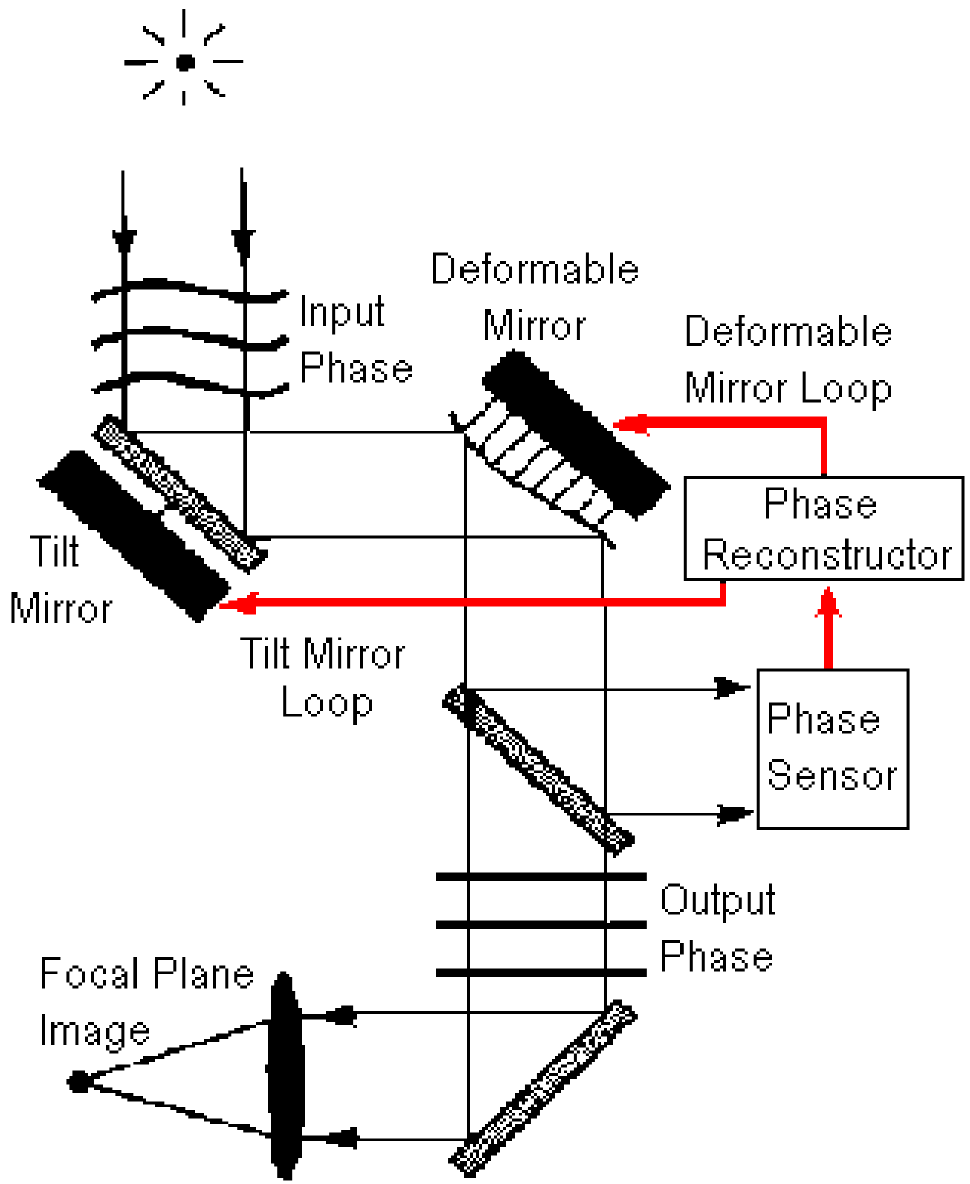
What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

5. Adaptive Optics

5.6 “Large” field of view Adaptive Optics systems

Motivation, field of view format

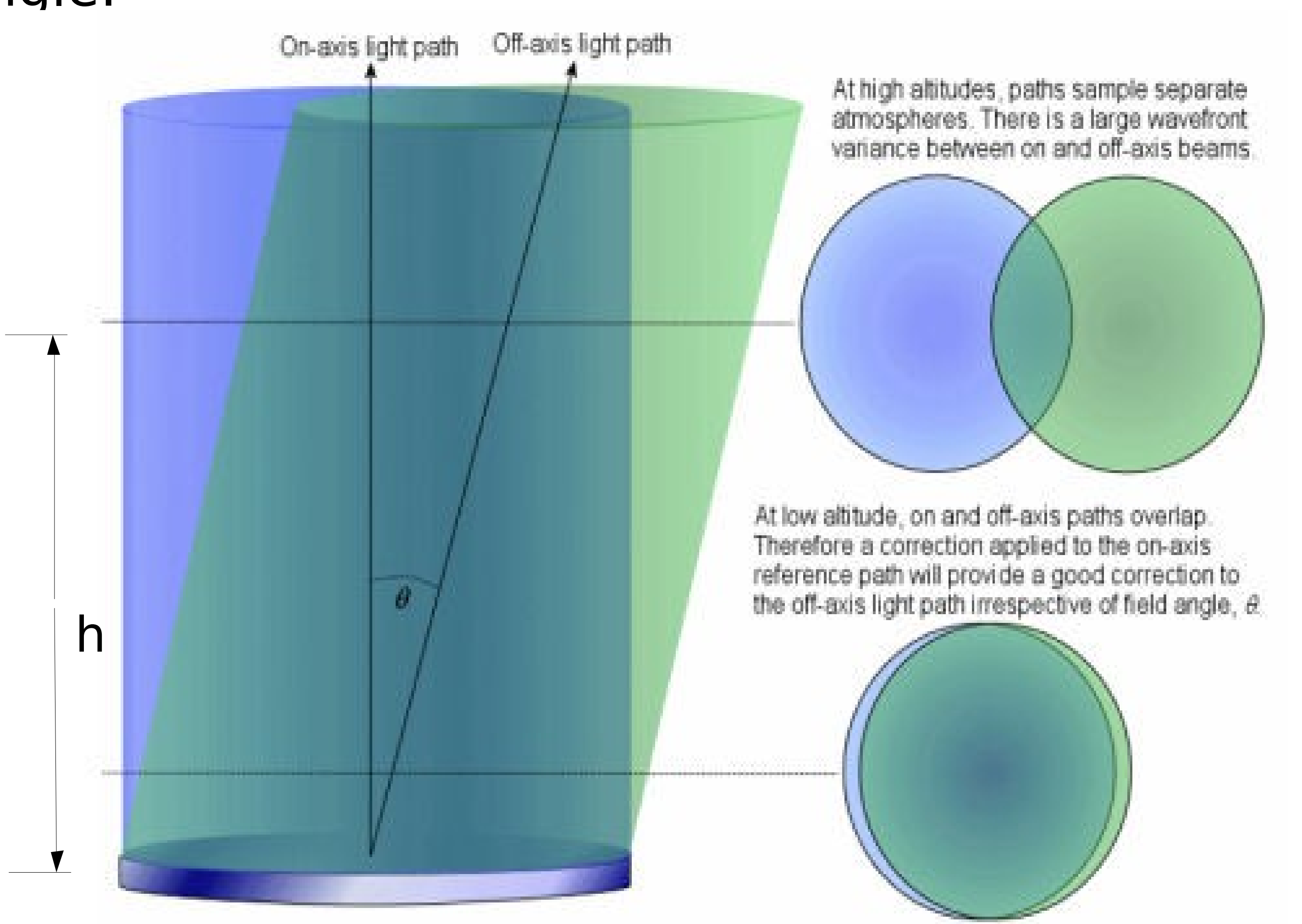
Types of system

- Ground-layer AO (GLAO)
- Multi-conjugate AO (MCAO)
- Multi-Object AO (MOAO)
- Laser Tomography AO (LTAO)

Fundamental problem to solve: Isoplanatic Angle

If we assume perfect on-axis correction,
and a single turbulent layer at altitude h,
the variance (sq. radian) is :
$\sigma^2 = 1.03\ (\theta/\theta_0)^{5/3}$
Where α is the angle to the optical axis,
θ_0 is the isoplanatic angle:
$\theta_0 = 0.31\ (r_0/h)$

$D = 8$ m, $r_0 = 0.8$ m,
$h = 5$ km $\rightarrow \theta_0 = 10''$



Solution:

Wavefront mesurement: Several guide stars needed

Several guide stars (Laser and/or natural) → volumetric knowledge of atmospheric turbulence, instead of simply collapsed turbulence

Wavefront correction:
Several DMs if good correction over a large FOV
Or, single DM driven to correct average wavefront error over wide FOV (Ground-layer AO, partial correction)

With single DM, there is a fundamental limit in the wavefront error vs. FOV tradeoff. Multiple DMs is the only way to break this limit.

The required field of view & field “format” drives the AO system optical design (& more)

Example 1: System offering wide FOV over full continuous field
-> large optics, several large Deformable Mirrors (MCAO)
-> AO system works in closed loop, with several WFSs and several DMs
-> Multiple guide stars needed, with required positioning devices (NGS) or several laser beacons.

Example 2: Several small individual FOVs spread over a large field
-> The instrument could have small independent wavefront correction units (1 per small field) to minimize optical size/complexity
-> These small units should be fed by a smaller number of WFSs using tomographic reconstruction.
-> The WFSs would be running in open loop, and do not see the correction by the DMs.
-> The DMs would therefore need to be very well calibrated

Cone effect

Cone effect due to finite altitude of LGS (90km sodium, ~10-20 km for Rayleigh)

$\sigma^2 = 1.03 \, (D / (2.91\theta_0 H))^{5/3}$

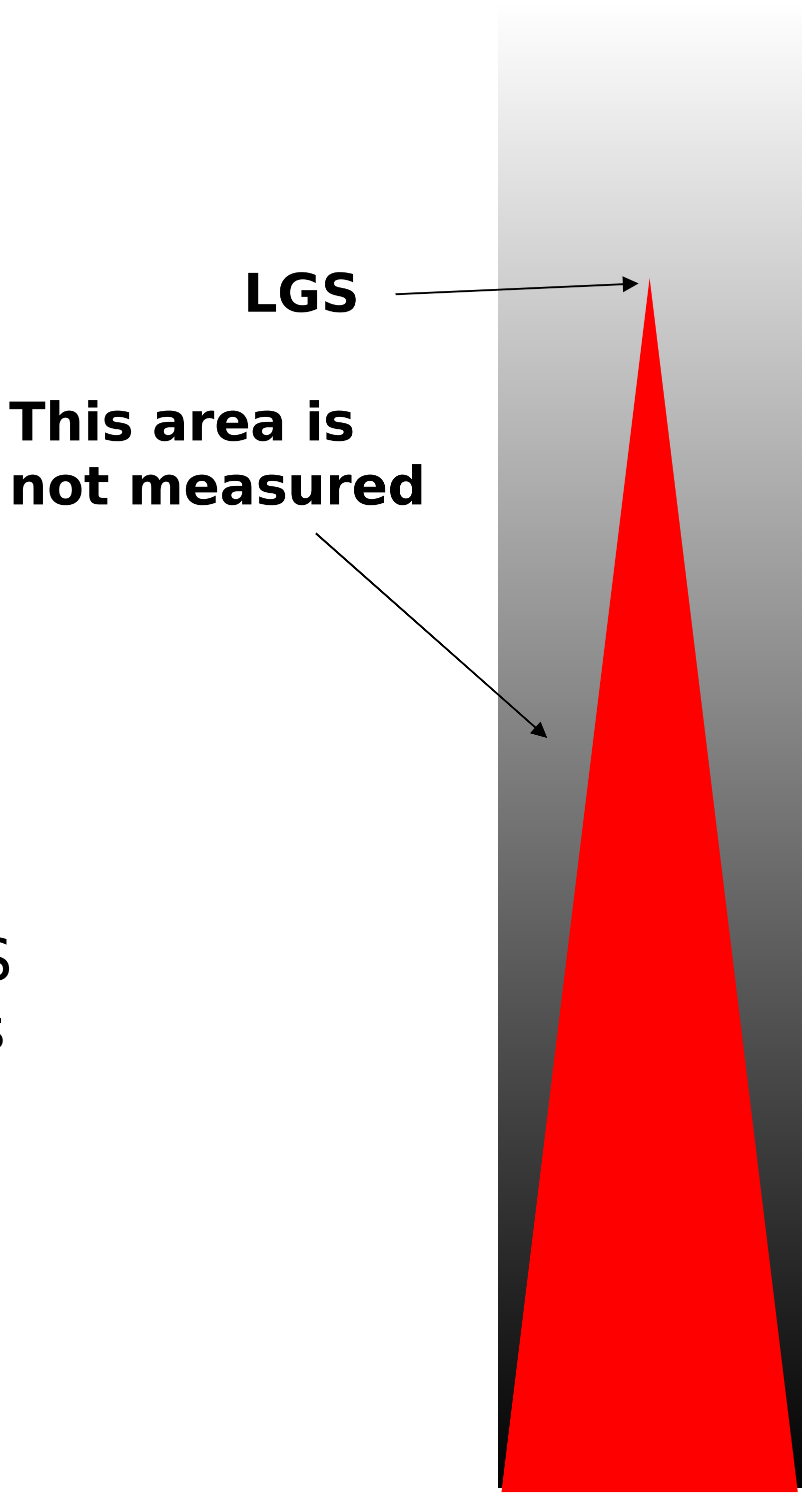
θ_0: isoplantic angle

H : LGS altitude

D : Telescope diameter

→ impact is smaller for sodium LGS

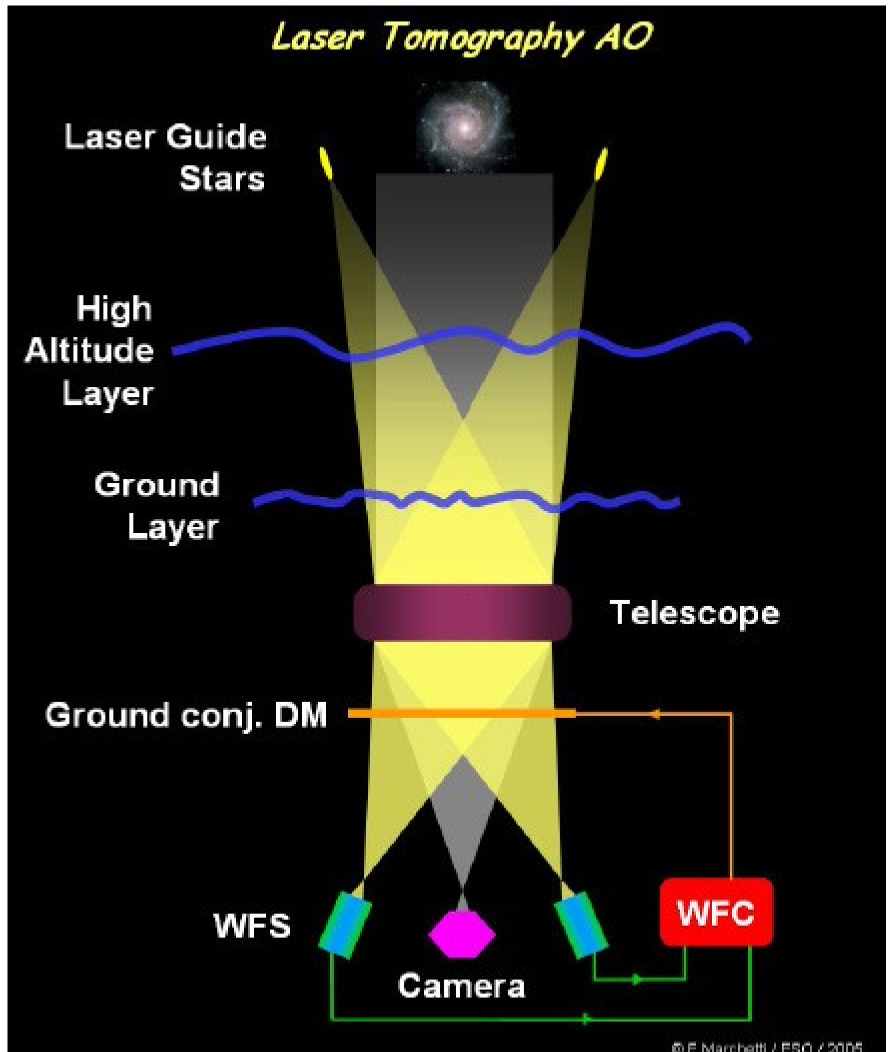
→ larger effect for large telescopes



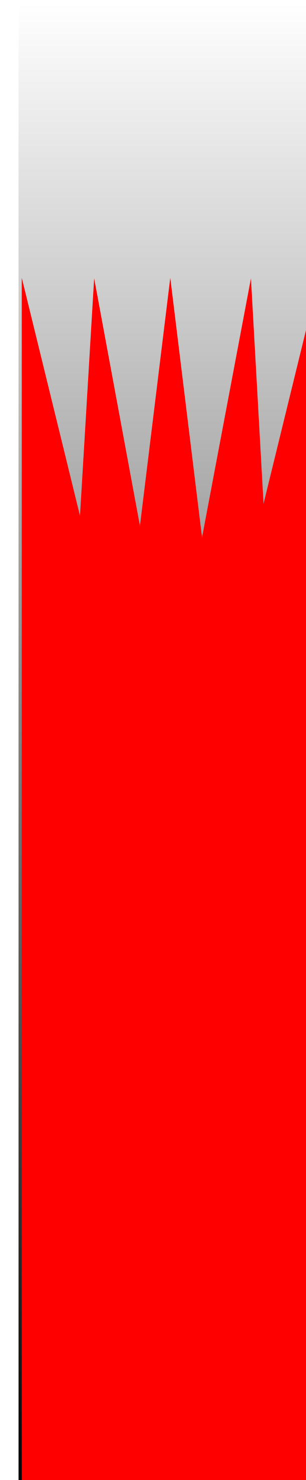
Laser Tomography AO (LTAO)

Tomography (usually with LGSs, but can also use NGSs) can mitigate cone effect by combining wavefront information from several guide stars.

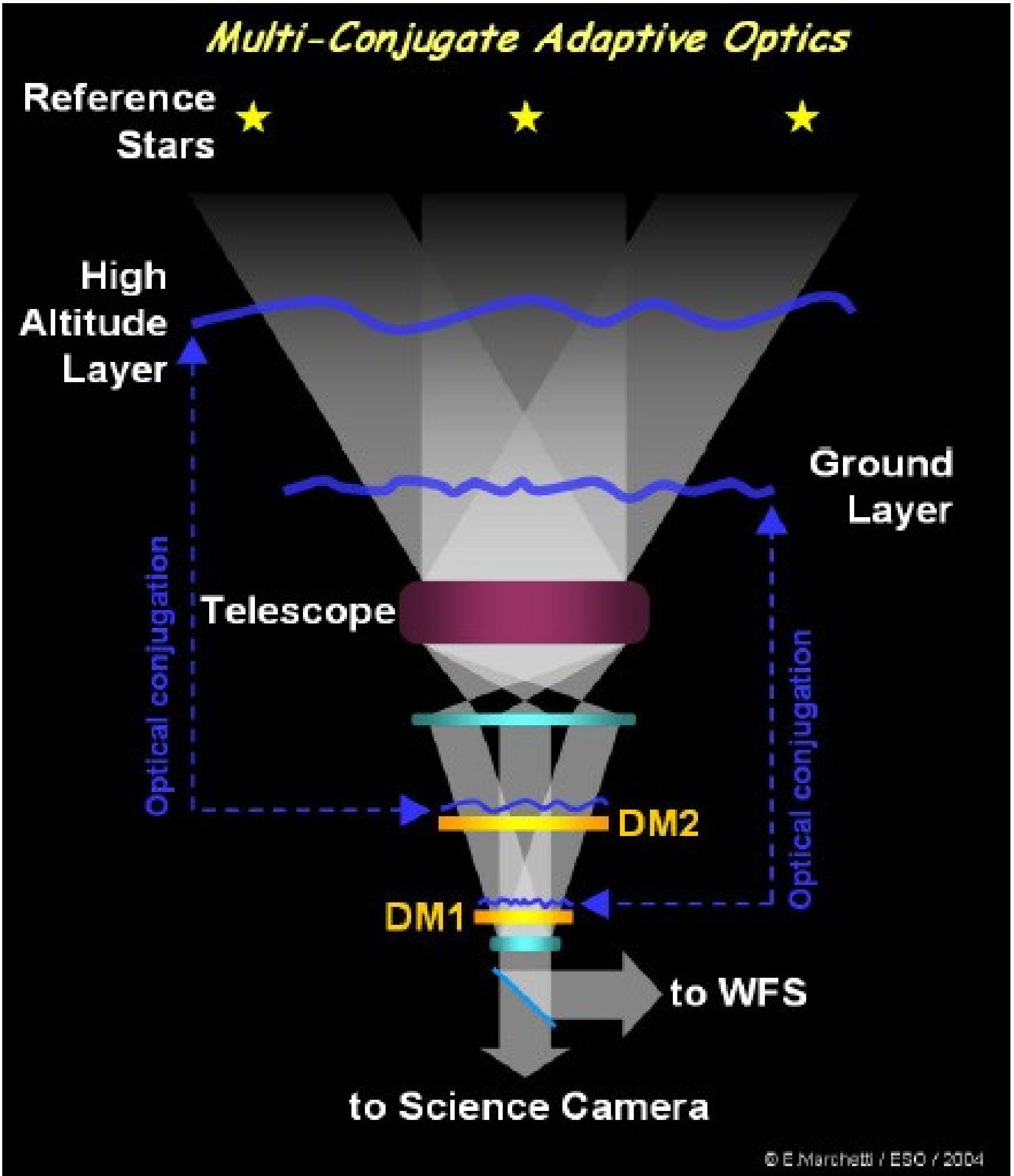
This technique used with a single DM to reduce cone effect error (no increase of FOV)



LGSs

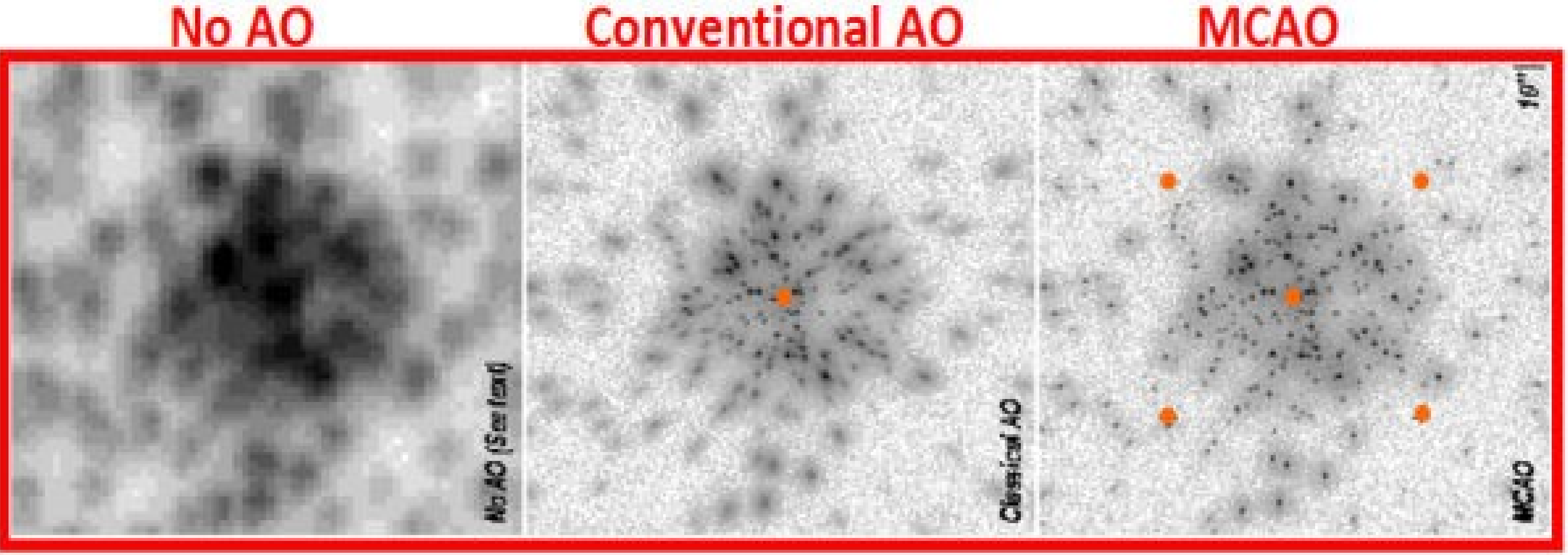


Multi-Conjugate Adaptive Optics (MCAO)
Concept: Use several DMs conjugated at different altitudes to perform correction over a wide fielf of view



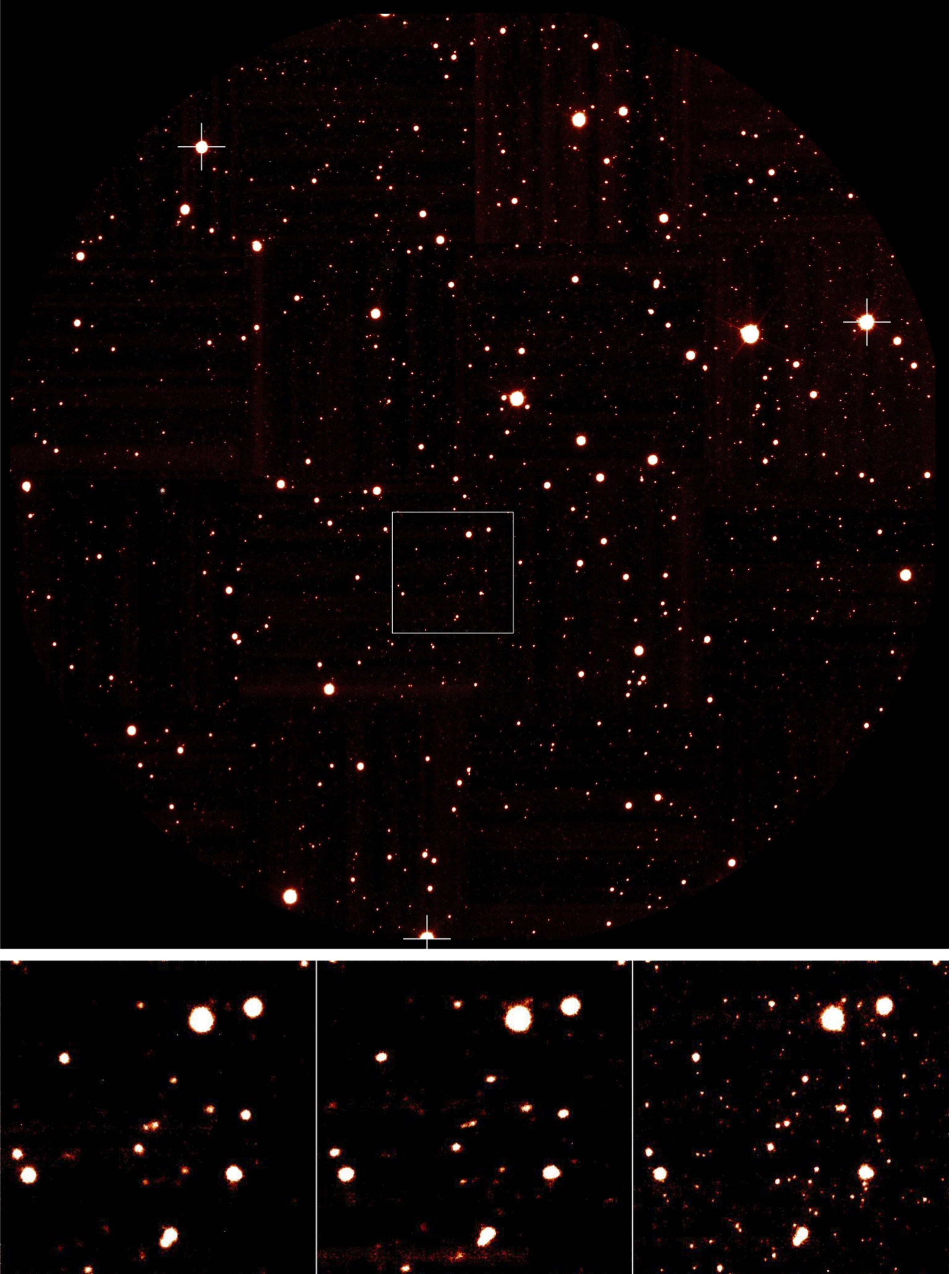
Gemini South MCAO system

MCAO performance improvement (Simulations)



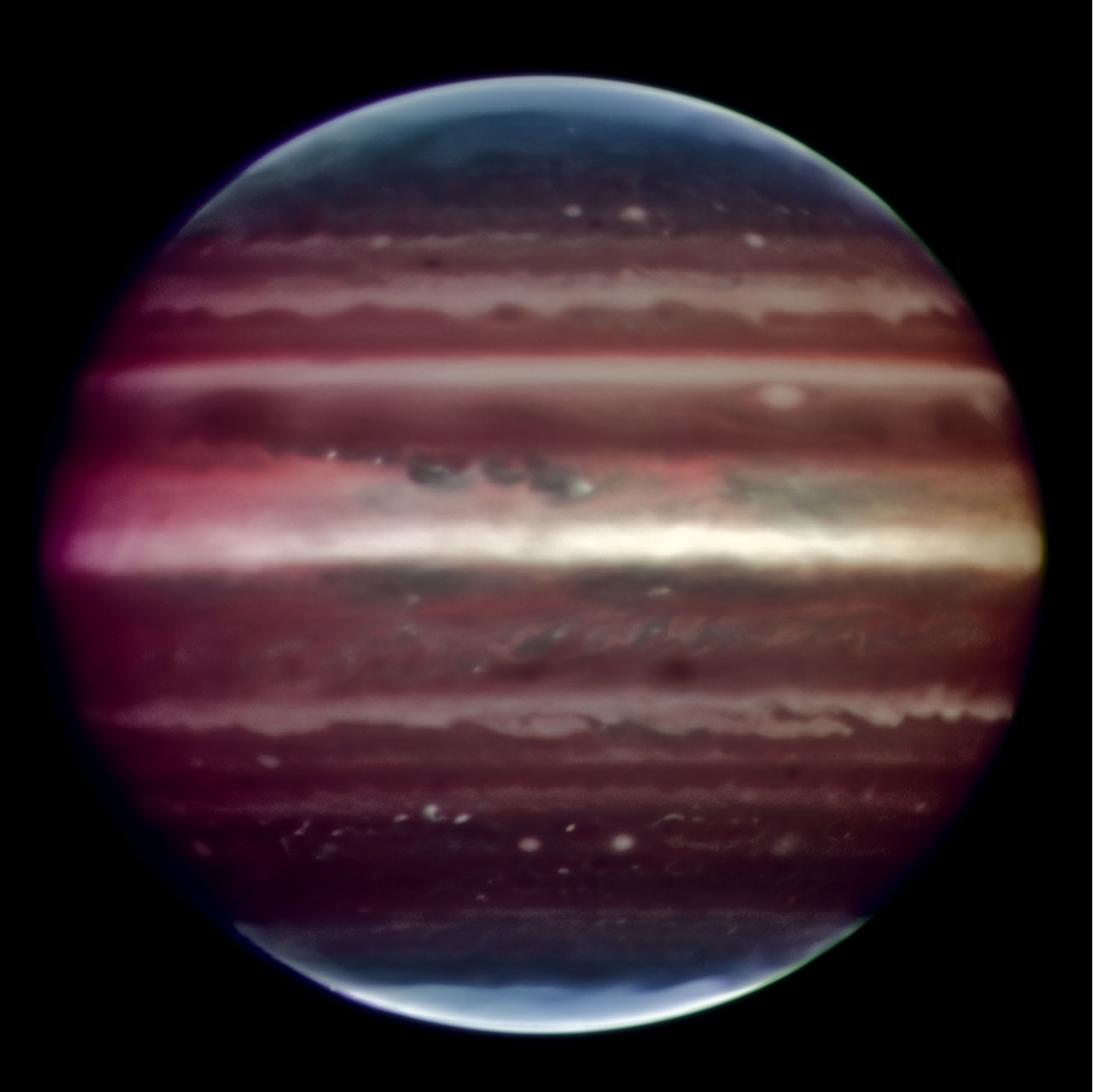
MCAO on-sky performance

MCAO improves image quality where there is no single nearby bright guide star



Central parts of the globular cluster Omega Centauri, as seen using different adaptive optics techniques. The upper image is a reproduction of ESO Press Photo eso0719, with the guide stars used for the MCAO correction identified with a cross. A box shows a 14 arcsec area that is then observed while applying different or no AO corrections, as shown in the bottom images. From left to right : No Adaptive Optics, Single Conjugate and Multi-Conjugate Adaptive Optics corrections. SCAO has almost no effect in sharpening the star images while the improvement provided by MCAO is remarkable.

Credit: ESO



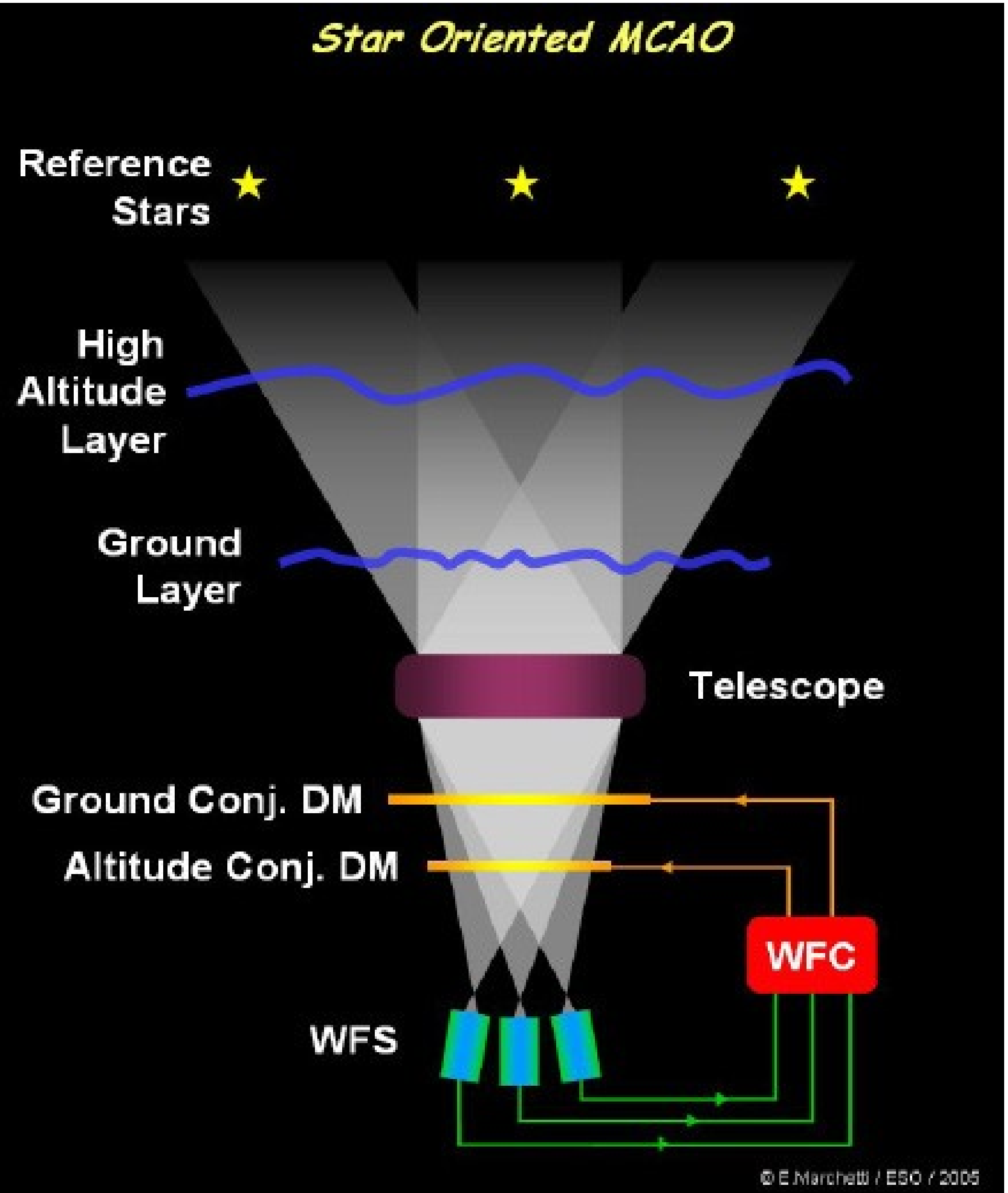
MCAO

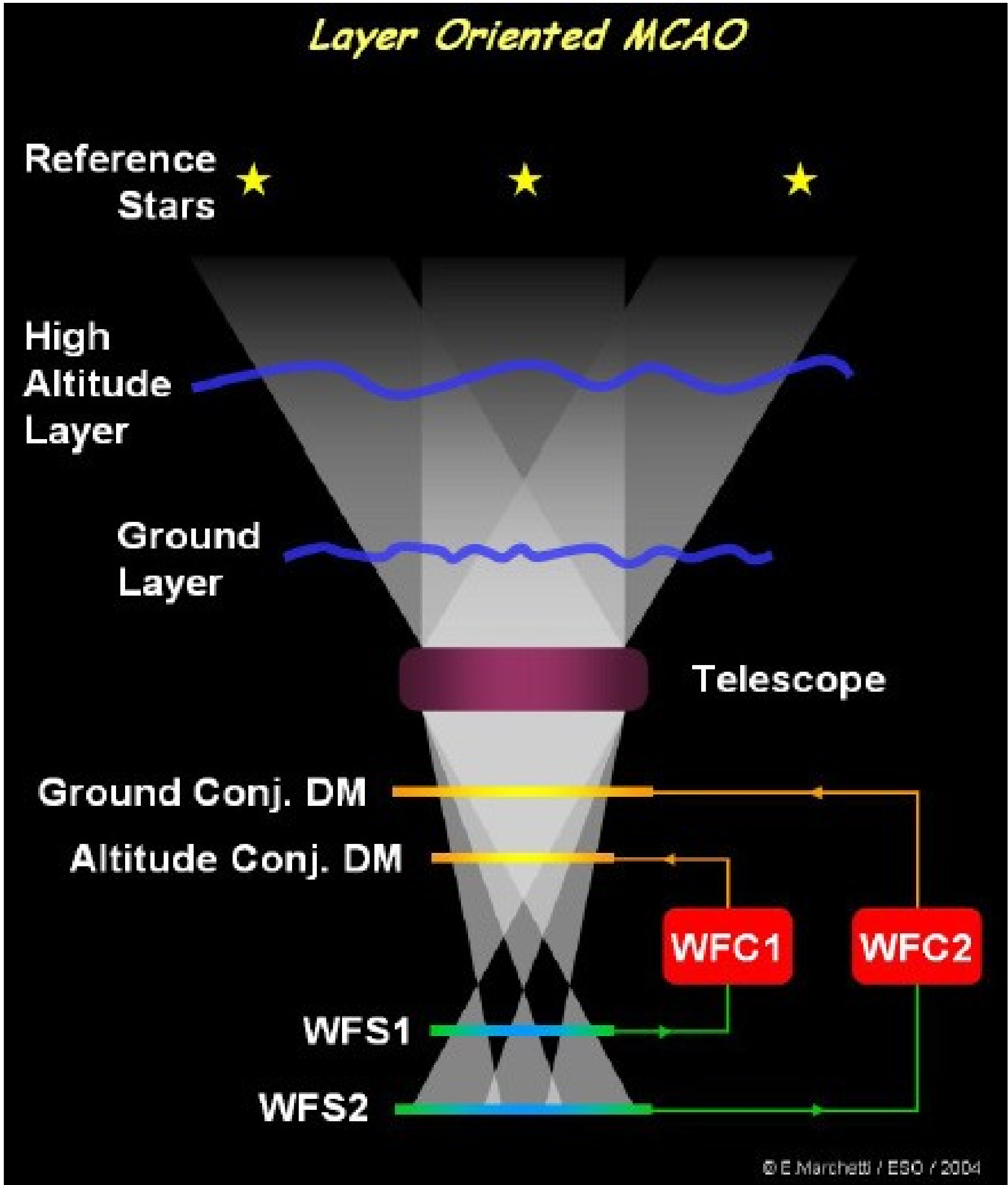
Jupiter imaged with ESO's Multi-conjugate Adaptive Optics Demonstrator (MAD)

MCAO wavefront sensing:

Star-oriented: 1 WFS per star

Layer-oriented: 1 WFS per layer

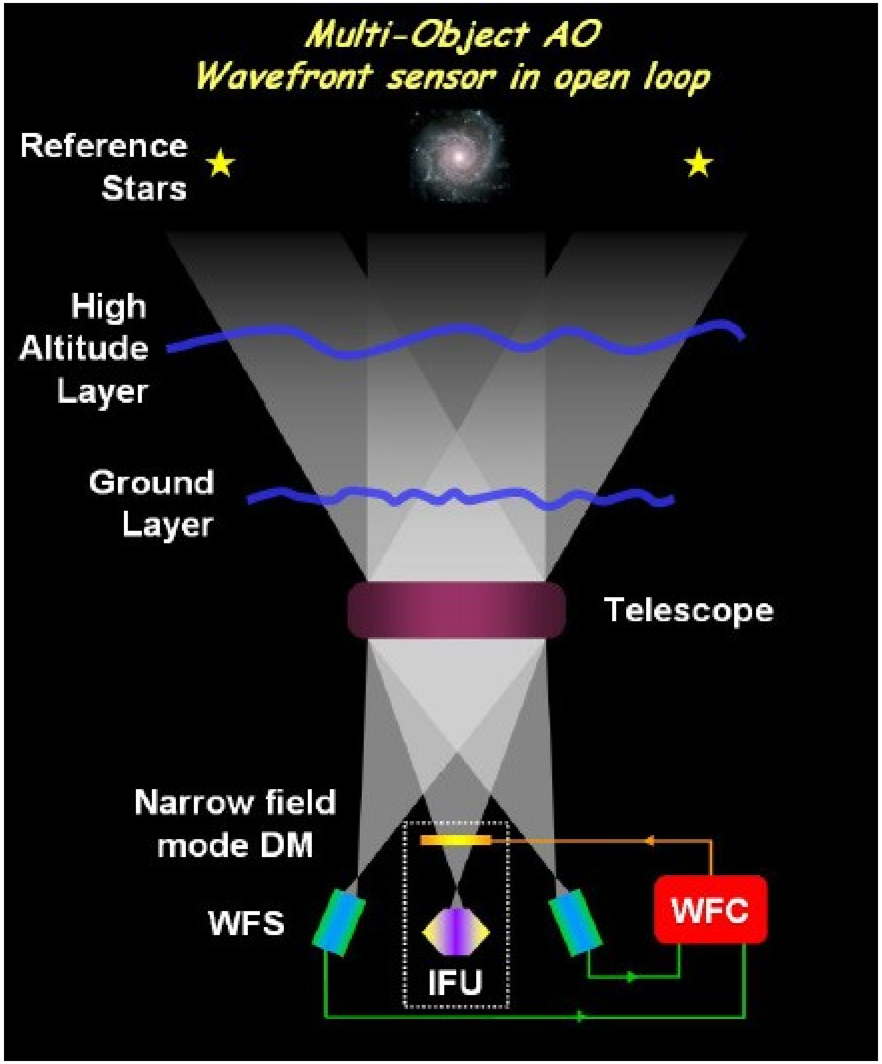


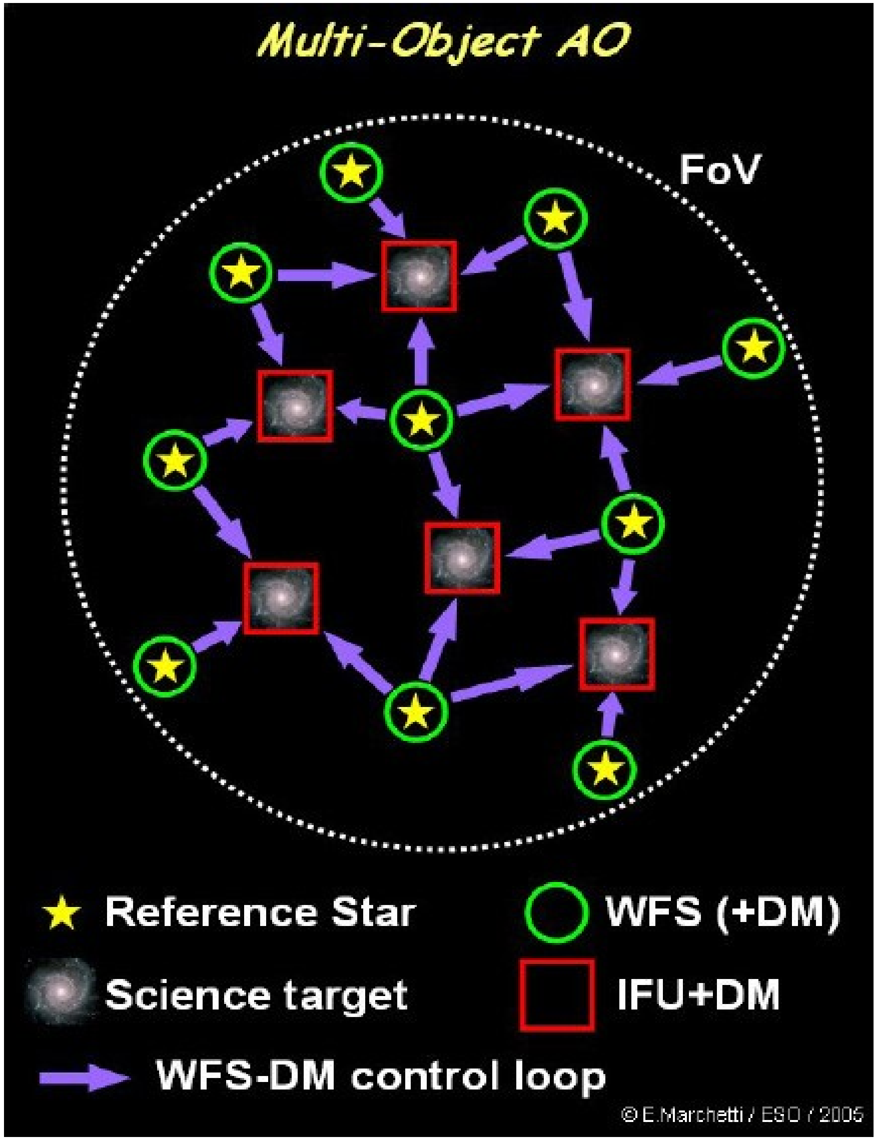


Multi Object Adaptive Optics (MOAO)

Can be visualized as several tomographic AO systems sharing the same set of wavefront sensors: 1 DM per object of interest

MOAO runs DMs in open loop → need for good DM calibration (WFSs do not see DMs)

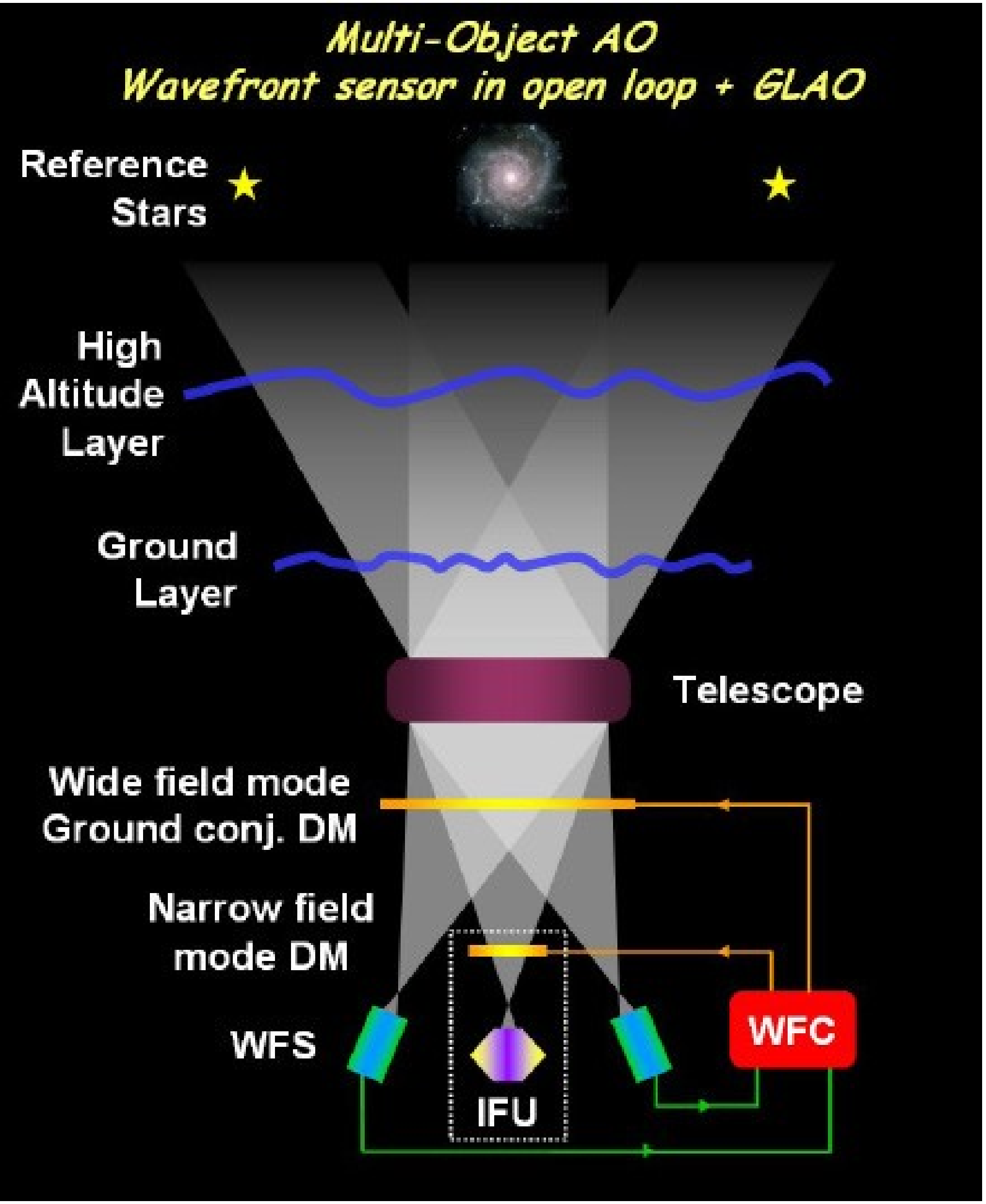


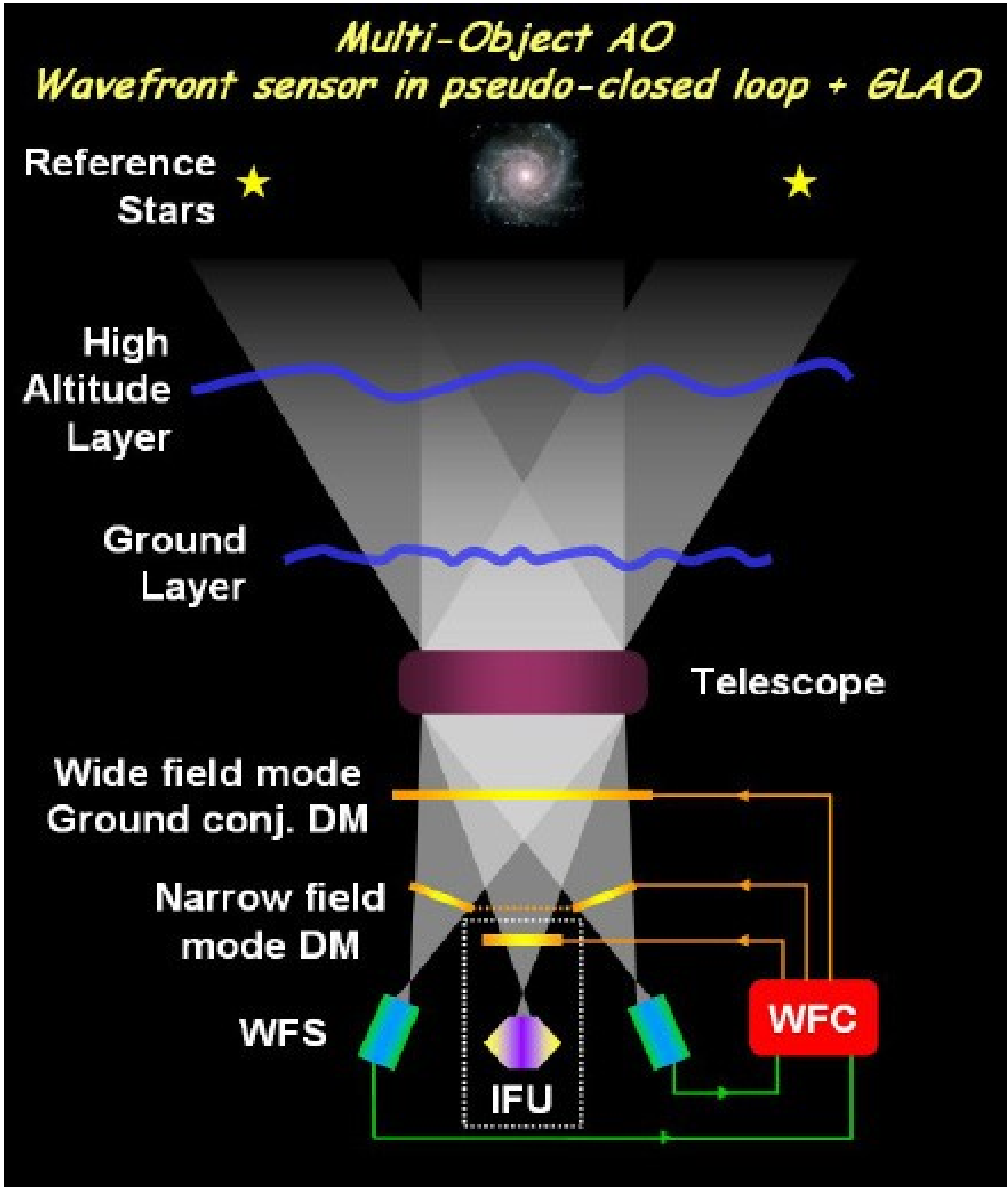


MOAO: hybrid correction schemes

Offload part of the correction to a common DM

Perform correction in individual WFSs to gain sensitivity





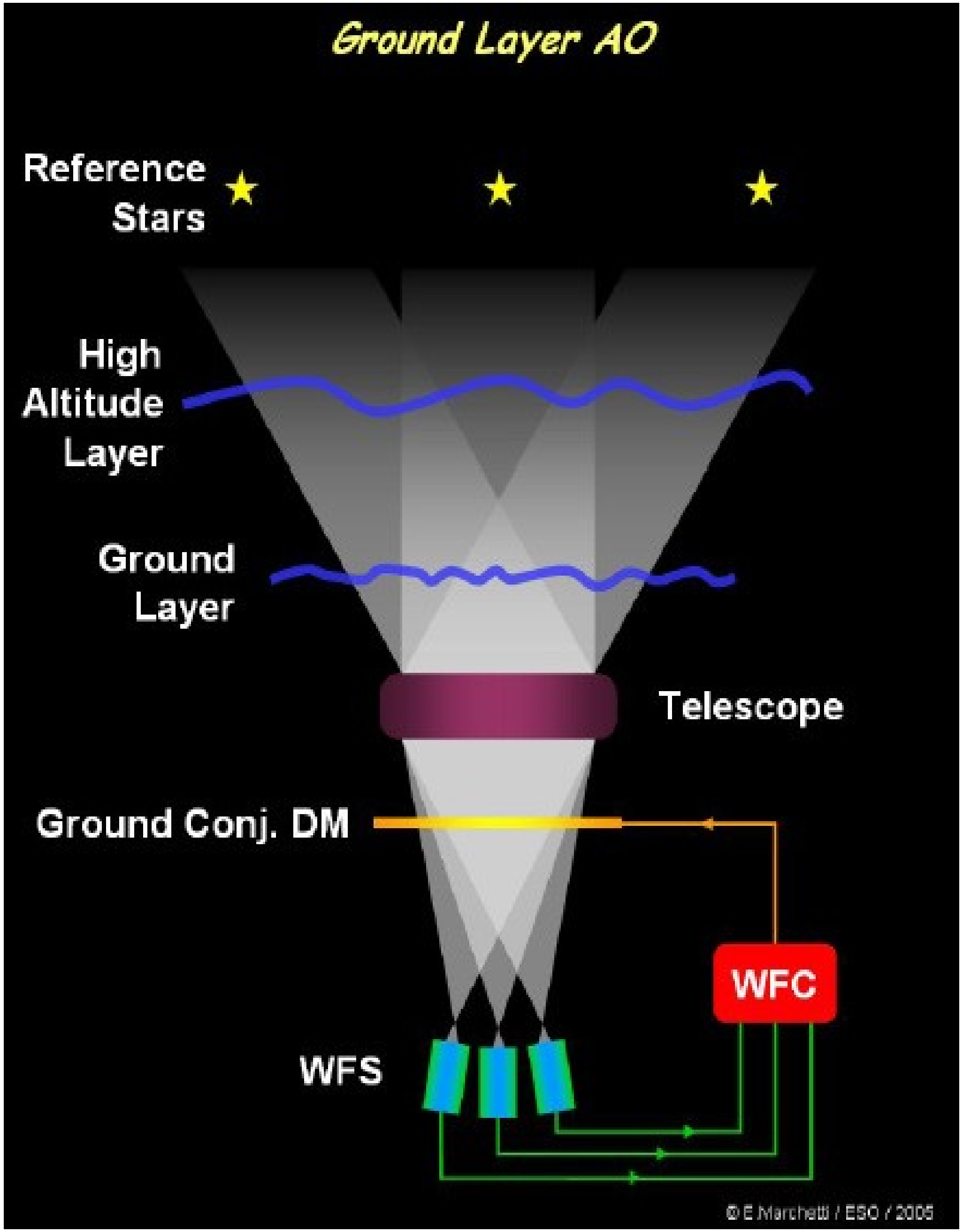
Ground Layer Adaptive Optics (GLAO)

•Significant part of turbulence (~50% or more) is located near ground level
•Ground layer turbulence is common to sources in a wide field of view

→ With correction of ground layer, image quality is improved over a wide field of view

Problem: how to isolate ground layer turbulence from high altitude turbulence.

Solution: use several WFSs. The part of the wavefront common to all WFSs is the ground layer



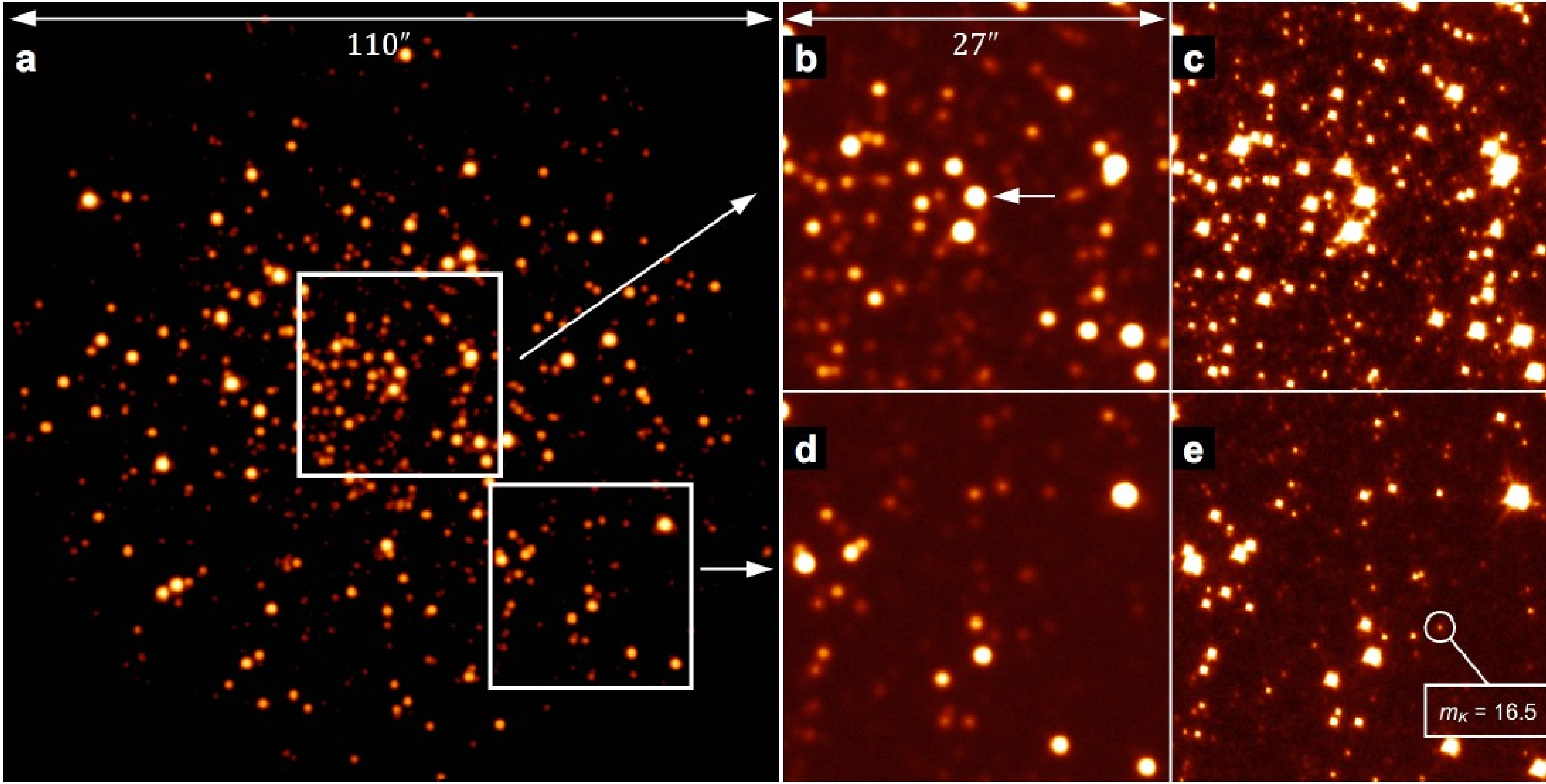


Fig. 8. The core of M3 imaged at 2.2 μm in two 60 s exposures. a) The full 110 arc sec field of the IR camera in the native seeing limit of 0.7 arc sec, on a logarithmic intensity scale. b,d) Two smaller 27 arc sec regions of the same image, indicated by the boxes in a) shown on a truncated linear scale in which bright stars appear saturated but which reaches the noise floor and brings out the faintest observable stars. c,e) In a second 60 s exposure of the same two regions, taken with GLAO running at 400 Hz and shown on the same linear scale as b) and d), the stellar image width is reduced to 0.3 arc sec and has a very similar PSF morphology across the whole field of view. For reference, we highlight a star in the corrected image with K band magnitude of 16.5, detected at a SNR of 26. In the uncorrected image, stars must be 2 mag brighter to be seen at the same SNR.

GLAO @ MMT, Hart et al., 2010

MOAO & GLAO bring huge efficiency gain, But are more complex than single guide star systems

MOAO & GLAO require **several natural guide stars**:
- Tip-tilt and focus not measured by LGSs
- Tip-tilt & Focus change across the field of view

MOAO and GLAO systems are quite complex, as they combine several NGS WFSs and often several LGS WFSs.
- LGS pattern on the sky can be fixed or variable (emphasis on FOV vs. image quality)
- LGS WFSs need variable focus stage (for Sodium), as altitude of LGS is function of pointing and varies with time due to Sodium Layer variations
- NGS pattern on the sky is different for each pointing: need for moving optics to acquire NGSs

SUGGESTIONS/IDEAS FOR TEAM PROJECTS ON ADAPTIVE OPTICS

Extreme-AO system for direct imaging of exoplanets

- Design AO system (not coronagraph – assume that coronagraph works very well, and will be limited by wavefront errors)
- Always a bright star on-axis
- WFS choice, DM choice ? Which telescope (LBT as baseline ?)
- Try to do better (or different) than SPHERE (ESO) or GPI (Gemini)

Super-wide field ground-layer AO sytem

- Lots of instruments & surveys will soon produce deep wide FOV seeing-limited images (Hyper Suprime Cam, Pan-STARRS, LSST)
- Can a wide field visible AO system provide deep images over most of the sky at better than seeing limit ?
- Choose telescope, AO system and camera, but focus on what the AO system would look like and main challenges

Visible AO sytem, narrow field of view for LBT

- Offers diffraction limit in visible around bright stars
- Try to design system that can have decent sky coverage, even if it does not reach visible diffraction limit for part of the sky coverage