Astronomical Adaptative Optics

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[https://lagrange.oca.eu/carbillet/enseignement/METEOR-AAO]

METEOR AAO in practice -1

- METEOR = 10h CM + 20h TD + 5h TPE
- AO theory, numerical modelling, individual projects: 7h CM + 20h TD + 2.5h TPE (w/myself)
- Practical wf sensing: 3h CM + 2.5h TPE (w/A.Ziad)
- From your point of view: ≈35h/week, 7 weeks

METEOR AAO in practice -2

SESSIONS: #01 Mond. May 13th 14h-16h,
#02 Tuesd. May 14th 09h-10:30,
#03 Wedn. May 15th 09h-11h,
#04 Tuesd. May 21st 09h-11h,
#A1 Tuesd. May 21st 14h-16h (**AZ**),
#A2 Wedn. May 22nd 14h-16h (**AZ**),
#05 Thurs. May 23rd 09h-11h,
#06 Friday May 24th 09h-11h,
#07 Wedn. May 29th 09h-11h,
#08 Thurs. May 30th 09h-11h,
#09 Mond. June 3rd 09h-11h,
#10 Wedn. June 5th 09h-11h,
#A3 Mond. June 10th 14h-15:30 (**AZ**),
#11 Tuesd. June 11th 09h-10:30,
#12 Friday June 14th 09h-11h,
#13 Tuesd. June 18th 14h-16h,
#14 Thurs. June 20th 09h-11h,
#15 Tuesd. June 25th 14h-16:30.

METEOR AAO in practice -3

- Marks: 30% theory (A. Ziad and myself)+ 30% projects (myself)+ 40% defence (METEOR jury)

- Theoretical part
  - Exercices along the lecture /05
  - Rigaut's paper presentation /05
  - WF sensing report (A. Ziad) /20
  - AO system performance w/photon noise /20
    - context and CAOS modelling /05
    - gain optimisation /05
    - rms(N) & rms(mag) /04
    - => $\sigma^2 \propto 1/N$ /01
    - Strehl & FWHM(mag, lambda), conclusion /05

- Individual project part /50
  - details depending on the project (XAO, GLAO, LGS AO, etc.)

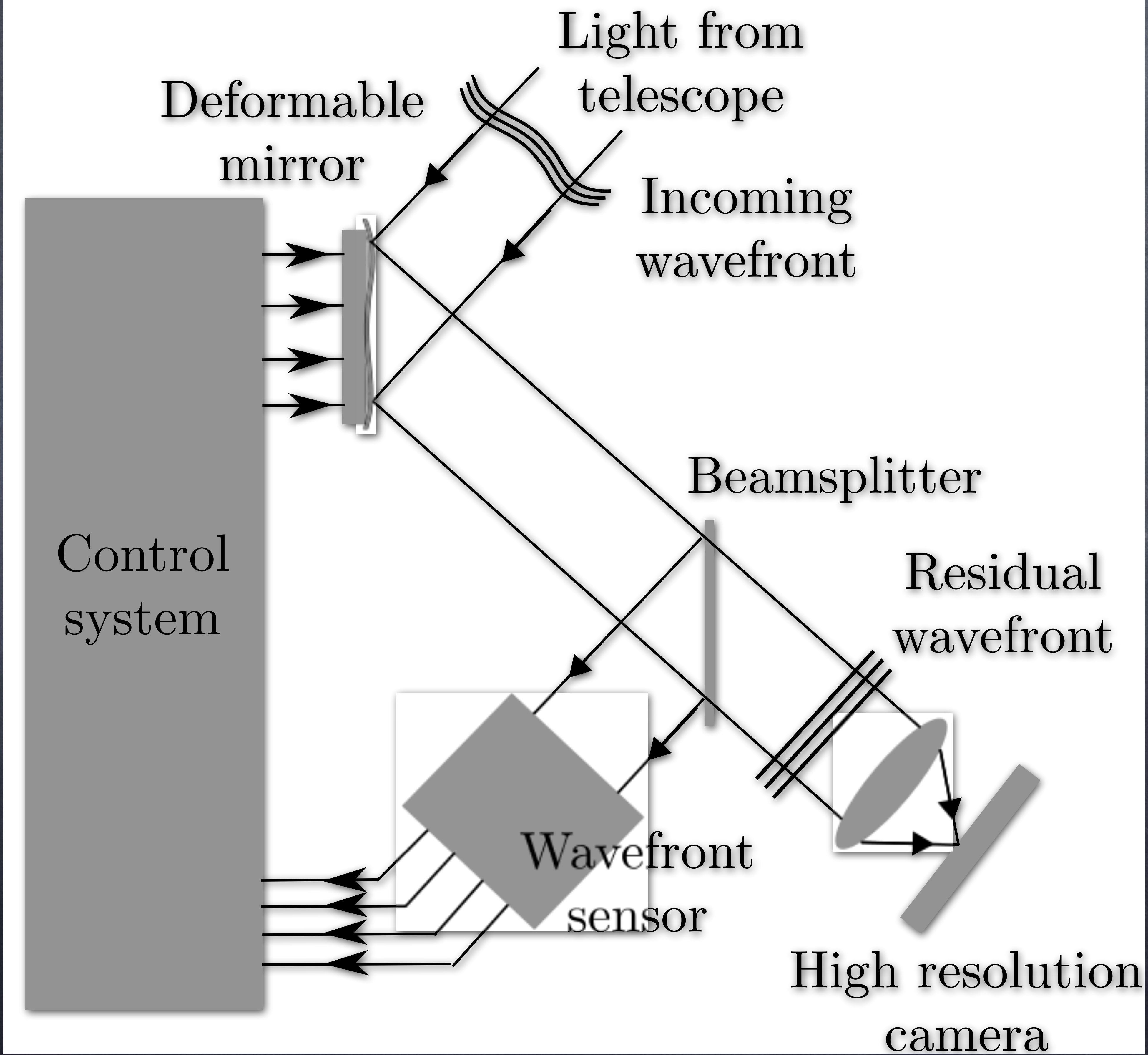
AO theory points studied

- Introduction to adaptive optics (AO)
  - AO error budget
  - Post-AO PSF morphology
  - The *hard* side of AO:
    - wf sensing,
    - real-time wf reconstruction, command/control,
    - wf correction.
  - Numerical modelling/simulations:
    - AO system dimensioning,
    - end-to-end modelling,
    - performance evaluation.

- eXtreme AO, Wide-Field AO, Laser Guide Star AO, Ground-Layer AO, Multi-Conjugate AO, etc.

Adaptive optics - 1

Adaptive optics - 2

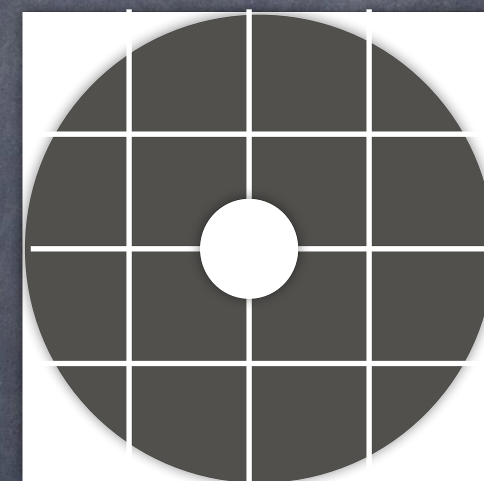


Adaptive optics - 3

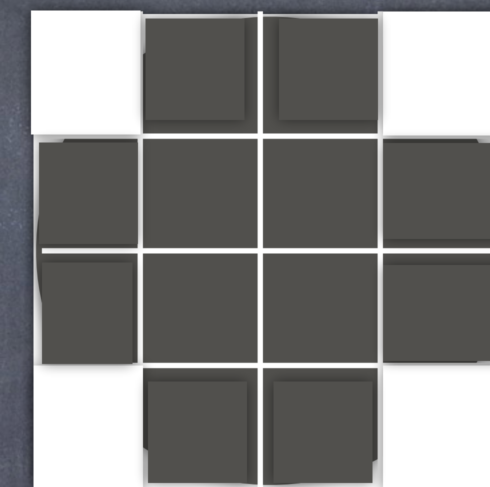
Fried configuration

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)…

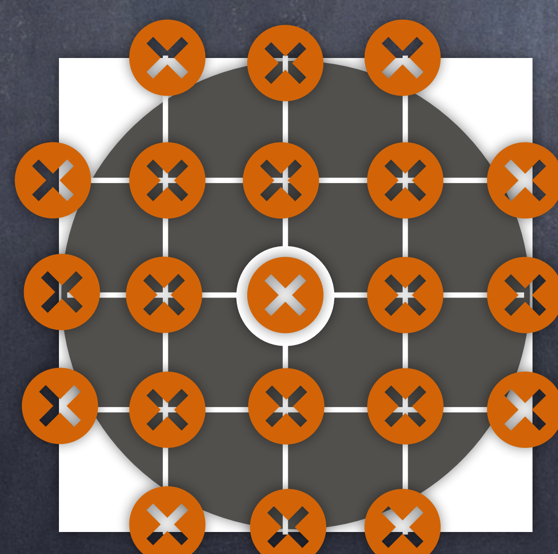
Entrance pupil of the telescope



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



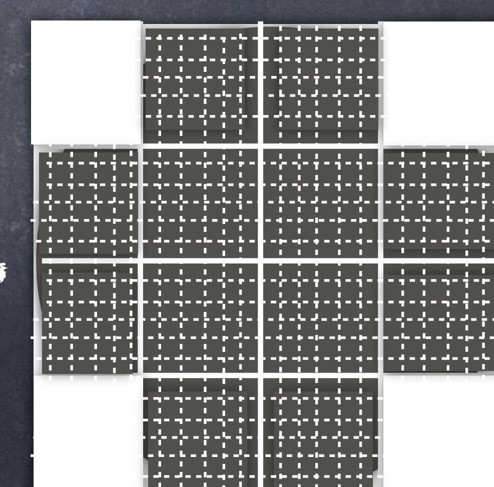
12 valid sub-apertures of the Shack-Hartmann (onto the 4x4 array)



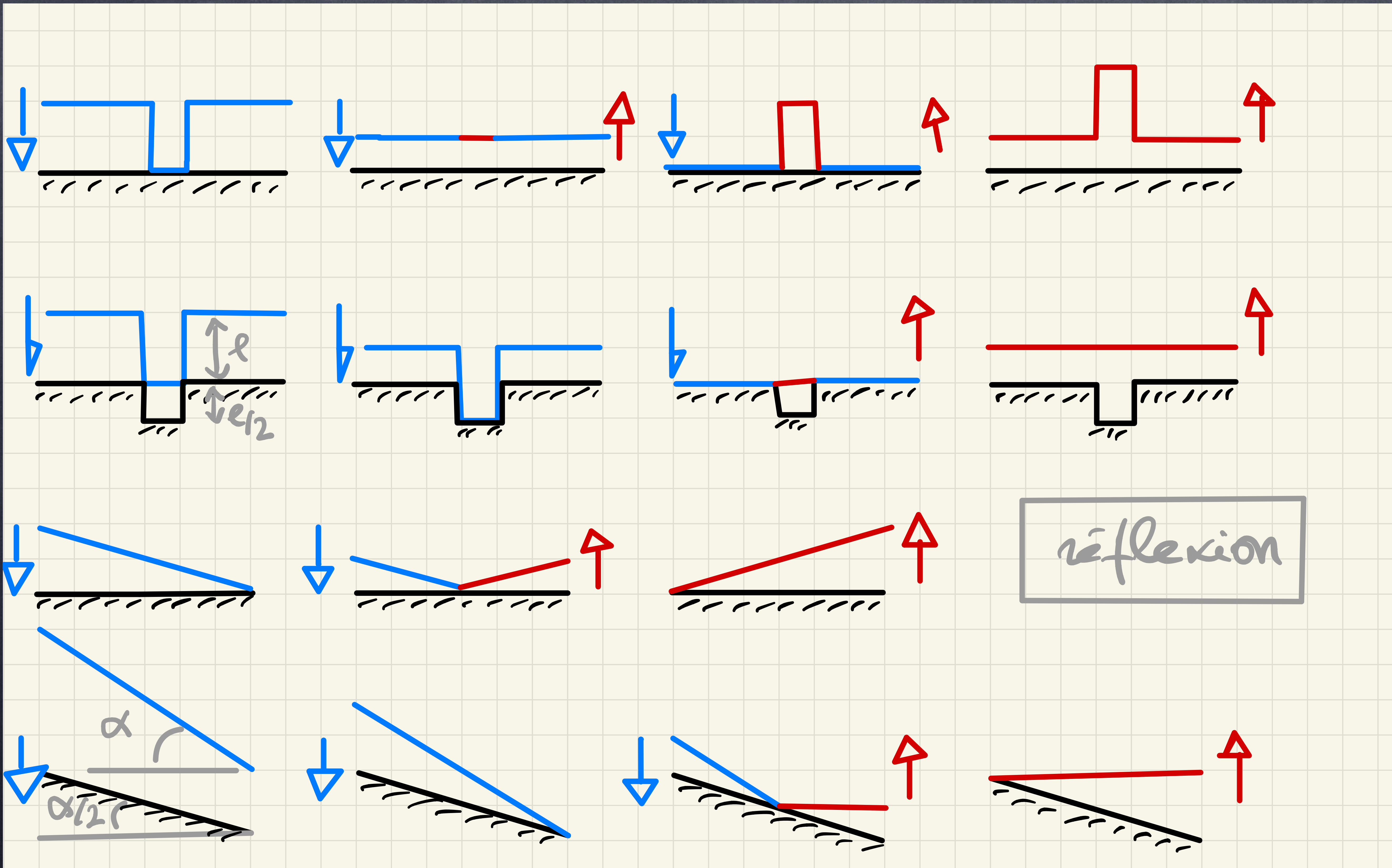
Pupil projected on the deformable mirror with its 21 actuators (on the 5x5 corresponding array)

commands for 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


e
e/2
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α/2
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Adaptive optics - 4

Some orders of magnitude concerning AO systems:

	@500nm	@2.2µm
spatial sampling (WFS analysis elements size) $\rightarrow d \simeq r_0$	10 cm	60 cm
number of WFS analysis elements (and 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 - 5

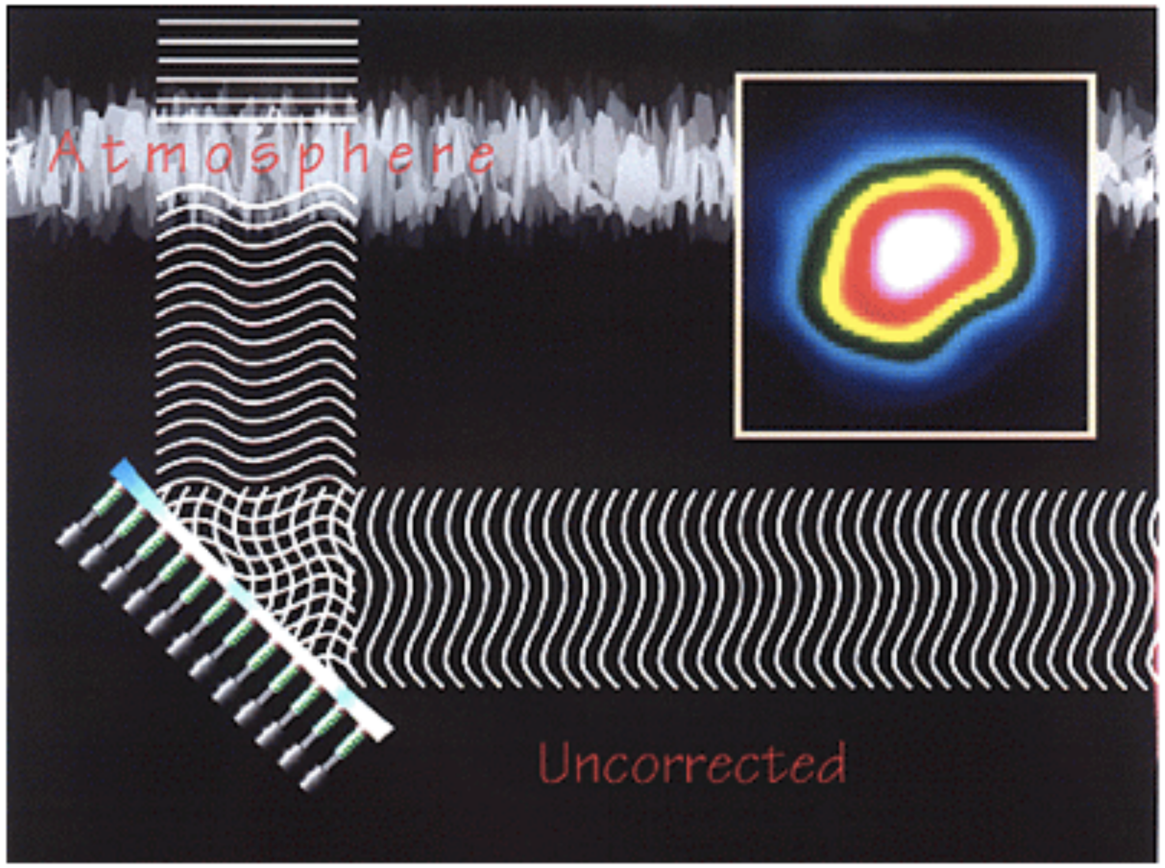
Introduction to Adaptive Optics

Credits: ESO and Jennifer Lotz

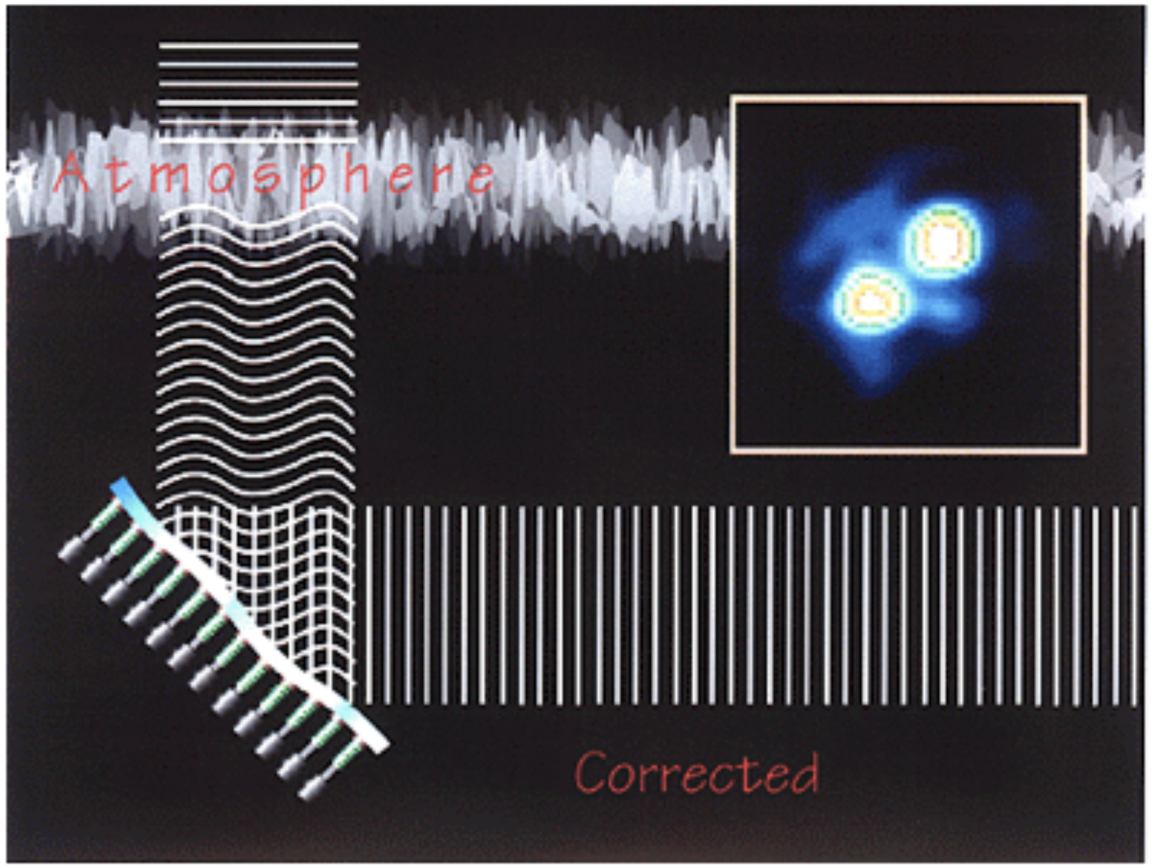
As astronomers attempt to understand the limits of the physical universe, they must look deep into the night sky with a sharp eye. Unfortunately, looking into the night sky is like looking up from the bottom of a swimming pool. Turbulence in the upper atmosphere causes spatial and temporal anomalies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

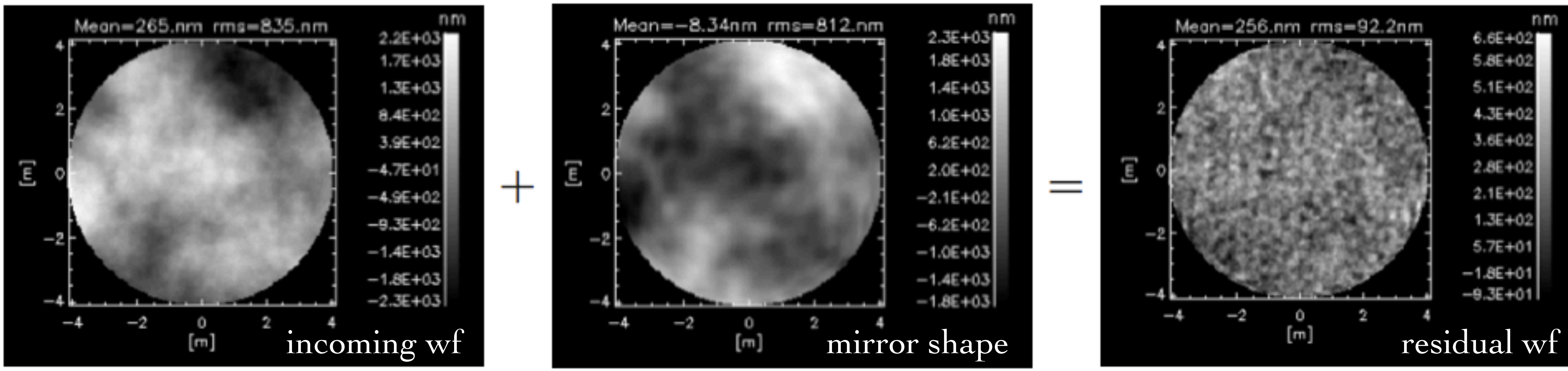


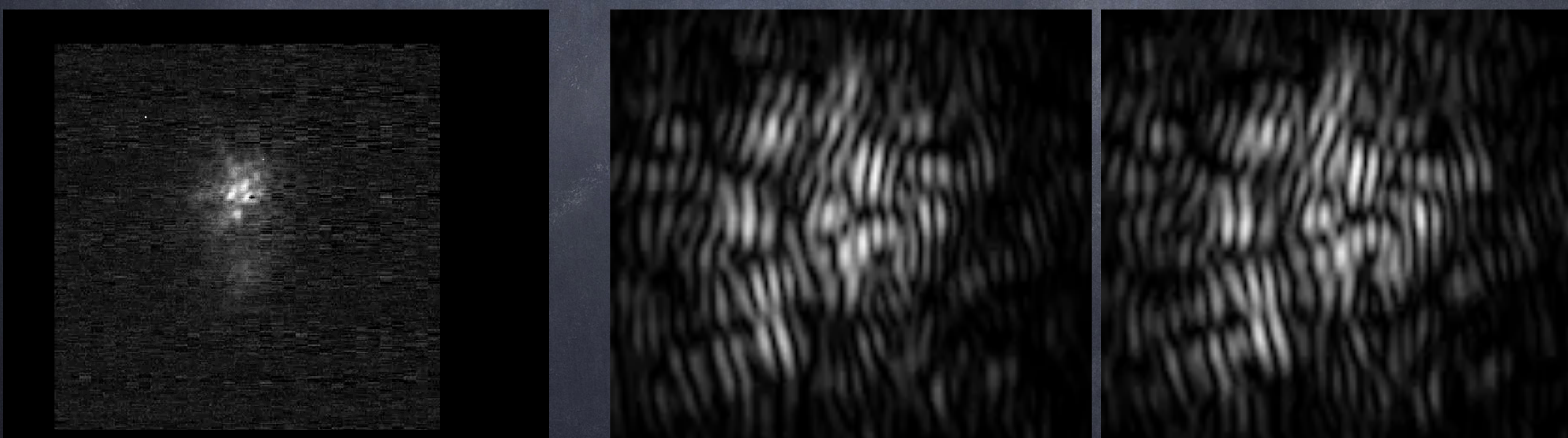
With Adaptive Optics corrected image

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

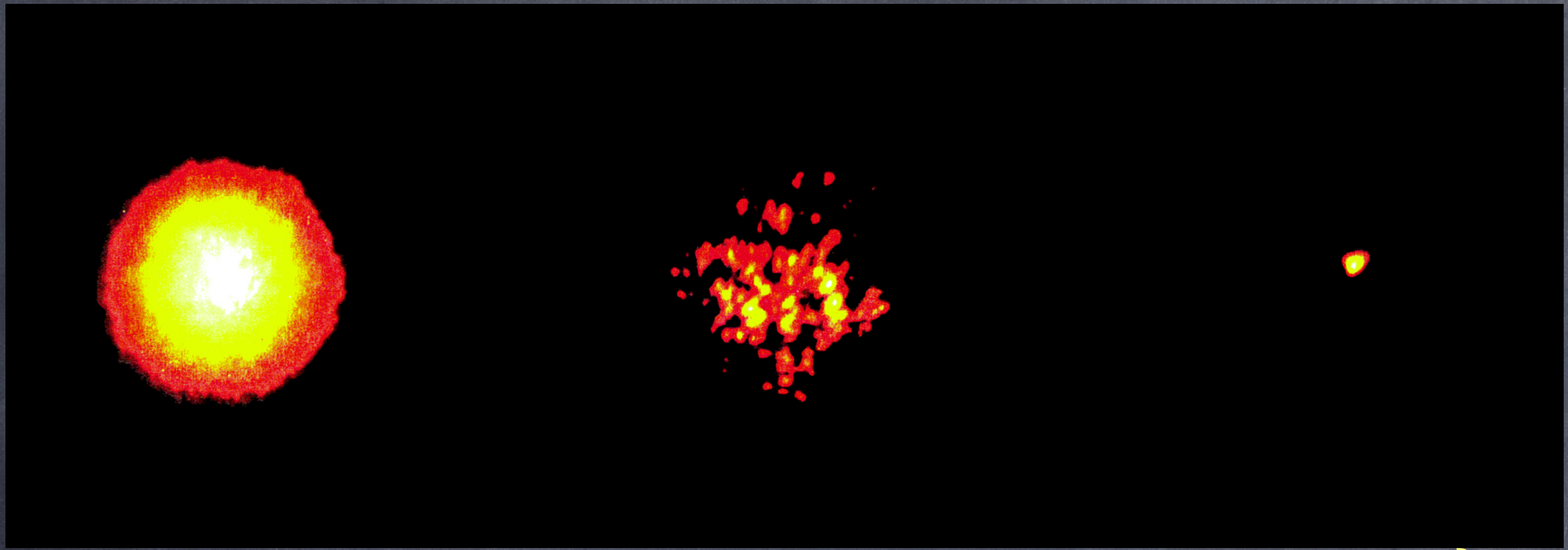
last update: 3 April 2007
editor of this page: Stefan Hippler

Adaptive optics - 6

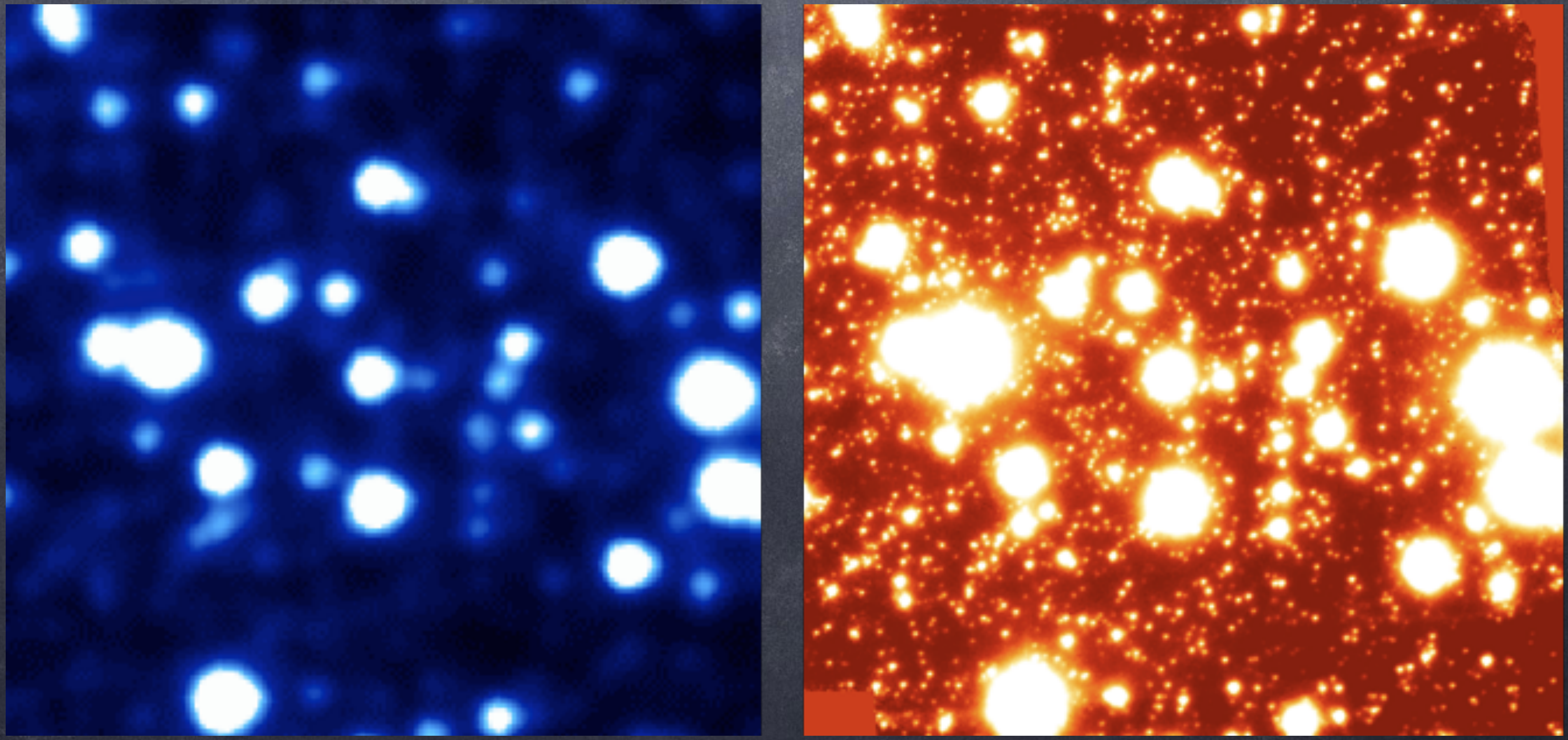




Adaptive optics - 7

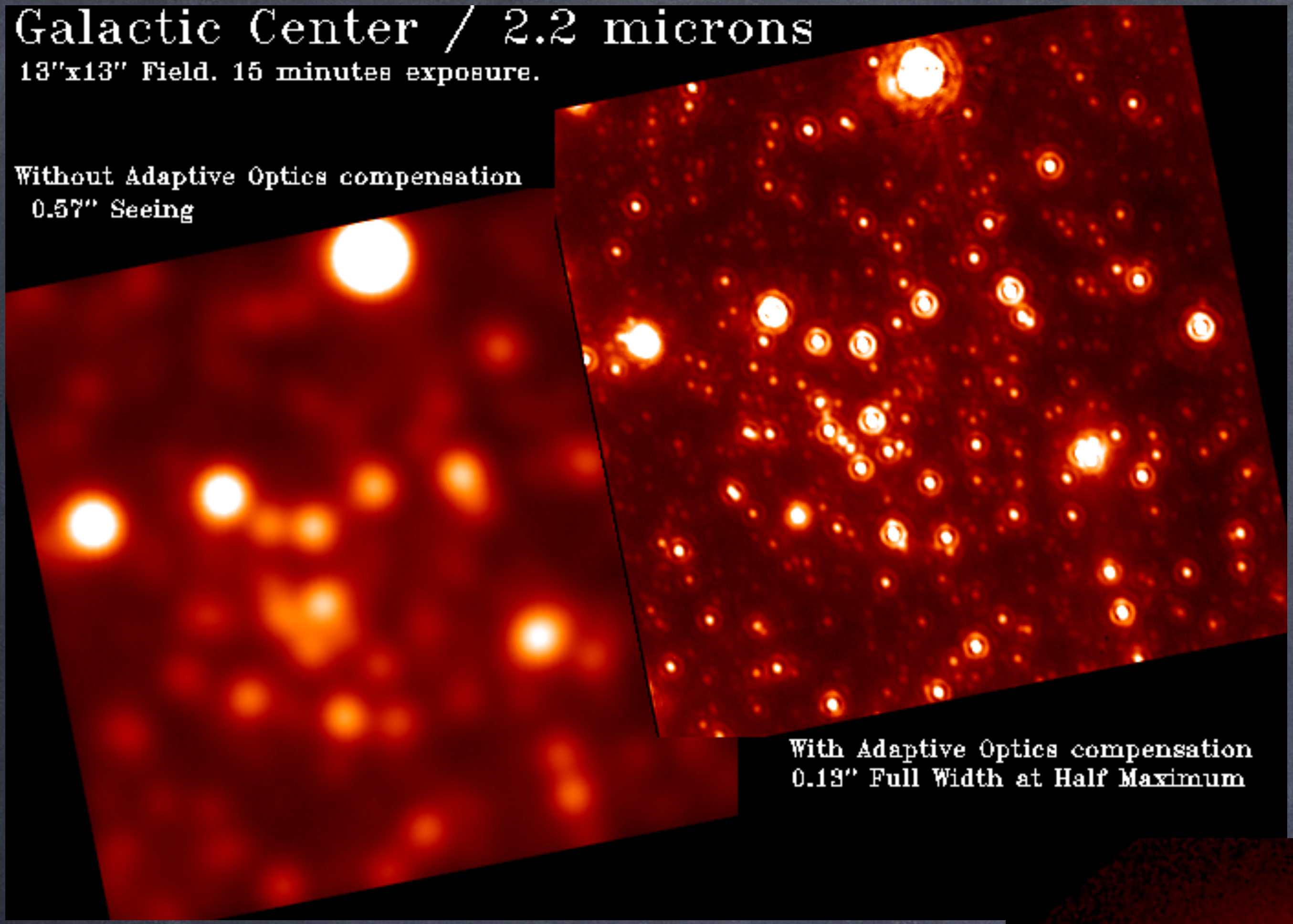


(Lick Observatory, 1-m telescope, left: FWHM~1", right: FWHM~λ/D)

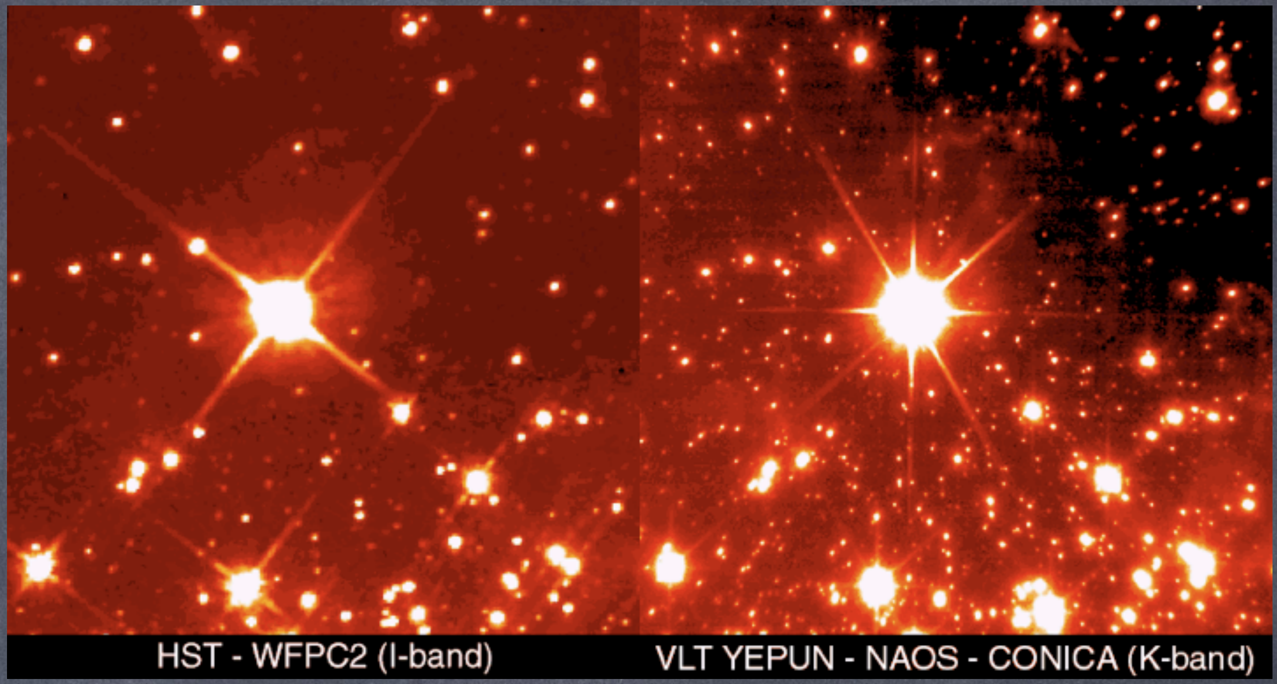


(Gemini Observatory, Hokupa'a+Quirc, left: FWHM~0"85, right: FWHM~0"09)

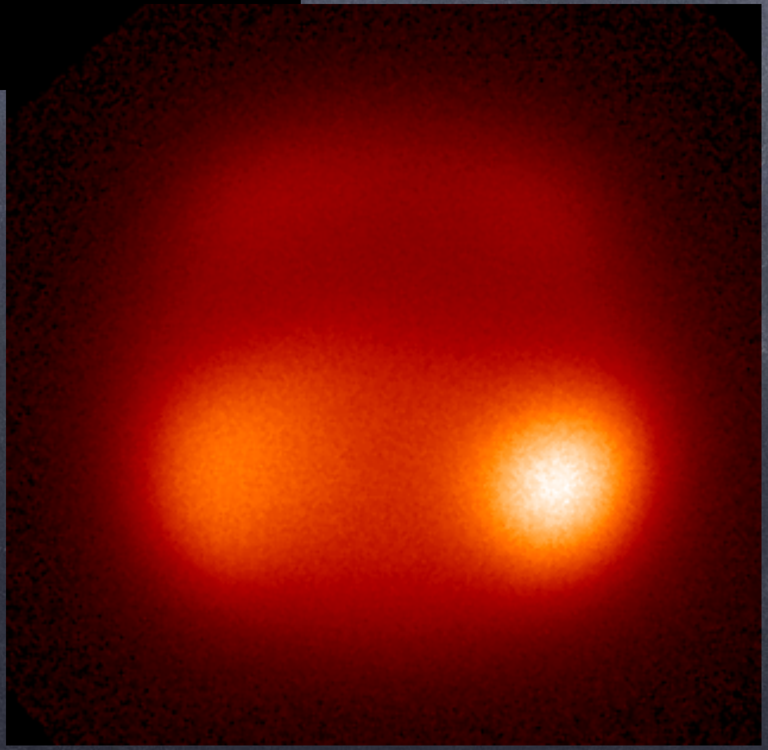
Adaptive optics - 8

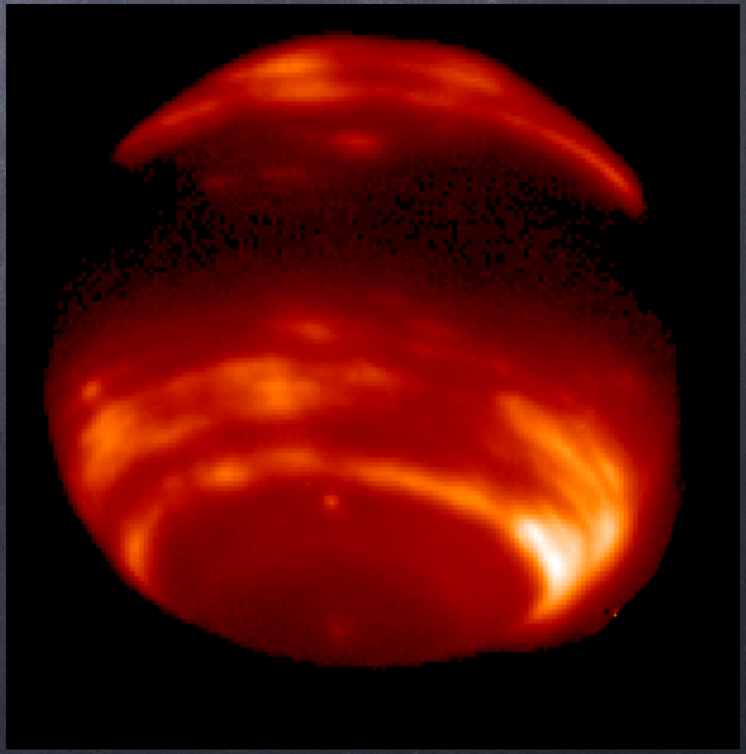


(CFHT, long-exposure image (15'))



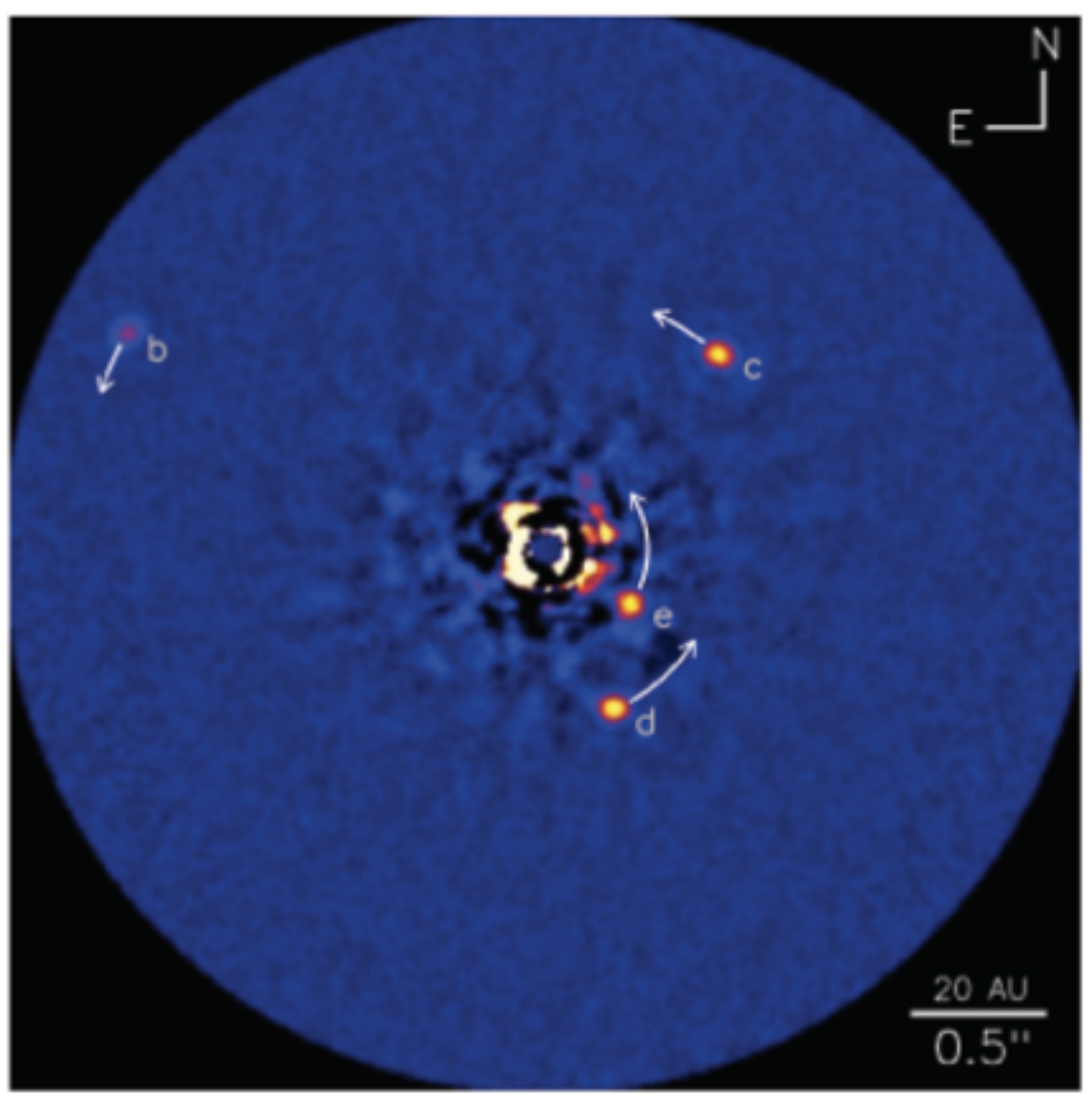
(HST in I band vs. NACO/VLT in K band)





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

Adaptive optics - 9



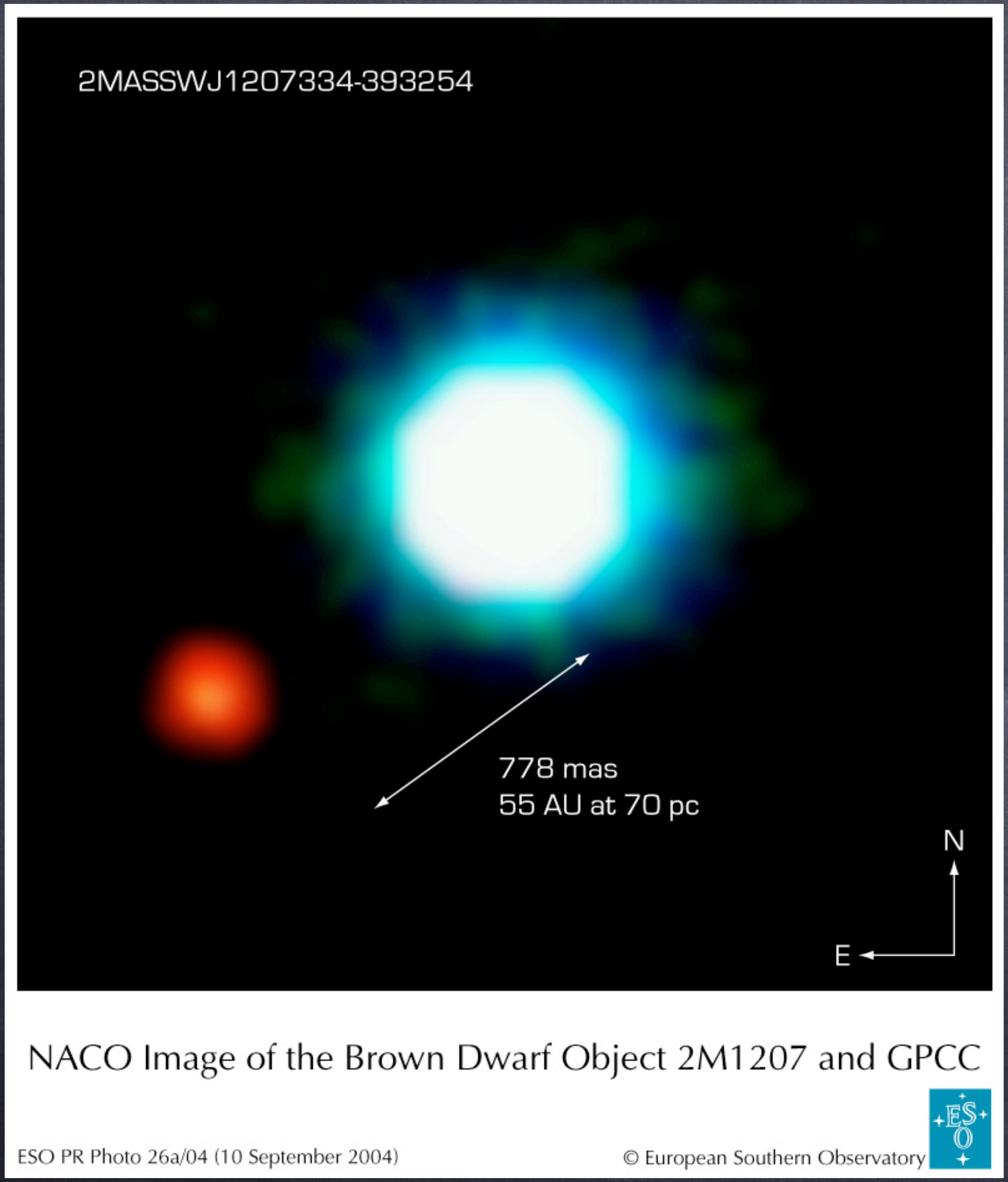
From Marois et al. 2010:
main sequence star HD8799, six exoplanets detected in 2013, from which 5 from (X)AO systems and 1 from HST.

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



From Chauvin et al., A&A, 2004 & 2005:
Brown dwarf at 70pc, young star < 10 million years,
sep.~0"8, int.ratio~100, M_{star}~20 $M_{Jupiter}$, M_{planet}~5 $M_{Jupiter}$

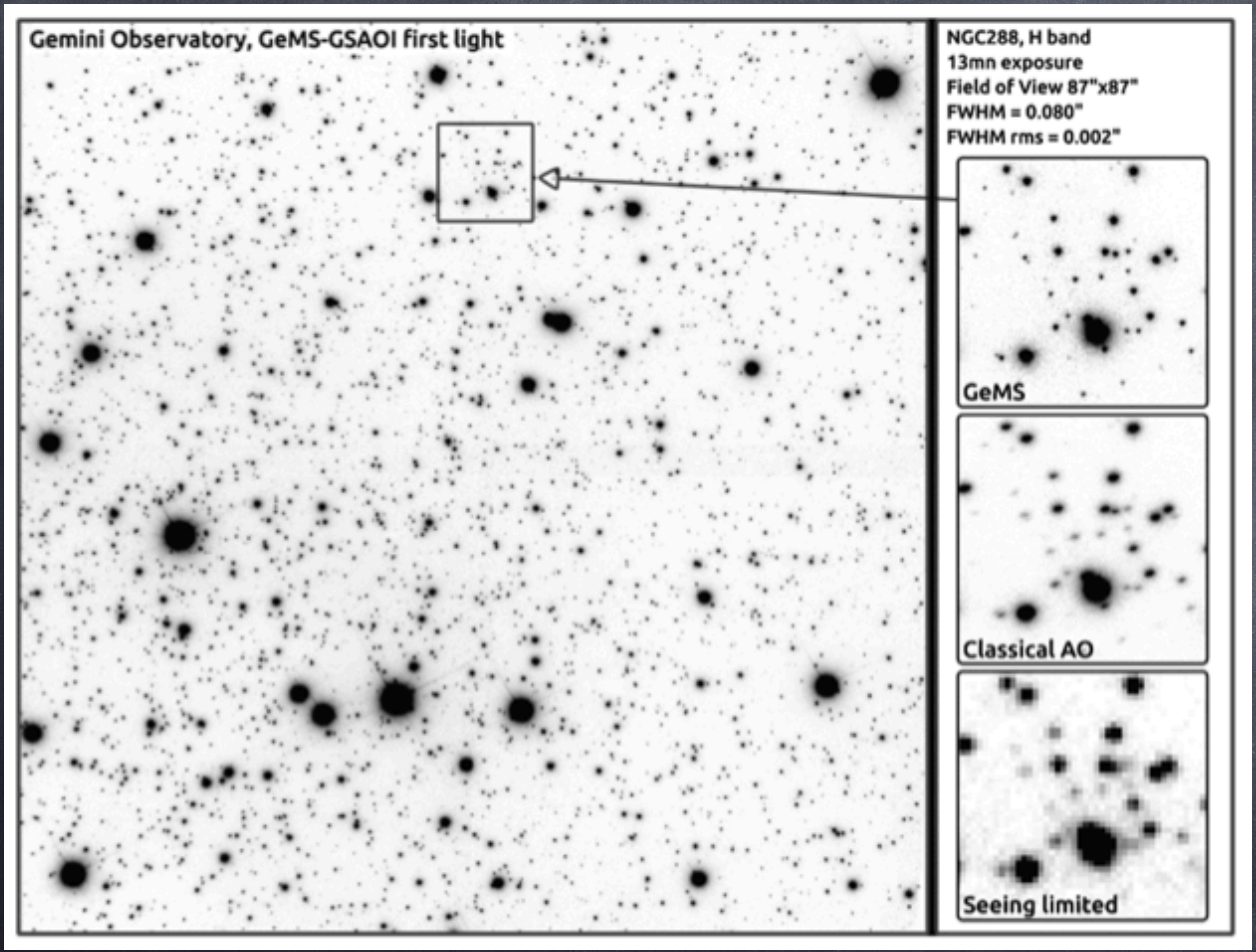
Context: detection & characterisation of exoplanets

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.

XAO = standard AO with lots of everything ! (actuators, sub-apertures, cycles/s, photons, etc.)

Adaptive optics - 11

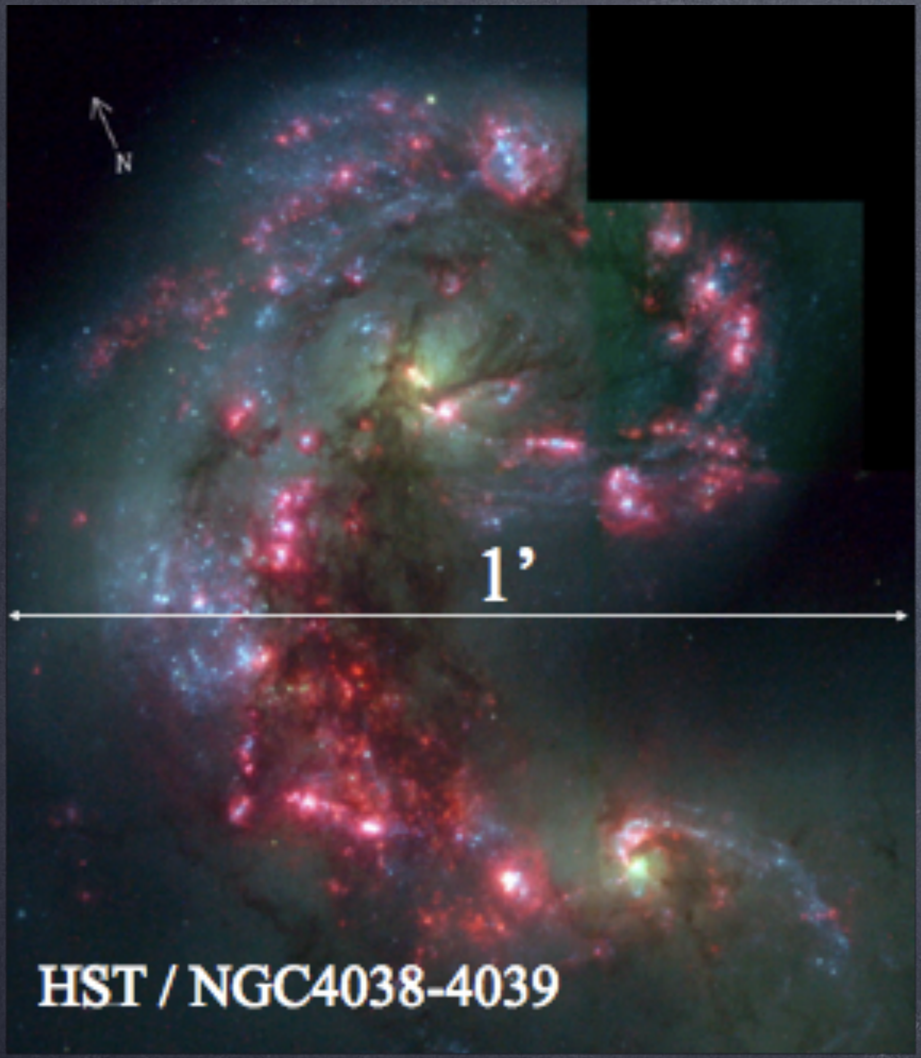


First-light image of GeMS, the MCAO system of Gemini
diffraction limit over a 2' square FoV - vs. a few arcsec !

Context: wide-field astronomical imaging

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

Adaptive optics - 12



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

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

- evolution of the mass function of stars of our Galaxy
- evolution of the star formation in nearby galaxies
- history of farer galaxies

Adaptive optics - 13

Zoology of present AO systems:

- **Observe at high-angular resolution (HAR) generic 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).

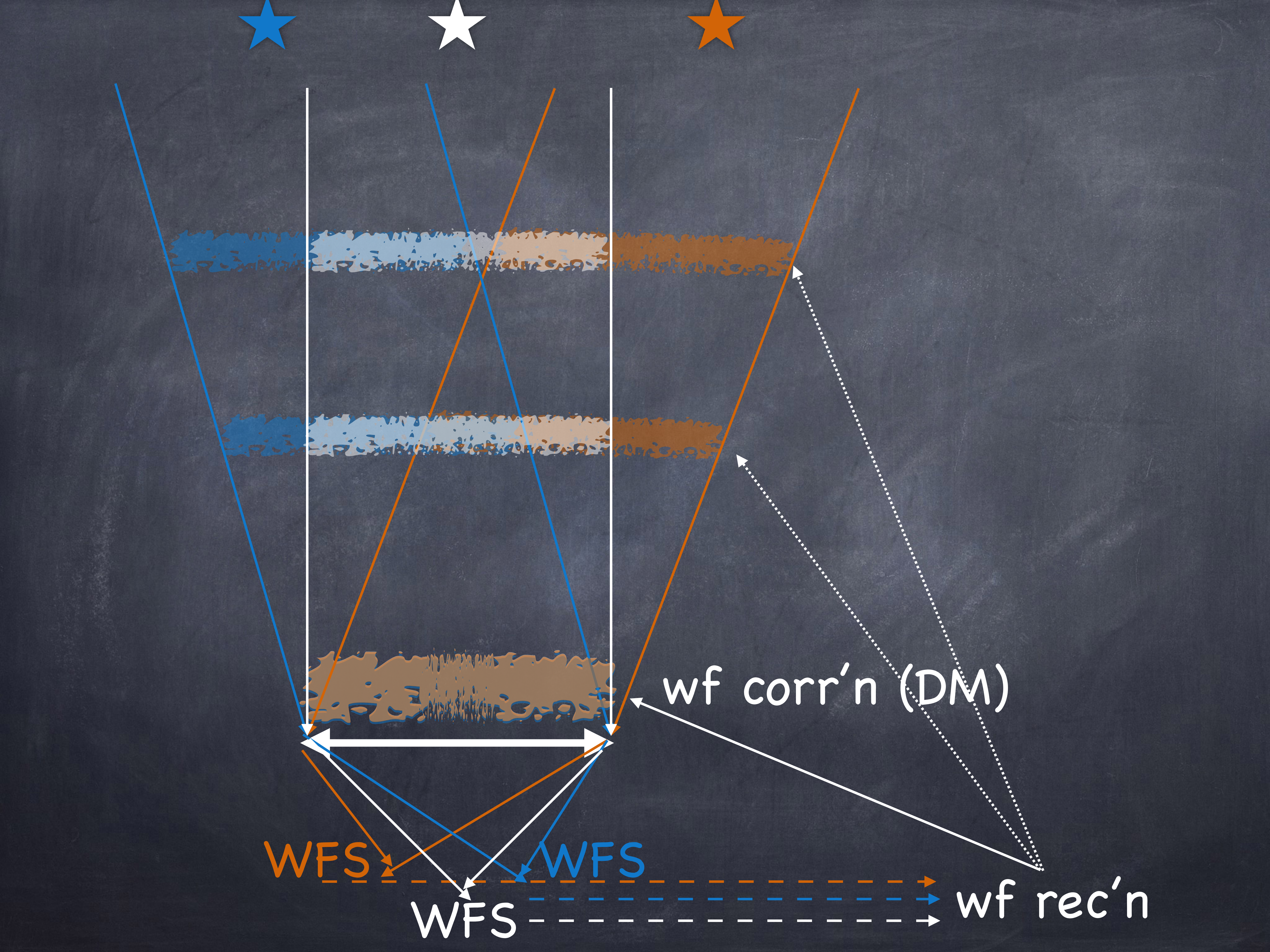
- **Have in addition a wide field of correction**
  => multi-reference AO systems, such as:
  - ground-layer AO (GLAO) systems,
  - multi-conjugate AO (MCAO) systems,
  - multiple-objects AO (MOAO) systems,
  - laser tomography AO (LTAO) systems.

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

Adaptive optics - 14

<u>In terms of science drivers:</u>

- **Stellar populations (FoV≈1', photometry => MCAO).**
- **Exoplanets (High contrast => XAO).**
- **Galactic center (astrometry, lack of NGS => LGS AO, LTAO).**
- **Galaxy dynamics (sky coverage, small sources over large FoV => MOAO, LTAO).**
- **Solar system (FoV≈10"—60", competition w/probes => MCAO).**
- **Also for the Sun (GLAO, MCAO)**


wf corr'n (DM)
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 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

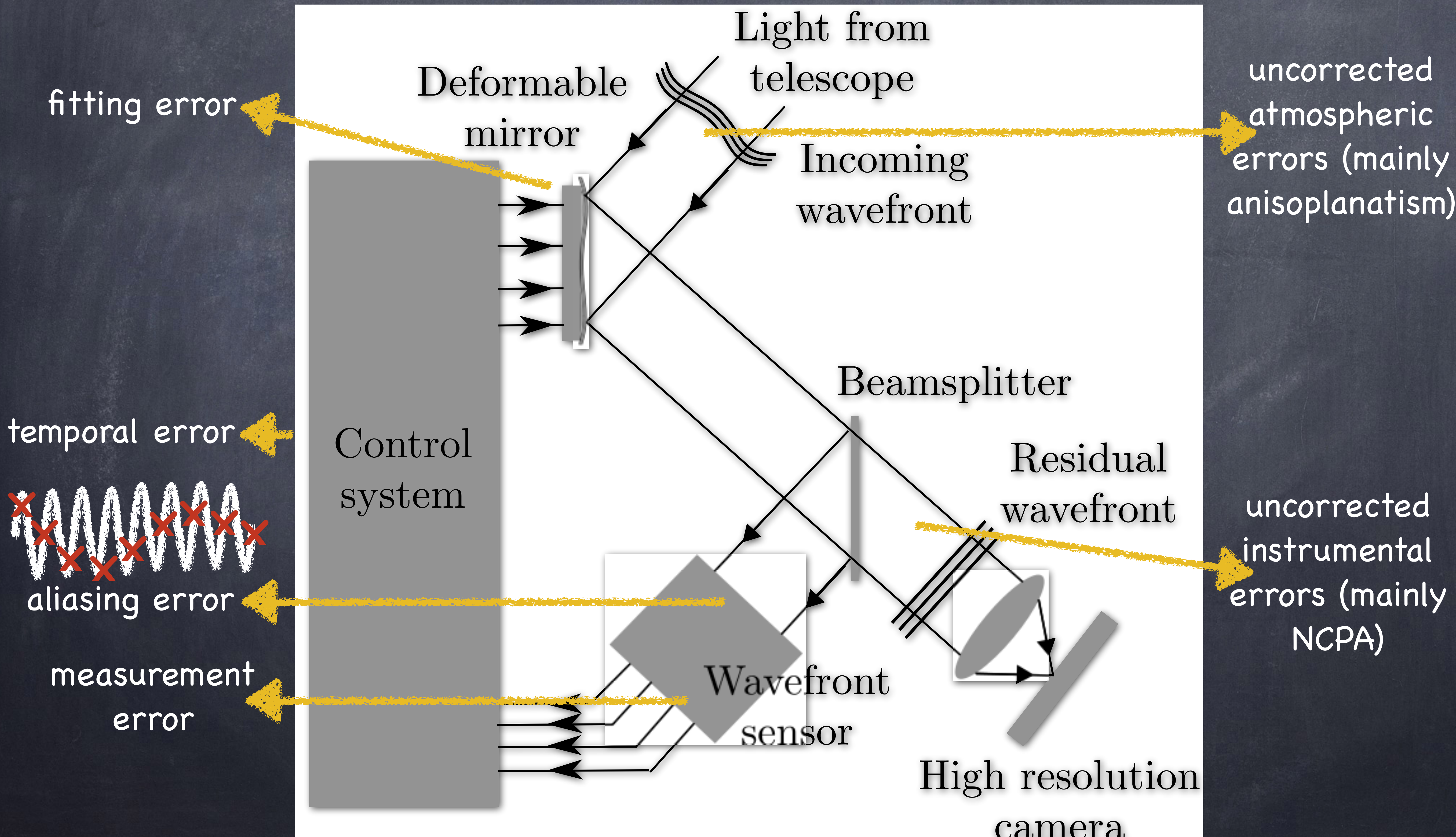
In 1953, Horace Babcock, an American astronomer, proposed the concept of adaptive optics (AO). The wavefront aberrations induced by atmospheric turbulence could be measured by a wavefront sensor and compensated for by a wavefront corrector, thereby deblurring the images in part or entirely. Babcock had 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

-> For next session : prepare an informal presentation of Rigaut's paper !!

Post-AO error budget - 1



Post-AO error budget - 2

Global error (variance on the corrected phase/wavefront)

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

- Error term due to turbulent atmosphere alone
- Residual error of the AO system itself
- Other error terms…

Post-AO error budget - 3

Other errors

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

- <u>Error term due to Non-Common Path Aberrations</u>
- Error term due to the calibration of the AO system
- etc.

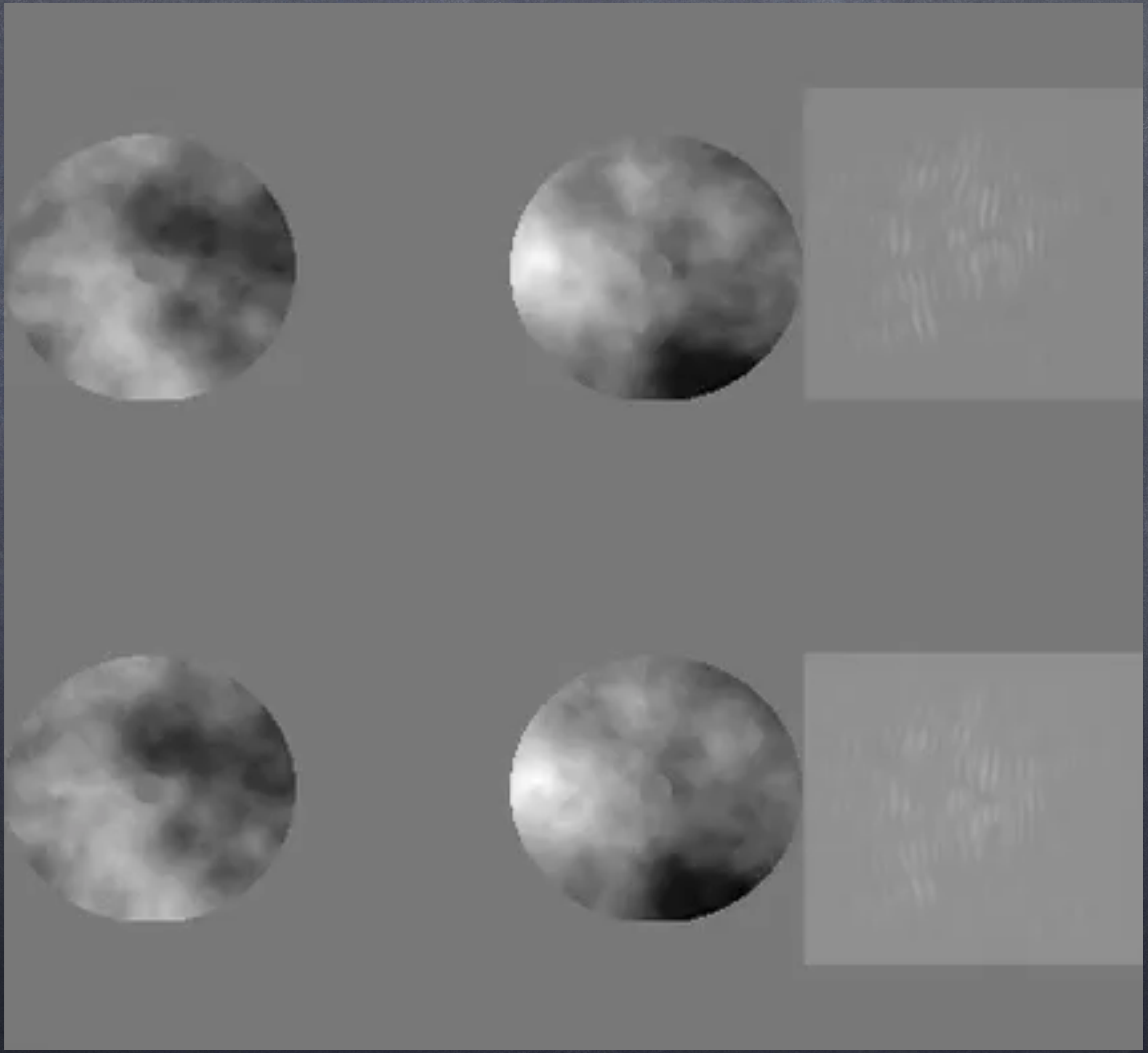
Post-AO error budget - 4

Error due to atmospheric turbulence alone

$$\sigma^2_{\mathrm{atm.}} = \sigma^2_{\mathrm{aniso}} + \sigma^2_{\mathrm{scint..}} + \sigma^2_{\mathrm{diff.}} + \sigma^2_{\mathrm{chrom.}}$$

- Error term due to anisoplanatism
- Error term due to scintillation
- Error term due to diffractive effects
- Error term due to differential refraction

Post-AO error budget - 5



Post-AO error budget - 6

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 - 7

Fitting error

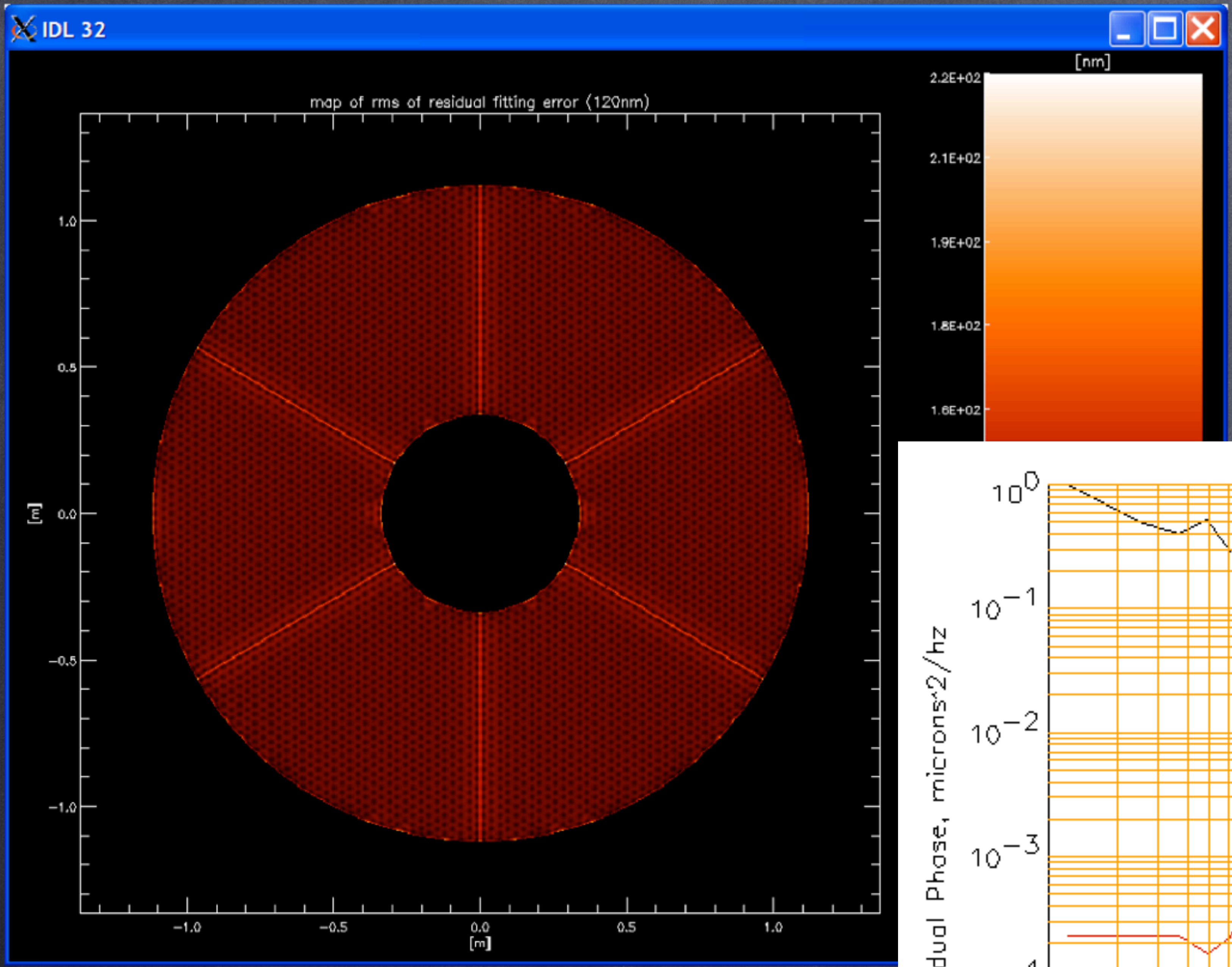
$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

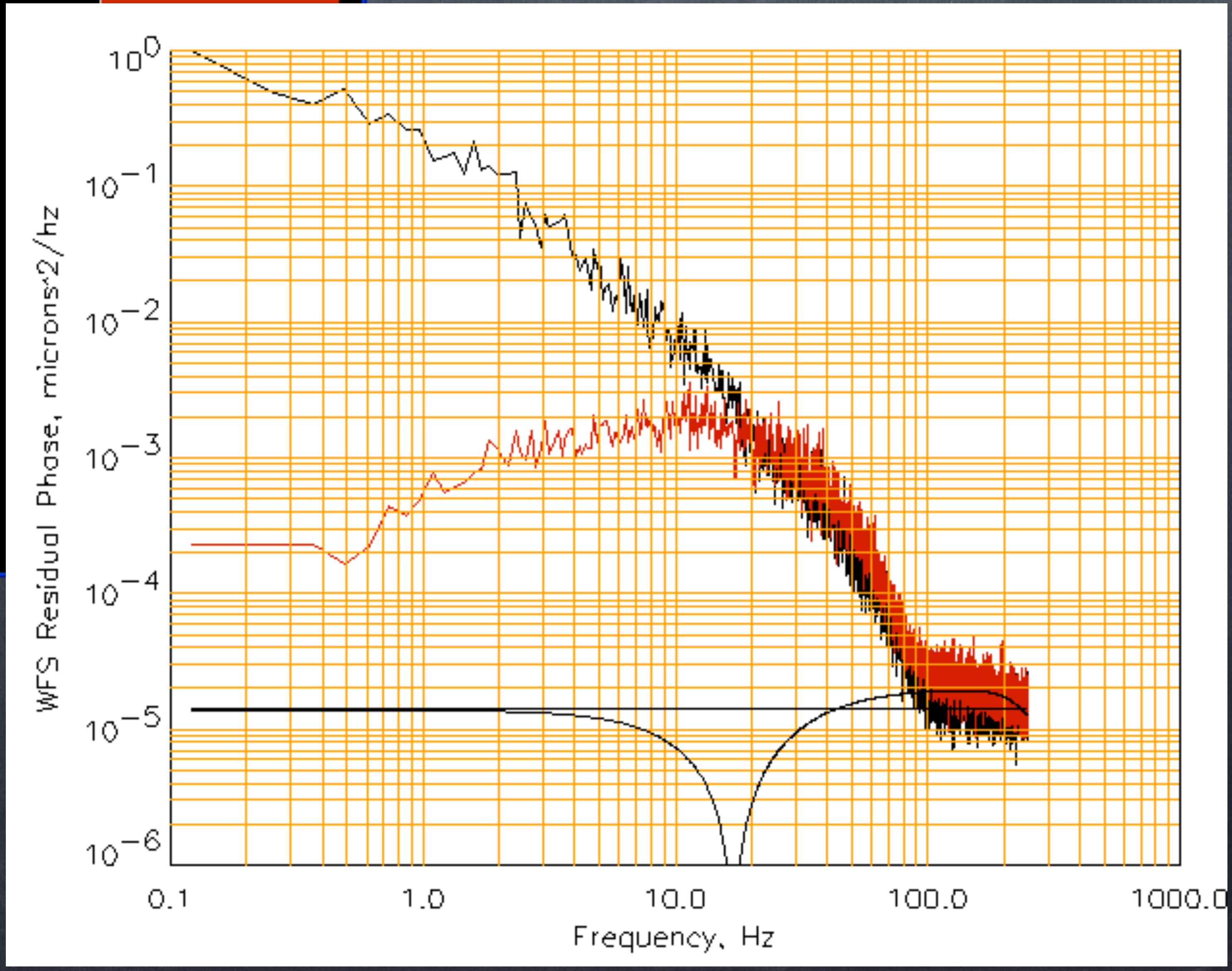
$$\sigma^2_{\text{fitt.}} \propto \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

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

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

Post-AO error budget - 8





(Noll: residual error - 1)

If, instead of having actuators, one could have a mirror capable of forming perfect Zernike polynomials, one would have (admitting that atmosphere exactly follows a Kolmogorov model):

$$\Delta_J \simeq 0.2944 \; J^{-\sqrt{3}/2} \left(\frac{D}{r_0}\right)^{5/3}, J \geq 20$$

Hence, in meters:

$$\sigma_J[m] \simeq \frac{\lambda}{2\pi}\sqrt{\Delta_J} \simeq 0.352 \; J^{-\sqrt{3}/4} \; D^{5/6} \; \left(\int_0^\infty C_n^2(z) \; dz\right)^{1/2}$$

With, thanks to Maréchal's approximation:

$$S \simeq \exp\{-\Delta\}$$

(Noll: residual error - 2)

TABLE IV. Zernike-Kolmogoroff residual errors (Δ_J). (D is the aperture diameter.)

$\Delta_1 = 1.0299\ (D/r_0)^{5/3}$	$\Delta_{12} = 0.0352\ (D/r_0)^{5/3}$
$\Delta_2 = 0.582\ (D/r_0)^{5/3}$	$\Delta_{13} = 0.0328\ (D/r_0)^{5/3}$
$\Delta_3 = 0.134\ (D/r_0)^{5/3}$	$\Delta_{14} = 0.0304\ (D/r_0)^{5/3}$
$\Delta_4 = 0.111\ (D/r_0)^{5/3}$	$\Delta_{15} = 0.0279\ (D/r_0)^{5/3}$
$\Delta_5 = 0.0880\ (D/r_0)^{5/3}$	$\Delta_{16} = 0.0267\ (D/r_0)^{5/3}$
$\Delta_6 = 0.0648\ (D/r_0)^{5/3}$	$\Delta_{17} = 0.0255\ (D/r_0)^{5/3}$
$\Delta_7 = 0.0587\ (D/r_0)^{5/3}$	$\Delta_{18} = 0.0243\ (D/r_0)^{5/3}$
$\Delta_8 = 0.0525\ (D/r_0)^{5/3}$	$\Delta_{19} = 0.0232\ (D/r_0)^{5/3}$
$\Delta_9 = 0.0463\ (D/r_0)^{5/3}$	$\Delta_{20} = 0.0220\ (D/r_0)^{5/3}$
$\Delta_{10} = 0.0401\ (D/r_0)^{5/3}$	$\Delta_{21} = 0.0208\ (D/r_0)^{5/3}$
$\Delta_{11} = 0.0377\ (D/r_0)^{5/3}$	

$$\Delta_J \sim 0.2944\, J^{-\sqrt{3}/2}\, (D/r_0)^{5/3} \quad \text{(For large } J\text{)}$$

(From Noll, JOSA 66, 1976)

(Noll: residual error - 3)

Exercice 1: Which mirror configuration for a (minimum, other errors excluded) goal Strehl ratio of 30% in band J (1.25um) ?
[r0@500nm=10cm, D=8m]