Analyse de surface d'onde pour l'optique adaptative

Webinar MOI - Thème 2 - Session 1

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retour sur innovation

Un point central pour l'astronomie moderne

- Les aberrations optiques

- L'optique adaptative

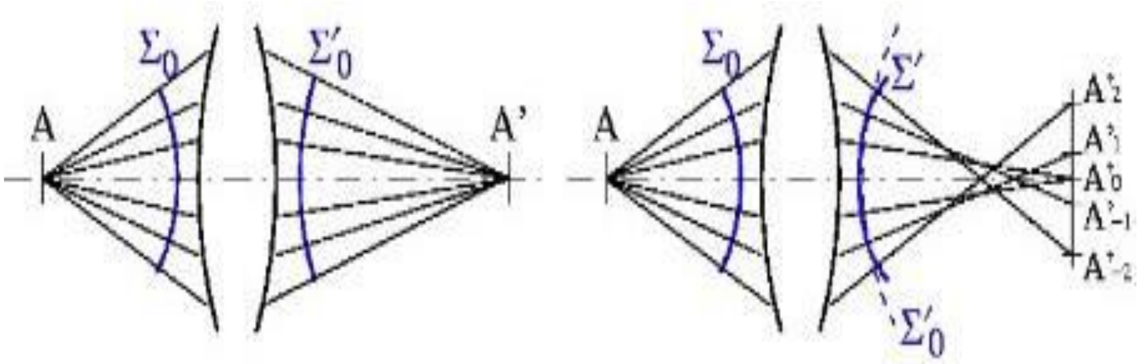
- L'importance de l'analyse de surface d'onde

- Analyseurs de surface d'onde
  - Dans la pupille
    - Shack-Hartmann
    - Pyramid
  - Dans le plan focal
    - Diversité de phase

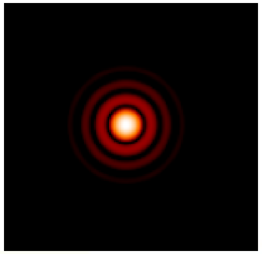
Effet d’une aberration optique

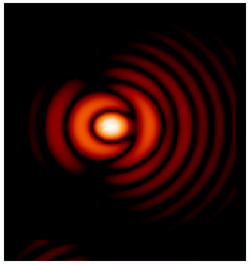
- Sans aberration :
  - Corpusculaire : tous les **rayons** issus de A convergent exactement en A'.
  - Ondulatoire : la **surface d'onde** sphérique S_0 qui diverge de A se transforme en une surface d'onde sphérique S'_0 qui converge en A'.

- En présence d’aberrations : ce n’est plus le cas



Tache de diffraction d’Airy





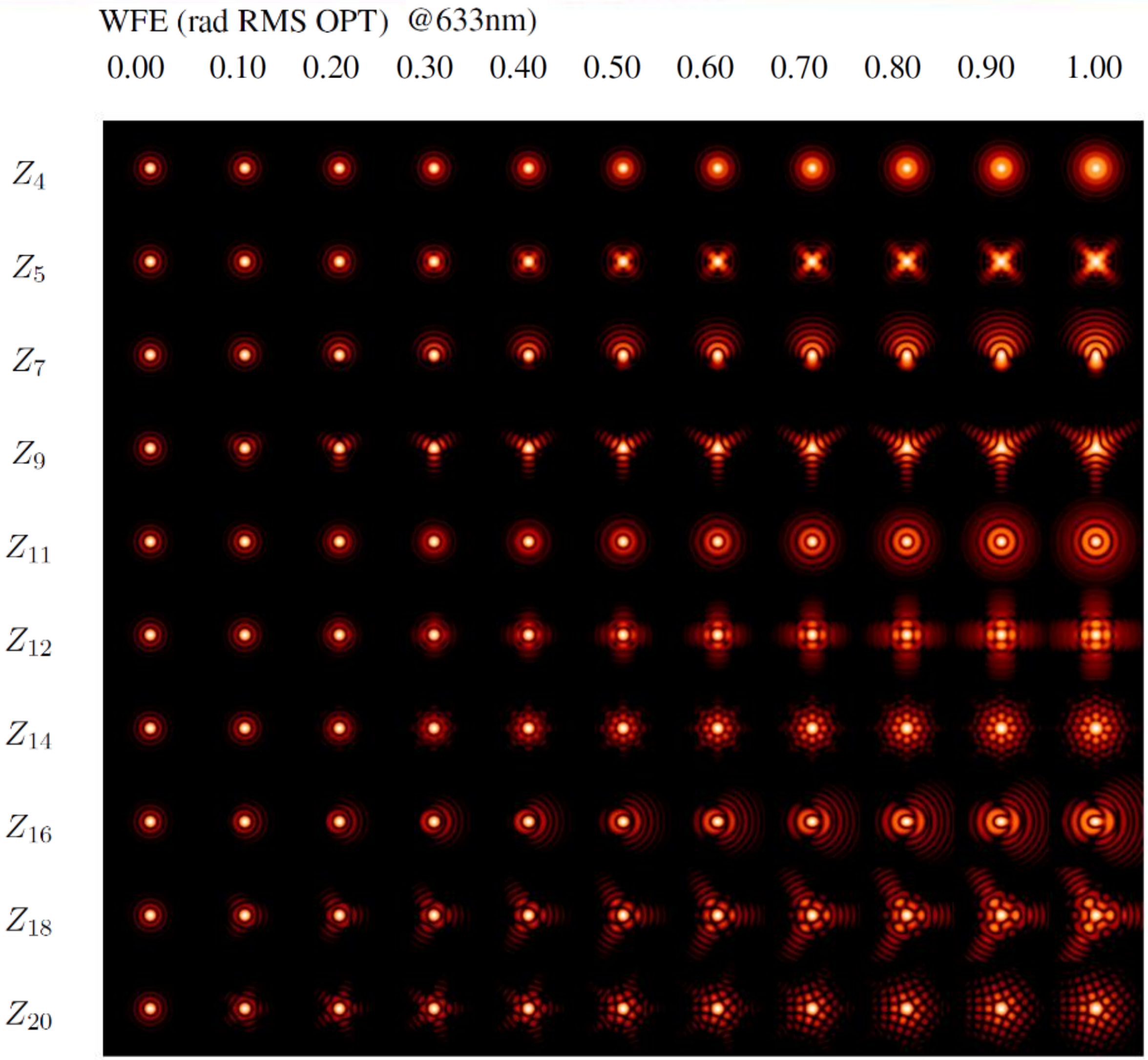
Tache de diffraction aberrante

Les aberrations optiques

- On parle (presque) indiféremment :
    - D’aberrations optiques
    - De phase
    - De front d’onde aberrant
    - De surface d’onde aberrante
    - D’avance / retard de phase

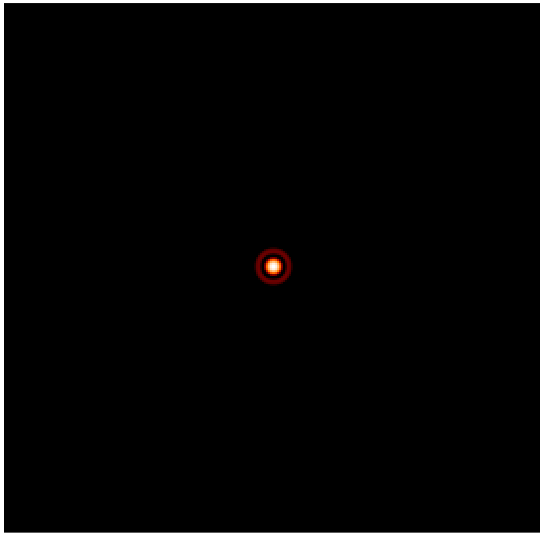
- …pour parler de la même chose : un écart à la situation parfaite qui crée un défaut dans le plan focal d’imagerie

Polynômes de Zernike vus dans le plan image



Les effets de la turbulence

Dans l’espace

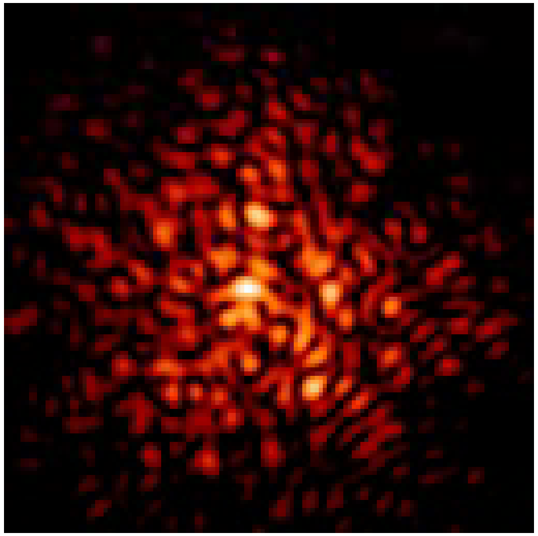


λ/D

Résolution
limité par les effets de diffraction

turbulence atmosphérique

Au sol

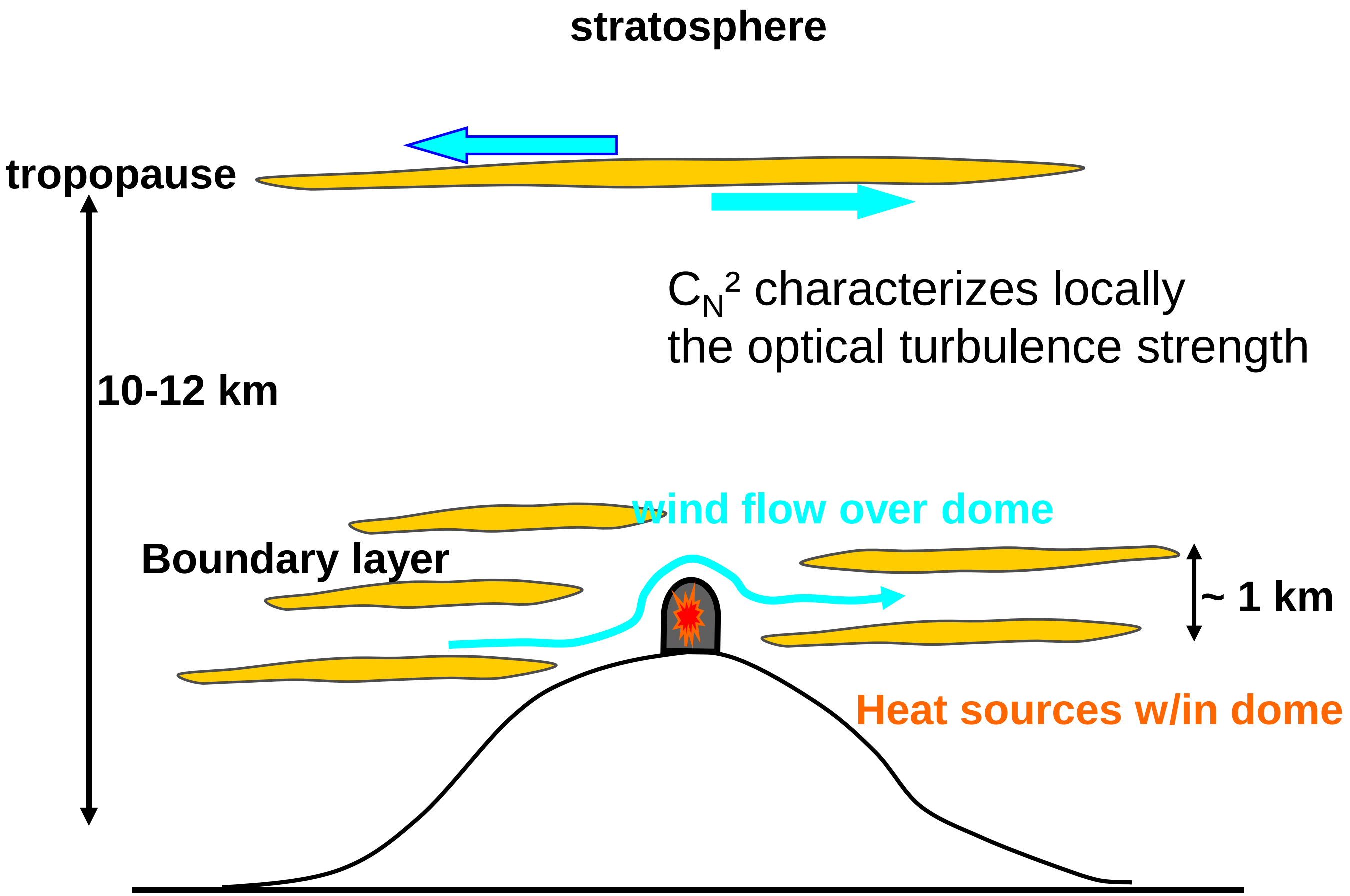


λ/r_0

Résolution
limité par la turbulence

From Mechanical to Optical Turbulence

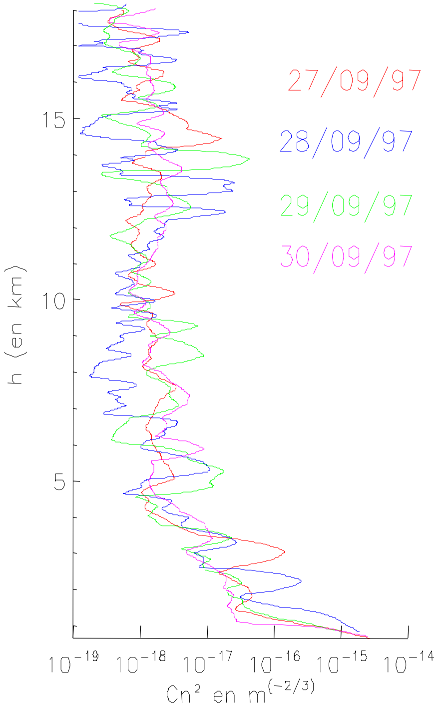
- Mechanical turbulence (turbulent velocities) mixes air at different **temperature** hence inducing “turbulent” temperature fluctuations
- The air refractive index being a function of temperature it therefore induces **refractive index** fluctuation



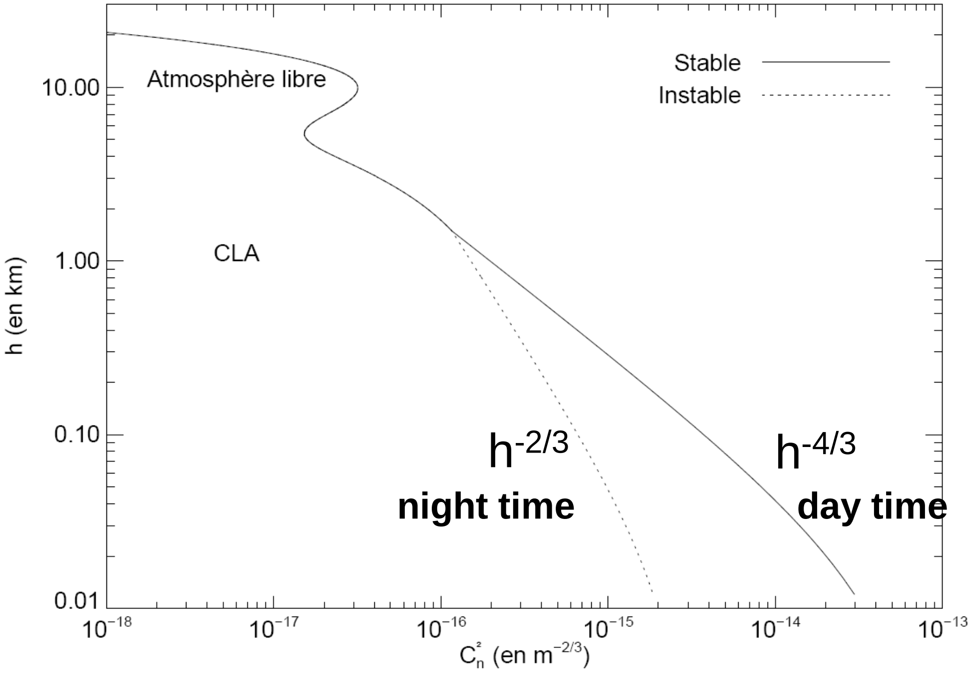
C_N^2 characterizes locally
the optical turbulence strength

+ convection effects due to heat exchange between ground and air

C_N^2 : typical vertical distribution



Balloon probe profiles
Haute Provence Observatory Sept. 1997



Typical averaged C_n^2 profile

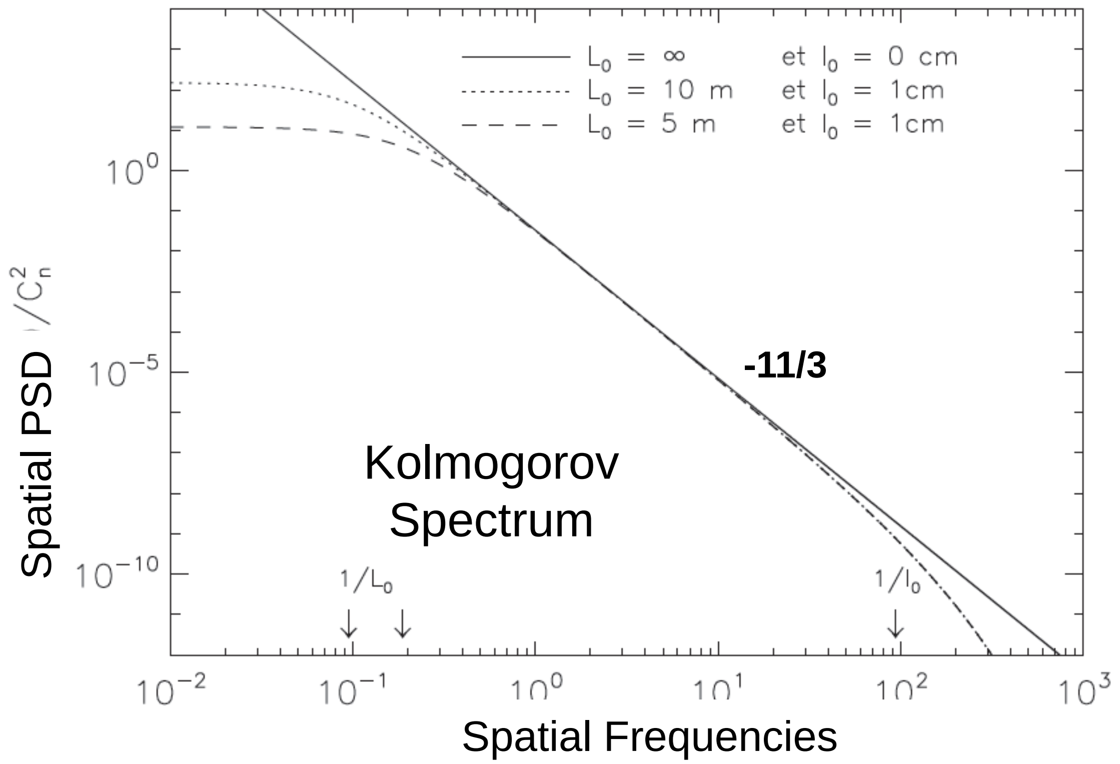
Usual approximation:

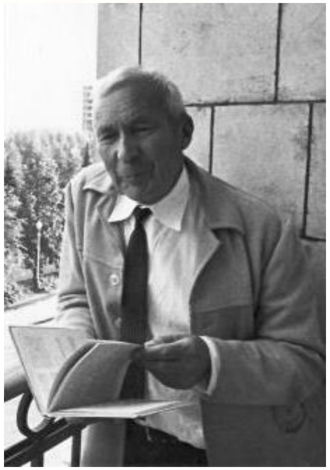
Atmosphere is horizontally stratified (thin indepedent layers) and non absorbing

Turbulent Phase: Kolmogorov Statistics

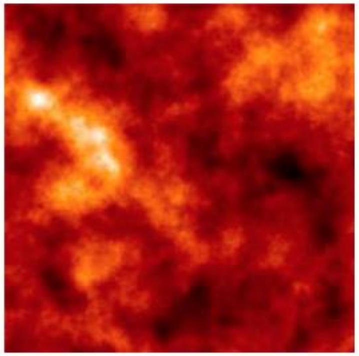
Overall phase integrated over the line of sight profile Cn²(z)

φ(**x**) : 2D Centered Gaussian Stationary Process characterized by its Spatial Power Spectral Density (PSD)





$$r_0 = \left(0,423\, k_0^2 \int_0^L C_n^2(z)dz\right)^{-\frac{3}{5}}$$



Typical turbulent phase
20 microns PV OPD

$$\boxed{W_\varphi(\mathbf{f}) = 0.023 \left(\frac{1}{r_0}\right)^{\frac{5}{3}} f^{-\frac{11}{3}}}$$

$$\boxed{D_\varphi(\rho) = 6.88(\rho / r_0)^{5/3}}$$

La turbulence : un problème d'aberrations optiques

Un point central pour l’astronomie moderne

- Turbulence : la cause du problème

- L’Optique Adaptative (OA)

- L’importance de l’analyse de surface d’onde

- Analyseurs de surface d’onde
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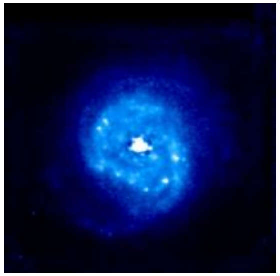
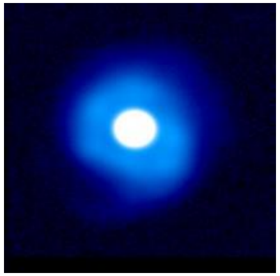
    - Shack-Hartmann
    - Pyramid
  - Dans le plan focal
    - Diversité de phase

Adaptive Optics Principle

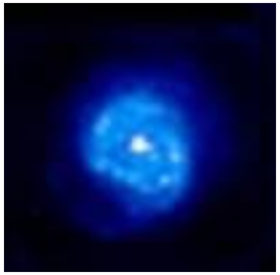
Object

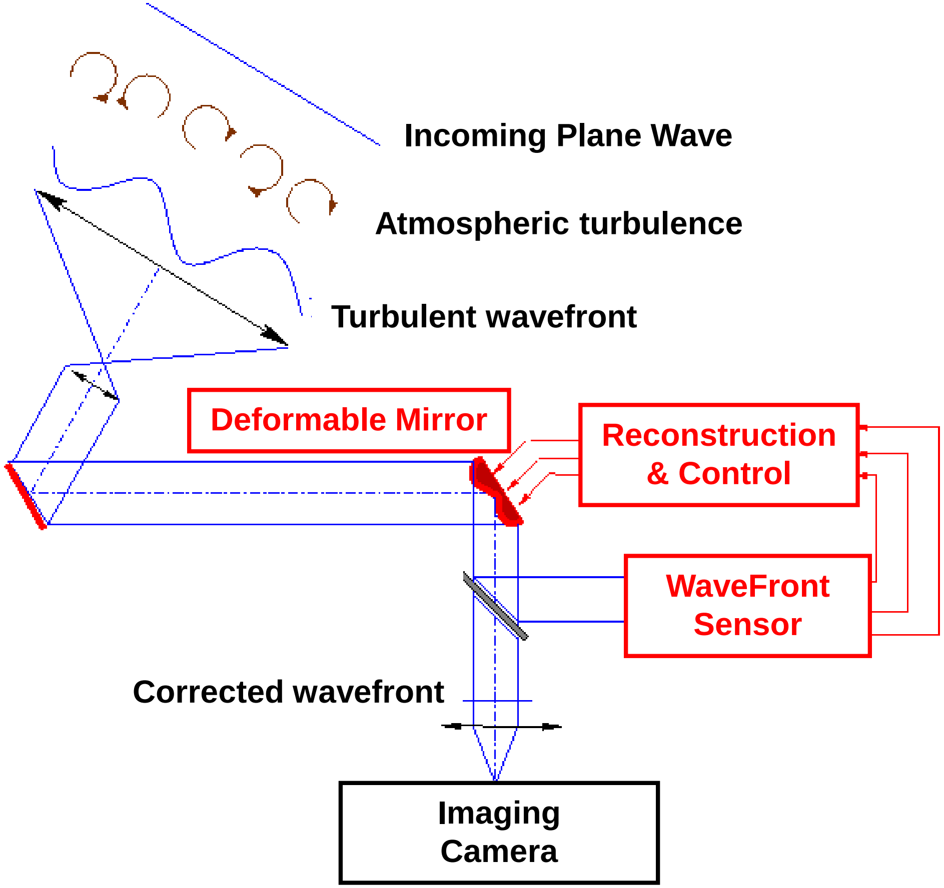


Uncorrected Image



Corrected Image





Incoming Plane Wave

Atmospheric turbulence

Turbulent wavefront

Deformable Mirror

Reconstruction & Control

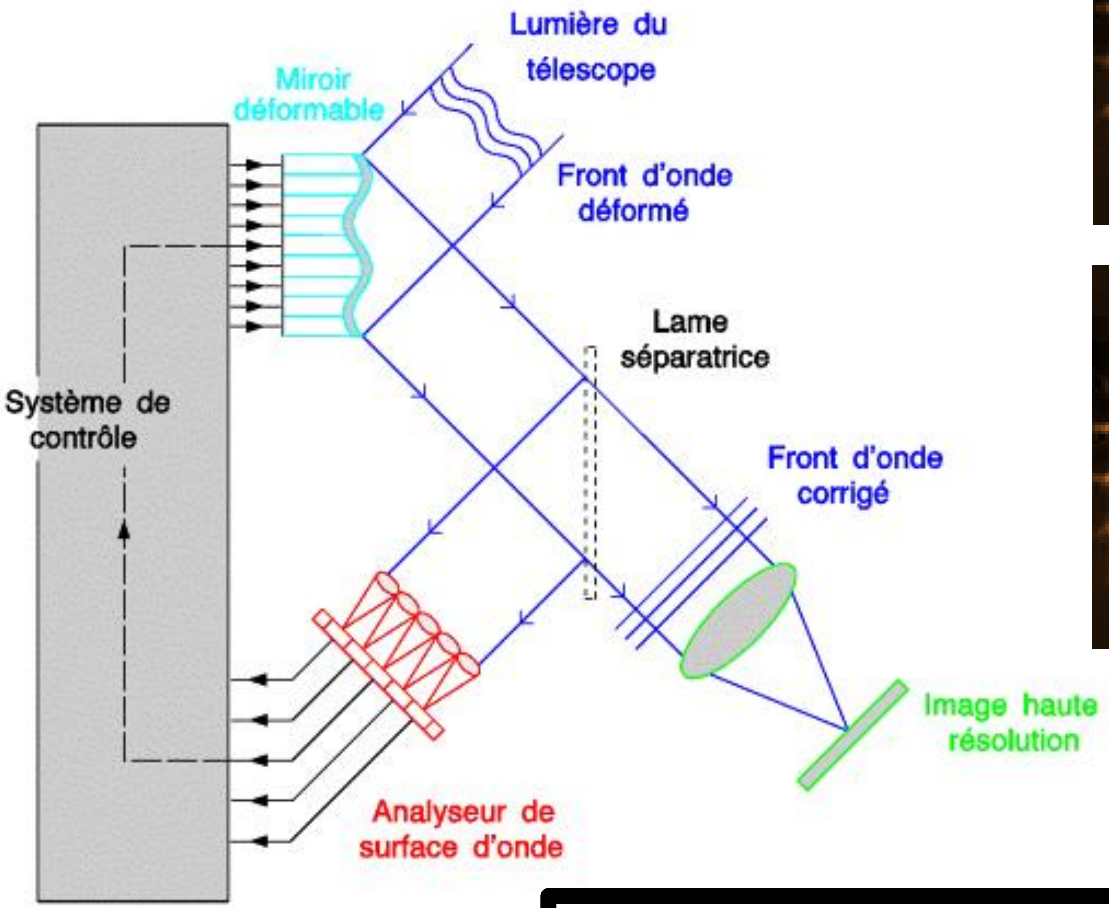
WaveFront Sensor

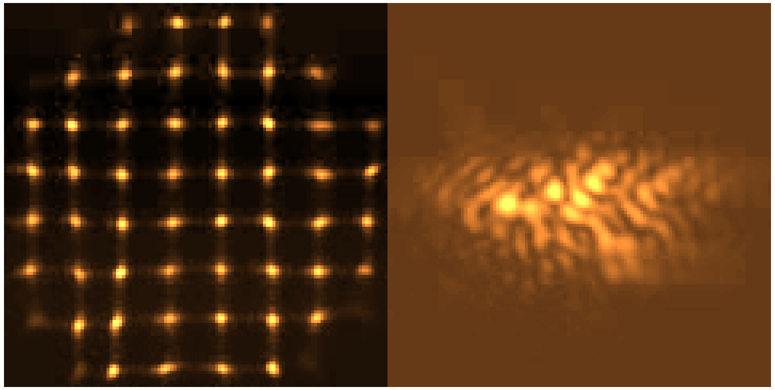
Corrected wavefront

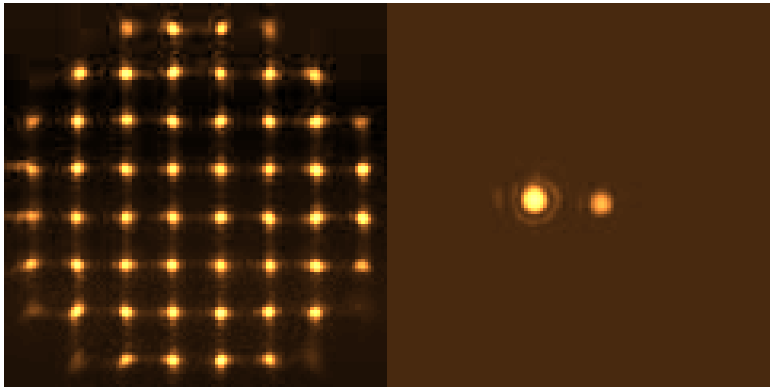
Imaging Camera

- ➢ Adaptive Optics allows to reach diffraction limited angular resolution
- ➢ Main components: Turbulence ; Def. Mirror ; Wave-Front Sensor ; Rec. & Control

Correction des effets de la turbulence : l’optique adaptative

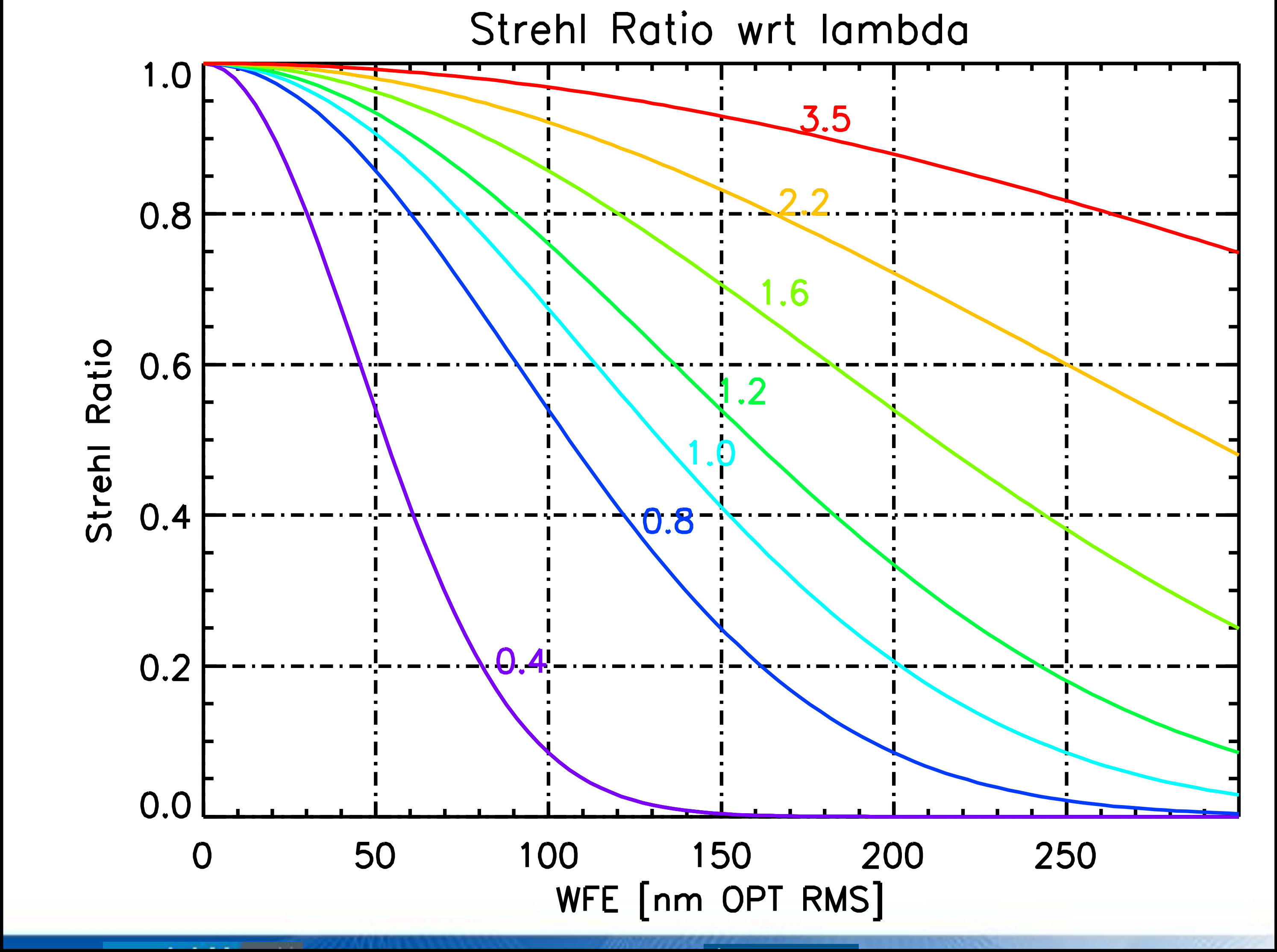




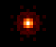


La mesure de front d’onde : un point central en optique

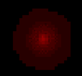
AO correction criterion : Strehl Ratio



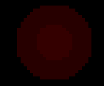
Télescope parfait
100% Strehl



Correction OA
~20% Strehl



Turbulence
~1% Strehl



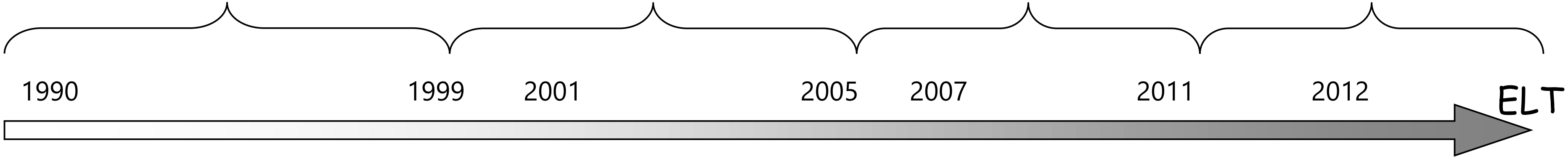
2 decades of AO for astronomy …

- **The “learning” times**
- First AO systems on 4m class telescopes
- System for Engineers
- Small systems
    - < 100 actuators
- Few astrophysical results

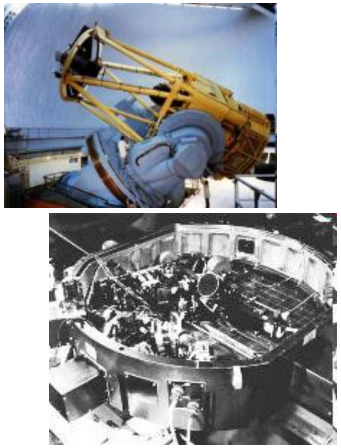
- **The “operation” times**
- First AO systems on 8m class telescopes
- Systems for astronomers
- Medium systems
    - around 200 actuators
- numerous astrophysical results

- **The “LASER” times**
- Upgrade of AO systems on 8m class telescopes
- improvement of sky coverage
- LASER => increase complexity
- numerous astrophysical results

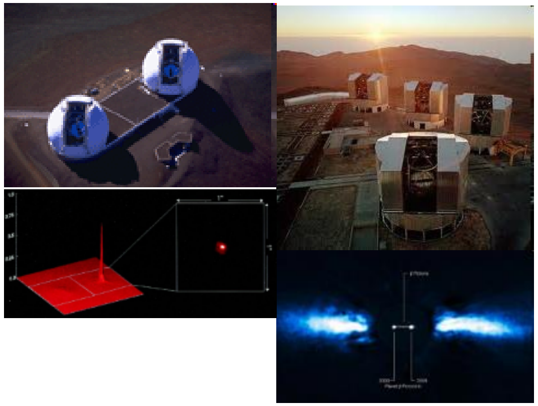
- **The “specialization” times**
- dedicated AO systems for specific scientific programs
- Wide Field AO or XAO
- Huge increase of complexity
    - > 1000 actuators
- numerous astrophysical results



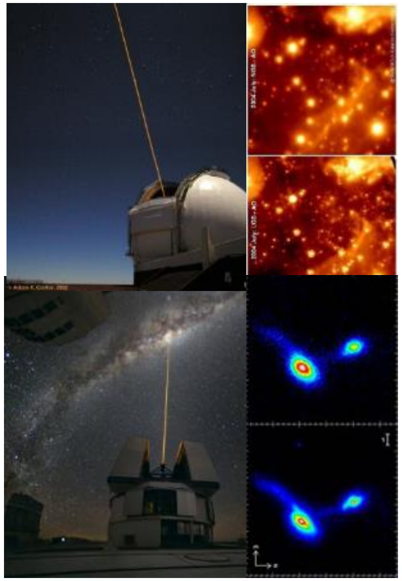
Come-on @ La Silla
3.6 m telescope



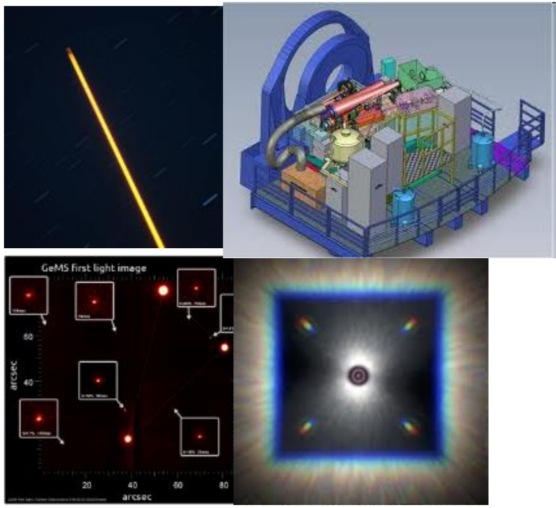
Keck AO **NAOS (VLT)**
ALTAIR (Gemini)



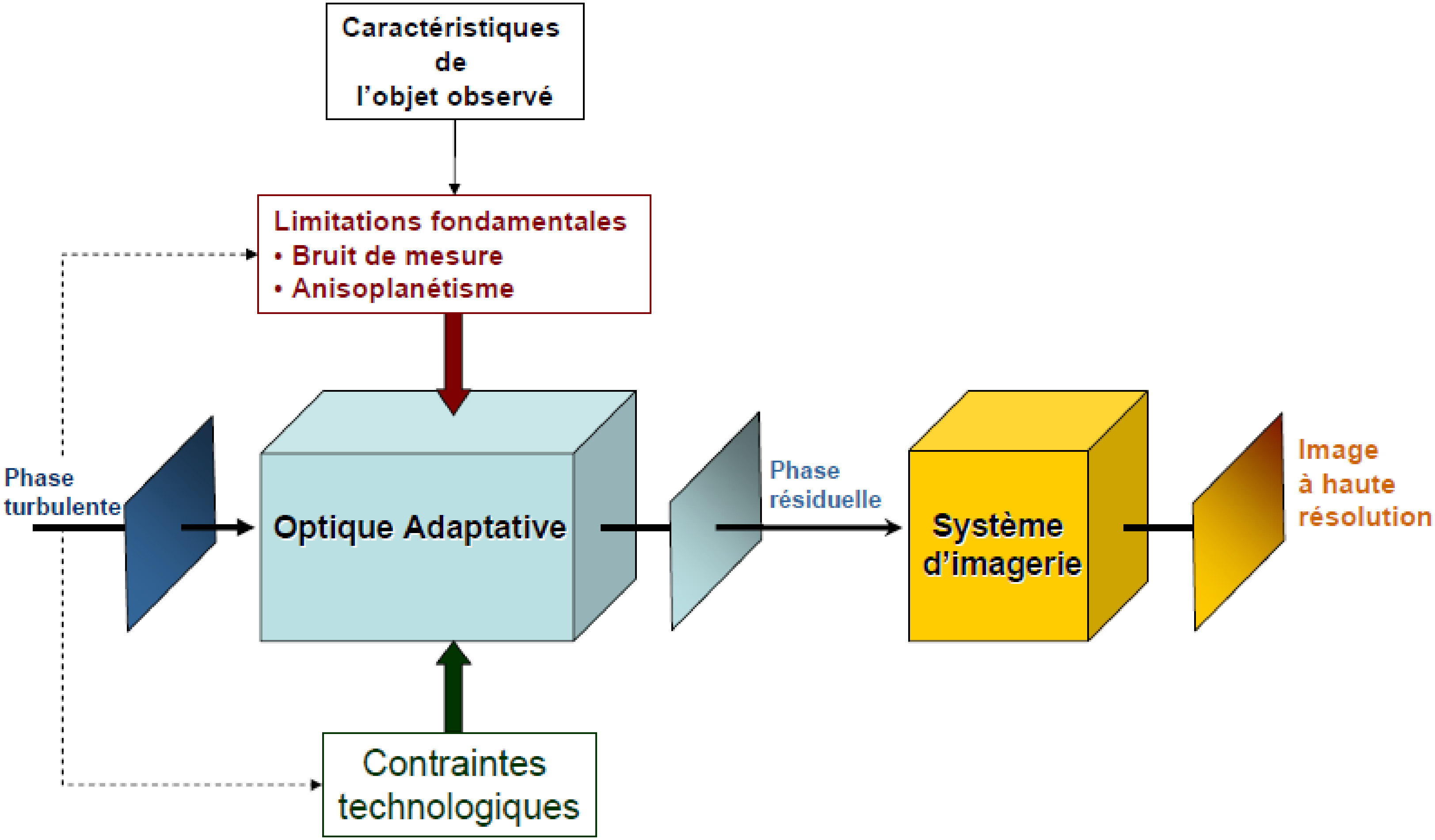
Keck LGS NAOS LGS



Gems (Gemini) **SPHERE (VLT)**
GPI (Gemini)



L'OA : un filtre passe haut !



Caractéristiques de l'objet observé

Limitations fondamentales
- Bruit de mesure
- Anisoplanétisme

Phase turbulente

Optique Adaptative

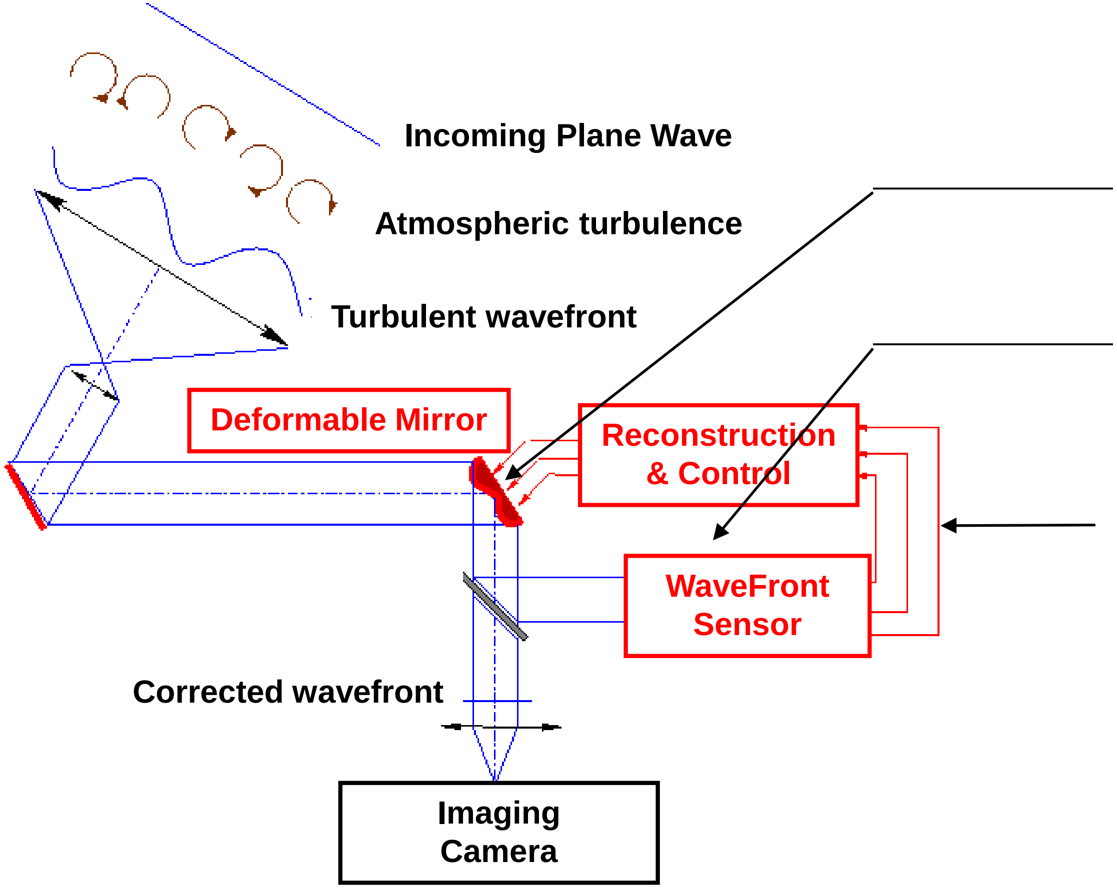
Phase résiduelle

Système d'imagerie

Image à haute résolution

Contraintes technologiques

Adaptive Optics: Main Contributors to Residual Phase



Residual phase variance

$$\sigma^2_{\phi\ \text{residual}}$$

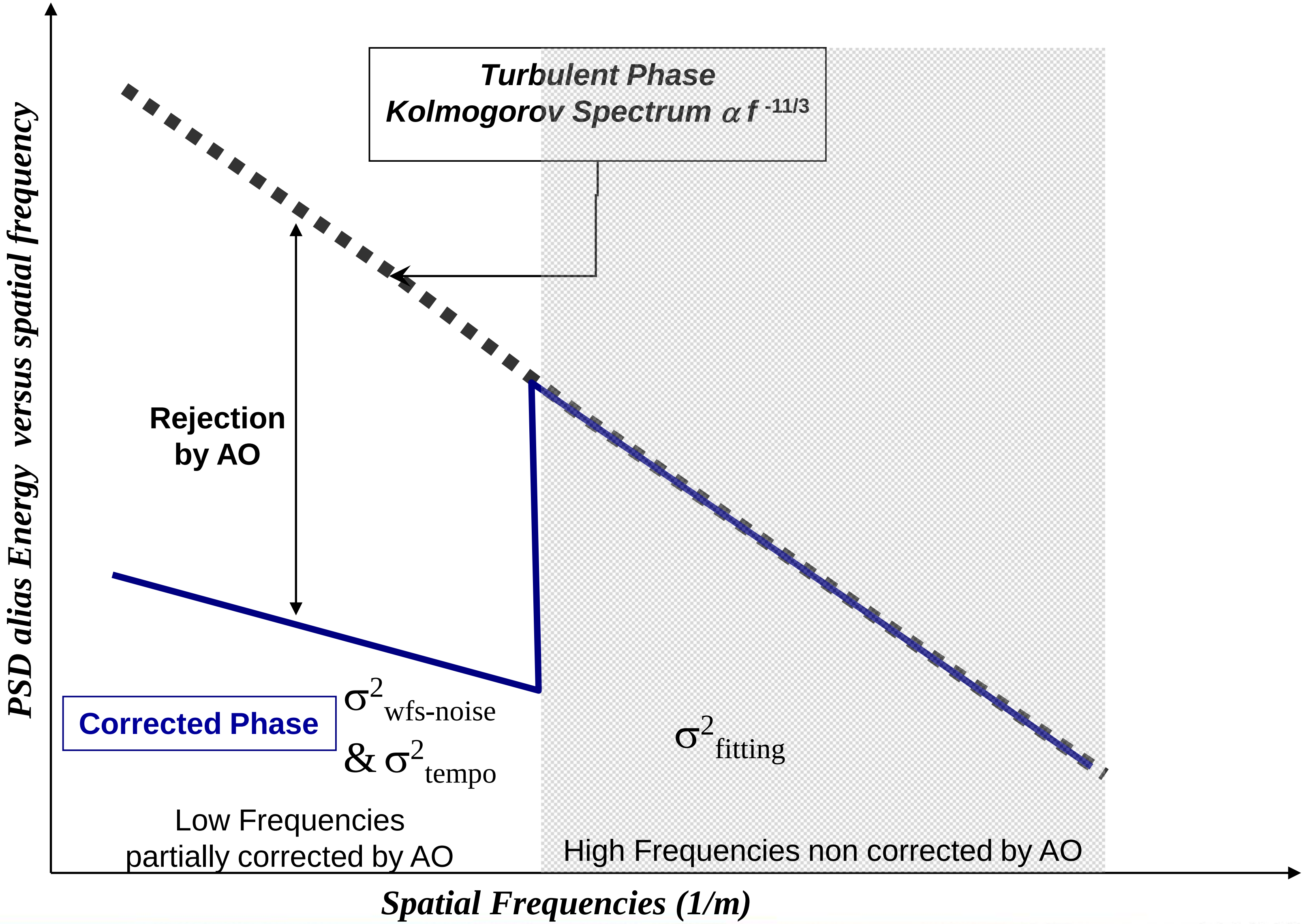
$$=$$

$$\sigma^2_{\text{fitting}}$$

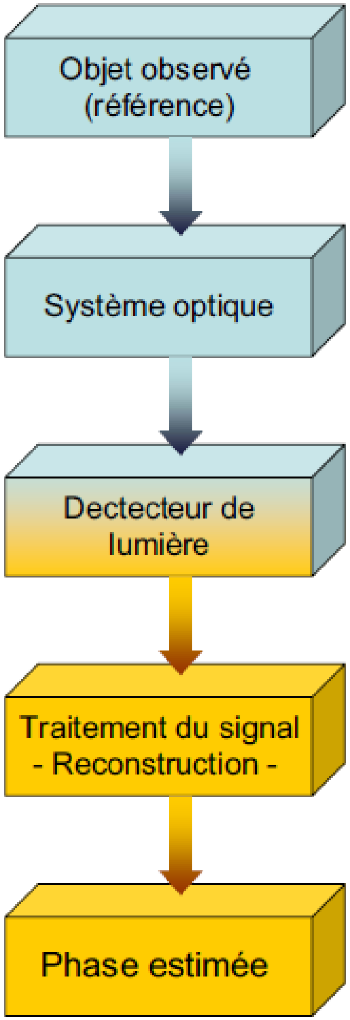
$$+\ \sigma^2_{\text{wfs-noise}}$$

$$+\ \sigma^2_{\text{tempo}}$$

Residual Phase after AO Correction



Analyse de front d'onde : schéma générique



Objet observé (référence)

Système optique

Dectecteur de lumière

Traitement du signal - Reconstruction -

Phase estimée

Signal à mesurer. Objet ponctuel (étoile, point brillant) ou étendu (galaxie, sol terrestre…)

Codage de l'information :
transformation de phase en intensités
Shack-Hartman, courbure, pyramide,
3/4 ondes, interféromètres, diversité de phase …

$$I = F(\phi)$$

Detection des photons :
$\Rightarrow$rapide (kHz), sensible (faible flux), large bande (R ~1)

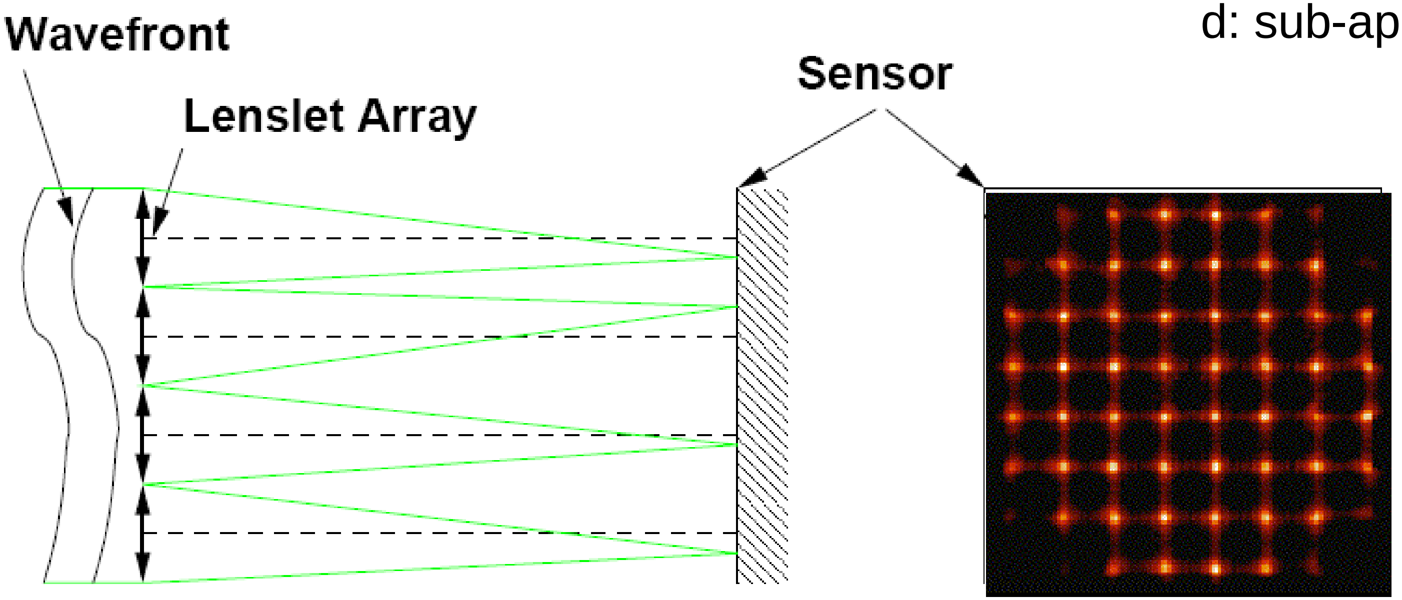
Inversion du signal
→Model de formation de données
→Approximation linéaire (pour temps réel)
→Choix d'un base (modale, zonale)
=> Approximation de F^{-1}

$$\phi = F^{-1}(I)$$

Données finales utilisables dans la boucle d'OA

Shack-Hartmann Wave-Front Sensor (WFS)

d: sub-aperture size



K sub-apertures $\longrightarrow 2\,K$ centers of gravity $\{s_{x/y,i}\} = \mathrm{s}$

Principle: measurement of the wave-front local slope:

$$s_{x,i} = \frac{\lambda\, f}{2\,\pi\, S_i} \int_{S_i} \frac{\partial \phi(x,y)}{\partial x} \mathrm{d}x\, \mathrm{d}y + noise$$

WFS data are called “slopes”

❑ **Linear model :**

$$\mathrm{s} = D\phi + \mathrm{w}$$

- Shack-H. Slope is achromatic!!
- Slope generally expressed in $\Delta\phi$ phase difference at the edge of sub-ap.

Measurement Noise on Shack-Hartmann Slopes

Case of a Detector limited by Photon Noise

Slope noise variance expressed in phase difference at sup-aperture edge at the WFS wavelength

$$\sigma^2_{\Delta\varphi} = \frac{\pi^2}{2}\frac{1}{n_{ph}}\left(\frac{\theta}{\lambda / d}\right)^2 \quad (rad^2)$$

θ : angular size of the sub-aperture spot
  - o λ/d if limited by diffraction
  - o λ/r_0 if limited by seeing
  - o θ_{object} if resolved object

n_{ph}: number of photons per <u>sub-aperture</u> & per frame

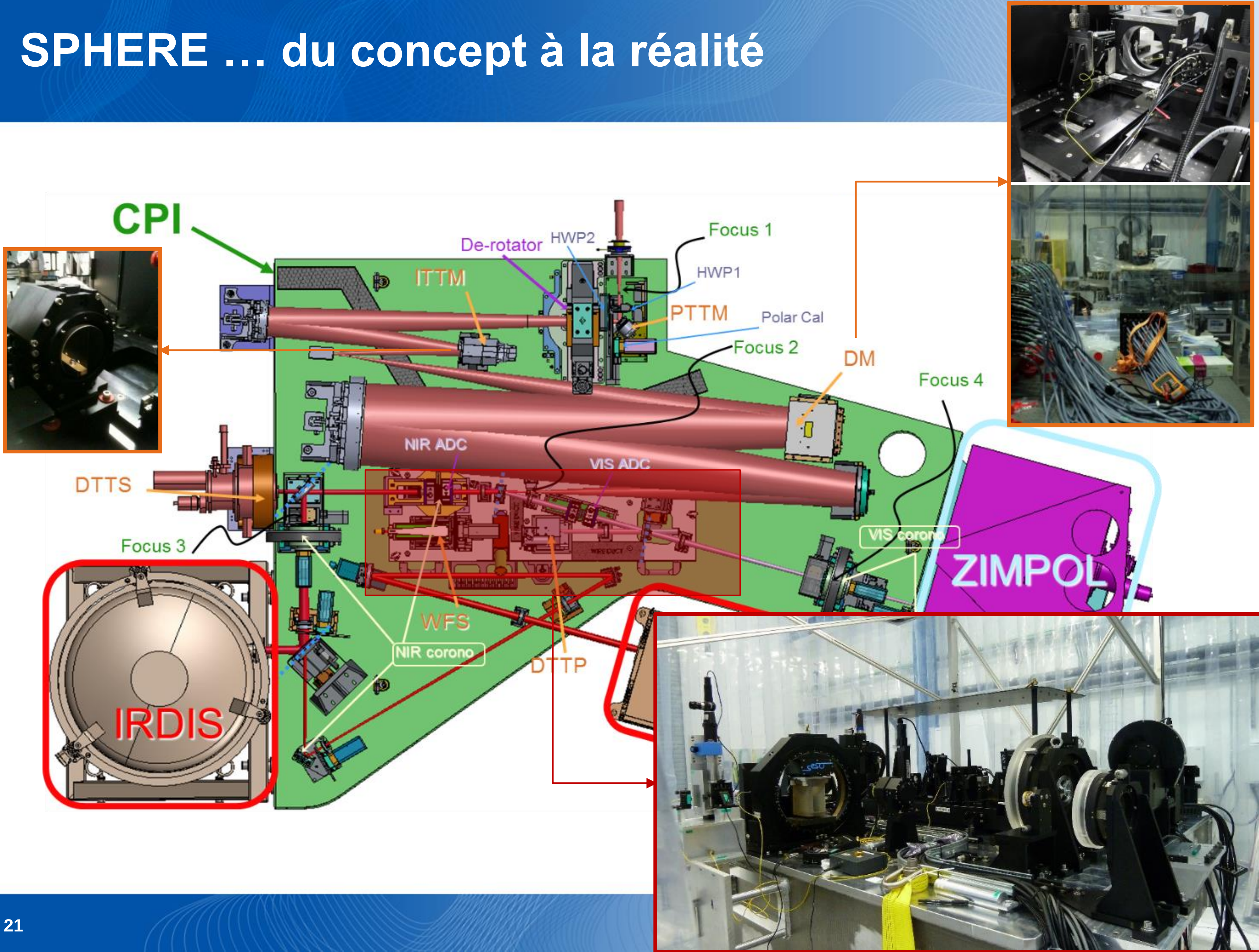
- In practice : d ~ pitch
- Trade off between :
  - reduction of fitting error => d ↘
  - reduction of noise error => d ↗

Depends on the applications
(ultimate perf / limit magnitude …)

Users specifications
are
ESSENTIALS !!!!

Interactions with end-users
(astronomers)
During all the AO system development

SPHERE … du concept à la réalité

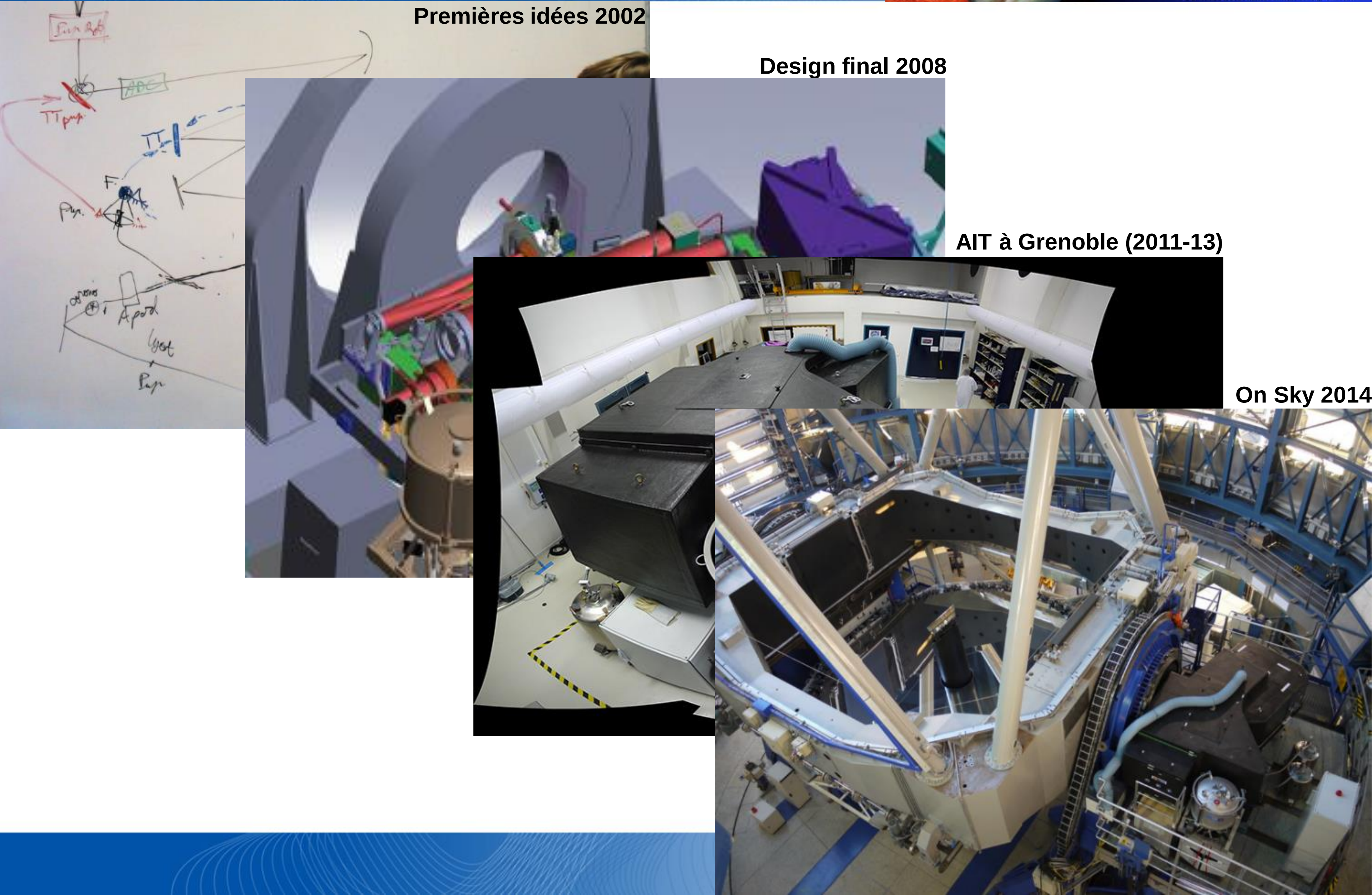


Il était une fois … SPHERE …

Une longue histoire, qui se finit bien !

SPHERE

Spectro-Polarimetric
High-contrast
Exoplanet REsearch



Premières idées 2002

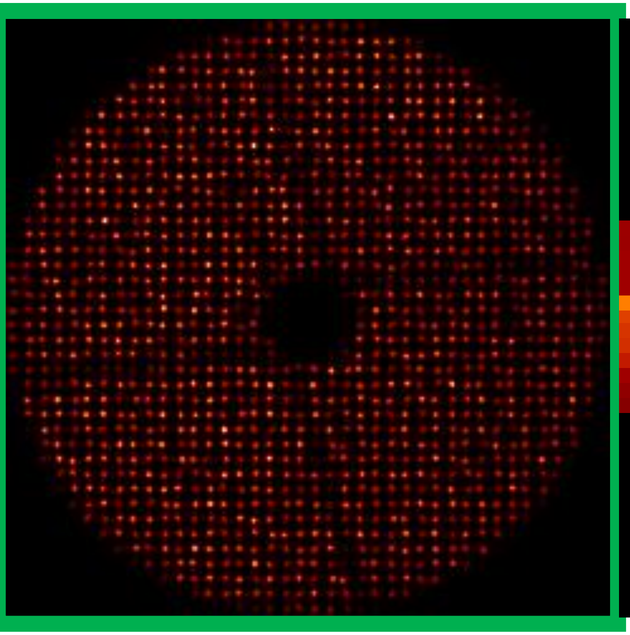
Design final 2008

AIT à Grenoble (2011-13)

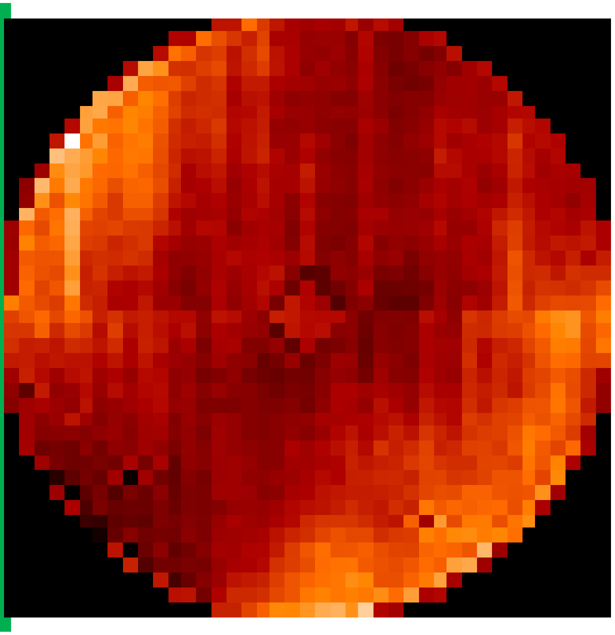
On Sky 2014

Optique adaptative extreme… …analyse de front d'onde extrême

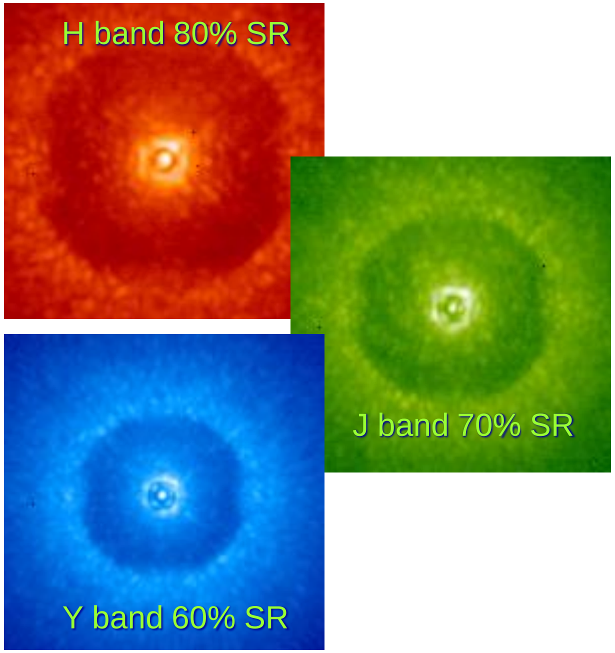
On sky data (May 2014)



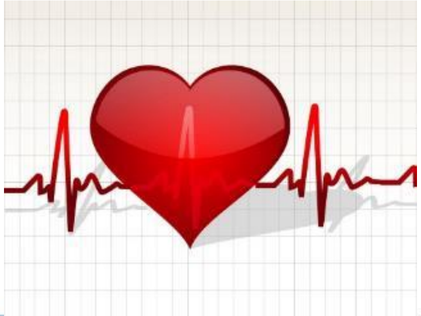
40x40 EMCCD filtered SH WFS



41x41 Piezzo DM



SAXO, le cœur de SPHERE
un cœur qui bat 1200 fois par seconde

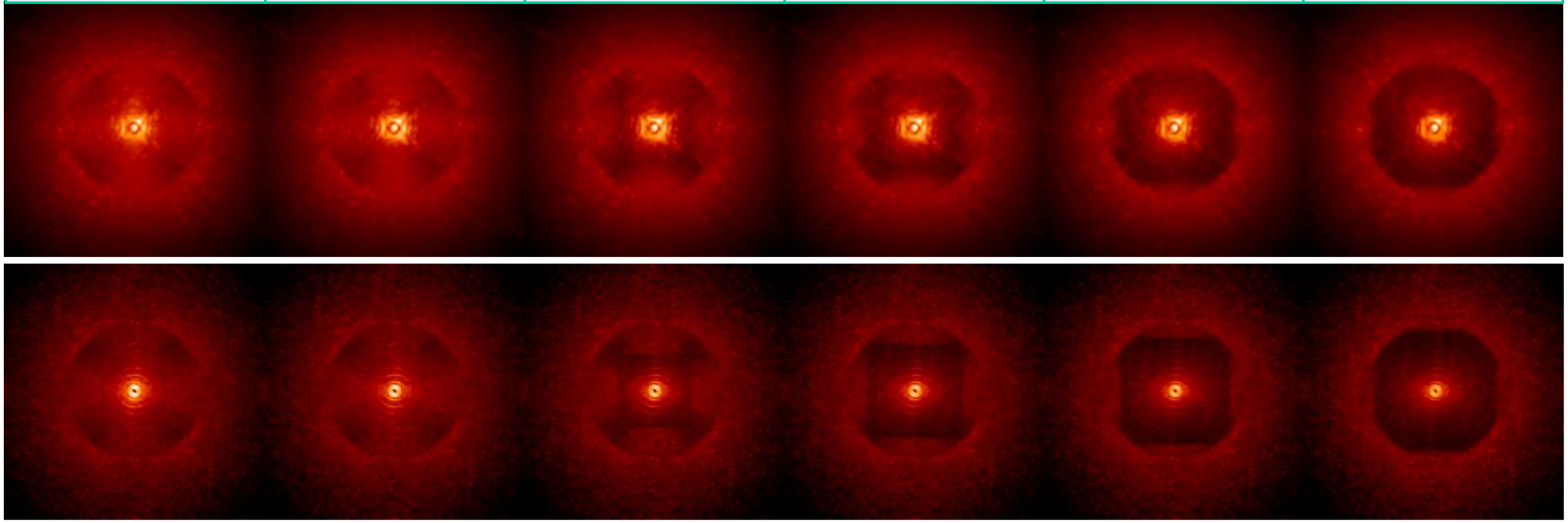


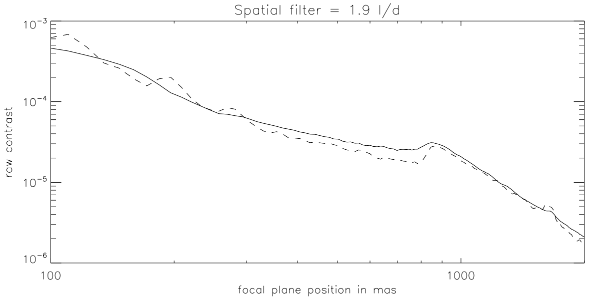
Experience vs simulation

On sky data

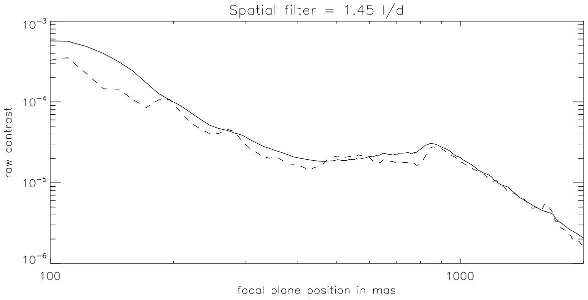
2014/05/16
05:37 UT
seeing ~ 0.7

1.9 λ/d	1.8 λ/d	1.45 λ/d	1.3 λ/d	1.2 λ/d	1.1 λ/d

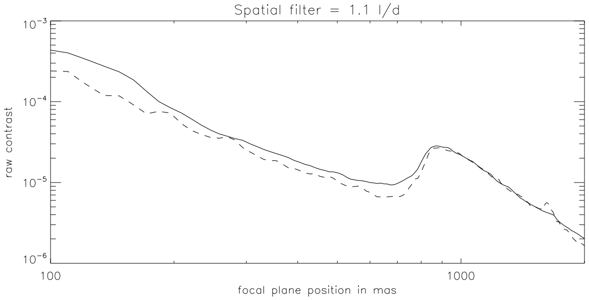




Spatial filter = 1.9 l/d

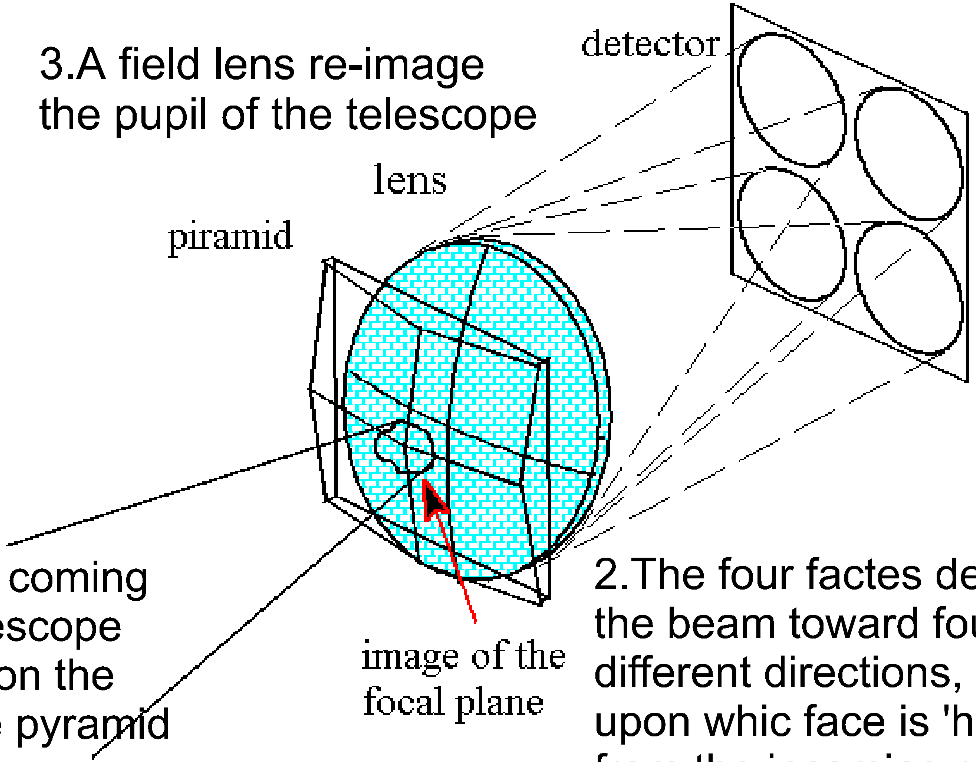


Spatial filter = 1.45 l/d



Spatial filter = 1.1 l/d

Pyramid WFS concept

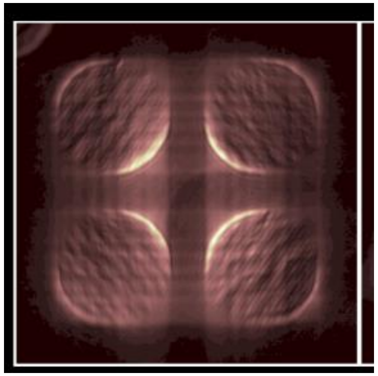


3.A field lens re-image the pupil of the telescope

4.On the detectors four pupils are obtained: their illumination reflects the region of the pupil owner of the rays going through one of the four faces.

1.The beam coming from the telescope is focussed on the vertex of the pyramid

2.The four factes deflects the beam toward four different directions, depending upon whic face is 'hitted' from the incoming ray



LOOPS bench, LAM

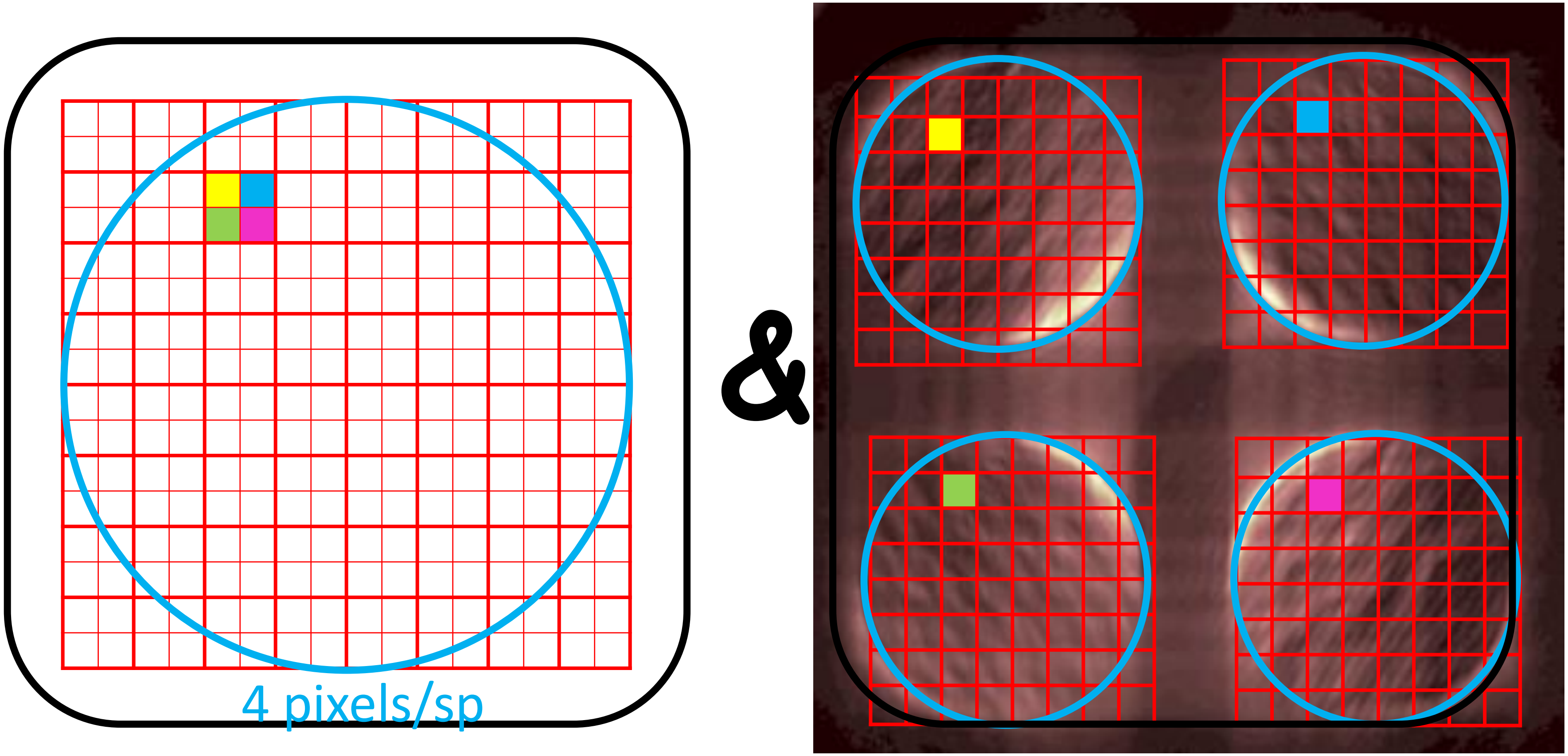
Pyramid WFS

- ☐ Variable Gain
- ☐ Higher Sensitivity (uses whole telescope aperture)
- ☐ Higher Dynamic Range
- ☐ Easily rebinnable (no extra RON)
- ☐ Easy alignment with the CCD
- ☐ Modulation???

$(D/r_0)^2$ in closed loop

From λ/D to Pyramid size

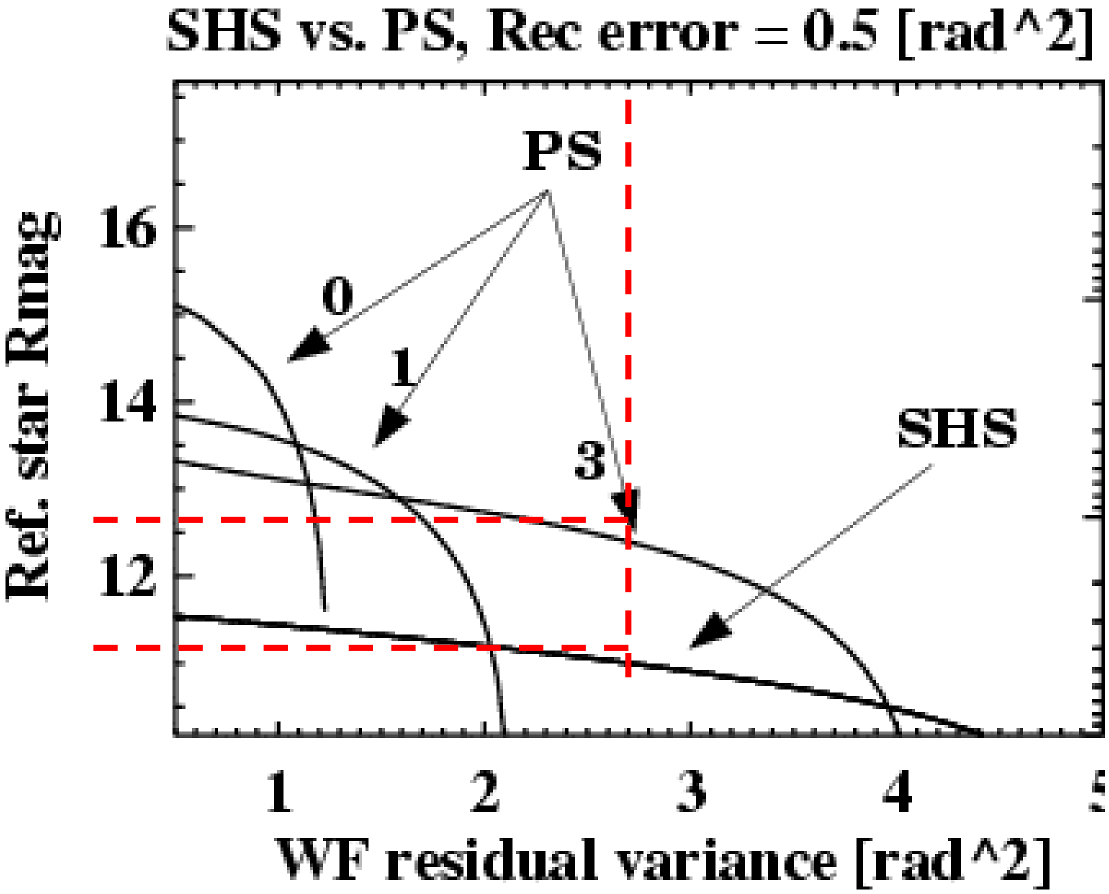
Pyramid WFS



- ✓ SH WFS: pupil→sp (MLA) & field→quadrants (pixels)
- ✓ PWFS: field →quadrants (pyramid) & pupil→sp (pixels)

→ Identical (geom. optics) but rearrangement of pixels is different

Pyramid wrt SHWFS sensitivity



PYR : gain wrt SHWFS depend also on N subaperture.
d=0.5m

- **1.5 mag sur VLT**
- **3.0 mag sur ELT**

Esposito 2000

- Analytics
- Num simulation
- Visible WFS

Pyramid vs Sack-Hartmann WFS

❑ Wavefront measurement error can be much lower

- Shack-Hartmann: size of spot limited to λ / d, where d is size of a sub-aperture and usually d ~ r_0
- Pyramid: size of spot can be as small as λ / D, where D is size of whole telescope. So spot can be D/r_0 = 20 - 100 times smaller than for Shack-Hartmann
- Measurement error (e.g. centroiding) is proportional to spot size/SNR. Smaller spot = lower error.

❑ Avoids bad effects of charge diffusion in CCD detectors

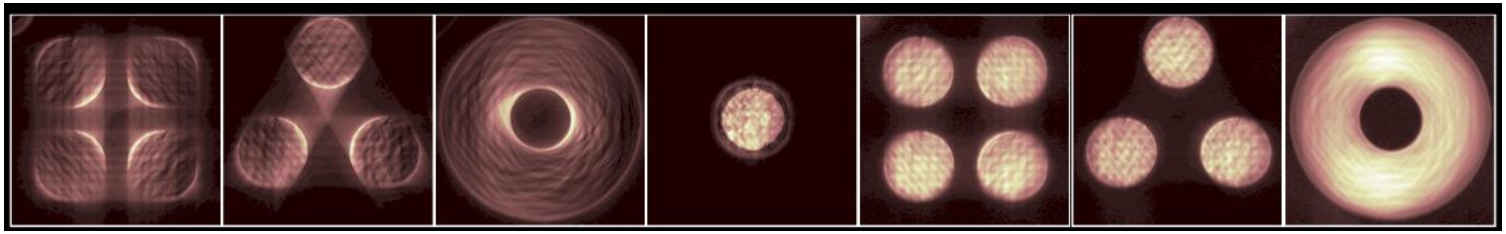
- Fuzzes out edges of pixels. Pyramid doesn't mind as much as S-H.

❑ Linear response over a larger dynamic range

❑ Naturally filters out high spatial frequency information that you can't correct anyway

Analyseur à Pyramide…et après ?

- Analyseurs à filtrage de Fourier
  - Projet national WOLF porté par l’ONERA / LAM (Fusco)
- Développement de modèles analytiques récent (Fauvarque, Chambouleyron)
- Développement de moyens expérimentaux (LOOPS, Janin-Potiron)
- Promet une large gamme d’améliorations



Classique…

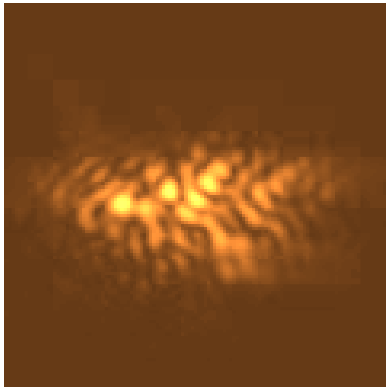
Nombre de faces…

Angle applati

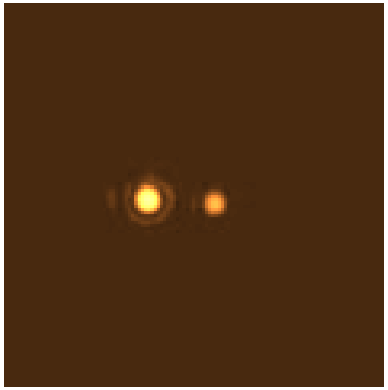
Modulation…

Diversité de phase

- Déformation **de front d’onde** => Déformation de **l’image**
- Or dans l’imagerie, la grandeur d’intérêt : **image**



- Analyse de front d’onde plan-focal :
  - Et si l’image suffisait à mesurer les aberrations ?

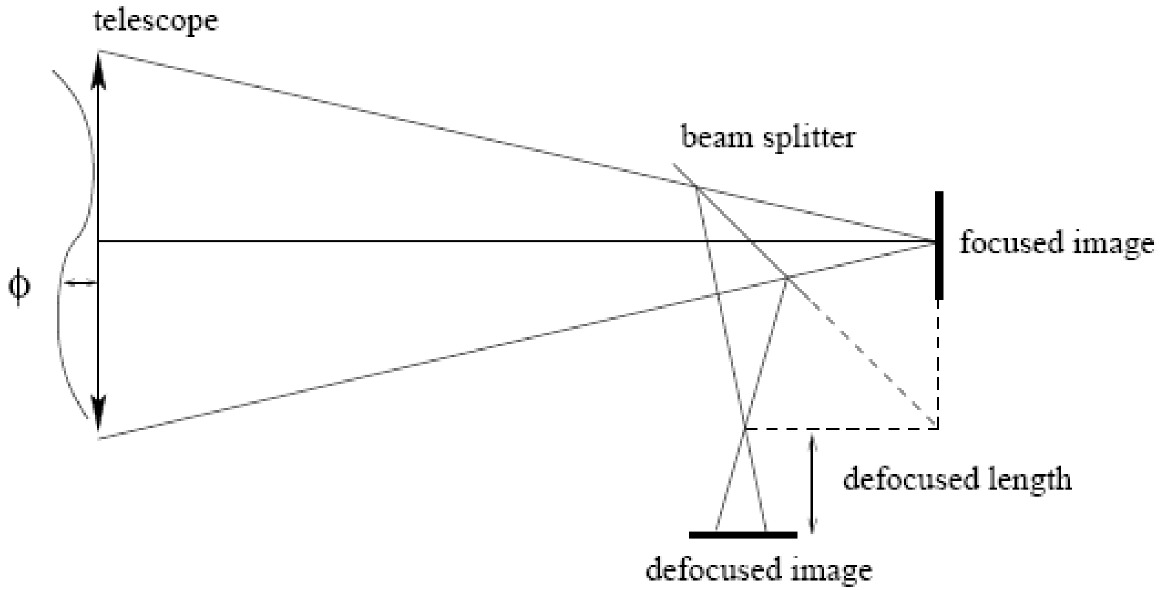


- Modèle de formation d’image ?
  - $\Phi \rightarrow$ Image
  - Cas d’une source ponctuelle : Image = $|TF(Pe^{i\Phi})|^2$
  - Cas d’une source étendue : Image = objet * $TF(Pe^{i\Phi})|^2$

Diversité de phase

- 1 seule image suffit presque…mais il subsiste une indétermination
- 2 images sont nécessaires en pratique

From the 2 images, one can imagine an algorithm to obtain the phase

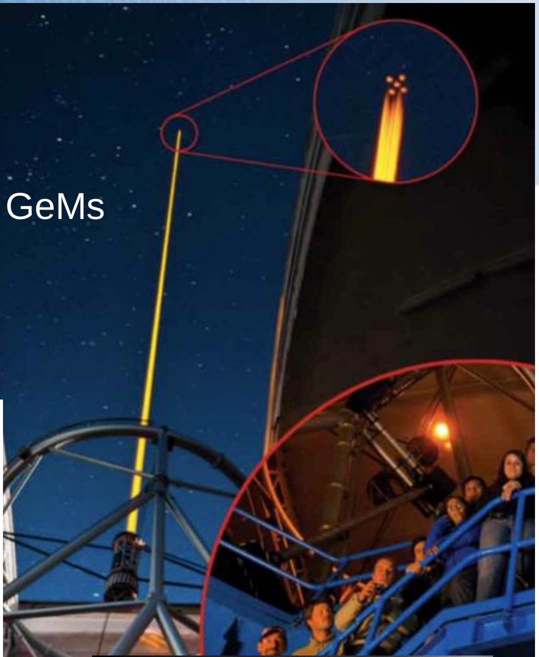


Diversité de phase

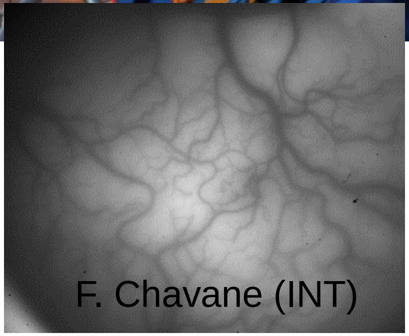
- Estimation du front d’onde directement dans l’image
    - Au plus près du signal d’intérêt
- Pas de voie optique différentielle
- Modèle de formation d’image non linéaire => Algorithme + complexe, lent (minute)
- Utilisé aujourd’hui principalement pour des aberrations lentement variables.

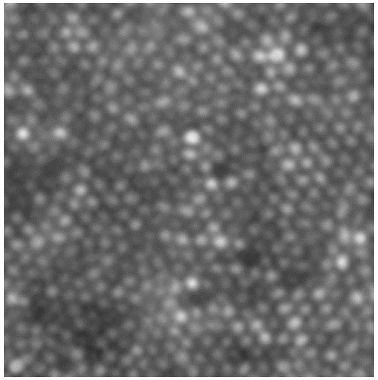
Analyse de front d’onde : de multiples applications

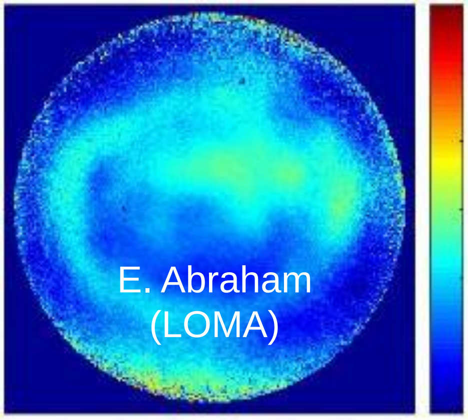
- Astronomie
  - Etoiles Laser
- Spatial
  - Observation de la Terre
- Microscopie
  - Imagerie du cortex
- Ophtalmologie
  - Imagerie rétinienne
- Domaine TeraHertz
  - Mesure / contrôle de front d’onde


GeMs


ONERA


F. Chavane (INT)


Joe Carroll
2 µm resolution


E. Abraham
(LOMA)