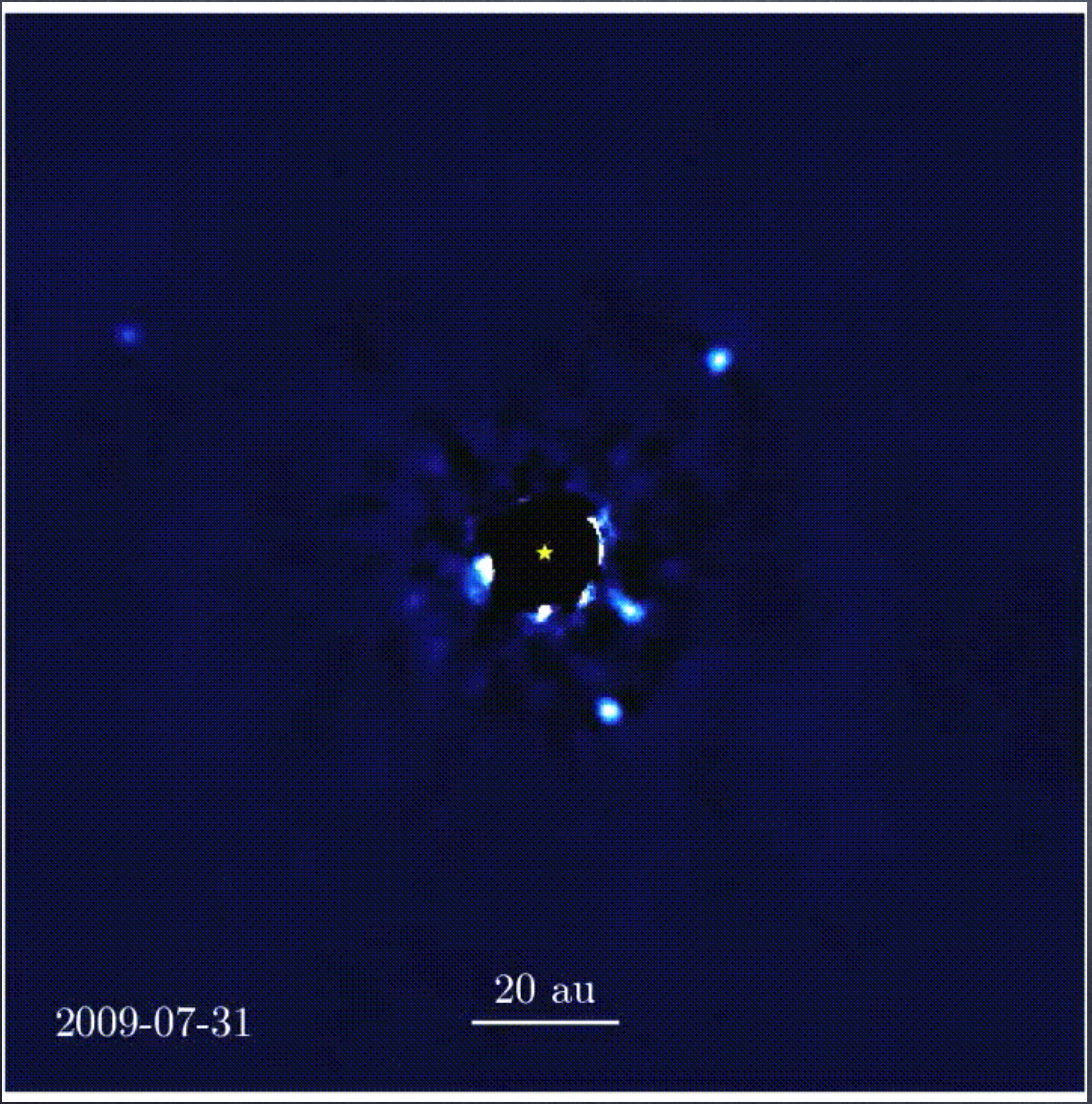


(HST vs. NACO/VLT)



(Neptune à 1.65 microns, Keck Observatory, mai et juin 1999)

Adaptive optics - 9



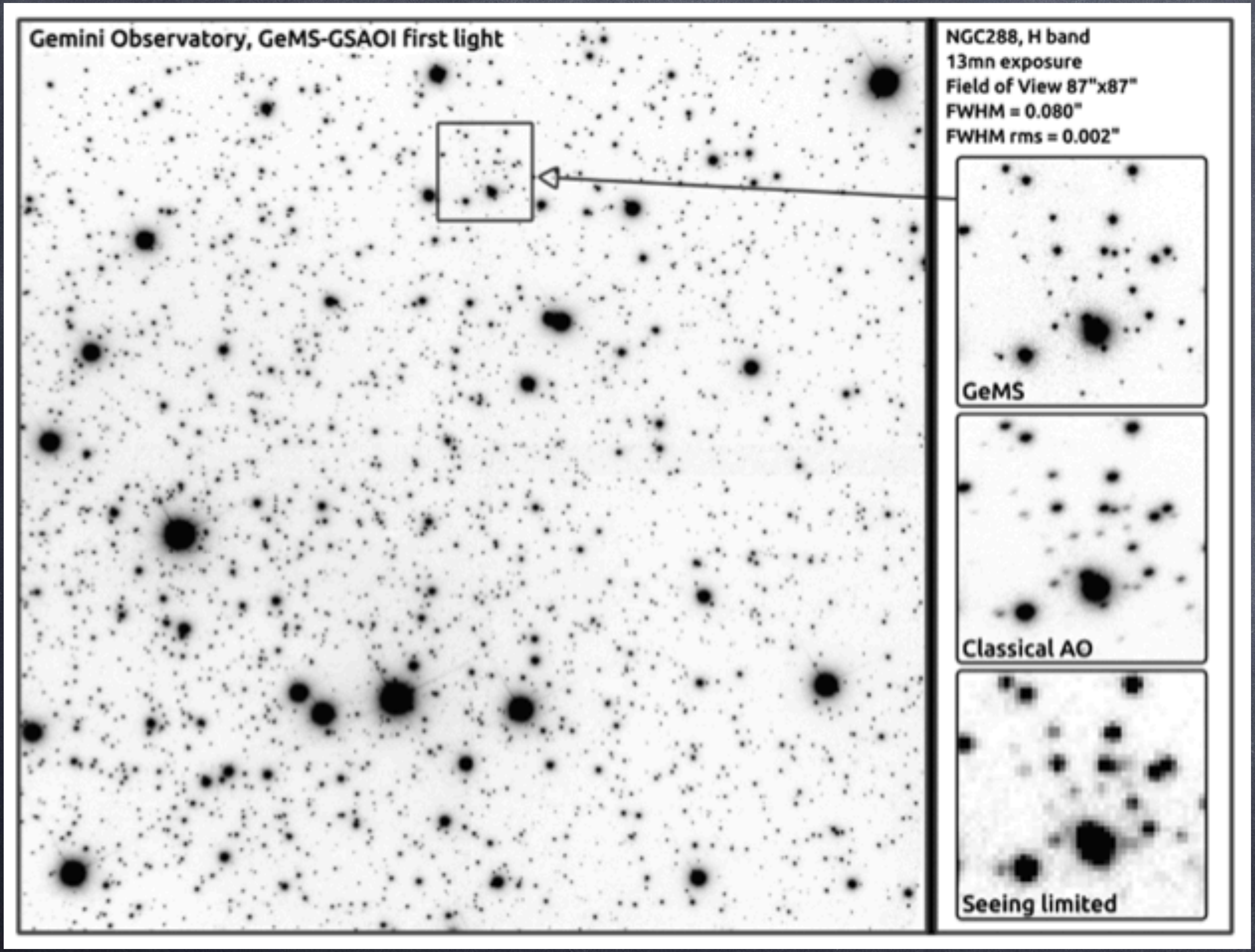
From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in 2013, from which 5 from (X)AO systems and 1 from HST.

Context: detection & characterisation of exoplanets

very high dynamic range
=> coronagraphy + extreme AO (XAO)

XAO usefull also for observing other types of faint objects (close to much brighter ones): circumstellar matter, (disks, jets), AGN, quasars, etc.

Adaptive optics - 10



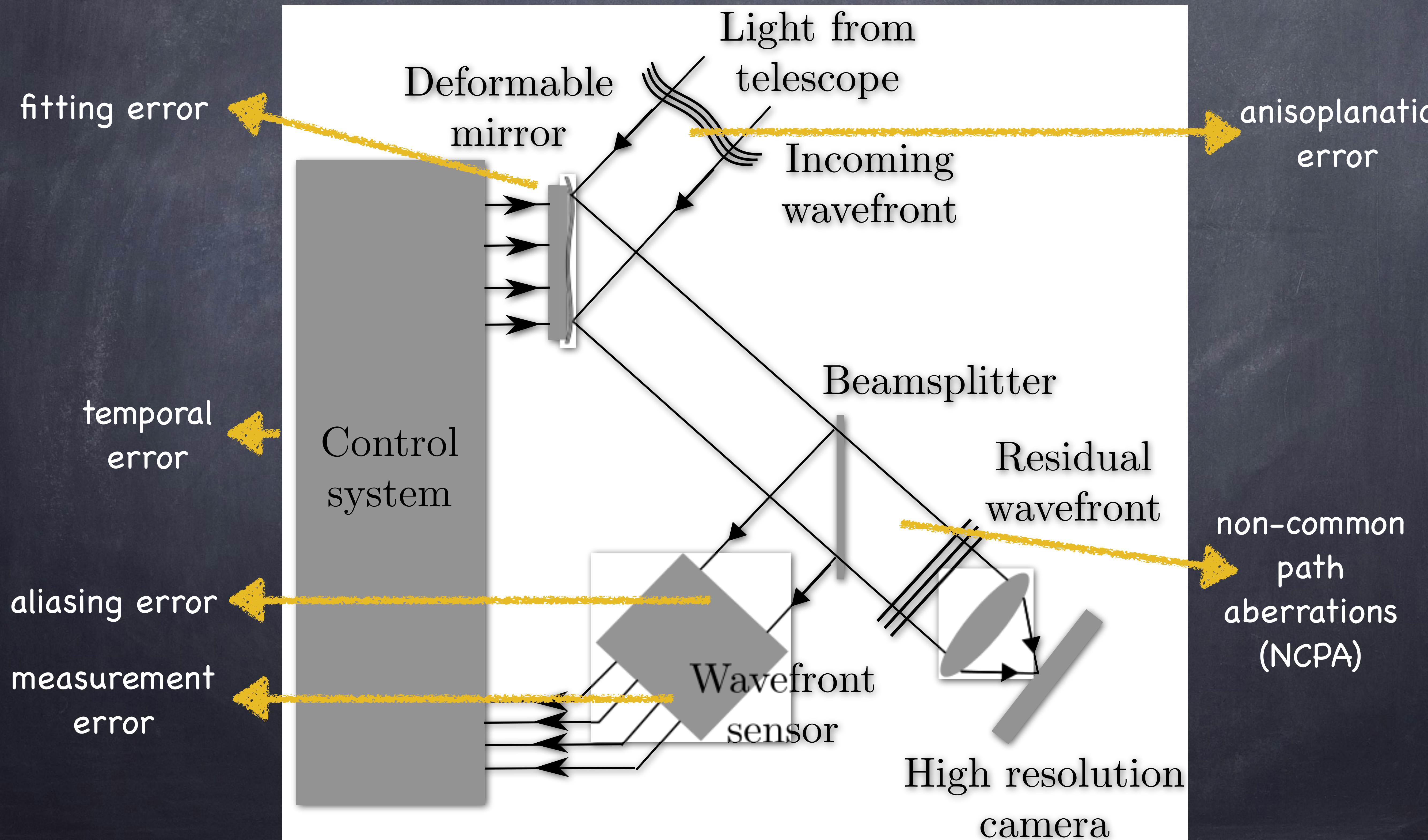
First-light image of GeMS, the MCAO system of Gemini
diffraction limit over a 2' square FoV - vs. a few arcsec !

Context: wide-field astronomical imaging

very wide fields
=> multi-reference
(& multi-conjugate)
AO systems...

-> Also read Rigaut's paper...

Post-AO error budget & PSF morphology - 1

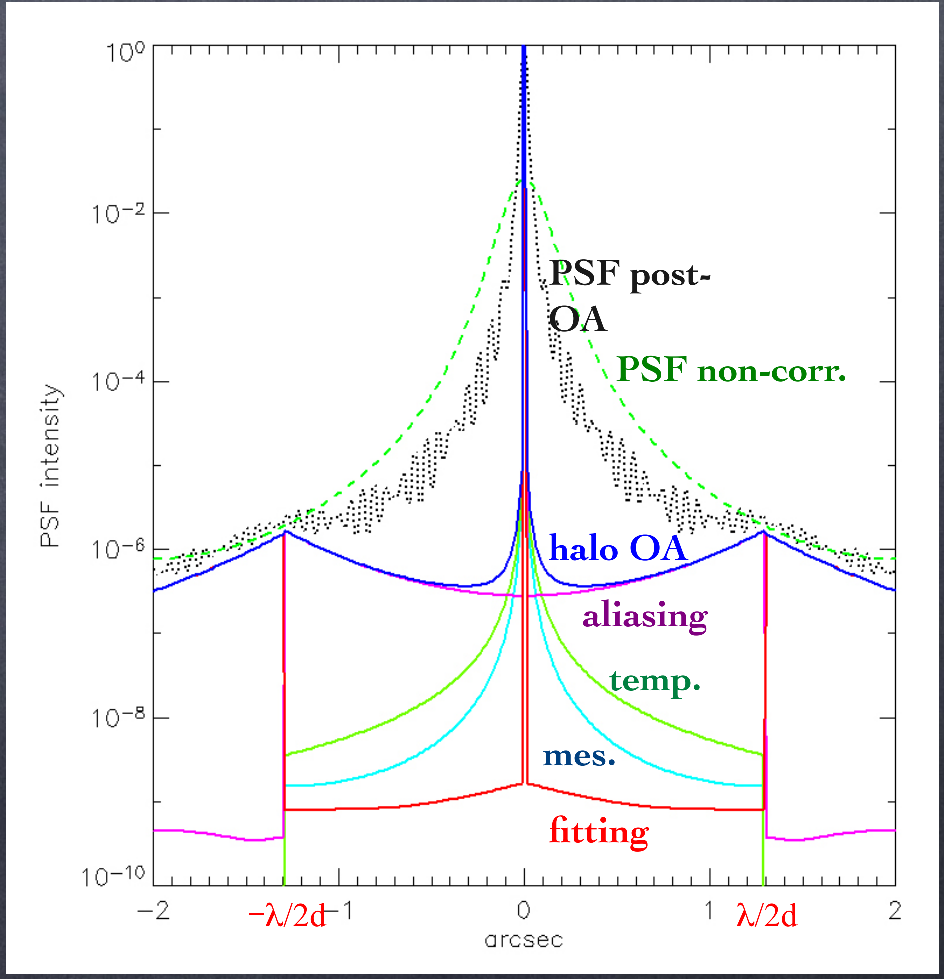


Post-AO error budget & PSF morphology - 2

$$\sigma^2_{\mathrm{post-AO}} = \sigma^2_{\mathrm{atm.}} + \sigma^2_{\mathrm{AO\ \ syst.}} + \sigma^2_{\mathrm{others}}$$

$$\sigma^2_{\mathrm{atm.}} = \sigma^2_{\mathrm{aniso.}} + \ldots$$

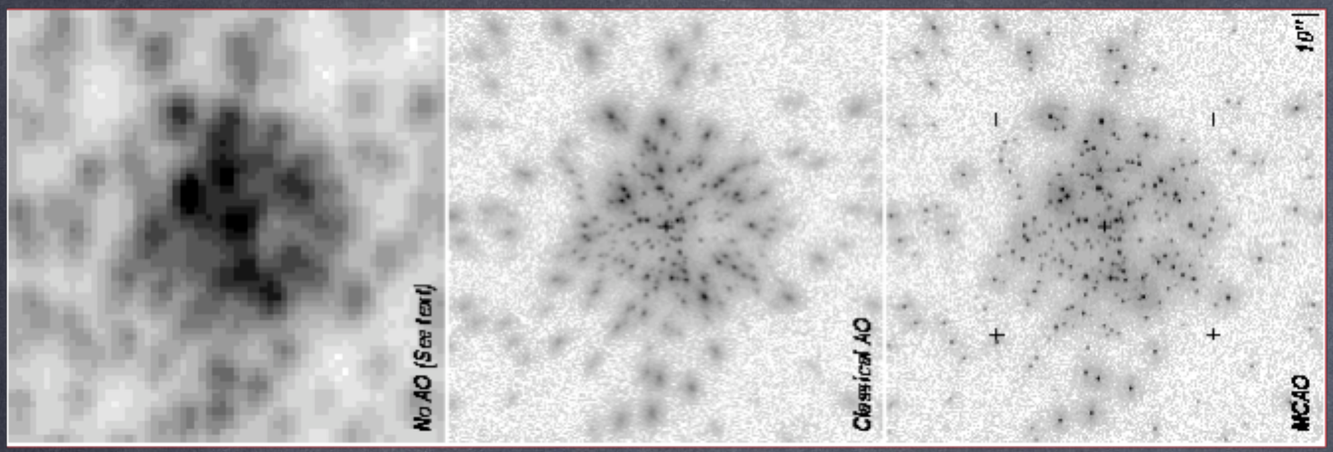
$$\sigma^2_{\mathrm{others}} = \sigma^2_{\mathrm{NCPA}} + \ldots$$



$$\sigma^2_{\mathrm{AO\ \ syst.}} = \sigma^2_{\mathrm{fitt.}} + \sigma^2_{\mathrm{meas.}} + \sigma^2_{\mathrm{alias.}} + \sigma^2_{\mathrm{temp.}} + \ldots$$

Anisoplanatic error - 1

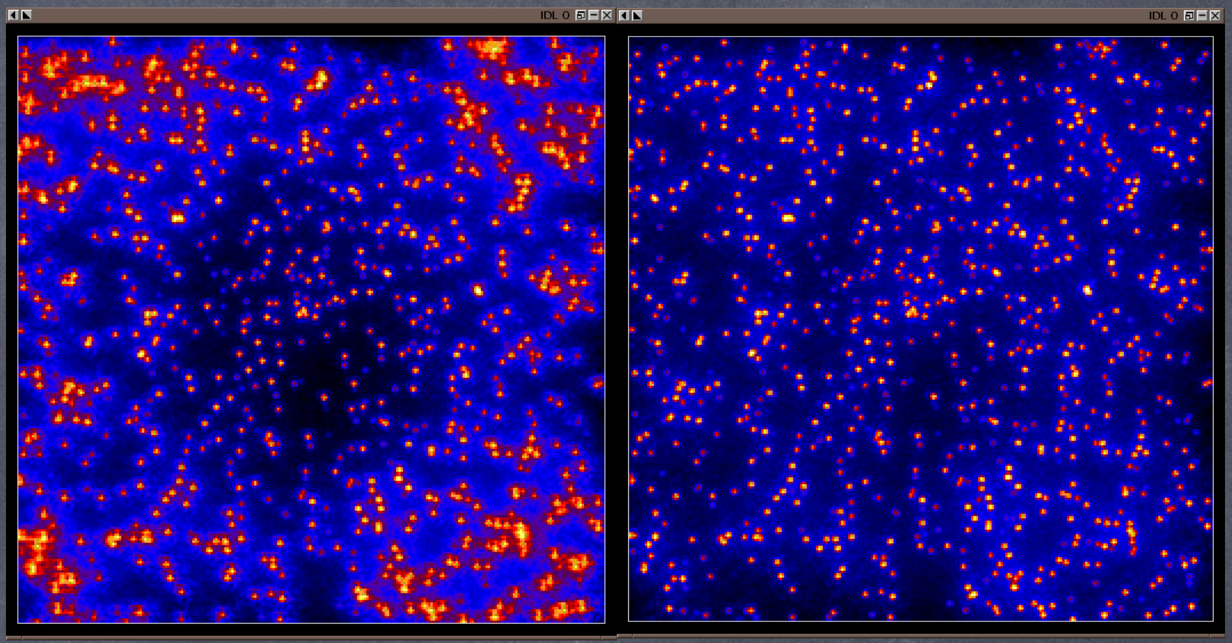
165"



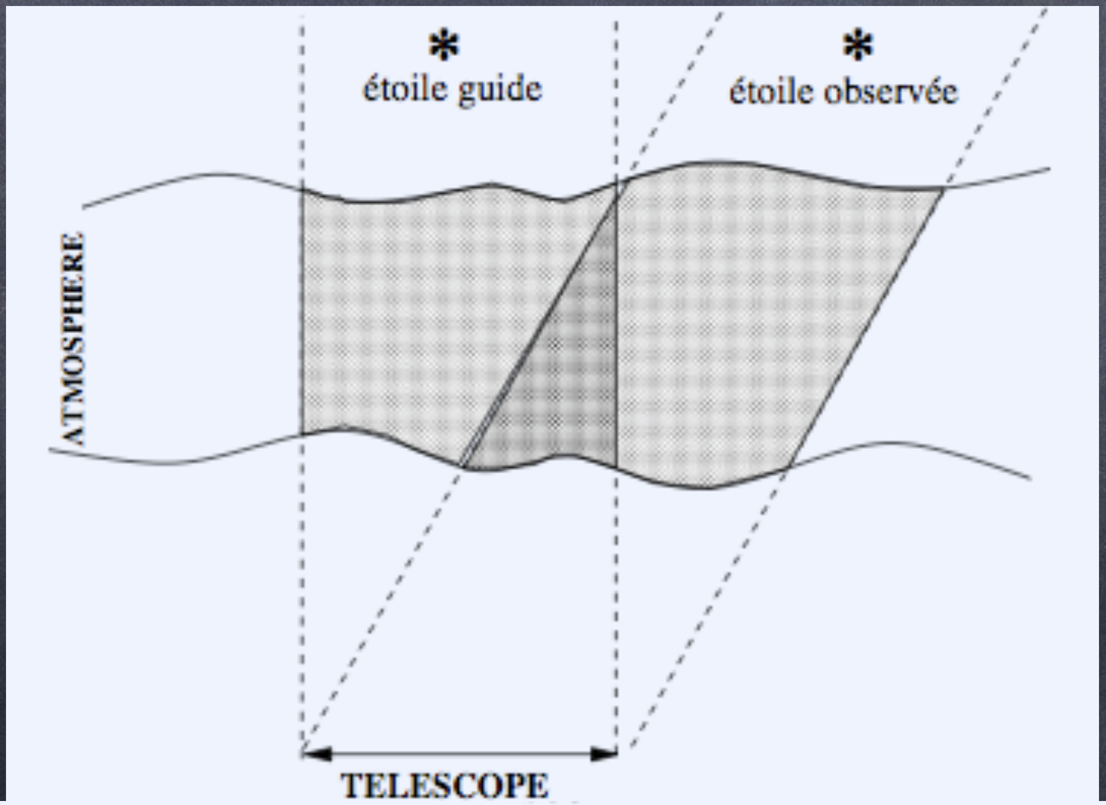
No AO

classical AO
(1 DM, 1 NGS)

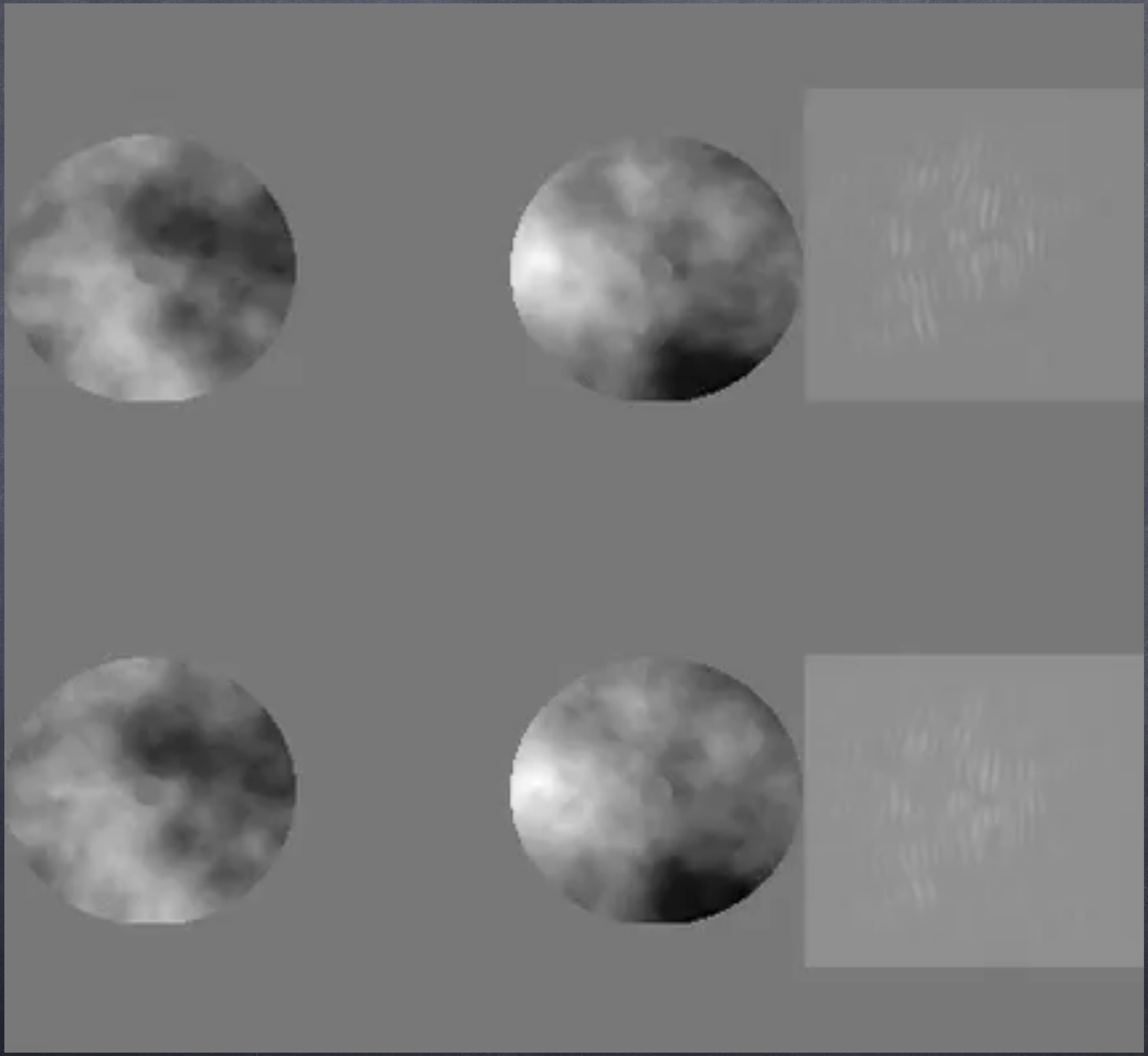
MCAO
(2 DM, 5 NGS)



(bande J, champ de 1', simu. B.Ellerbroek, Gemini Obs.)



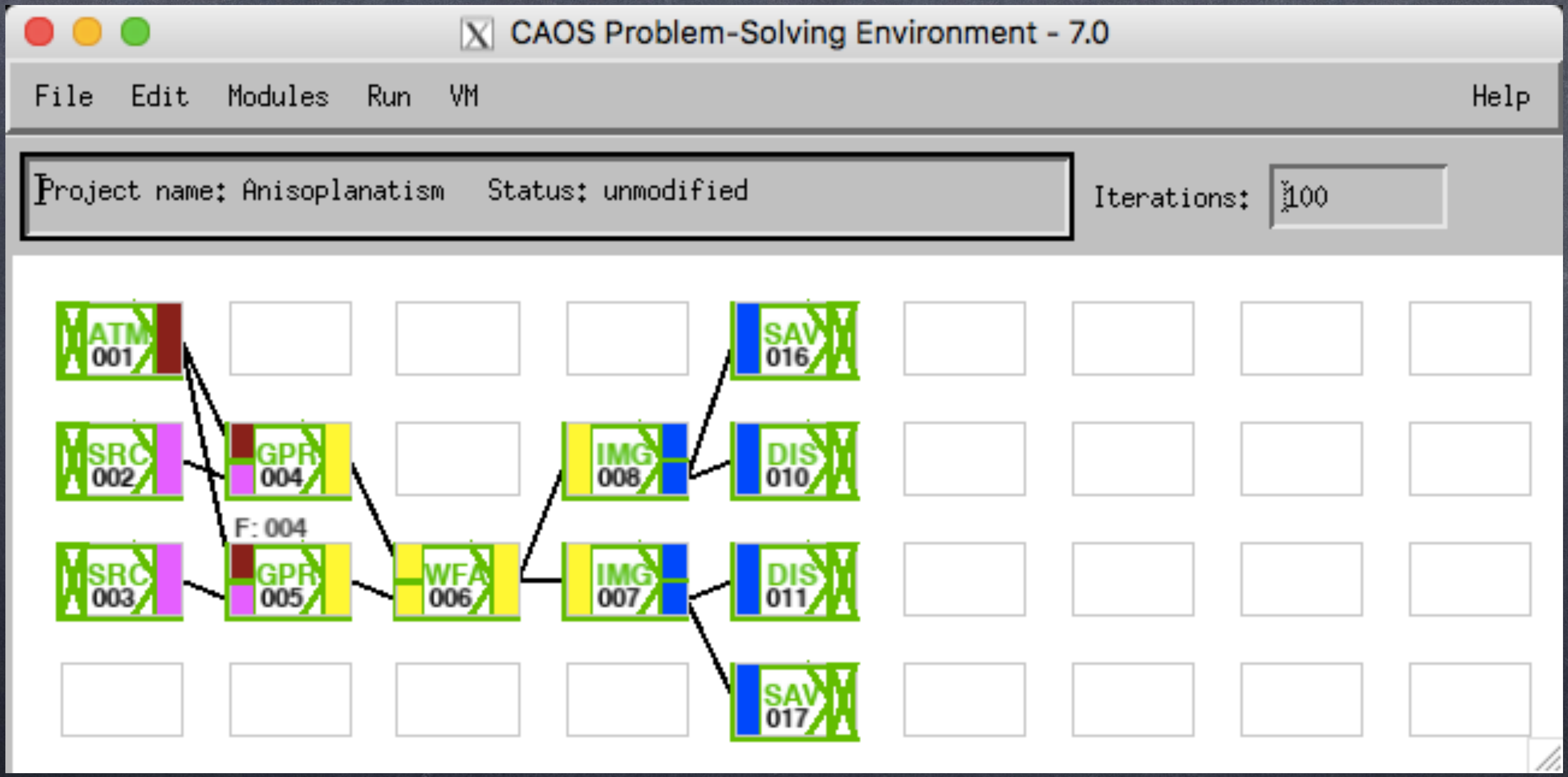
(Anisoplanatic error - 2)



Anisoplanatic error - 3

Numerical tool used for this study: CAOS

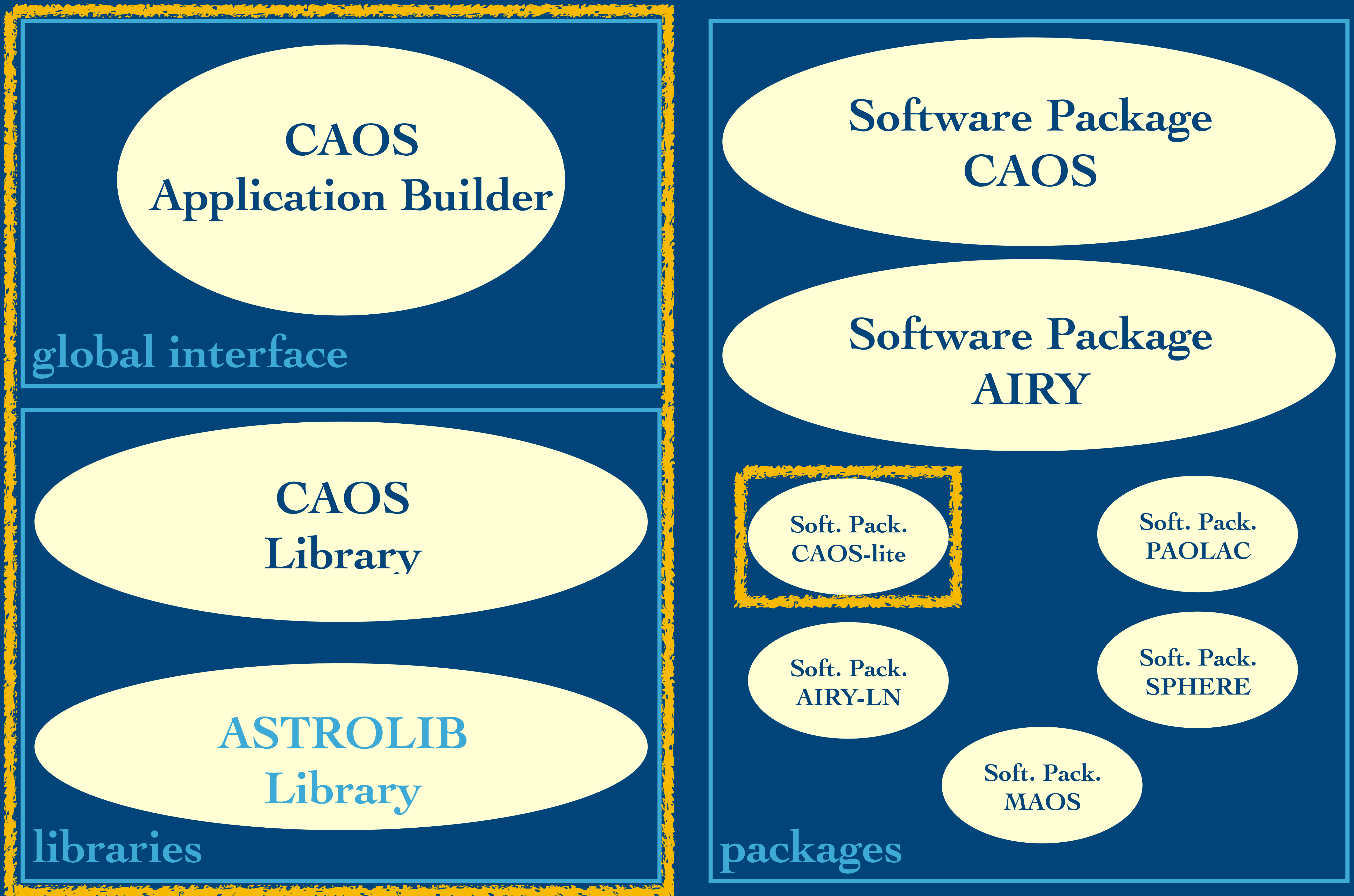
(CAOS Problem-Solving Environment + Software Package CAOS + Example project ``Anisoplanatism"...)



The CAOS "PSE"...

- CAOS means Code for *Adaptive Optics* Systems.
- "PSE" means Problem-Solving Environment.
- It is written in IDL, and based on a modular structure.
- It is composed of a global interface (the CAOS Application Builder), a library of utility routines (the CAOS Library), and some scientific packages (the Software Packages).
- a Software Package is a set of modules dedicated to a given scientific subject (AO, imaging, whatever).

CAOS Problem Solving Environment -1

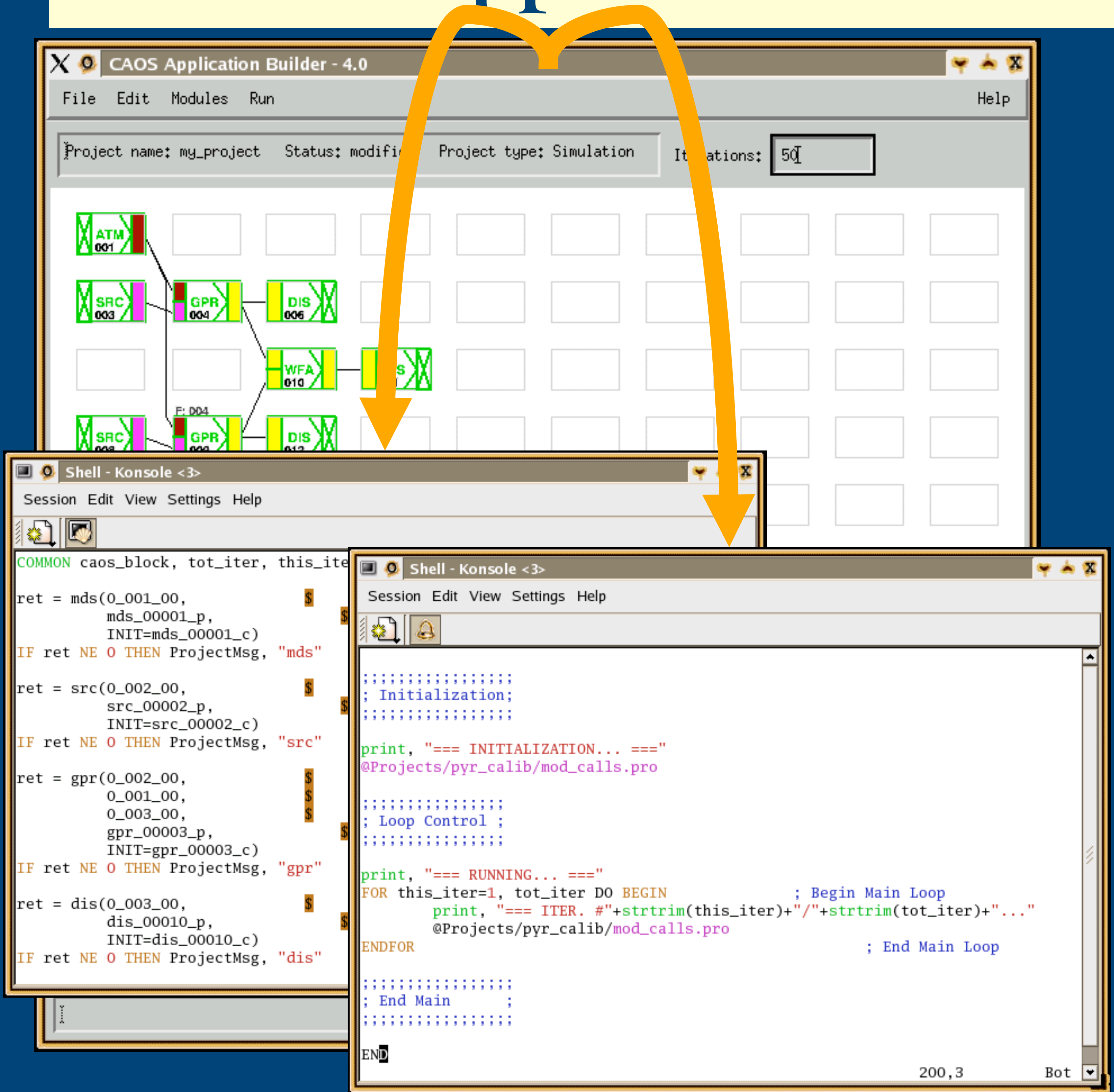


CAOS Problem Solving Environment -2

- caos_pse
  - appbuilder
  - library
  - packages
    - Soft. Pack. CAOS-lite
    - Utilities
  - work_caos
    - admin. files
    - Projects
      - example projects
      - your own projects
    - other routines

somewhere else: astrolib, possibly some other library

CAOS Application Builder



It is the global user interface of the CAOS PSE: essentially a **worksheet** where the user can place small blocks, the modules, and connect them with data paths to form a **project.**

When the project is designed, it can be saved on disk, **generating the IDL code** which implements the simulation program.

The "virtual machine" feature of IDL permits in addition to have an IDL-licence-free version of a given project...

CAOS PSE: availability

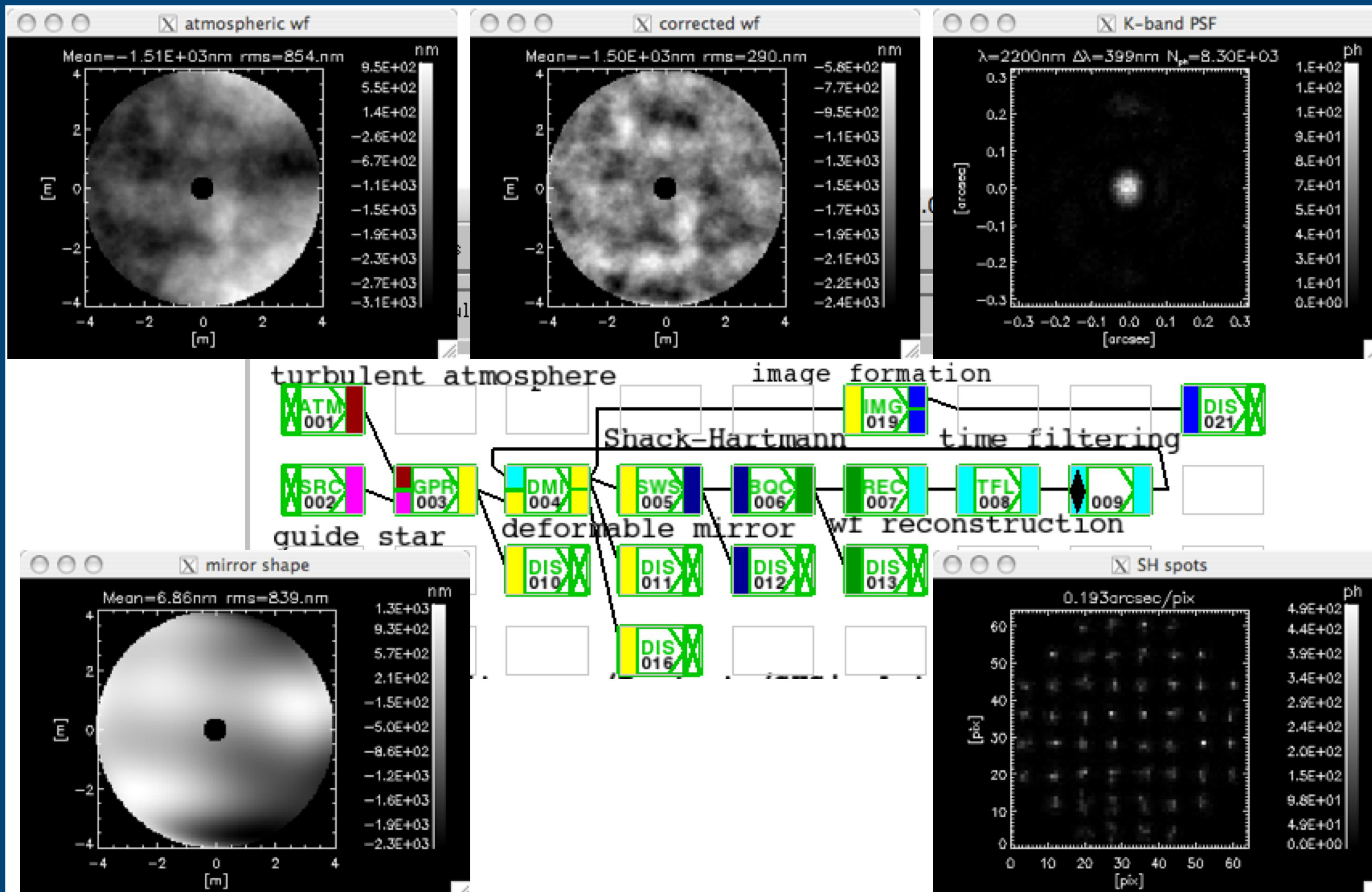
All (*public!*) parts of the CAOS PSE are available for download:

lagrange.oca.eu/caos/

Current status of the dedicated mailing-lists (as on February 2024):

- **Soft. Pack. CAOS: 100 subscribers,**
- **Soft. Pack. AIRY: 24 subscribers.**

End-to-end AO modeling with the Software Package CAOS

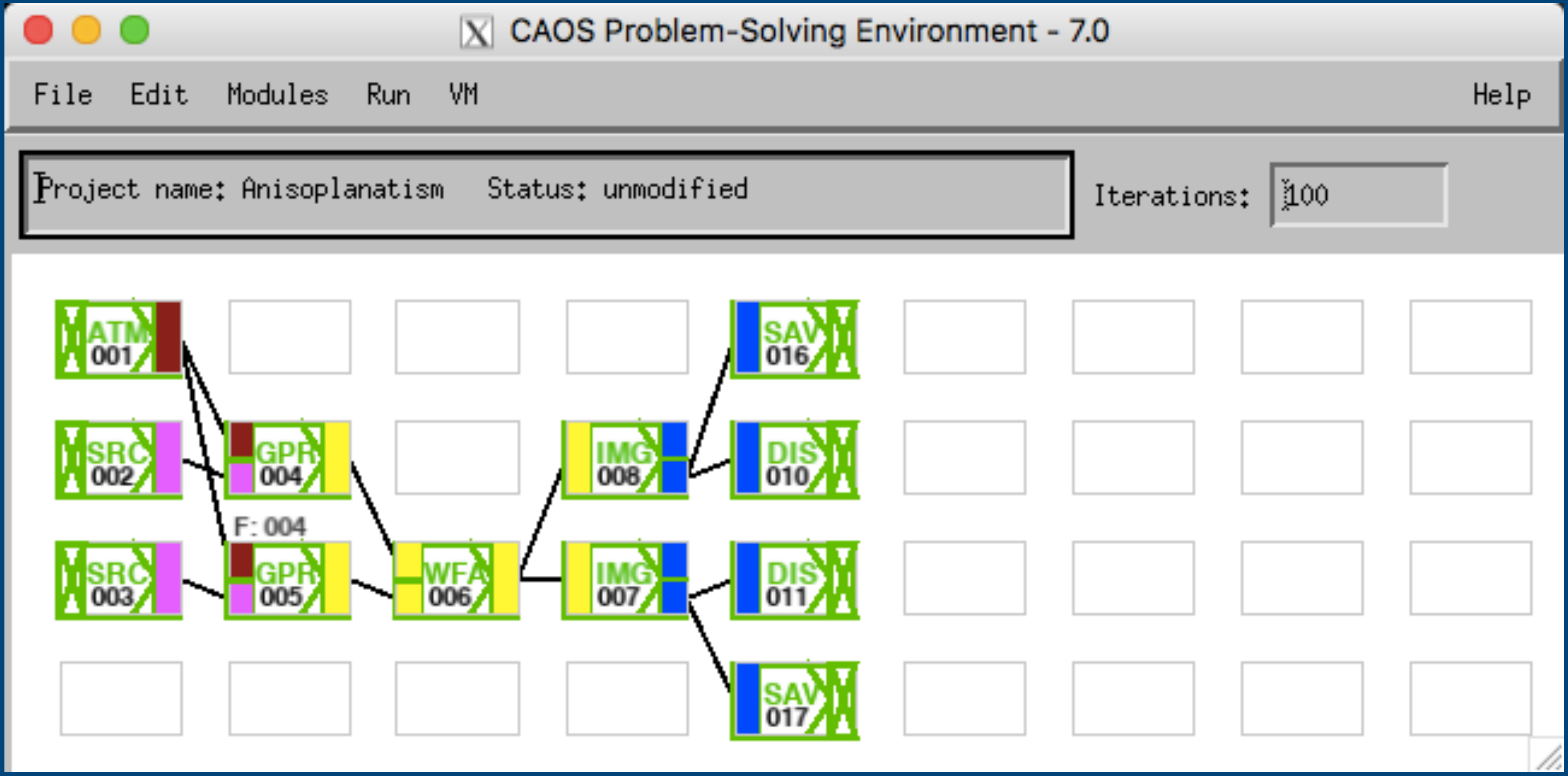


Imaging through the turbulent atmosphere: anisoplanatism ! – 1

Table 1. The 31 modules of the **Software Package CAOS**, version 7.0.

Module	Purpose
[illegible]	
ATM - ATMosphere building	-builds the turbulent atmosphere (FFT+subharmonics, Zernike) (see also utility PSG - Phase Screen Generation)
SRC - SouRCe definition	-characterizes the guide star/observed object
GPR - Geometrical PRopagator	-propagates light from source to telescope through atmosphere
IMG - IMaGing device	-forms an image of the observed object (+detector noises)
Wavefront sensing	
PYR - PYRamid wavefront sensor	-simulates the pyramid wavefront sensor
SLO - SLOpe computation	-computes the slopes from the pyramid signals
SWS - Shack-Hartman Wavefront Sensor	-simulates the Shack-Hartmann (SH) wavefront sensor
BQC - Barycentre/Quad-cell Centroiding	-compute the signals from the SH spots centroiding calculus
IWS - Ideal Wavefront Sensing	-applies "ideal" wavefront sensing (see text)
TCE - Tip-tilt CEntroiding	-computes and reconstructs tip-tilt
Wavefront reconstruction, control & correction	
REC - wavefront REConstruction	-reconstructs the wavefront
TFL - Time-FiLtering	-applies time-filtering after wavefront reconstruction
SSC - State-Space Control	-applies state-space control
DMI - Deformable MIrror	-simulates the behavior of a deformable mirror (DM)
TTM - Tip-Tilt Mirror	-simulates the behavior of a tip-tilt mirror
Calibration	
CFB - Calibration FiBer characterization	-defines a fiber to be used for calibration purpose
MDS - Mirror Deformation Sequencer	-generates a sequence of DM modes or influence functions
SCD - Save Calibration Data	-saves the calibration data (interaction matrix+set of deformates)
Wide-field AO	
AVE - signals AVEraging	-averages measurements from various wavefront sensors
COM - COMbine measurements	-combines measurements from various wavefront sensors
DMC - Deformable Mirror Conjugated	-corrects at different conjugated altitudes
Other modelling modules	
LAS - LASer characterization	-defines laser projector characteristics
NLS - Na-Layer Spot definition	-characterizes the Sodium-layer behavior
IBC - Interferometric Beam Combiner	-combines the light from two apertures
COR - CORonagraphic module	-simulates various coronagraphs (Lyot, Roddier&Roddier, FQPM)
AIC - Achromatic Interfero-Coronagraph	-simulates the Achromatic Interfero-Coronagraph
BSP - Beam SPlitter	-splits the light beam
Other utility modules	
WFA - WaveFront Adding	-adds or combines together wavefronts
[illegible]	[illegible]
IMA - IMage Adding	-adds or combines together images
STF - STructure Function	-calculates the structure function and compares to theory

Imaging through the turbulent atmosphere: anisoplanatism ! – 2



Installation of CAOS-lite — 1
(CAOS PSE + lite version of Soft.Pack.CAOS)

```
-------------------------------------------
INSTALLATION PROCESS (& BRIEF INTRODUCTION):
-------------------------------------------
(CAOS-lite, version 2021)

01-Unpack CAOS-install.zip somewhere on your account, the directory
   "CAOS-install/" is created, and it contains both a lite version of CAOS
   (within directory "CAOS-lite/") and the IDL Astronomy Library (within
   directory "astrolib/"). The lite version of CAOS contains itself both
   the CAOS PSE (Problem-Solving Environment - the IDL-based CAOS global
   architecture and interface) and a special lite edition of the CAOS
   Software Package (based on CAOS Software Package version 7.0), as well
   as a working directory, "work_caos/".

02-Go to the working directory "work_caos/" and fix the paths in the
   environment-parameters files "caos_env.sh" and "caos_startup.pro".

03-Still within the working directory, type "source caos_env.sh".

04-Launch IDL.

05-Type "@compile_all_CAOSlite_modules" in order to re-generate the
   default parameter files of the whole set of modules (upgrading so
   any possible pre-defined path).

06-Type "worksheet" at the CAOS prompt in order to use the CAOS
   Application Builder (the global interface of the tool).

NB-1: Steps 01,02,05 are necessary just once, during installation.
NB-2: Steps 03,04,06 are necessary for each opened terminal from which
      you wish to use IDL together with CAOS.
```

Installation of CAOS-lite — 2
(CAOS PSE + lite version of Soft.Pack.CAOS)

```
------------------------
SOME ADDITIONAL REMARKS:
------------------------

01-Refer to
      http://lagrange.oca.eu/caos
   for further informations on the CAOS PSE and its official packages.

02-Please never redistribute any CAOS part by yourself, rather refer to
   http://lagrange.oca.eu/caos.

03-New projects start within the worksheet with "File"->"New Project". Modules
   are put within the worksheet through button "Modules", and can be cloned
   or deleted using "Edit"->"Clone module" or "Edit"->"Delete item". Each color
   at the left- or right-side of a module represents a type of input or output.
   In order to link two modules, click on the output of the first one and then
   click on the input of the second one. When the design of your simulation is
   completed, including setting of the total number of iterations, save the
   project using "File"->"Save Project". Then you can set the parameters related
   to each module using its dedicated GUI called by clicking on the module at
   any moment.

04-For a detailed tutorial refer to:
      http://lagrange.oca.eu/caos/tutorial/tutorial.html

05-In order to run a project, for example a project named "Anisoplanatism":
   > .rn ./Projects/Anisoplanatism/project.pro
   or alternatively use button "Run" from the CAOS PSE worksheet.
```

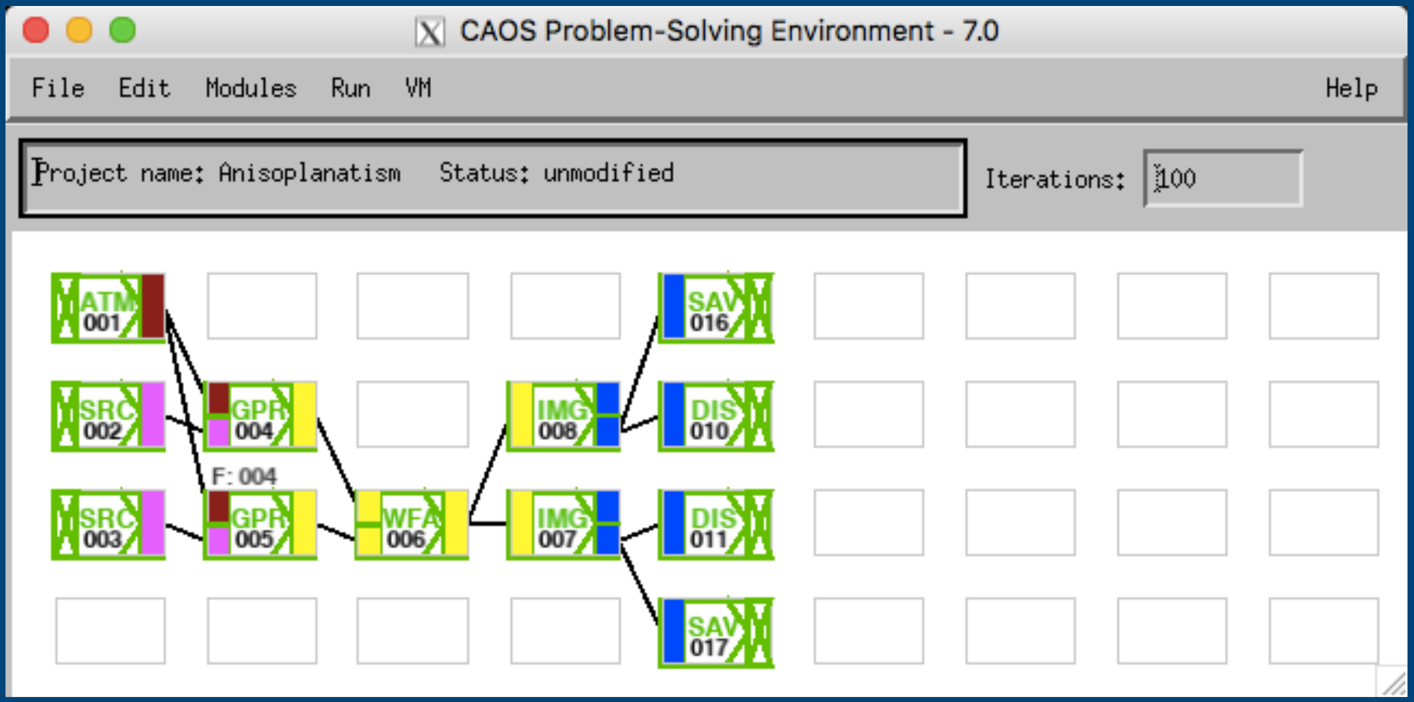
Build project for anisoplanatism…

0- COMPLETELY FINALISE INSTALLATION OF THE CAOS PSE AND THE SOFTWARE PACKAGE CAOS (POSSIBLY THE LITE VERSION OF IT) BEFORE GOING ON !!

Then, within the CAOS interface…

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- 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 within the two modules SAV (one for each module IMG, i.e. one for each considered wavelength: for example 500nm and 1650nm).

4- Fix the parameters of the other modules.

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 3 to 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 routine ``dataprocessing.pro".