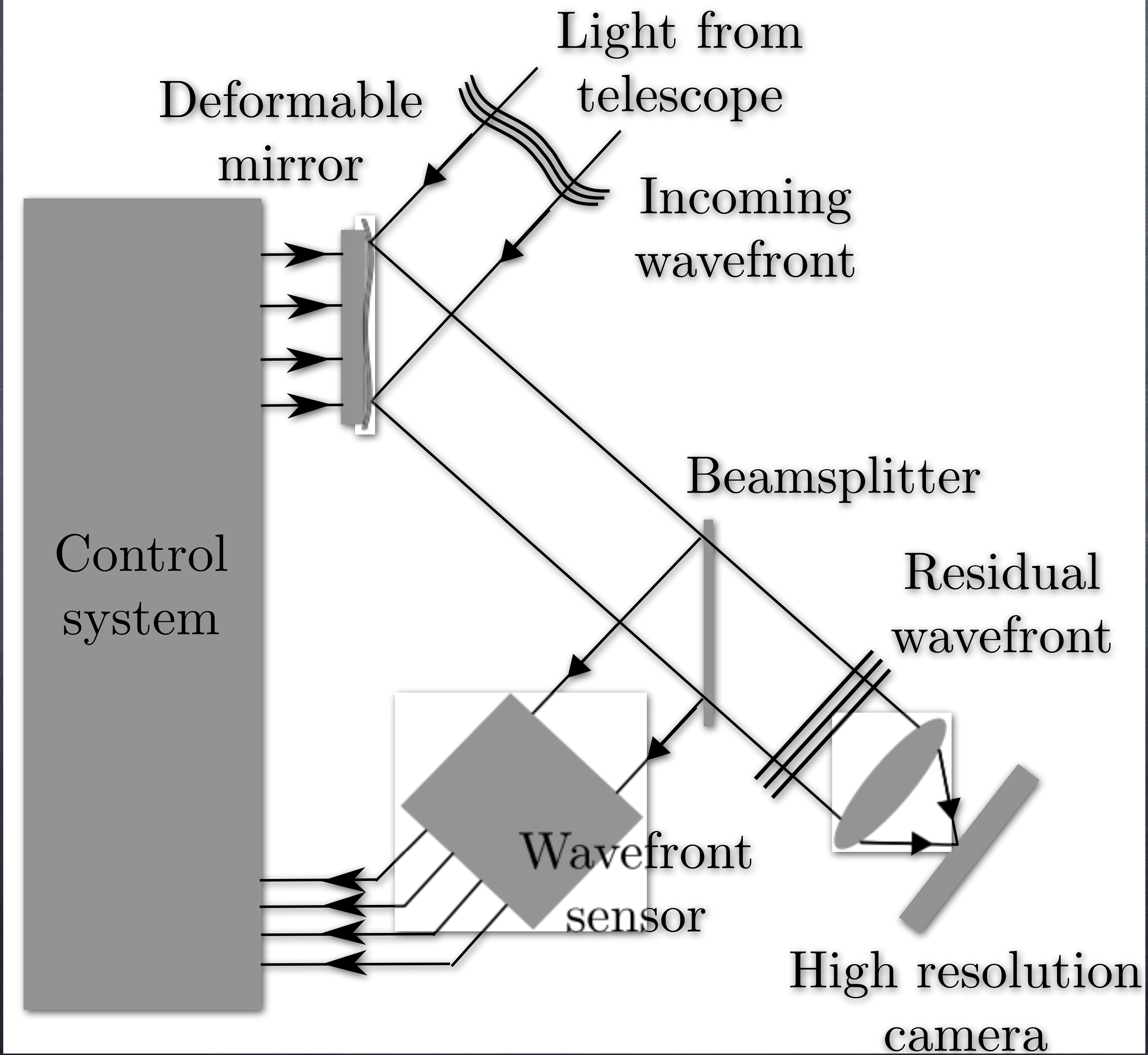
Adaptive optics — 01

Adaptive optics — 02

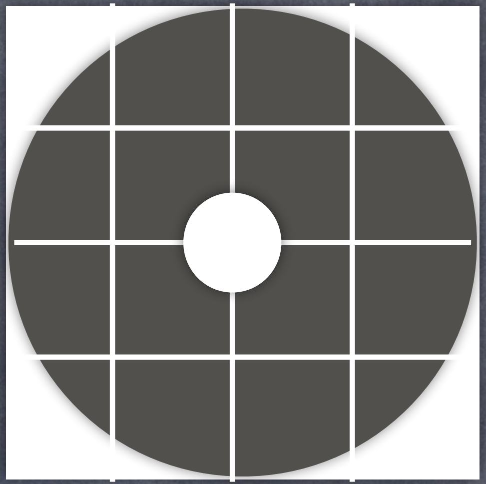


Adaptive optics — 03

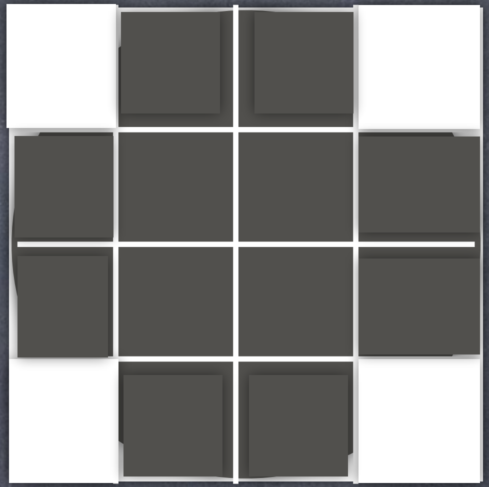
Fried configuration

Here is an example of an AO system based on a 4x4 lenslet array (i.e. a 4x4 SH WFS) and a 5x5 actuators array (i.e. a 5x5 DM)…

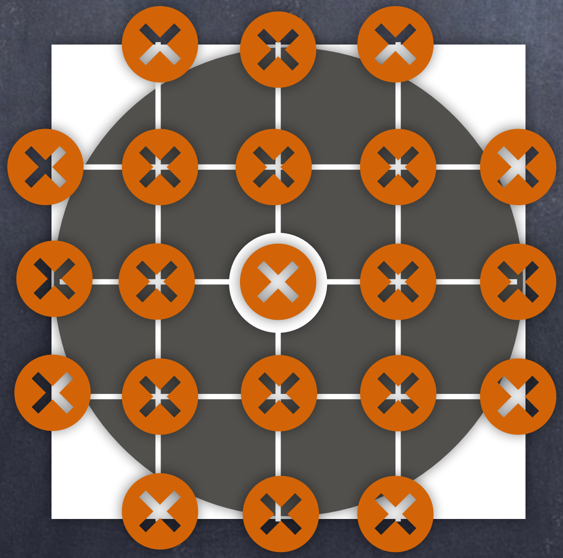
Entrance pupil of the telescope



Pupil projected onto
the 4x4 lenslet array
of the wavefront sensor
(a 4x4 Shack-Hartman)



12 valid sub-apertures
of the Shack-Hartmann
(onto the 4x4 array)

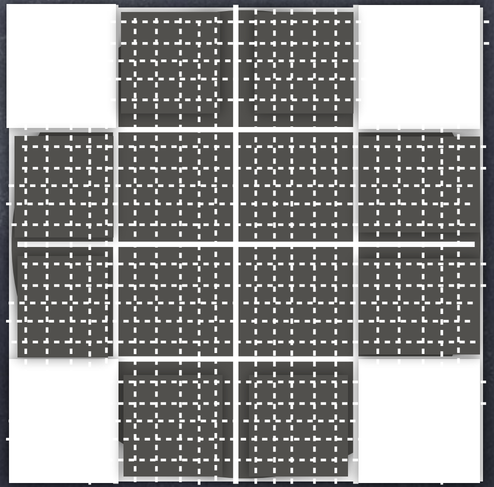


Pupil projected on the deformable
mirror with its 21 actuators
(on the 5x5 corresponding array)

commands
to the DM

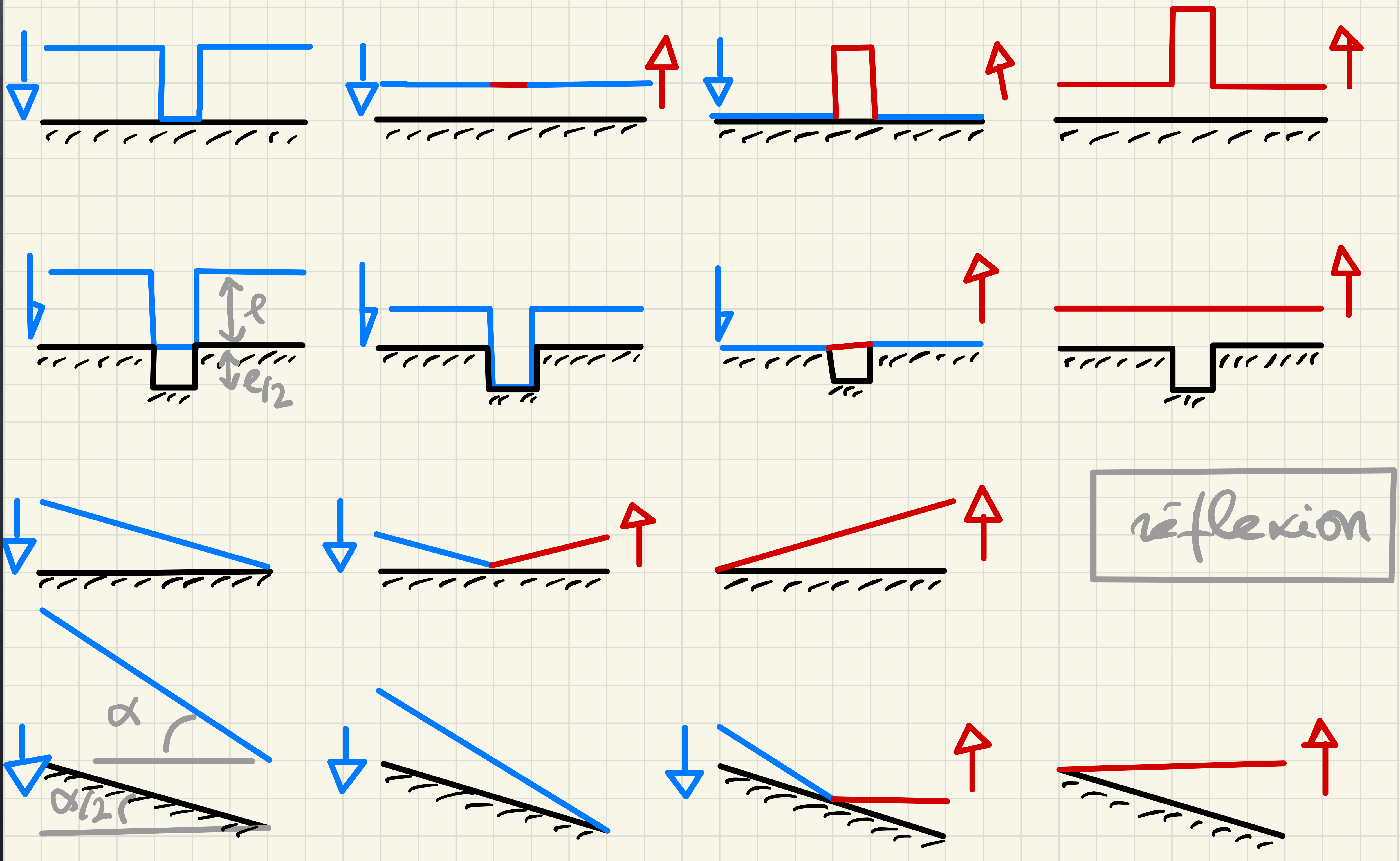
measures
from WFS

reconstruction
of the wavefront,
control of the command



12 sub-parts of the detector
placed in the focal plane
of the SH lenslet array,
with 6x6 pixels each

Adaptive optics — 04

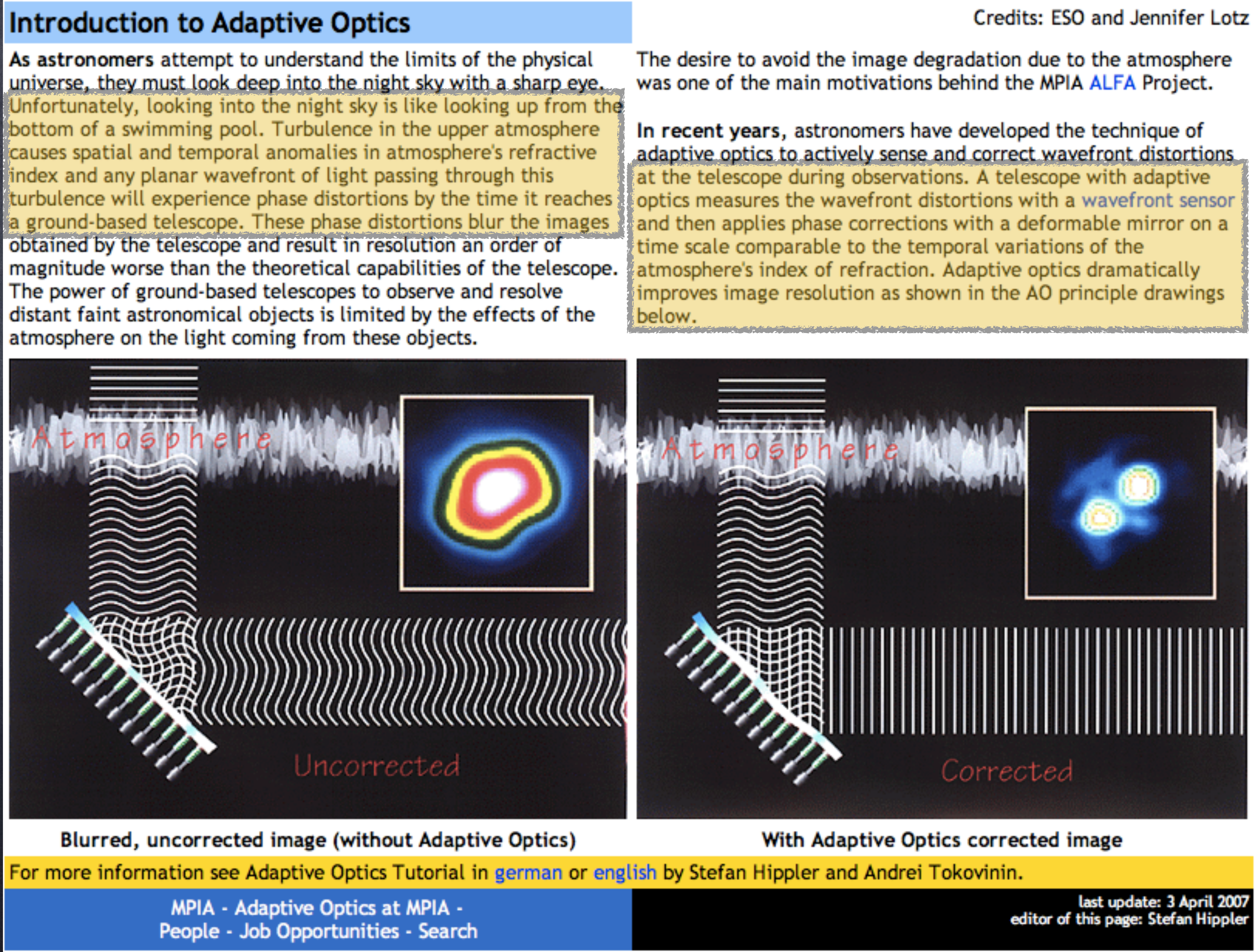


Adaptive optics — 05

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 — 06



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)

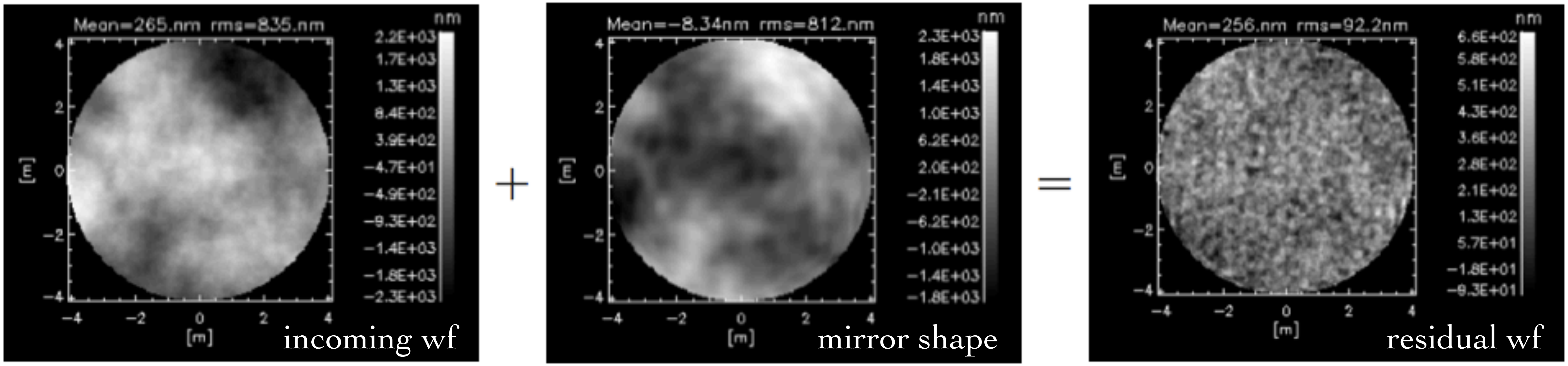
With Adaptive Optics corrected image

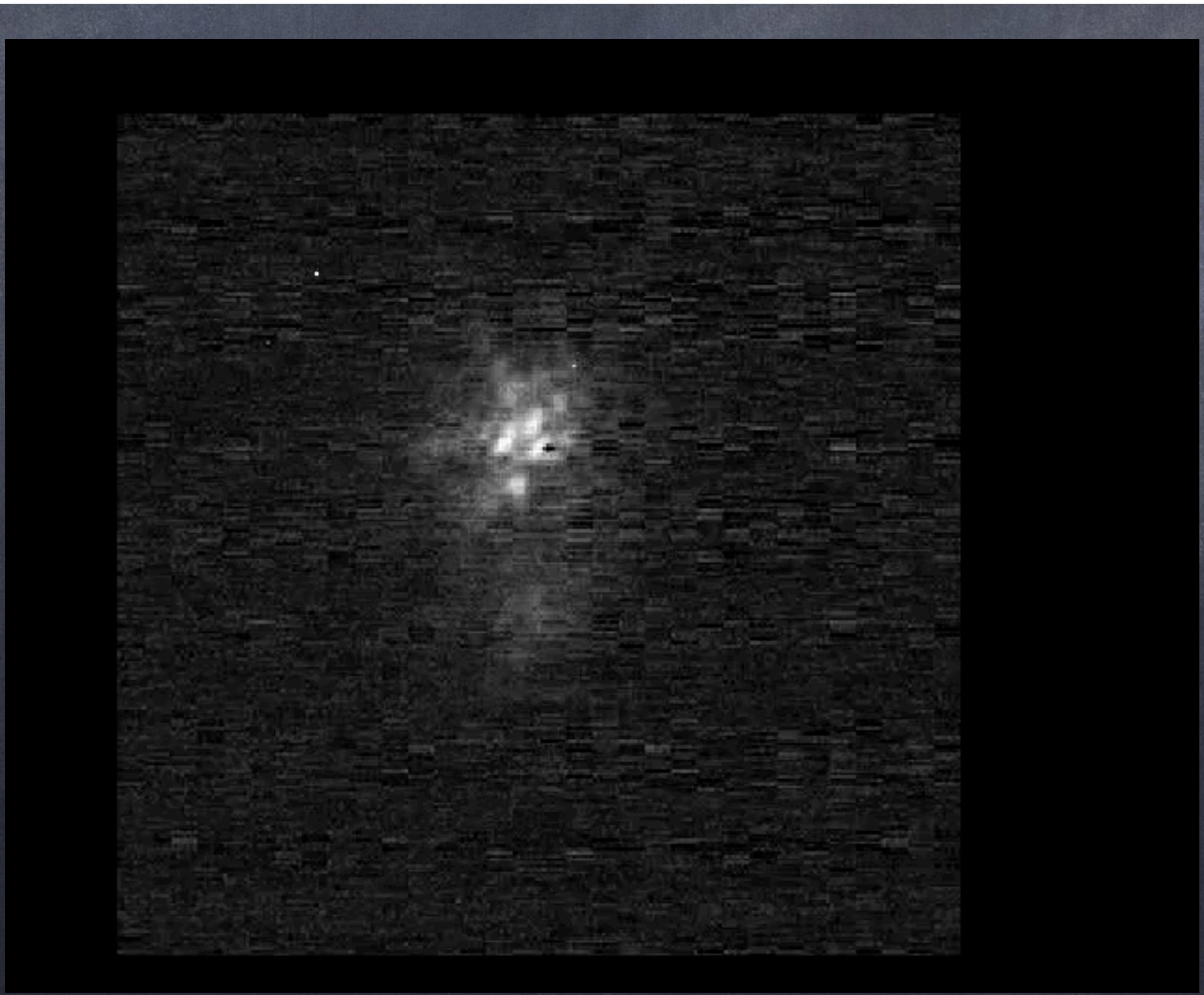
For more information see Adaptive Optics Tutorial in german or english by Stefan Hippler and Andrei Tokovinin.

MPIA - Adaptive Optics at MPIA -
People - Job Opportunities - Search

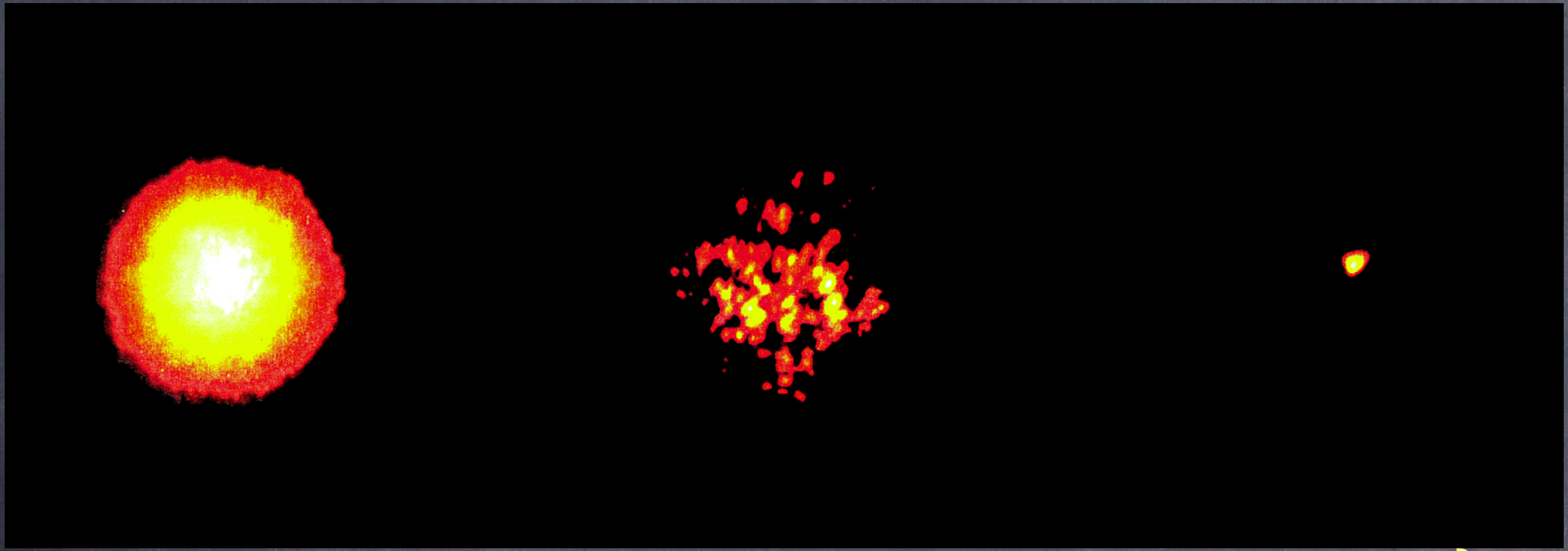
last update: 3 April 2007
editor of this page: Stefan Hippler

Adaptive optics — 07

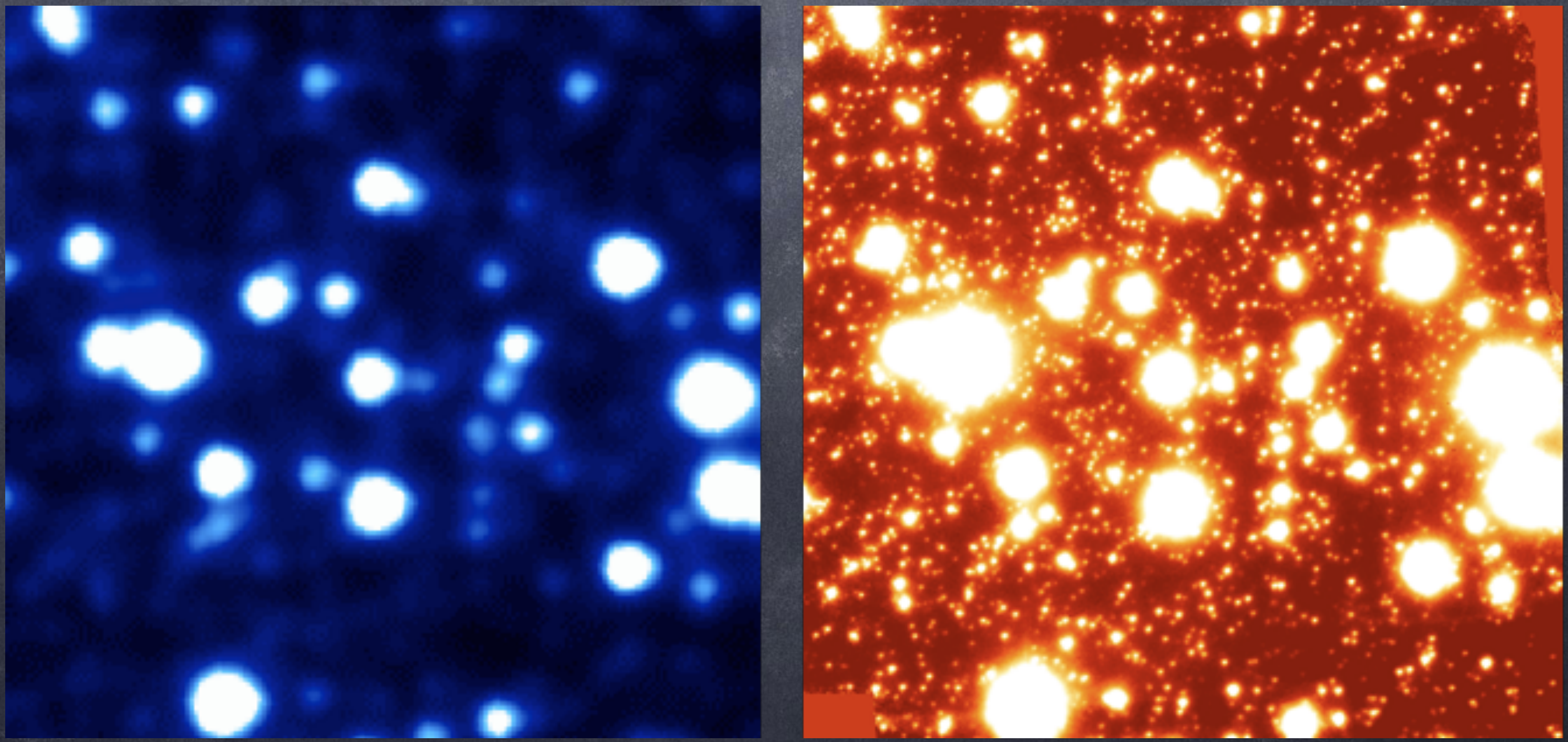




Adaptive optics — 08

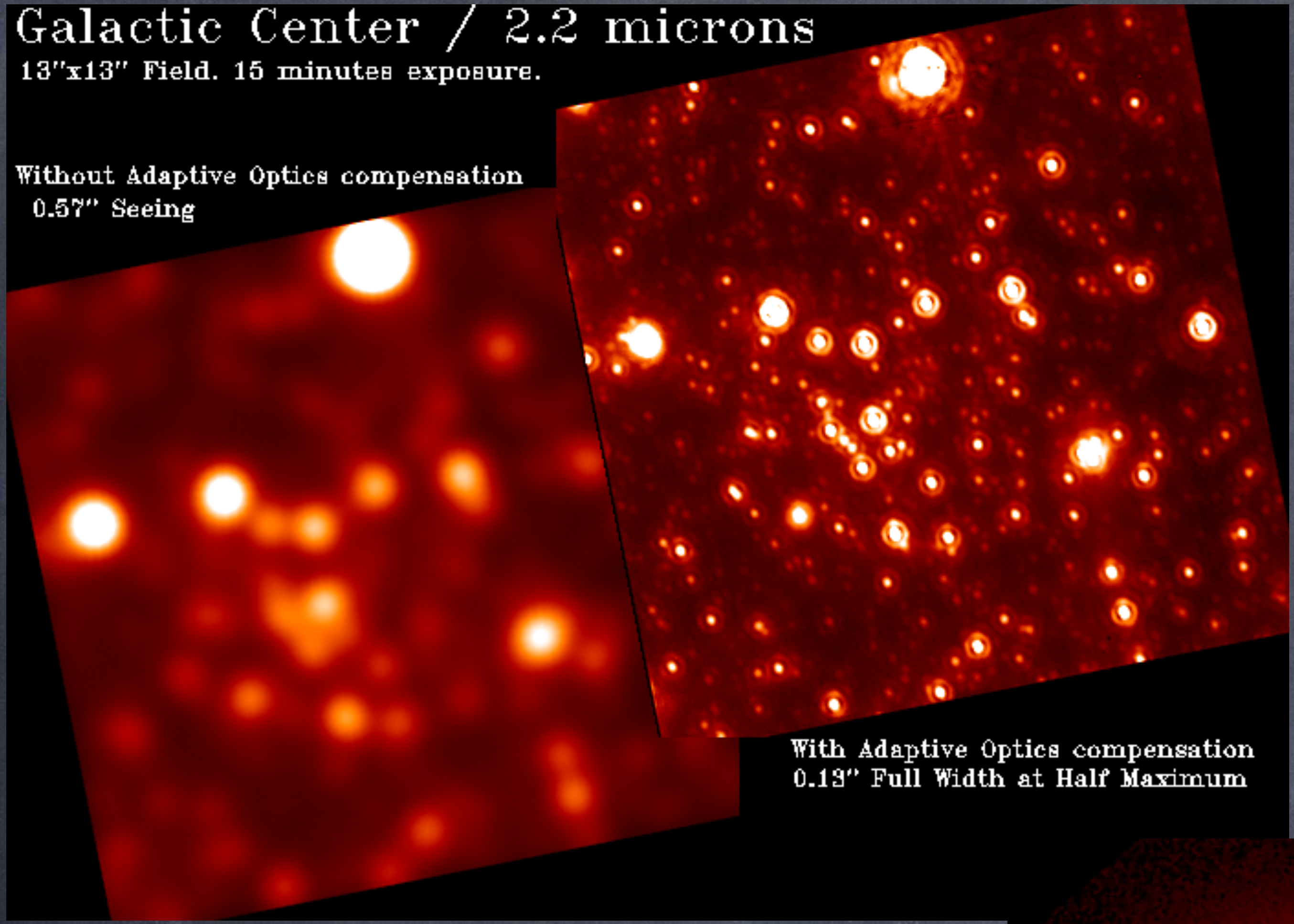


(Lick Observatory, 1-m telescope, left: FWHM≈1", right: FWHM≈λ/D)

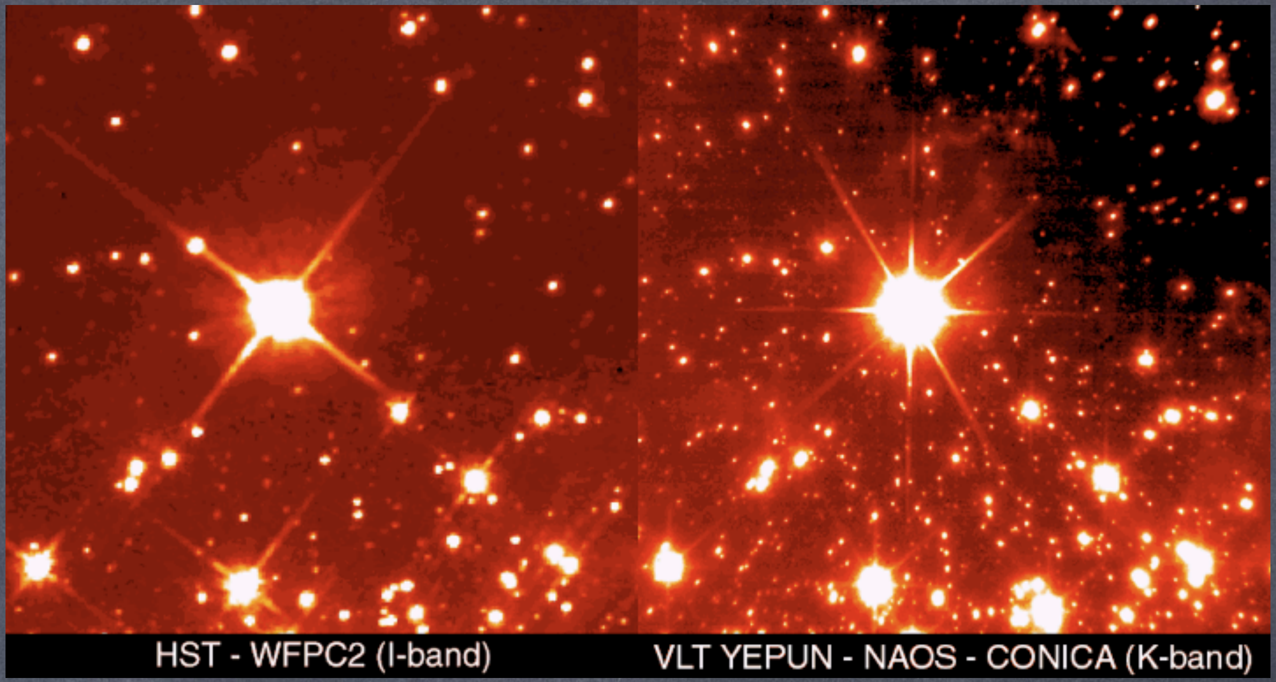


(Gemini Observatory, Hokupa'a+Quirc, left: FWHM≈0"85, right: FWHM≈0"09)

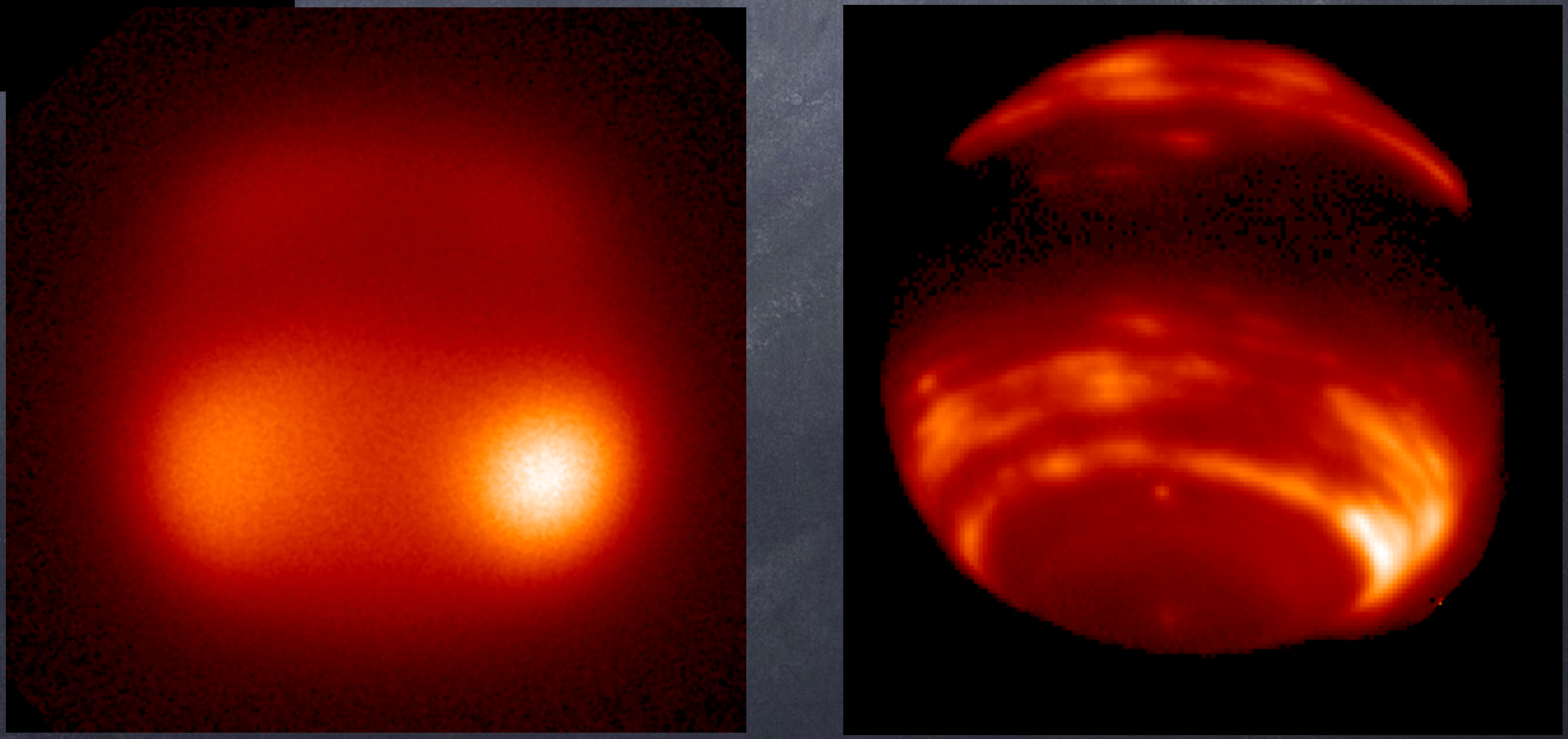
Adaptive optics — 09



(CFHT, long-exp. images (15’))

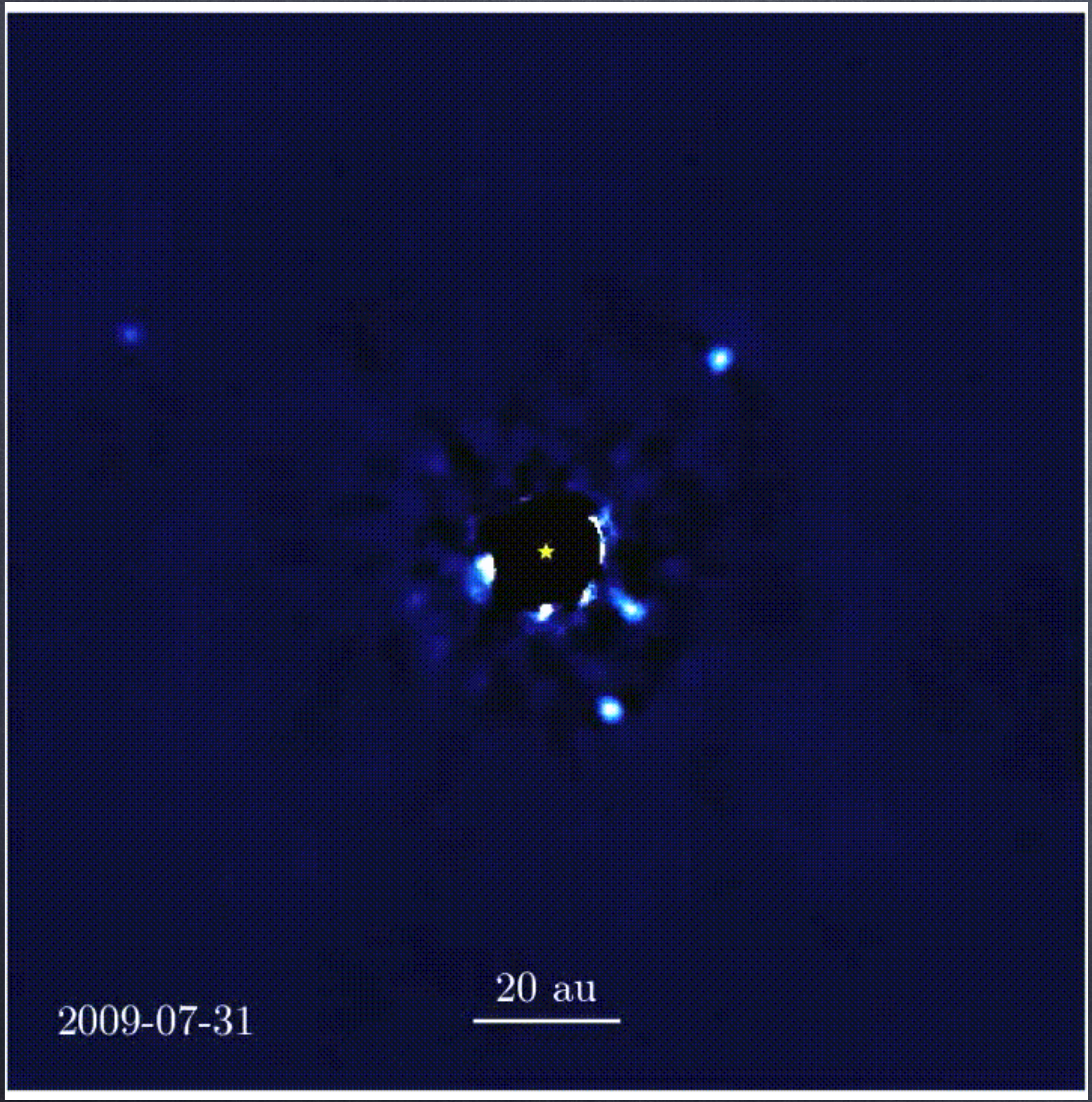


(HST vs. NACO/VLT)



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

Adaptive optics — 10



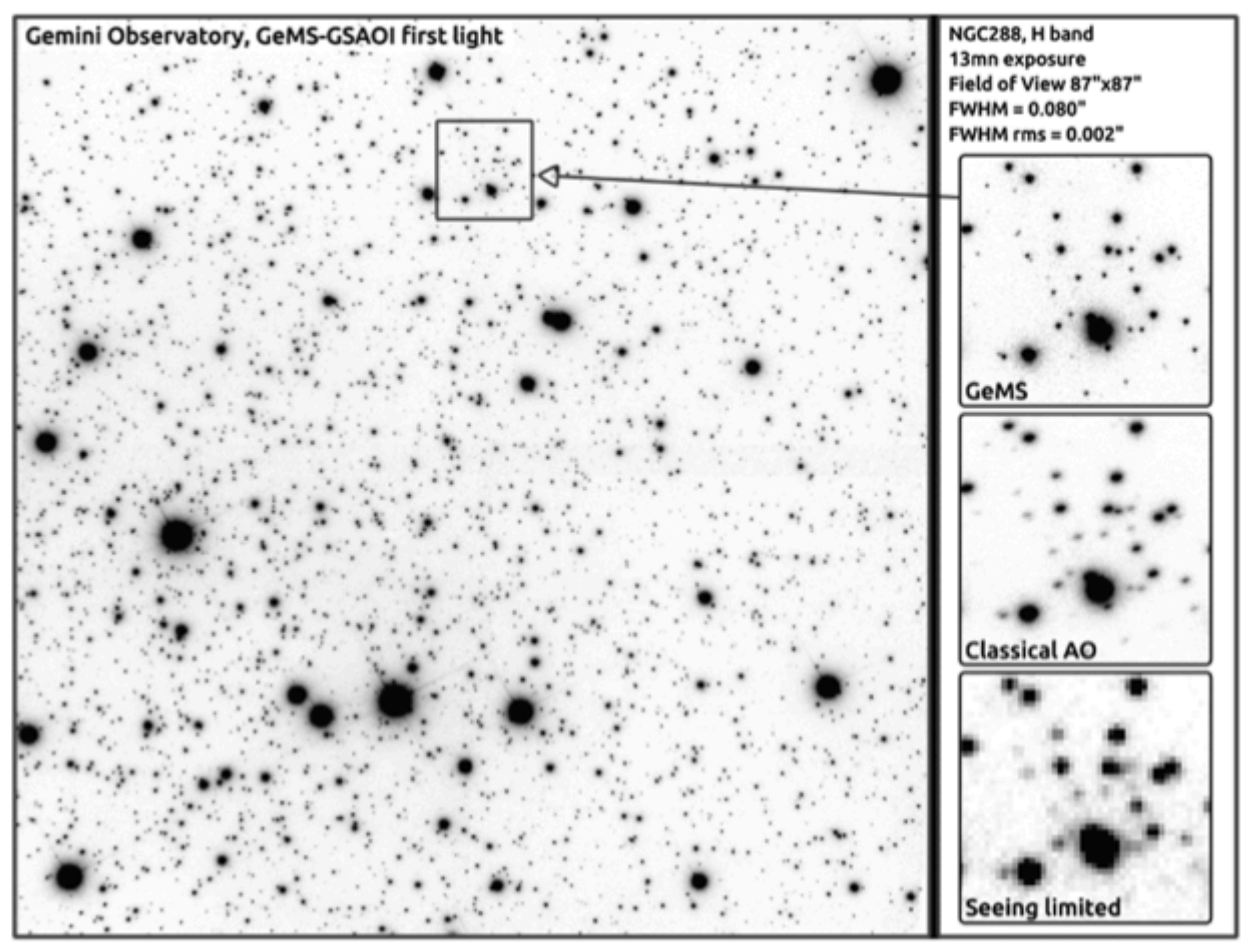
From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in 2013, from which 5 from (X)AO systems and 1 from HST.

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 — 11



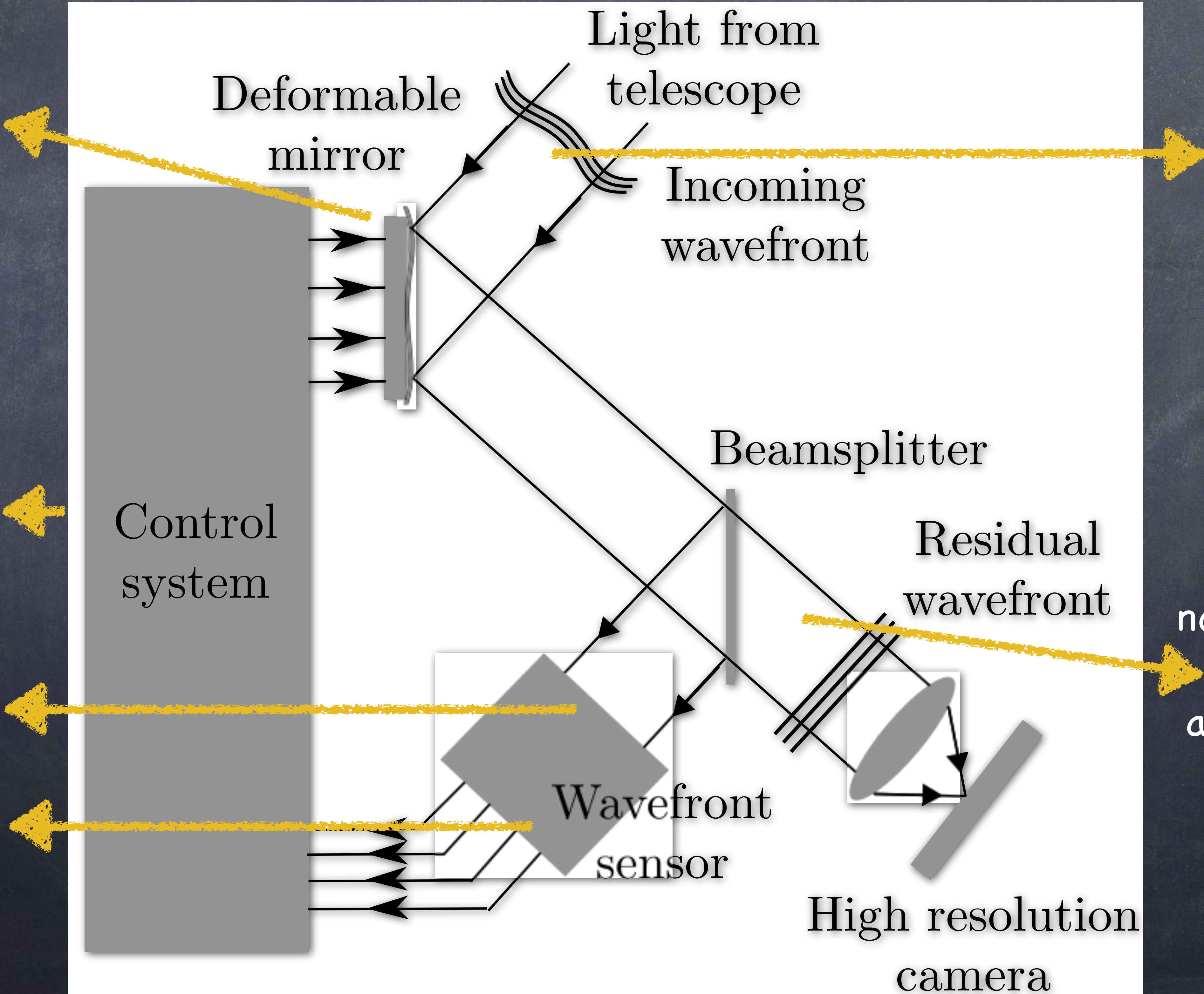
First-light image of GeMS, the MCAO system of Gemini diffraction limit over a 2' square FoV - vs. a few arcsec !

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



fitting error

temporal error

aliasing error

measurement error

anisoplanatic error

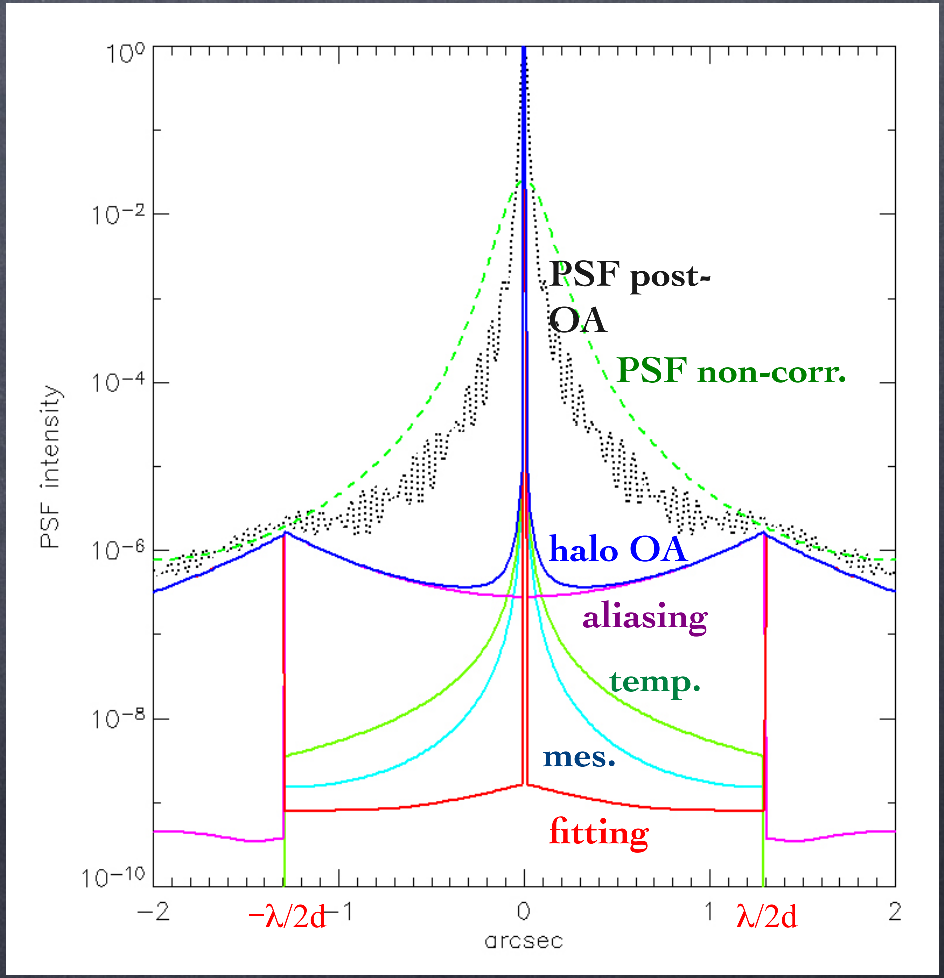
non-common path aberrations (NCPA)

Post-AO error budget & PSF morphology – 2

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

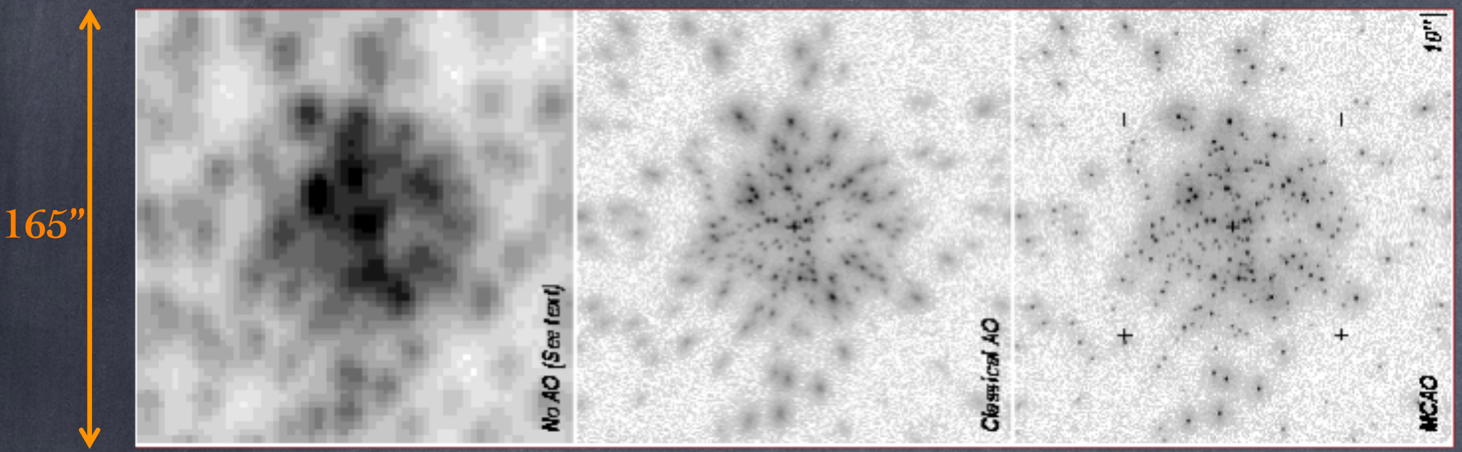
$$\sigma^2_{\mathrm{atm.}} = \sigma^2_{\mathrm{aniso.}} + \ldots$$

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



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

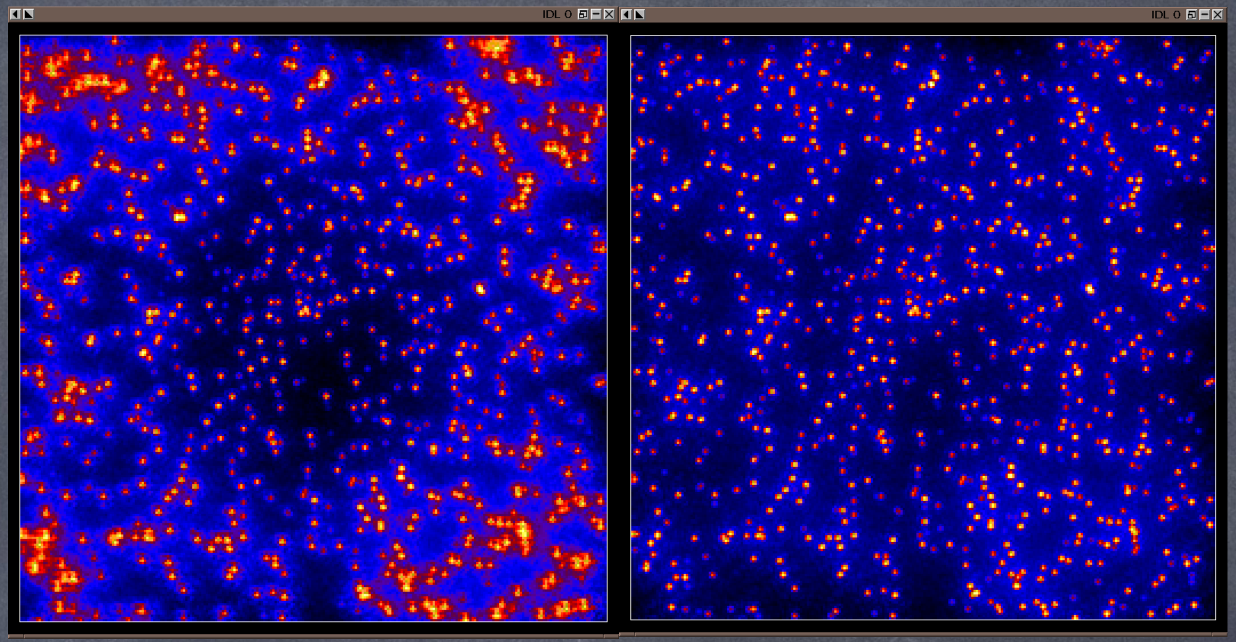
Anisoplanatic error — 1



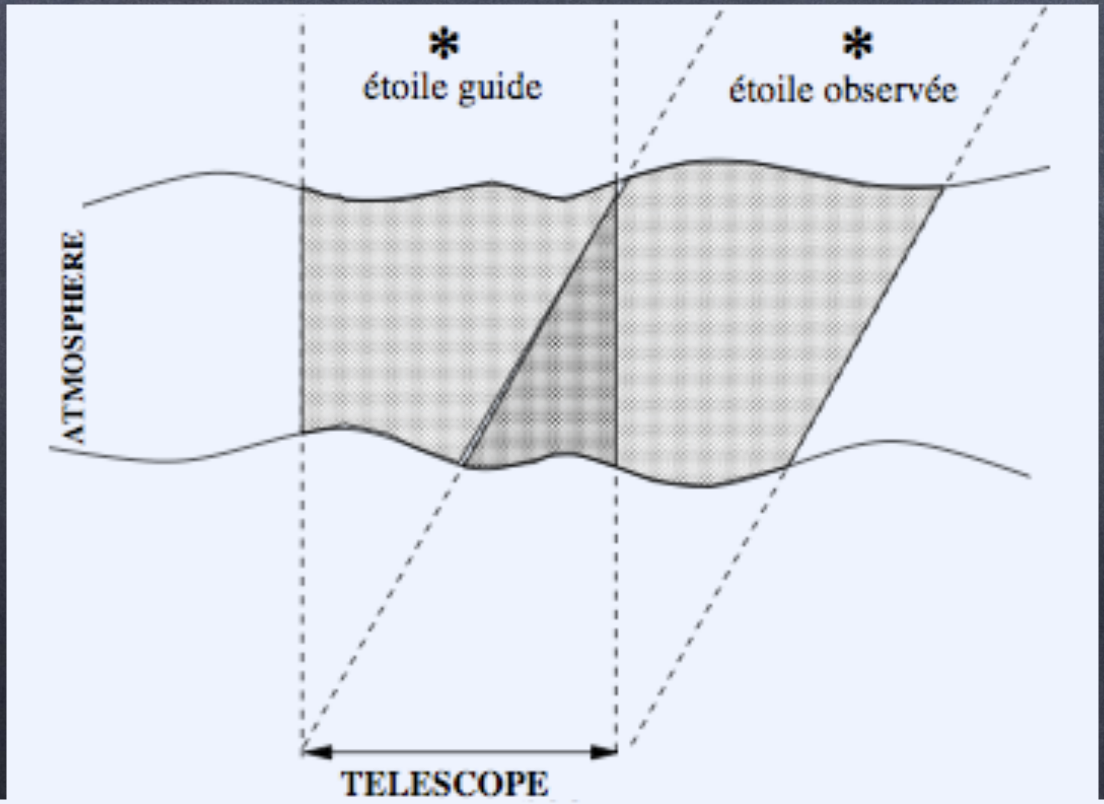
No AO

classical AO
(1 DM, 1 NGS)

MCAO
(2 DM, 5 NGS)



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

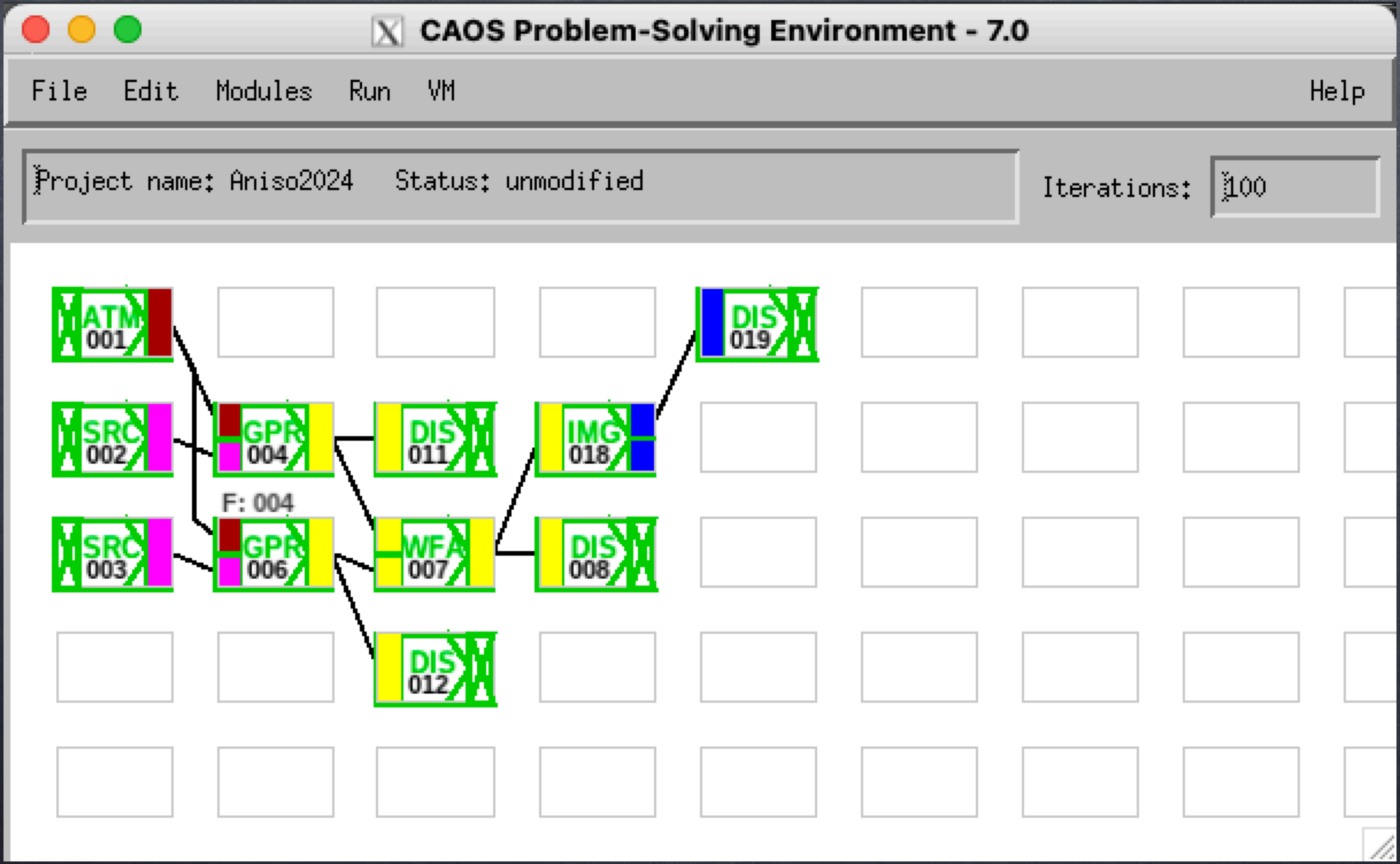


$$\sigma^2_{\text{aniso}} \propto \left(\frac{\theta}{\theta_0}\right)^{\frac{5}{3}}$$

Anisoplanatic error — 2

Numerical tool used for this study: CAOS

(CAOS Problem-Solving Environment + Software Package CAOS + project ``Aniso2024”...)



CAOS Problem-Solving Environment - 7.0

Project name: Aniso2024 Status: unmodified

Iterations: 100

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

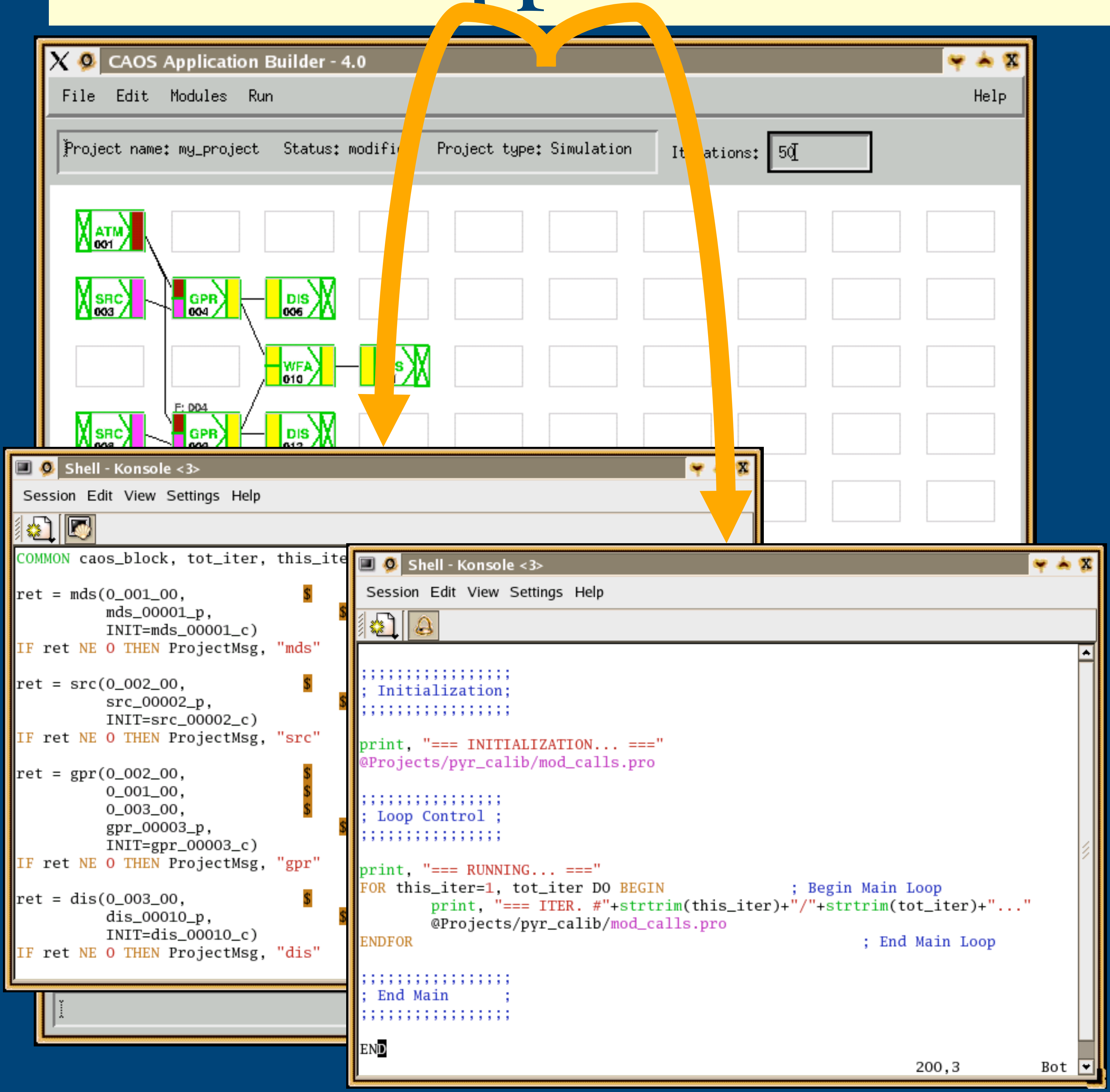
libraries

Software Package
CAOS

Software Package
AIRY

packages

CAOS Application Builder



Project name: my_project Status: modifi Project type: Simulation It ations: 50

```
COMMON caos_block, tot_iter, this_ite

ret = mds(O_001_00,                $
          mds_00001_p,
          INIT=mds_00001_c)
IF ret NE 0 THEN ProjectMsg, "mds"

ret = src(O_002_00,                $
          src_00002_p,
          INIT=src_00002_c)
IF ret NE 0 THEN ProjectMsg, "src"

ret = gpr(O_002_00,                $
          O_001_00,                $
          O_003_00,                $
          gpr_00003_p,
          INIT=gpr_00003_c)
IF ret NE 0 THEN ProjectMsg, "gpr"

ret = dis(O_003_00,                $
          dis_00010_p,
          INIT=dis_00010_c)
IF ret NE 0 THEN ProjectMsg, "dis"
```

```
;;;;;;;;;;;;;;;;;
; Initialization;
;;;;;;;;;;;;;;;;;

print, "=== INITIALIZATION... ==="
@Projects/pyr_calib/mod_calls.pro

;;;;;;;;;;;;;;;;
; Loop Control ;
;;;;;;;;;;;;;;;;

print, "=== RUNNING... ==="
FOR this_iter=1, tot_iter DO BEGIN              ; Begin Main Loop
        print, "=== ITER. #"+strtrim(this_iter)+"/"+strtrim(tot_iter)+"..."
        @Projects/pyr_calib/mod_calls.pro
ENDFOR                                                  ; End Main Loop

;;;;;;;;;;;;;;;;;
; End Main      ;
;;;;;;;;;;;;;;;;;

END
                                                 200,3          Bot
```

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.

CAOS PSE: availability

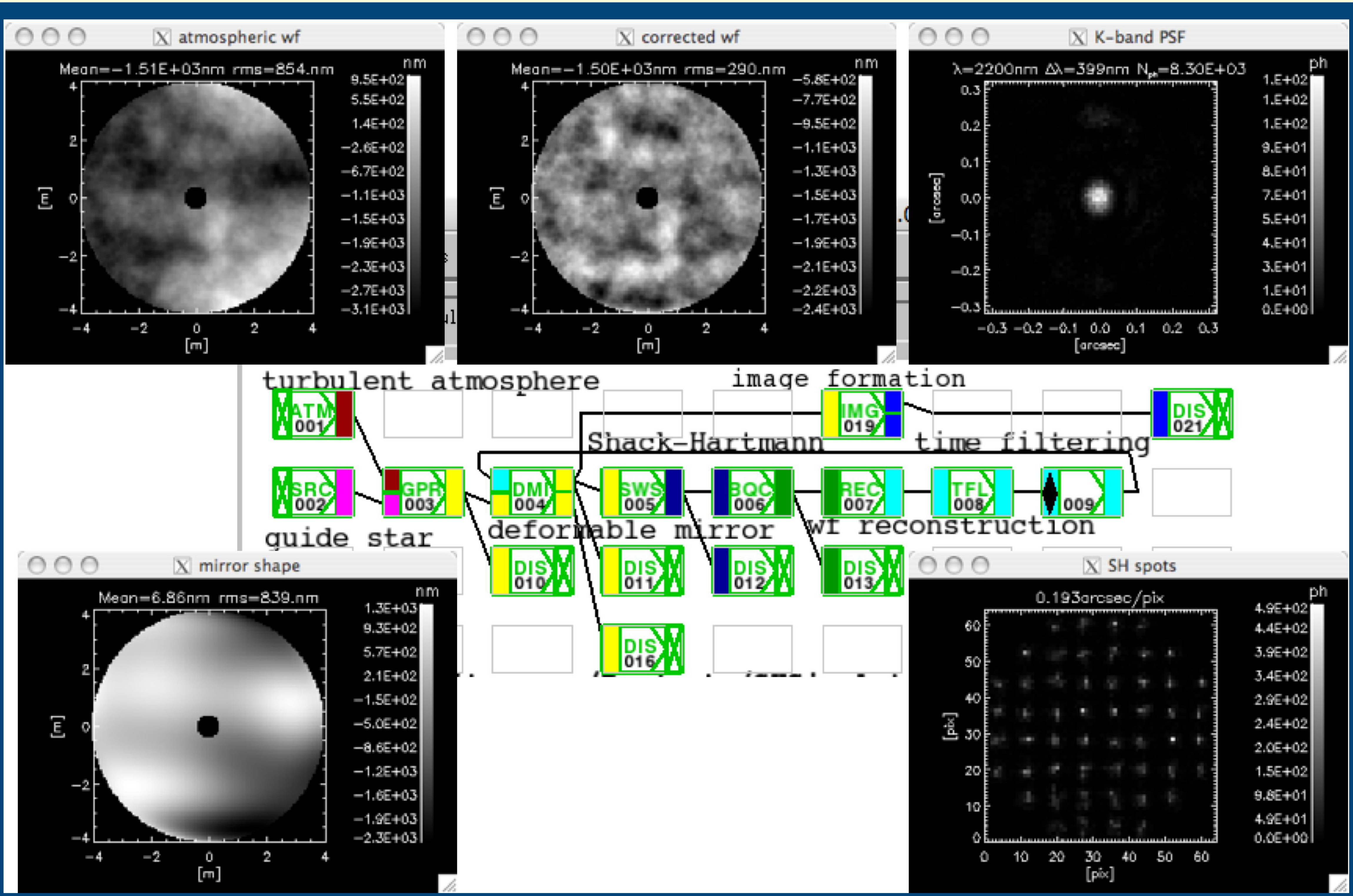
All (*public!*) parts of the CAOS PSE are available for download:

lagrange.oca.eu/caos/

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

- Soft. Pack. CAOS: 101 subscribers,
- Soft. Pack. AIRY: 23 subscribers.

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



Imaging through the turbulent atmosphere: anisoplanatism ! – 1

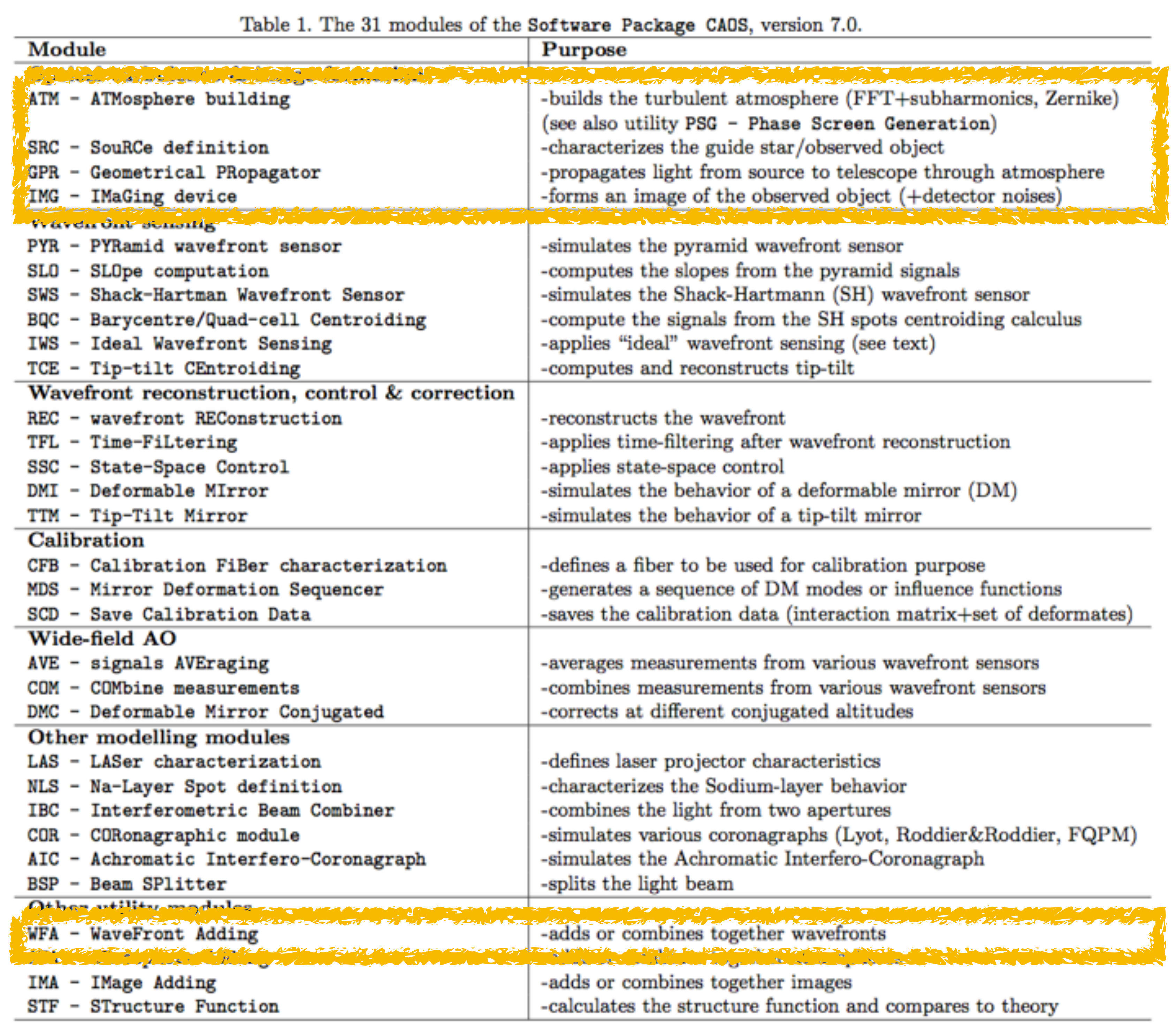
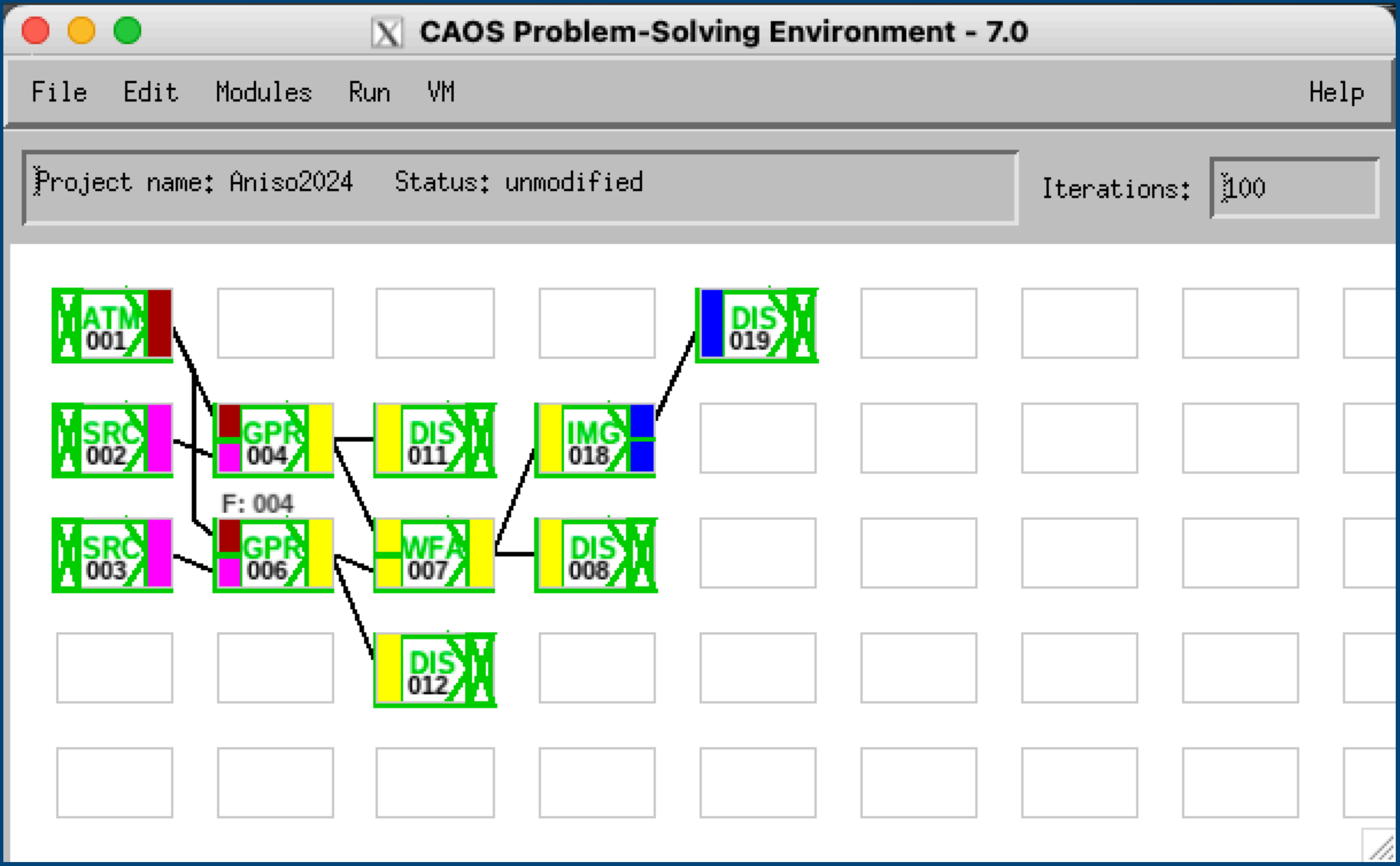


Table 1. The 31 modules of the `Software Package CAOS`, version 7.0.

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 - COResonagraphic 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



Project name: Aniso2024   Status: unmodified

Iterations: 100

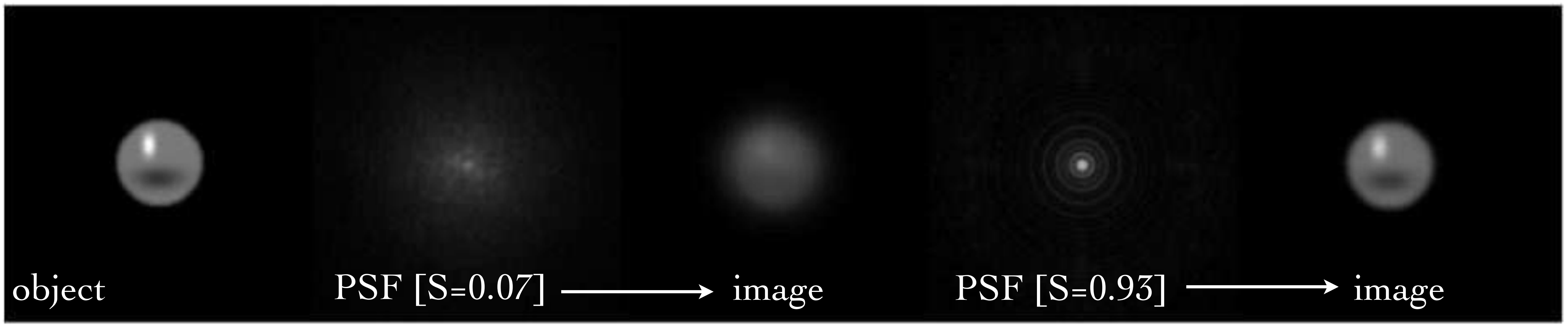
(Another useful metrics: the Strehl ratio)

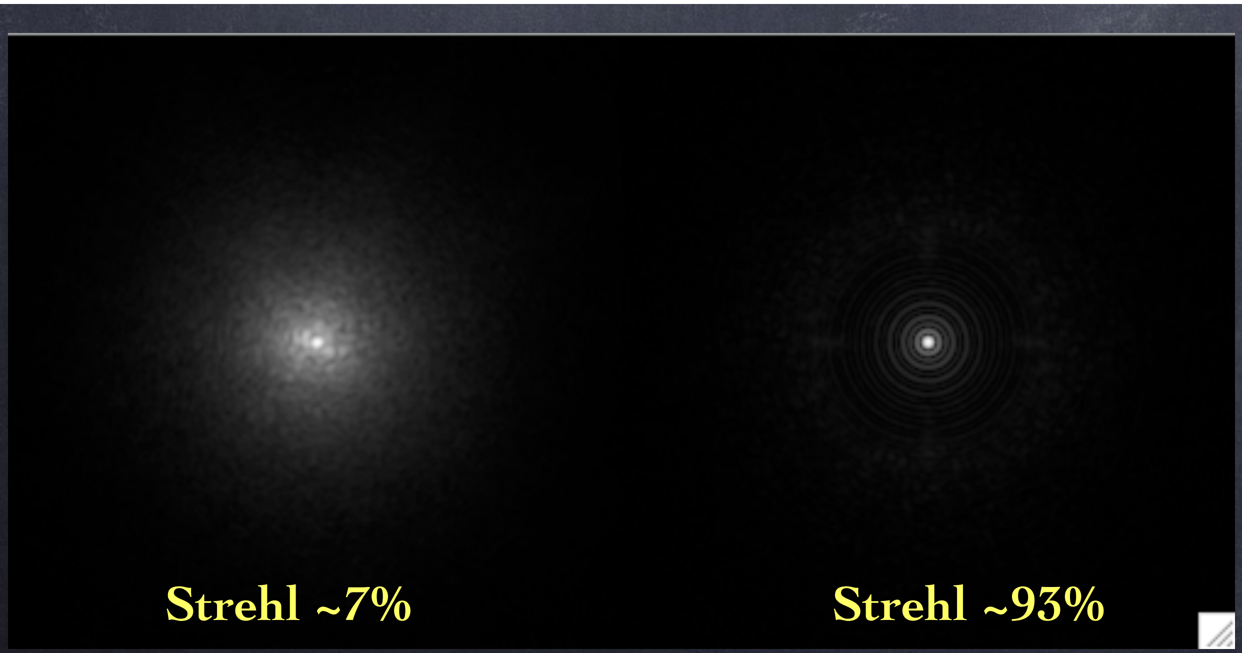
$$S = \frac{I_{\text{post AO}}[0,0]}{I_{\text{perfect}}[0,0]}$$

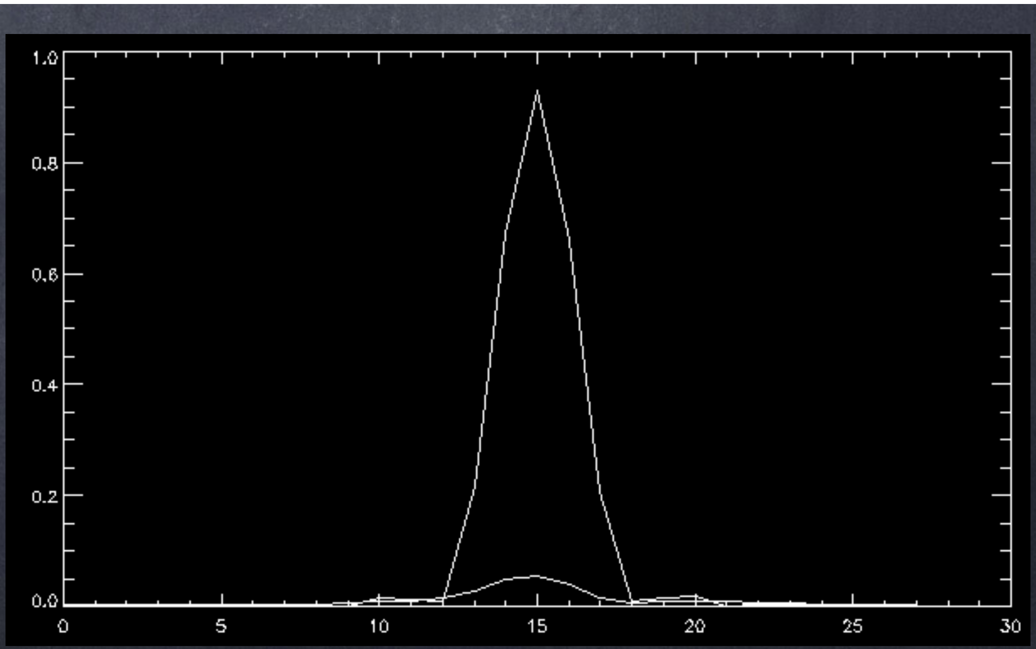
where *I[0,0]* is the intensity of the PSF at the optical center of the field (K. Strehl, Zeit. Instrumenkde 22, 213 (1902)).

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

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







(Another useful metrics: the Strehl ratio)

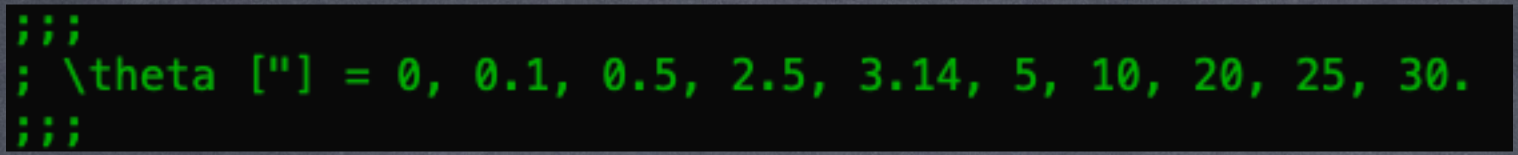
- Approximation that neglects tip-tilt: ratio of the maxima ($S \approx \max(I)/\max(I_{ideal})$)

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

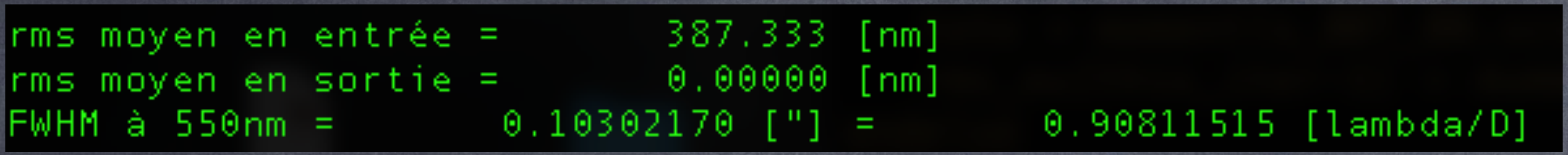
- From Tokovinin (PASP, 2002):

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

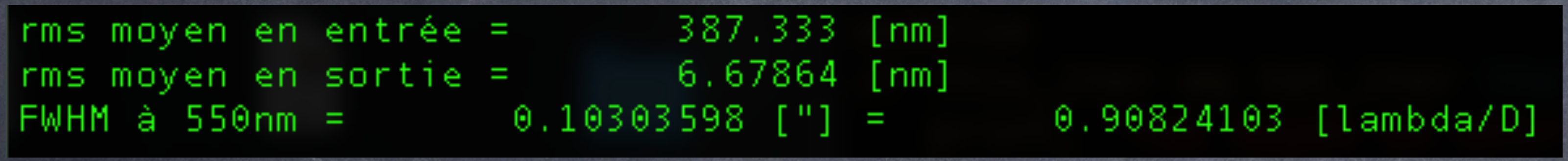
projet Aniso2024



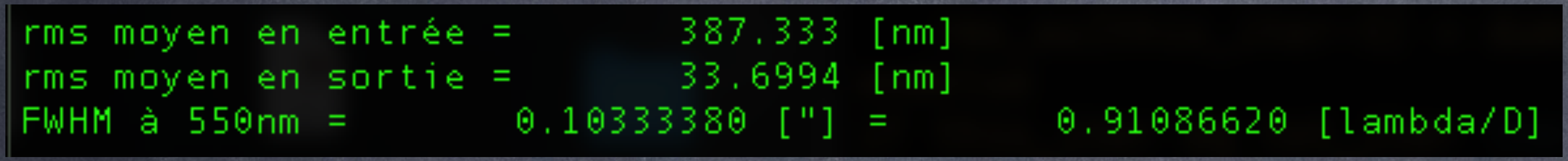
```
;;;
; \theta ["] = 0, 0.1, 0.5, 2.5, 3.14, 5, 10, 20, 25, 30.
;;;
```



```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        0.00000 [nm]
FWHM à 550nm =        0.10302170 ["] =        0.90811515 [lambda/D]
```



```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        6.67864 [nm]
FWHM à 550nm =        0.10303598 ["] =        0.90824103 [lambda/D]
```



```
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rms moyen en sortie =        33.6994 [nm]
FWHM à 550nm =        0.10333380 ["] =        0.91086620 [lambda/D]
```

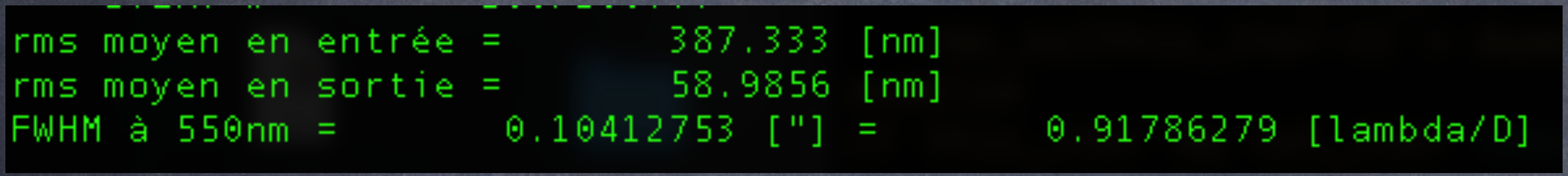

```
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rms moyen en sortie =        58.9856 [nm]
FWHM à 550nm =        0.10412753 ["] =        0.91786279 [lambda/D]
```

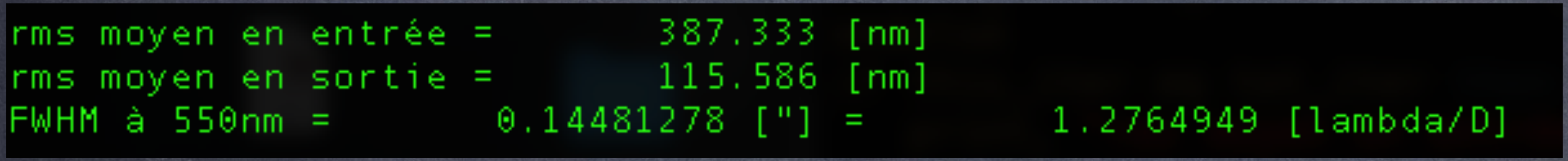

```
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rms moyen en sortie =        115.586 [nm]
FWHM à 550nm =        0.14481278 ["] =        1.2764949 [lambda/D]
```

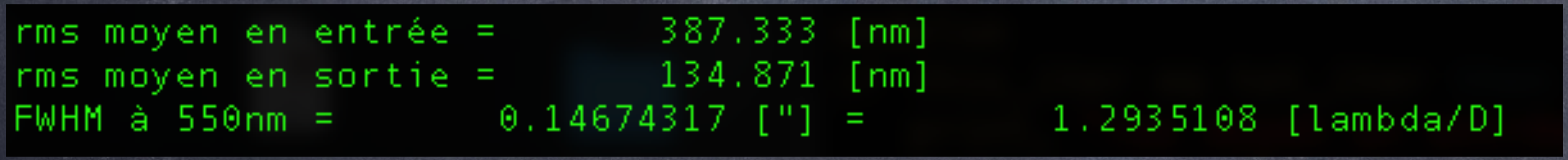

```
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rms moyen en sortie =        134.871 [nm]
FWHM à 550nm =        0.14674317 ["] =        1.2935108 [lambda/D]
```
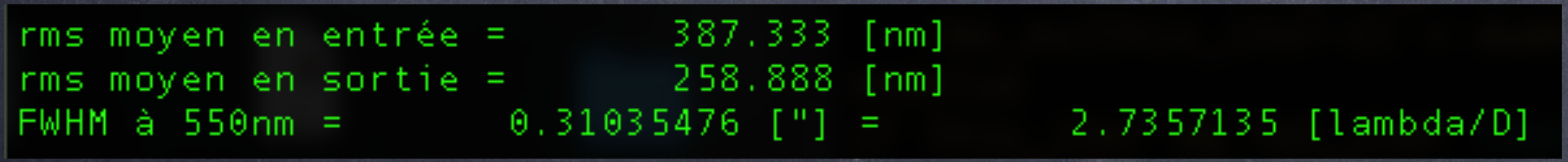
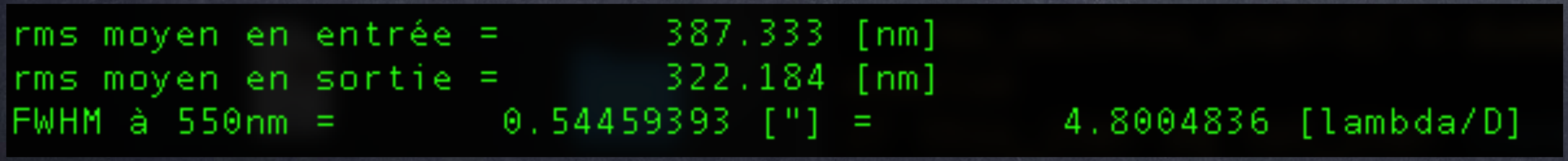
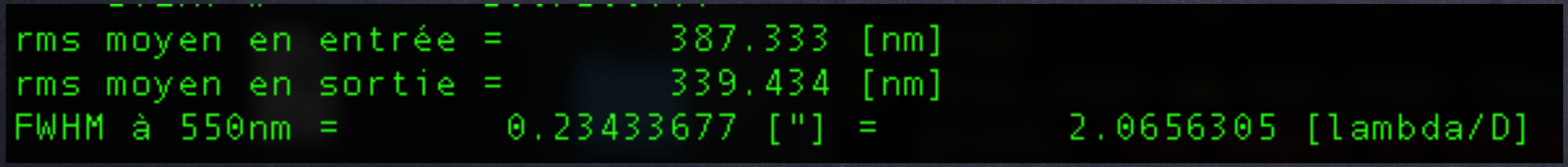



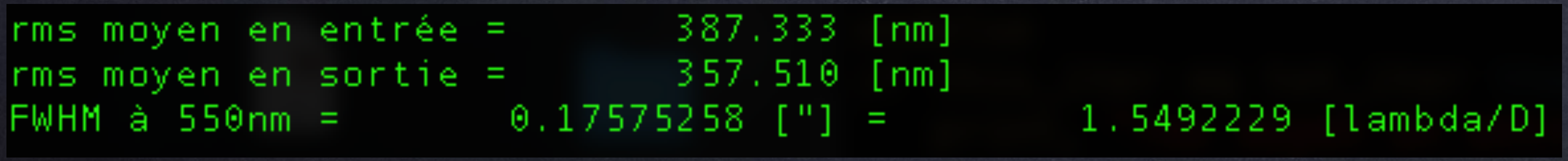
```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        258.888 [nm]
FWHM à 550nm =        0.31035476 ["] =        2.7357135 [lambda/D]
```



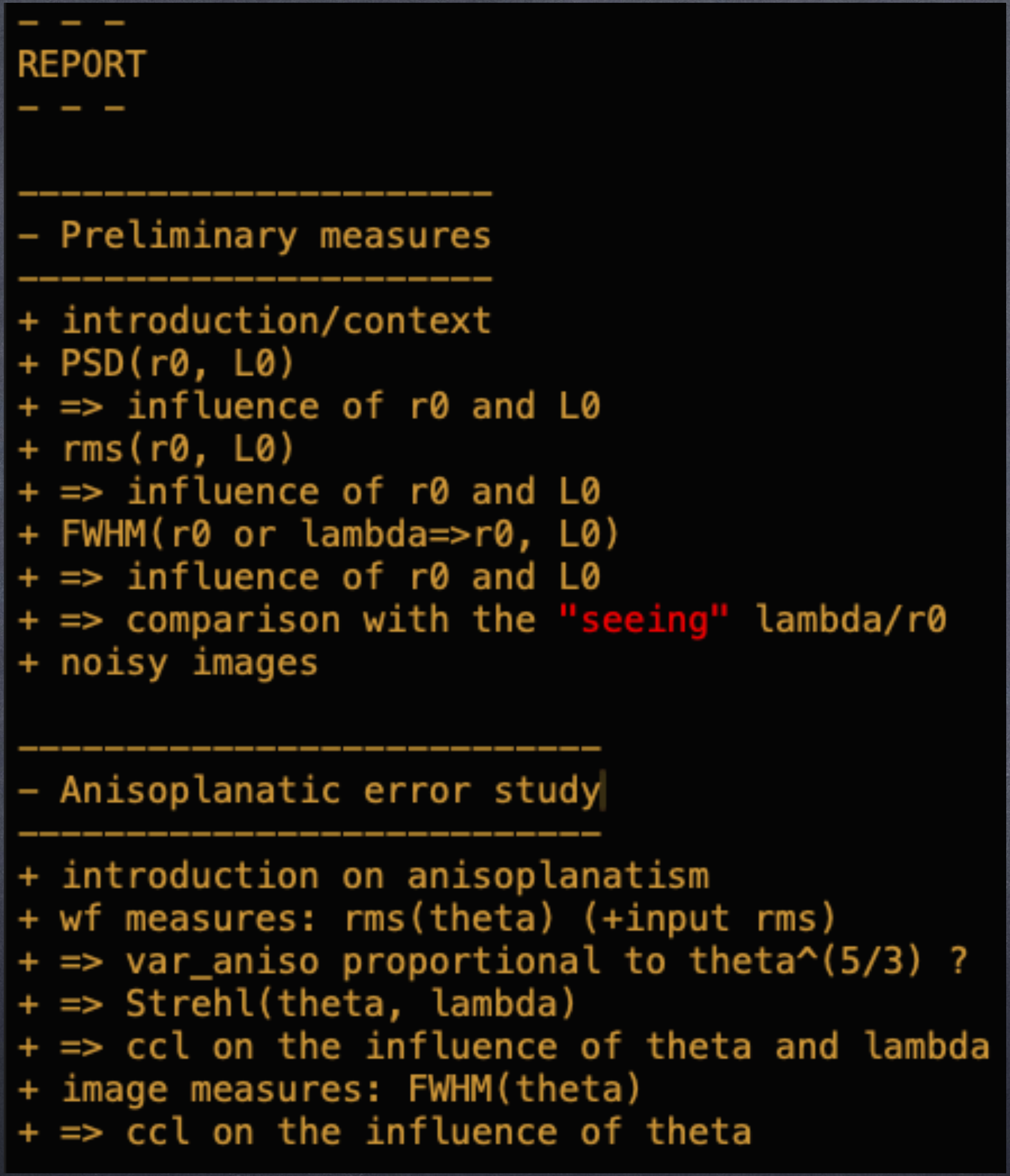
```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        322.184 [nm]
FWHM à 550nm =        0.54459393 ["] =        4.8004836 [lambda/D]
```



```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        339.434 [nm]
FWHM à 550nm =        0.23433677 ["] =        2.0656305 [lambda/D]
```



```
rms moyen en entrée =        387.333 [nm]
rms moyen en sortie =        357.510 [nm]
FWHM à 550nm =        0.17575258 ["] =        1.5492229 [lambda/D]
```



```
- - -
REPORT
- - -


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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


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- Anisoplanatic error study
---------------------------
+ introduction on anisoplanatism
+ wf measures: rms(theta) (+input rms)
+ => var_aniso proportional to theta^(5/3) ?
+ => Strehl(theta, lambda)
+ => ccl on the influence of theta and lambda
+ image measures: FWHM(theta)
+ => ccl on the influence of theta
```

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Astronomical Adaptive Optics

FRANÇOIS RIGAUT
Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia

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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 λ/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 32×32 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