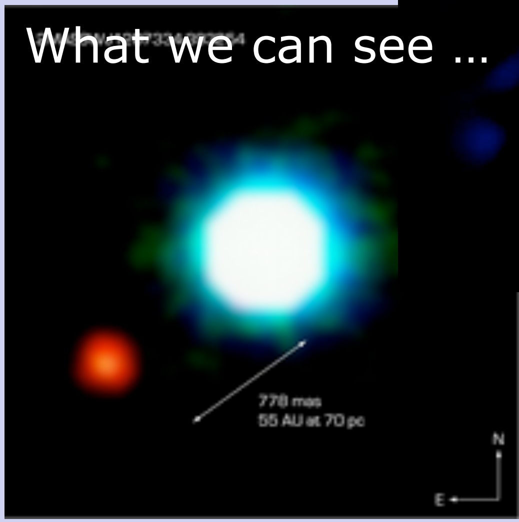
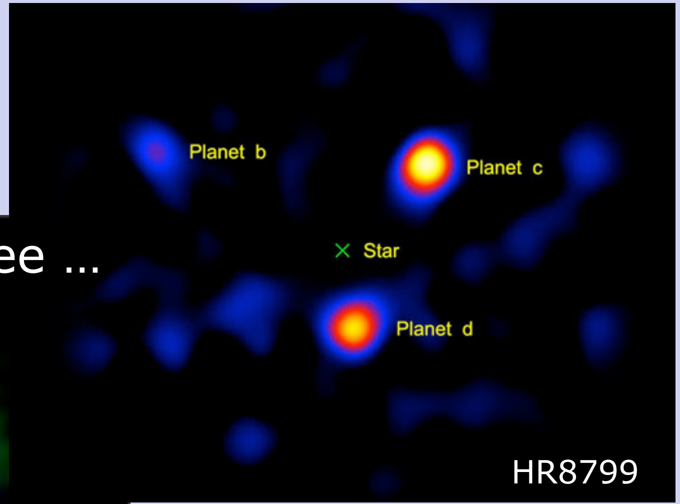
Interferometric direct imaging

From fringes to images
From interference to diffraction
From a telescope to a hypertelescope
From a segmented to a discretized telescope

Fabien Patru, Osservatorio astrofisico di Arcetri, Firenze (INAF)

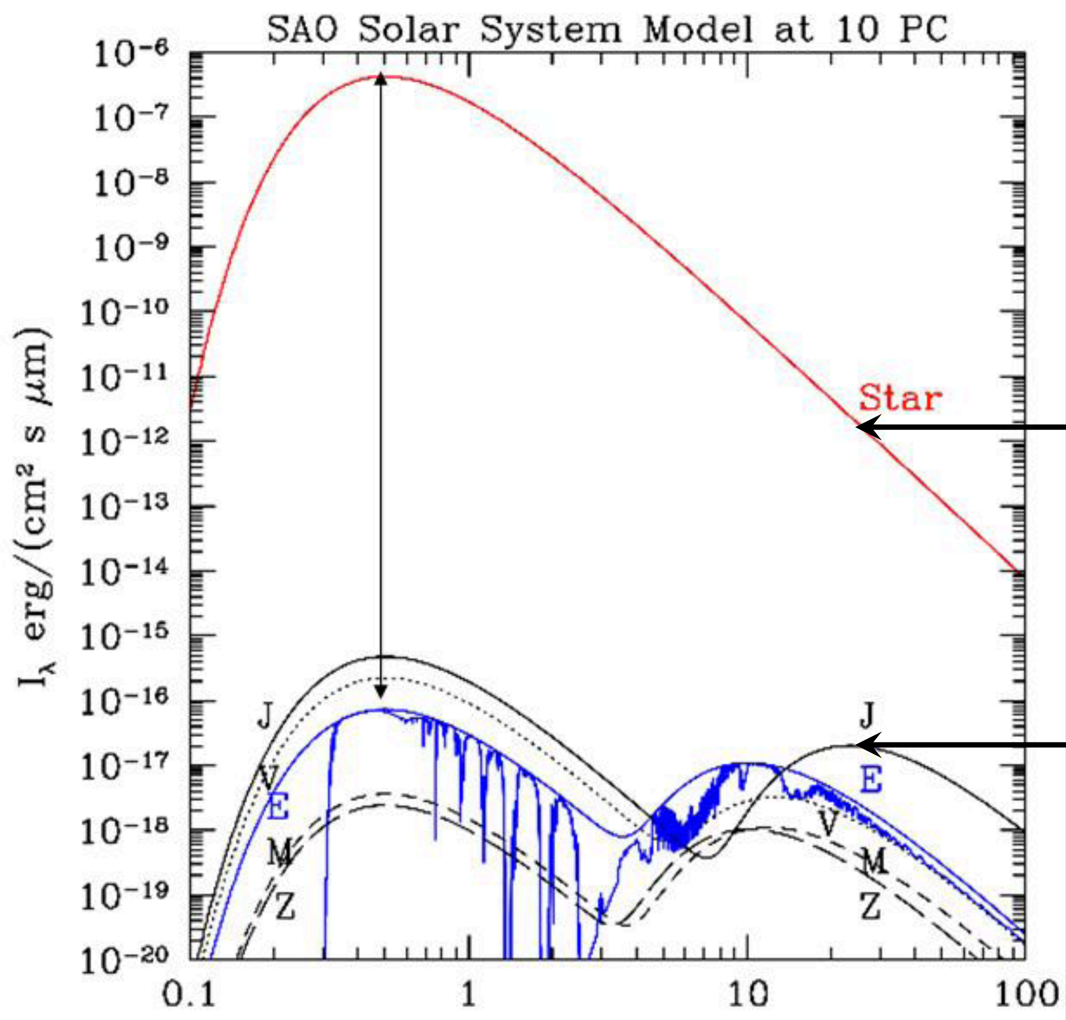
The exoplanets, new words of science





- **Directly imaging exoplanets** requires :
  - High **spatial resolution** to detect close planet (in the habitable zone)
  - High **contrast** to detect faint planets (one million or billion fainter)
  - High **sensitivity** to maximize the sky coverage
  - High **spectral resolution** to get a "direct spectrum" of a planet

Planet flux & contrast



(Vérinaud et al. 2006)

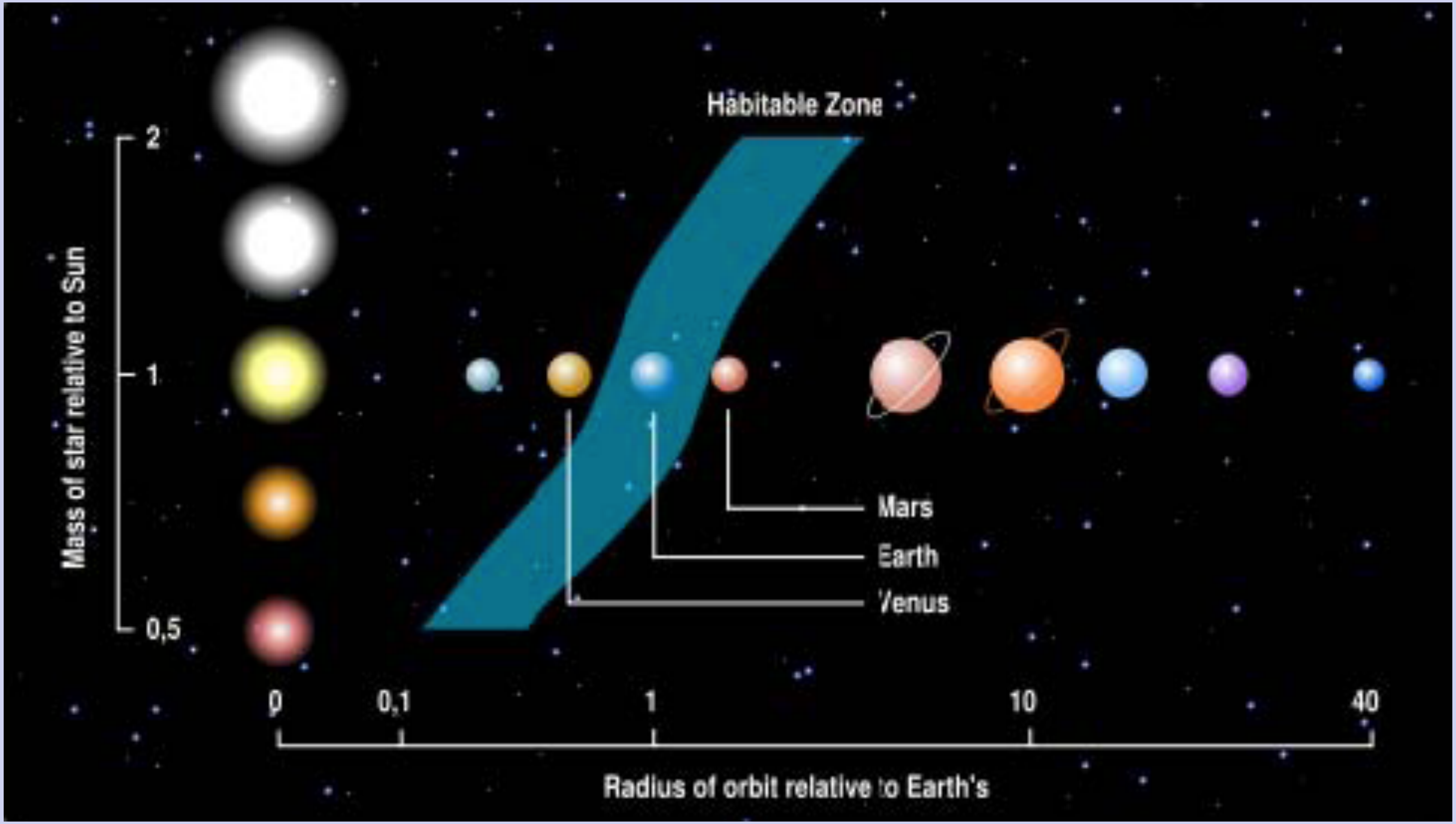
Contrast in luminosity
(visible wavelength)
- Hot-Jupiter/Exo-sun=$\mathbf{10^{-7}}$
- Exo-Earth/Exo-sun=$\mathbf{10^{-10}}$

Flux emitted by the Sun

Reflected light from the planets of the Solar System

J=Jupiter
V=Venus
E=Earth
M=Mars
Z=Zodiacal light

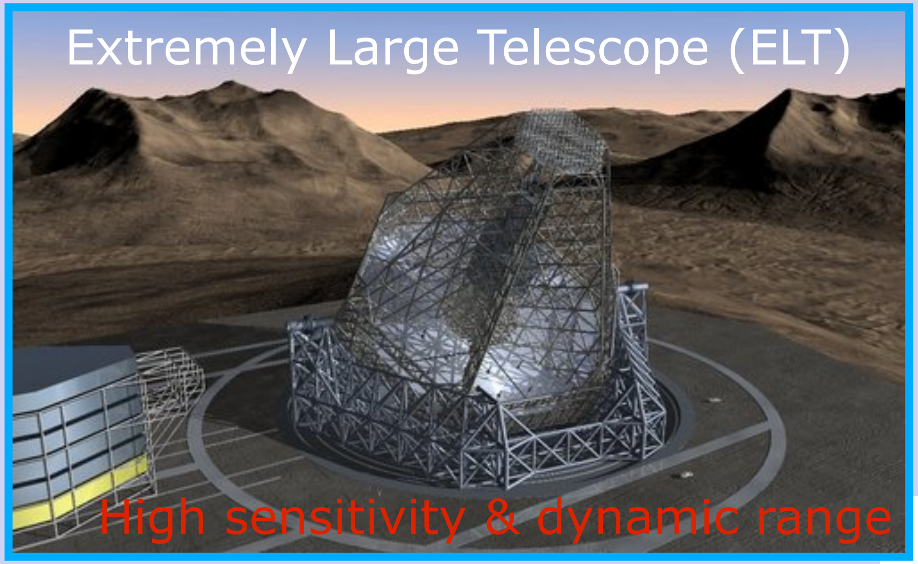
Planet mass & separation

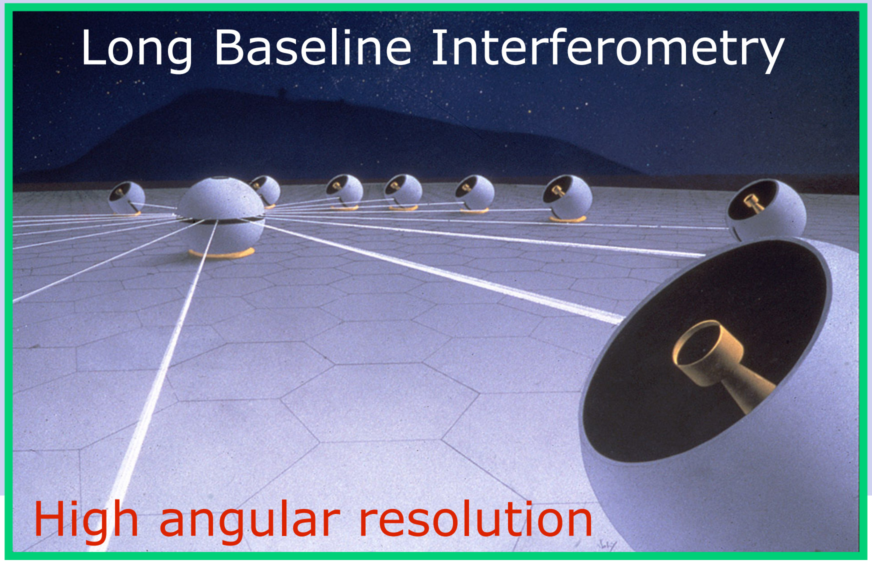


The habitable zone is around one astronomical unit (1 AU)

1 AU = **1arc-second** @ 1 parsec ⇔ **100milli-arc-second** @ 10 parsec

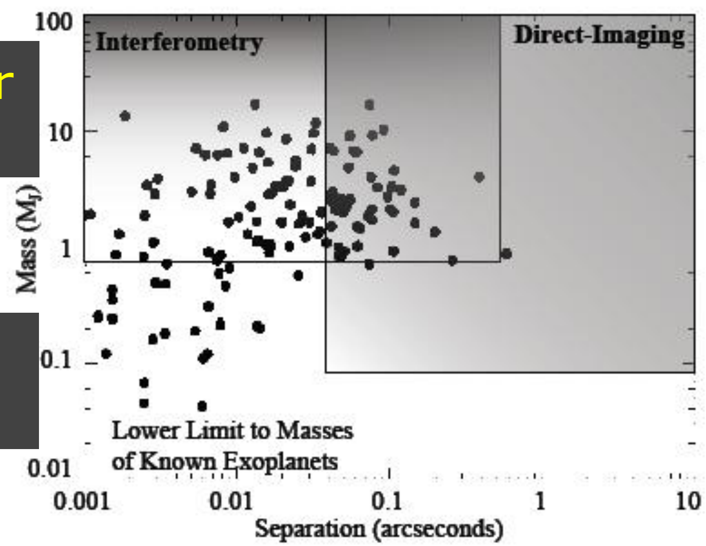
The future of high angular resolution





How to optimize an optical interferometer for direct imaging ?

How to optimize a large telescope thanks to optical interferometry?

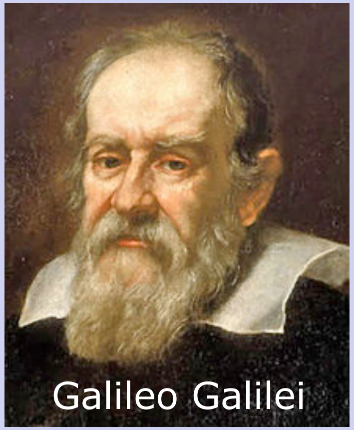


Imaging techniques (r)evolution

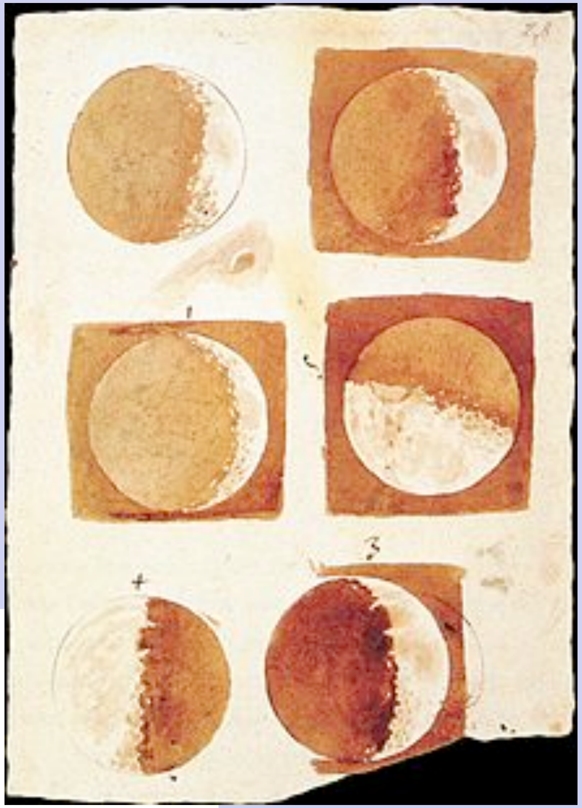
Technical step	Single Pupil Telescope	Stellar Interferometer
New optics: lens, mirror, periscope	Larger telescope *Galilée XVI th*	Larger array *Fizeau 1868, Michelson 1921*

! Atmosphere

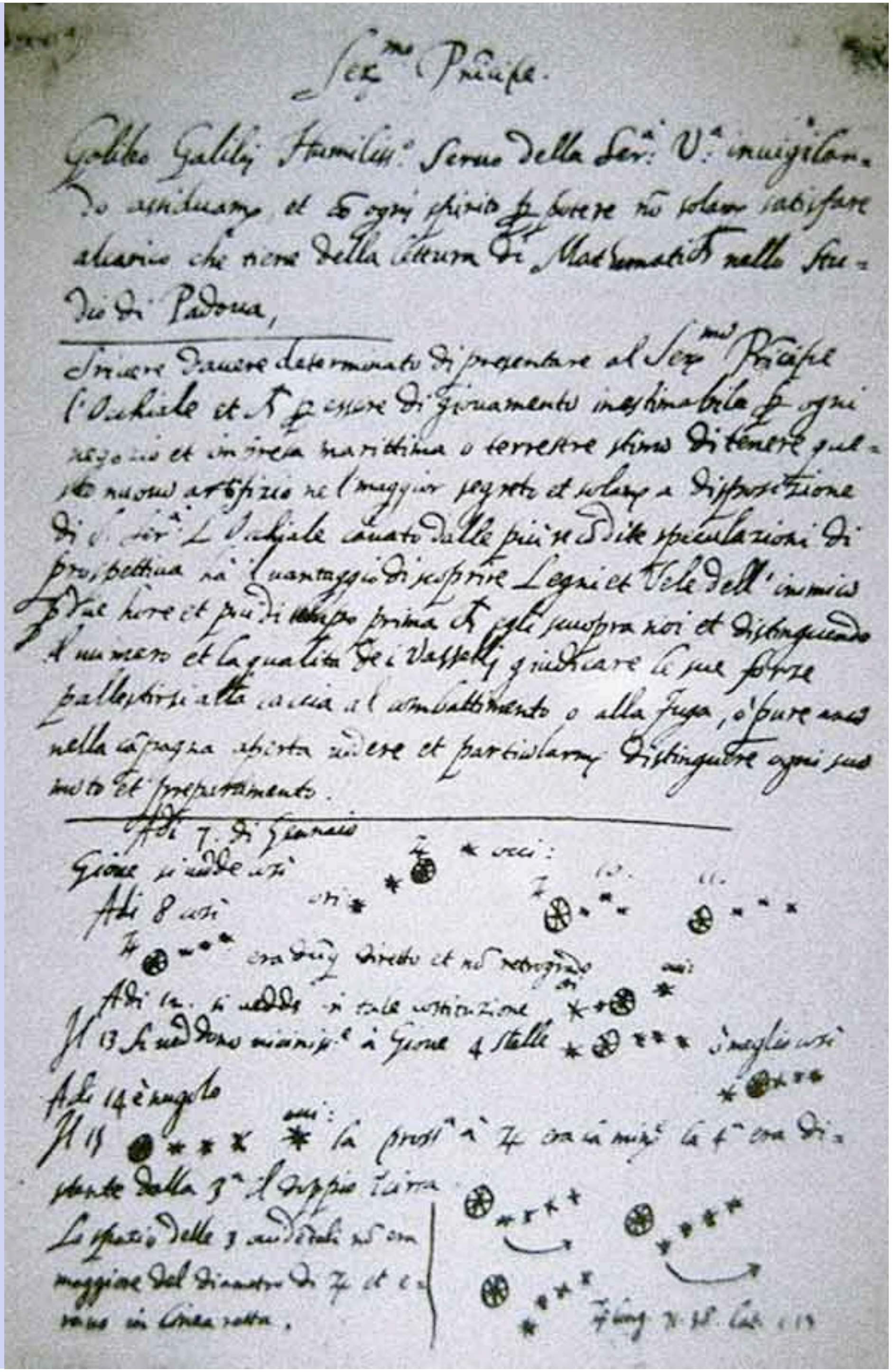
Galileo



Galileo Galilei



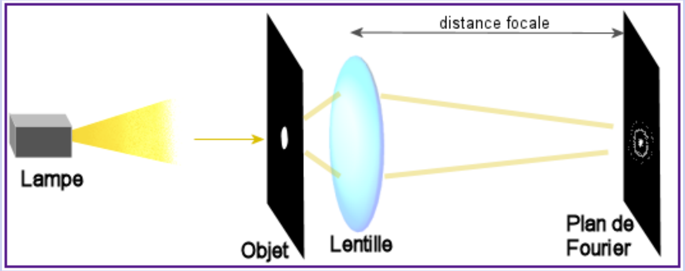
The moon

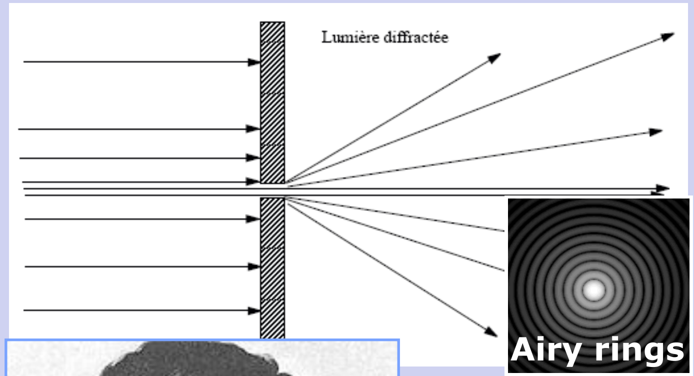


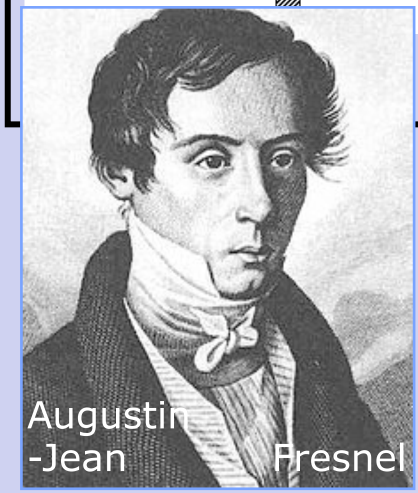
The satellites of Jupiter

From interference to diffraction

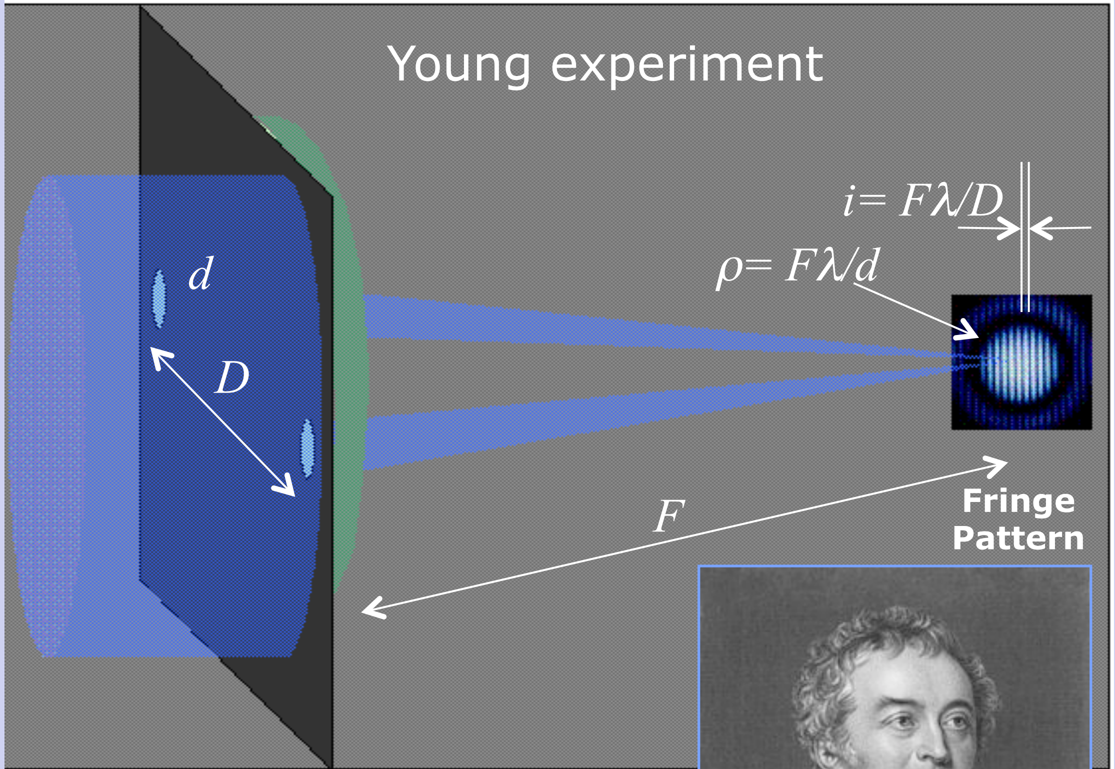
DIFFRACTION



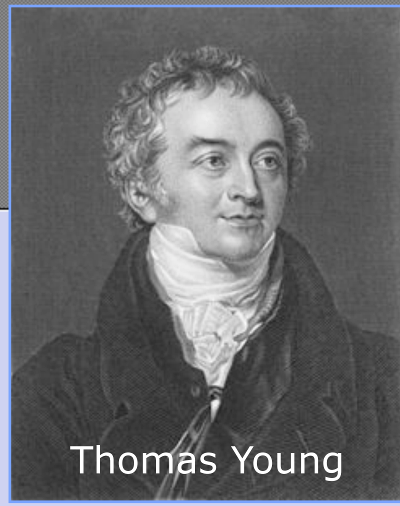




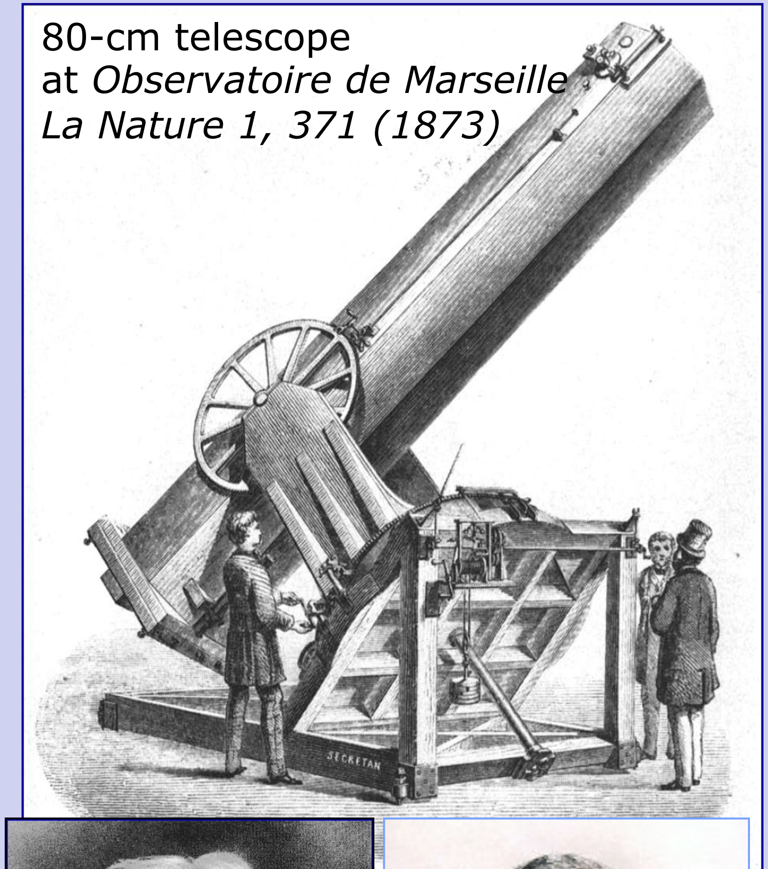
INTERFERENCE



In 1815 and 1818, Augustin-Jean Fresnel firmly established the mathematics of how wave interference can account for diffraction.



First light with a Fizeau interferometer



80-cm telescope
at *Observatoire de Marseille*
La Nature 1, 371 (1873)

(1008)

Compt.Rend.Acad.Sci. Paris **78**, 108 (1874)

MÉMOIRES LUS.

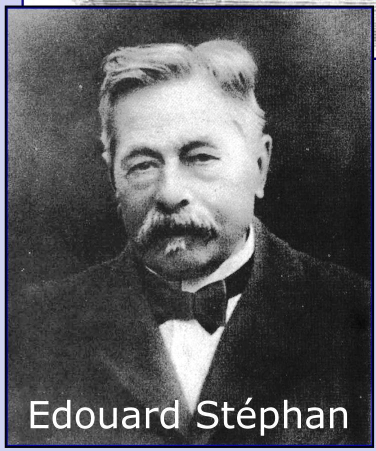
ASTRONOMIE PHYSIQUE. — *Sur l'extrême petitesse du diamètre apparent des étoiles fixes.* Note de M. Stéphan.

(Commissaires : MM. Le Verrier, Fizeau, Janssen.)

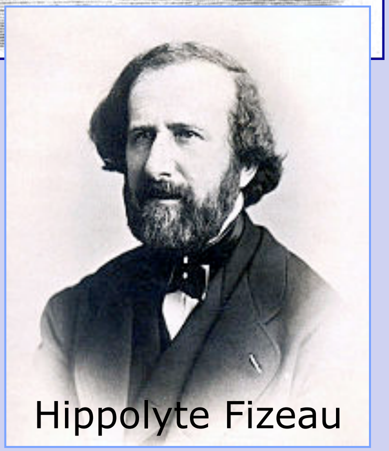
« Dans une Communication précédente (*Comptes rendus*, t. LXXVI, p. 1008), j'ai eu l'honneur de rappeler à l'Académie une idée anciennement émise par M. Fizeau sous forme de simple aperçu et qui, jusque-là, semblait être restée dans l'oubli, bien que renfermant le germe de conséquences fort importantes. Cette idée peut se formuler comme il suit : Dans plusieurs cas, en donnant naissance à certains phénomènes d'interférence, on peut augmenter la sensibilité des instruments d'optique ordinaires.

» Guidé par l'illustre physicien, j'ai cherché à déduire de cette conception originale quelques notions précises sur le diamètre apparent des étoiles fixes, et, dans la Note citée plus haut, j'ai fait connaître à l'Académie le résultat de quelques expériences préliminaires dont il convient de rappeler le principe général.

système. En d'autres termes, les expériences citées ne prouvent pas seulement que le diamètre apparent des étoiles examinées est inférieur à 0",158, elles montrent encore que ce diamètre est une très-faible fraction du nombre précédent. »

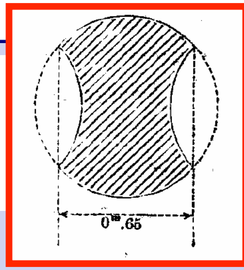


Edouard Stéphan

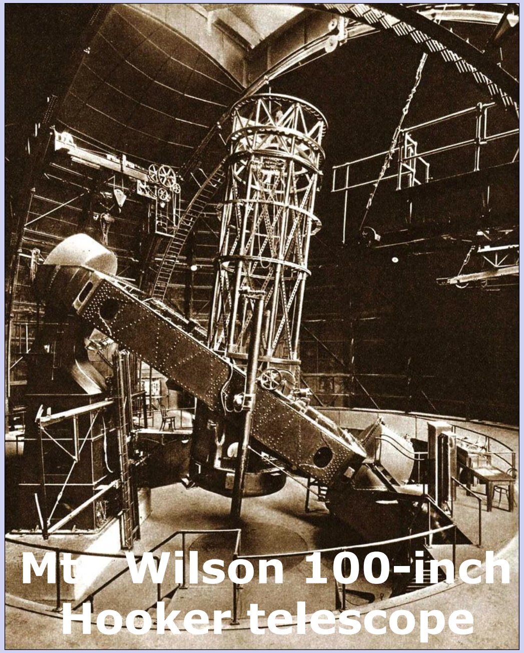


Hippolyte Fizeau

The Fizeau mask
used by Stéphan
on a 80cm telescope



First light with a slight hypertelescope



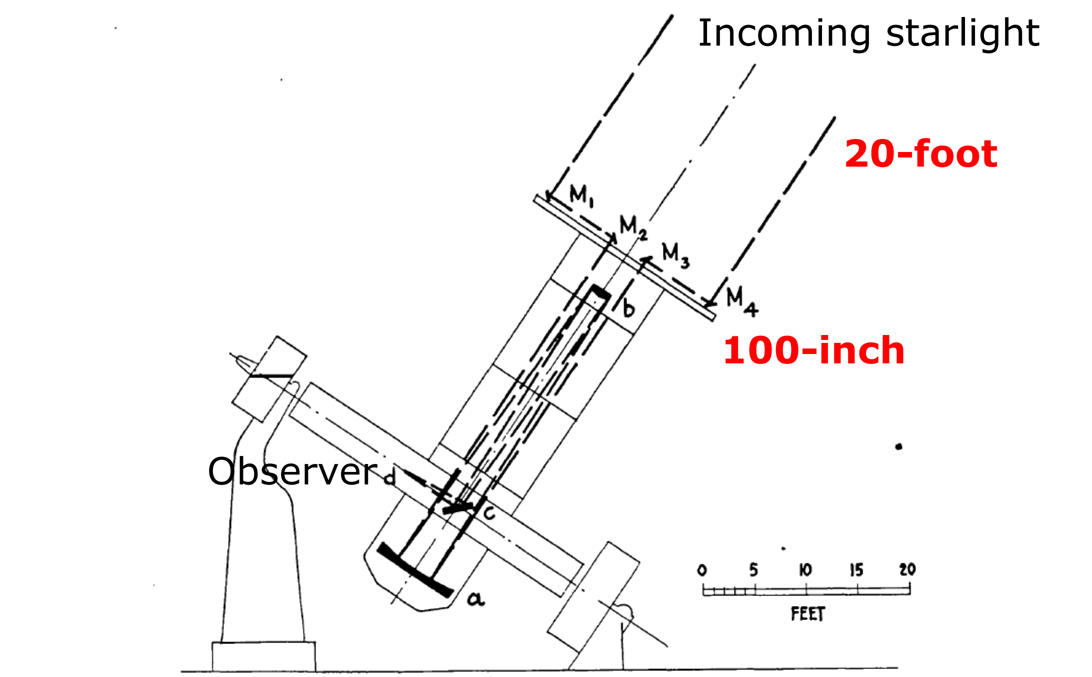
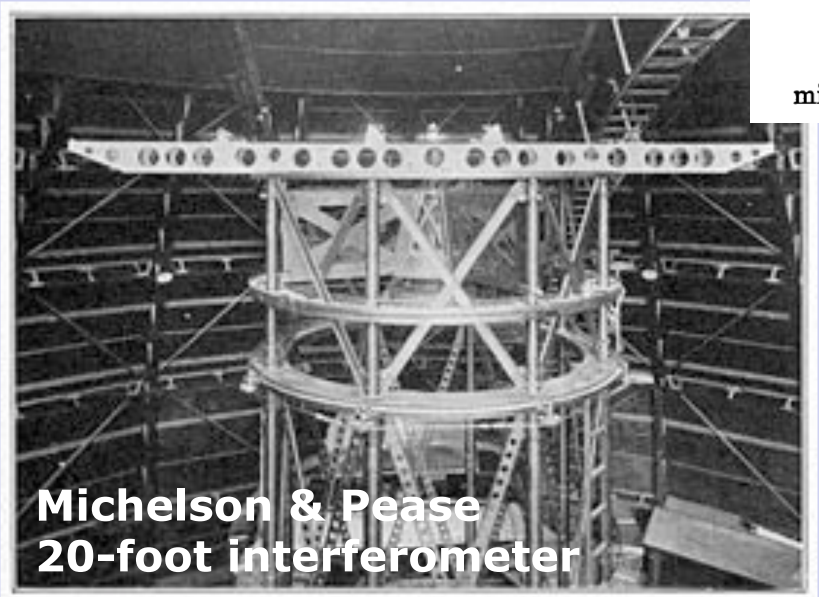


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; a, 100-inch paraboloid; b, convex mirror; c, coudé flat; d, focus.



MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

A. A. **Michelson** & F. G. Pease
Astrophys.J. 53, 249 (1921)

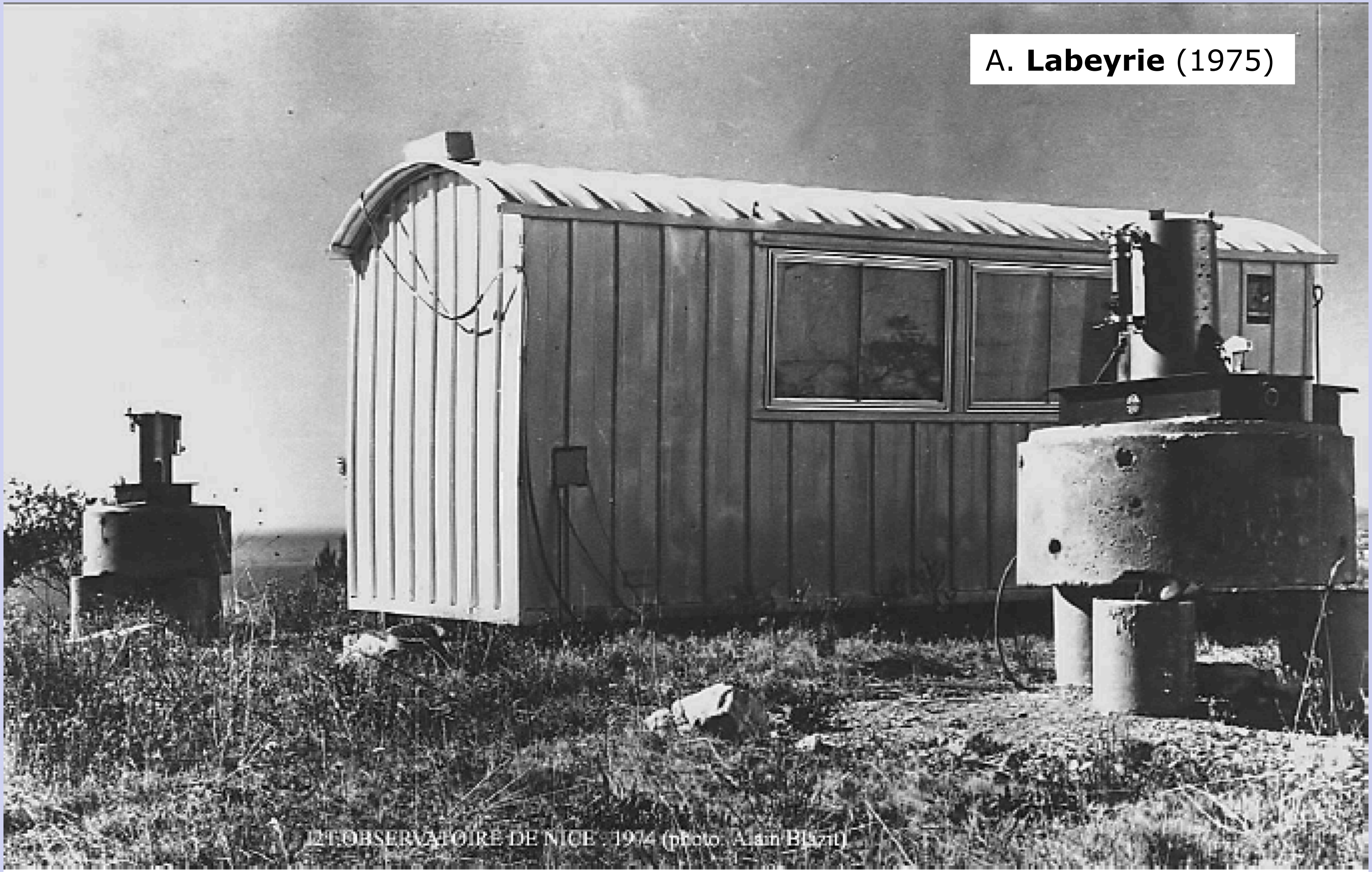
An unsucessful large interferometer

50-ft Pease Stellar Interferometer c. 1929

Imaging techniques (r)evolution

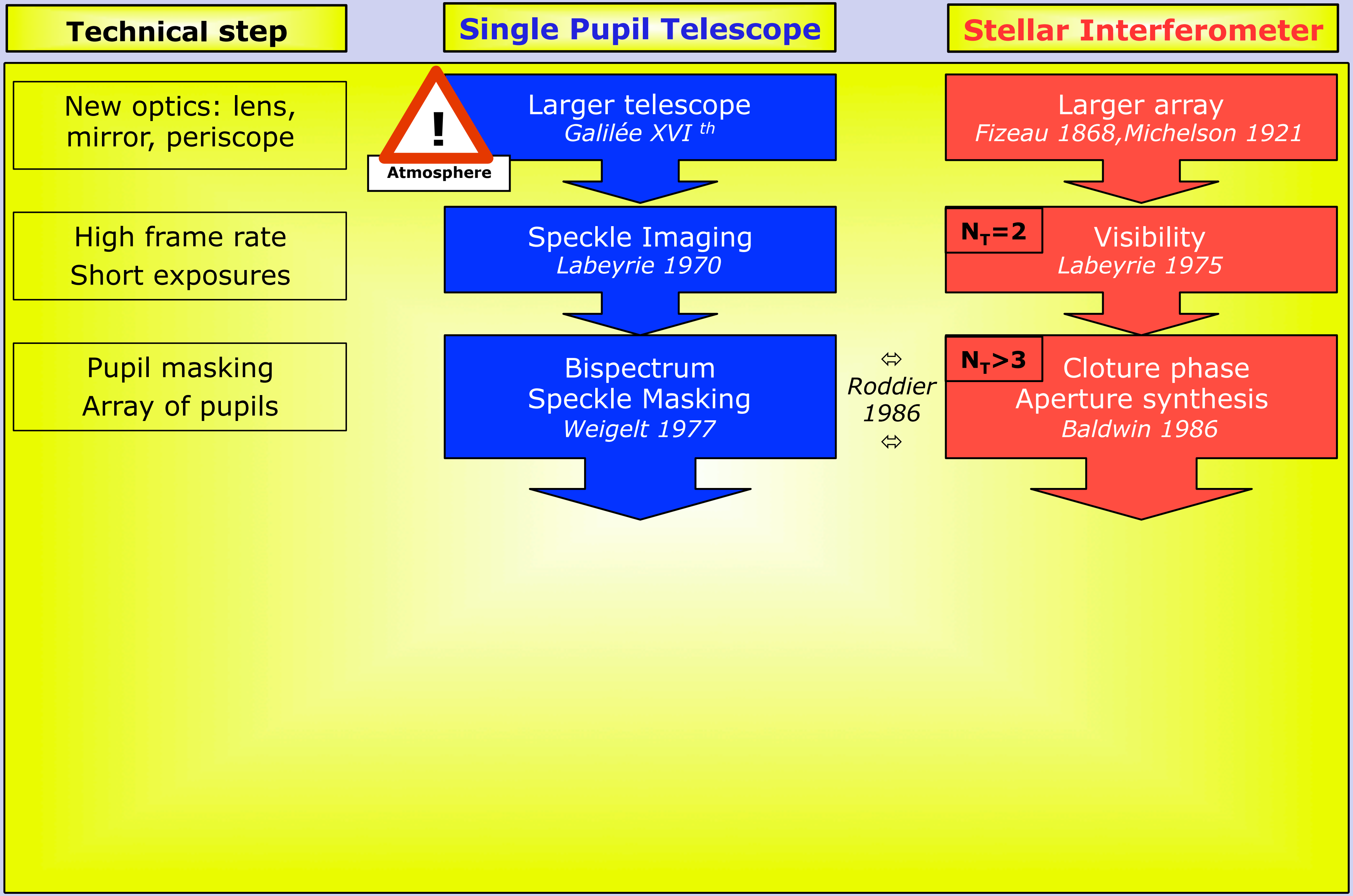
Technical step	Single Pupil Telescope	Stellar Interferometer
New optics: lens, mirror, periscope	Atmosphere Larger telescope *Galilée XVI th*	Larger array *Fizeau 1868,Michelson 1921*
High frame rate Short exposures	Speckle Imaging *Labeyrie 1970*	N_T=2 Visibility *Labeyrie 1975*

Two telescopes instead of one

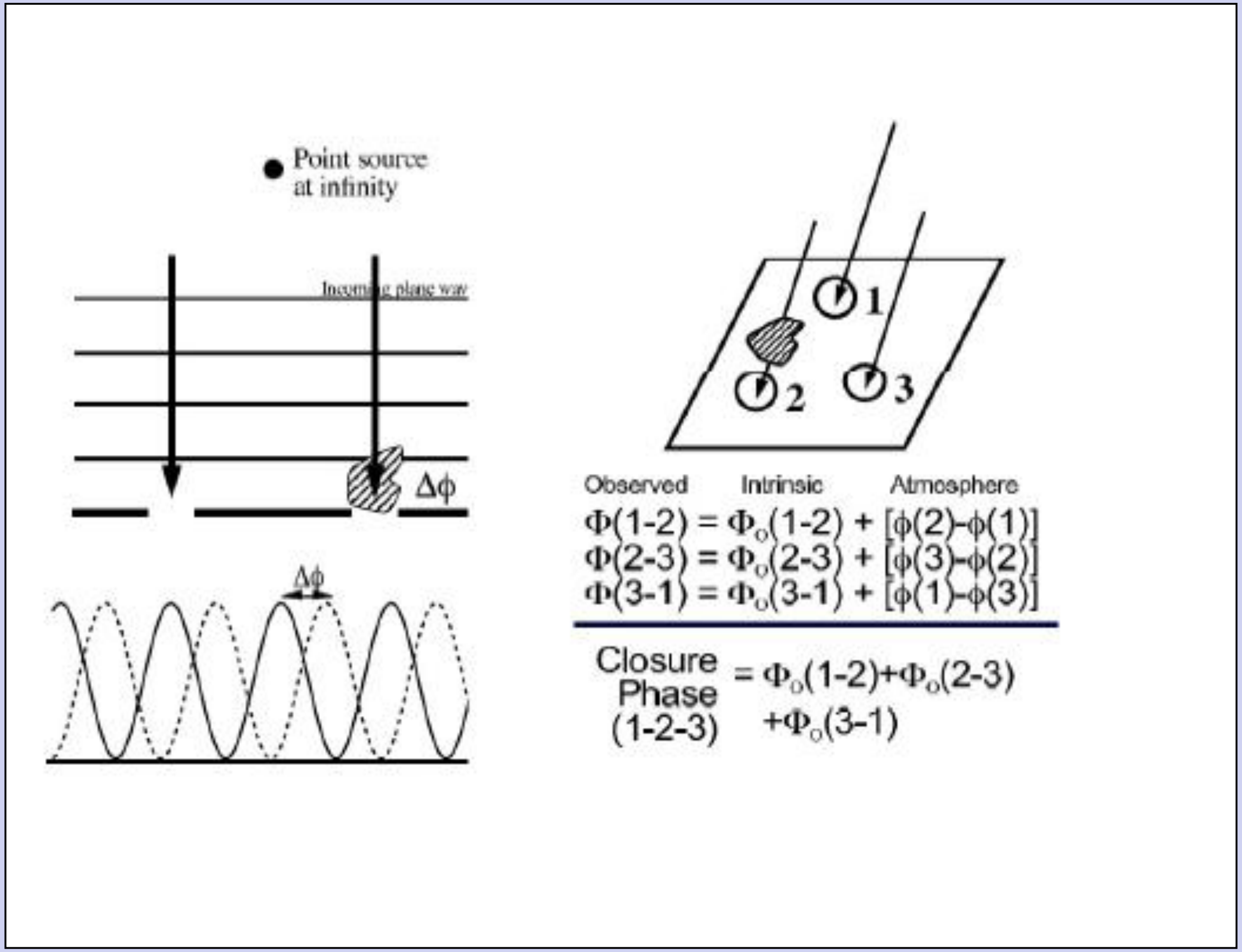


FIRST SUCCESSFUL OPTICAL INTERFEROMETER OF THE MODERN ERA (1974)
I2T, *Interféromètre à 2 Télescopes* (Observatoire de CERGA, France)

Imaging techniques (r)evolution



Cloture phase technique

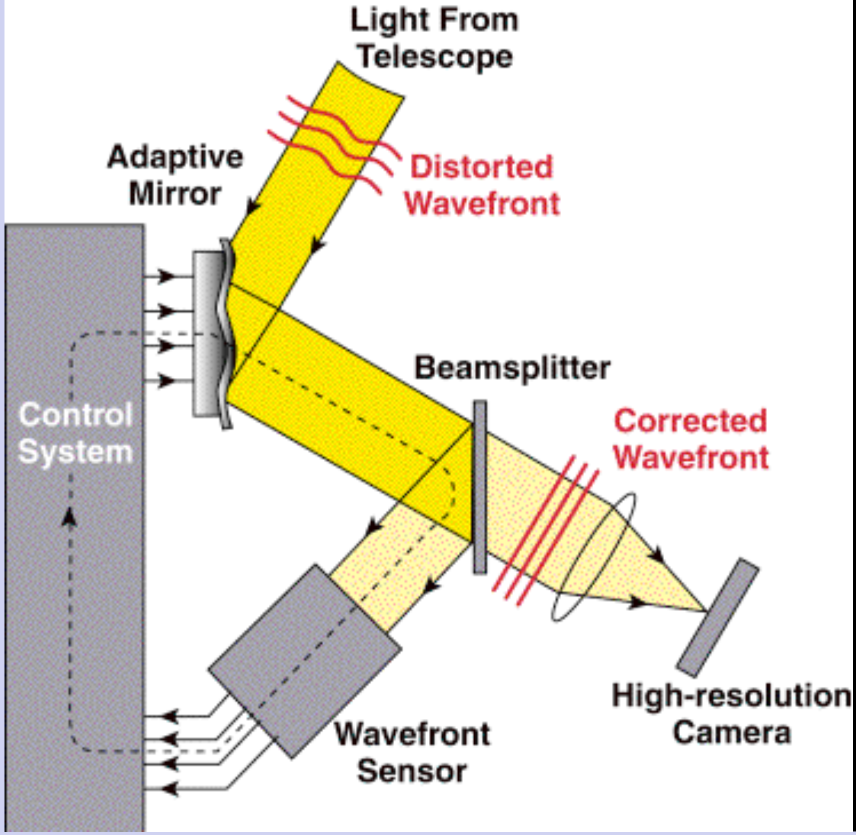


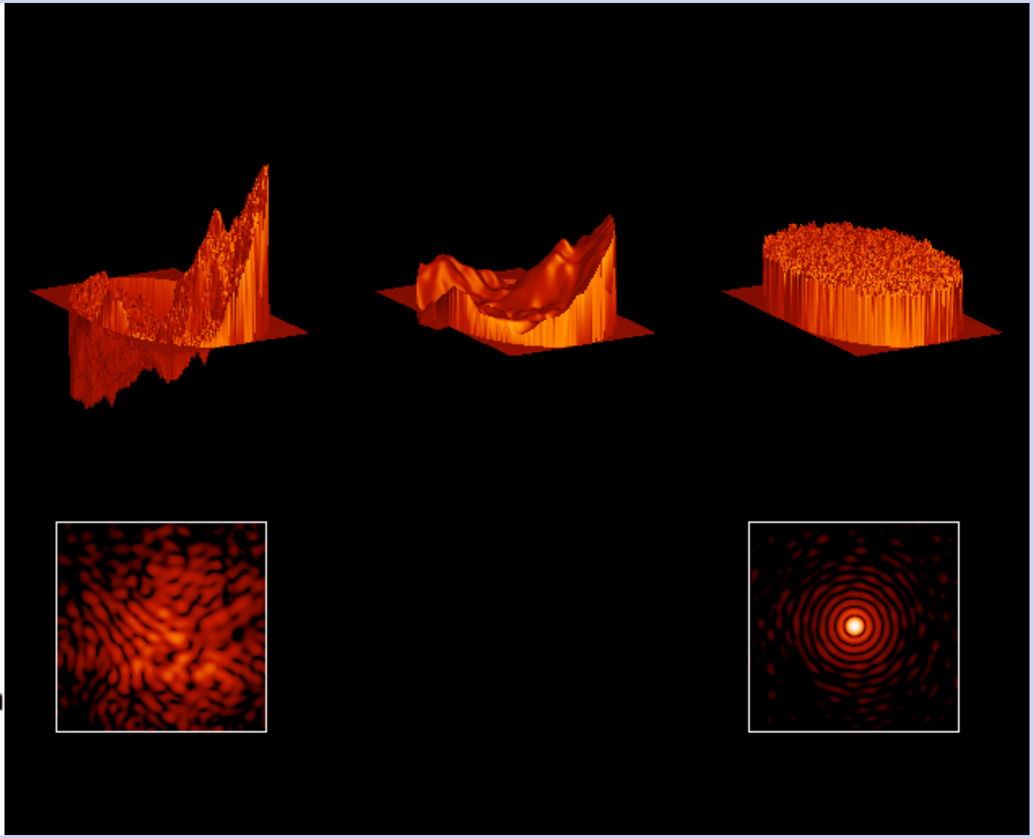
In an interferometer,
a phase delay above an aperture causes a phase shift in the detected fringe pattern.
Phase errors causes equal but opposite phase shifts, cancelling out in the closure phase.

Imaging techniques (r)evolution

Technical step	Single Pupil Telescope		Stellar Interferometer
New optics: lens, mirror, periscope	Larger telescope *Galilée XVI th* (! Atmosphere)		Larger array *Fizeau 1868, Michelson 1921*
High frame rate Short exposures	Speckle Imaging *Labeyrie 1970*		$N_T=2$ Visibility *Labeyrie 1975*
Pupil masking Array of pupils	Bispectrum Speckle Masking *Weigelt 1977*	⇔ *Roddier 1986* ⇔	$N_T>3$ Cloture phase Aperture synthesis *Baldwin 1986*
Cophasing system Long exposures	Adaptive optic — Direct imaging *Babcock 1953, Rousset 1990*		Fringe tracking — Hypertelescope *Labeyrie 1996*

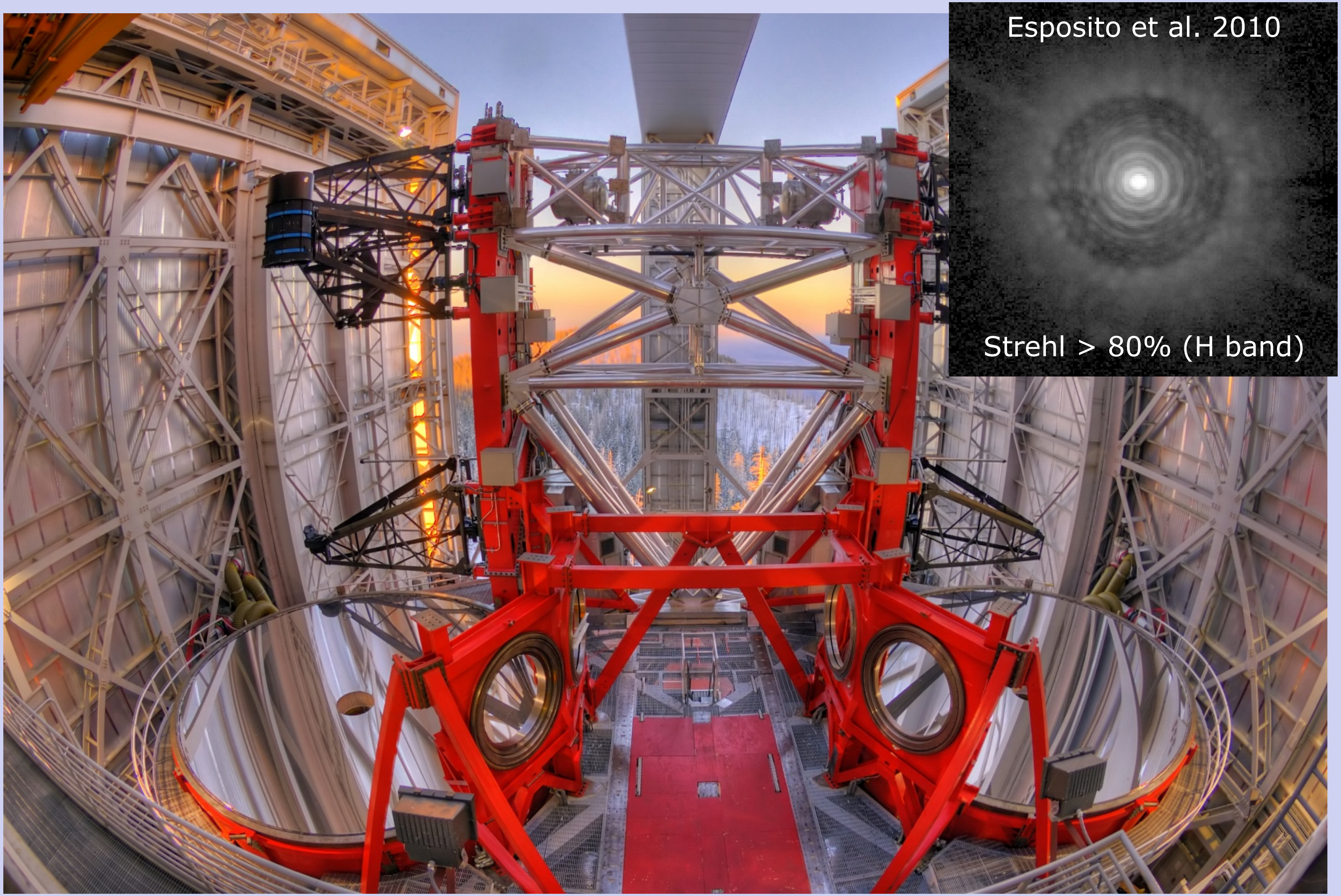
Adaptive optic principle





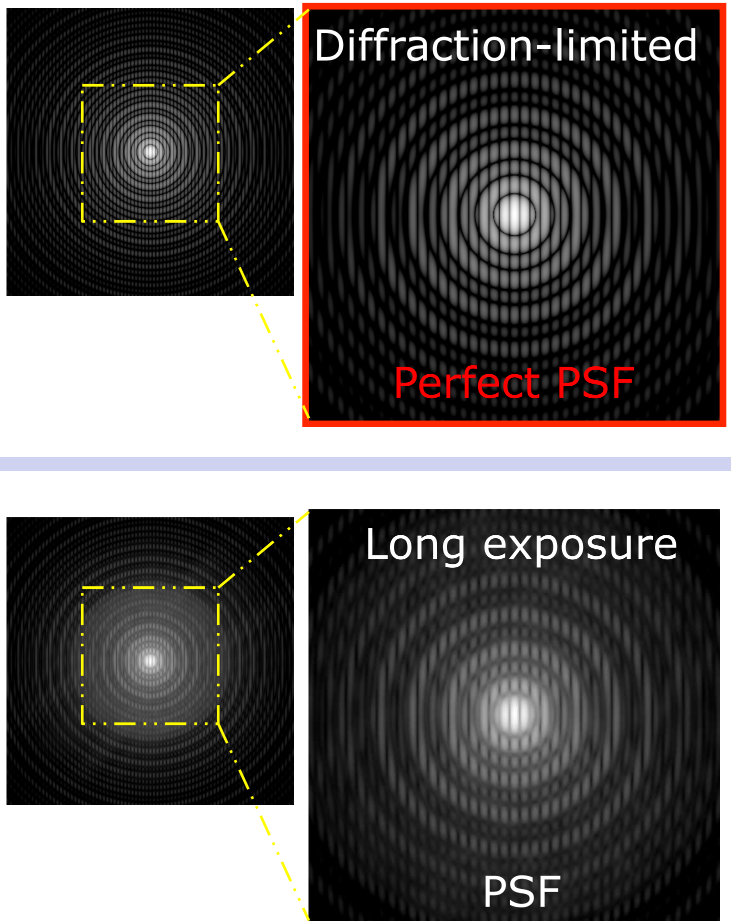
A flat wavefront (corrected by AO) provides a diffraction-limited image

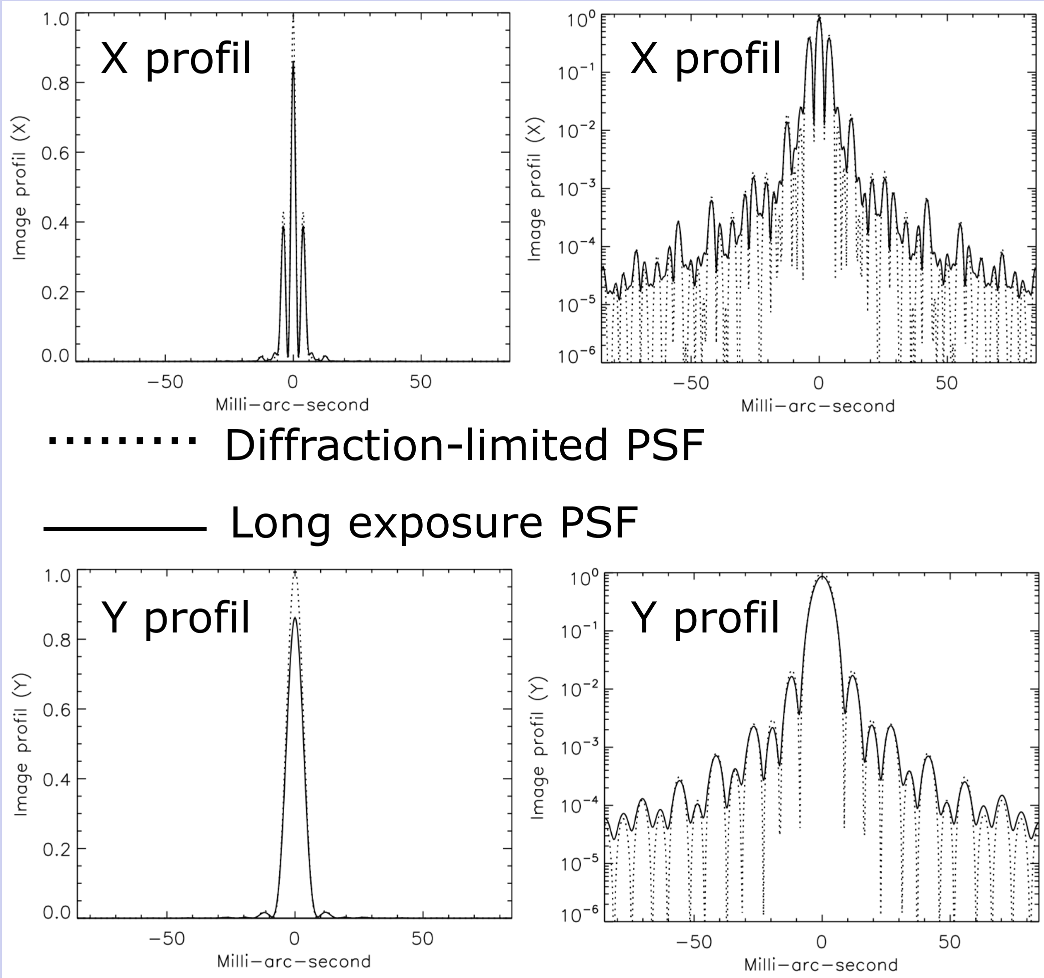
The Large Binocular Telescope (LBT)



LBTI long exposure PSF

Strehl of **90.9%** & **93.5%** (H band) for each sub-aperture.
Strehl of **86%** (@750nm) for the LBTI visible combiner.





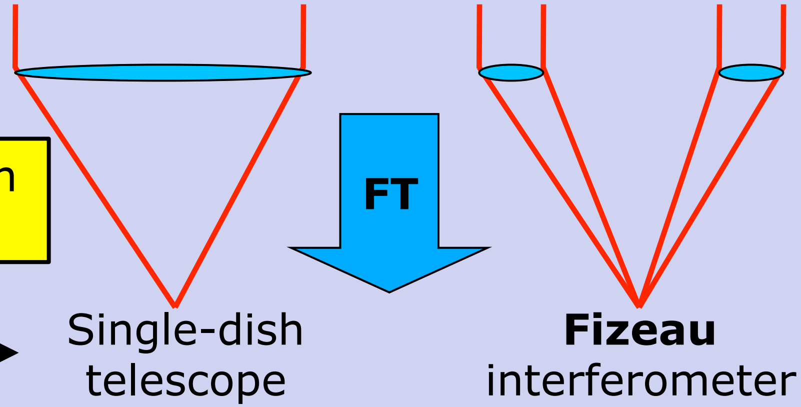
Requirement for standard imaging: WF-RMS + Differential piston < λ/10 = 75nm

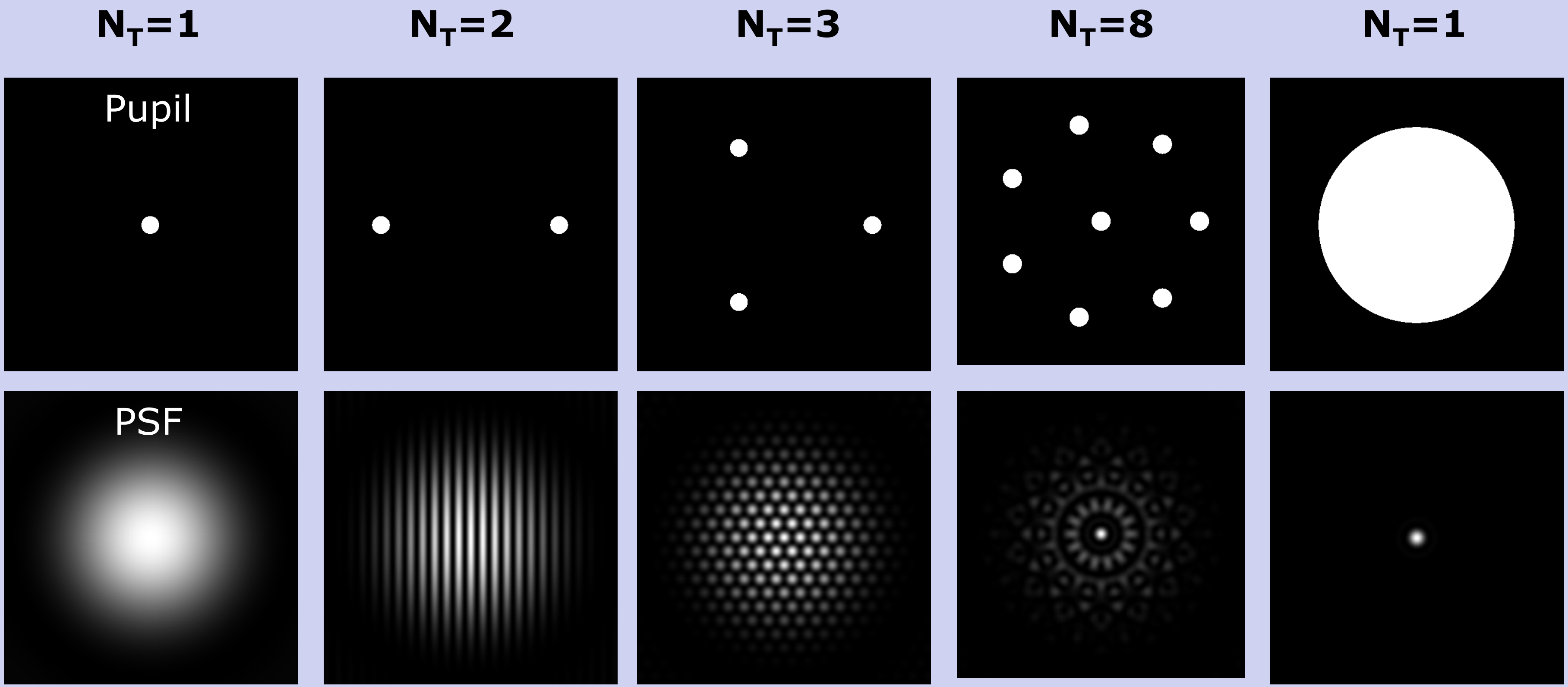
From fringes to images

Entrance **Pupil**

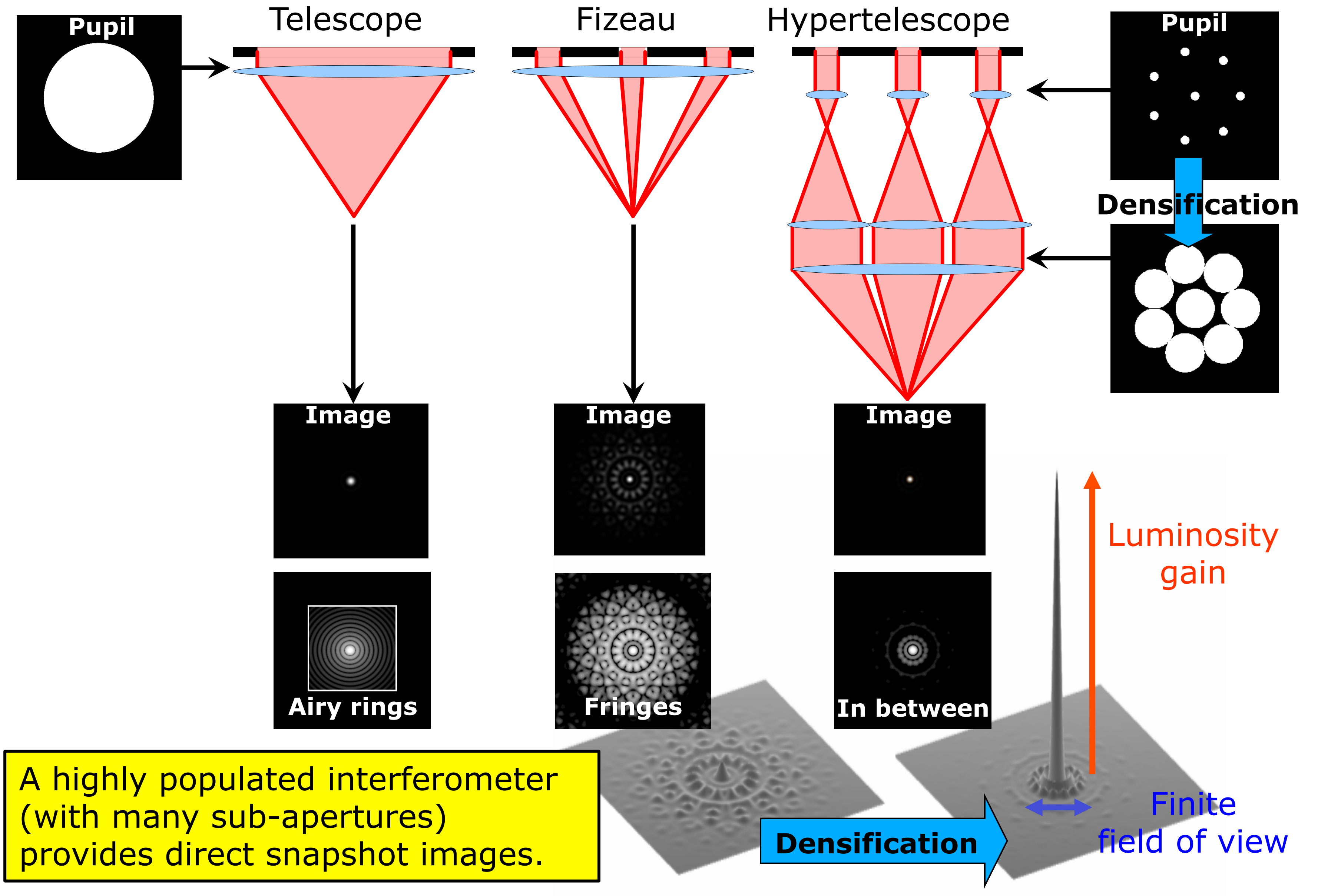
A diffraction-limited image can be seen as the sum of interferometric fringes.

Point Spread Function (**PSF**) = **Image** of a point-like star



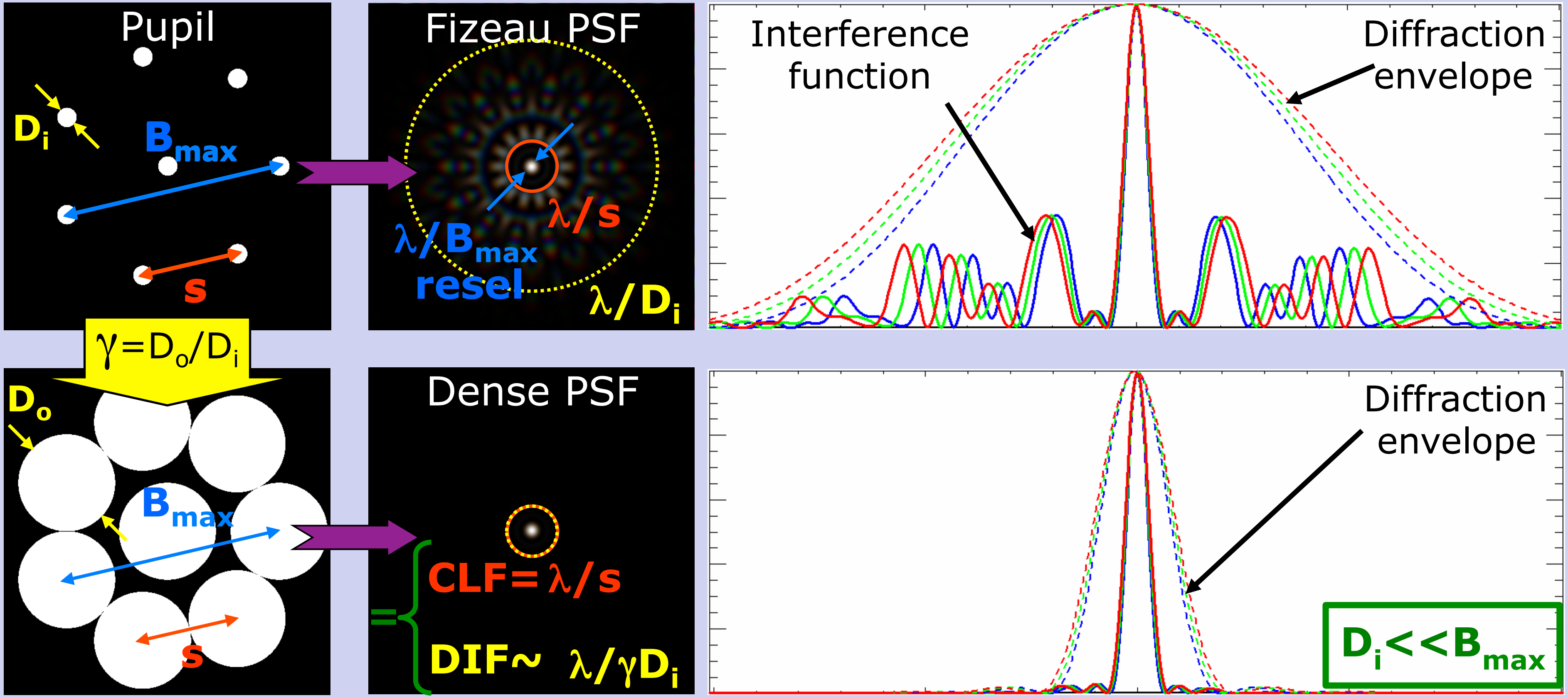


From a telescope to a hypertelescope



A highly populated interferometer
(with many sub-apertures)
provides direct snapshot images.

From a diluted to a densified pupil



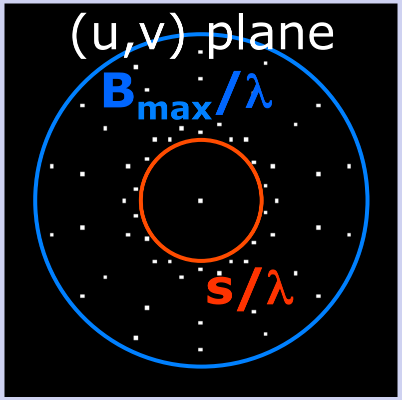
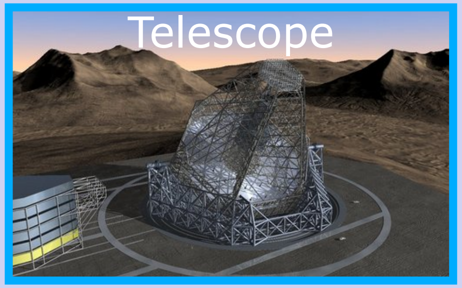


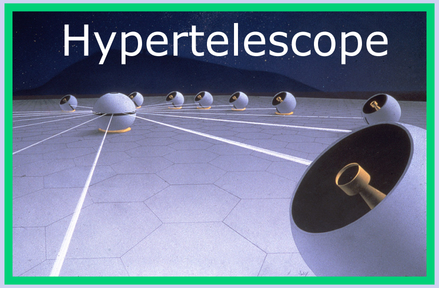
Image = (Object ⊗ Interference function) x Diffraction envelope

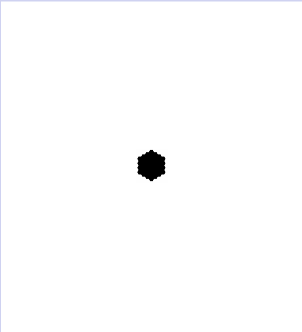
The pattern of the sub-aperture center positions are preserved. Only the high angular frequencies seen by the baselines are used (not the low angular frequencies seen by the sub-apertures).

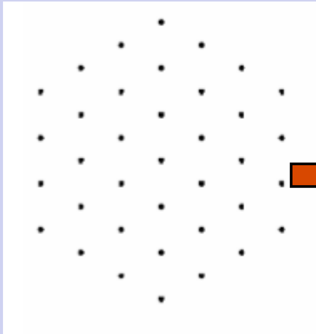
Telescope vs hypertelescope

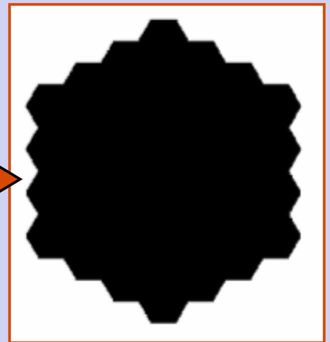


Complementarity



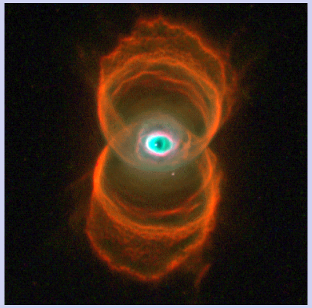


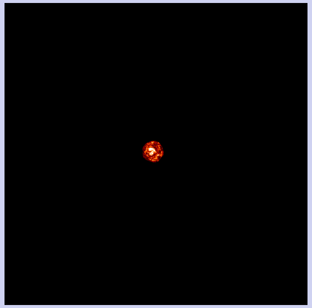




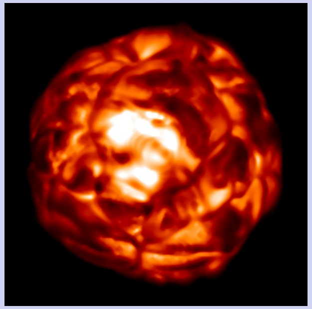
Ultimate gain in Sensitivity

Hypertelescope
Densified pupil





Wide field imaging
Low resolution => Extended objects



High resolution imaging
Narrow field => Compact objects

Imaging techniques (r)evolution

Atmosphere

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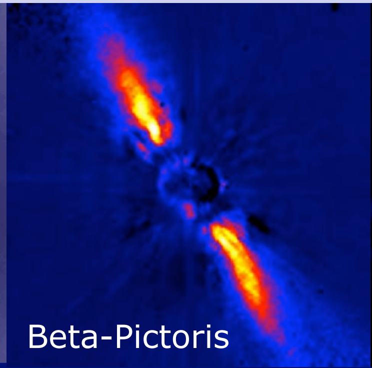
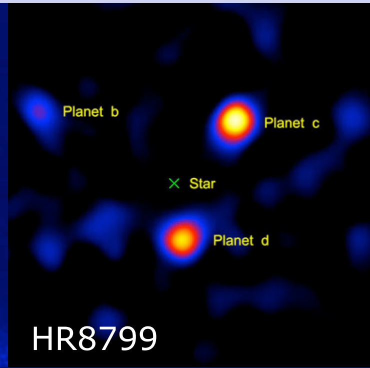
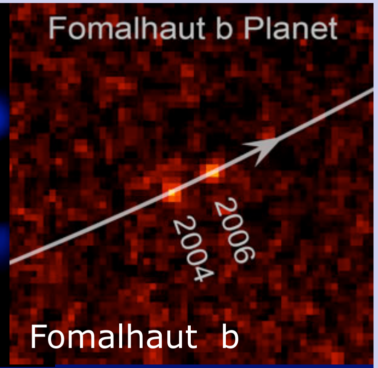
High contrast imaging techniques	Coronagraphy *Lyot 1931*		Nulling interferometry *Bracewell 1978*

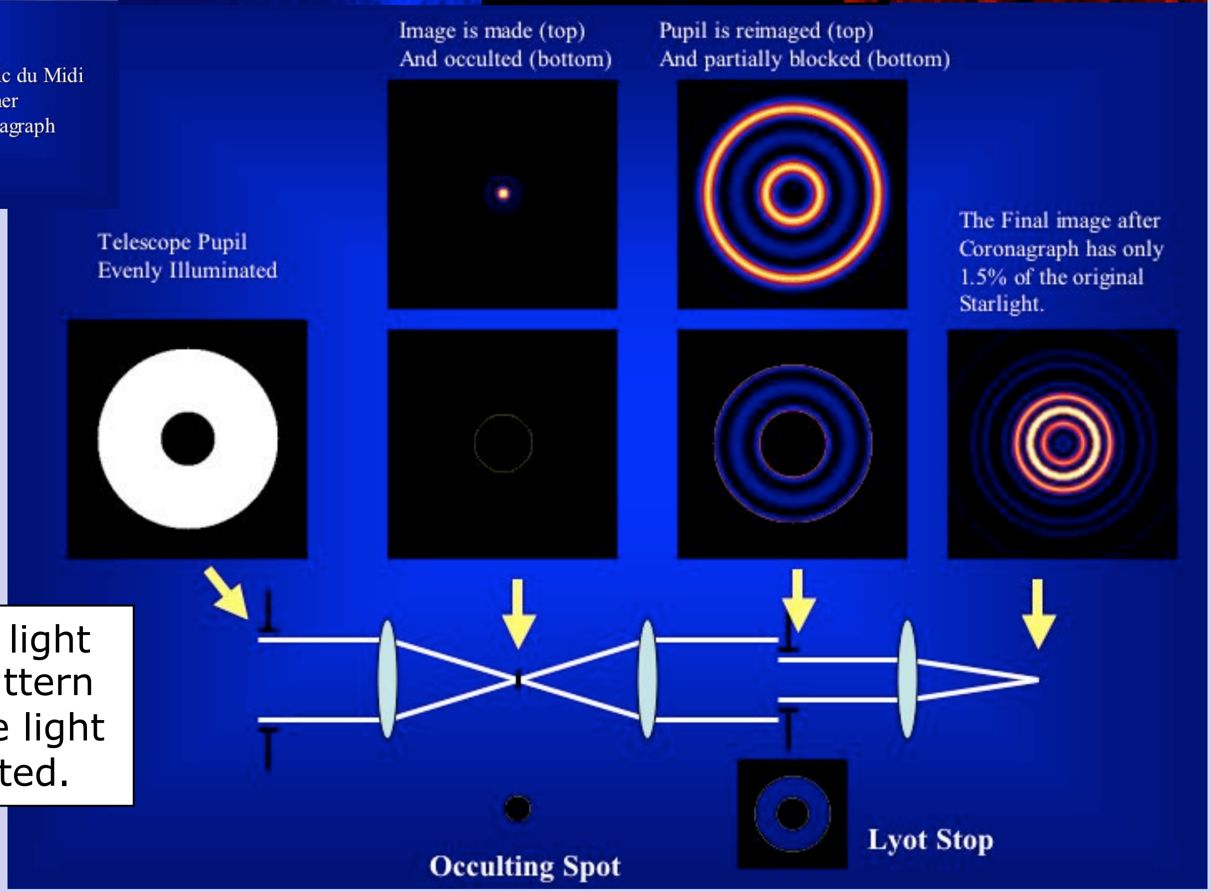
Coronagraphy





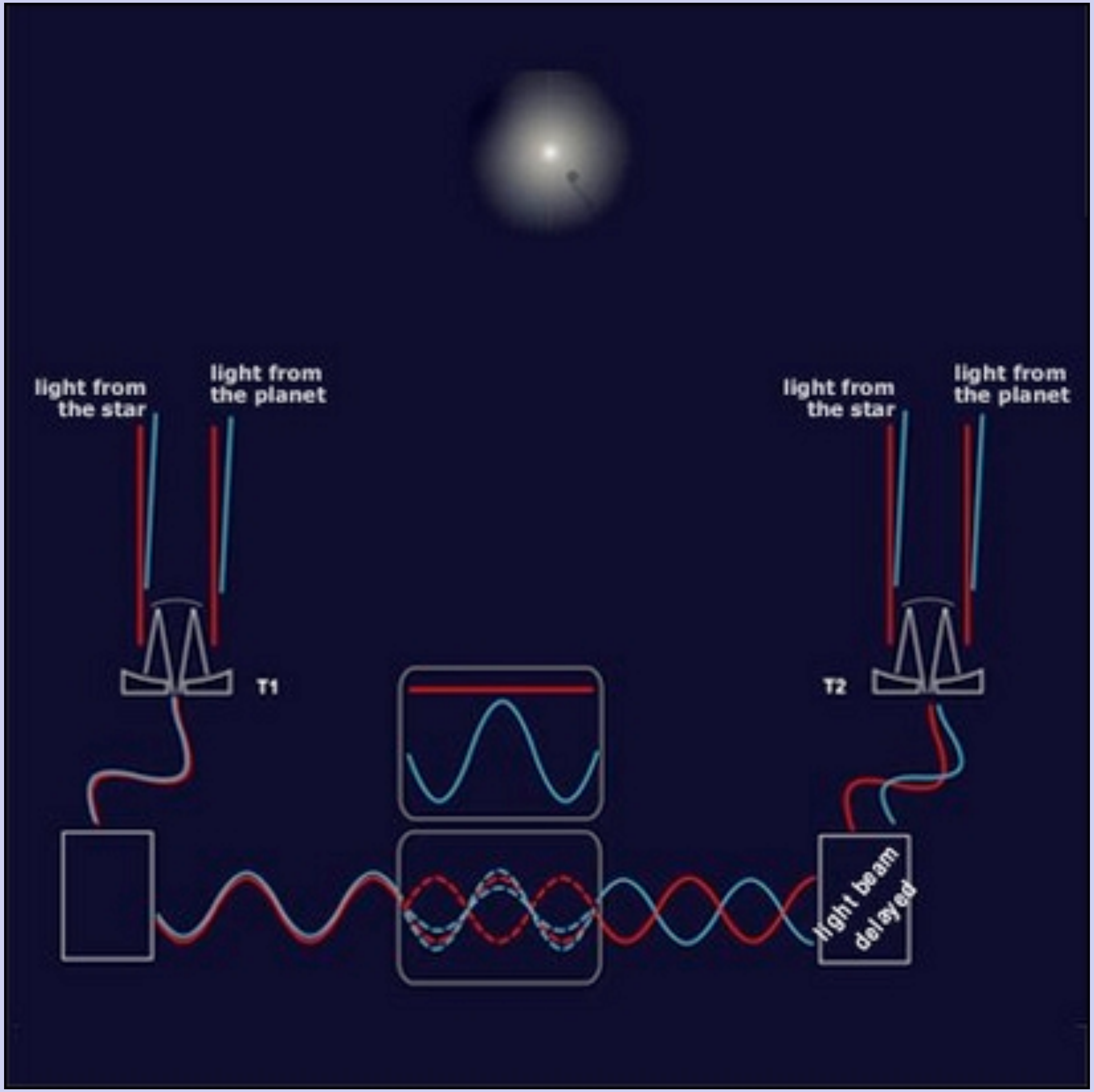


Bernard Lyot, 1939, at Pic du Midi
French Astronomer
Inventor of the Coronagraph



A Lyot coronagraph blocks the light to cancel out the diffraction pattern of an on-axis star, whereas the light of an off-axis planet is unaffected.

Nulling interferometry



The beam from one telescope is delayed by half a wavelength.

When the beams are combined, the light from the star (red) is cancelled out.

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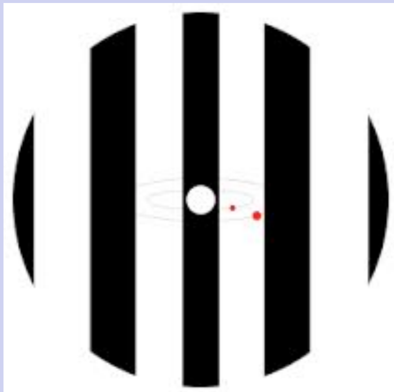
The incident angle of the light from the planet (blue) introduces a delay in the light.

The combined beams are reinforced.



Imaging techniques (r)evolution

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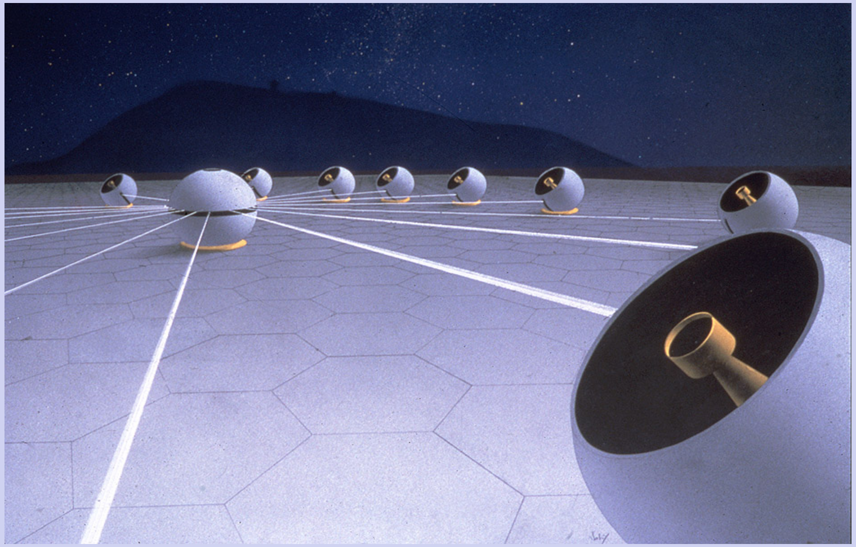
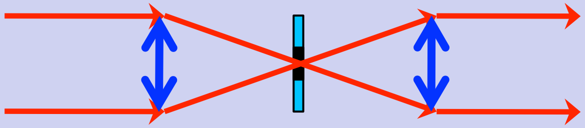
High contrast imaging techniques	Coronagraphy *Lyot 1931*		Nulling interferometry *Bracewell 1978*
Spatial filtering Modal filtering	Discretized aperture mapping (DAM) *Patru 2011*		Fibered pupil densifier (SIRIUS) *Patru 2008*



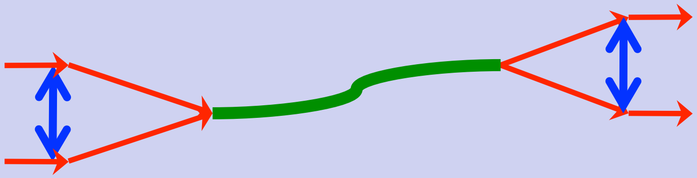
How to optimize an optical interferometer for direct imaging ?

Spatial filtering techniques (1)

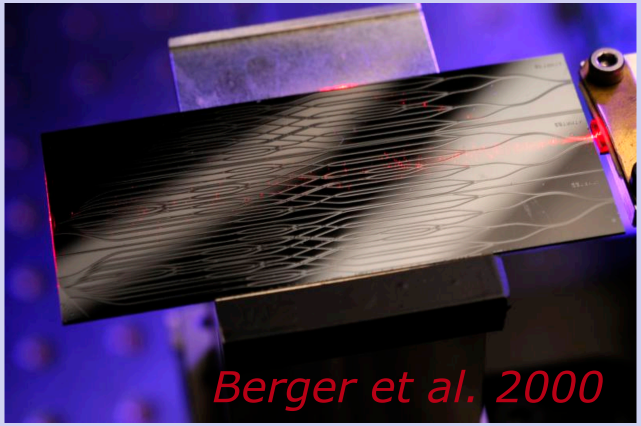
- **Hard-edge pin-hole**

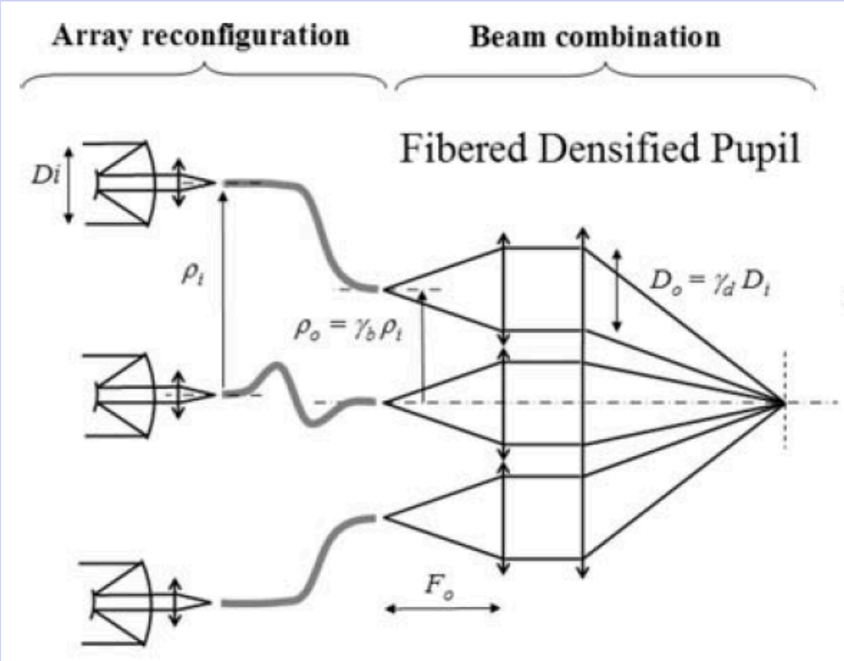


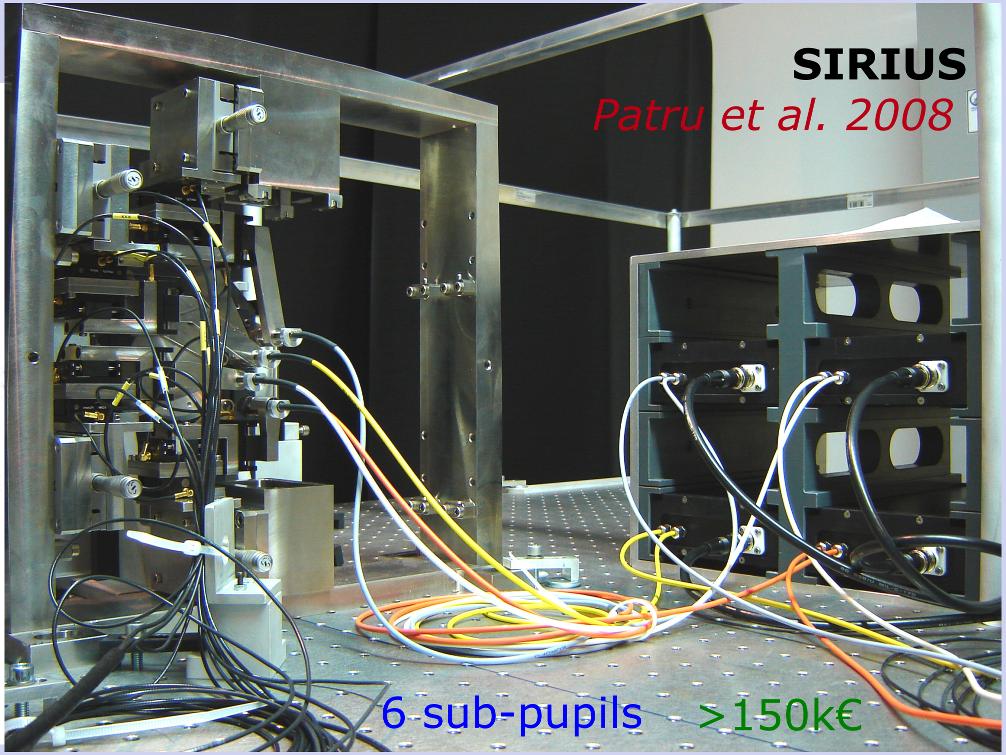
- **Single-mode fiber**



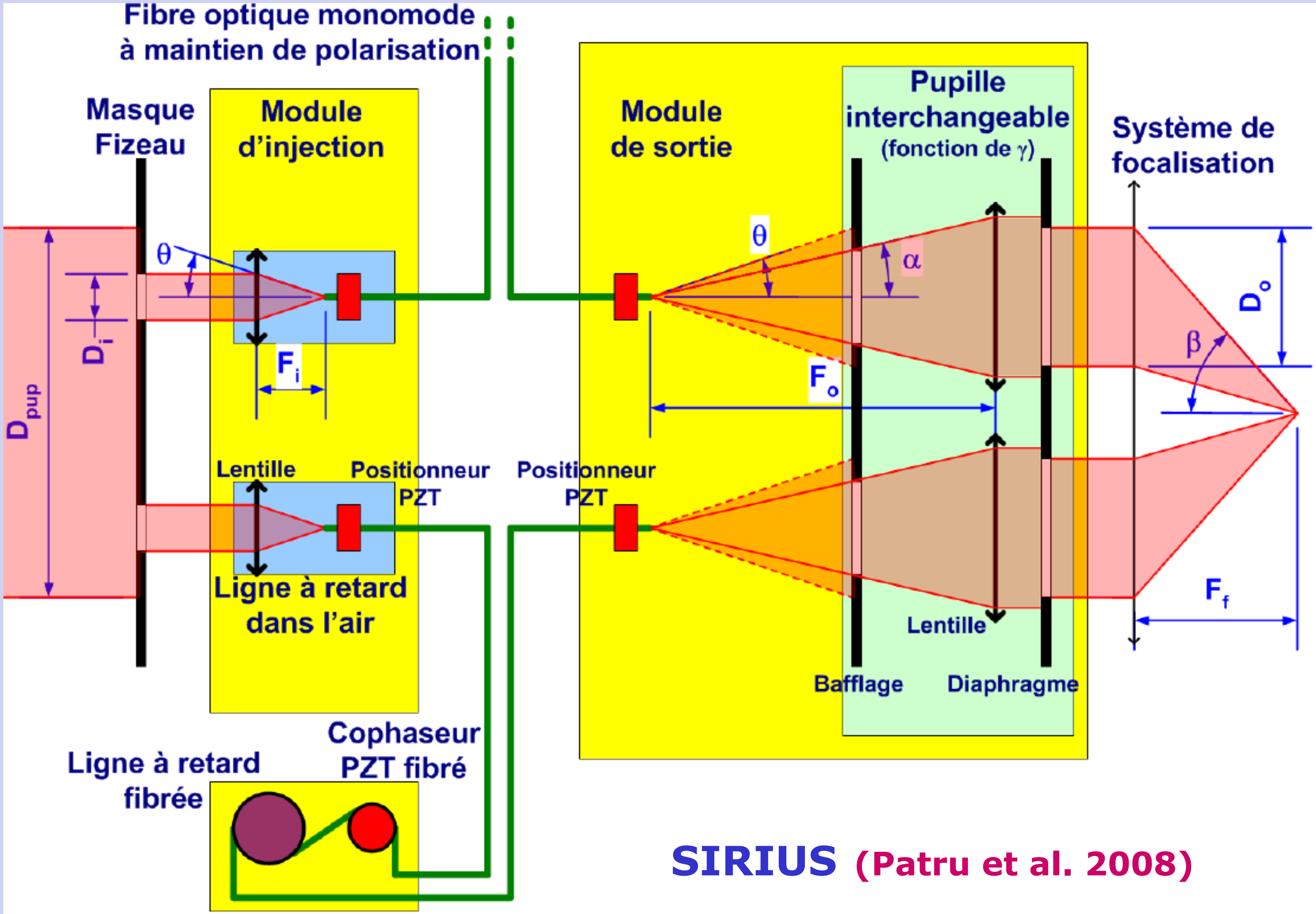
- **Integrated optic**







Fibered pupil densifier



SIRIUS (Patru et al. 2008)

1^{st} densified images with fibres

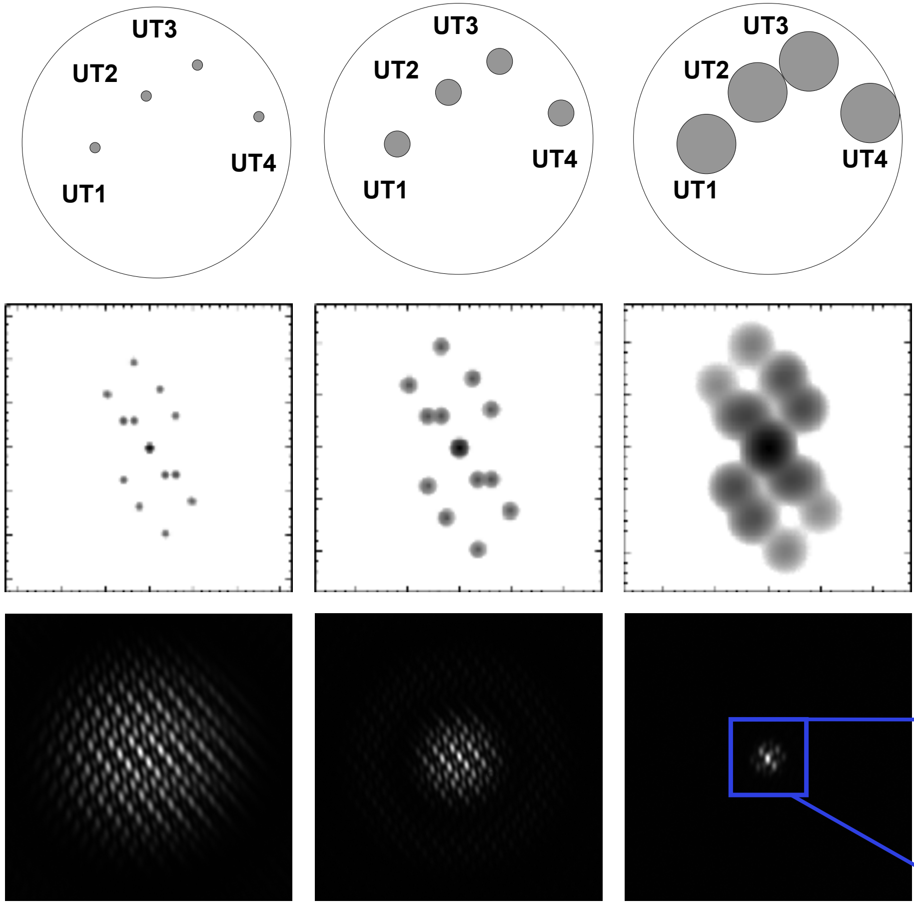
Variable Densification

	Fizeau	Partial Densification	Maximal Densification
	$\gamma=1$	$\gamma=2.5$	$\gamma=5$

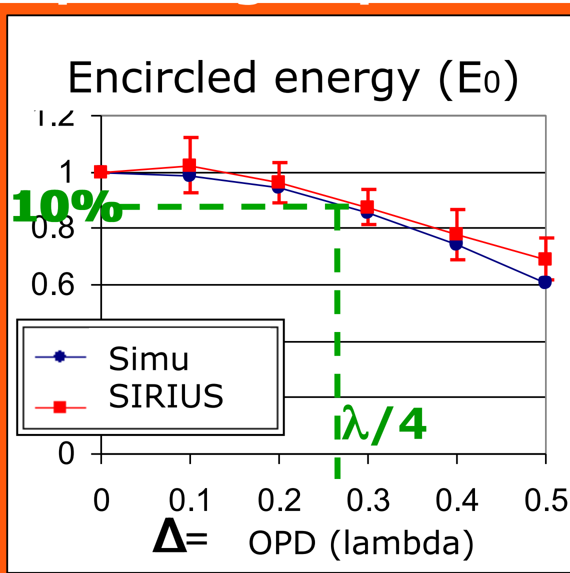
Output Pupil

(u,v) plane

Image (PSF)

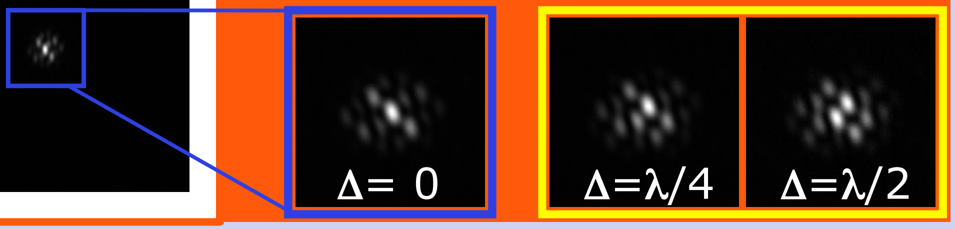


Cophasing requirement

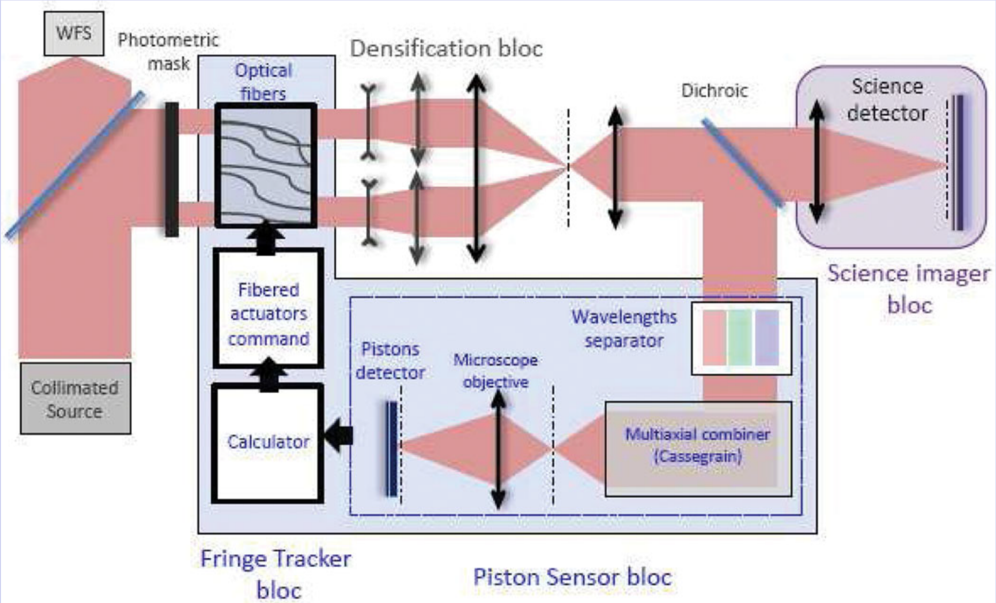


Patru & al.
SPIE 2004
SPIE 2006
MNRAS 2007
A&A 2008

Specification
$\Delta < \lambda/10$

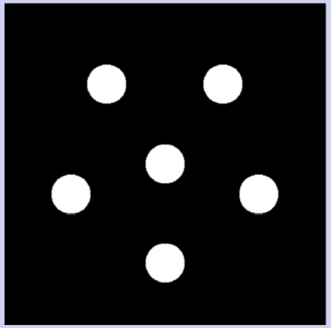


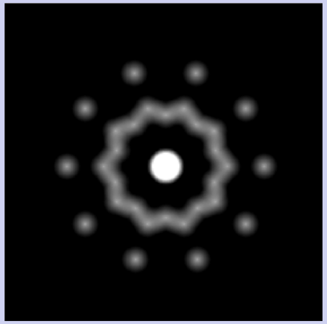
Chromatic phase diversity

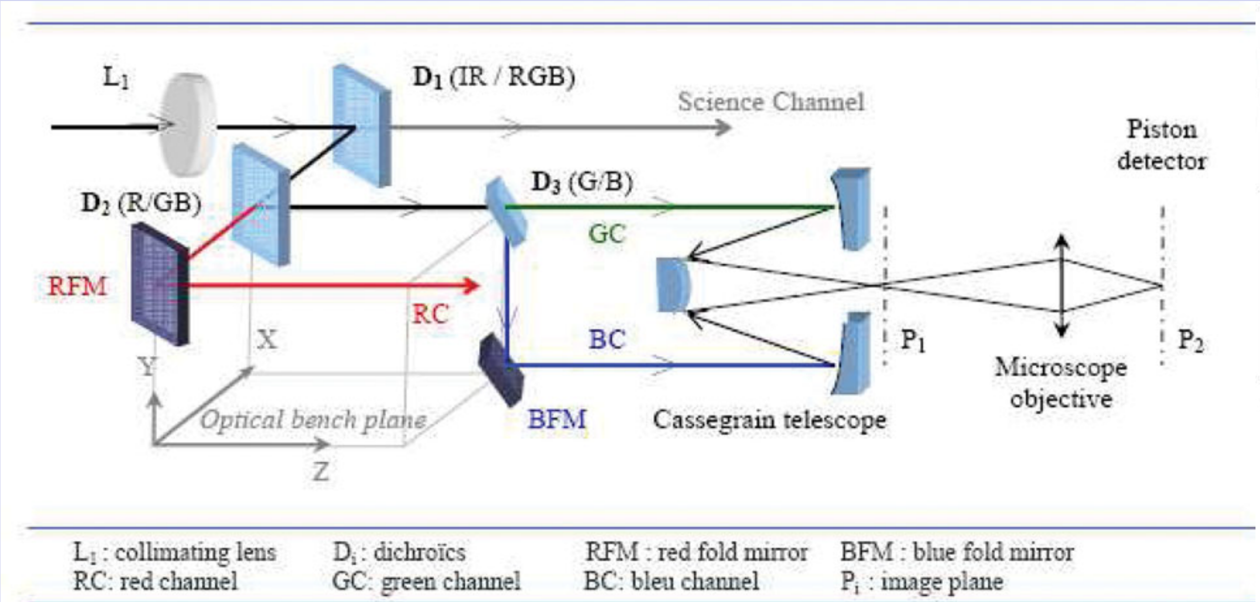


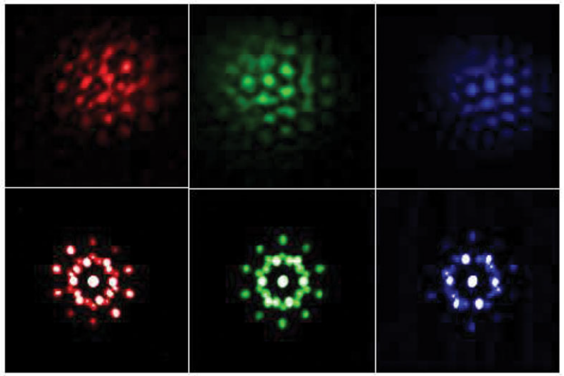
Group and phase delay sensing
for cophasing large optical arrays

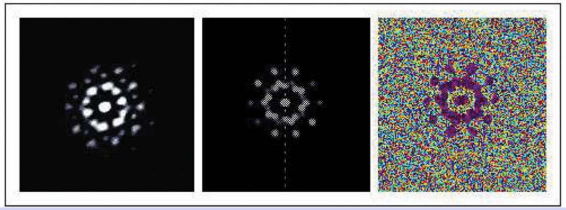
MNRAS 2014, Mourard, Patru et al.

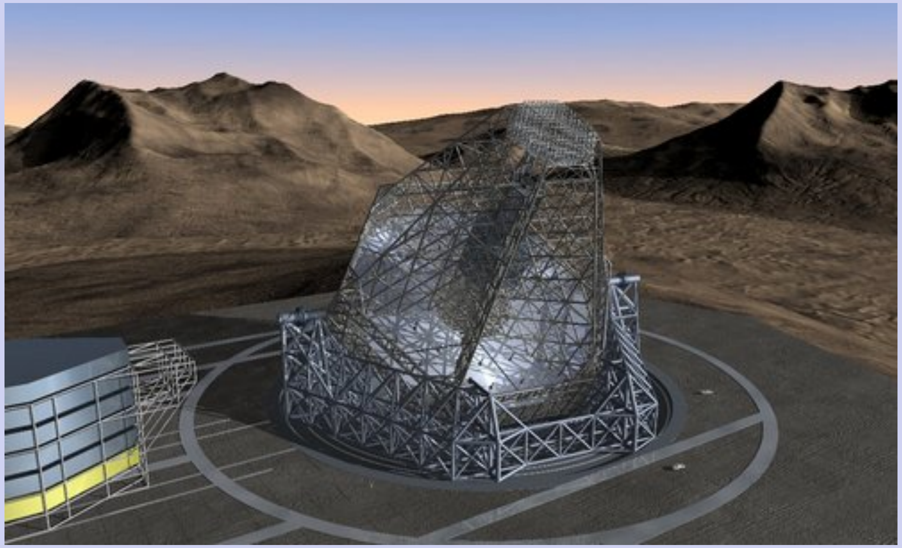












How to optimize a large telescope thanks to optical interferometry?

Call for partnership

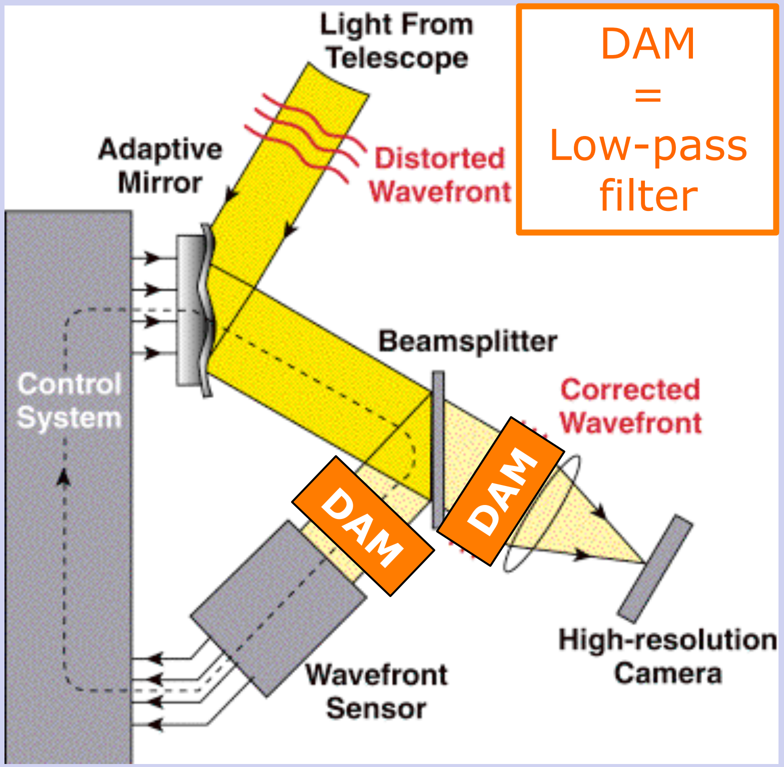
Discretized aperture mapping (DAM)

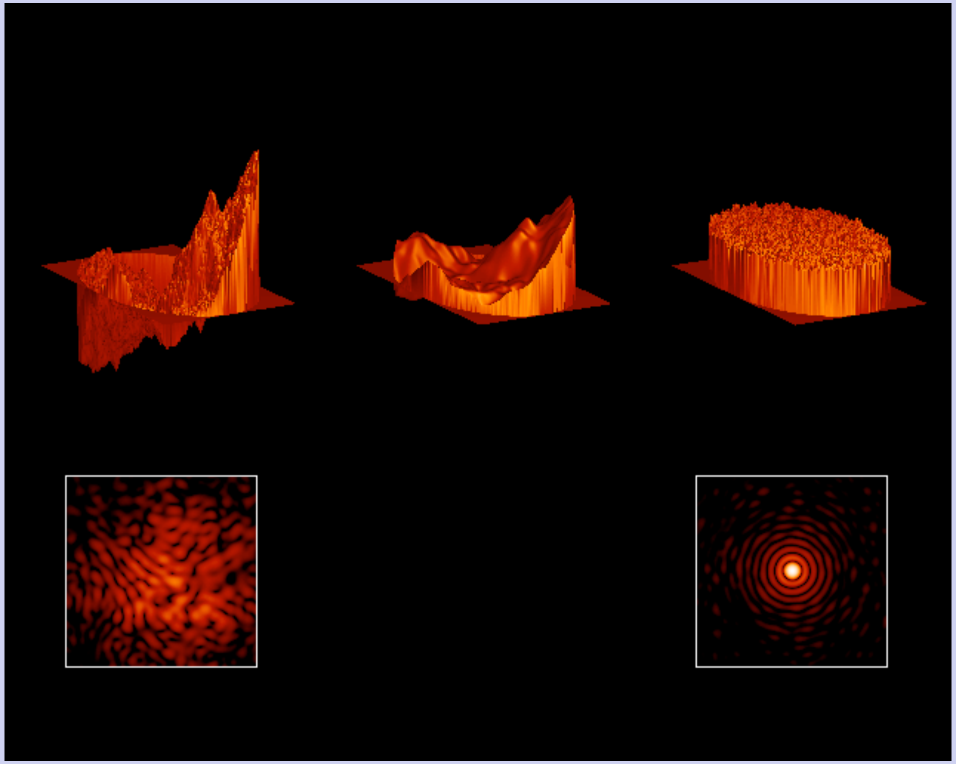
A high spatial frequency filter
for wavefront sensors, adaptive optics & direct imaging

(European funding: H2020 RIA FET open, 30/09/2015)

Fabien Patru, Osservatorio Astrofisico di Arcetri, Firenze, Italia

Adaptive optic fundamental limitation





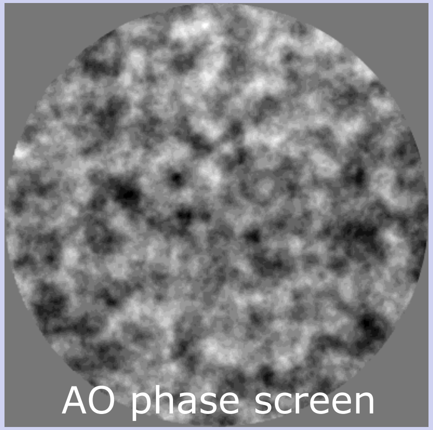
AO provides a flat wavefront and a diffraction-limited image.

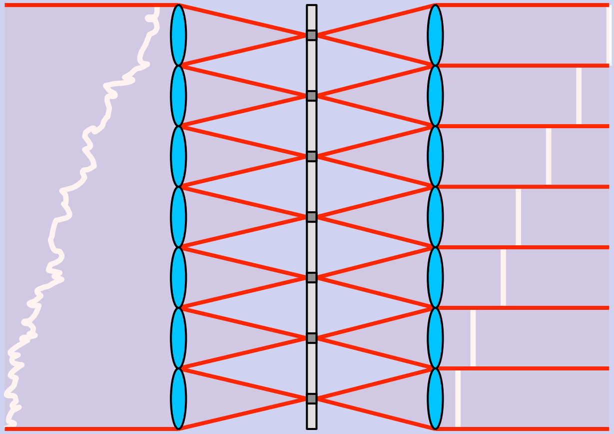
AO cannot correct small scale structures (smaller than the actuators pitch).
The high spatial frequency content is transmitted (AO is a high-pass filter),
preventing highly smooth wavefront and high contrast imaging.

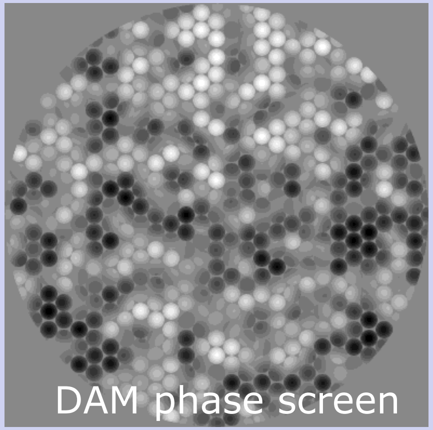
Can we correct a large number of Zernike modes? Yes, but complexe…

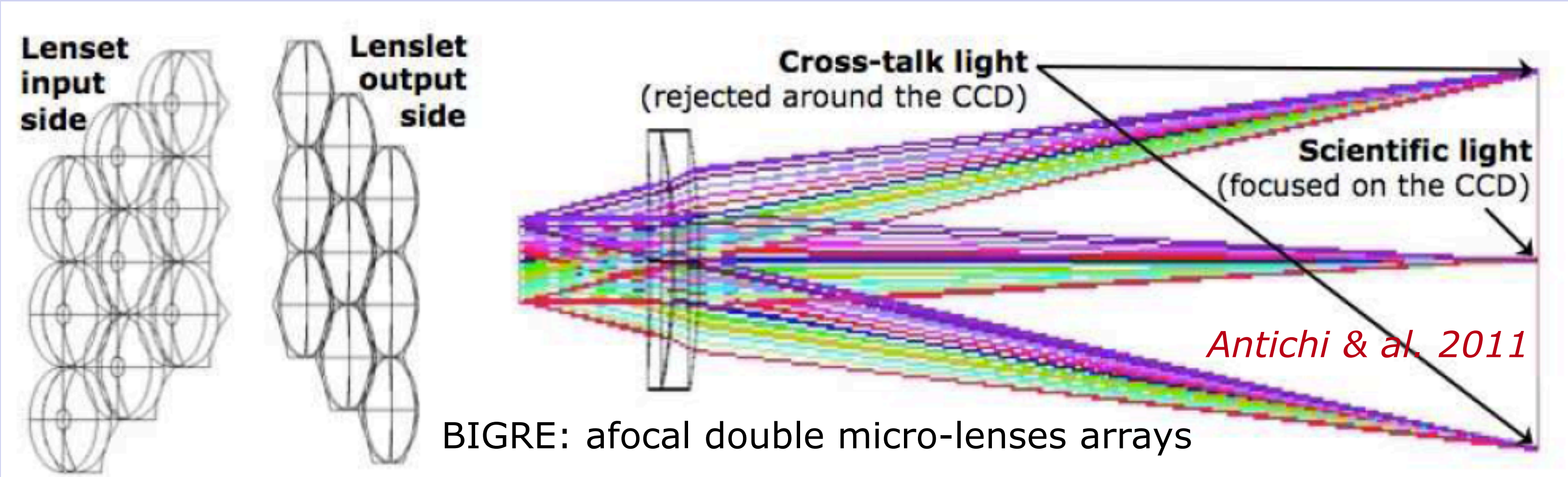
May we filter out the tricky high order aberrations? Yes, with a low-pass filter.

DAM filter optical scheme



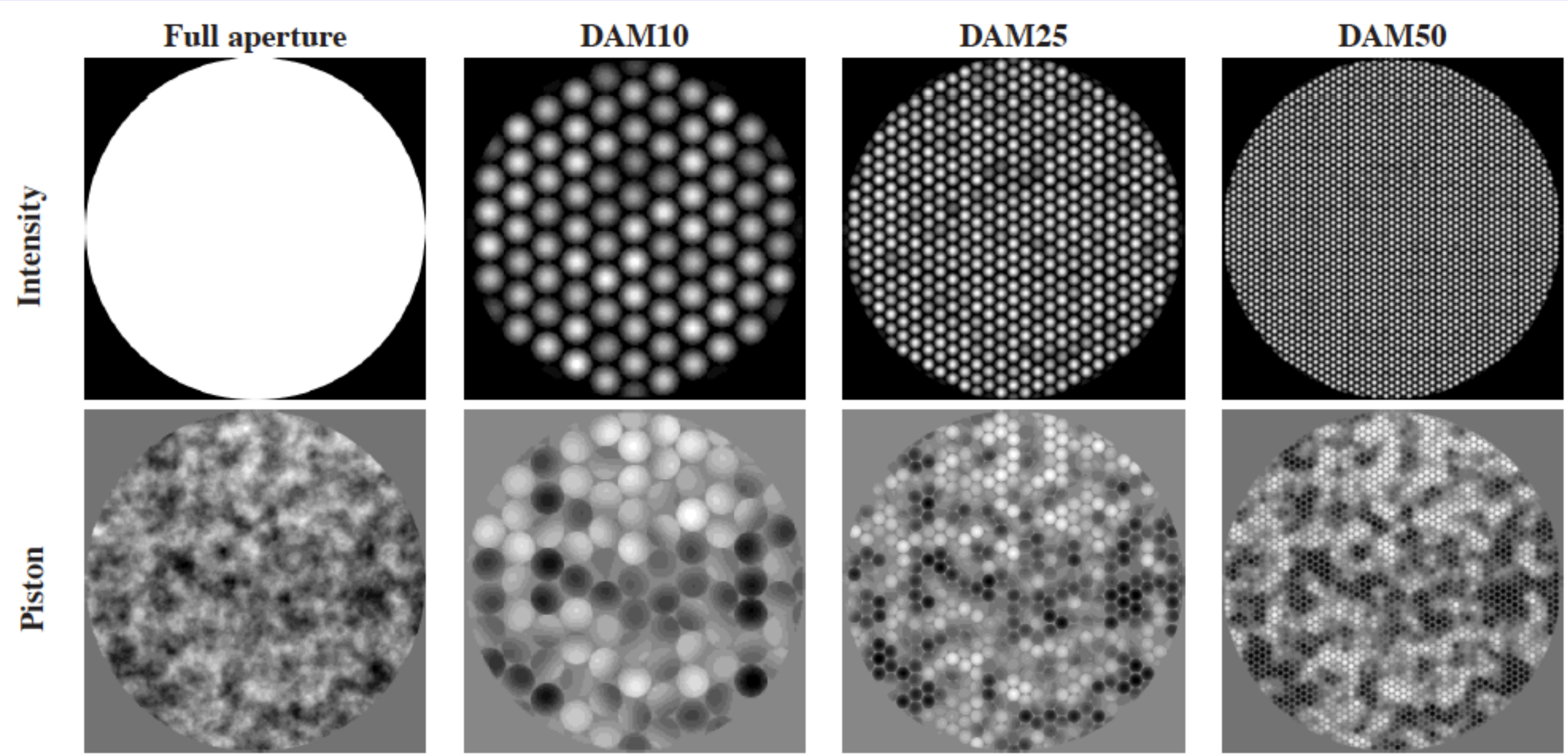






DAM is a passive filter located in a conjugated pupil plane.
DAM is based on **spatial filtering & interferometry**.
The turbulent wavefront is **discretized** into **coherent** sub-apertures.
The **high spatial frequencies** seen by the sub-apertures are **removed**.
The **low spatial frequencies** seen by the baselines are **preserved**.

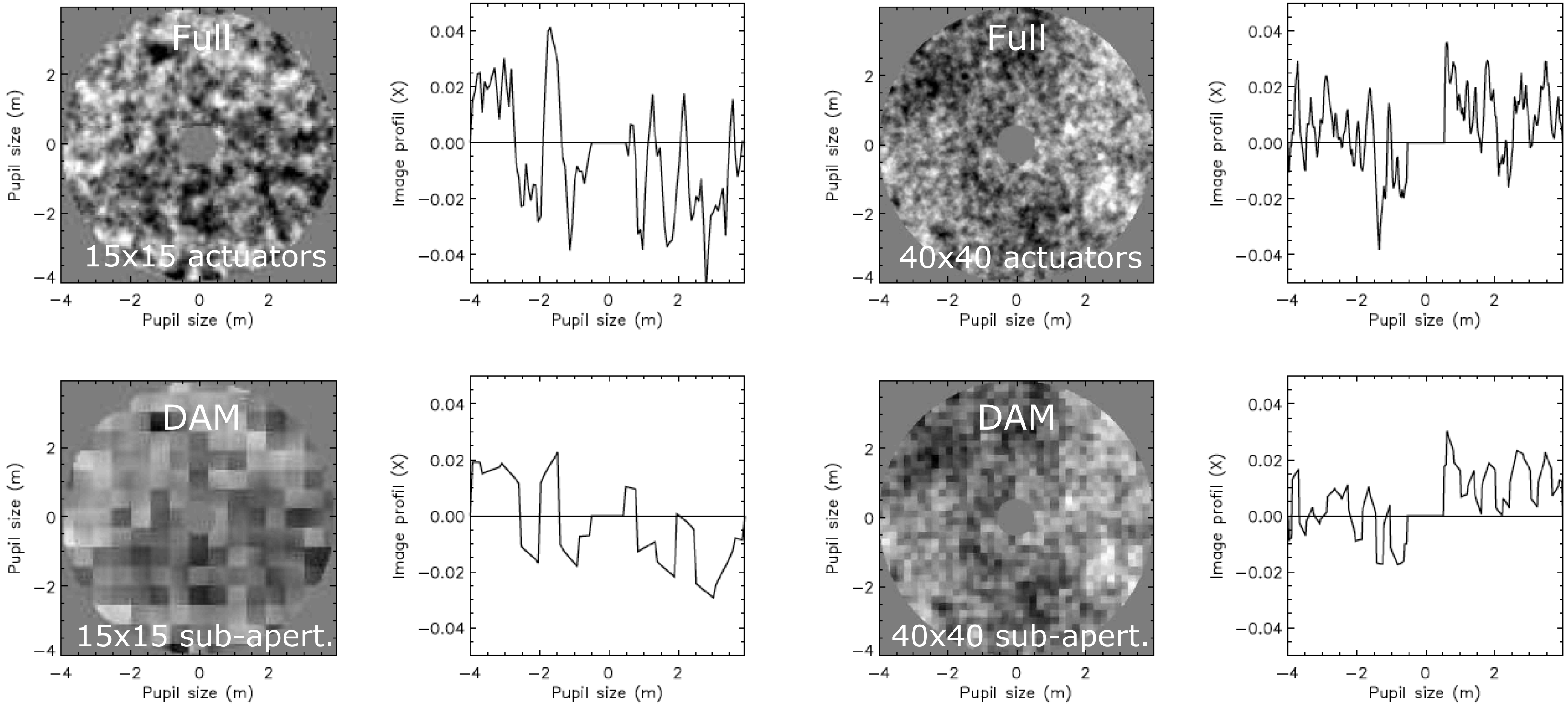
DAM wavefront sampling

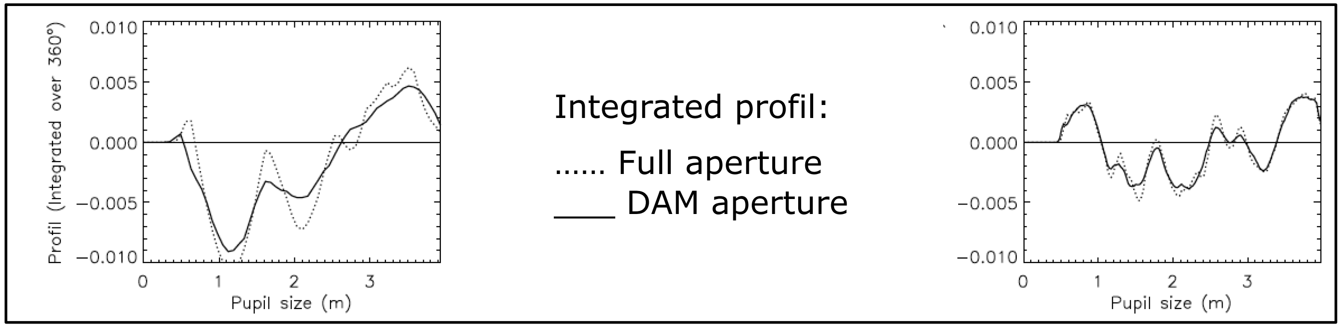


Instantaneous wavefront screen in intensity (top) and in piston (bottom)

The turbulent wavefront is discretized in phase and in amplitude by DAM.
A finite number of degrees of freedom (pistons) has to be corrected by AO.
If there are as many sub-apertures as actuators, it is a **well-posed problem**.

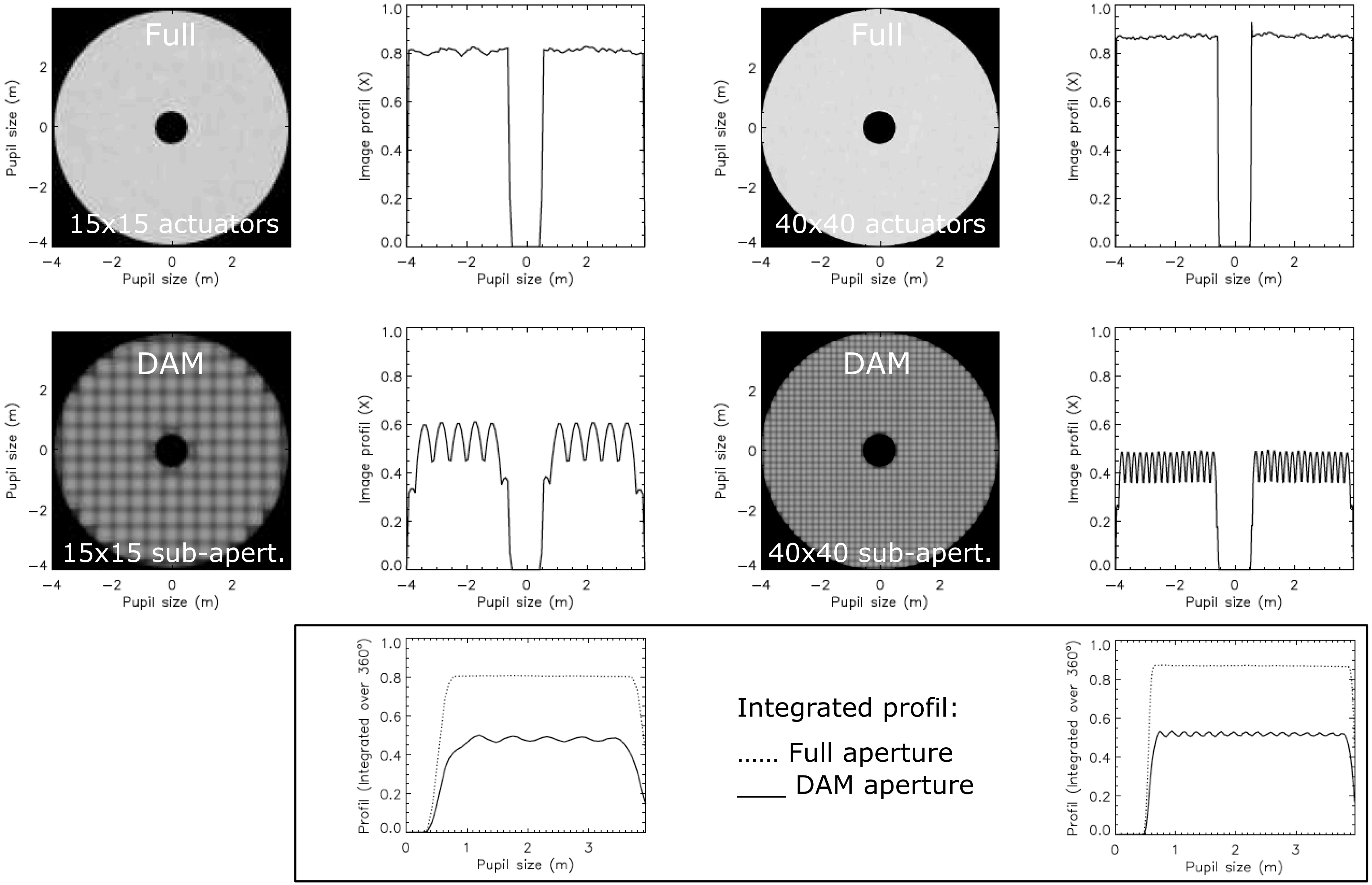
DAM wavefront phase





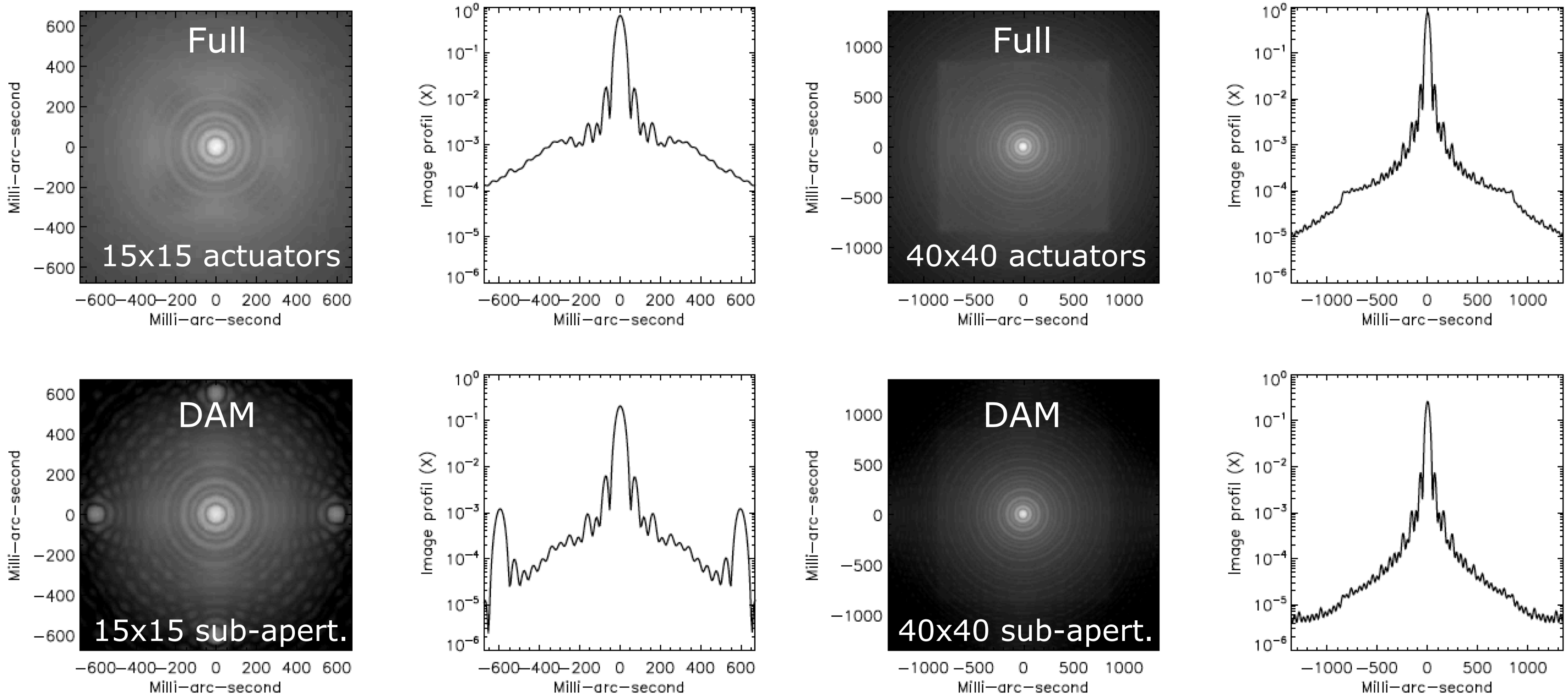
The spatial filtering averages out the phase within each sub-aperture.
The differential phases between the sub-apertures are preserved.

DAM wavefront amplitude

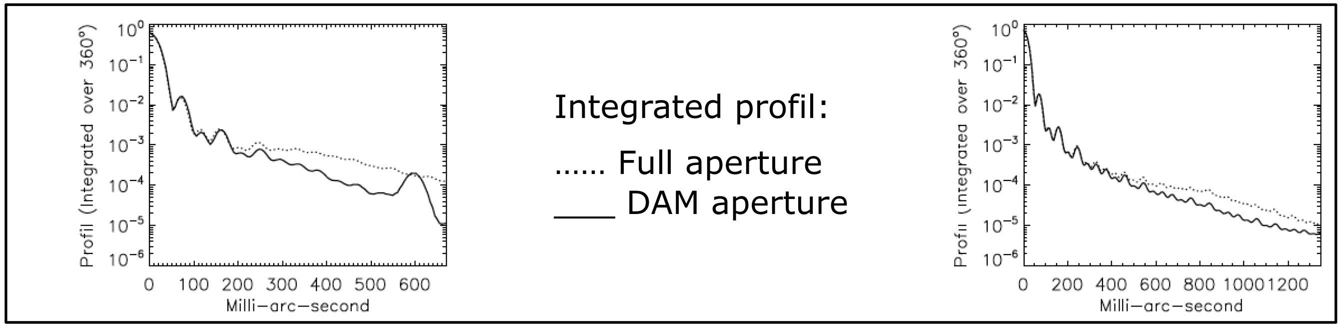


The spatial filtering averages out the amplitude within each sub-aperture.
The gaussian amplitude in each sub-aperture creates discontinuities.

DAM point spread function

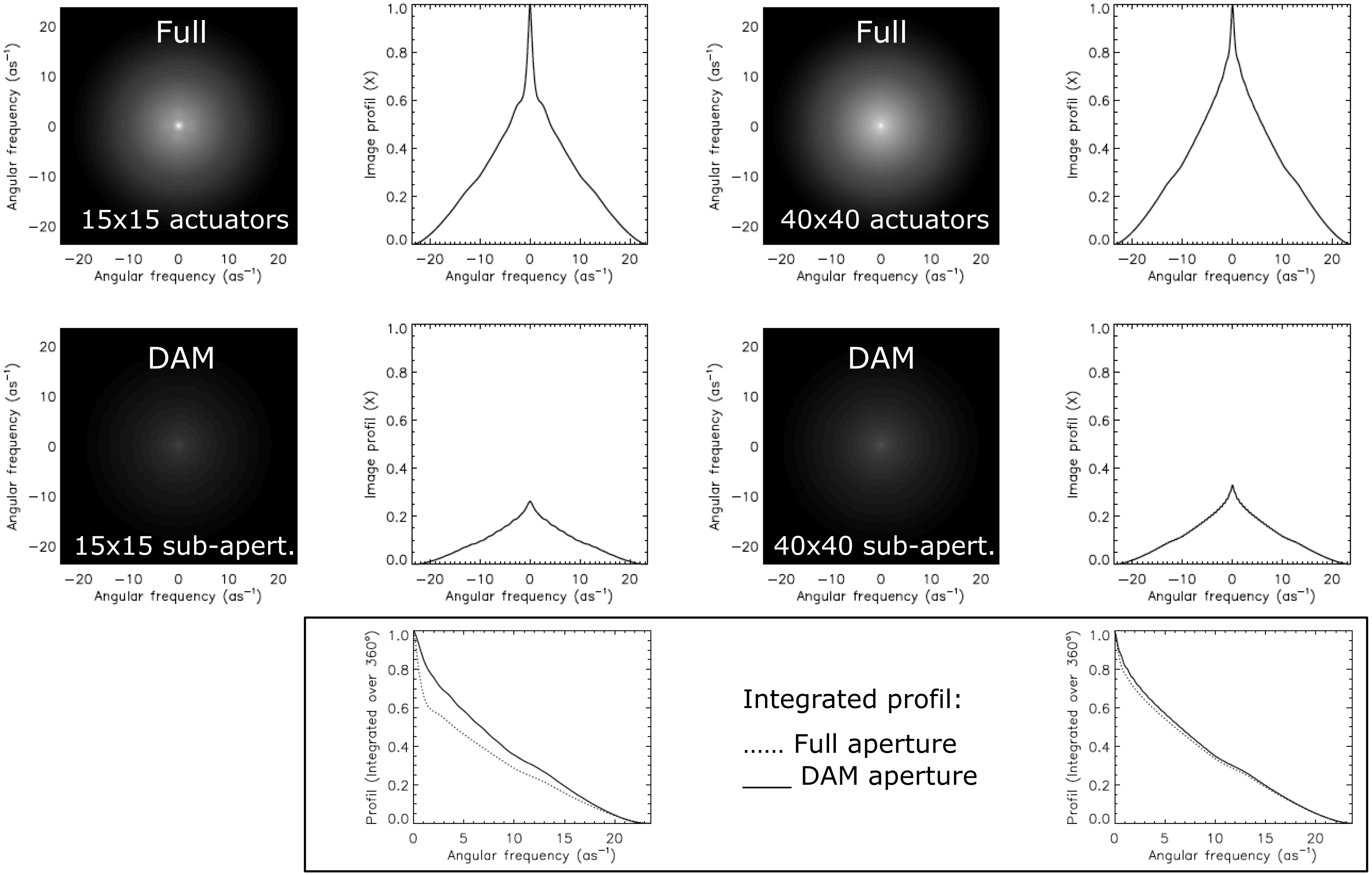


The halo is dimmed.



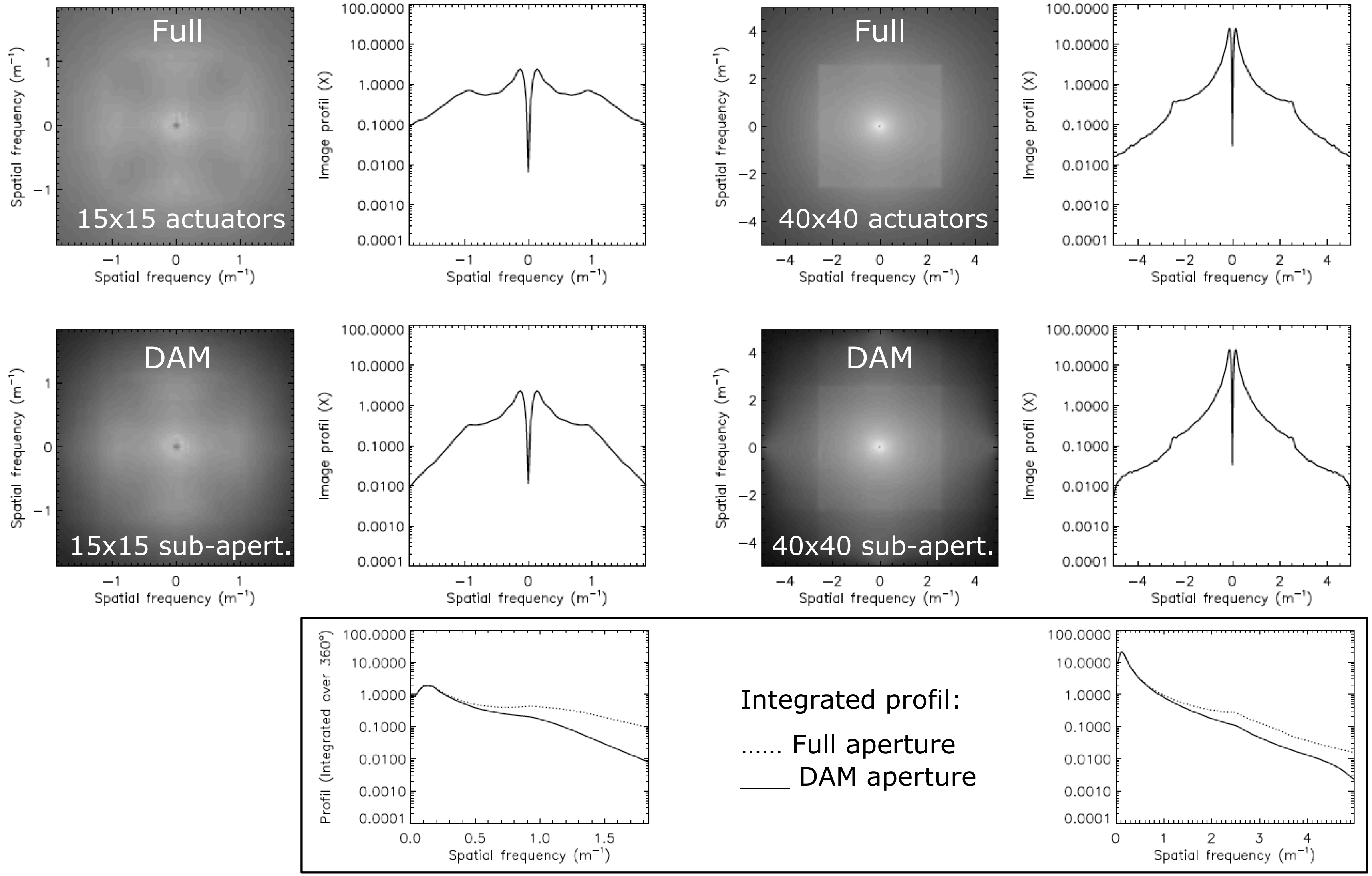
The field of view (in λ/D) equals to the number of sub-aperture along the diameter (D): 15 λ/D and 40 λ/D with DAM15x15 and DAM40x40.

DAM optical transfert function



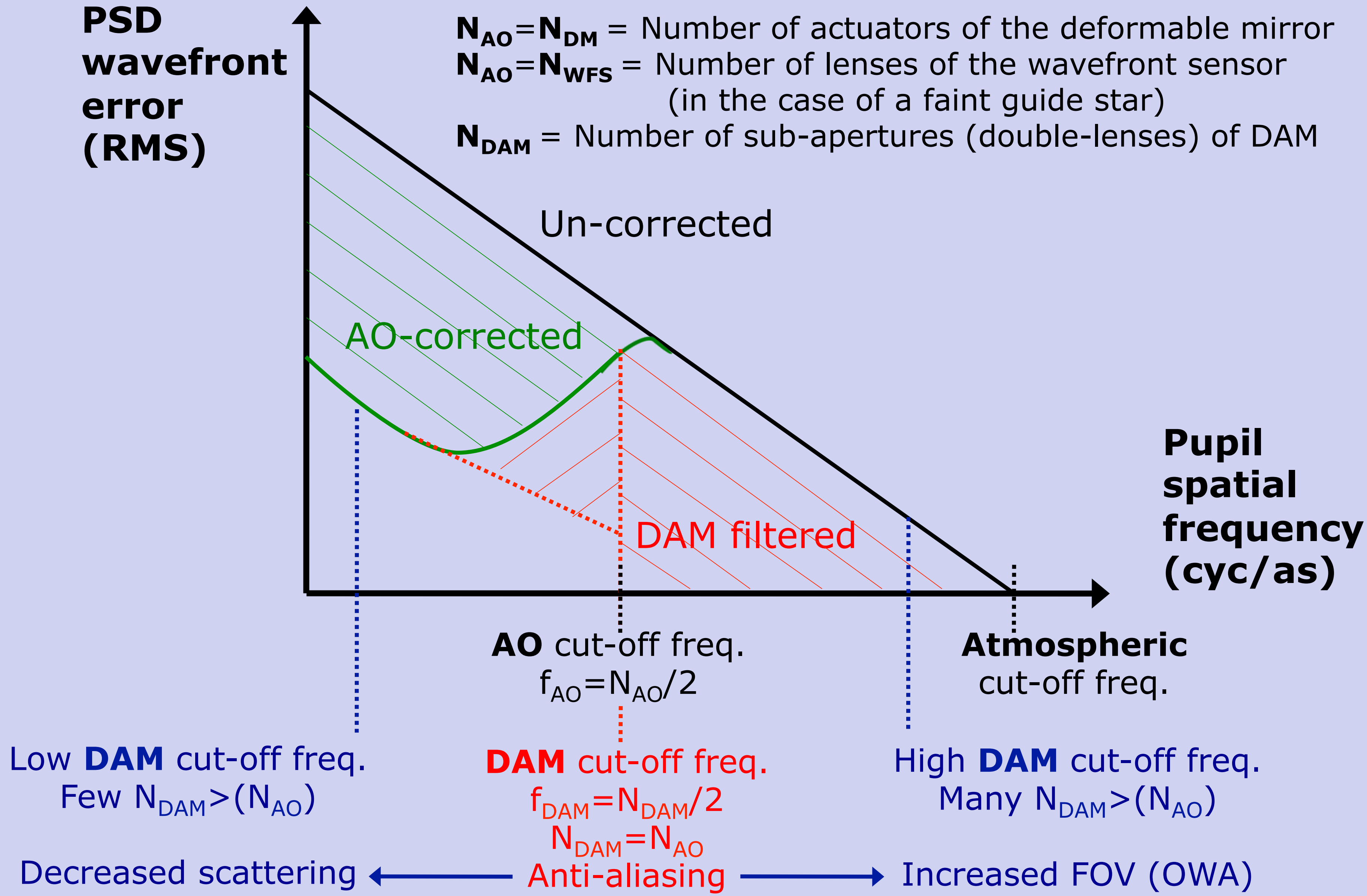
DAM recovers the triangular shape of the optical transfert function.
The central peak is smoothed by rejecting the un-coherent flux.

DAM phase power spectral density

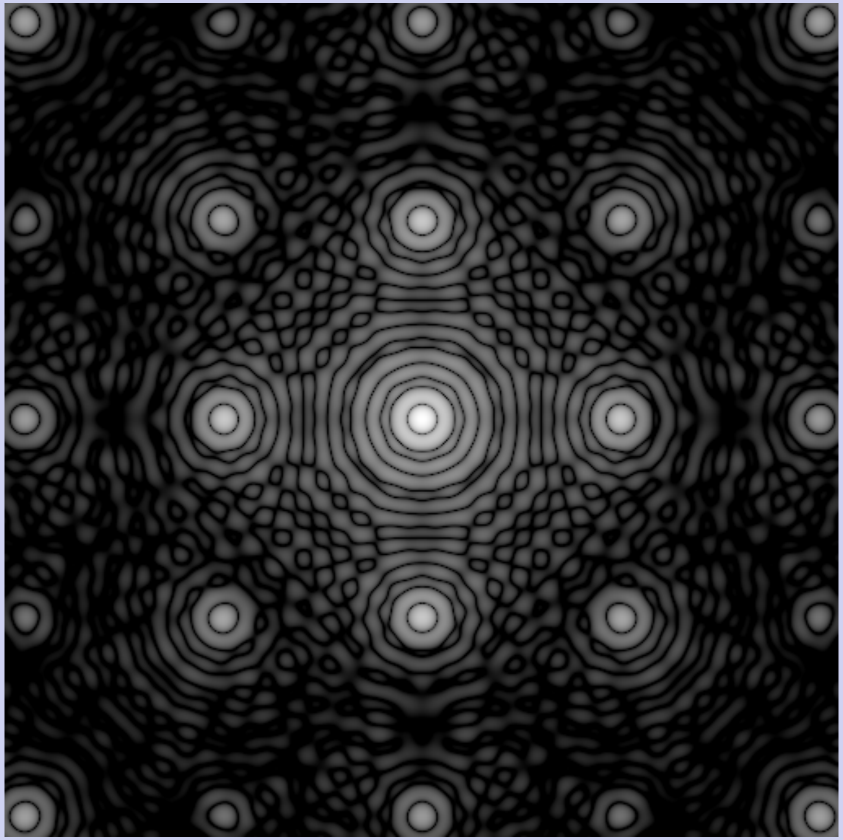
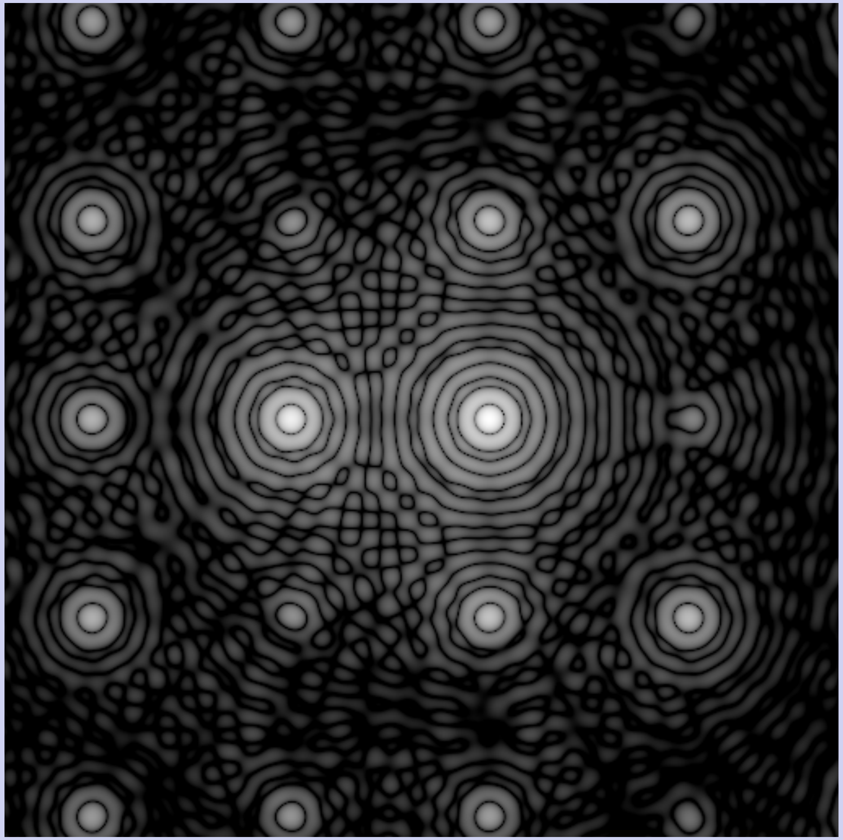


DAM removes part of the residual phase of the AO to enhance the Strehl. The high frequencies are filtered out. The low frequencies are preserved.

Phase power spectral density

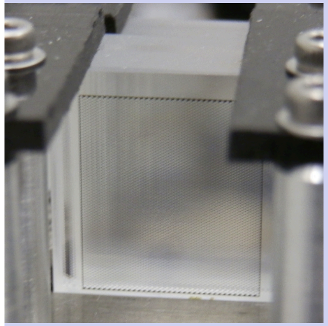


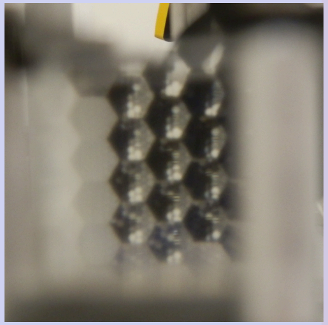
Off-axis behavior

The side-lobes can be used to calibrate the residual tip-tilt.
The side-lobes however limit the field of view and the target size.

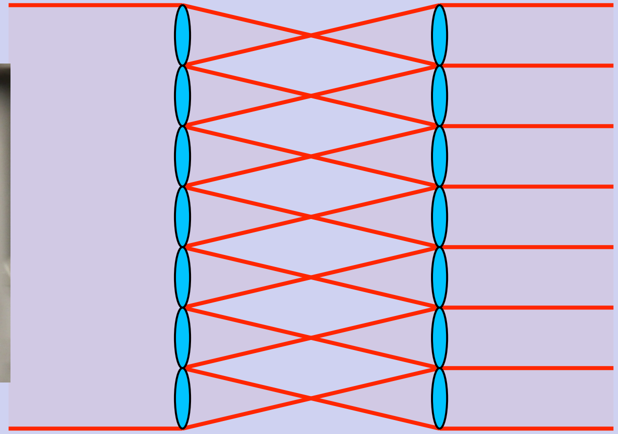
DAM technological devices





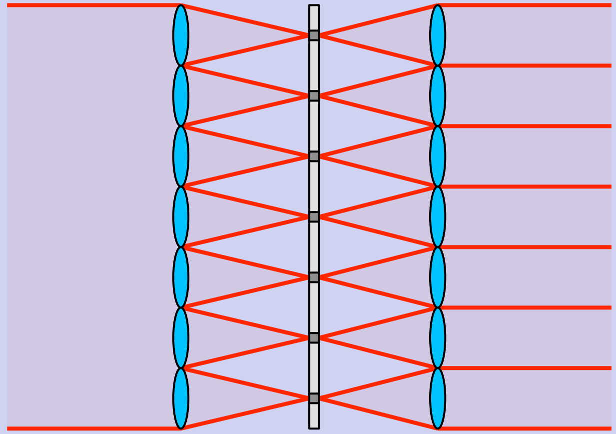
BIGRE-DAM

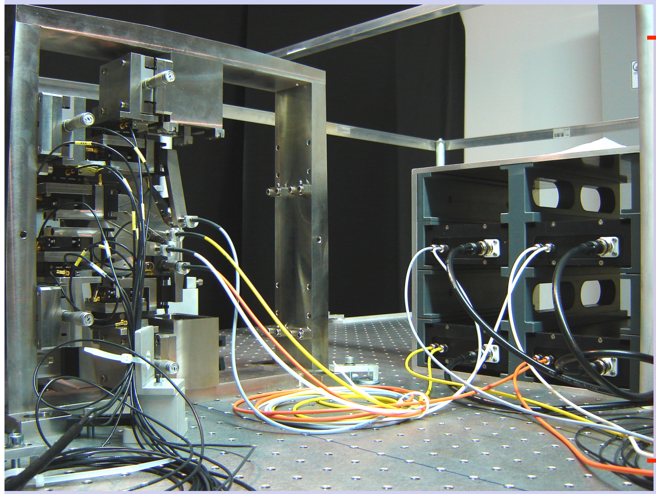
(BIGRE micro-lenses)



PI-DAM

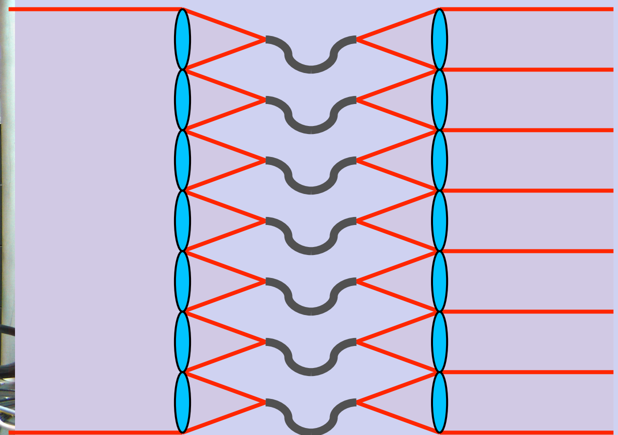
(Pinholes)





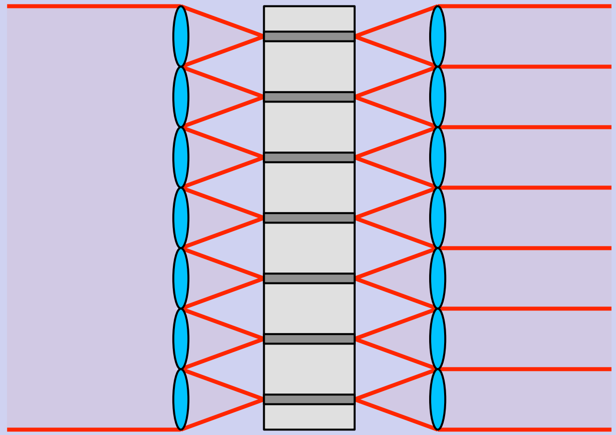
FI-DAM

(Single-mode fibers)

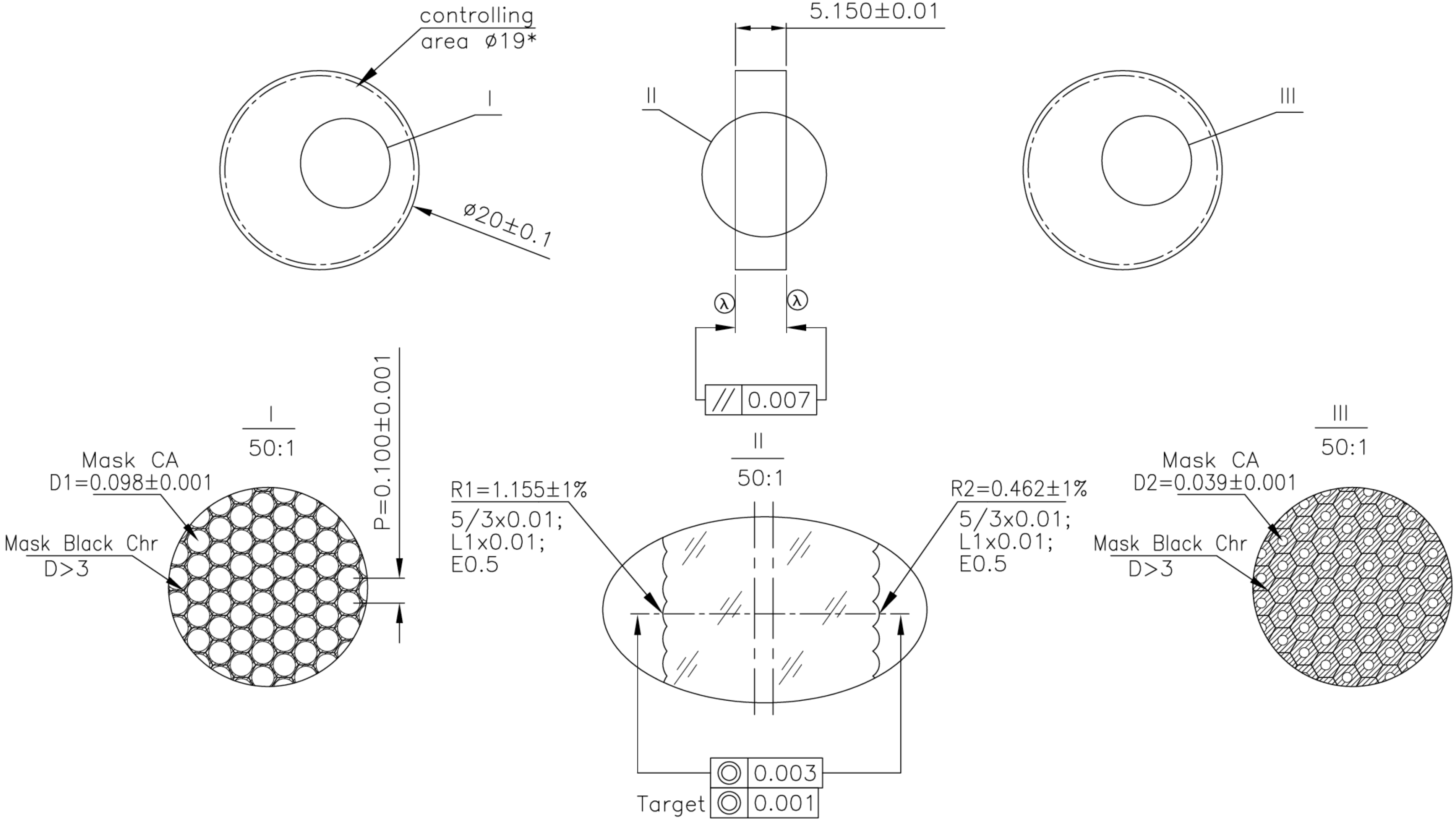


IO-DAM

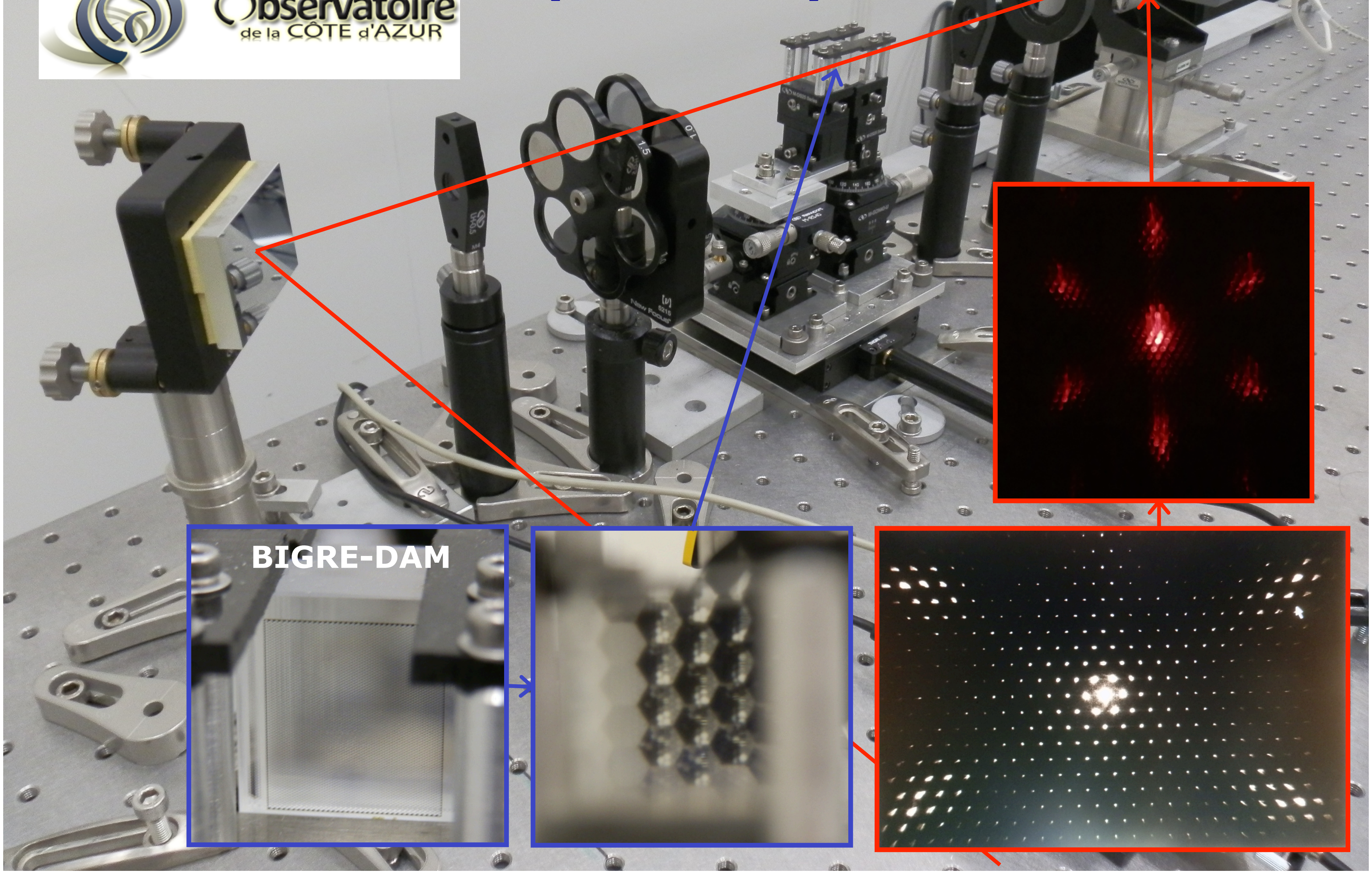
(Integrated optic waveguides)



DAM concept for in-lab testing

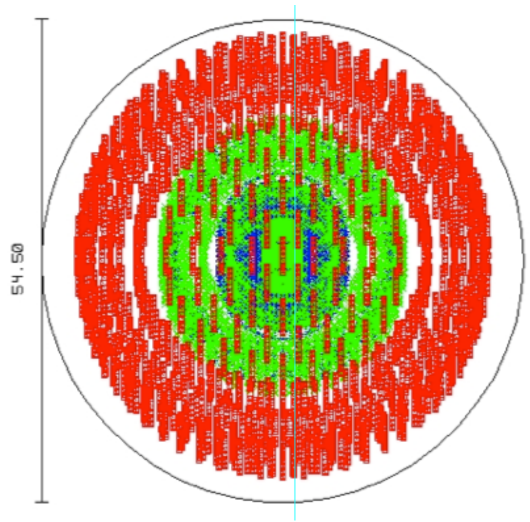


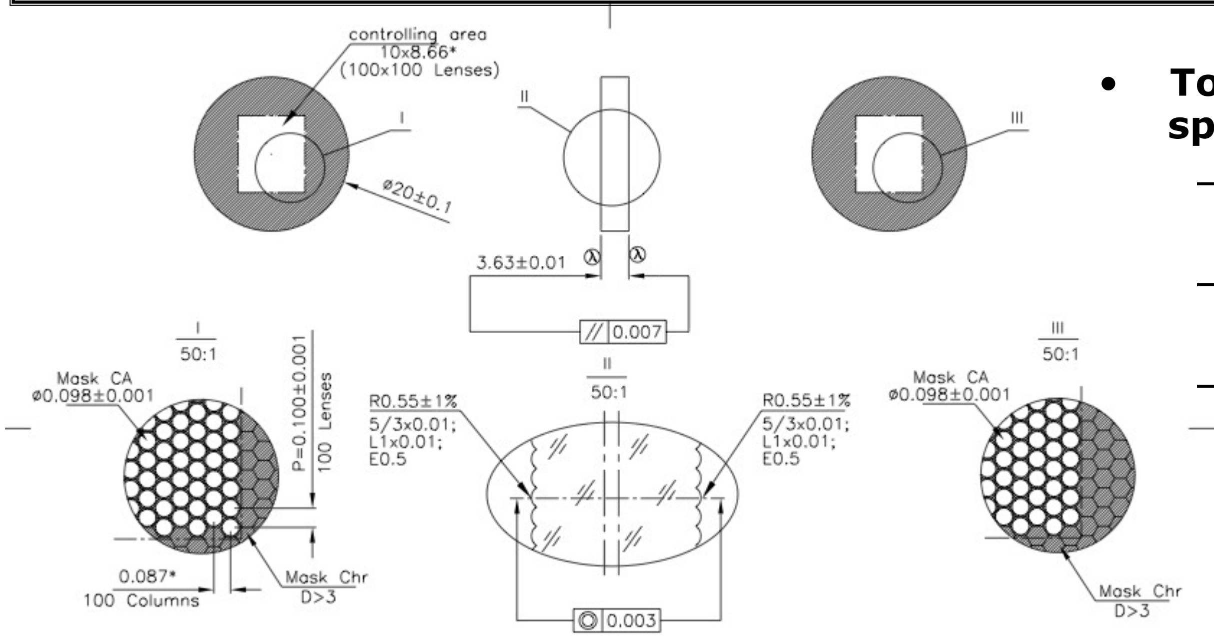
The VISIDAM testbed
(λ=633nm)



DAM concept on VLT/NACO

Resolution element	Resel=56 mas (= λ/D @ 2.2μm)
N sub-pupils	~2000 beams
N resels in the CLEAF	~2000 resels
N sub-pupils over the pupil diameter	50 beams
N resels over the CLEAF diameter	50 resels
CLean FOV (CLEAF)	CLEAF~50λ/D~2.4 as
Accessible FOV	Coupled FOV~200λ/D~10 as
Inner Working Angle	IWA~1 resel (in good conditions)
Outer Working Angle	OWA~1.2as~25λ/D
Maximum Outer Working Angle	Max OWA~100λ/D~5as
Sub-pupil diameter on the sky	16 cm (< r0 in K band)
Direct dynamic range @10λ/D	<1E-06
Transmission (vs full pupil)	~80 % (in good conditions)

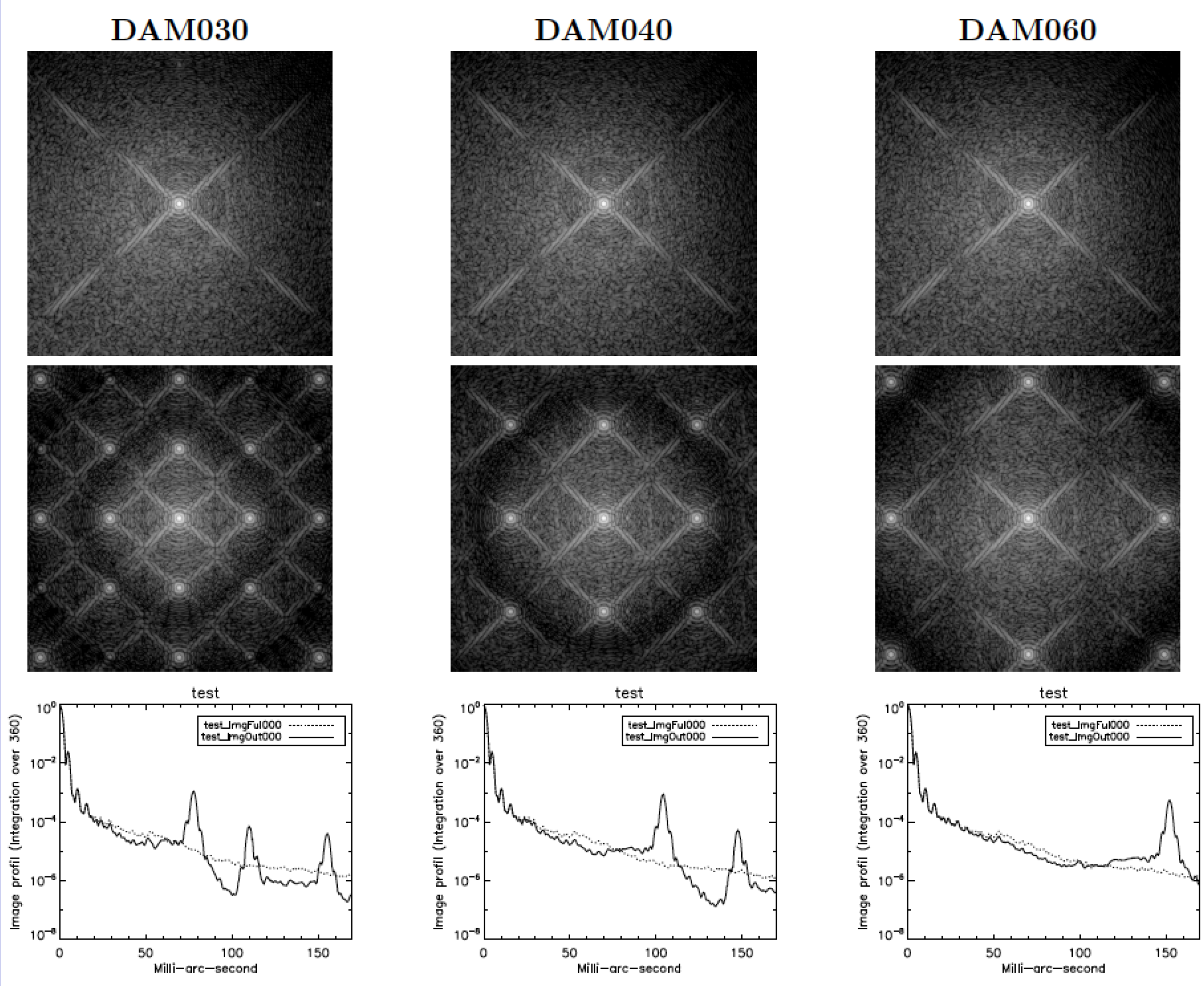




- **Tolerances are within the specifications fixed by Vendors:**
  - Lenslets' requested centering = 3 micron
  - Lenslets' requested relative tilt = 0.007 deg
  - Thickness requested tolerance = 10 micron

DAM on VLT/SPHERE

PSF



DAM : quid ?

- **Discretized Aperture Mapping (DAM)** [Patru & al. 2011, 2014]
  - **High spatial frequency filter** by using spatial filtering or modal filtering.
  - **Low spatial frequency sampler** for direct imaging (translation invariance).
  - Contrast gain on a finite field of view with full resolution & lower throughput.
  - **Scintillation filter** due to the propagation in a medium (amplitude errors).
  - **Light scattering filter** d tics, such as surface roughness and ripples o

Laser microscopy ?
Optical coherent tomography ?

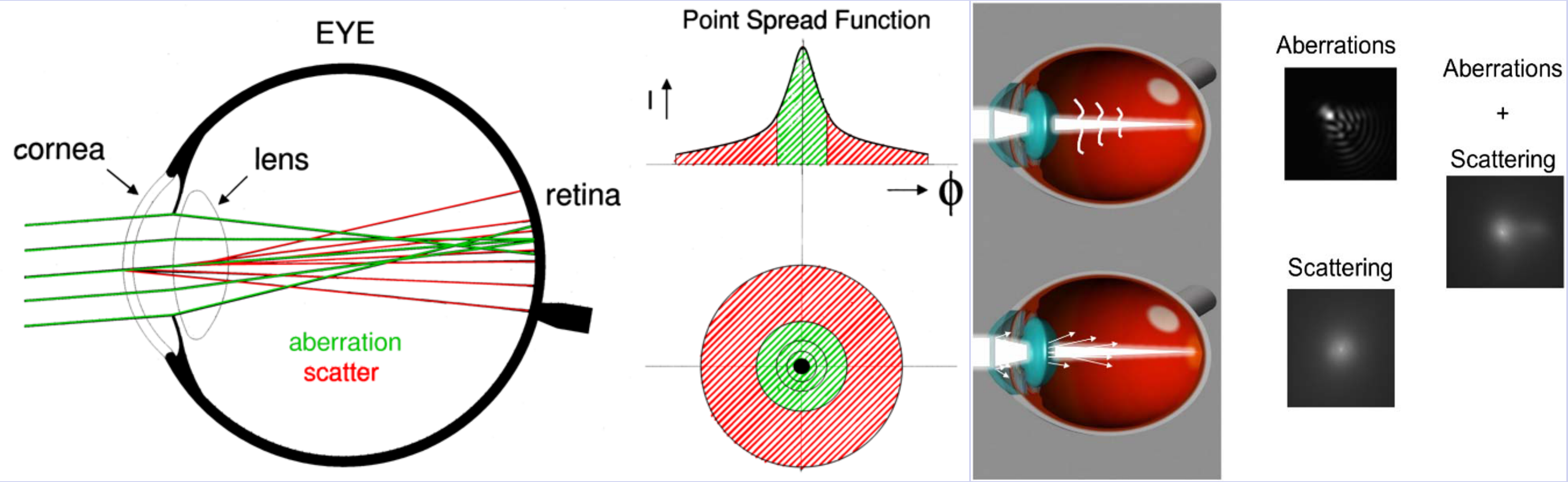
  - **Anti-aliasing filter** for **wavefront sensors** (Shack-Hartmann, Pyramid, …).
  - **Fresnel propagation filter** d

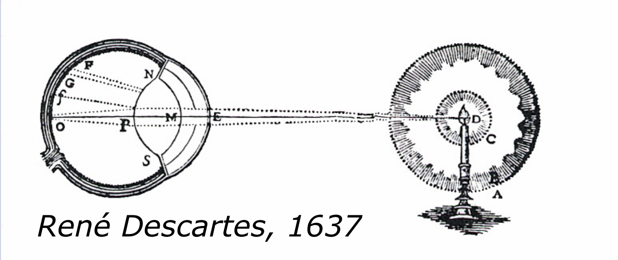
High power laser
telecommunication ?

  - **Revisited adaptive optic systems:**
    - The AO corrects the low order while DAM filters the high order aberrations.
    - Finite number of pistons => Well-posed problem => Simpler AO control.
    - Tip-tilt calibration by considering the side-lobes intensity (barycenter).
    - Focal plane wavefront sensor and imager to avoid non-common path.
  - Suited to **high contrast imaging** by reducing the halo in the image.

- **The BIGRE-DAM double micro-lenses array** [Antichi & al. 2011]
  - **Small** (~1cm^3), **stable** (integrated optic), **simple** (easy plug-and-play), **passive** (no control loops in), **low-cost** (~20k€ for 3 identical components) & **versatile** (filtering, sensing, imaging, spectrometry, coronagraphy).

Light scattering in the eye





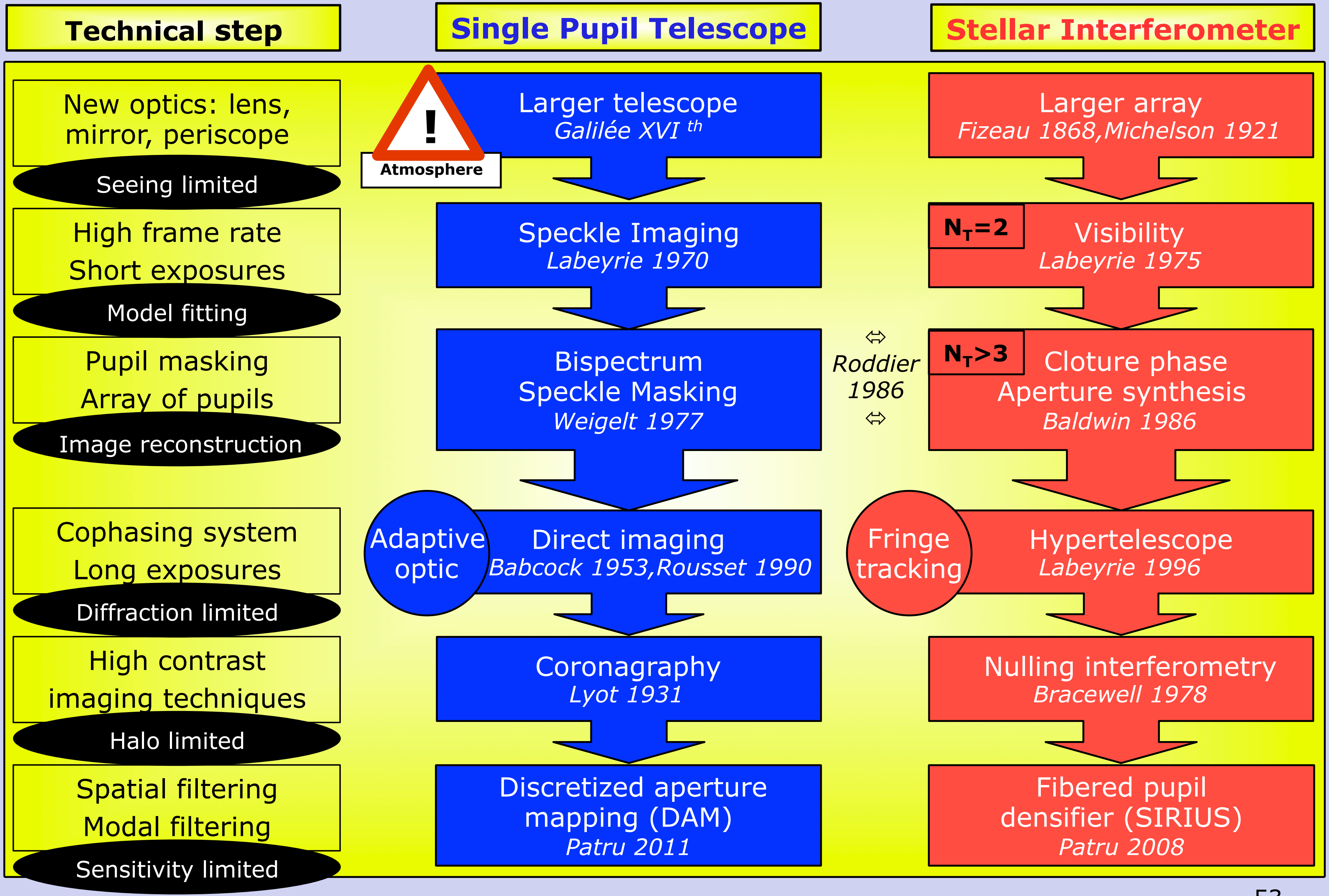
- 2 domains of retinal image quality:
  - **Light scattering** leads to retinal straylight (>1 degree), and **blinding/contrast loss**.
  - **Aberration/refraction errors** lead to small angle effects (<0.3°), and **visual acuity/contrast loss**.

DAM project

- **European funding opportunity - Horizon 2020 – RIA – FET open**
  Research and Innovation action - Future and Emerging Technologies

  - **Financial support**: From 2 000 000 € up to 4 000 000 €.
  - **Deadline**: September 29th 2015.
  - **Originality & interdisciplinarity**: Various fields of applications (astronomy, medecine, metrology, space, etc.).
  - **Collaborative research project**:
    - The Côte d'Azur observatory (OCA, Nice) is the leader.
    - The other institutes are participants and can request their own budget.
  - **Funding**:
    - Manpower (PhDs & post-docs & optical engineers)
    - Equipment (DAM devices, DMs)
    - Travelling
    - Workshops and colloquium
  - The devices are paid by the institutes (minus the depreciation rate).
  - **Planning**: 2016 to 2021 (5 years duration), in-lab testing after 2018.
  - <u>**Your contribution**</u>: Laboratory validation and scientific qualification.

Imaging techniques (r)evolution



End

DAM, discretize the pupil

DAM project

- **Workpackages**
  - WP1. BIGRE-DADI (pupil dilution)
    based on micro-lenses arrays yielding spatial filtering.
  - WP2. BIGRE-DAM (pupil mapping)
    based on micro-lenses arrays yielding spatial filtering.
  - WP3. IO-DAM (pupil mapping)
    based on integrated optic devices yielding modal filtering.
  - WP4. FI-DAM (pupil mapping)
    based on single-mode fibers yielding modal filtering.

- **Tasks**
  - Theoretical investigation (through numerical simulations with IDIS)
  - Optical design (with respect to the expertise of research institutes)
  - Manufacturing (achieved by industrial SME that are expert in micro-optic)
  - **Laboratory validation (by using existing in-lab testbeds)**
  - **Data reduction (by using existing and efficient tools)**
  - **Qualification for scientific applications**

DAM Implementation

Tasks / Workpackages	WP-1	WP-2	WP-3	WP-4
Optical properties				
Optical device	BIGRE-DAD \& BIGRE-DADI	BIGRE-DAM \& PI-DAM	IO-DAM	FI-DAM
Optical filter	Conjugated plane	2nd lens or pinhole	SM integrated optic	SM fiber
Spatial/Modal filtering	Spatial filter	Spatial filter	Modal filter	Modal filter
Densification/Dilution	Densification/Dilution	None	None	None
IWA	$\approx \lambda/2D$	$\approx \lambda/D$	$\approx \lambda/D$	$\approx \lambda/D$
FOV	Large (few AO radius)	Medium (AO radius)	Medium (AO radius)	Small ($< 3 \lambda/D$)
Flux throughput	Moderate	High	High	High
Diffractive efficiency factor	Low	High	High	High
Optical design \& Manufacturing				
Optical design	INAF(I)	INAF(I)	IPAG(F)	OCA(F) \& XLIM(F)???
Manufacturing	AMUS(G)	AMUS(G)	???	OCA(F) \& XLIM(F)???
Applications \& Testbeds locations				
Characterization	VISIDAM @OCA-Nice(F)	VISIDAM @OCA-Nice(F)	VISIDAM @OCA-Nice(F)	SIRIUS @OCA-Nice(F)
DAM-Filter		VISIDAM @OCA-Nice(F)	VISIDAM @OCA-Nice(F)	SIRIUS @OCA-Nice(F)
DAM-WFS		WFS @LAM-Marseille(F)		
DAM-Imager		WFS @LAM-Marseille(F)		SIRIUS @OCA-Nice(F)
DAM-Coronagraph		SPEED@OCA,VORTEX@ULG		
POAMI-DAM		POAMI @ULG-Lièges(B)		
Multi-DAM				
DAD	??? @LAM-Marseille(F)			SIRIUS @OCA-Nice(F)
DADI	SPEED @OCA-Nice(F)			SIRIUS @OCA-Nice(F)
DADI-FP-WFS	SPEED @OCA-Nice(F)			SIRIUS @OCA-Nice(F)
ADAM		SPEED @OCA-Nice(F)	SPEED @OCA-Nice(F)	
SADAM				SIRIUS @OCA-Nice(F)
SADAM-Windowing				SIRIUS @OCA-Nice(F)
DAMAO				
On-sky validation	ODYSSEY @OCA-Nice(F)	ODYSSEY @OCA-Nice(F)	ODYSSEY @OCA-Nice(F)	
On-sky demonstration	SPHERE @ESO(CH)	SPHERE @ESO(CH)	SPHERE @ESO(CH)	
Medical imaging		??? @MURCIA-U(E)		
???				

DAM Planning

Planning	1/7/16	1/1/17	1/7/17	1/1/18	1/7/18	1/1/19	1/7/19	1/1/20	1/7/20	1/7/21	
WP1,2,3,4											
Management											
Simulations											
WP4											
WP1											
Simulations											
Optical design											
Manufacturing										PI	
Implementation										PhD 1	
Characterization										PhD 2	
In-lab testing										PhD 3	
On-sky testing										Post-doc 1	
WP2										Post-doc 2	
Simulations										Post-doc 3	
Optical design										Post-doc 4	
Manufacturing										Engineer	
Implementation											
Characterization											
In-lab testing											
On-sky testing											
WP3											
Simulations											
Optical design											
Manufacturing											
Implementation											
Characterization											
In-lab testing											
On-sky testing											
WP4											
Simulations											
In-lab testing											

DAM Impact

Needs / Means	*Characterization*	DAM-Filter	DAM-WFS	DAM-Imager	DAM-Coronagraph	POAMI-DAM	Multi-DAM	DAD	DADI	DADI-FP-WFS	ADAM	SADAM	SADAM-Windowing	DAMAO
Mitigation of technical limitations														
DM fitting error				+	+	+	+		+	+	+	+	+	+
WFS aliasing error			+	+	+	+	+			+++				+++
Non-common path aberrations										+++				+++
Optical surface aberrations		+	+	+	+	+	+	+	+	+	+	+	+	+
Tip-tilt sensitivity				+	+	+	+	+	+	+	+++			+++
Coronagraph imperfections					+++	+++					+			+++
Stellar angular size (\& tip-tilt)													+++	+++
Zodi \& exozodi background													+	+
"Unfriendly" pupil shapes								+			+++			+++
Chromatic effects		+	+	+	+	+	+	+	+	+	+	+	+	+
Observation modes														
Passive filtering		+	+	+	+	+	+	+	+	+	+	+	+	+
Phase sensing			+							+				+
Direct imaging				+	+		+	+	+	+	+	+	+	+
Fourier Imaging									+	+				+
Coronagraphy / Apodization					+	+++		+			+++	+	+++	+++
Spectrometry								+	+	+++		+	+++	+++
Windowing	+++	Efficient											+	+++	+++
Mosaicing	+	Relevant											+	+++	+++

Interferometric imaging techniques on single-dish telescopes

	Fourier space	**Direct image space**
No filtering	Non-redundant Masking (NRM) Sparse Aperture Masking (SAM) Kernel phase *Weigelt 1977, Roddier 1986, Lacour 2011, Martinache 2010*	Pupil densification (Hypertelescope) *Labeyrie 1996, Pedretti 2000*
Spatial frequency filtering	Pupil remapping (FIRST) using single-mode fibers *Perrin 2006*	Pupil discretization (DAM) using single-mode waveguide or BIGRE micro-lenses *Patru 2011, 2014, Antichi 2011*

DAM
Pupil ➔ PSF

Aperture of diameter D
➔ *Image of 64x64 resels (λ/D)*

Pupil hexagonal/square pattern (top/bottom)
➔ PSF pattern of side-lobes

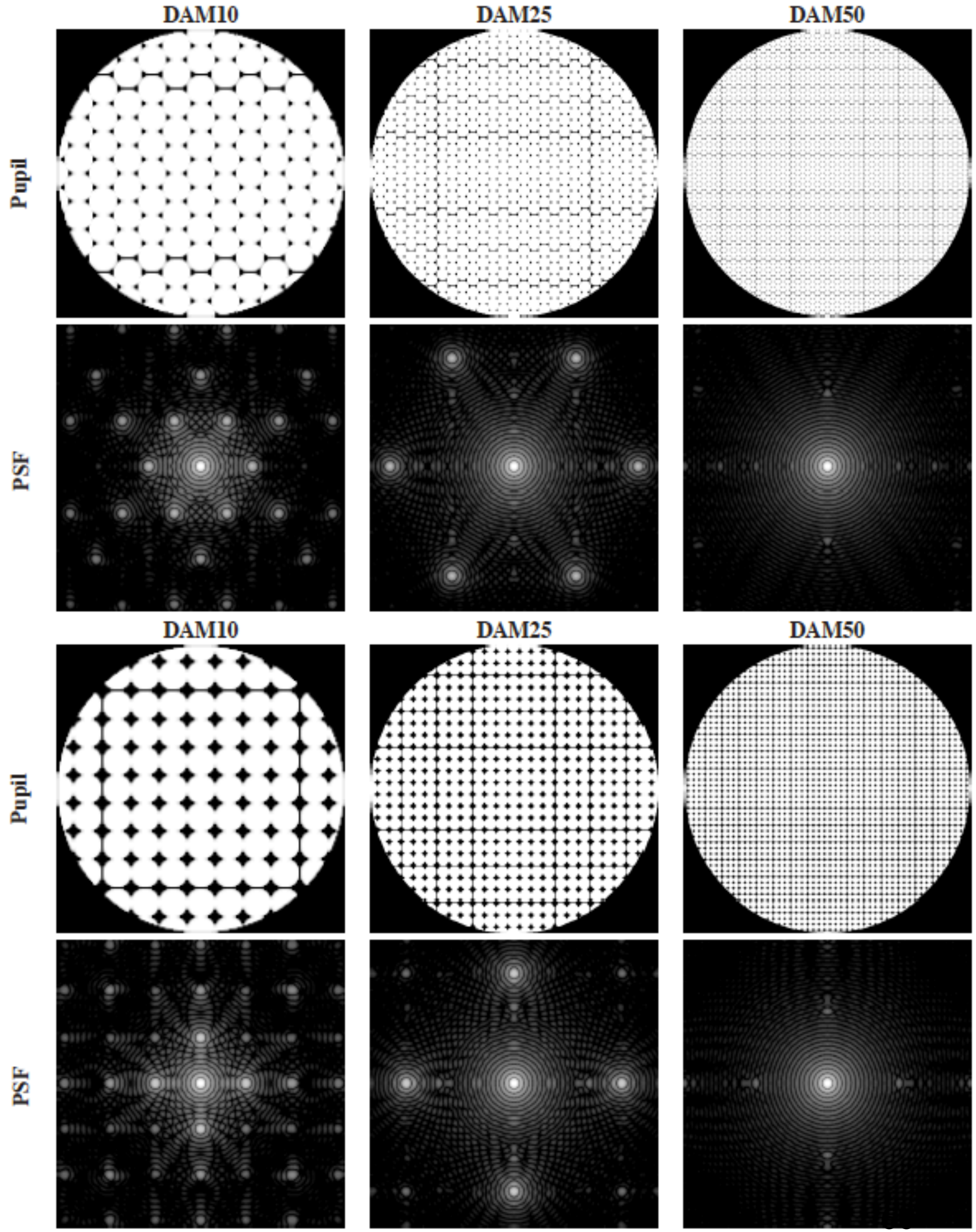
Pupil circular external shape
➔ PSF pattern of Airy rings

The useful field of view in number of resolution elements (resel=λ/D) equals to the number of sub-apertures along the diameter (D)

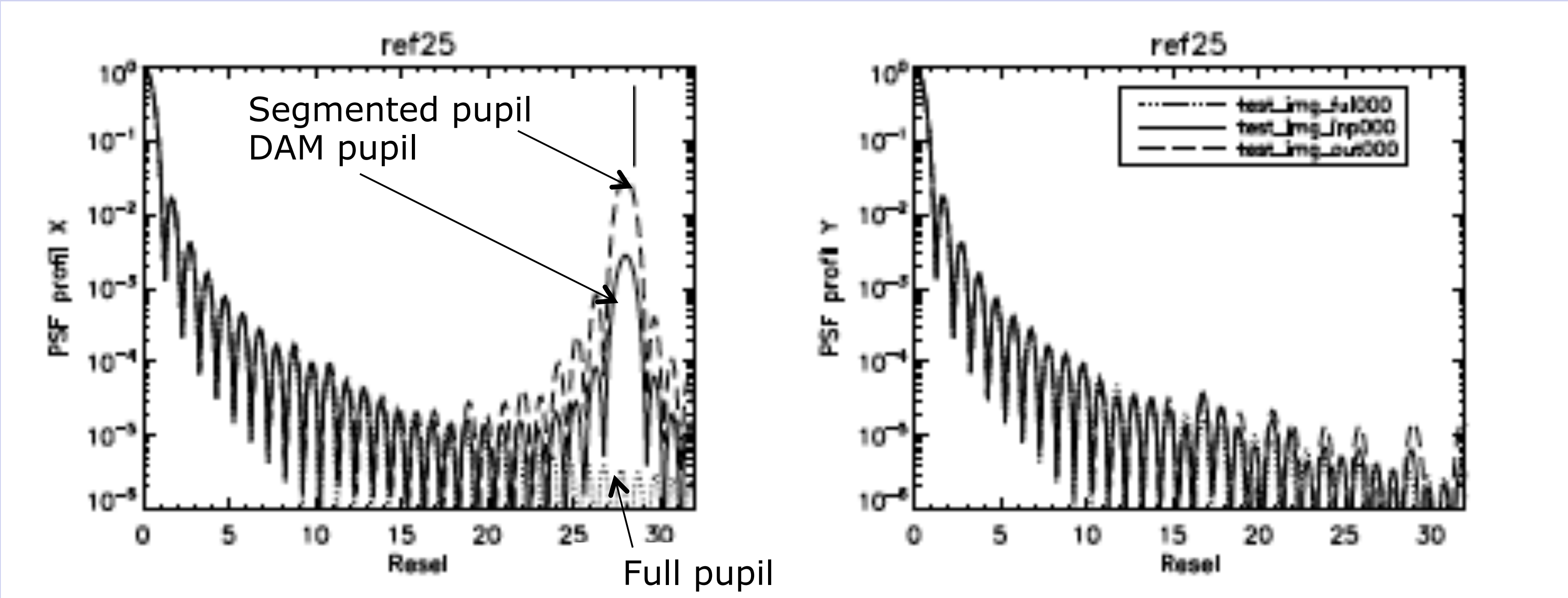
Inner/Outer Working Angle:

IWA = 1 λ/D = 1 resel

OWA ~ 5, 12, 25 resels for DAM10, DAM25, DAM50



Segmented vs discretized aperture *(PSF comparison)*



The perfect PSF of DAM is similar with the one of a segmented telescope

BIGRE-DAM optical scheme

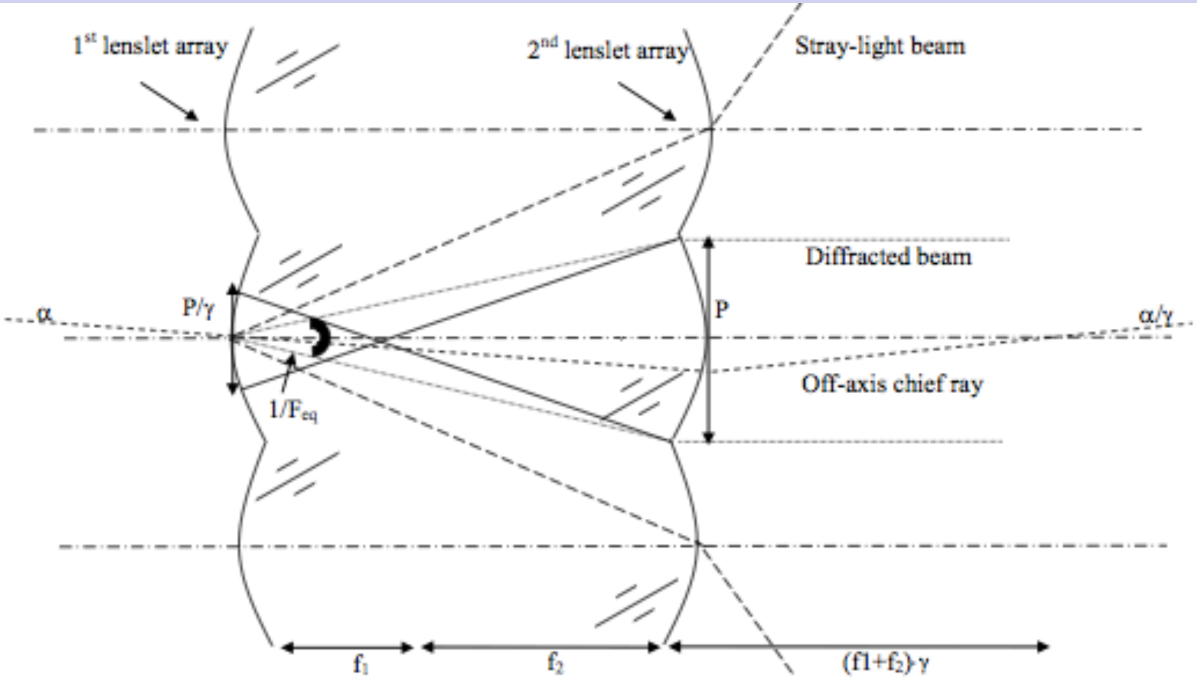
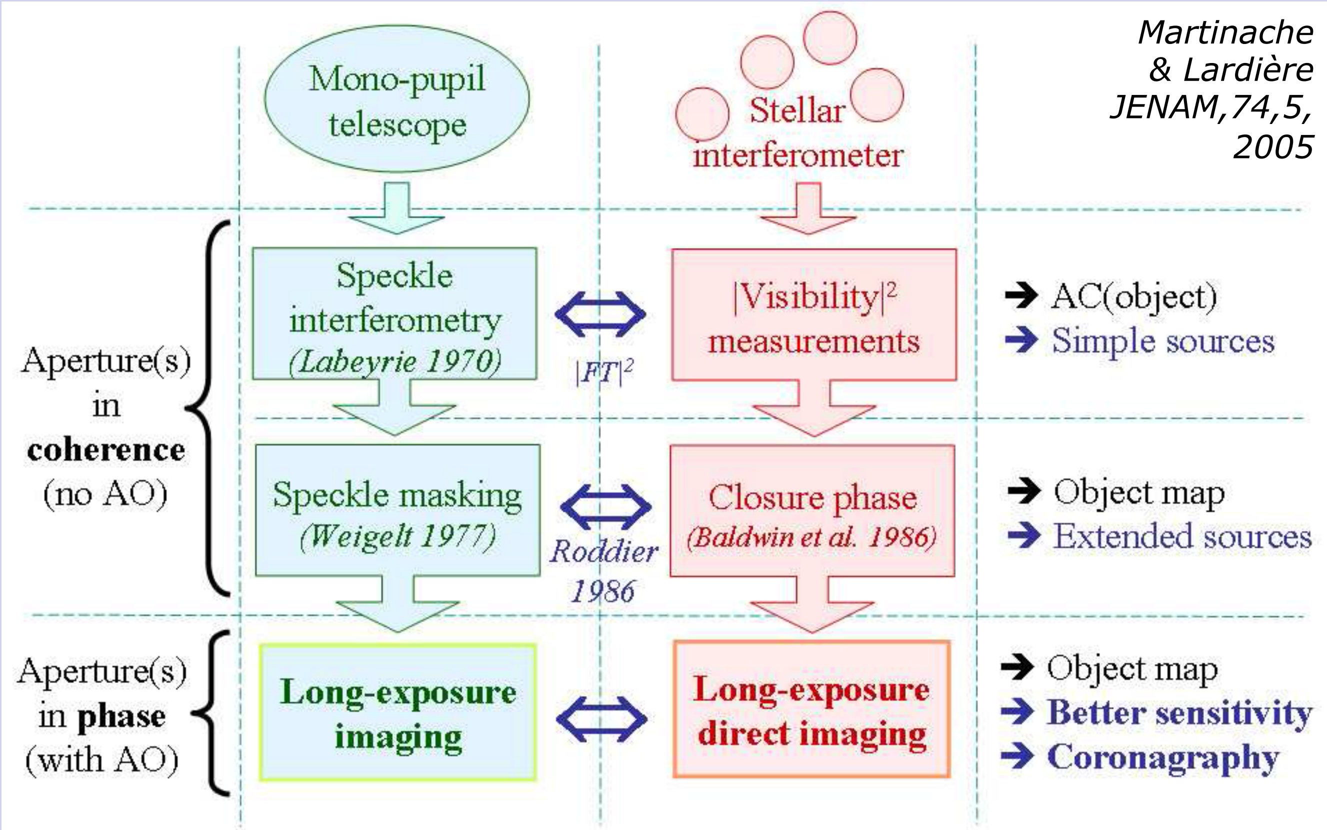


Figure 1: BIGRE-DAM double lenslet array scheme. The two optical surfaces are set in an afocal configuration and get different focal lengths with ratio equals *γ*. The first lens lies on a downstream image of a given mono-pupil telescope, its lens face being masked and having a usable width equals *P/γ*. The diffractive beams coming out from the first lenslet array – equivalent to a Fizeau mask – are densified with concentration factor equal *γ*, spatially filtered by the second lenset array and re-collimated downstream. Diffracted light falling over closest neighborhood lenses diverges out due to the geometrical arrangement of such double lenslet, and becomes a stray beam disjoined to the main diffracted beam. Finally, a spatially filtered array of sub-pupils forms at position *$(f_1+f_2)\cdot\gamma$*.

$$N = \frac{P^2}{\lambda\cdot(f_1+f_2)} \implies u_{\text{minimum}} \equiv \frac{2\cdot P}{N\cdot\lambda}$$

Imaging techniques evolution



Speckle interferometry (Labeyrie, 1970) and speckle masking (Weigelt, 1987) have been used on single telescope to recover a part of the information lost in the turbulence. Now, long-exposure imaging with adaptive optic systems is preferred to have a better sensitivity and to allow coronagraphy. Stellar interferometers know the same evolution: visibility modulus measurements and closure phase are equivalent to the speckle interferometry and the speckle masking respectively (Roddier, 1986). Then, direct imaging on cophased arrays is clearly the natural next step for stellar interferometry.

Interferometric direct imaging *Abstract*

The detection of exo-planets remains a challenge in direct imaging in term of separation and contrast of intensity planet-star. An evolution of the imaging techniques is presented here by showing the parallel between a large telescope and a large array of telescopes (interferometer). The very high-contrast imaging is up to now achieved only on large telescopes by means of efficient adaptive optics (AO) and coronagraphic techniques, while the very high-angular resolution imaging remains only accessible to the long baseline interferometry. However, recently, these two fields converge and complement each other. The modern stellar interferometry uses adaptive optics, and new interferometric concepts appear on large telescopes, as for instance the pupil masking.

Another innovative approach is the "interferometric direct imaging". It has already been shown that a "hypertelescope" (formed of numerous telescopes) is able to produce an image directly in the focal plane of an interferometric beam combiner by means of "pupil densification". We propose here a new technique of "pupil discretization" (DAM) based on the spatial filtering and the interferometry. DAM improves the ultimate contrast of an AO-equipped telescope, simply by using an integrated optic low-pass filter removing out the high spatial frequencies.