Deformable Mirrors for TMT

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Outline

- TMT Adaptive Optics Systems Concepts
- MEMS vs conventional DMs
- Deriving MEMS requirements
- MEMS requirements for particular sub systems

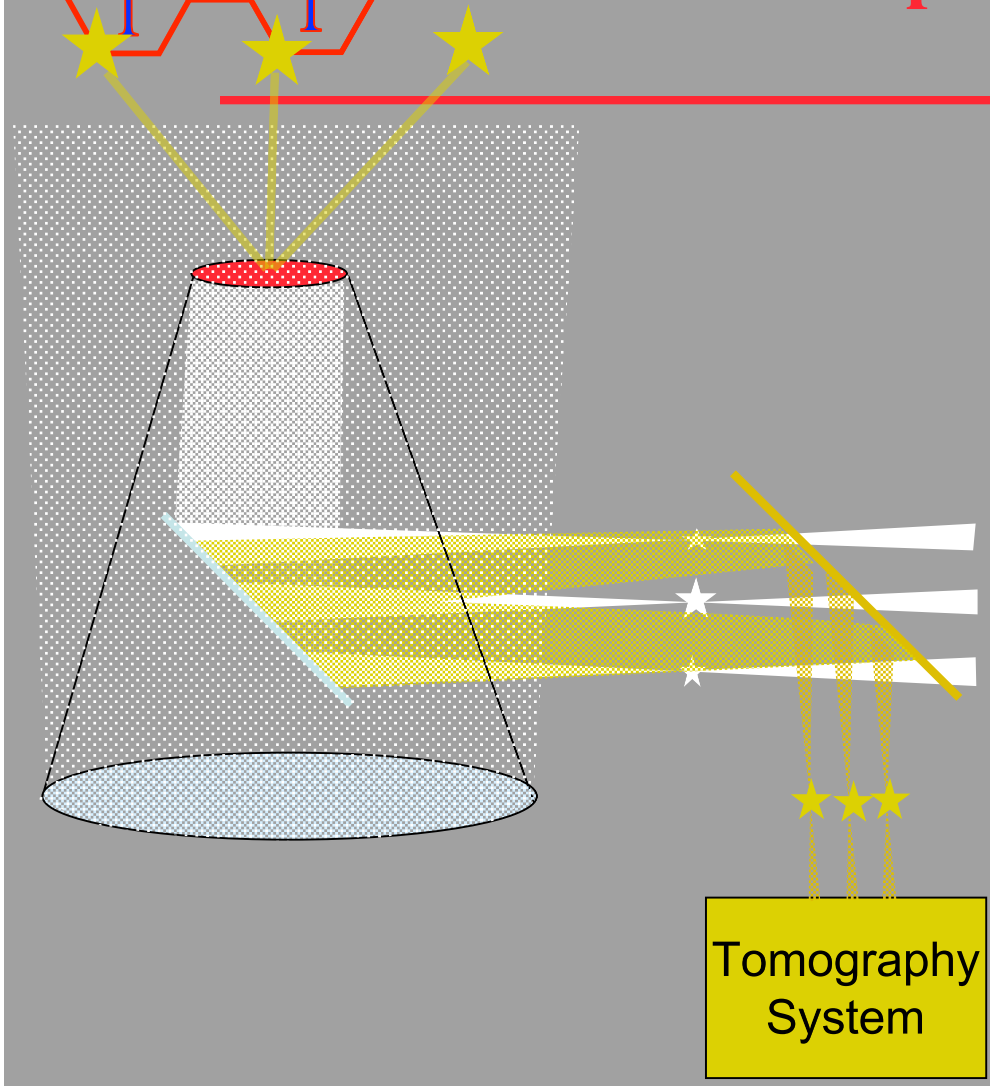
TMT Adaptive Optics Instruments

- **Diffraction-limited imaging spectrometer λ = 1-5μm**
  - Diffraction-limited (~7-14 mas)
  - 10 arcsec field
- **Near-infrared wide field spectrometer λ = 1-5μm**
  - Multiple Integral Field Units
    - Multiple 2 arcsecond fields, R=5000
    - 50 milli-arcsecond slit
  - 5 arcminute field of regard
- **Mid-IR spectrometer λ = 5-28μm**
- **Multi-conjugate adaptive optics moderate field imager λ=1-2.5μm**
  - Diffraction-limited
  - 30 arcsec field
- **Extra-solar planet imager (ExAO) λ = 1-2.5μm**
  - ~1 arcsec field
  - 50-100K? Actuators (>10^8 contrast)

Other possible MEMS applications in TMT AO systems

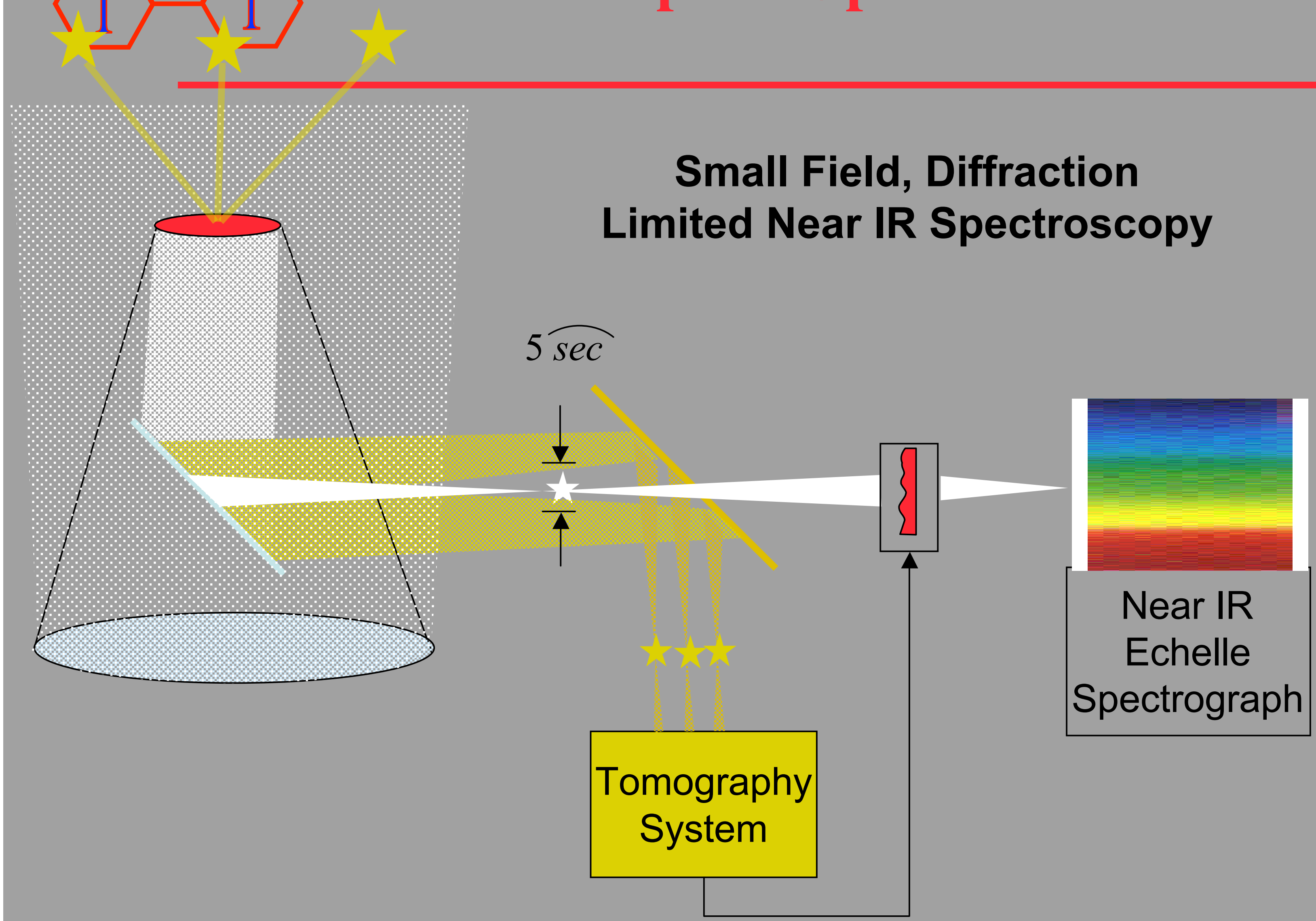
- **Wavefront sensor non-common path aberration correction**
- **Laser pulse tracking**

TMT Adaptive Optics Modes

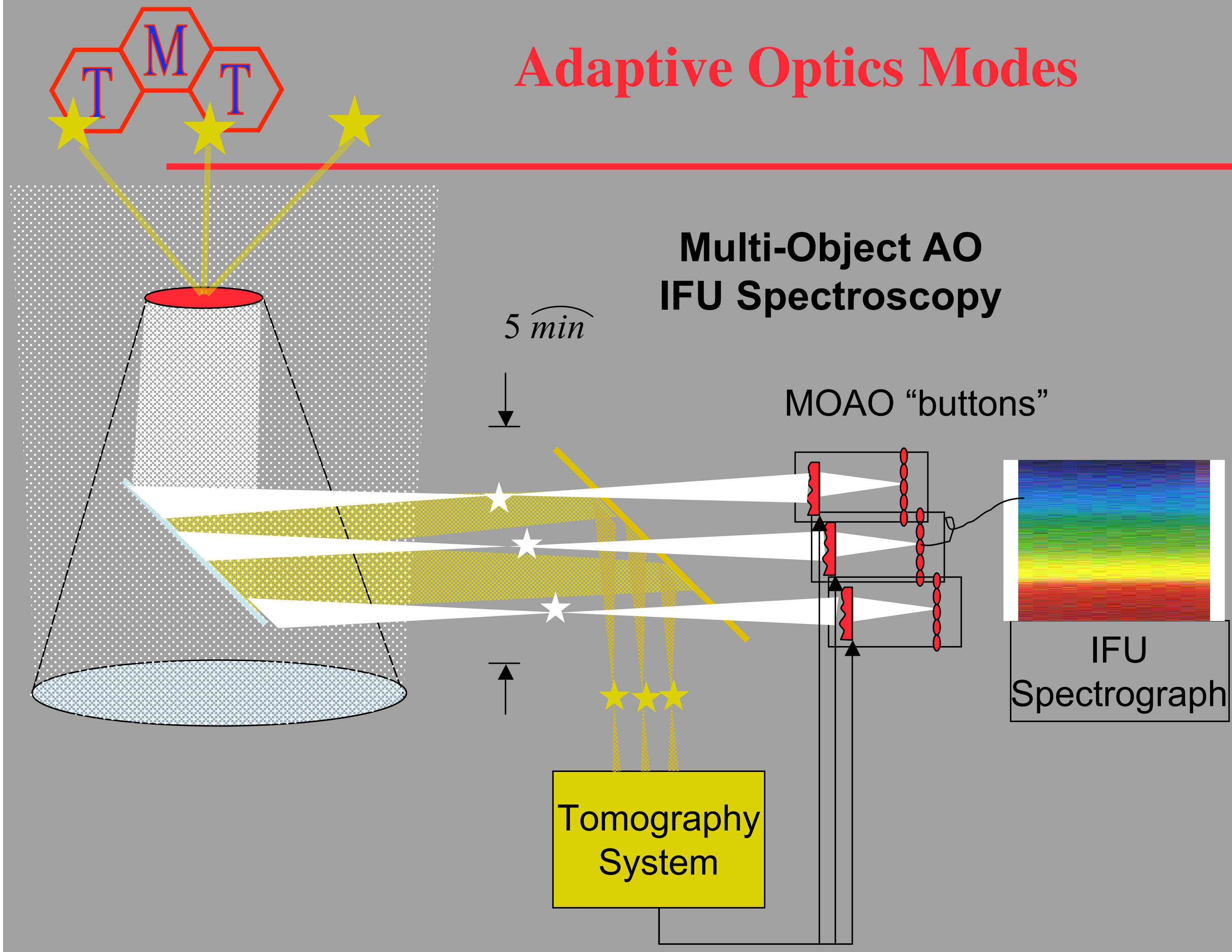


Adaptive Optics Modes

Small Field, Diffraction Limited Near IR Spectroscopy

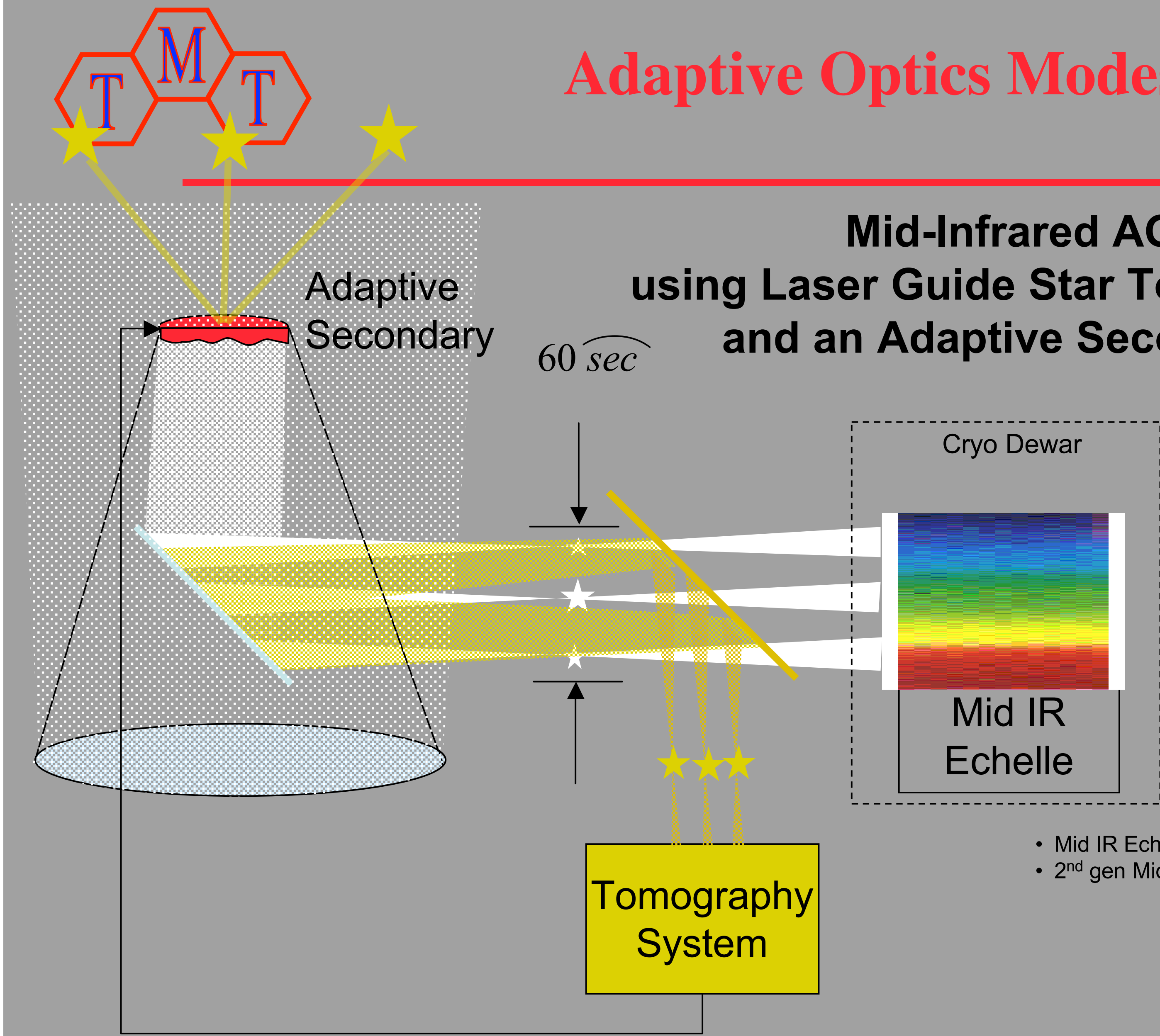


Adaptive Optics Modes



Adaptive Optics Modes

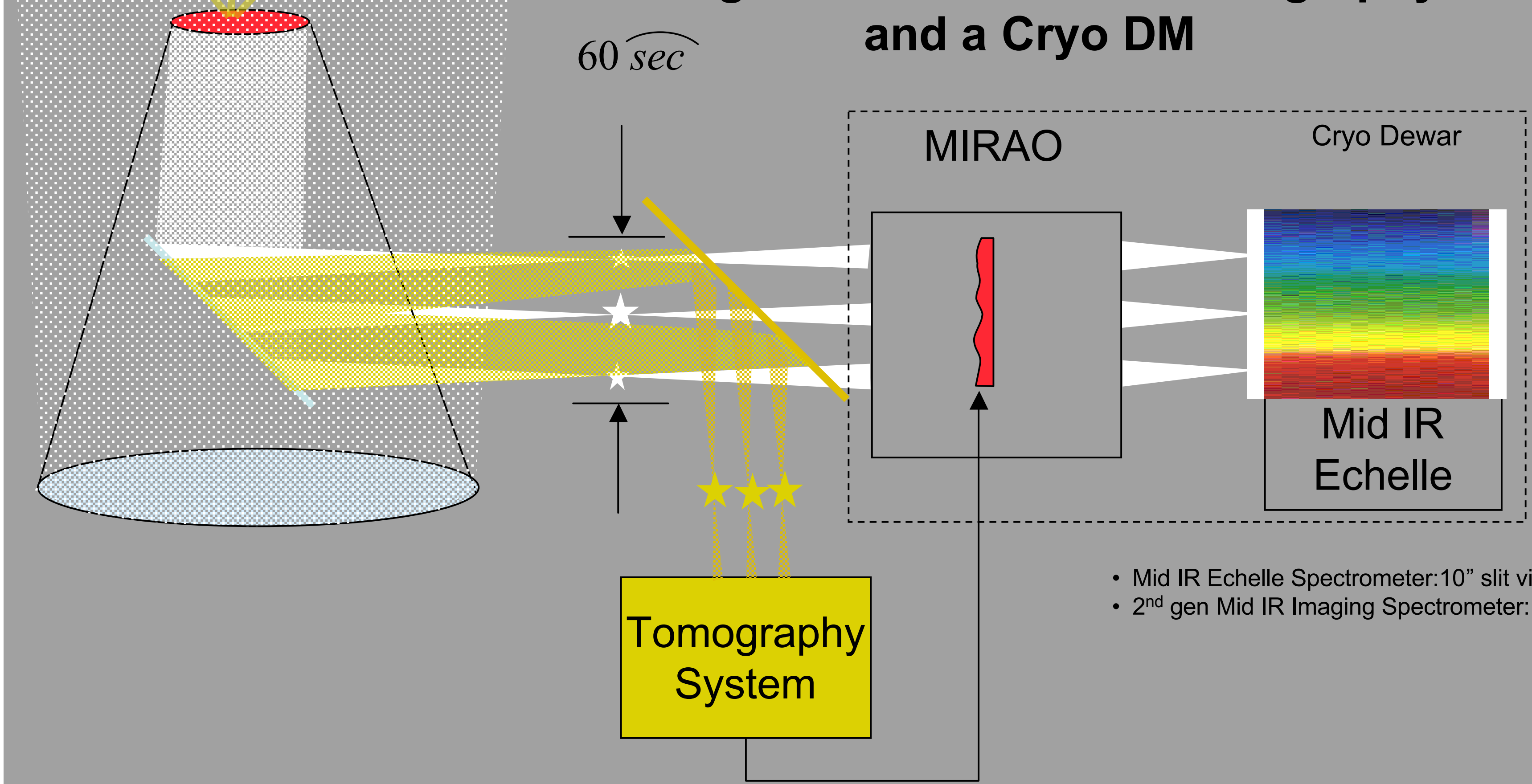
Mid-Infrared AO
using Laser Guide Star Tomography
and an Adaptive Secondary



- Mid IR Echelle Spectrometer:10” slit view
- 2nd gen Mid IR Imaging Spectrometer: >2’ FOV

Adaptive Optics Modes

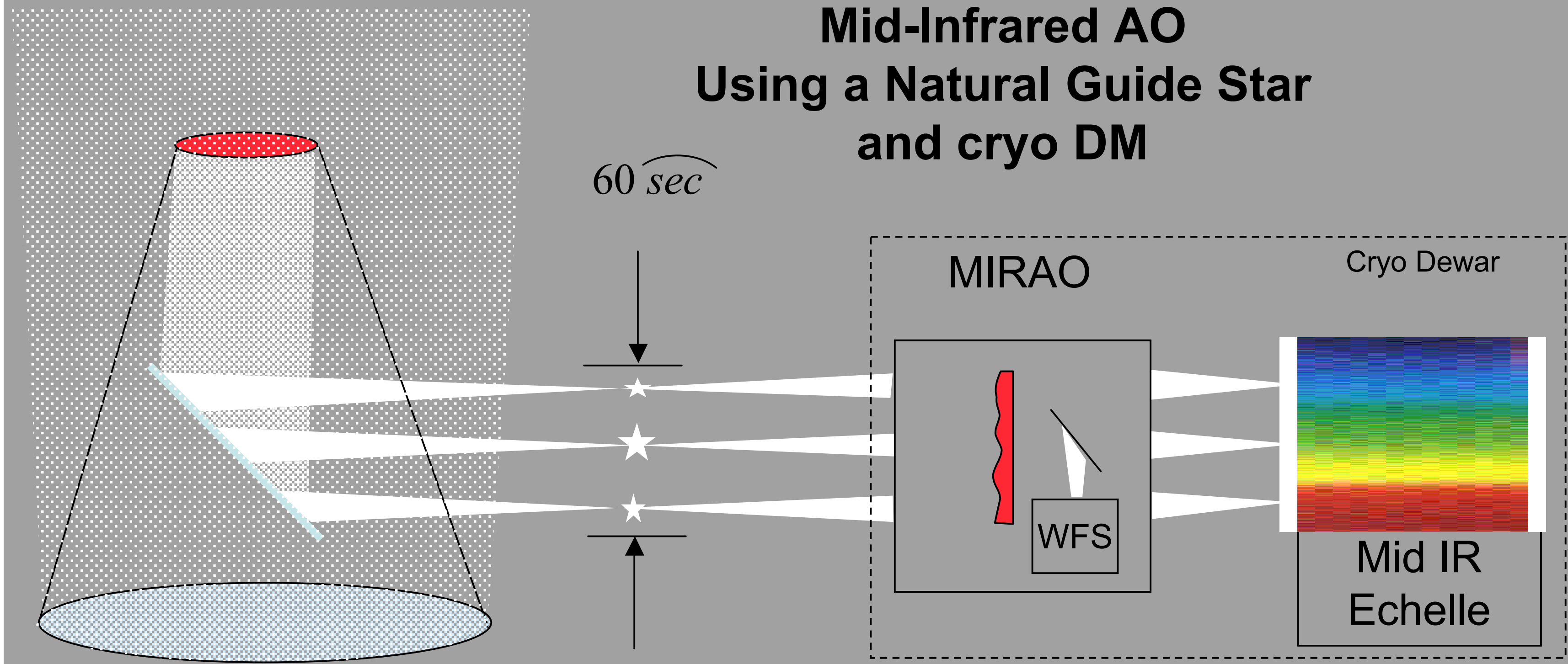
Mid-Infrared AO using Laser Guide Star Tomography and a Cryo DM



- Mid IR Echelle Spectrometer:10” slit view
- 2nd gen Mid IR Imaging Spectrometer: >2’ FOV

Adaptive Optics Modes

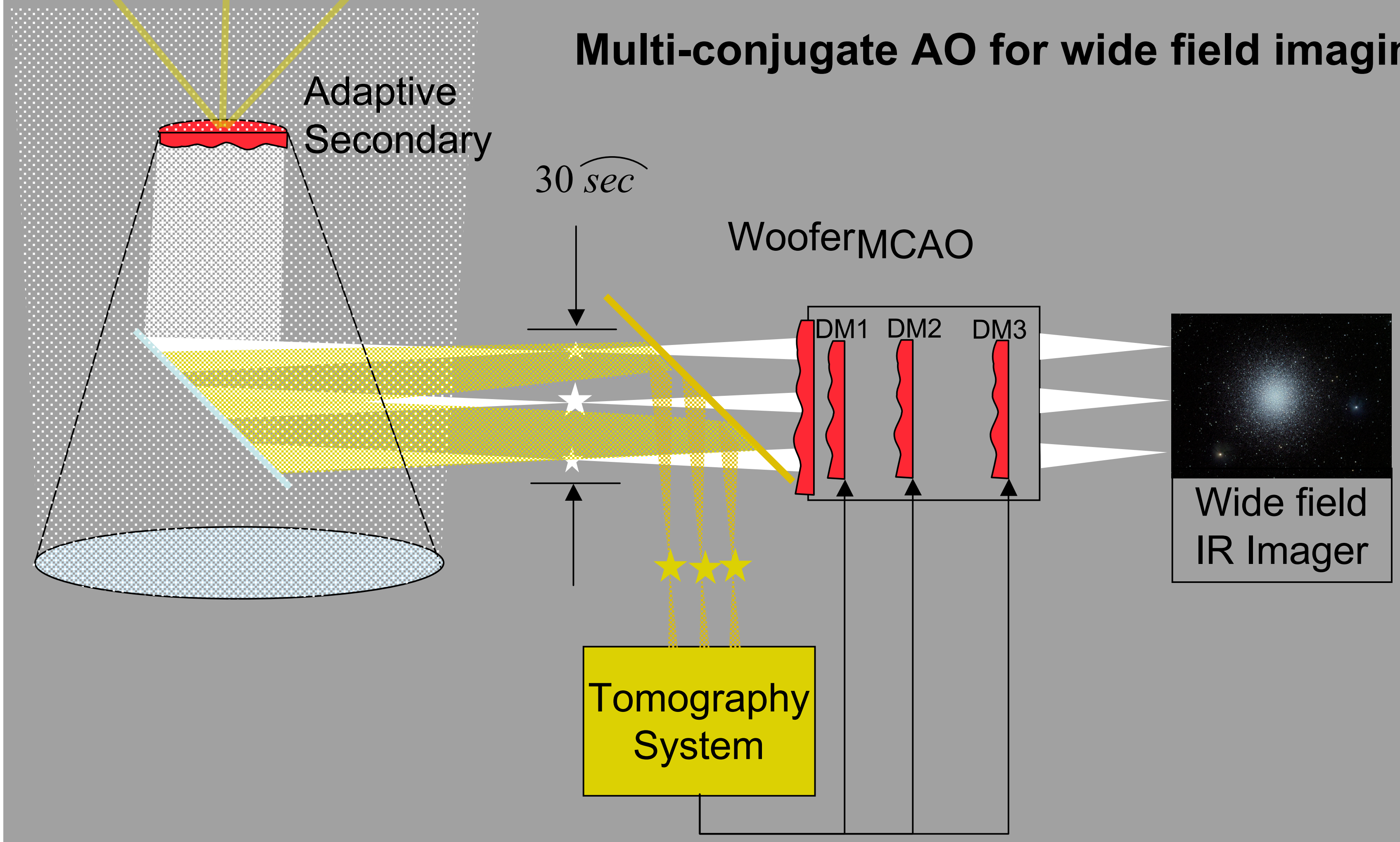
Mid-Infrared AO
Using a Natural Guide Star
and cryo DM



- Mid IR Echelle Spectrometer:10” slit view
- 2nd gen Mid IR Imaging Spectrometer: >2’ FOV

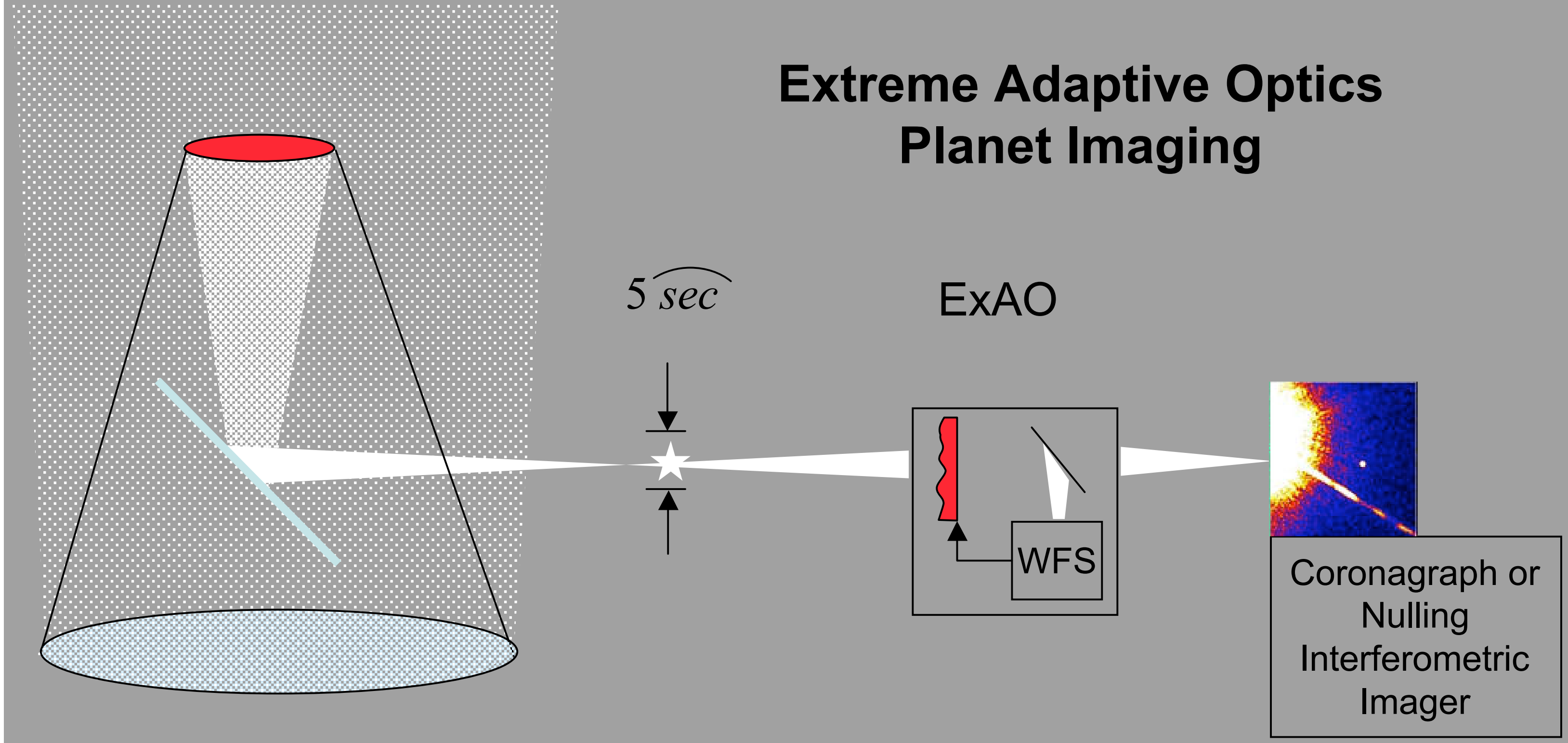
Adaptive Optics Modes

Multi-conjugate AO for wide field imaging



Adaptive Optics Modes

Extreme Adaptive Optics
Planet Imaging



DM type drawbacks

- **Non-MEMS**
  - DM's larger, leads to larger AO optical system
  - DM may have hysteresis, requiring interferometric DM monitor
  - Cryo DM may be difficult to achieve needed stroke
  - Precise repeatability required for open loop operation
  - Impractical for MOAO
- **MEMS**
  - Stroke may be insufficient for our need
  - May be too small for some applications
- **Adaptive secondary**
  - Very expensive
  - Diameter limited, restricts non AO science uses
  - Still requires additional DM's, as # actuators limited
- **All**
  - Not available
  - Order of correction does not meet our need

Derivation of DM requirements

Parameter	Driver
• Stroke	Atmospheric phase P-V
• Size	Physical size of AO package
– Actuator Spacing	
– Package size	
• Number of actuators	Degree of correction, r_0
• Fill factor	Throughput
• Flatness	Strehl performance
• Linearity	Dynamic range, open loop system
• Face sheet (continuous or segmented)	
• Speed	Wind speed, turbulence spectrum, τ_0
• Operating temperature	Cryo for mid-IR, cold (-30C) for near IR
• Repeatability (open loop)	Go-to system(s) – e.g. IFUs
• Mountable on tip-tilt stage	minimizes physical size, surface count
• Environment	
– Open vs window	
– Operate in vacuum	necessary in Cryo environment
• Coatings - want silver	best R for near-mid IR
• Surface roughness	≤ 10 nm rms
• When	TMT AO implementation time frame
• Cost	Competitive with alternatives

Calculating requirements

- **How to calculate stroke given r_0, L_0**
- **How to calculate dynamic range**
- **Offload options ("woofers")**
  – Conventional DM
  – Deformable secondary

Stroke Requirements

- **Atmosphere assumptions**
  - r_0 =15cm (λ=500nm) is median
  - r_0 =10cm is worst case for design to allow adequate performance over wide range of atmospheric conditions
  - L_0 may be finite, but probably highly variable and predominantly effects tilt, and not well known at any sites: we conservatively assume L_0 is infinite (Kolmogorov)
  - Rms wavefront error (tip-tilt removed)

$$\sigma = 0.366 \frac{\lambda}{2\pi} (\frac{D}{r_0})^{5/6} = 3.38 \mu m$$

For r_0=10cm

- **DM stroke**
  - Assume 5x for peak to valley, another 20% for systematics
  - so total stroke requirement is **10.1μm** (2x for wavefront)

Calculating requirements

- **How to calculate dynamic range**
  - Total error budget is ~130nm, digitization error is an error budget contributor
- **Offload options ("woofers") reduce MEMS range required**
  - Conventional DM
  - Deformable secondary
  - Residual Stroke (d_w=woofer inter-actuator spacing): $\sigma = \sqrt{0.3}\left(d_w / r_0\right)^{5/6}$
- **Inter-actuator stroke (d_a = MEMS inter-actuator spacing):**
  -

$$\sigma = \left\langle \left[\phi(x) - \phi(x + d_a)\right]^2 \right\rangle^{1/2} = \sqrt{6.88}\left(d_a / r_0\right)^{5/6}$$

Stroke requirements with woofer

- **Assume a low order, high stroke, high bandwidth DM is available**
  - Adaptive secondary
  - Conventional DM (will add extra surfaces)
  - Bimorph collimator (may be at an unpleasant conjugate height)
- **Residual stroke requirements for MEMS**
  - Tip tilt removed (2dof) 10.1μm
  - 2nd order removed (5dof) 7.0μm
  - 3rd order removed (9dof) 5.5μm
  - 4th order removed (14dof) 4.6μm
- **Field of view impact**
  - Woofer is not conjugate to source of all low order errors
  - So wide field of view will increase demands on MEMS stroke

Other MEMS requirements

- **Repeatability, dynamic range (and linearity if practical)**
  - Want rms wavefront repeatability errors ≤20 nm
  - Fractional requirement ~ 0.020/3.38 = 0.0059 (~ 0.5%)
  - Woofer reduces fractional requirement
- **Size**
  - Varies with system, ~ 40mm up to ?
- **Number of actuators**
  - 64x64 possibly acceptable
  - ~ 100x100 desired (varies with system)
- **When**
  - We need to make system design choices ~ 2 years from now
  - Requires cost estimates and confidence demonstrations by then
  - Require operational hardware for testing ~ 6 years from now
- **Cost (MEMS + all associated electronics)**
  - Inexpensive, affordable spares
  - Funds for needed development ~10^6-10^7 $

Number of DM's

- **MOAO**
  - 20 MEMS + 5 tt
- **Tomography**
  - 0-7
- **MIRAO**
  - 1-2 +1 tt
- **Narrow field**
  - 1-2 + 1 tt
- **MCAO**
  - ~7+3 tt

The importance of “Go-To” or open loop control

- Optical system greatly simplified (optical systems with both starlight and laser common paths is daunting for 30m)
- The measurement errors (from tomography) are a new error source and must be included in error budget and tightly limited
- The measured errors (from tomography) must be applied to the DM, yet the correction will not be sensed by the tomographic system (open loop)
- The DM correction errors (non repeatability) is a new error source and must be included in error budget and tightly limited
- Control bandwidth is relaxed, allowing smaller time delay errors or longer integration (lower laser power)

Stroke requirements for multi-conjugate AO imager

- **Multiple DMs at conjugate altitudes, each DM covers integrated OPD over a range of altitude**
- **2 DM's:**

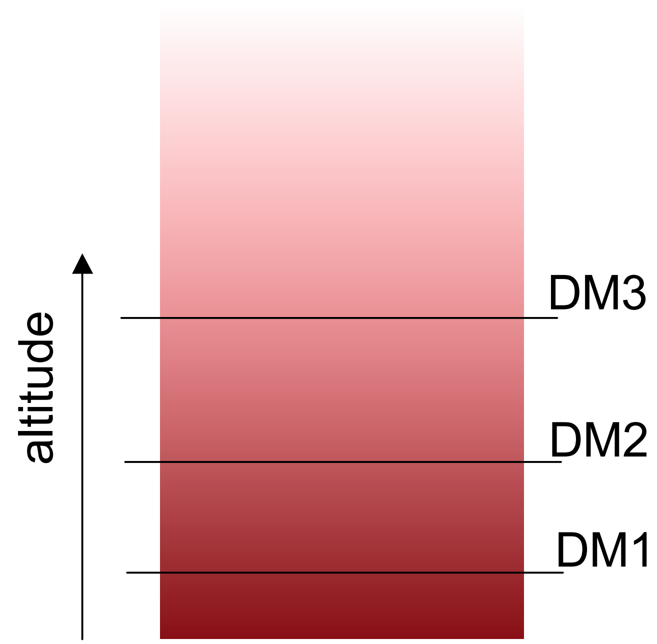
Mechanical Stroke vs r0, microns

r0	DM1 0 km	DM2 13 km
0.1	8.42	1.72
0.15	6.01	1.22
0.2	4.73	0.96

- **3 DM's:**

Mechanical Stroke vs r0, microns

r0	DM1 0 km	DM2 5 km	DM3 12 km
0.1	7.35	1.62	1.17
0.15	5.24	1.16	0.84
0.2	4.12	0.91	0.66



Open loop: non-common path aberration correction

- **AO relay optics (closed loop case)**
- **Dispersion (589 nm to near-IR)**
  - $$\delta\phi = \frac{n_{589} - n_{\lambda}}{n_{589} - 1}\phi$$
  - = 0.0125 x ϕ at $\lambda = 1\mu$m
  - $\phi = 6.6\ \mu$m; $\delta\phi = 83$ nm (for $r_0 = 15$cm)

Summary: DM requirements matrix

	DL spectrograph	NIR wide field spectrograph	Mid IR spectrometer	Multi-conjugate imager	Extra-solar planet imager
Stroke, μ	10 microns	10 microns	10 microns	8 microns	10 microns
Size, mm	20 mm	20 mm	20 mm	60-300 mm	60 mm
Actuator Spacing	200 microns	200 microns	200 microns	3 mm	200 microns
Package size	50 mm	50 mm	50 mm	400 mm	50 mm
Number of actuators	100 across	100 across	100 across	100 across	300 across
Fill factor, %	100%	100%	100%	100%	100%
Flattness, rms nm	< 20% stroke	< 20% stroke	< 20% stroke	< 20% stroke	< 20% stroke
Linearity, %	<0.5%	<0.5%	<0.5%	<0.5%	<0.5%
Face sheet	continuous	continuous	continuous	continuous	continuous
Speed, ms	0.5 ms	0.5 ms	0.5 ms	0.5 ms	0.1 ms
Operating temperature, C	77 K	77 K	5 K	-30 C	-5 C
Repeatability, nm	~ 5 nm	~ 5 nm	~ 5 nm	~ 5 nm	< 1 nm
Mountable on tt stage	yes	yes	yes	yes	yes
Environment					
Open vs window					
Operate in vacuum	yes	yes	yes	yes	no
Operate in cryo	yes	yes	yes	yes	no
Coating	silver	silver	silver	silver	silver
Surface roughness	1 nm	1 nm	1 nm	1 nm	1 nm
When	2 years	2 years	2 years	3 years	3 years
Cost, $					

Laser pulse tracking

- **Segmented (tip/tilt mirrors) – one per Hartmann subaperture**
- **Tracks laser pulse as it traverses the sodium layer**

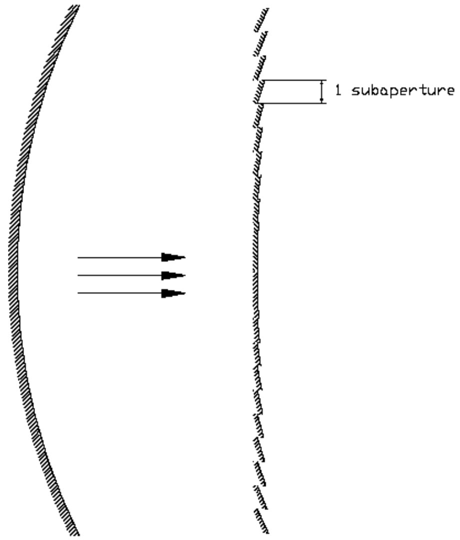


Figure 4- 7: Schematic of a segmented MEMS used for dynamic refocusing. The segmented MEMS at right is equivalent (over each subaperture) to the continuous mirror shape at left. Amplitudes are exaggerated.

Figure 4- 8: Shape of segmented MEMS during tracking of a LGS pulse. Amplitudes are exaggerated.

- ΔOPD = 30 cm x 4 arcsec = 5.7 μ; Δθ = 5.7μ ÷ 300 μ = 19 mr
- $t = \Delta h / c = 10\text{km} / 3\times 10^{8}\,\text{m/s} = 30\mu s$