Adaptive Optics: 50 years of development to serve photonics

Samuel Bucourt – sbucourt@imagine-optic.com

WAVEFRONT SENSORS

DEFORMABLE MIRRORS

METROLOGY SYSTEMS

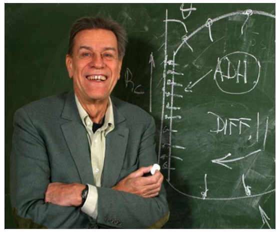
ADAPTIVE OPTICS SOLUTIONS

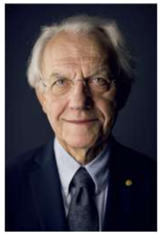
menu of the day

- Imagine Optic in one slide!
- Adaptive Optics: what and what for?
- Adaptive Optics: how?
- Adaptive Optics: then?
- Perspectives and take away

Imagine Optic in one slide

- Founded in **1996**, development and manufacturing of **wavefront sensing** & **adaptive optics**
- **55** employees, **> 7 M€** revenue + imagine eyes Since 2003
- 35+ patents granted
- > **2500 sensors** worldwide…
- > **250 Adaptive optics** systems with Mirao52e for ophthalmology and microscopy and
  > **70 adaptive optics** systems with ILAO & ILAO Star for high-power lasers in > 10 countries





WHAT
& WHAT FOR

What?

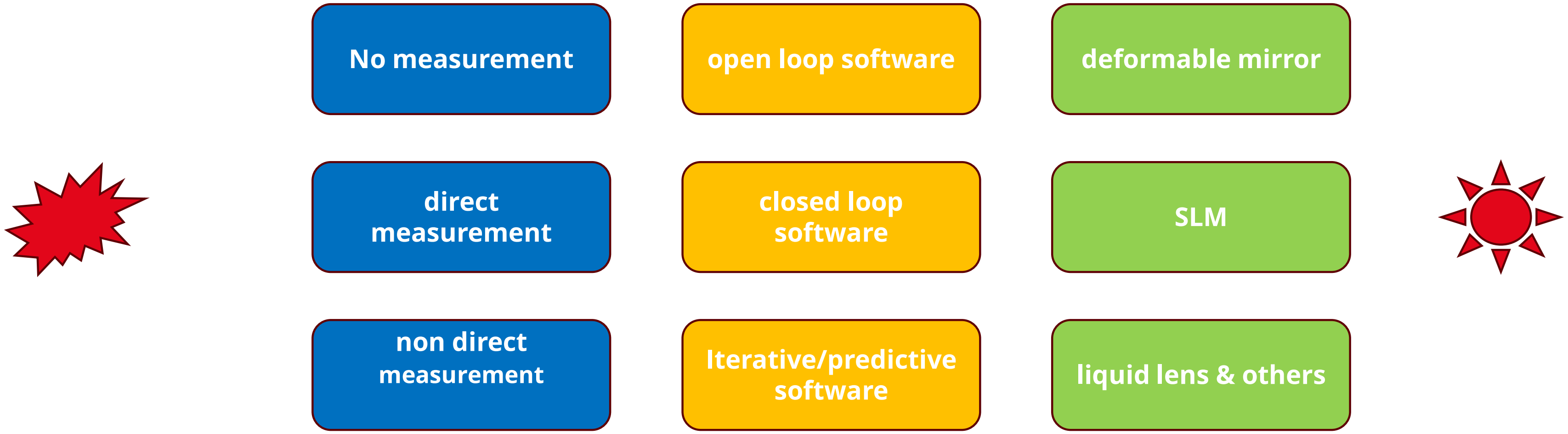
- Wiki: is a technique of precisely deforming a deformable mirror in order to compensate for light distorsion
- Wiki fr: is a technique that makes it possible to correct in real time the non predictive changing wavefront thank to a deformable mirror
- Imagine: is a technique to manipulate dynamically the wavefront of a beam

You need:

- A smart optics
- A wavefront evaluation
- A software to close the loop

What?

+ Imagine: is a technique to manipulate dynamically the wavefront of a beam

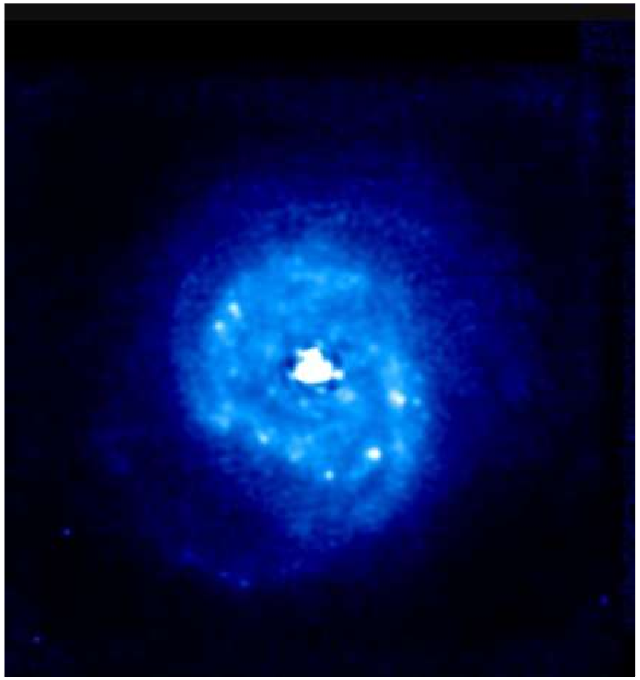


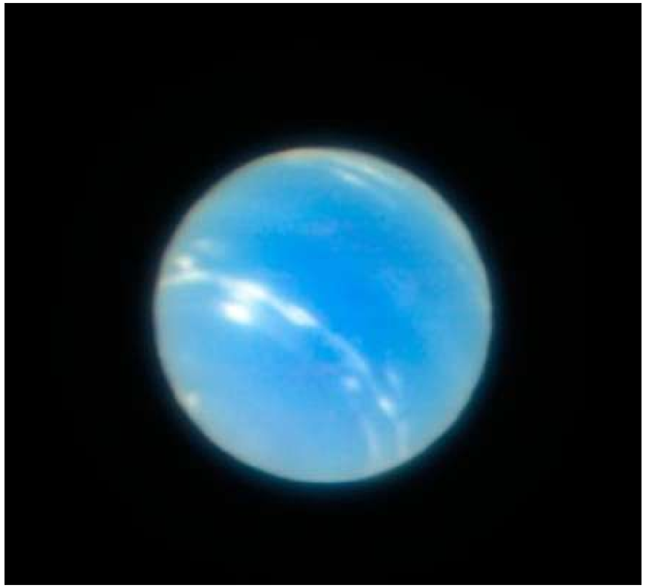
What for?

- astrophysics
- ultraintense laser
- ophthalmology
- microscopy
- satcom
- …

What for?

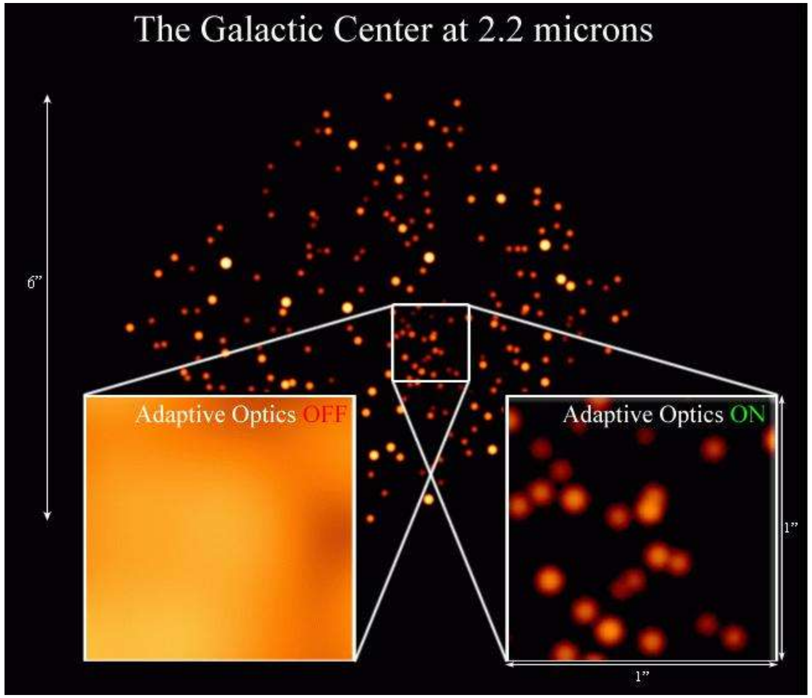
- **astrophysics**





What for?

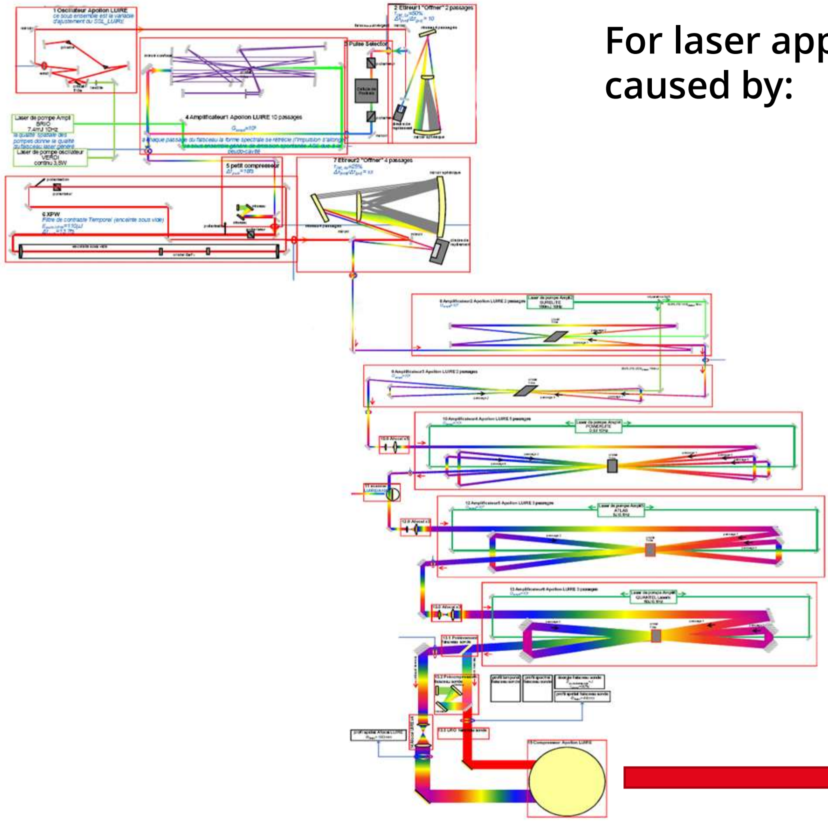
+ **astrophysics**



Andrea Ghez, 2020 Nobel prize

What for?

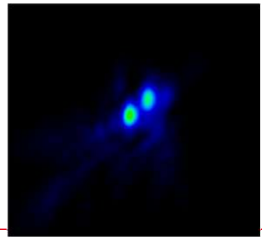
- **ultraintense laser**



For laser applications, the wavefront distortions are caused by:

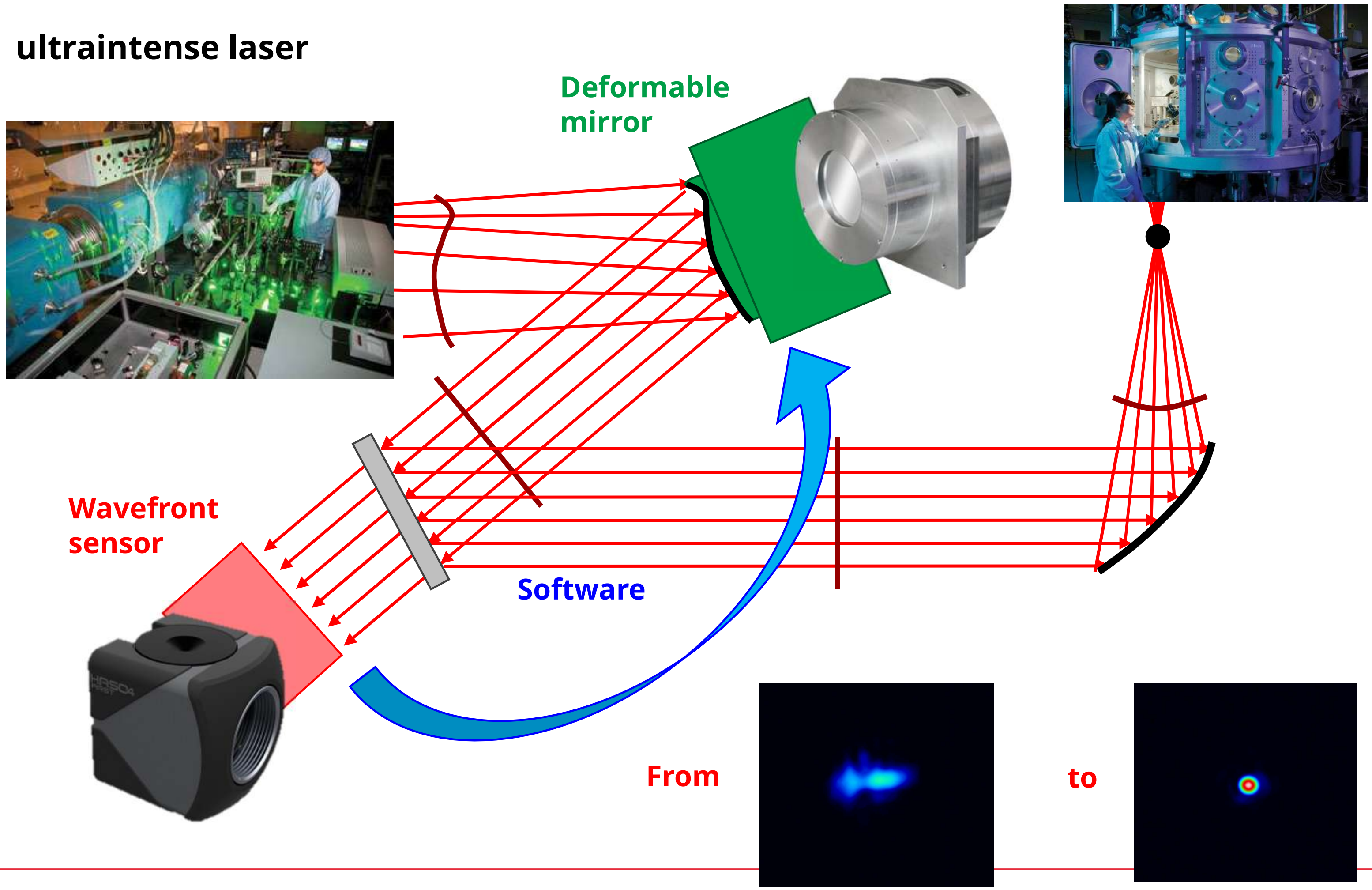
- *a large number of optical elements*
- *misalignment of optical elements (beam expanders …)*
- *Thermal effects in the amplifiers*
- *mechanical constraints on large optical elements*

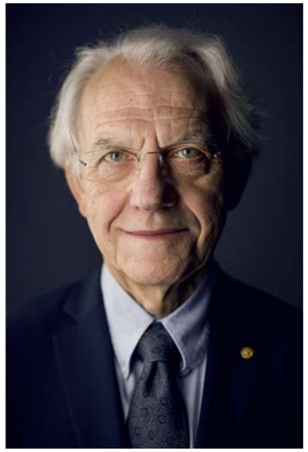
These wavefront distortions degrade the focused beam and decrease the maximum focused intensity



What for?

+ **ultraintense laser**





Gérard Mourou, 2018 Nobel prize

What for?

+ **ophthalmology**

Cellular resolution

- Microscopic signs of pathology
- Progression & regression tracked with micron precision
- Cellular and microvascular biomarkers

Usable by clinicians

- Approved by regulatory agencies in EU (CE mark) and Japan
- Comfortable and fast: images acquired in 2 sec
- Intuitive & complete software: including quantification and follow-up

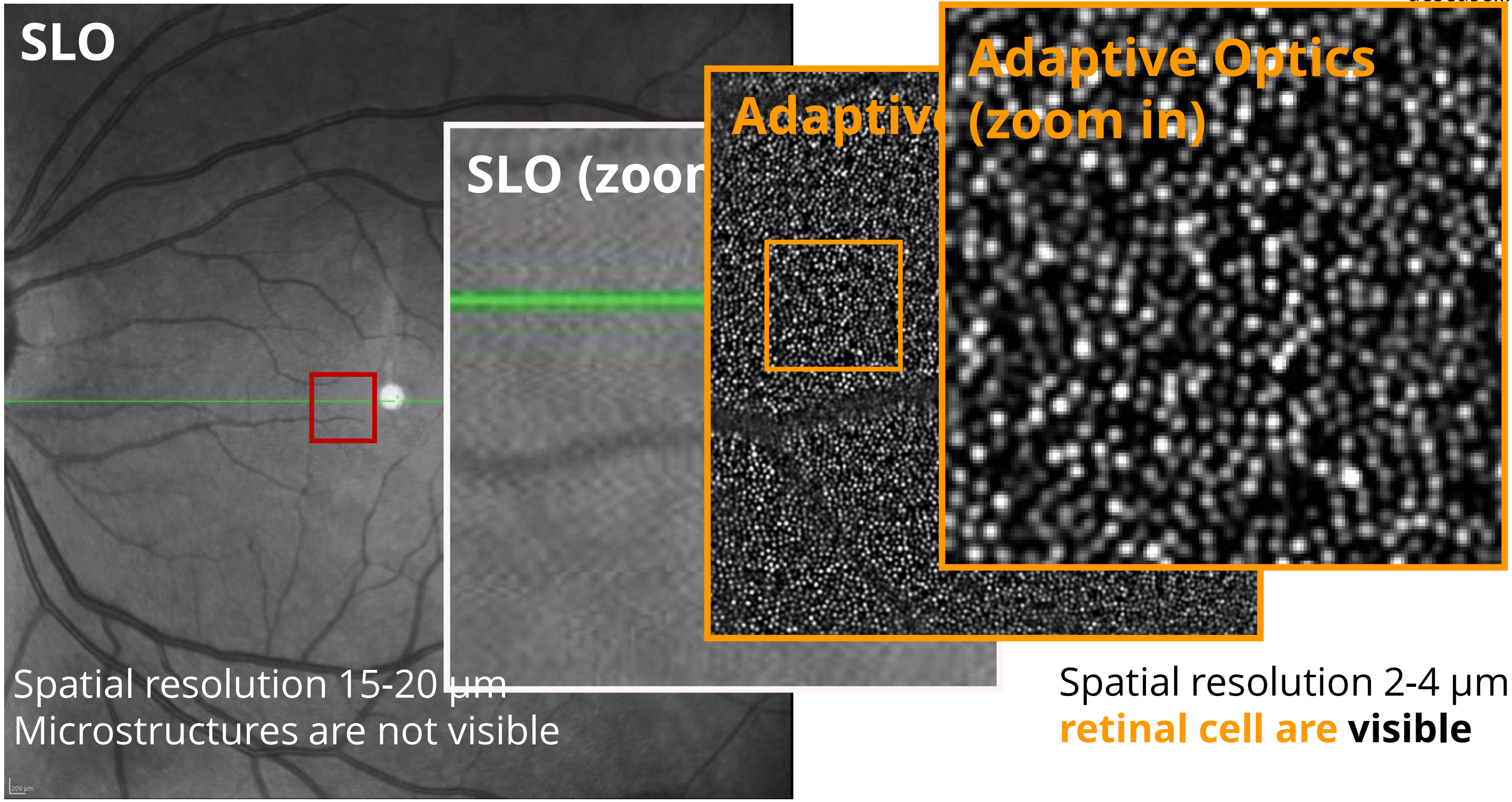
Reference product

- Adopted by more than 80 clinical research centers
- Compatible for large-scale studies that involve over 1000 patients
- Performance proven by over 150 peer-reviewed publications

What for?

+ **ophthalmology**

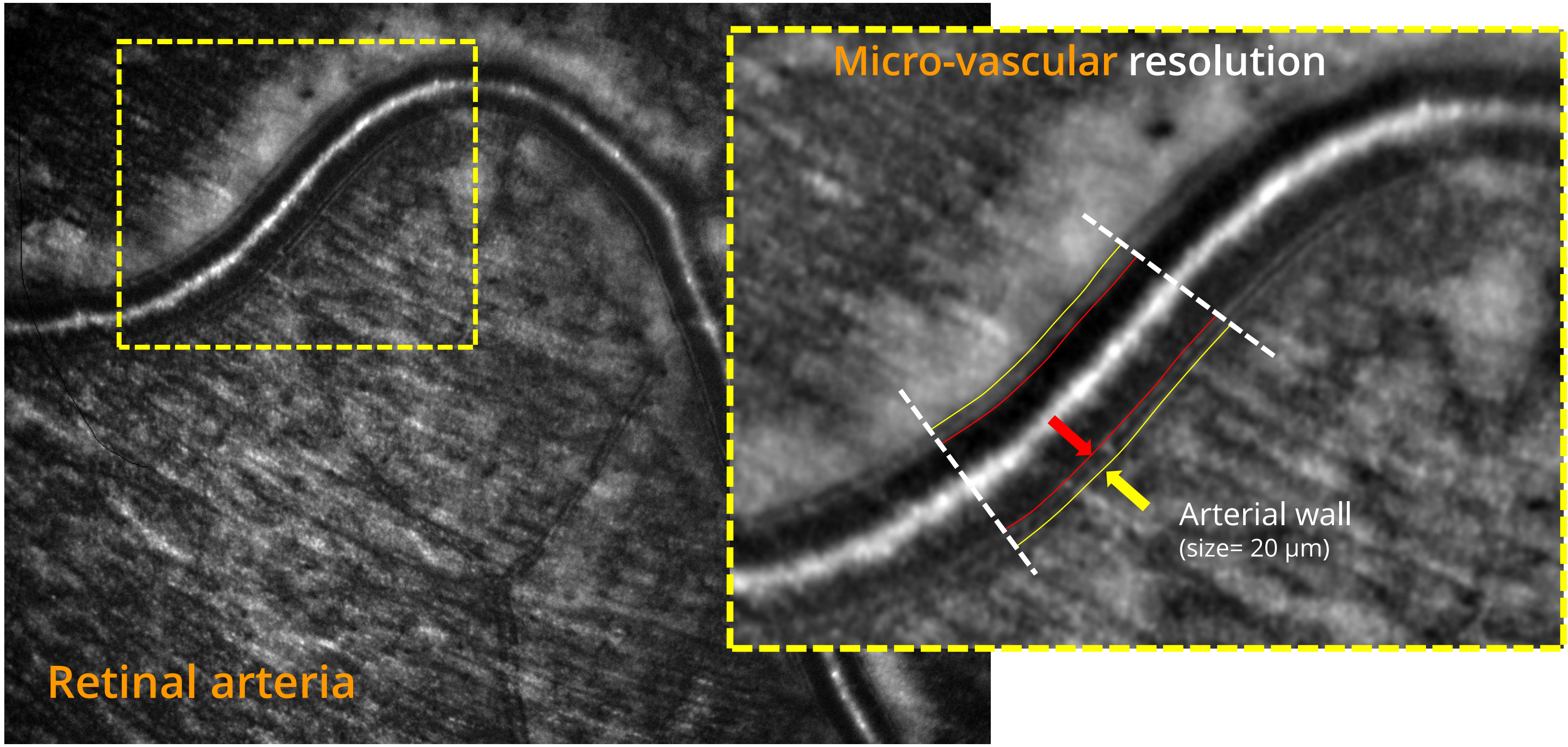
Ophthalmology: retinal microscopy for ocular desease...



Spatial resolution 2-4 µm
retinal cell are visible

What for?

- **ophthalmology**

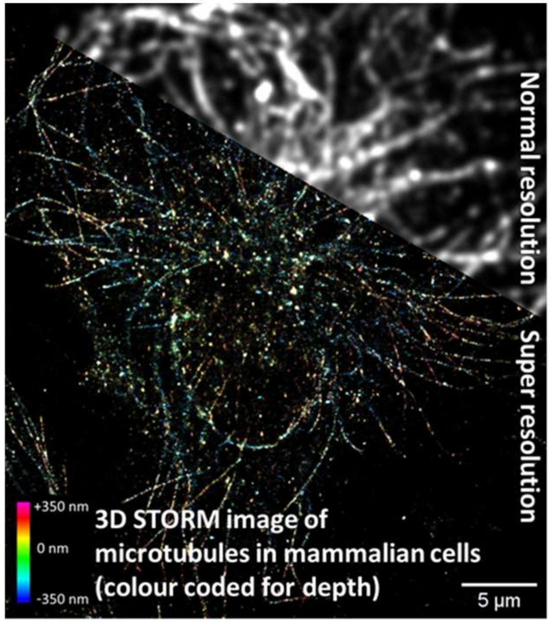


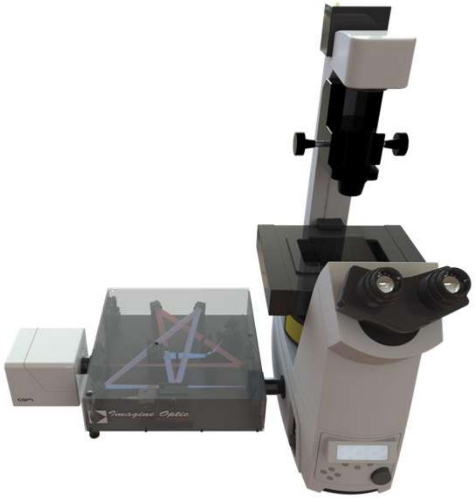
Michel Paques

José-Alain Sahel

What for?

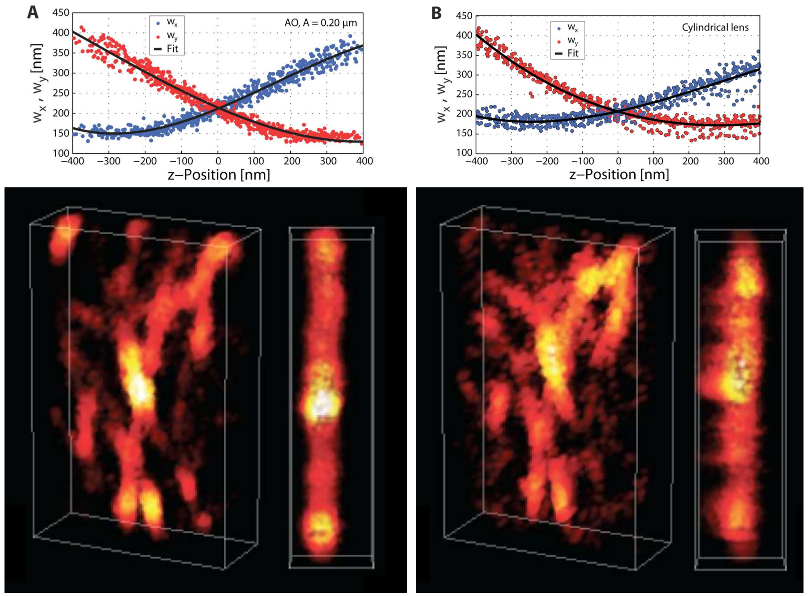
+ microscopy





Hell & Betzig, 2014 Nobel prize

Superresolution microscopy



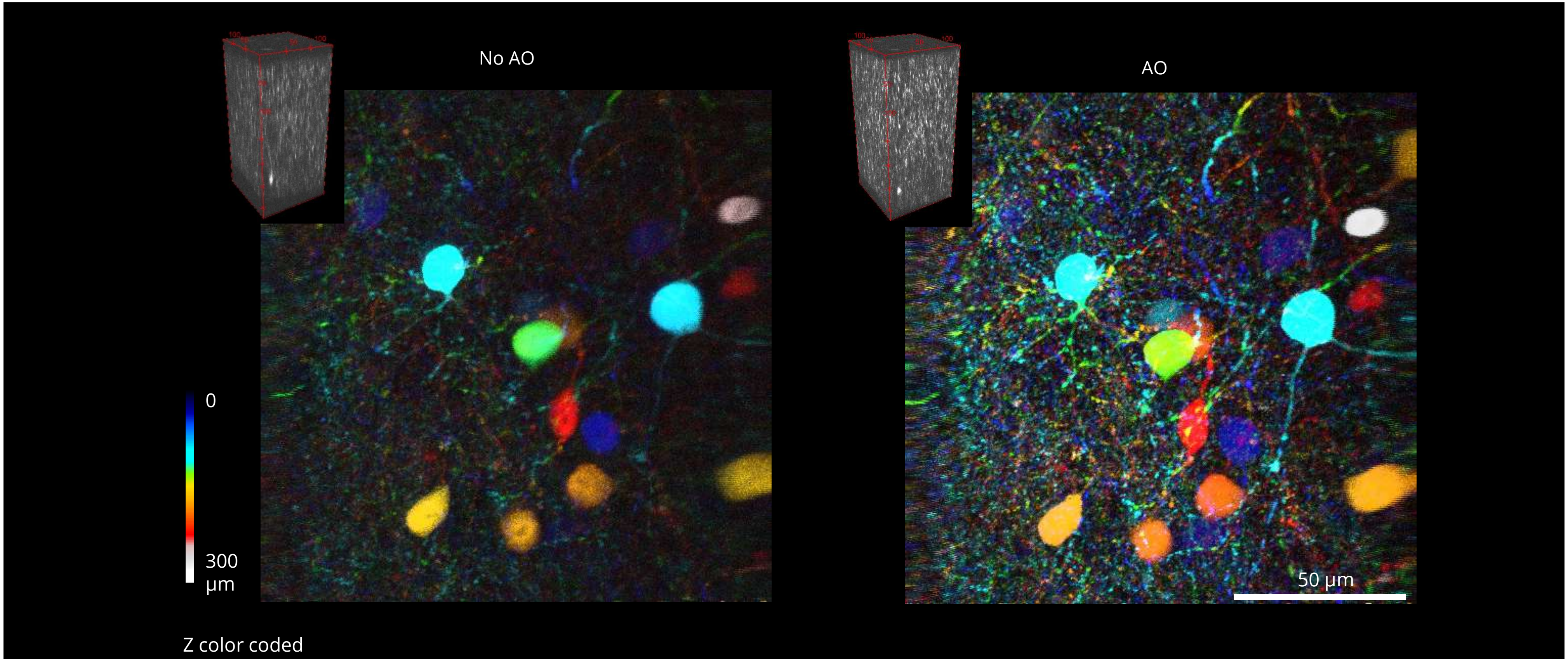
Z-resolution < 20nm

Z-resolution > 50nm

What for?

+ microscopy

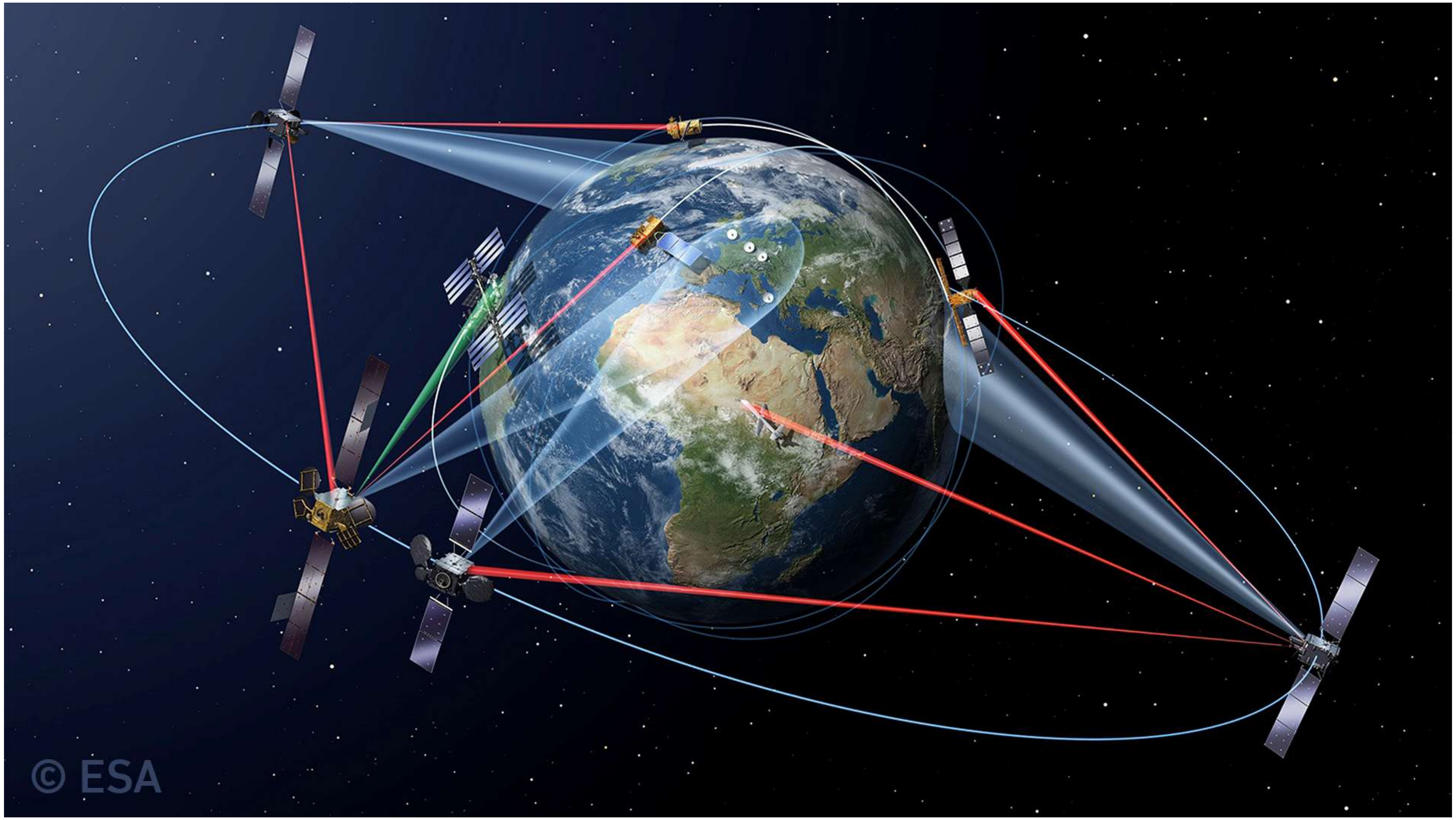
Fast AO for 2-photon fluorescence microscopy



fixed mouse brain slice, GADGFP neuronal labelling

What for?

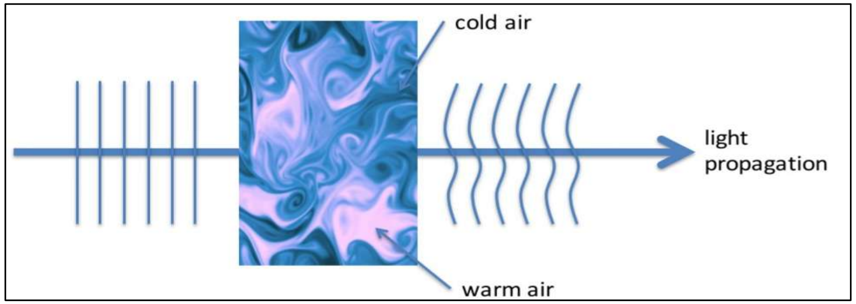
- **satcom**



What for

- **satcom**

- Speed of light in a medium of refractive index n: $v = \frac{c}{n}$
- The refractive index n is a function of the temperature
  - ➤ In the atmosphere, movements of hot and cold air masses disturb the propagation of light

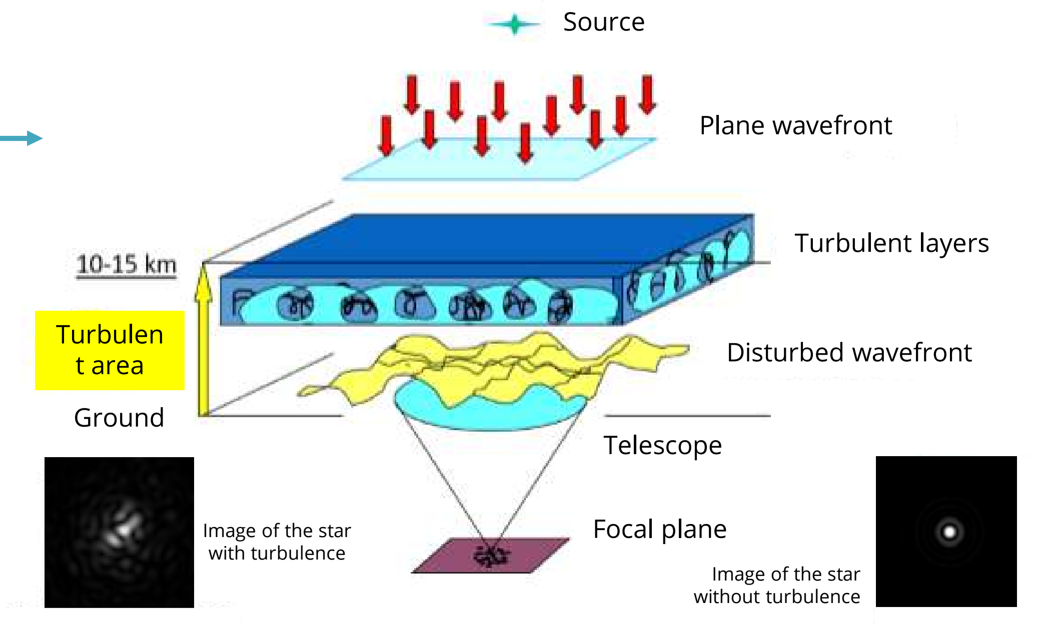


A plane wavefront passes through the atmosphere.

It goes across several areas of different optical indexes.

Light rays undergo a variation in the optical path: the wavefront is disturbed.

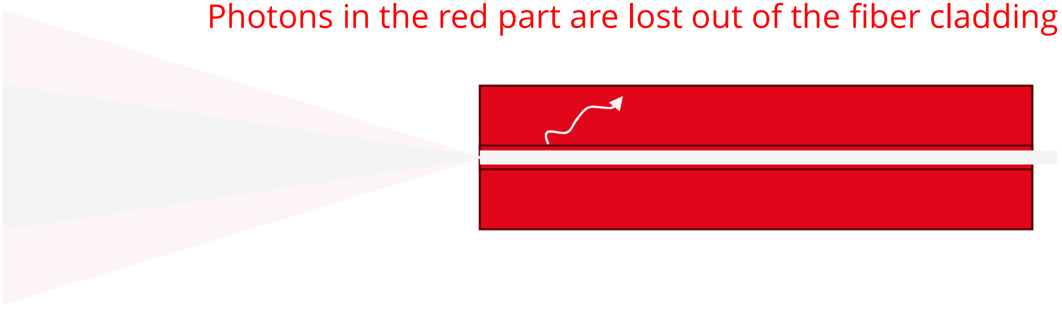
Rays do not all converge on the focus plane of the telescope and the image is distorted



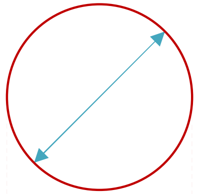
What for

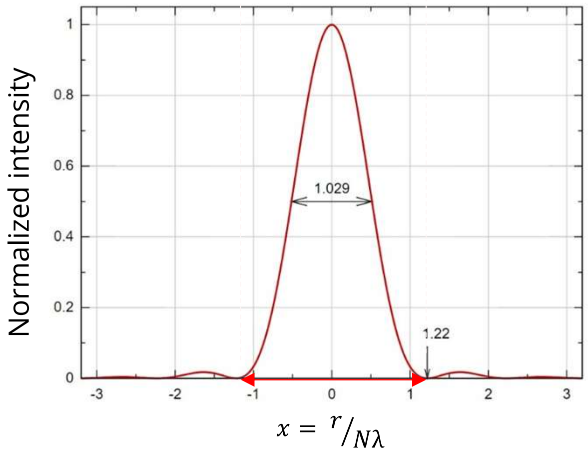
- **satcom**

Photons in the red part are lost out of the fiber cladding



Fiber diameter : 10µm
Fiber input surface : 78.5 µm²





- The numerical aperture of a fiber characterizes the range of angles which it can accept light: the fiber will propagate light that enters within its acceptance cone.
- For a single mode fiber, the maximum f# is defined by: $N = \frac{fiber\ core\ diameter}{2.44 * \lambda}$

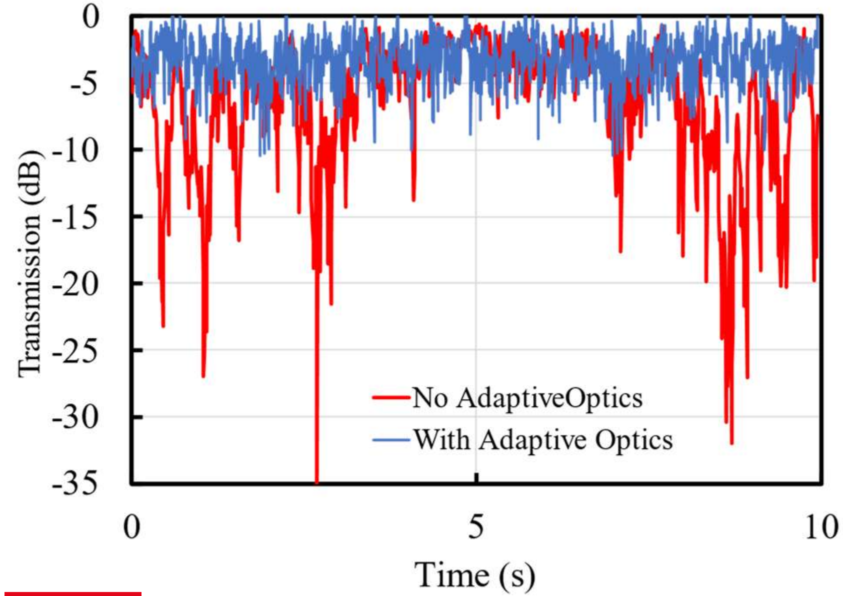
  For multimode fibers, the acceptance cone is bigger, so the maximum acceptable f# is higher: even in poor seeing conditions, one can inject the entire light by adjusting the f# before the fiber
- To make the size of the star fit with the diameter of the single mode fiber, the focal length must therefore be sufficiently large.

Spot disk diameter = $2.44 * \lambda N \ with \ N = f\# = \frac{f}{D}$

To have an optimal amount of light into the fiber, the diameter of the Airy disk peak must be equal to the diameter of the fiber

What for?

+ **satcom**



AO OFF

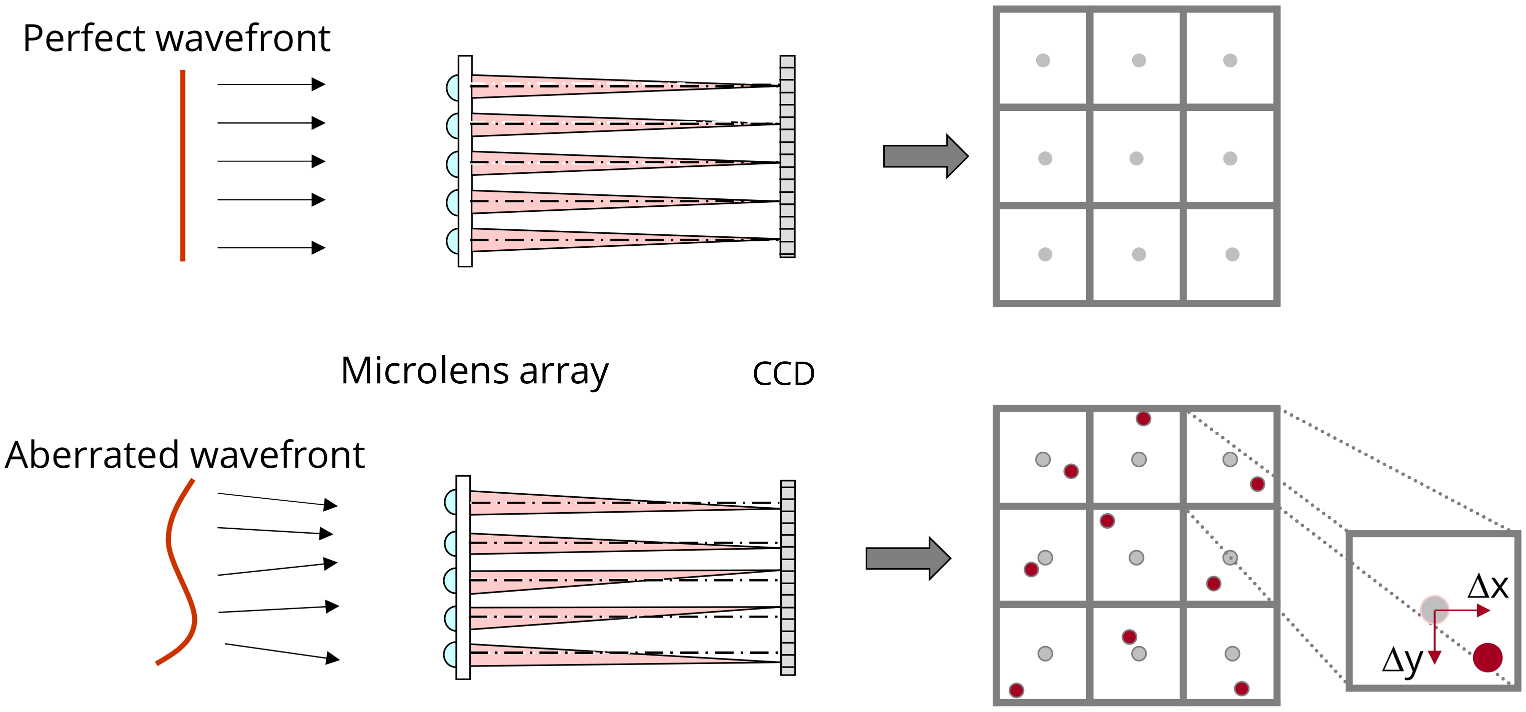
0,4m telescope	
r0	Coupling efficiency
0,05	0,0121
0,1	0,0486
0,15	0,1092
0,2	0,1942

AO ON

0,4m telescope	
r0	Coupling efficiency
0,05	0,367
0,1	0,684
0,15	0,750
0,2	0,790

HOW

How: the Shack-Hartman Wavefront sensor

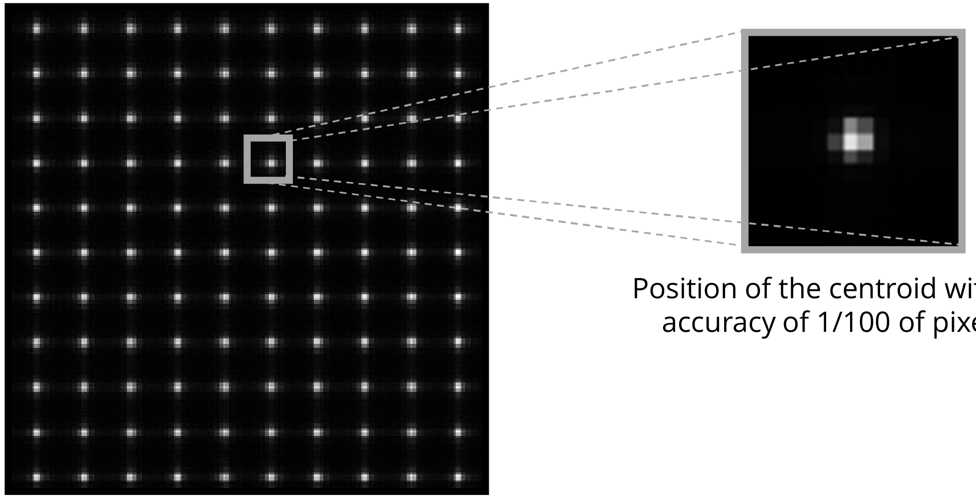


local slope measured ➔ slopes map ➔ wavefront map [integrator]

How: the Shack-Hartman Wavefront sensor

The **optical quality** of the refractive microlenses (typ. λ/50) and the low numerical aperture allows to work at the diffraction limit

Camera signal



Diffraction pattern of one microlens

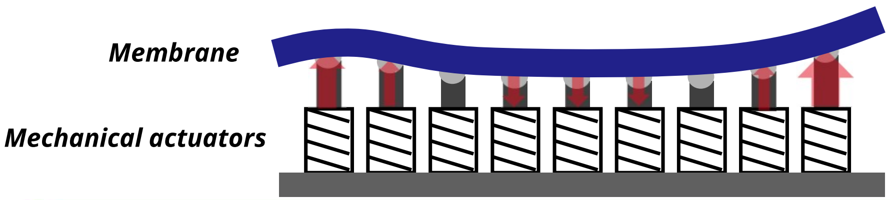
Position of the centroid with a typ. accuracy of 1/100 of pixel size

Wavefront measurement accuracy: λ/100 rms typ.

How: a deformable mirror

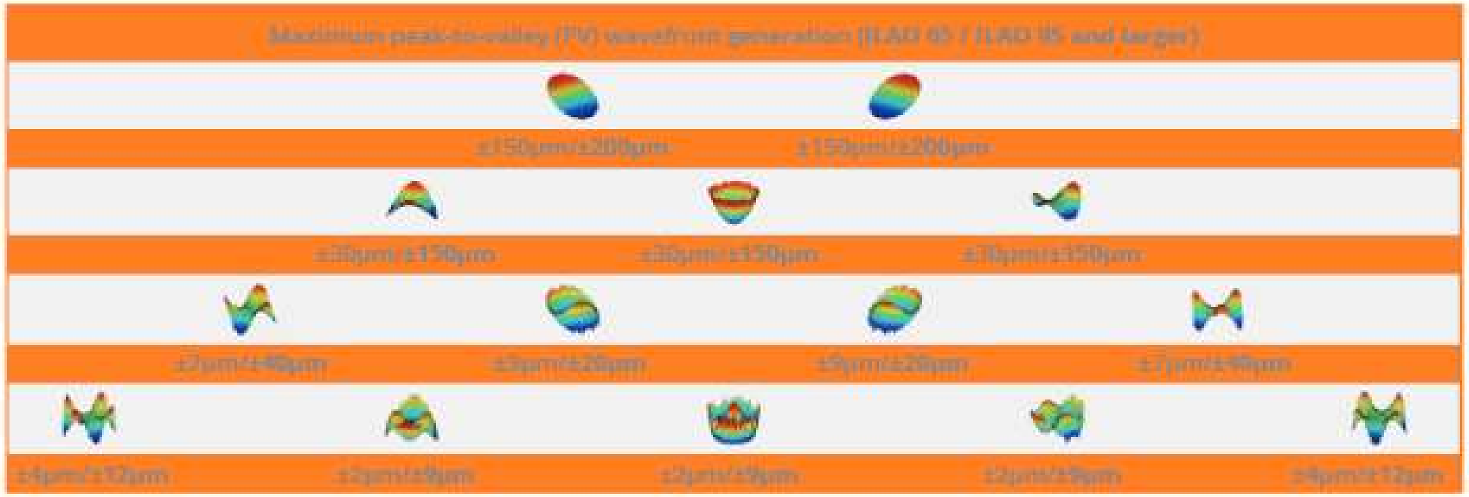
+ Various technologies based on actuators pushing/pulling a *thin* reflective membrane

+ Actuators: mechanical, piezo, electrostatic, electromagnetic…

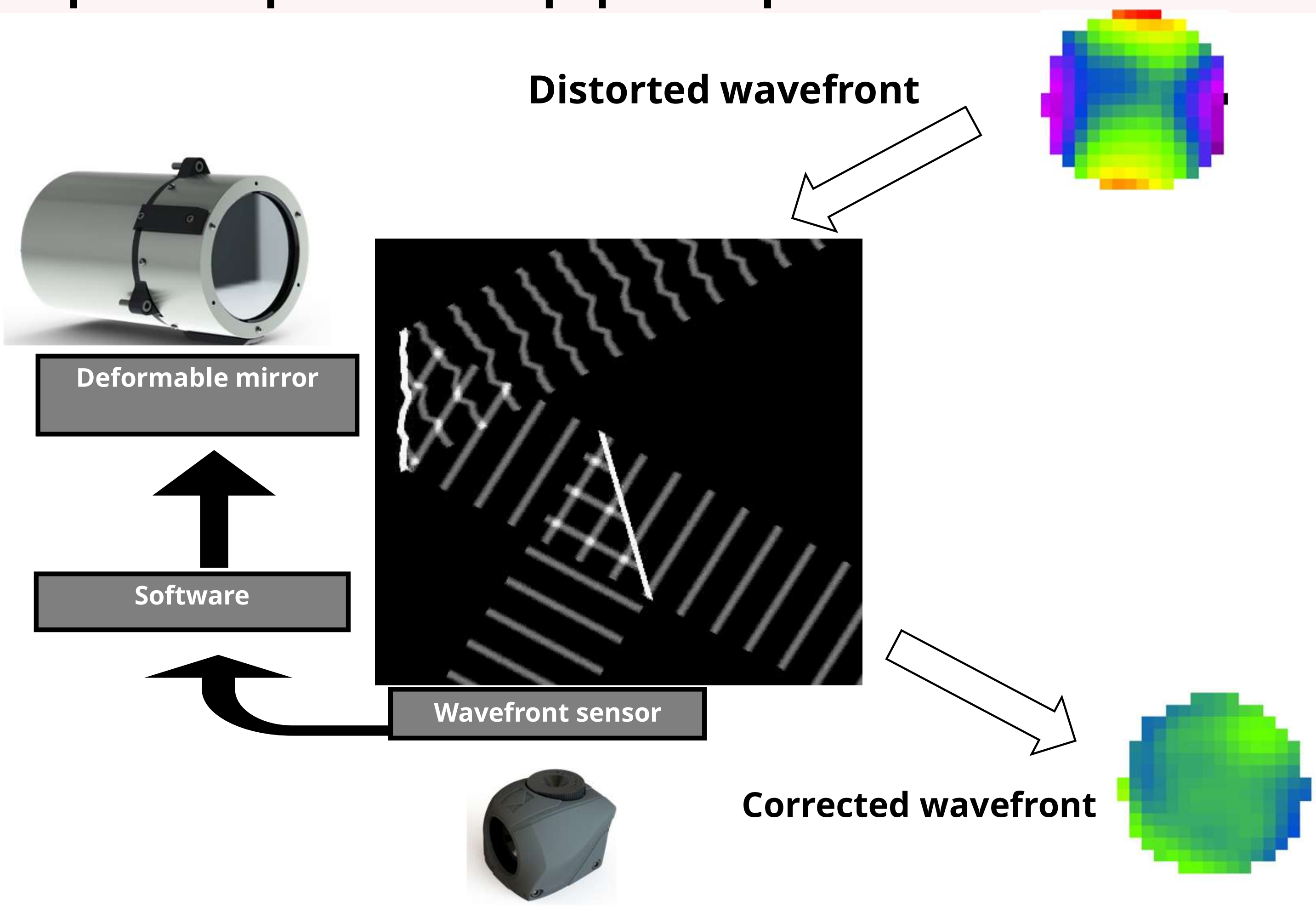


• Mechanical parts macroscopic motion sets a force on the back of the surface

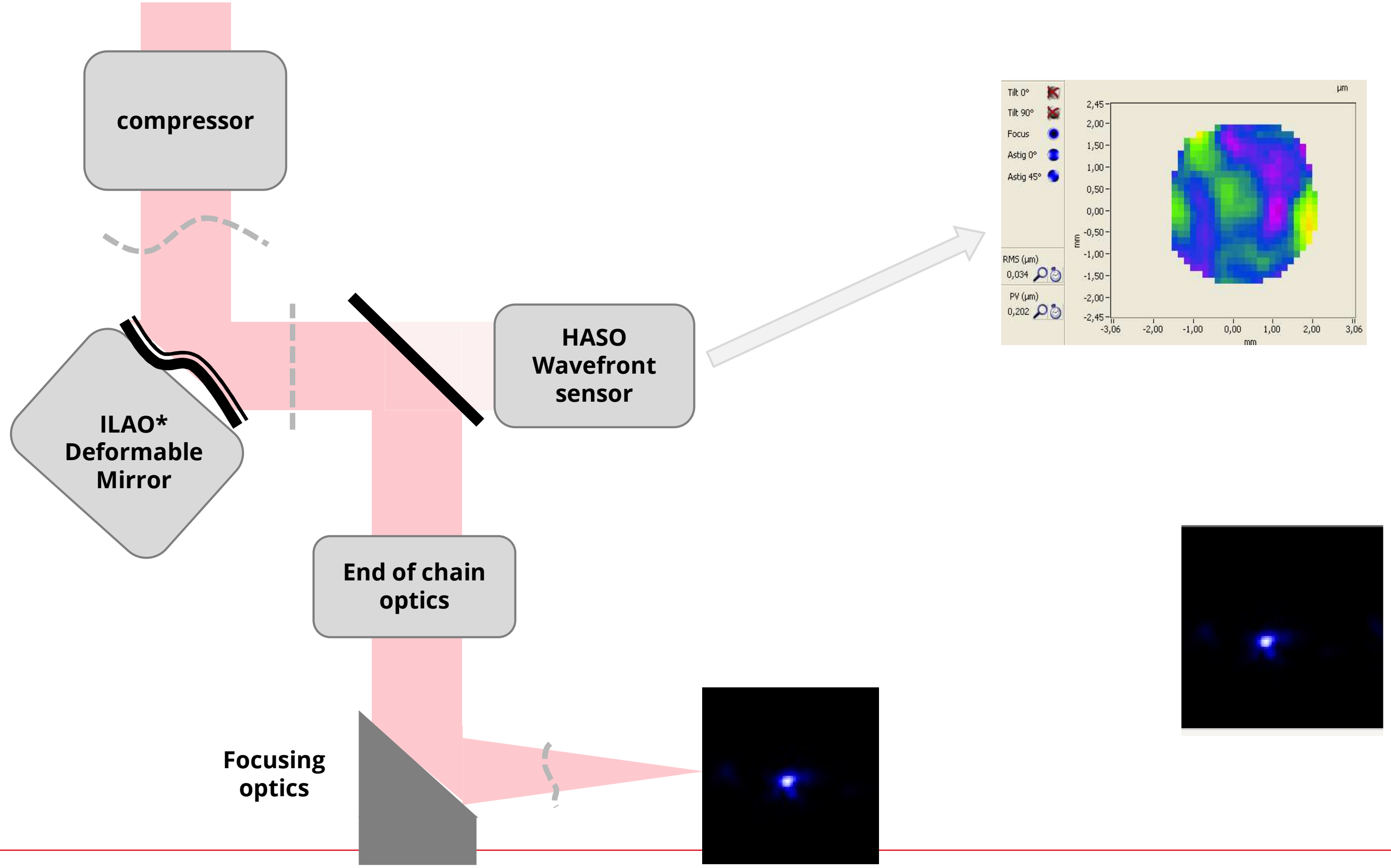
• This force modifies at a microscopic scale the shape of the membrane



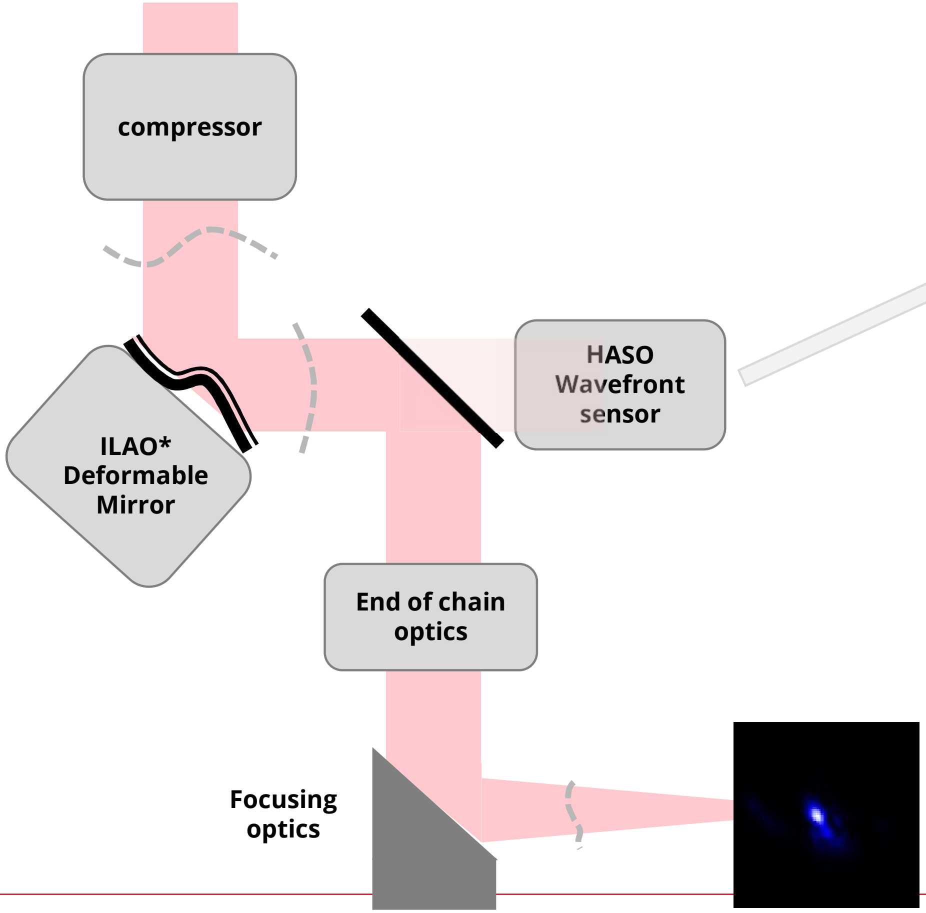
How: adaptive optics setup principle

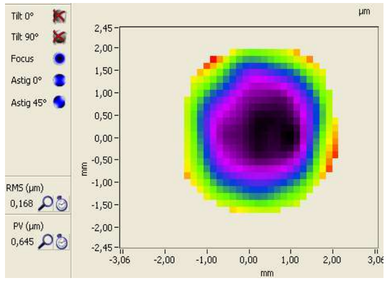


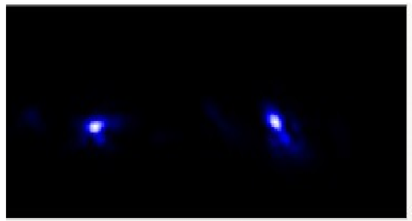
How: a user case



How: a user case







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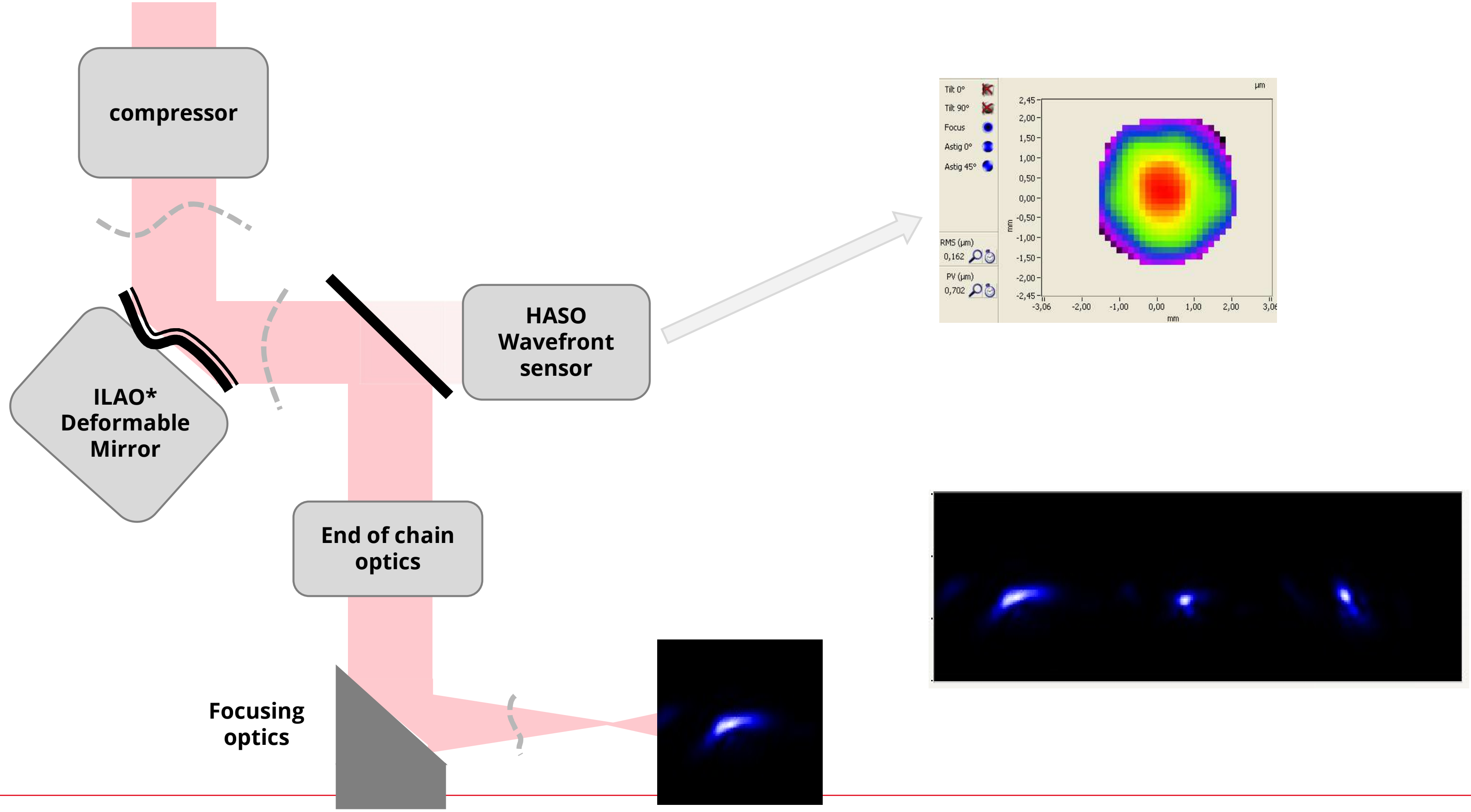
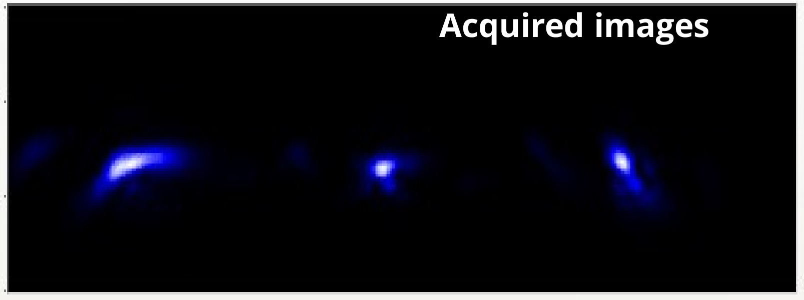
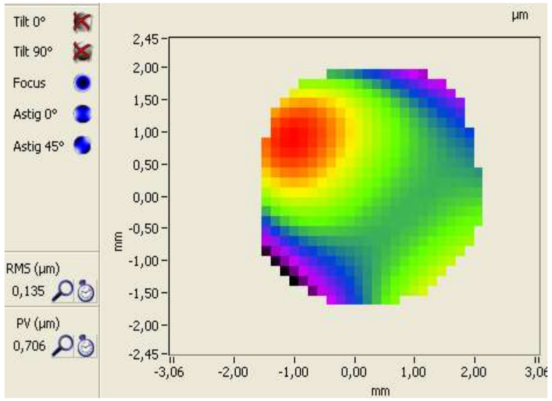


How: a user case

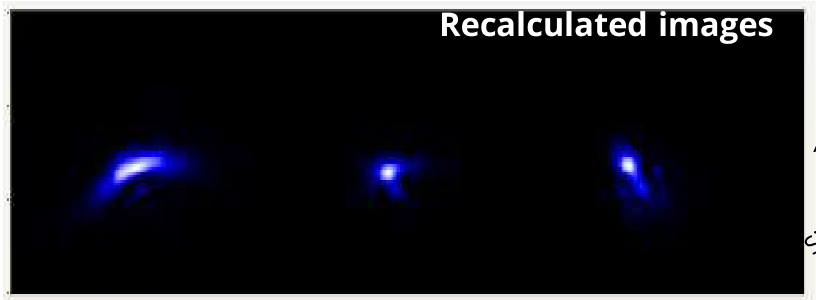


Phase retrieval

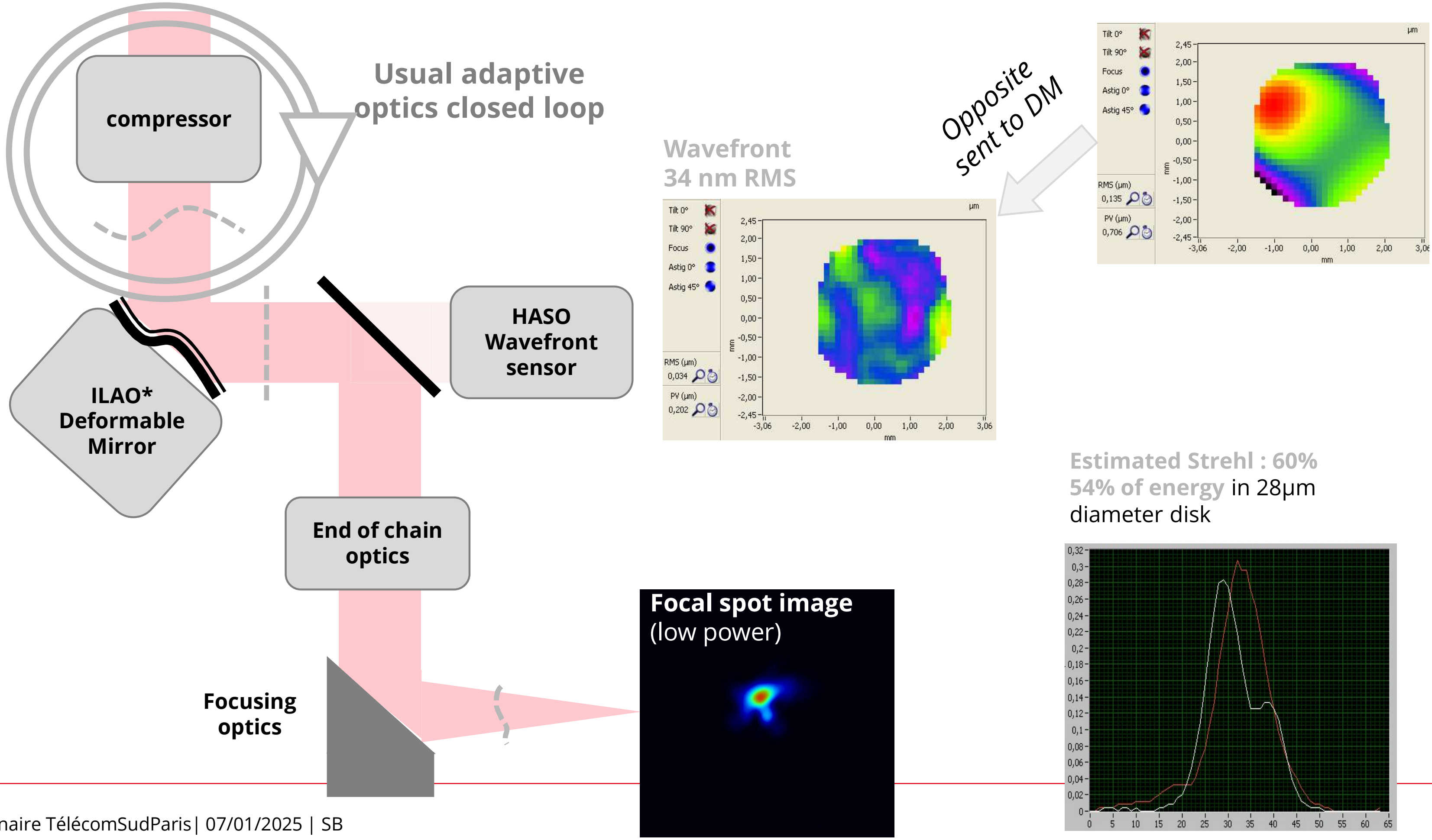


Wavefront responsible of the focal spot aberrations = 135nm RMS

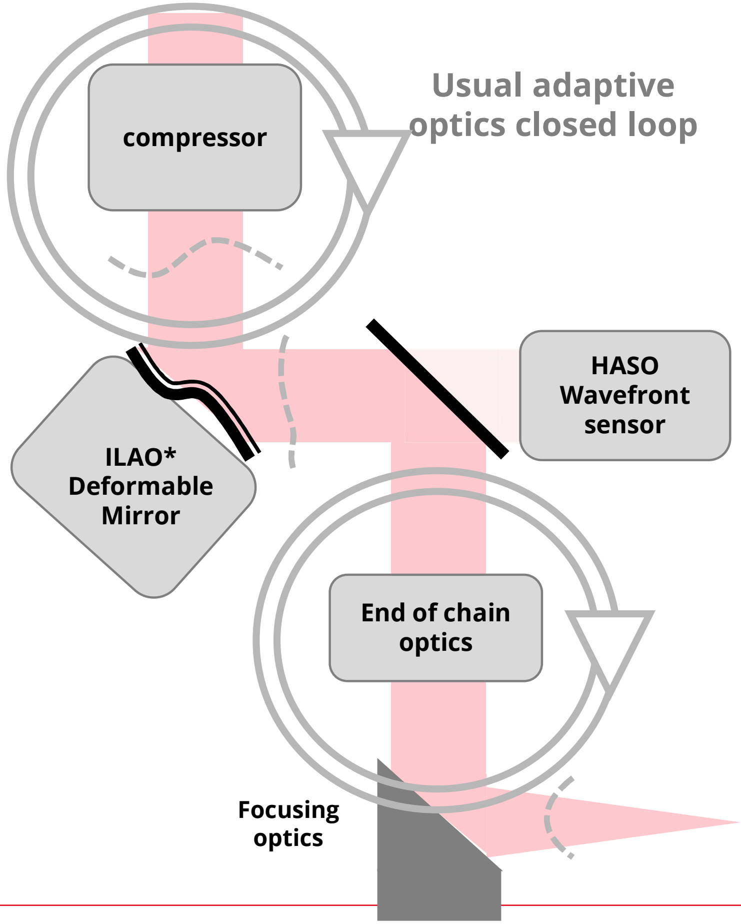
Simple Fourier transform to check Phase Retrieval result



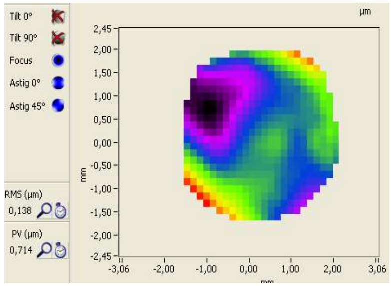
How: a user case

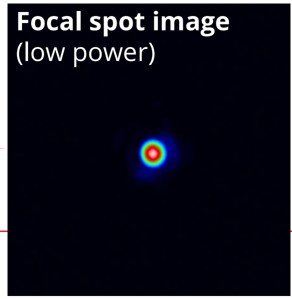


How: a user case

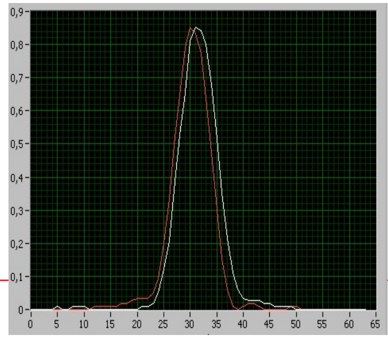


Wavefront
138nm RMS





Estimated Strehl : 93%
82% of energy in 28µm diameter disk

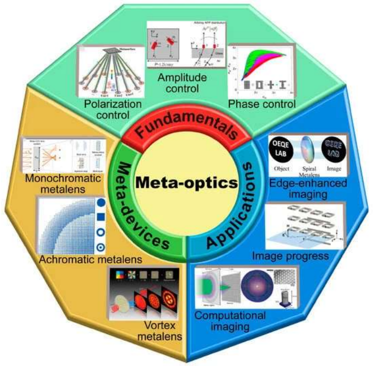


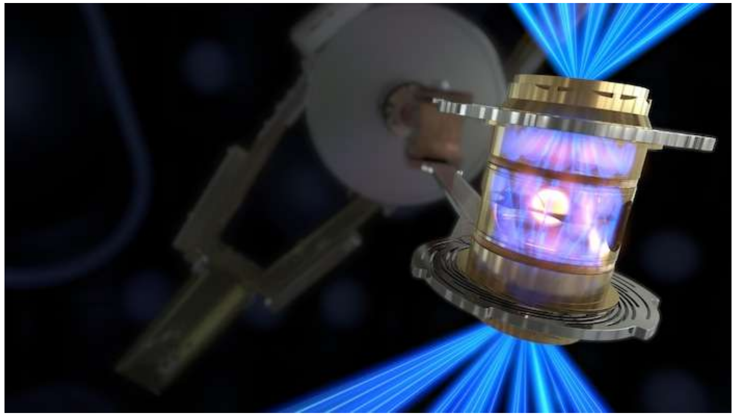
Then

Perspectives

Technologies

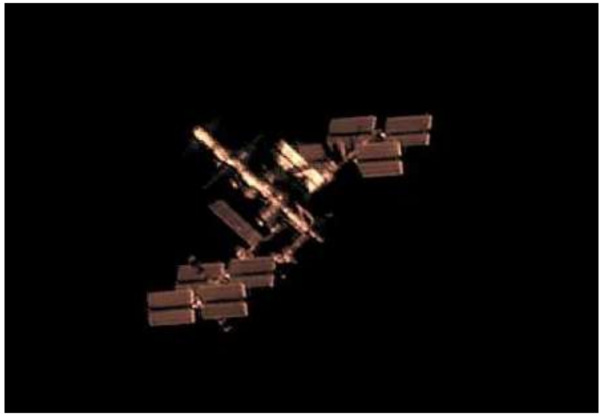
+ metaoptics
+ AI





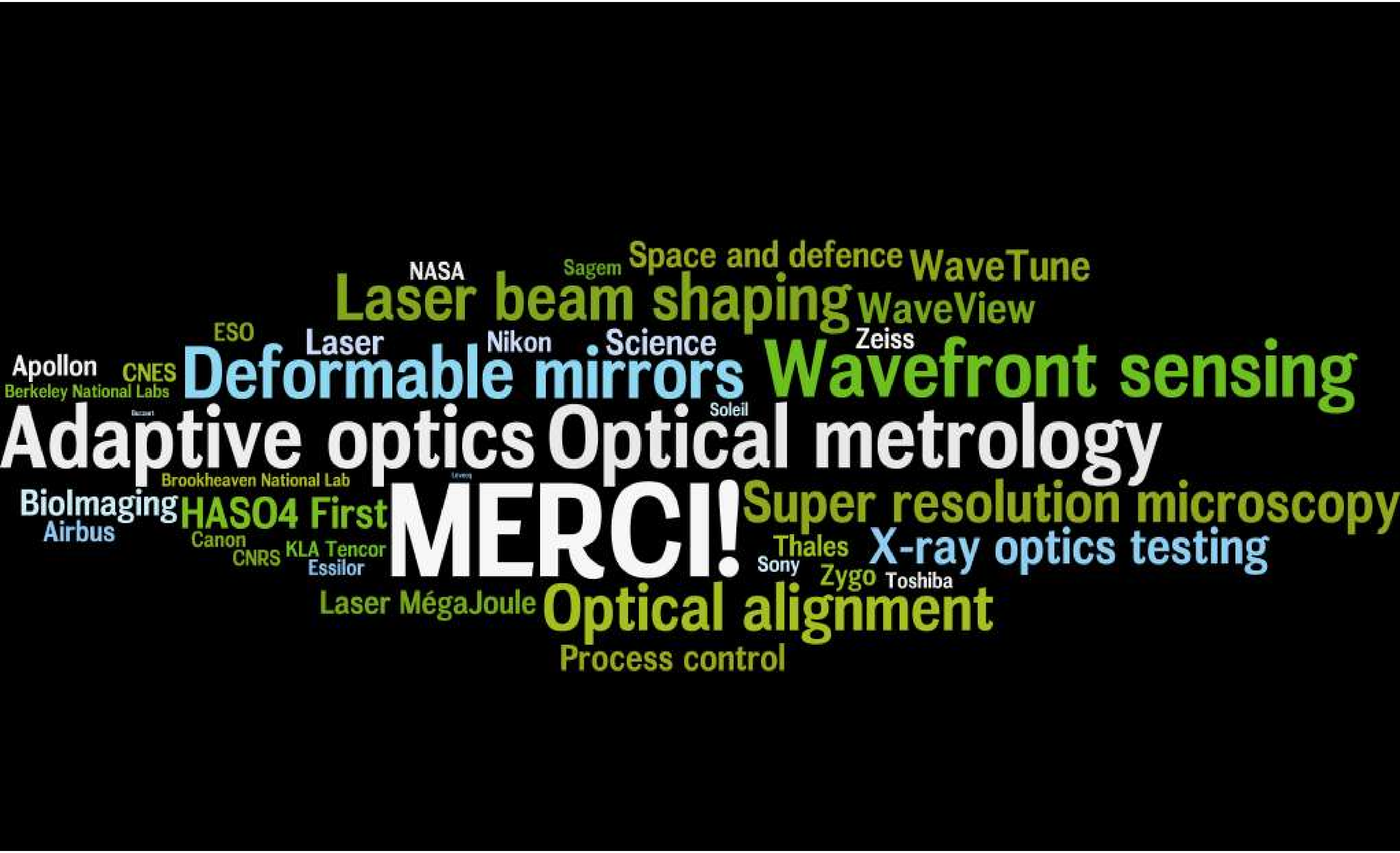
Applications

+ nuclear photonics: energy, proton therapy, nuclear waste *cleaning*
+ table accelerator
+ X-Ray imaging
+ laser processing
+ quantum optics
+ advanced imaging
+ SSA
+ …



Take away

+ Adaptive Optics is a « technique », note a modality
+ When introduces in a new field, Adaptive Optics leads to a techno breakthrough
+ Applications are mature, changing from *nice to have* to *must have* in some fields
+ Adaptive Optics allow to reach an optical quality up to $\lambda/100$
+ New AO user Nobel prizes to come ☺!


NASA
Sagem
Space and defence
WaveTune
Laser beam shaping
WaveView
ESO
Laser
Nikon
Science
Zeiss
Apollon
CNES
Deformable mirrors
Wavefront sensing
Berkeley National Labs
Soleil
Adaptive optics
Optical metrology
Brookheaven National Lab
BioImaging
HASO4 First
MERCI!
Super resolution microscopy
Airbus
Canon
CNRS
KLA Tencor
Essilor
Thales
Sony
X-ray optics testing
Zygo
Toshiba
Laser MégaJoule
Optical alignment
Process control