Optique adaptative pour l'E-ELT : état actuel et enjeux

Michel Tallon (CRAL), Gérard Rousset (LESIA), Thierry Fusco (ONERA)

ASHRA

« Maîtrise du front d'onde pour aller vers la limite de résolution »

Preamble

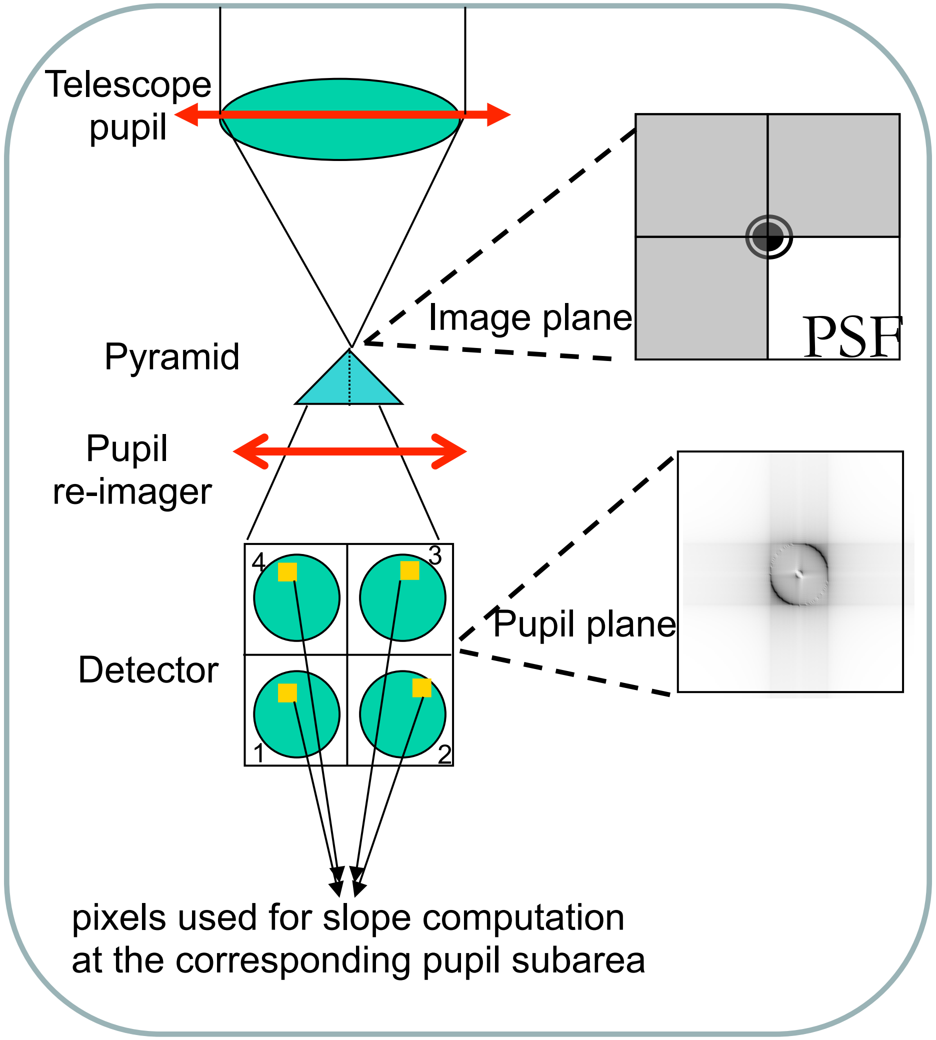
- Sampling of activities in AO rather than exhaustive overview
- Aim: to give an feeling of the current preparation in AO for E-ELT
- Attempt to present the activities the most critical first

Sorry for the english + français mix

Wavefront sensing on Natural Guide Stars

- Maximize the sky coverage !
- For SCAO (first light AO)
- For low modes sensing with tomography

Pyramid WFS development @ LAM



Ragazzoni 1996

Senseur à pyramide, rapide, sensible, destiné aux premiers instruments de l'E-ELT

<u>Principe & avantages</u>

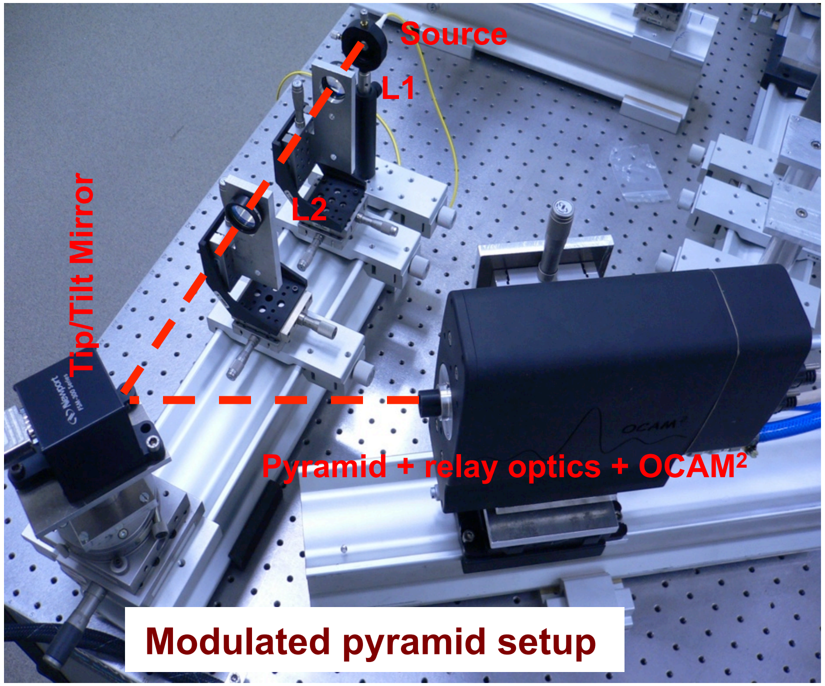
- mesure du gradient du front d'onde
- plus sensible que Shack-Hartmann
- échantillonnage réglable (et fin)

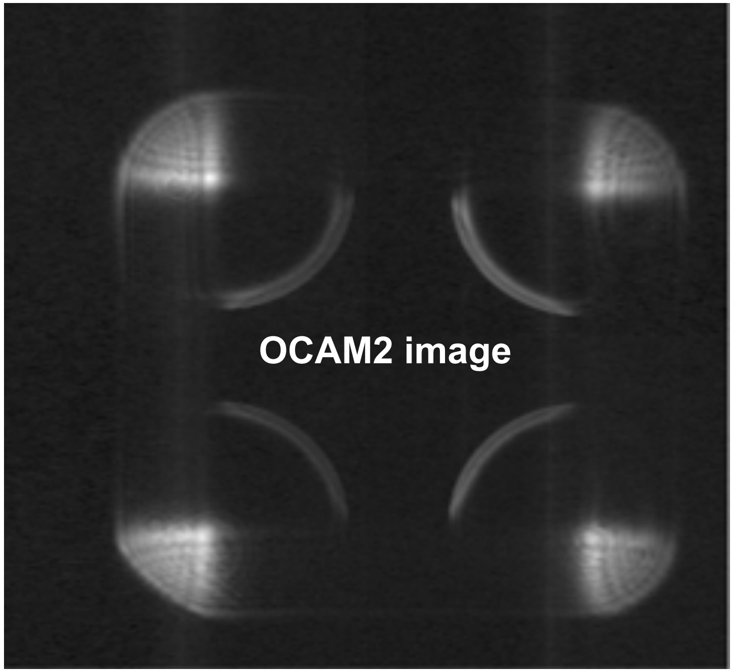
<u>Efficacité démontrée</u>

- Esposito et al. First Light AO for LBT
  - ~12 ans de développement…

<u>Originalité : caméra OCAM2 (1.5 kHz)</u>

Pyramid WFS development @ LAM





Planning

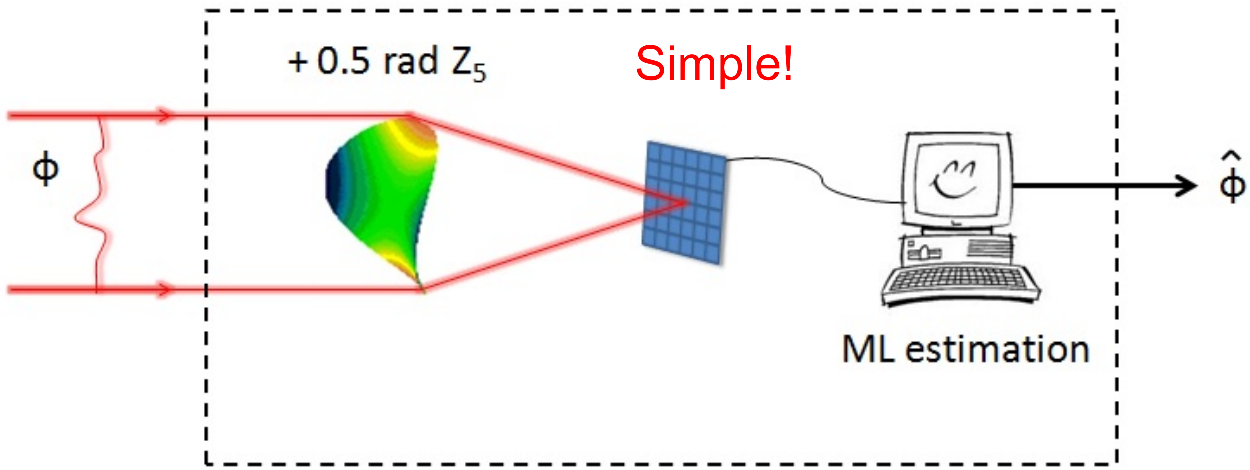
- full lab validation: 2013
- on-sky validation @ OCA: 2014
- IR pyramid WFS using RAPID camera: 2015

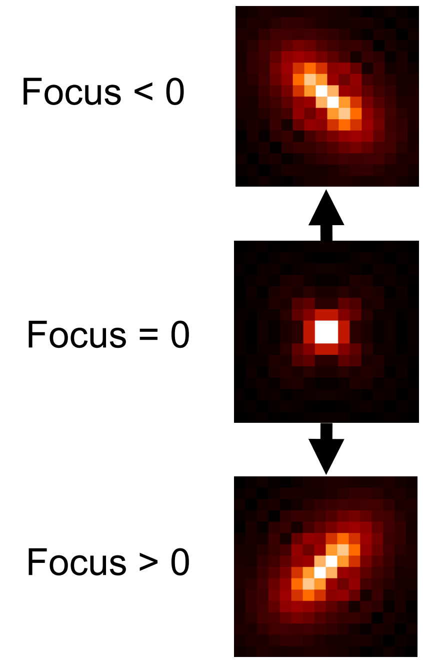
Features

- 64x64 sub-apertures (down to 2x2 using CCD binning)
- 1.5 kHz (up to 2 kHz with OCAM2k version)

Collaboration : LAM, ONERA, INAF-Arcetri, IPAG

LIFT : LInearized Focal-plane Technique





- For tip/tilt/focus measurement on NGS
  - higher modes measured with LGS

- Linearization → Direct LO linear estimation (≡ WCoG) → Fast
- Full aperture diffraction-limited focal-plane sensor
- Maximum Likelihood estimation

  } → Optimized SNR
- Astigmatism offset: removes the focus sign ambiguity
- → Simple, fast, full aperture gain

[Meimon10, Opt. Lett.]

LIFT : noise propagation comparison with the SH 2x2 and the pyramid

- Variance of estimation error in a WFS: $\sum_i \sigma^2(\hat{a}_i - a_i) = \overbrace{\left(\sum_i \alpha_i\right)}^{\alpha} \frac{1}{n_{ph}^{tot}} + \overbrace{\left(\sum_i \beta_i\right)}^{\beta} \left(\frac{\sigma_e}{n_{ph}^{tot}}\right)^2$
- Comparison of noise sensitivity for the estimation of tip/tilt and focus:

Coefficient	SH 2x2 (WCoG)	LIFT	Pyramid
Photon noise (α)	8.19	1.71	2.3
Read-out noise (β)	334	87	62

[Plantet13, Opt. Exp. (accepted)]

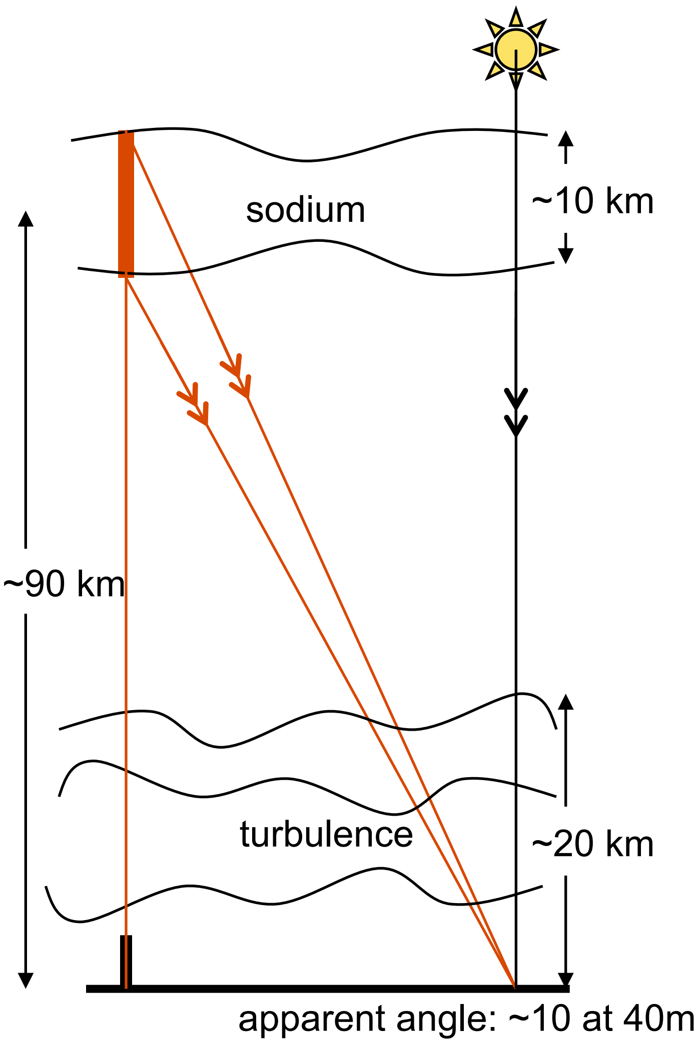
- Pyramid model: no modulation, pupil sampled on 4 pixels, ML estimation

→ Much more sensitive than a SH 2x2
→ Performance comparable to the pyramid
→ Now validated on sky (GeMS)

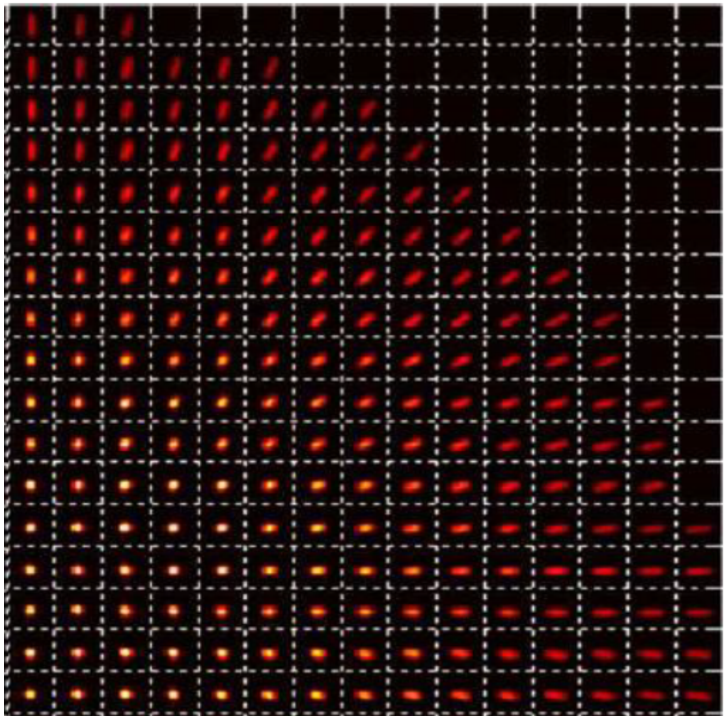
Wavefront reconstruction issues

- Elongation of laser guide stars (E-ELT)
- Fragmentation of the pupil (E-ELT)

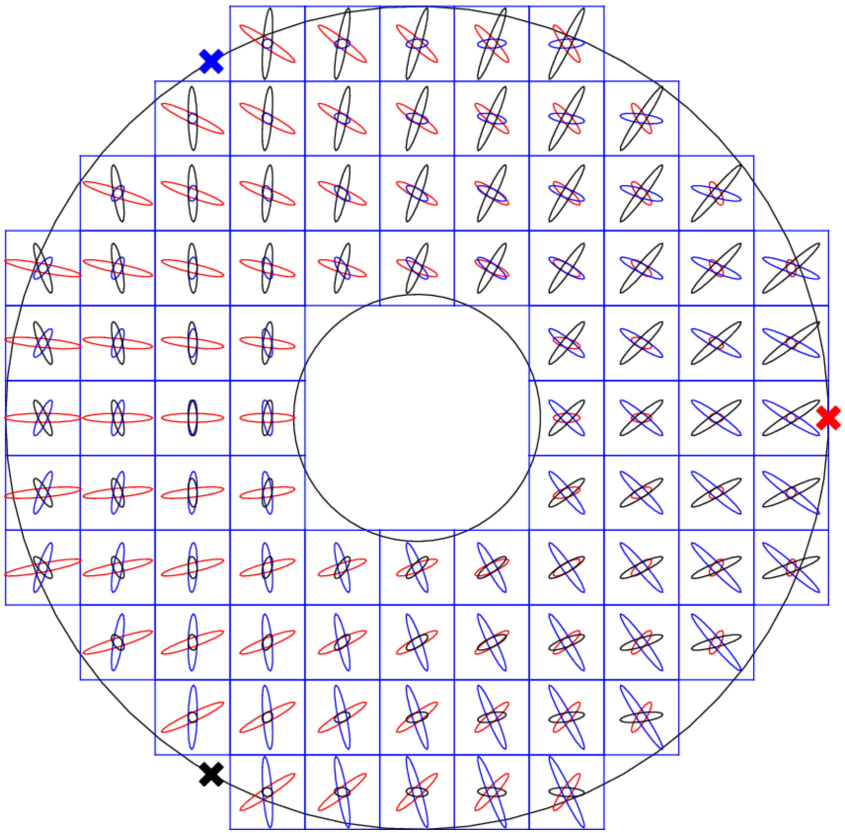
Laser spot elongation / problem



- laser source is ~1m in diameter x 10 km long



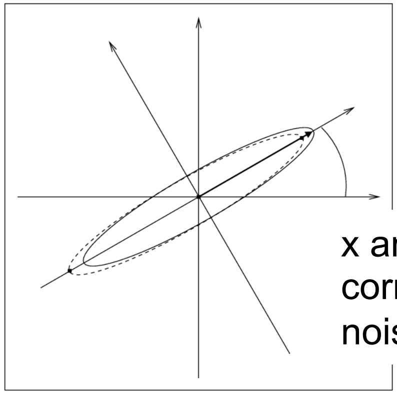
Laser spot elongation / reconstruction



Tallon et al 2008

- Side launch is better than central launch !
  - elongation (and noise) is twice as large
  - but diversity of elong. orientations
  - => better wavefront reconstruction
- **ONLY IF** noise correlation is taken into account in the wavefront reconstruction
- Limited loss of accuracy if wavefront reconstruction with MAP.
- But detector twice as large !
  - 1600x1600 pixels (at 0.7 – 1 kHz)

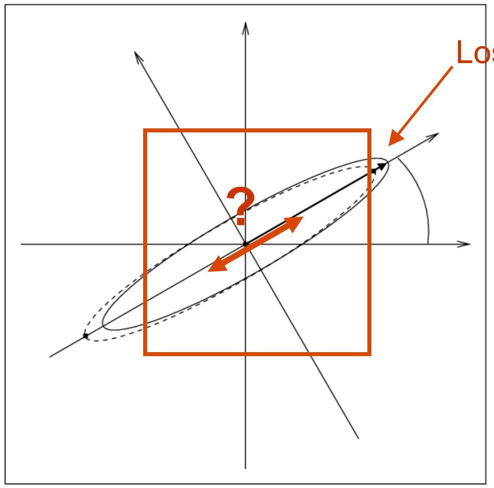
Side launch is now the baseline for ELTs



x and y correlated noise

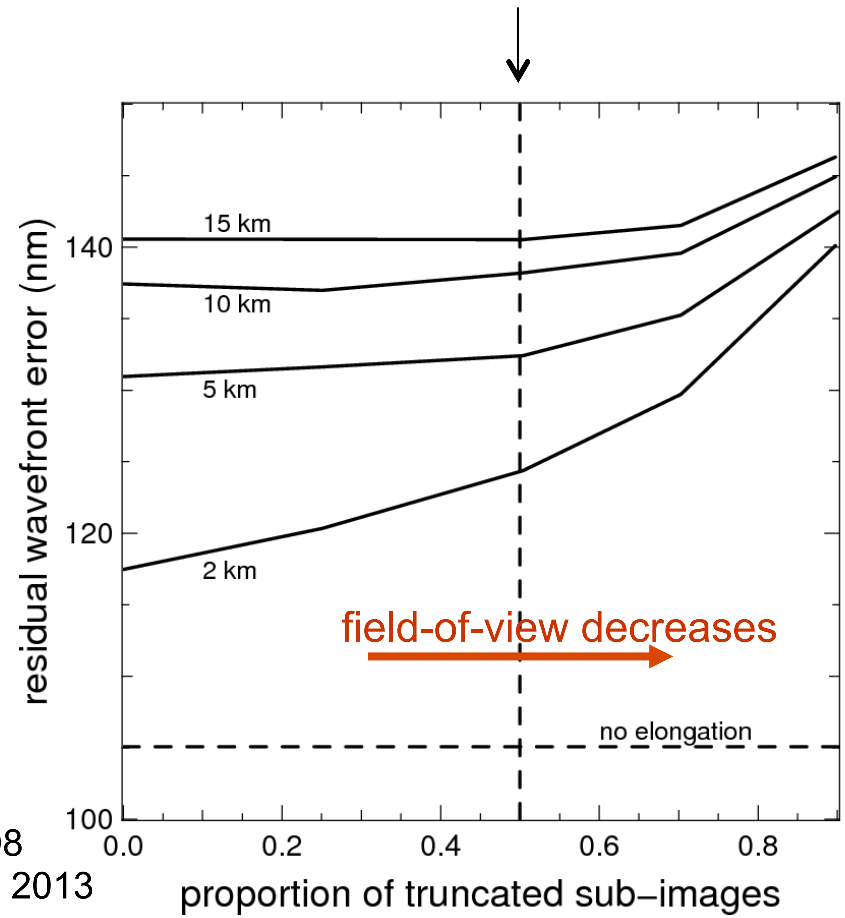
Laser spot elongation / just truncate !

Reduction of field-of-view



Assume a smart centroiding algorithm still measures one coordinate of the gradient.

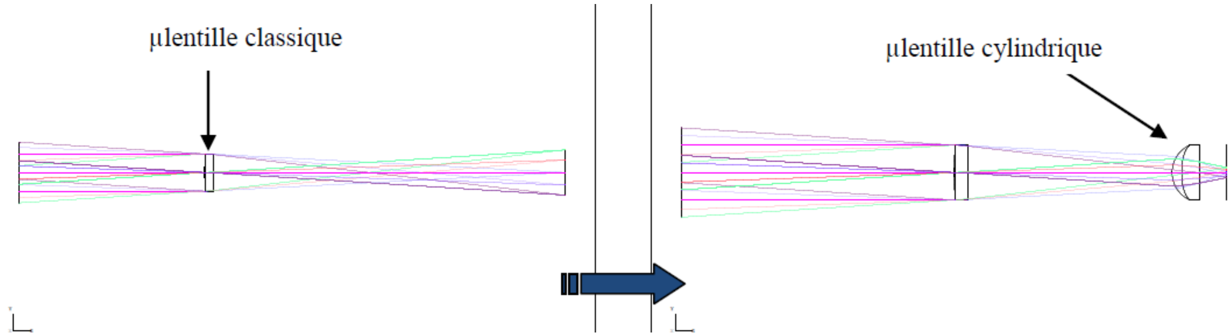
same detector size as central launch: 50% of subapertures give only one gradient coordinate.



Tallon et al 2008
Le Louarn et al 2013

Laser spot elongation / smart optics !

Modified SH for LGS spot compression

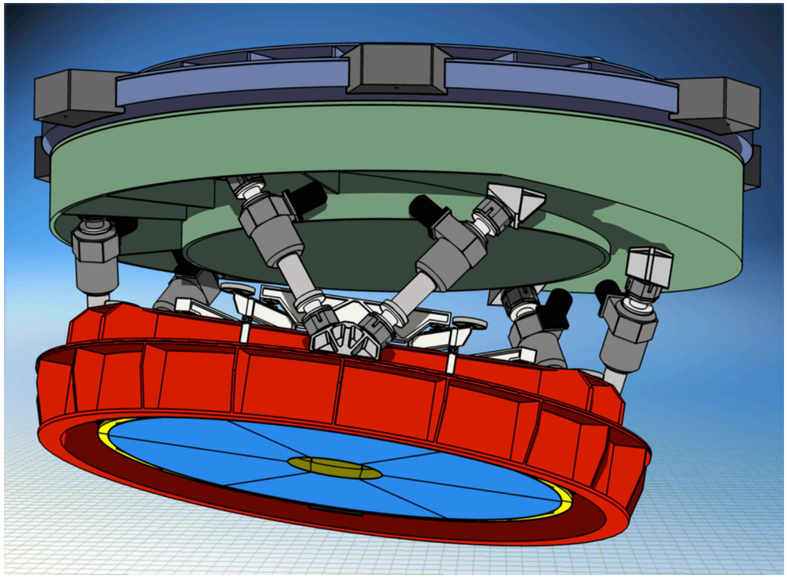


- **Proposal LAM / ONERA / STScI: optical compression**
  - Optical spot compression before the detector
    → uses arrays of cylindrical µlens
    → allows existing detectors to be used

- **On-going work**
  - Numerical simulations to derive the performances
  - Feasibility of manufacturing (contacts with companies)

Deformable mirror M4 … segmented !

Adaptive 2.5 m M4 unit for 39 m

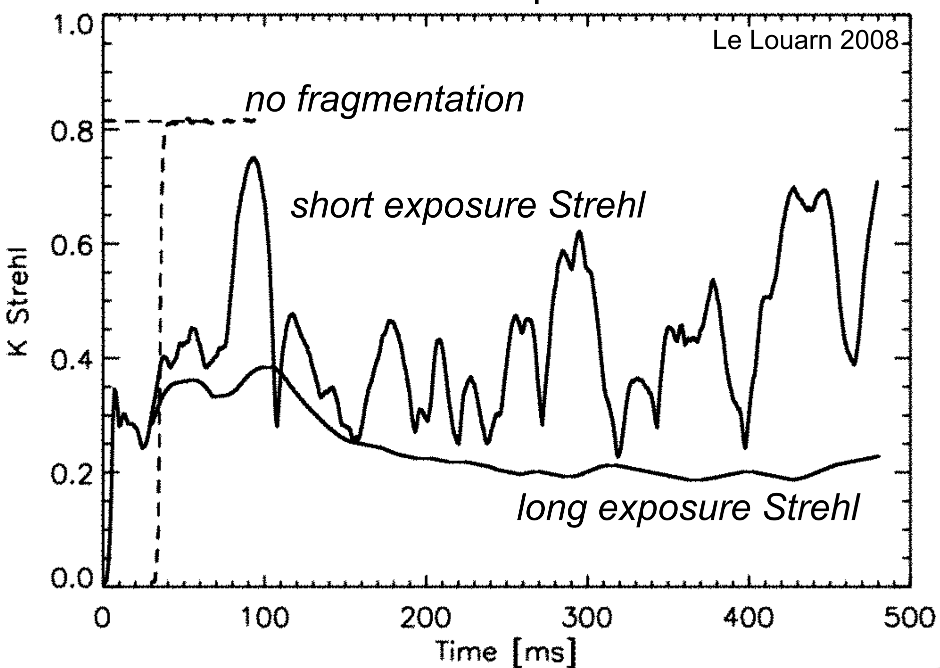


© ESO

- **6 petals**
- 4974 contactless actuators in optical area
- Segmented Zerodur 1.95mm thin shell

- Pupil fragmented :
  - M4 segmented
  - spider arms are much wider than wavefront sensing samples
- Basic assumption of wavefront reconstruction from gradients :
  - wavefront is a continuous surface

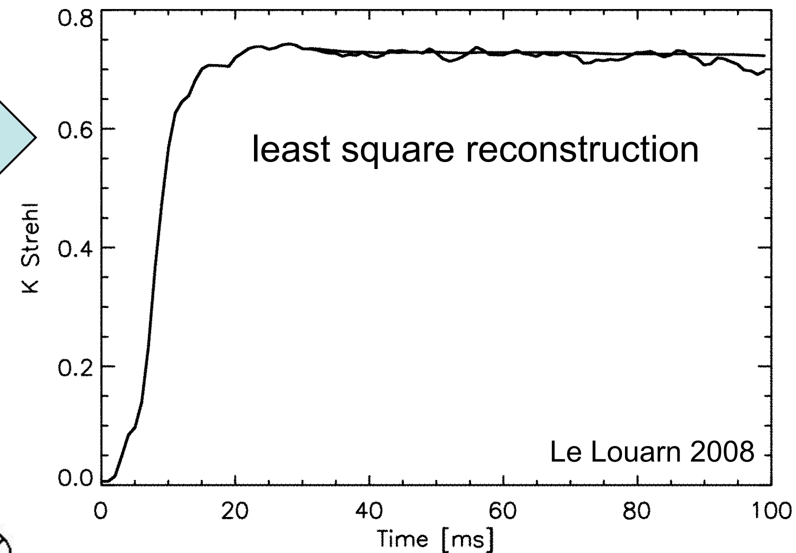
Least square reconstruction



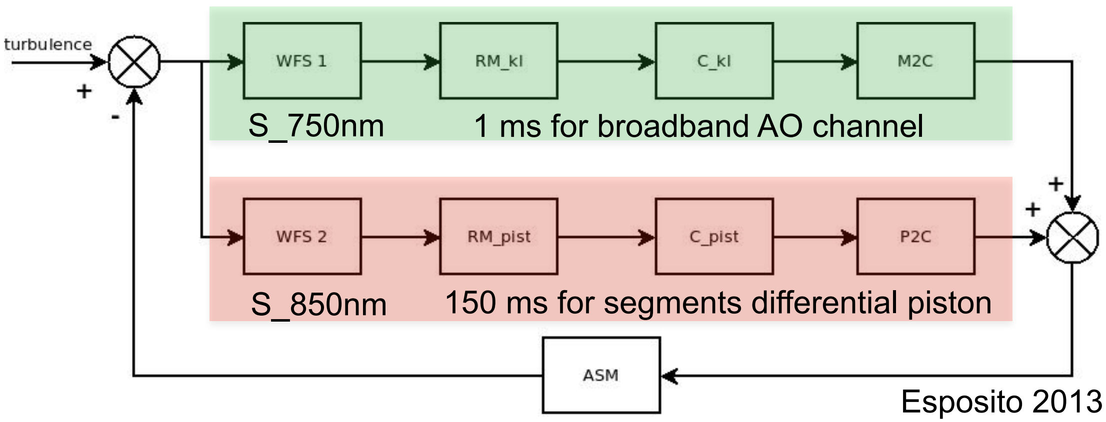
Deformable mirror M4 … solutions ?

Use more hardware

- Add a 3x3 wavefront sensor (NGS)



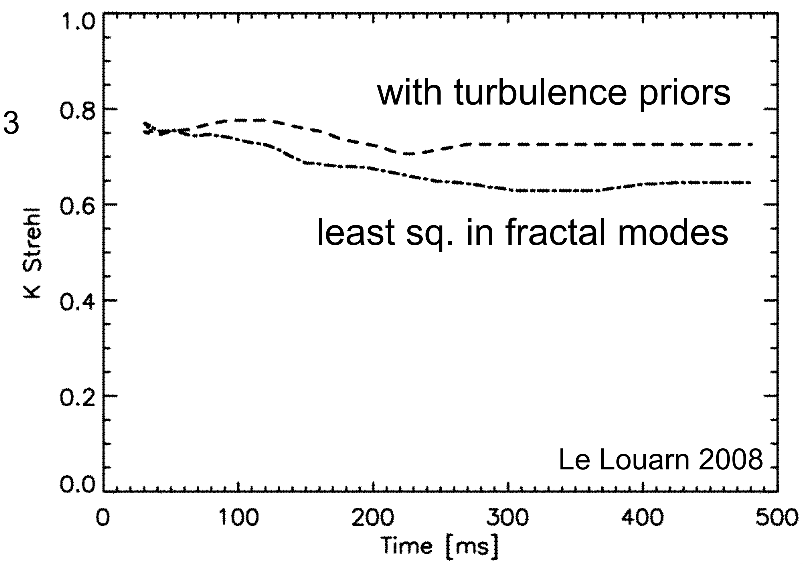
- Also example of GMT :



Esposito 2013

Use more maths

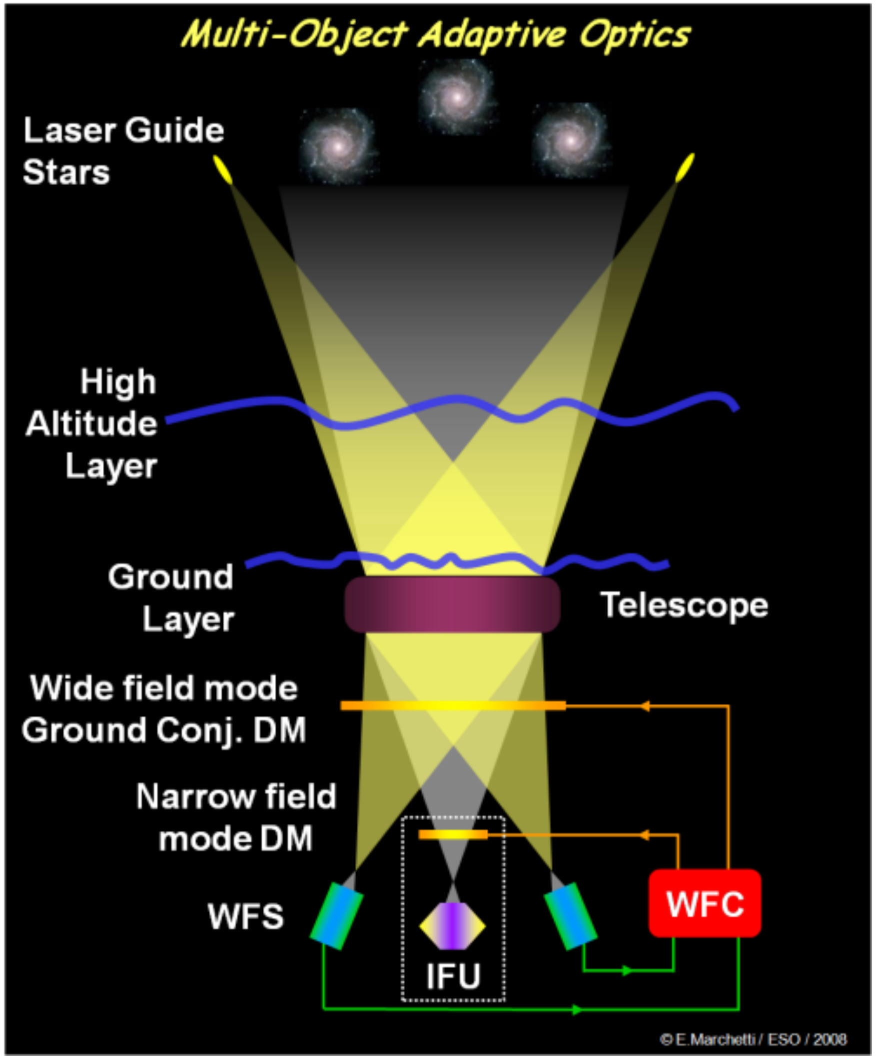
- Reconstruction in fractal modes
- Use (good) turbulence priors (MAP)
- Use spider priors : ***yet to be done***



MOAO = open loop

- CANARY

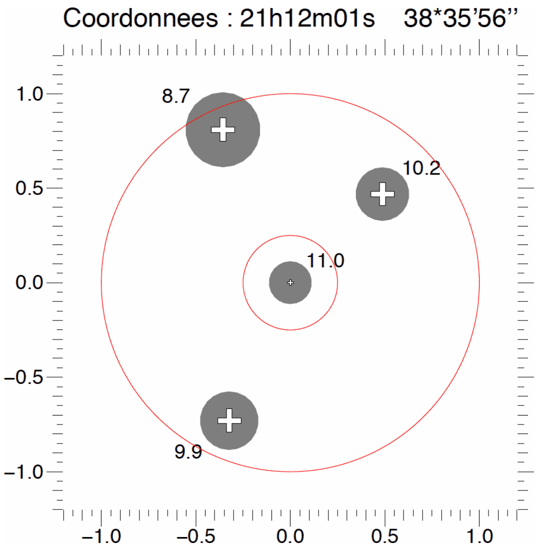
CANARY experiment

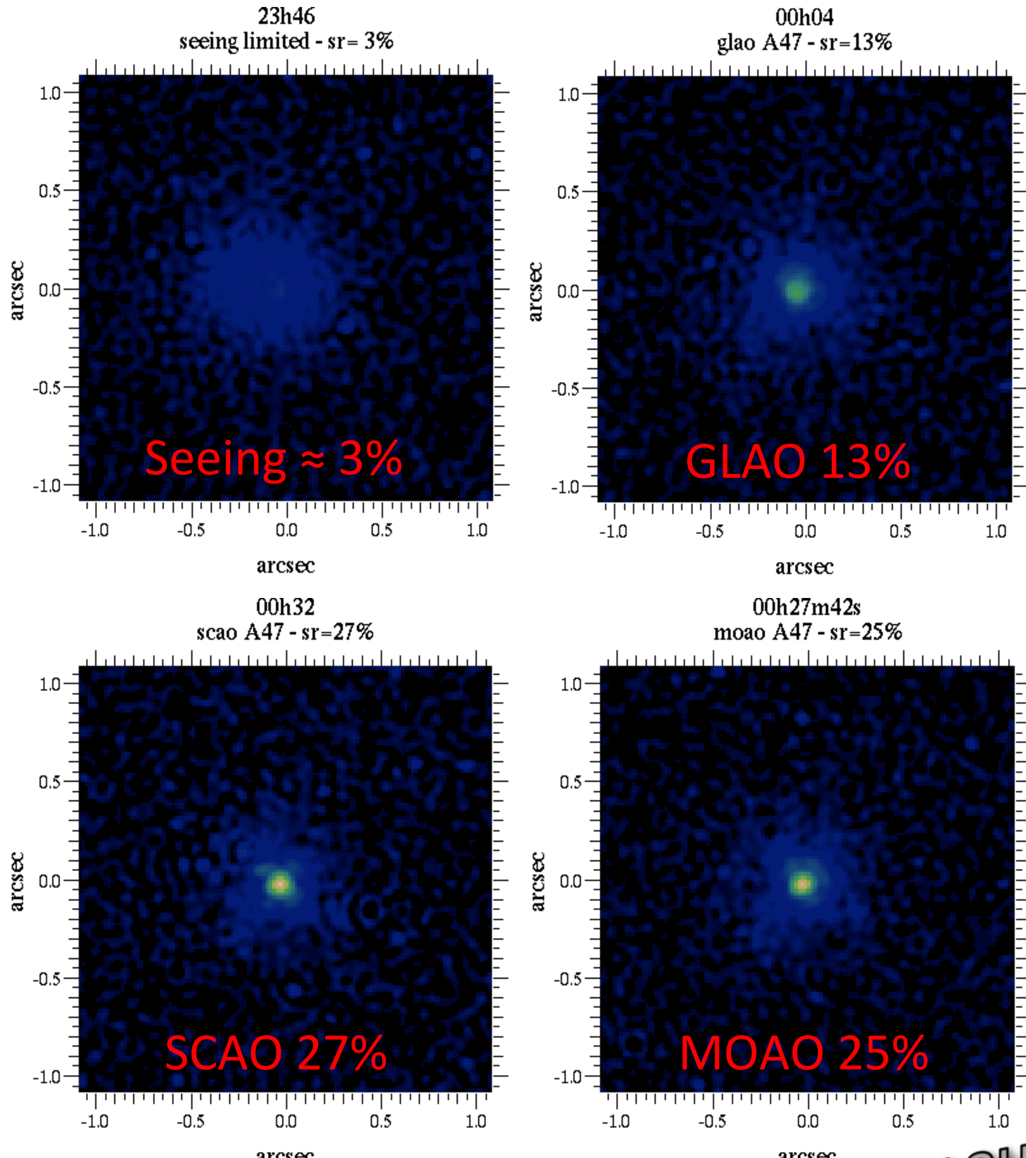


- Multi-Object Adaptive Optics (MOAO)
  - Correction in few directions in a wide field-of-view
    - *OPEN LOOP*
  - But wavefront sensing in <u>other</u> directions (=> tomography)
- CANARY : on-sky study of MOAO in several configurations.
  - William Hershell telescope (4.2m)
  - Durham Univ. (UK), LESIA, UK ATC, GEPI, ONERA, IOGS, LAM
- Aim: MOAO for near IR (0.8 - 2.4 µm) E-MOS instrument
  - 10 – 20 corrected ~1.7"x1.7" FoV within > ∅ 5'
  - > 30% of PSF energy in < 80x80 mas^2 in H band
  - Maximal sky coverage

CANARY experiment / 2010

- First results on sky (WHT, sept. 2010)
  - With natural guide stars
- New methods for calibration and control
  - *OPEN LOOP*
  - atmospheric tomography

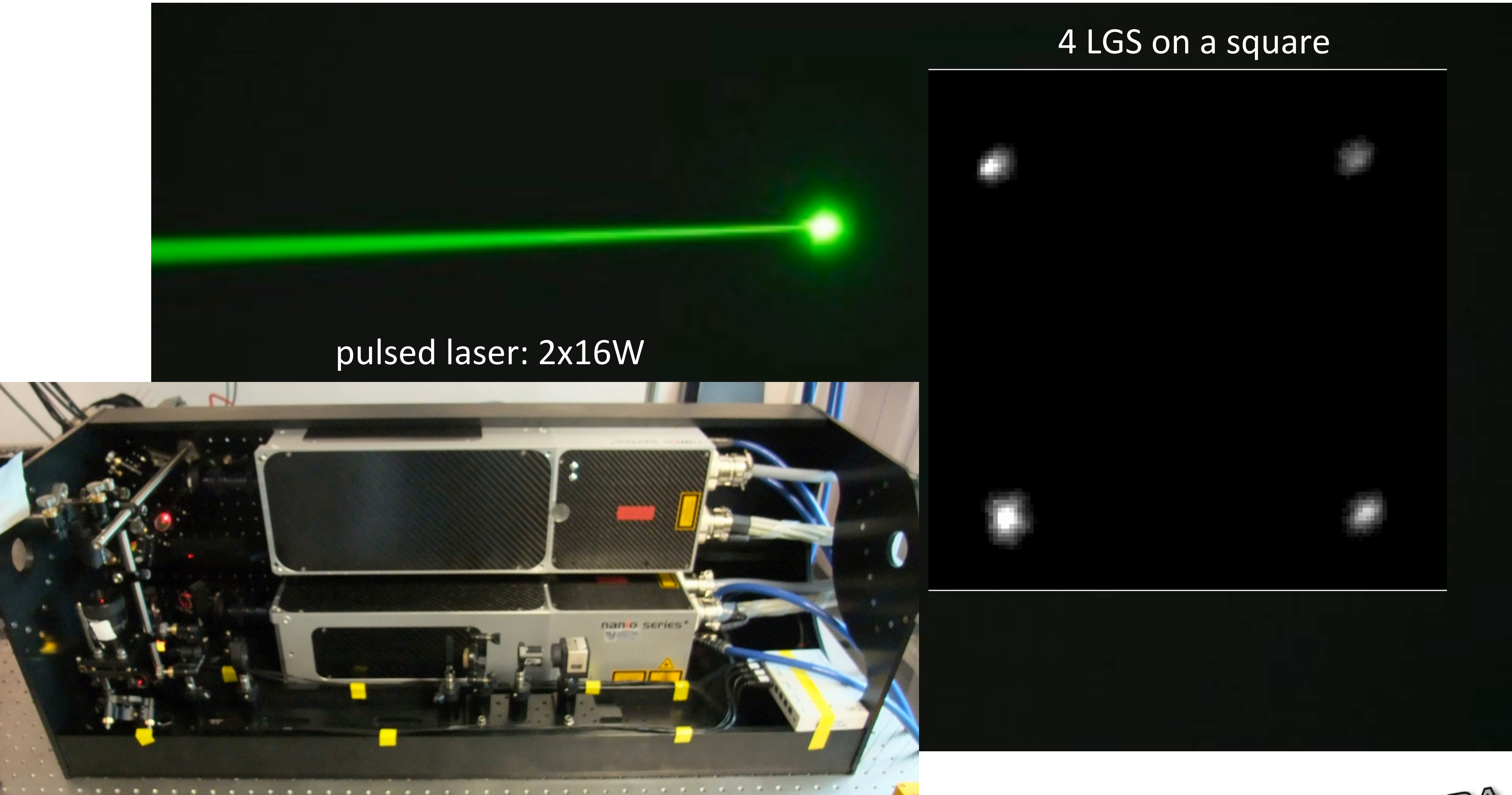




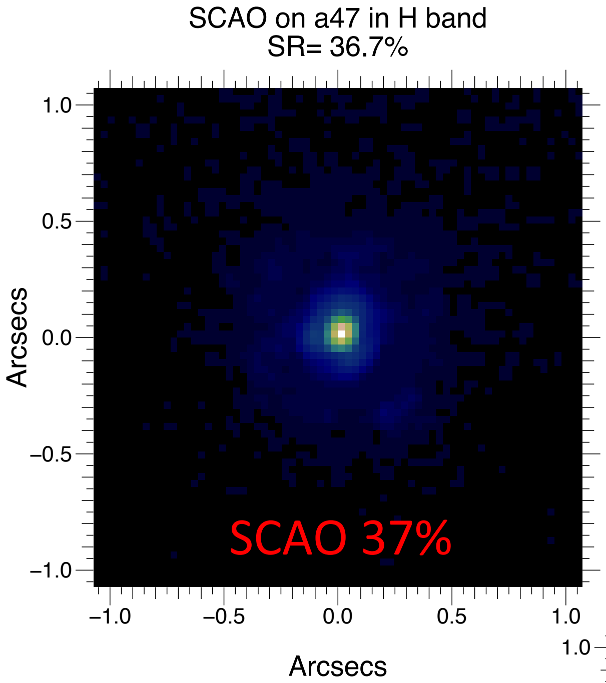
CANARY experiment / lasers

Rayleigh laser guide stars (2x16W)

- mid-2012 : 1 laser guide star
- May & July 2013 : 4 laser guide stars

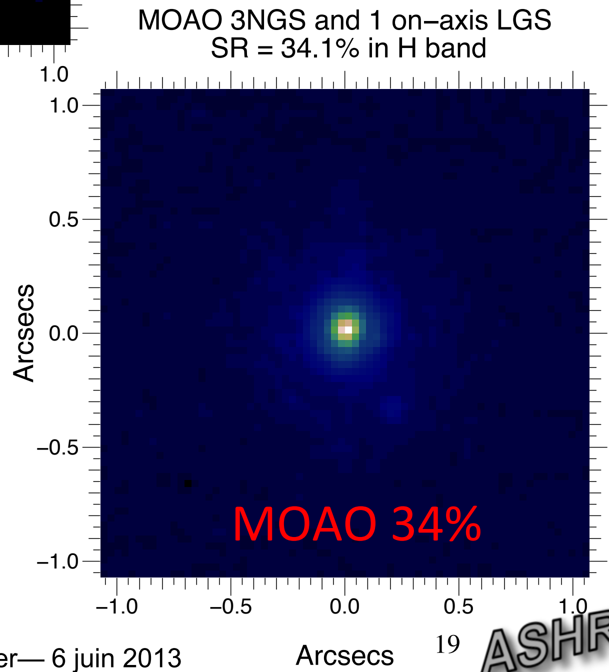


CANARY experiment / 2012

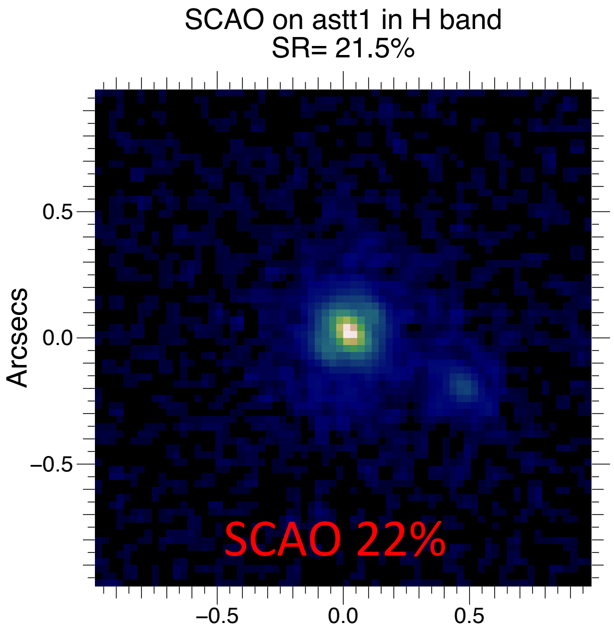


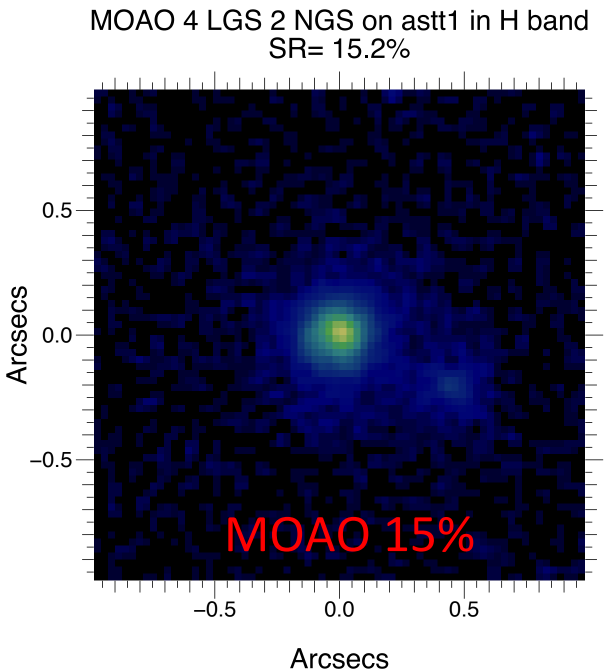
- Guide Stars :
  - 3 natural GS
  - 1 laser GS
- open loop
- 2012

Performances depend on vertical profile of turbulence



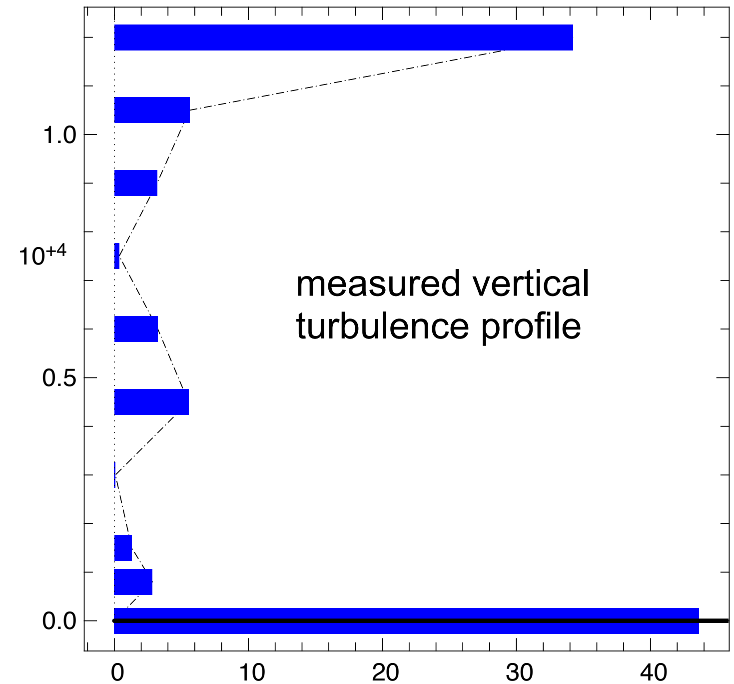
CANARY experiment / 2013





Corrected binary

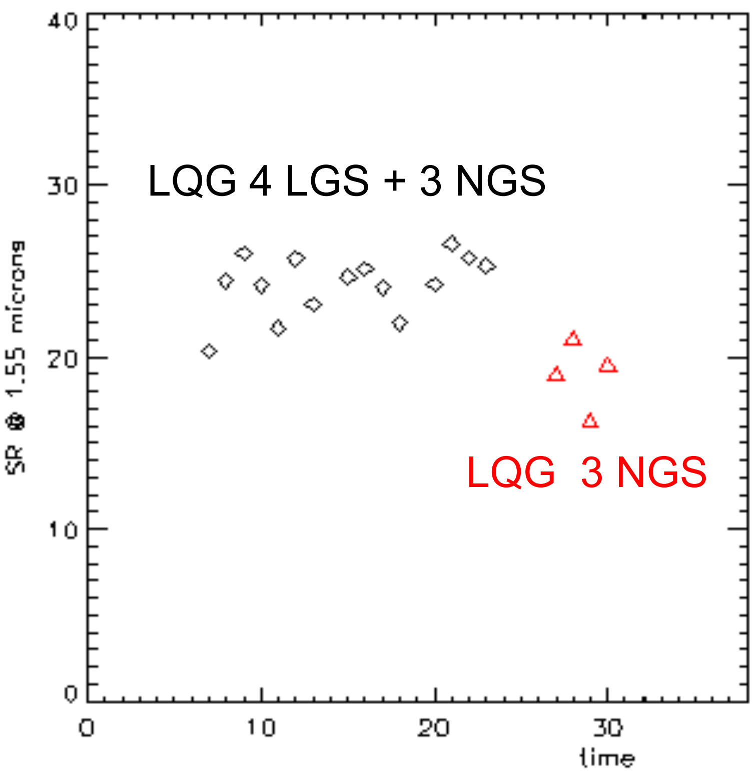
- Guide Stars :
  - 2 natural GS
  - 4 laser GS (15 km)
- open loop
- May 2013



CANARY experiment / LQG

Résultats sur le ciel de la commande LQG

LQG MOAO (25 mai 2013)



Gaetano SIVO & al, AO4ELT, 2013

- LQG = prise en compte de la dynamique des perturbations pour la correction
- Reconstruction tomographique avec norme de la vitesse du vent en altitude
  - Possibilité de prendre en compte les directions de vent
- Extensions :
  - Adaptable aux différents concepts optiques : SCAO, MOAO, LTAO, MCAO, GLAO
  - Formulation possible pour les ELT (coût calculatoire allégé, Massioni & al, 2011)

CANARY experiment / next steps

- mid-2013 (next run in July)
  - 4 laser GS + 3 natural GS, various command laws
  - first science objects
- 1st semester 2014
  - change to closed-loop LTAO (i.e. woofer for 2015 config.)
  - tests on sky mid-2014
- 1st semester 2015
  - change to woofer/tweeter mode, with diagnostic channel in opened loop (truth sensor)
  - tests on sky mid-2015
- mid-2015
  - upgrade to sodium laser from ESO (TBC)

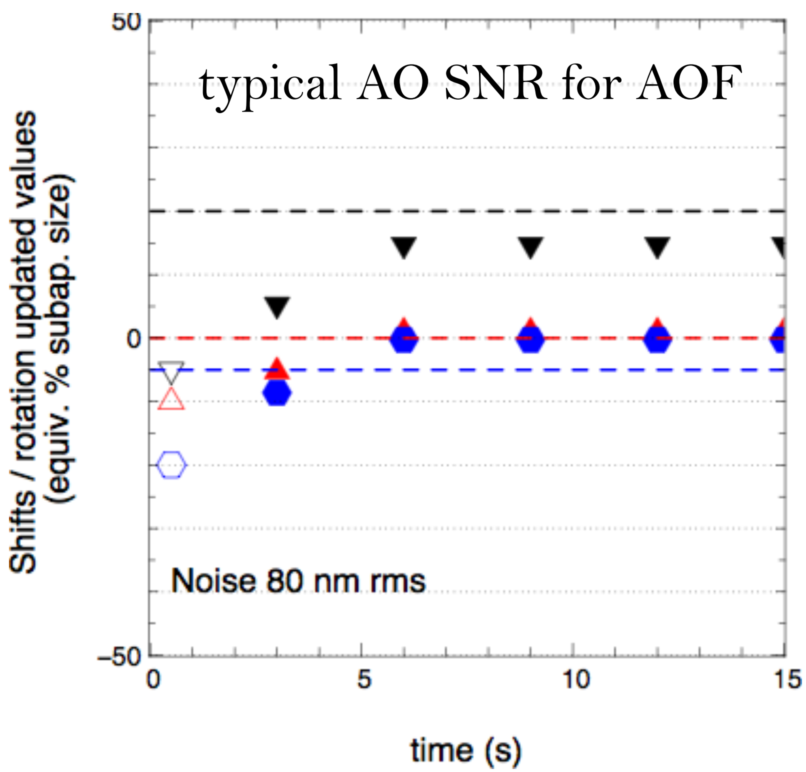
Just one button ON/OFF !

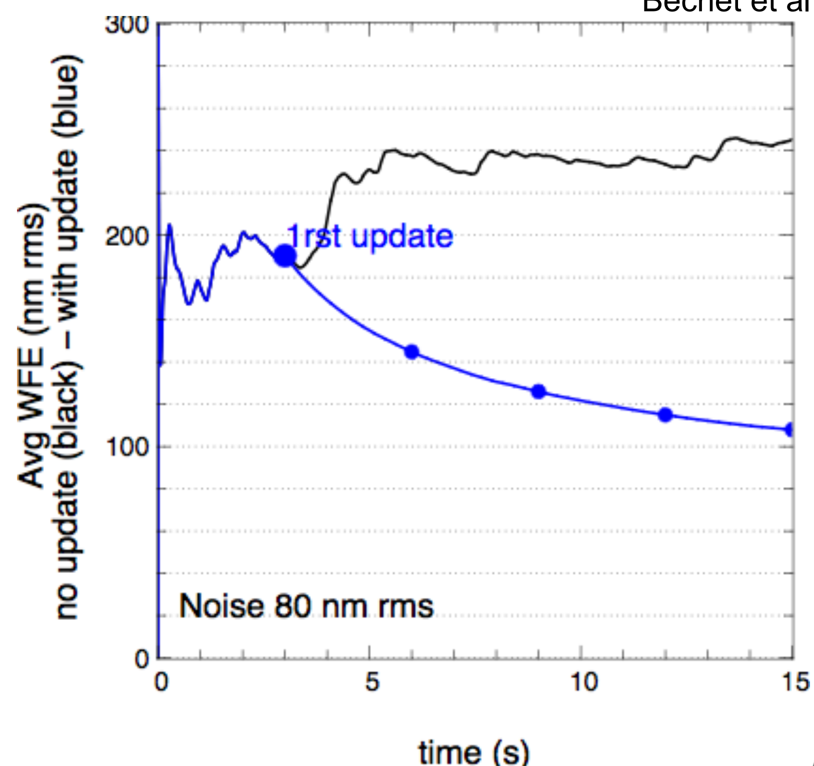
- Identification

Auto-Adaptive Optics

- Deformable mirror is in the telescope. Calibration !
  - telescope is now very flexible
  - differential rotation of the deformable mirror during the observation
- Need to maintain the optimum performance during the operation
  - on-sky identification of geometry in closed-loop : Auto-Adaptive Optics
  - update of the model of the system

Béchet et al 2011





Missing items

- Techno: deformable mirrors, RTC, detectors, lasers
- XAO (E-PCS)
  - prediction of wavefront evolution
  - fast reconstructors (large AO size)
  - other specific wavefront sensors (non linear curvature WFS, Mach-Zehnder, …)
- Measurements of the turbulence
  - on-line Cn2 vertical profiling (with more vertical resolution)
  - wind vertical profiling
  - outer scale monitoring
- Calibrations and system monitoring
  - Maintain the E-ELT diffraction limit with less stiffness (wind, vibrations, …)
  - non-common path aberrations
- Dynamics of the sodium layer
- Control algorithms
  - various methods, but comparisons needed
- Numerical simulations
- Real time computer
- Post-processing
  - astrometry, photometry in AO fields
  - PSF reconstruction from AO data
- …

Slide from Norbert Hubin (head of ESO AO group), conference AO4ELT 2013

Global vision & walking before running

- All AO systems for E-ELT are challenging & costly:
  - Many new concepts are still in demonstration phase or have not been fully operated on smaller telescopes for science ➔ **Pathfinders**
  - Technologies required are often one step behind ➔ **Dev. needed**
  - Operation, Control & calibration strategies are still being figured out ➔ crucial effective operation of AO system for science ➔ **Pathfinders**
- Global vision is essential to reduce cost & risks for all
  - 1 observatory cannot cope with all challenges alone➔ Fair collaboration is highly desirable: TMT-GMT-ESO-LBT-Gemini-Keck-WHT-SUBARU...
  - **Reasonable global** pathfinding vision, good view of essential **technological bricks** & cross fertilization of ideas between teams is **vital […]**

Slide from Norbert Hubin (head of ESO AO group), conference AO4ELT 2013

Global vision & walking before running

- All AO systems for E-ELT are challenging & costly:
  - Many new concepts are still in demonstration phase or have not been fully operated on smaller telescopes for science ➔ **Pathfinders**
  - Technologies required are often one step behind ➔ **Dev. needed**
  - Operation, Control & calibration strategies are still being figured out ➔ crucial effective operation of AO system for science ➔ **Pathfinders**
- Global vision is essential to reduce cost & risks for all
  - 1 observatory cannot cope with all challenges alone➔ Fair collaboration is highly desirable: TMT-GMT-ESO-LBT-Gemini-Keck-WHT-SUBARU...
  - **Reasonable global** pathfinding vision, good view of essential **technological bricks** & cross fertilization of ideas between teams is **vital […]**

My added comment : Adaptive optics is not only engineering !

Thanks to Clémentine Béchet, Simone Esposito, Caroline Kulcsár, Cédric Plantet, Kacem El Hadi, Norbert Hubin, Emmanuel Hugot, Miska Le Louarn, Gaetano Sivo, …