# Adaptive optics - 2

# Adaptive optics - 3

**Some orders of magnitude concerning AO systems:**

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

# Adaptive optics - 4

## Introduction to Adaptive Optics

**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.
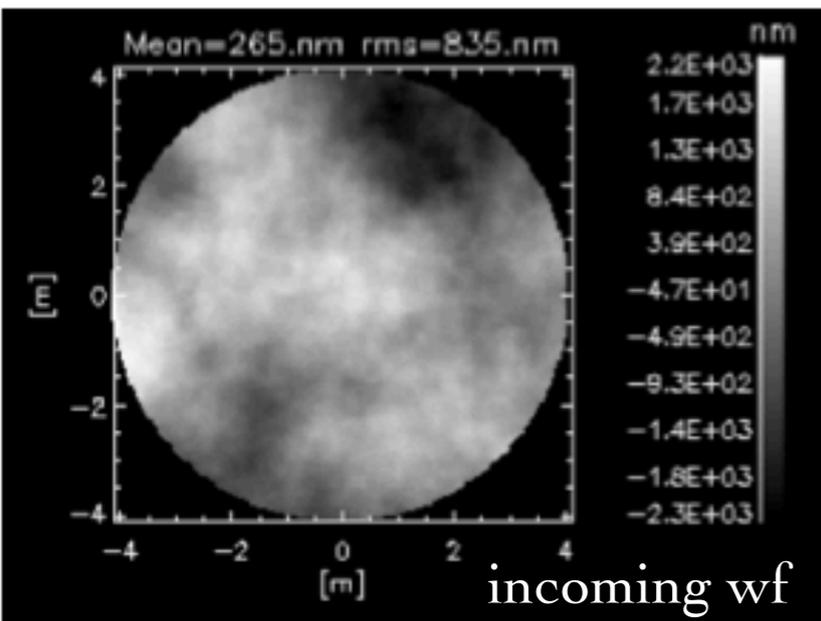
Atmosphere
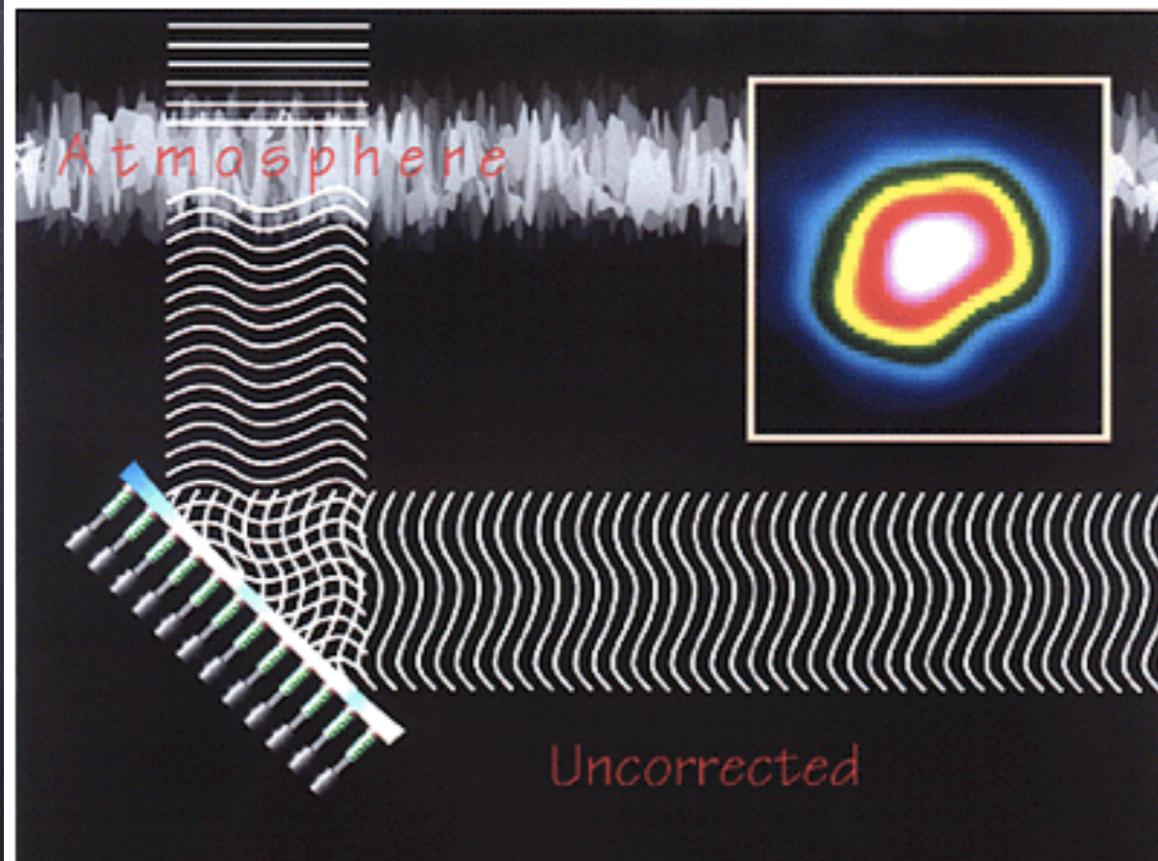
Uncorrected

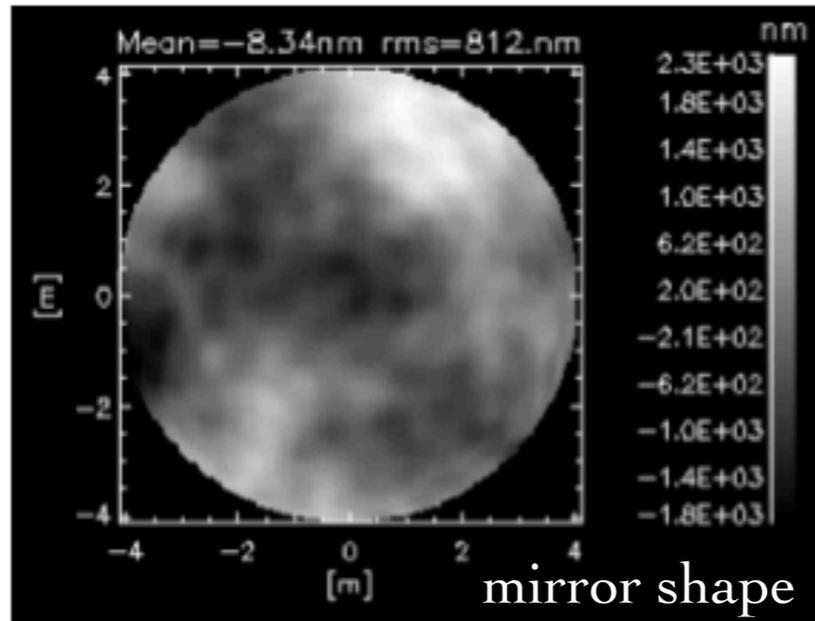**Blurred, uncorrected image (without Adaptive Optics)**

Atmosphere
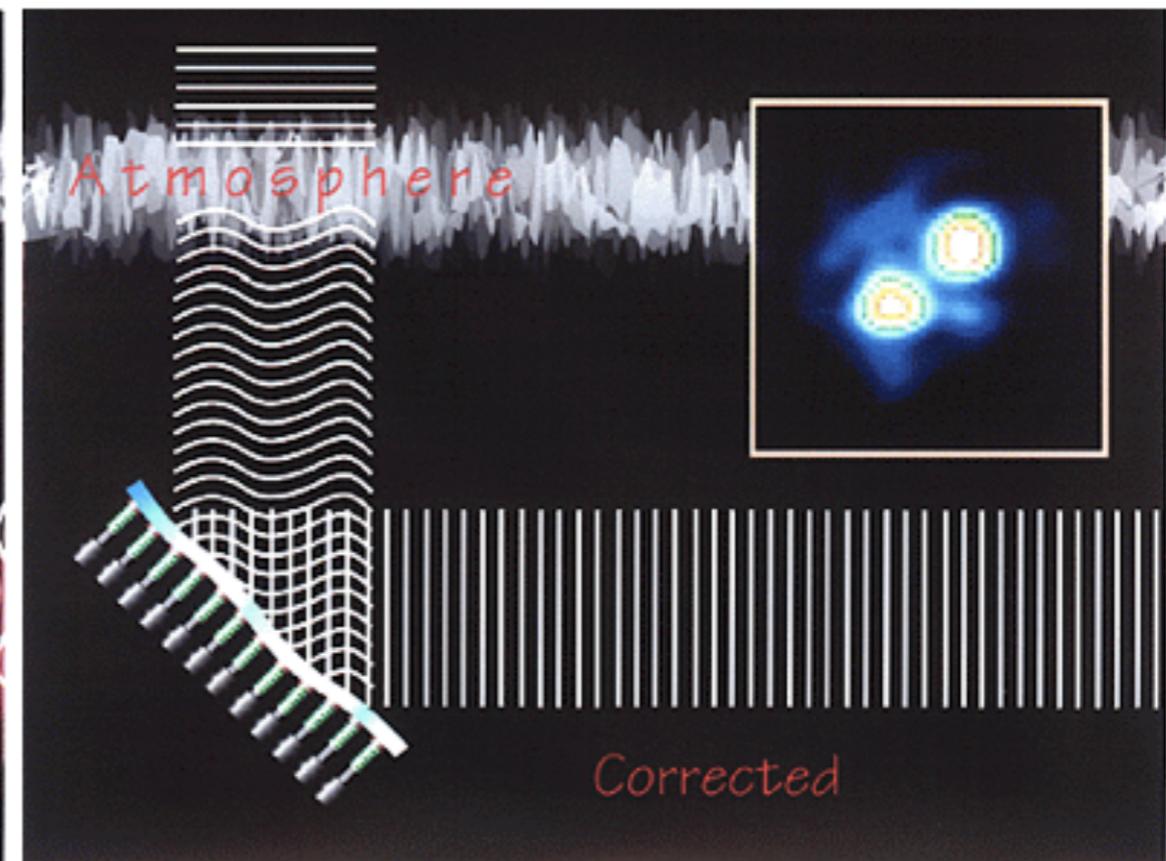
Corrected

**With Adaptive Optics corrected image**

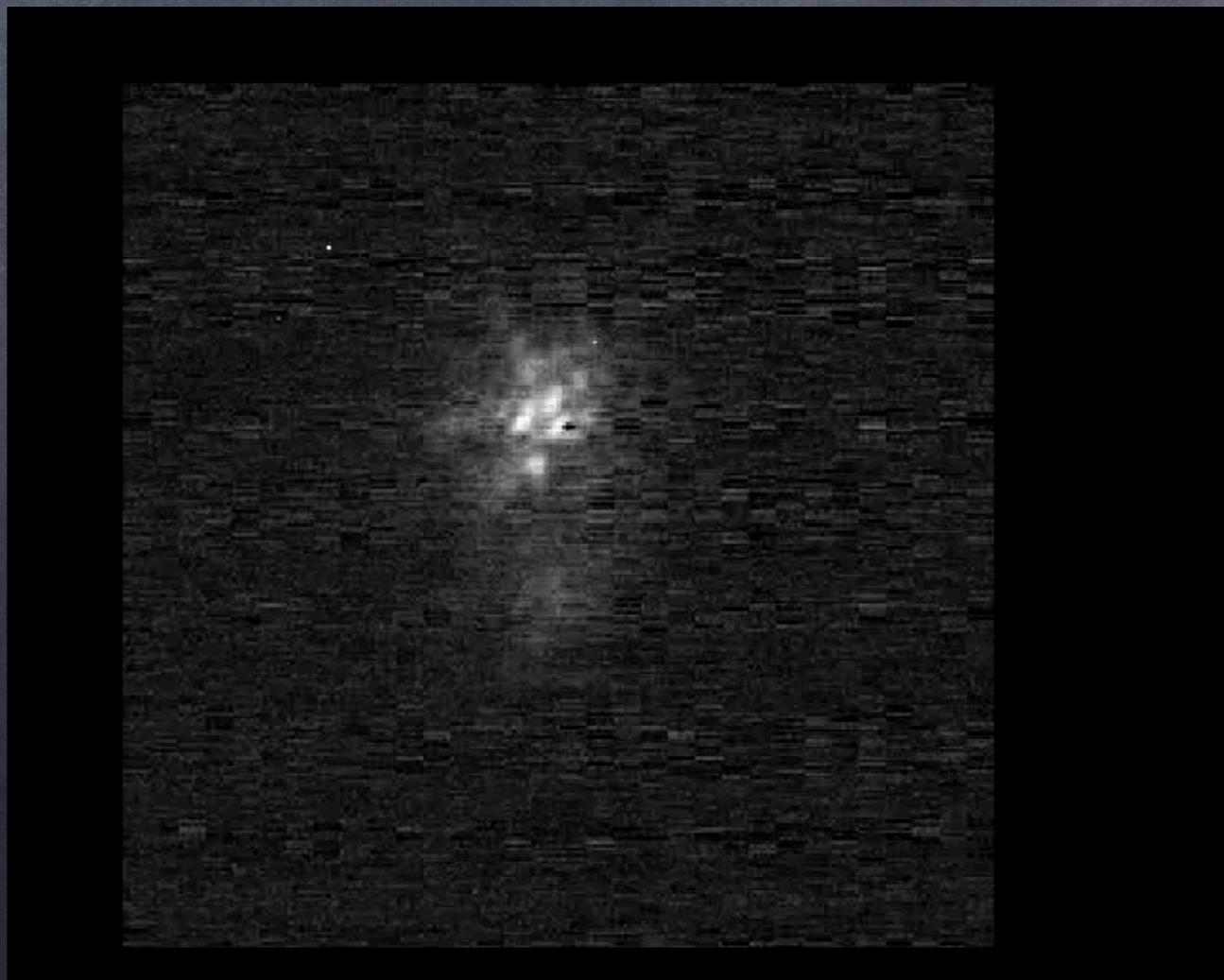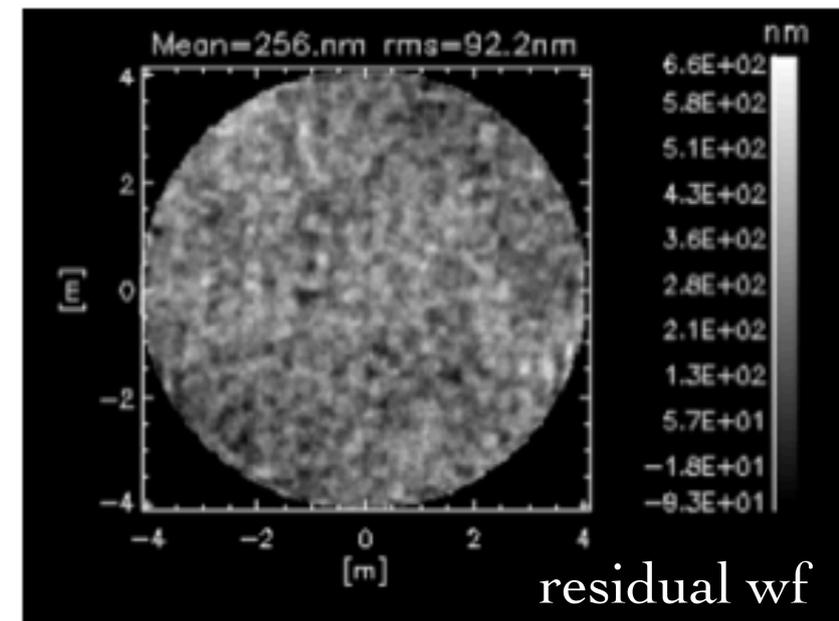For more information see Adaptive Optics Tutorial in german or english by Stefan Hippler and Andrei Tokovinin.

# Adaptive optics - 5



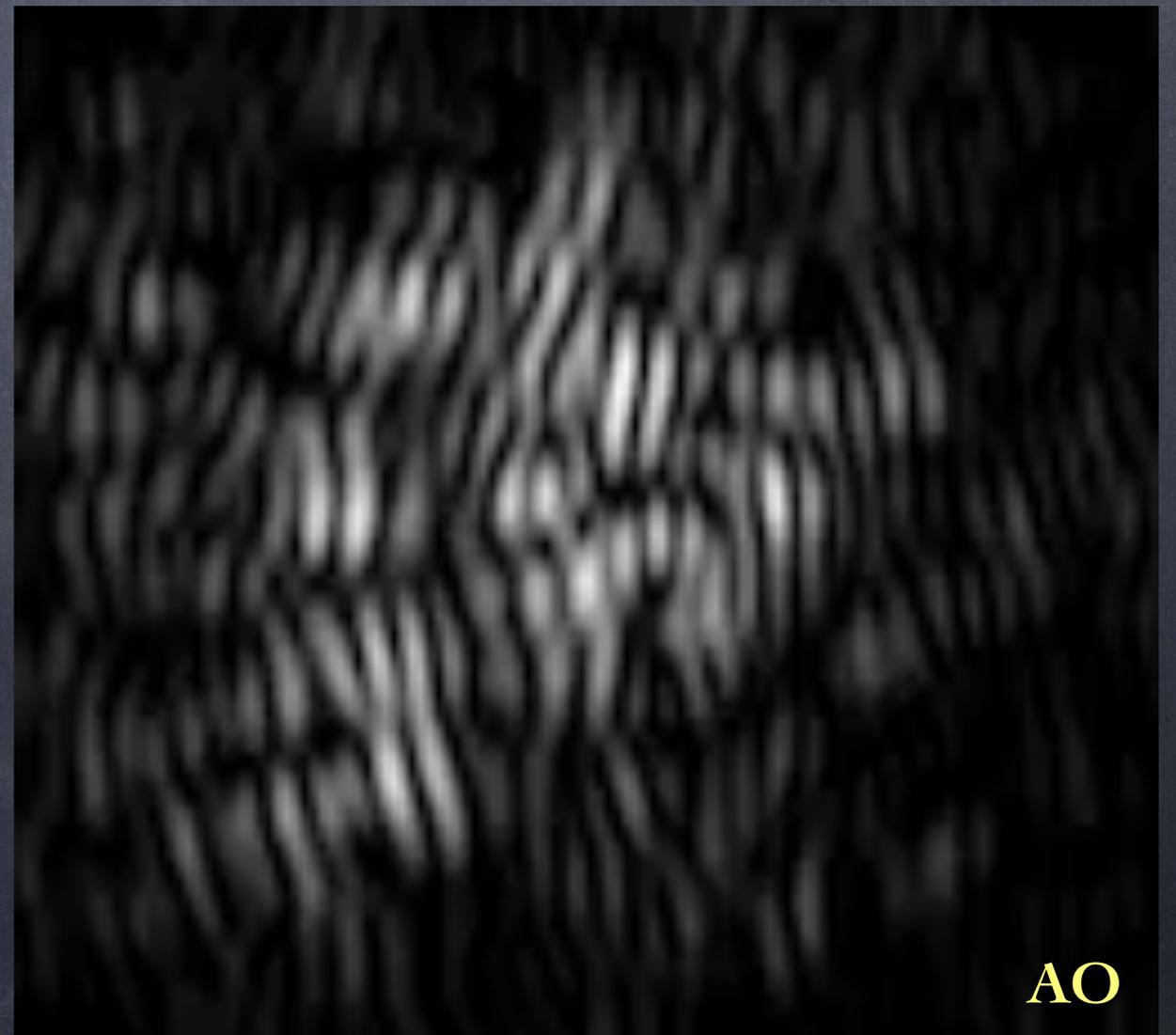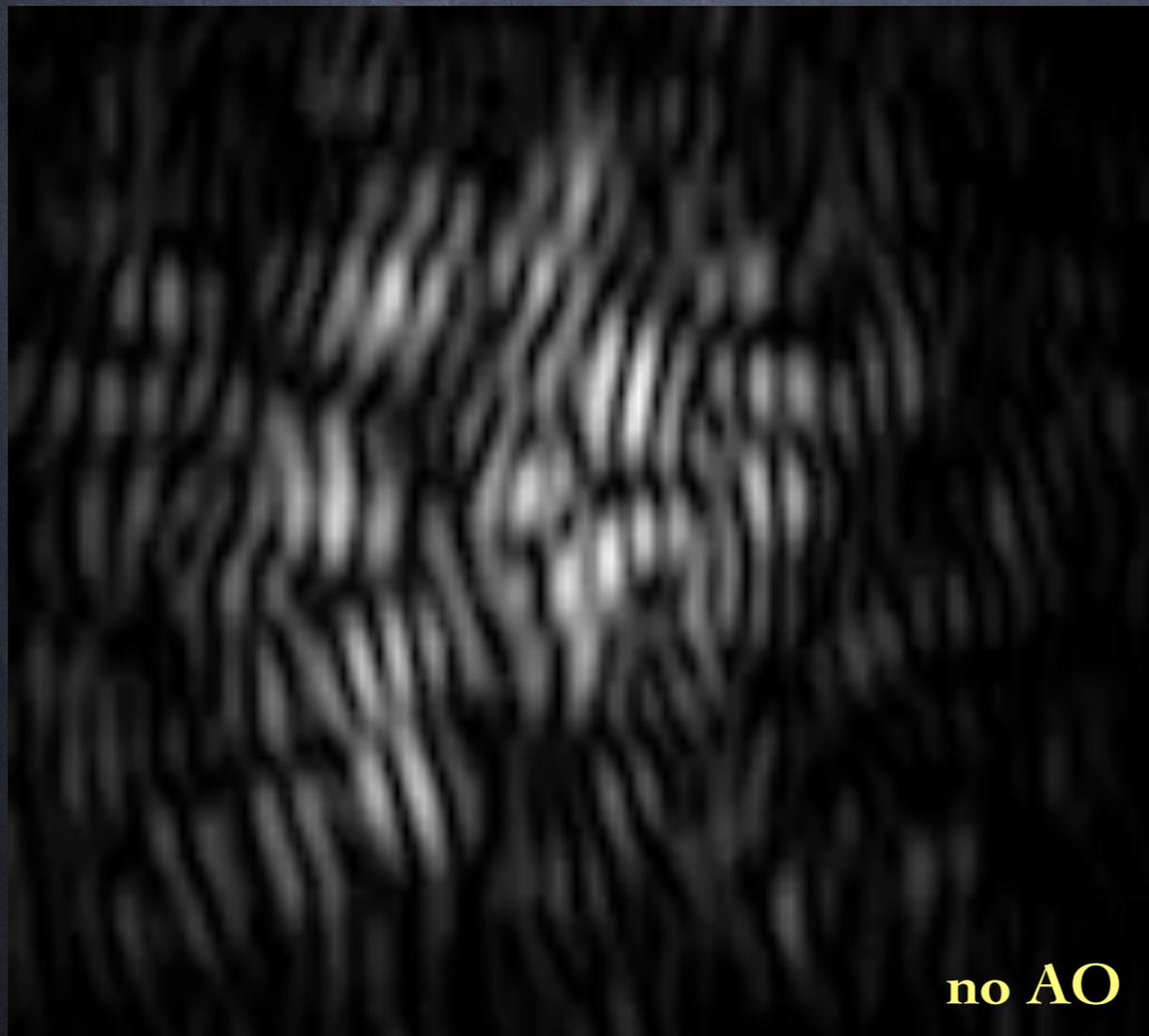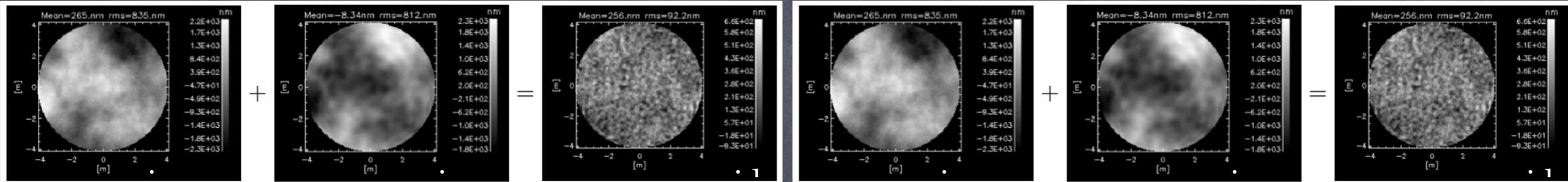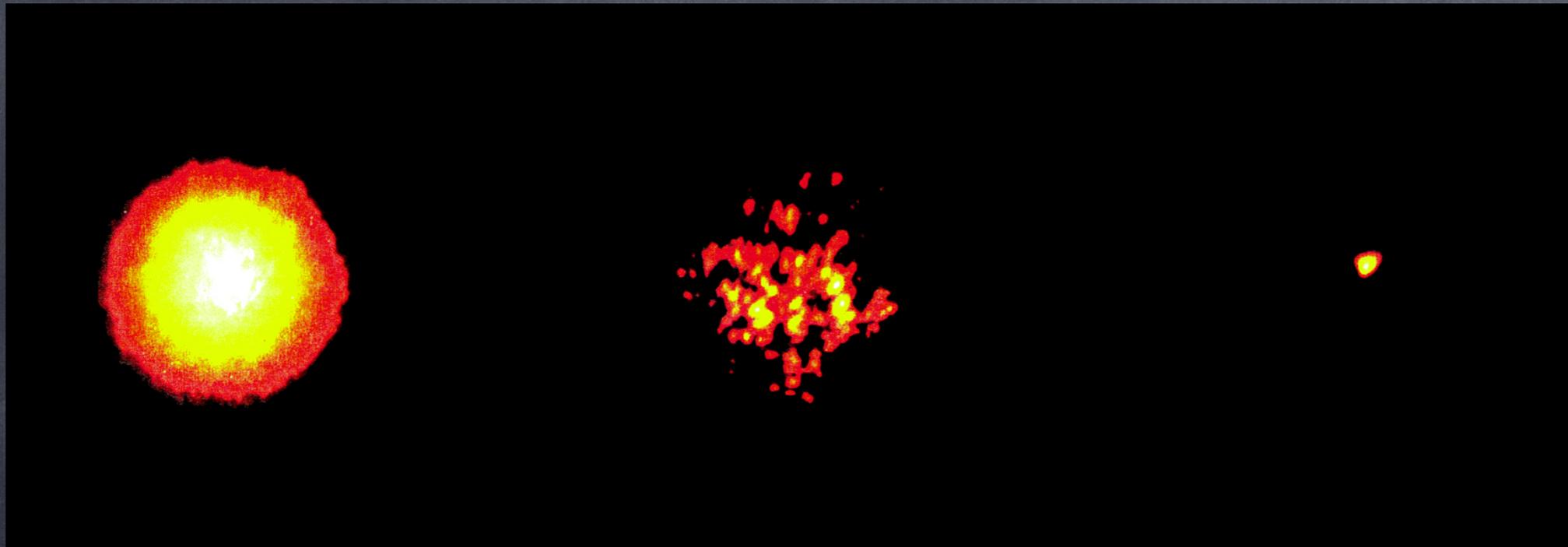incoming wf + mirror shape = residual wf

no AO

AO

# Adaptive optics - 7



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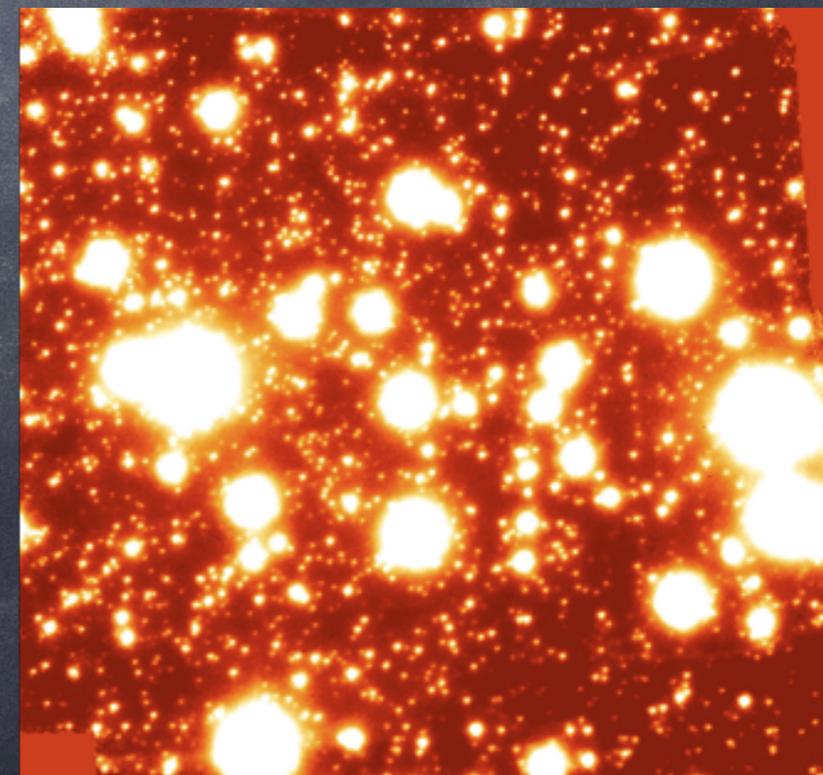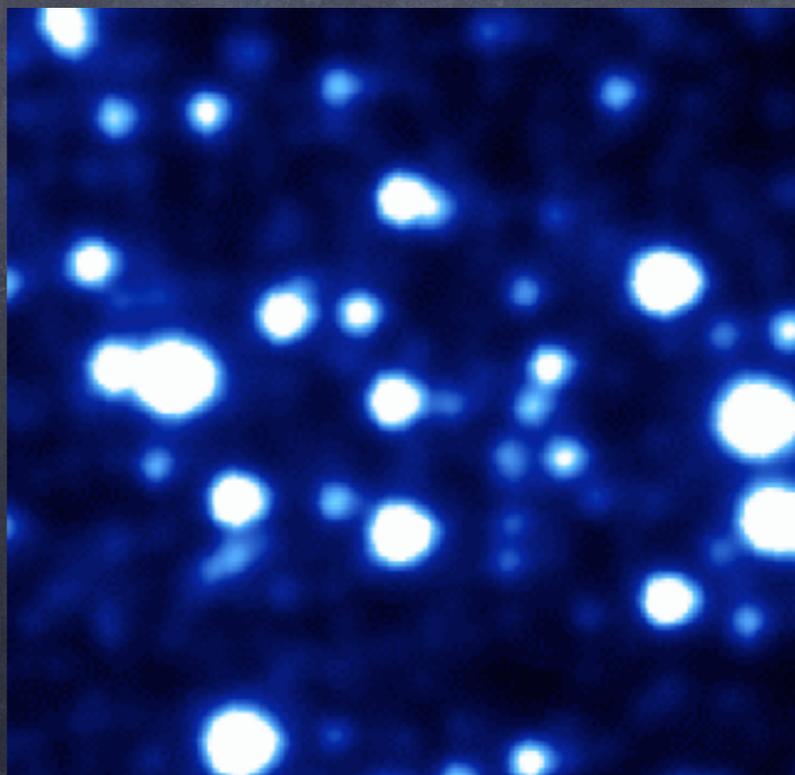


(Gemini Observatory, Hokupa'a+Quirc, left: FWHM≈0"85, right: FWHM≈0"09)

# Adaptive optics - 8



Galactic Center / 2.2 microns
13"x13" Field. 15 minutes exposure.

Without Adaptive Optics compensation
0.57" Seeing
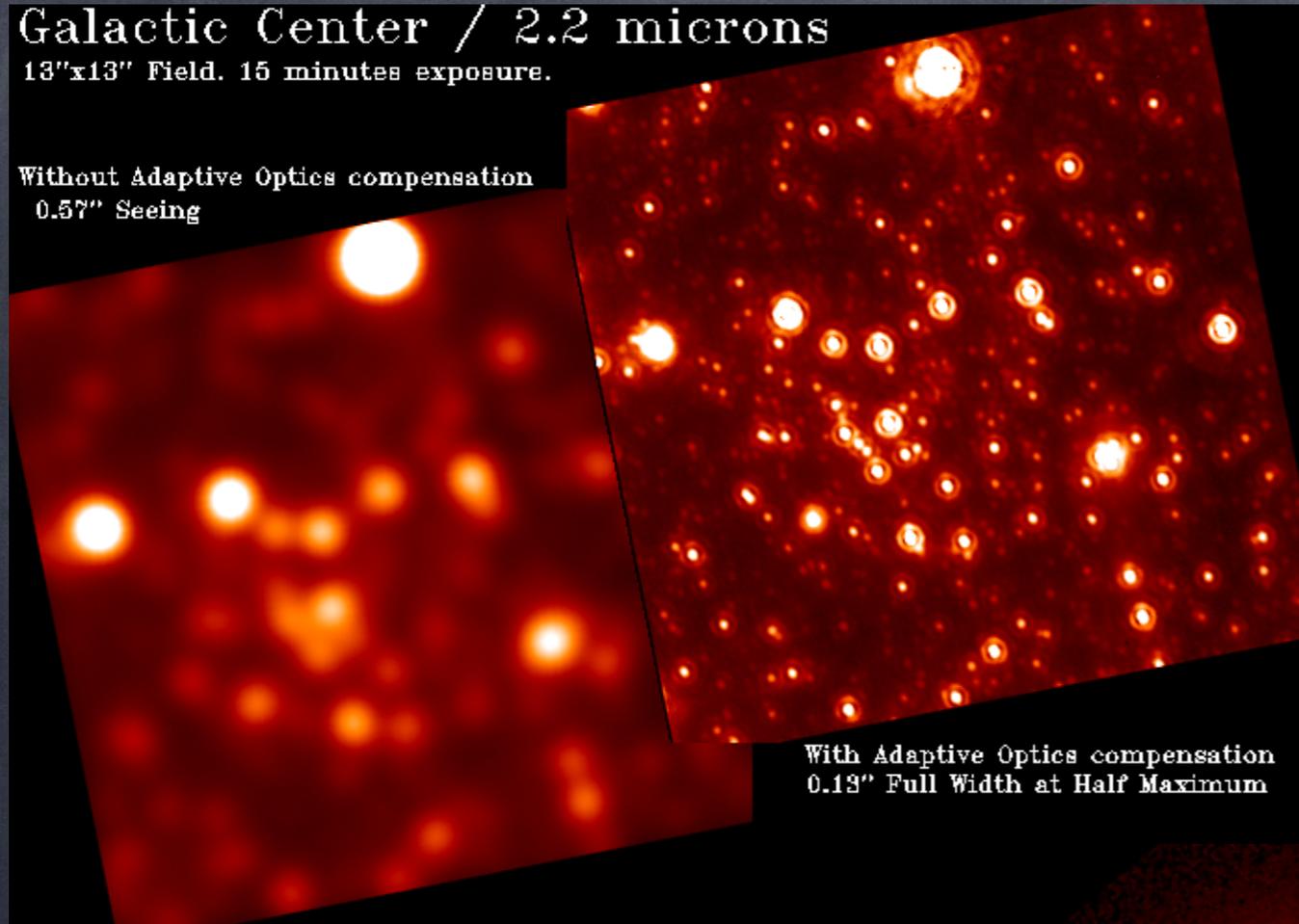
With Adaptive Optics compensation
0.13" Full Width at Half Maximum
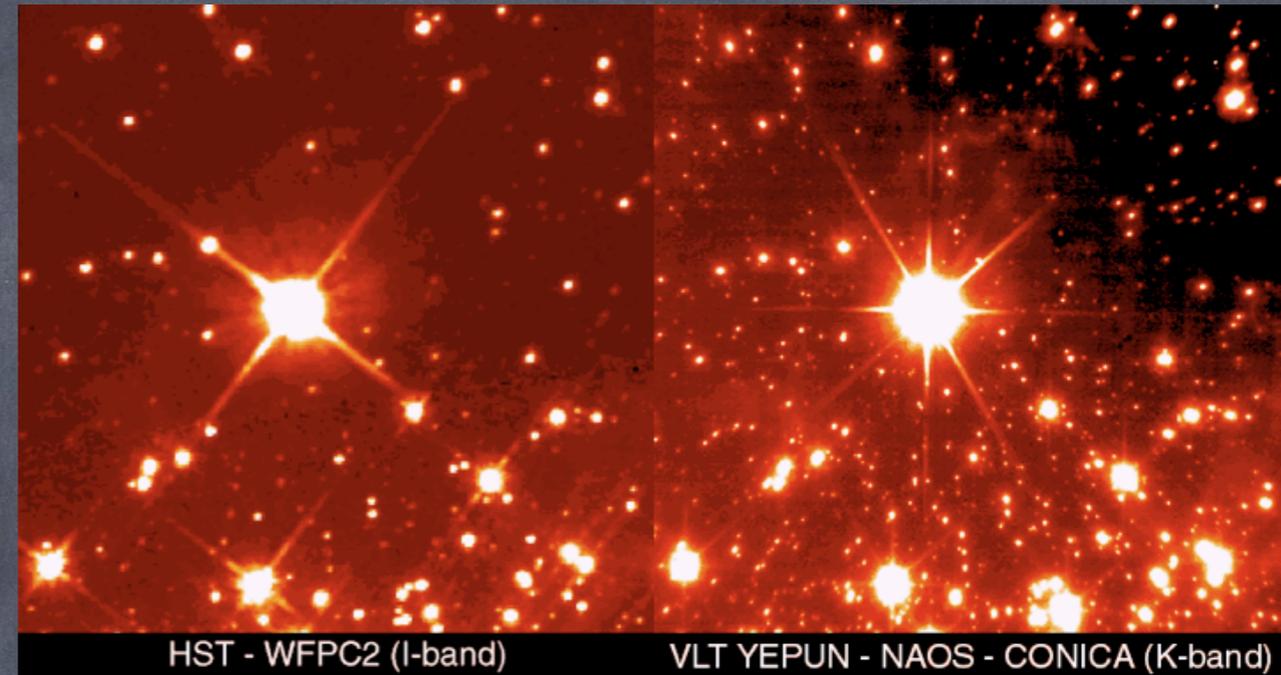
(HST vs. NACO/VLT)

HST - WFPC2 (I-band)        VLT YEPUN - NAOS - CONICA (K-band)

(CFHT, long-exp. images (15'))
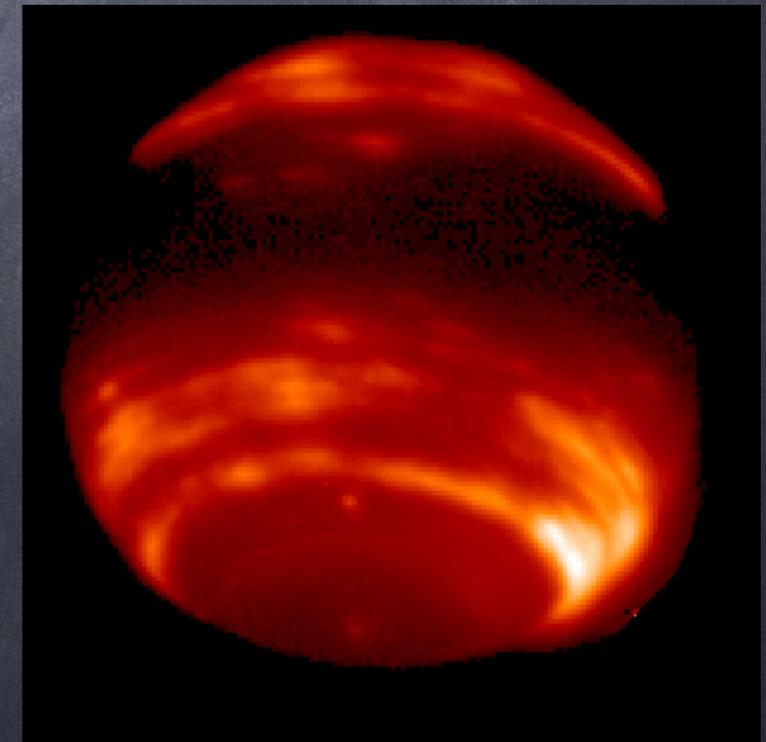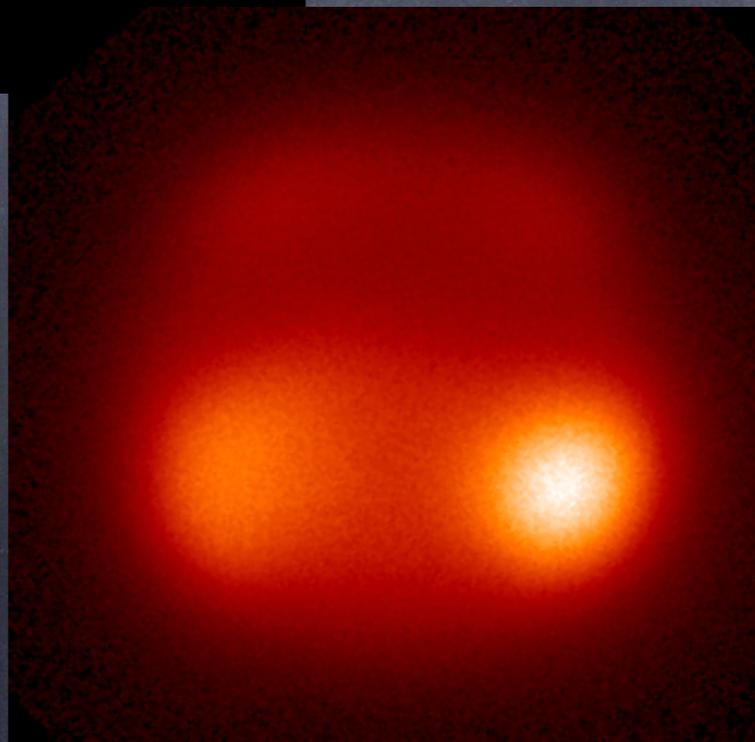
(Neptune à 1.65 microns, Keck Observatory, mai et juin 1999)

# Adaptive optics - 9



20 au

2009-07-31

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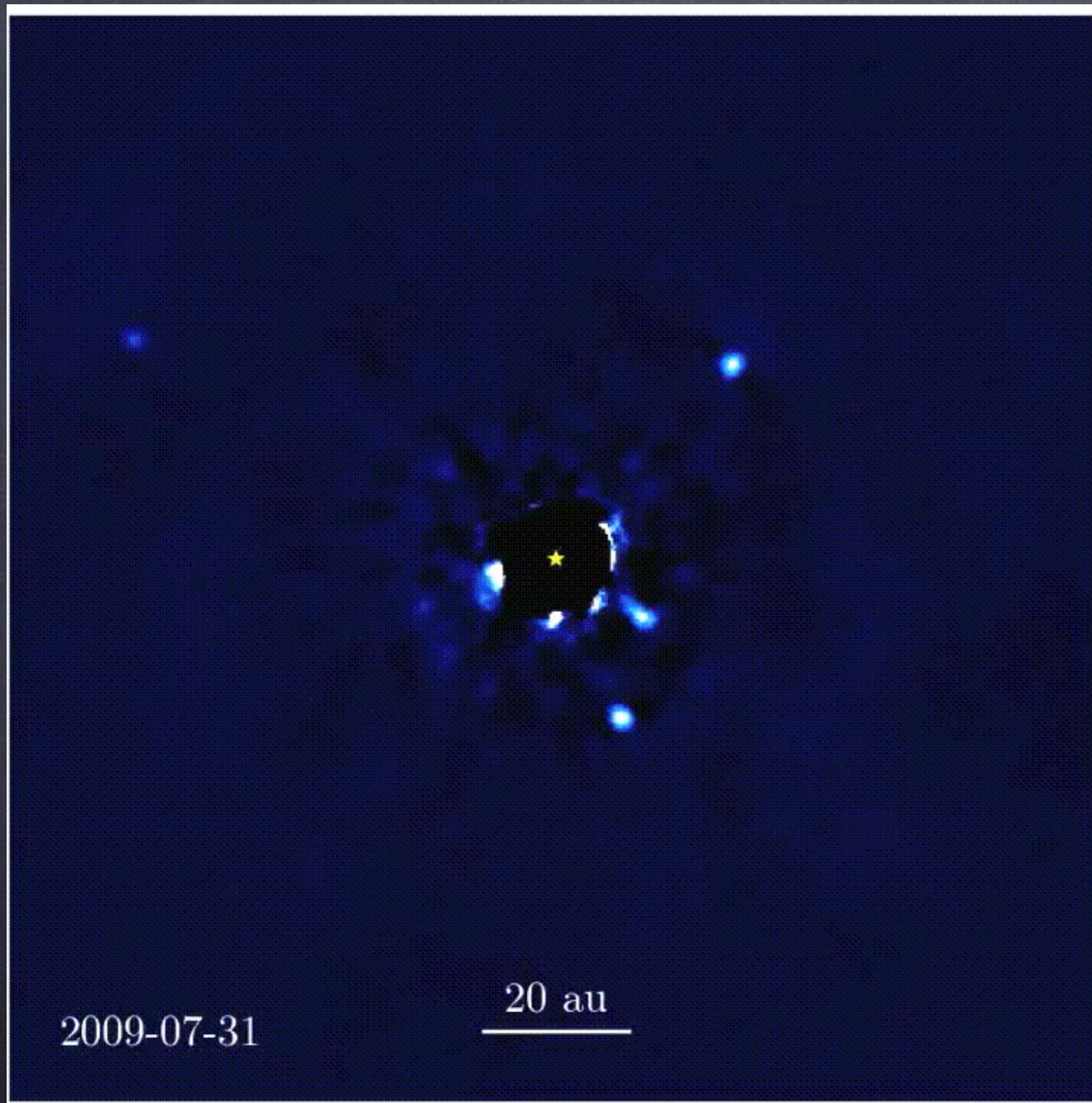
From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in
2013, from which 5 from (X)AO systems and 1 from HST.

Gemini Observatory, GeMS-GSAOI first light

NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"

GeMS

Classical AO

Seeing limited

**Context: wide-field astronomical imaging**

very wide fields
=> multi-reference
(& multi-conjugate)
AO systems...
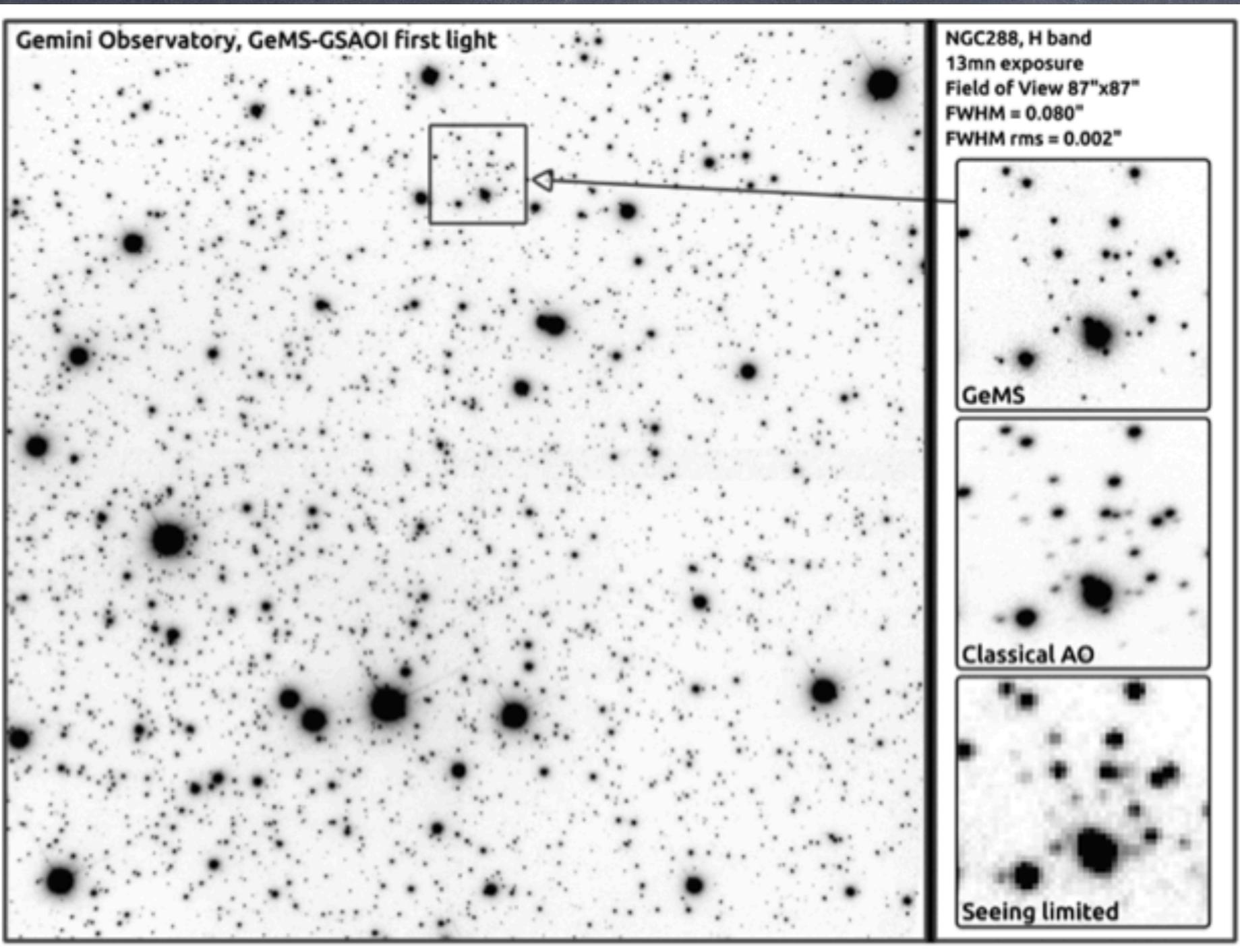
First-light image of GeMS, the MCAO system of Gemini
diffraction limit over a 2' square FoV - vs. a few arcsec !

-> Also read Rigaut's paper...

# Post-AO error budget & PSF morphology - 1
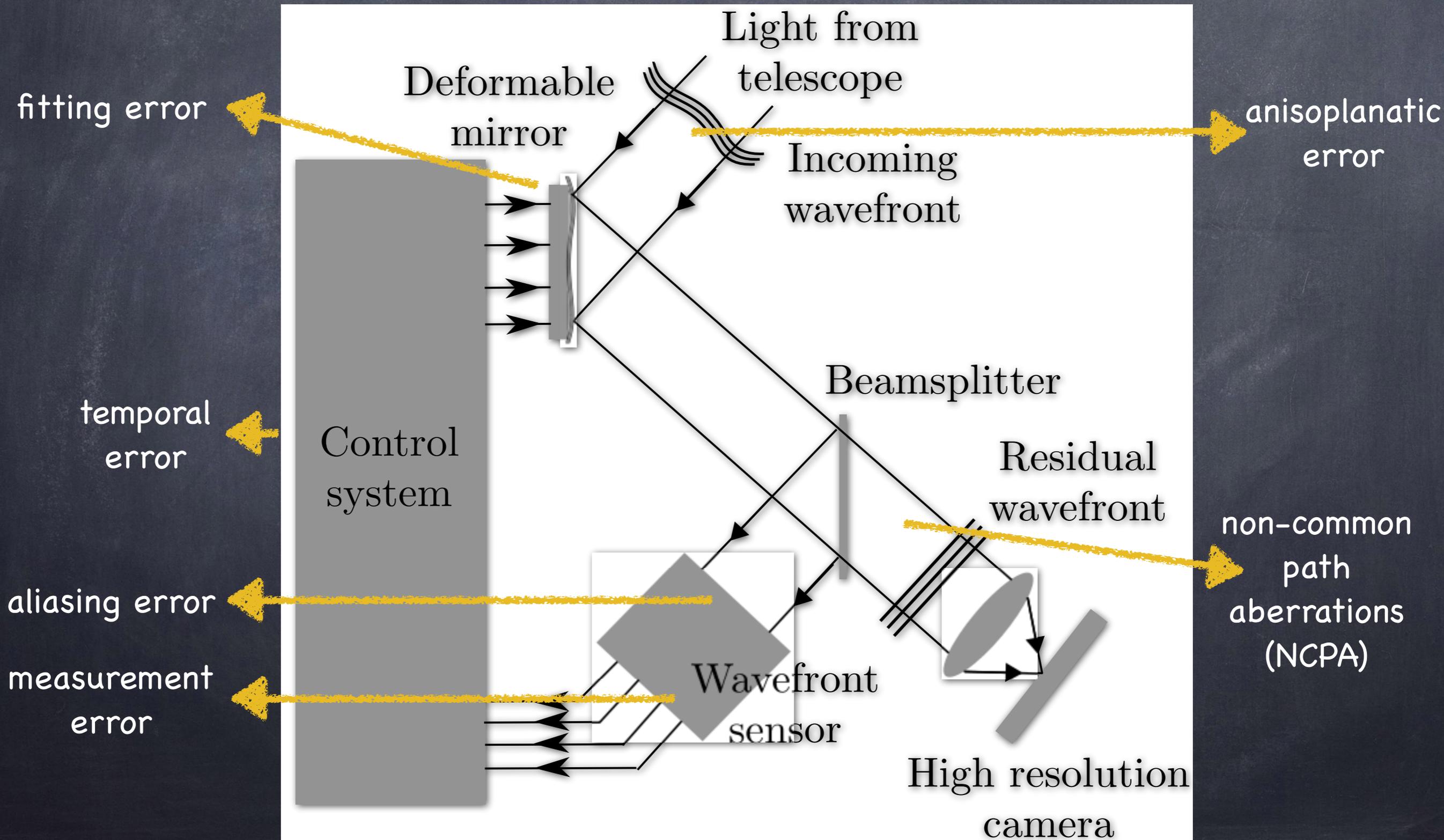
# Post-AO error budget & PSF morphology - 2

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

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

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



$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$
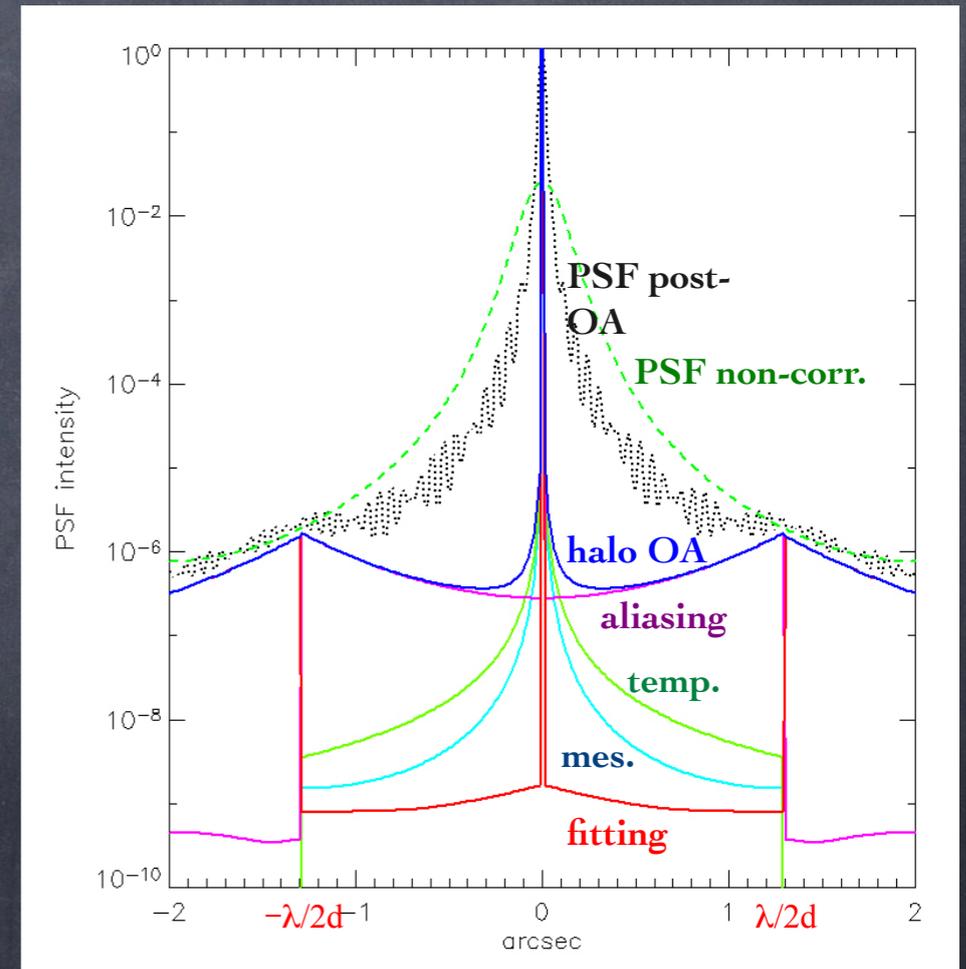
# Anisoplanatic error - 1

165"
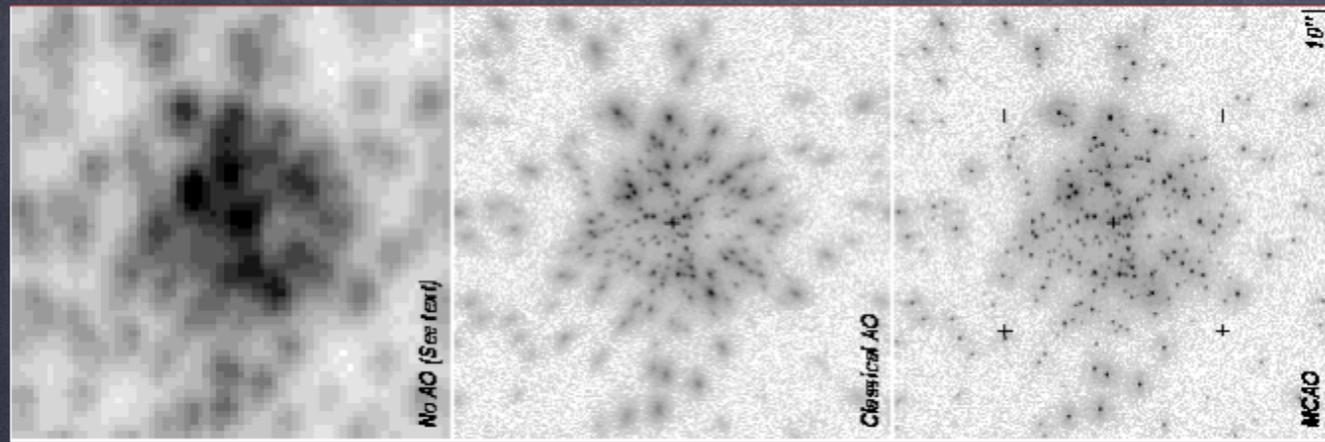
No AO

classical AO
(1 DM, 1 NGS)

MCAO
(2 DM, 5 NGS)
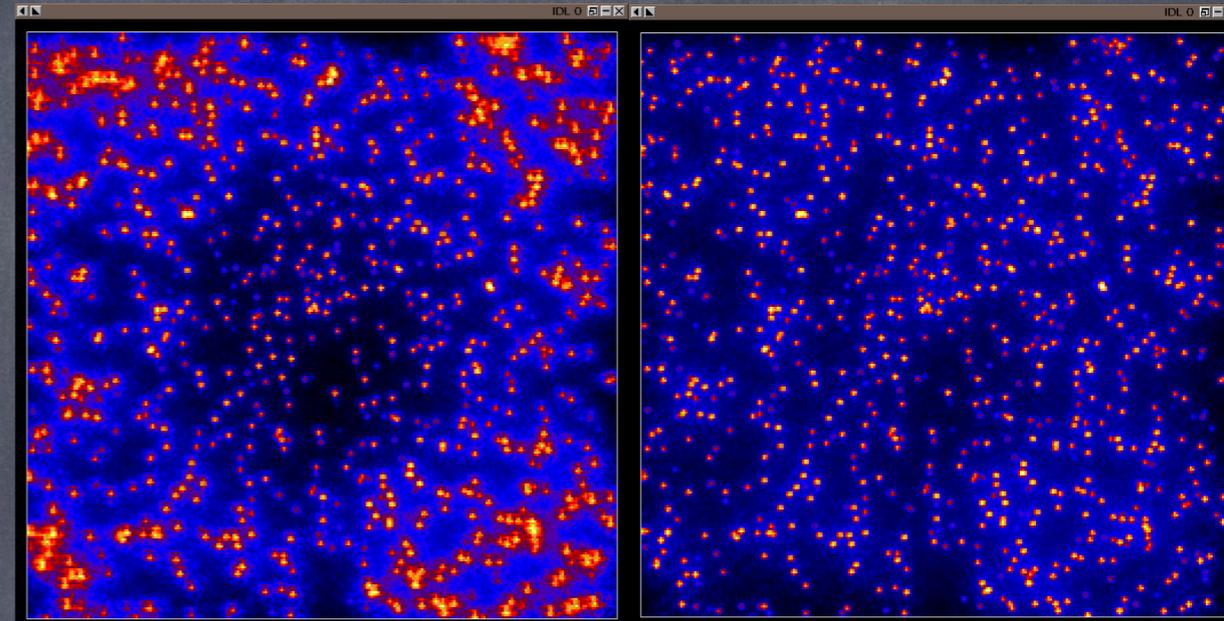
(bande J, champ de 1', simu. B.Ellerbroek, Gemini Obs.)

ATMOSPHERE

étoile guide

étoile observée

TELESCOPE

$$\sigma^2_{\text{aniso}} \propto \left( \frac{\theta}{\theta_0} \right)^{5/3}$$

60 arcsecondes
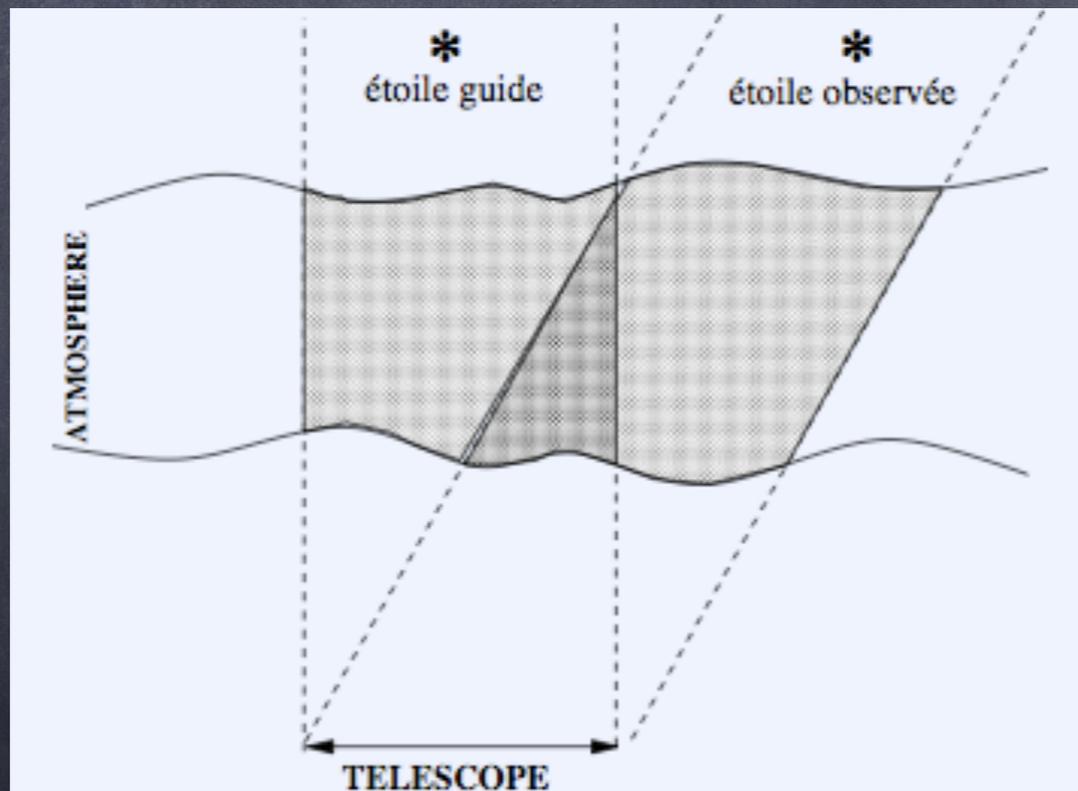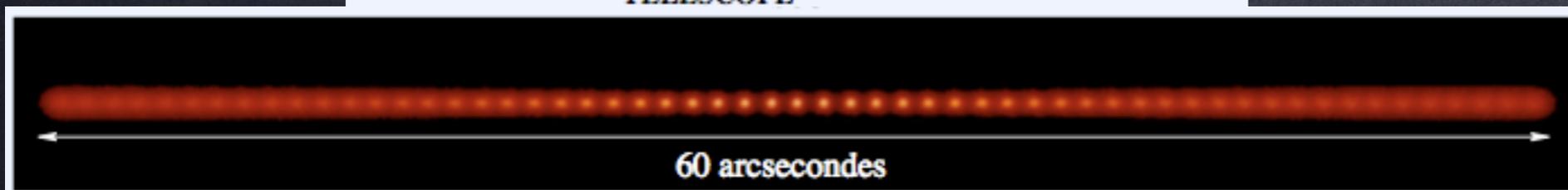
(Anisoplanatic error - 2)
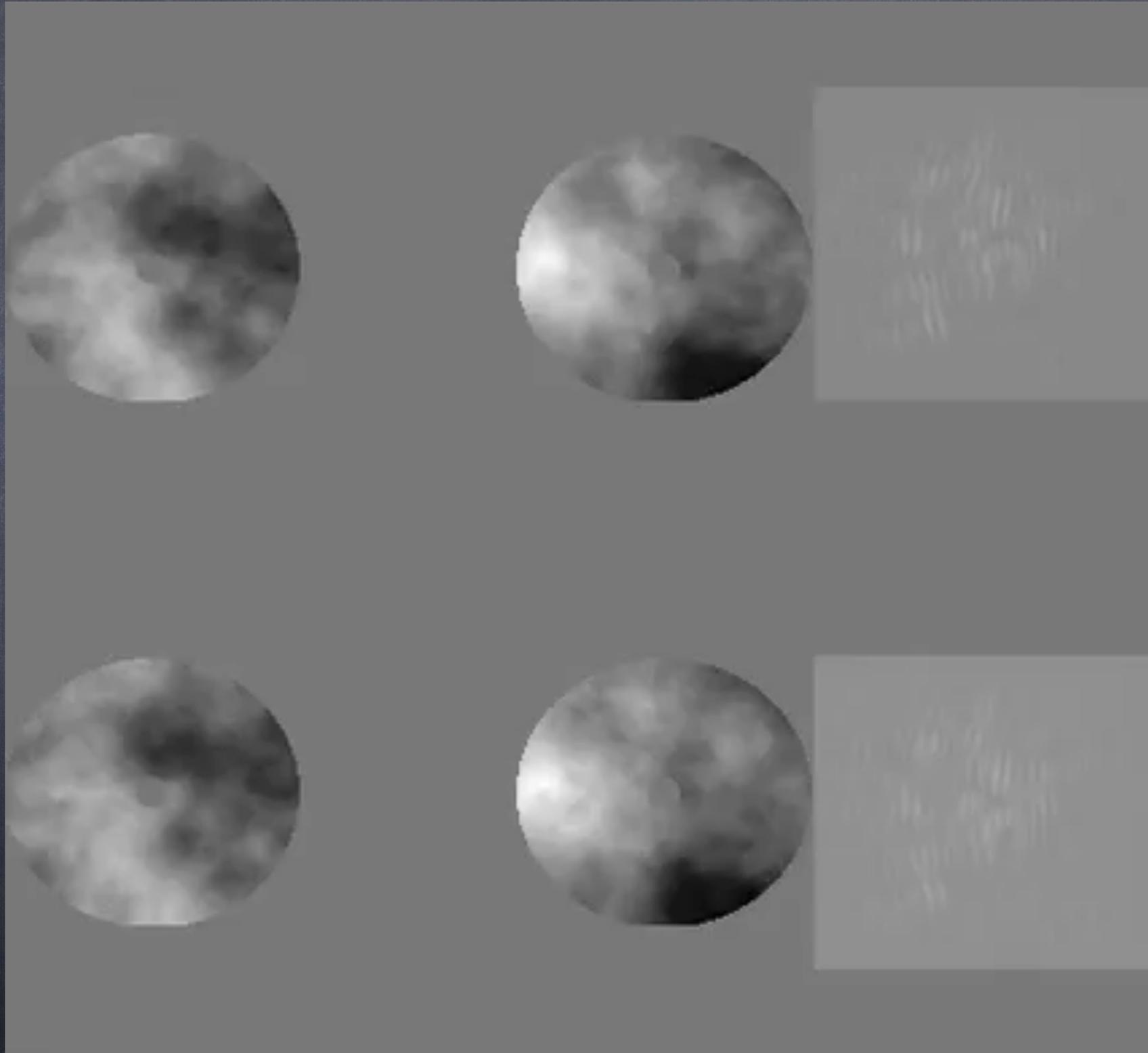
# Anisoplanatic error - 3

Numerical tool used for this study: CAOS
(CAOS Problem-Solving Environment + Software Package CAOS + Example project ``Anisoplanatism''...)
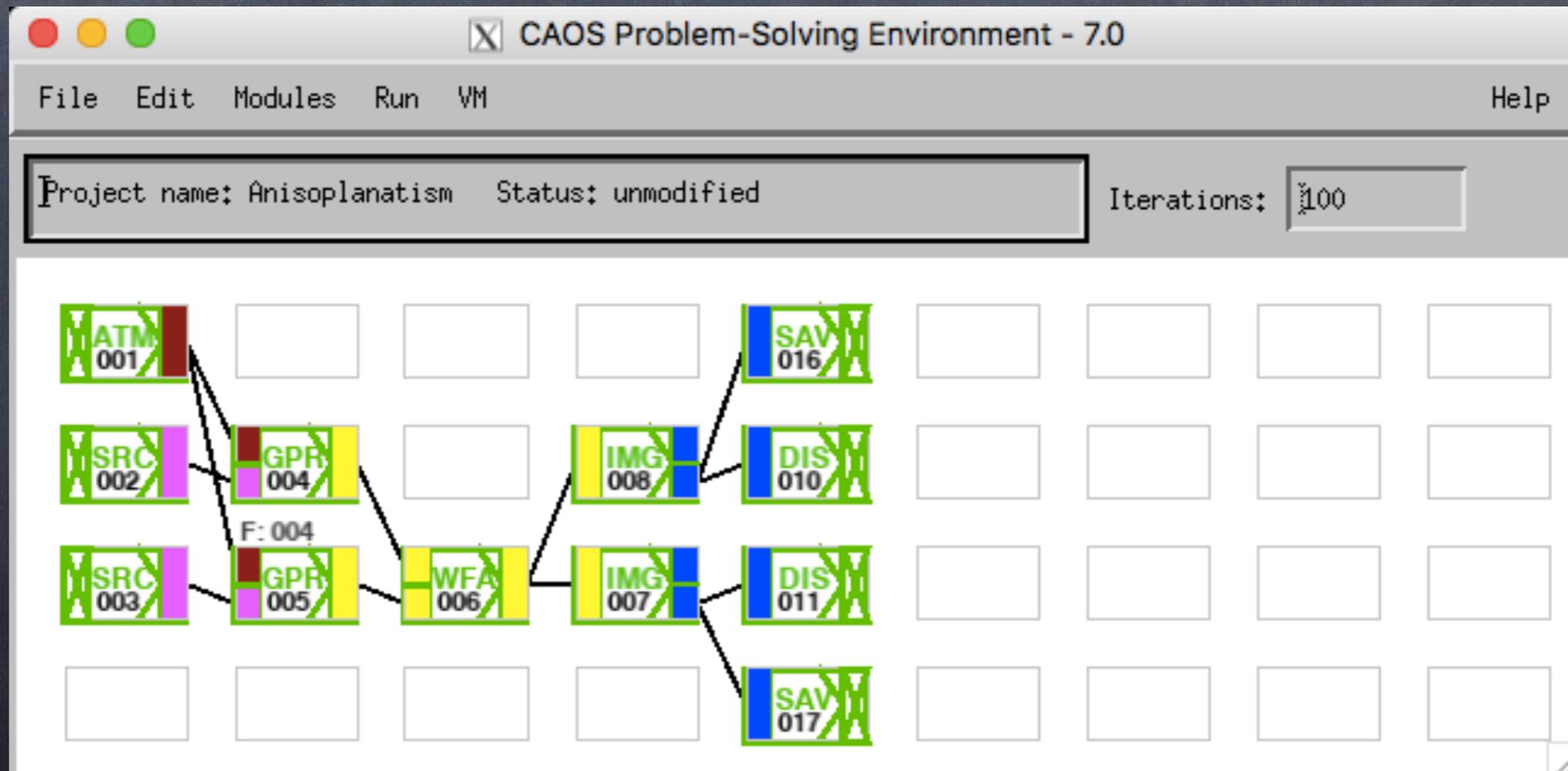
# The CAOS "PSE"...

- **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 Application Builder**

global interface

**CAOS Library**

**ASTROLIB Library**

libraries

**Software Package CAOS**

**Software Package AIRY**

Soft. Pack. CAOS-lite

Soft. Pack. PAOLAC

Soft. Pack. AIRY-LN

Soft. Pack. SPHERE

Soft. Pack. MAOS

packages

# 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
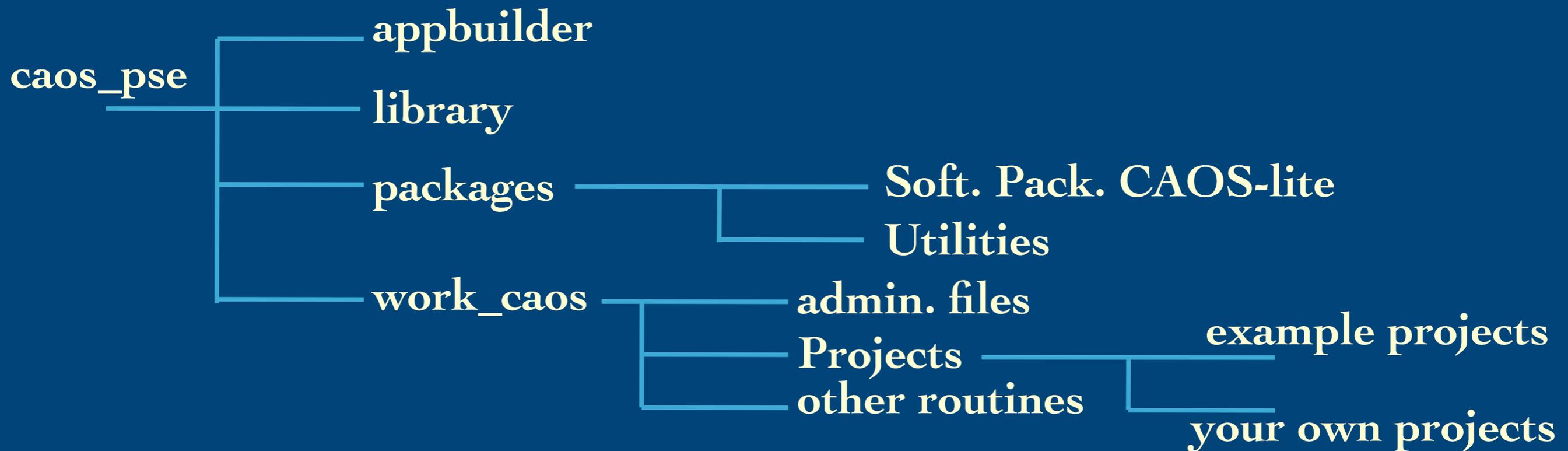
somewhere else: astrolib, possibly some other library

# CAOS Application Builder
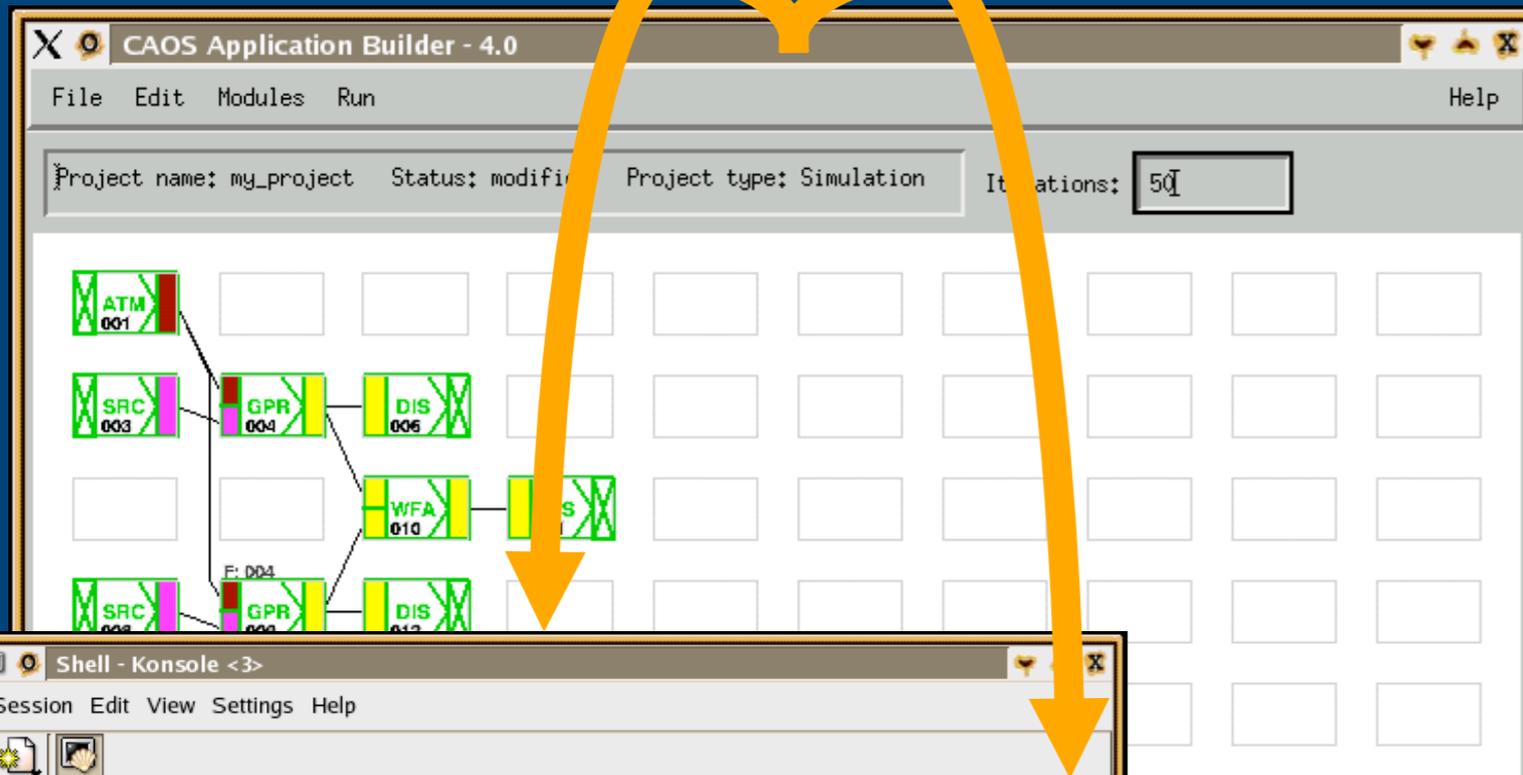


It is the global user interface of the CAOS PSE: essentially a **worksheet** where the user can place small blocks, the modules, and connect them with data paths to form a **project**.

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.

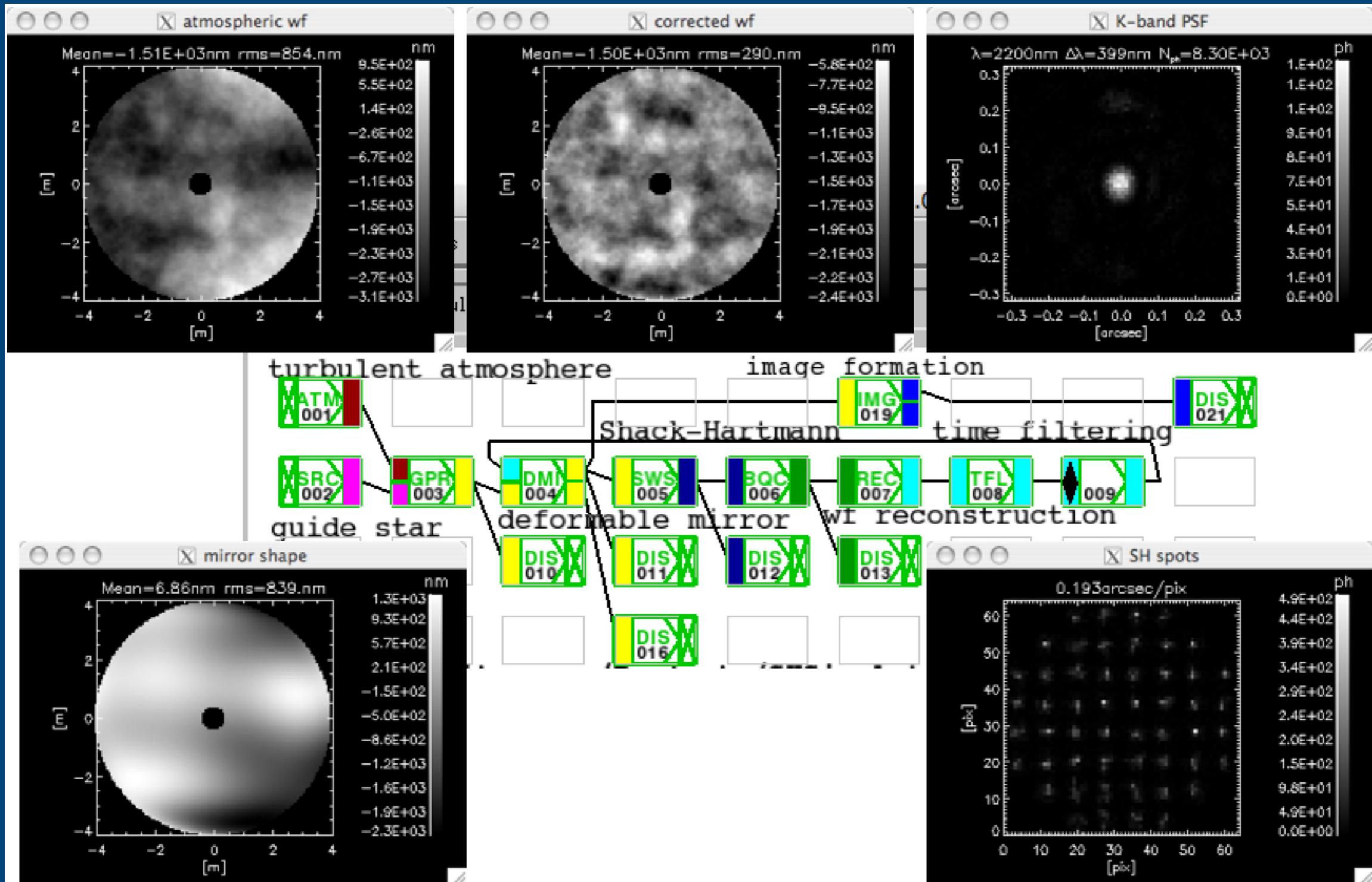| Module | Purpose |
|---|---|
| ATM - ATMosphere building | -builds the turbulent atmosphere (FFT+subharmonics, Zernike) (see also utility PSG - Phase Screen Generation) |
| SRC - SouRCe definition | -characterizes the guide star/observed object |
| GPR - Geometrical PRopagator | -propagates light from 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 |
| 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
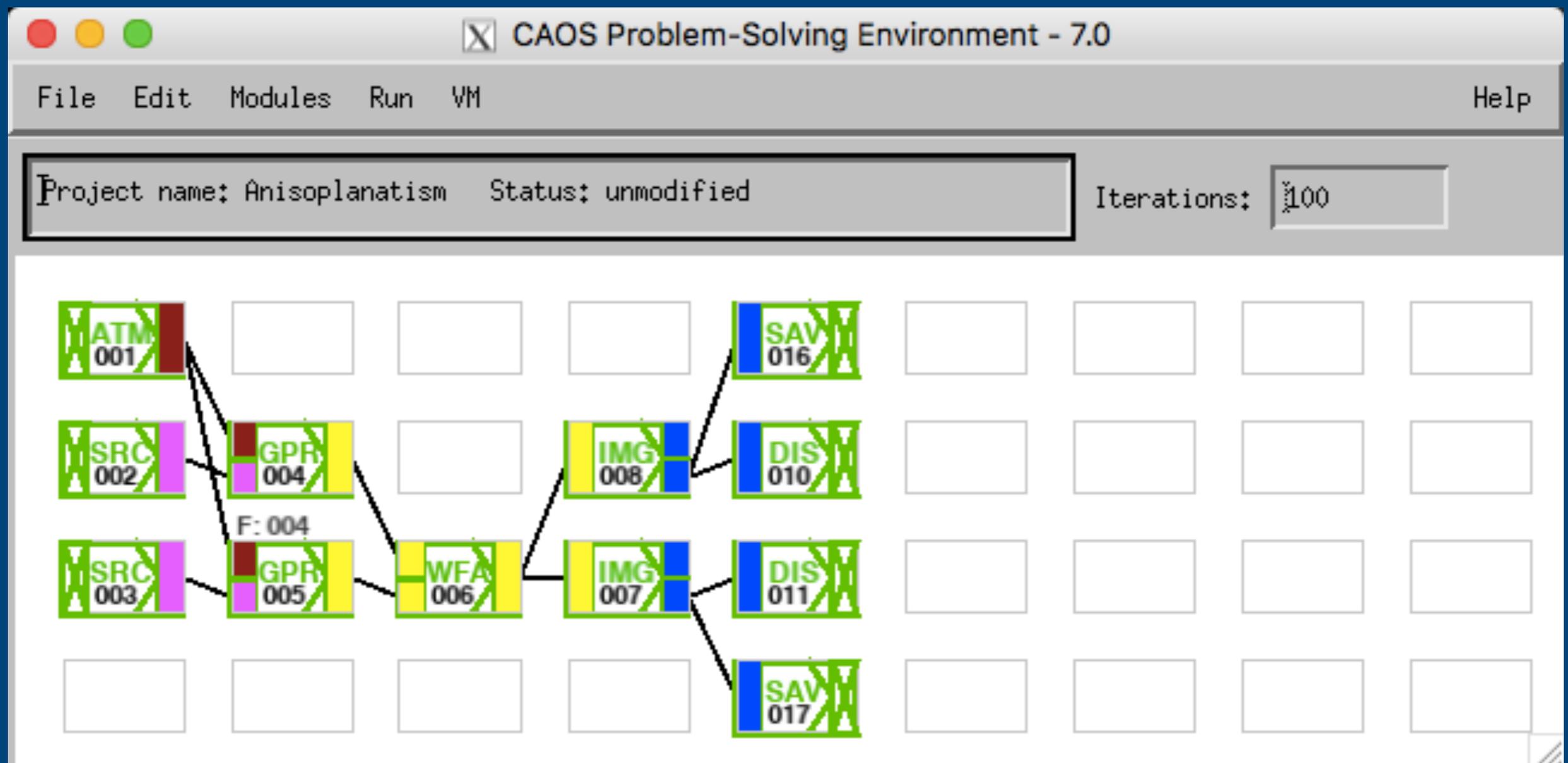
# Installation of CAOS-lite — 1
## (CAOS PSE + lite version of Soft.Pack.CAOS)

```
 1  |---------------------------------------------------
 2  INSTALLATION PROCESS (& BRIEF INTRODUCTION):
 3  ---------------------------------------------------
 4  (CAOS-lite, version 2024)
 5
 6  01-Unpack CAOS-install.zip somewhere on your account, the directory
 7     "CAOS-install/" is created, and it contains both a lite version of CAOS
 8     (within directory "CAOS-lite/") and the IDL Astronomy Library (within
 9     directory "astrolib/"). The lite version of CAOS contains itself both
10     the CAOS PSE (Problem-Solving Environment - the IDL-based CAOS global
11     architecture and interface) and a special lite edition of the CAOS
12     Software Package (based on CAOS Software Package version 7.0), as well
13     as a working directory, "work_caos/".
14
15  02-Go to the working directory "work_caos/" and fix the paths in the
16     environment-parameters files "caos_env.sh" and "caos_startup.pro".
17
18  03-Still within the working directory, type "source caos_env.sh".
19
20  04-Launch IDL.
21
22  05-Type "@compile_all_CAOSlite_modules" in order to re-generate the
23     default parameter files of the whole set of modules (upgrading so
24     any possible pre-defined path).
25
26  06-Type "worksheet" at the CAOS prompt in order to use the CAOS
27     Application Builder (the global interface of the tool).
28
29  NB-1: Steps 01,02,05 are necessary just once, during installation.
30  NB-2: Steps 03,04,06 are necessary for each opened terminal from which
31        you wish to use IDL together with CAOS.
```

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

```
34  -----------------------------
35  SOME ADDITIONAL REMARKS:
36  -----------------------------
37
38  01-Refer to
39          http://lagrange.oca.eu/caos
40      for further informations on the CAOS PSE and its official packages.
41
42  02-Please never redistribute any CAOS part by yourself, rather refer to
43      http://lagrange.oca.eu/caos.
44
45  03-New projects start within the worksheet with "File"->"New Project". Modules
46      are put within the worksheet through button "Modules", and can be cloned
47      or deleted using "Edit"->"Clone module" or "Edit"->"Delete item". Each color
48      at the left- or right-side of a module represents a type of input or output.
49      In order to link two modules, click on the output of the first one and then
50      click on the input of the second one. When the design of your simulation is
51      completed, including setting of the total number of iterations, save the
52      project using "File"->"Save Project". Then you can set the parameters related
53      to each module using its dedicated GUI called by clicking on the module at
54      any moment.
55
56  04-For a detailed tutorial refer to:
57          http://lagrange.oca.eu/caos/tutorial/tutorial.html
58
59  05-In order to run a project, for example a project named "Anisoplanatism":
60      > .rn ./Projects/Anisoplanatism/project.pro
61      or alternatively use button "Run" from the CAOS PSE worksheet.
62
63
64  -------------------------------------------
65  Completed March 2024 - Marcel Carbillet
```