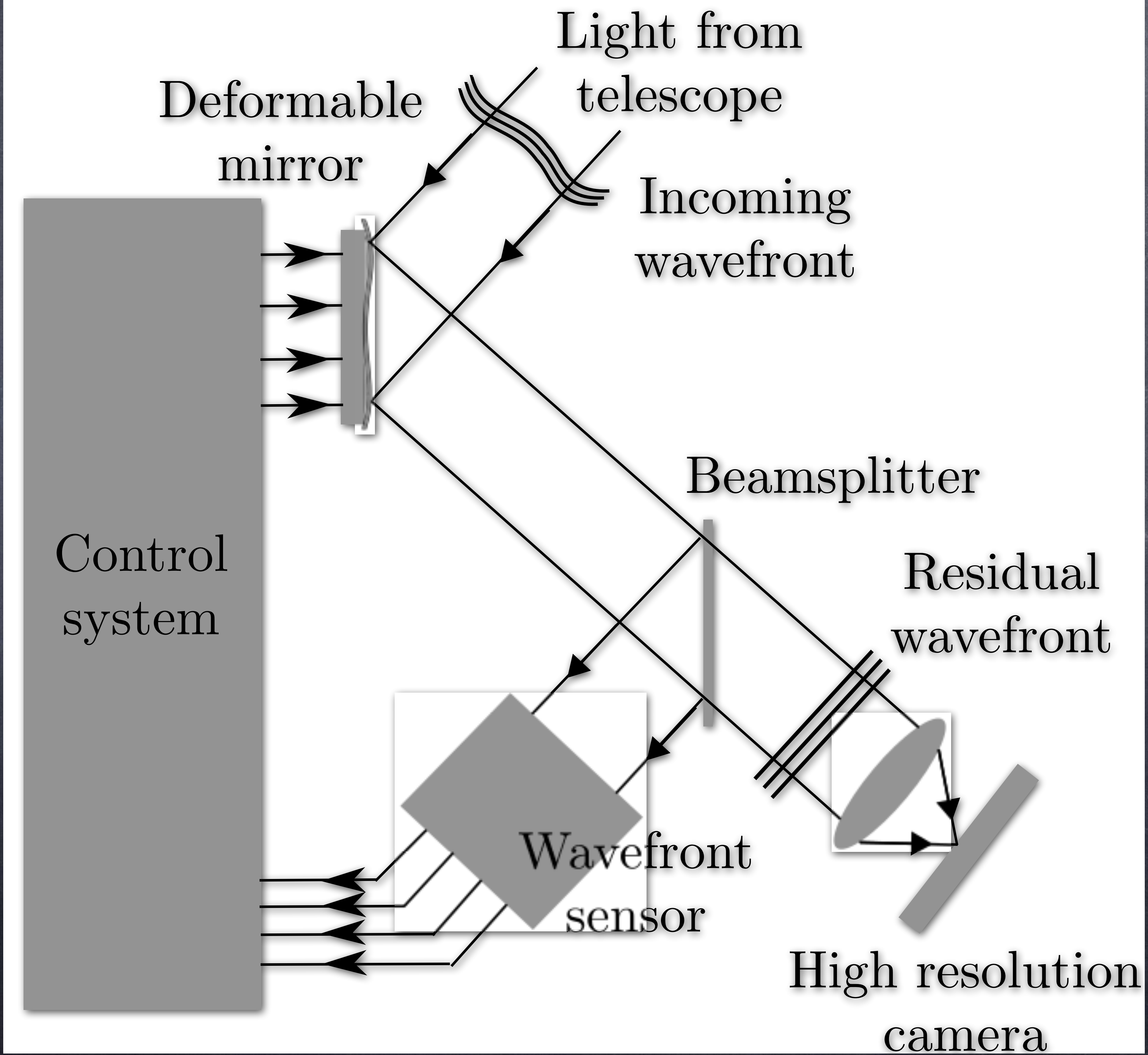
# Adaptive optics — 01

# Adaptive optics — 02



# Adaptive optics — 03

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

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

# Adaptive optics — 04

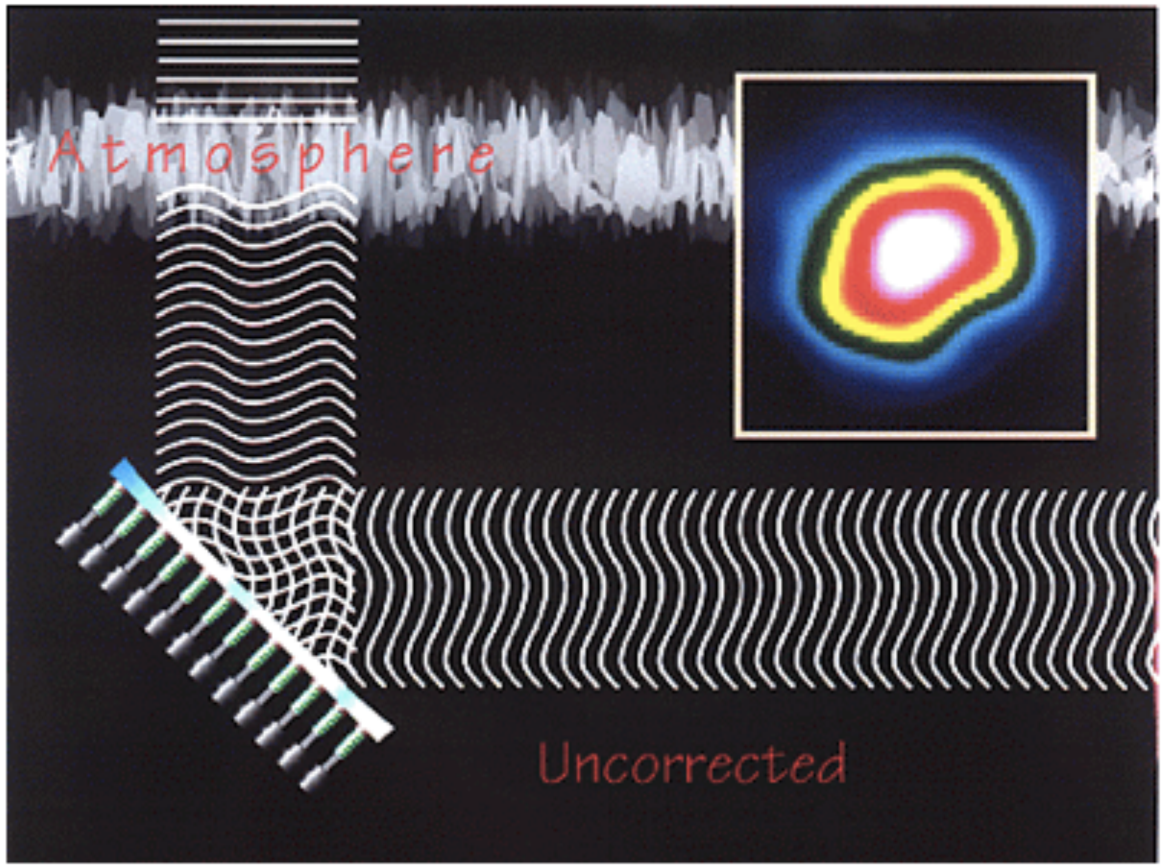
## Introduction to Adaptive Optics

Credits: ESO and Jennifer Lotz

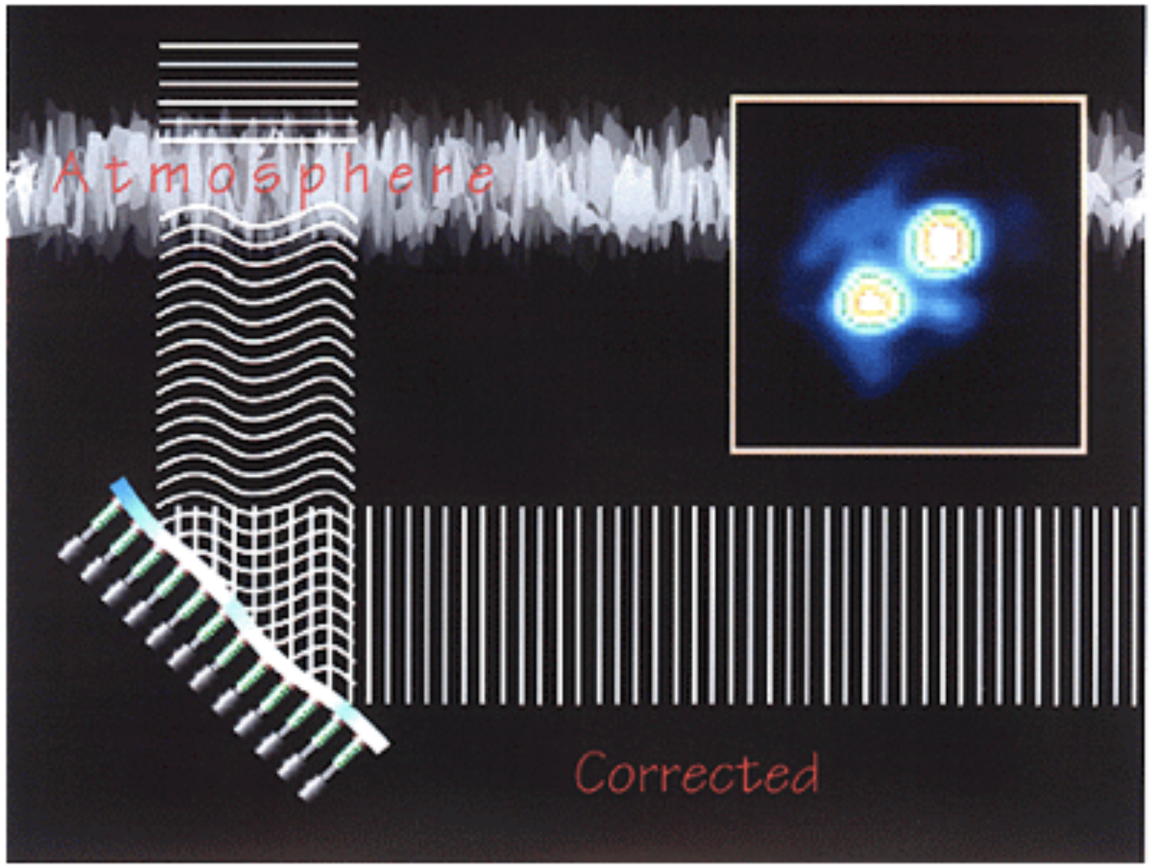
**As astronomers** attempt to understand the limits of the physical universe, they must look deep into the night sky with a sharp eye. Unfortunately, looking into the night sky is like looking up from the bottom of a swimming pool. Turbulence in the upper atmosphere causes spatial and temporal anomalies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



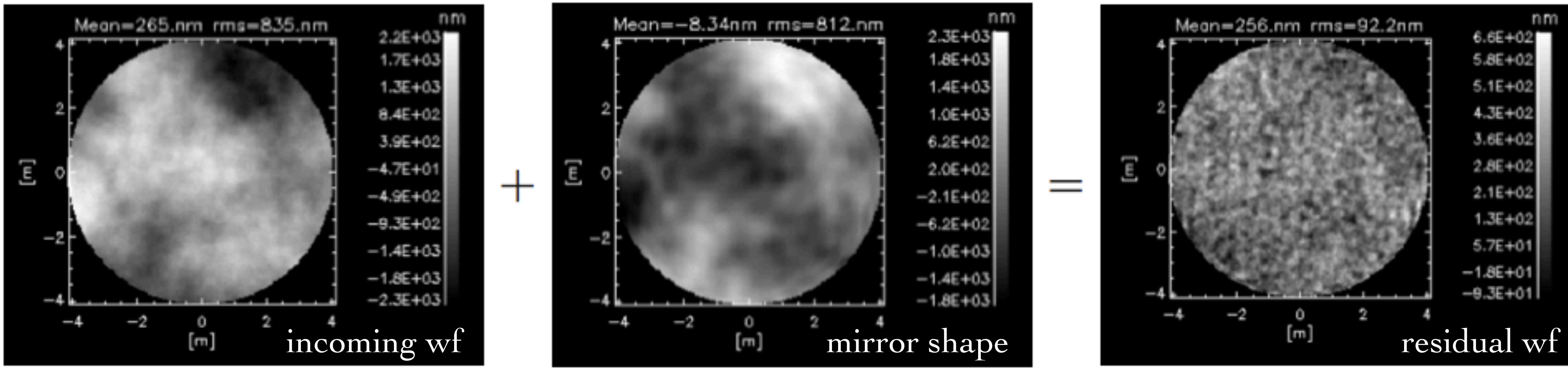

With Adaptive Optics corrected image

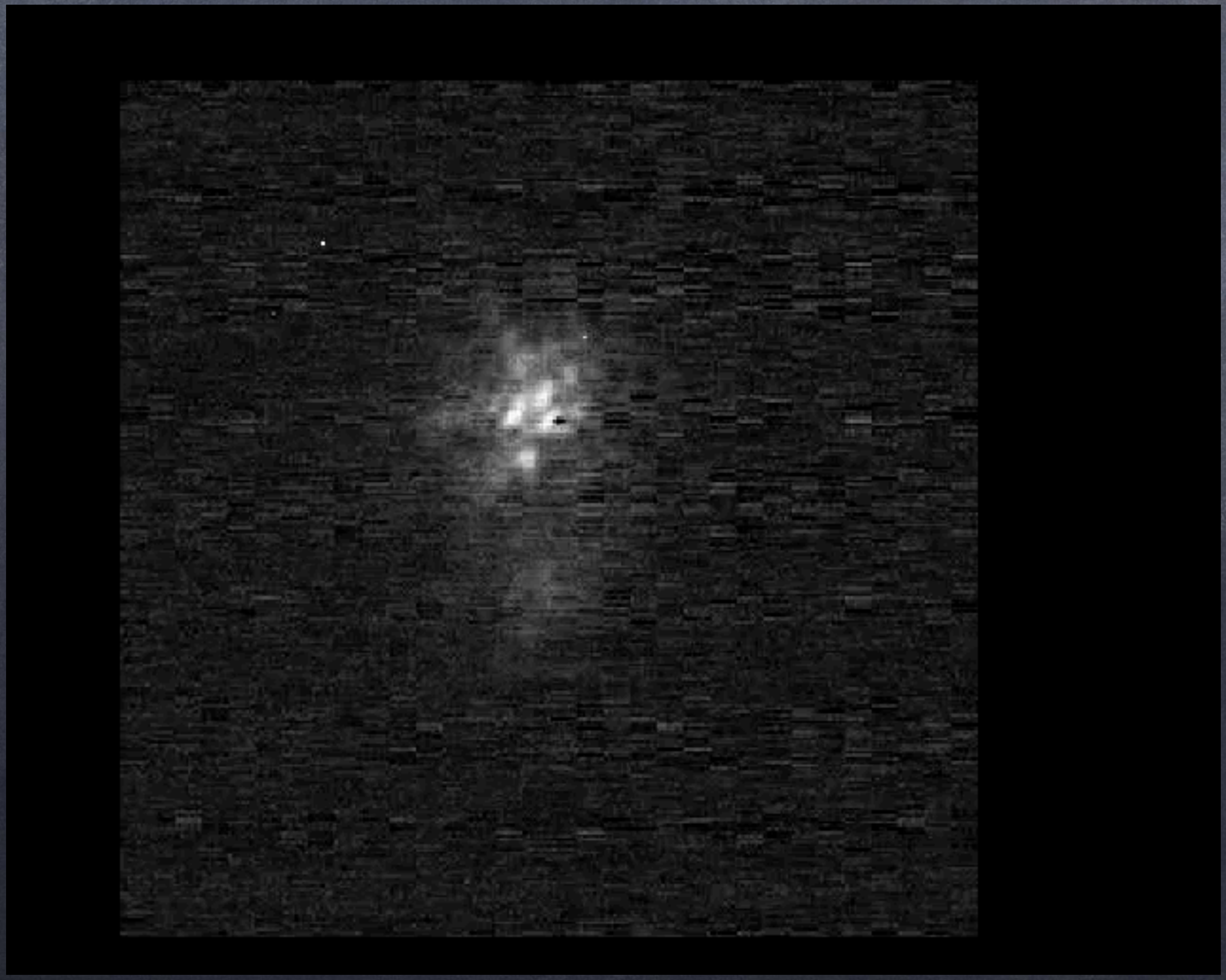
For more information see Adaptive Optics Tutorial in german or english by Stefan Hippler and Andrei Tokovinin.



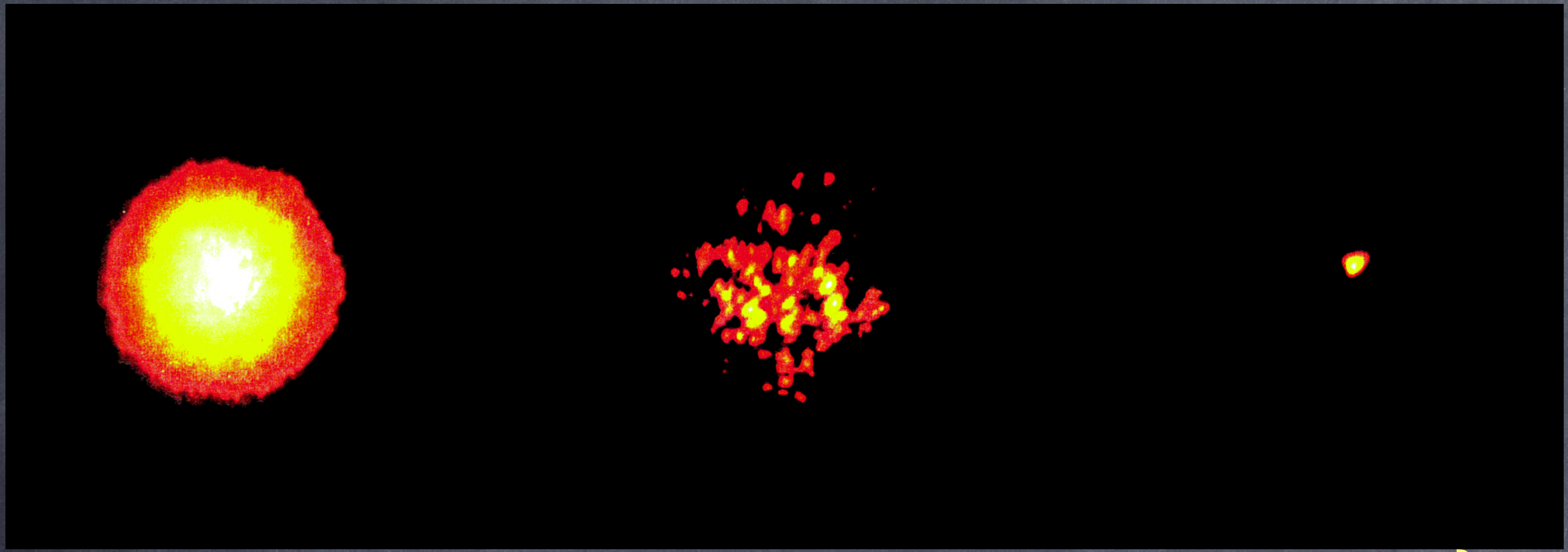
last update: 3 April 2007
editor of this page: Stefan Hippler

# Adaptive optics — 05

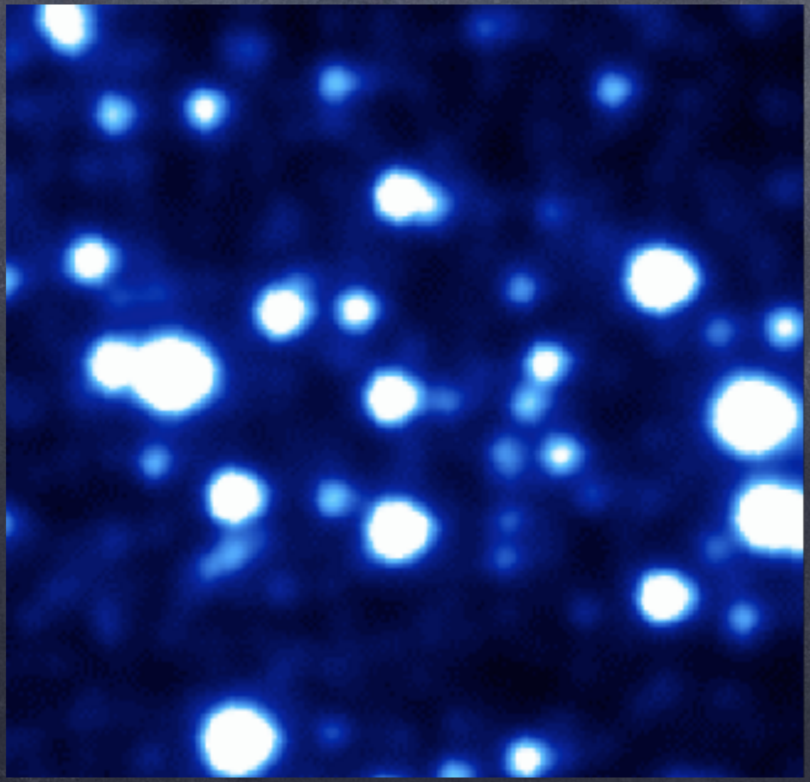


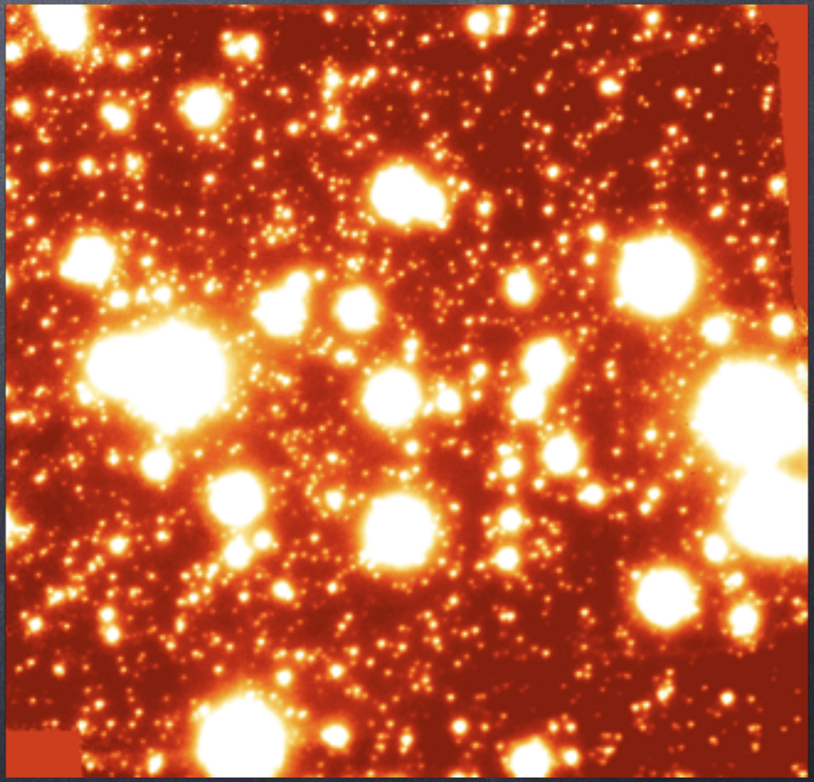



# Adaptive optics — 07



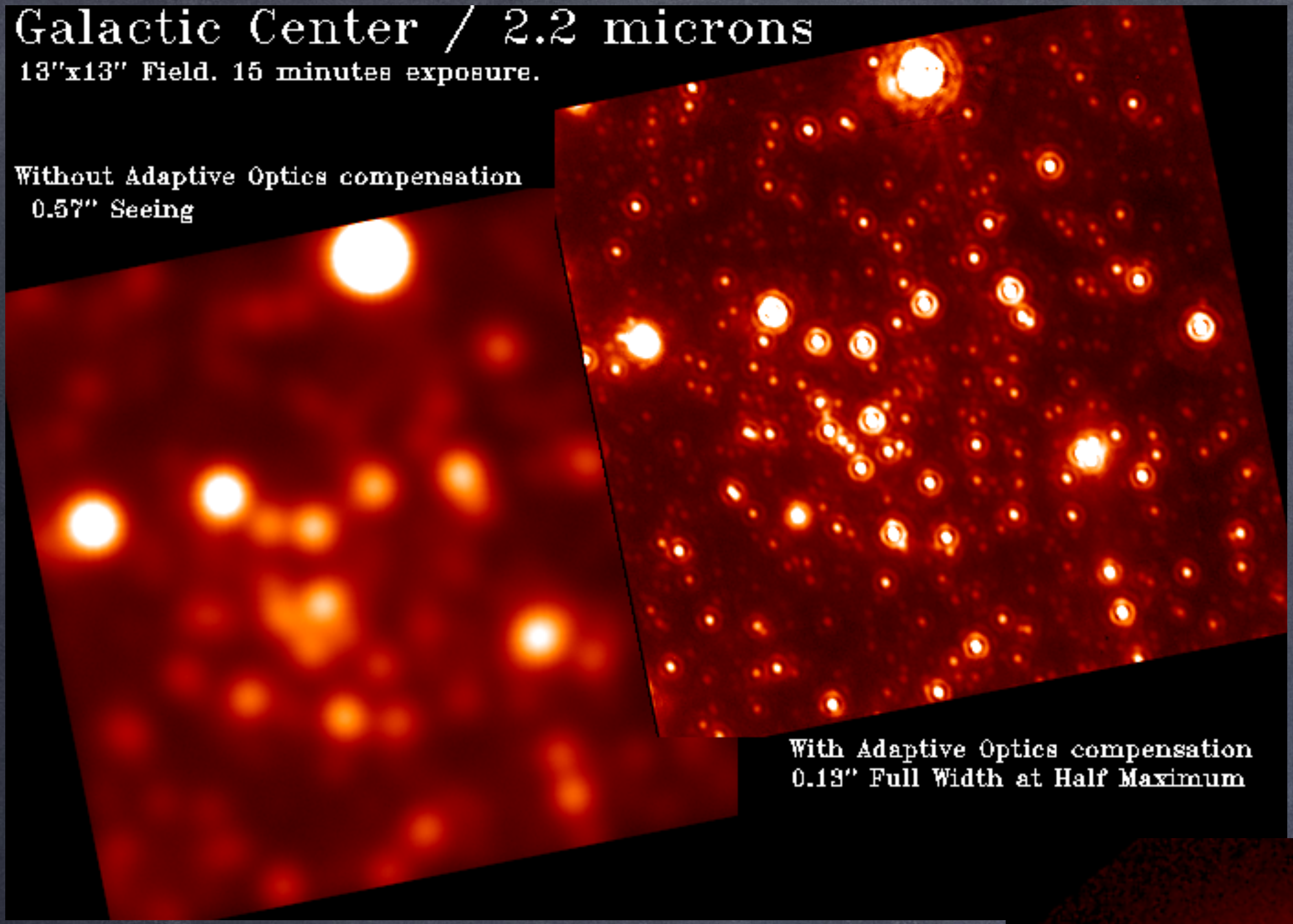
**(Lick Observatory, 1-m telescope, left: FWHM≈1", right: FWHM≈λ/D)**



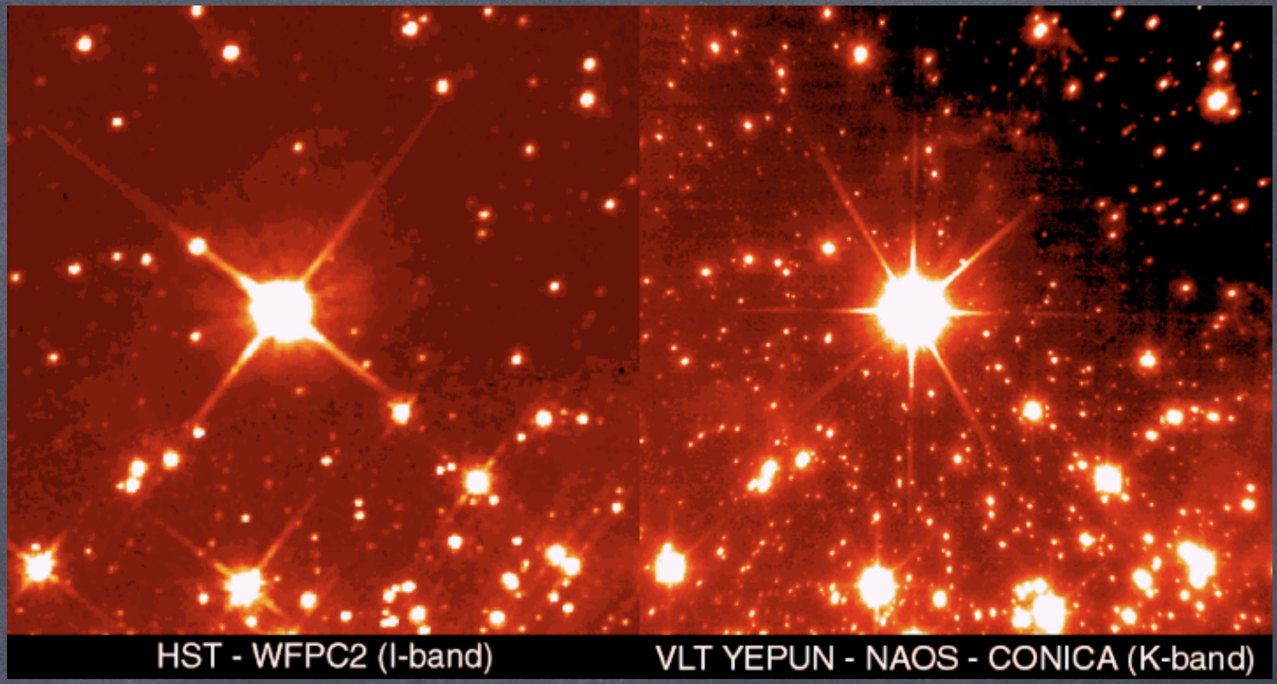


**(Gemini Observatory, Hokupa'a+Quirc, left: FWHM≈0"85, right: FWHM≈0"09)**

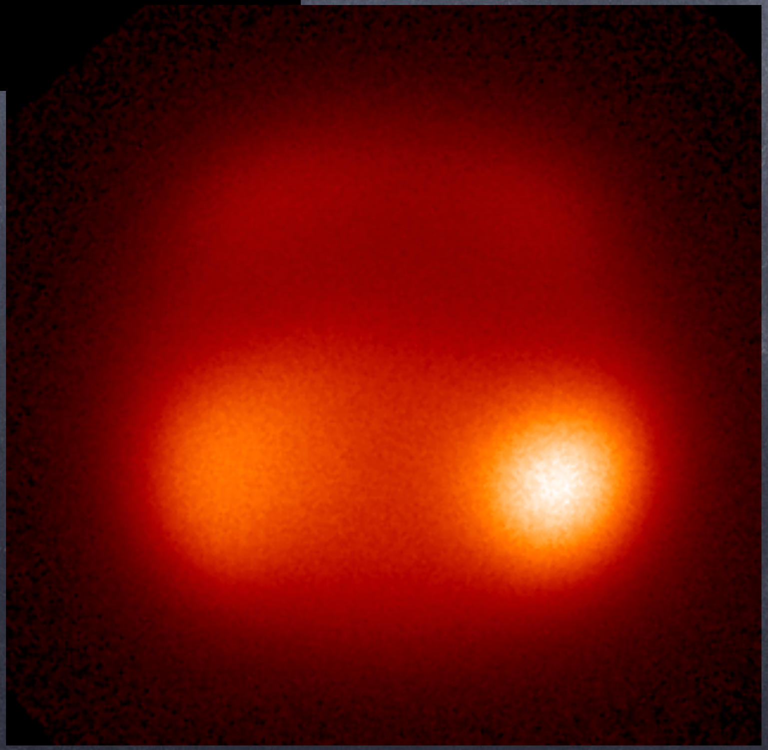
# Adaptive optics — 08

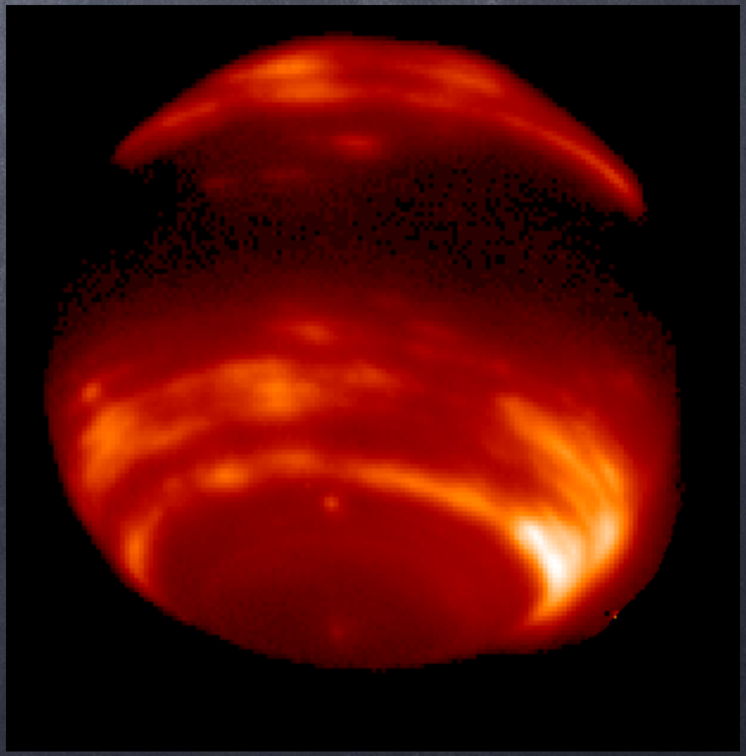



(CFHT, long-exp. images (15'))



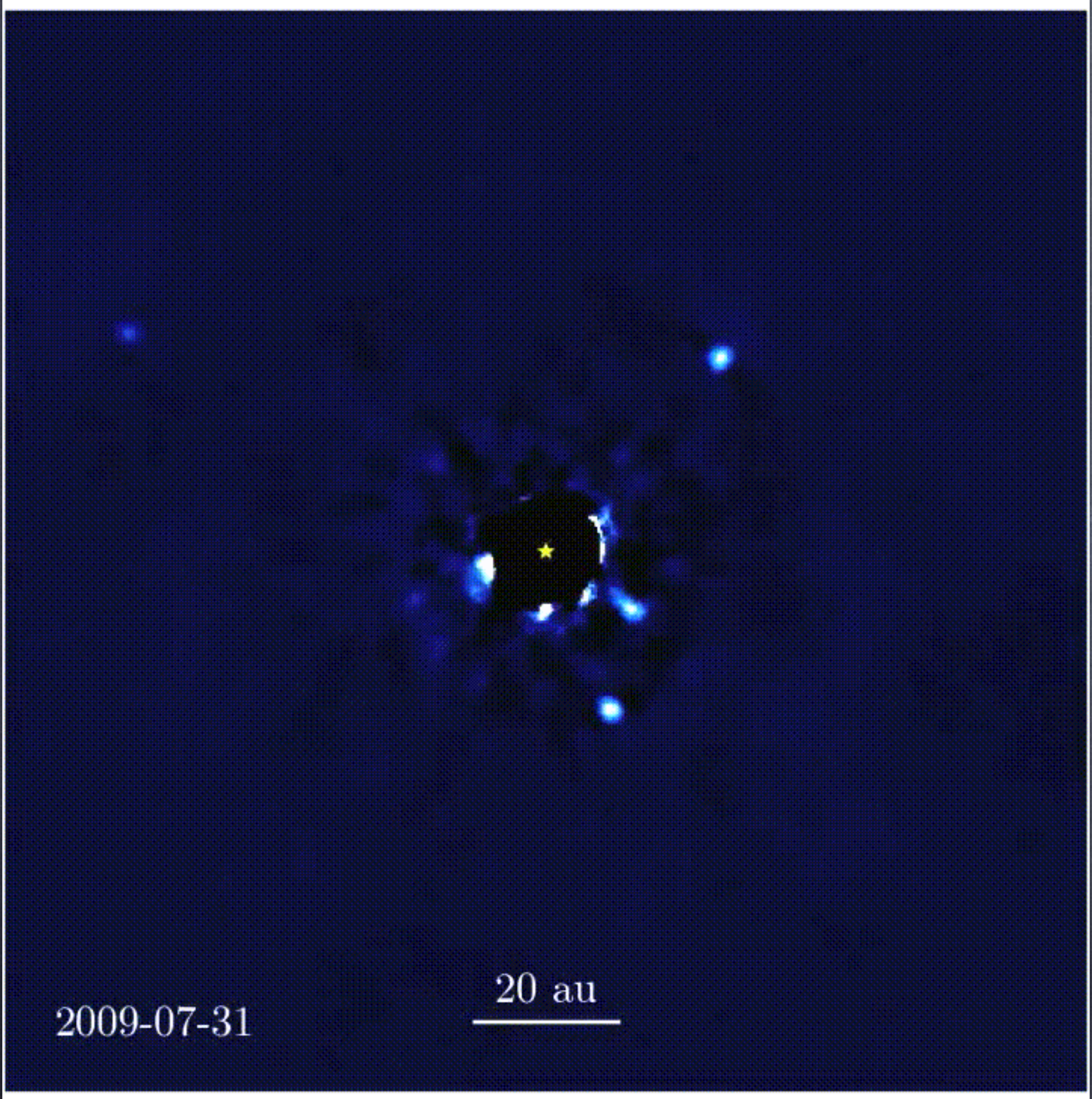

(HST vs. NACO/VLT)





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

# Adaptive optics — 09



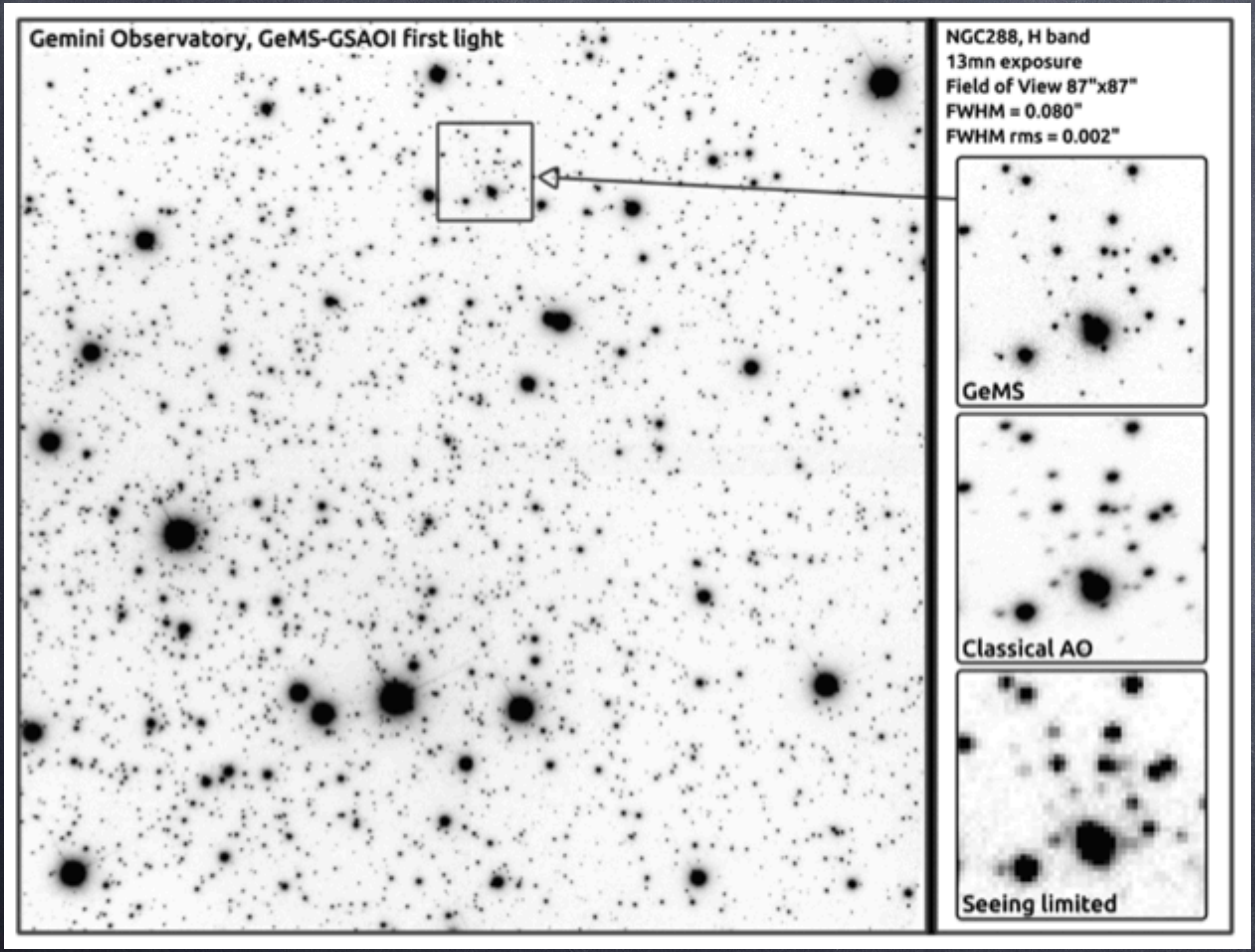

From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in 2013, from which 5 from (X)AO systems and 1 from HST.

## 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



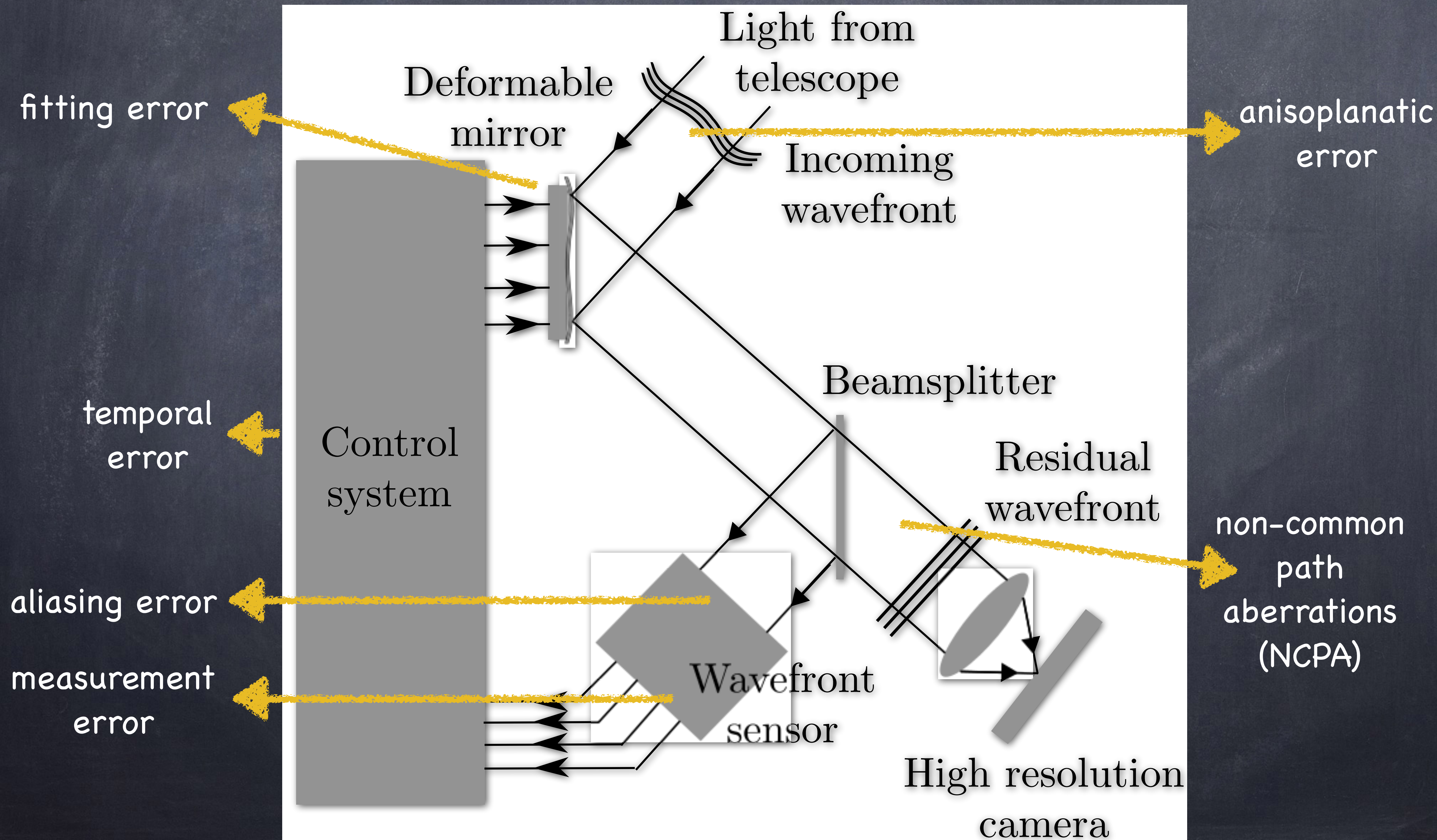

First-light image of GeMS, the MCAO system of Gemini
diffraction limit over a 2' square FoV - vs. a few arcsec !

<u>Context: wide-field astronomical imaging</u>

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

-> Also read Rigaut's paper...

# Post-AO error budget & PSF morphology — 1

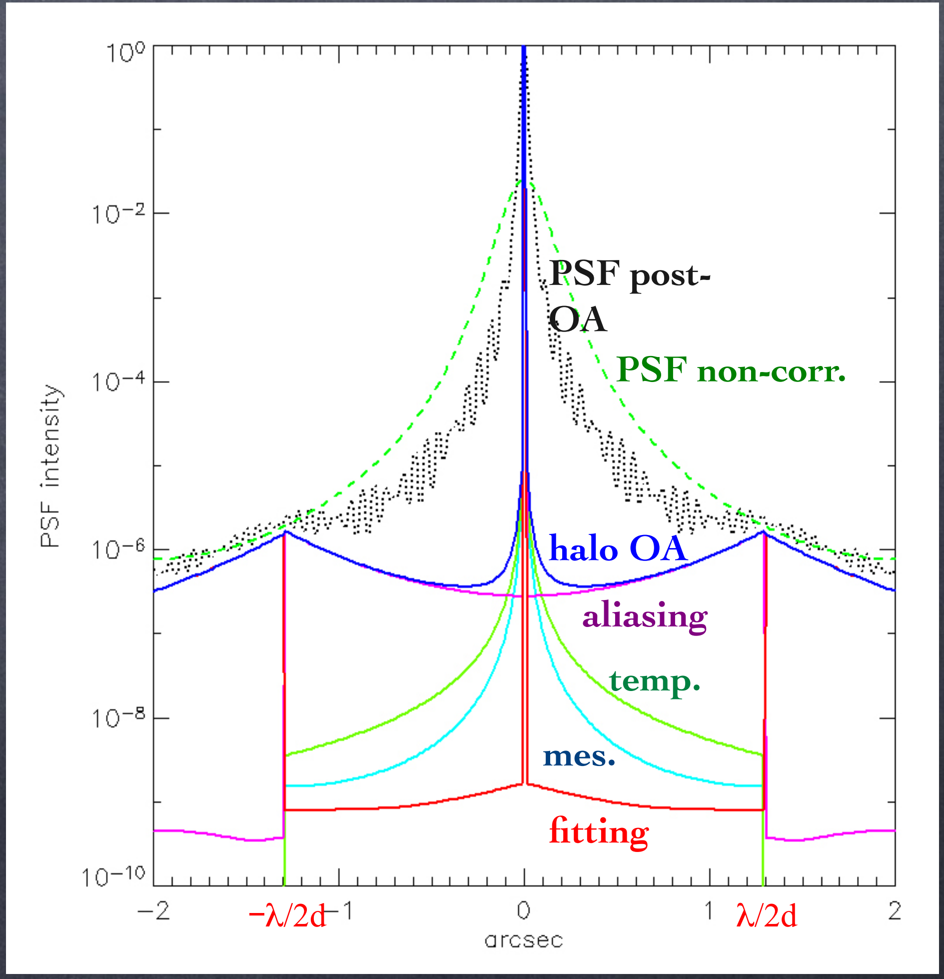


# Post-AO error budget & PSF morphology — 2

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

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

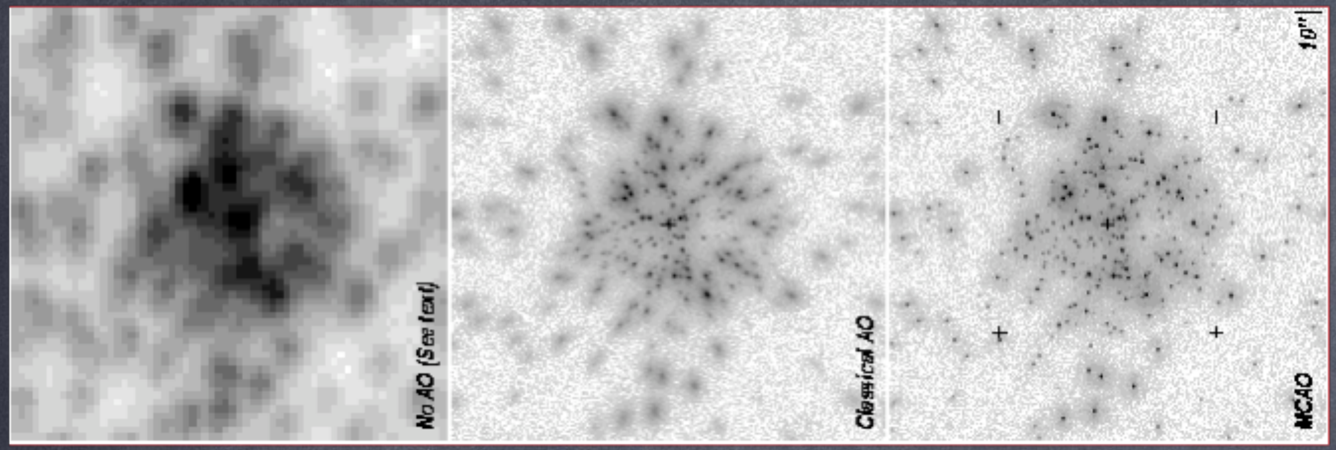
$$\sigma^2_{\mathrm{others}} = \sigma^2_{\mathrm{NCPA}} + \ldots$$




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

# Anisoplanatic error — 1

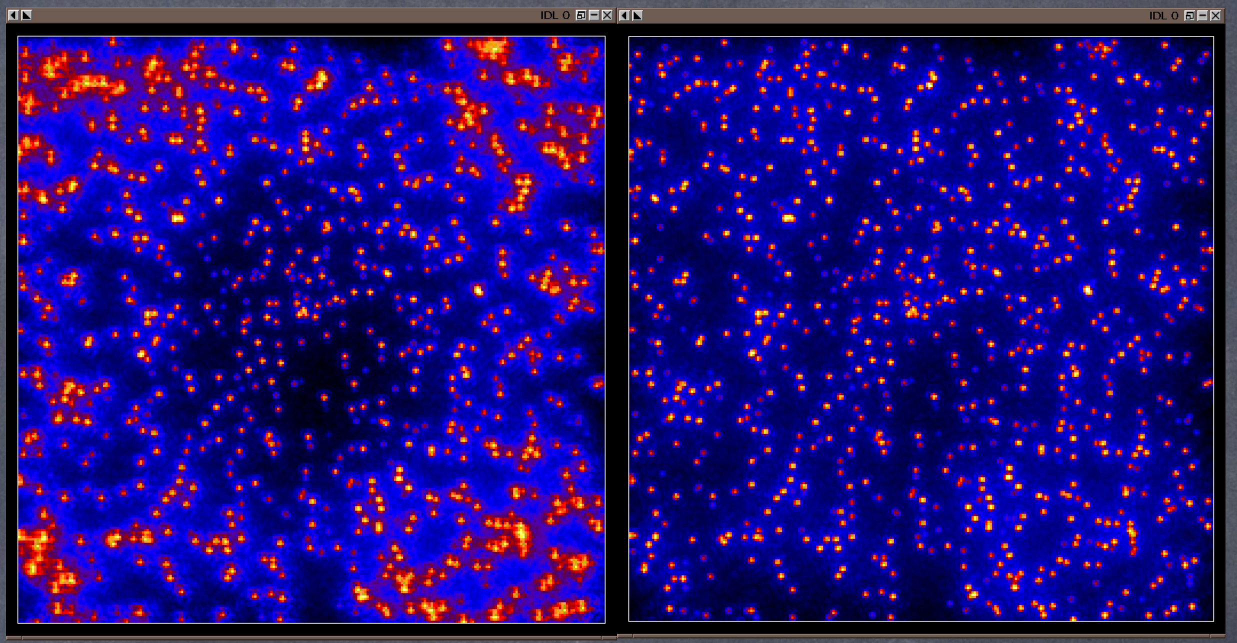
165”



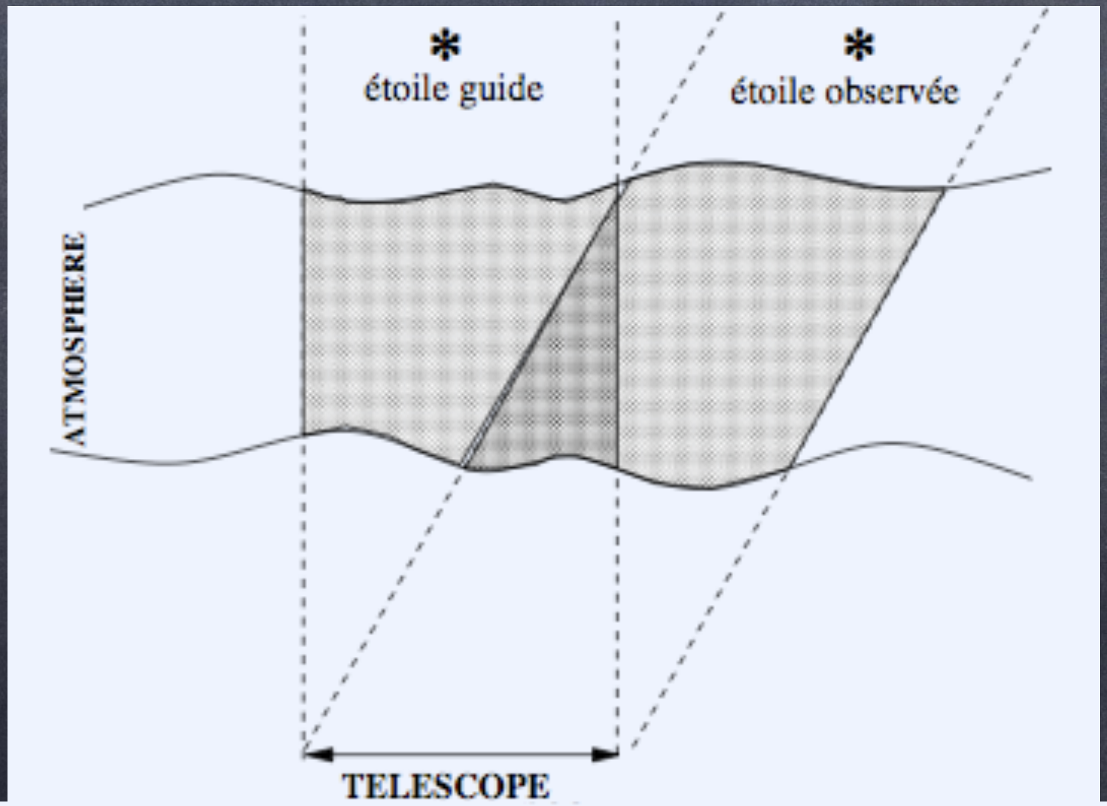

No AO

classical AO
(1 DM, 1 NGS)

MCAO
(2 DM, 5 NGS)



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



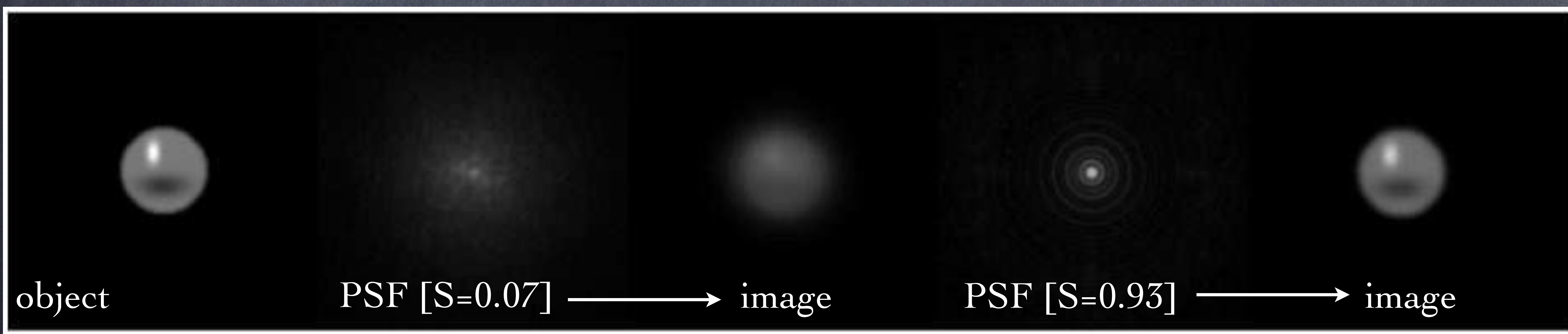

# (Another useful metrics: the Strehl ratio)

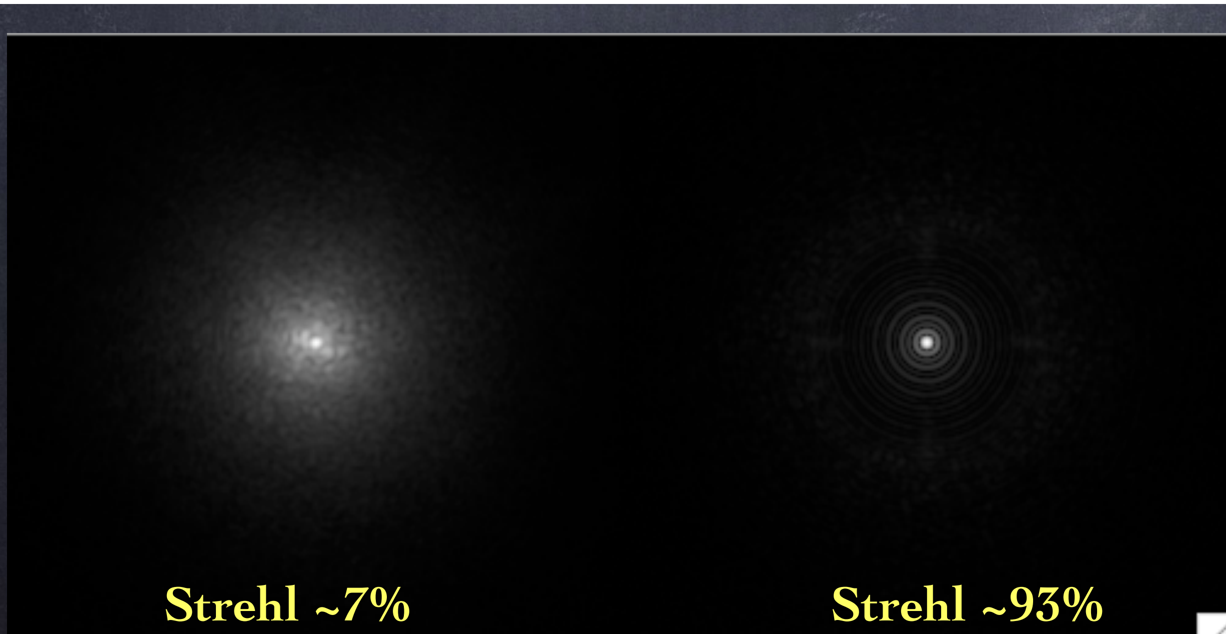
$$S = \frac{I_{\text{post AO}}[0,0]}{I_{\text{perfect}}[0,0]}$$

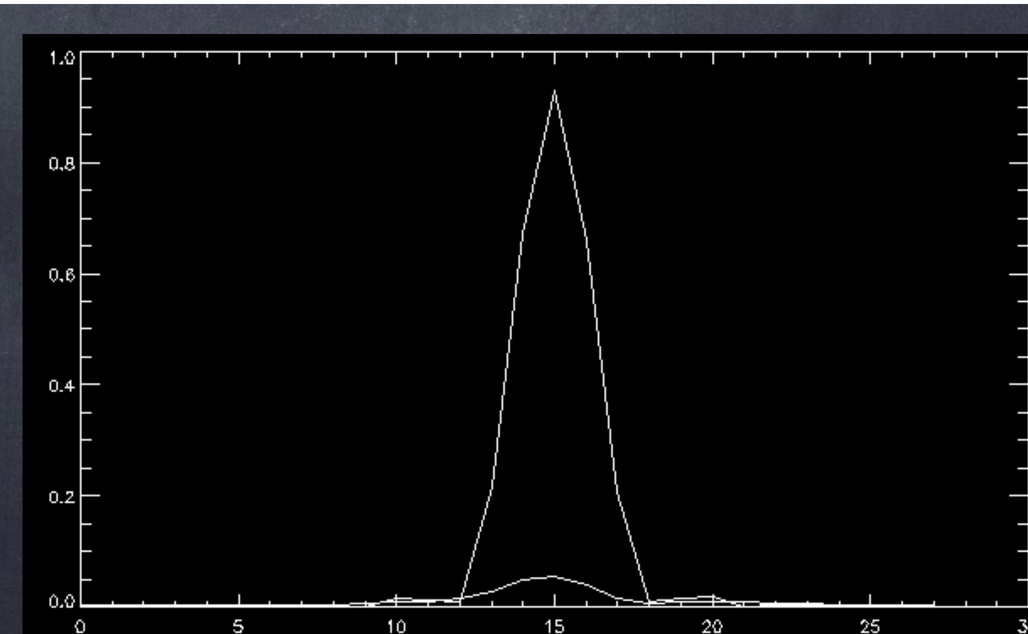
where *I[0,0]* is the intensity of the PSF at the optical center of the field (K. Strehl, Zeit. Instrumenkde 22, 213 (1902)).

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

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):

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

# Adaptive optics — 11

**Zoology of present AO systems**

- Observe at high-angular resolution astrophysical objects
  => classical/standard Natural Guide Star (NGS) AO systems

- Have in addition a sky coverage of 100%
  => Laser Guide Star (LGS) AO systems (Sodium or Rayleigh)

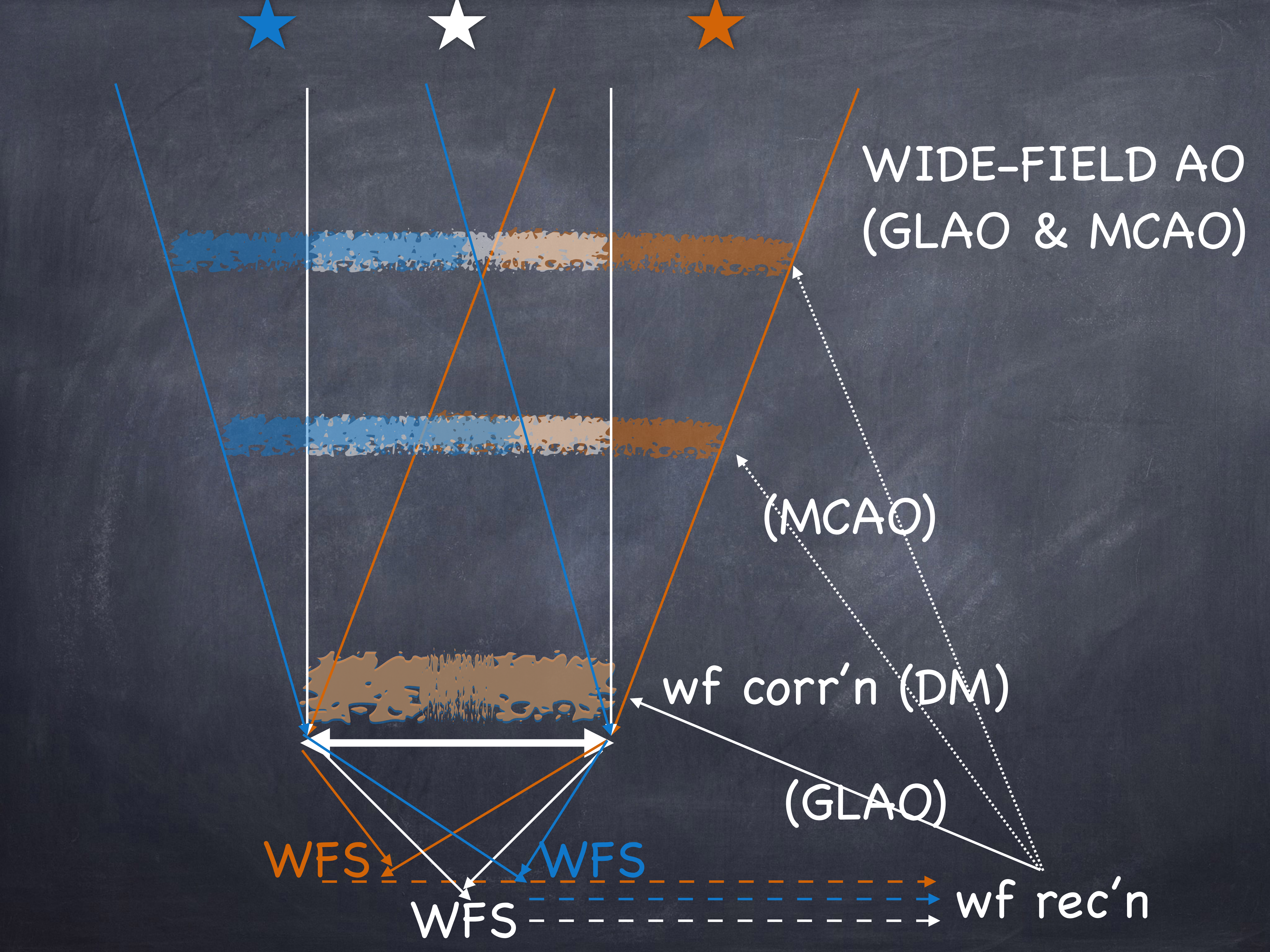
- Have in addition a wide field of correction
  => wide-field AO systems
  aka multi-reference AO systems, such as:
  - ground-layer AO (GLAO) systems,
  - multi-conjugate AO (MCAO) systems,
  - multiple-objects AO (MOAO) systems,
  - laser tomography AO (LTAO) systems.

- Have in addition very high-contrast capabilities
  => eXtreme AO (XAO) systems.

# Adaptive optics — 12

**In terms of science drivers:**

- **Stellar populations (FoV≈1′, wide-field AO).**
- **Exoplanets (very high contrast on a small field=> XAO).**
- **Galactic center (lack of NGS => LGS AO).**
- **Solar system (FoV≈10″—1′, wide-field AO).**


WIDE-FIELD AO
(GLAO & MCAO)
(MCAO)
wf corr'n (DM)
(GLAO)
WFS
WFS
WFS
wf rec'n

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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

# Post-AO error budget — 3

**Residual error of the AO system itself**

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

$$\dots + \sigma^2_{\mathrm{LGS}} + \sigma^2_{\mathrm{MCAO}}$$

- Fitting error (due to spatial under-sampling of the DM)
- Measurement error (due to photon noise, RON, etc. - WFS)
- Aliasing error (due to spatial under-sampling of the WFS)
- Temporal error (due to finite temporal bandwidth of the whole system)

- Specific errors of the LGS
- Specific errors of the MCAO (*et similia*)

# Post-AO error budget — 4

**Fitting error**

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

$$\sigma^2_{\mathrm{fitt.}} \propto \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

$$\sigma^2_{fitt.} \approx 0.34 \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

**Reduce the fitting error <=> increase the number of actuators of the DM…**

# Post-AO error budget — 6

**Aliasing error**

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

$$\sigma^2_{\text{alias.}} \propto \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

$$\sigma^2_{alias.} \approx 0.17 \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

**Reduce the aliasing error <=> increase the number of sensing elements (Shack-Hartmann sub-apertures, pixels of the pyramid) within the WFS**

# Post-AO error budget — 7

**Temporal error**

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

$$\sigma^2_{\mathrm{temp.}} \propto \left(\frac{\Delta t_{\mathrm{AO}}}{\tau_0}\right)^{\frac{5}{3}}$$

$$\sigma^2_{temp.} \approx \left(\frac{\Delta t_{AO}}{\tau_0}\right)^{\frac{5}{3}}$$

**Reduce the temporal error <=> make a faster system (exposure time of the WFS, computing time for the wavefront reconstruction, actuating time for the DM)**

# Post-AO error budget — 8

**Measurement error**

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

$$\sigma^2_{\text{mes.}} = \sigma^2_{\text{phot.}} + \sigma^2_{\text{RON}} + \ldots$$

**The measurement error has many origins:**

- **photon noise**
- **read-out noise (RON)**
- **dark-current noise**
- **sky background and possibly instrumental background**
- **in case of EMCCD: (almost) no RON but additional noises (exotic dark, « excess noise factor » => Gamma-distributed noise)**

# Post-AO error budget — 9

**Photon noise error term**

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

$$\sigma^2_{\mathrm{mes.}} = \sigma^2_{\mathrm{phot.}} + \sigma^2_{\mathrm{RON}} + \ldots$$

$$\sigma^2_{\mathrm{phot.}} \propto \frac{1}{N_{\mathrm{phot.}}}$$

$$\sigma^2_{\mathrm{phot.}} \propto \frac{1}{N_{\mathrm{phot.}}\, r_0^2\, \tau_0}, \quad \tau_0 \propto r_0$$

**(with $N_{phot}$=number of photons/exposure time/subaperture)**

**Reduce the photon noise error term <=>**
**1- reduce the number of WFS elements => increase the aliasing error !!**
**2- increase the exposure time => increase the temporal error !!**

# Post-AO error budget — 10

**Read-out noise error term**

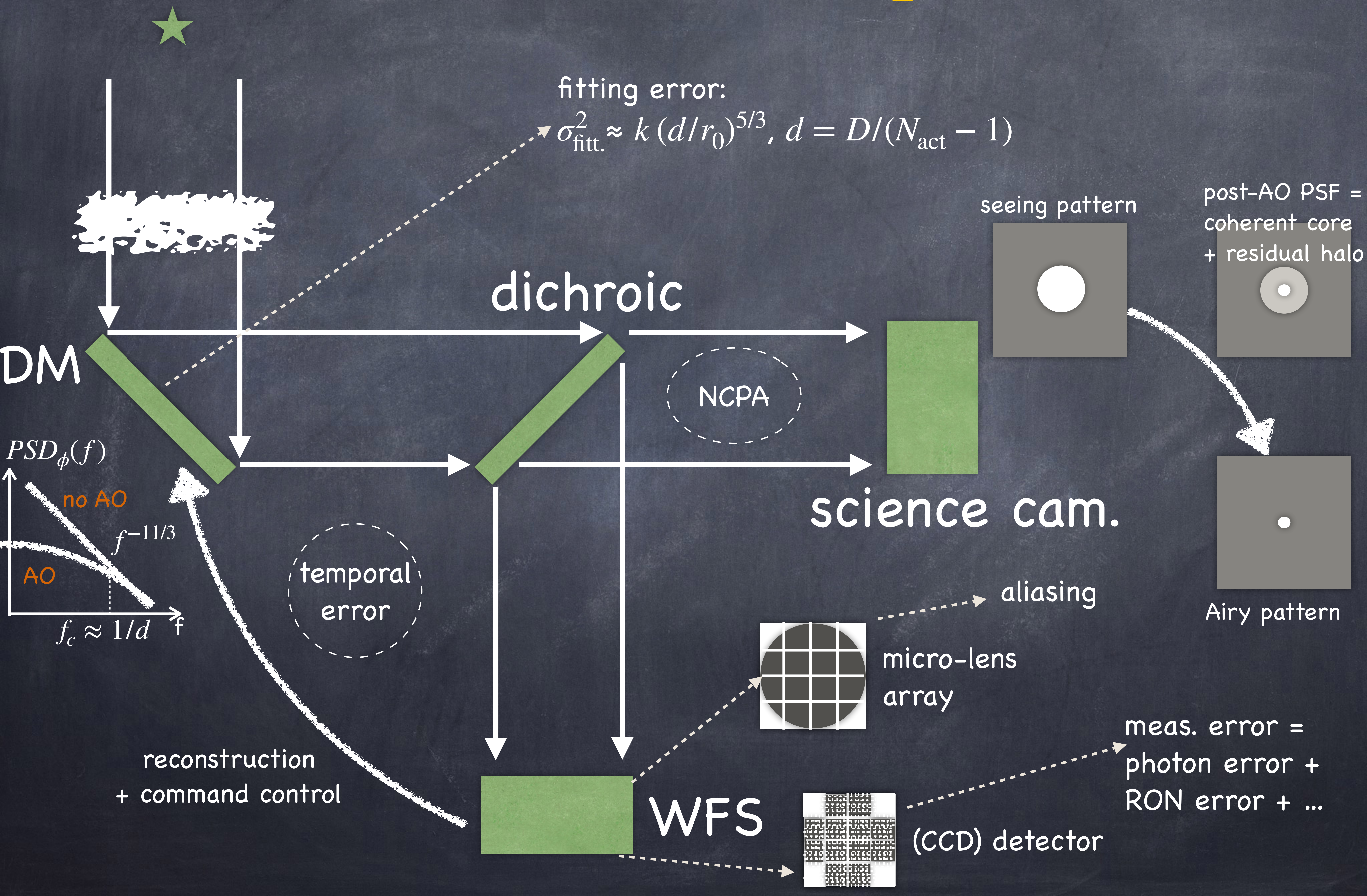
$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

$$\sigma^2_{\text{mes.}} = \sigma^2_{\text{phot.}} + \sigma^2_{\text{RON}} + \ldots$$

$$\sigma^2_{\text{lect.}} \propto \frac{\sigma_e}{N^2_{\text{phot.}}}$$

Reduce the RON error term <=>
1- reduce the number of WFS elements => increase the aliasing error !!
2- increase the exposure time => increase the temporal error !!
3- but also: reduce the impact of RON => use of EMCCDs…

# Post-AO error budget — 11



# Post-AO error budget — 12

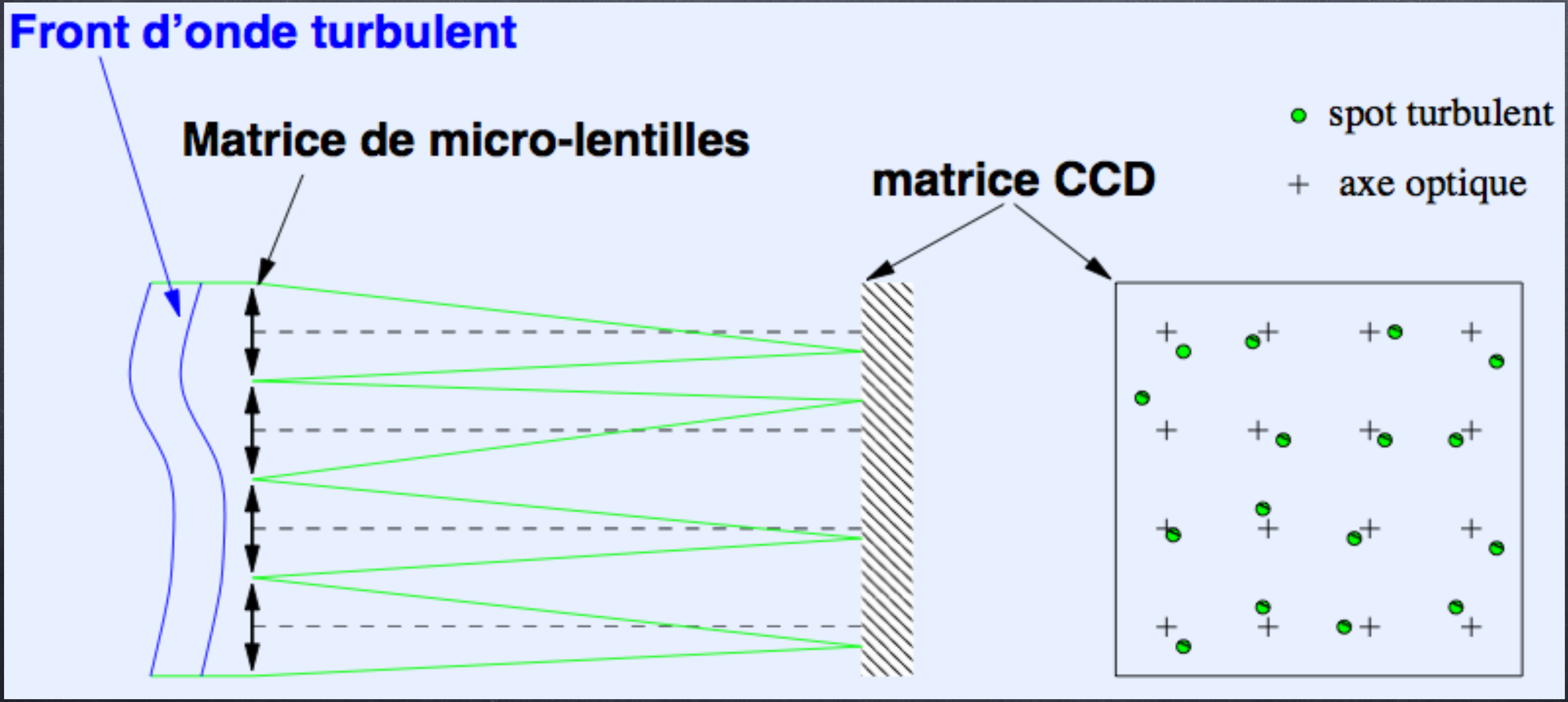
Generic case: observe as much sources as possible
Problem: most sources are (obviously!) too faint

1- find and use brighter NGS nearby…
=> anisoplanatic error !
=> use more than one brighter NGS nearby…
=> multi-reference AO system (GLAO, MCAO, MOAO)
=> yes, but: specific errors !
=> limited quality of correction

2- create a brighter source (LGS)
=> 100% sky coverage
=> yes, but here again: specific errors !
=> limited quality of correction

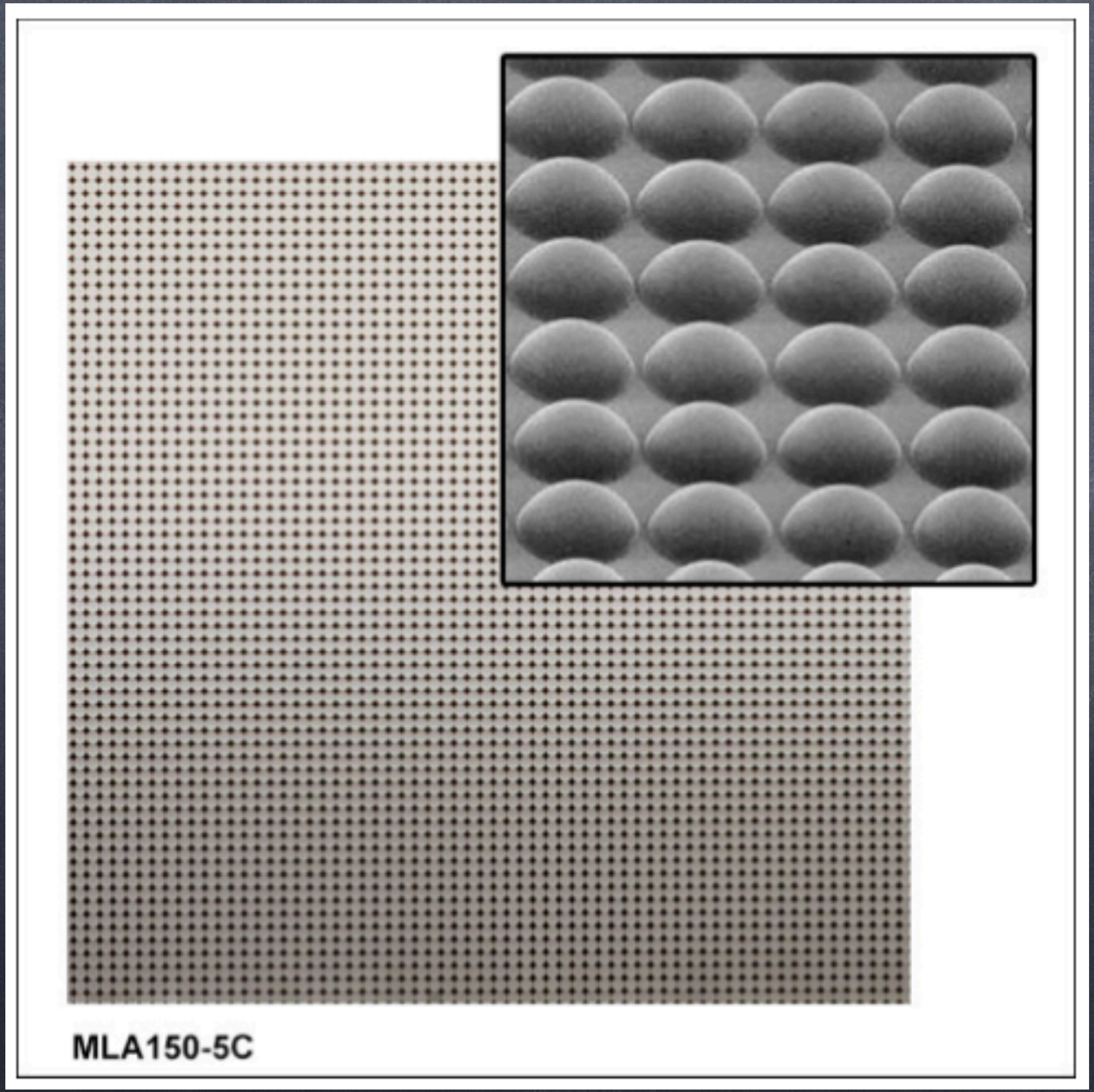
# Wavefront sensors — 1

## Example of a wavefront sensor: Shack-Hartmann



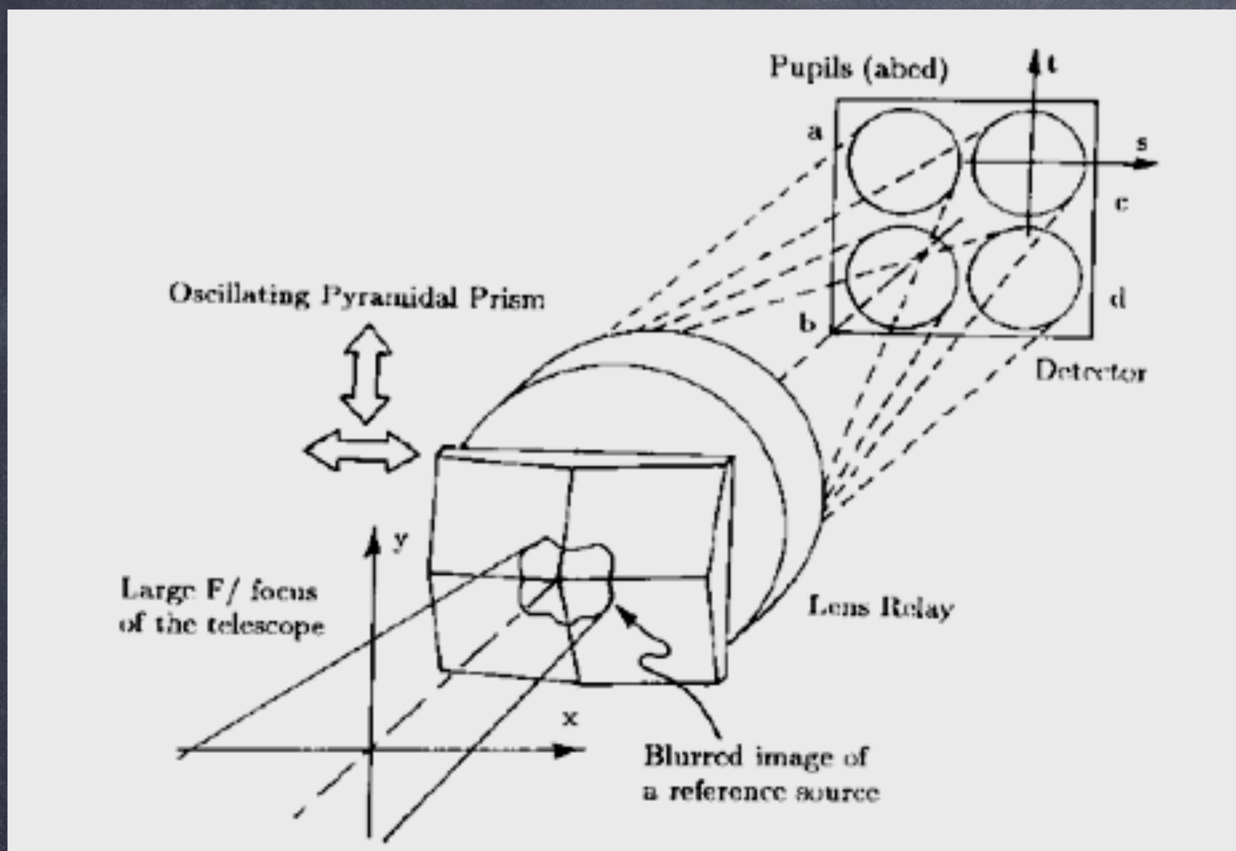
# Wavefront sensors — 2

**Example of a wavefront sensor: Shack-Hartmann**

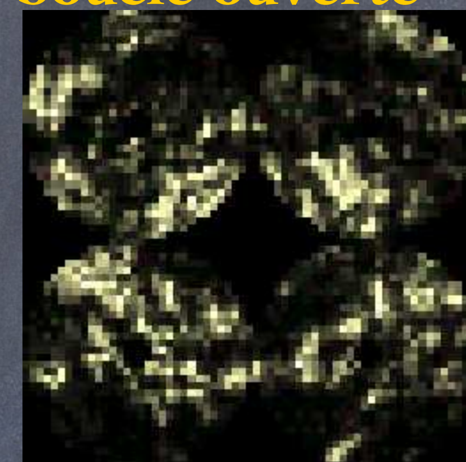


# Wavefront sensors – 3

## Another example: the Pyramid WFS



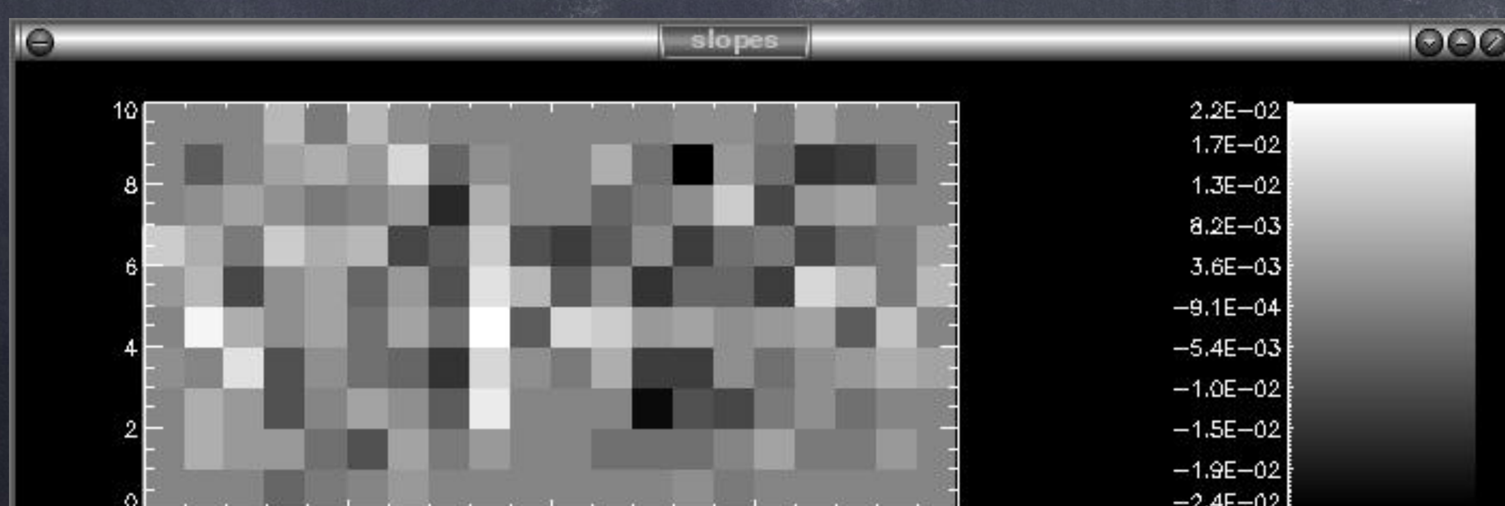

boucle ouverte



boucle fermée


$$S_x(x,y) = \frac{(I_1 + I_4) - (I_2 + I_3)}{\sum_i I_i}$$

$$S_y(x,y) = \frac{(I_1 + I_2) - (I_3 + I_4)}{\sum_i I_i}$$




pentes mesurées

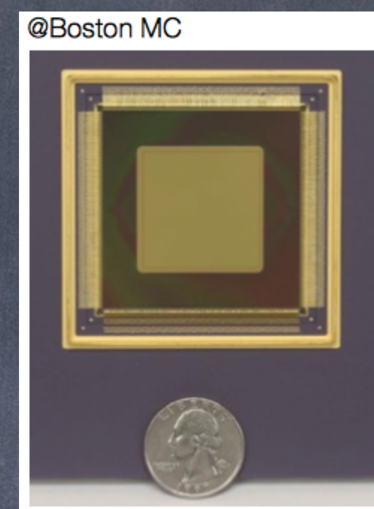
# Wavefront sensors — 4

## Another example: the Pyramid WFS

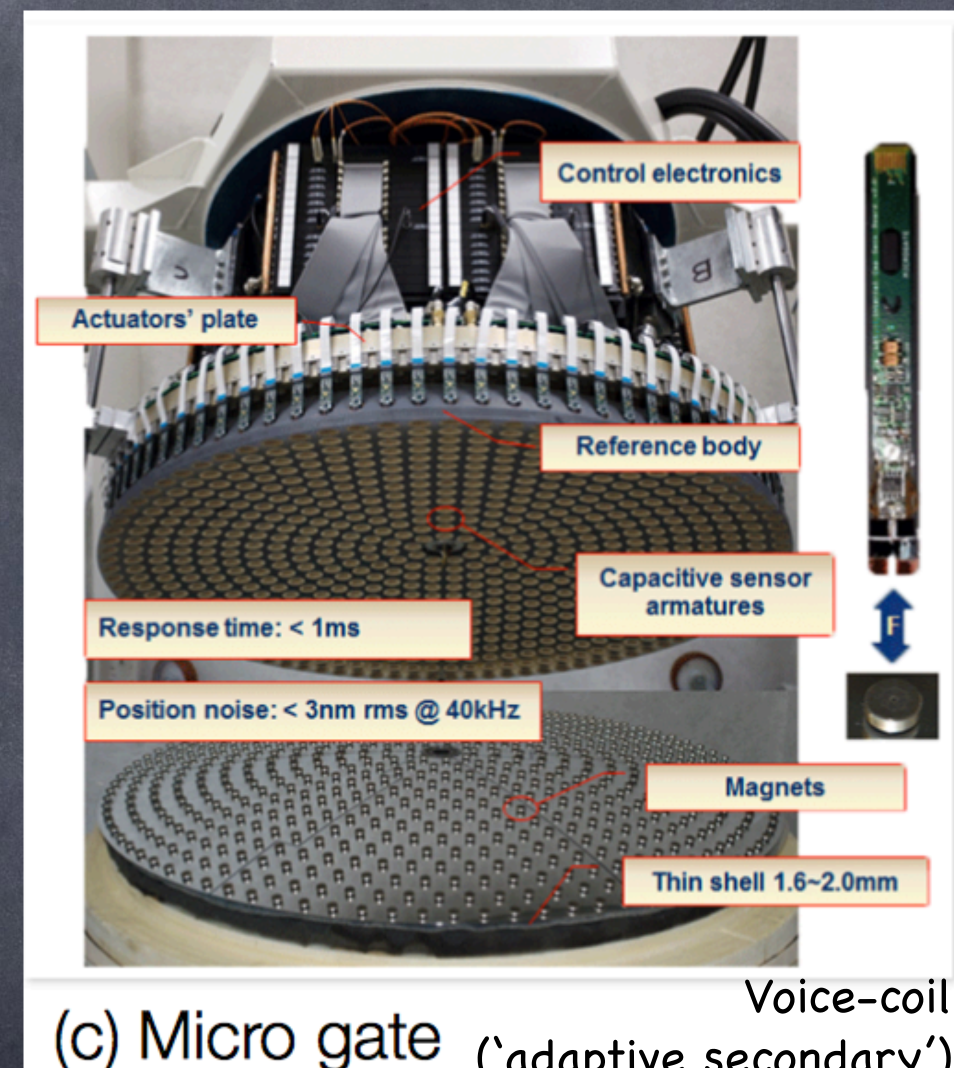
WH telescope's AO system

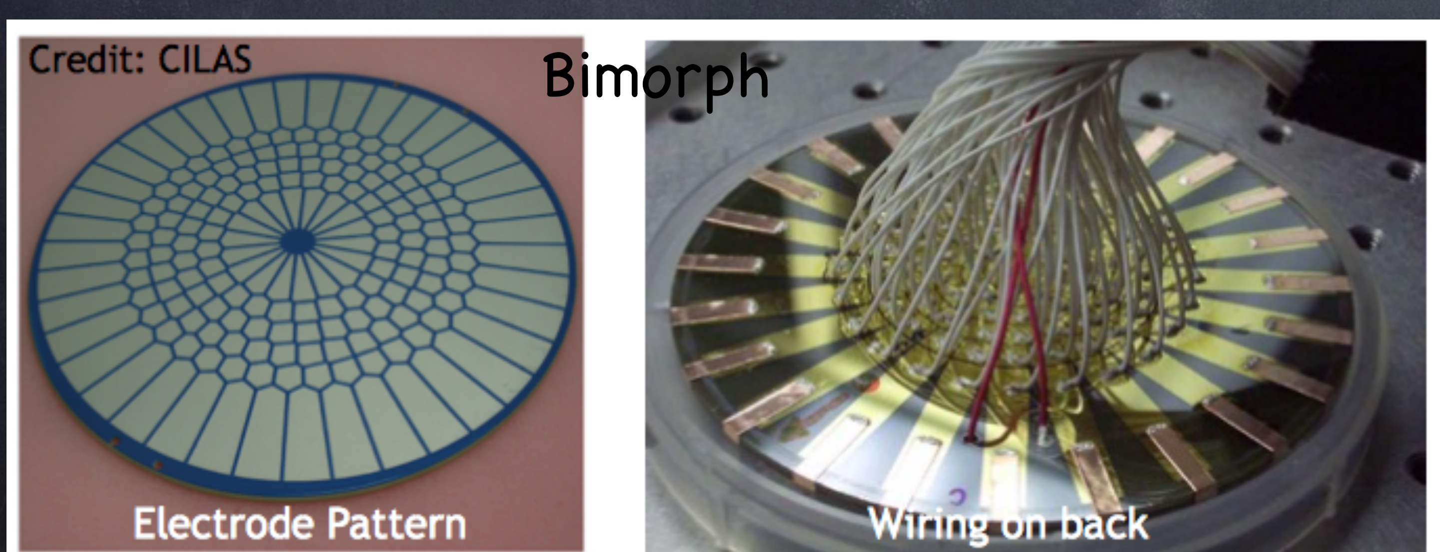
# Deformable correctors — 1

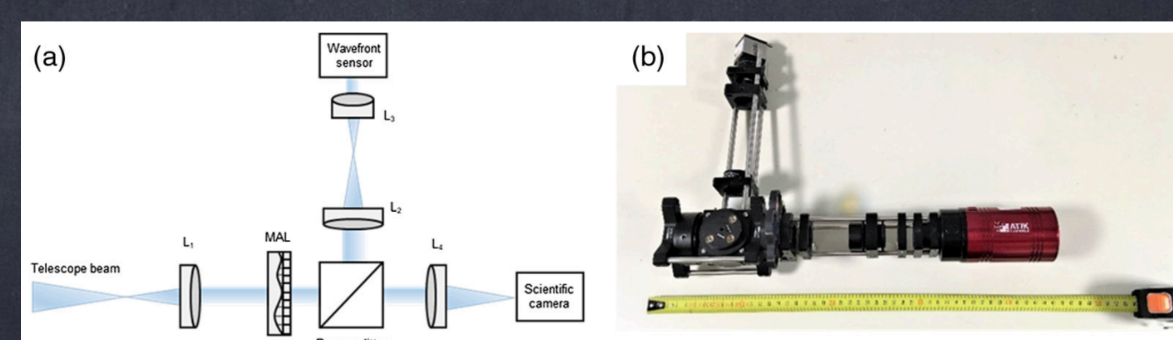
- Different technologies for correctors:
  - piezo-stacked arrays
  - piezo-electric bimorph mirrors
  - MEMS
  - voice-coil adaptive secondary mirrors (ASM)
  - multi-actuator adaptive <u>lens</u> (MAL) (!)
- ≠ coefficients for the fitting error, ≠ strokes, ≠ possible bandwidths, ≠ possible nb of modes, possible hysteresis, etc.


MEMS



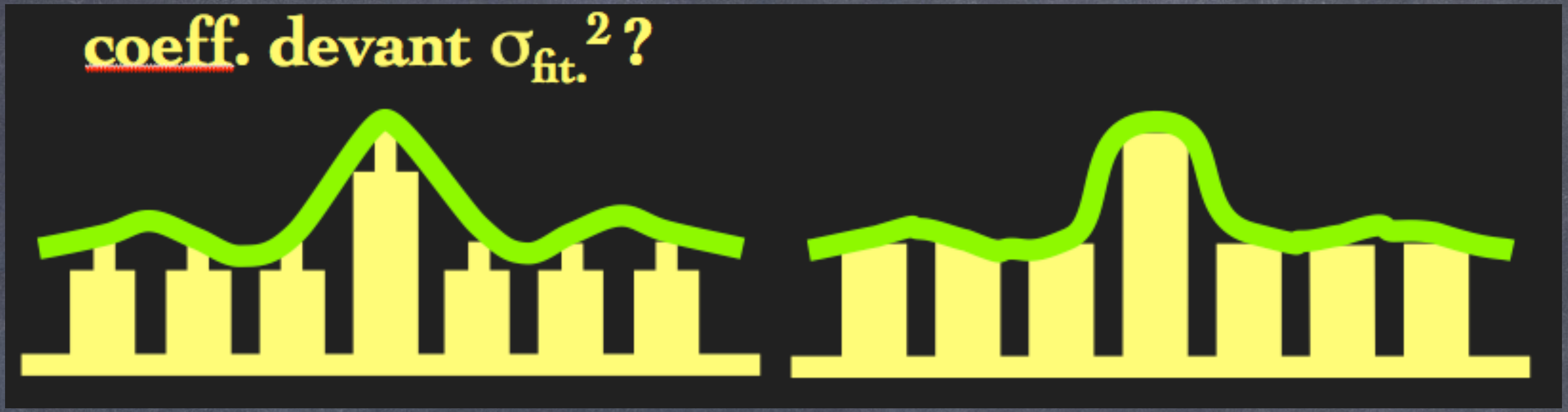




multi-actuator lens (MAL)

# Deformable correctors — 2

- **Different coefficients for the fitting error:**




- **Is the stroke enough ?**
  **If not, necessity to add a tip-tilt mirror**

- **How many actuators for a given Strehl ratio ?**
  **(considering a coeff. 0.3 for the fitting error)**

$$\sigma_{\text{fit.}}^2 = 0.3 \left(\frac{d_{\text{act.}}}{r_0}\right)^{\frac{5}{3}}$$

$$S_{\max} = \exp\left(-\sigma_{\text{fit.}}^2\right)$$

- **if d = $r_0$ , then: $S_{max}$=exp(-0.3) ≈ 0.74**
  **if d = $r_0/2$, then: $S_{max}$=exp($-0.3/2^{5/3}$) ≈ 0.91**

# Deformable correctors — 3

- Influence functions —> mirror modes

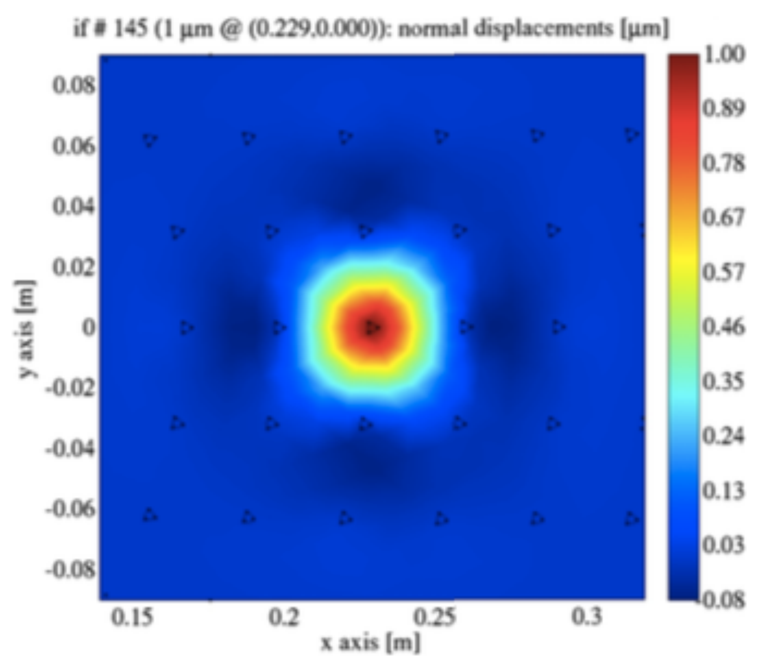
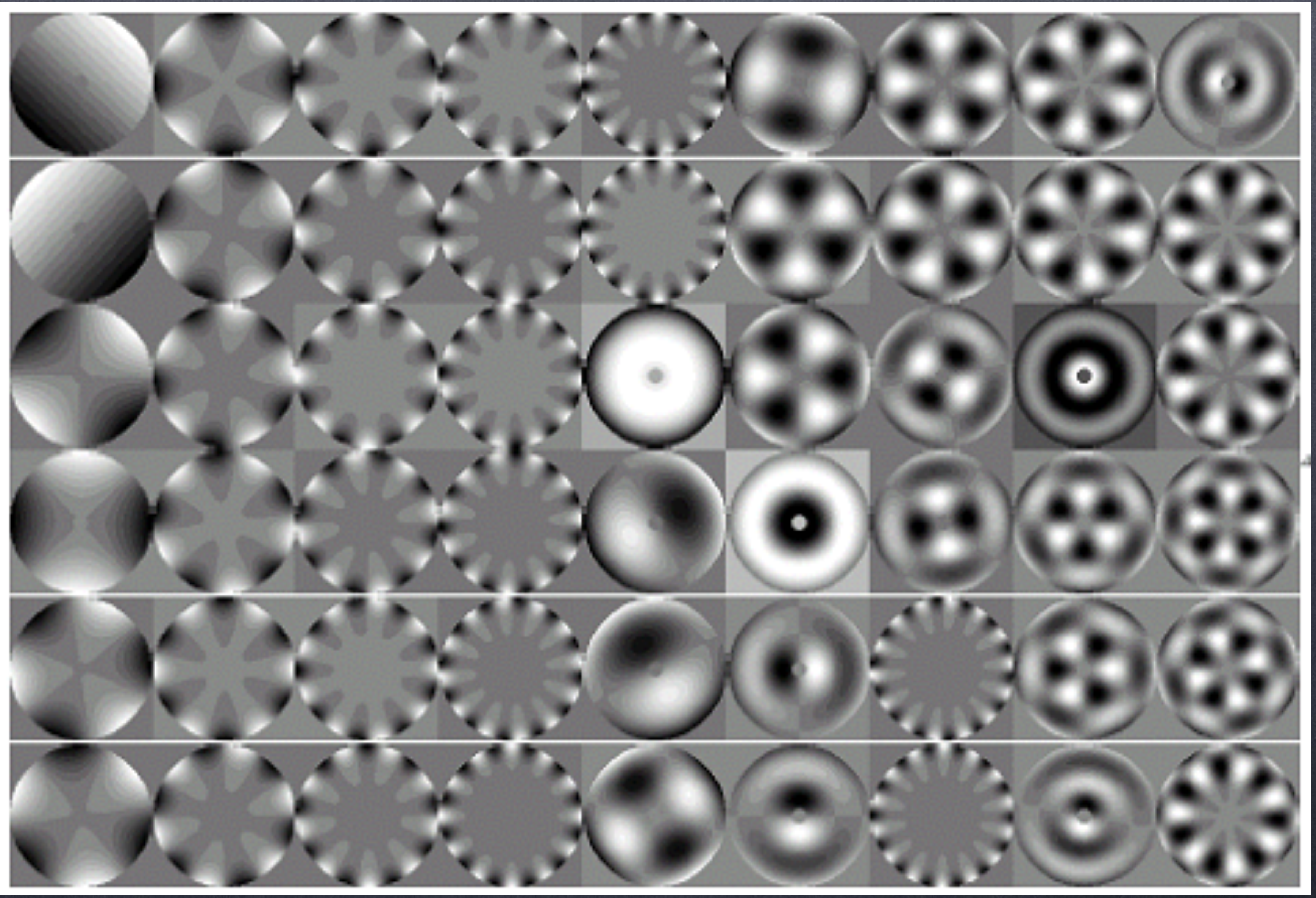



Figure 5: LBT DM: displacement normal to the surface when the actuator #145 is displaced by $w^* = 1$ µm.



# Reconstruction & control of the commands — 1

Pure integrator case:

$$c_{t+1} = c_t + g\, A\, m_t$$

where ***c*** is the commands vector (*n* actuators), ***m*** the measurement vector (*m* elements), ***g*** a scalar loop gain (usually < 1), ***A*** the (*n*x*m*) control matrix.

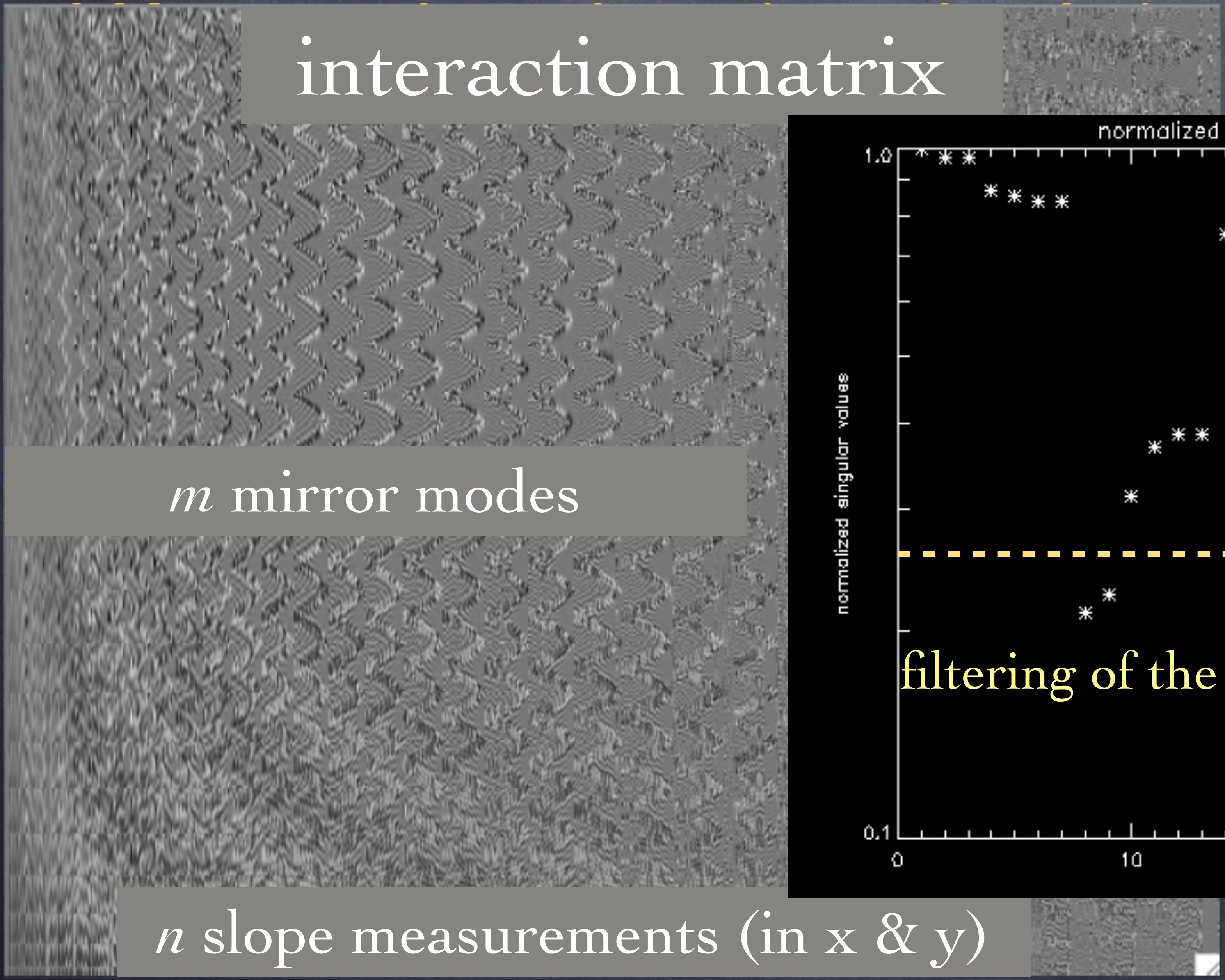
The commands matrix ***A*** is, in practice, the pseudo-inverse (SVD) of the measured (during calibration stage) interaction matrix ***D*** (*m*x*n*):

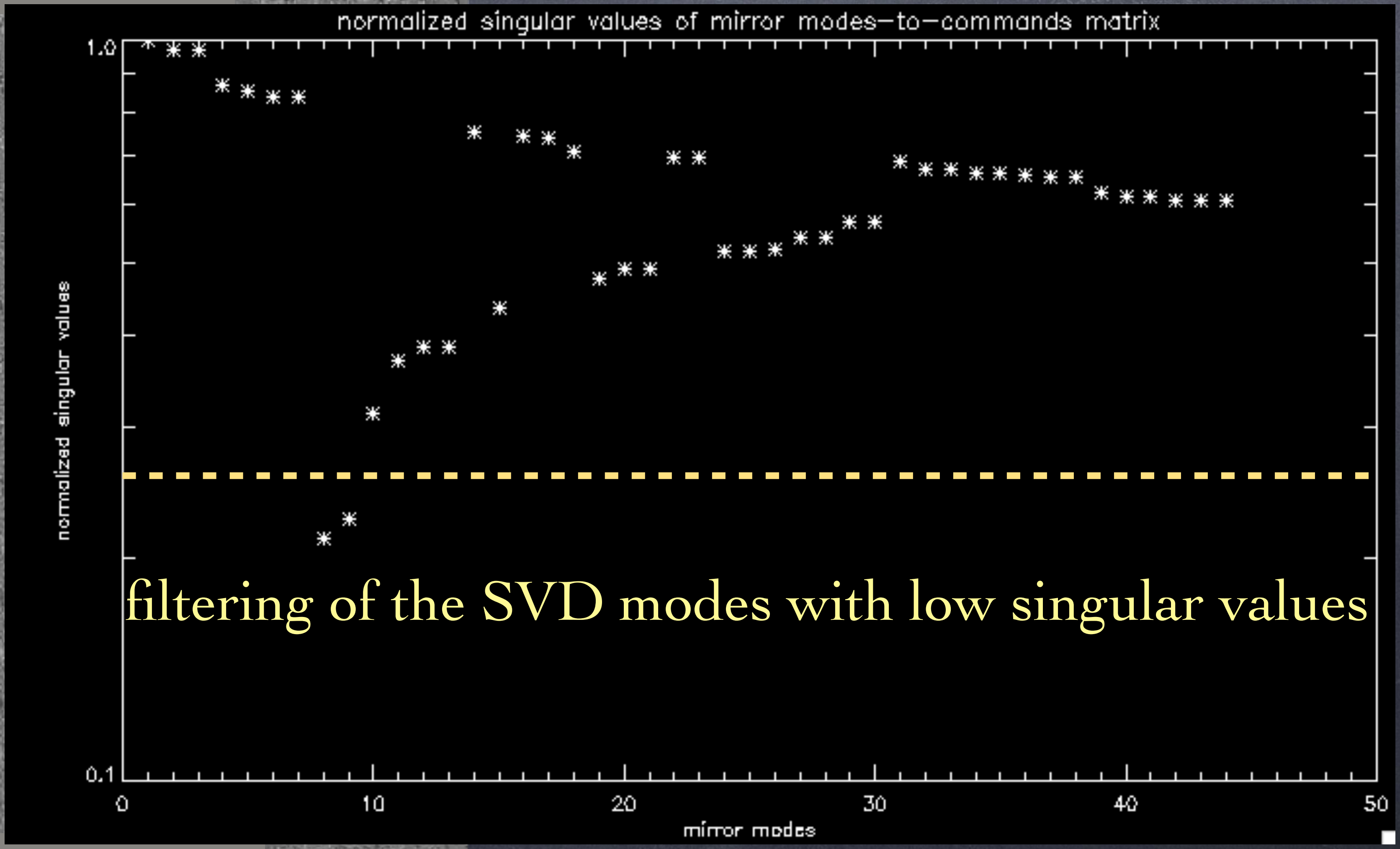
$$A = D^{+} = V\ \Sigma^{+}\ U^{*}$$

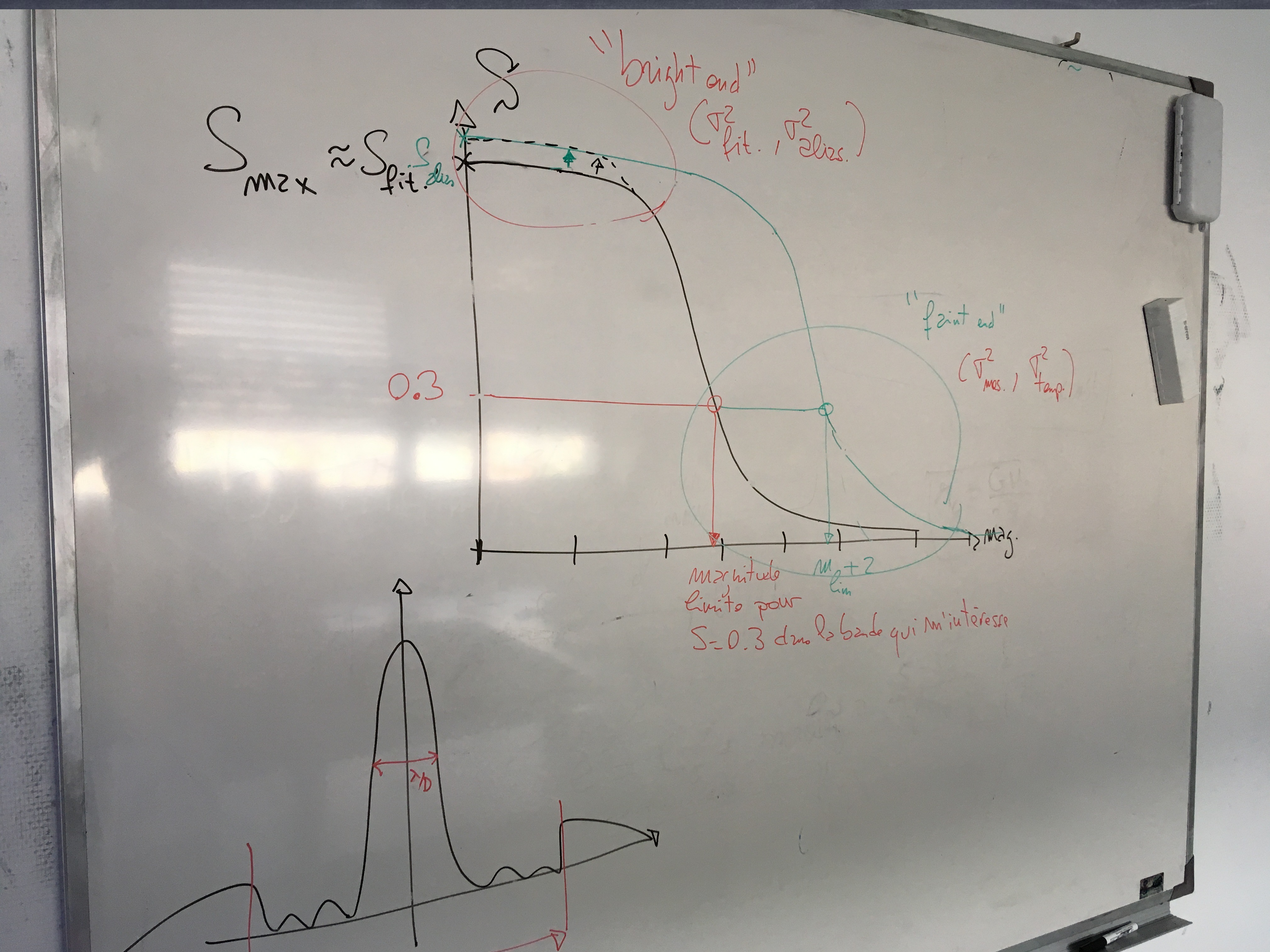
where $\Sigma$ is an *m*x*n* rectangular diagonal matrix with non-negative numbers on the diagonal ($\Sigma_{ii}$ are the singular values of ***D***), and ***U*** (*m*x*m*) and ***V*** (*n*x*n*) are orthonormal unitary matrices.

Filtering of SVD modes: $\Sigma_{ii}$ 'too small' => $\Sigma^{+}_{ii}$ set to ***0*** (truncated SVD).

# Reconstruction & control of the commands — 2





S_max ≈ S_fit. S_alias
S
"bright end"
(σ²fit., σ²alias.)
"faint end"
(σ²mes., σ²temp.)
0.3
mag.
magnitude limite pour S=0.3 dans la bande qui m'intéresse
m_lim + 2
λ/D