Laboratory for Adaptive Optics
UCO/Lick Observatory
University of California, Santa Cruz

MEMS for Astronomy

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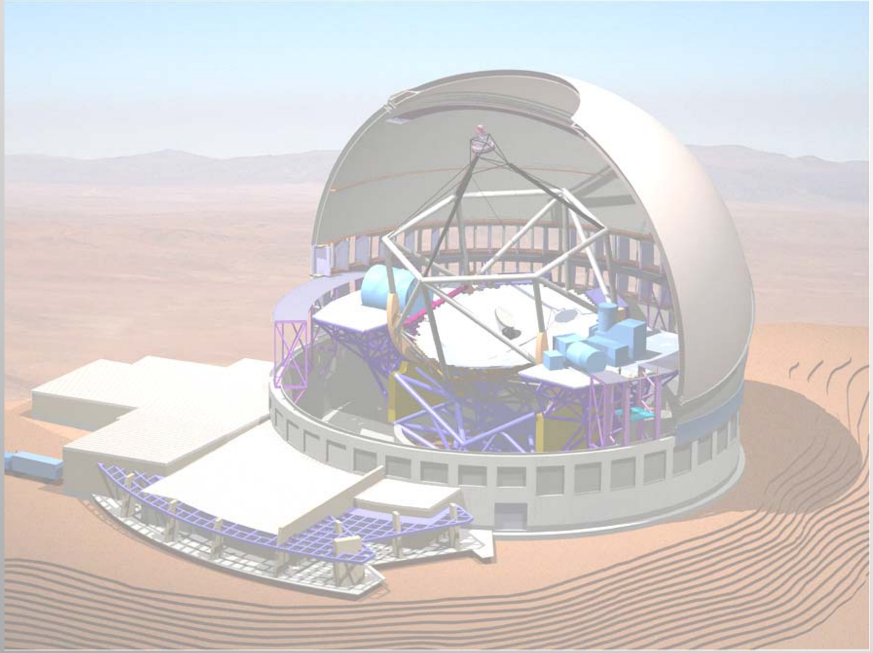


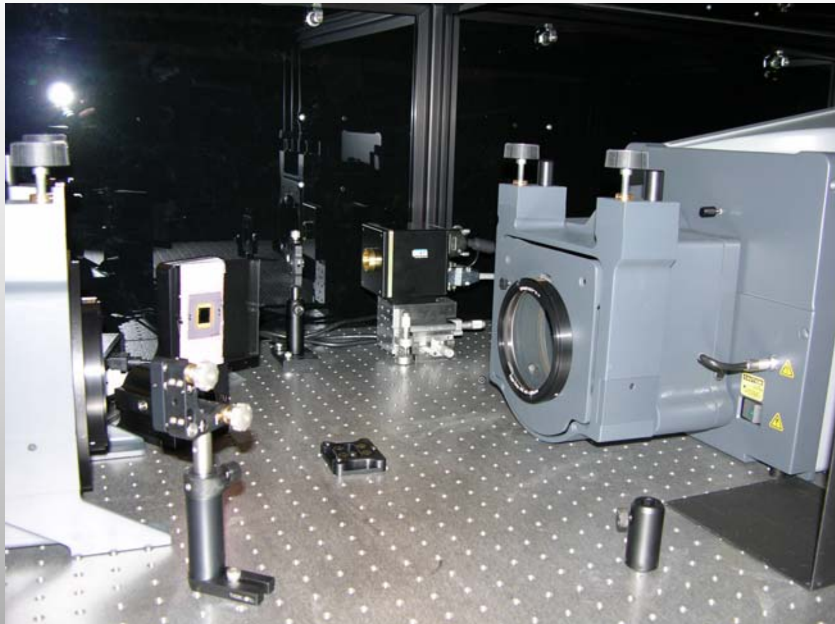
Thirty Meter Telescope artist's conception

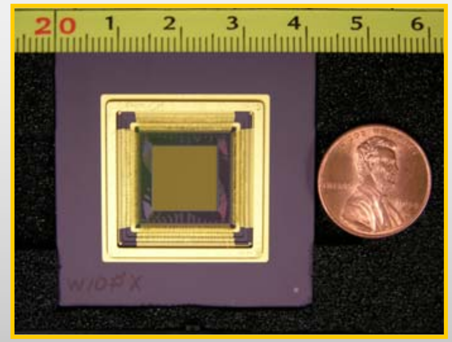
Center for Adaptive Optics Fall Retreat, Yosemite, CA, November, 2006

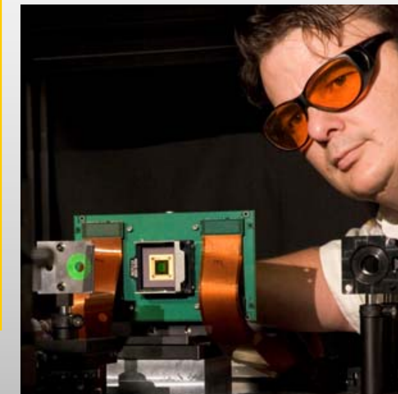
Why astronomers want MEMS

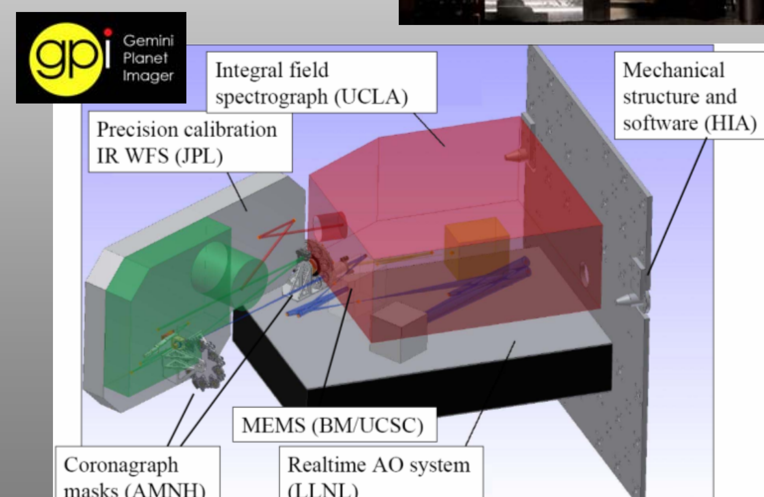
- Smaller beam size means smaller instruments
  - Less weight, less flexure, simpler mechanically
  - Less expense in support optics
  - However, pupil size has a lower limit in wide-field AO
- Cost
  - More actuators / $ than conventional piezo technology
  - 1000’s of actuators practical at low cost
- Accuracy
  - Extreme AO, visible λ AO
- Go-to (open-loop correction)
  - Enables multi-object AO
  - Tip/tilt star correction for higher sky coverage

Micro DMs enable small high order AO systems









MEMS device in lab testing now:

- 32x32 array
- 360μ actuator spacing

Under development:

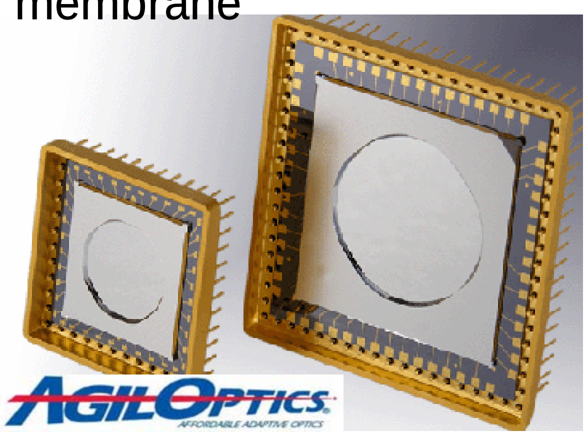
- 64x64 array – planet finder for 8 m telescope
- 100x100 array – 30 m telescope general use

MEMS DMs are available in low-order ("Woofer") varieties

Needed for the low-order large-stroke components of the wavefront, when high-order MEMS don't have enough stroke

Silicon membrane	10μ*	37-61 dof
Piezo-bimorph	25μ*	36-100 dof
Magnetic	100μ*	50 dof

Electrostatic actuated membrane

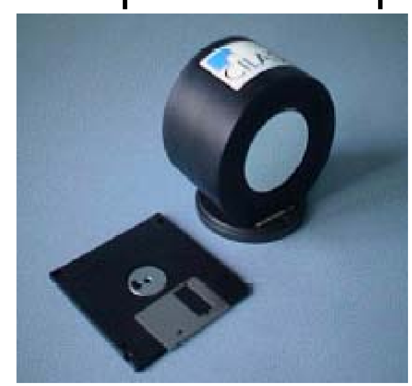


Magnetically actuated membrane

- Imagine Optic -

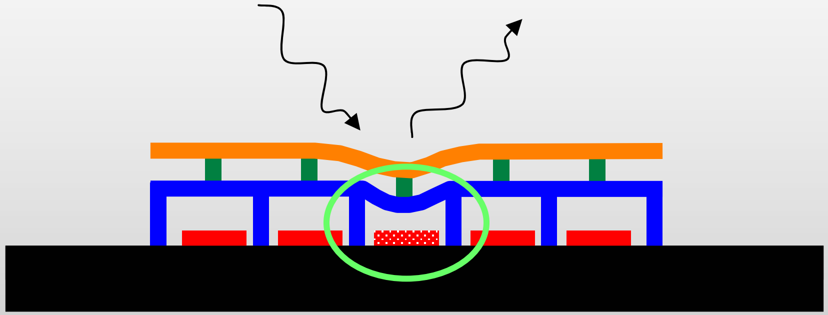
MIRAO 52 D

Electrically actuated bimorph material plate

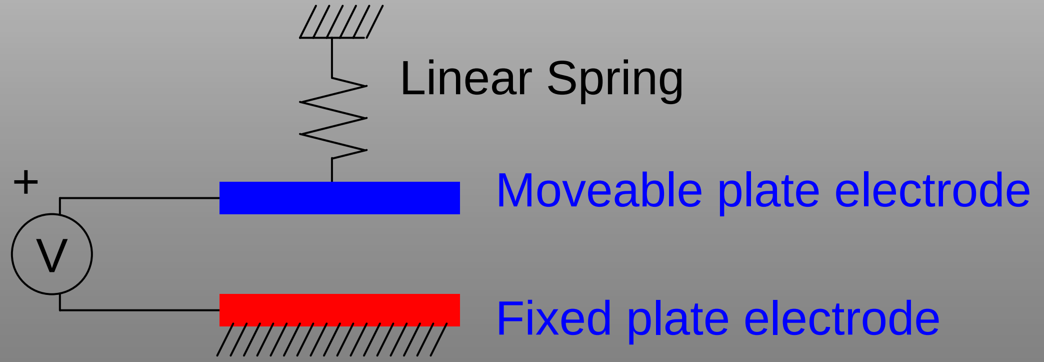


CILAS BIM31

Electrostatic actuators: predictable response with no hysteresis



Simplified actuator model:



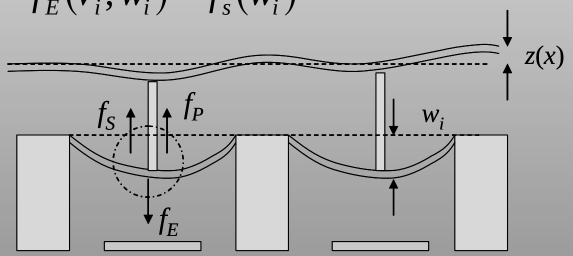
MEMS Open-Loop Modeling for "Go-To" Operation

- Step 1: Use the thin plate equation to solve for the required plate force distribution

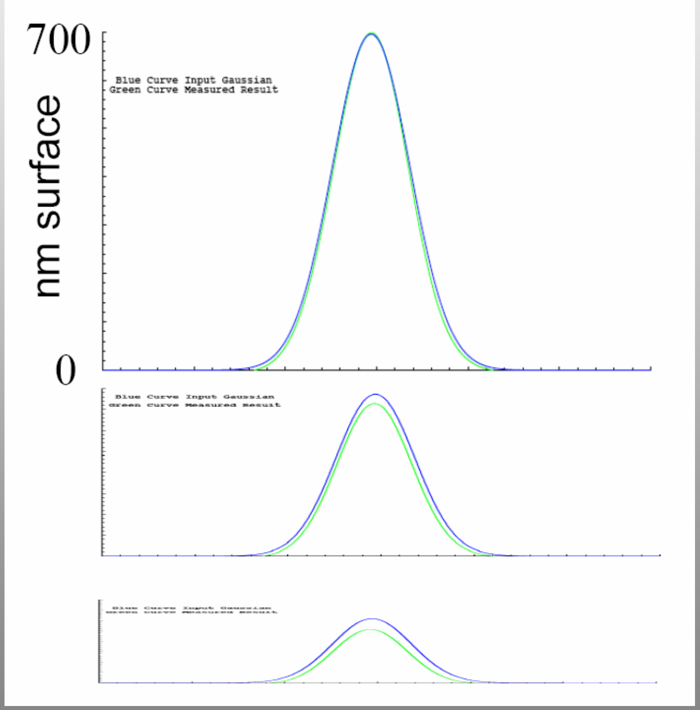
$$D\nabla^4 z(x) = f_p(x) = \sum_{i=1\ldots n} f_{p_i}(x - x_i)$$

- Step 2: Look up the actuator spring force at that displacement

$$f_p(z_i) = f_E(V_i, w_i) - f_s(w_i)$$



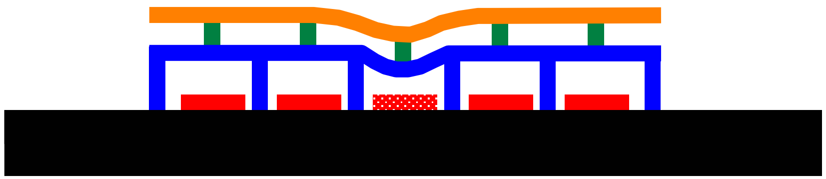
- Step 3: Resultant force is the electrostatic force. Look up the voltage that provides that force at that displacement.



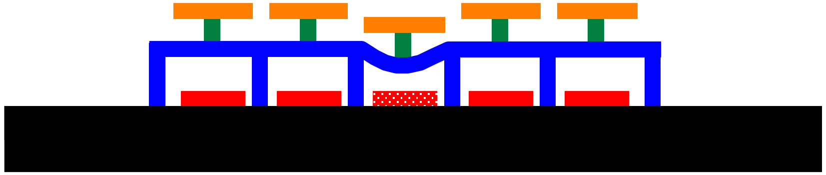
Open loop control to **15 nm surface demonstrated in the lab**.

We expect to get better than this with calibration refinement.

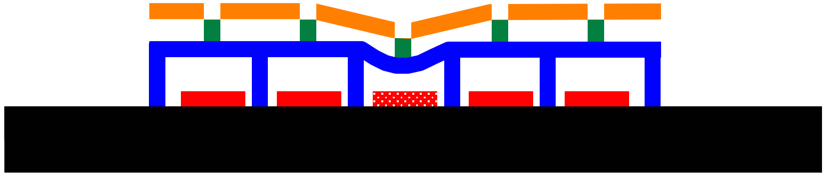
Face Sheet Types and Wavefront Fitting



Continuous



Piston



Tip-Tilt

To get the same AO fitting error (Kolmogorov turbulence)

$N_{piston}/N_{continuous} = 6.2$

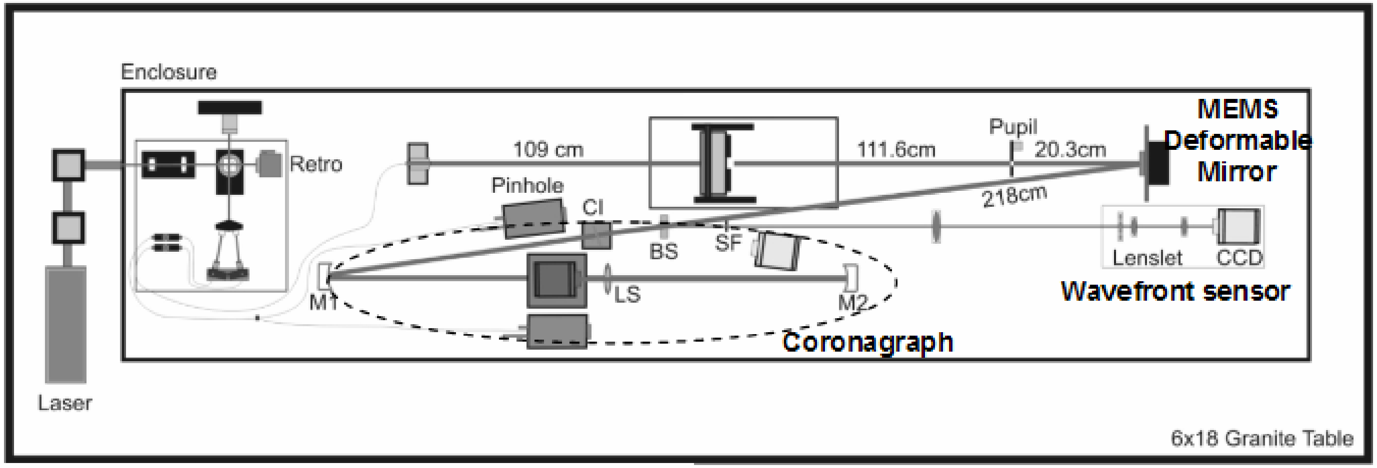
$N_{tip\text{-}tilt}/N_{continuous} = 1.8$

(C. Max, CfAO website)

BOSTON MICROMACHINES CORPORATION

ExAO Development and Instrument Prototype

at the UCO/Lick Laboratory for Adaptive Optics



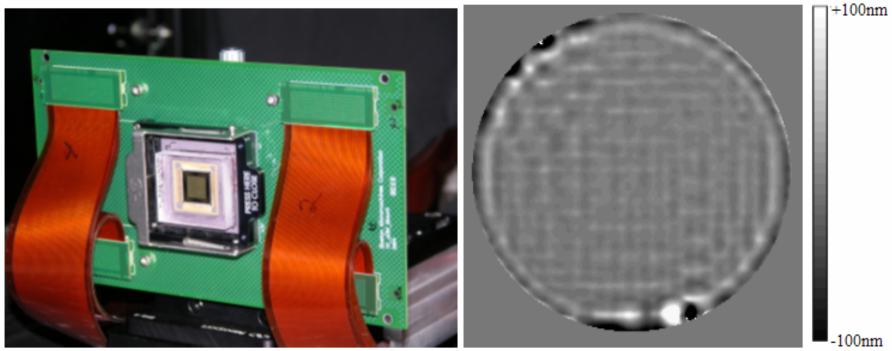


Figure 5. Left: the MEMS deformable mirror is shown in its mount. Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI measurements determines the voltage commands required to achieve maximum flatness. The residual wavefront error visible, on the order of 5 nm rms, is mostly "print-through" of actuator mounting structure to the continuous mirror surface. This high spatial frequency ripple scatters light mostly outside of the discovery region in the final image.

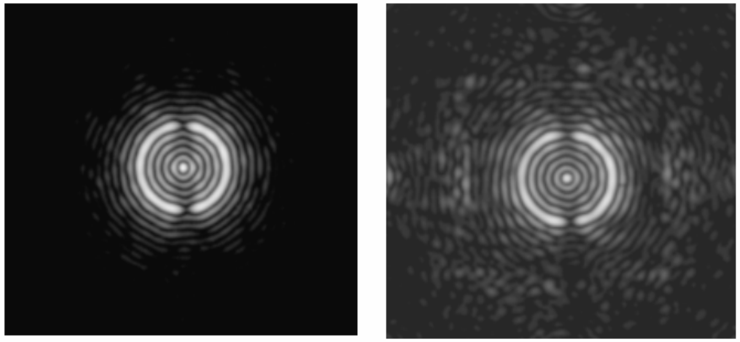
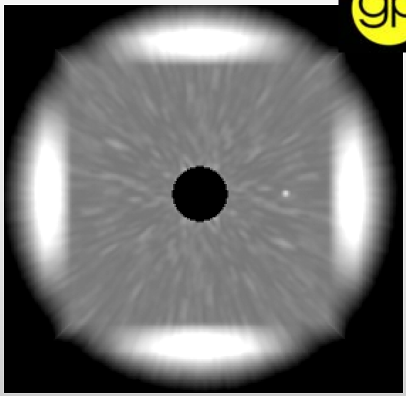
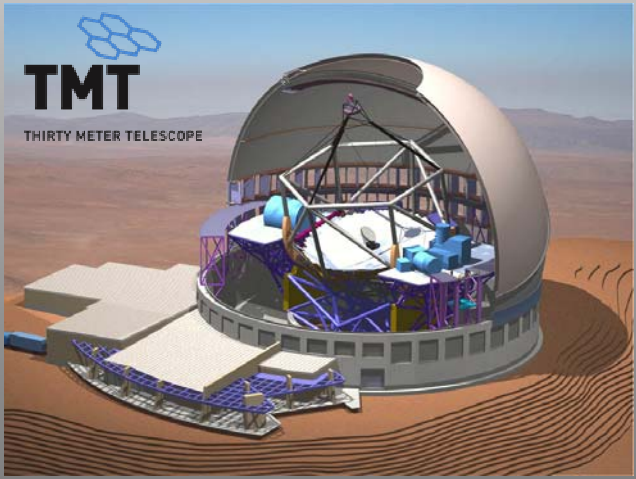


Figure 4. Early test results from the coronagraph upgrade showing far-field images, using a flat mirror in place of the MEMS mirror (left) and using a flattened MEMS (right). The diffraction rings in this image are considerably suppressed owing to the coronagraph, leaving the discovery region dark enough to image a planet. The grey-scale stretch of this image is 10,000 times higher than that of Figure 3; the residual scattered light outside of the 5'th ring from the center (the diameter of the coronagraph stop) is falling between 10^{-5} and 10^{-6} of the peak of the light which is blocked by the stop. We will also be testing an apodizing coronagraph stop that should further suppress the diffraction.

High-order MEMS Consortium



- Joint effort of CfAO, LAO, Gemini (GPI), TMT
- Target Instruments:
  - Gemini Planet Imager
  - Thirty Meter Telescope AO systems
- Specifications: GPI [TMT]
  - Number of actuators 4096 [10,000]
  - Continuous face sheet, gold coated
  - 4 microns surface stroke
  - 1 micron differential stroke
  - < 10 nm open loop accuracy
  - 2 kHz sample frequency
  - -30 C operating temperature
  - Working actuator percentage 100% [99%]
- Relaxed stroke requirement (<10μ) => each instrument will need woofer DMs



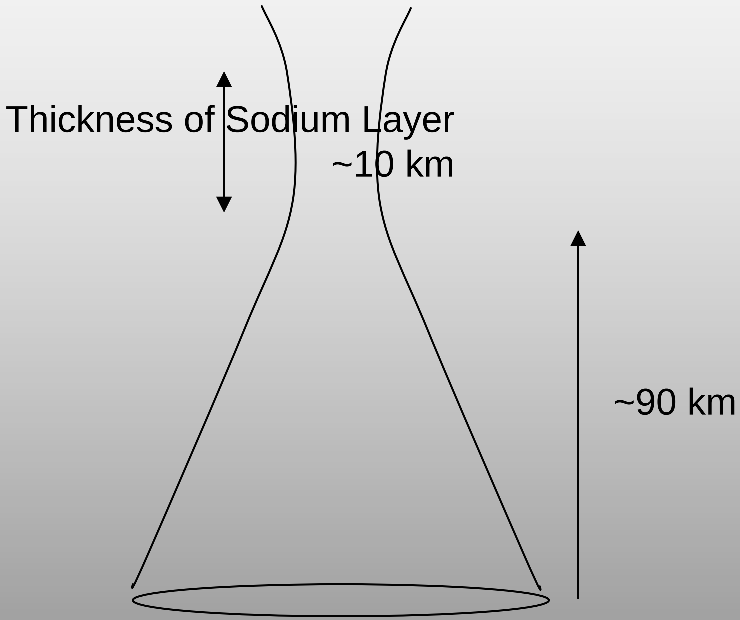
Ubiquitous MEMS (cheap, and many of them)

- Conventional AO role as science wavefront corrector(s)
  - Multi-conjugate AO (MCAO)
  - Multi-object AO (MOAO) – maybe 20 DMs in IRMOS
- Unconventional roles
  - Variable aberration corrections (e.g. in LGS wavefront sensors)
  - Laser uplink AO
  - Laser pulse tracking

Laser Guidestar Uplink

- MEMS can be used to correct the outgoing lasers
- Could potentially produce a 10x smaller spot – equivalent to 100x increase in laser power! (it's the surface brightness that counts)
- Implies
  - Lower power lasers needed (cost advantage)
  - Visible wavelength LGS AO enabled

Optimum Laser Projector



Projection Telescope
Diameter D_p=70cm

- Thickness of Sodium Layer = Depth of Focus

$$(f\#)^2\lambda = 10km$$
$$\left(9\times10^4/D_p\right)^2\times 0.6\times10^{-6} = 10^4$$
$$D_p = 70cm$$

- Spot Size

$$\frac{\lambda}{D_p} = \frac{0.6\times10^{-6}}{0.7} \approx 1\mu r$$
$$z_{Na}\frac{\lambda}{D_p} = 9\times10^4\times10^{-6} = 9cm$$

- Wavefront Sensor – 20 cm subaps

$$d = r_0$$
$$\frac{\lambda}{d} = \frac{0.6\times10^{-6}}{0.2} = 3\mu r$$

- Need to AO-correct Laser uplink (~$(70/20)^2$ = 12 dof AO system)
- Hartmann subaperture diffraction dominates
- Gain in equivalent laser power: $(10\mu r/3\mu r)^2$ = 11x

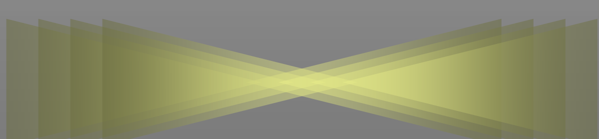
And… another factor of ten:

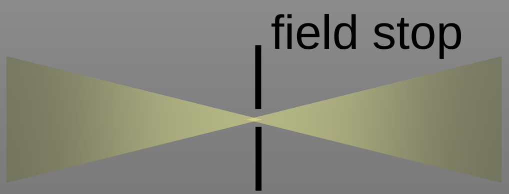
- Pyramid wavefront sensing
  - which is not limited by subaperture diffraction
  - 1μr spot determines centroiding error

    $(3\mu r / 1\mu r)^2 = 9$ x

And more…

- Spatial filtering (3μr field stop)
  - Removes aliasing error ~ 1/3 of fitting error
  - Requires mechanical pulse tracking – which also eliminates LGS elongation





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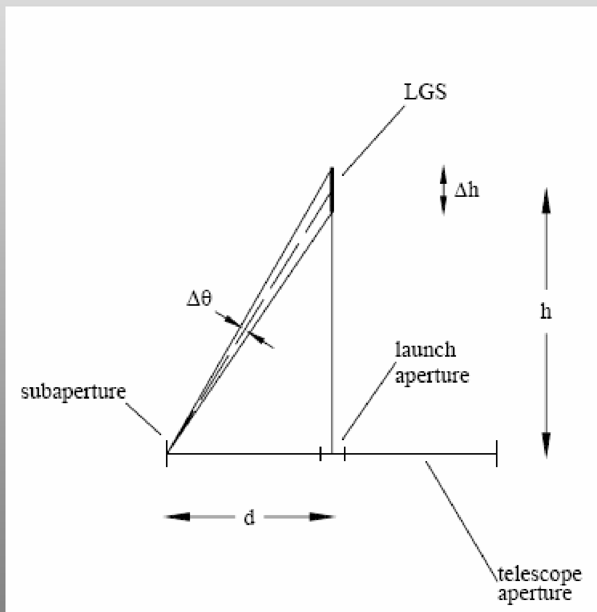
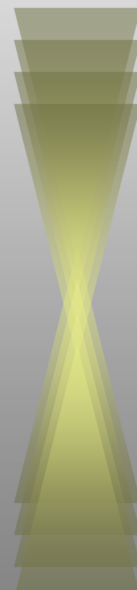
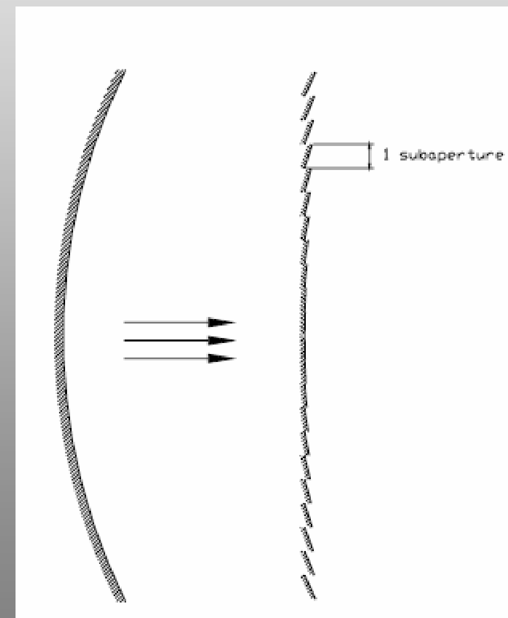
Laser Pulse Tracking

- MEMS can be used to mechanically track the laser pulse through the sodium layer
  - Better signal-to-noise performance with compressed pulse
  - Enables spatial filtering – eliminating aliasing error in the wavefront sensor

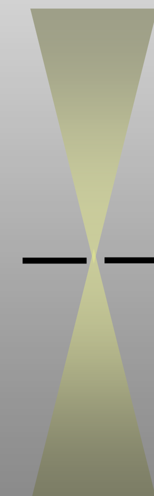


Laser illuminates mesospheric sodium layer creating a guide star



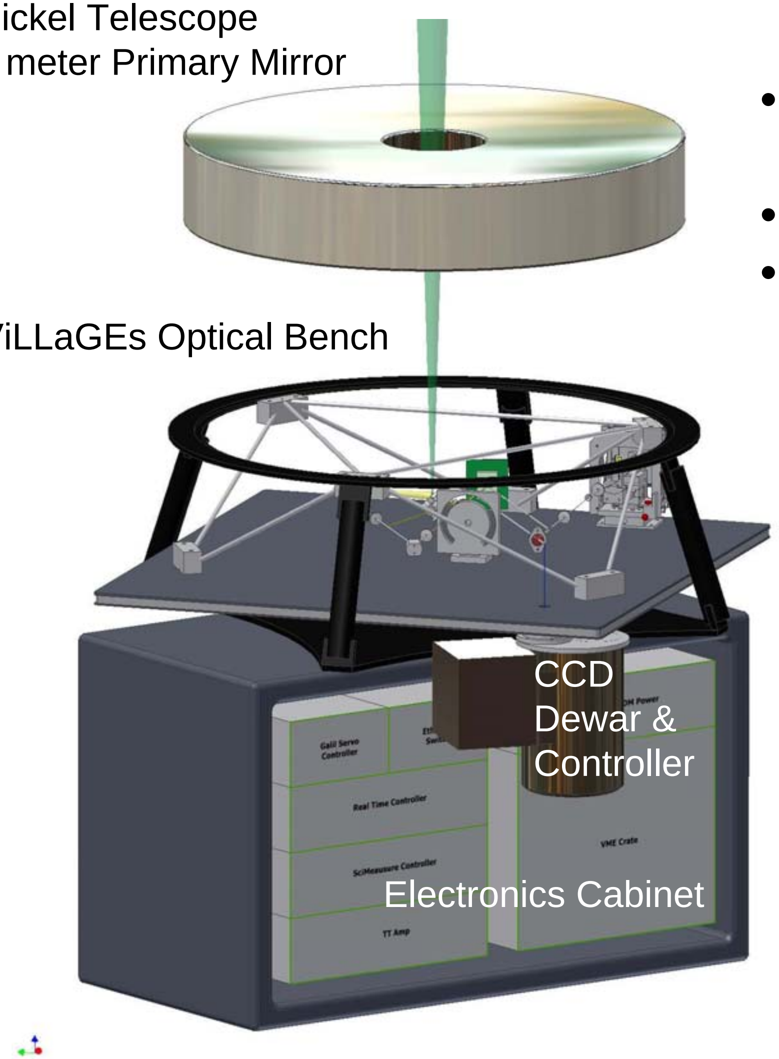


MEMS device acts as dynamic focus element

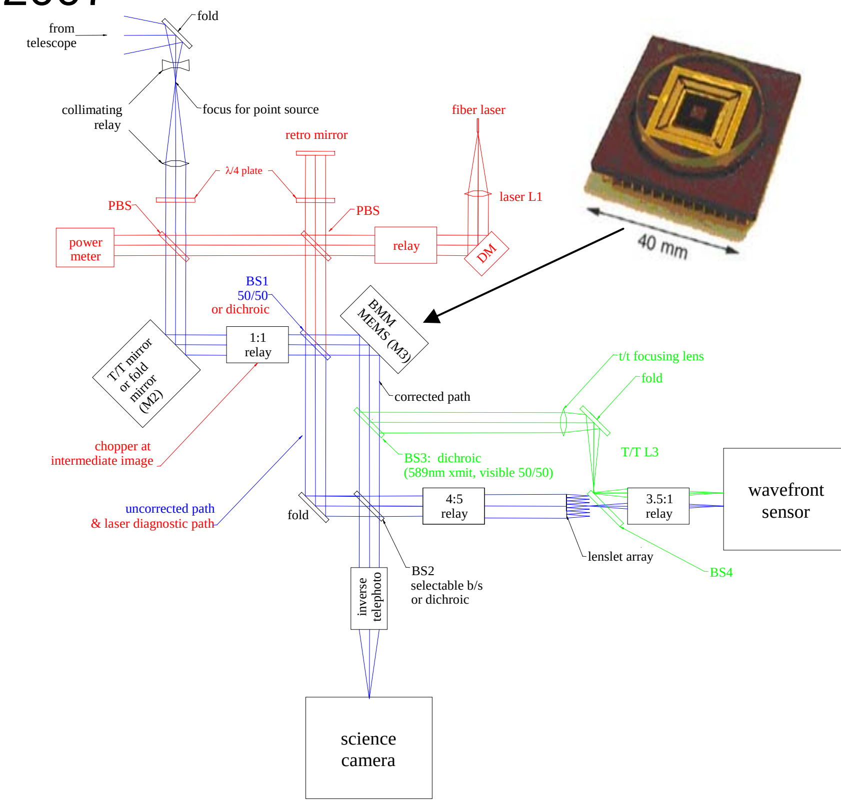


spatial filter

Visible Light Laser Guidestar AO System Experiments



- Designed for Nickel 1-m Telescope, Mt. Hamilton
- Proof of concept for MEMS deformable mirrors in astronomical AO instruments
- PoC of AO uplink correction of laser beam
- In construction phase – experiments start mid 2007



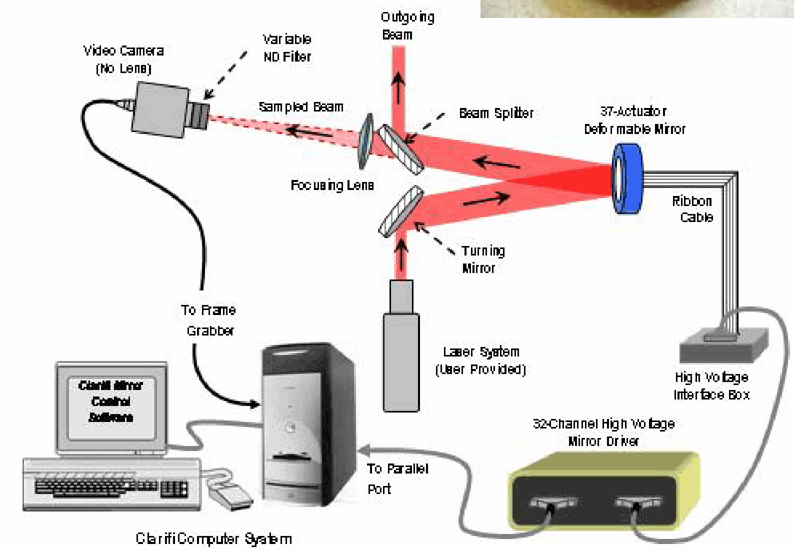
Summary

- MEMS are the wave of the future for Astronomical AO
  - Lab tests showing performance (with the exception of stroke at high order) equal to or exceeding piezo mirrors
  - They're a whole lot cheaper and smaller, enabling AO architectures not otherwise considered, solving other optical problems not traditionally assigned to DMs.
- MEMS Path to the telescope:
  - Demonstrations in lab testbeds (LAO)
  - On-sky demos planned (Lick)
  - MEMS in instruments (GPI, NGAO, IRMOS)
- Visible wavelength AO systems are on the horizon

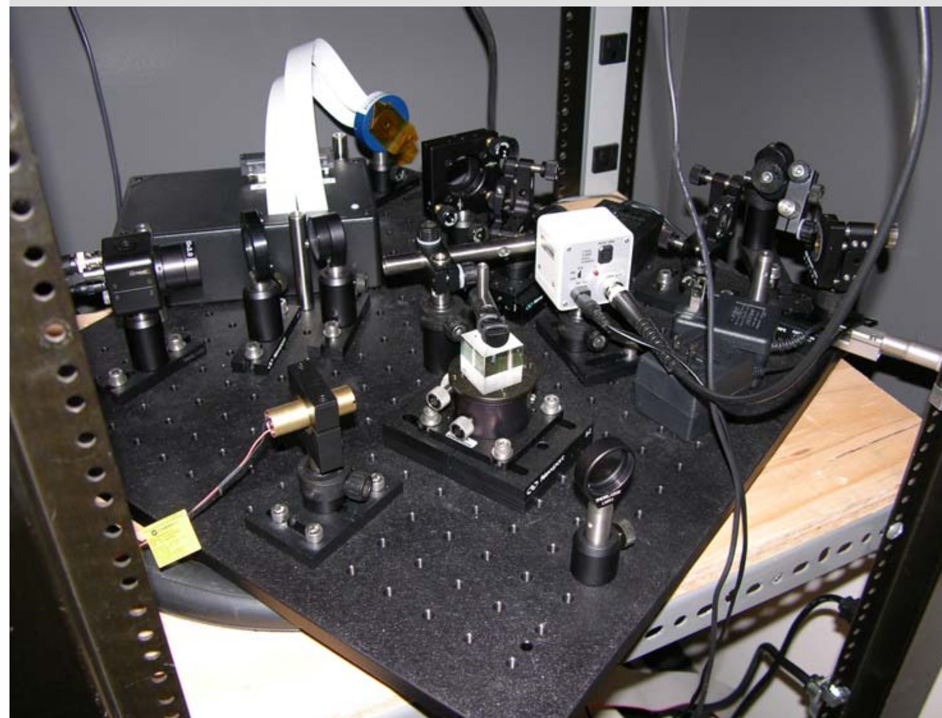
Laboratory for Adaptive Optics

Single Conjugate AO Demonstrator

Using a Membrane Deformable Mirror



The Clarifi™ Adaptive Optics System provides researchers and product developers with the tools needed for exploring closed-loop adaptive optics applications such as far-field beam optimization, shown here.



Agiloptics "Clarifi" system