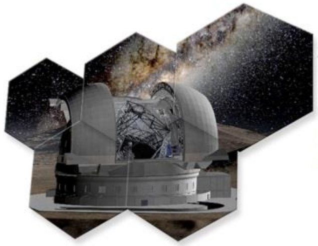


# Modeling the multi-conjugate adaptive optics system of the E-ELT

Laura Schreiber

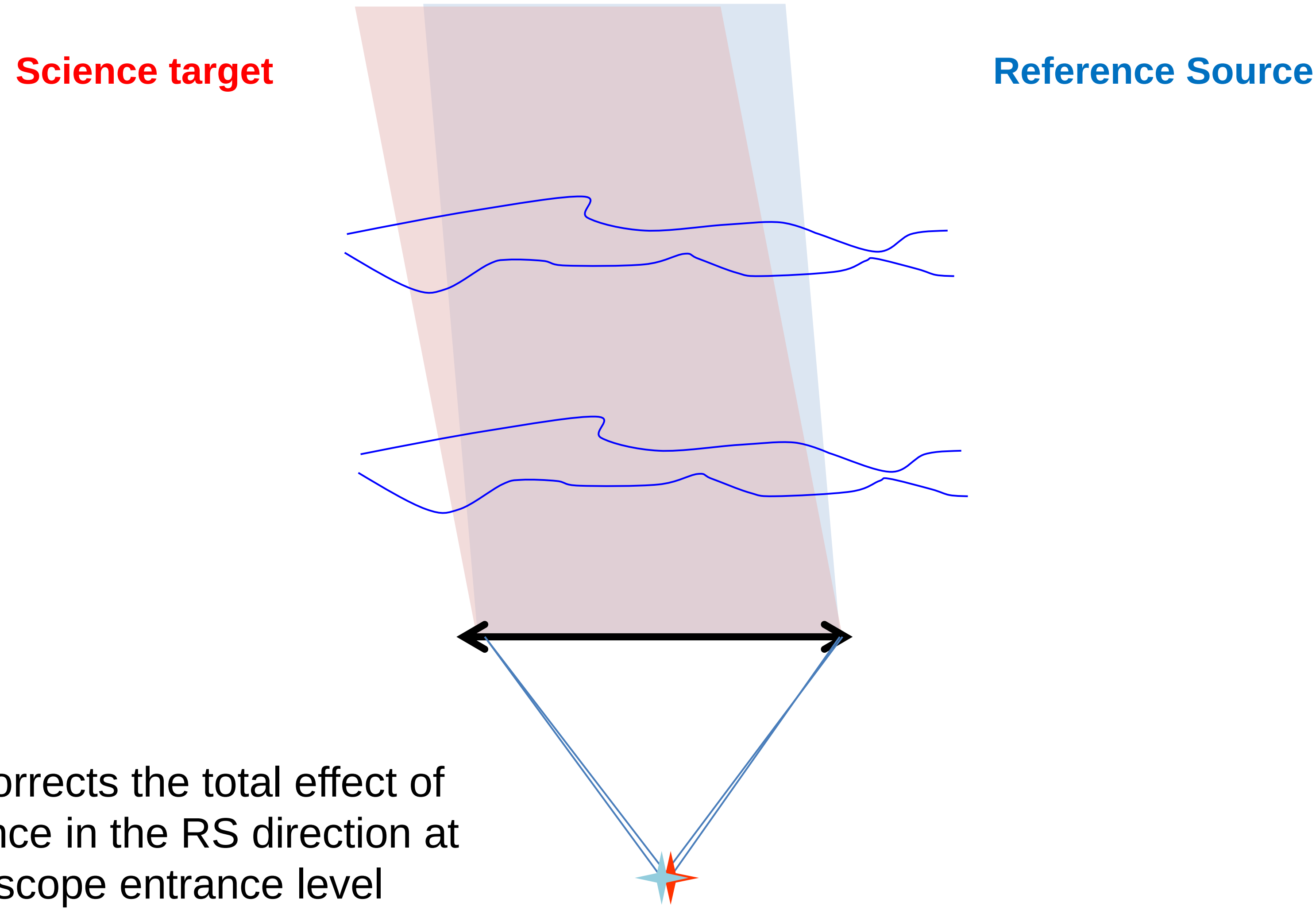
Carmelo Arcidiacono

Giovanni Bregoli

# MAORY

- E-ELT **M**ulti Conjugate **A**daptive **O**ptics **R**ela**y**
- Wavefront sensing based on 6 (4) Sodium LGS and 3 NGS
- Wavefront Correction operated by M4/M5 (Telescope) and 1+1 Post focal deformable mirror(s) conjugated at (5 km and) 12.7 km
- MCAO and SCAO modes

# What's LGS (+ NGS) MCAO?

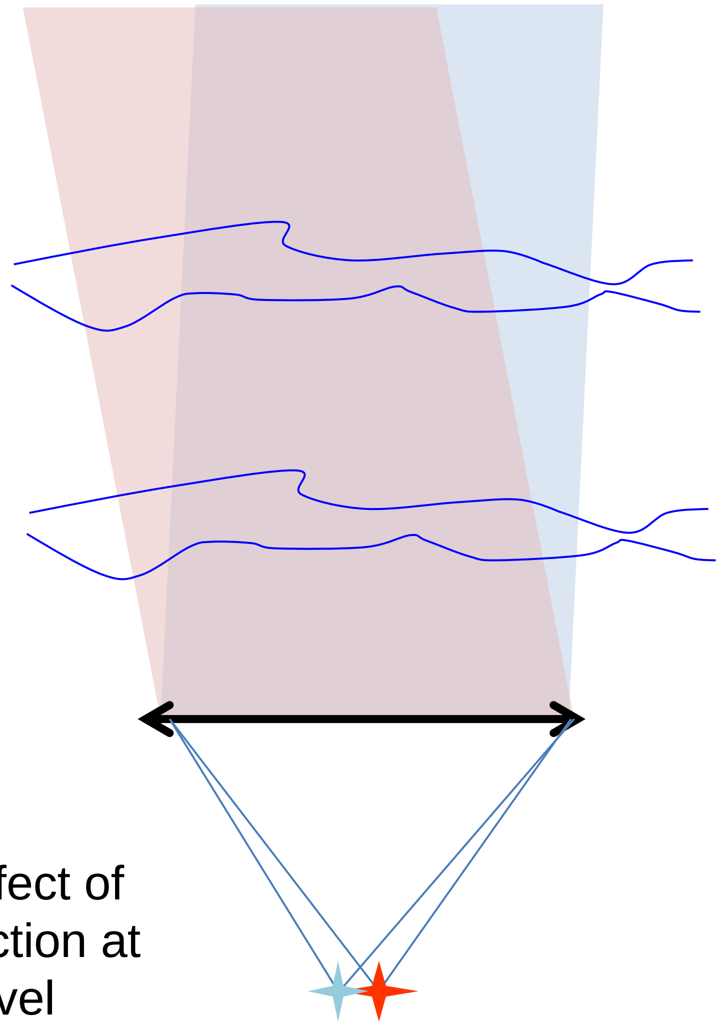



**1 DM** corrects the total effect of turbulence in the RS direction at the telescope entrance level

# What's LGS (+ NGS) MCAO?

Science target

Reference Source



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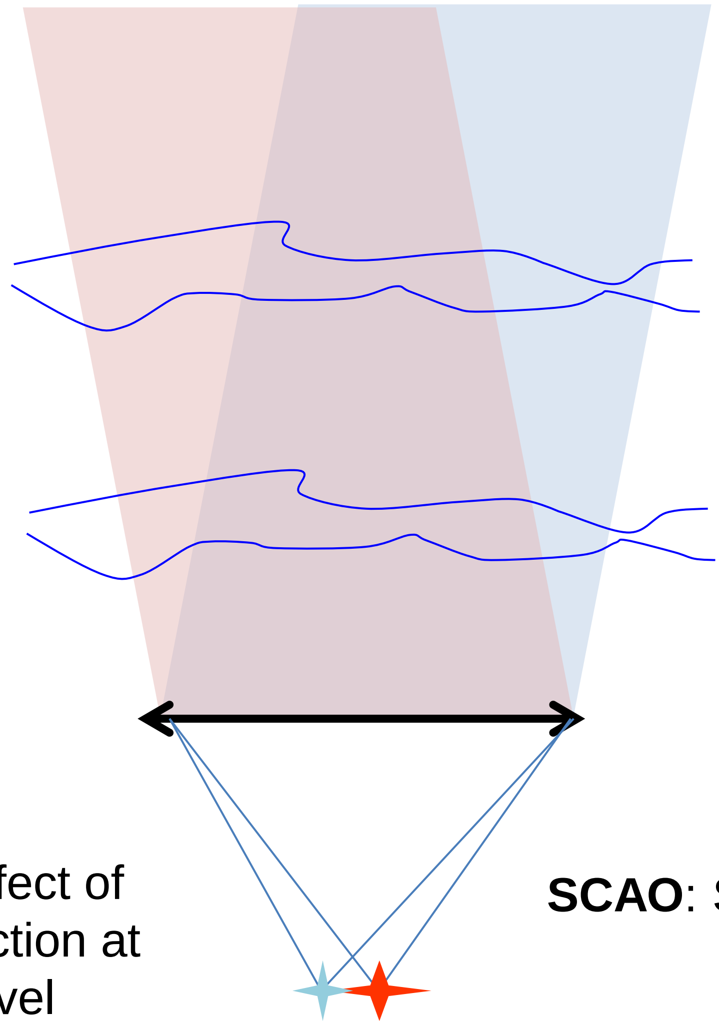


**1 DM** corrects the total effect of turbulence in the RS direction at the telescope entrance level

**SCAO**: Small corrected FoV
Low Sky coverage
PSF variability

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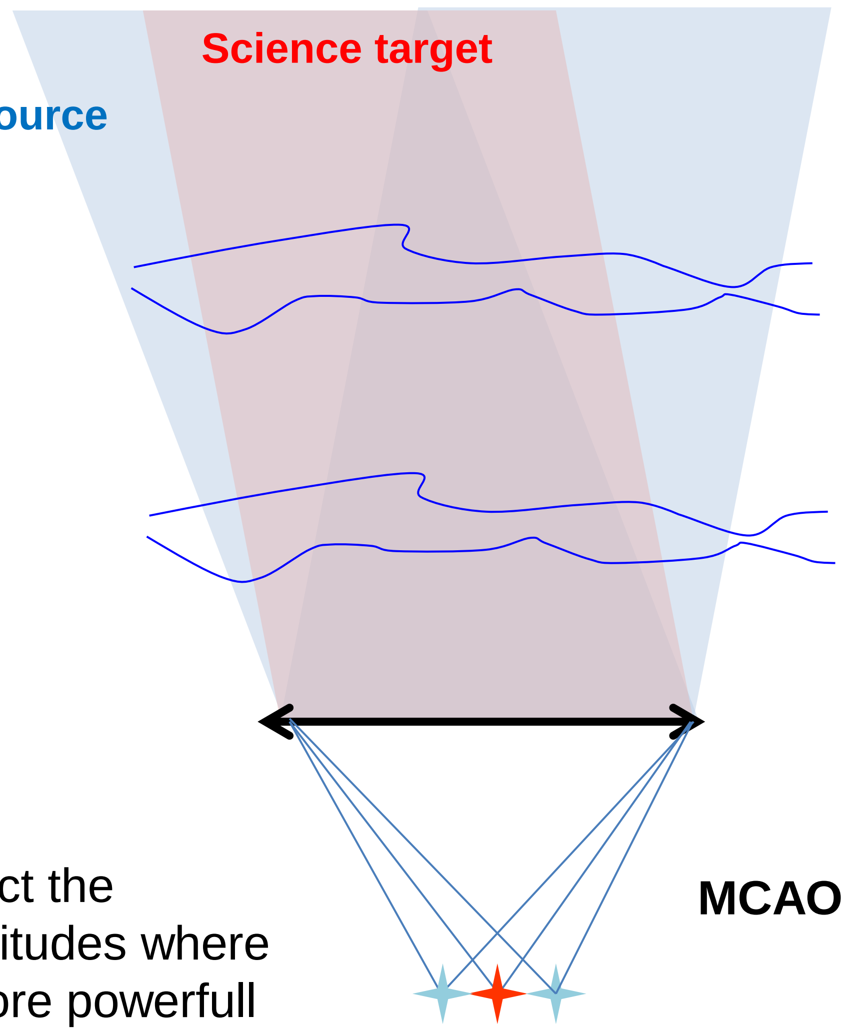
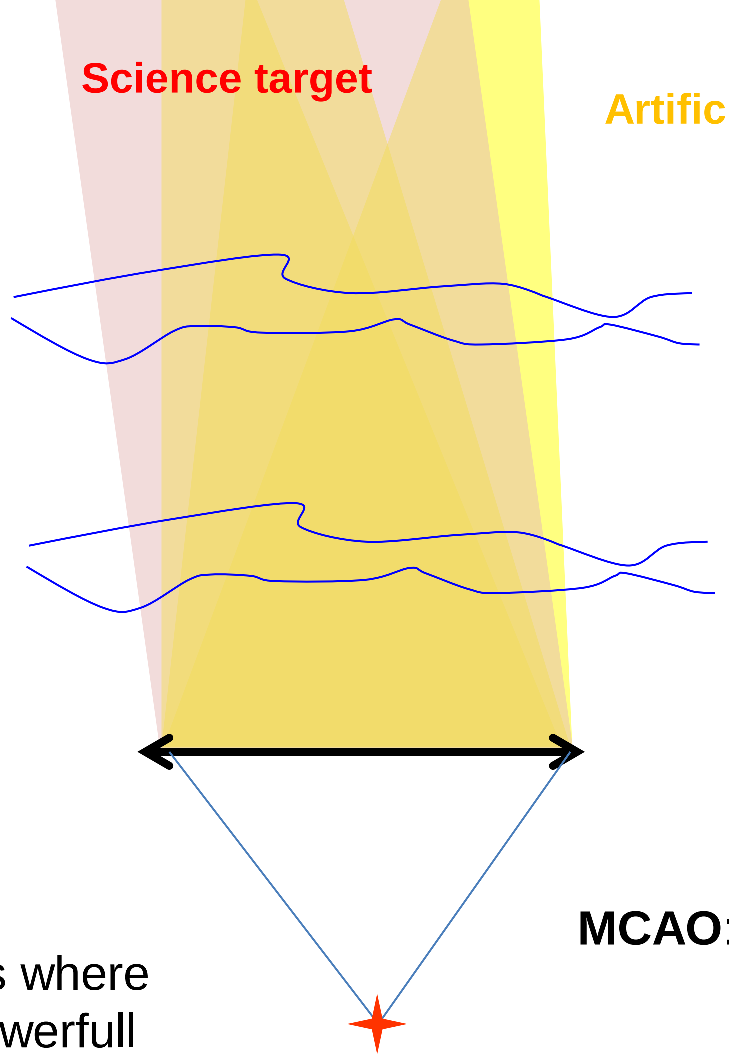



**Multiple DMs** correct the turbulence at the altitudes where the turbulence is more powerfull

**MCAO**: Large corrected FoV
Low Sky coverage
PSF stability

# What’s LGS (+ NGS) MCAO?




**LGSs** : Artificial reference sources can be created to ensure high sky coverage

**Multiple DMs** correct the turbulence at the altitudes where the turbulence is more powerfull

**MCAO**: Large corrected FoV
High Sky coverage
PSF stability

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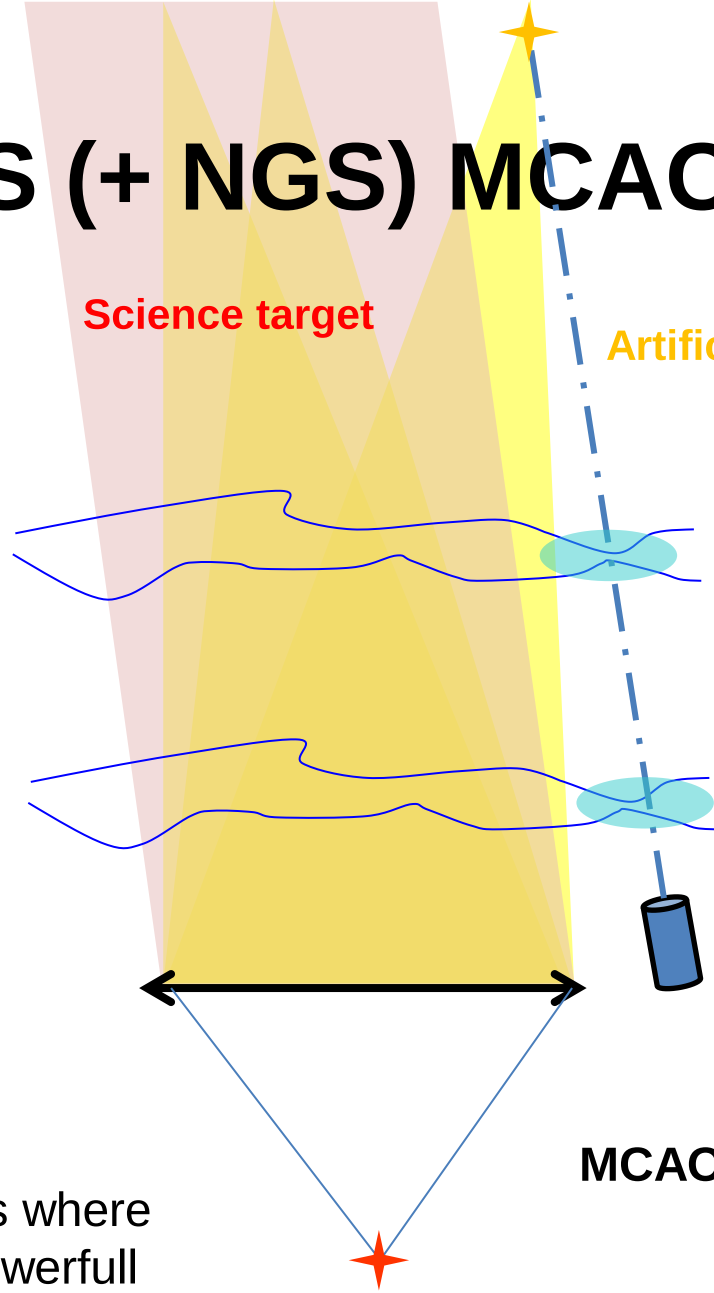


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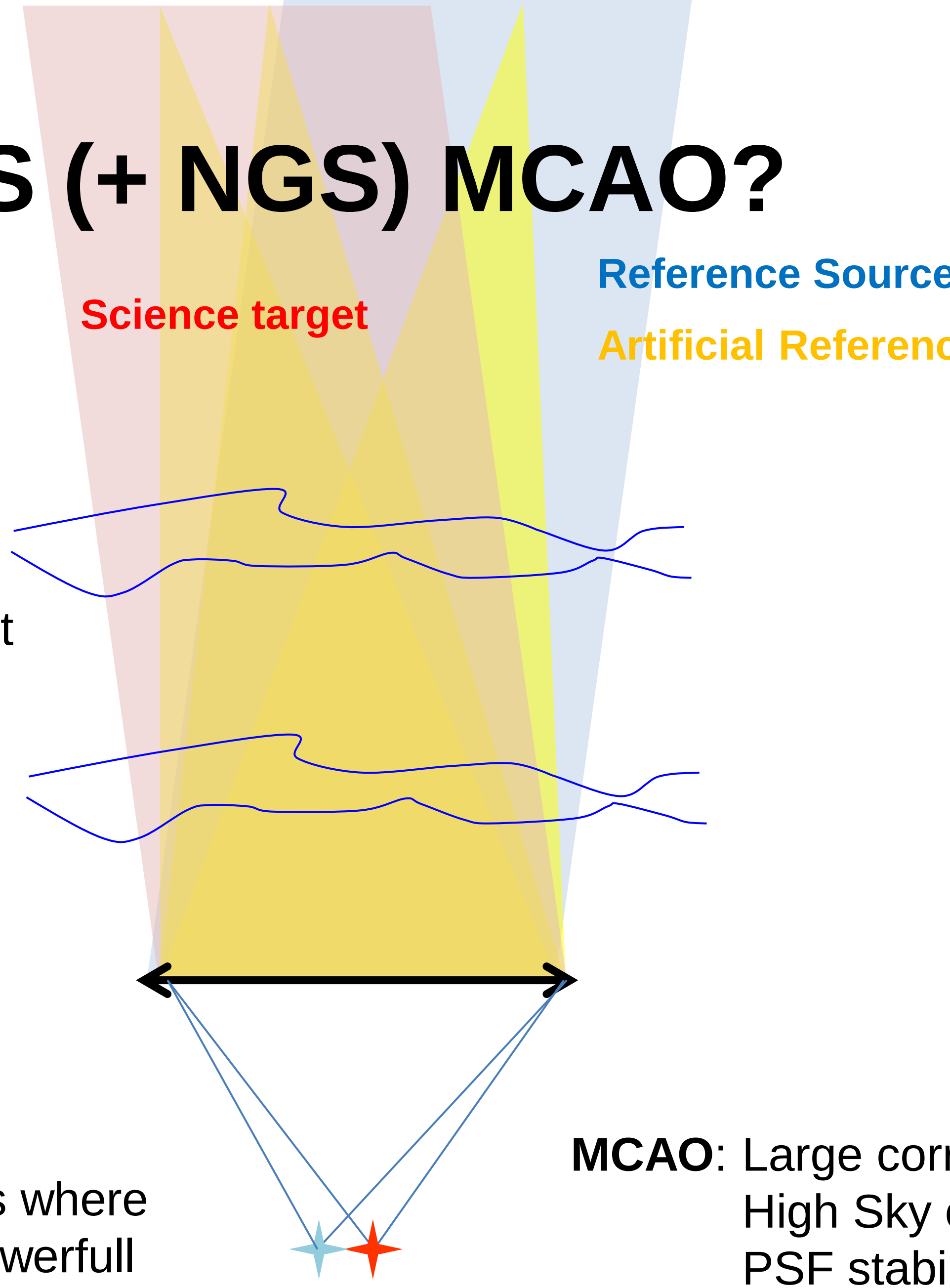


**NGS** : A natural Source is required to misure fast tip/tilt

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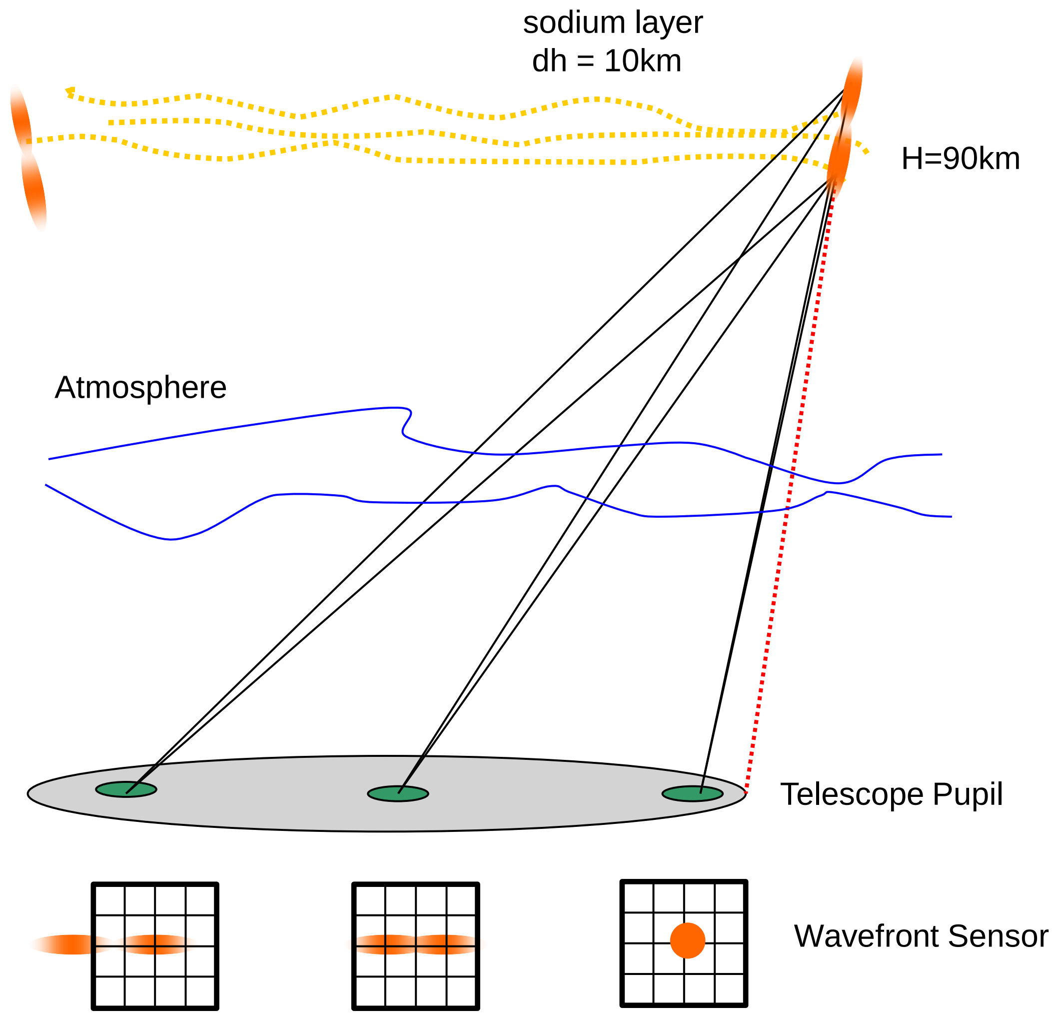
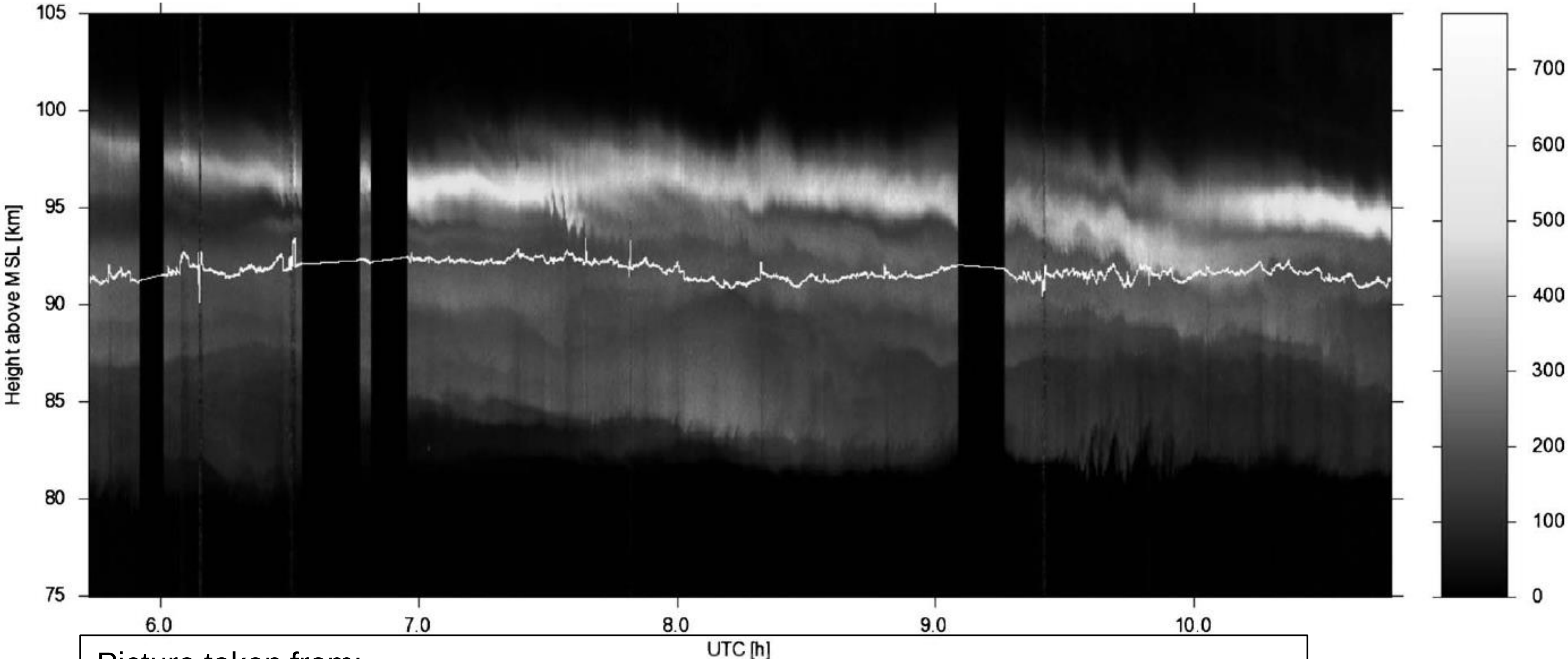


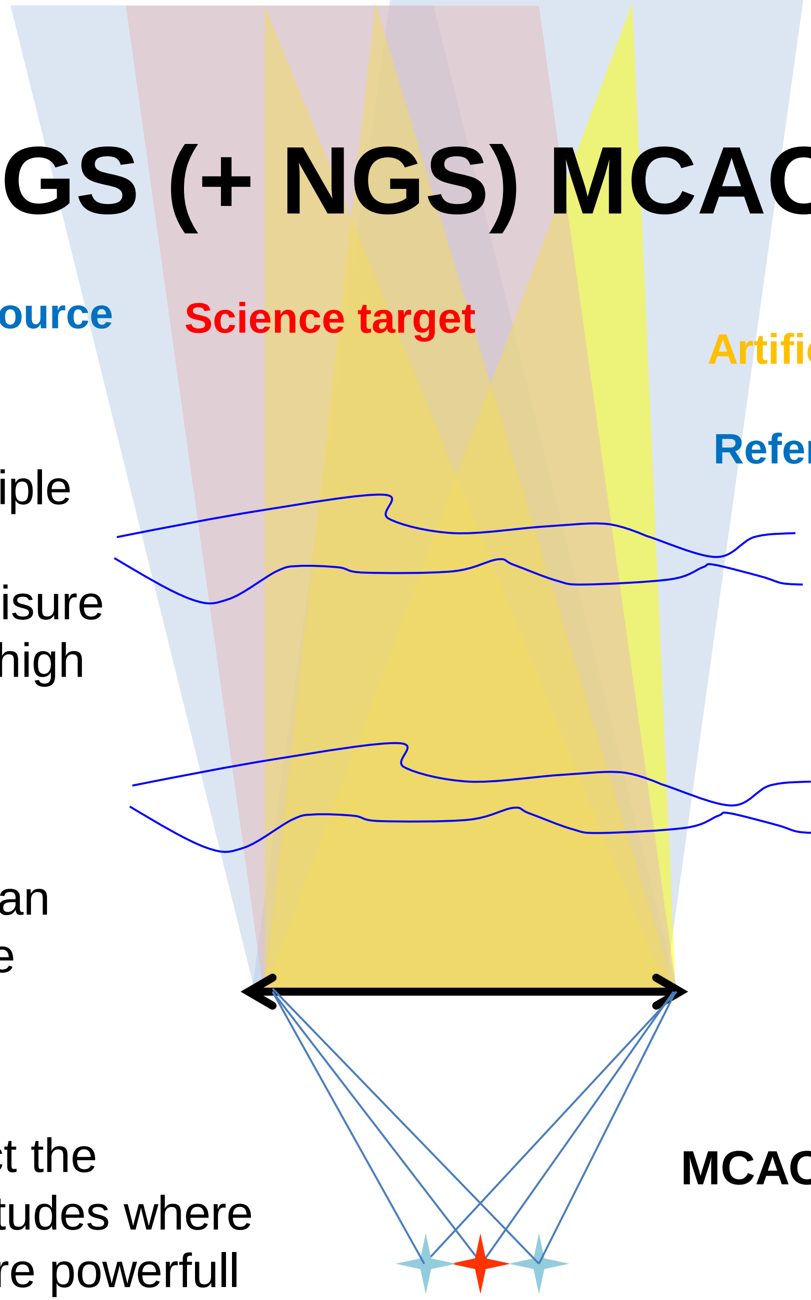
# Sodium layer profile features




Picture taken from:
T. Pfrommer and P. Hickson, 2010, J. Opt. Soc. Am. A Vol. 27 No. 11

Impact of mean altitude variations:
On 40 m telescope, 7 nm defocus per meter of altitude change
Focus effect is big and fast and requires measurement by fast TTF WFS

# What's LGS (+ NGS) MCAO?




**MCAO NGSs** : Multiple natural Sourcea are maybe needed to misure fast tip/tilt and slow high order modes

**LGSs** : Artificial reference sources can be created to ensure high sky coverage

**Multiple DMs** correct the turbulence at the altitudes where the turbulence is more powerfull

**MCAO**: Large corrected FoV
High Sky coverage
PSF stability

# What’s LGS (+ NGS) MCAO?

- Multi-reference for atmospheric turbulence tomography
- Multi-DM for 3D correction → large corrected FoV
- Artificial Sources for sky coverage
  - 6 SH LGS WFSs 80X80 500 Hz (detector 800X800 px → 10 px FoV)
  - Some problems related to LGS:
    - Tilt indetermination
    - In MCAO, tilt anisoplanatism (see Ellerbroek & Rigaut 2001)
    - Sodium layer features (density profile, variability)
- Natural Sources needed → effect on Sky coverage
  - multiple NGS measuring:
    - fast (100 – 500 Hz) Tip-Tilt, Focus and astigmatisms, Shack-Hartmann infrared sensor
    - Slow (0,1 Hz) low/medium (~50 modes) order modes variations, NXN subapertures (TBD) in the optical range (0.6-0.9 µm).  (Arcetri group)

# Why a simulation code?

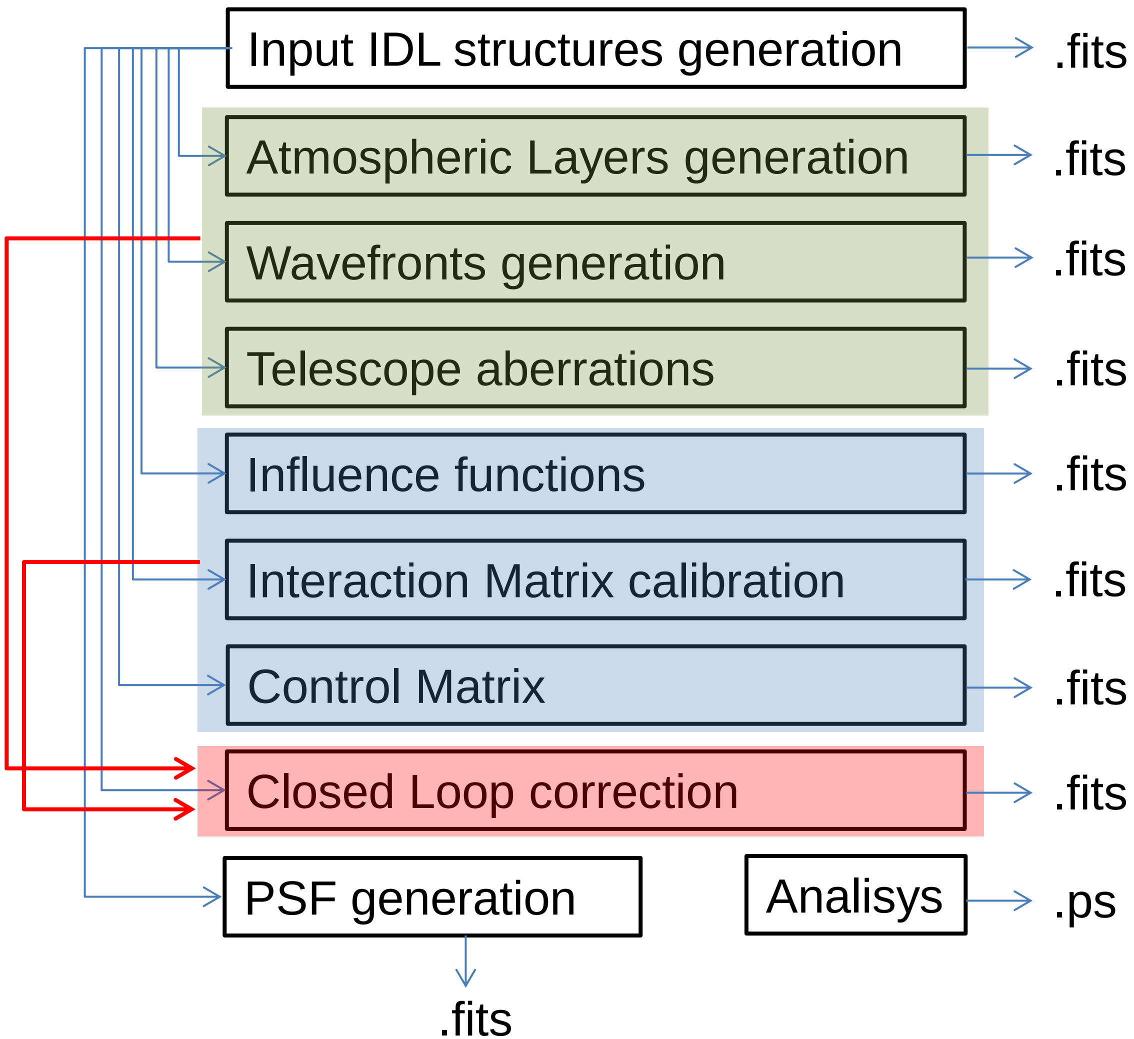
Due to the complexity of the system

- It is a **necessary tool for AO system design**
  - System dimensioning and optimization
  - Key/critical components design (WFS detectors, DMs…)
  - Operation/calibration/control strategy evaluation
  - External disturbances impact (telescope residual wavefront errors, wind shake, reference sources elongation, nasmith vibrations, non common path aberrations…)
  - Error budget
- **… in order to assure the scientific requirements fullfillment**
  - Performance evaluation (SR, sky coverage, EE…)

# MAORY MAO

- End-to-end MonteCarlo code for MAORY simulations
- Modular
  - Each step of the simulation is designed to be an independent process
  - The outputs are saved as fits files
- «Embarassingly» parallel
- Extensive use of GPUs
- Adaptable
  - Easy to adapt in order to explore the full space of parameters
- Fast and accurate mode supported

# MAORY MAO: The modules

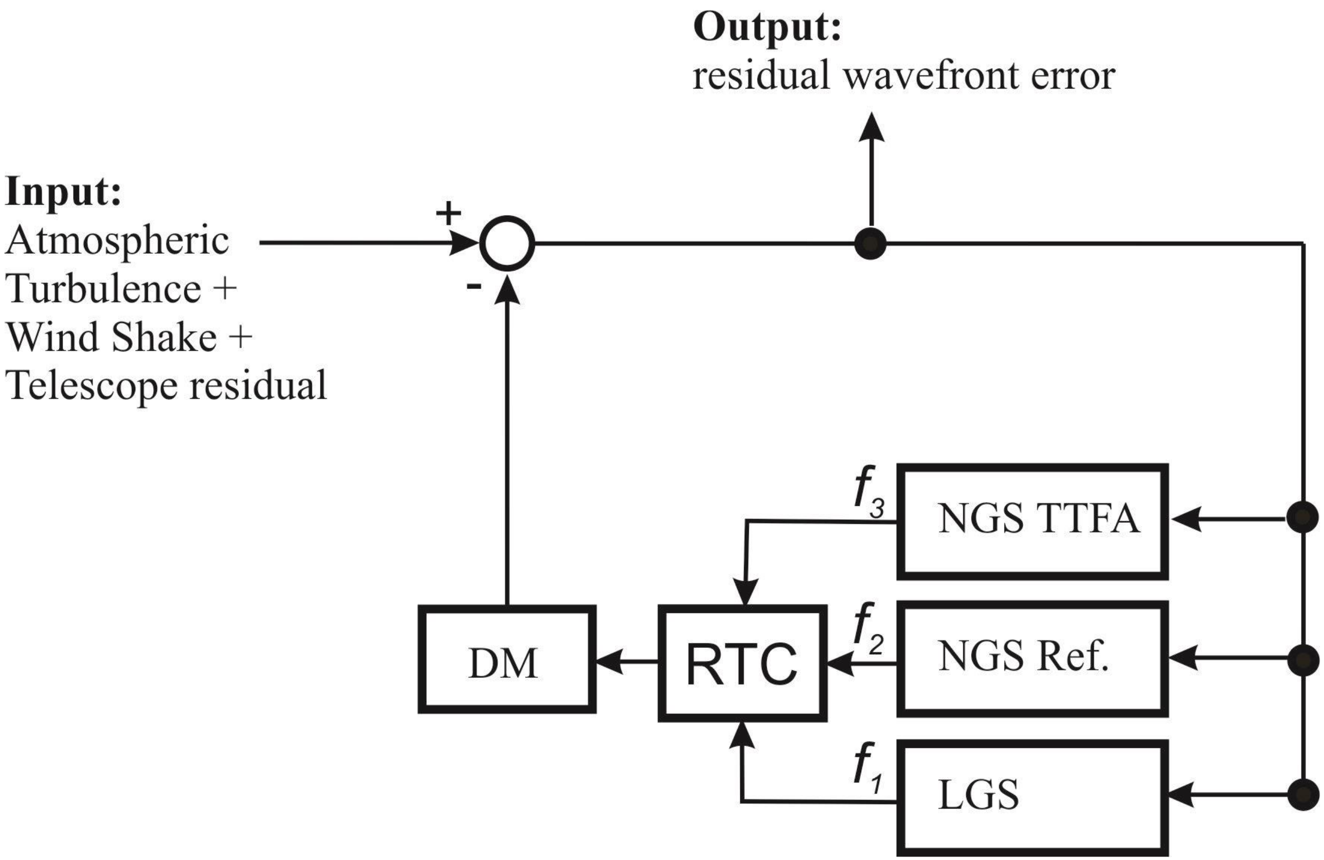


# MAORY MAO: Highlights

- **Atmospheric layer generation**
  - Multi-layered athmospheric model
  - Cn2 profile, r0, layer altitudes and velocity
- **Wavefronts generation**
  - Generated in Open Loop and stored
  - Cone effect, laser uplink propagation
- **Telescope aberrations**
  - E-ELT telescope wavefront perturbations residuals after active compensation by its control system
- **Wavefront sensors**
  - Arbitrary number of Shack-Hartmann / Pyramid
  - Natural and Laser Guide Stars (variable sodium profile supported)
  - Different centroid algorithms
- **Main and auxiliary loops independency**
- **Arbitrary number of DMs**

# Focus: Closed loop

- Maory simulation conceptual scheme



# Focus: LGS WFS simulation

- Sodium profile, pupil and intrinsic laser image **can be updated every simulation step**
- For each sub-aperture
  - For each sodium sub-layer
    - Diffraction Limited PSF through sub-WF FFT
    - Convolution for the relative sodium profile portion projected in the sub-aperture (computed considering the sub-aperture position w.r.t the laser launcher position and the WFS pixel FoV)
    - Integration
  - Convolution for the intrinsic laser image (gaussian)
  - Resizing and rebinning (if required)
  - Write in the image array
- Background addiction
- Photon and readout noise addiction
- Centroid algorithms: pure centroid, weighted centroid, threshold c.

# MAORY MAO: hard & soft

- Multi-core and multi-GPU workstation:
  - 2 Processors Intel Xeon E5-2630 v2, 2.6 GHz frequency (6 cores each);
  - 256 GB RAM on 16 GB group;
  - 4 GPU Nvidia TESLA K20X (6 GB, 2688 CUDA cores each);
  - 4 Hard Disk, 2 TB each for data storing
  - Fedora 19

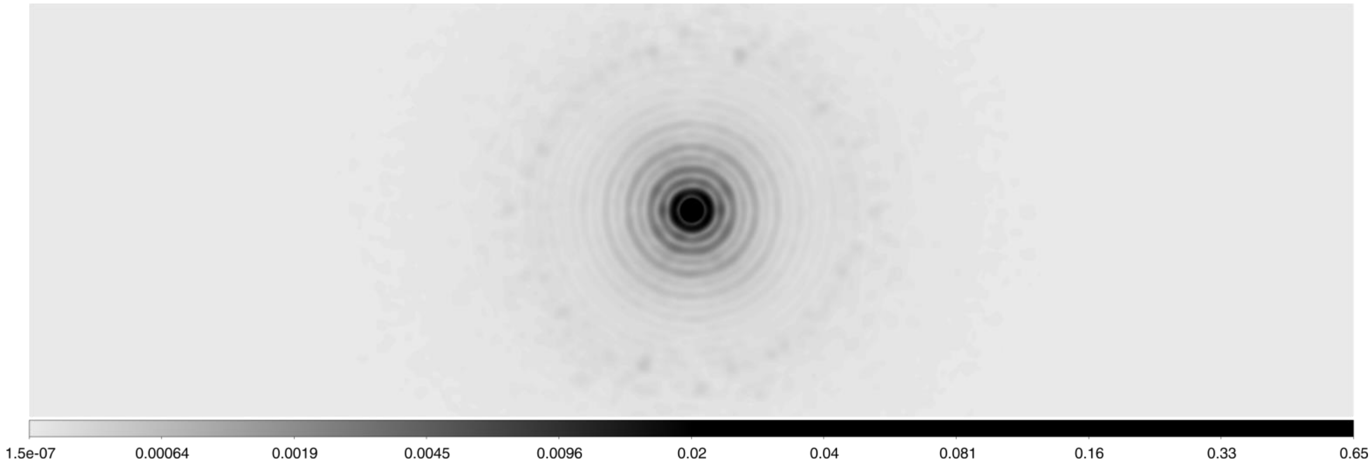
- Adopted languages:
  - IDL 8.3 for the architecture
  - Compute Unified Device Architecture (CUDA - GPUs) for the WFSs in closed loop and for the PSF computation (G. Bregoli)
  - Parallel optimized C/C++ and Intel libraries

# MAORY MAO: fast mode

- The speed computation bottleneck is due to LGS WFSs simulation (~4 sec each) → total computation time per simulation step (6 LGS): 8 sec
- In order to evaluate the effects on perfomance of LGS spot truncation due to sodium layer variation, we need to simulate long time series (minutes)
- A fast mode for WFSs simulation is foreseen:
  - Slope computation throght wavefront derivative x/y
  - WFS error due to noisy spot centroid computation added through analytical / empirical computation
  - 'Low' and slow varying order modes due to laser spot truncation computed in a side with a dedicate module [Schreiber 2014, SPIE] and injected in the NGS loop as non common path aberrations

# MAORY MAO: Conclusions

- MAO is a general E2E code that can simulate many AO configurations systems
- GPU LGS WFS just integrated in the code
- Verification is on going considering present systems paramenters (es: LBT)



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# Grazie