# DEFORMABLE MIRRORS FOR WAVEFRONT TOMOGRAPHY

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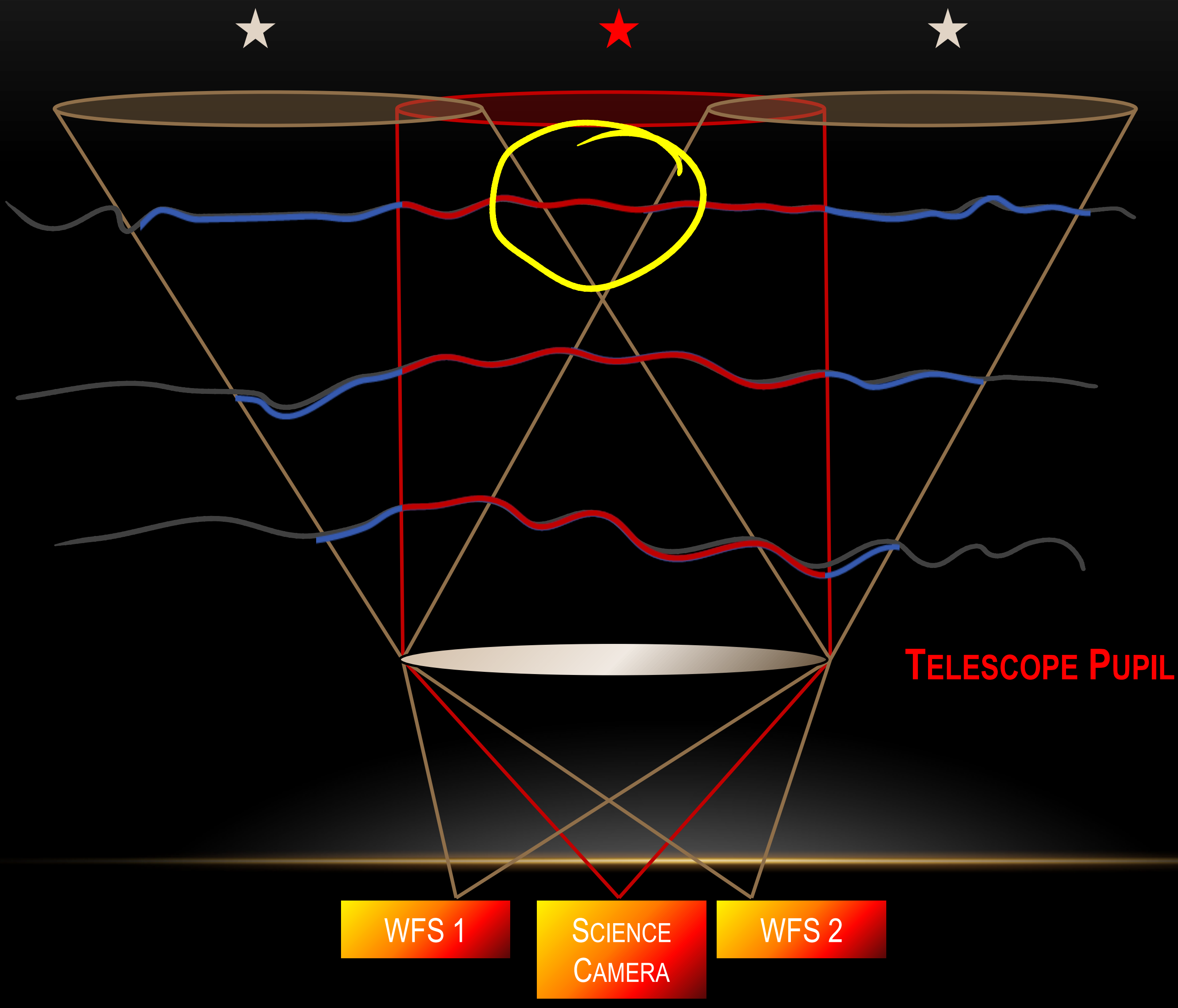
# INTRODUCTION

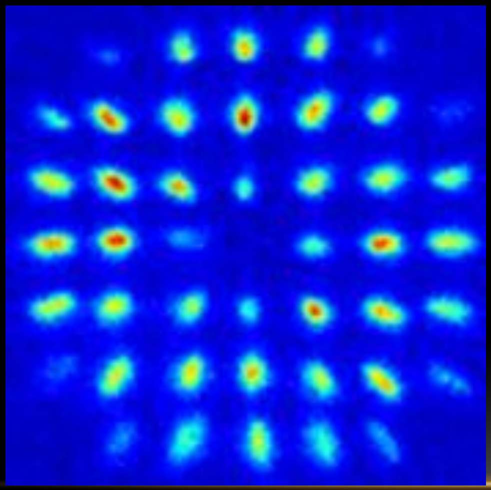
- The majority of future astronomical Adaptive Optics systems will use some form of wavefront tomography
- Tomographic wavefront sensing allows us to:
  - Perform wide field of view correction
  - Use multiple laser guide star systems efficiently
- Controlling a tomographic AO system optimally places some additional requirements on the deformable mirror
- In this talk I aim to provide:
  - A (very brief) overview of how we perform tomography
  - A discussion of the main issues relating to performing tomography
  - Some results from the CANARY on-sky AO demonstrator
  - A description of my ‘perfect’ DM

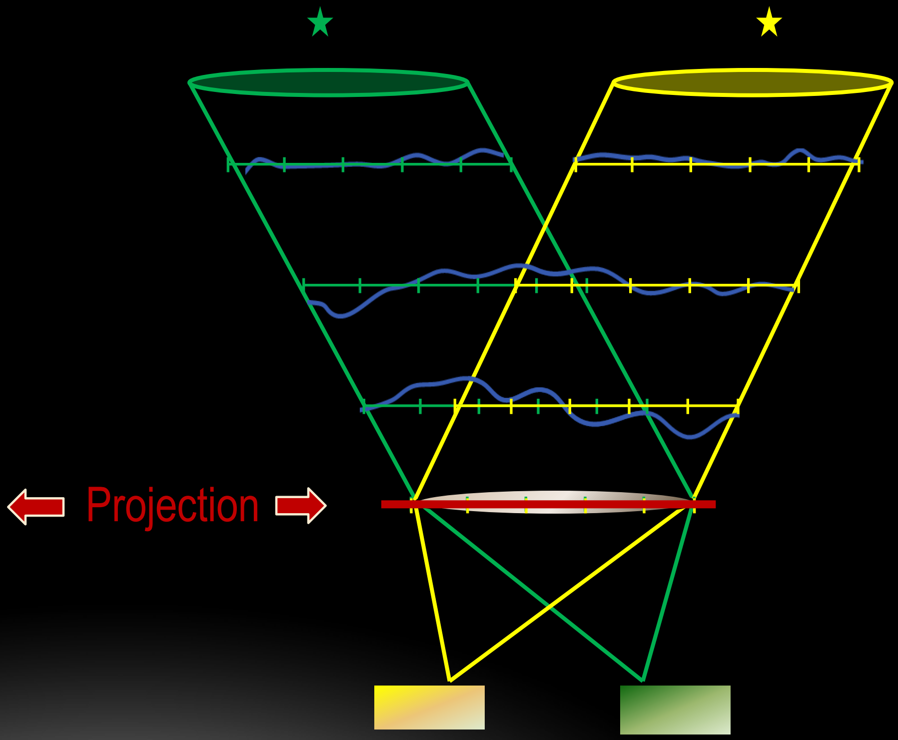
# WAVEFRONT TOMOGRAPHY



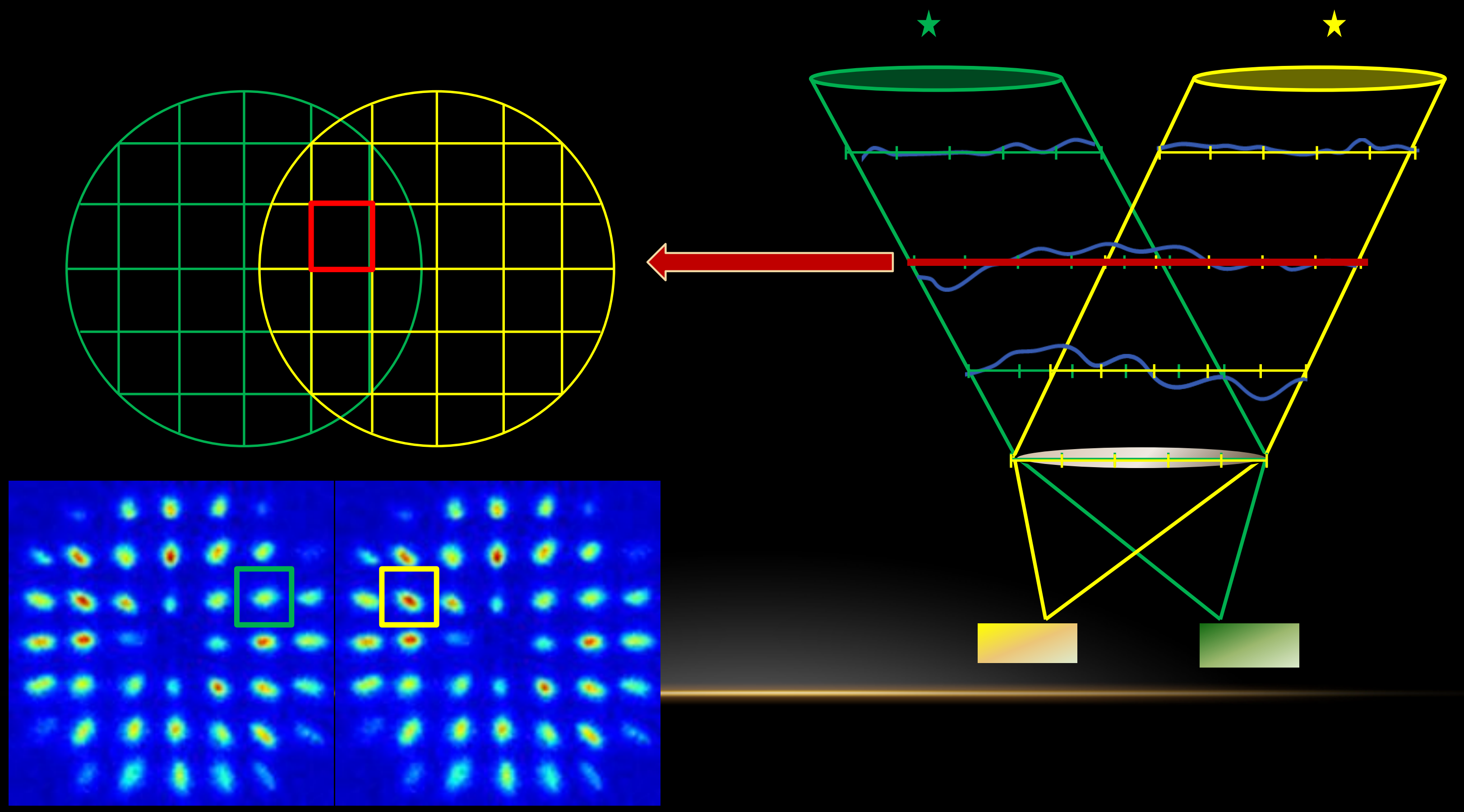
# WAVEFRONT TOMOGRAPHY

- Projection of wavefront sensors as they move up in altitude:



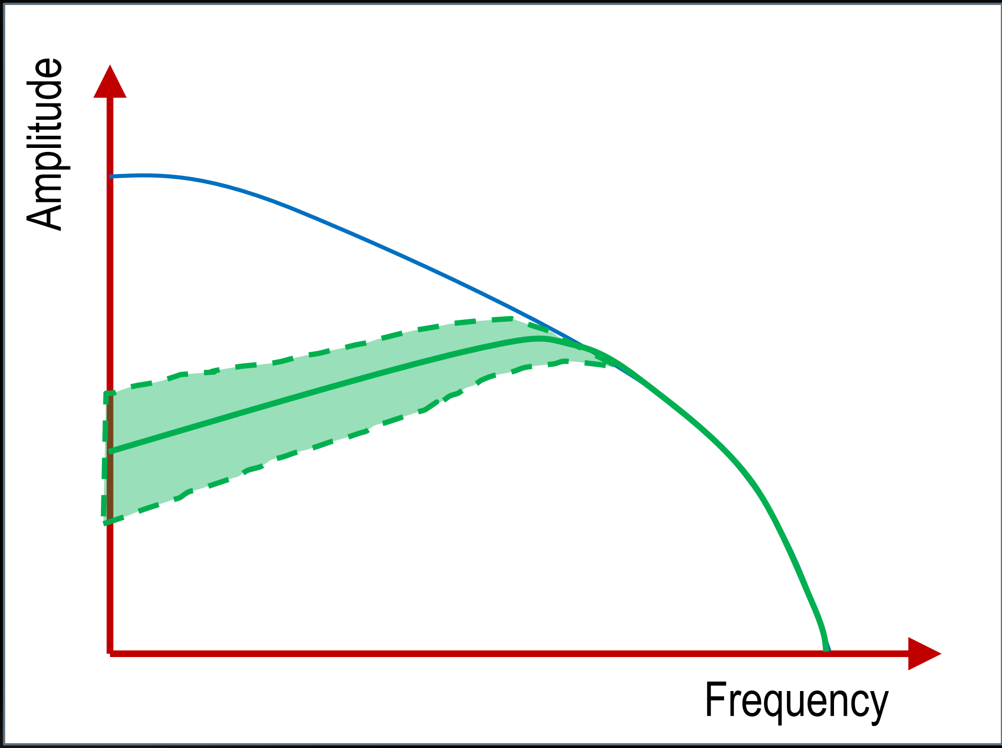


- By comparing common wavefronts between sheared wavefront sensor images



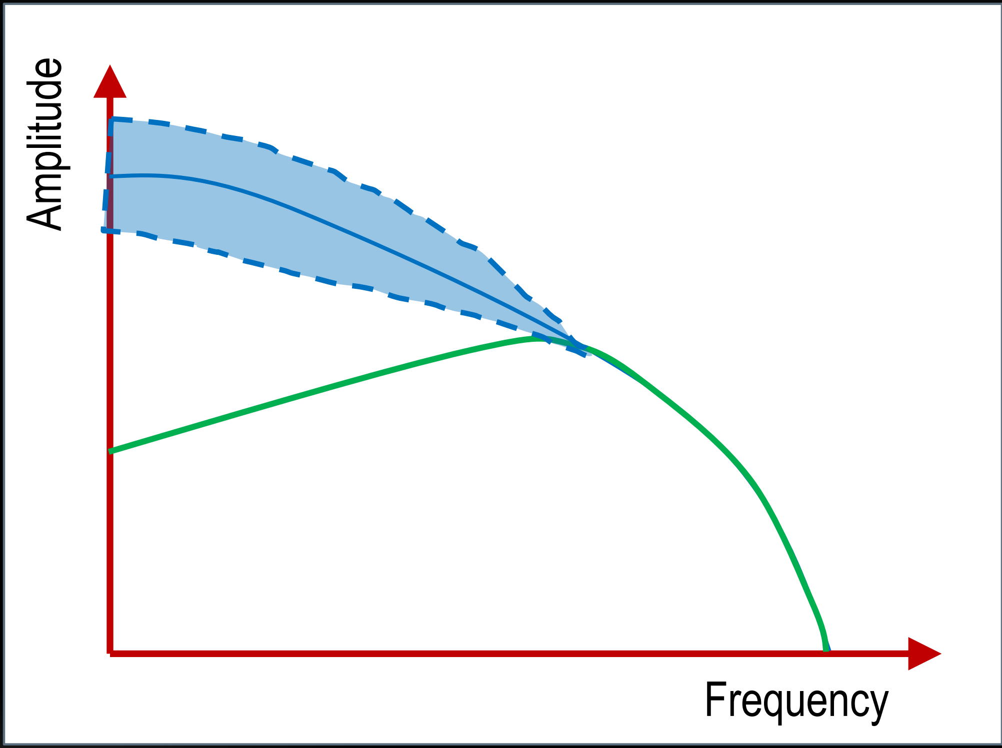
# WAVEFRONT TOMOGRAPHY

- Separating the contribution of the different turbulent layers relies on accurate knowledge of the statistical properties of the turbulence under correction
- Atmospheric turbulence obeys a well understood spatial power spectral distribution
- If you run the system in open-loop e.g. MOAO:
    - You end up with an unknown mirror shape that can't be determined directly
    - 'Go-to' error



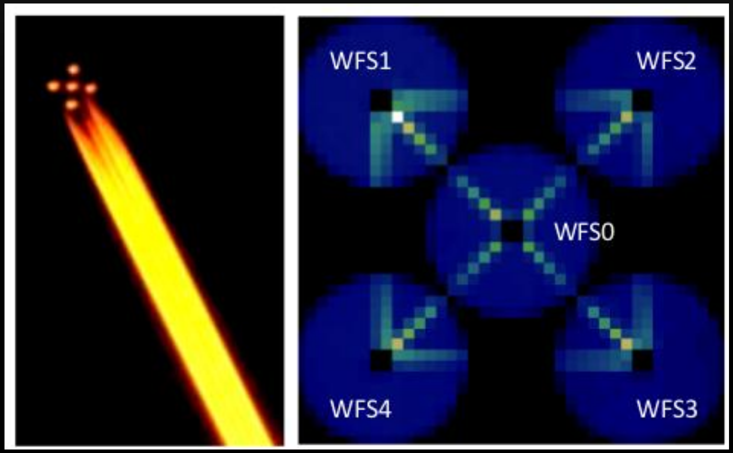
# WAVEFRONT TOMOGRAPHY

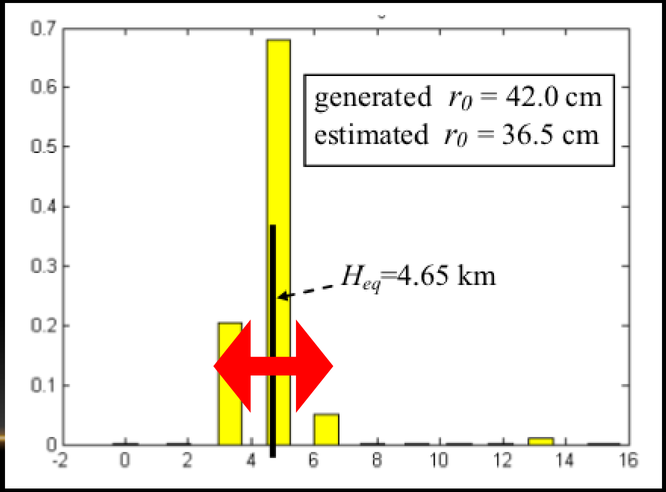
- If you operate the DM in a closed-loop tomographic system e.g. LTAO, MCAO:
  - Optimal performance requires you to reconstruct the uncorrected wavefront slopes
  - Pseudo open-loop slopes
  - Open-loop ‘go-to’ error becomes an unknown
- Causes errors in measurements of
  - Absolute turbulence strength
  - Thickness of layers
- Impact on PSF reconstruction?



# EXAMPLE: TURBULENCE PROFILING USING AN MCAO SYSTEM

- Cortes *et al*[1] analysed wavefront sensor data from Gemini South's MCAO system (5 laser guide stars)
- 3 deformable mirrors in the system must be removed to create pseudo-open loop data
- Tested on-sky and using DM-induced turbulence
- Cannot distinguish between WFS errors and open-loop DM errors
- Up to 10% error (worst case) in total turbulence strength estimate
- Influence of a single DM @ 4.5km was spread over 3-7km when WFS data analysed.
- Early results, so it may get better than this
- Scope for further analysis…

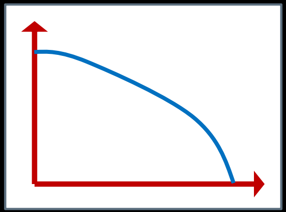



[1] Cortez *et al*, http://arxiv.org/abs/1210.1999 (2012)

# FULLY OPEN-LOOP WITH CANARY

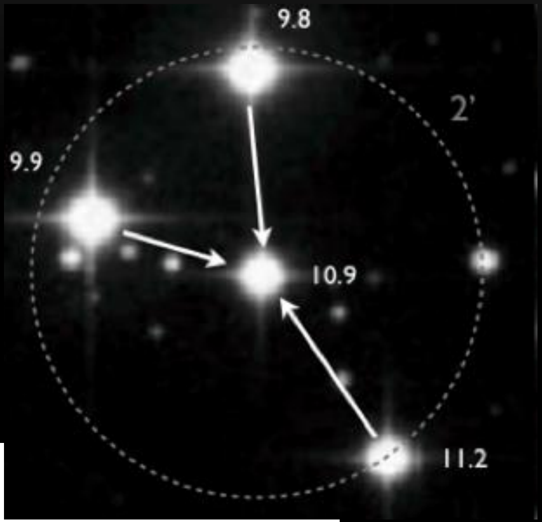
- CANARY is a low-order on-sky tomographic adaptive optics demonstrator that runs in open-loop
  - Phase A: 3 off-axis WFSs measuring uncorrected wavefronts
  - Measured statistics are not ‘contaminated’

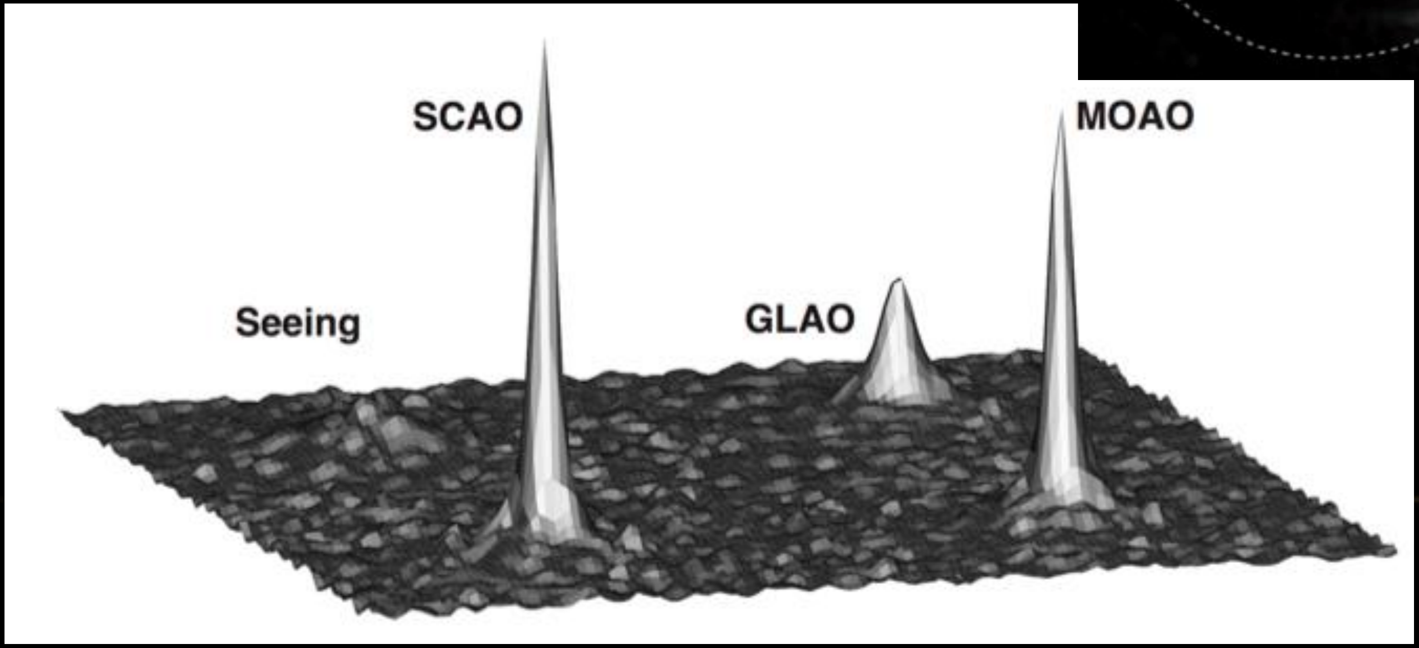


- AO Correction applied in open-loop on-axis
- A closed loop WFS (‘Truth’ Sensor)
  - Can measure open-loop error
  - Noise terms have to be removed making analysis complicated
- Initial phase contained a closed-loop DM figure sensor on an internal reference source
  - Precisely to measure the ‘go-to’ or open-loop error
  - Was also used to control DM shape (briefly)

# STREHL RATIO COMPARISON IMAGE

- Images recorded at a central wavelength of 1.495µm
- Seeing-limited (NoAO) (SR=1% at 00h59mn)
- GLAO (SR=9% at 00h42mn)
- MOAO (SR=19.4% at 00h29mn)
- SCAO (SR=23.8% at 00h32mn)

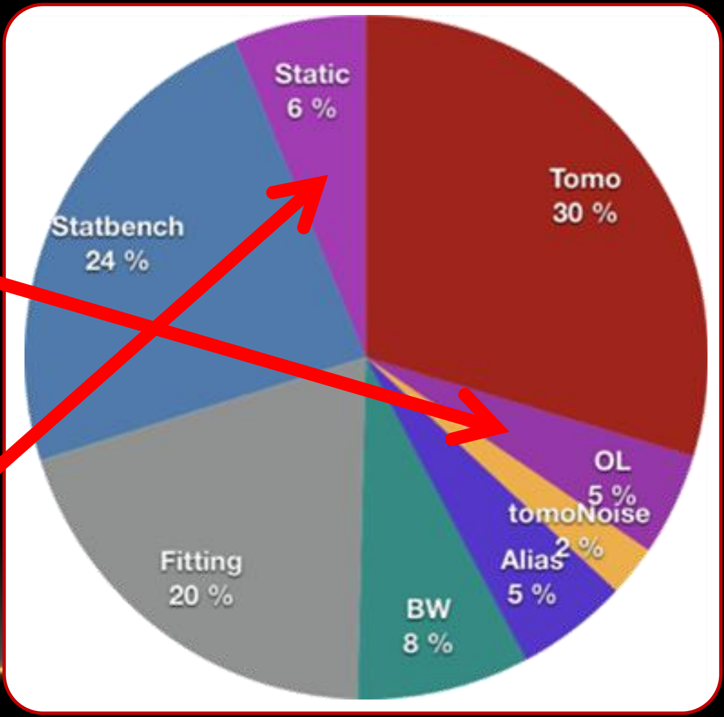


# BACK TO THE ERROR BUDGET…

- Analysed from 7 seconds of synchronised data at 00h10mn12s on Sept 27th Asterism #47)
- 150Hz frame rate, $r_0$ = 16.3cm (natural seeing 0.69”)

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



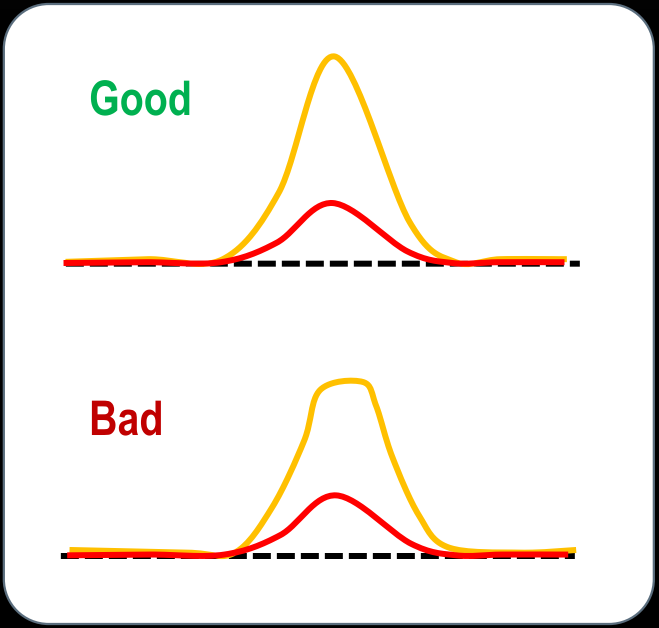

Expected SR = 19.0%@1.49µm => measured = 21%

# THE 'PERFECT' TOMOGRAPHIC DM

- EAGLE Phase A study required a 49nm RMS open-loop error total
  - CANARY has between 68-102nm RMS depending in source of quasi-static term
- The open-loop error has to be small
  - <35nm RMS would make it a minor term in the CANARY error budget
  - Impact on pseudo-open loop reconstruction requires a lot of additional analysis
- It has to be stable
  - The 'quasi-static' shape should remain <35nm RMS over observing period
    - ELT/VLT this would get offloaded to the active optics potentially
  - Maintained over all environmental/gravitational conditions
- WE DON'T WANT TO INCORPORATE A FIGURE SENSOR
  - Not so much of a problem for CANARY, but ELT-scales?
  - Low-order for slowly varying terms is a good option

# THE 'PERFECT' TOMOGRAPHIC DM

- Linearity not so much of an issue, but influence functions must be reproducible
  - Actuator response to voltage/charge need not be linear
  - Relatively minor computational overhead
- Linear summation of actuators should be valid
  - Additional computation if it's not
  - Cross-coupling not an issue
- Influence functions must retain shape from small to large influence
- Actuator yield is not critical for most AO applications
  - Strehl loss (*very* rough worst case) is $N_{failed}/N_{total}$
  - 1-3 actuators per 100?



# CONCLUSION

- Irrespective of whether you run in open- or closed-loop, tomographic AO system performance is improved by  an open-loop capable DM
- Places additional requirements on DM stability
- Many of the requirements are already being addressed
- Calibration is key!