

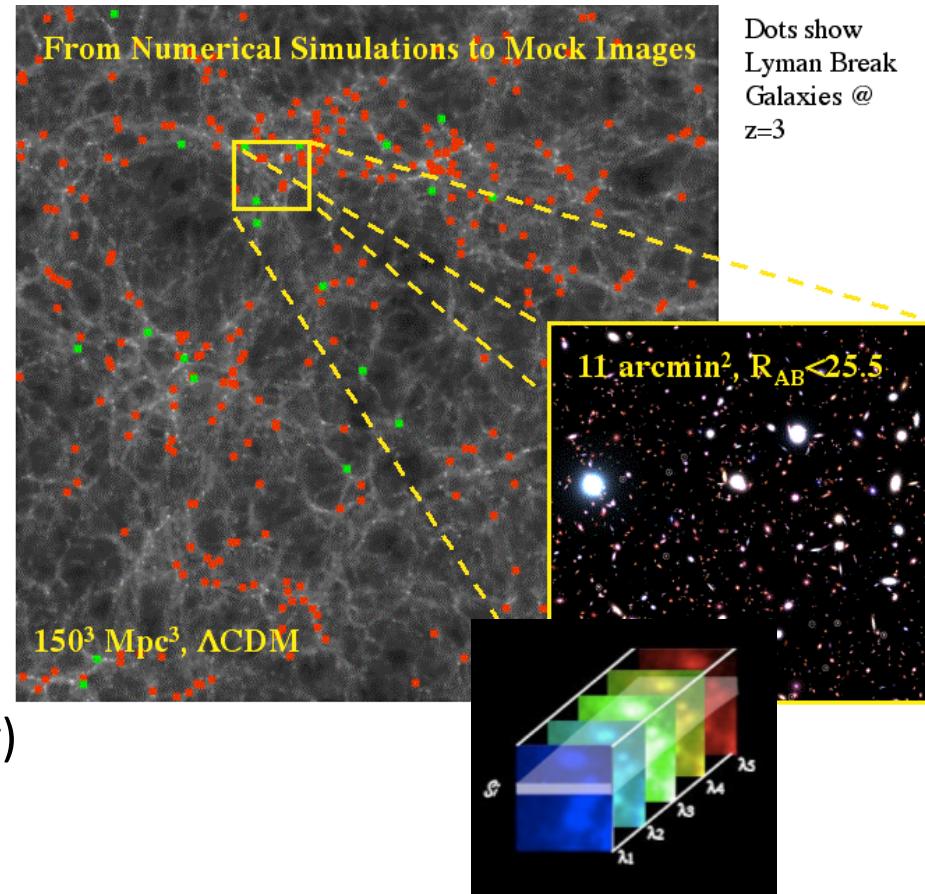


Towards MOAO on the ELT : the CANARY program

E. Gendron, T. Morris, F. Vidal, A. Basden, M. Brangier,
Z. Hubert, R. Myers, G. Rousset, F. Chemla, A.
Longmore, T. Butterley, N. Dipper, C. Dunlop, D. Geng,
D. Gratadour, D. Henry, P. Laporte, N. Looker, D. Perret,
A. Sevin, G. Talbot, E. Younger

Scientific drivers

- Formation of distant galaxies
 - chemistry
 - mass, dynamics
 - stellar populations
 - cosmic variance
 - small
 - low surface brightness
- Need
 - spectral resolution $R \approx 3000$ to 15000
 - 3D spectro in the near IR (high z)
 - concentrate light : AO
 - wide field ($\approx 10\text{-}20$ arcmin)
 - multiplex : numerous tiny objects, statistical studies



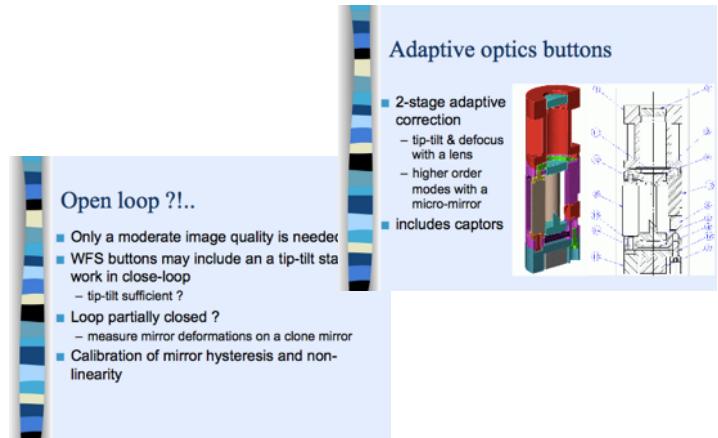


A section where it comes to some oldies but goldies ...

A LITTLE BIT OF HISTORY

MOAO's roots ?

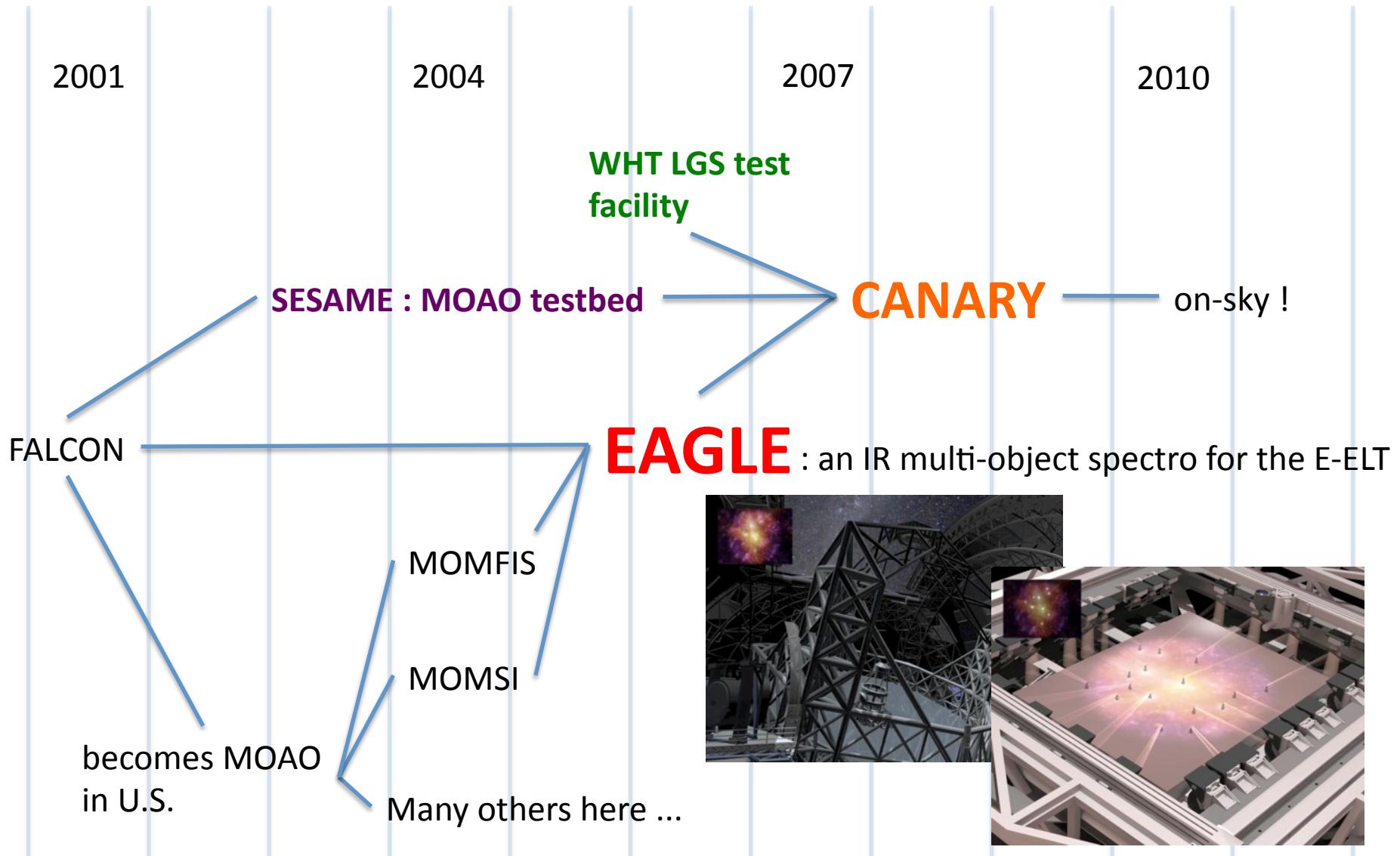
- FALCON: Earliest concept, May 2001
 - 2001 : Venice conf. « Beyond conventional AO »
 - FALCON « buttons » = IFUs that incorporate tiny open-loop AO systems inside
 - 2002 : Hammer et al., « The FALCON Concept », Scientific Drivers for ESO Future VLT/VLTI Instrumentation: Proceedings of the ESO Workshop
- LAO Director D. Gavel PI for the TMT MOAO instrument feasibility study
 - 2003-04 : “button” concept become “Prieto-Taylor” new design
 - Dekany et al. (2004), « AO requirements definition for TMT », Proc. SPIE 5490, 879 : MOAO becomes part of TMT instrumentation plan
 - IRMOS/TiPi (Aspen conf., sept 2005), Dekany R.
- MOMFIS
 - 2005 : presented at the Rindberg conf., opt. design Prieto.
 - Cuby et al., « The first galaxies: instrument requirements and concept study for OWL », conf. The scientific Reqs for ELTs, proc. 232nd Symp. of IAU, Cape Town, South Africa, November 14-18, 2005
- MOMSI
 - 2004 : Russel et al., “Instruments for a E-ELT”, SPIE 5492
 - 2006 : Evans et al., “A multi-object multi-field spectrometer and imager for a European ELT”, SPIE 6269



MOAO studies and prototypes

- SESAME testbed at Paris Obs.
 - laboratory MOAO testbed, feeding CANARY and EAGLE
- Tomographic AO at UCSC/LAO
 - laboratory high-order testbed
- Keck *Next Generation AO*
 - MOAO appears in the landscape in 2004
- Tohoku University
 - lab high-stroke MEMS devt and tomographic reconstruction
- MMT/GMT
 - on-sky, Rayleigh open-loop tomographic measurements in 2006
- Victoria Open Loop Testbed
 - on-sky, NGS I band open-loop experiment
- ViLLaGEs
 - on-sky open-loop MEMS experiment
- CANARY, Univ Durham & Paris Obs
 - on-sky MOAO demonstrator/pathfinder for EAGLE
- RAVEN, Uvic, HIA
 - scientific, on-sky MOAO demonstrator/instrument on 8m in 2013/14

The genealogy of CANARY

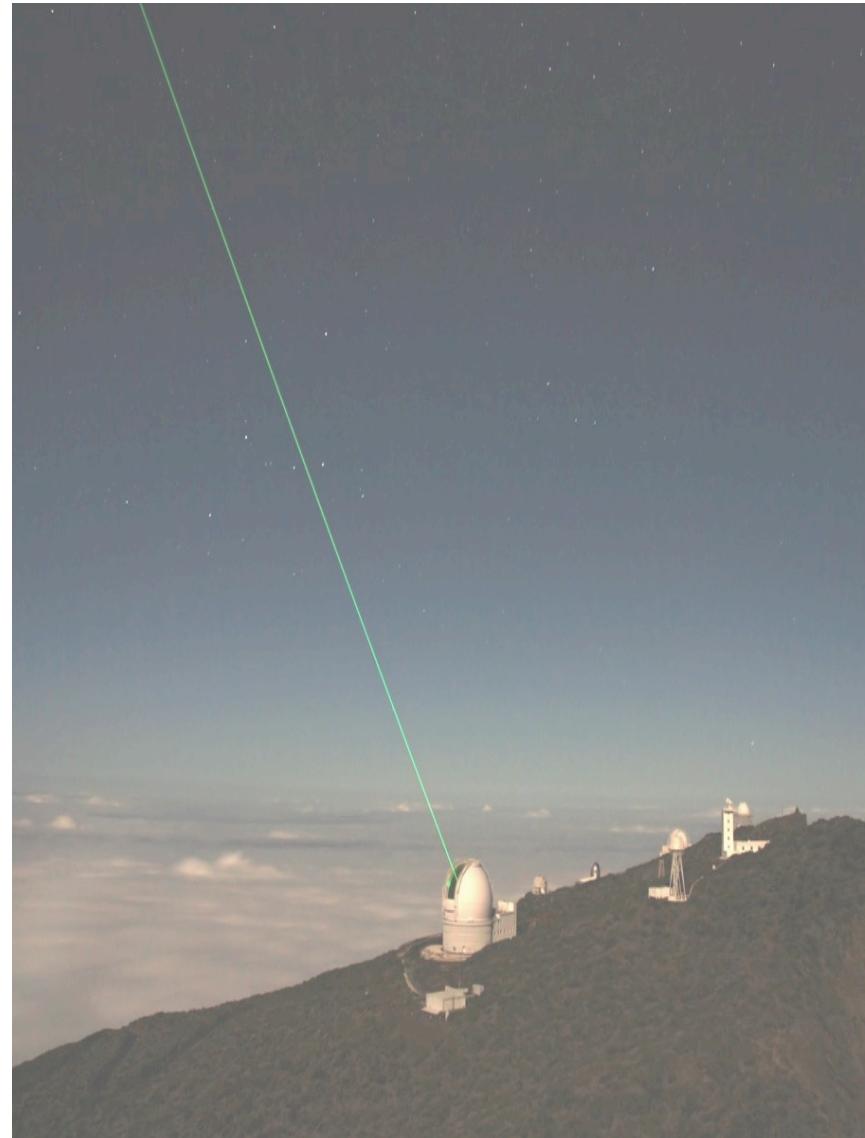


CANARY

- CANARY : the MOAO pathfinder for EAGLE
- No scientific goal –at least at the beginning–
- Technical goals
 - demonstrate **open-loop** functionning of a DM
 - demonstrate ability of doing **tomography**
 - demonstrate ability of system **calibrations**
 - ... all above simultaneously, and **on-sky**.

CANARY Phases

- Kick-off : 2007
- **PHASE A**
 - 2010
 - 3 natural guide stars (NGS) in open-loop
- **PHASE B**
 - 2011 & 2012
 - 4 rayleigh LGS in open-loop + NGS
- **PHASE C**
 - 2013
 - 2 DMs : woofer-tweeter
 - 4 LGS + NGS in closed-loop on the woofer, plus open-loop on the tweeter



CANARY : consortium



Observatoire de Paris : LESIA + GEPI

LESIA PI 2010



Université de Durham

PI 2011



Science & Technology Facilities Council
UK Astronomy Technology Centre

Astronomy Technology Centre, Edinburgh



Isaac Newton Group



L2TI and ONERA, Phases B et C

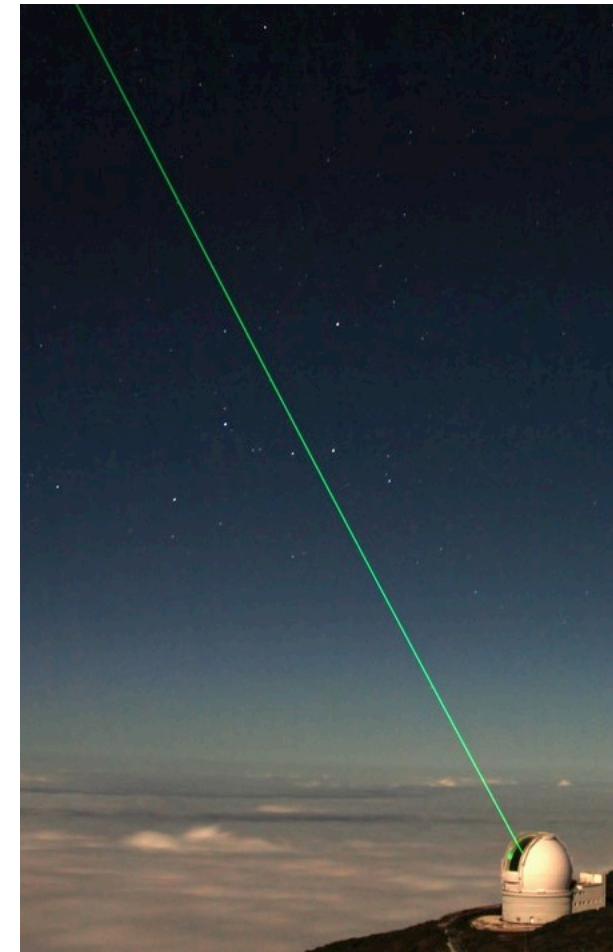


where it comes to hardware ...

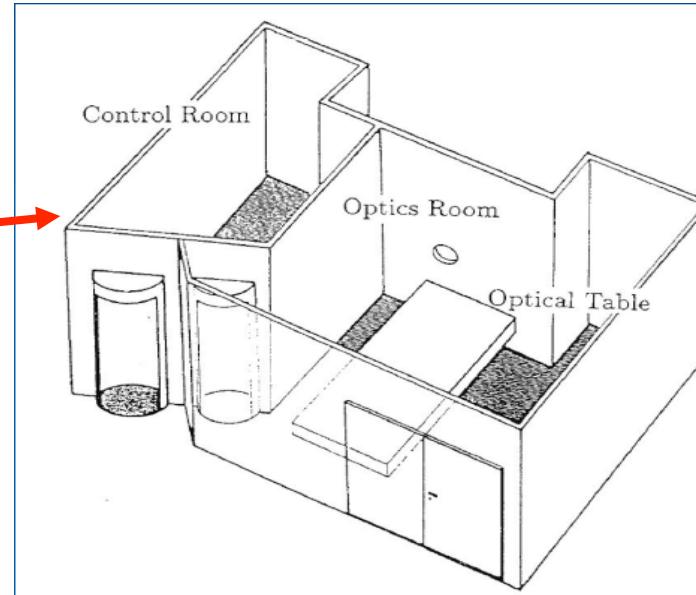
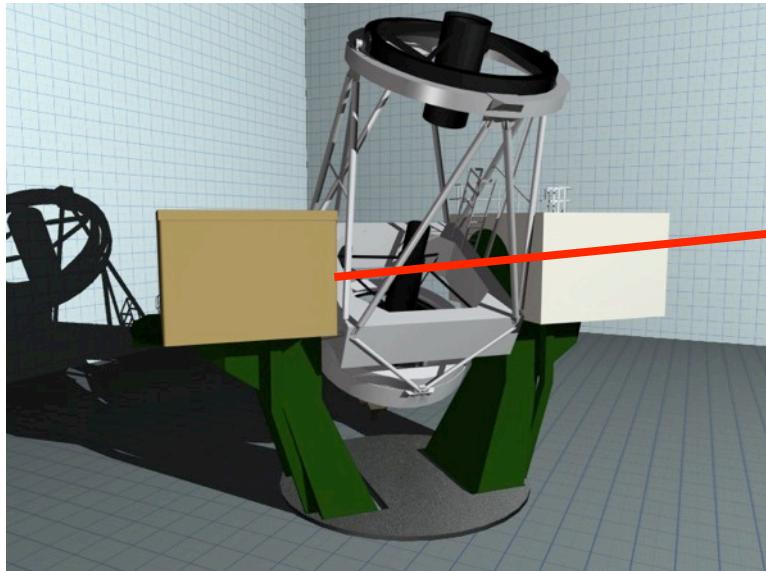
TECHNICAL DESCRIPTION

William Herschel Telescope

- 4.2m Alt-Az, La Palma
- Operational Rayleigh LGS: **GLAS Grond-laag Laser Adaptieve optiek Systeem (Ground-layer Laser AO System)**
 - 18 W 515nm
 - Launch System
 - 35cm telescope above M2
 - Safety Infrastructure
 - No fly zone
 - Launch permission
 - Traffic Control
 - MK clone
- MASS/DIMM 20m from WHT
 - SCIDAR 340m from WHT



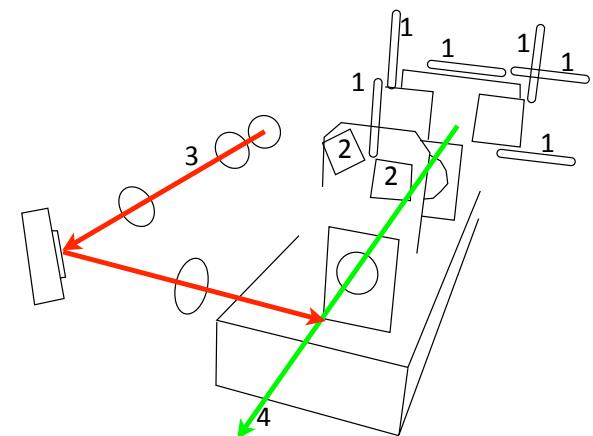
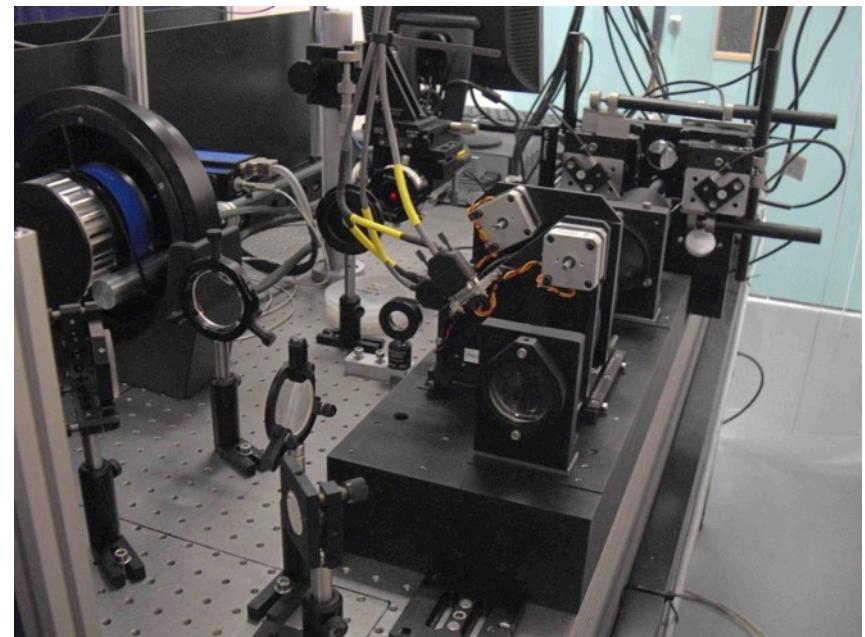
Nasmyth enclosure



- Entirely temperature controlled enclosure, humidity controlled
- Separation optics / electronics cabinets
- Rotater
- TCS Software

Telescope simulator

- Part of the CANARY bench
- Alignment laser
- 2.5 arcminute field-of-view
- achromatic
- **movable sources** : 5 seeing-limited + 5 diffraction-limited sources
- 1 central diffraction-limited IR source
- Light intensity : **remote controlled**
 - photometric calibration
- x-y positions : fully controllable
 - calibration
- 2 **phase screens** : controllable speed
- 5 **pupil masks**
 - telescope simul, alignment hole, 4 squares, full aperture, no pupil



Fold mirror / field lens

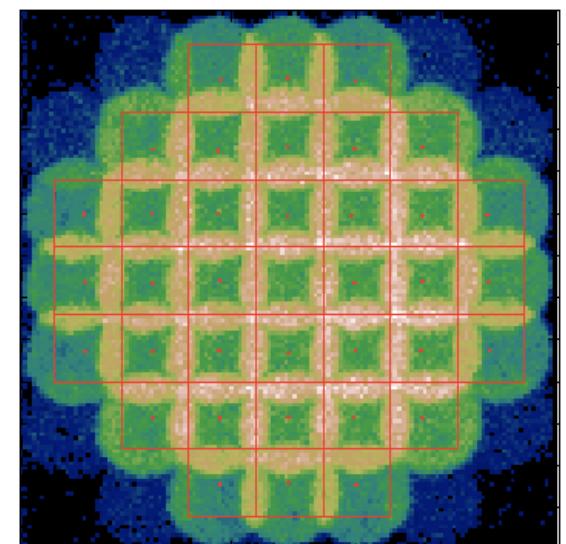
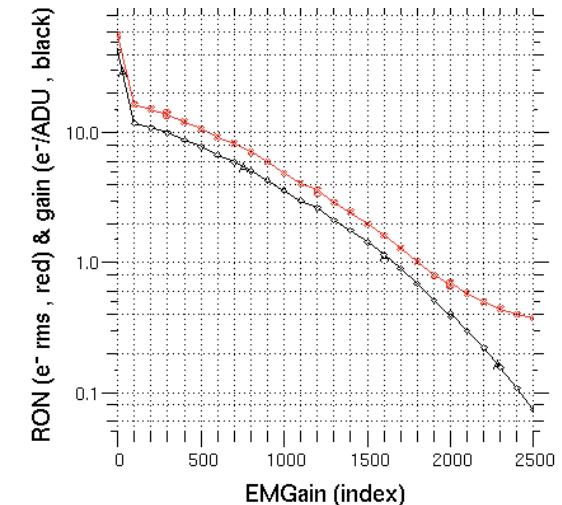
- 1 stage with 2 positions bears :
 - fold mirror : telescope simulator light
 - field lens (pupil at infinity conjugate) : WHT

Focal plane sources

- Translation stage remote controlled with :
- 1 seeing-limited IR source + 1 diffraction-limited visible
 - remote controlled
- 1 diffraction-limited IR
- retroreflector for reverse-path source
 - later on
- 1 free position

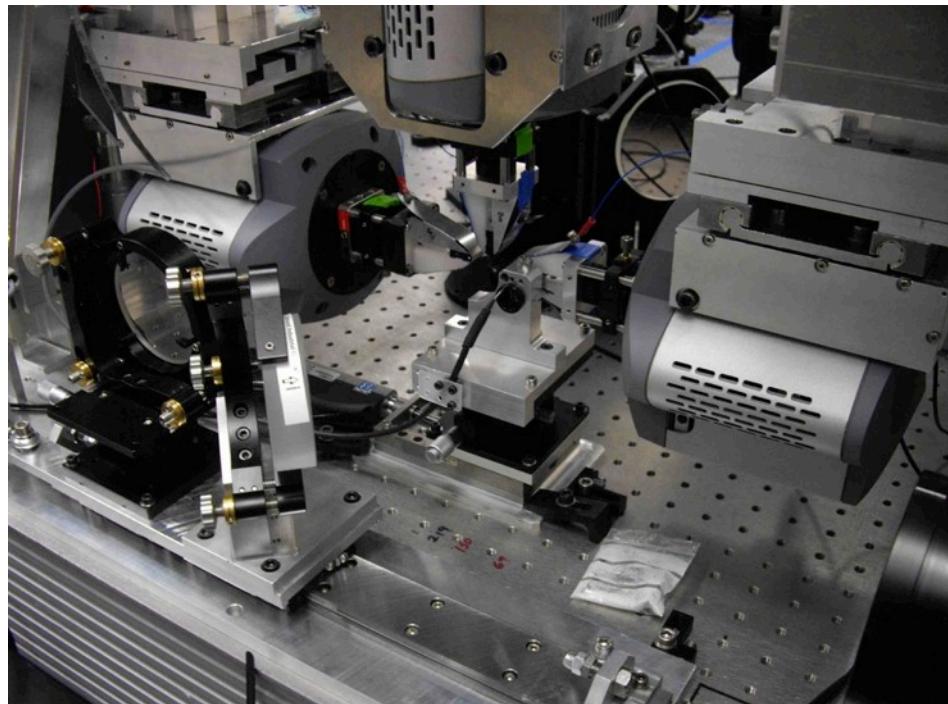
WFSs

- 3 x ANDOR iXonEM 860 EMCCD cameras
 - 128x128 pixels, 24 μ m
 - RON : 0.3 to 0.7 electron rms per pixel
 - cooled down to -60° (mandatory to get RON perf)
 - water-cooled
- 3 x WFS optics
 - 16x16 pixel / subaperture
 - 0.28"/pixel
 - microlenses 380 μ m pitch on a negative lens, 12mm focal length
 - optical alignment capabilities (pupil and field)
 - pick-off prism with field stop 6 arcsec
- Minimum distance : 20 arcsec

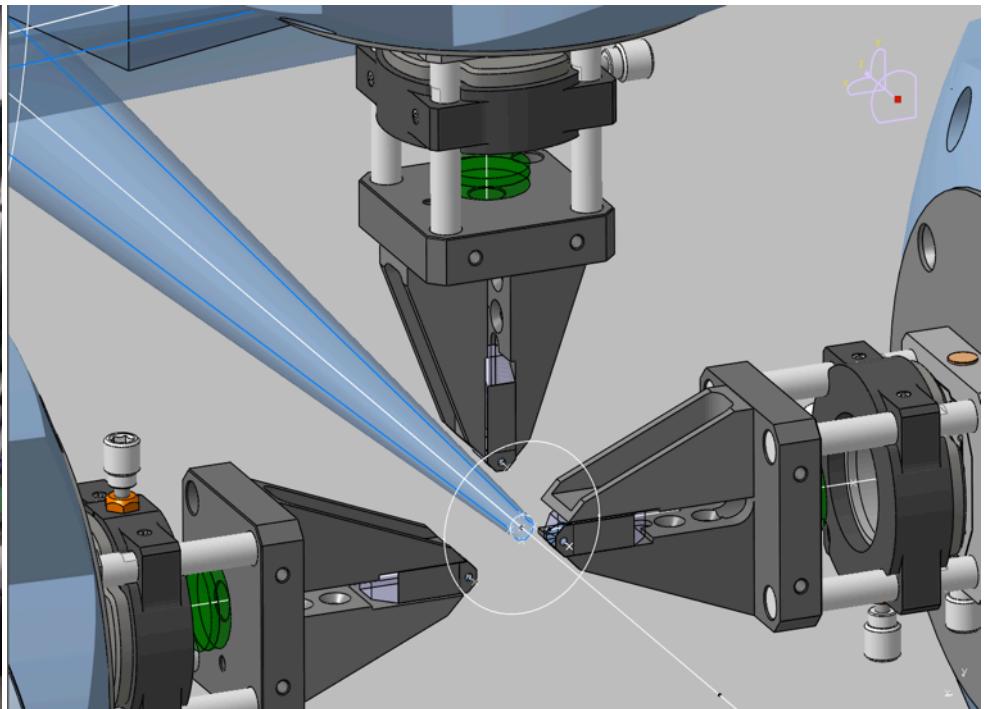
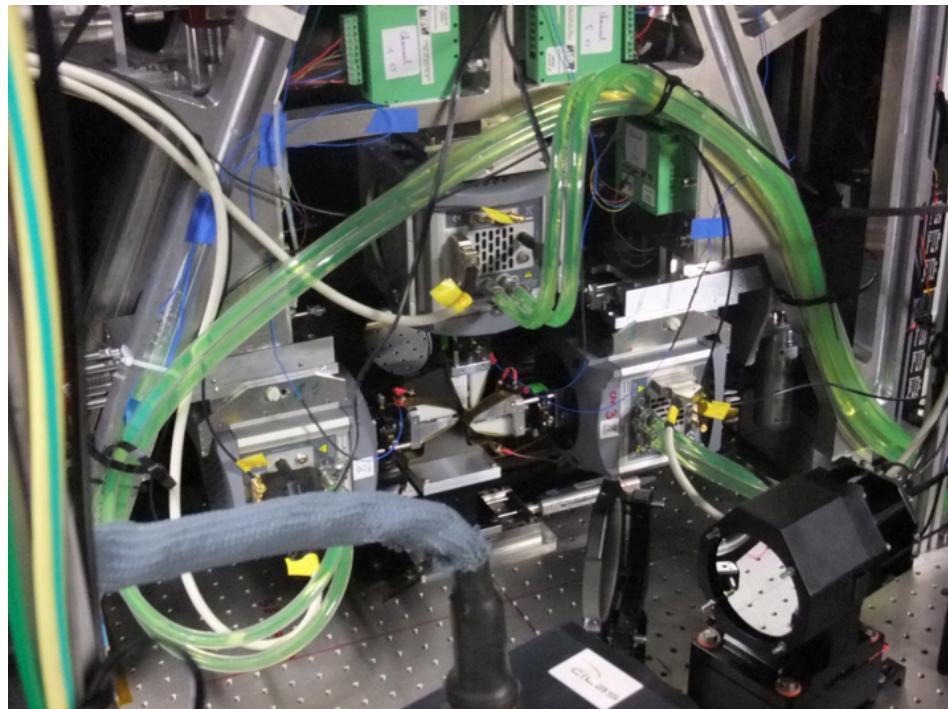
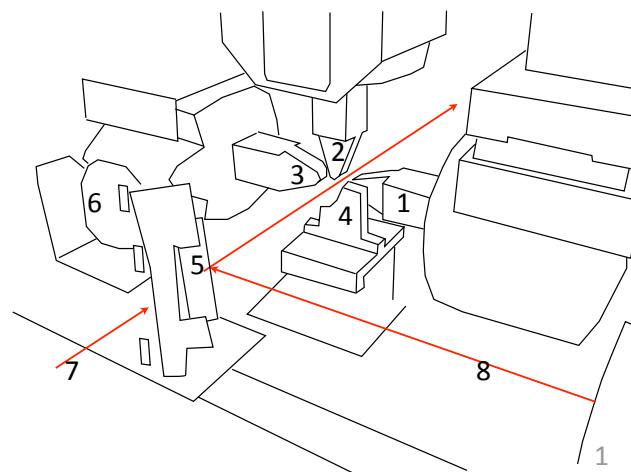


Target Acquisition System (TAS)

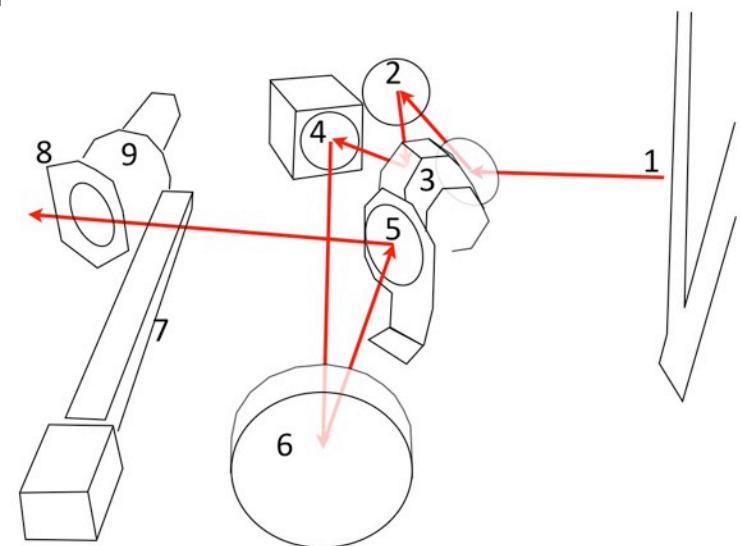
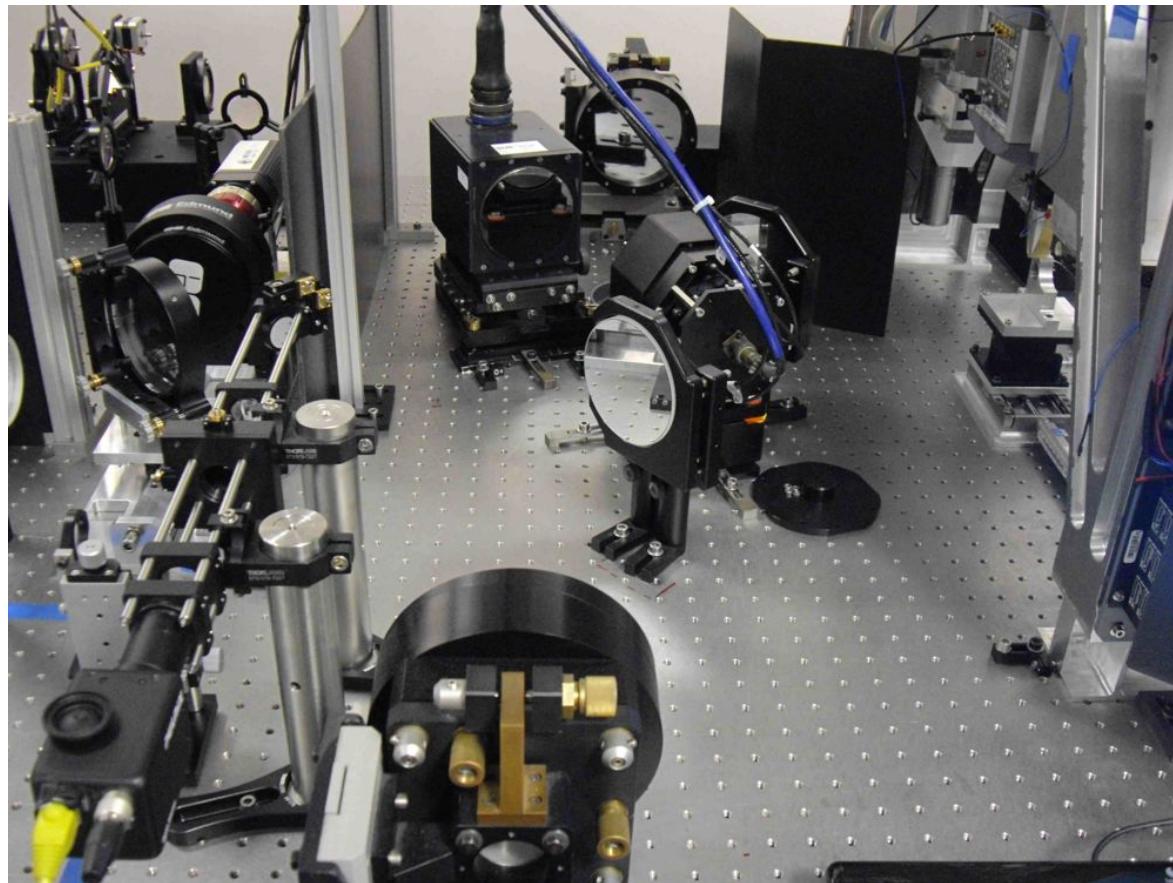
- 50 kg, 6 DC motors with 6 LVDT (position sensors)
- moves the 3 ANDOR cameras (4kg each) across the field of view
- abs. accuracy ≈ 0.1 mm (0.5 arcsec)
- fidelity better than $10\ \mu\text{m}$
- field of view > 2.5 arcmin (35 mm)
- anti-collision systems (hardware, low-level soft, soft)

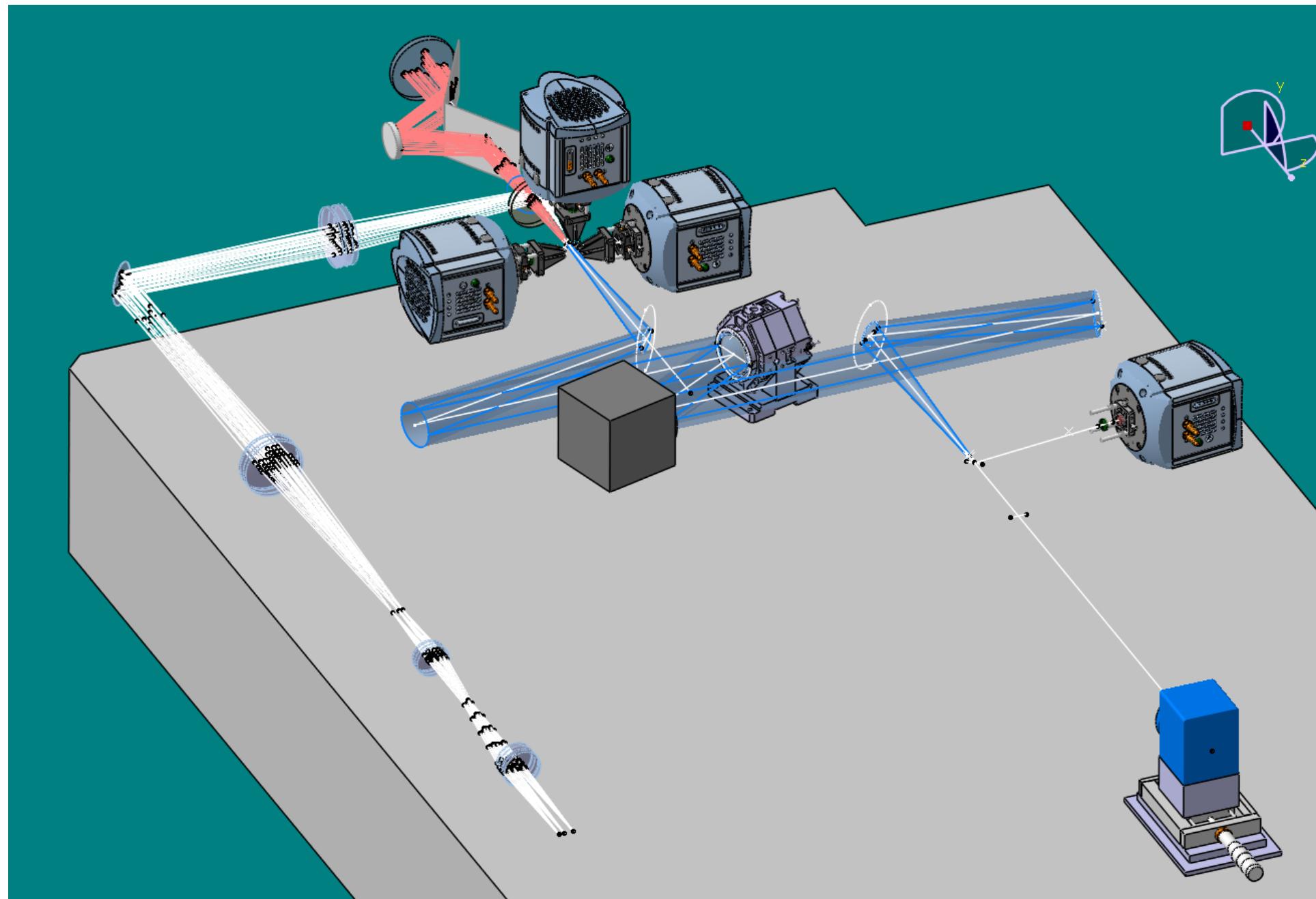


TAS



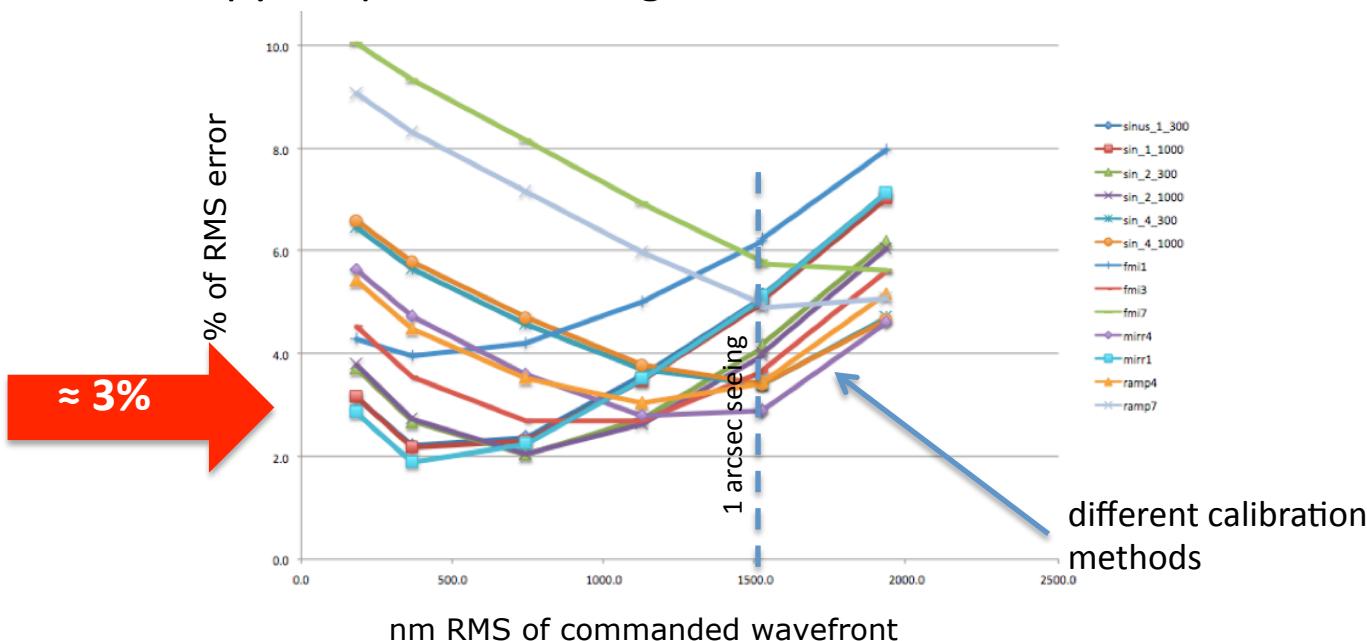
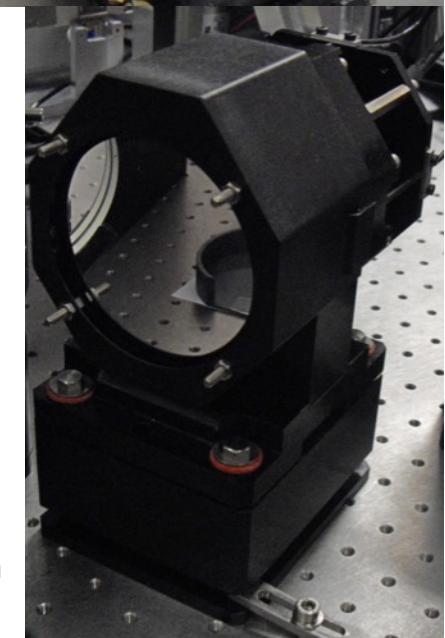
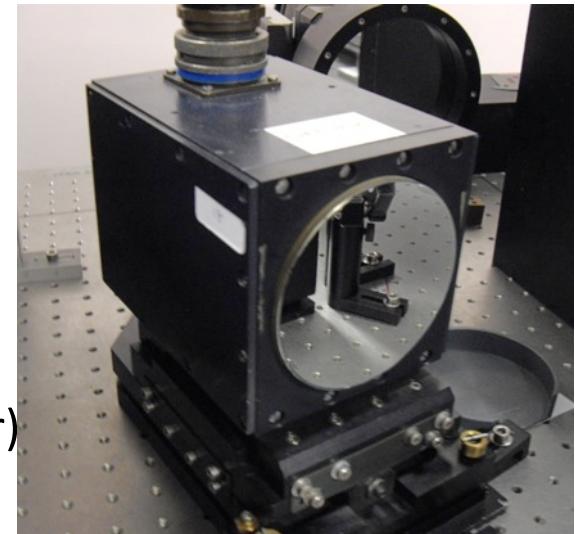
Common path





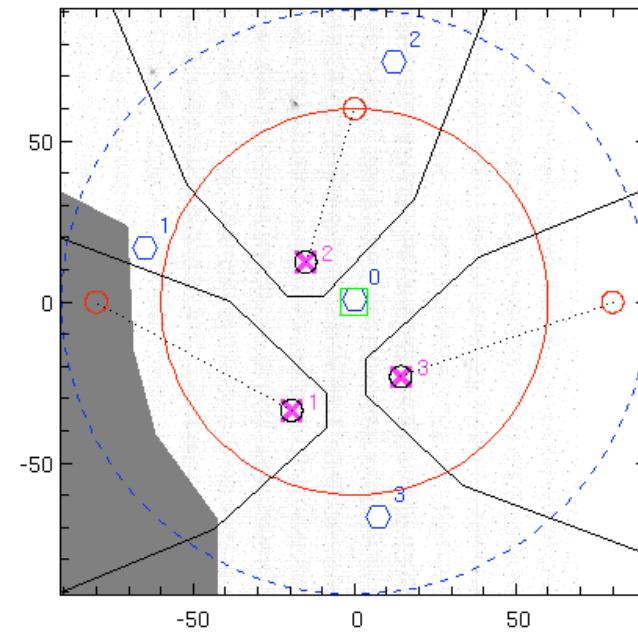
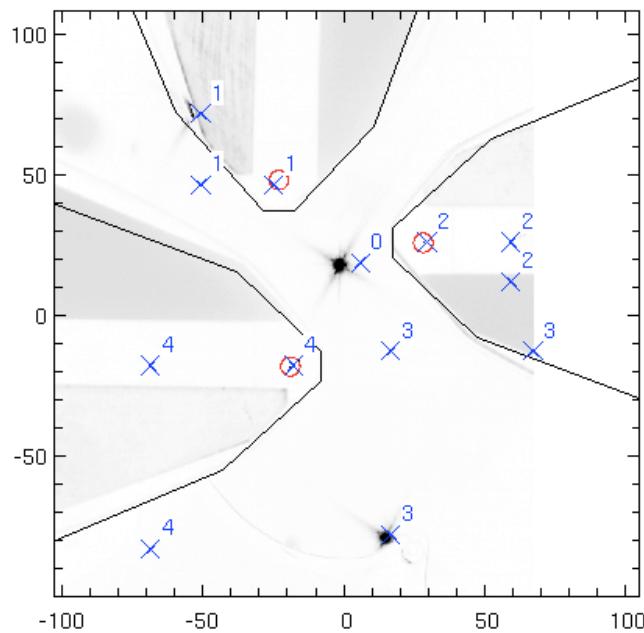
Corrective on-axis path

- 2 off-axis parabolae
- 2 fold mirrors
- 1 DM built by CILAS
 - piezostack, 8x8 actuators (52 useful in the pupil)
 - best flat 50 nm rms
 - characterized with Sesame already (<4% go-to error)
- 1 tip-tilt from Paris Observatory :
 - copy of sphere, but larger mirror surface



Acquisition camera

- Allows us to see the whole field and do the acquisition
- allows us to calibrate TAS and telescope simulator motion

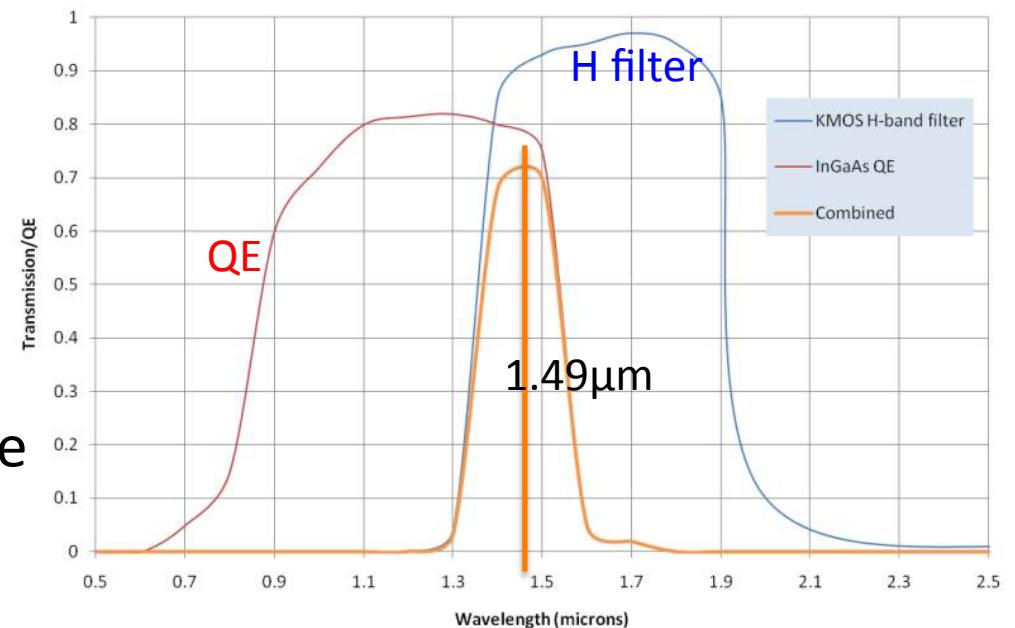


Output focal plane

- f/10.84, pupil at infinity conjugate
- Dichroic plate
 - 37° incidence
 - H band transmitted to imaging camera
 - visible reflected to **truth sensor**
- truth sensor seeing-limited ref source
- reverse path seeing-limited source
 - both remote controlled in position and intensity

IR camera

- Xeva-1.7-320 from Xenics
- pixel sampling of $0.037''$ on sky ($\lambda_{\text{H}}/\text{D} = 0.073''$)
- RON of 200 e⁻ rms per pixel
- 10 e⁻/ADU
- beam is opened at f/42.25
- 30 μm pitch
- 320×256 pixels
- filter : centred on $1.49\mu\text{m}$
- plug-and-play, FireWire
- interfaced with AO software



Truth sensor

- Clone of focal-plane WFS
- sees
 - the on-axis turbulence simulator
 - the DM
 - the whole bench
- allows us to **check image quality when loop engaged**
- allows us to **close the loop in classical mode (SCAO)**
- allows us to **measure the tomographic reconstructor (Learn & Apply algo)**

DARC : Durham Ao Real-time Controller

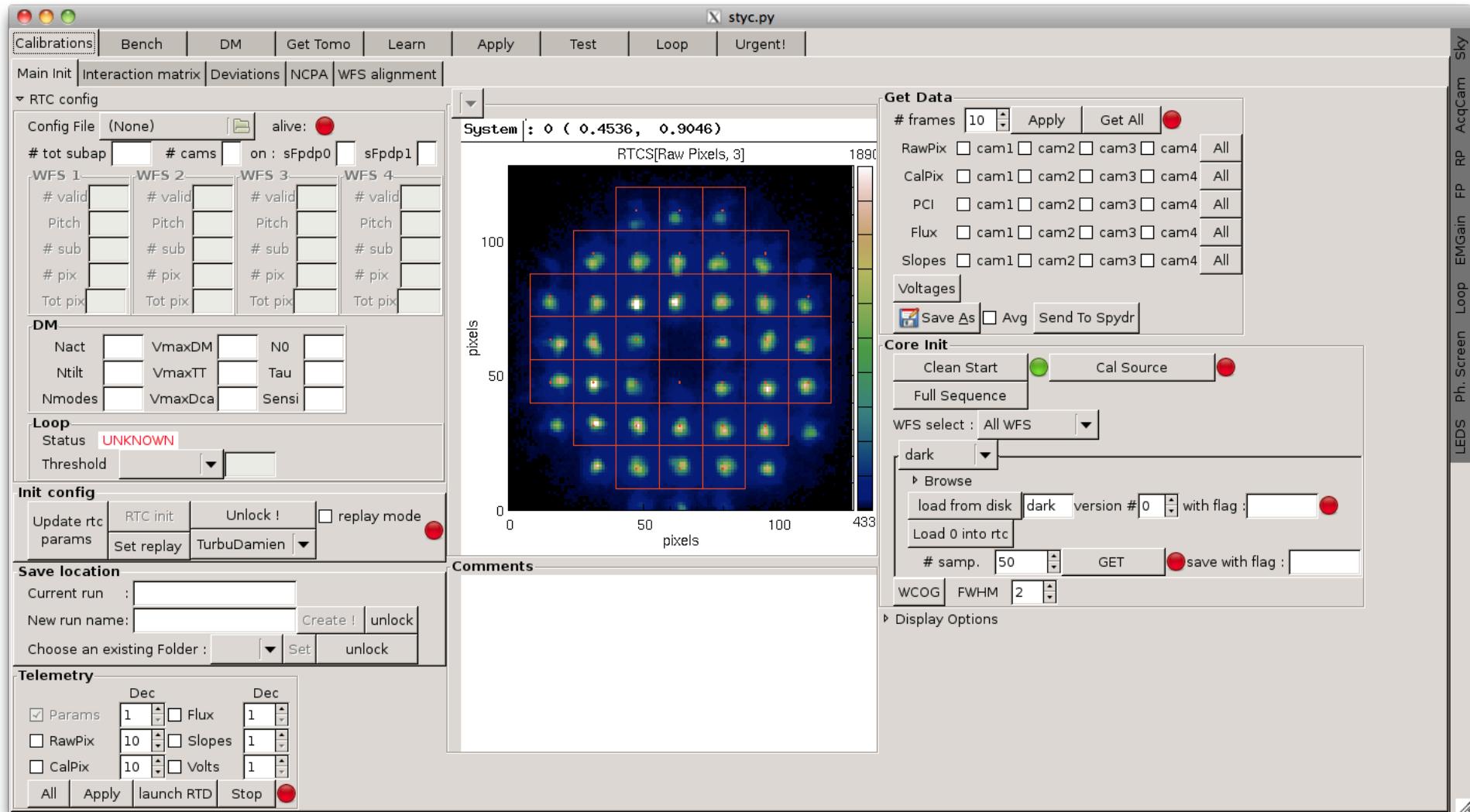
- CPU-based, Linux PC, multi-core, multi-threaded
- GPU-based, not tested on-sky yet
- Performs real-time control pipeline :
 - data acquisition from sFPDP
 - centroiding (if not done by WPU)
 - matrix multiply
 - temporal reconstructor
- Control software
- Telemetry streams (=data)
 - pixels, slopes, volts, and much more.
- Scripting either with
 - CORBA library from C, python, java etc
 - line-command interface
- Latency (reception of last pixel → 50% actuator movement) ≈ 1 ms
- talk by Ali Basden this Friday, 9h40

Centroiding

- Floating adaptive windows (**1st time on sky**)
 - smoothly track the movement of the spot
- Adaptive threshold (**1st time on sky**)
 - brightest pixels algorithm
- Correlation
- WCoG

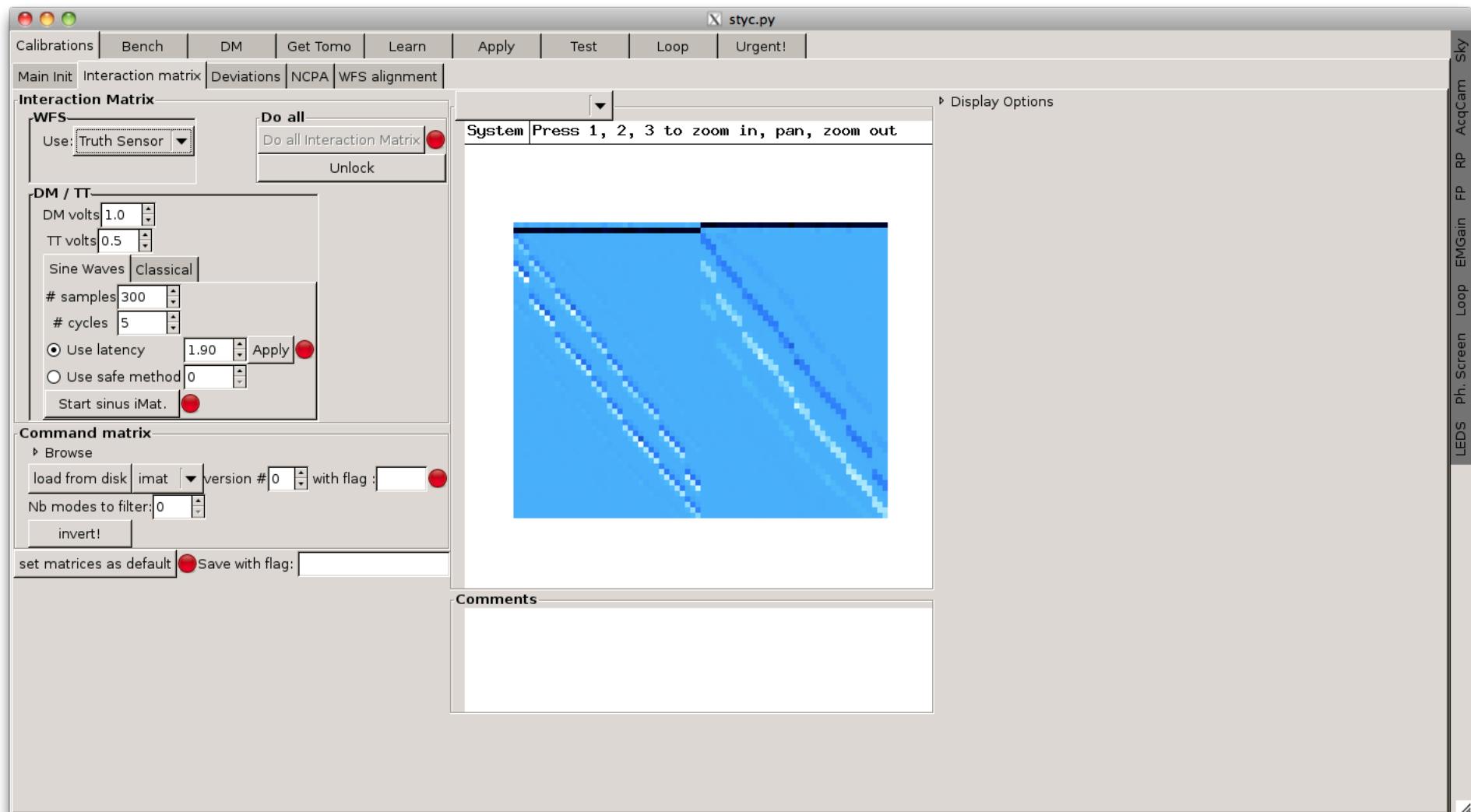
General panel

- Configure the state
- Get engineering data
- Calibrate ref slopes, dark, flats, background
- compute threshold



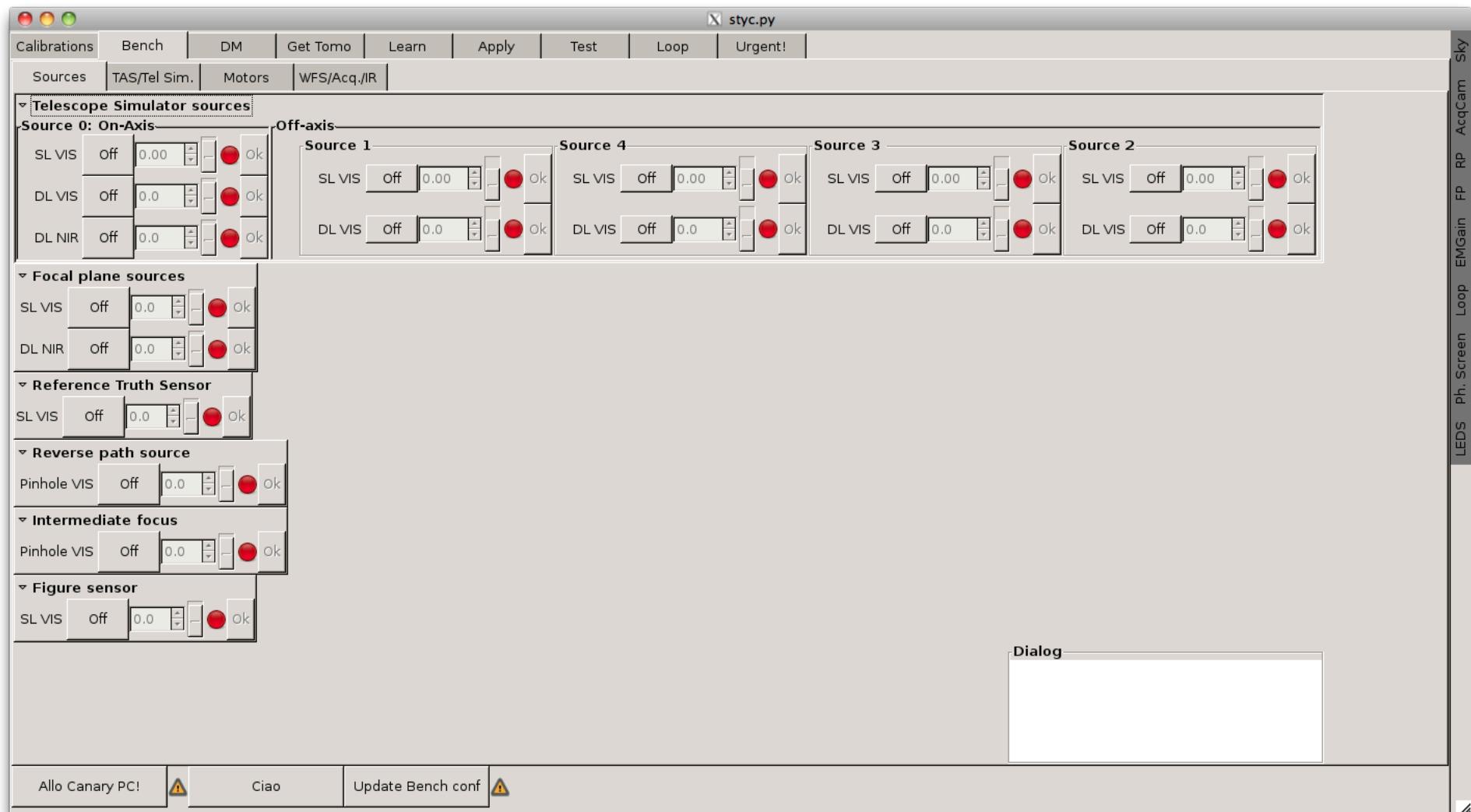
Interact. matrices

- Get interaction matrix (several methods)
- Invert it, diagnostic, save it
- manage 4 WFSs



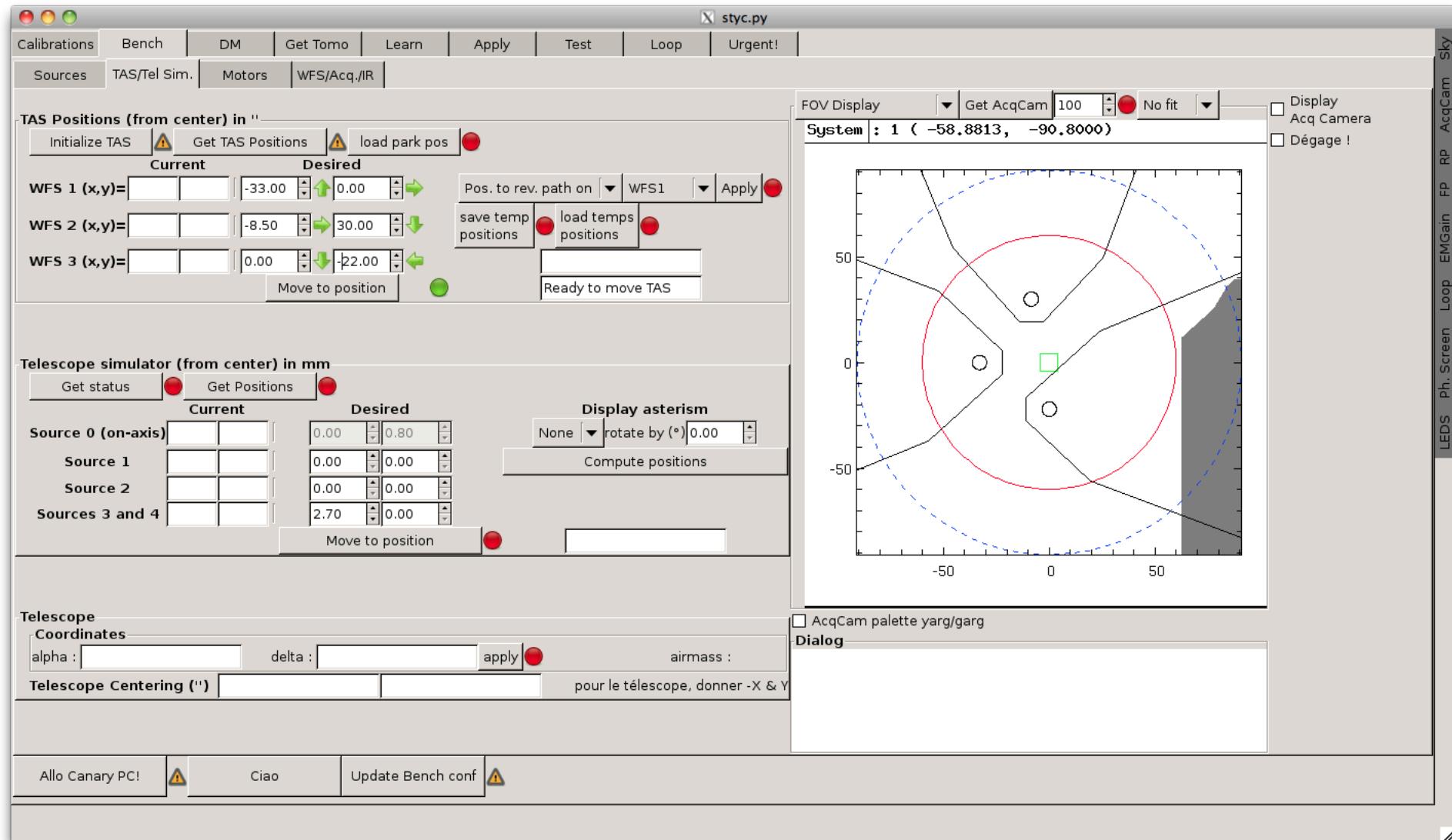
Bench: sources

- Control sources



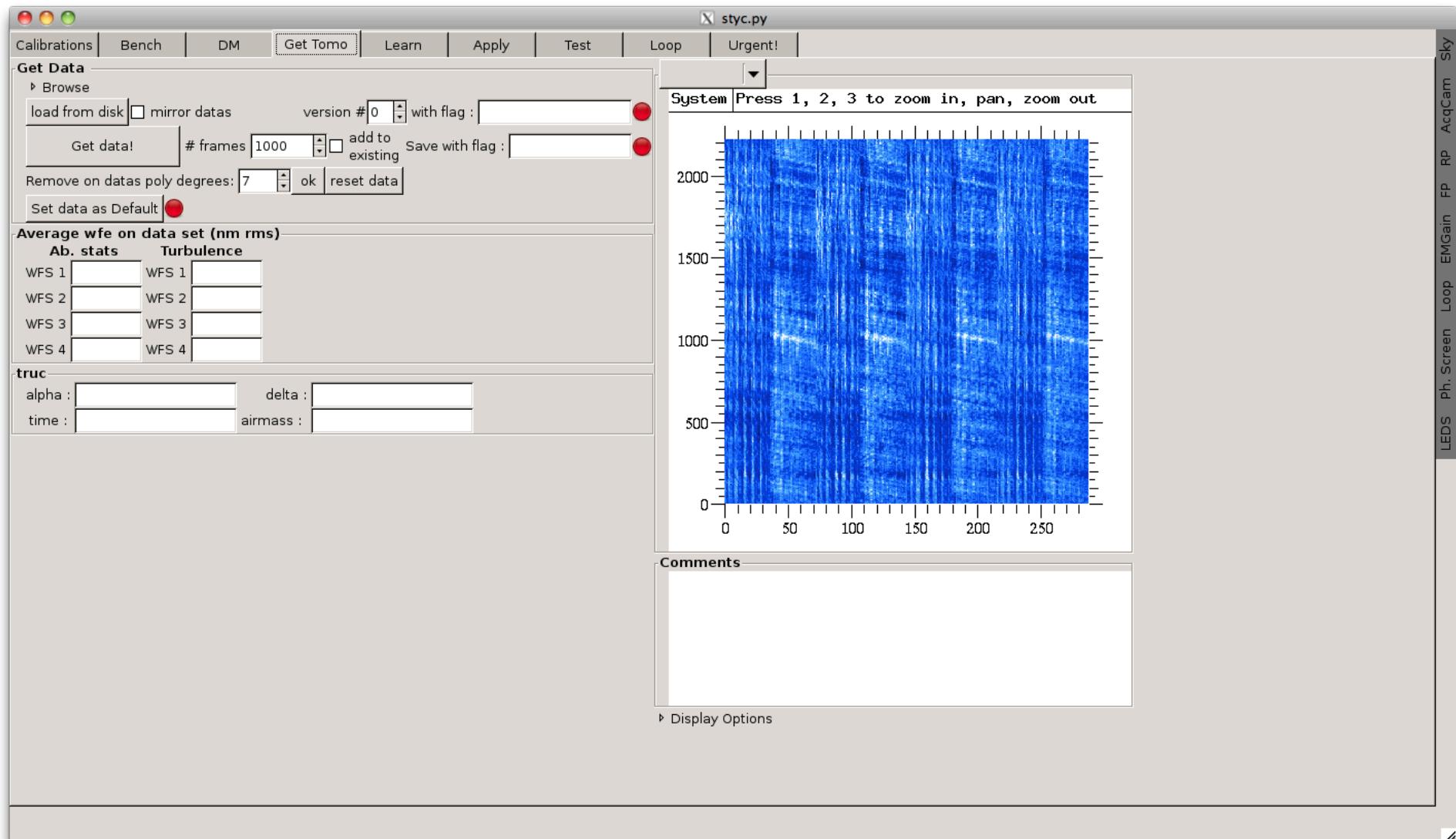
Bench: WFS positions & sources

- Control positions



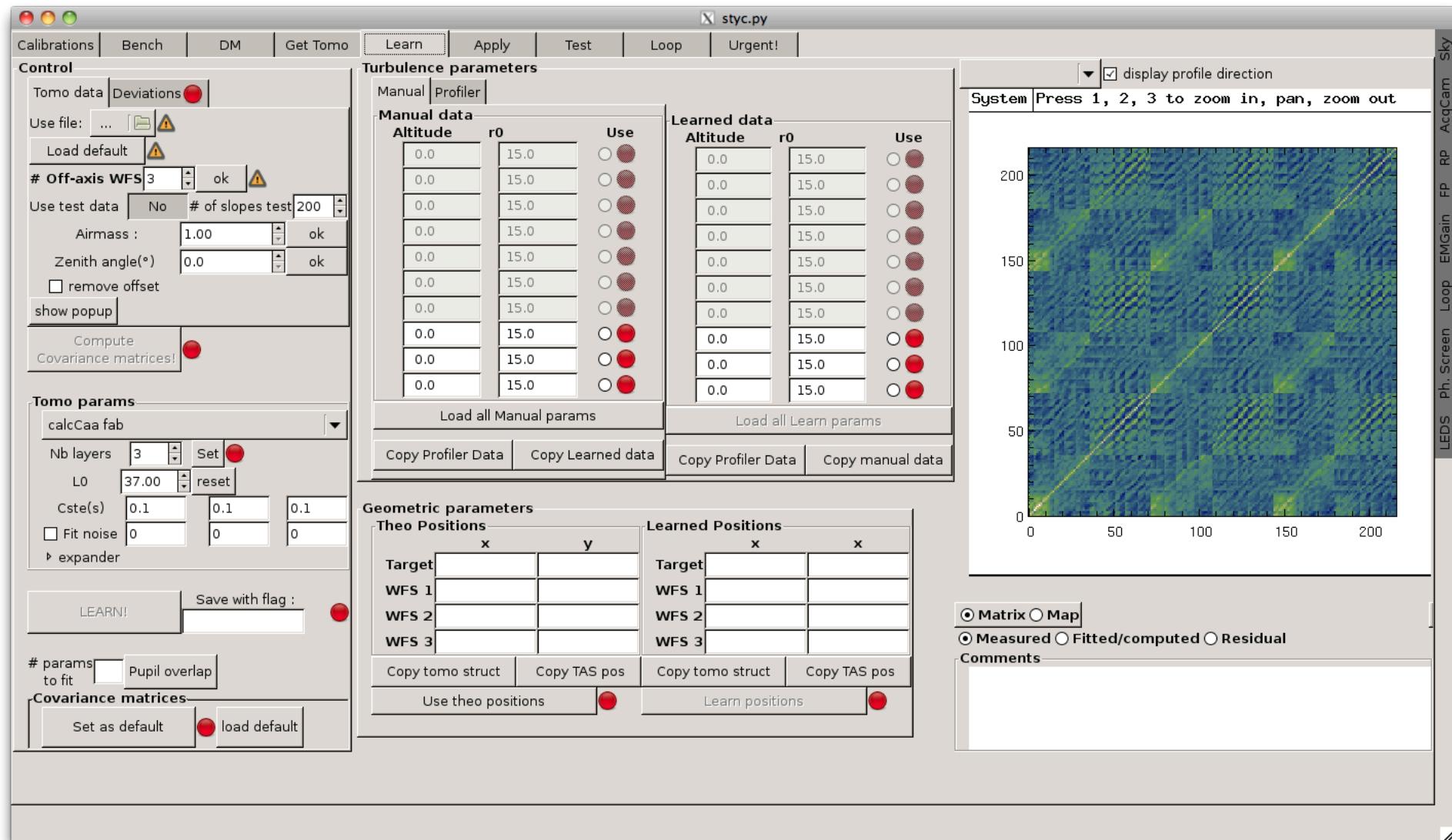
AO : get data for tomography

- Get data to compute the tomographic reconstructor



AO : processing data for tomography

- Learn profile

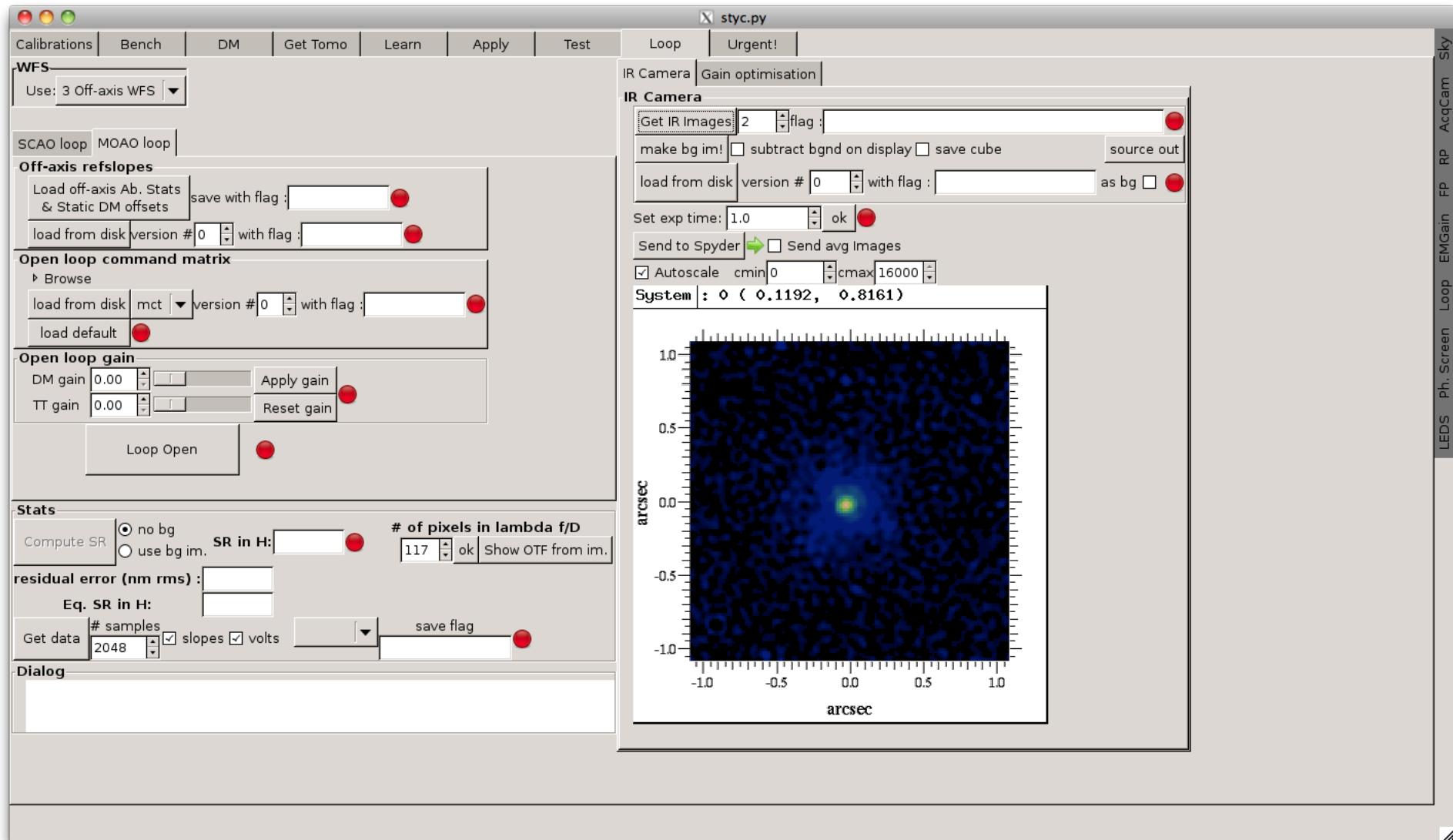


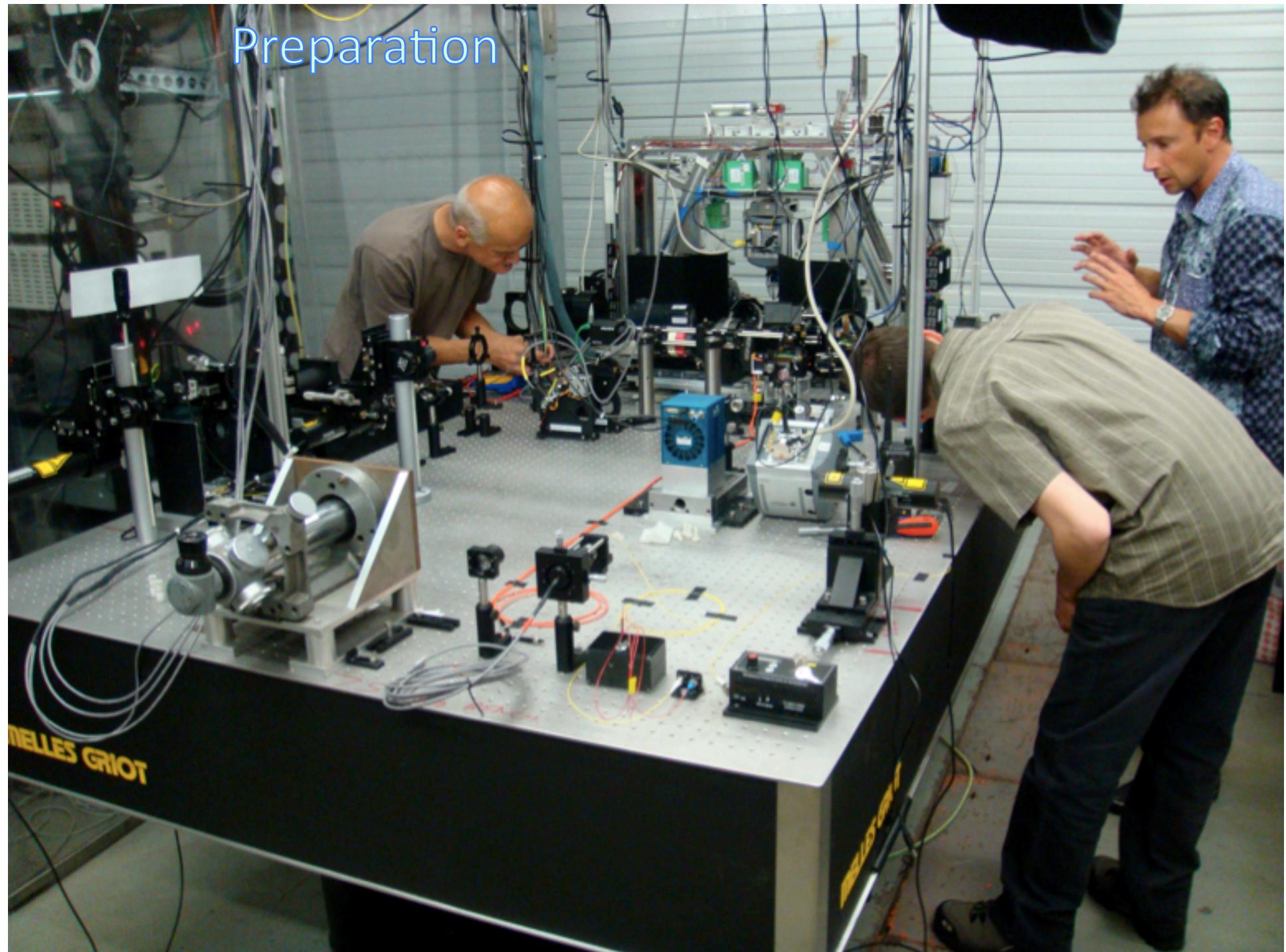
Full MOAO control algo

- **Learn and Apply** : optimal static approach (MMSE)
 - get data from turbulence
 - learn, from the truth sensor, what is the tomographic reconstructor (approximative)
 - introduce turbulence knowledge + a priori (kolmo, deviations)
 - introduce system command matrix (truth → DM)
 - get your final reconstructor
 - Vidal et al., « A tomography approach for MOAO », JOSA A, **27**, 253
- **Temporal optimization** : optimal temporal filtering
 - optimize the gain of an integrating filter versus
 - turbulence speed
 - noise propagated after tomographic reconstruction

AO : engage the loop and get IR data

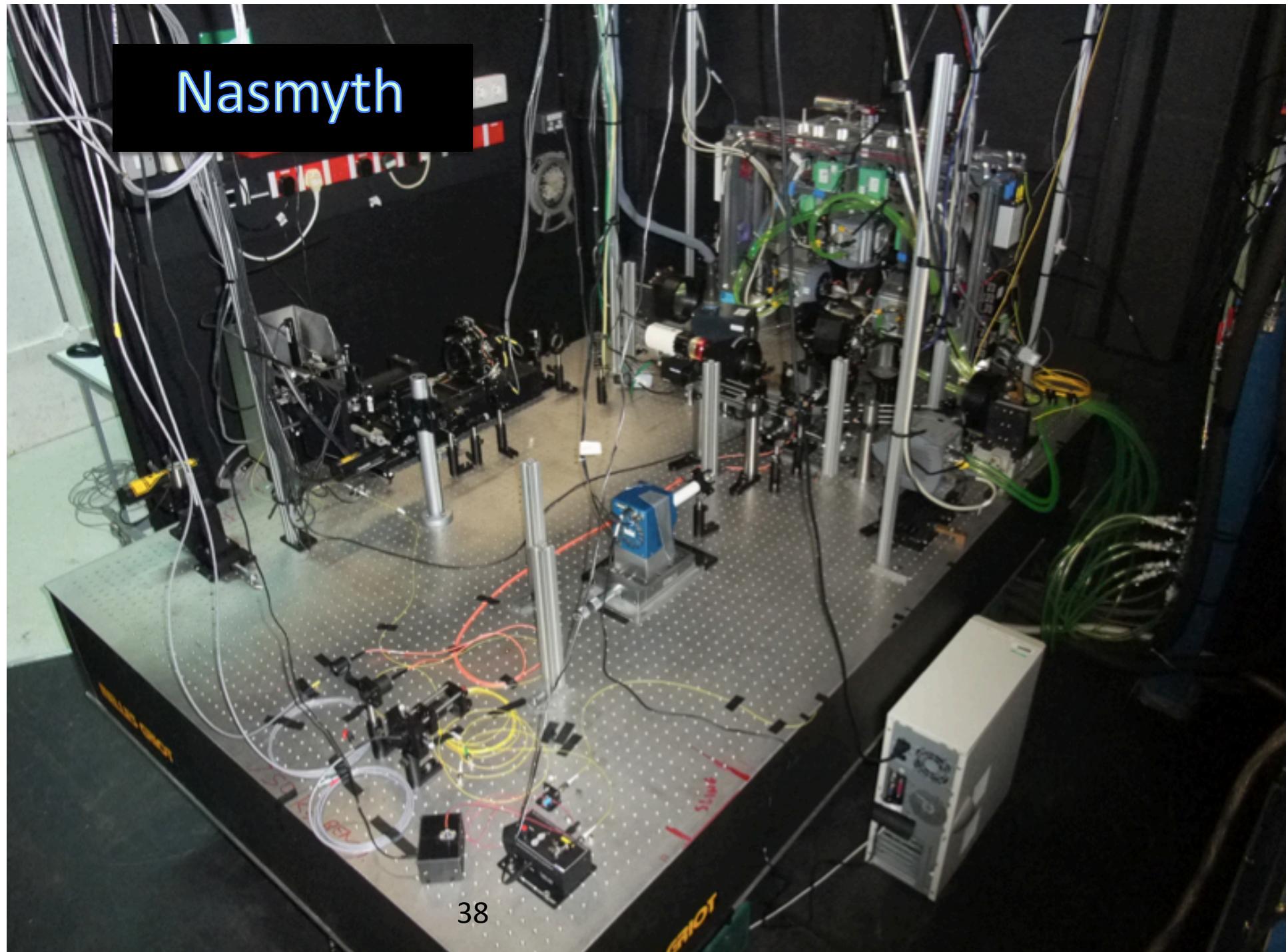
- get engaged-loop slopes data
- compute Strehl on IR image
- optimizes the loop gain for optimal noise rejection







Nasmyth





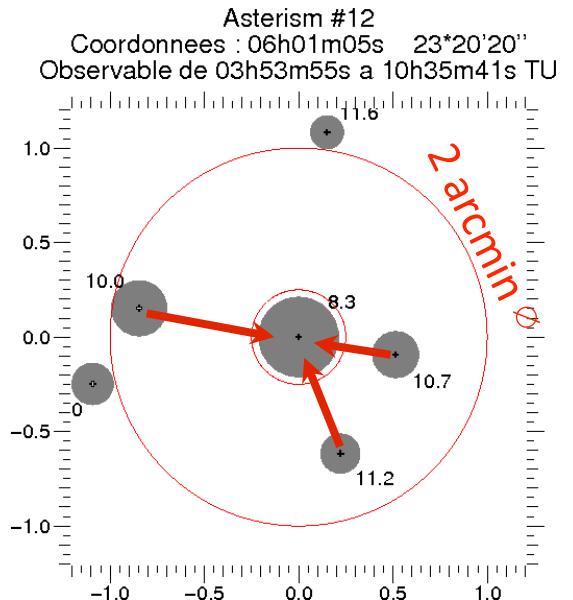
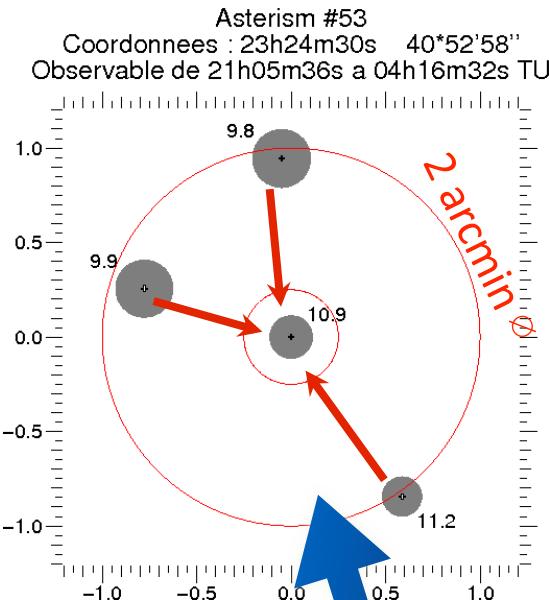
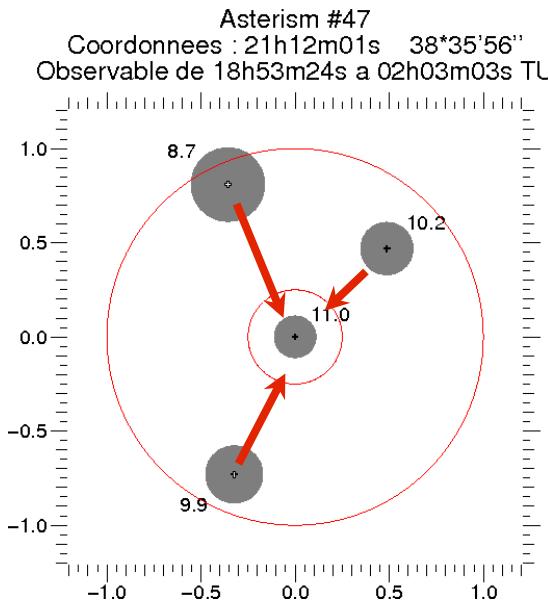
when it comes to numbers ...

ON-SKY RESULTS

Nights of Phase A

Nights	remarks
Sept. 19-20 2010	Telescope+canary calibrations No altitude layer (confirmed by slodar)
Sept. 22-23	--- bad weather
Sept. 26-27	--- bad weather 2h at the end of the night
Sept. 27-28	THE night.
Nov. 23-24	Difficult night
Nov. 24-25	--- bad weather
Nov. 25-26	--- bad weather
Nov. 26-27	--- bad weather

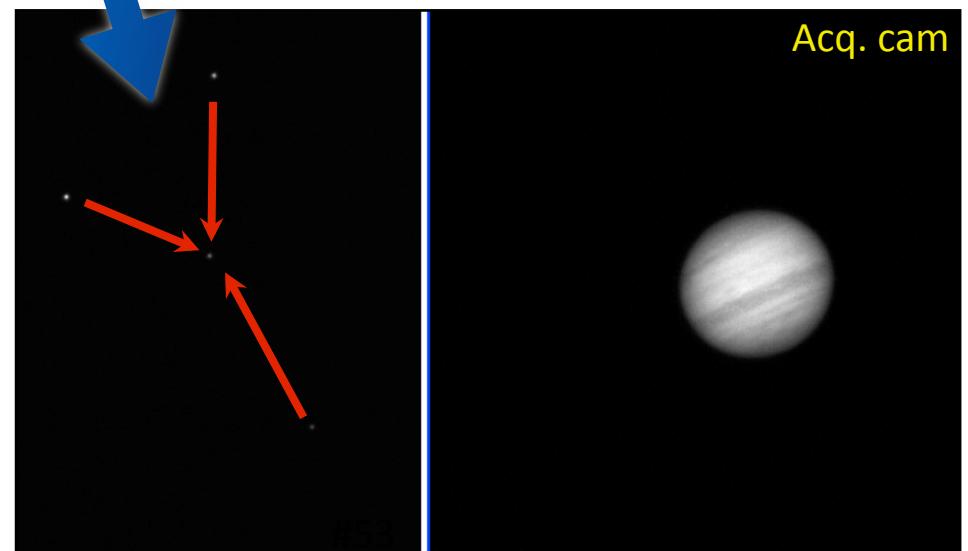
Observed asterisms



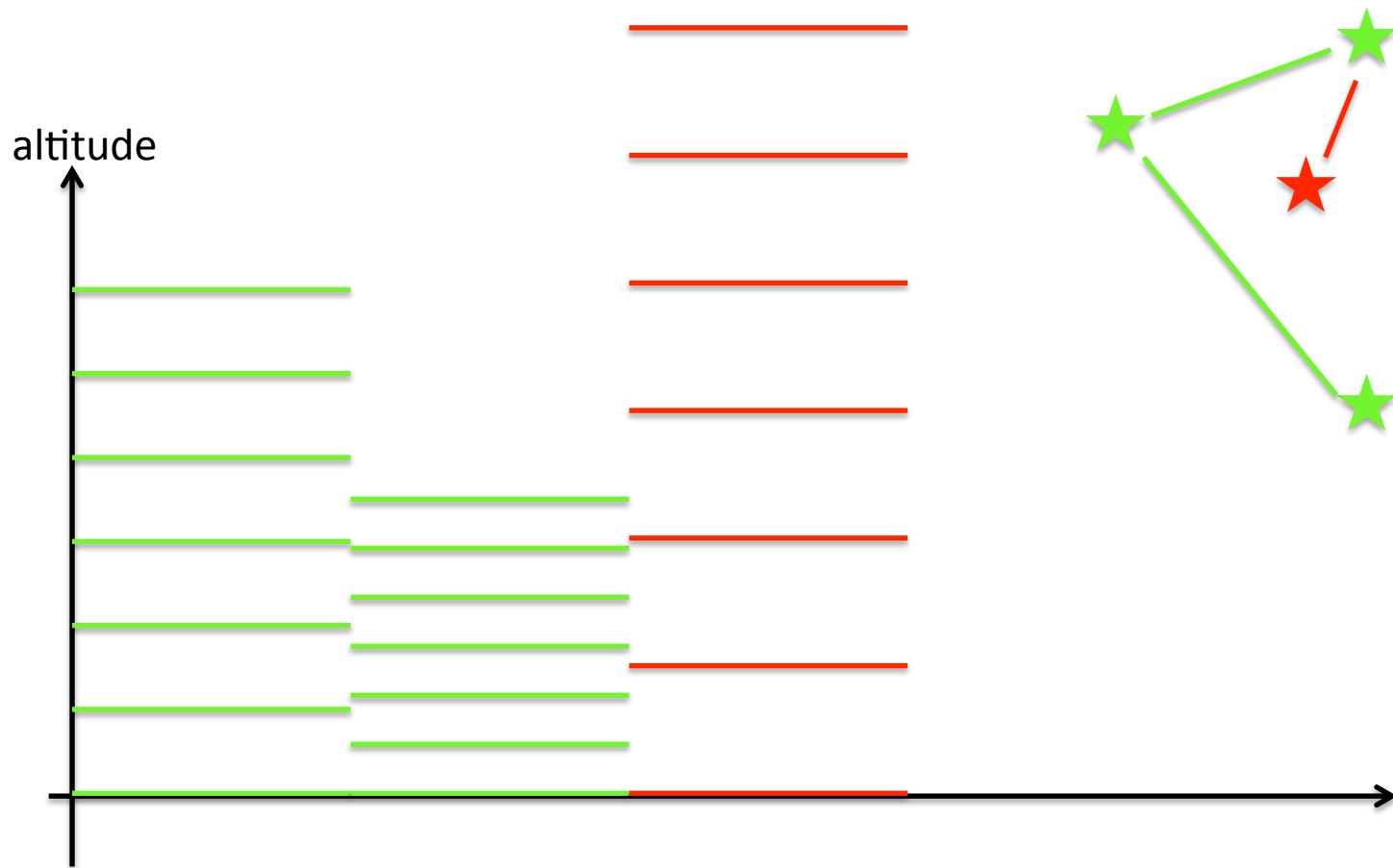
8.3 < magnitudes R < 11.2

25'' < Dist. from center < 65''

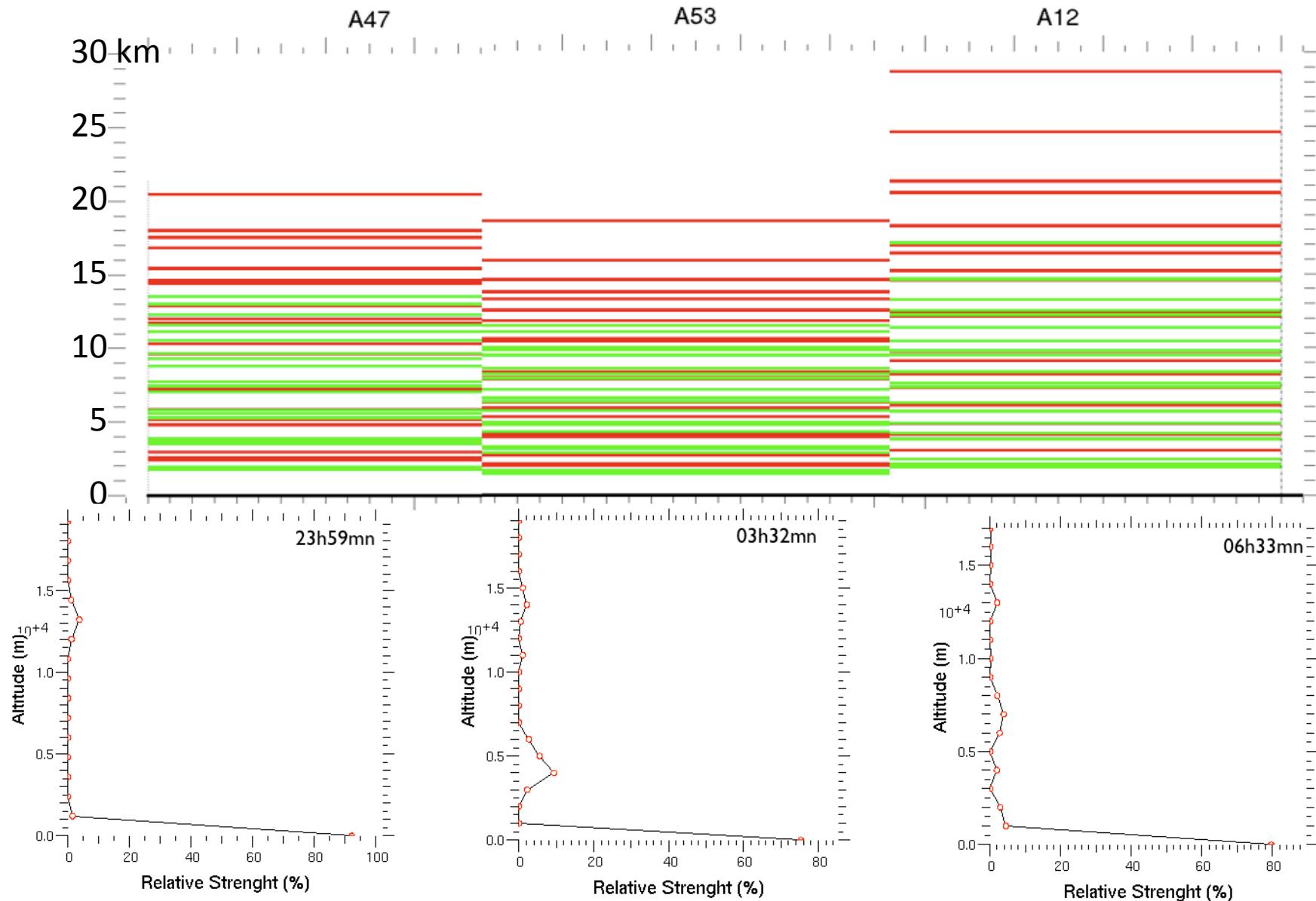
2.5' field of view



Built-in profiling

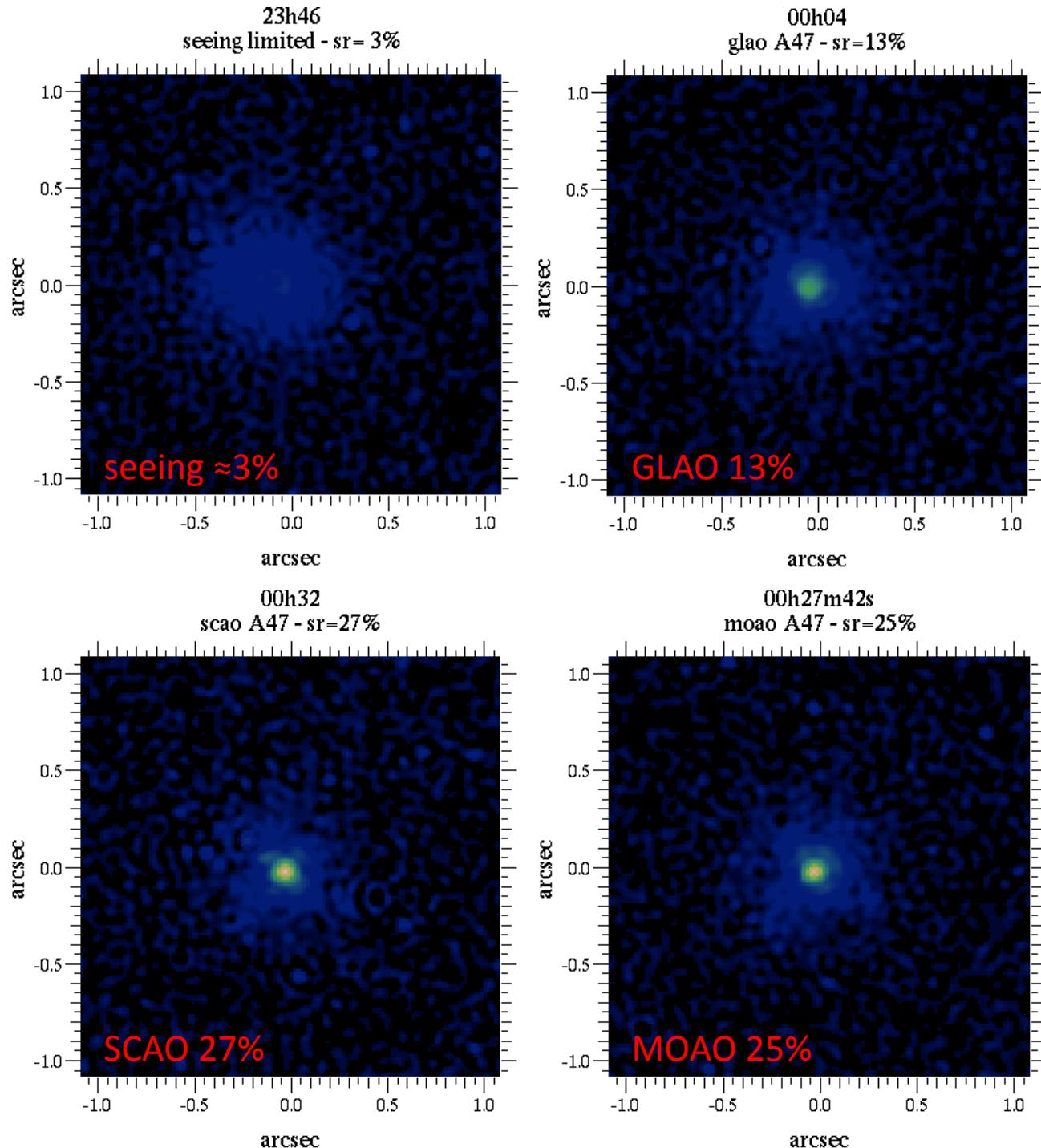


Built-in profiling

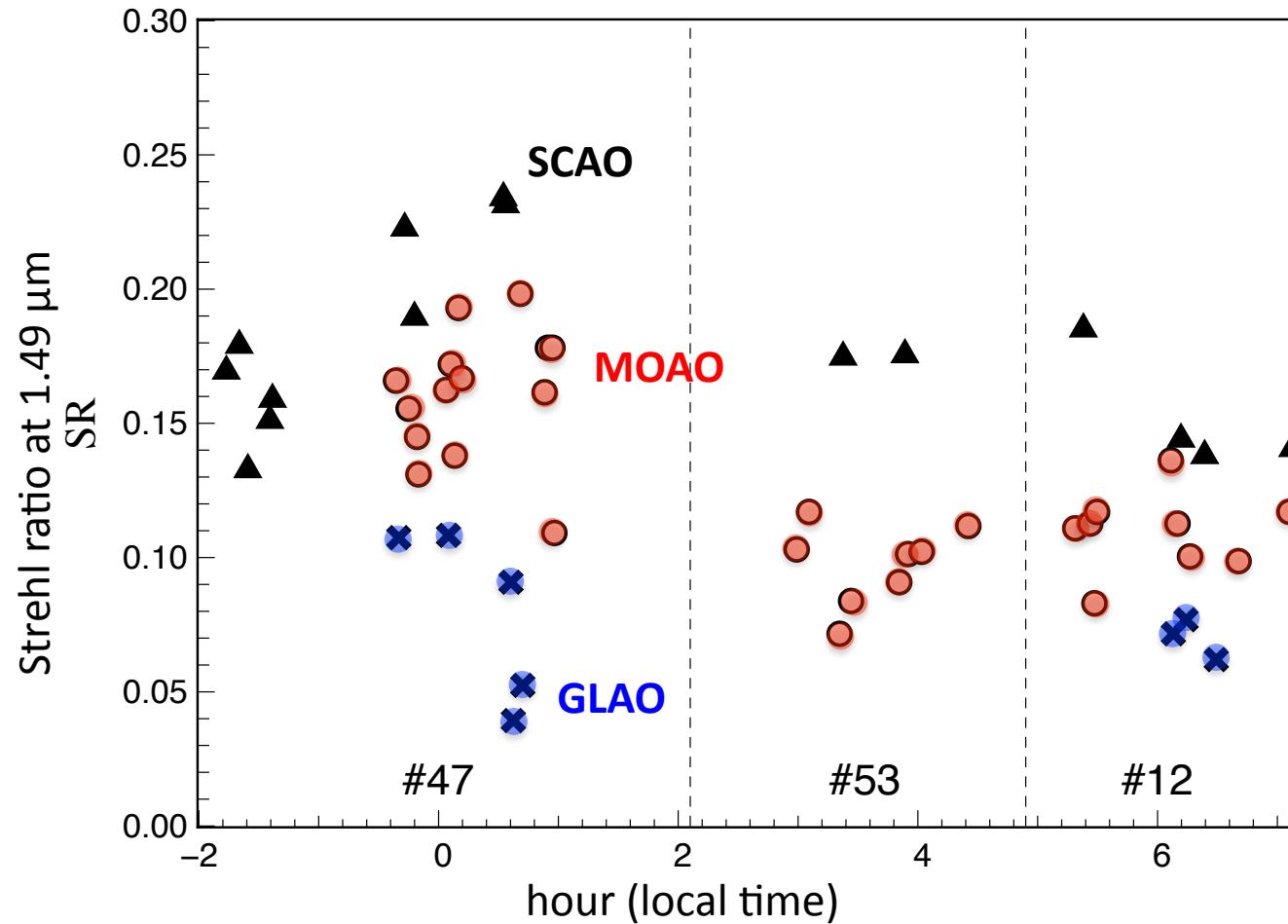


Results: Example

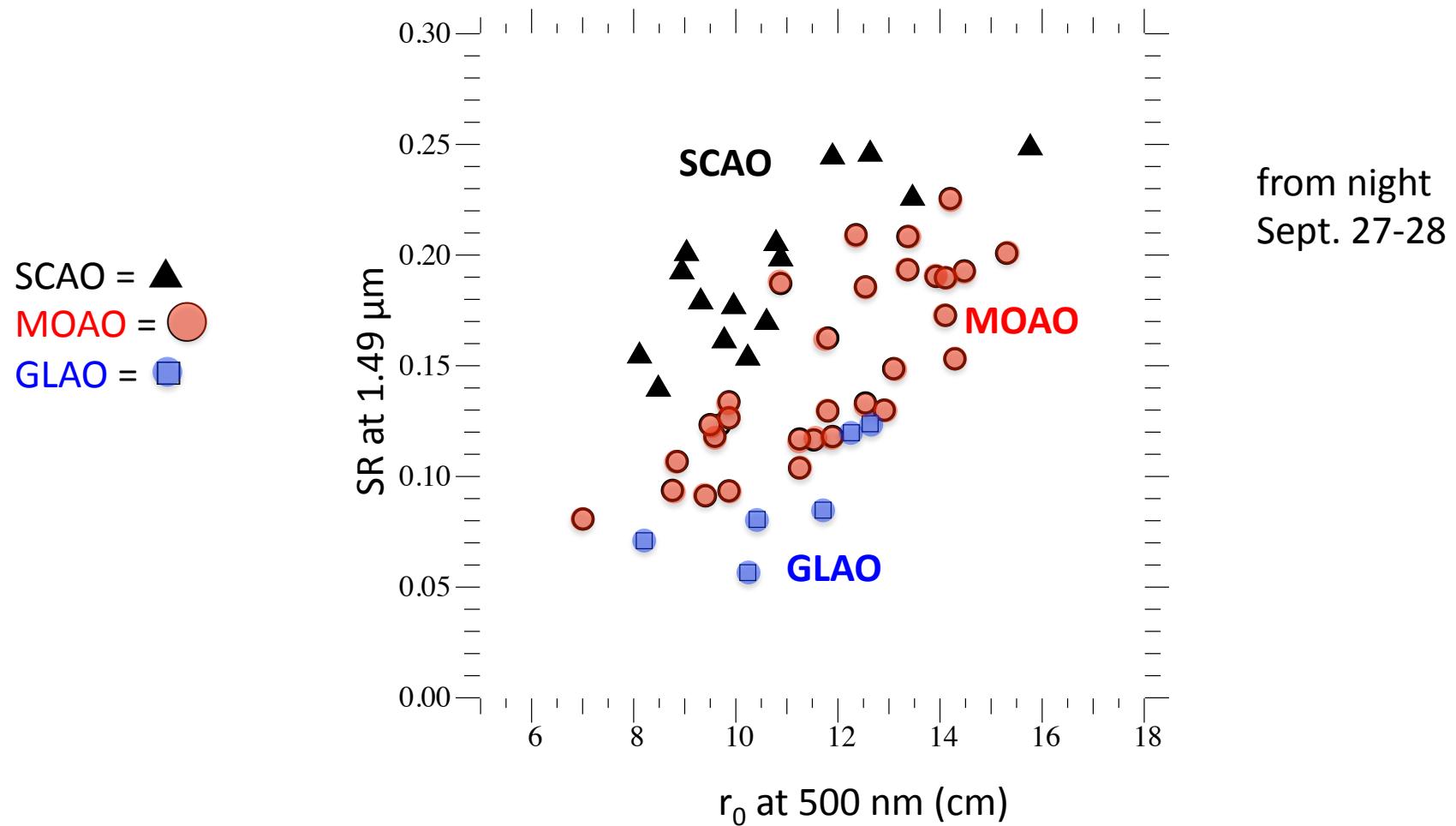
- 1.49 μm
- field 2'' x 2''
- 30 seconds exposure



Strehl results



SR vs r_0



Terms of the error budget

σ^2_{tomo}	Tomographic error
σ^2_{OL}	Open loop error (go-to error)
$\sigma^2_{\text{tomonoise}}$	noise propagated through reconstructor on the DM
$\sigma^2_{\text{aliasing}}$	Aliasing correlated (ground) and not correlated (alt)
σ^2_{BW}	Bandwidth error (temporal error)
$\sigma^2_{\text{fitting}}$	Fitting error
$\sigma^2_{\text{statbench}}$	internal Strehl (best SR on bench without turbulence)
σ^2_{static}	MOAO measured telescope+Canary field static aberrations
$\sigma^2_{\text{noiseTS}}$	Noise on Truth Sensor
σ^2_{others}	???

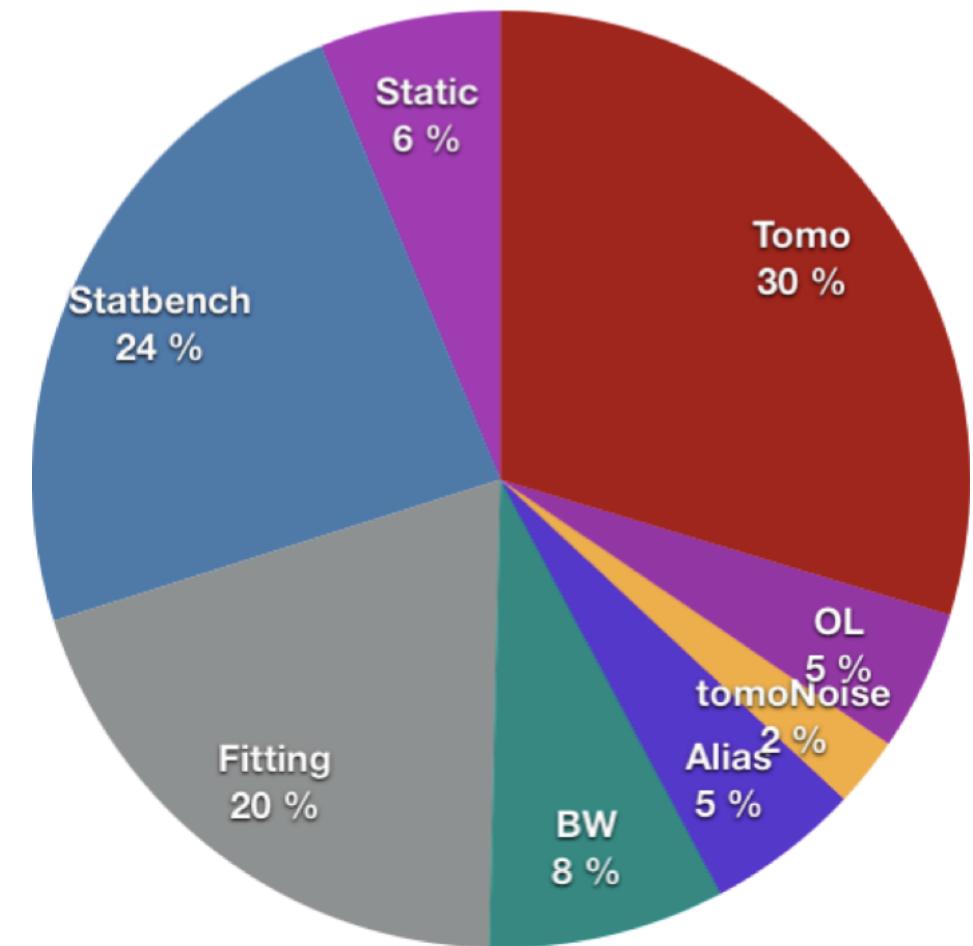
How ?

Error	How do we get it ?
<u>tomographic error</u>	From disengaged slopes: compare wavefront reconstructed from off-axis wfs to truth sensor with no delay, unbiasing from noise propagation, and rescaled from seeing variations
noise propagated through reconstructor	Compute noise from off-axis wfs (white noise temporal autocorrelation peaks on top of smooth turbu autocor), propagate though reconstructor, compute effect of temporal filtering
aliasing and fitting error	use determination of r0, with Kolmogorov a priori and basic analytical formulae. For aliasing, need to separate aliasing effects in altitude or ground
bandwidth error	simulate the loop filtering (with fractional delay and gain), unbiasing from noise propagation (important !)
static bench aberrations	From on-bench IR image Strehl measurement
<u>static MOAO aberrations</u>	measured static aberrations seen by the truth sensor when loop engaged
<u>open-loop error</u>	difference between the sum of all the terms, and the error measured by the truth sensor (unbiasing from noise effect)
truth sensor noise	needed to compute some of the other terms

From synchronised data at 00h10mn12s (Asterism #47)

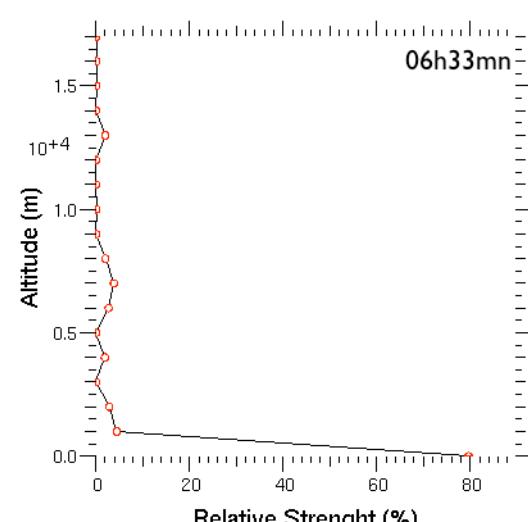
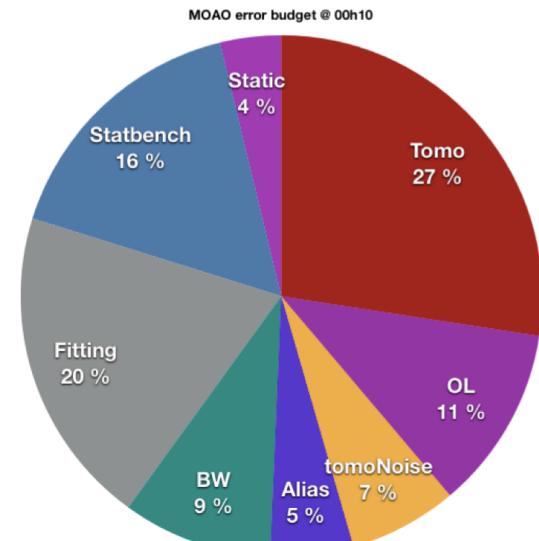
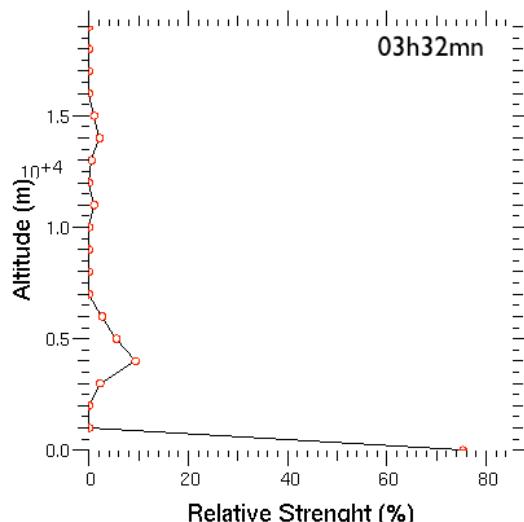
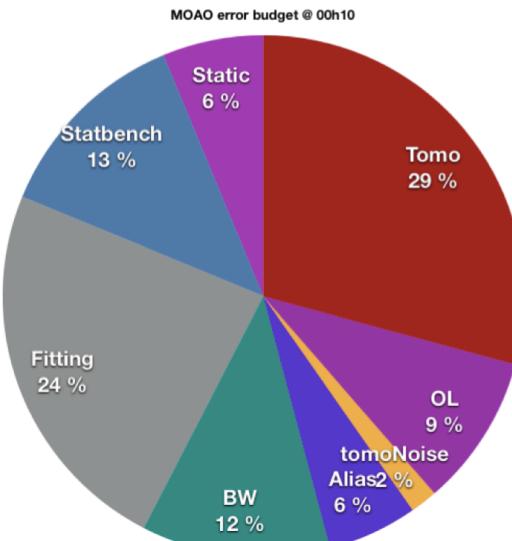
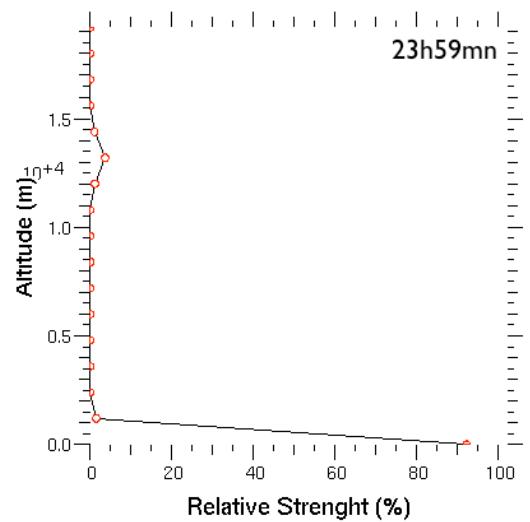
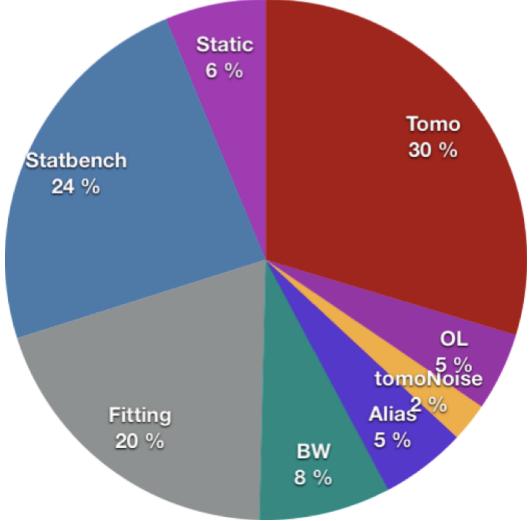
Error	Estimated value (nm rms)
σ^2_{tomo}	168
σ^2_{OL}	68
$\sigma^2_{\text{tomonoise}}$	48
$\sigma^2_{\text{aliasing}}$	71
σ^2_{BW}	88
$\sigma^2_{\text{fitting}}$	137
$\sigma^2_{\text{statbench}}$	150
σ^2_{static}	77
Total	308

7 seconds of data (fe=150Hz)
 $r_0=16.3\text{cm}$ (**0.69''** seeing)



Expected SR = 19.0%@1.49μm => measured = 21%

Comparison



AO Error budget : FDR predictions

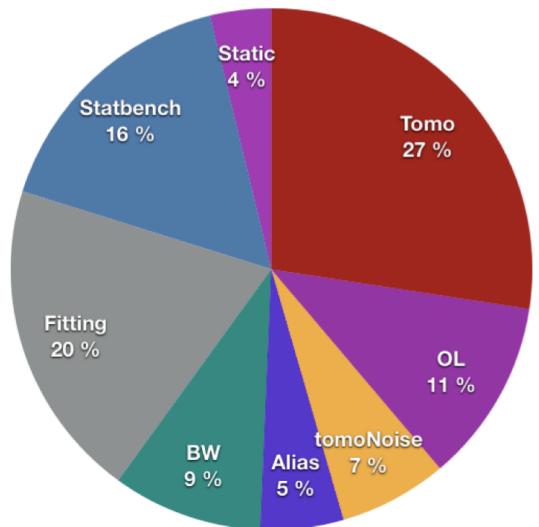
Numbers presented for CANARY FDR :

Source of error	WFE (nm rms)
WFS open-loop estimation	63 (from YAO) 30 (from single subap simul)
WFS noise (quantum + readout)	40 at $m_R=10$ 80 at $m_R=12$ 190 at $m_R=14$
Tomographic reconstruction (30' radius)	260 (GLAO least-square) 220 (tomographic least square) 170 (« L&A » MMSE ?)
DM fitting	140
DM go-on error	48 19 with DMC
Tip-tilt go-on error	26
Temporal and aliasing	113
Residual high-orders from optics	50
TOTAL	$m_R=12$: 285 to 340

Comparison with simulations

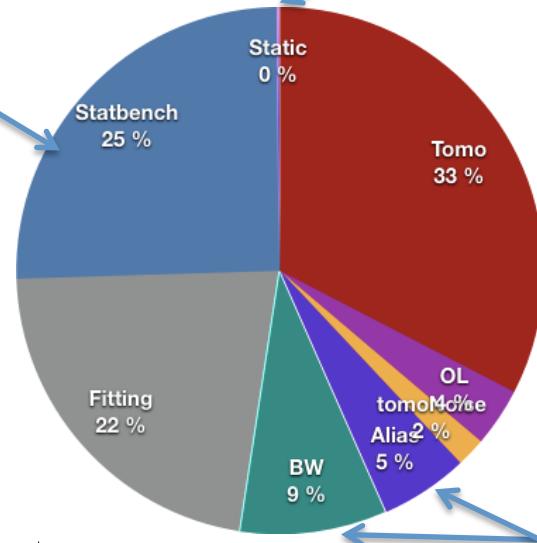
(nearly without cheating !)

MEASURED



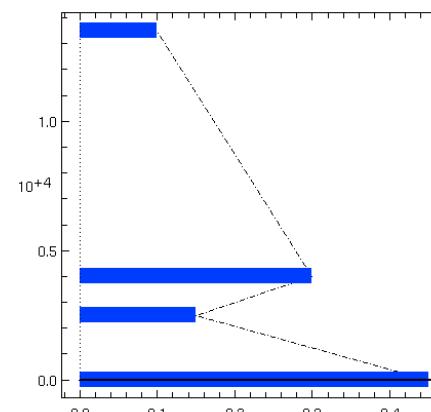
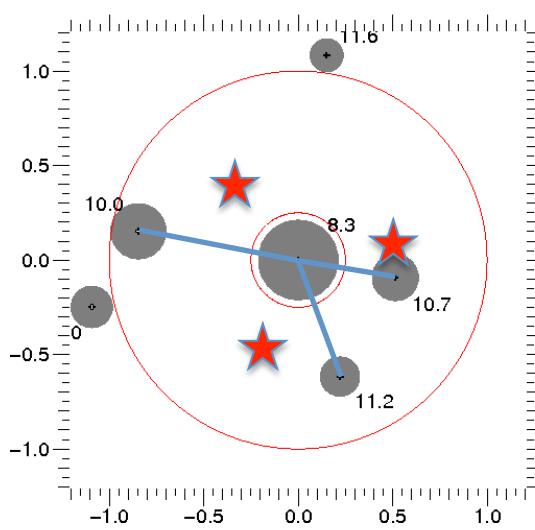
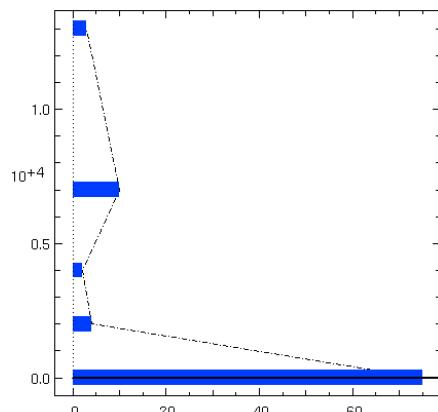
measured
static bench
aberr

FDR



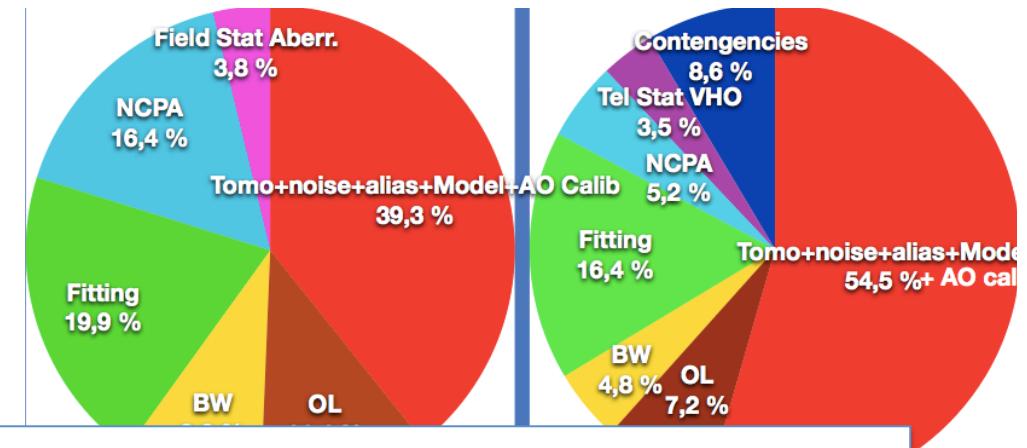
on-sky static aberr
were not expected
in early simulations

splitting between
those 2 has been
adapted to fit
measured data



Comparison with EAGLE

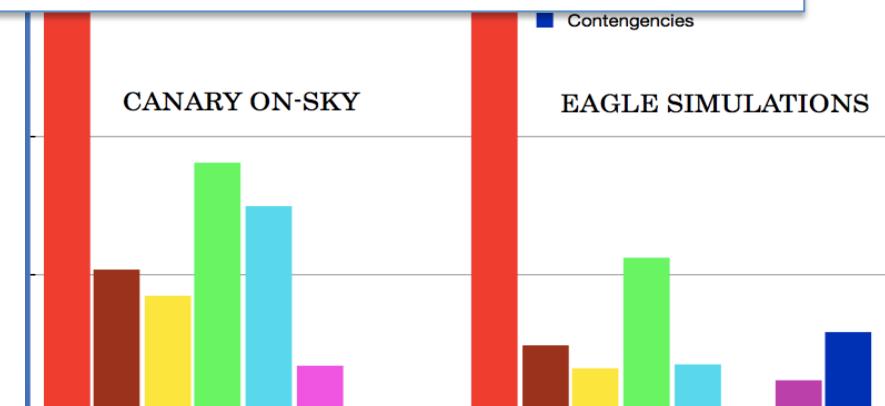
- Comparable r_0
- $C_n^2(h)$ slightly favourable to Canary
- Eagle faster (250 Hz) than Canary (150 Hz)



Poster 16 :
« Detailed analysis of the first MOAO results obtained by CANARY at the WHT »
by Fabrice VIDAL

underestimated

- Order of magnitude of the error budget is ok

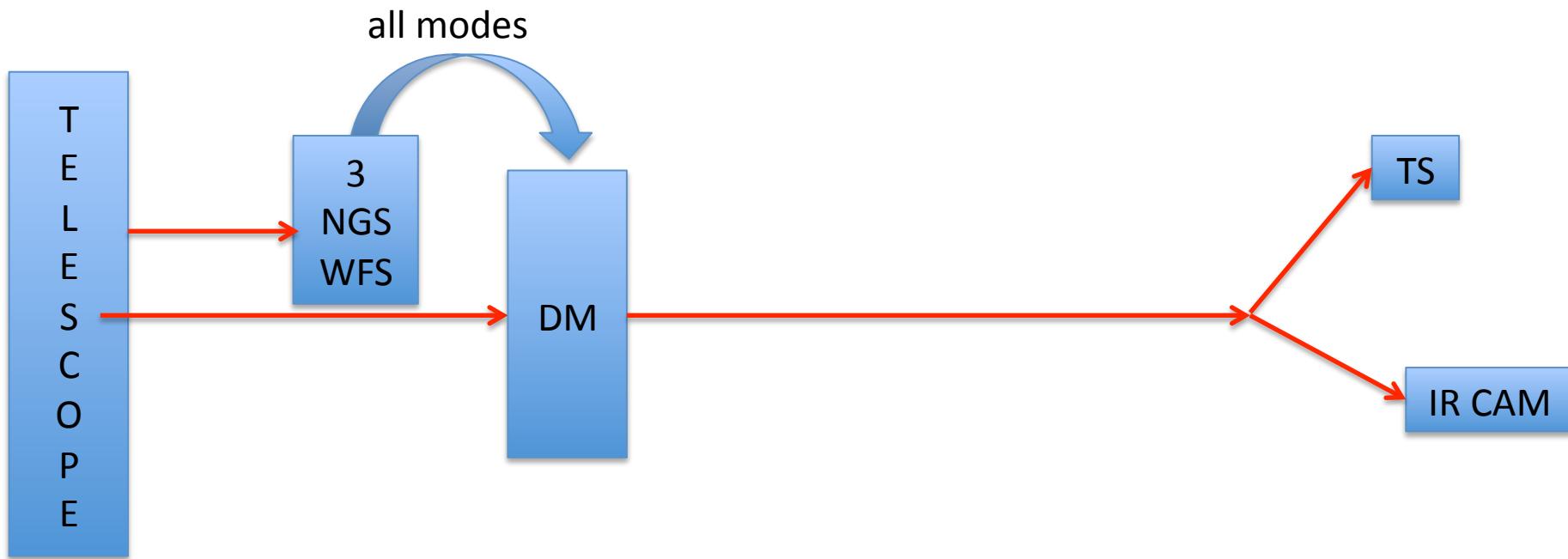




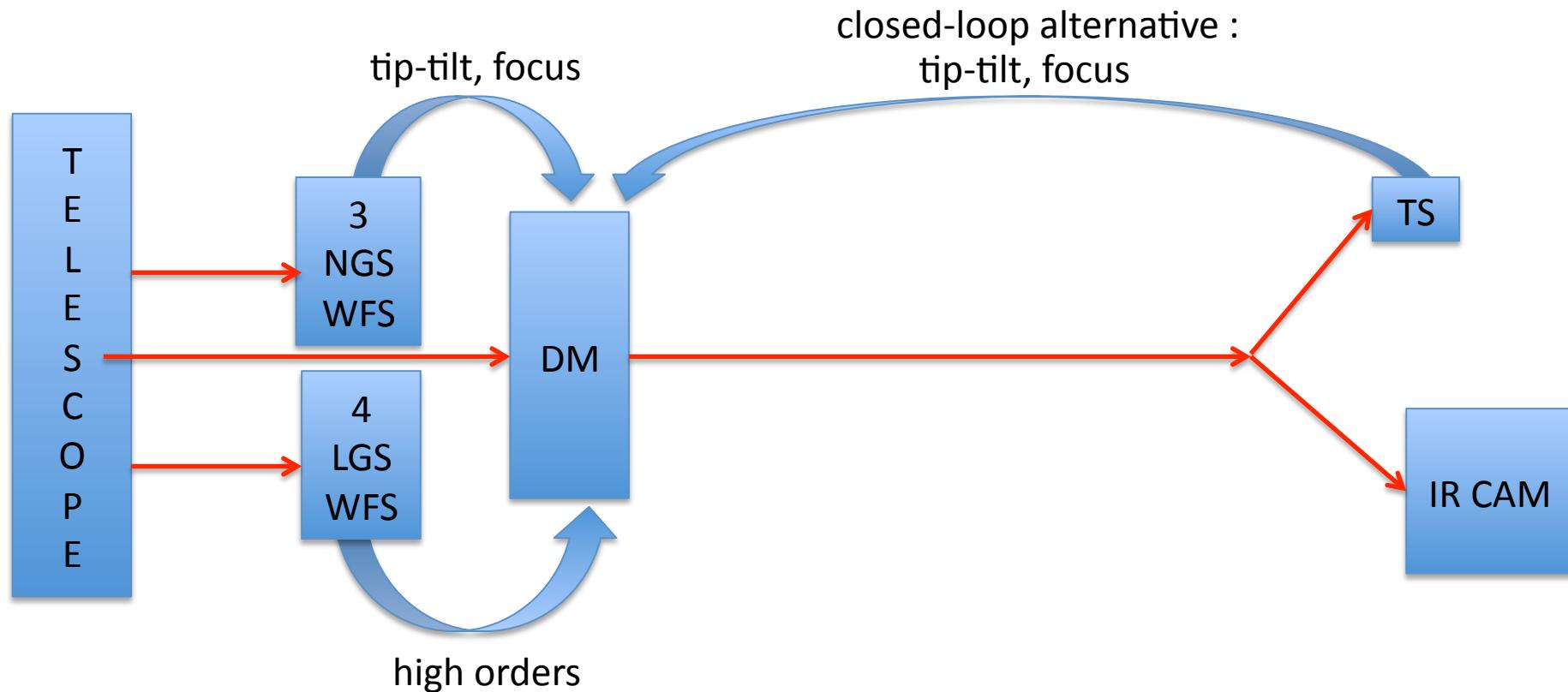
Where it comes to what we'll do in the next years ...

FUTURE STEPS

CANARY Phase A



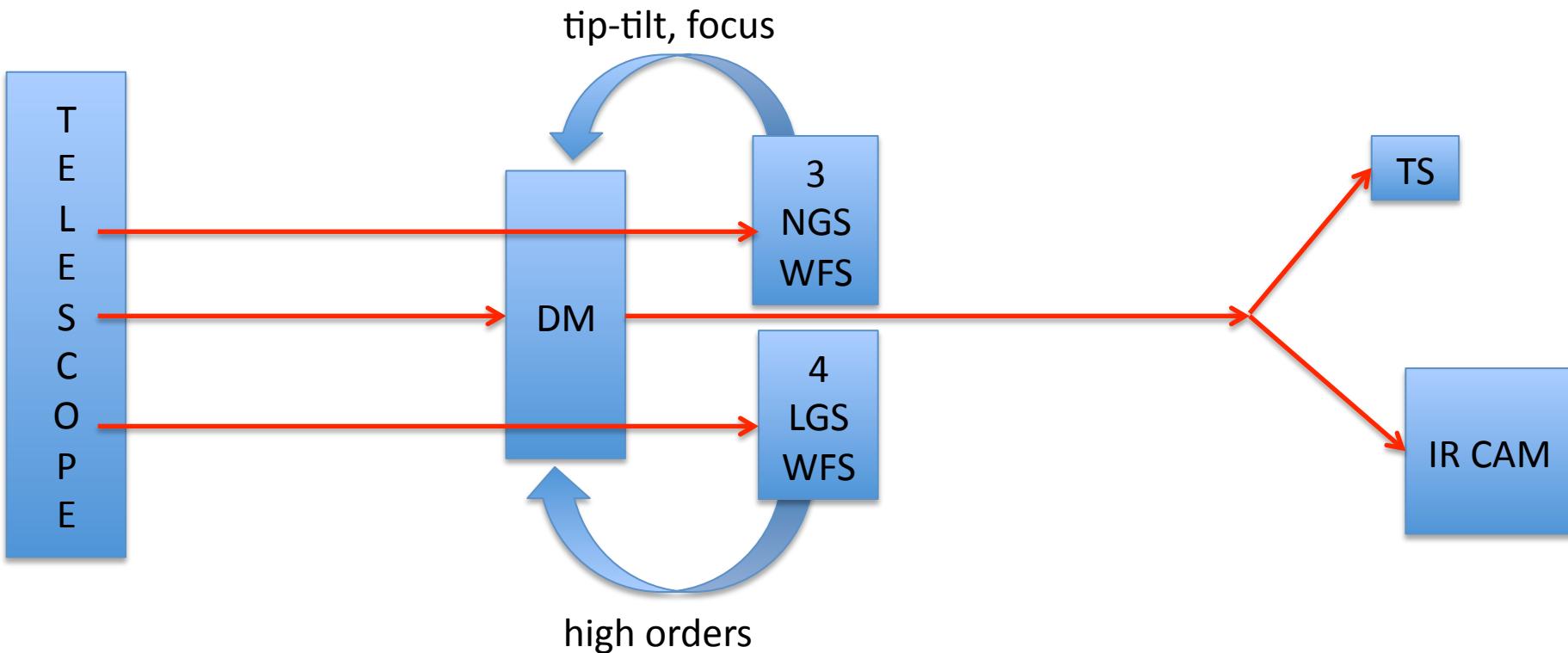
CANARY Phase B



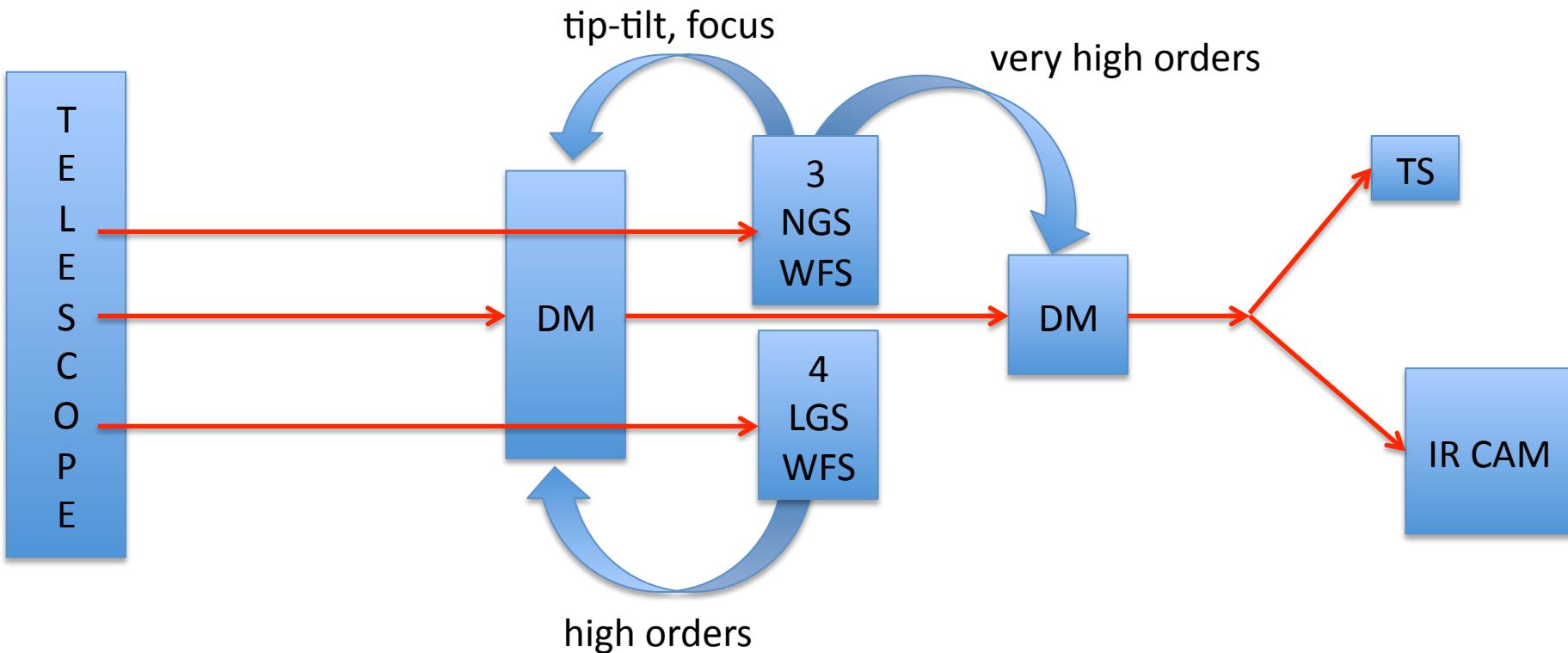
Poster 19 :

« CANARY Phase B: the LGS upgrade to the CANARY tomographic MOAO pathfinder »
by Tim Morris

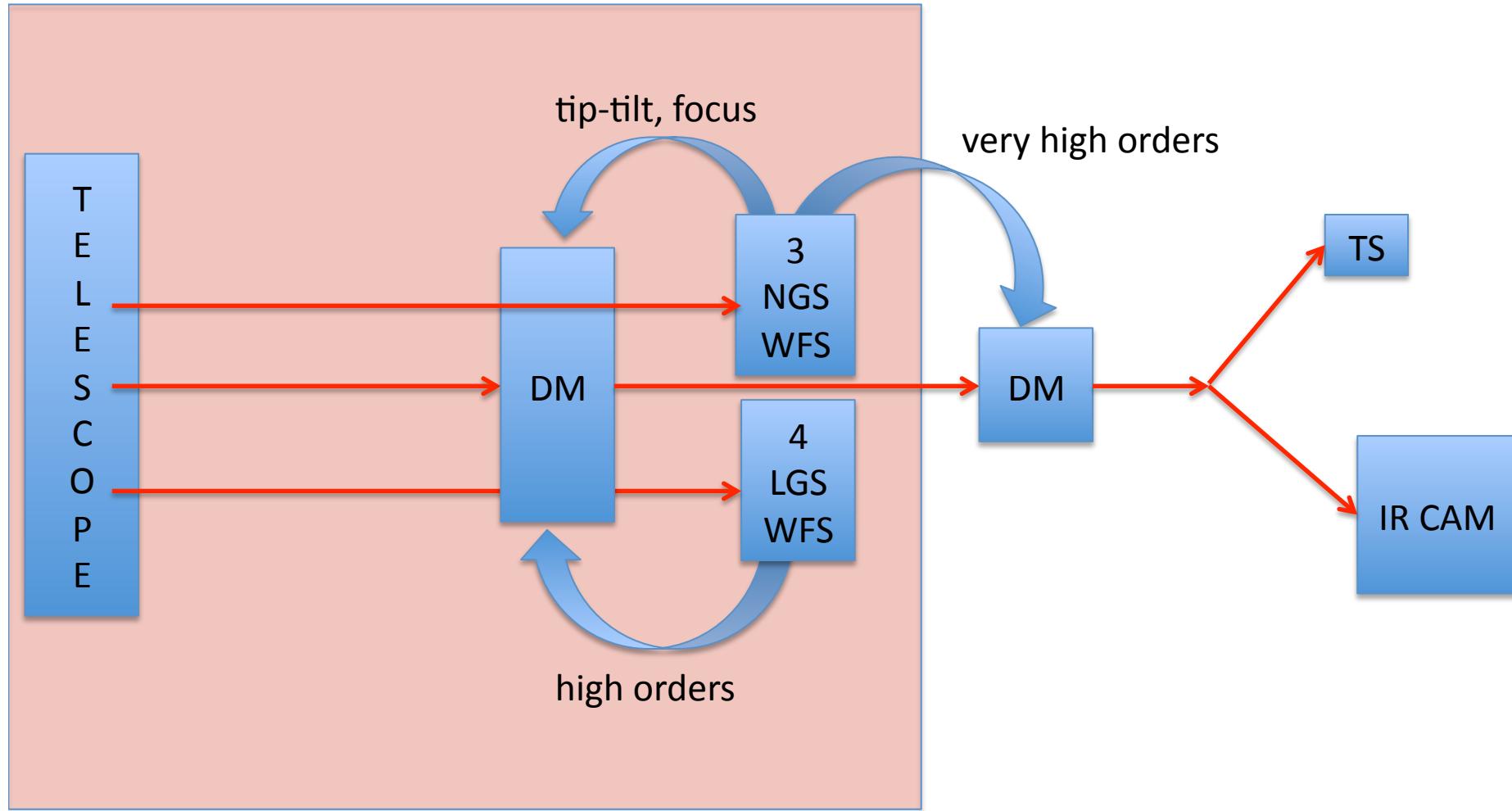
CANARY Phase C-1



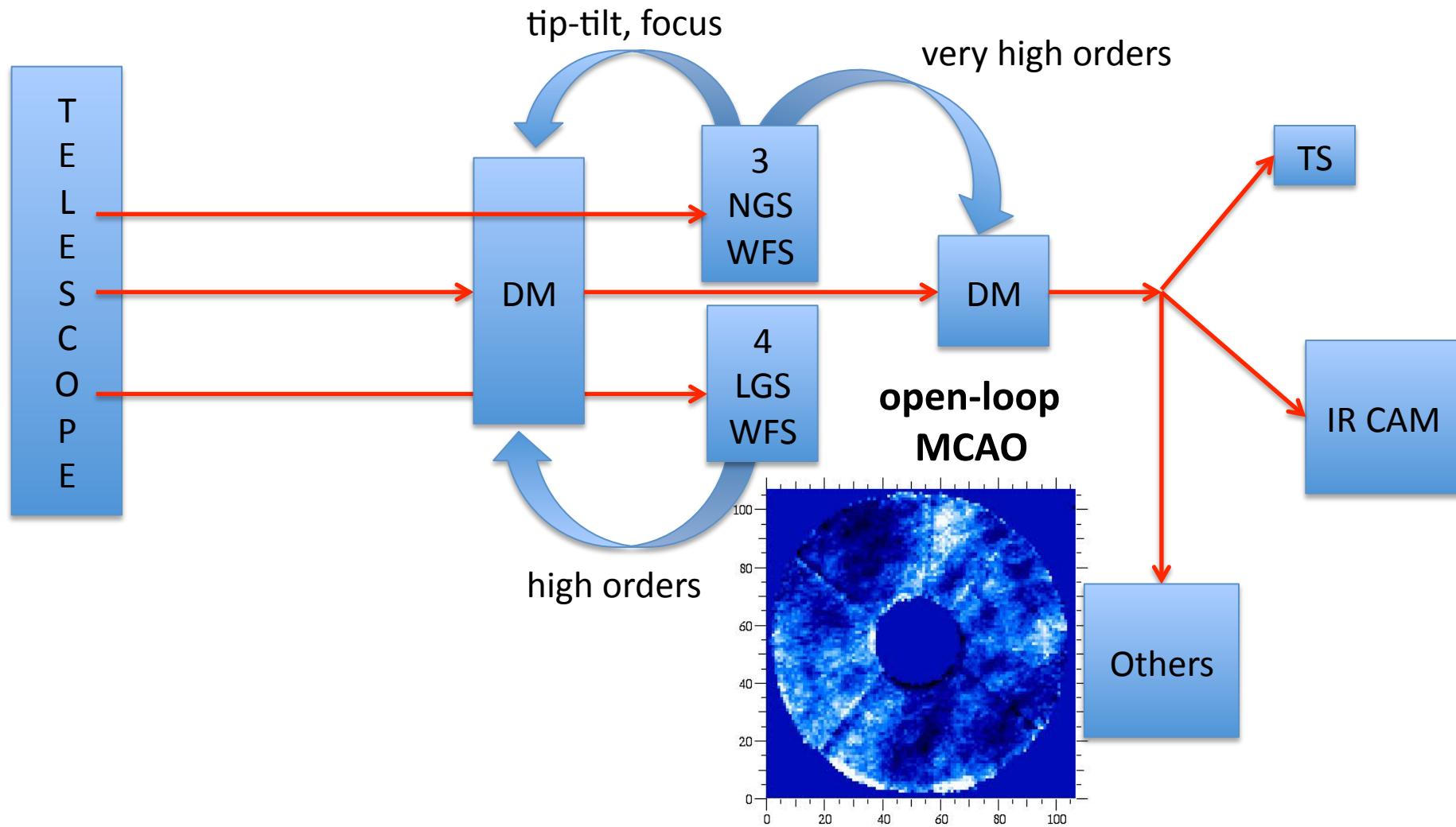
CANARY Phase C-2



CANARY Phase C-2



CANARY Phase D



Towards EAGLE ?

	CANARY	EAGLE
M4 – pupil drifts/shifts during operation	DM is fixed No pupil shift	M4 moves and rotates WFSs move wrt openloop DMs Pupil markers in the telescope
Tel aberrations	fixed	drifting (active telescope) - either MOAO controls telescope - or close coordination with telescope (2 nd open-loop level)
System stability	stable bench temperature controlled	... control temperature of critical elements
DM influence functions	thanks to <i>Learn & Apply</i> not needed yet : all WFS are similar -> phase C	truth sensor calibration and alignment sensor

Conclusion



- MOAO has been demonstrated on-sky
 - within schedule & budgets
 - successful instrument calibration
 - successful on-sky open-loop operation
 - successful on-sky use of a tomographic MMSE-type reconstructor (Learn & Apply)
 - on-sky, *in situ* measurement of the turbulence vertical profile and reconstructor
 - no major show-stopper identified
- Thanks to : Agence Nationale de la Recherche (ANR) program 06-BLAN-0191, CNRS/INSU (France), the Observatoire de Paris, the Université de Paris Diderot - Paris 7, the Science and Technology Facilities Council, the University of Durham, the European Commission (Framework Programme 7, E-ELT Preparation Infrastructure 2007-1 Grant 211257), the program OPTICON JRA1 WP1.2.