Adaptive Optics

(Presented by N. Hubin)

Overview

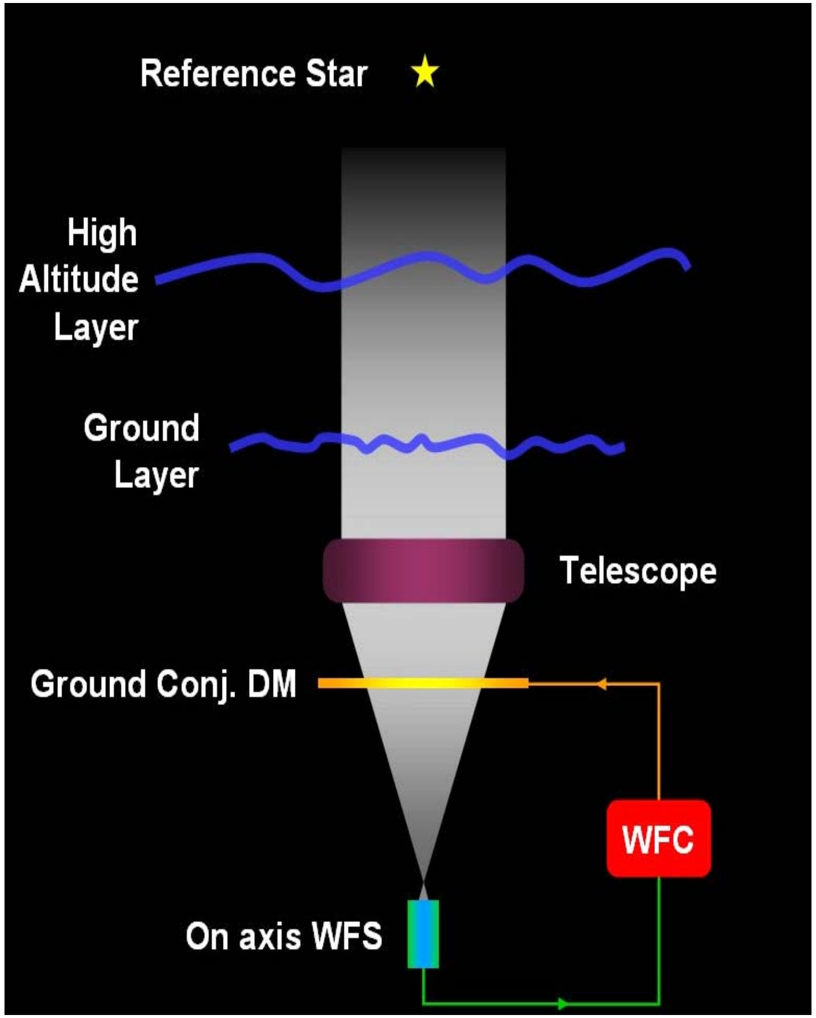
- **Adaptive Optics concepts and performances**
  - Single Conjugate Adaptive Optics (SCAO)
  - Ground Layer Adaptive Optics (GLAO)
  - Multi Object Adaptive Optics (MOAO)
  - Multi-Conjugate Adaptive Optics (MCAO)
  - High Contrast Adaptive Optics (EPICS)
- **Demonstrators & pathfinders**
  - MCAO demonstrator (MAD)
  - High Order Test bench (HOT)
  - VLT Adaptive Optics Facility
  - VLT Planet Finder
  - Required field tests on Laser Guide Star issues
- **Enabling technology roadmap**
  - Deformable mirrors & wavefront sensor detectors
  - Real Time Computers & algorithms
  - Lasers and beam transport/projection

ADAPTIVE OPTICS CONCEPTS & PERFORMANCE

Single Conjugate AO concept

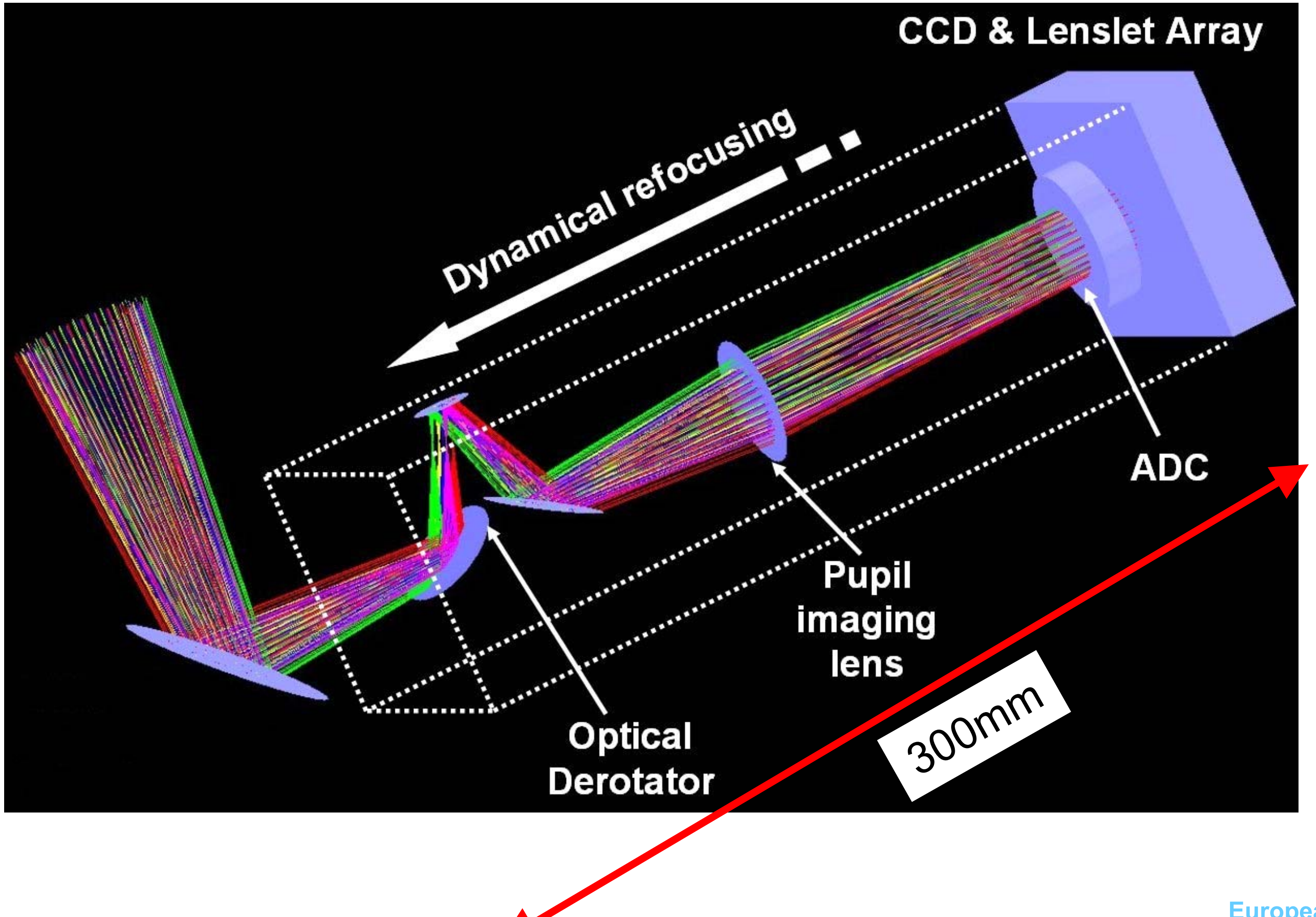
On-axis, NIR, medium Strehl ratio AO using NGSs

- Visible Shack-Hartmann WFS
- IR pyramid WFS
- 97^2 sub-apertures
- Zero noise 582^2 pixels CCD
- Low noise 194^2 pixels IR detector
- 500 Hz update frequency
- 2’ patrolled field
- 98^2 actuators
- 2.5 m Deformable Mirror at M6
- Computing power:
  - 2000 x NAOS
  - Or 10 x VLT AO Facility



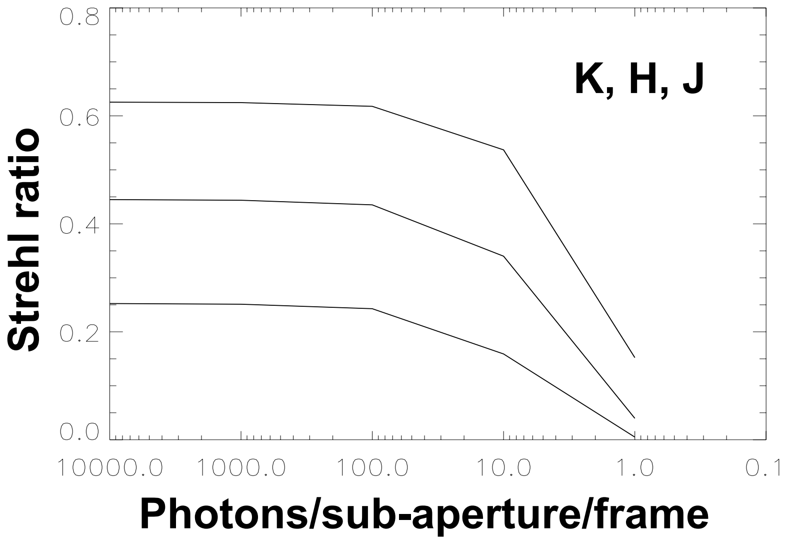
SCAO Wavefront sensor pick-up arm

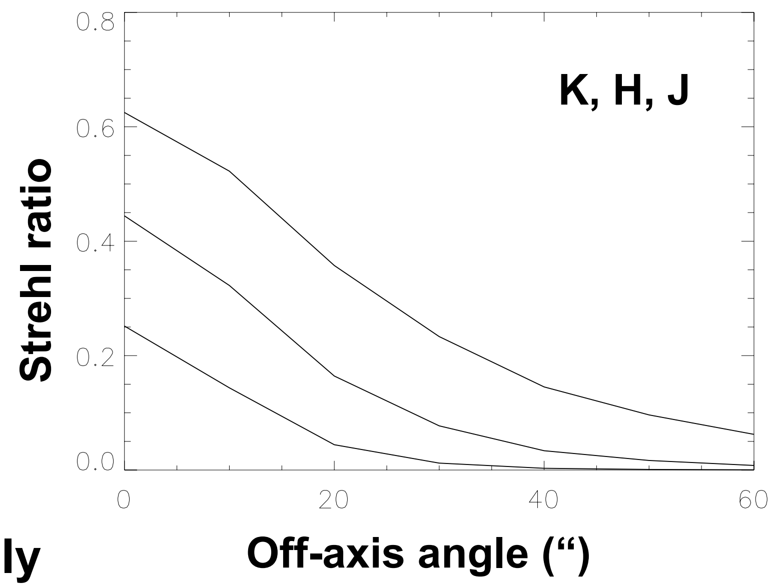
- Patrolling pick-up arm in the Adapter-rotator
- Same wavefront unit (s) for all 6 focal stations



Single Conjugate AO performance *

Good seeing: 0.53”





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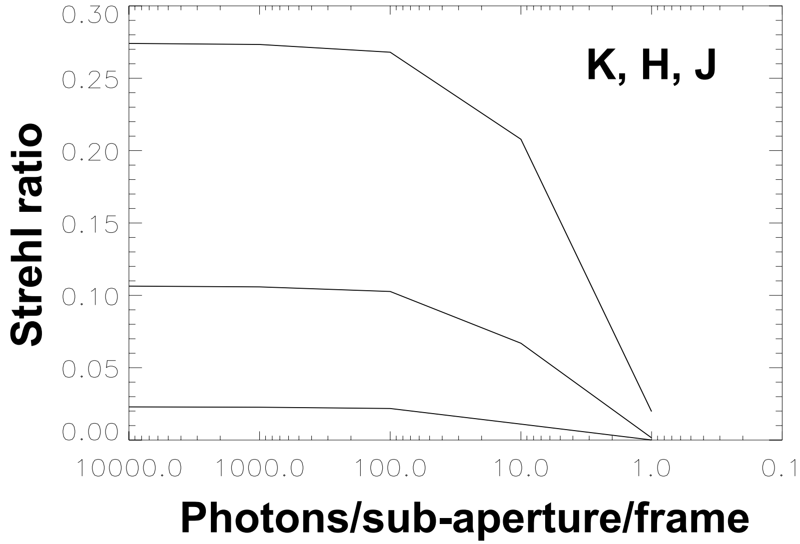
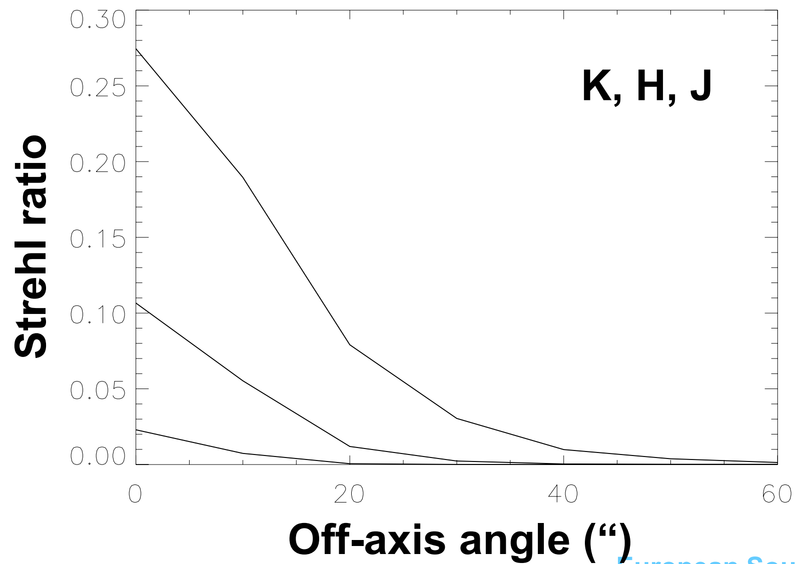


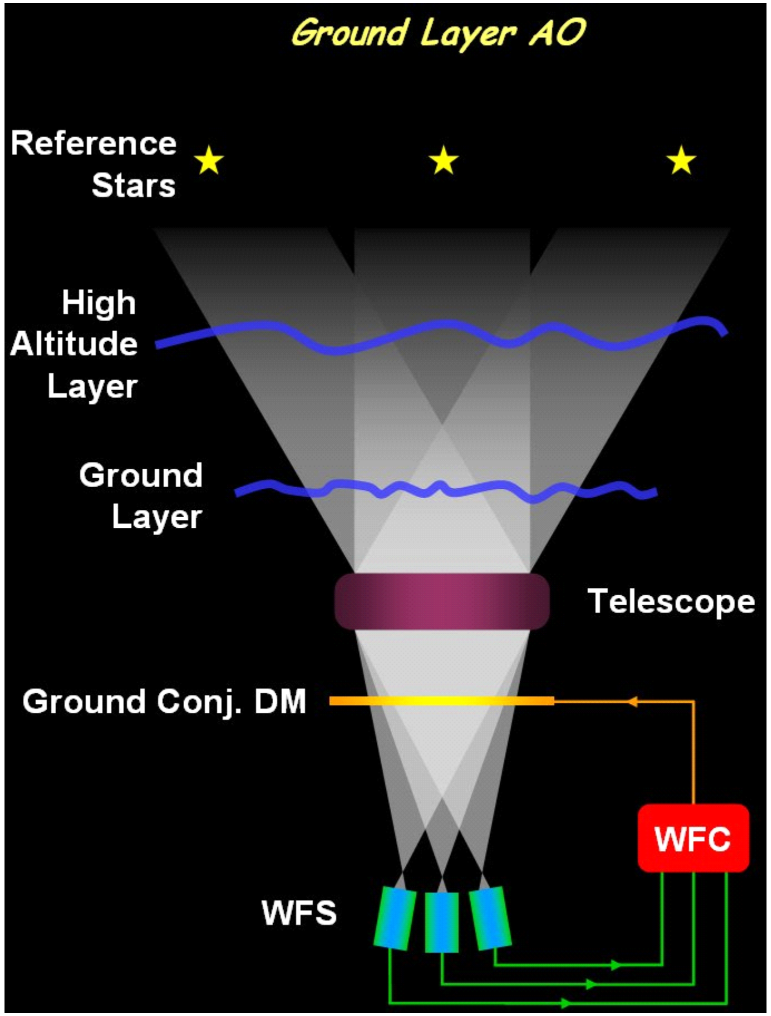


*AO only

Ground Layer AO concept

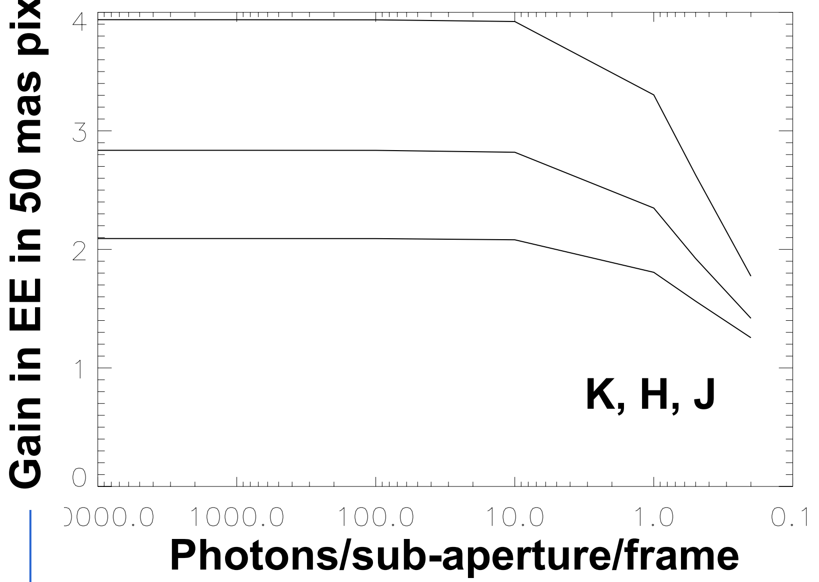
3 - 6’ FoV Near IR Seeing Reducer using NGSs

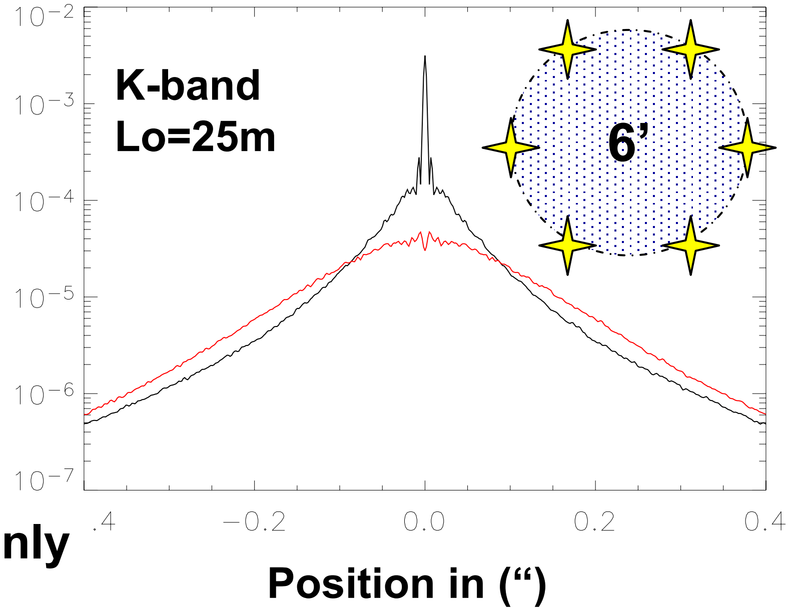
- 6 Visible Shack-Hartmann WFSs
- 97^2 sub-apertures (id. SCAO)
- 6’ Patrolled FoV
- Zero noise 582^2 pixels CCD
- 500 Hz update frequency
- 2.5 m Deformable Mirror at M6
- 3-6’ and narrow FoV modes
- Computing power:
  - 10 x VLT AO Facility
  - 0.3 10^4 x AOF with full reconst.



Ground Layer AO performance*

Good seeing: 0.53”





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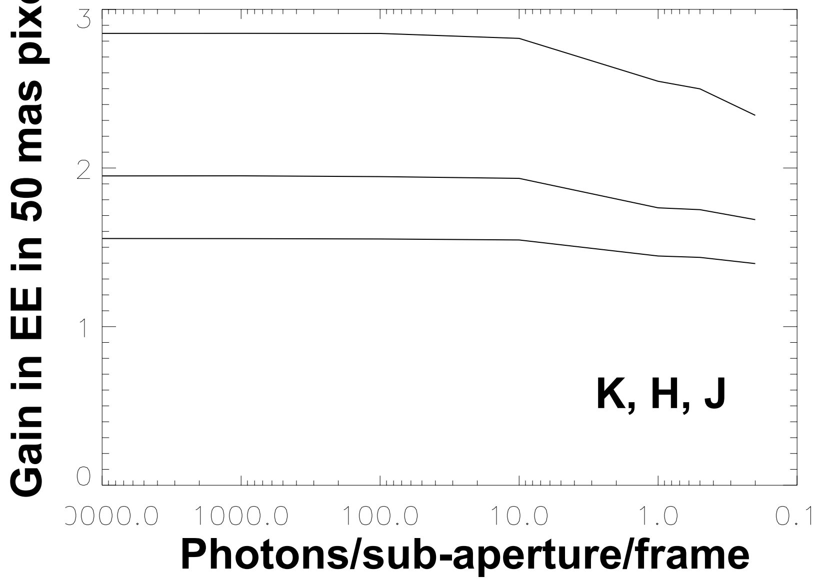
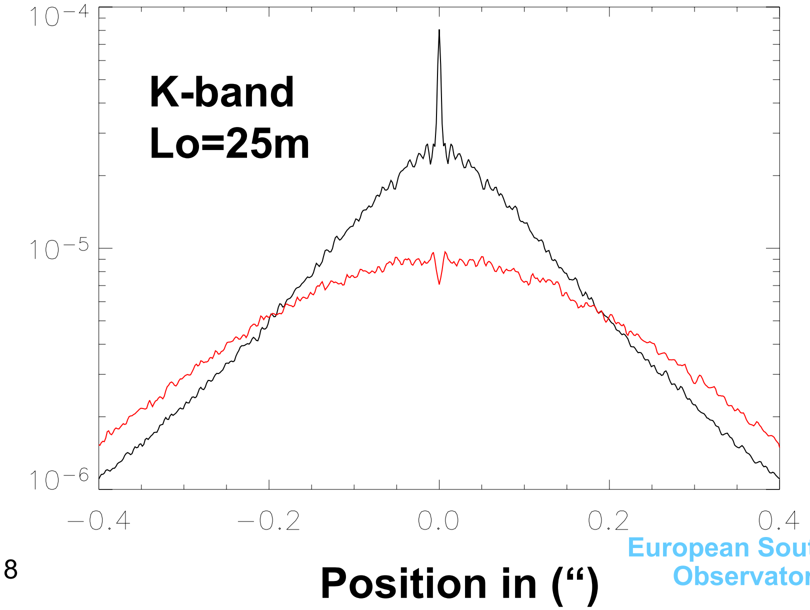


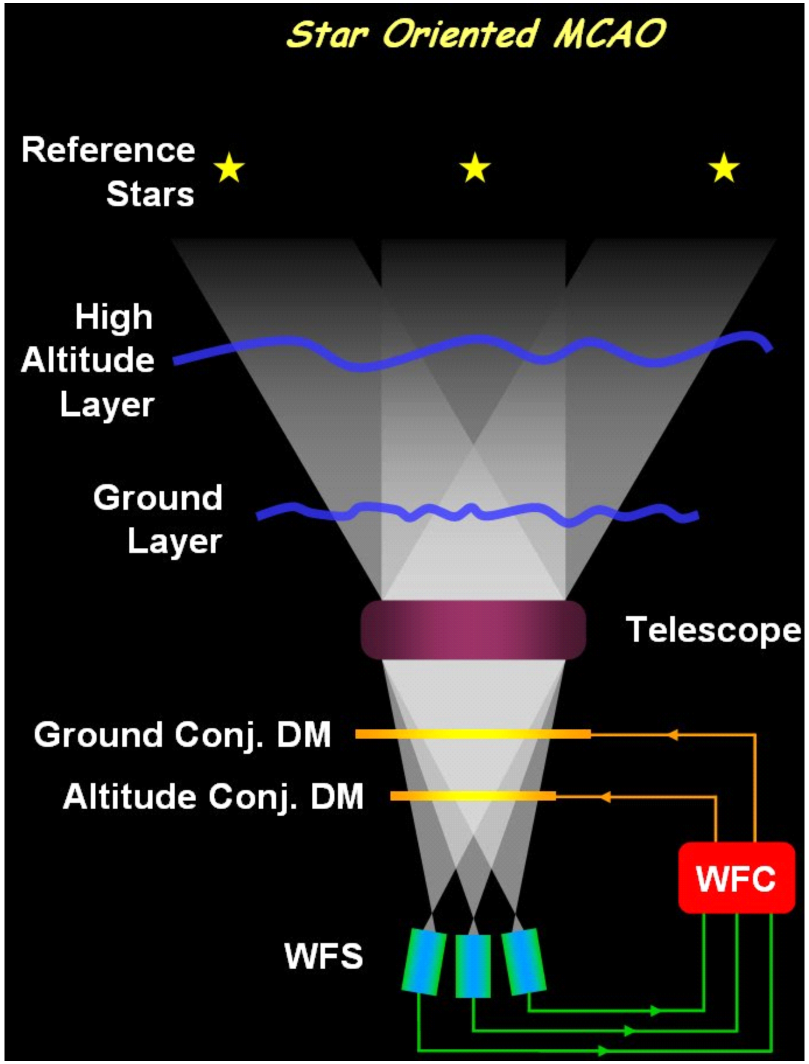


*AO only

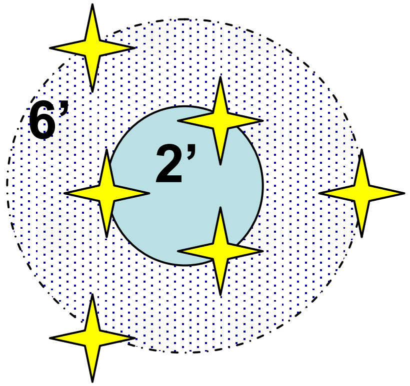
Multi-Conjugate AO concept

1-2' FoV, Near IR, medium Strehl ratio AO using NGSs

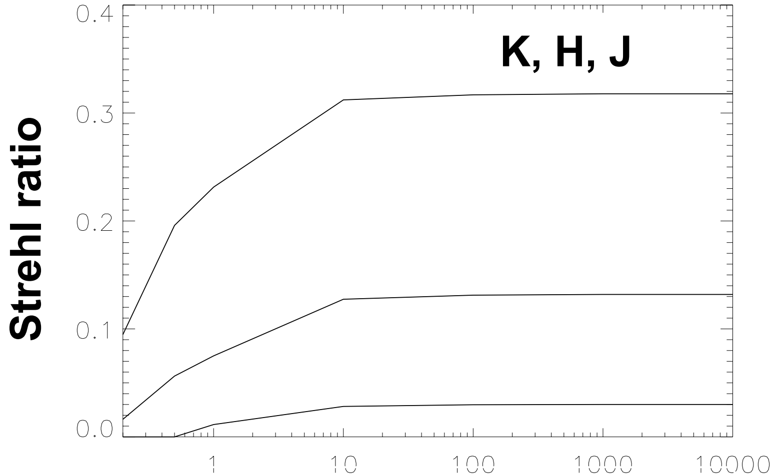
- 6 Visible Shack-Hartmann WFSs
- 97^2 sub-apertures (SCAO)
- 6' Patrolled FoV
- Zero noise 582^2 pixels CCD
- 500 Hz update frequency
- 2.5 m Deformable Mirror at M6
- 3.5 m Deformable Mirror at 7km
- 145^2 actuators over meta-pupil
- Computing power 10^4 x VLT AOF
- 1' corrected FoV



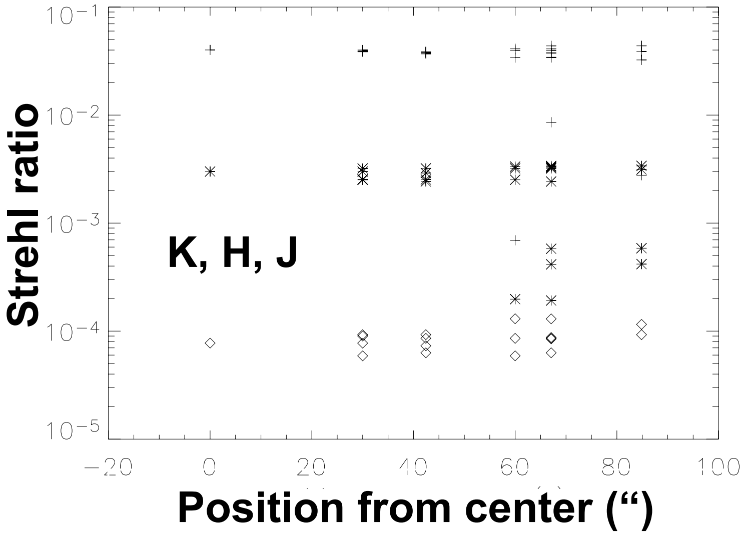
Multi-Conjugate AO performance*

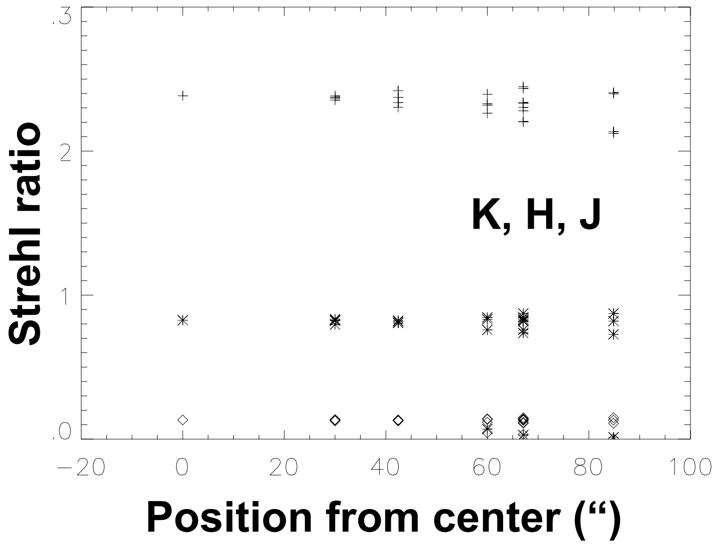


Good seeing: 0.53”, 1’ FOV



Bad seeing: 1”, 1’ FOV



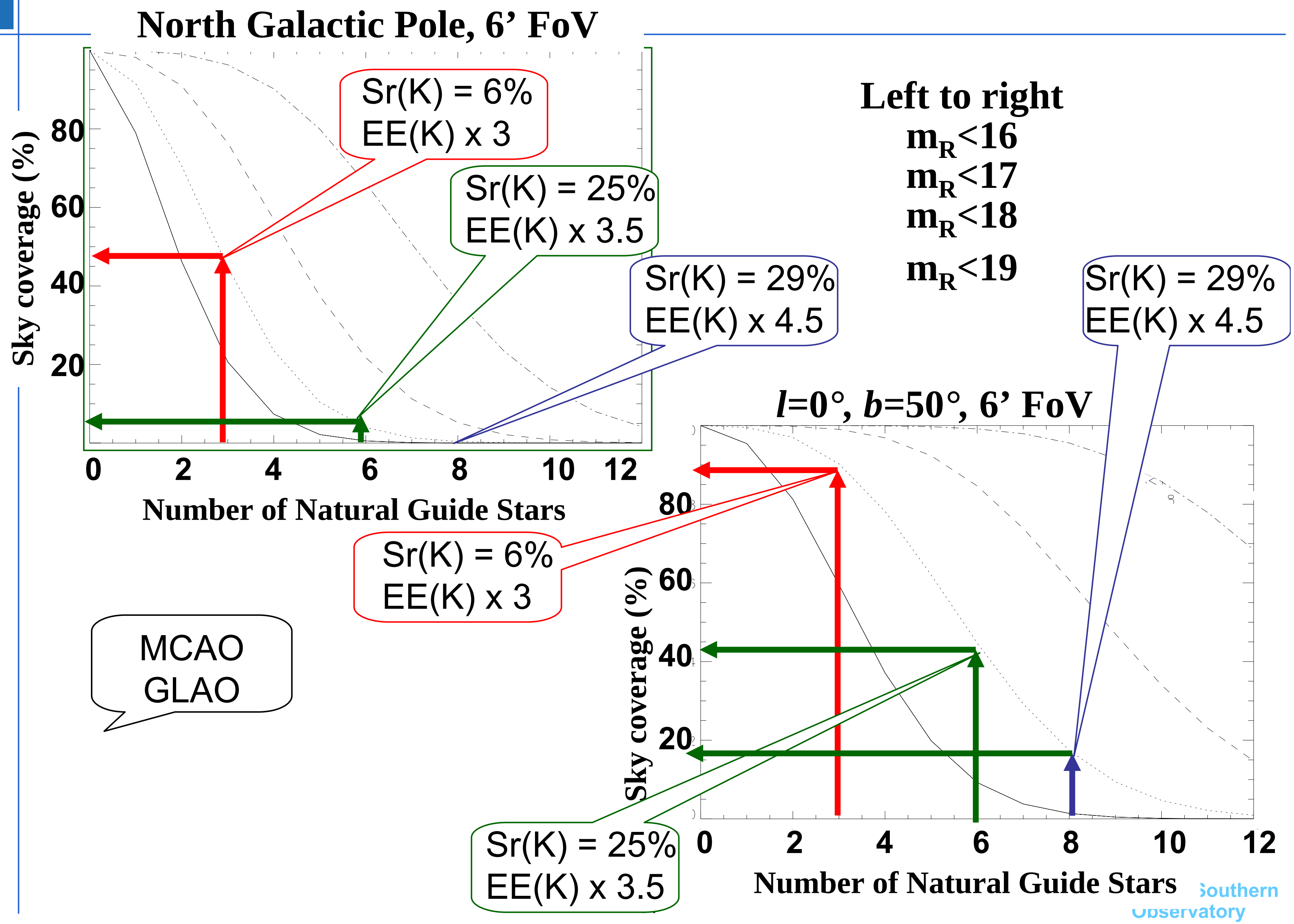


*AO only

NGS flux: 1ph/subap/frame

European Southern Observatory

GLAO & MCAO sky coverage using NGSs



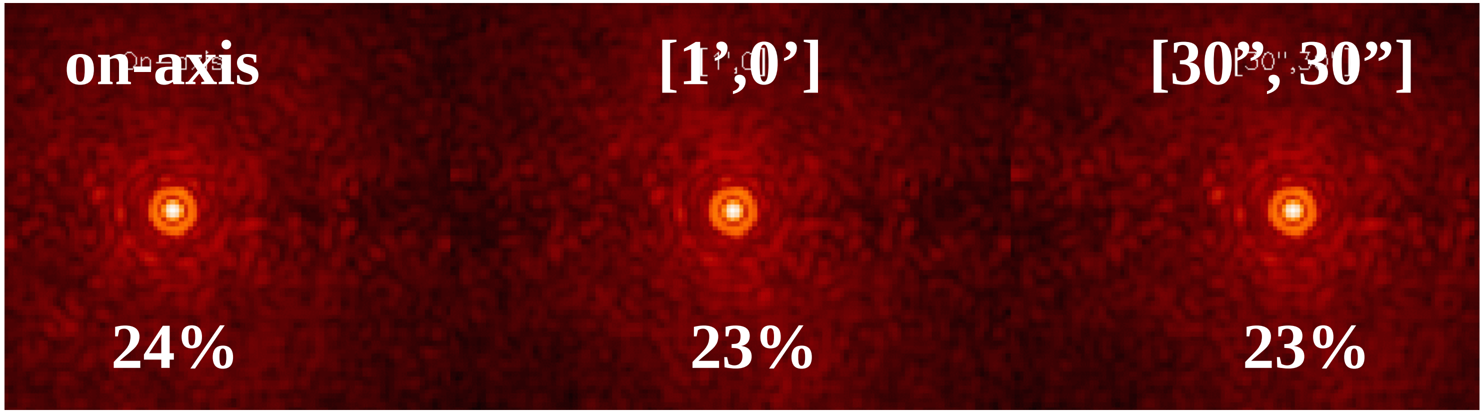
Southern
Observatory

Multi Conjugate AO Point Spread Functions

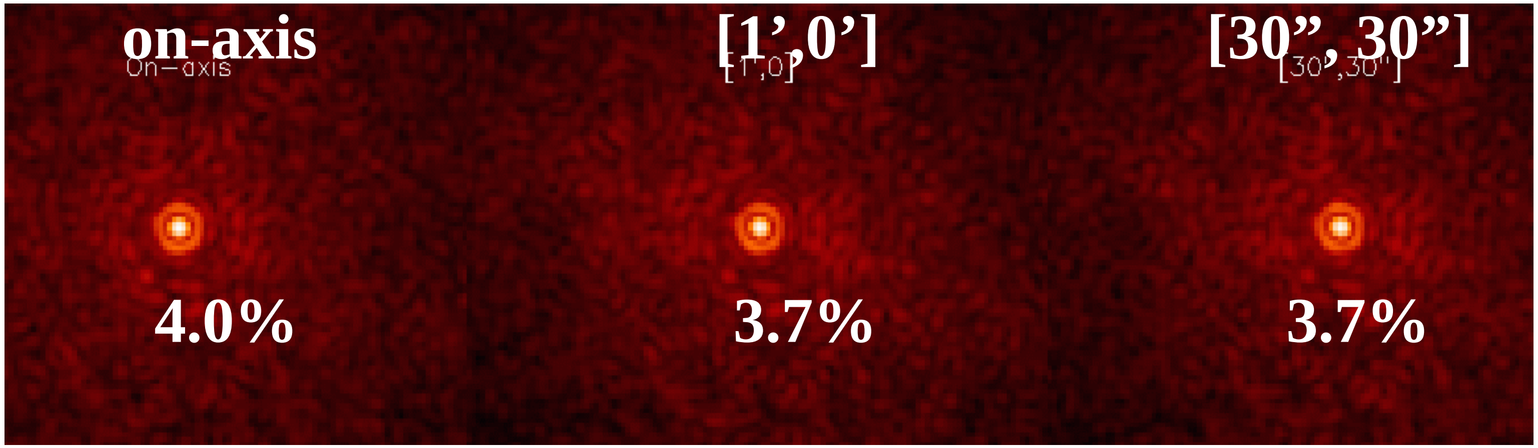
Log stretch

K-Band

Good seeing, 0.5”



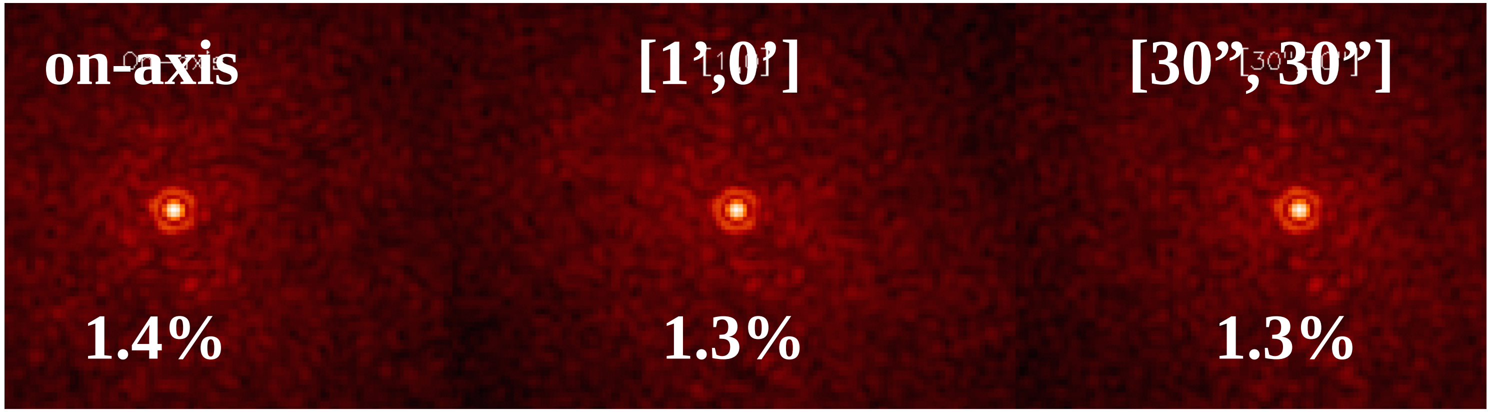
Bad seeing, 1”



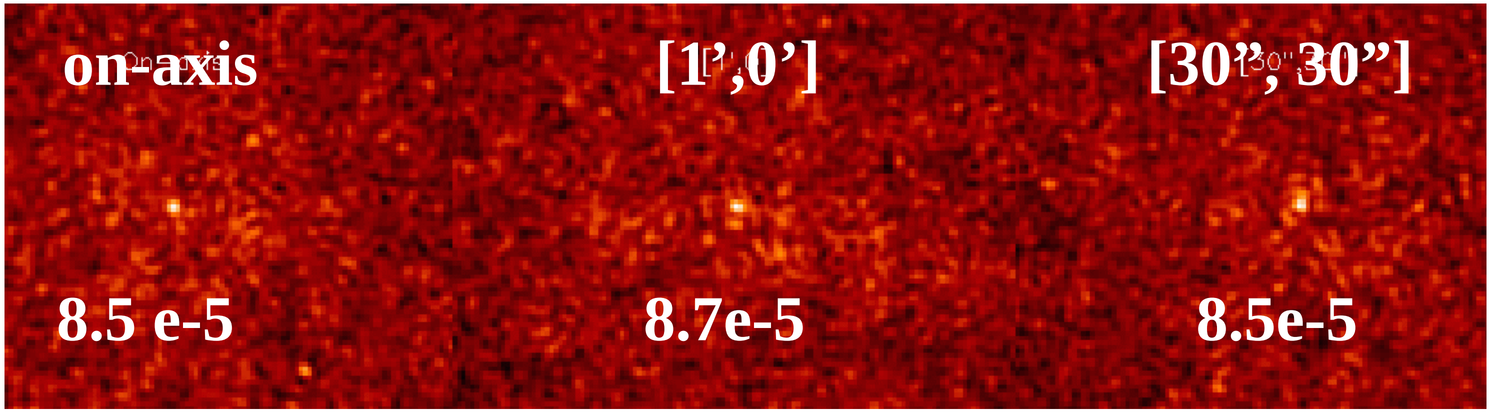
NGS flux: 1 ph / subap / frame

Multi Conjugate AO Point Spread Functions

Good seeing, 0.5”   J-Band



Bad seeing, 1”

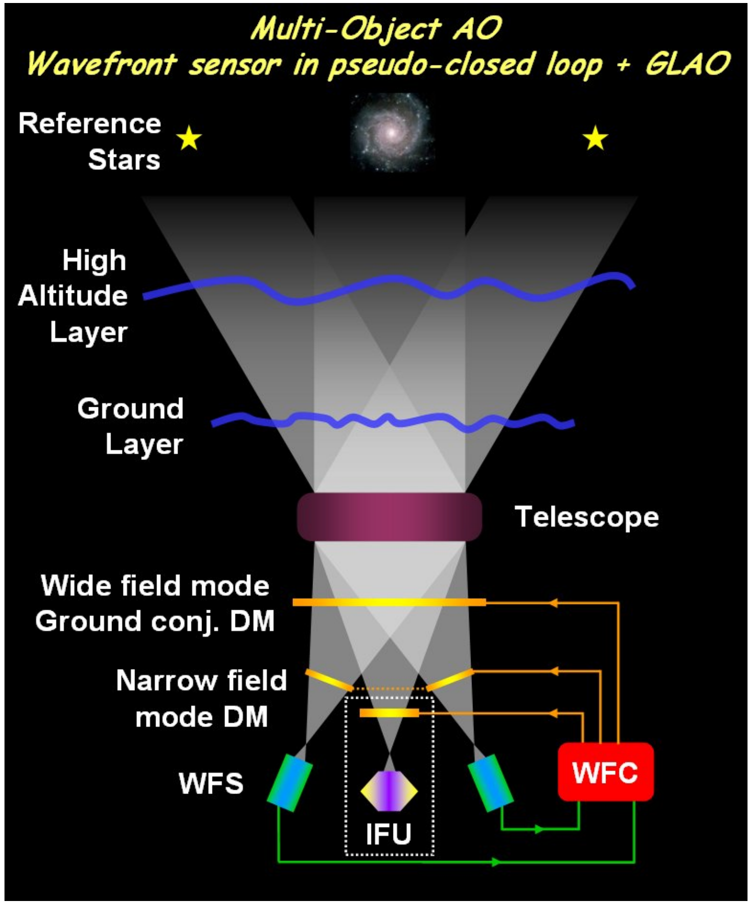


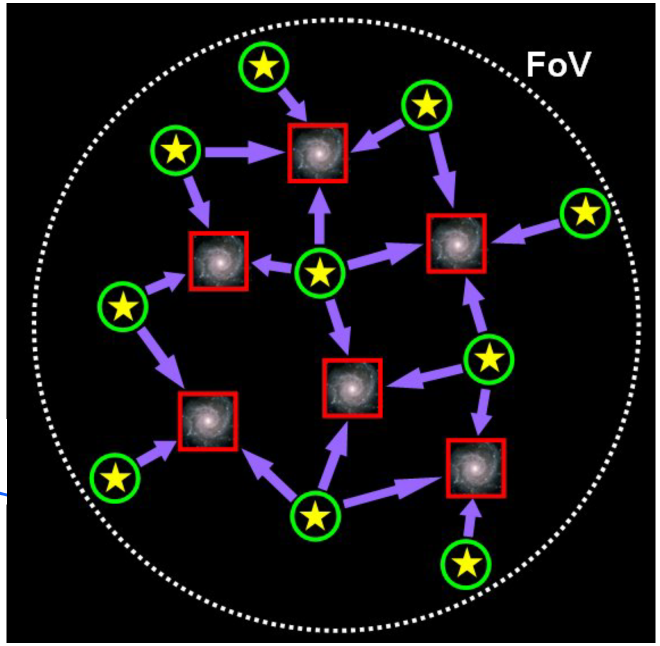
NGS flux: 1 ph / subap / frame

Multi-Object AO concept

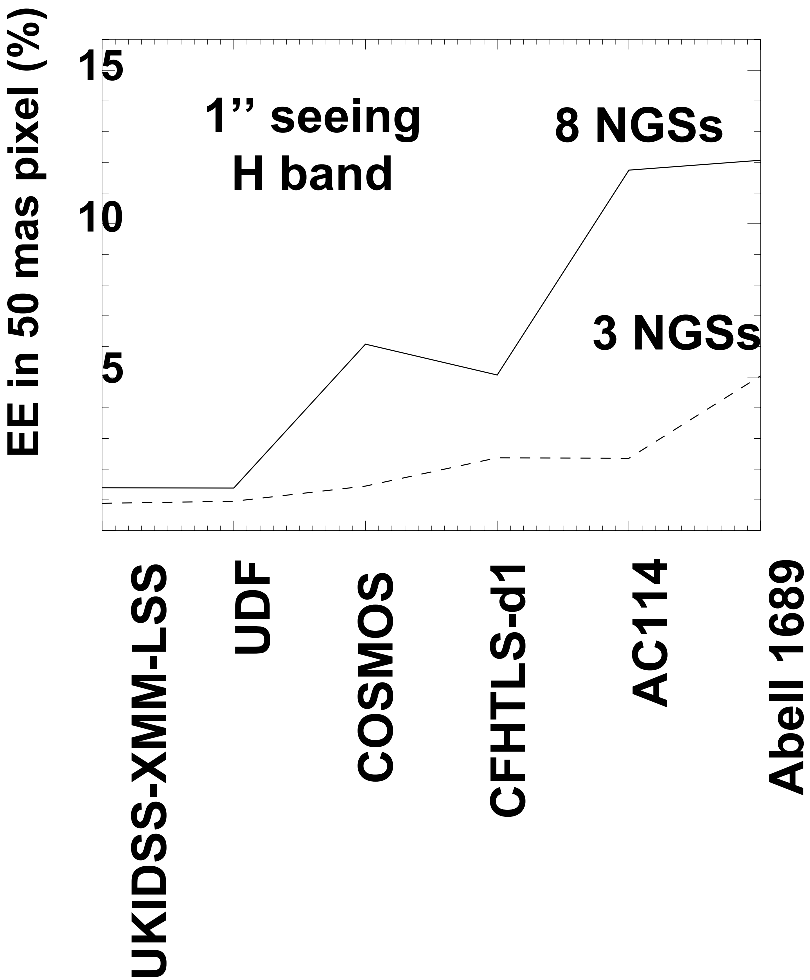
Multi narrow field AO over 6' FoV using NGSs

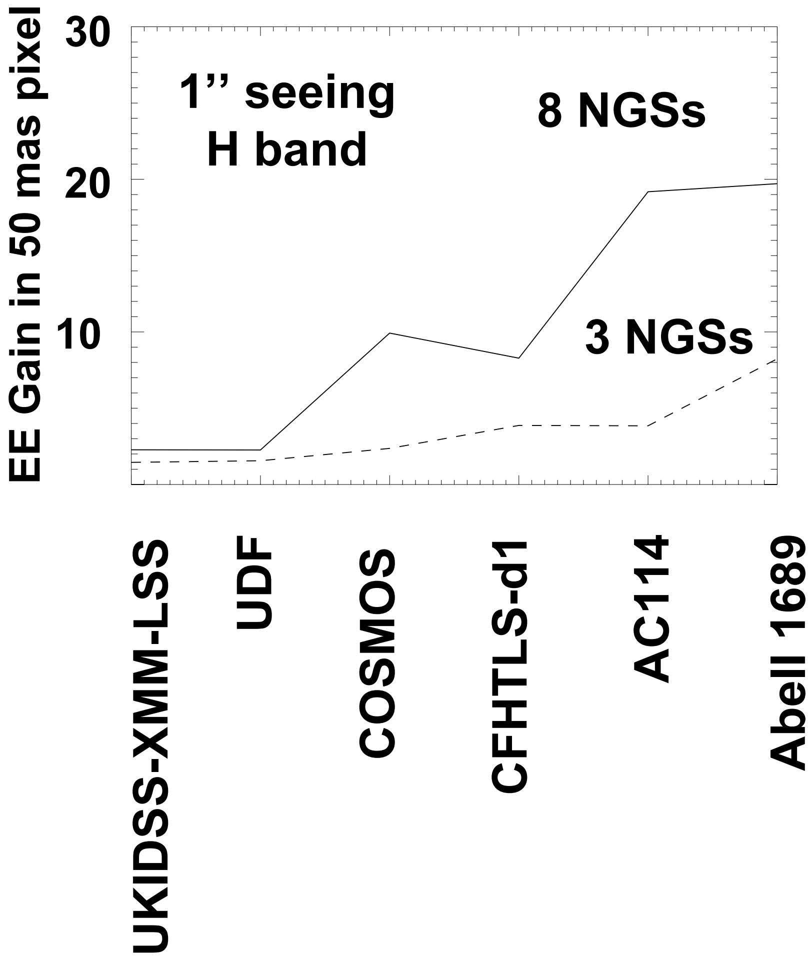
- 10 Vis. WFSs patrolling 6', f=500Hz
- 1st stage GLAO using M6 DM
- 10 kact. MDMs for WFSs & IFUs
- Optimized correction in N directions
- Linear MDMs; pseudo closed loop
- Computing power 3 10^5 x NAOS x10





Multi-Object AO performance

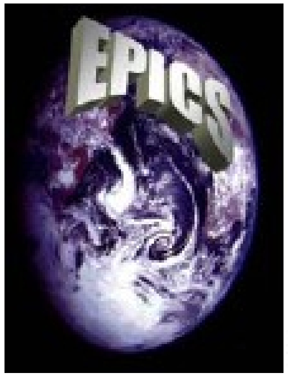




EPICS:
Earth-like Planets Imaging Camera Spectrograph

- Primary science goal: Rocky planets in habitable zone up to 25 pc in VIS and NIR
- Goal: contrast of 2×10^{-10} at 50 mas
  - Need high Strehl Ratio → large number of actuators: $1.7\text{x}10^5$
  - Need high halo rejection → fast correction
- → Double stage system
  - Shack-Hartmann 500^2 at 1 kHz, Fourier reconstructor
  - Pyramid 150^2 at 3 kHz, Matrix-Vector reconstructor
- Computationally feasible with OWL/SPARTA + ~10 years
- Very tight error budget for systematic errors control
  - Need active correction of non common-path errors at 0.3 nm rms (similar achieved with HCIT) for spat. freq. 10 – 75 cycles/pupil

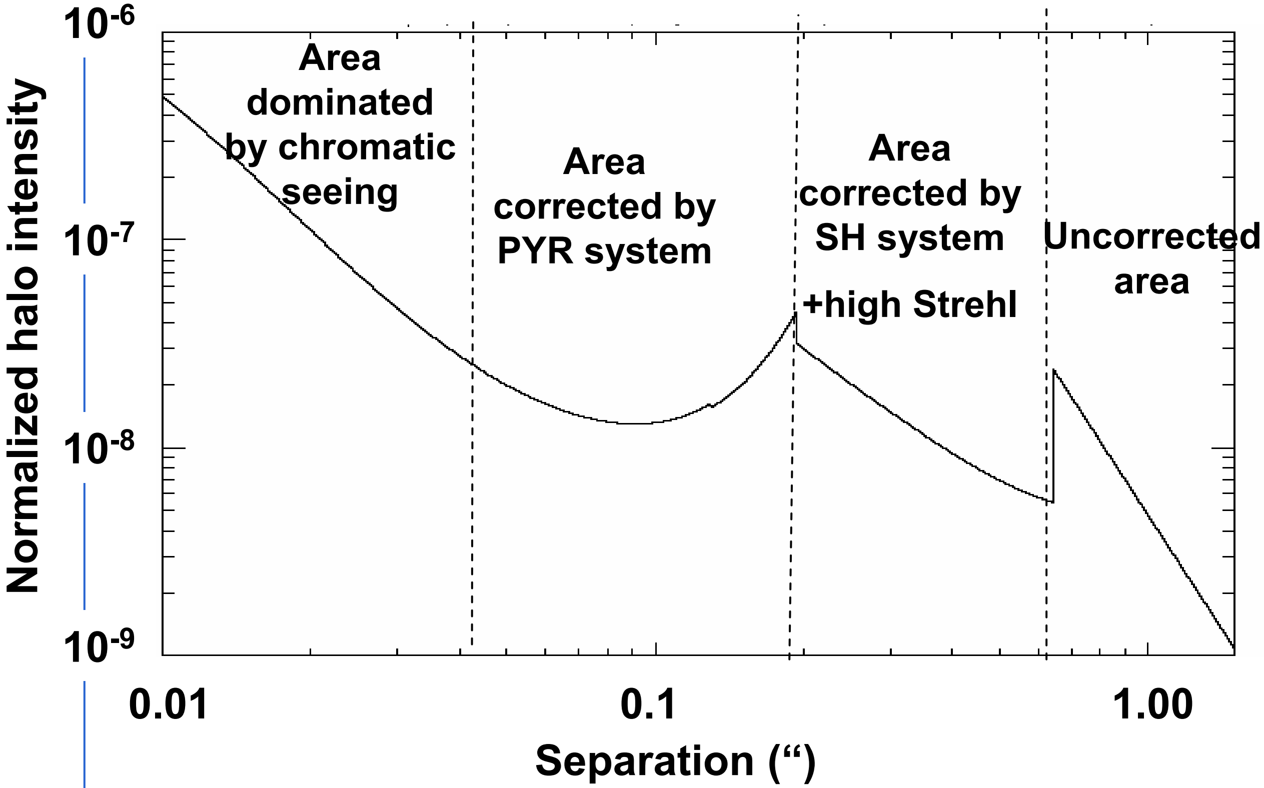
*HCIT: High Contrast Imaging Test bed TPFC



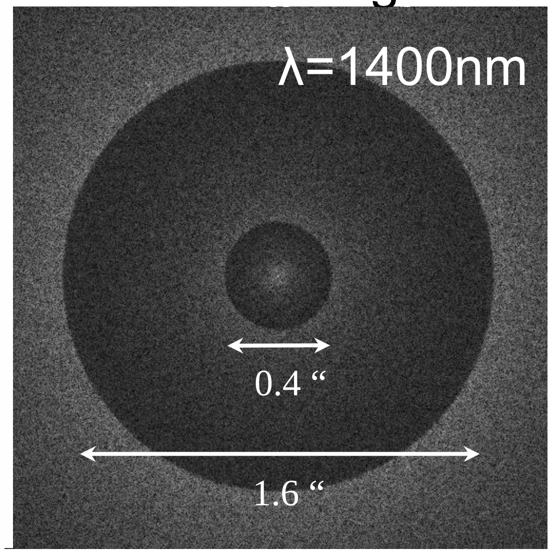
ENS Lyon
ONERA
Max-Planck-Institut für Sonnensystemforschung
MPS
LAOG
Observatoire Midi-Pyrénées
l'Observatoire de Paris
LESIA
MPIA
UK Astronomy Technology Centre
LAM
University of Amsterdam
INAF, Padua
ETH
American Museum of Natural History
ASTRON

EPICS Adaptive Optics performance (AO only)

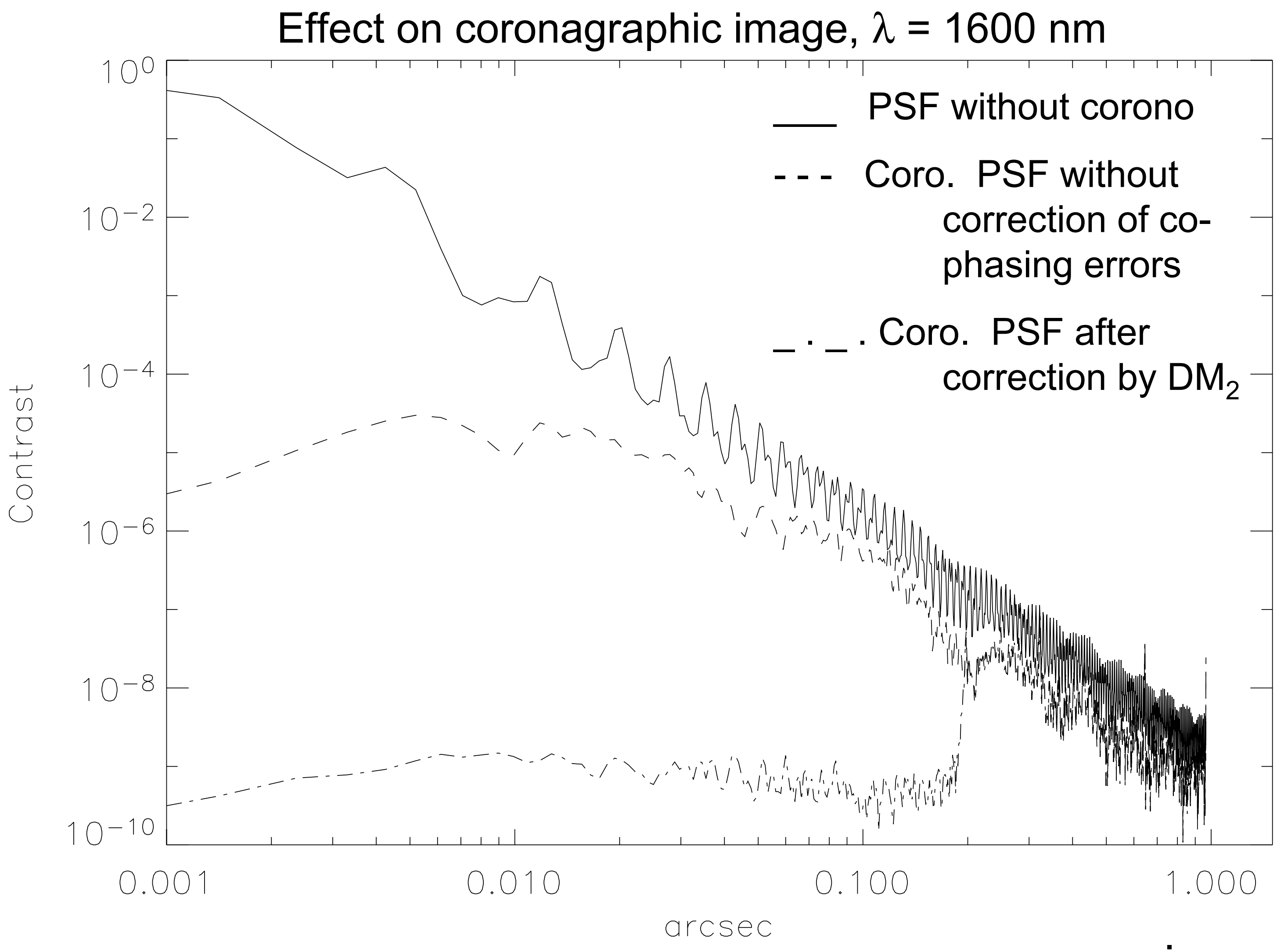
- Mv=7 G2 star at 25 pc
- Strehl (J band) 91 %
- Perfect Coronagraph



2 AO stages

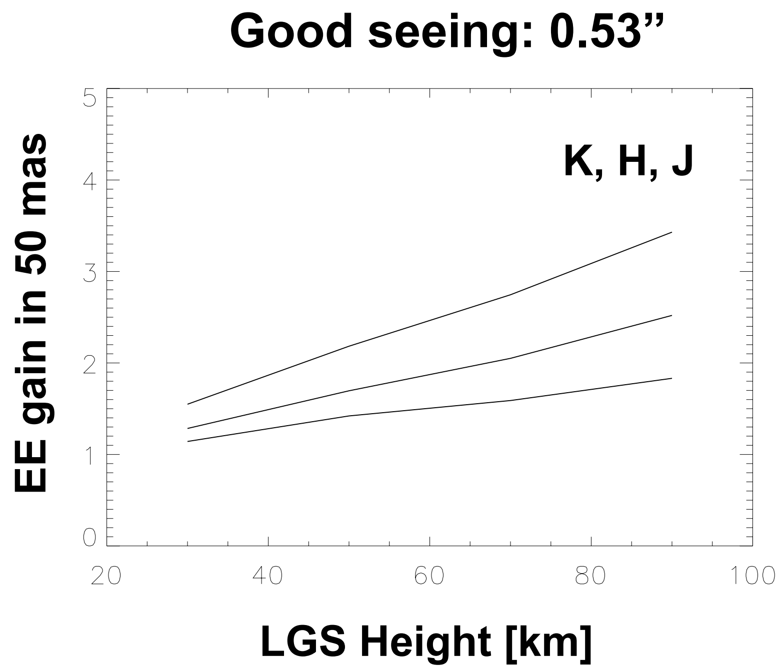


Reduction of Co-phasing residuals after XAO



Laser Guide Star Adaptive Optics: GLAO

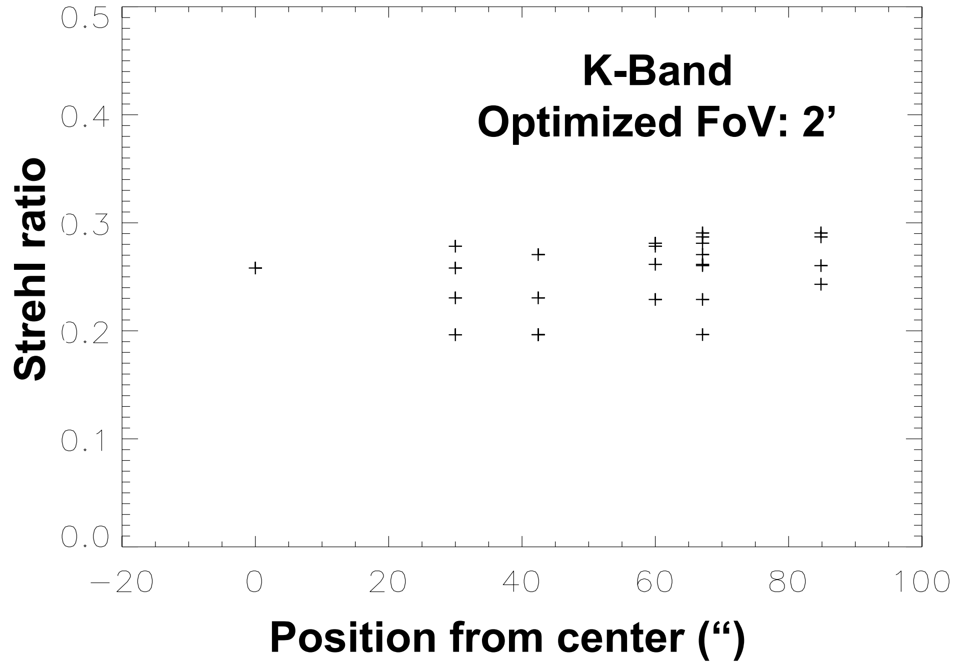
- Use single LGS on ELT
  - Cone effect Low Strehl ratio
  - Ground layer Correction
  - "High" sky coverage
- 1st analysis shows promising results
- Assumed ELT LGSs issues solved (spot elongation,…)



Multi Conjugate AO with Laser Guide Stars

- 5 LGSs
- High sky coverage
- High WFS flux
  - More sub-apertures
  - More DMs
- Assumed ELT LGSs issues solved (spot elongation,…)

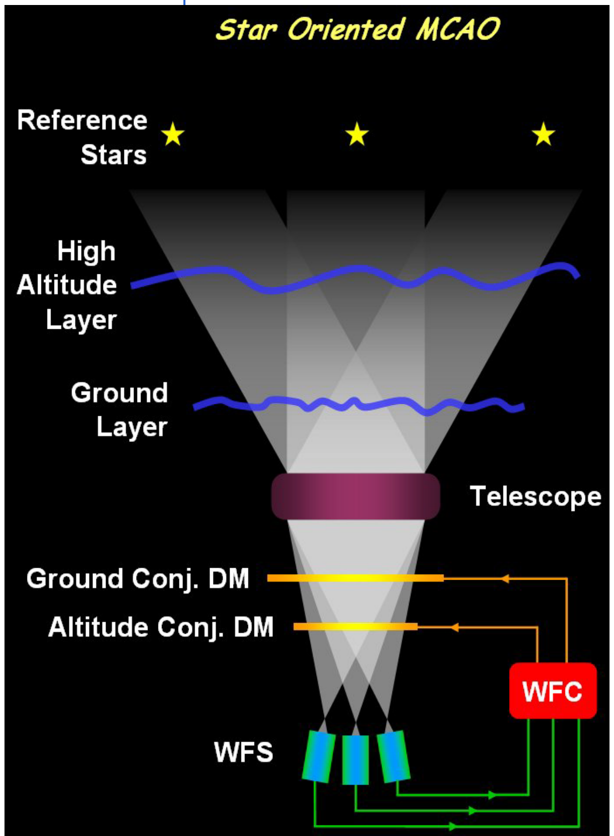
Good seeing: 0.53”



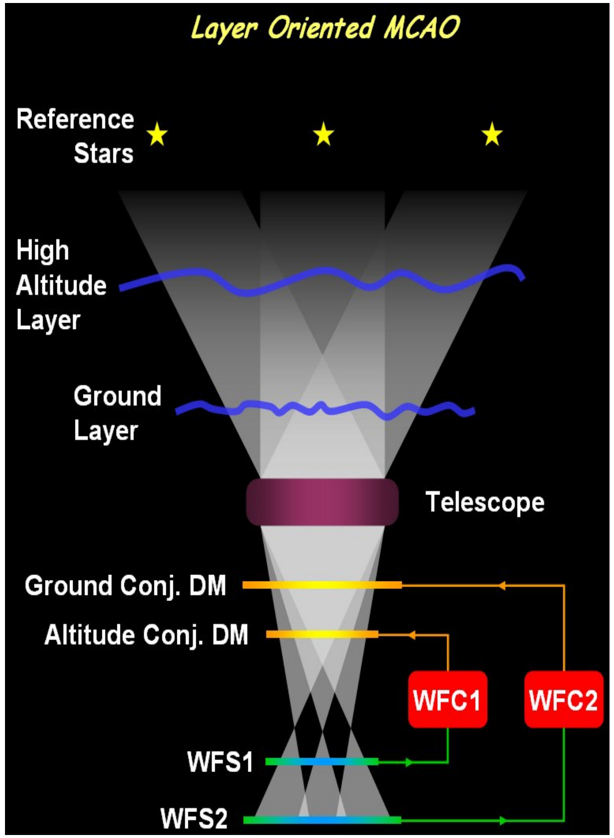
Demonstrators and Pathfinders

MAD: The GLAO & MCAO demonstrator

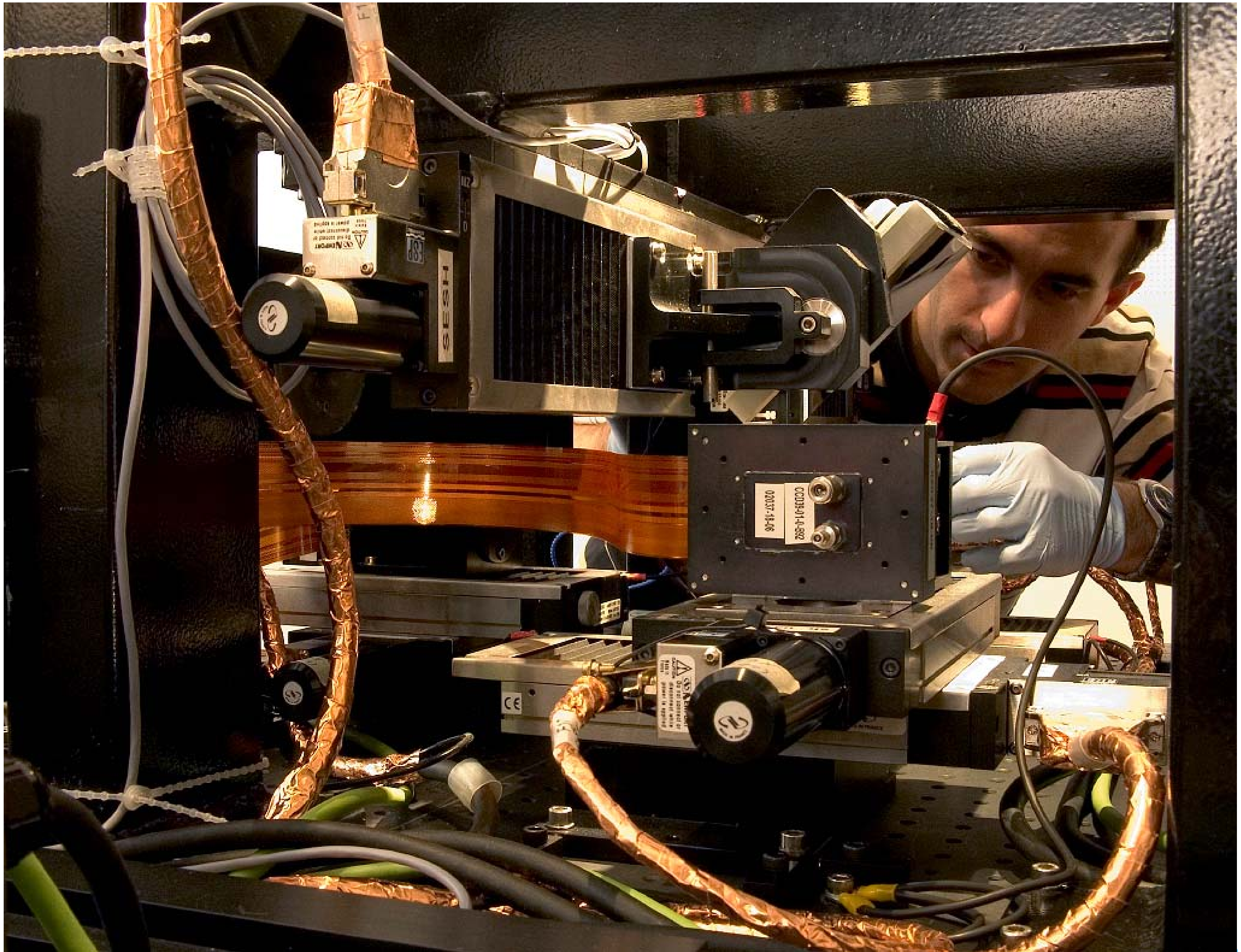
Demonstrate Ground Layer and Multi Conjugate AO



- Star Oriented 3 SH WFSs
- Layer Oriented pyr. WFS
- Study control algorithms
- 3 D turbulence generator
- MAD status:
  - SCAO
  - GLAO loop: 06.05
  - MCAO loop:10.05
  - Layer oriented: 2Q ‘06
  - On-sky 3Q ‘06
- Study calibration issues:
  - Non-common aberrations
  - Interaction matrix

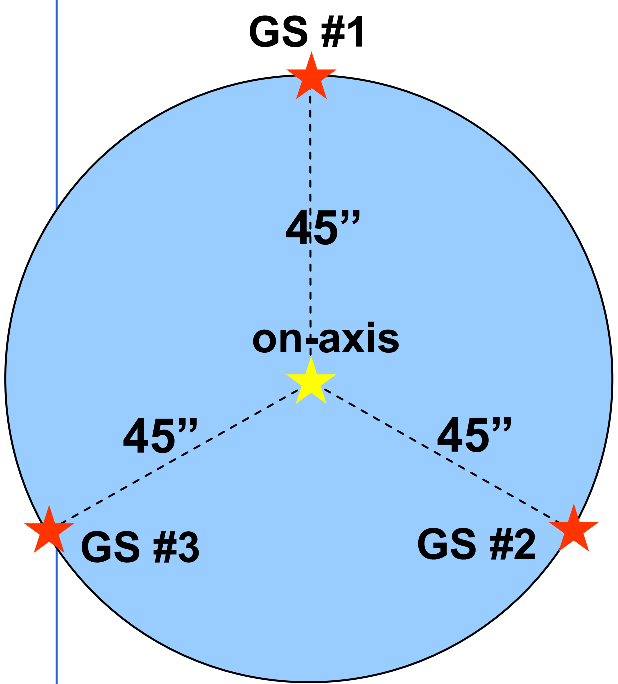


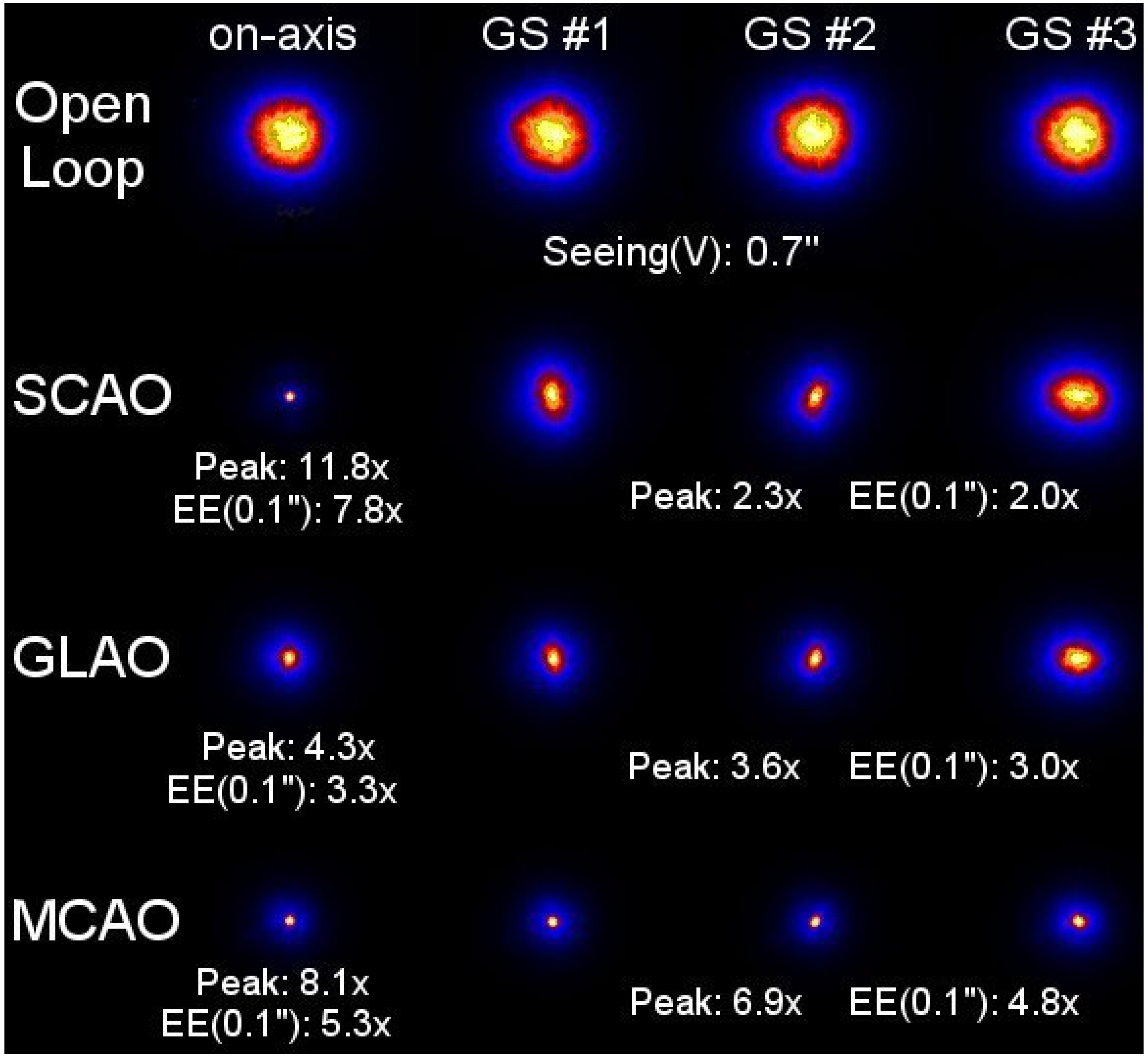
MAD design & implementation



MAD preliminary results

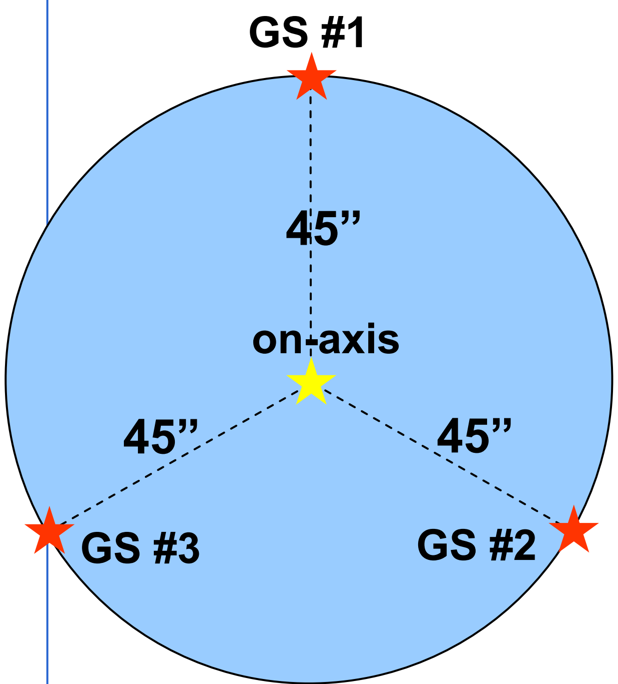
- Star oriented mode
- 3 Visible SH WFSs
- 8^2 sub-apertures
- K-band

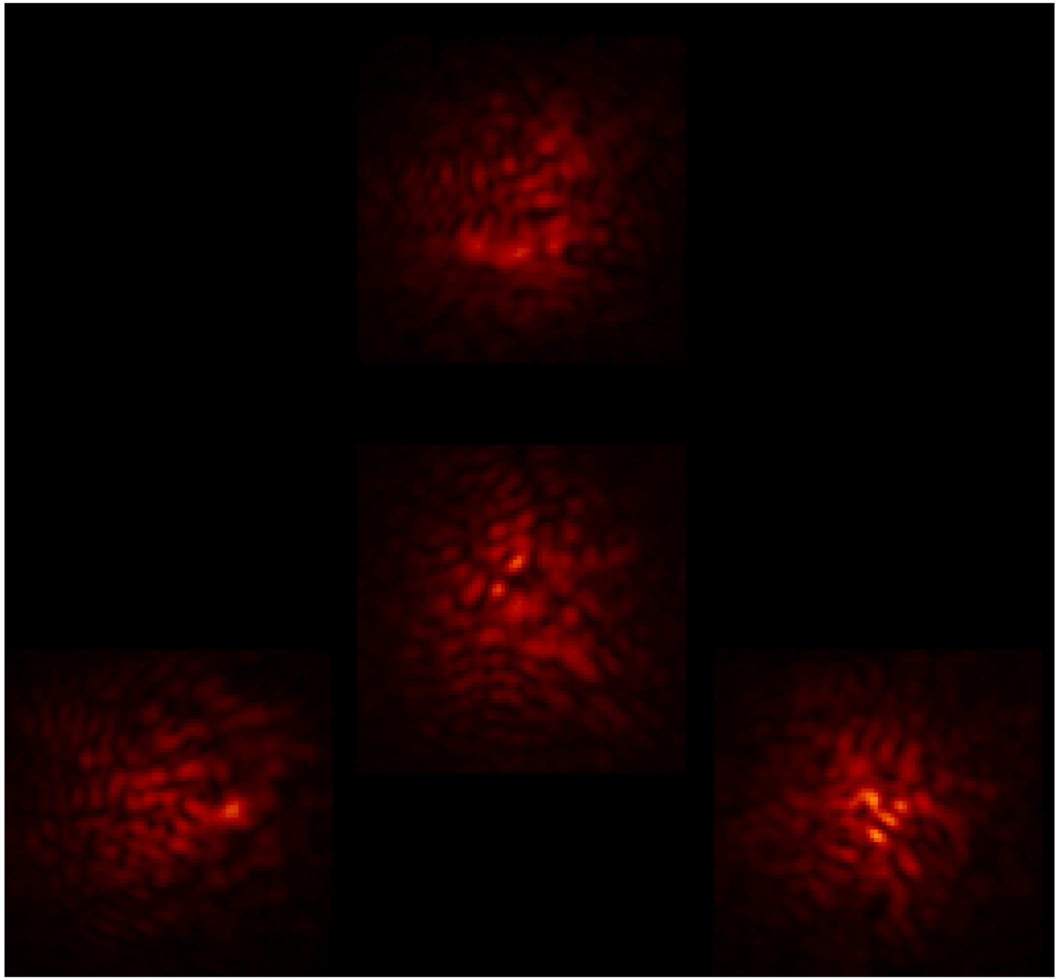




MCAO closed loop of MAD

K Band; Seeing 0.7”; τo=3.3 ms





Gs magnitudes = 8

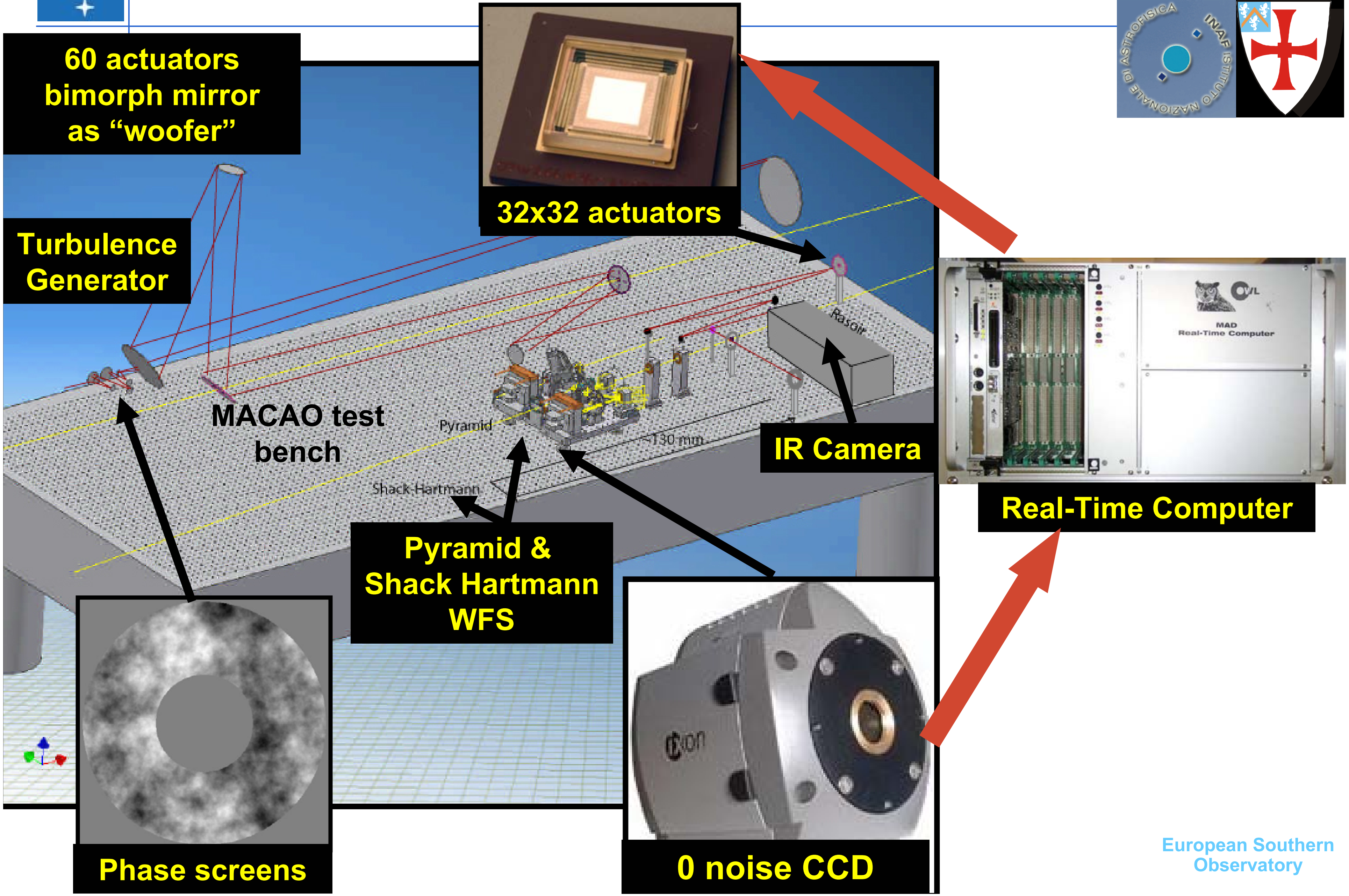
200Hz frame rate

HOT: High Order Test bench

Demonstrate Extreme AO & High contrast imaging

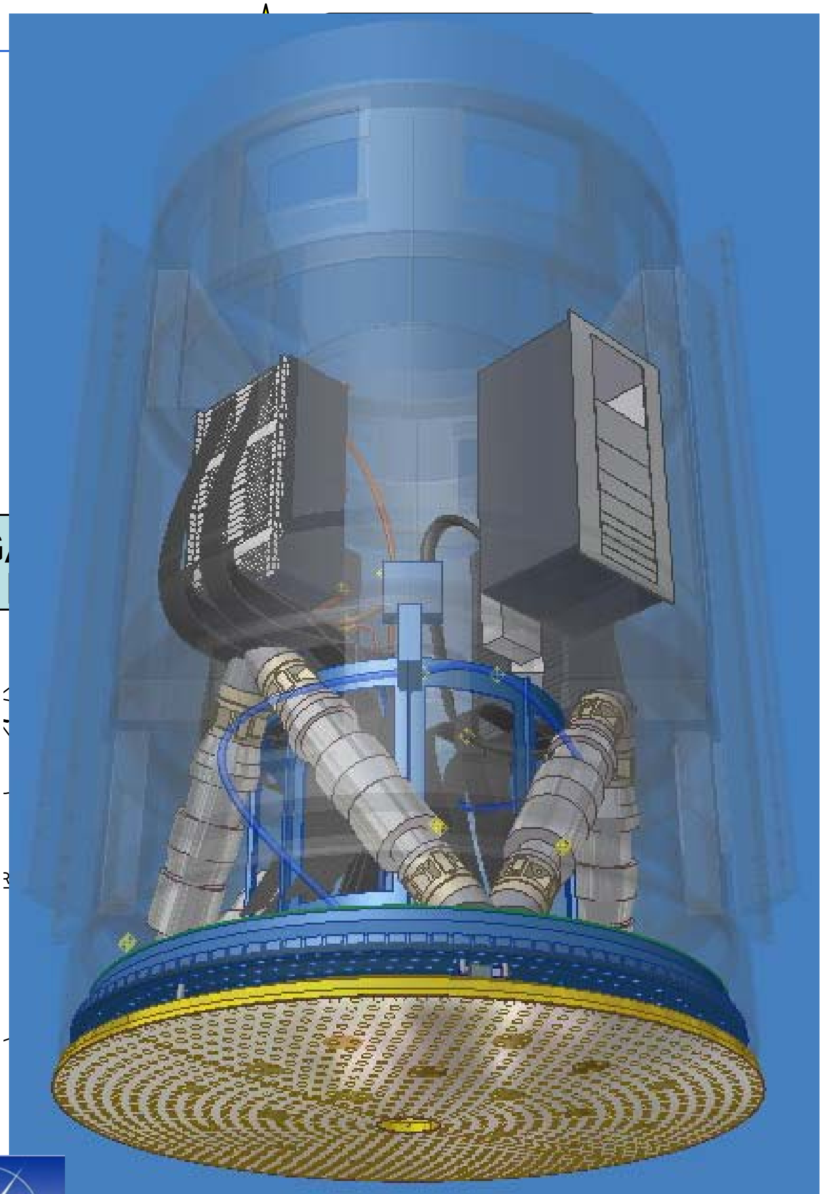
- Study optimum wavefront sensor for high contrast imaging
  - Spatially filtered SH WFS with weighted centre of Gravity
  - Pyramid WFS in diffraction regime w &w/o modulation
- Study error sources & final contrast: misregistration, aliasing,..)
- Study Point Spread Function characteristics & residual aberrations
- Investigate coronagraph concepts
- Study pupil segmentation effect on final PSF after AO correction
- Validate new components:
  - Micro Deformable mirrors
  - New low noise CCD for WFS
  - ESO Real Time computer platform
  - New control algorithms
  - Focal plane WFS
  - Super polished filters for differential imaging

HOT: a high contrast imaging test bench



VLT AO Facility: A Pathfinder for OWL

- Concept of Active/Adaptive Telescope
- Four Sodium Laser Guide Stars
- 2 GLAO syst. (GALACSI, GRAAL)
  - 10' NIR seeing reducer (HAWK-I)
  - 1' visible seeing reducer (MUSE)
- Laser Tomography AO: Sr(v)~10%
- Enabling technologies:
  - 1.1 m convex aspherical Deformable M2, 1170 act.
  - 2 mm Zerodur thin shell
  - Raman fibre laser
  - ~0 noise, 240^2 pix., 1kHz WFS-CCD
  - Computing power 200 x NAOS
- Laboratory testing facility (ASSIST)



ADS International

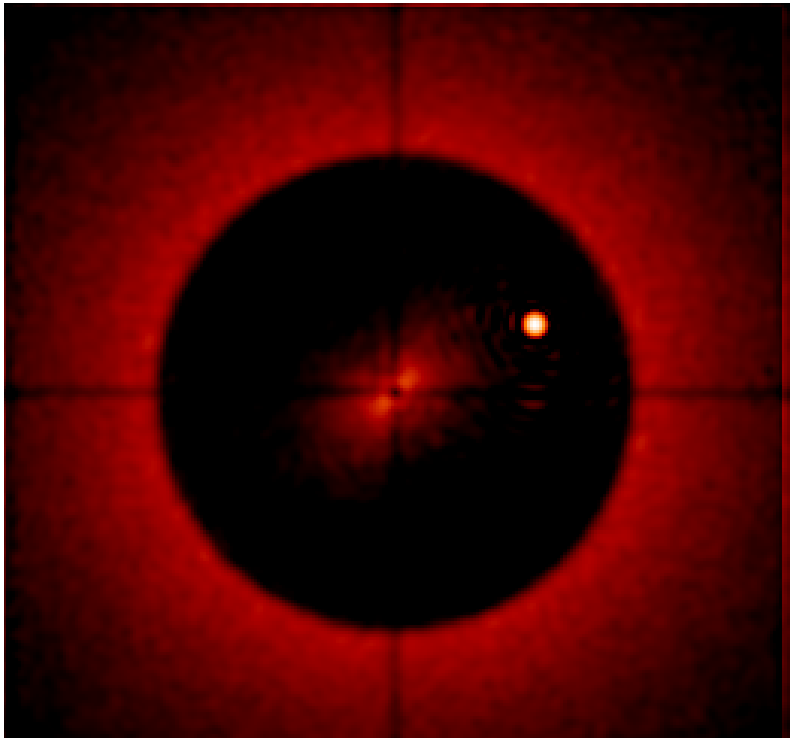
VLT Planet Finder: An XAO Pathfinder for OWL

Planet detection with contrast 10^{-5} at 0.1” separation

- **Detection**
  - **Extreme AO (SR ~ 90% in H band)**
  - **Coronagraphy (contrast at 0.1” separation)**
  - **Differential imaging (residual halo)**

- **Characterization**
  - **Integral Field Spectroscopy**

- **Visible Channel**
  - **Imaging / Polarimetry (SR 90% in H at 65% in R)**



Courtesy J. L. Beuzit

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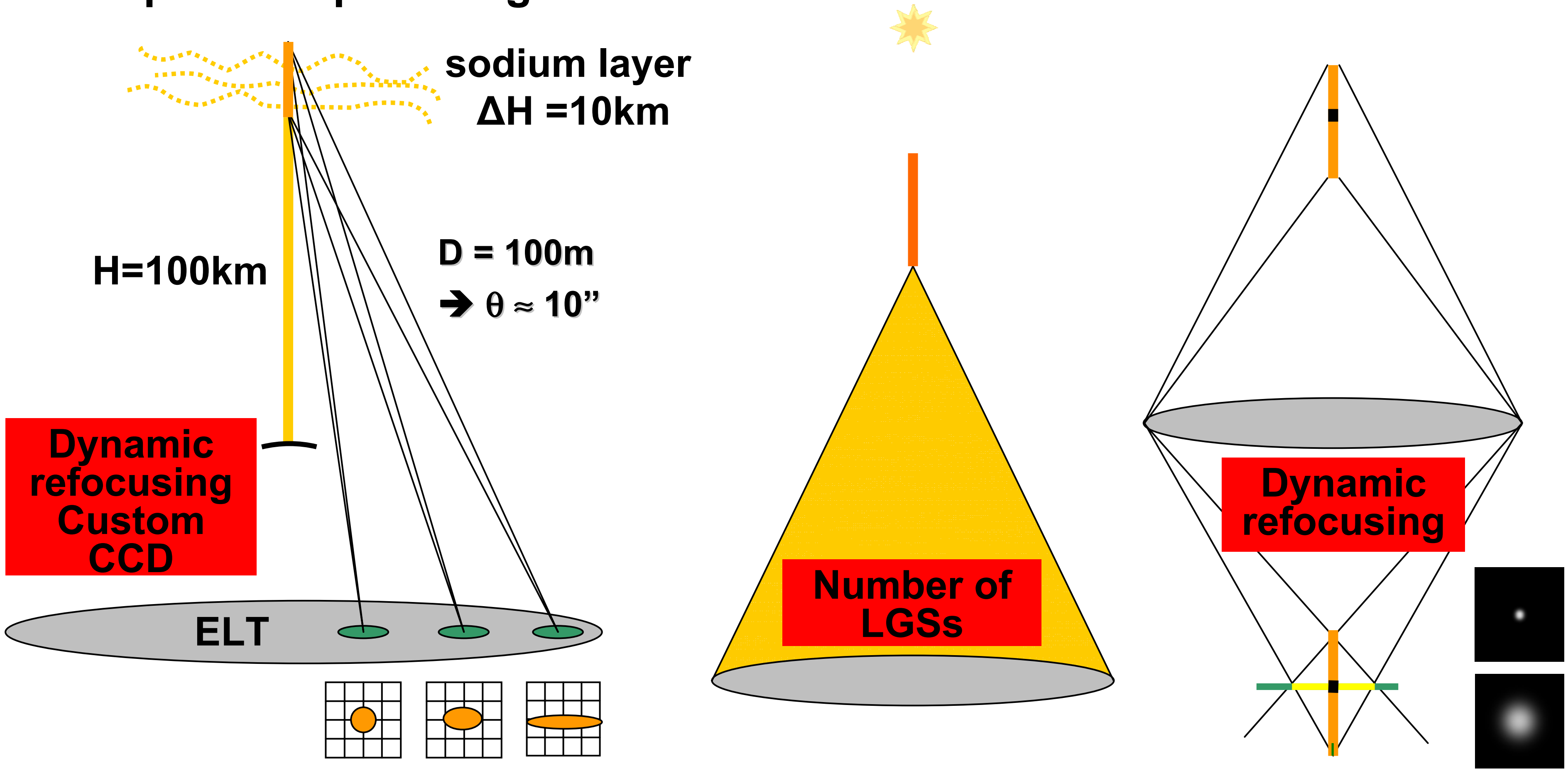
ETH Zurich

European Southern Observatory

Required field tests on LGS issues

Perspective spot elongation | **Cone effect** | **Defocus**

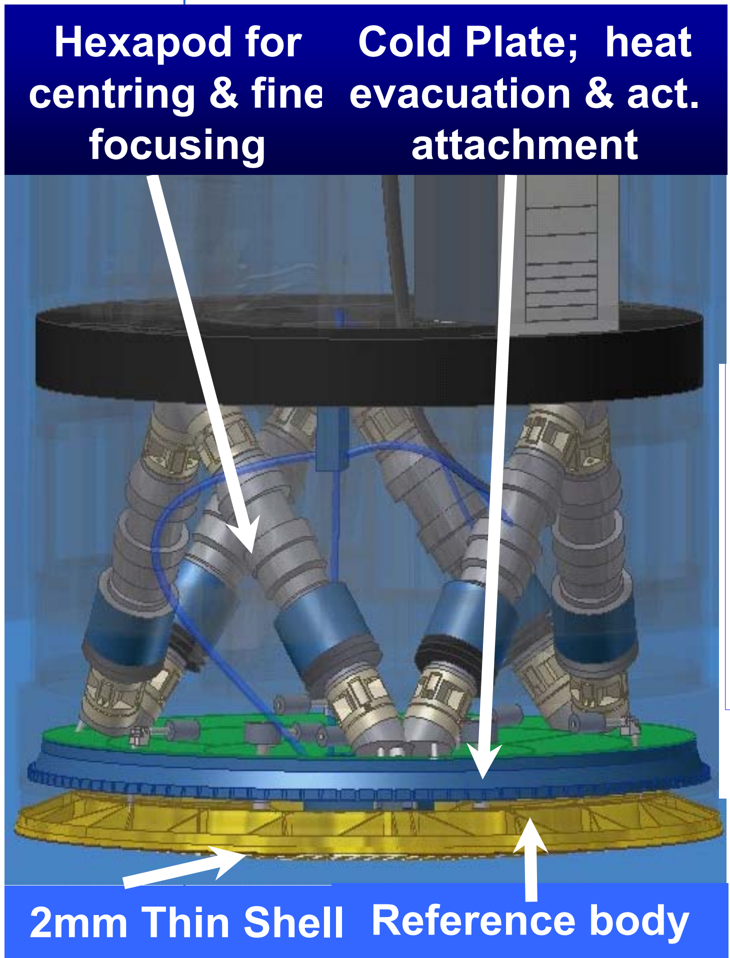


- WFS spot aberrations: **Optical corrector in WFS**
- Fratricide effects: **Number of launch telescopes, Pulsed lasers**
- Low order with NGS: **In some cases, helped by outer scale**

NEW LGS CONCEPTS BETTER SUITED FOR ELTs NEEDED?

Enabling technology roadmap

Large Deformable mirrors: from VLT to OWL

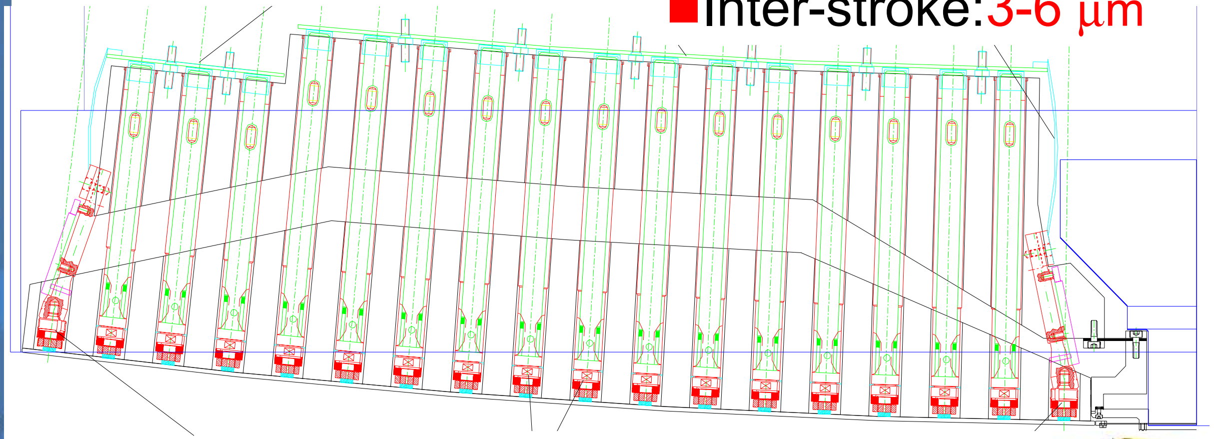


VLT Deformable M2

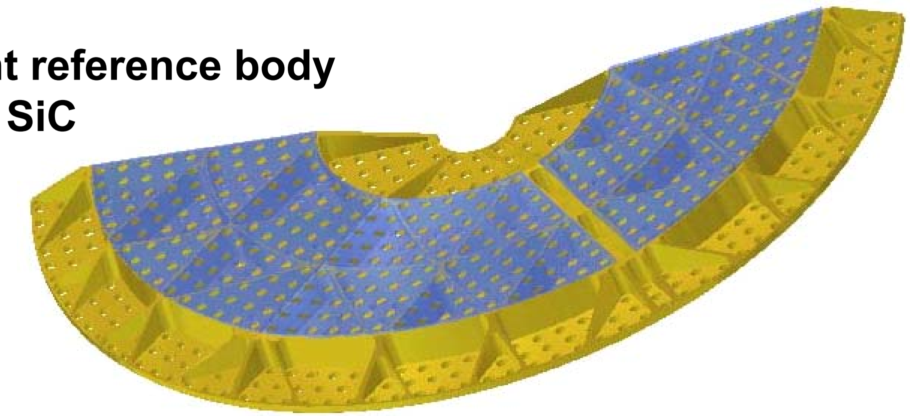
- Ø 1.1m convex
- 1170 actuators
- 29 mm pitch
- 1 ms response
- Stroke 50 / 1.5 μm

OWL M6

- 2.6 x 2.4 m flat
- 7000 actuators
- 24 mm pitch
- 1 ms response
- Stroke 25-90 μm
- Inter-stroke: 3-6 μm



Lightweight reference body
Zerodur or SiC



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MICROGATE

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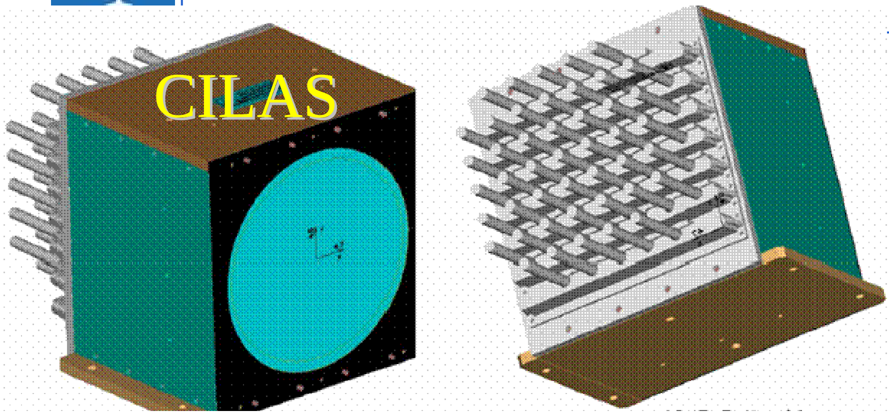
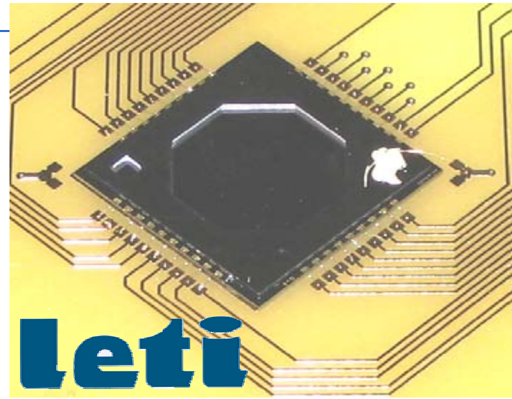
High density Deformable Mirror roadmap





VLT Planet Finder

- 41^2 act. Piezo DM (1370)
- 4.5 mm pitch; 10 KHz
- 8 µm stroke

- 19 actuators; continuous membrane
- 1mm pitch
- 4.5 µm mech. stroke for 60V
- WF error: 1.5nm rms

Funded by OPTICON

- 2k actuators with 1mm pitch
- 5-10 µm mechanical stroke
- 1-2 µm inter-actuator stroke
- 10 nm rms

OWL Planet Finder & MOAO

- 10k & 100 k actuators
- 1 mm pitch; 3-5 KHz
- 1-5 µm stroke
- WF error: 1-10 nm rms

Wavefront Sensor detectors roadmap

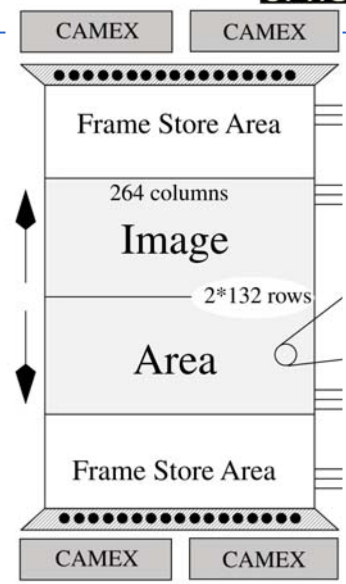
MPI

VLT Planet Finder

- 240^2 pix. L3CCD
- 8 outputs
- 1.5 kfr/s, 90 Mpixels/s
- 0.2 e^- RON
- Blue QE low depletion

OPTICON-JRA3

- 264^2 pixels
- 528 outputs
- 1.1 kfr/s
- 3 e^- RON ↓
- High QE deep depletion



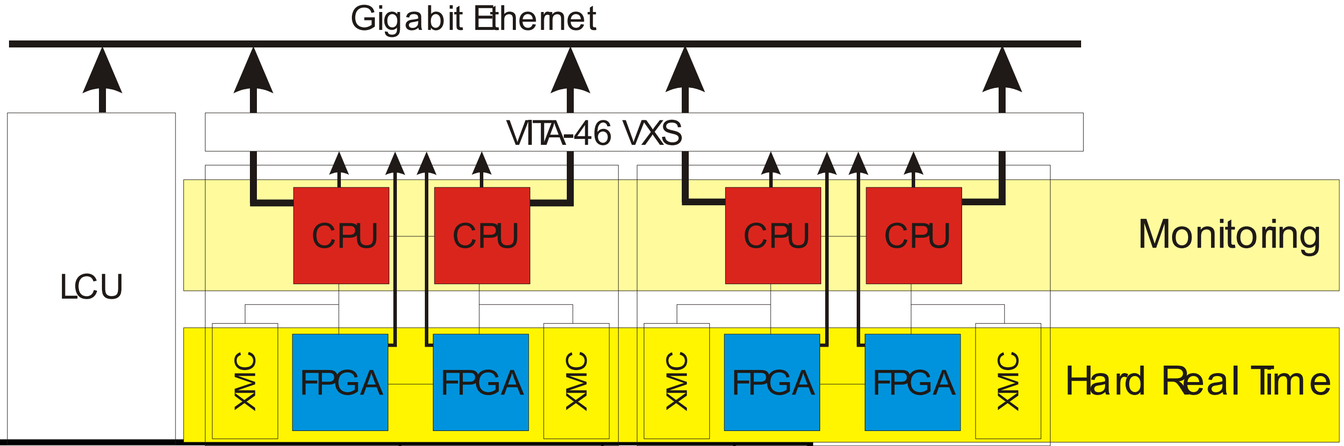
OWL SC- GL- MC- MO- X AO

- 600^2 to 1000^2 pixels
- 500 to 1 kfr / s (goal 3kHz)
- 0 e^- RON ↓
- High QE
- Good PSF

IR WFS detector R&D

Real-Time Computers roadmap

- SPARTA-for-OWL concept shows **feasibility** of the RTC for OWL projecting the current architecture for VLT 2ng Gen AO
- Even better architecture will be available at that time



System	Size (grad. * act. * freq)	G-FMAC	Ratio	
SCAO	13800*7600@500Hz	52	1	👍
GLAO	13800*7600@500Hz 82800*7600@500Hz	52 314	1 6	👍
MOAO	14400*7600@500Hz 43200*7600@500Hz	54 164	1 3	👍
MCAO	82800*24000@500Hz	993	19	👍
XAO	400.000*200.000@1kHz 35000*18000@3 kHz	80000 2000	1500 40	☹

SCAO@52 GMAC achievable in 3-4Y
Moore's law in 10 Y factor 100
SCAO@52➔ 5200

G-FMAC: Giga Floating Point Multiply accumulate

Computer power & new algorithms

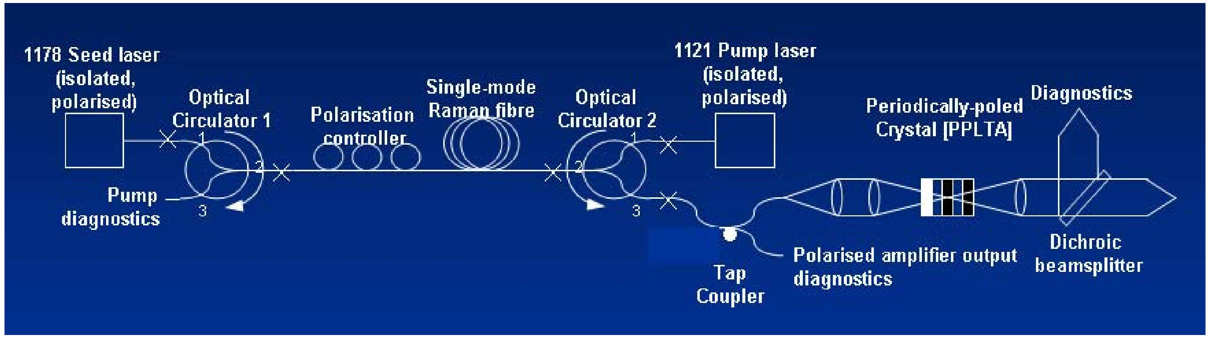
- All RTCs but X-AO possible with standard methods (Matrix Vector Multiply)
- New algorithms reducing computing power needed for X-AO
- Can be retrofitted to the other systems to lower their cost
- Current portfolio of methods:

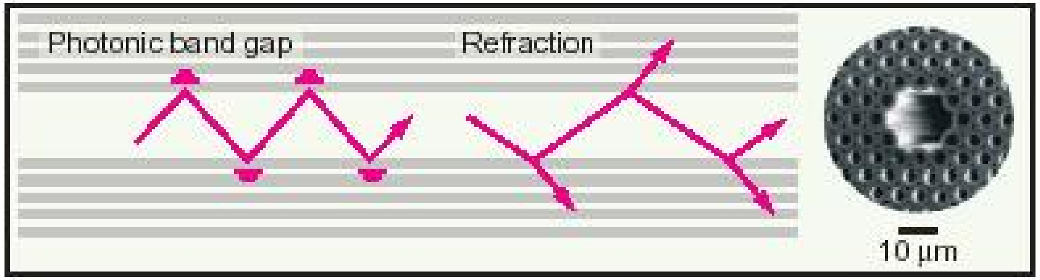
Method/gain	98x98	250x250	500x500	Precision	f(D)
Direct sparse	1-50	7-340	10 - 1300	Perfect	$\propto \frac{D^2}{k \cdot \alpha}$
Iterative Multi-grid - PCG	1-30	4-200	15-800	High	$\propto \frac{D^2}{N_{iter}}$
Iterative FD-PCG & Fourier-domain	45-230	250-1250	1250-5000	High	$\propto \frac{D^2}{\log(D^2)}$
Local & hierarchic	~600	~3700	~15000	low	$\propto k$

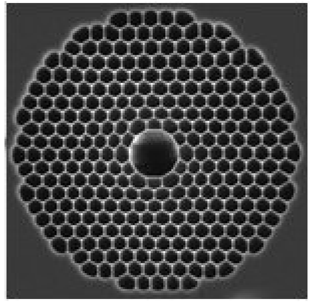
PCG: Pre-conditioned Conjugate Gradients

Laser Guide Stars enabling Technologies

- Components being developed:
  - Fiber laser sources (Raman and Sum-frequency [LLNL]) (IPF Technologies, Volius)







System design roadmap

- Explore actual limit of “classical” Laser schemes for GLAO, LTAO, MCAO & MOAO systems
- Study promising novel LGS-AO concepts & field test (FP6, FP7)
- Science cases – instrument & AO designs trade-offs
- Fully design SCAO with M6 adaptive mirror
- NGS- LGS design trade-offs for GL-LT-MC-MO AO
- Pursue AO key technologies roadmap (FP7, OWL Phase B):
  - Large & micro deformable mirrors
  - Visible & NIR WFS detectors
  - Lasers & beam projectors
  - New control algorithms and Real Time Computers
- Feedback from VLT AO systems & demonstrators
- Explore fundamental limits of EPICS with HOT

Conclusions

- Several AO concepts studied; performance evaluated
- LGSs - NGSs trade-off to be explored further
- Ground Layer & Multi-Conjugate Demonstrators on-track
- VLT AO Facility & Planet Finder pathfinders for OWL
- EPICS design study calls for several bread boards (HOT)
- LGS-ELT demonstrators needed
- Aggressive roadmap for AO key technologies (OPTICON, FP6)
  - CCD, IR WFSs
  - Large & μ DMs (two competitive M6 feasibility studies; CfT out)
  - Control & algorithms
  - Lasers
- Strong involvement of the AO community; THANKS….!
- Active preparation of a FP7 AO R&D program (2007-2014)
- 33% of the OWL R&D effort for AO