Lecture 13

The applications of tomography: MCAO, MOAO, GLAO

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AY 289

February 20, 2020

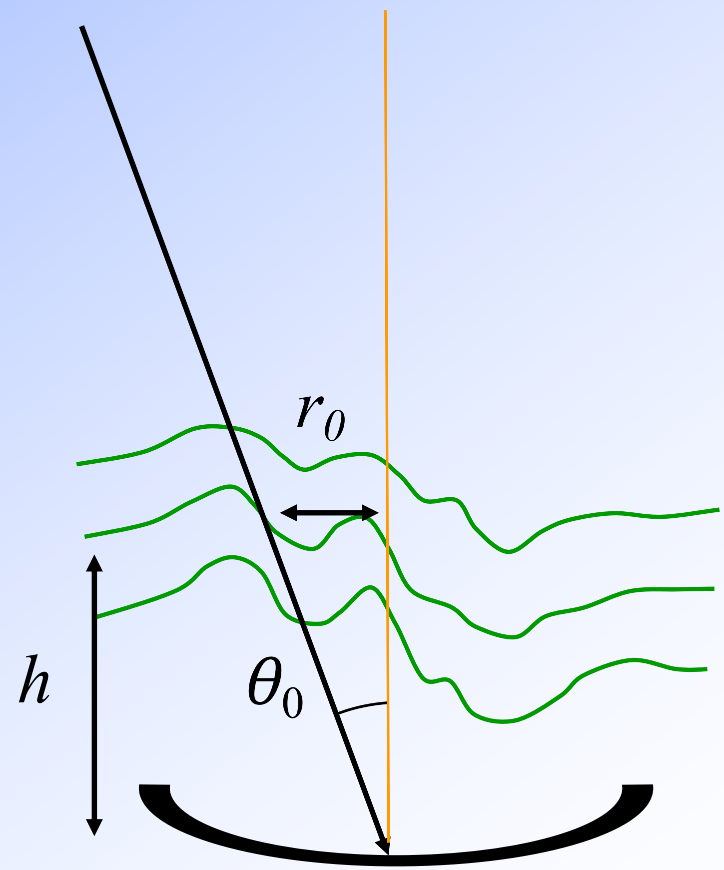
Outline of lecture

- What is AO tomography?
- Applications of AO tomography
  - Laser tomography AO (LTAO)
  - Multi-conjugate AO (MCAO)
  - Multi-object AO (MOAO)
  - Ground-layer AO (GLAO)
- Much of this lecture is based on presentations by Don Gavel, Lisa Poyneer, Francois Rigaut, and Olivier Guyon. Thanks!

Limitations for AO systems with one guide star

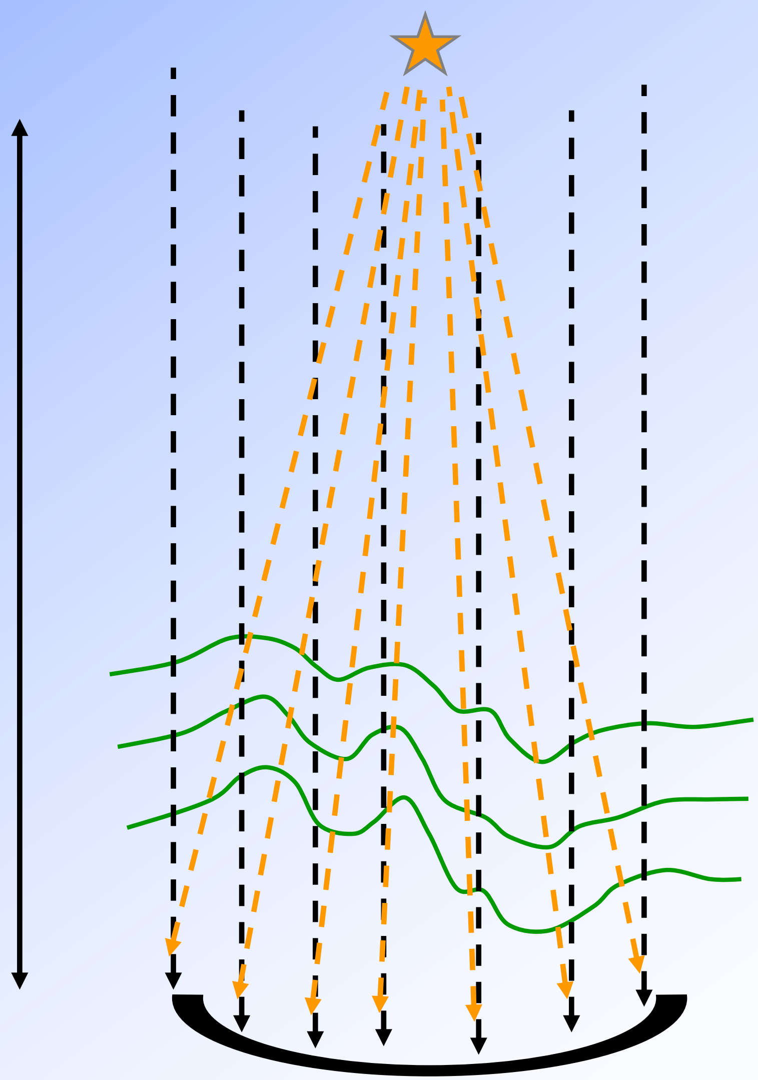
- Isoplanatic Angle

  Limits the corrected field



Limitations for AO systems with one guide star

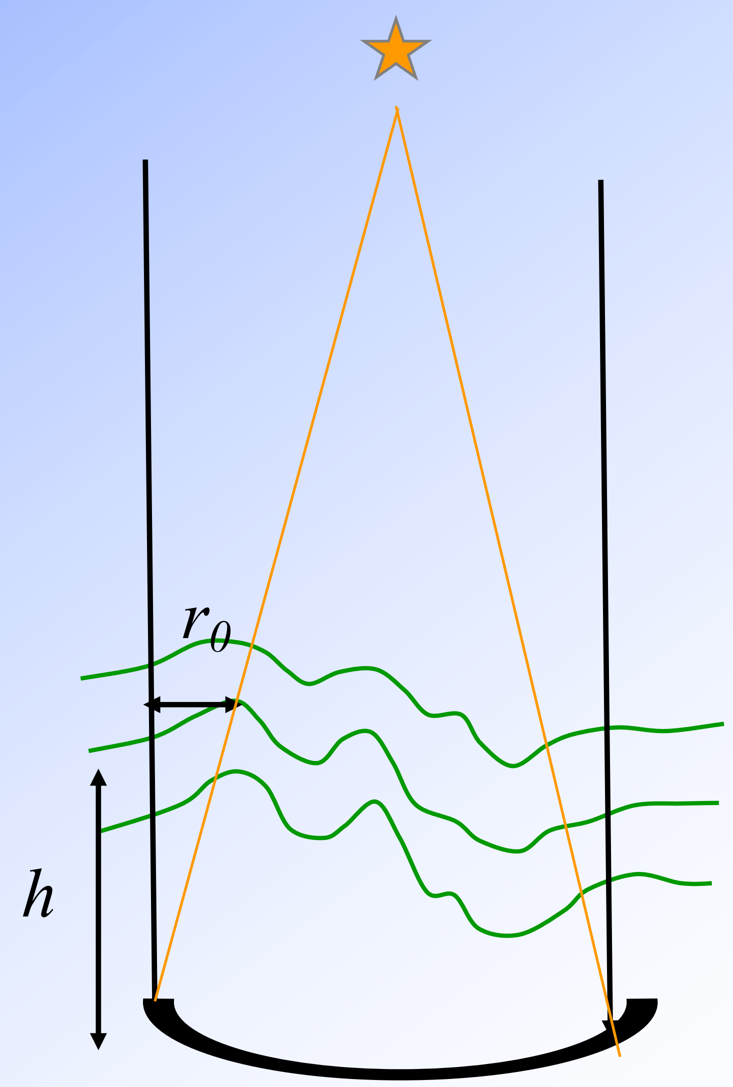
- Cone effect



Limitations for AO systems with one guide star

- Cone effect
  1. Missing turbulence outside and above cone
  2. Spherical wave "stretching" of wavefront

  More severe for larger telescope diameters



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 :

$\sigma^2 = 1.03\ (\theta/\theta_0)^{5/3}$

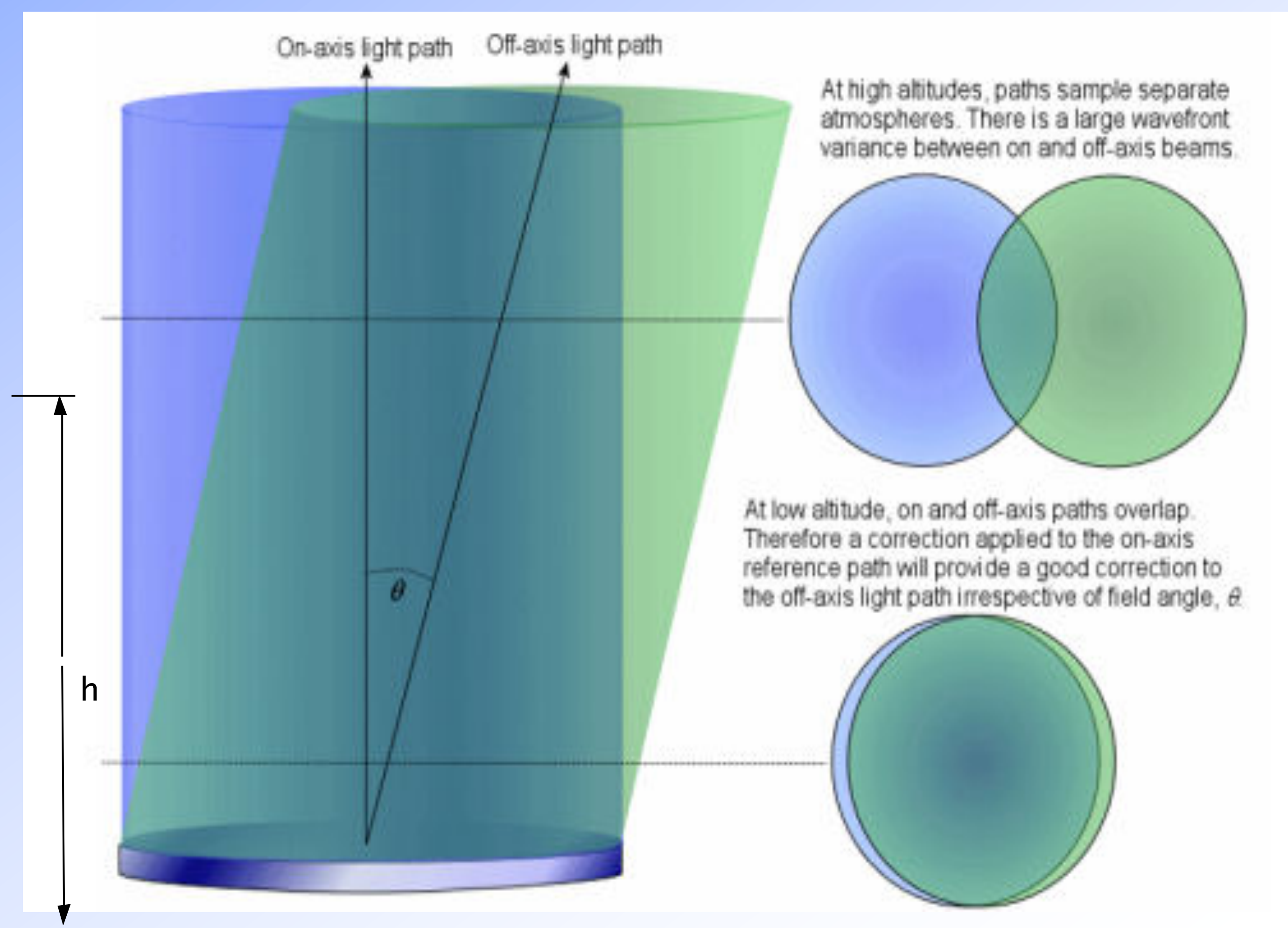
Θ = angle to optical axis,

θ_0 = isoplanatic angle:

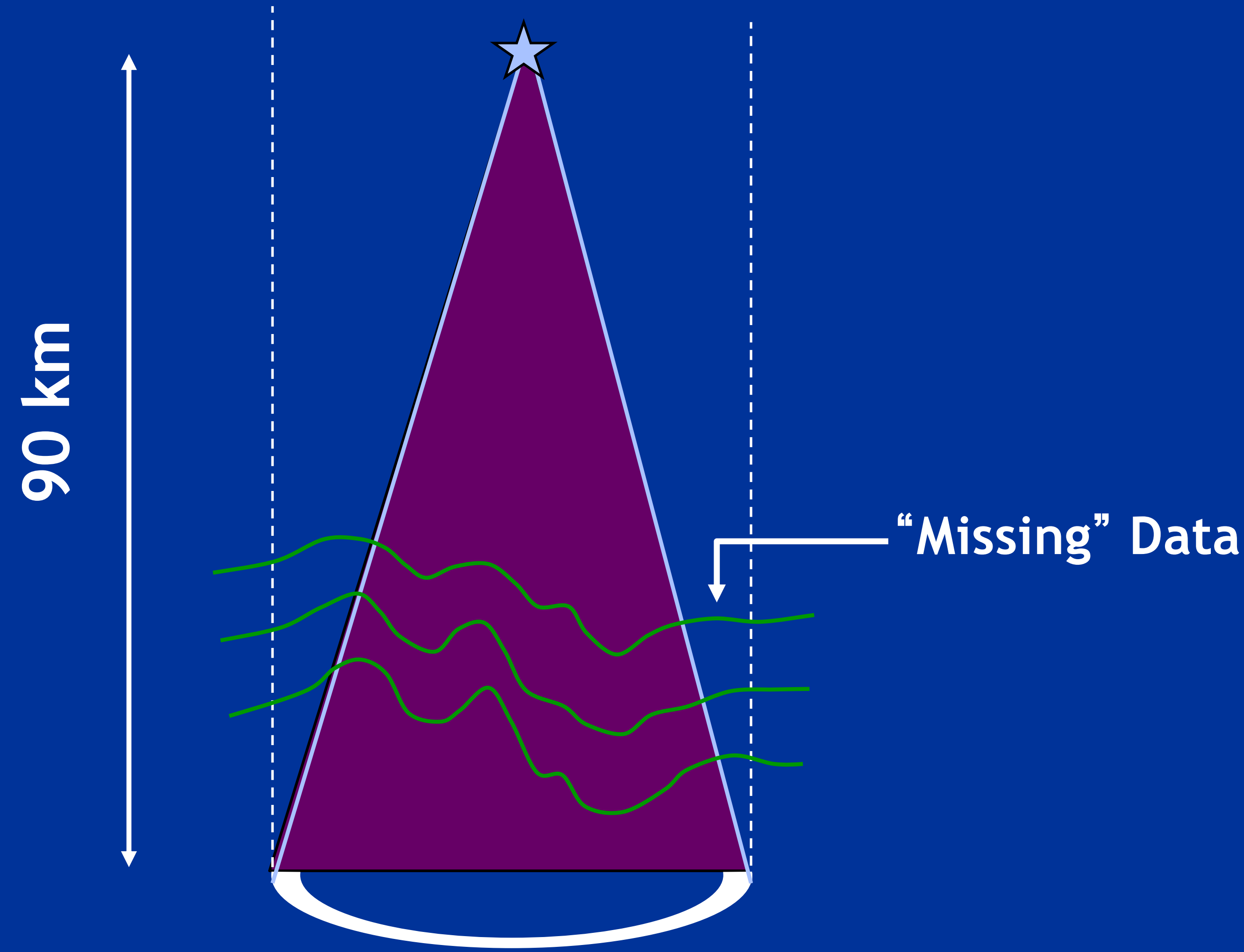
$\theta_0 = 0.31\ (r_0/\langle h\rangle)$

D = 8 m, r_0 = 0.8 m,

$\langle h\rangle$ = 5 km => θ_0 = 10”

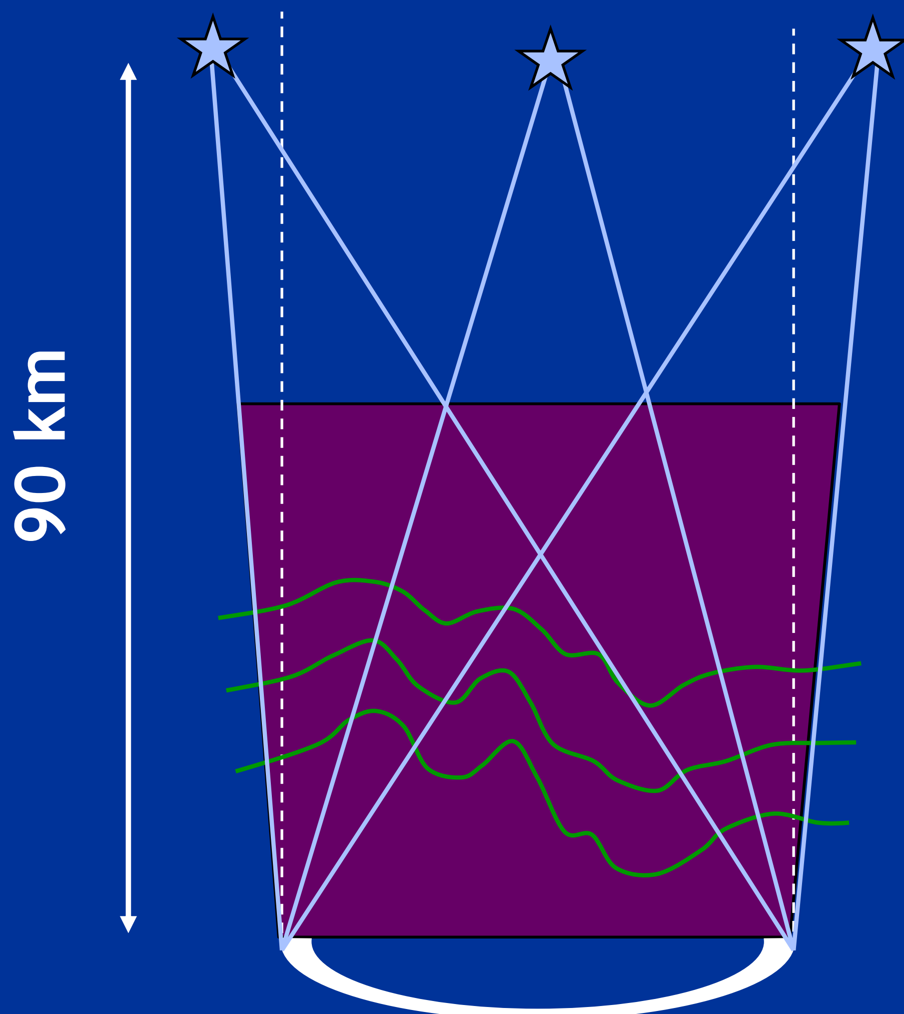


Francois Rigaut's diagrams of tomography for AO



Credit: Rigaut, MCAO for Dummies

What is Tomography ?
2. Wider field of view, no cone effect



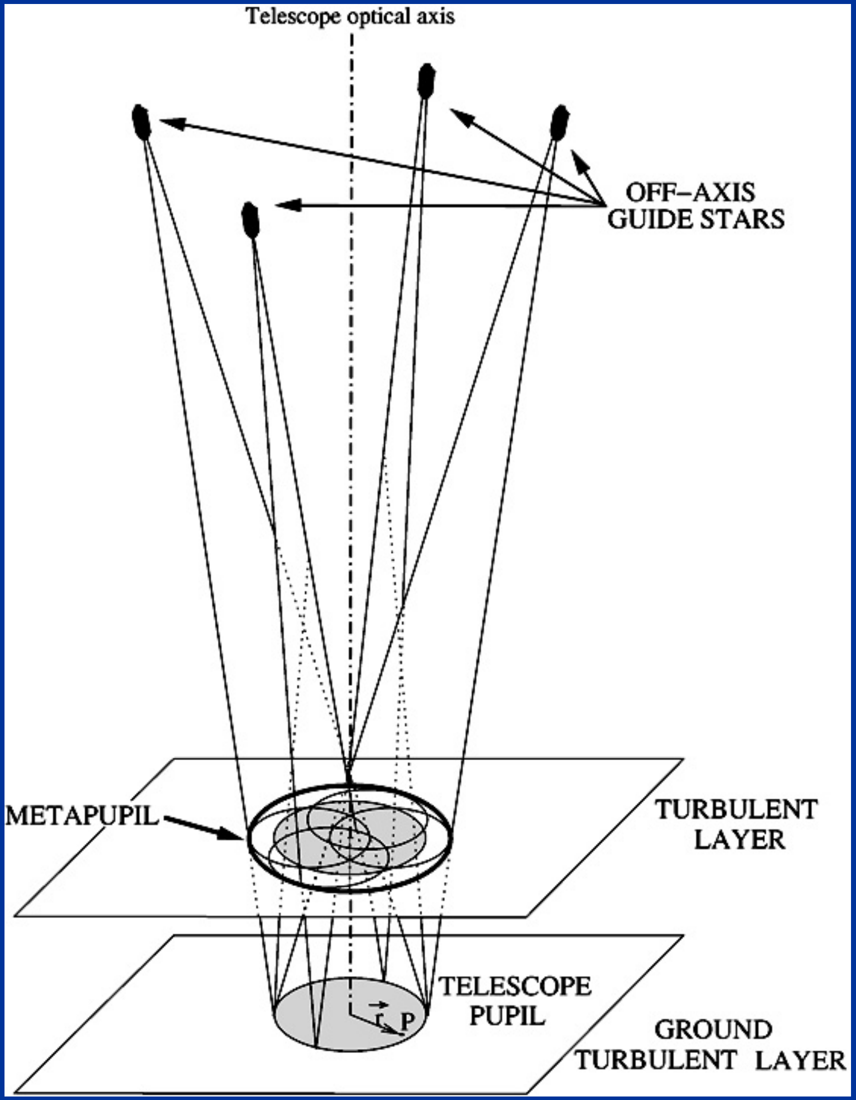
Tomography lets you reconstruct turbulence in the entire cylinder of air above the telescope mirror

Credit: Rigaut, MCAO for Dummies

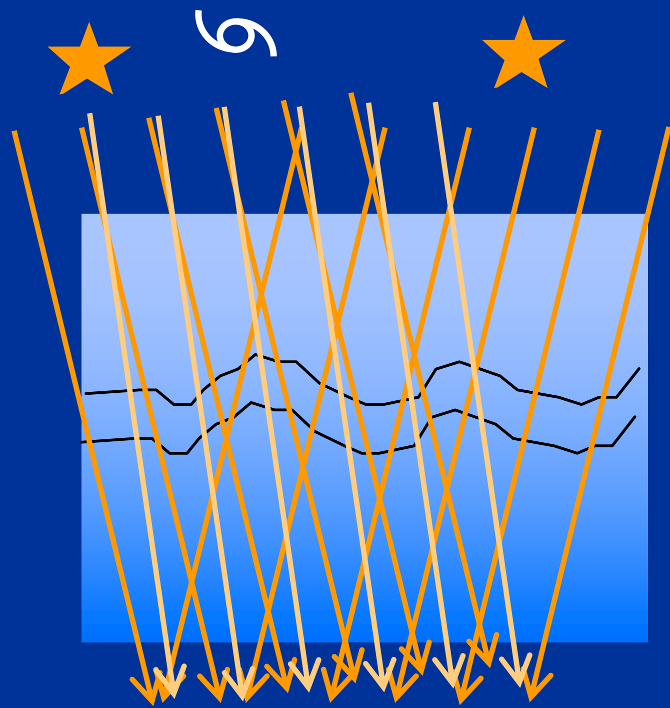
Concept of a metapupil

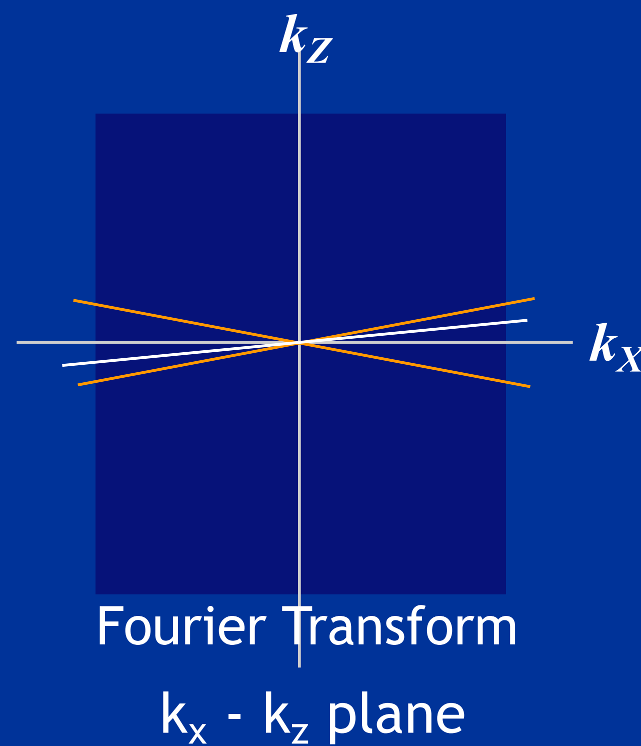
- Can be made larger than “real” telescope pupil

- Increased field of view due to overlap of fields toward multiple guide stars



How tomography works: from Don Gavel



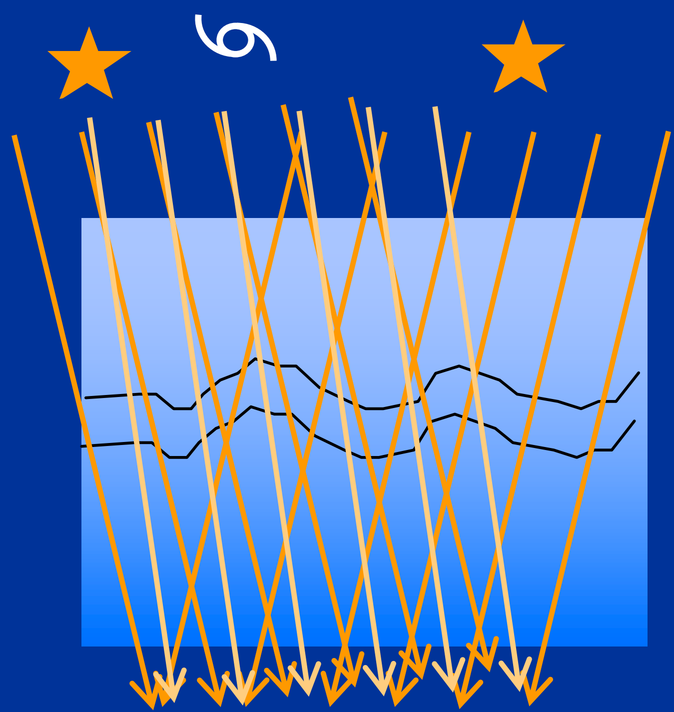


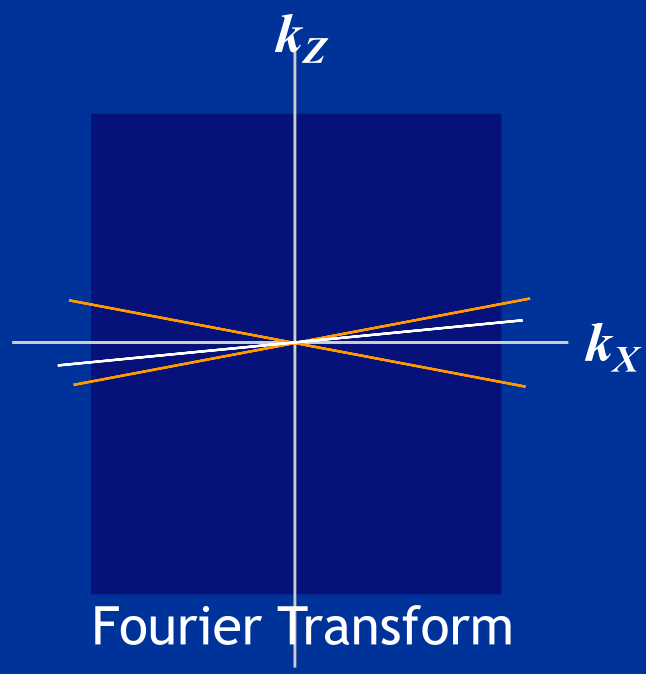
Fourier slice theorem in tomography

(Kak, *Computer Aided Tomography*, 1988)

- **Each wavefront sensor measures the integral of index variation along the ray lines**
- **The line integral along z determines the k_z=0 Fourier spatial frequency component**
- **Projections at several angles sample the k_x,k_y,k_z volume**

How tomography works: from Don Gavel

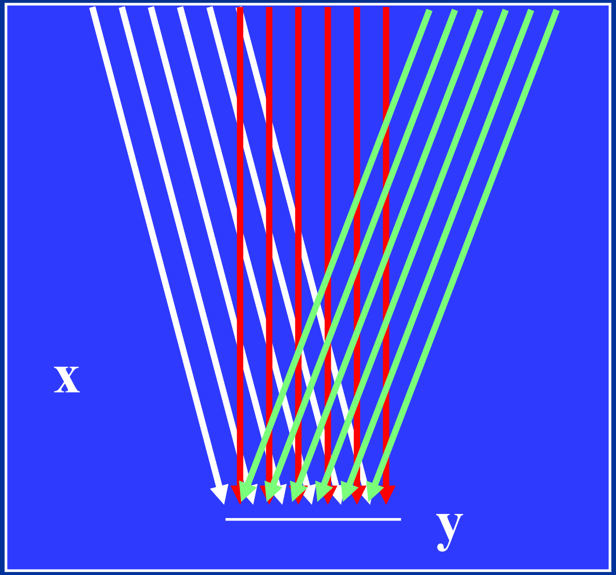




- The larger the telescope's primary mirror, the wider the range of angles accessible for measurement
- In Fourier space, this means that the "bow-tie" becomes wider
- More information about the full volume of turbulence above the telescope

How tomography works: some math

$$\mathbf{y} = \mathbf{A}\mathbf{x}$$



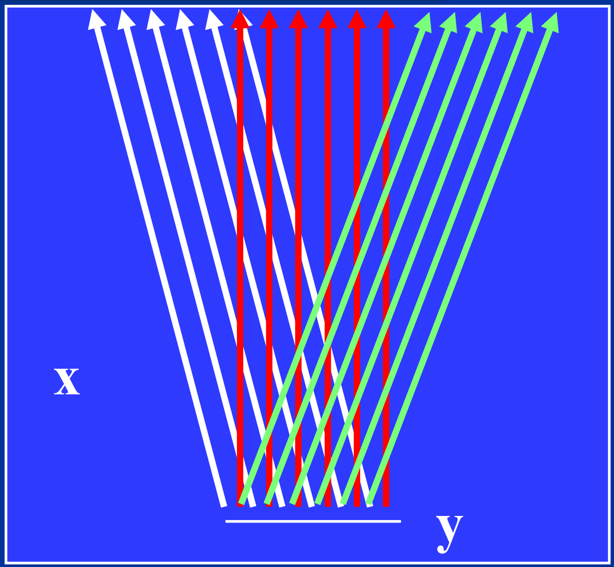
- where
  y = vector of all WFS measurements
  x = value of δ(OPD) at each voxel in turbulent volume above telescope

$\mathbf{A}$ is a *forward propagator*

- Assume we measure y with our wavefront sensors
- Want to solve for x = value of δ(OPD)
- The equations are underdetermined - there are more unknown voxel values than measured phases $\Rightarrow$ blind modes. Need a few natural guide stars to determine these.

Solve for the full turbulence above the telescope using the back-propagator

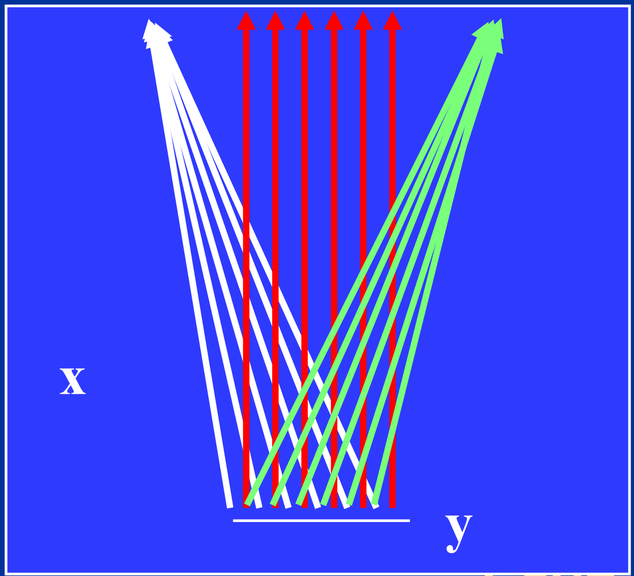
$$\mathbf{x} = \mathbf{A}^T \mathbf{y}$$



y = vector of all WFS measurements

x = value of δ(OPD) at each voxel in turbulent volume above telescope

$\mathbf{A}^T$ is a *back propagator* along rays back toward the guidestars



Use iterative algorithms to converge on the solution.

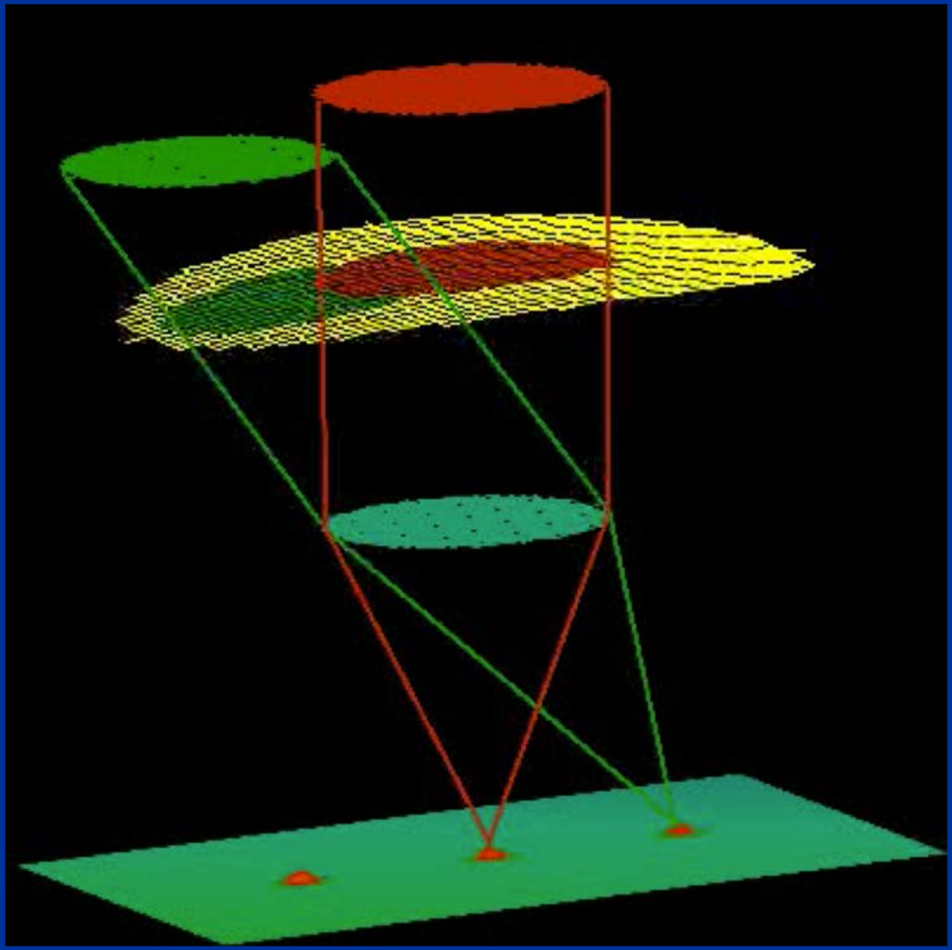
LGS Related Problems: "Null modes"

- **Tilt Anisoplanatism** :
  Low order modes produce Tip-Tilt at altitude

  → Dynamic Plate Scale changes

- Five "**Null Modes**" are not seen by LGS (Tilt indetermination problem)

- Need 3 well spread tip-tilt stars to control these modes

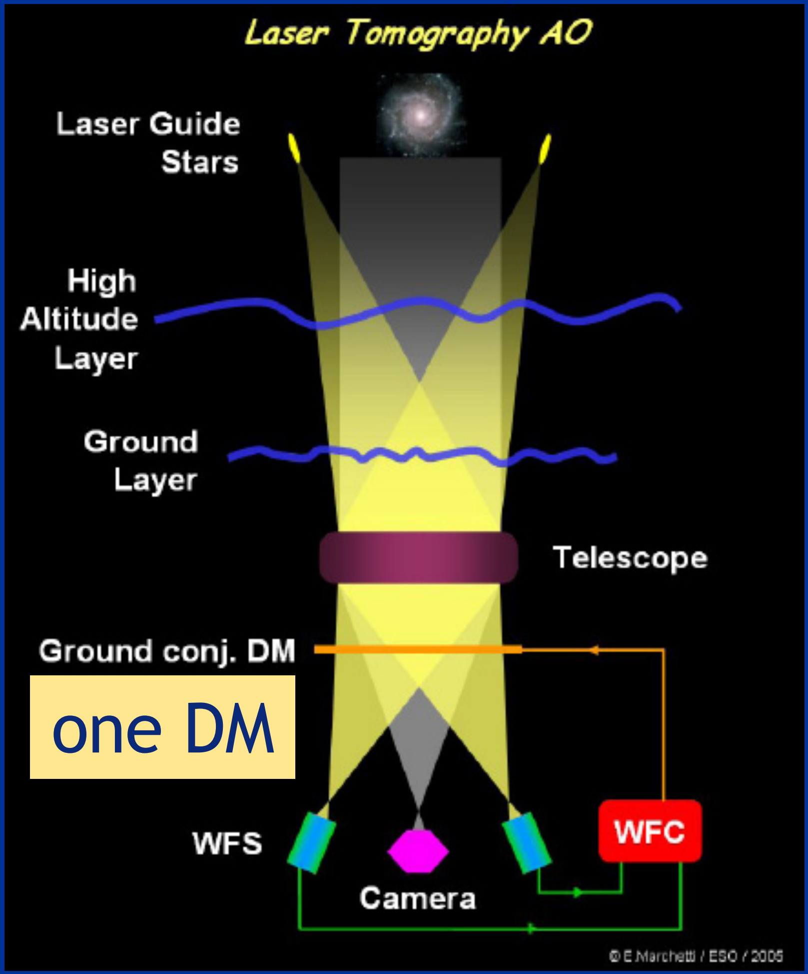


Credit: Rigaut, MCAO for Dummies

Outline of lecture

- Review of AO tomography concepts
- AO applications of tomography
  - Laser tomography AO (LTAO)
  - Multi-conjugate AO (MCAO)
  - Multi-object AO (MOAO)
  - Ground-layer AO (GLAO)

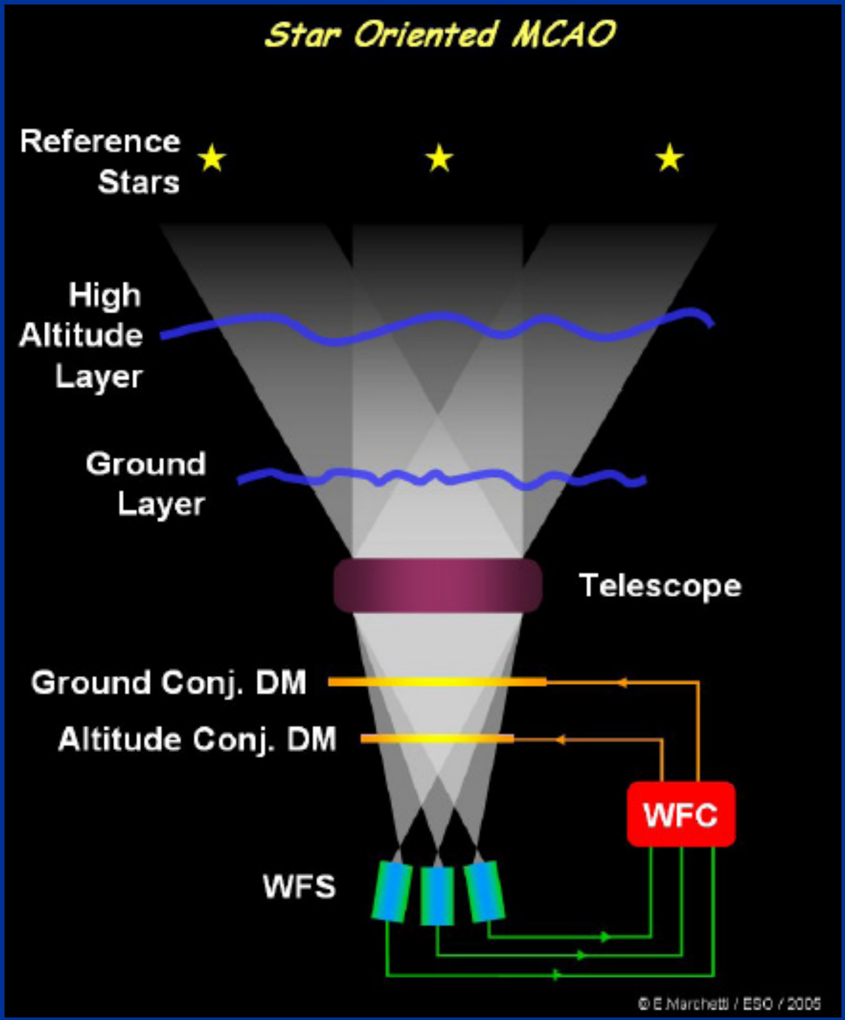
Laser Tomography AO: High-Order Correction; Fixes Cone Effect



Narrow field, cone effect fixed

Corrected field: 10's of arc sec

Multi-Conjugate AO: Wider Field Correction

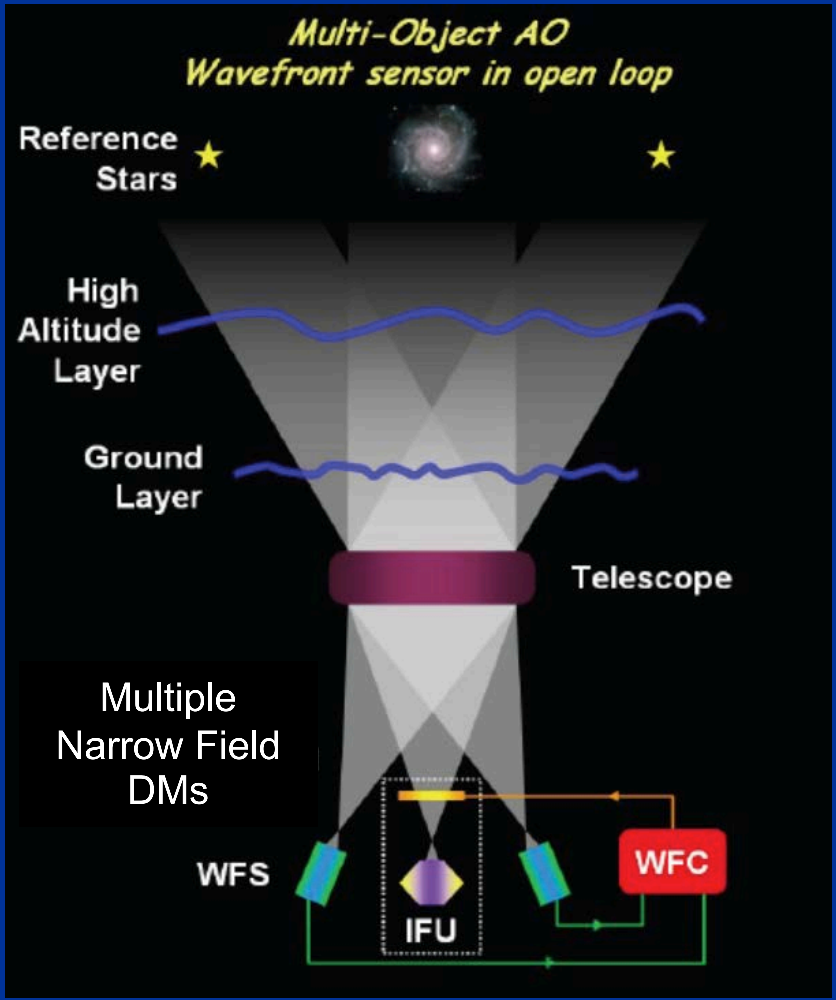


Corrected field: up to ~2 arc min

≥ 2 DMs

Corrects over wider field, at a penalty in peak Strehl

Multi-Object AO: Wider Field but only correct objects you are interested in

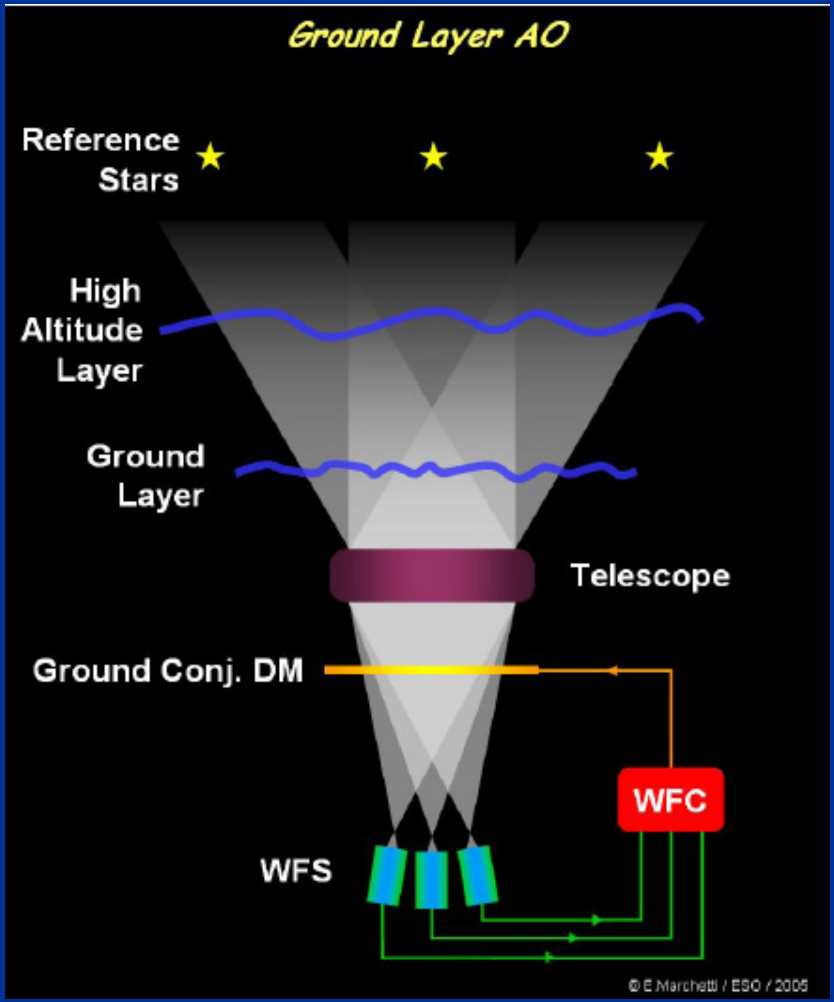


Corrected field: N x 10's of arc sec

One DM for each object of interest

Correct over narrow field of view located anywhere w/in wide field of regard

Ground Layer AO: Widest field, only modest AO correction



Corrected field: 5 -10 arc min

One DM conjugate to ground

Quite modest correction over a much wider field of view

Corrected fields of view vary depending on method

Method		Corrected field of view
Laser Tomography AO	LTAO	10’s of arc sec
Multi-Object AO	MOAO	N x 10’s of arc sec
Multi-Conjugate AO	MCAO	≤ about 2 arc min
Ground Layer AO	GLAO	A few to 10 arc min

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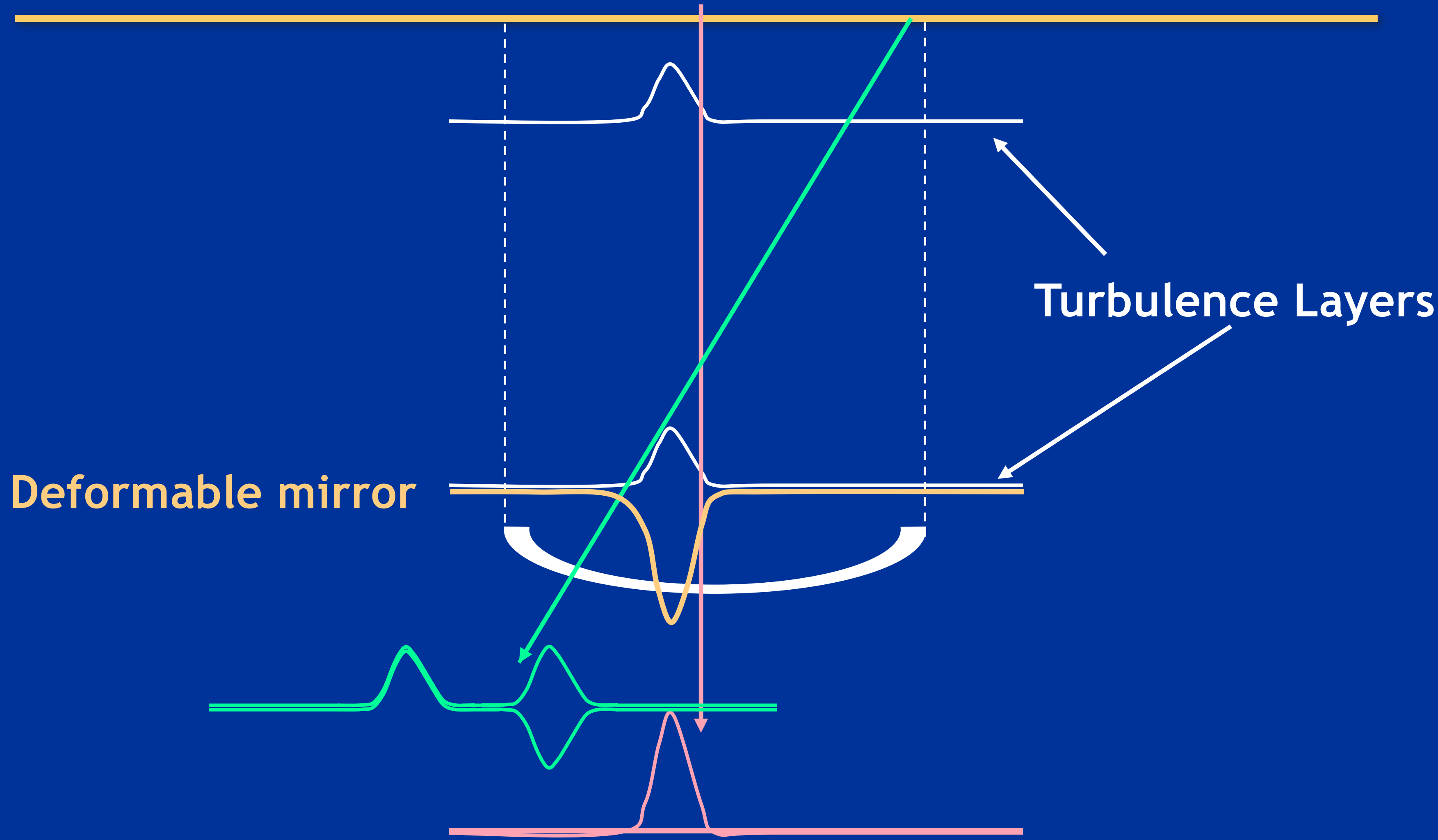
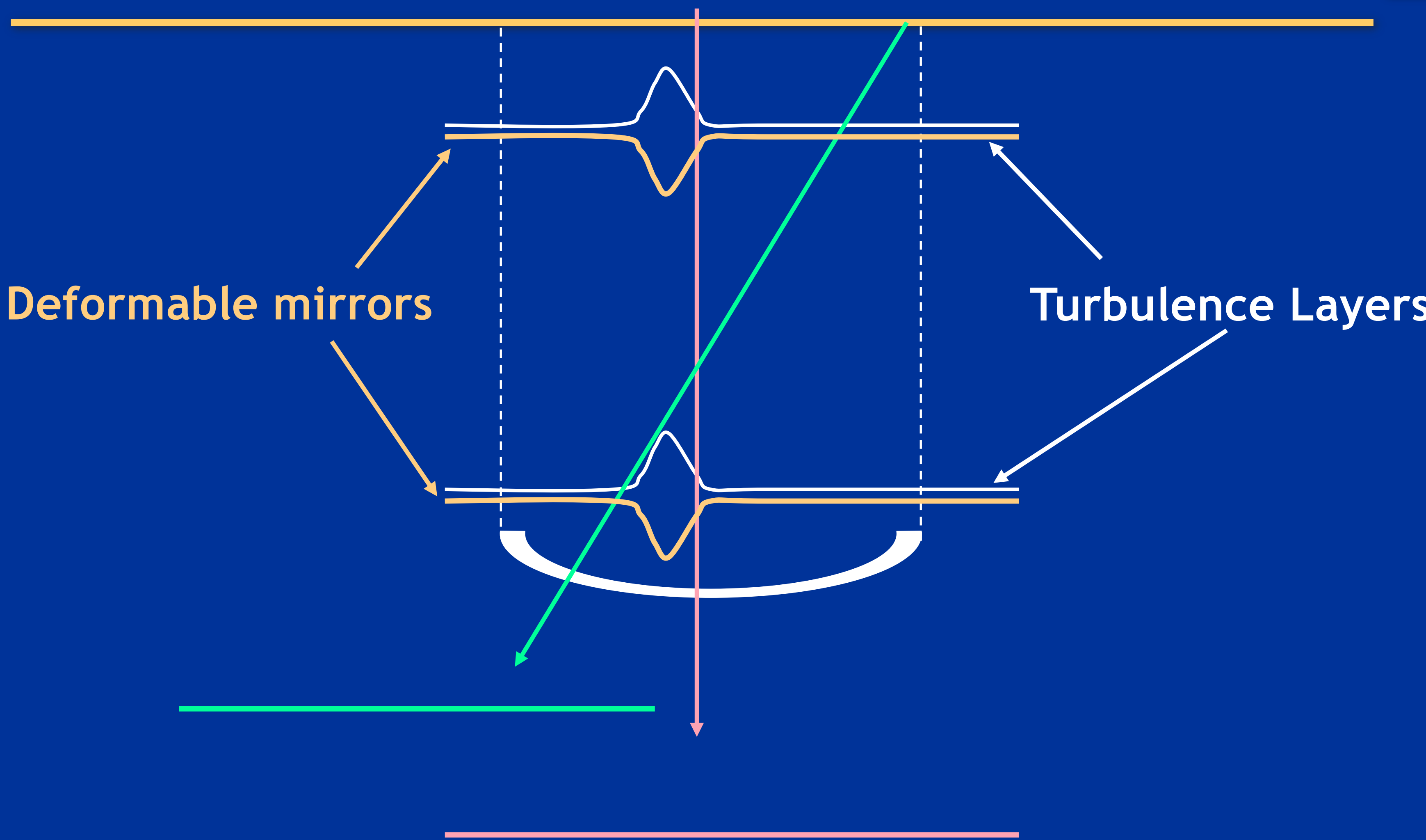
What is multiconjugate AO?



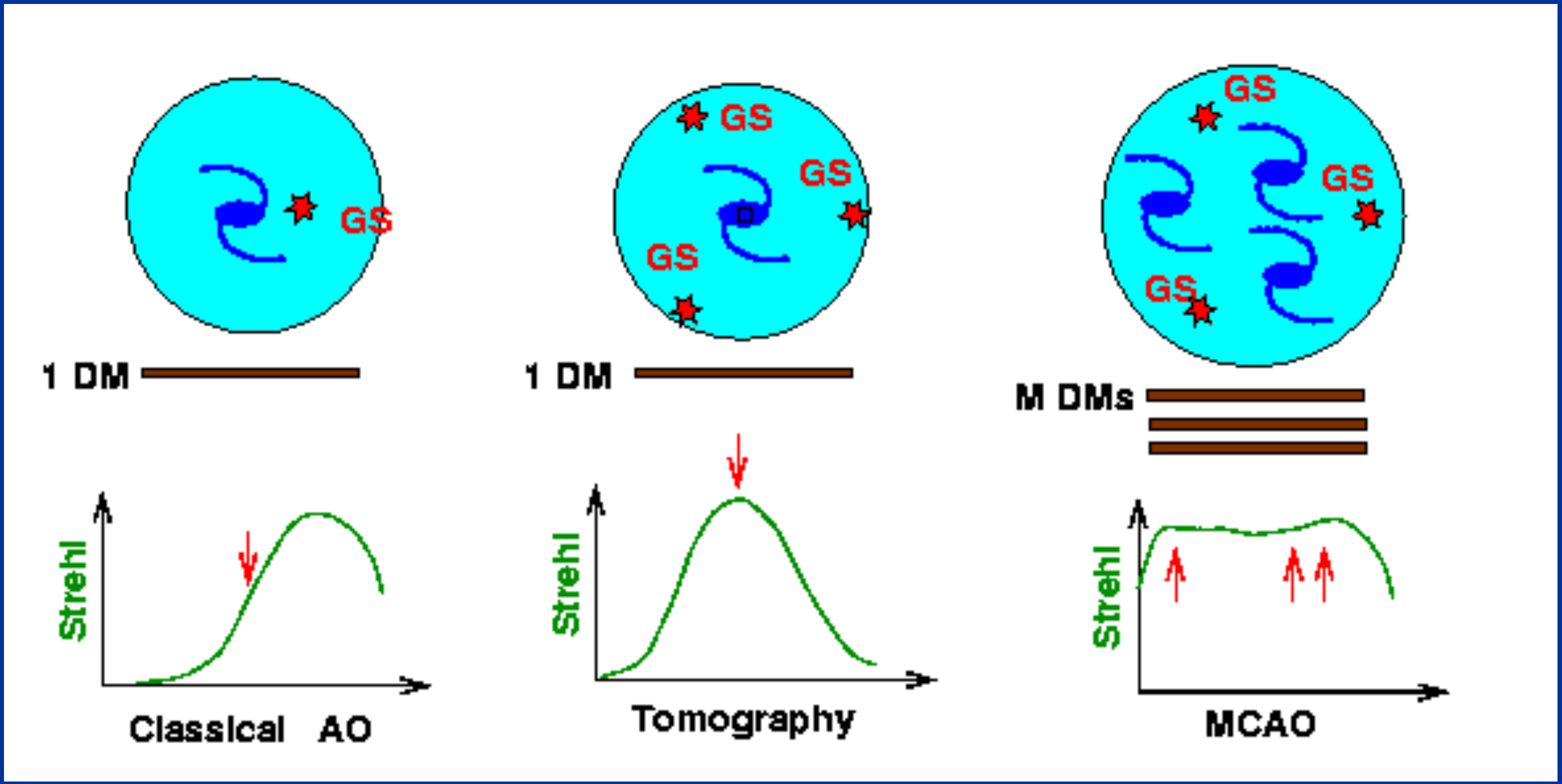
Credit: Rigaut, MCAO for Dummies

What is multiconjugate AO?



Credit: Rigaut, MCAO for Dummies

Difference between Laser Tomography AO and MCAO

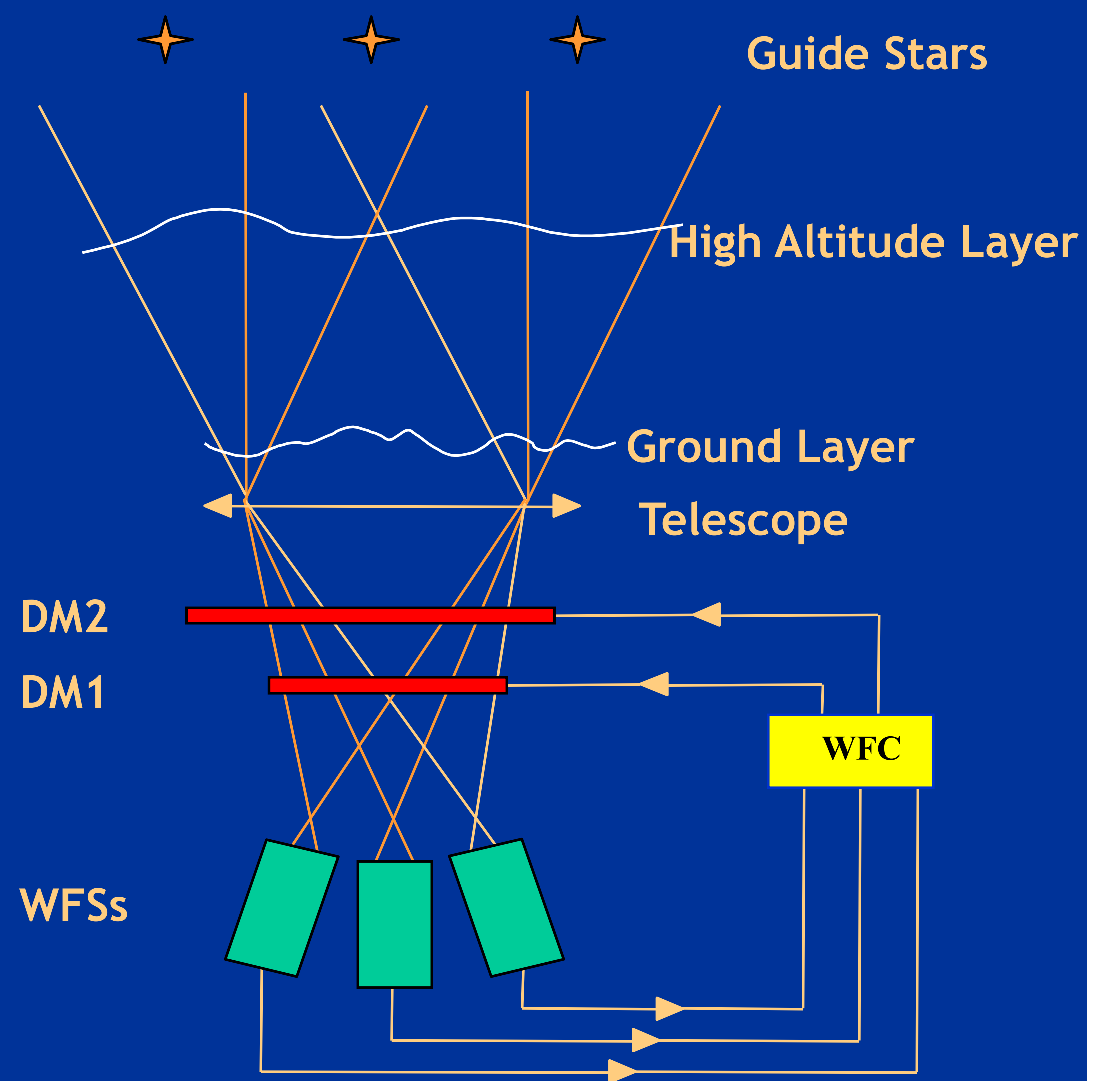


- Laser Tomography AO can be done with only 1 deformable mirror
- If used with multiple laser guide stars, reduces cone effect
- MCAO uses multiple DMs, increases field of view

"Star Oriented" MCAO

- Each WFS looks at one star
- Global Reconstruction
- *n* GS, *n* WFS, *m* DMs
- 1 Real Time Controller

- The correction applied at each DM is computed using all the input data.

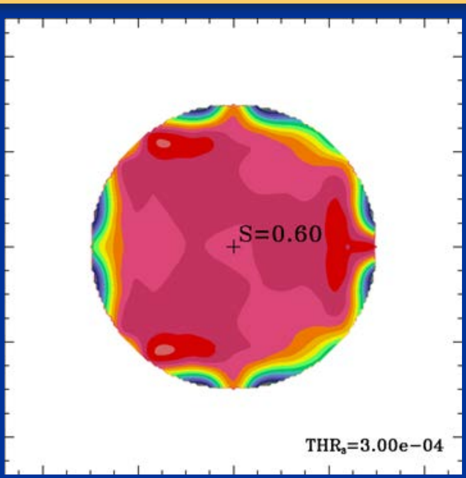


Credit: N. Devaney

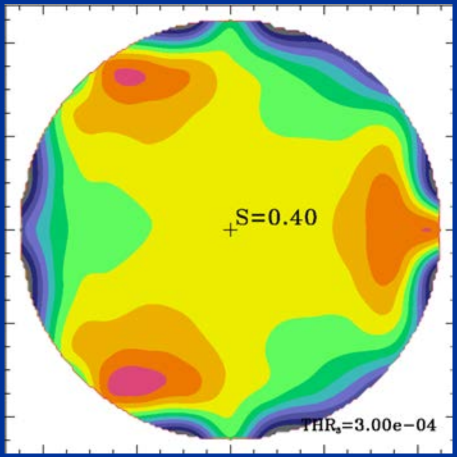
MCAO Simulations, 3 guide stars

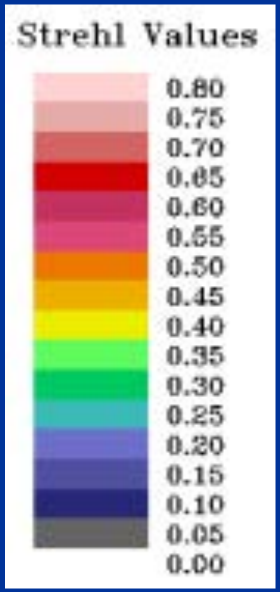
Strehl at 2.2 μm

3 guide stars,
FoV = 1 arc min



3 guide stars,
FoV = 1.5 arc min

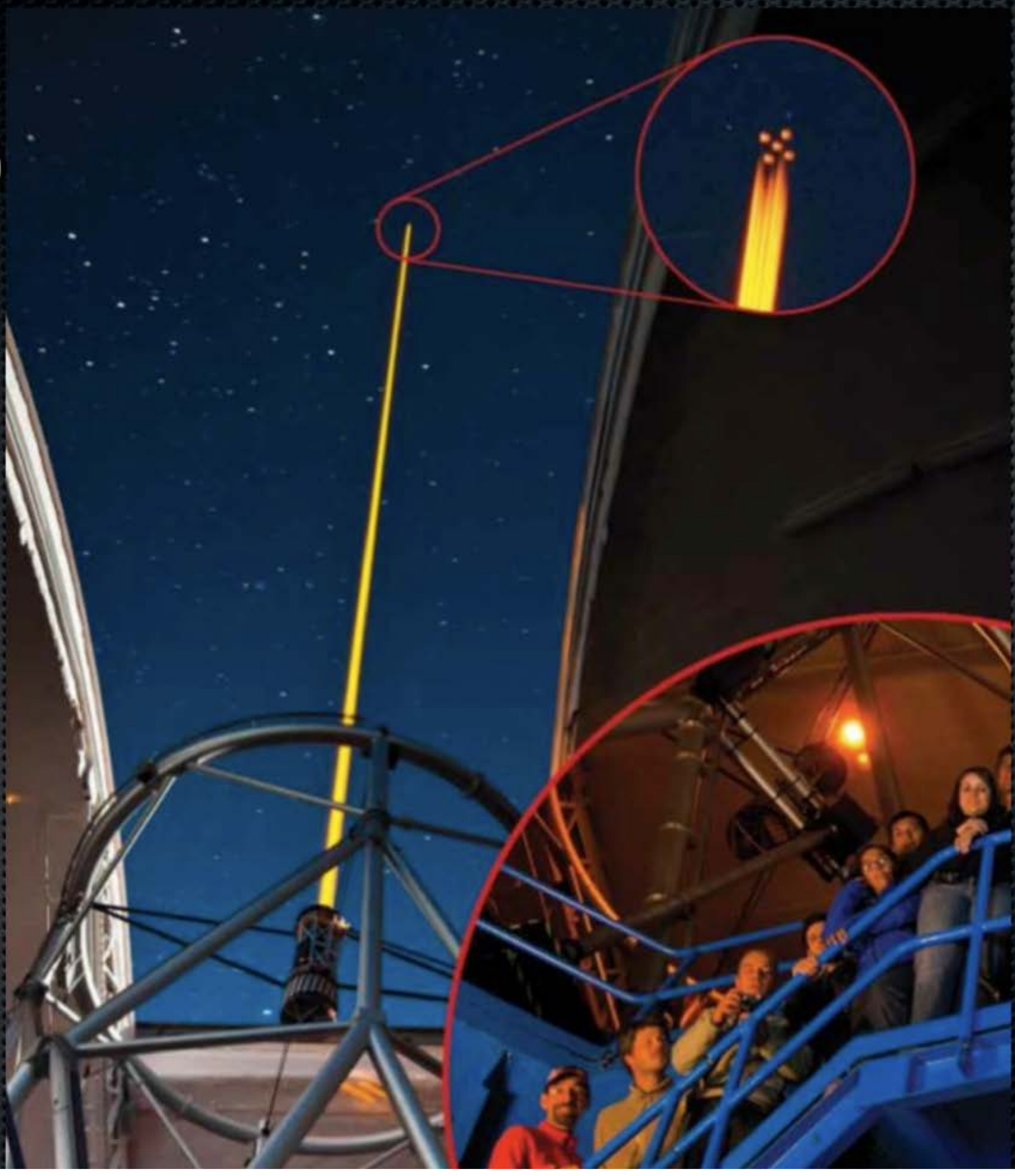




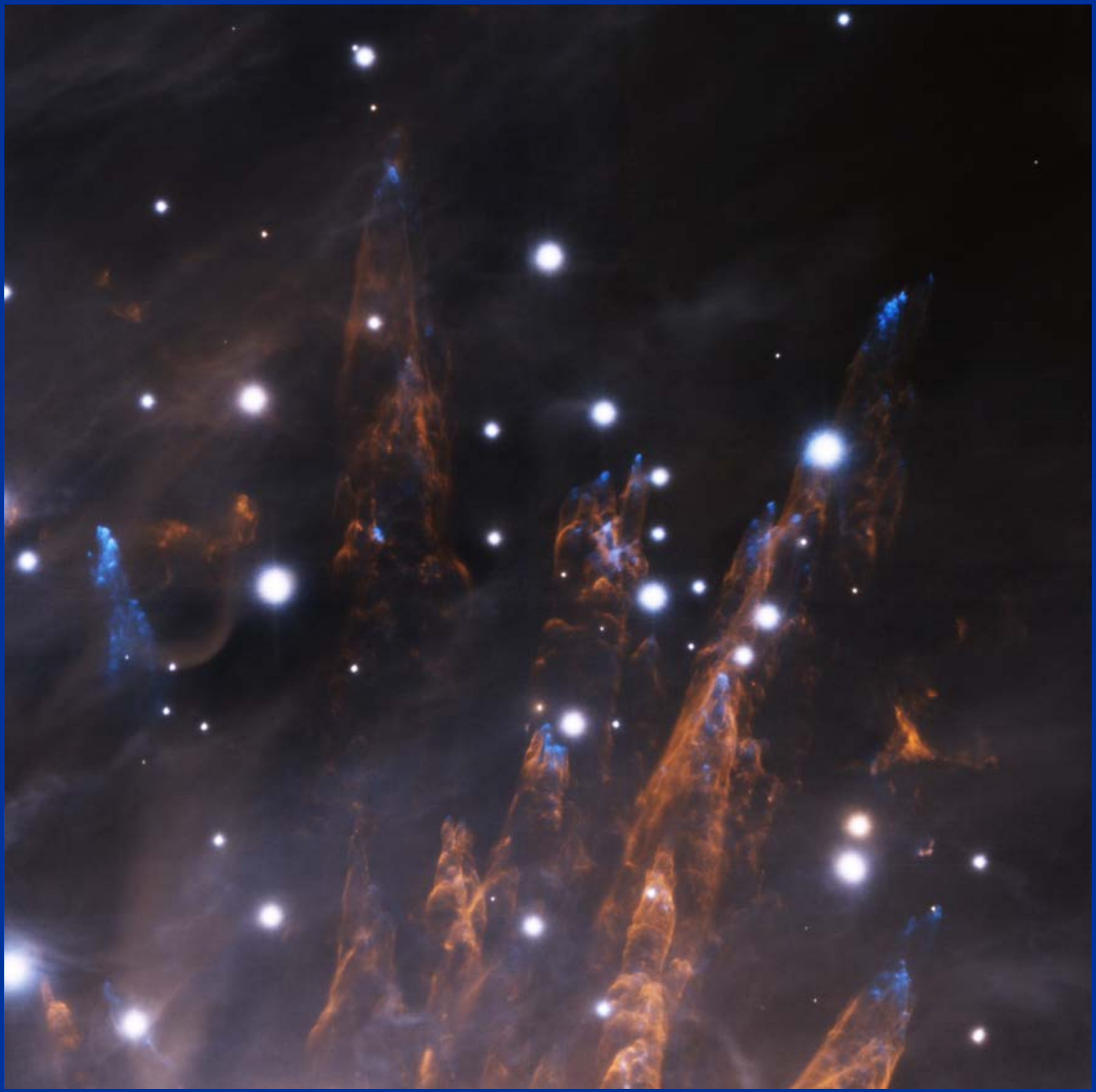
Optimum guide star separation: about one isoplanatic angle

Credit: N. Devaney

First operational MCAO system: GEMS at Gemini South 8m telescope



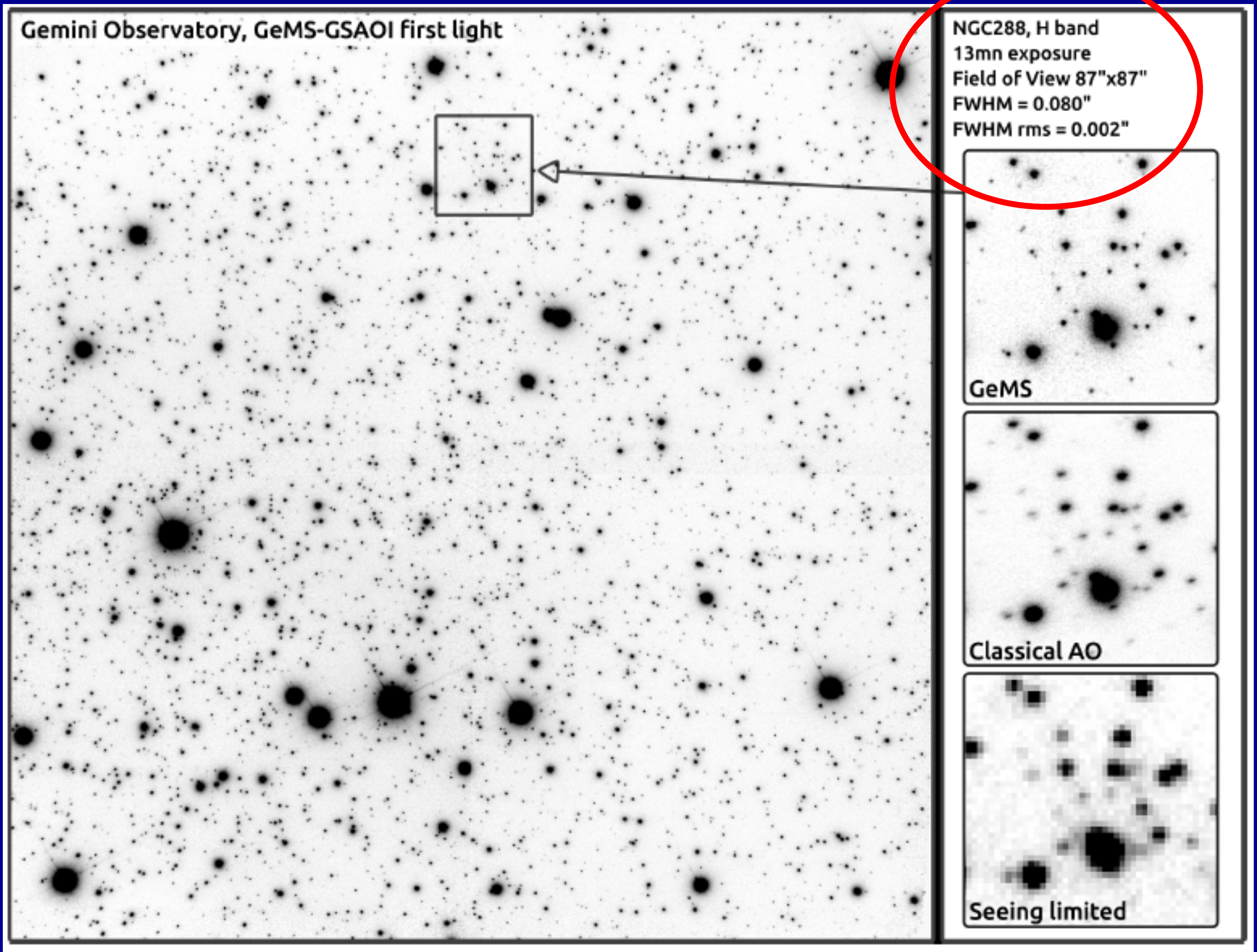
GEMS image of star formation in Orion



- Orion star forming region:
- Compare GEMS MCAO with ALTAIR single conjugate AO on Gemini North Telescope

ALTAIR GEMS

GEMS MCAO: very good uniformity across 87" x 87" field



Credit: Rigaut et al. 2013

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- Review of AO tomography concepts
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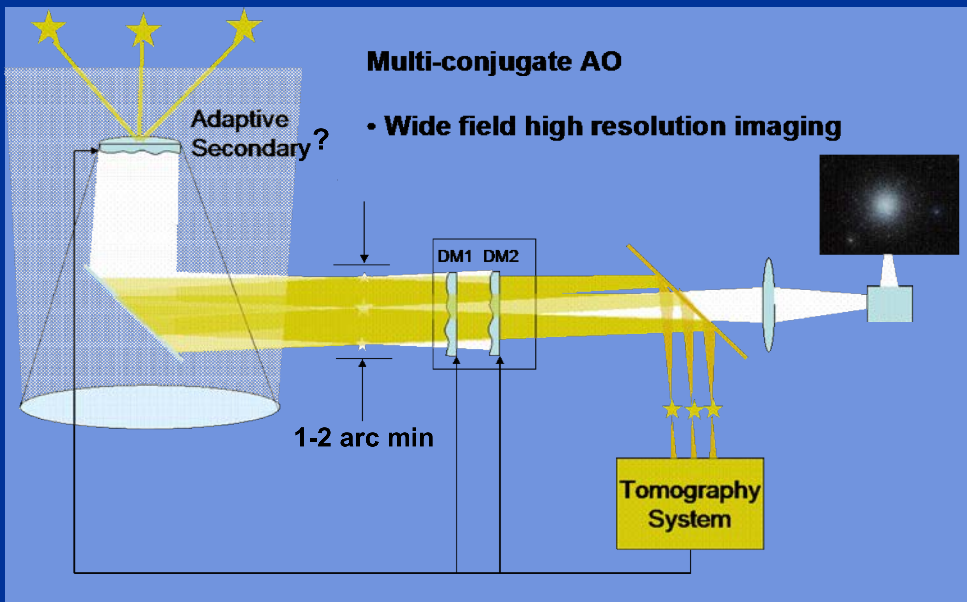
  - Multi-conjugate adaptive optics (MCAO)
  - **Multi-object adaptive optics (MOAO)**
  - Ground-layer AO (GLAO)

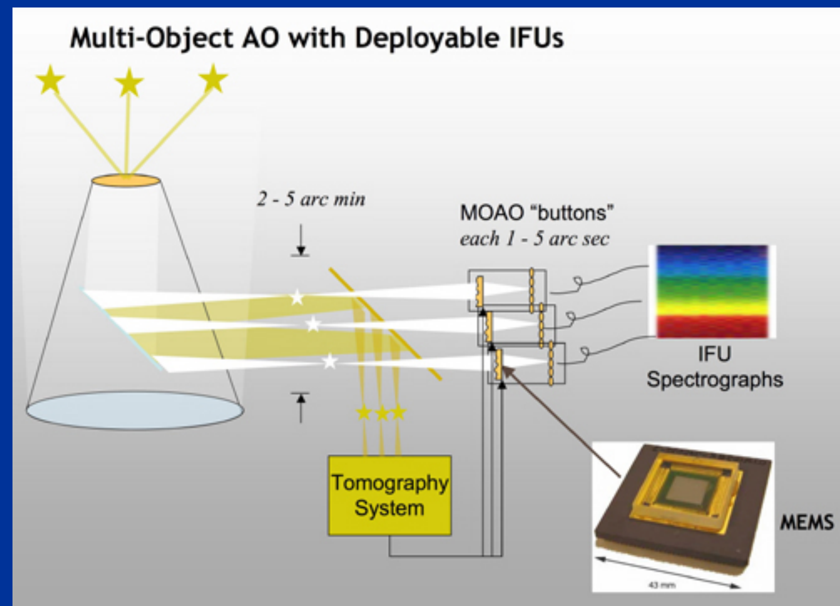
Distinctions between multi-conjugate and multi-object AO

Closed-Loop



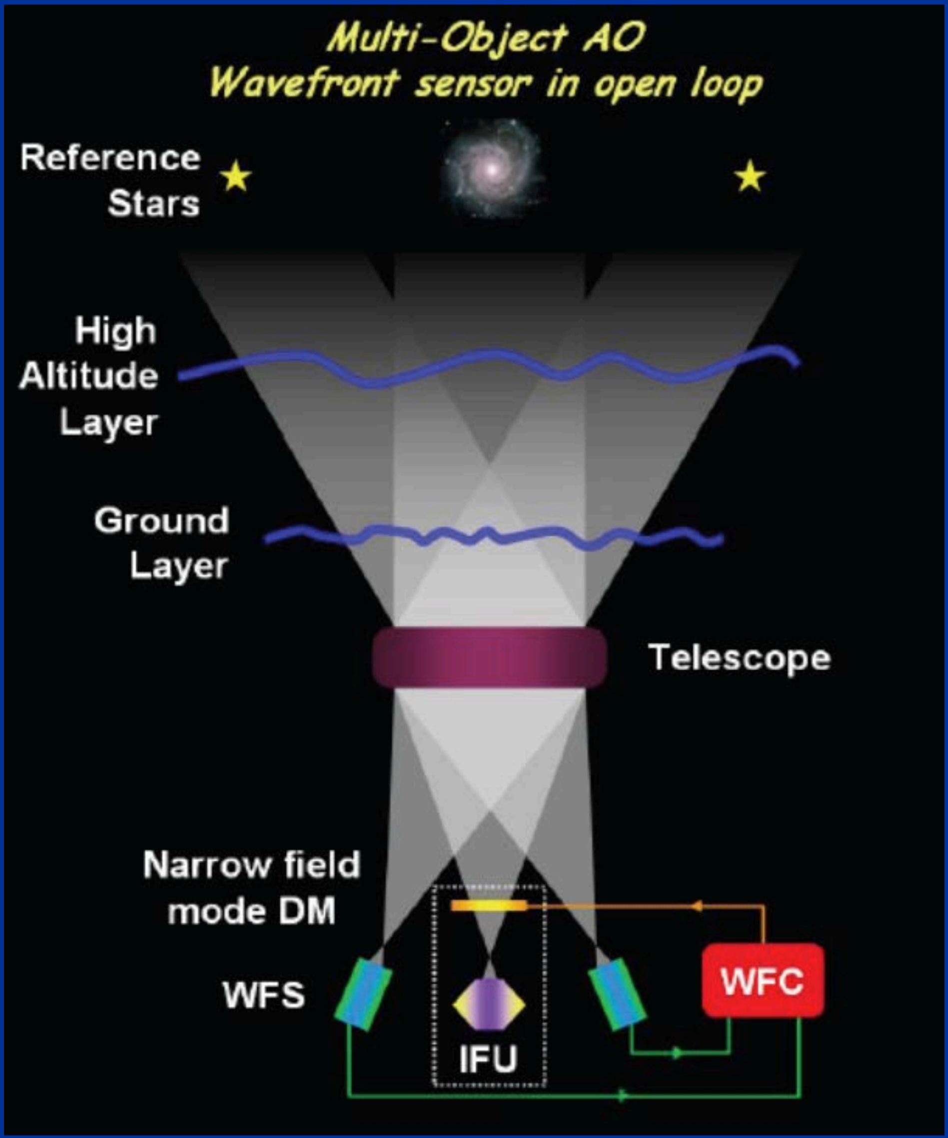
- DMs conjugate to different altitudes in the atmosphere
- Guide star light is corrected by DMs before its wavefront is measured

Open-Loop



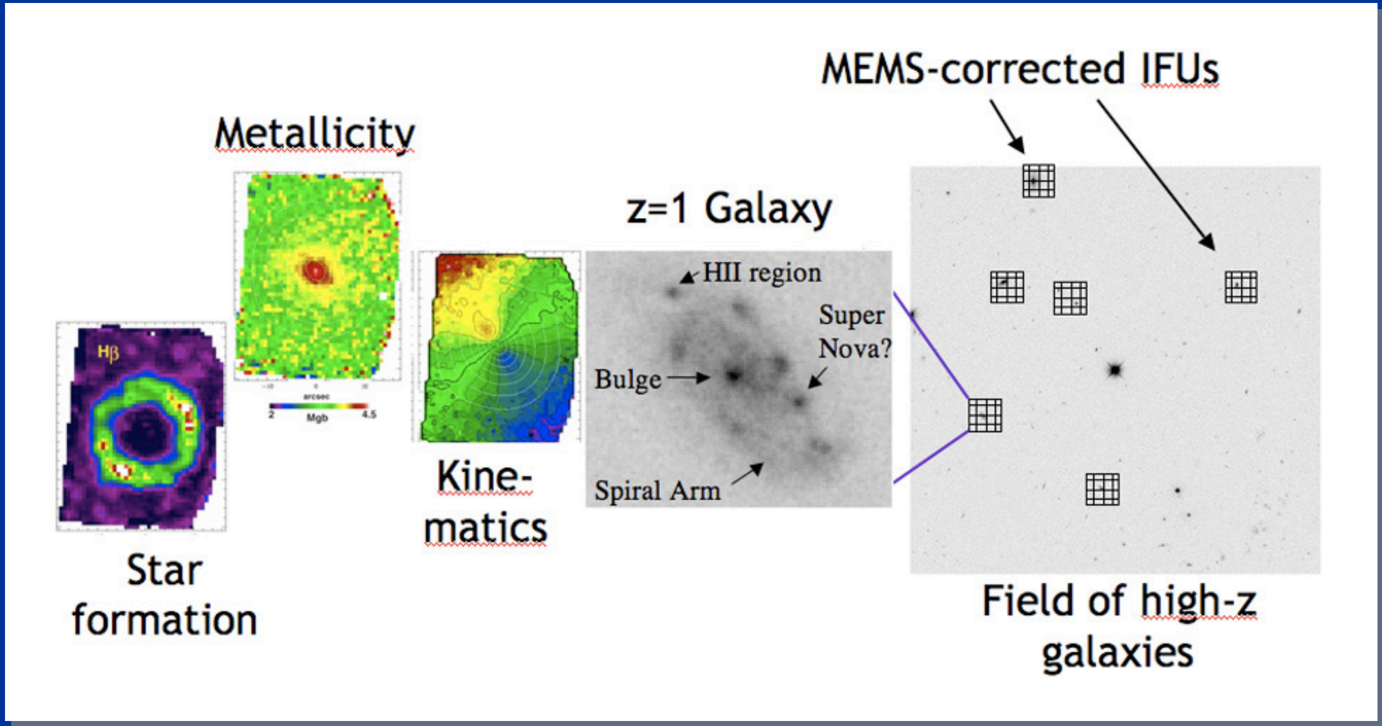
- Only one DM per object, conjugate to ground
- Guide star light doesn't bounce off small MEMS DMs in multi-object spectrograph

Multi-Object AO



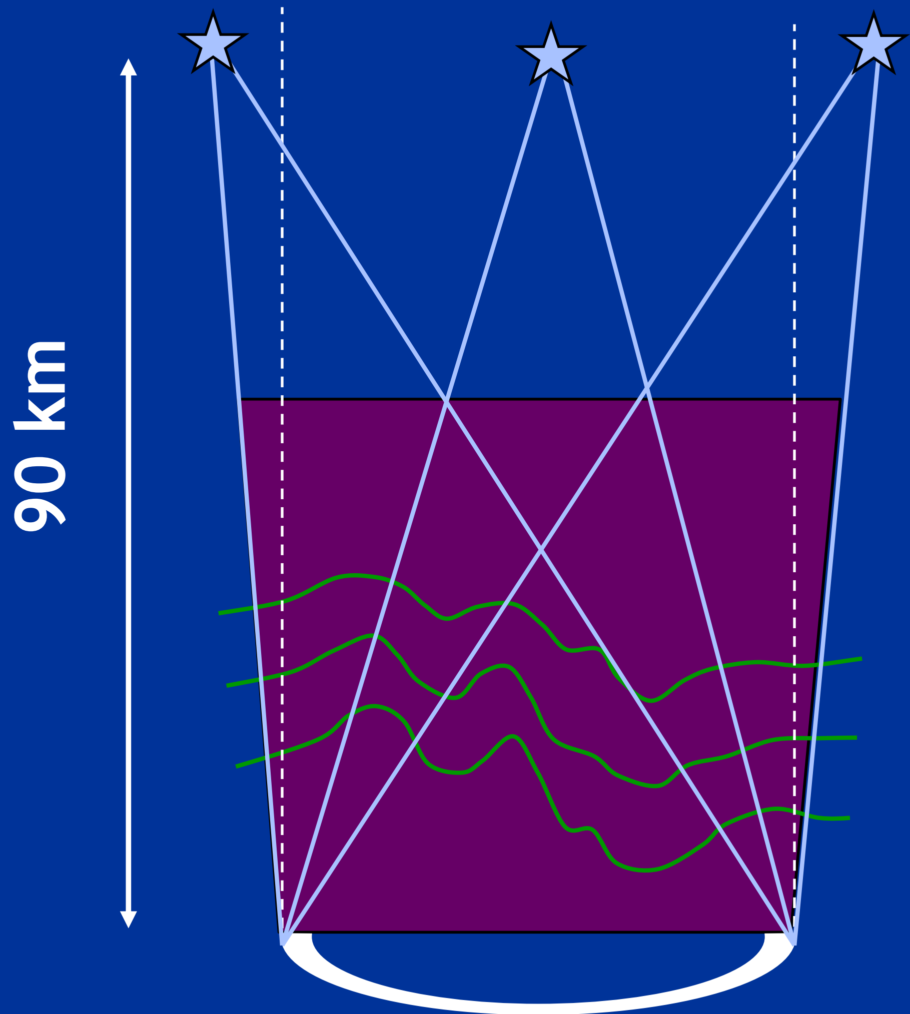
- Correct over multiple narrow fields of view located anywhere w/in wide field of regard
- In most versions, each spectrograph or imager has its own MEMS AO mirror, which laser guide star lights doesn't bounce off of
- Hence this scheme is called "open loop": DM doesn't correct laser guide star wavefronts before LGS light goes to wavefront sensors
- In one version, each LGS also has its own MEMS correction

Science with MOAO: multiple deployable spatially resolved spectrographs



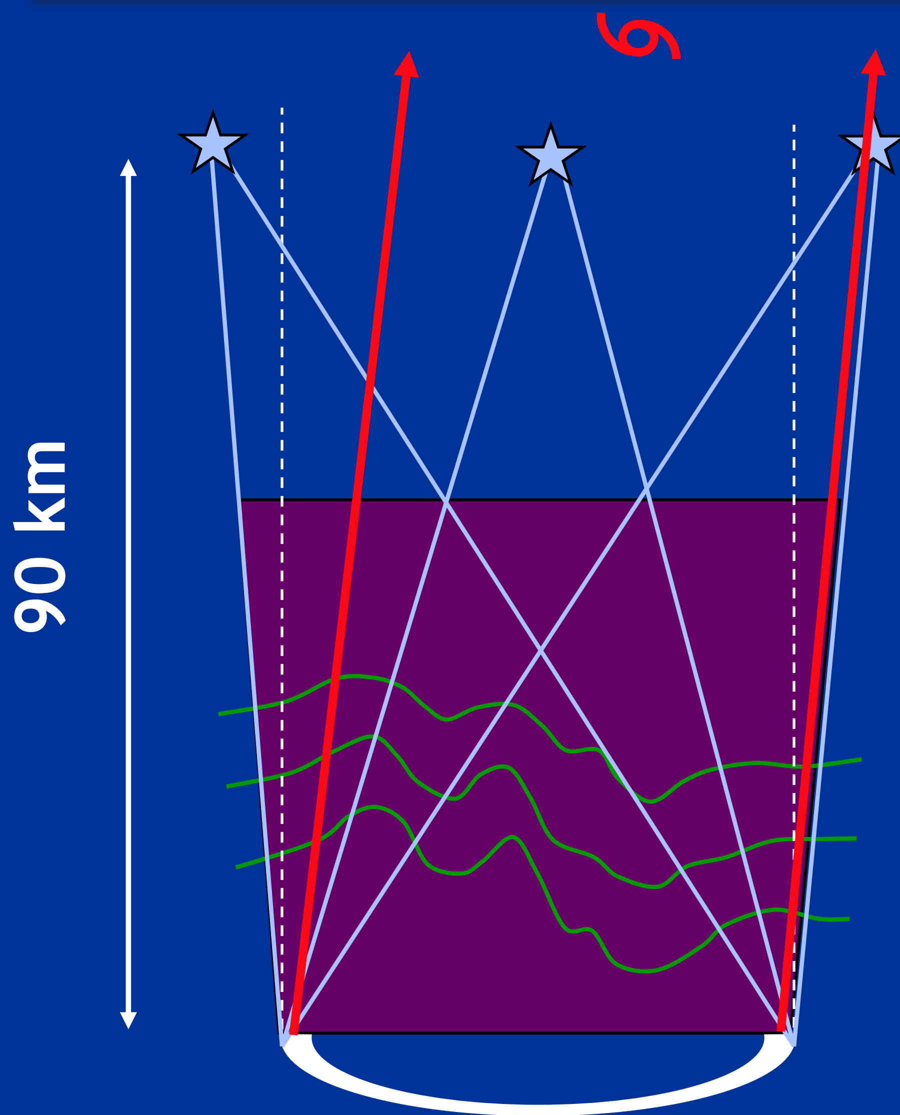
- A MEMS DM underneath each high-redshift galaxy, feeding a narrow-field spatially resolved spectrograph (IFU)
- No need to do AO correction on the blank spaces between the galaxies

Why does MOAO work if there is only one deformable mirror in the science path?



- Tomography lets you measure the turbulence throughout the volume above the telescope

Why does MOAO work if there is only one deformable mirror in the science path?



- Tomography lets you measure the turbulence throughout the volume above the telescope
- In the direction to each galaxy, you can then project out the turbulence you need to cancel out for that galaxy

MOAO Demonstration Systems

- CANARY (Durham, Obs. de Paris, ONERA, ESO)
  - MOAO pathfinder for E-ELT
  - On William Herschel Telescope
  - First NGS, then Rayleigh guide stars
- RAVEN (U Victoria, Subaru, INO, Canadian NRC)
  - MOAO demonstrator for Subaru telescope
  - 3 NGS wavefront sensors
  - Field of regard > 2.7 arc min

Analysis of on-sky MOAO performance of CANARY using natural guide stars

Fabrice Vidal[1], Eric Gendron[1], Gérard Rousset[1], Tim Morris[2], Alastair Basden[2], Richard Myers[2], Matthieu Brangier[1], Fanny Chemla[3], Nigel Dipper[2], Damien Gratadour[1], David Henry[4], Zoltan Hubert[1], Andy Longmore[4], Olivier Martin[1], Gordon Talbot[2], and Eddy Younger[2]

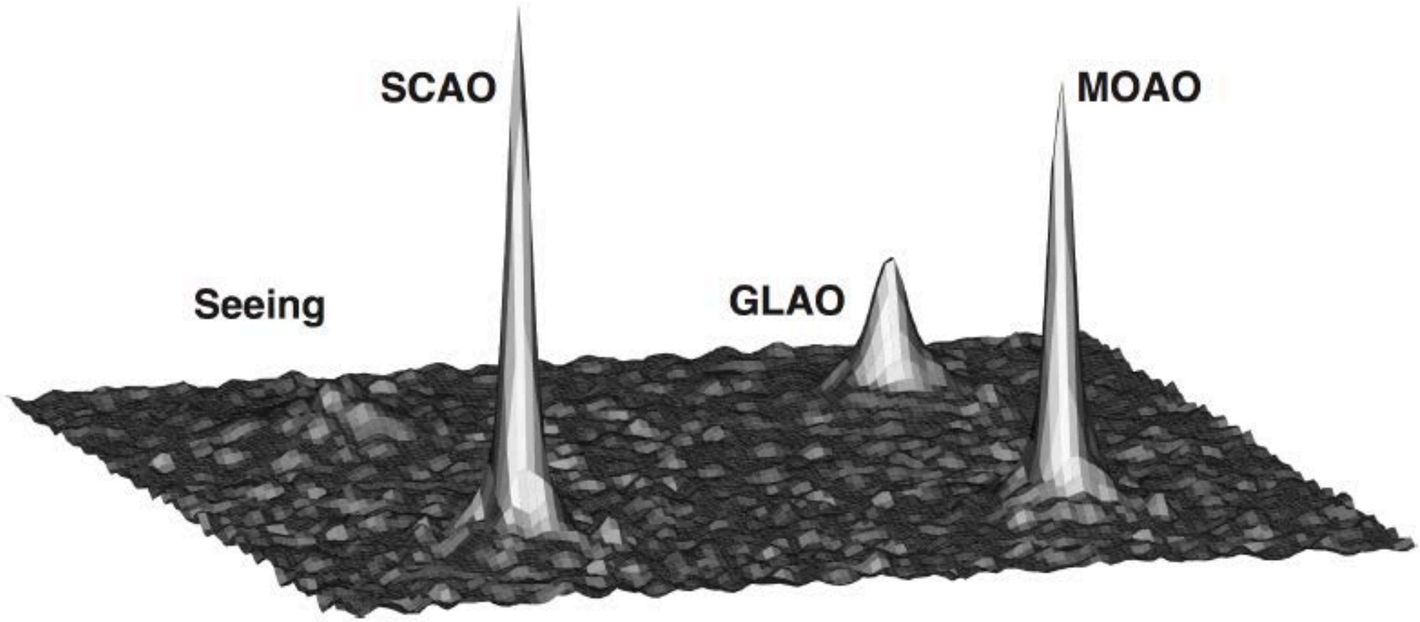
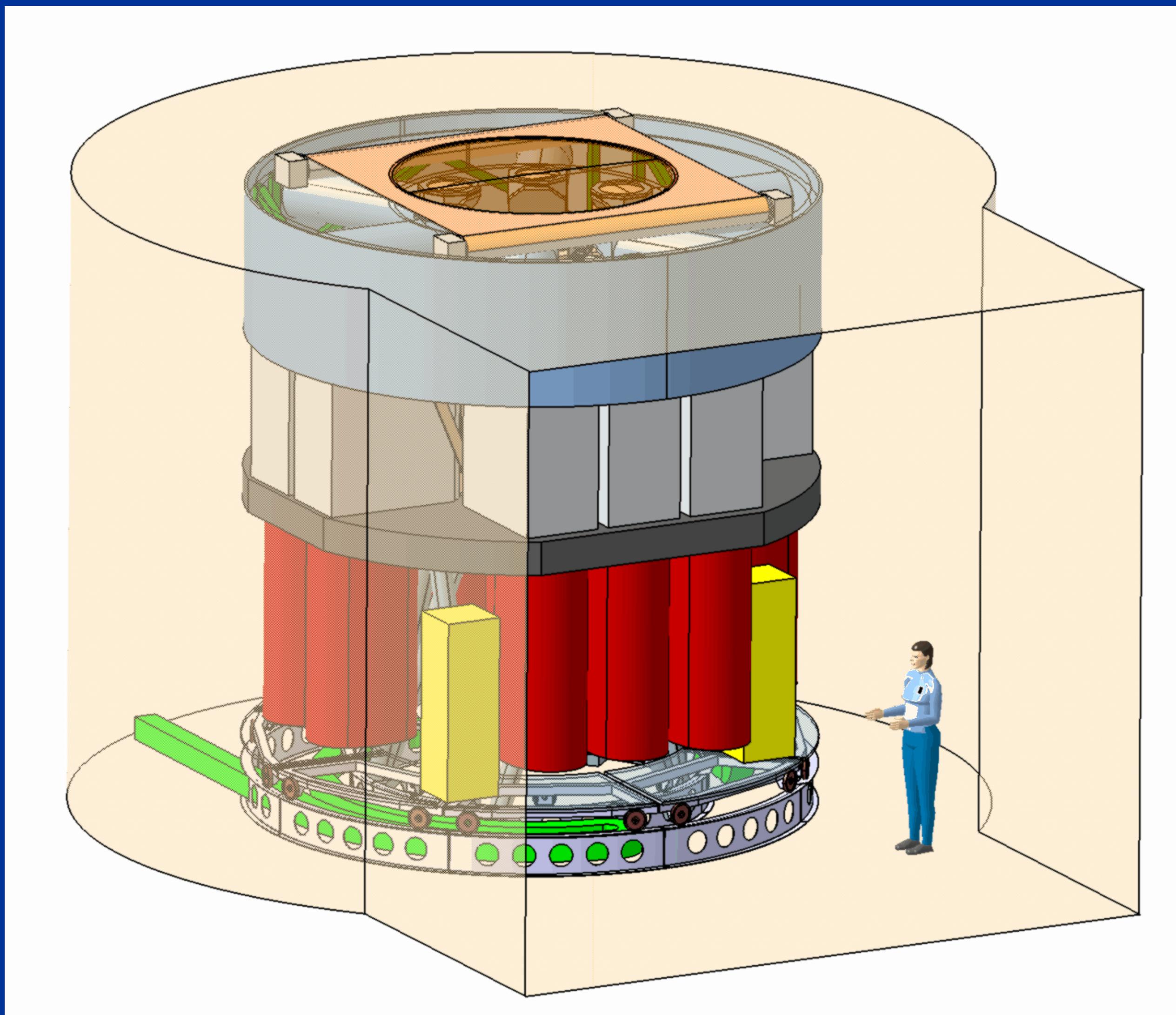


Fig. 7. IR image comparison at λ = 1 530 nm. The four images of 30 seconds exposure each were taken at $00^h59^m18^s$ (Seeing), $00^h42^m10^s$ (GLAO), $00^h29^m22^s$ (MOAO) and $00^h32^m28^s$ (SCAO). Measured SR are respectively: 1%, 9%, 19.4% and 23.8%.

Both E-ELT and TMT have done early designs for MOAO systems



- Artist's sketch of EAGLE MOAO system for E-ELT
- One of the constraints is that the spectrographs are very large!
- Hard (and expensive) to fit in a lot of them

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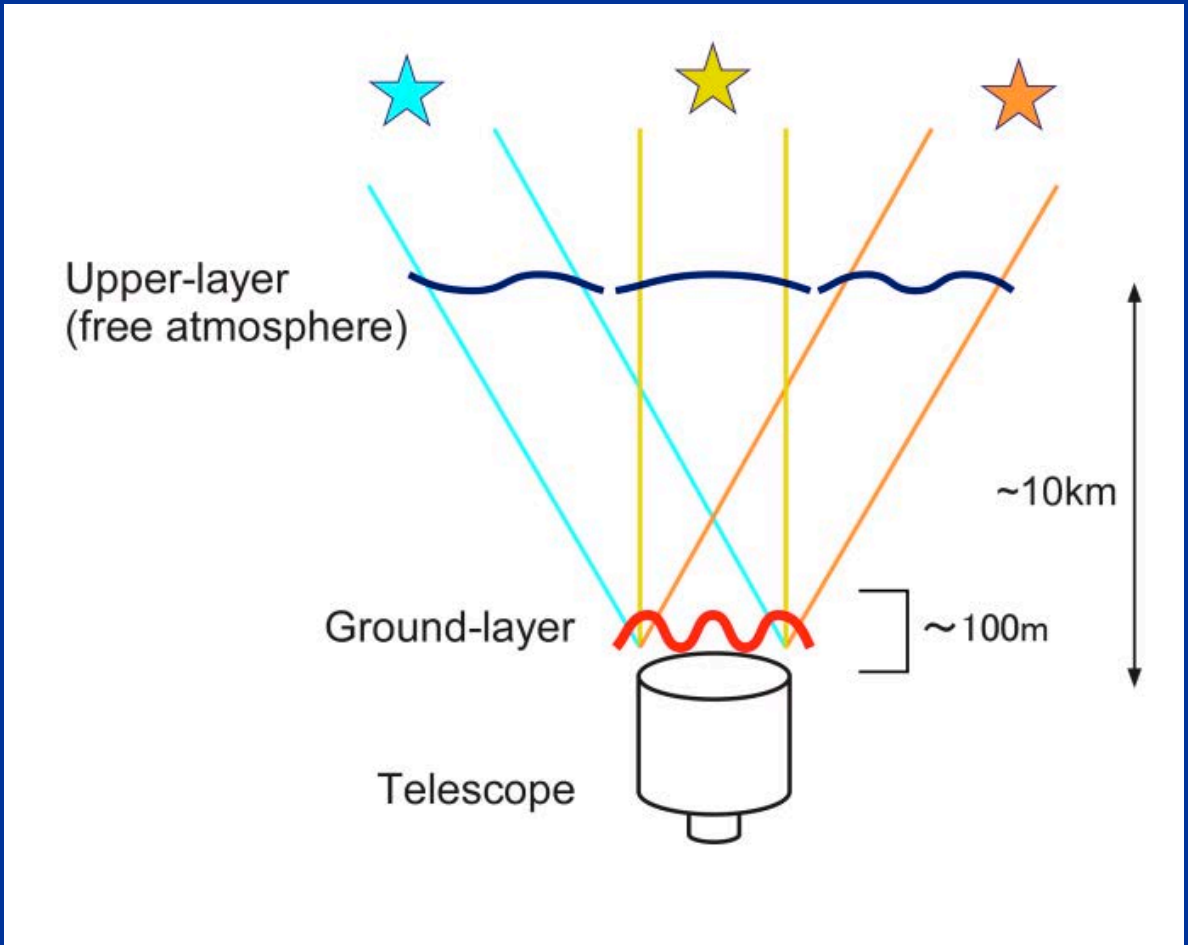
Ground layer AO: do tomography, but only use 1 DM (conjugate to ground layer)



Or instead of tomography, can just average over the guide stars

GLAO uses 1 ground-conjugated DM, corrects near-ground turbulence

Credit: J-M Conan

Correcting just the ground layer gives a very large isoplanatic angle

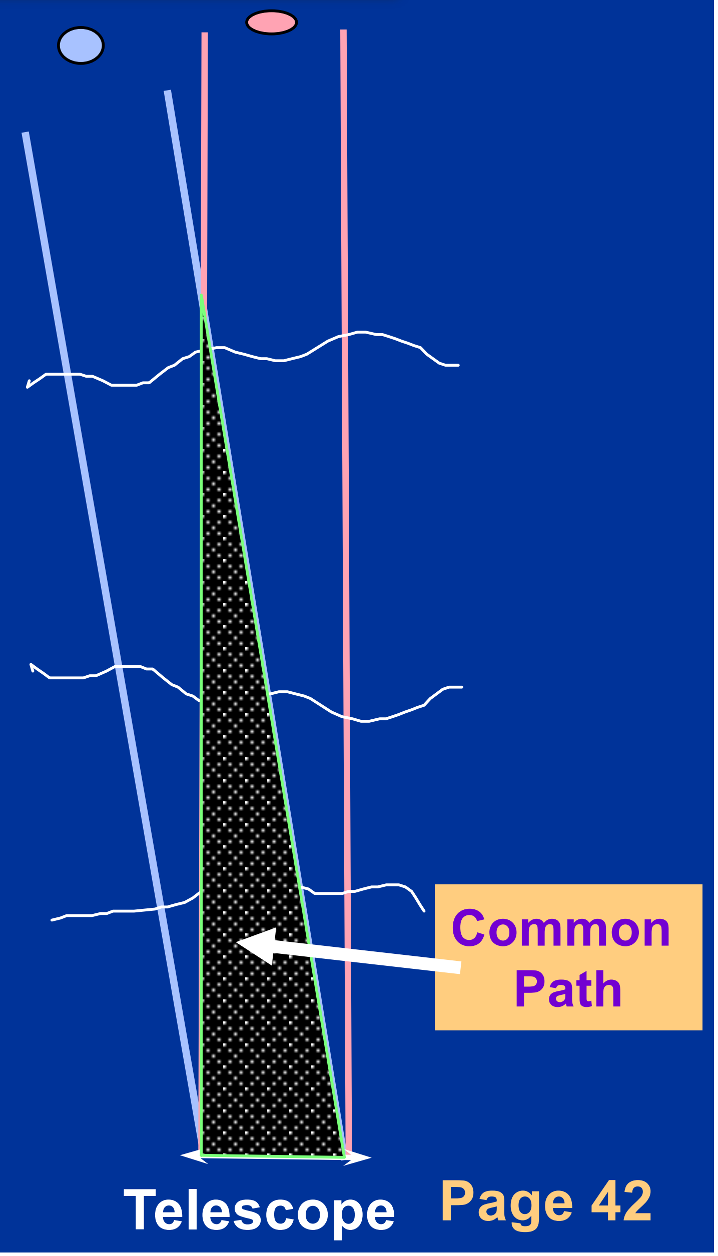
- Strehl = 0.38 at $\theta = \theta_0$

θ_0 is isoplanatic angle

$$\vartheta_0 = \left[2.914\ k^2 (\sec\zeta)^{8/3} \int_0^\infty dz\, C_N^2(z)\, z^{5/3} \right]^{-3/5}$$

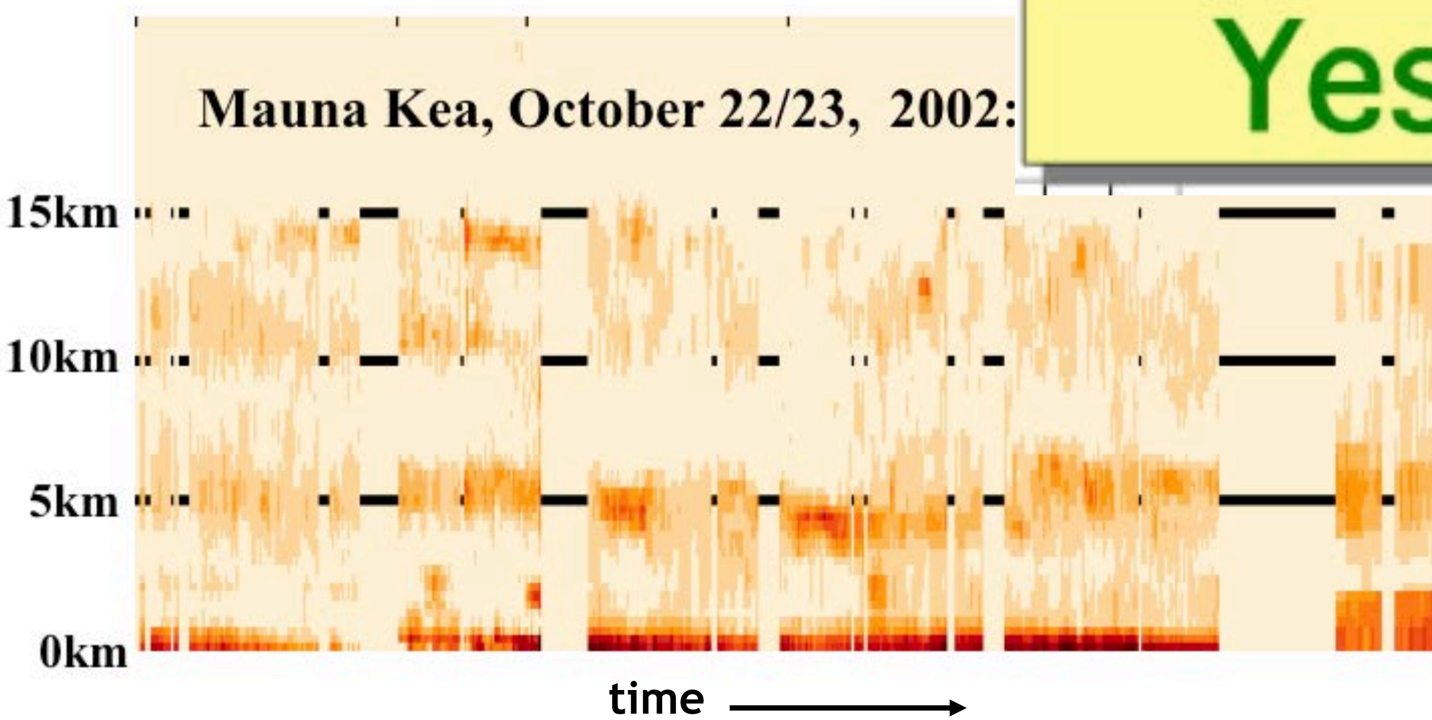
θ_0 is weighted by <u>high-altitude</u> turbulence ($z^{5/3}$)

- If turbulence is only at low altitude, overlap is very high.
- If you only correct the low altitude turbulence, the isoplanatic angle will be large (but the correction will be only modest)



Is there a ground layer?

Yes!

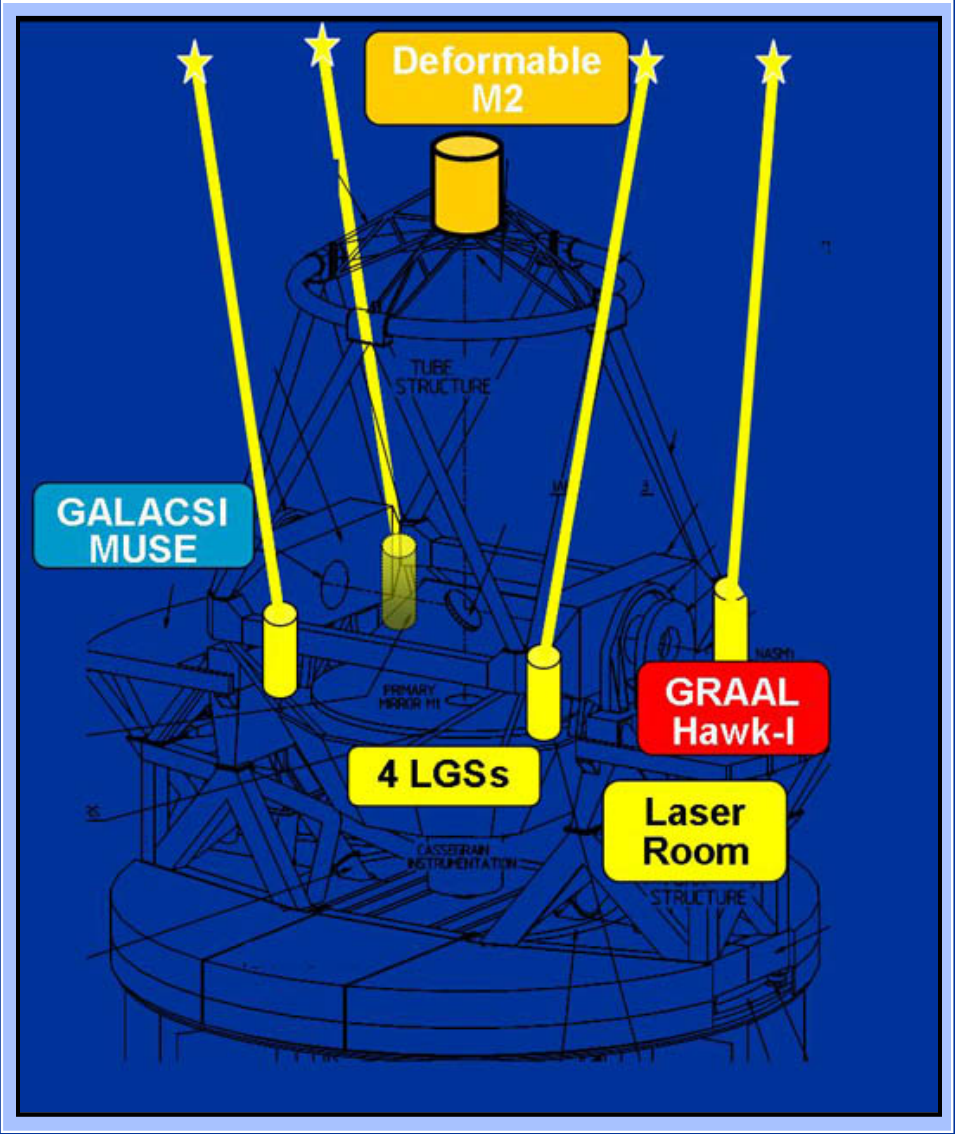


AO Roadmap, April 2004 6

Credit: A. Tokovinin

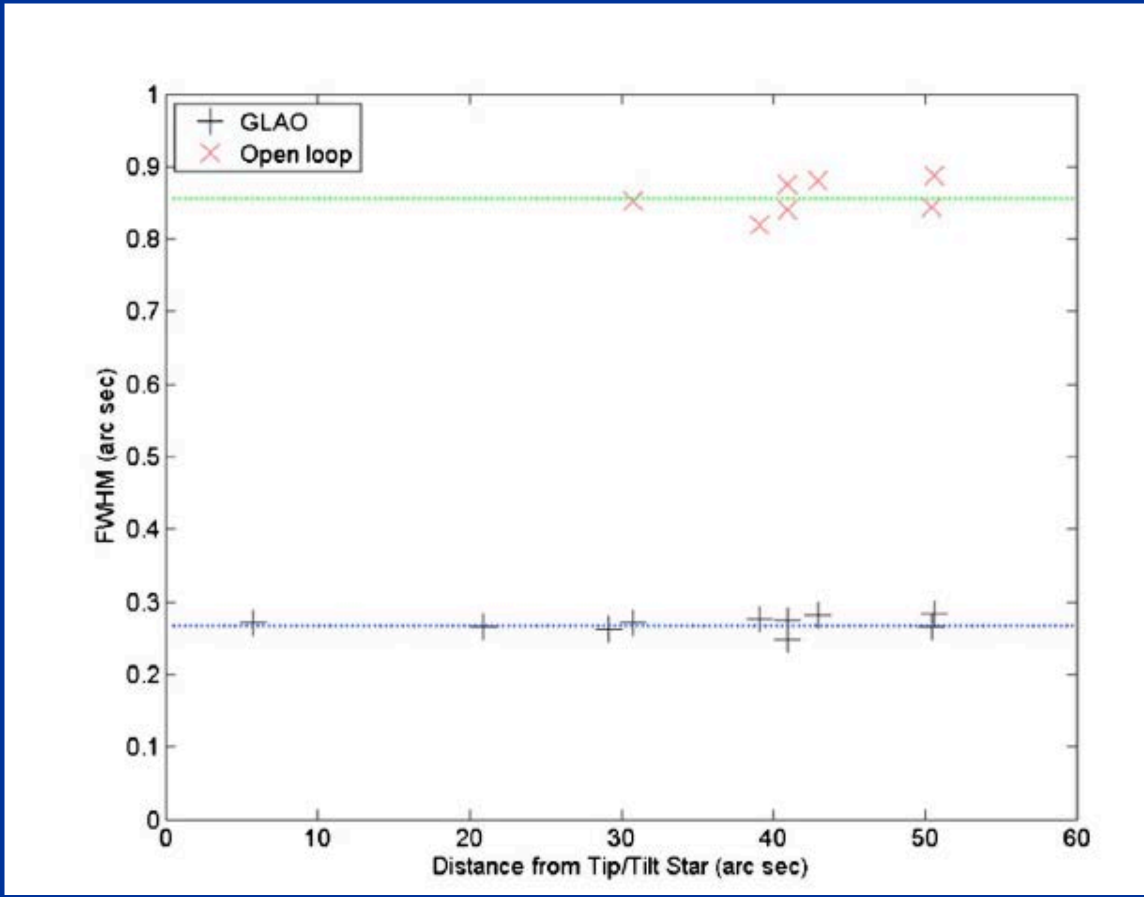
Several observatories have ambitious GLAO projects today

- Early pathfinders: SOAR (4.25m), William Herschel Telescope (4.2m), MMT (6.5m)
- Recently on VLT (8m), LBT (2x8m)
- Longer term on Giant Magellan Telescope, E-ELT
- Why is it worth the large investment "just" to decrease "seeing" disk by factor of 1.5 to 2 ?
  - Large spectrographs can take advantage of smaller image (smaller slit)
  - Potential improved SNR for background-limited point sources
  - Less variability in PSF



GLAO on the MMT Telescope

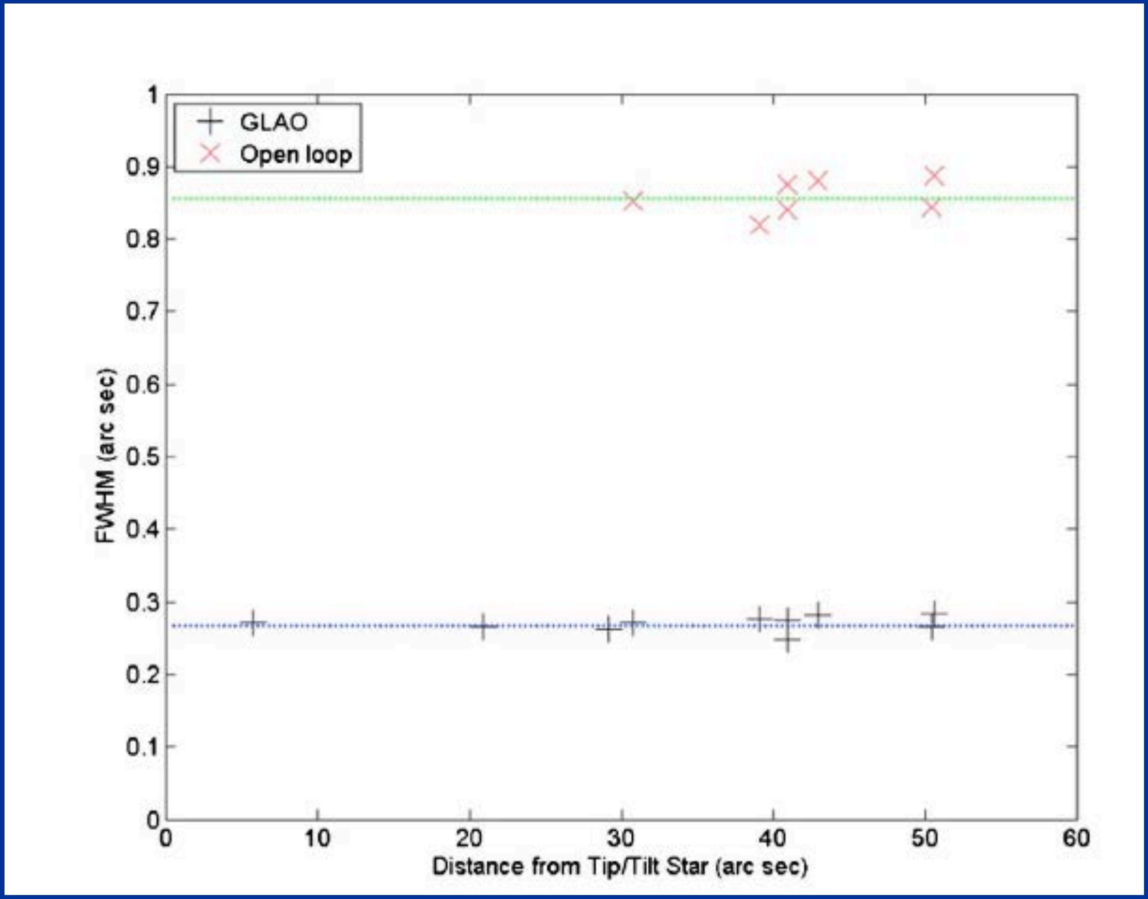
- Michael Hart et al. , 5 Rayleigh laser guide stars

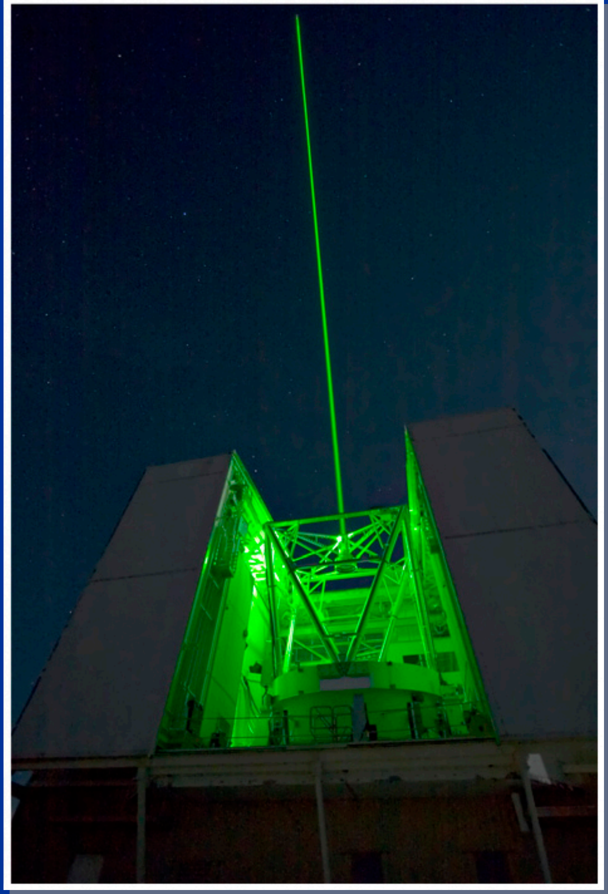


FWHM decreased from 0.85 arc sec to 0.28 arc sec (!)

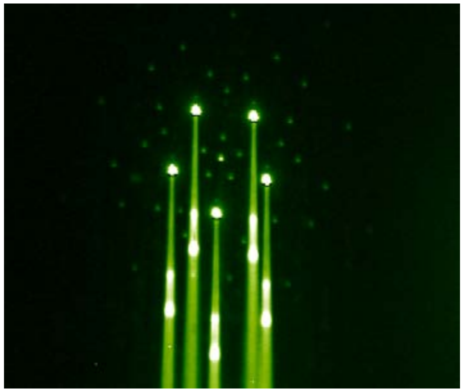
GLAO on the MMT Telescope

- Michael Hart et al. , 5 Rayleigh laser guide stars





Example #2: The MMT multi-laser Ground Layer AO (GLAO) system

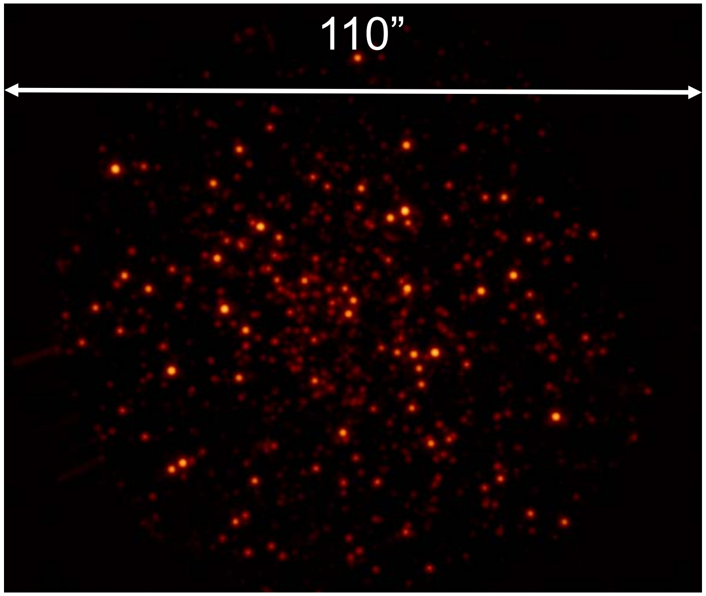


5 laser guide stars → 5 wavefront measurements
Reconstructor keeps only ground layer, common to the 5 wavefronts
Single DM corrects for the ground layer: correction is valid over a large field

MMT results: M3 globular cluster

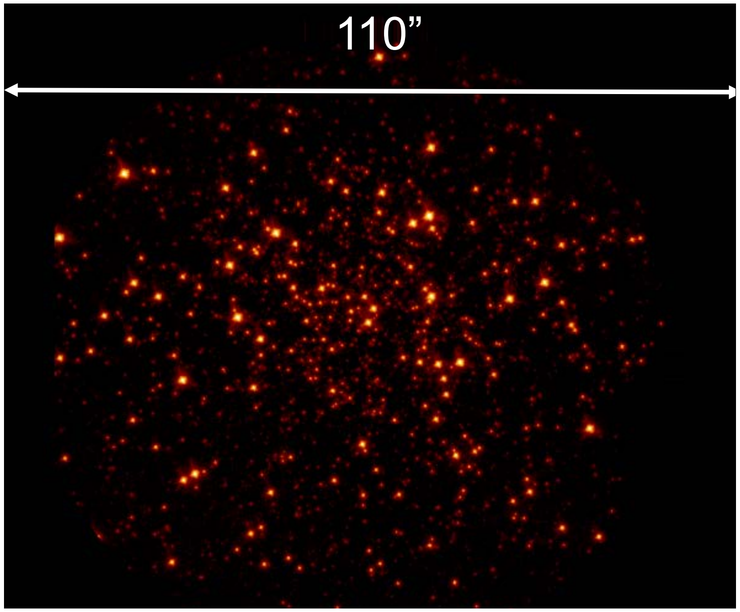
Open loop, K_s filter, FWHM 0.70”

Logarithmic scale



Closed loop GLAO, K_s filter, FWHM 0.30”

Logarithmic scale



ʻImaka: GLAO on UH 88" Telescope

Natural guide star constellation

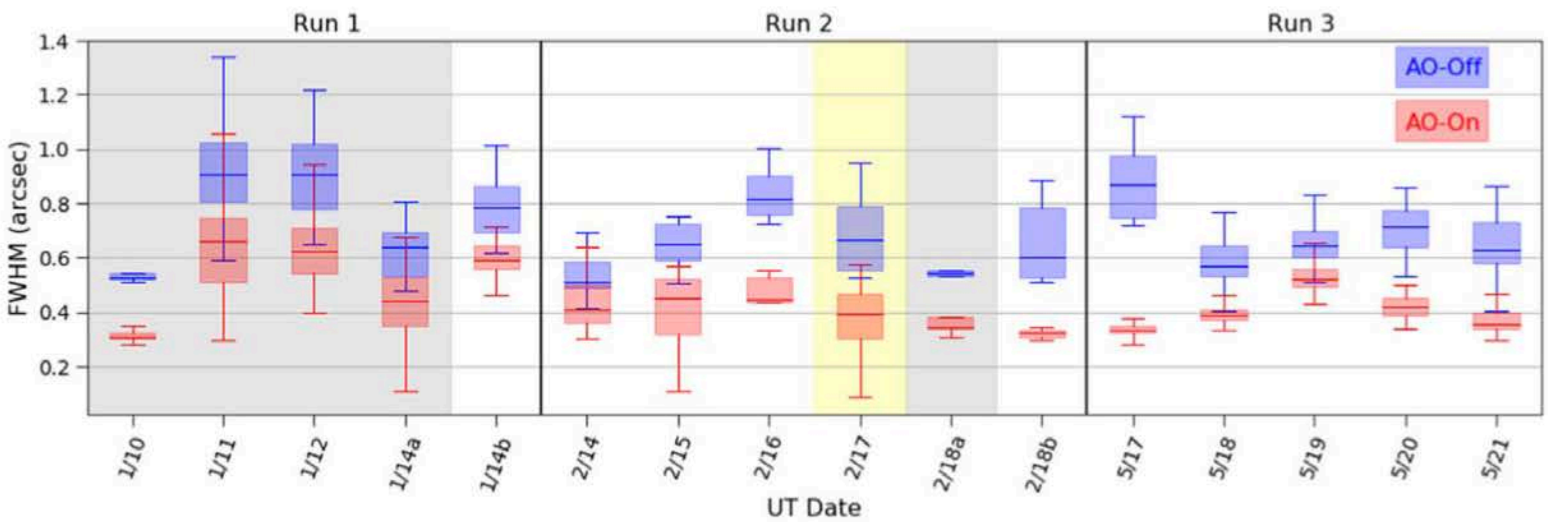


Figure 10. Comparison of the PSF stability between AO-off (blue) and AO-on (red) across all nights. For each data point, the median value of the empirical FWHM is represented by the center line, with a box surrounding it and spanning the second and third quartiles of the data. The full range of data is shown by the extended lines. Shaded regions refer to the observation wavelength: *R* band in gray, 1000 nm in yellow, and *I* band is unshaded.

GLAO reduces two things:

- FWHM
- Variability of FWHM

‘Imaka GLAO reduces PSF variability

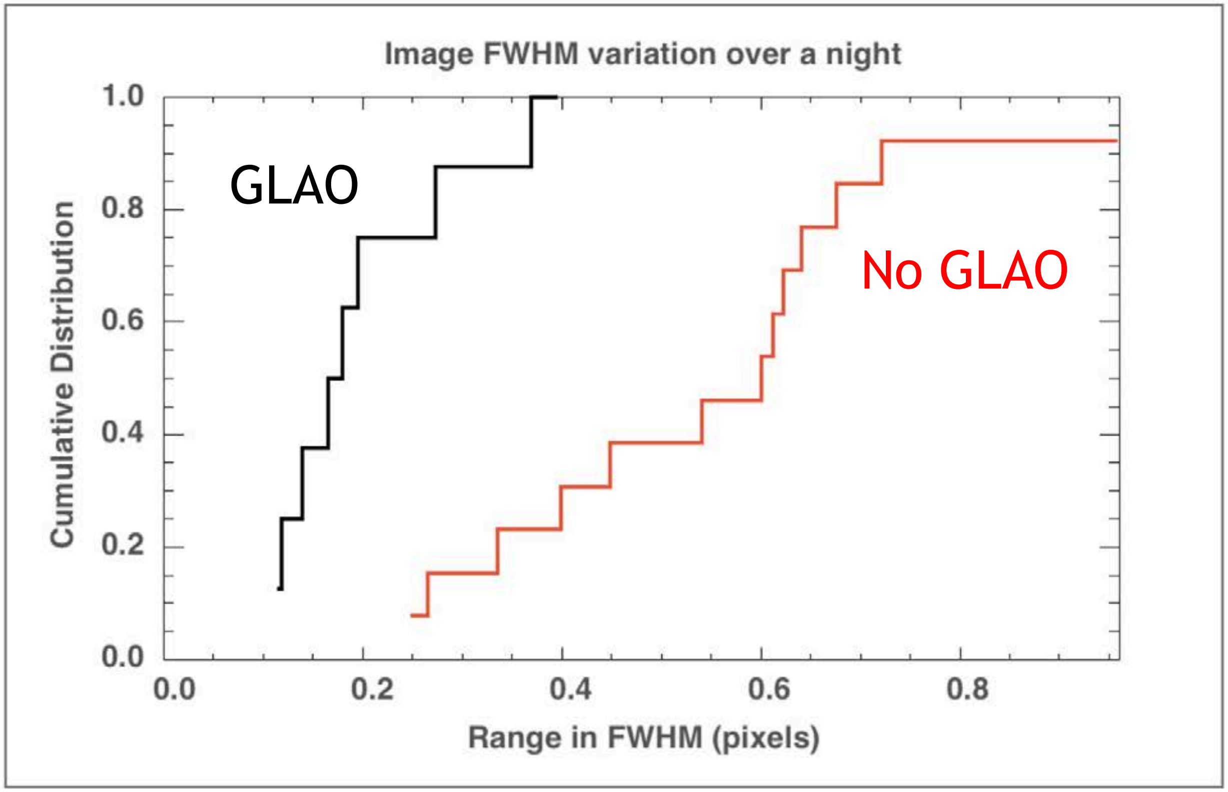


Figure 3. The variation of the image FWHM for GLAO (black) and no GLAO (red) plotted as a cumulative distribution from data taken over a variety of seeing conditions. The variation is plotted as the range of FWHM seen over the course of the night.

Summary

- Tomography: a way to measure the full volume of turbulence above the telescope
- Once you have measured the turbulence there are several ways to do the wavefront correction
  - Laser Tomography AO: Multiple laser guide stars, 1 DM, corrects cone effect. Narrow field.
  - Multi-conjugate AO: Multiple DMs, each optically conjugate to a different layer in atmosphere. Wider field of view.
  - Multi-object AO: Correct many individual objects, each over a small field. Each has very good correction. Wider field of regard.
  - Ground-layer AO: Correct just ground layer turbulence. Very large field of view but only modest correction.
- All four methods will be used in the future

Corrected fields of view vary depending on method

Method		Corrected field of view
Laser Tomography AO	LTAO	10’s of arc sec
Multi-Object AO	MOAO	N x 10’s of arc sec
Multi-Conjugate AO	MCAO	≤ about 2 arc min
Ground Layer AO	GLAO	A few to 10 arc min