Images & turbulence - 24

-> Detector noises:

• At first: *photon noise* (or *shot noise*), poissonian, actually a transformation of the image.

$$p(n) = \frac{N^n e^{-N}}{n!}, \text{with} : N = \frac{L\Delta t}{h\nu}, L = \text{luminosity}, \Delta t = \text{time exp.}$$

p(n) = probability to detect n photons when N are expected

For large N: ~gaussian…

$$p(n) \simeq \exp\left(-\frac{(n-N)^2}{2N}\right)$$

Images & turbulence - 25

-> Detector noises:

• At first: *photon noise* (or *shot noise*), poissonian, actually a transformation of the image.

• At last: *read-out noise* (*RON*), gaussian with zero mean and rms σ_e [e-/px], additive noise.

• In between: *dark current noise*, *amplification noise* & *exotic dark current noise* in the case of EMCCDs, noise due to the *calibration* of the *flat field*, *'salt & pepper' noise* ('hot' and 'cold' pixels), etc.

Images & turbulence - 26

```
;; Photon noise (Poisson)
if keyword_set(PHOT_NOISE) then begin
   idx=where((image GT 0.) AND (image LT 1E8),c)
                                                   ; For values higher than 1E8, should one
   if (c NE 0) then for i=0l,c-1l do $             ; really has to worry about photon noise ?
      noisy_image[idx[i]]=randomn(seed_pn,POISSON=image[idx[i]],/DOUBLE)
endif

;; Additive dark-current noise (Poisson)
if keyword_set(SIGMA_DARK) then begin
   if not(keyword_set(DELTA_T)) then begin
      message, "dark-current noise calculation does need a time exposure value!!"
   endif else noisy_image+=randomn(seed_dark,npx,npy,POISSON=sigma_dark*delta_t,/DOUBLE)
endif

;; EMCCD noises
; Additive exotic (time-exposure-independent) dark-current noise (Poisson)
if keyword_set(EXODARK) then noisy_image+=randomn(seed_xd,npx,npy,POISSON=exodark,/DOUBLE)

; Additive main EMCCD noise (Gamma)
if keyword_set(GAIN_L3CCD) then begin
   idx=where(image GT 0, c)
   if (c NE 0) then for i=0l,c-1l do $
      noisy_image[idx[i]]+=gain_l3ccd*randomn(seed_l3ccd,GAMMA=image[idx[i]],/DOUBLE)
;   noisy_image=long(temporary(noisy_image))
endif

;; Flat-field calibration residuals
if keyword_set(FFOFFSET) then begin
   ffres=randomn(seed_ff,npx,npy)*ffoffset+1.
   idx = where(ffres LE 0., c)
   if (c NE 0) then ffres[idx]=1.           ; Put possible<=0 ff values to 1.
   noisy_image*=ffres
endif

;; Additive read-out noise (Gaussian)
if keyword_set(SIGMA_RON) then $
   noisy_image+=randomn(seed_ron,npx,npy,/NORMAL,/DOUBLE)*sigma_ron

; Force to zero negative values
if keyword_set(POSITIVE) then begin
   idx=where(noisy_image LT 0, c)
   if (c GT 0) then noisy_image[idx]=0.
endif
```

```
CALLING SEQUENCE
  noisy_image = addnoise(input_image,               $
                         PHOT_NOISE=phot_noise,     $
                         SIGMA_DARK=sigma_dark,     $
                         DELTA_T=delta_t,           $
                         EXODARK=exodark,           $
                         GAIN_L3CCD=gain_l3ccd,     $
                         FFOFFSET=ffoffset,         $
                         SIGMA_RON=sigma_ron,       $
                         POSITIVE=positive,         $
                         OUT_TYPE=out_type          )
```

img formation w/noise:

1- ‘add’ photon noise on one short-exp. PSF (in function of N…),
2- long-exp. PSF (100N photons!),
3- ‘add’ photon noise on the long-exp. PSF,
4- compare long-exp. & short-exp. noisy images (and ‘clean’ images).

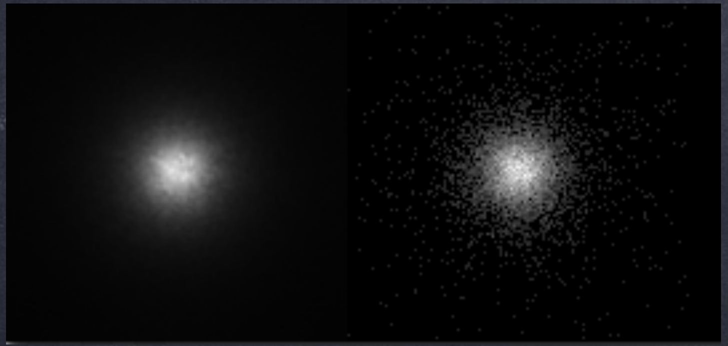
Images & turbulence - 27

```
IDL> restore, 'PSF_r0=10cm_L0=10m_lambda=500nm.sav'
IDL> help
% At $MAIN$
CUBE_PSF          FLOAT     = Array[128, 128, 100]
SHORTEXP          DOUBLE    = Array[128, 128]
Compiled Procedures:
    $MAIN$

Compiled Functions:

IDL> shortexp=cube_PSF[*,*,0]
IDL> total(shortexp)
      0.19702147
IDL> shortexp=shortexp/total(shortexp)*100.
IDL> total(shortexp)
       99.999664
IDL> .r addnoise
% Compiled module: ADDNOISE.
IDL> shortnoisy=addnoise(shortexp, /PHOT_NOISE)
```

```
IDL> tvscl, [shortexp,shortnoisy]^.5
IDL> longexp=total(cube,3)
IDL> longexp=longexp/total(longexp)*100.*100L
IDL> longnoisy=addnoise(longexp, /PHOT_NOISE)
IDL> tvscl, [longexp,longnoisy]^.5
```



<u>img formation w/noise:</u>

1- 'add' photon noise on one short-exp. PSF (in function of N...),
2- long-exp. PSF (100N photons!),
3- 'add' photon noise on the long-exp. PSF,
4- compare long-exp. & short-exp. noisy images (and 'clean' images).

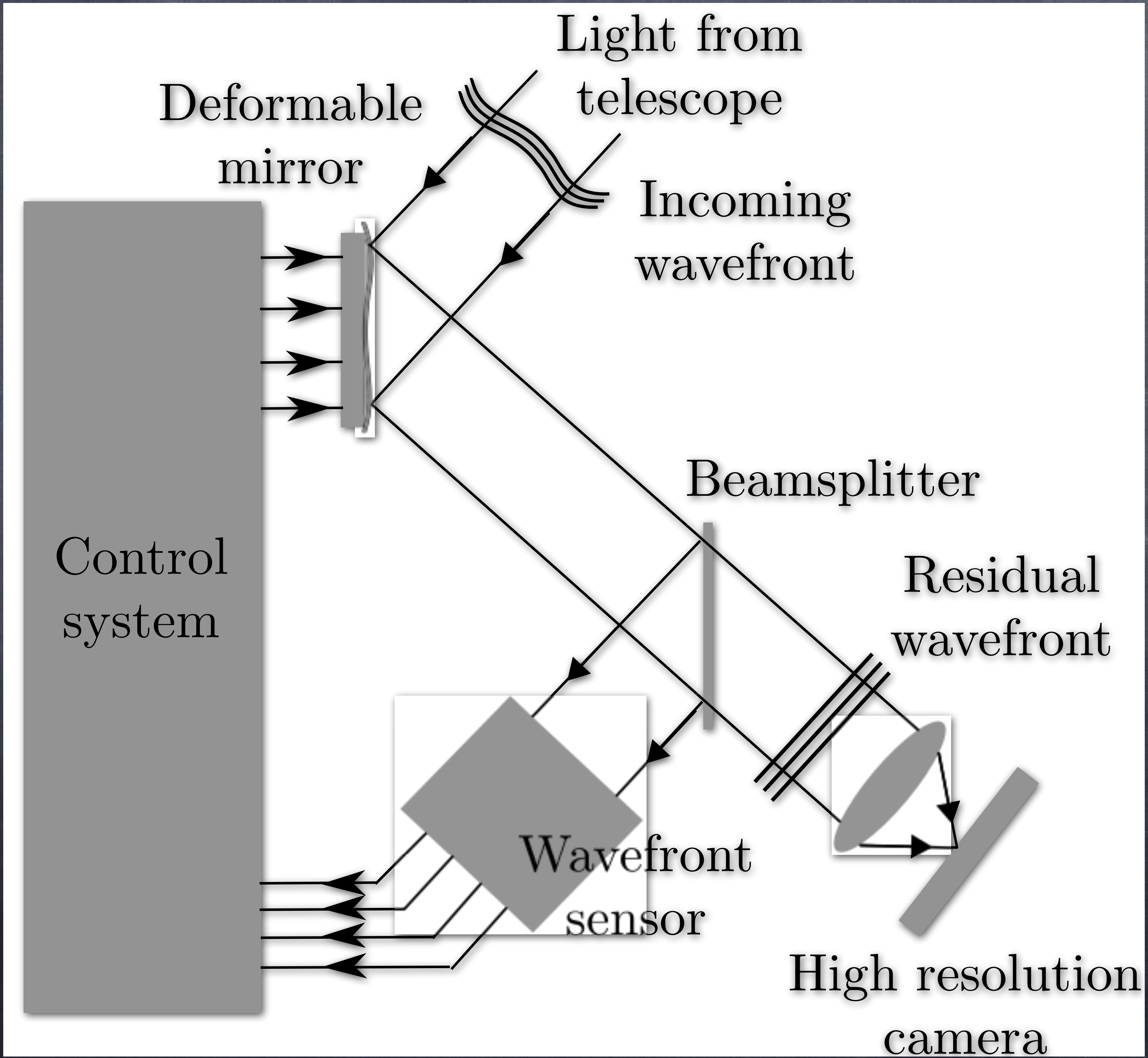
```
-----------------------------------------------
 Report "Imaging through turbulence" (M1 MAUCA)
-----------------------------------------------

----------------------
- Preliminary measures      (individual)    [/10]
----------------------
+ 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 development ?
```

(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 ≈ r_0	**≈ 10 cm**	**≈ 60 cm**
number of WFS analysis elements (≈ number of DM actuators)		
→ N ∝ $(D/d)^2$, with D=10m	**≈ 7500**	**≈ 200**
temporal sampling		
→ f ∝10 v/r_0	**≈ 1 kHz**	**≈ 0.2 kHz**

Adaptive optics - 4

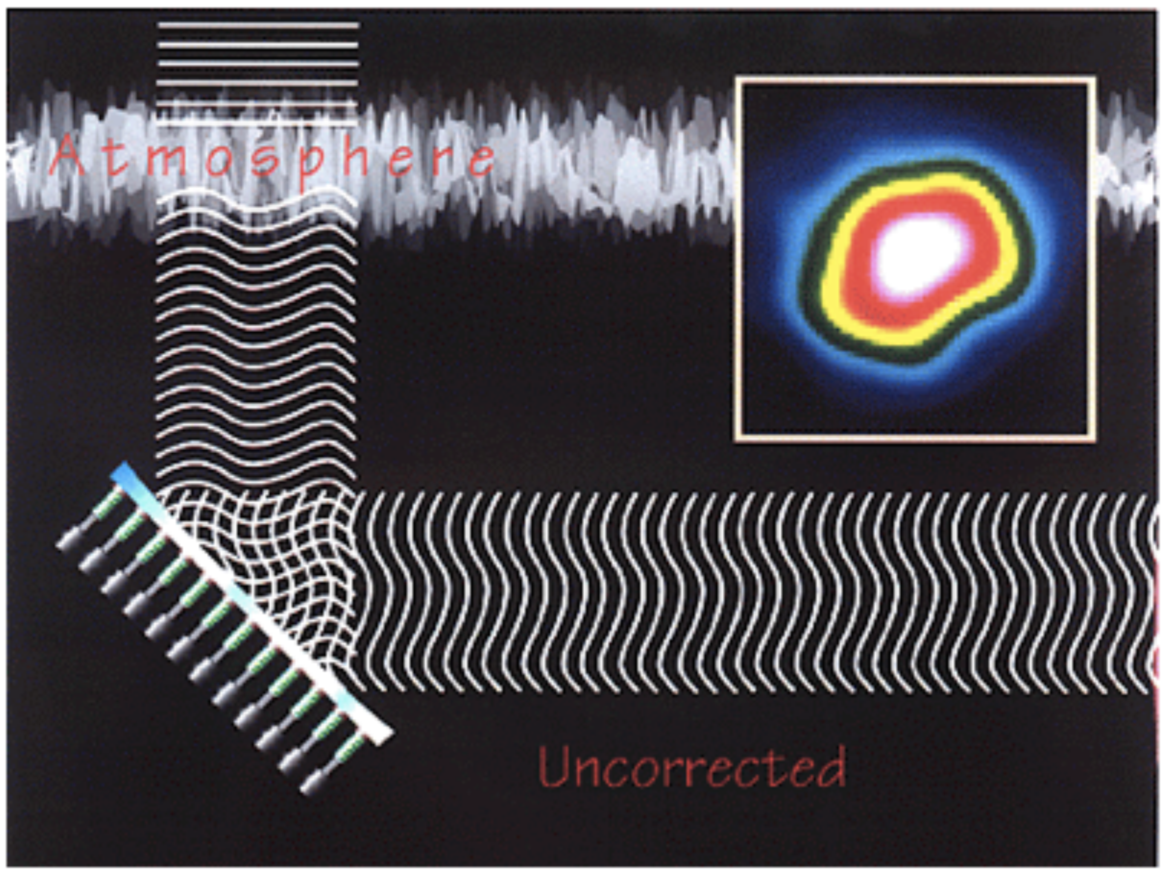
Introduction to Adaptive Optics

Credits: ESO and Jennifer Lotz

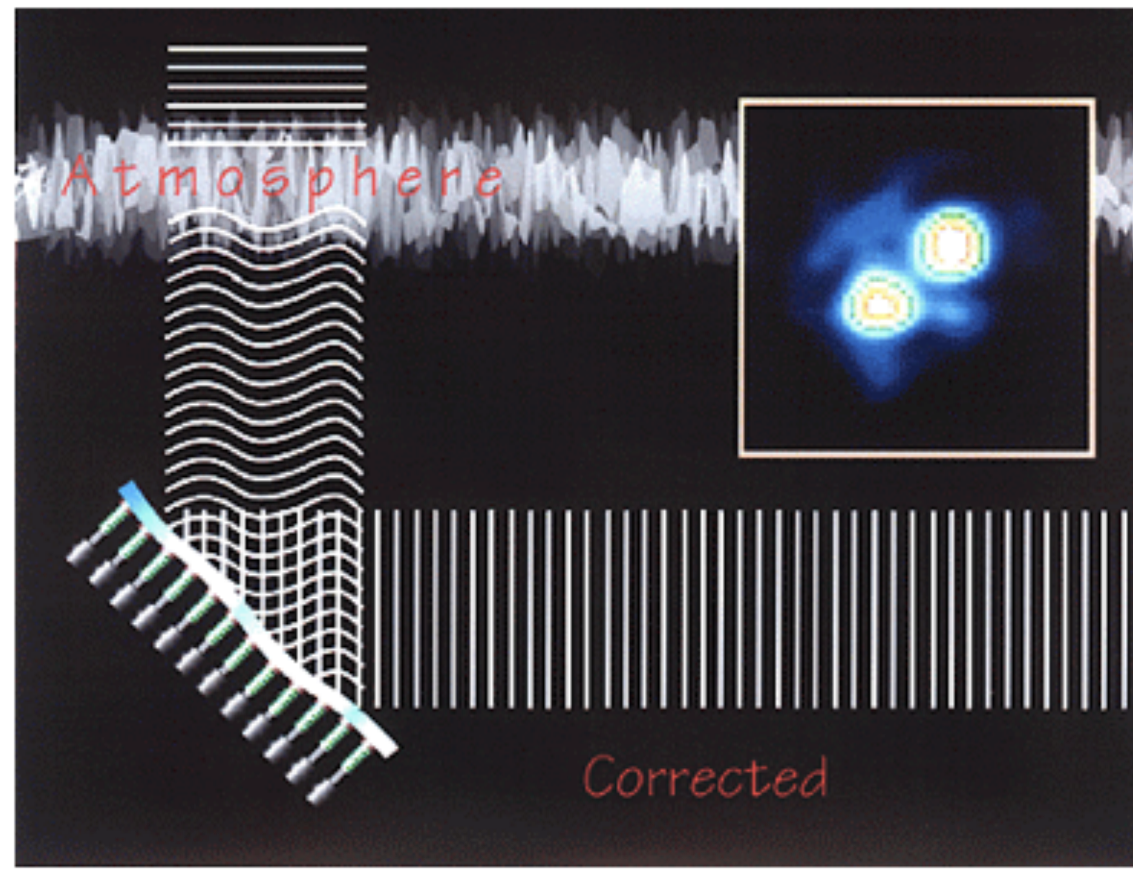
As astronomers attempt to understand the limits of the physical universe, they must look deep into the night sky with a sharp eye. Unfortunately, looking into the night sky is like looking up from the bottom of a swimming pool. Turbulence in the upper atmosphere causes spatial and temporal anomalies 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)

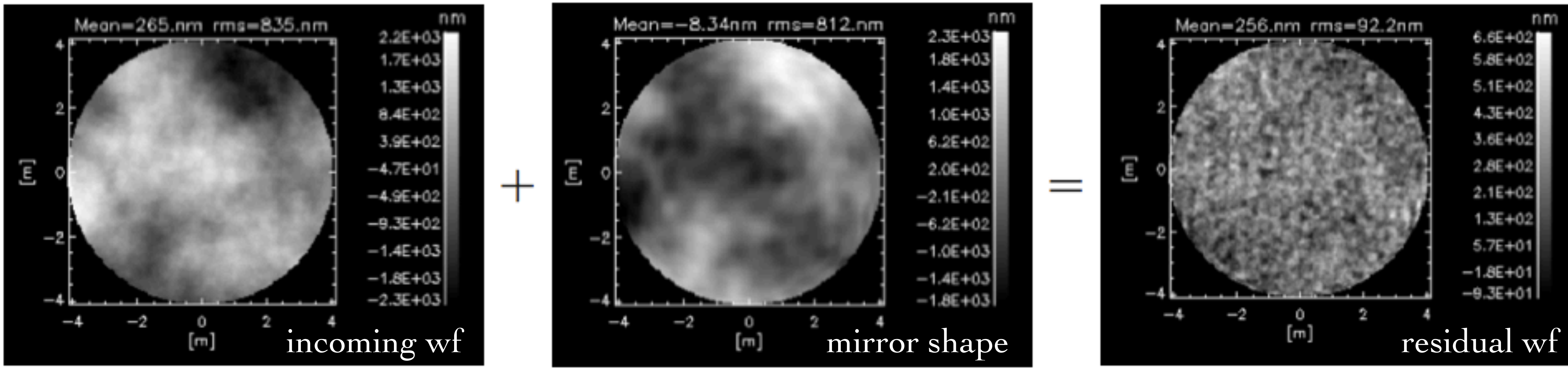


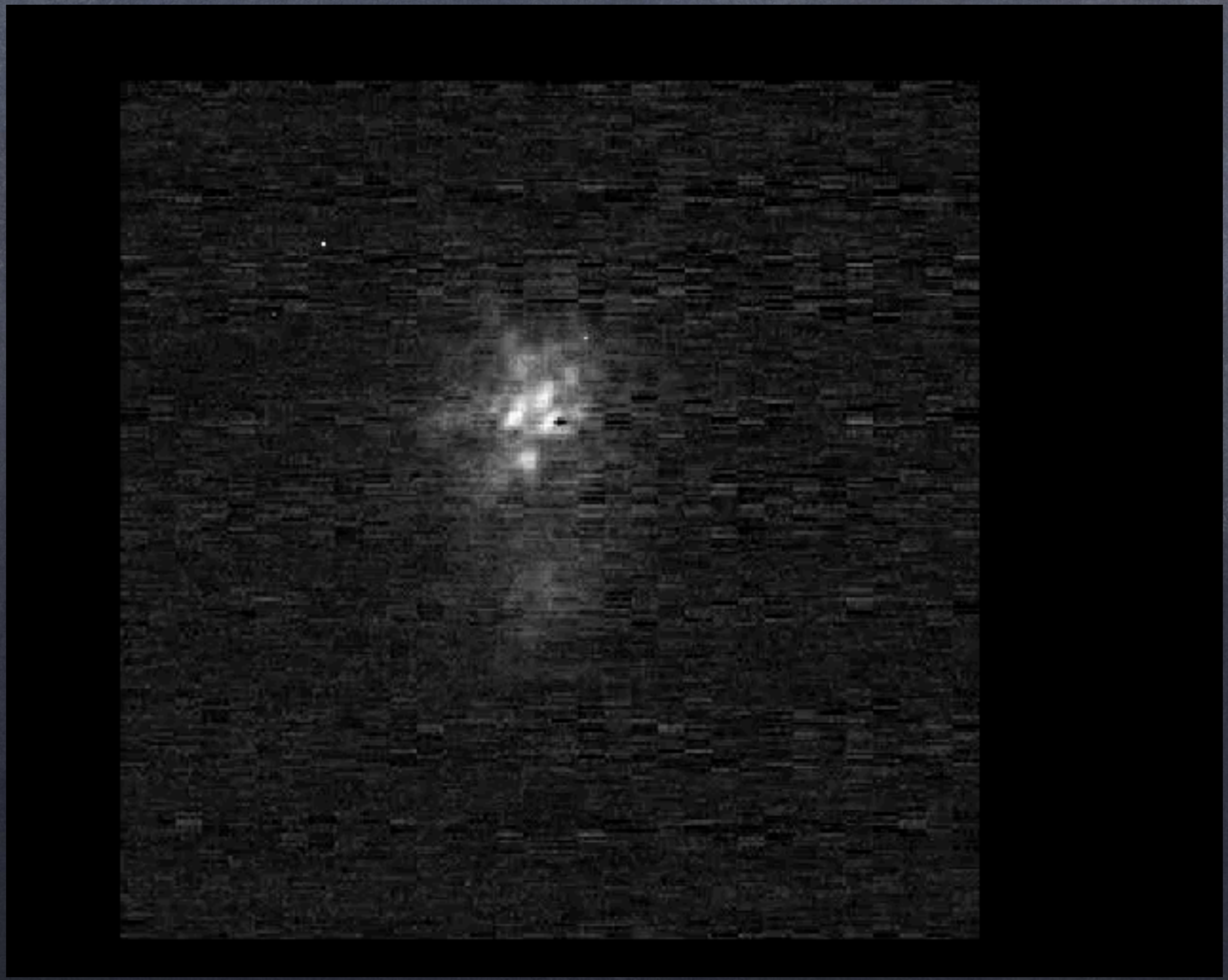
With Adaptive Optics corrected image

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

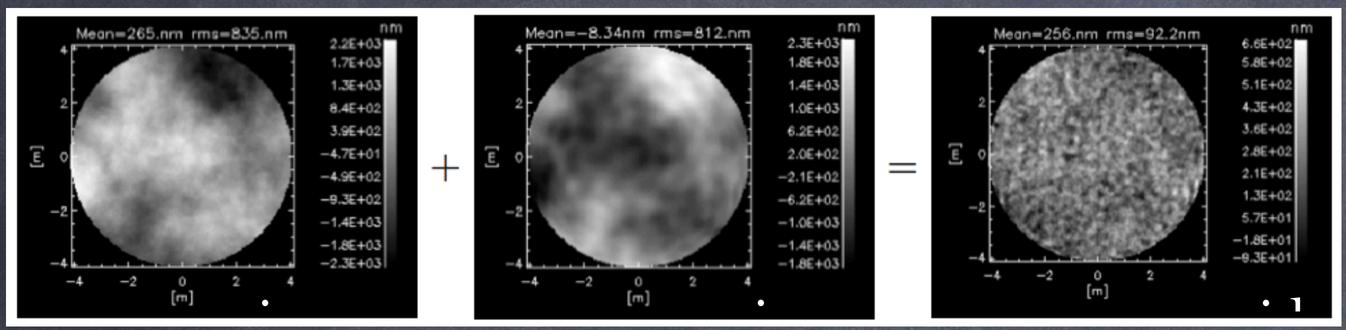
last update: 3 April 2007
editor of this page: Stefan Hippler

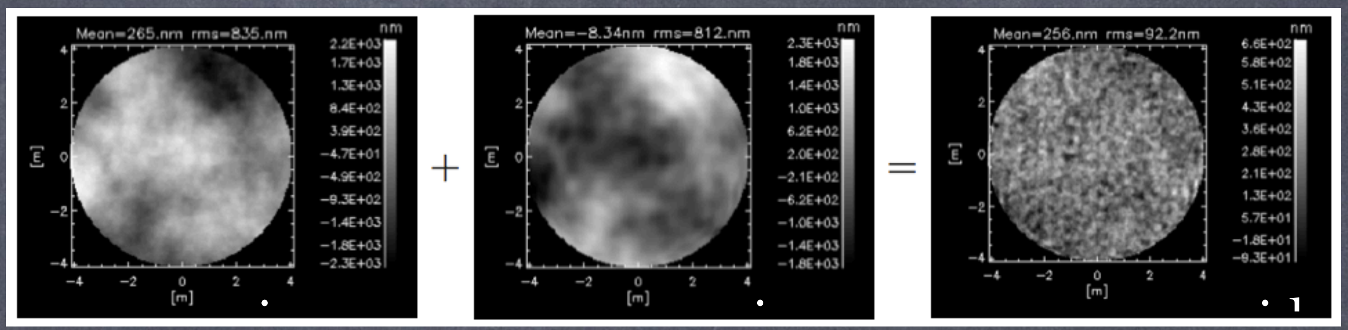
Adaptive optics - 5

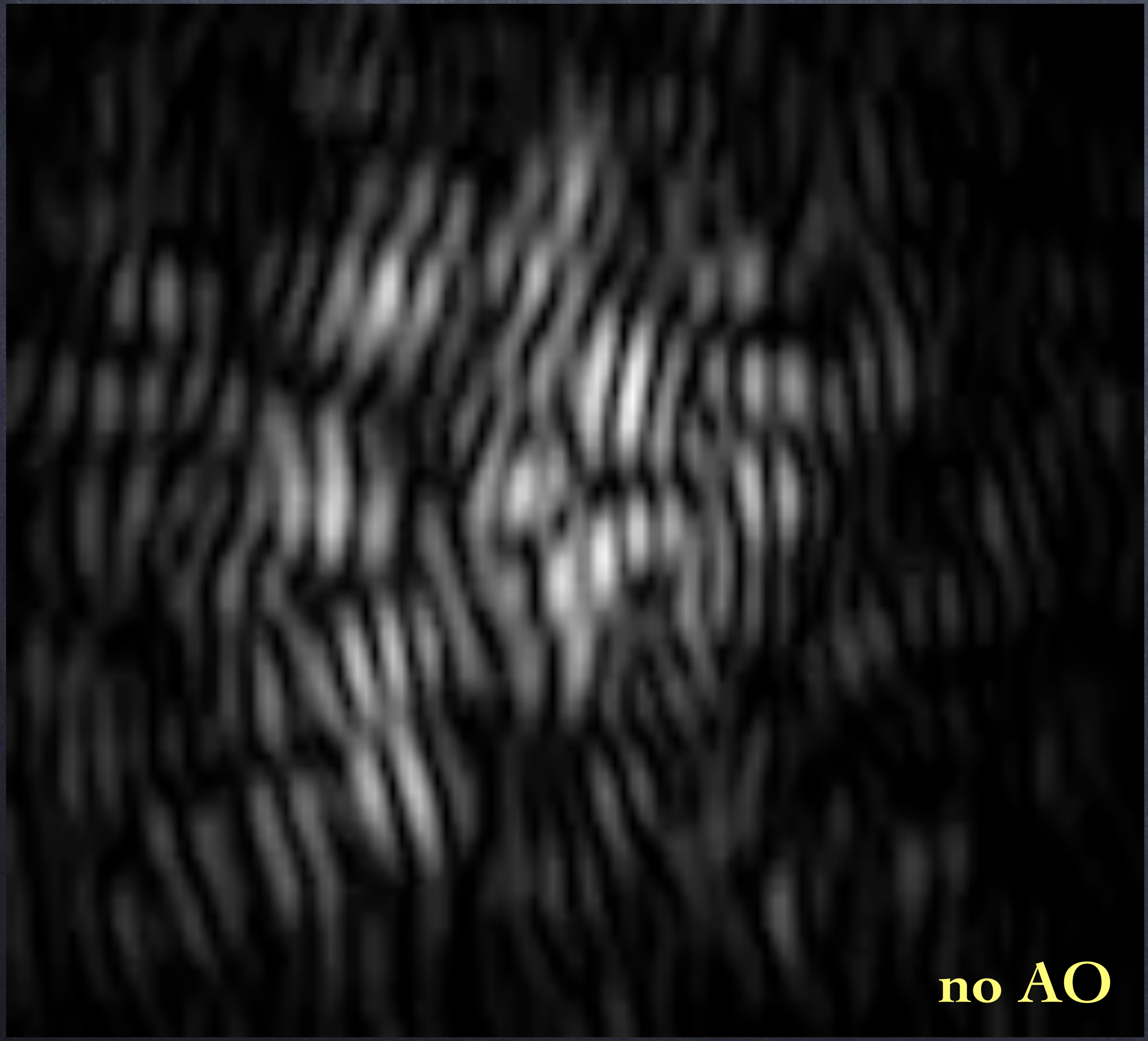


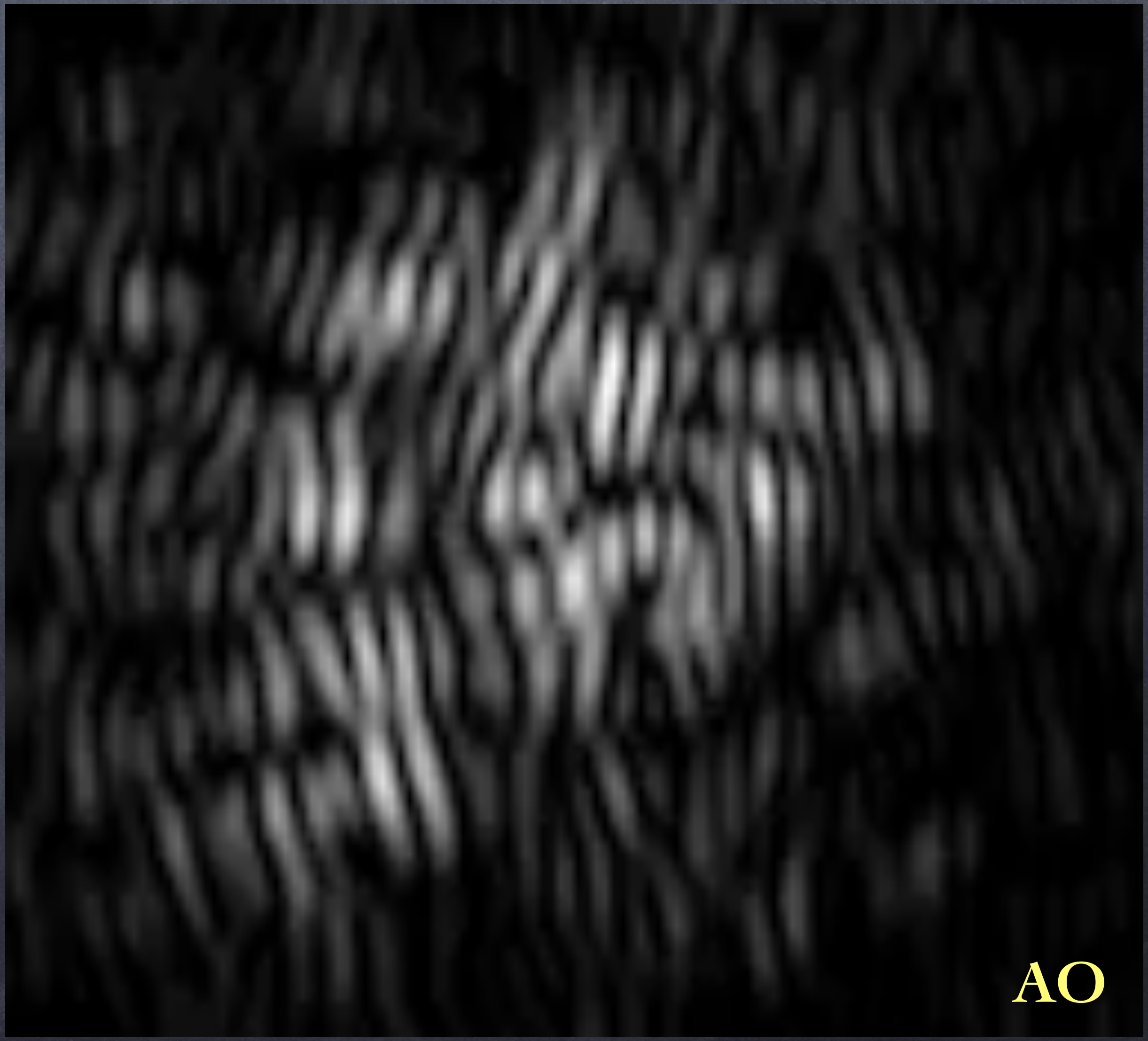


(Adaptive optics - 6)

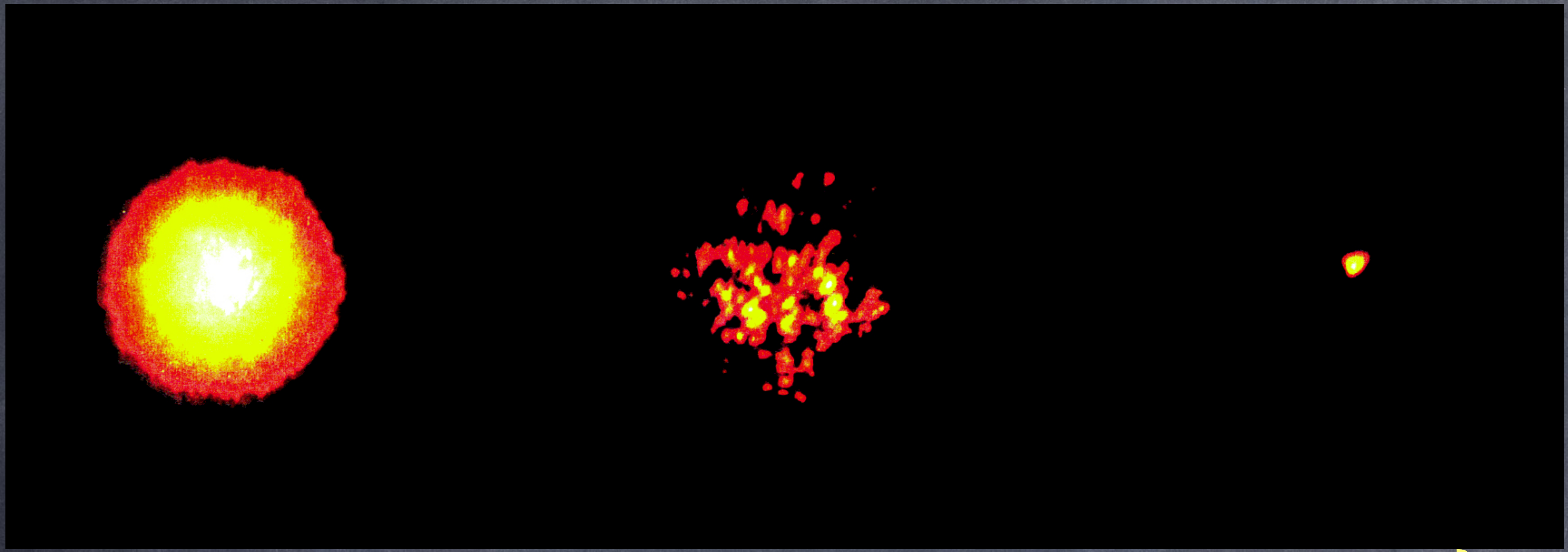




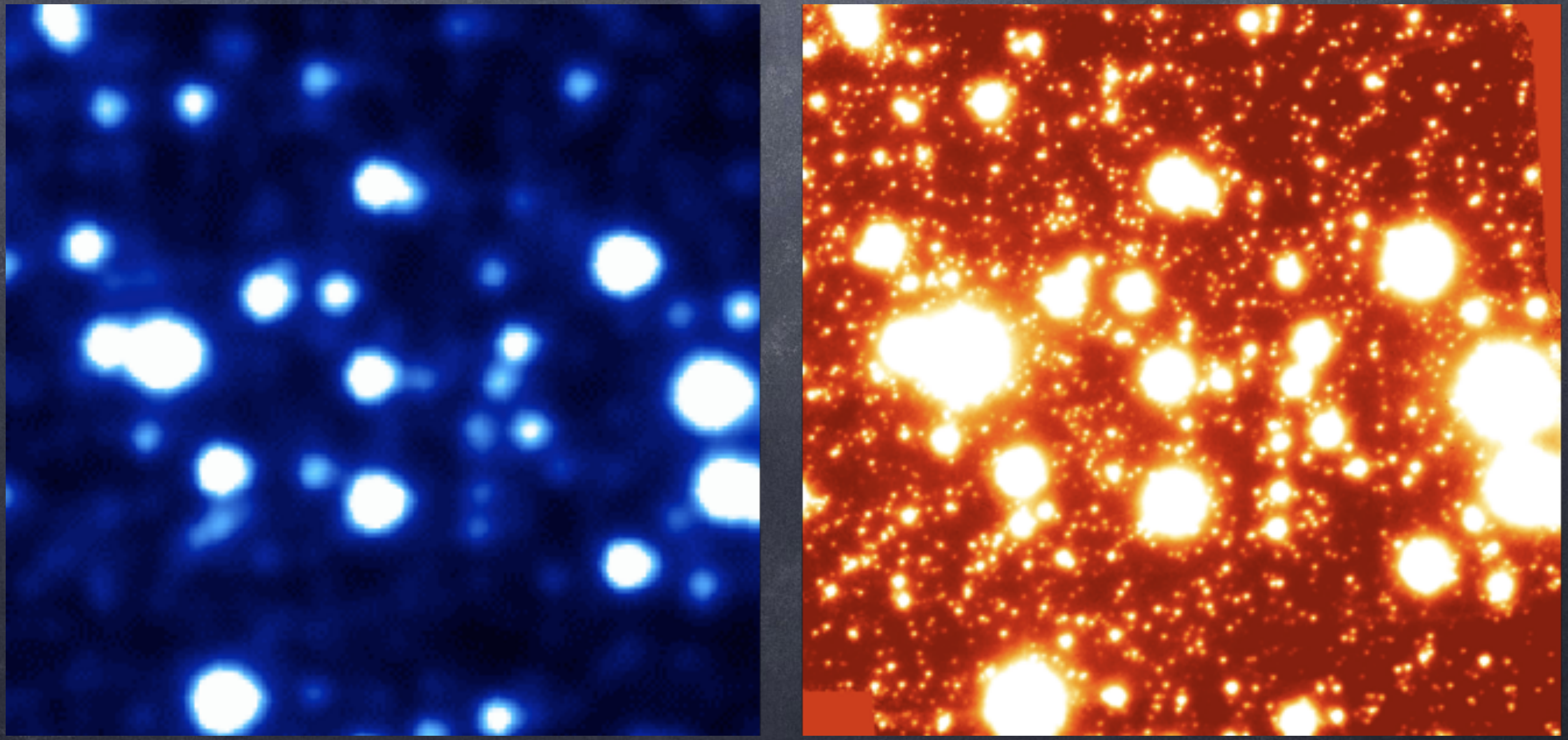




Adaptive optics - 7

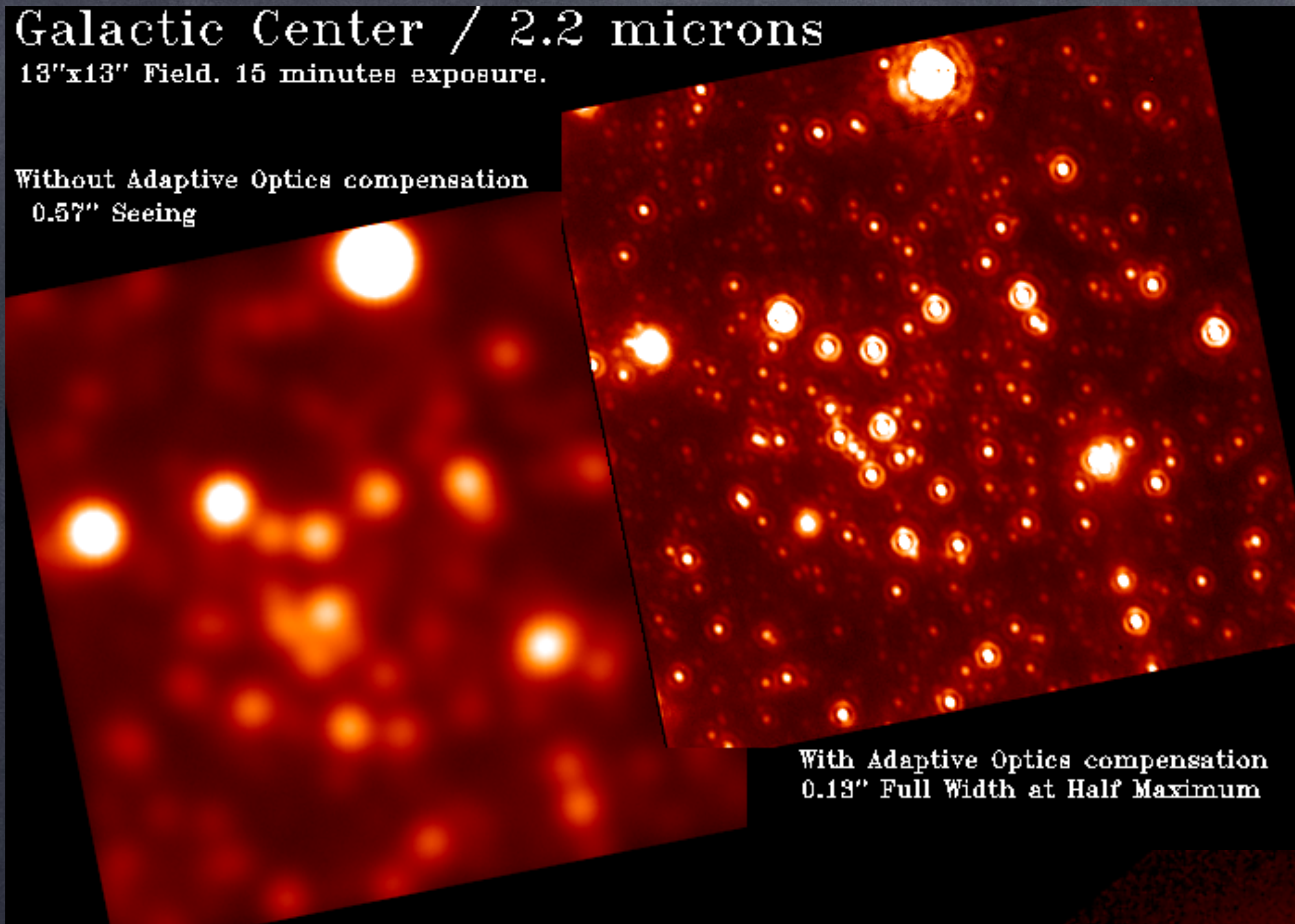


(Lick Observatory, 1-m telescope, left: FWHM≈1", right: FWHM≈λ/D)

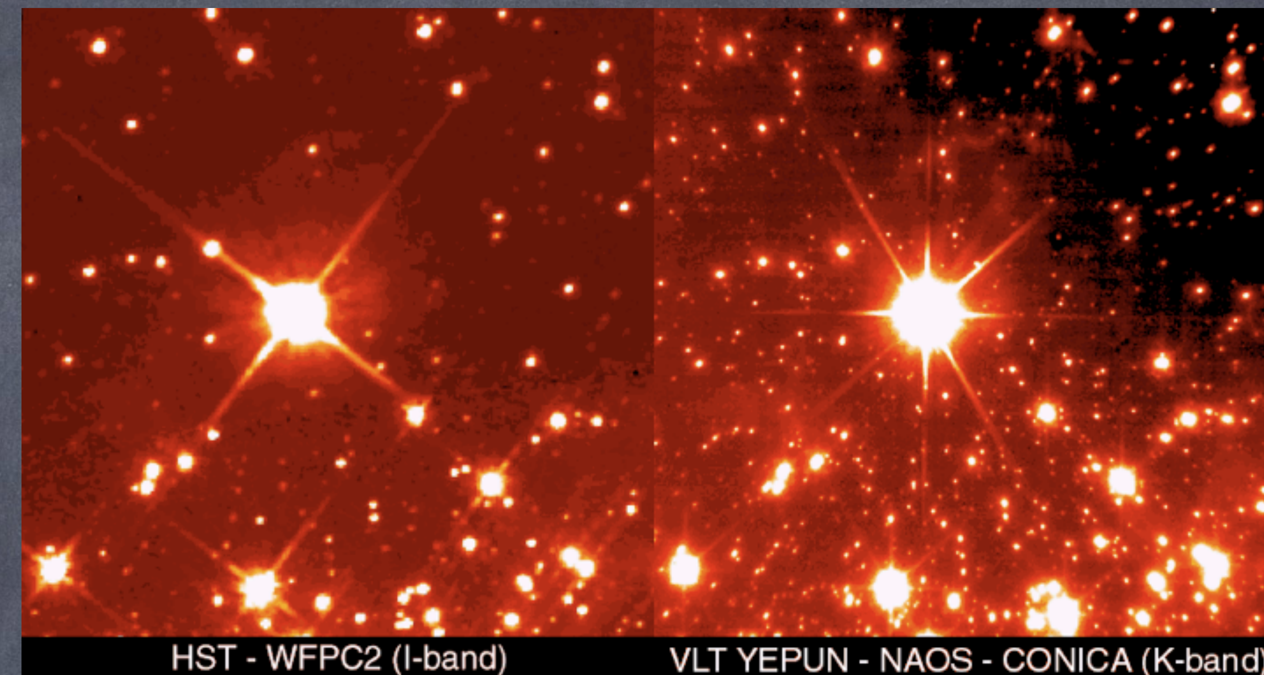


(Gemini Observatory, Hokupa'a+Quirc, left: FWHM≈0"85, right: FWHM≈0"09)

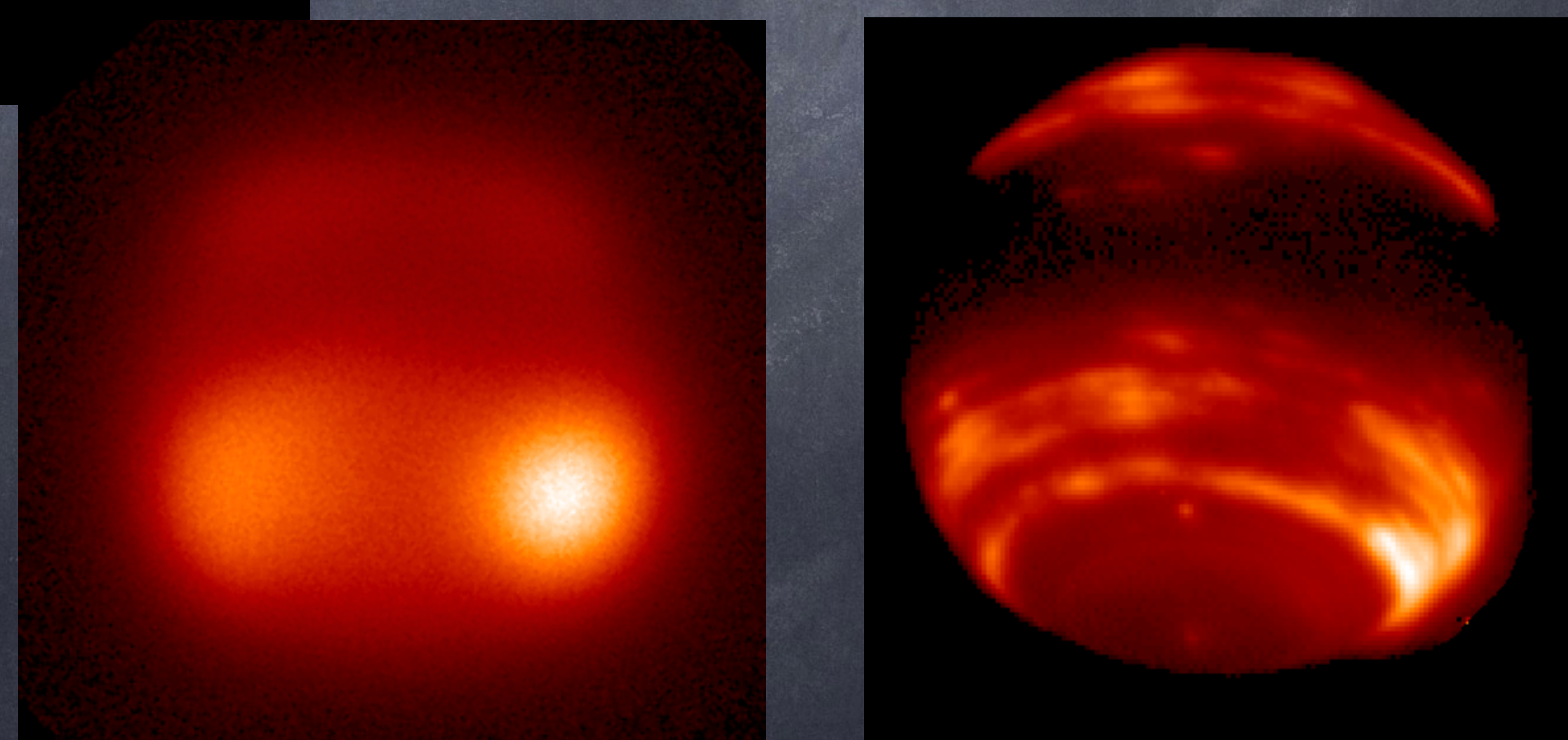
Adaptive optics - 8



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

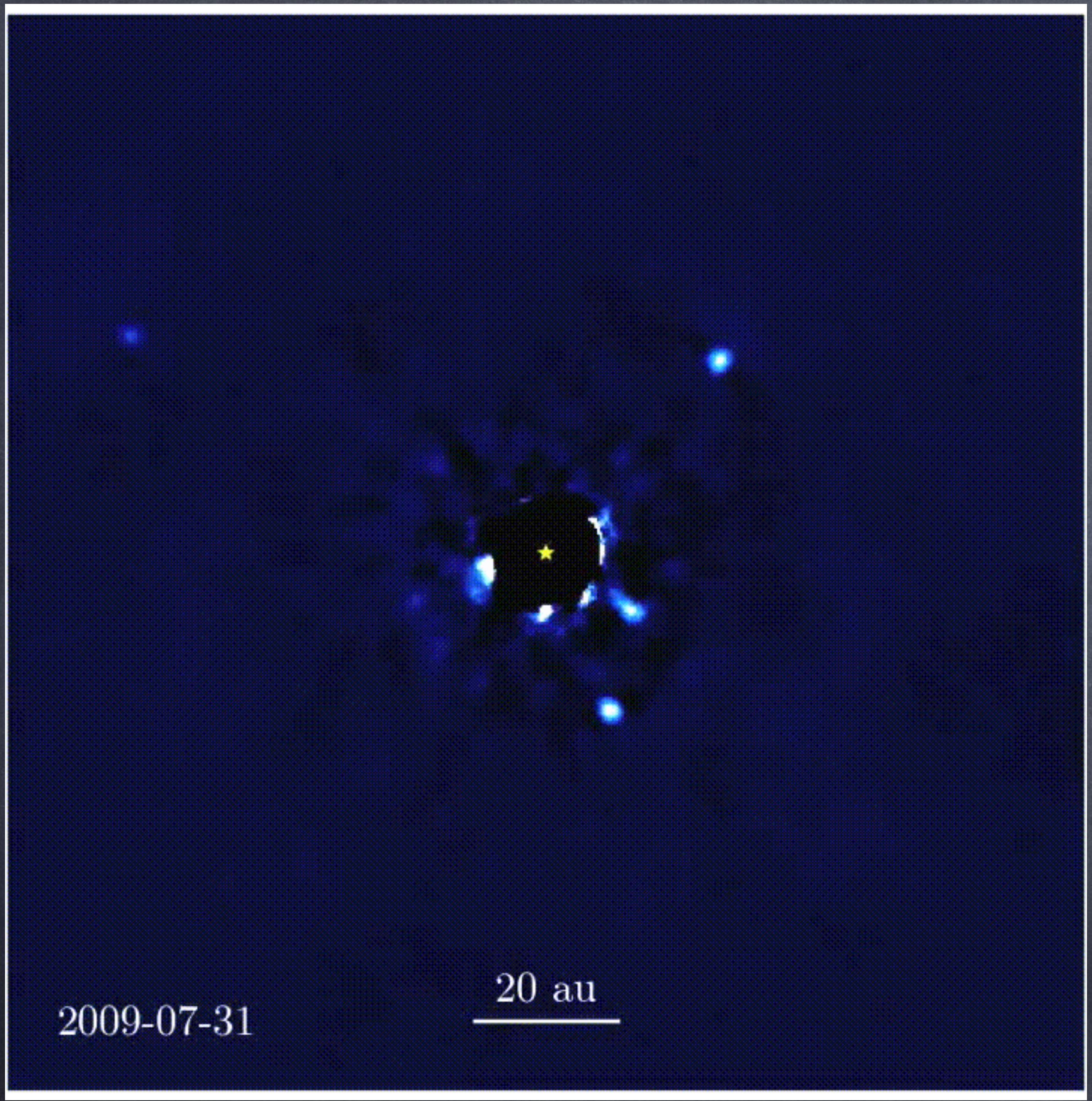


(HST vs. NACO/VLT)



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

Adaptive optics - 9



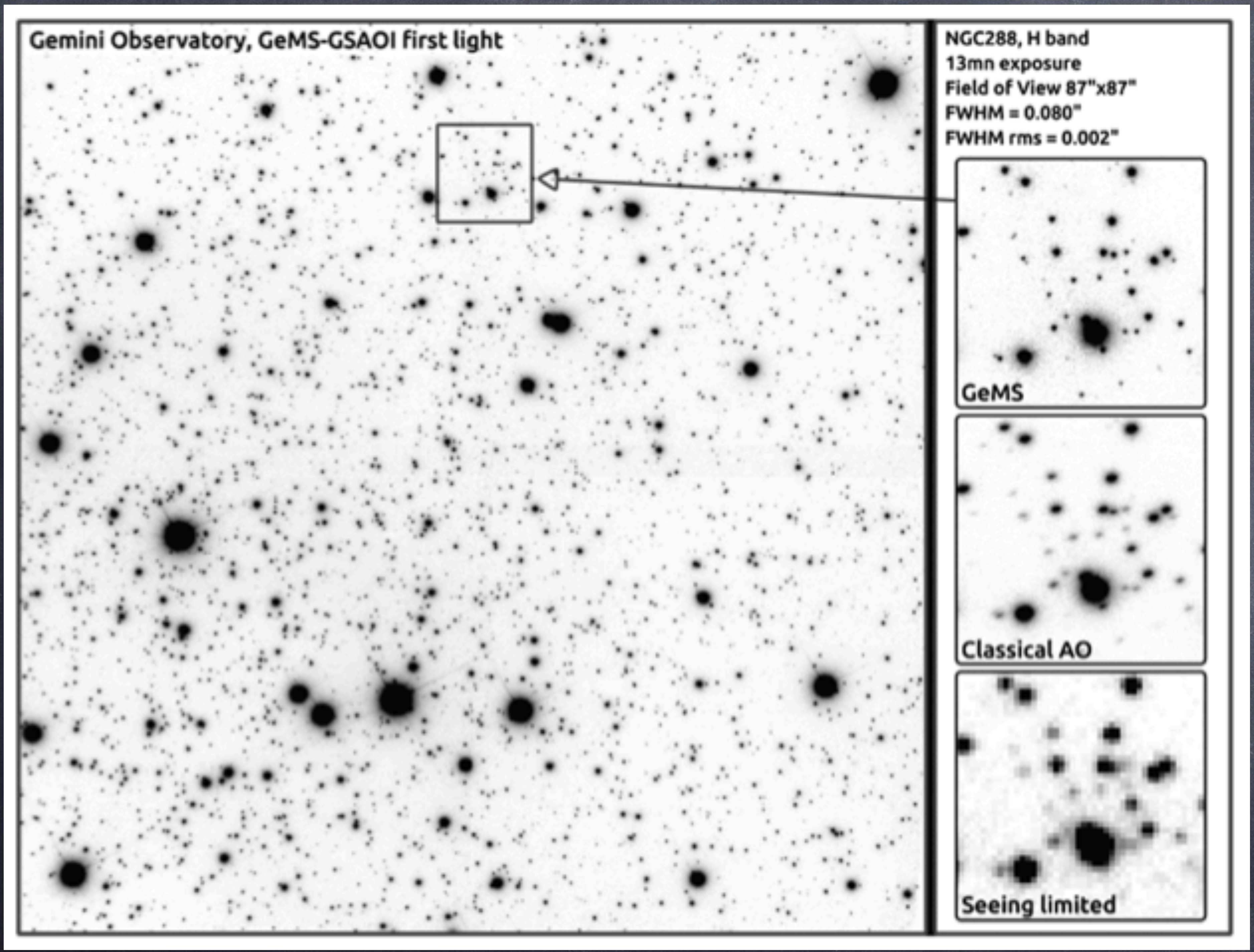
From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in 2013, from which 5 from (X)AO systems and 1 from HST.

<u>Context: detection & characterisation of exoplanets</u>

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



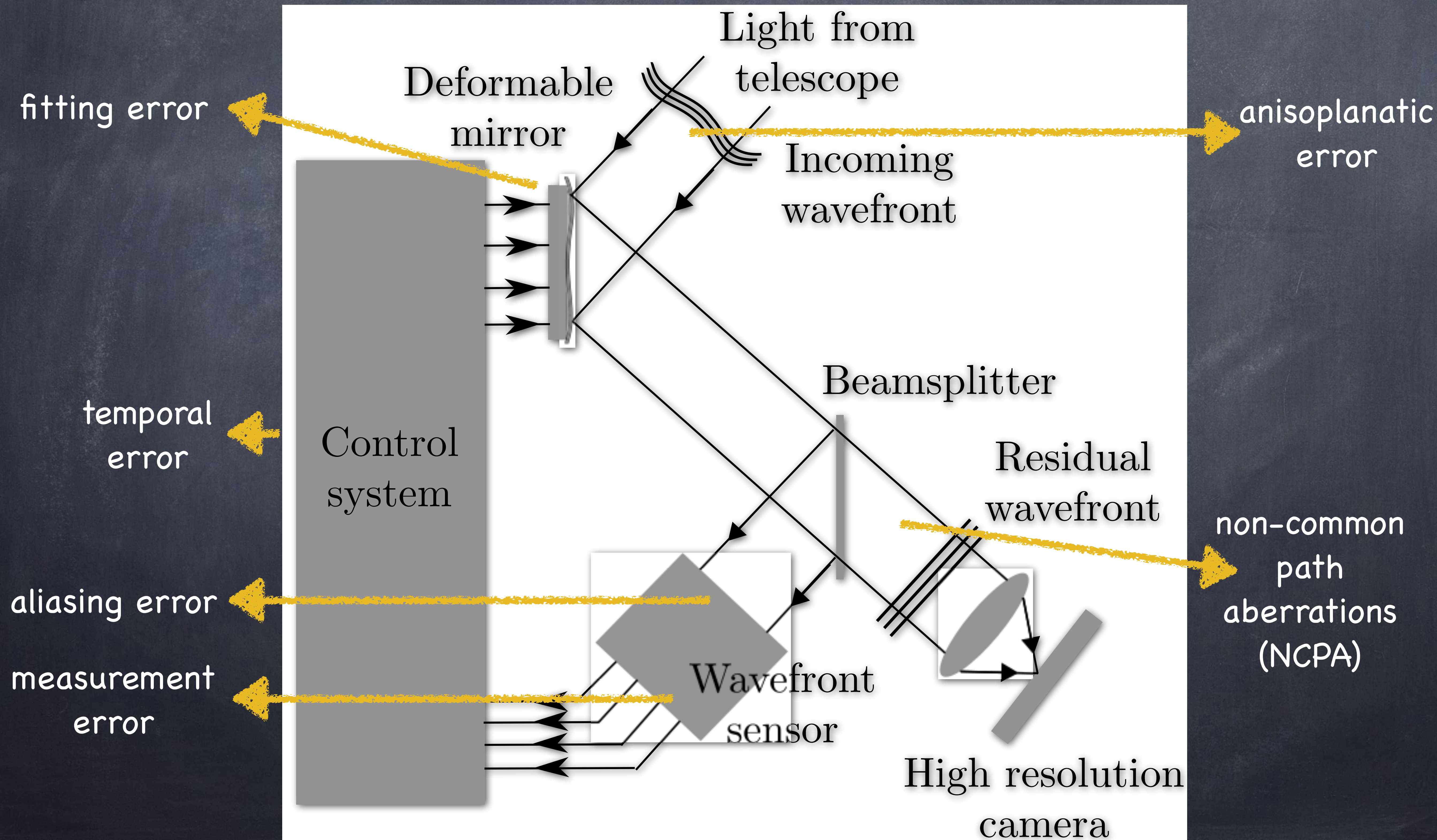
First-light image of GeMS, the MCAO system of Gemini
diffraction limit over a 2' square FoV - vs. a few arcsec !

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

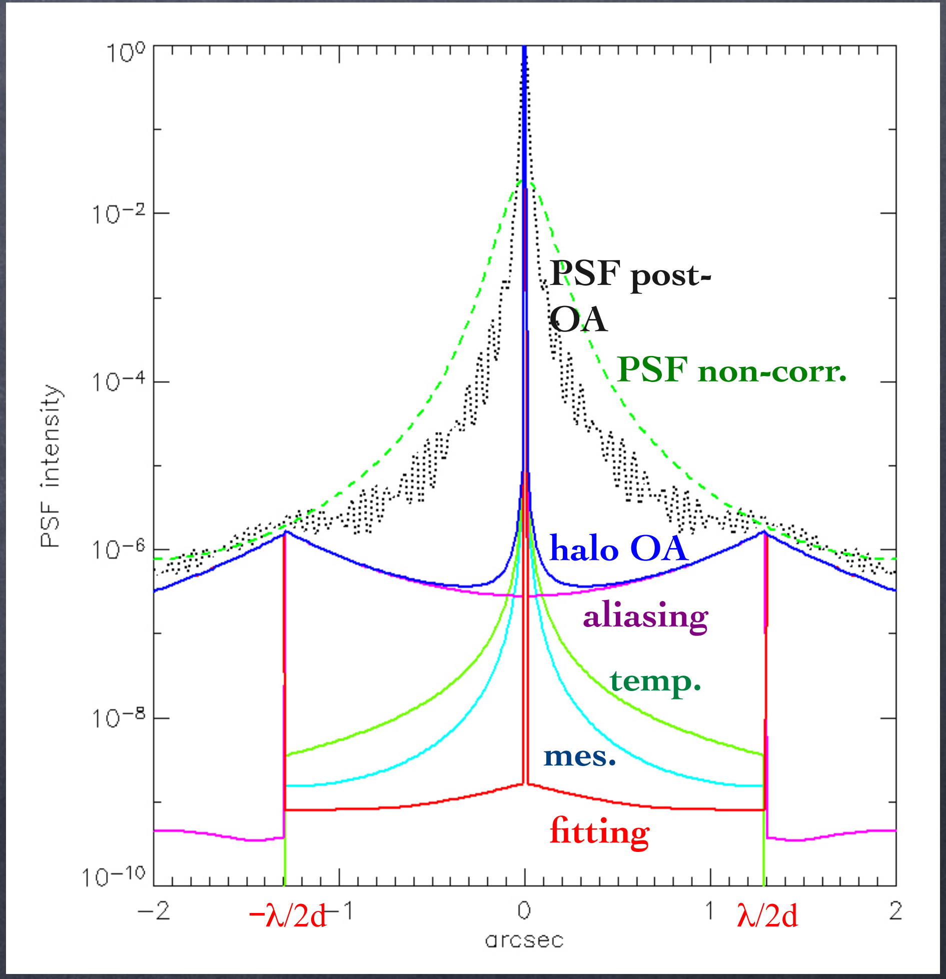


Post-AO error budget & PSF morphology - 2

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

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

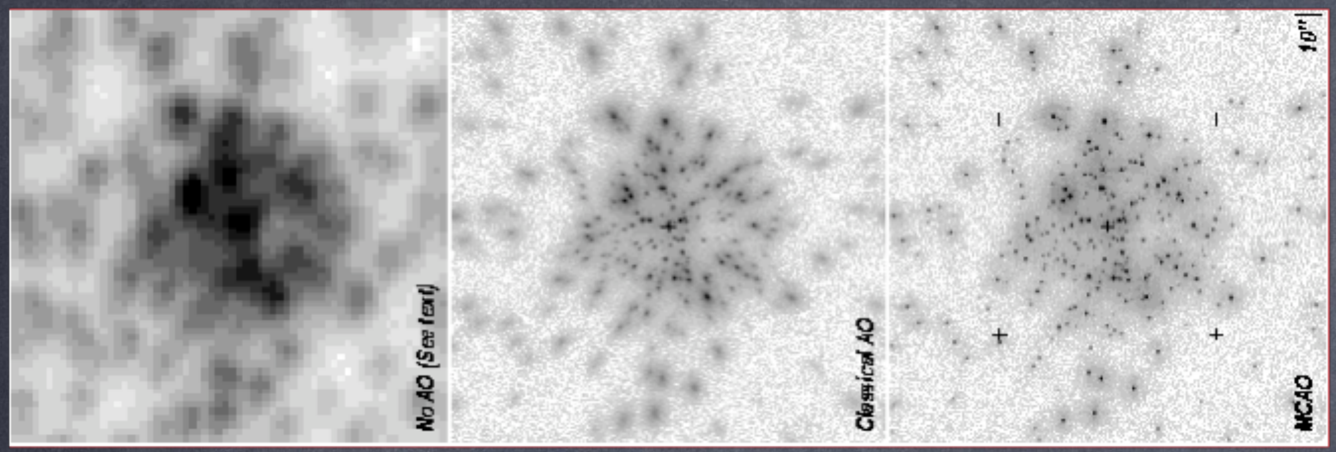
$$\sigma^2_{\mathrm{others}} = \sigma^2_{\mathrm{NCPA}} + \ldots$$



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

Anisoplanatic error - 1

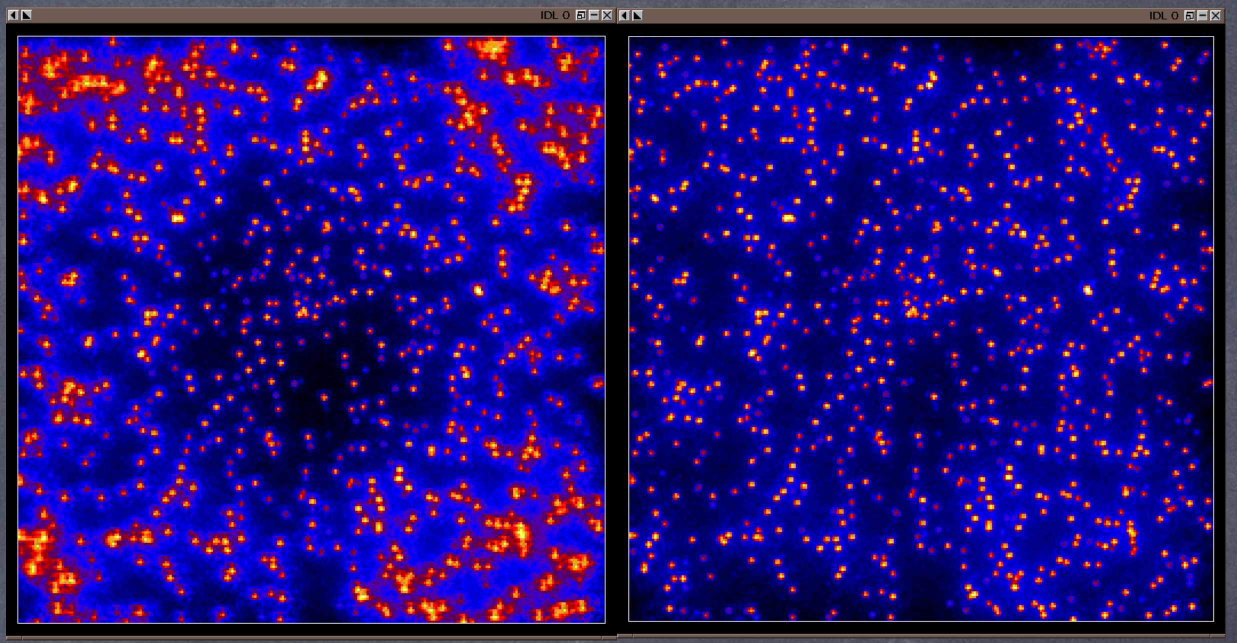
165"



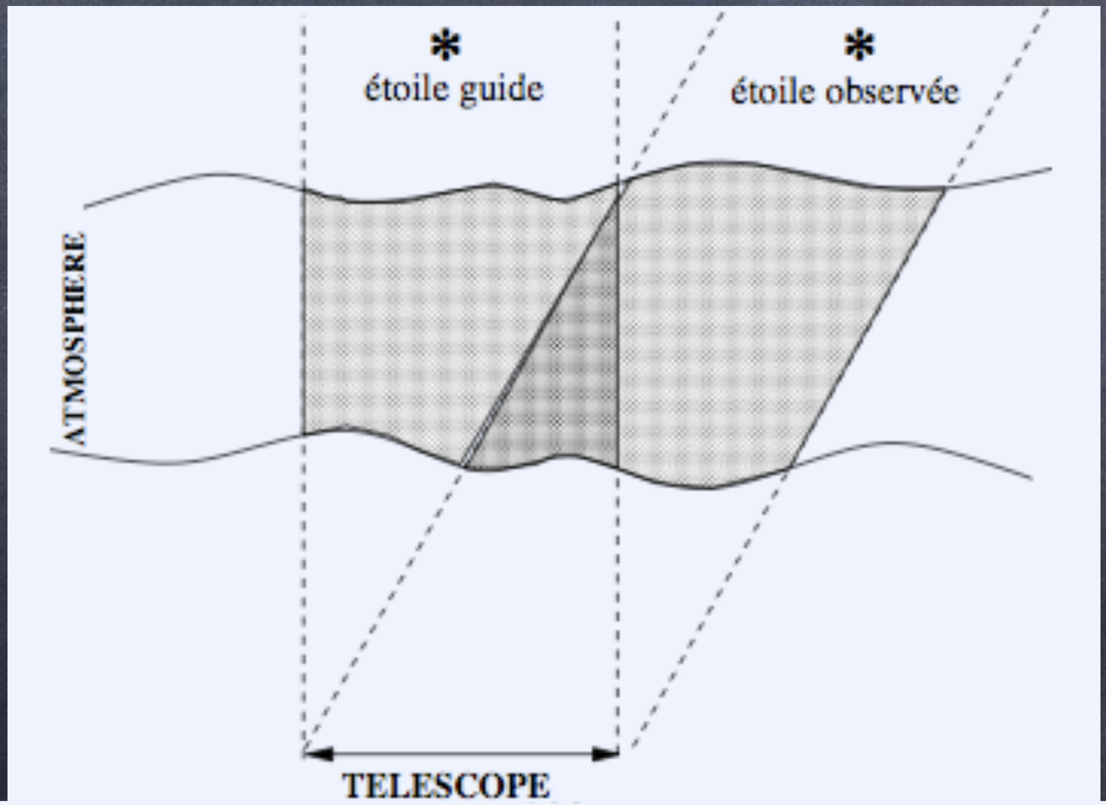
No AO

classical AO
(1 DM, 1 NGS)

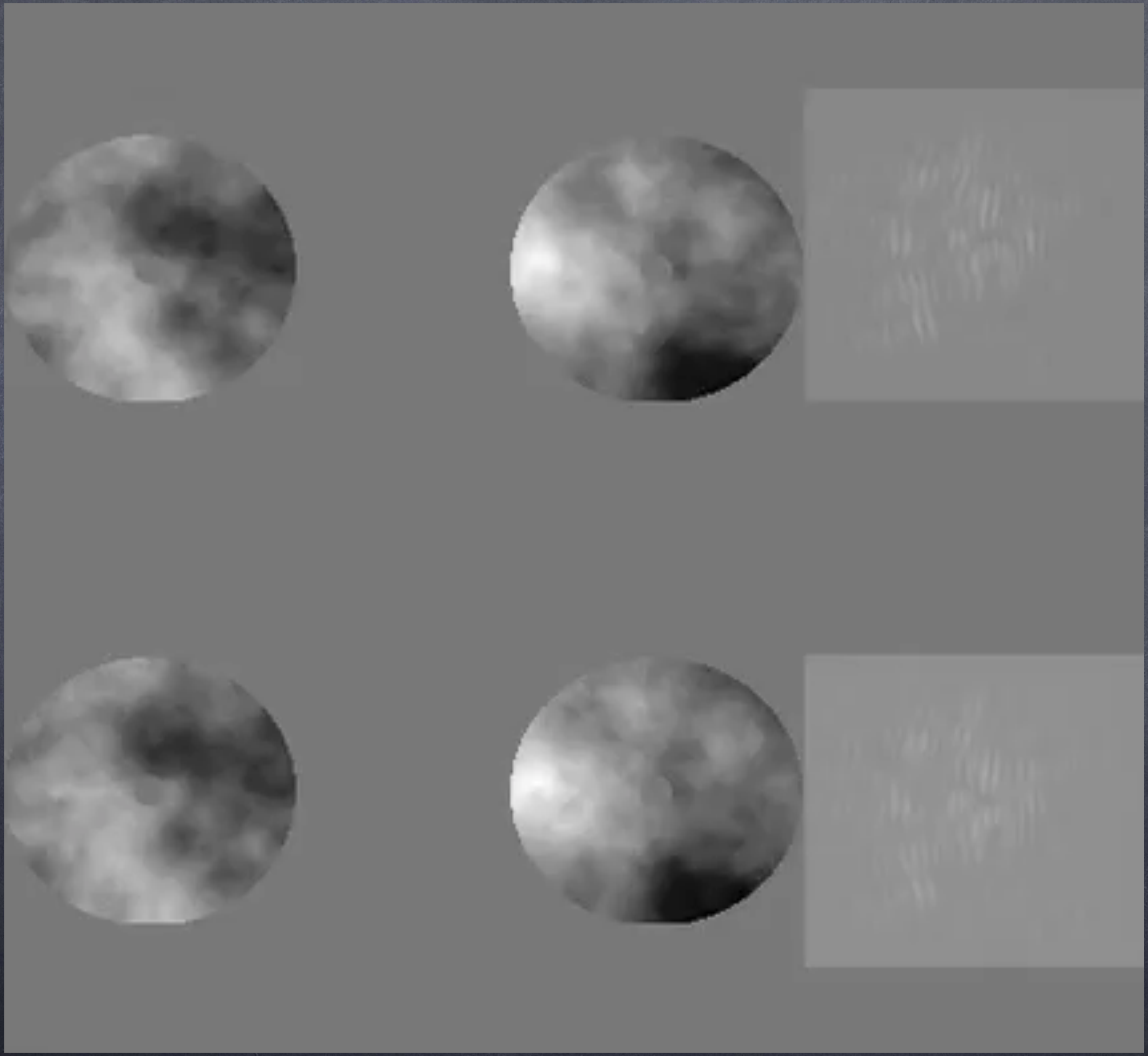
MCAO
(2 DM, 5 NGS)



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



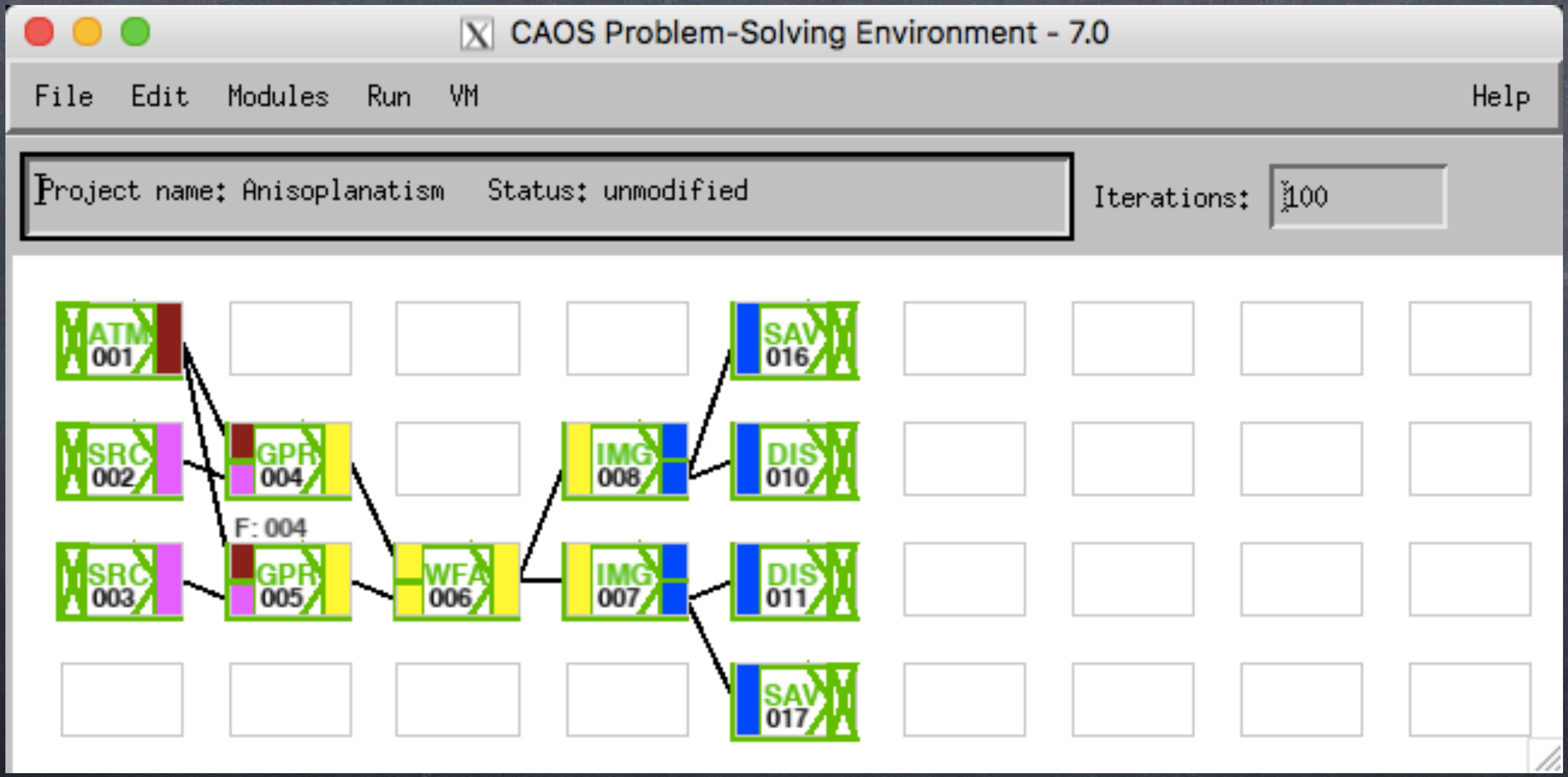
(Anisoplanatic error - 2)



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
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

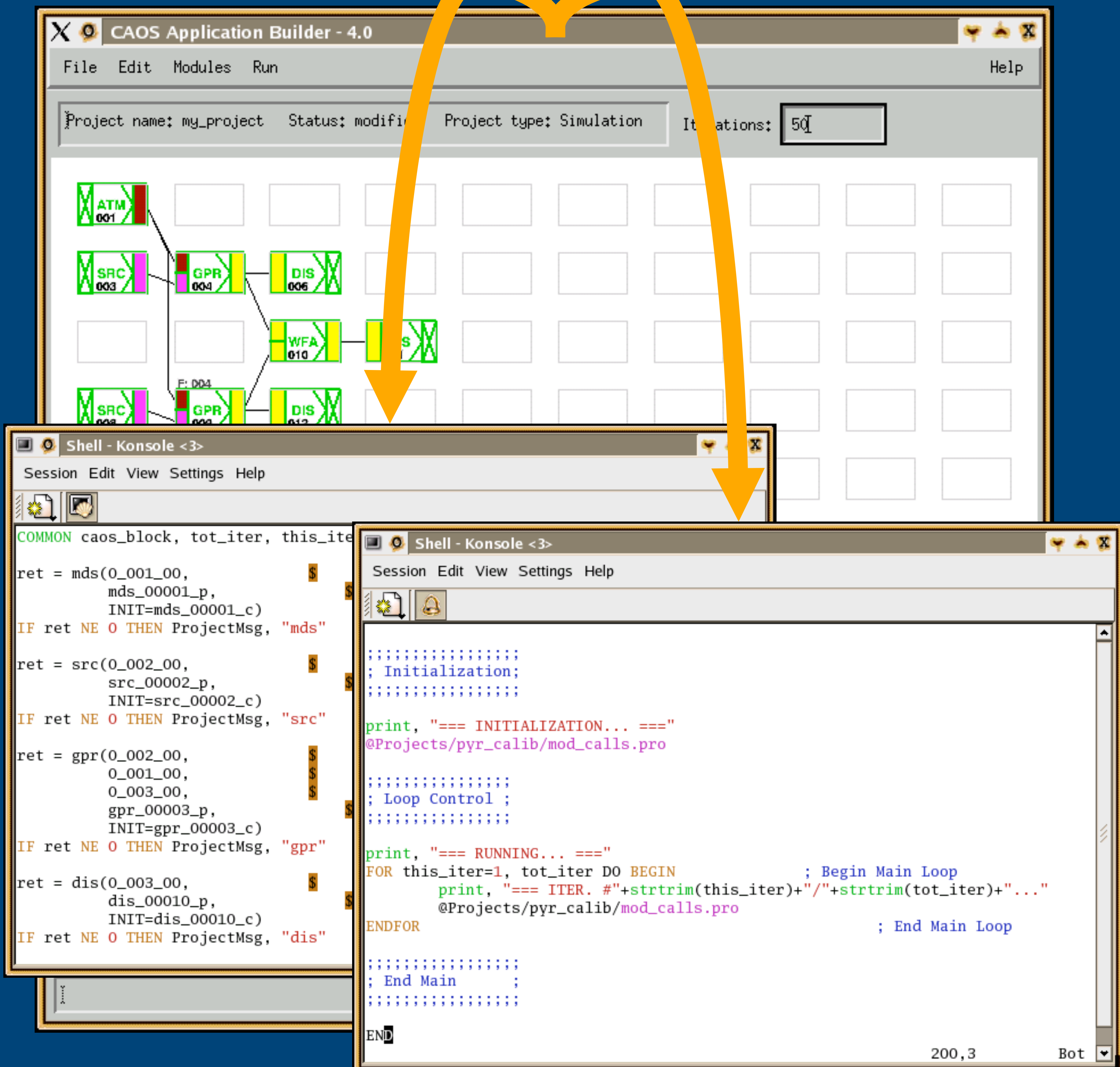
packages

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

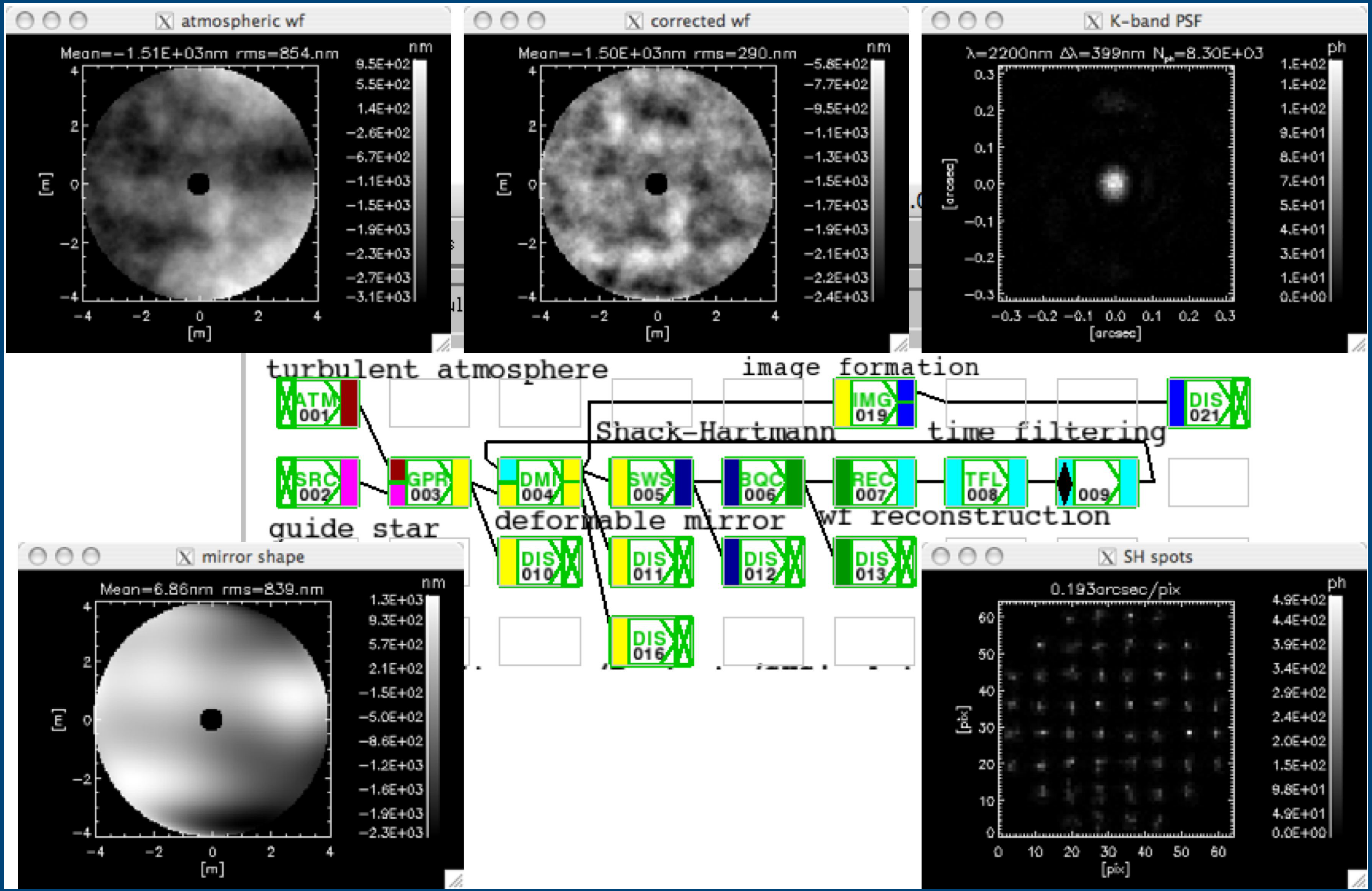
All (*public!*) parts of the CAOS PSE are available for download:

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
[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