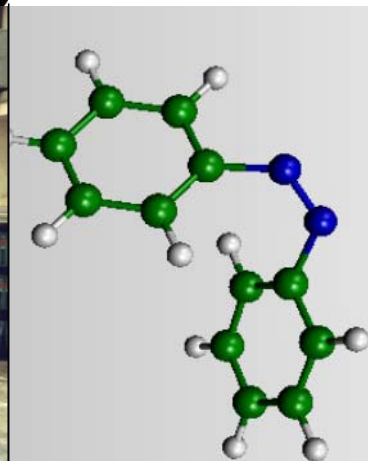
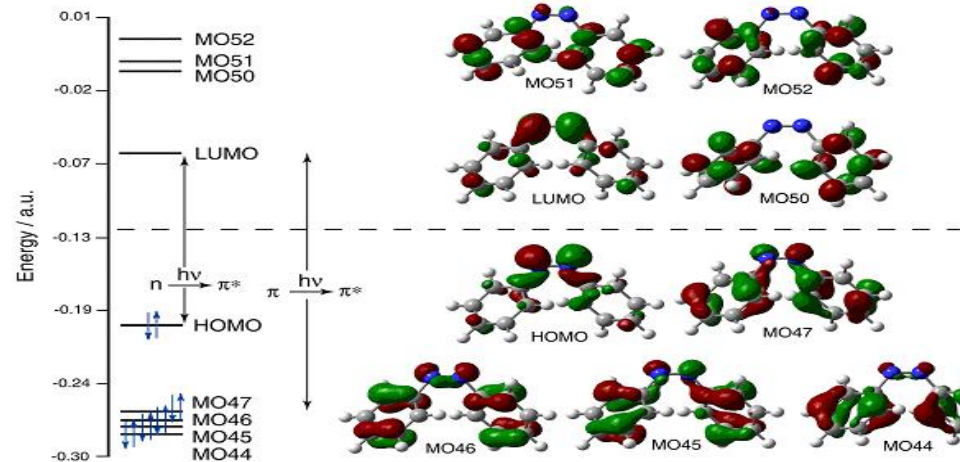
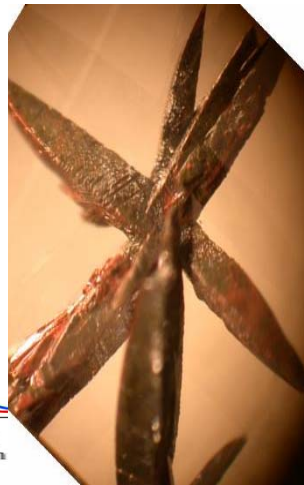
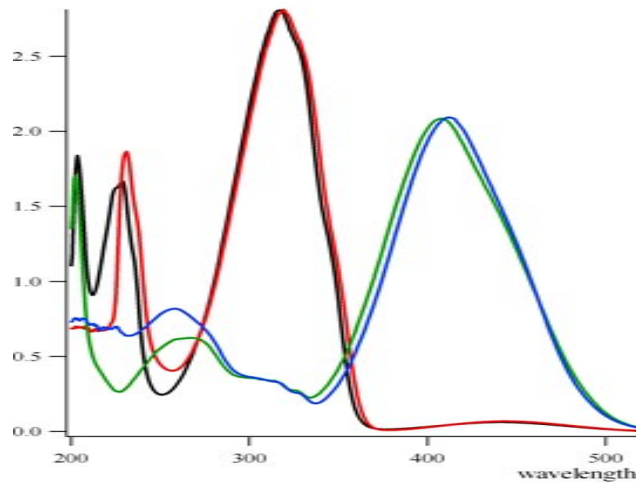


# Large Ultra-Lightweight Photonic Muscle Telescope

(Active Optics With  $10^{23}$  Actuators)



**Joe Ritter**  
**University of Hawaii**  
**Institute for Astronomy**  
**Jim Brozik WSU, Ethan Holt AFRL**



# Background

- The development of novel lightweight space qualified optics is of vital importance to scientific exploration as well as to national defense.
- The resolution of optical systems is inversely proportional to the diameter of the primary optic. Resolution drives primary mirror size.
- PM size is constrained by production cost, launch vehicle diameter and lift capability.
- High resolution space imaging requires the production of lightweight large aperture optics subject to design tradespace constraints based on:
  - Nanometer physical tolerances
  - Low integrated system aerial density
  - Wave front control authority
  - Deployment
  - Thermal and mechanical properties (both vehicle and optics)
  - Launch vehicle volume constraints
  - Production cost and schedule risk mitigation
- Segmented aperture systems impose an even tougher set of requirements on segment alignment, wavefront phasing, deployment and mass constraints.

**Photons weigh nothing.**

**Q:Why must even small space telescopes weigh tons?**

**A1:**Telescopes require sub-wavelength figure (shape) error in order to achieve acceptable Strehl ratios. Traditional methods of achieving this require rigid and therefore heavy mirrors and reaction structures as well as proportionally expensive spacecraft busses and launch vehicles.

Using advances in nanoengineered-materials we have made a laser actuated polymer material with controllable reversible bi-directional bending.

Photoactive isomers will be incorporated into space durable membrane optics to construct giant active **primary membrane mirrors utilizing over  $10^{23}$  of our nanomachine “laser controlled molecular actuators.”**

- We have rudimentally demonstrated a completely novel approach to producing and correcting active optical primary mirrors.

- Using **optically controlled molecular actuators** will allow the substitution of optically induced control for rigidity and mass.

- I claim that **Photonic Muscle substrates** can make precision control of Membrane mirror shape and dynamics possible giant apertures.

If I am right, this will enable a revolutionary leap in high-resolution imaging capabilities, **This is the vision.**

**A2: Tons? this is NOT required.**

# What we are doing:

- Interdisciplinary research;  
Optics, Physics, Chemistry, Control systems
- Advanced methods for active optical compensation and control
- Elegant rather than brute force methods

## The Path for this project:

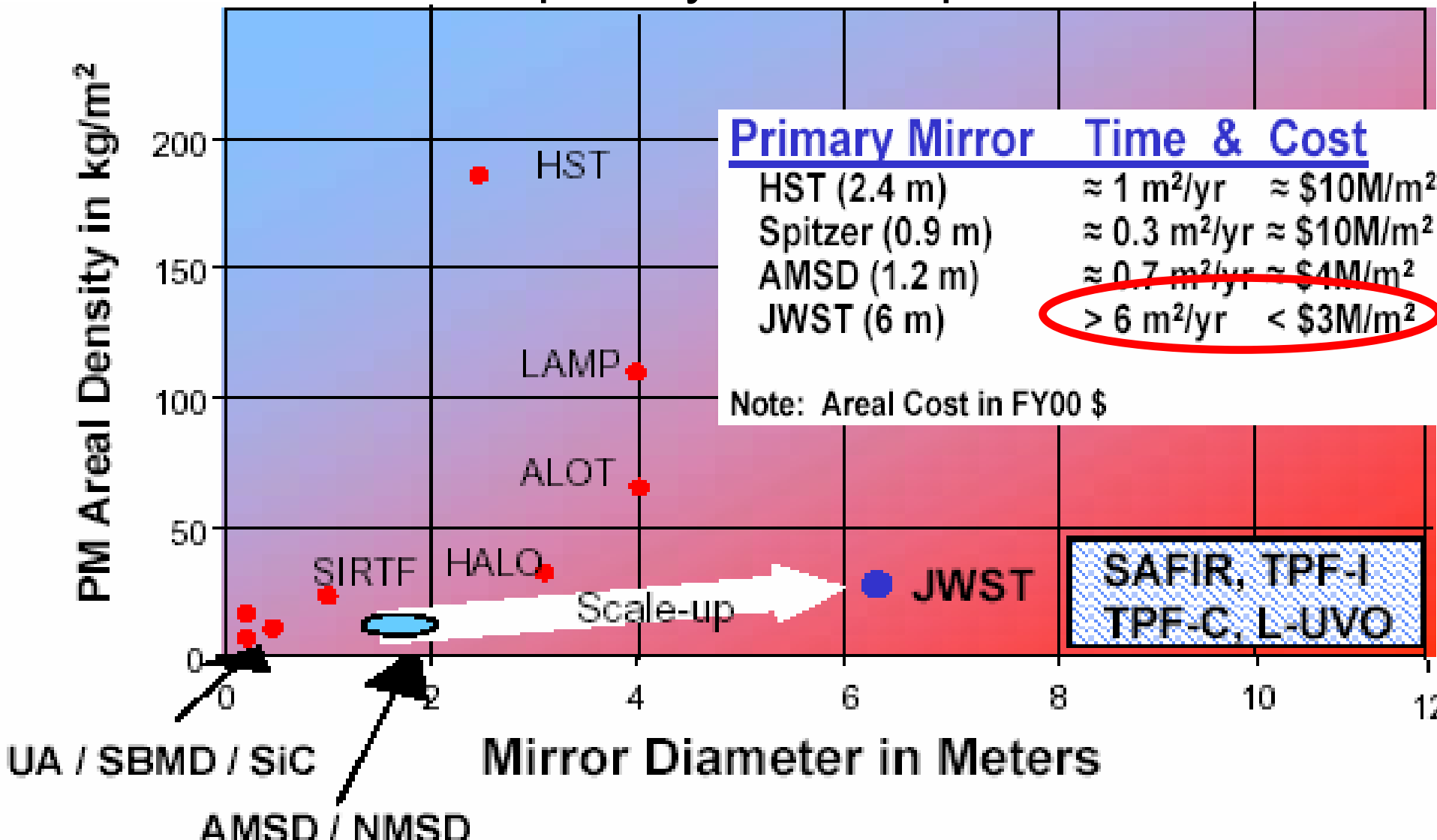
Application of interesting physics, chemistry, optics e.g.

- How is light converted to motion in photonic muscles?
- How can we control and utilize novel transducer systems of this sort?

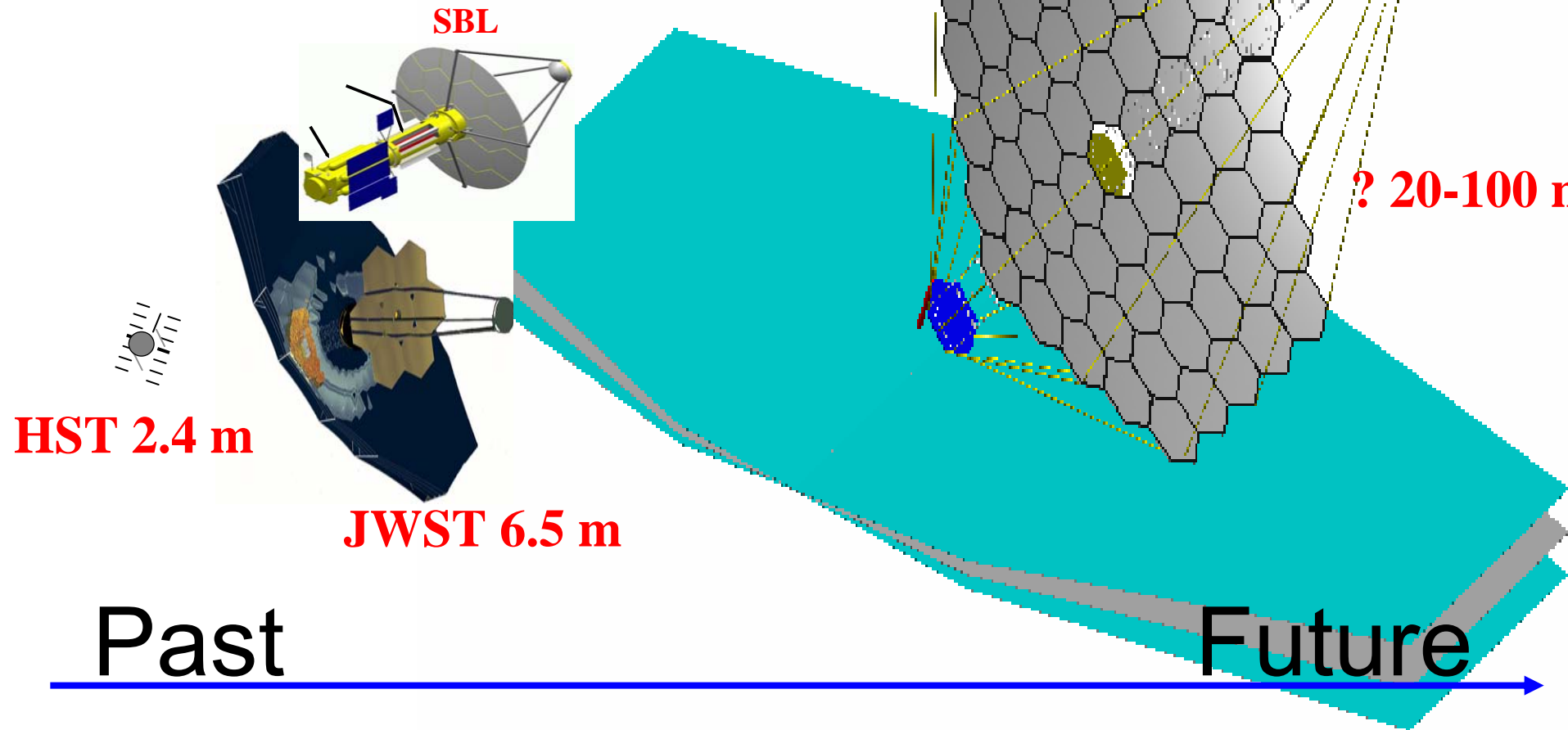
## How it is done now:

From: Advanced Telescope and Observatories

### Capability Roadmap



# Current route:

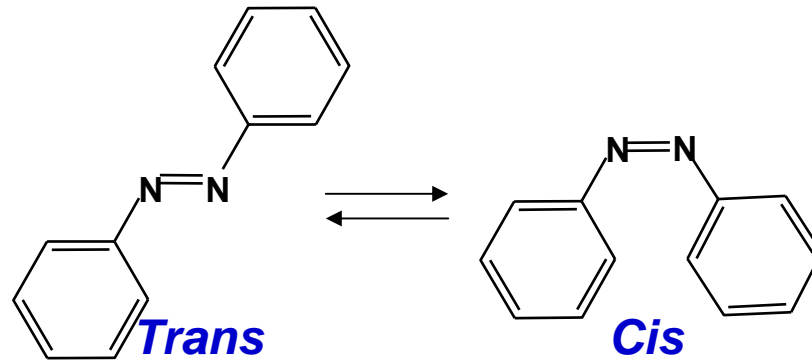


•Segmentation- Contrast Issues

•Actuation Density-  $(0 \rightarrow \infty)$  Tradespace

# How Does a Photonic Muscle Work?

The Chromophore molecule azo-benzene has two isomer structures; “Cis” and “Trans”, which can be switched by using specific wavelengths of light

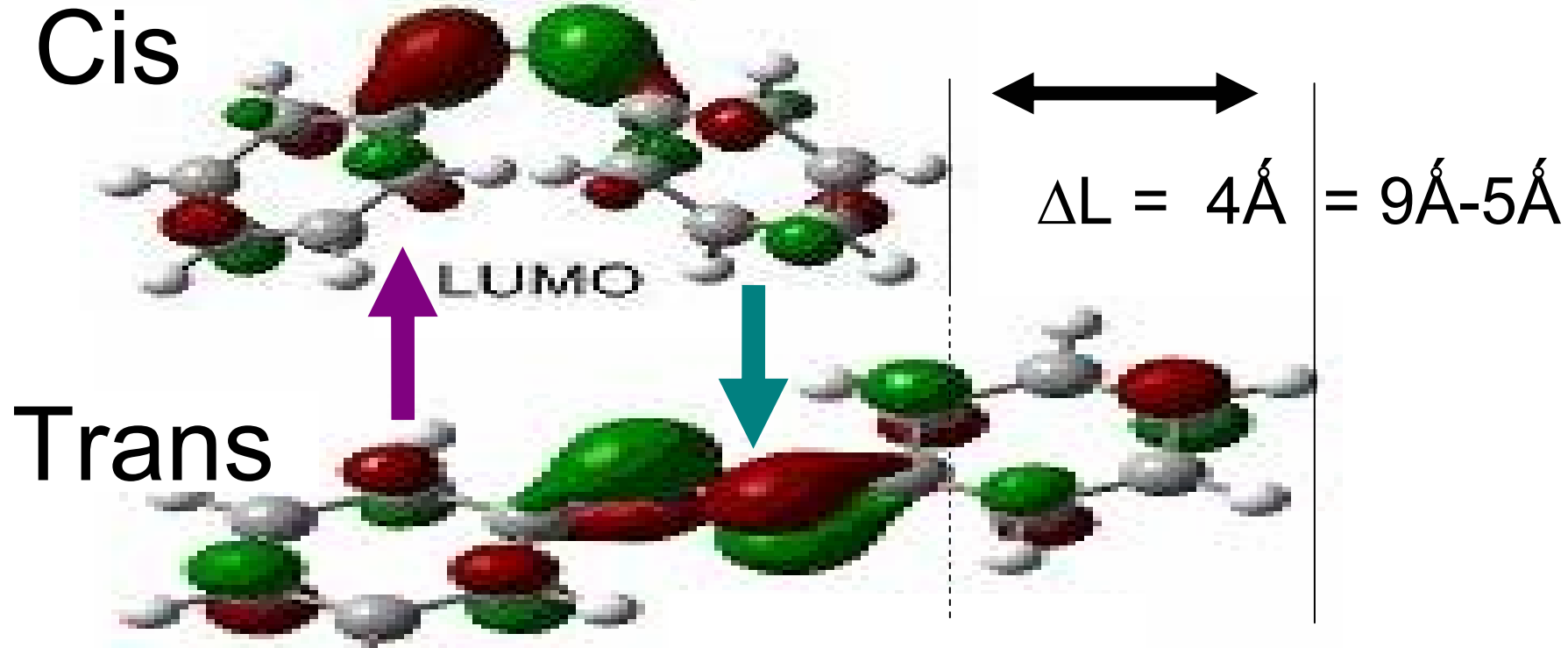


Cis-Trans photoisomerization is a reversible reorganization of molecular structure induced by light, which is accompanied by a change in the overall shape and volume of the molecule.

**Induced strain is over 40%.**  
**Forces are pico-newtons/molecule.**



# Cis Trans Photoisomerization



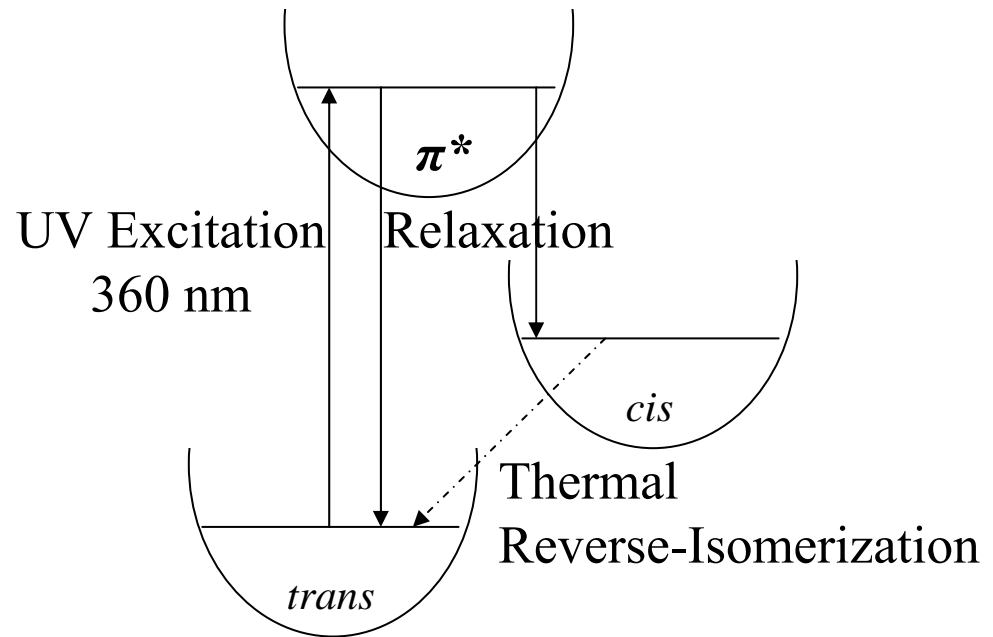
The idea: Exploit the optically induced strain to make **polymers which change shape with light** (photonic muscles).

We seek to understand the energy conversion and how microscale structure affects control properties,

then to apply this basic science knowledge to **control of optical figure and dynamics.**

# *trans-cis* Photoisomerization Theory

- UV irradiation: A  $\pi$ - $\pi^*$  transition corresponds to exciting an electron from a bonding  $\pi$  orbital to an 'antibonding'  $\pi^*$  orbital.
- Rotation at azo bond in the excited (photolyzed) state causes interconversion between isomers
- Inversion at azo bond in the excited (photolyzed state) causes bending into higher energy conformations



Upon de-excitation, some molecules are trapped in the *cis* conformation  
# Predicted by Boltzmann distribution

$$\frac{cis}{trans} = \exp\left(-\frac{E_{cis} - E_{trans}}{k_B T}\right)_0$$

# What about mirrors (Polymers)

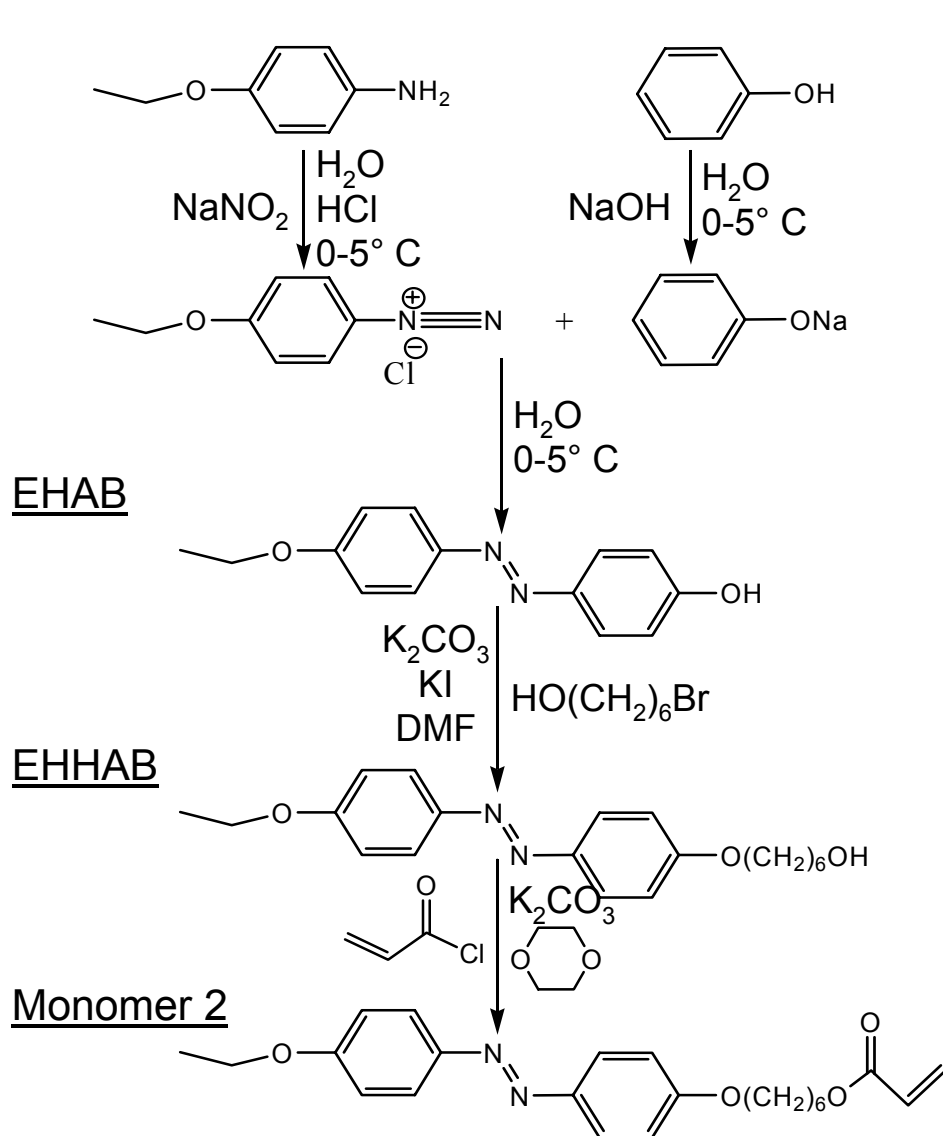
- We have made  $\pi$ - $\pi^*$  mixed valence azo-polymer membranes,
- Using different wavelengths and polarizations provides the capability to **actively reversibly and remotely control membrane mirror shape** and dynamics

*Vision reminder: use beams of light, instead of bulky actuators and wires.*

# How to Control a Membrane: Orientation & Photo-Isomerization

- Deformation is produced along the polarization direction of linearly polarized light
- Polarized beams can exploit these traits to control shape changes in 3 dimensions in a deformable mirror
- Use: to compensate for errors in primary mirror figure due to processing, or to damp out oscillations caused by telescope slewing and environmental perturbations
- The possibility of using light to control a device that controls light itself opens the possibility of novel optical feedback control systems based on analog optical computation

# Synthesis: Monomer 2



EHAB  
4-ethyloxy-4'-hydroxyazobenzene



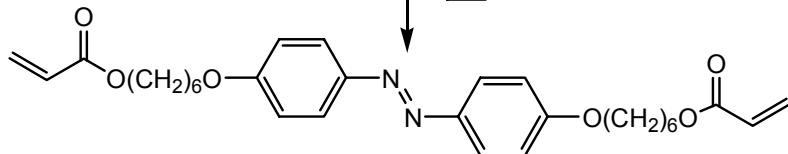
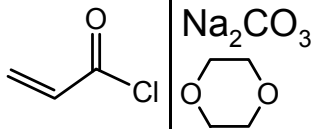
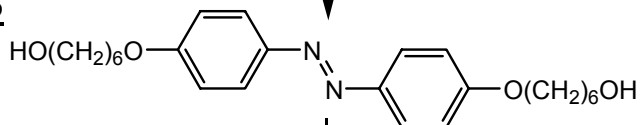
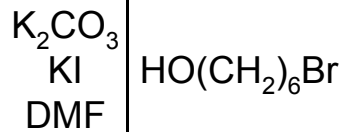
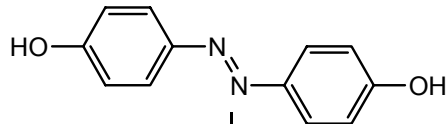
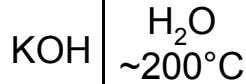
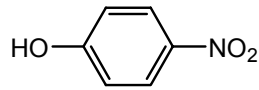
EHHAB  
4-ethyloxy-4'-(6-hydroxyhexyloxy)azobenzene



Monomer 2  
4-ethyloxy-4'-(6-acryloyloxyhexyloxy)azobenzene



# Synthesis: Crosslinker



DHAB

4,4'-dihydroxyazobenzene



BHHAB

4,4'-bis(6-hydroxyhexyloxy)azobenzene



Crosslinker

4,4'-bis(6-acryloyloxyhexyloxy)azobenzene

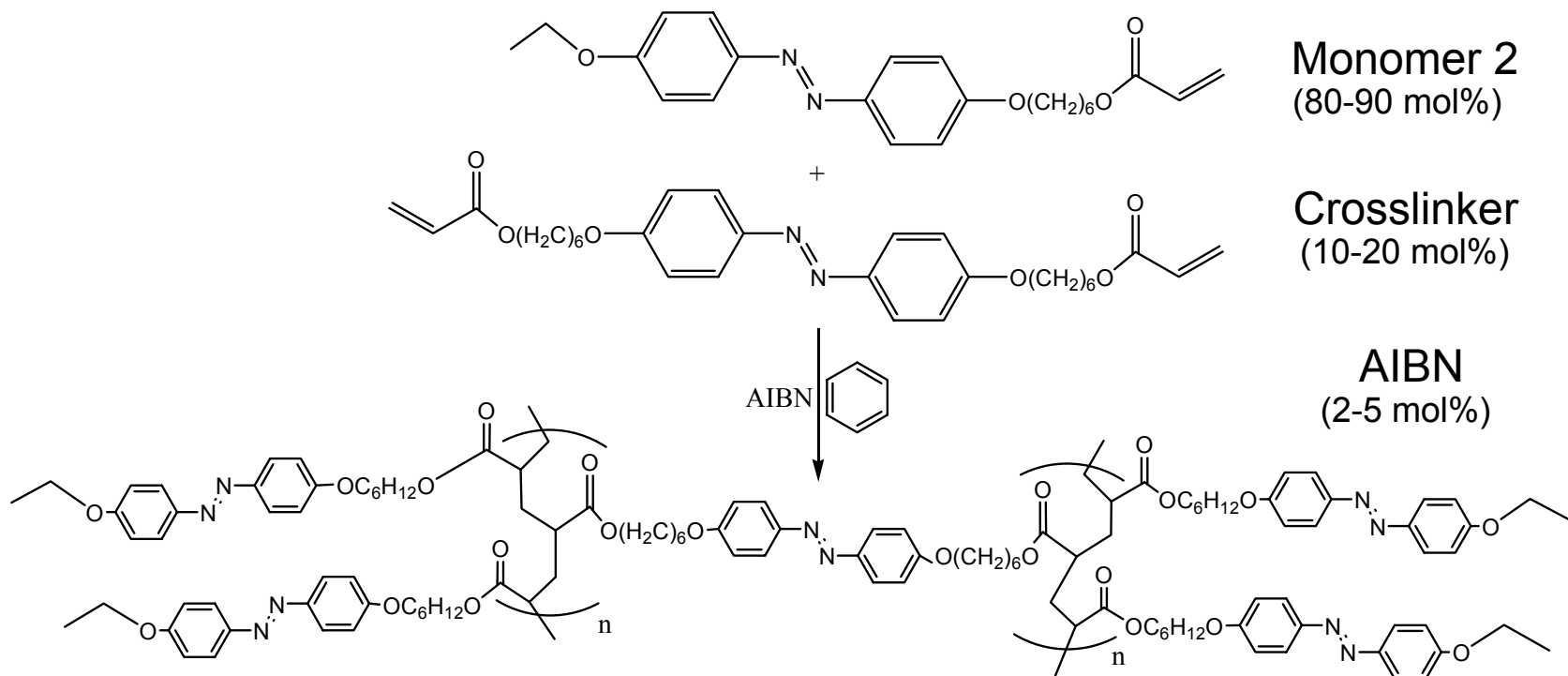


DHAB

BHHAB

Crosslinker

# Polymer Syntheses

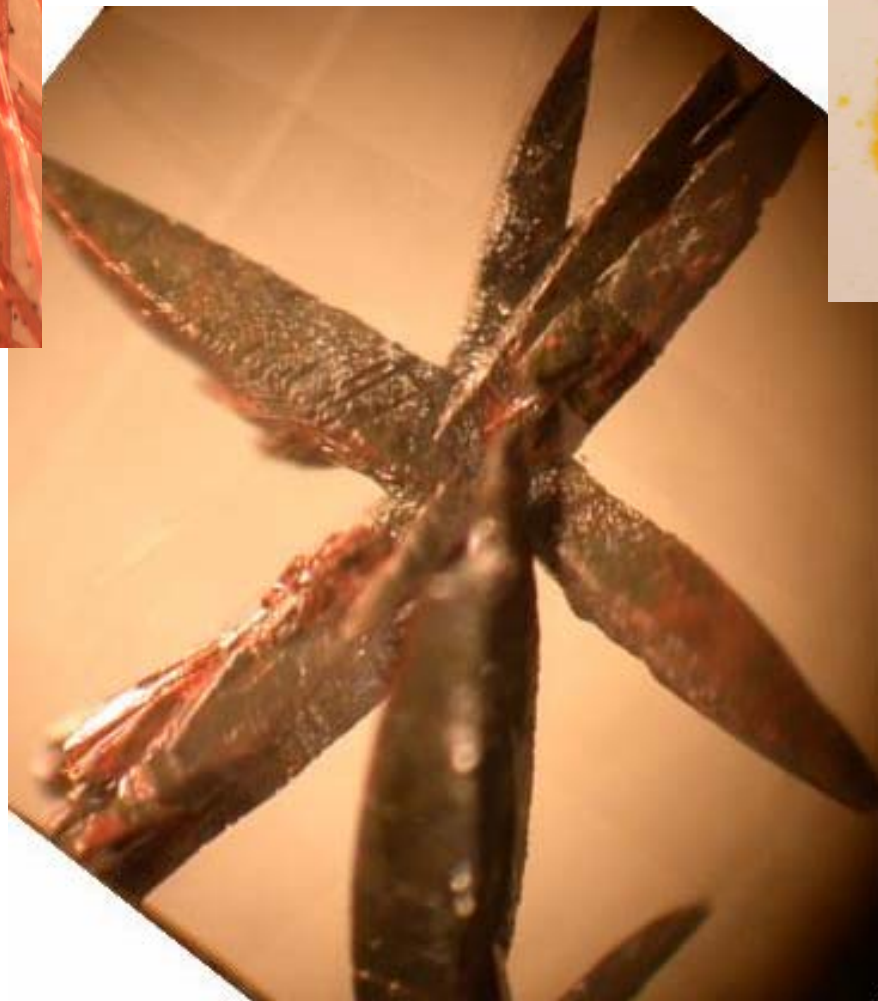
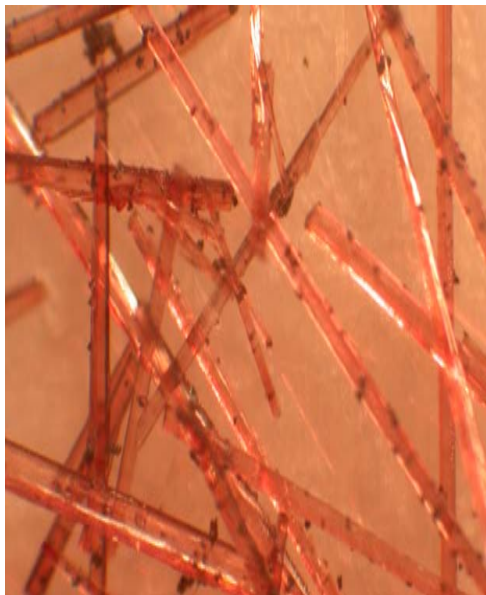


- Freeze-pump-thawed 3-5 times
- Heated in oil bath at 100 °C for 48 hours
- Solution rinsed with methanol to dissolve unreacted molecules; dried under vacuum





# Some Intermediate Azo Compounds

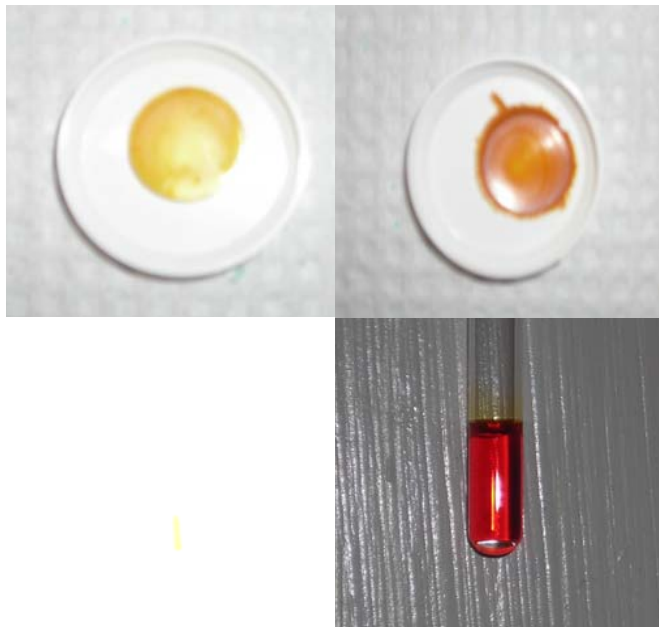
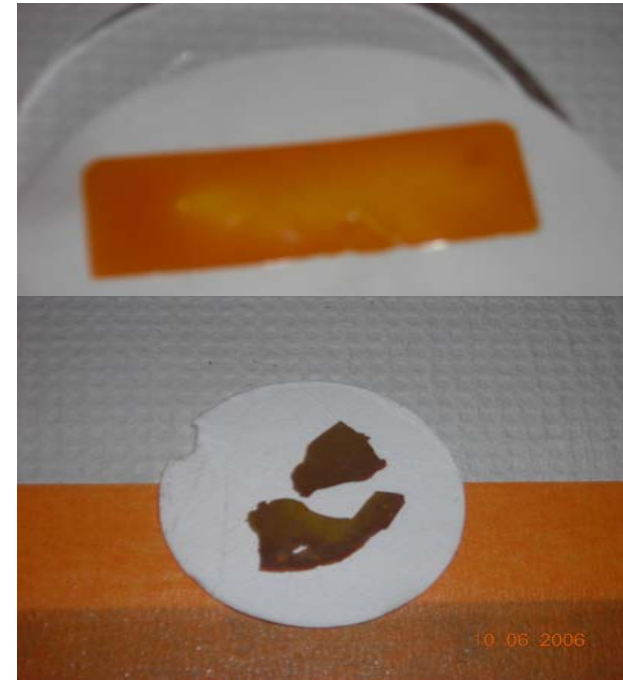


Azo Palm Tree



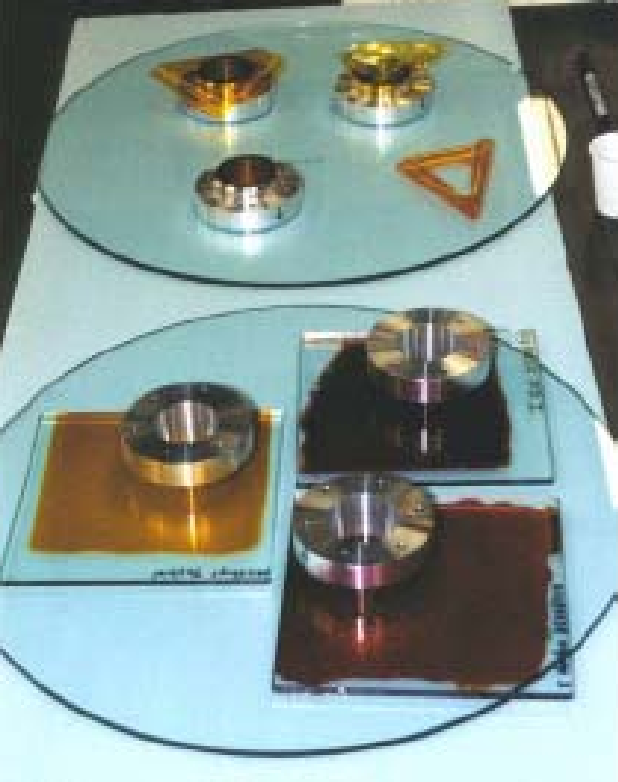
# Oversimplified Polymer Preparation

- Aligned polymer film
  - Polyvinyl alcohol spin-coated on glass slide
  - Brushed to create aligned substrate
  - Polymer dissolved in solvent; deposited onto substrate
  - Delaminated with warm water

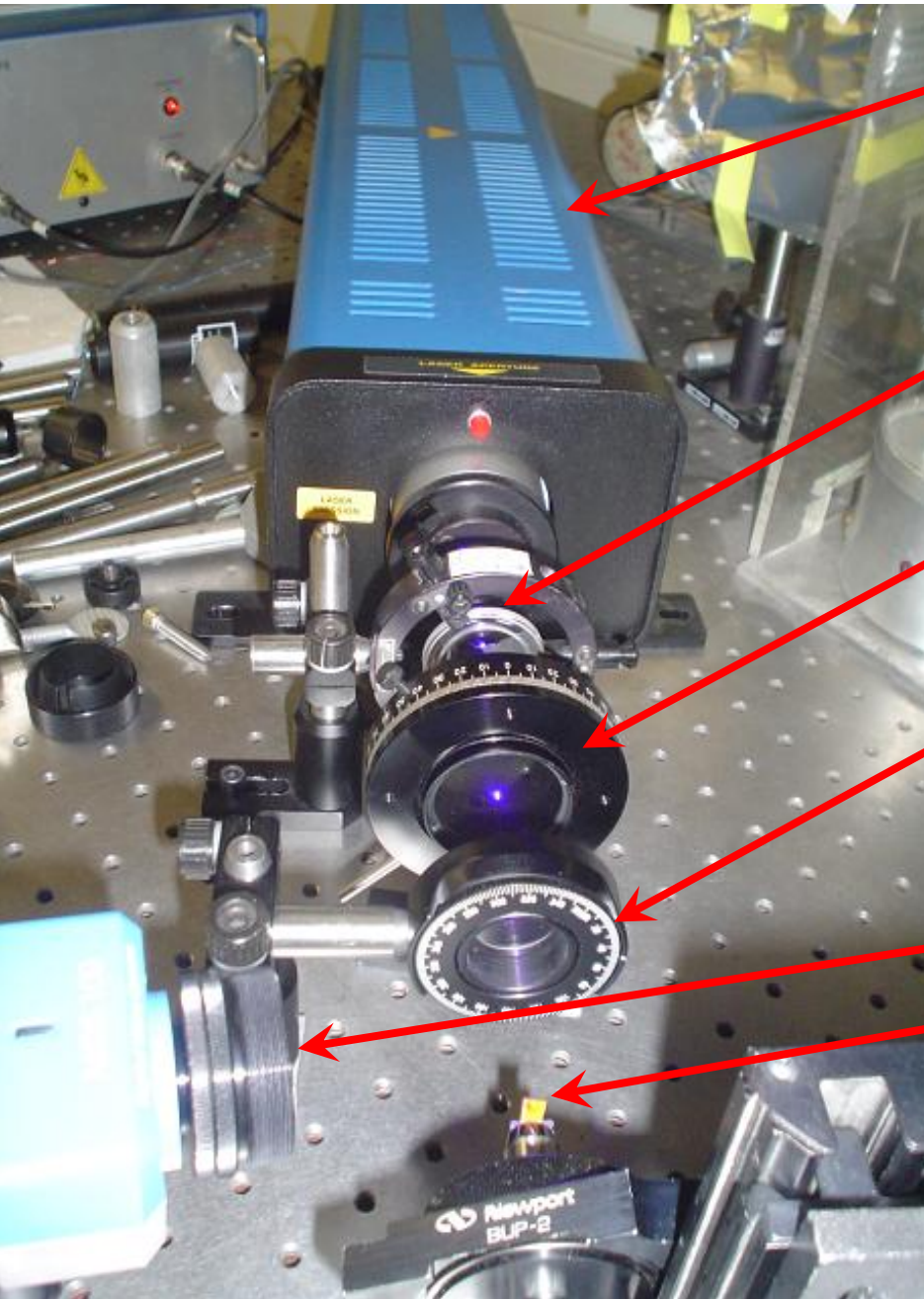


- Spectroscopic samples
  - Cast in aluminum boats
  - Spin-coated on  $\text{CaF}_2$  optical flats
  - Packed in capillary tubes
  - Dissolved in 2-methyl THF (NMR tube)

# Sample coating and Mounting



## Yes it actually works



A Helium Cadmium laser was used to illuminate samples with linearly polarized 442nm light.

A diverger reduced beam power so we would not melt samples.

A polarization analyzer ensured pure linearly polarized light

A  $\frac{1}{2}$  wave plate (optical retarder) was used to rotate the polarization direction of linear polarized light actuating the sample.

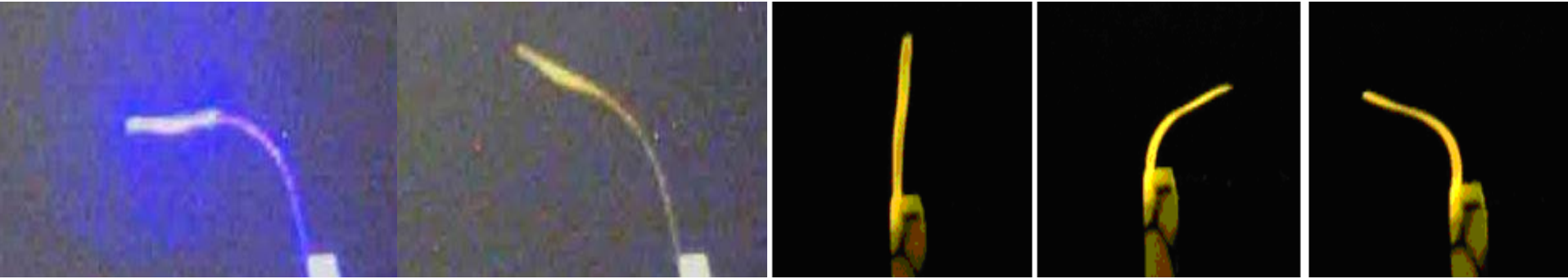
A CMOS camera digitized the live video

Various test samples were illuminated

Realtime  
Result:



# Functional Characteristics



Photonic Muscle Membrane Actuation with left IFA sample HeCd Laser (>3000 microns), right Beamco sample 140°

The laser-induced figure variations include;

- A set and forget polymer (zero power consumption mode)
- Reversible bi-directional bending of the polymer by switching the polarization of the beam in orthogonal directions
- Large deformation range, over 140° slope of deformation
- demonstrated micron scale control
- High speed of photoinduced deformations (1000 microns/second)
- One mode allows control with a single laser beam
- Stability for weeks

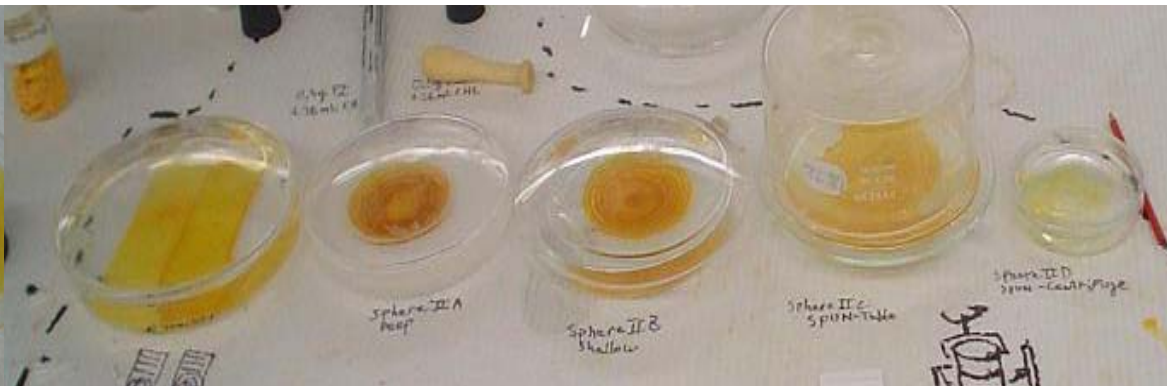
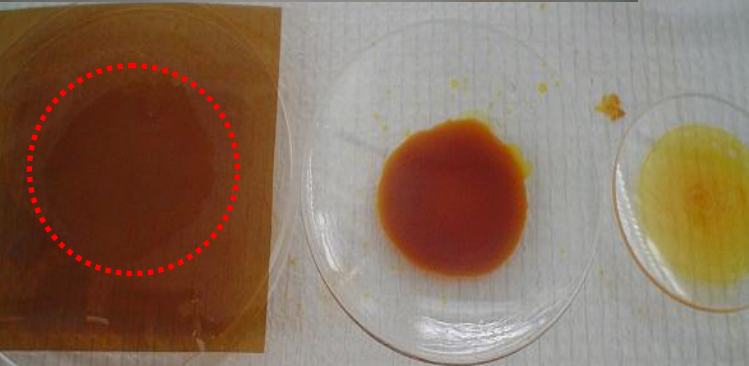
The large photomechanical effect is obtained in thin polymers (10-50  $\mu\text{m}$  thick) and is controlled with low power radiation ( $\sim 0.1 \text{ W/cm}^2$ ). (Also a fast polymer for AO?)



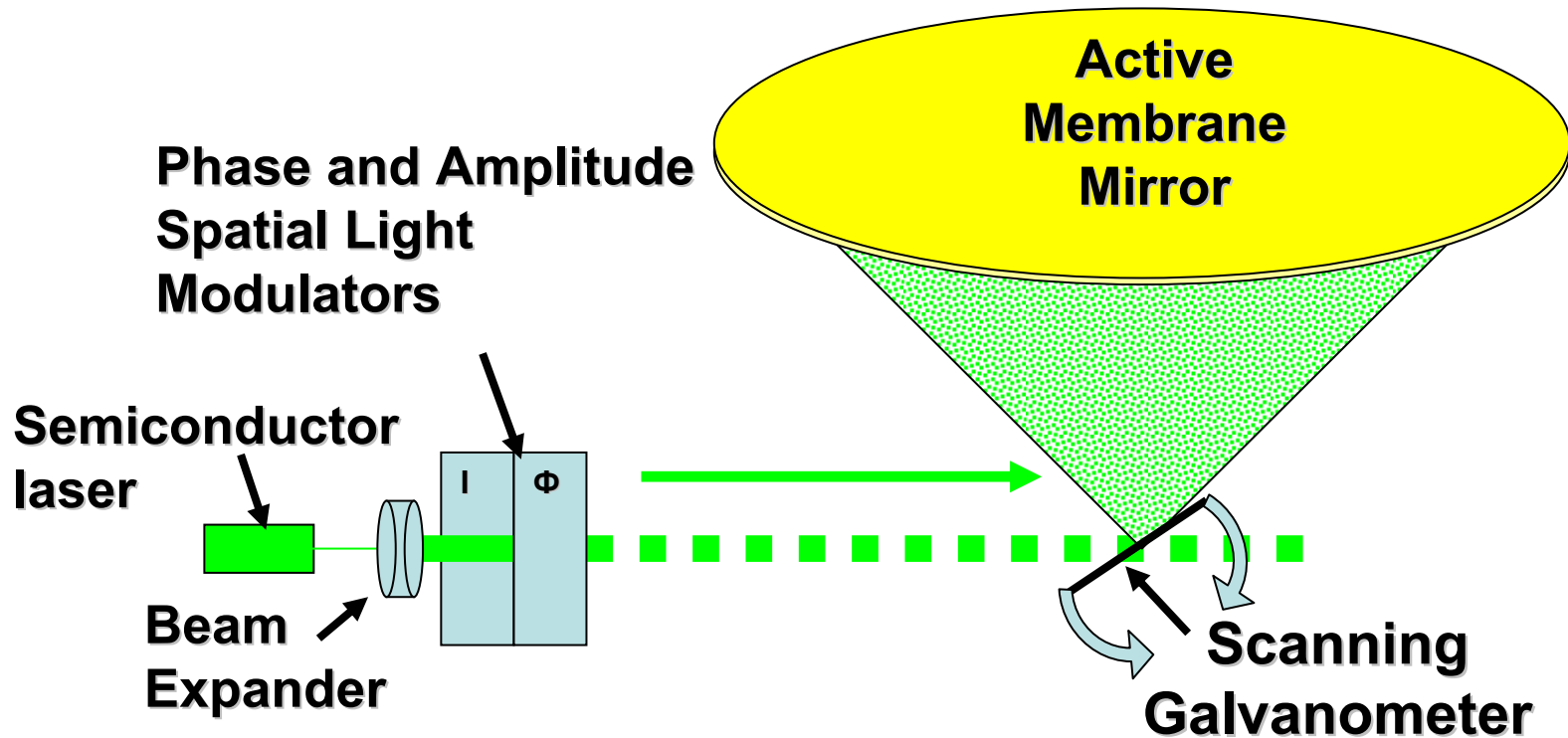
# Early prototype photonic muscle deformable mirrors

While investigating many parallel approaches such as evaporation while spinning a paraboloidal fluid surface, we seek to develop a spray on approach so that we can utilize existing membrane mirror fabrication techniques.

**Some delays. Not there yet....**

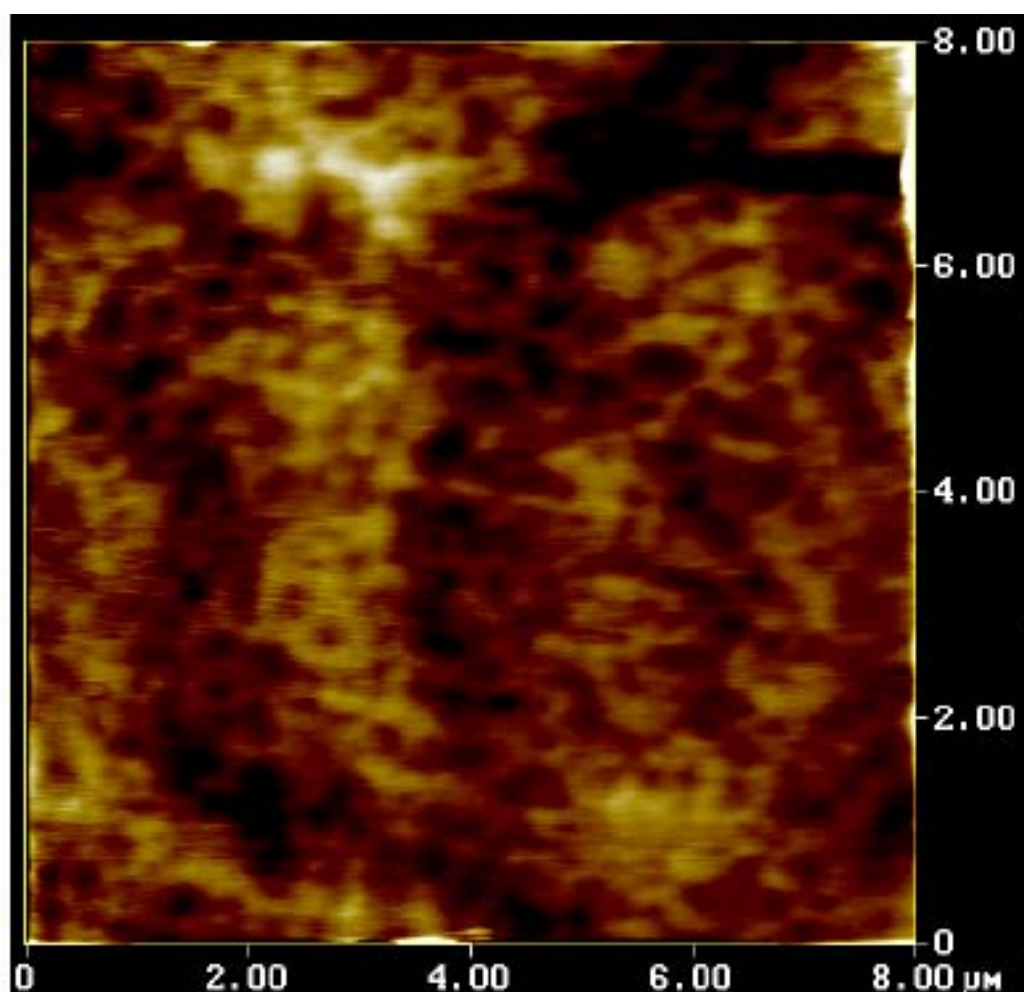


# PMT Actuation Design



**I haven't built this yet**

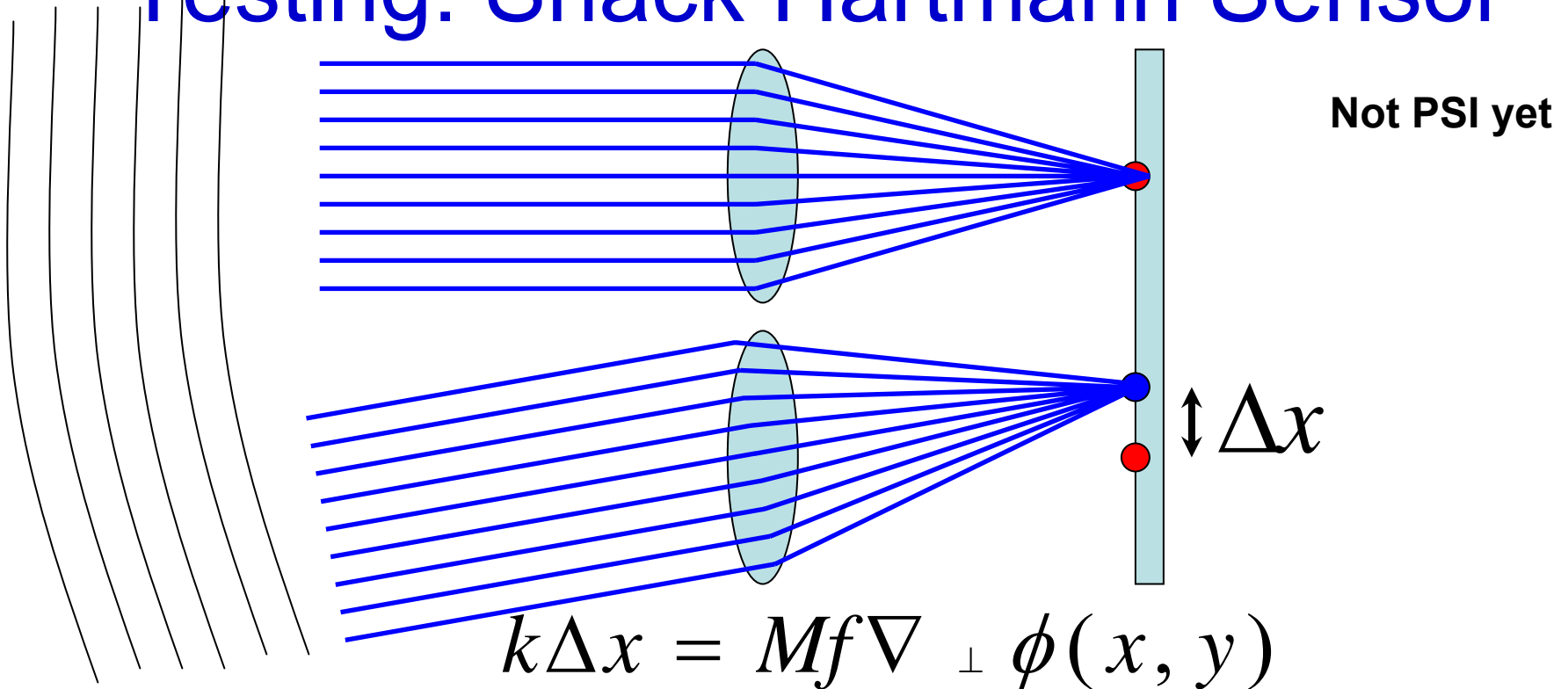
**Contrast is in part driven by not only the figure, but also the roughness (high spatial frequency) of the mirrors, the stability of the telescope system, and the basic architecture (e.g., active control)**



**We are addressing all of these issues**

- Atomic Force Microscopy**  
**RMS roughness 1nm**
- Control of dynamics**

# Testing: Shack Hartmann Sensor

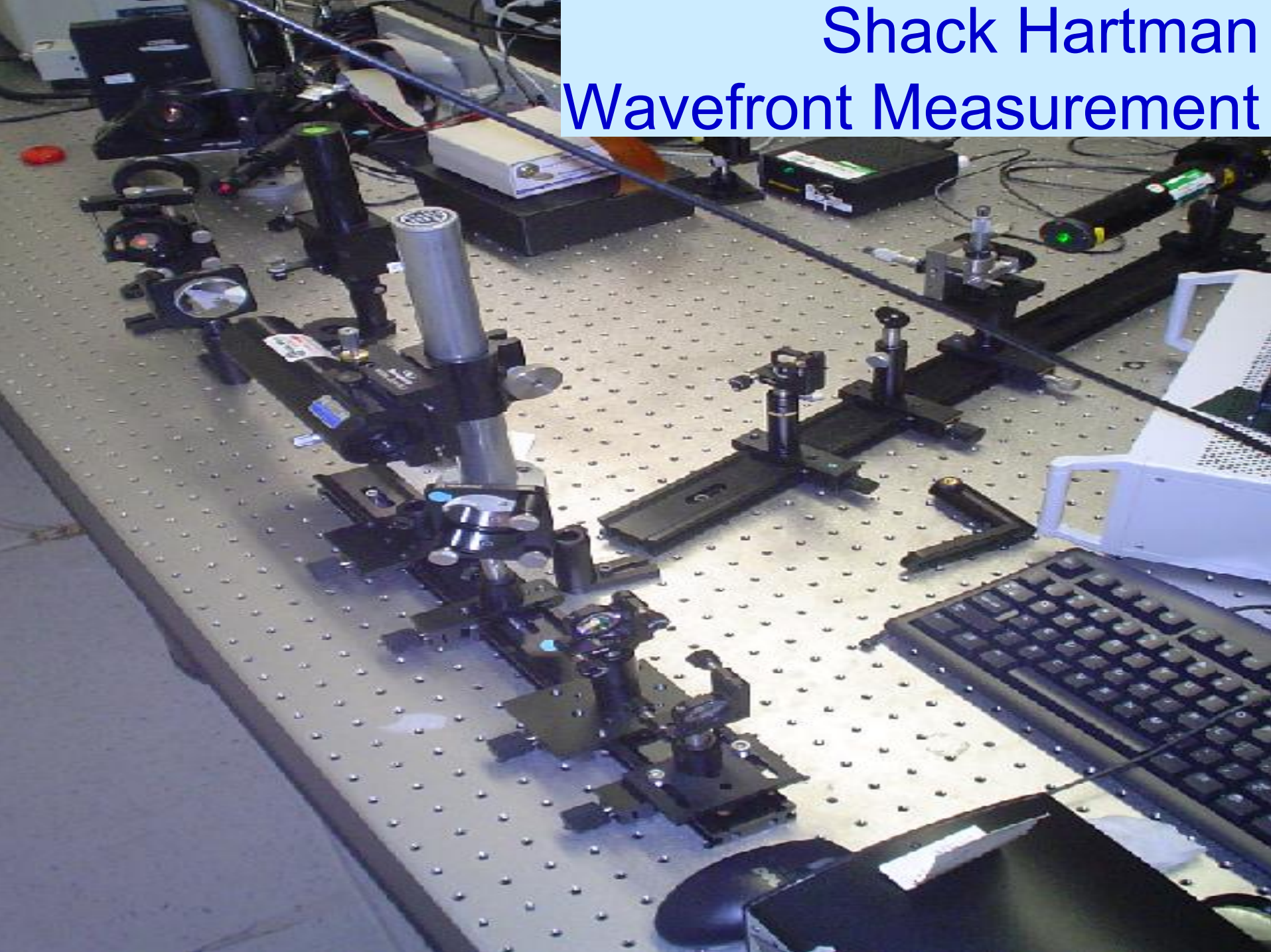


is the Relation between displacement of Hartmann spots and slope of wavefront where:

- $k = 2\pi/\lambda$
- $\Delta \mathbf{x}$  = lateral displacement of a subaperture image
- $M = f_{\text{telescope}} / f_{\text{collimator}}$  is the demagnification of the system
- $f$  = focal length of the lenslets in the lenslet array
- $\phi(\mathbf{x}, \mathbf{y})$  is the incoming wavefront

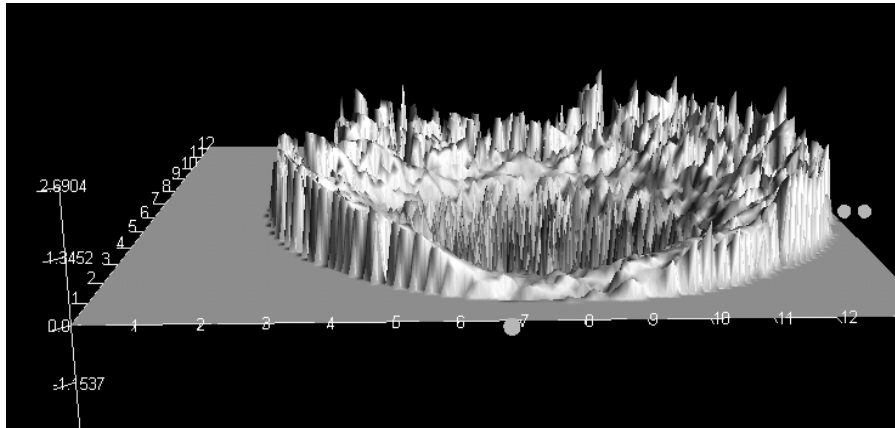


# Shack Hartman Wavefront Measurement

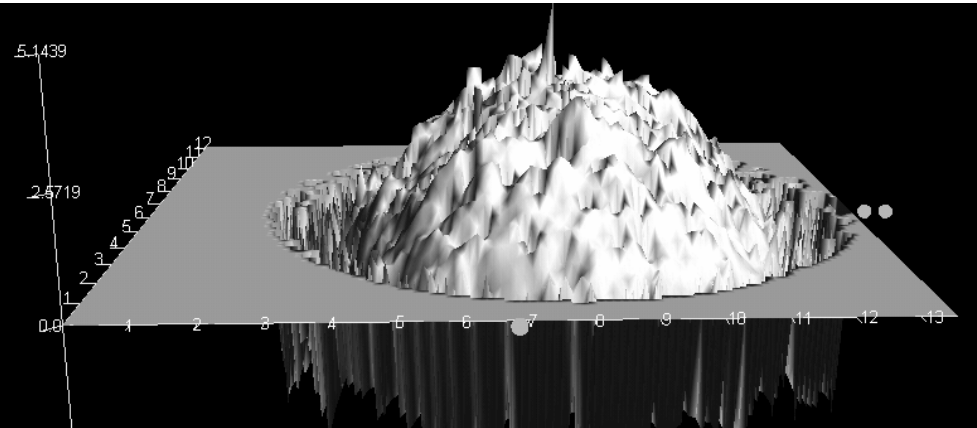


# Some results:

## Polarized illumination controls the sample



Polarized



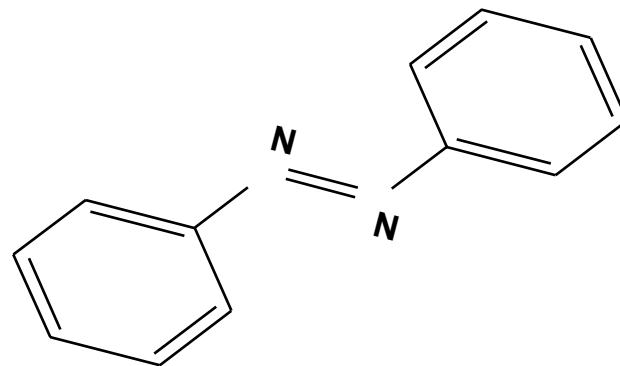
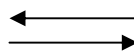
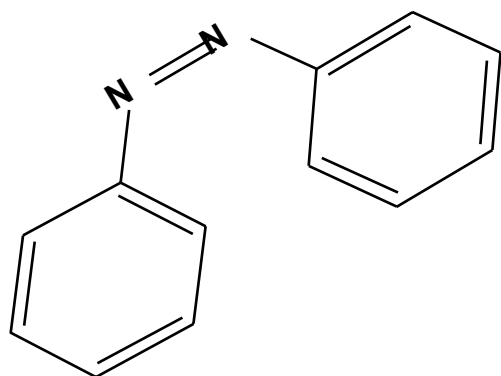
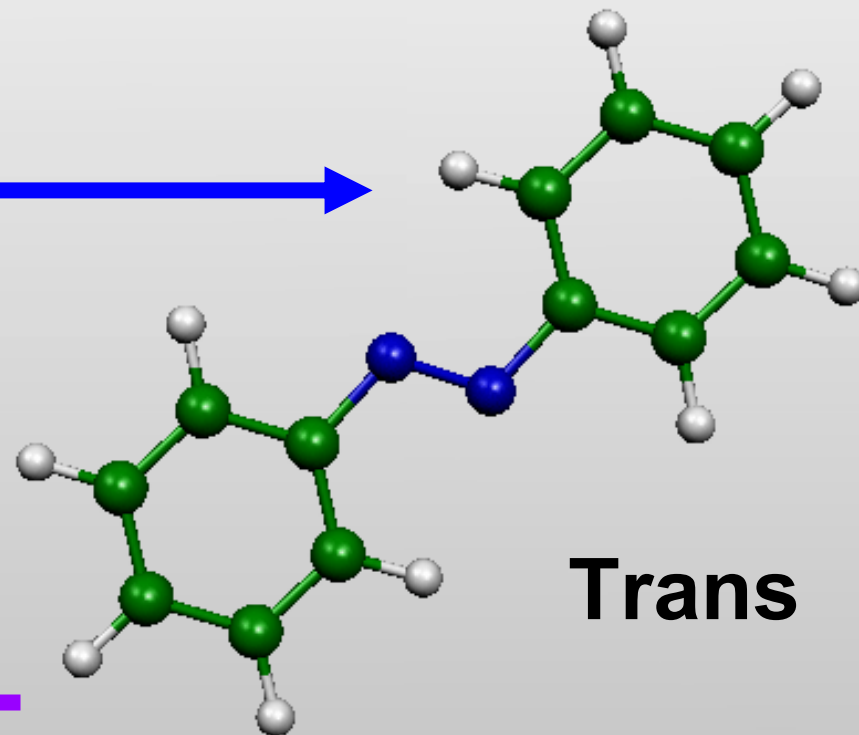
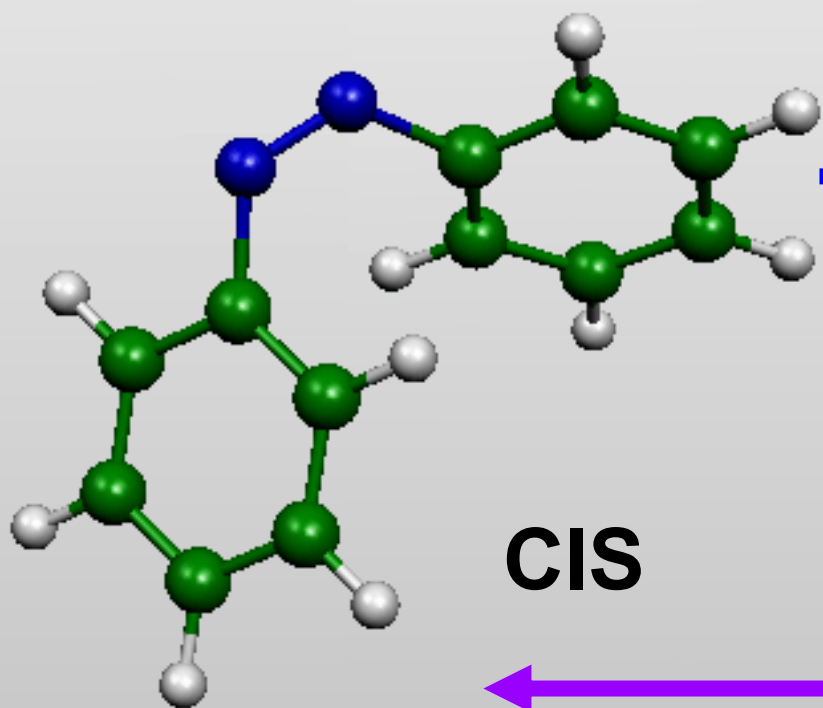
Unpolarized

In addition to large motion for control of dynamics we are also studying **micron scale control authority**

Here polarized illumination selectively flattens the sample where illuminated

# IR Vibrational modes

## Quantum *ab-initio* Calculation



# Theoretical Calculations

- Done as a basis for spectroscopic study
- Revealed frequency and intensity of molecular vibrations in infrared and Raman spectra
- Gaussian 03W / GaussView software used for calculation and analysis
- Calculations performed included semi-empirical AM1, *ab-initio* Hartree-Fock and DFT methods with a 6-31g basis set

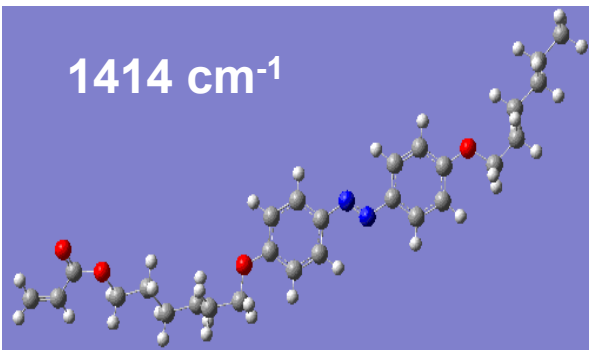
# IR and RAMAN Theoretical

## Calculations

Azo Stretches - DFT 6-31g

### trans molecules

1414  $\text{cm}^{-1}$



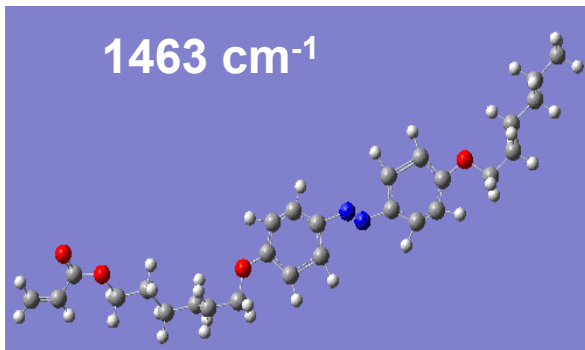
IR Intensity

2.8

Raman

Intensity  
**11356**

1463  $\text{cm}^{-1}$



IR Intensity

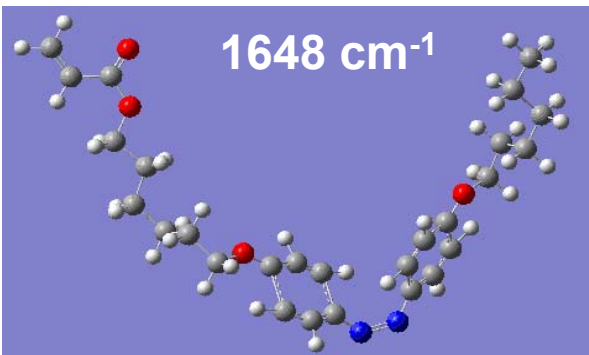
0.0905

Raman Intensity

**3088**

### cis molecules

1648  $\text{cm}^{-1}$



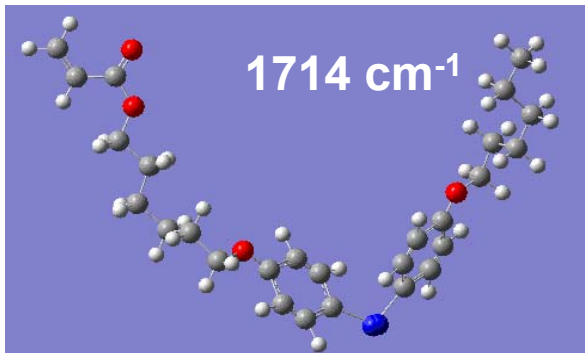
IR Intensity

116

Raman Intensity

**565**

1714  $\text{cm}^{-1}$



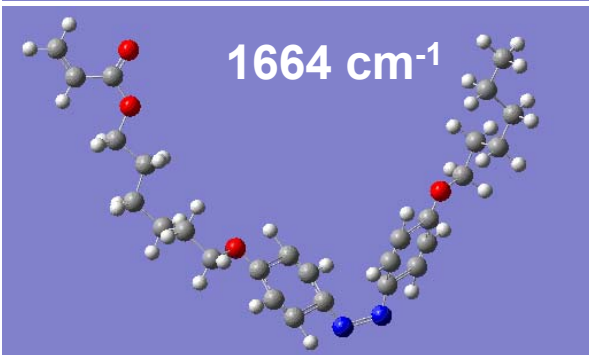
IR Intensity

14.1

Raman Intensity

**405**

1664  $\text{cm}^{-1}$



IR Intensity

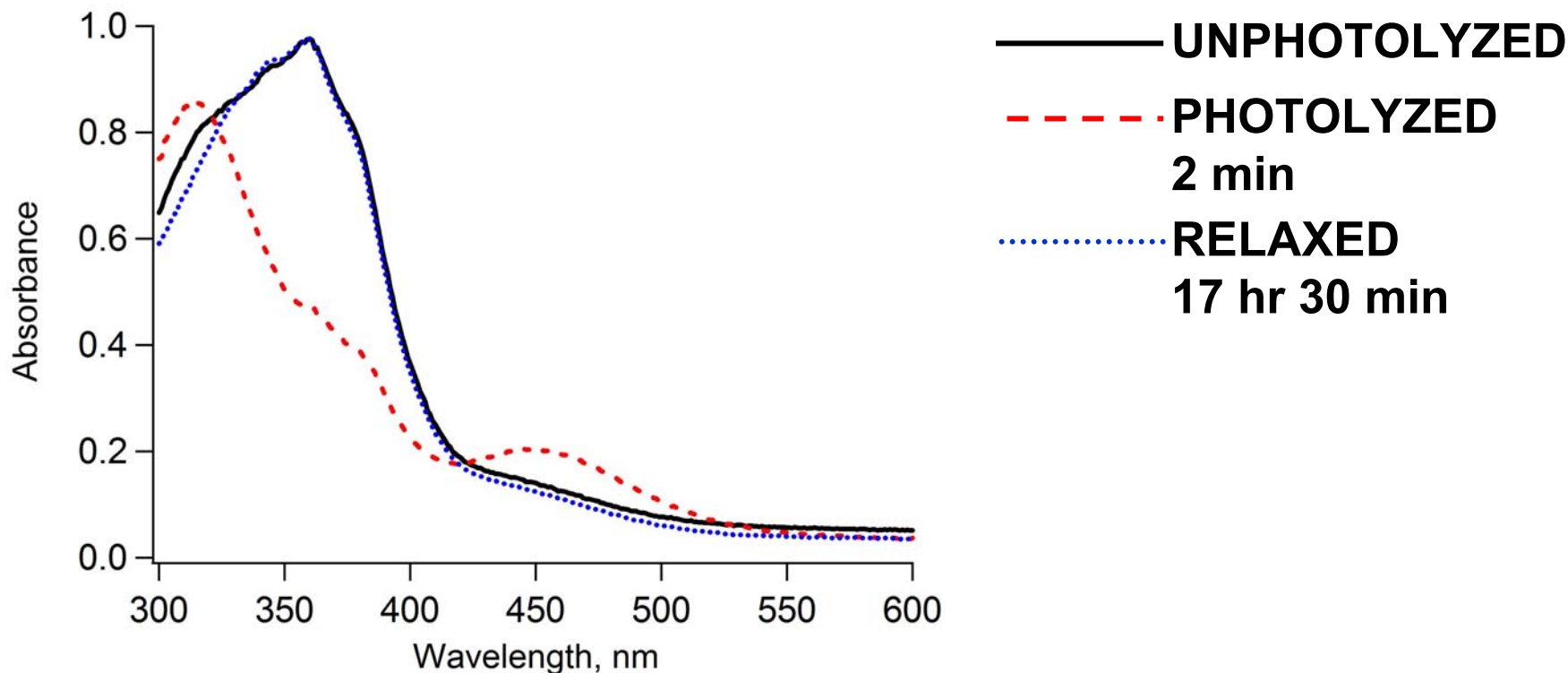
76.3

Raman Intensity

**1171**



# UV/Vis Absorption: Polymer 1



## UNPHOTOLYZED

- Characteristic *trans* peak at 360 nm

## PHOTOLYZED

- *trans* peak disappears
- Characteristic *cis* peaks appear at 315 and 450 nm

## RELAXED

- *cis* peaks disappear
- Characteristic *trans* peaks return to original unphotolyzed intensity

# FTIR Measurements



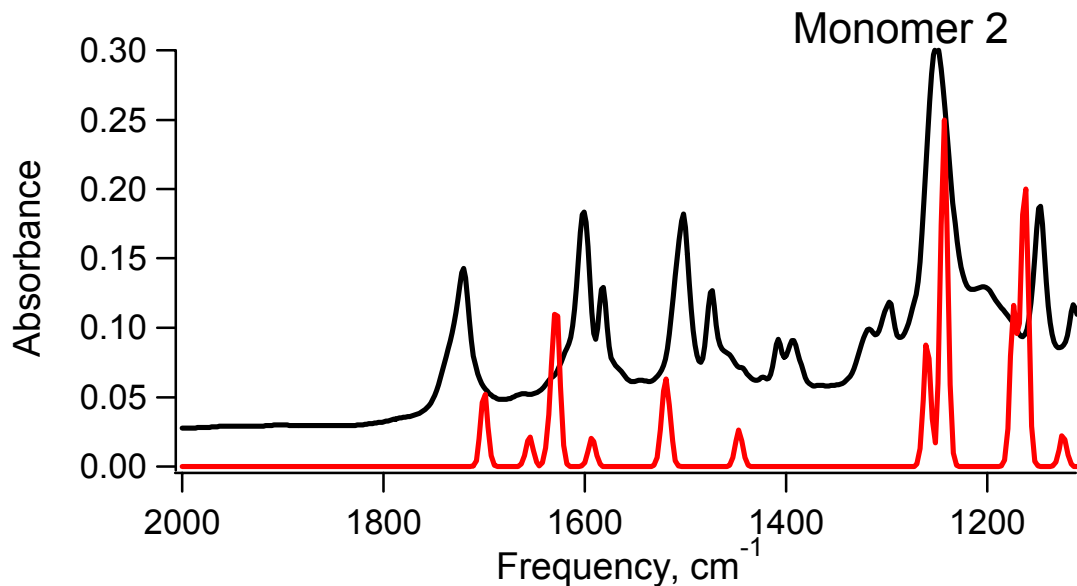
Nicolet Nexus 870 Spectrometer

- 128 scans
- 4  $\text{cm}^{-1}$  resolution
- DTGS detector

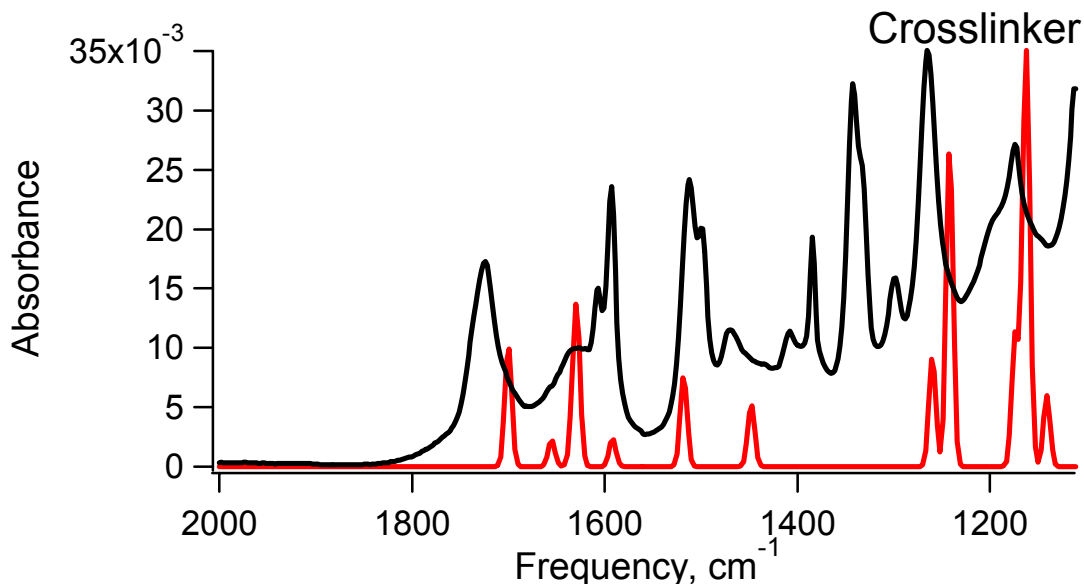
## Sample Preparation

- Polymer films cast in aluminum boats
- Polymer spin-coated on  $\text{CaF}_2$  flats (1111-4000  $\text{cm}^{-1}$ )
- Precursors mixed with KBr, dried, pressed into optical pellet (400-4000  $\text{cm}^{-1}$ )
- Sample chamber purged with dry  $\text{N}_2$  to eliminate  $\text{CO}_2$  and  $\text{H}_2\text{O}$

# Experimental vs. Theoretical – Infrared



- *trans* spectra for monomer 2 and crosslinker show many similarities between experimental and theoretical

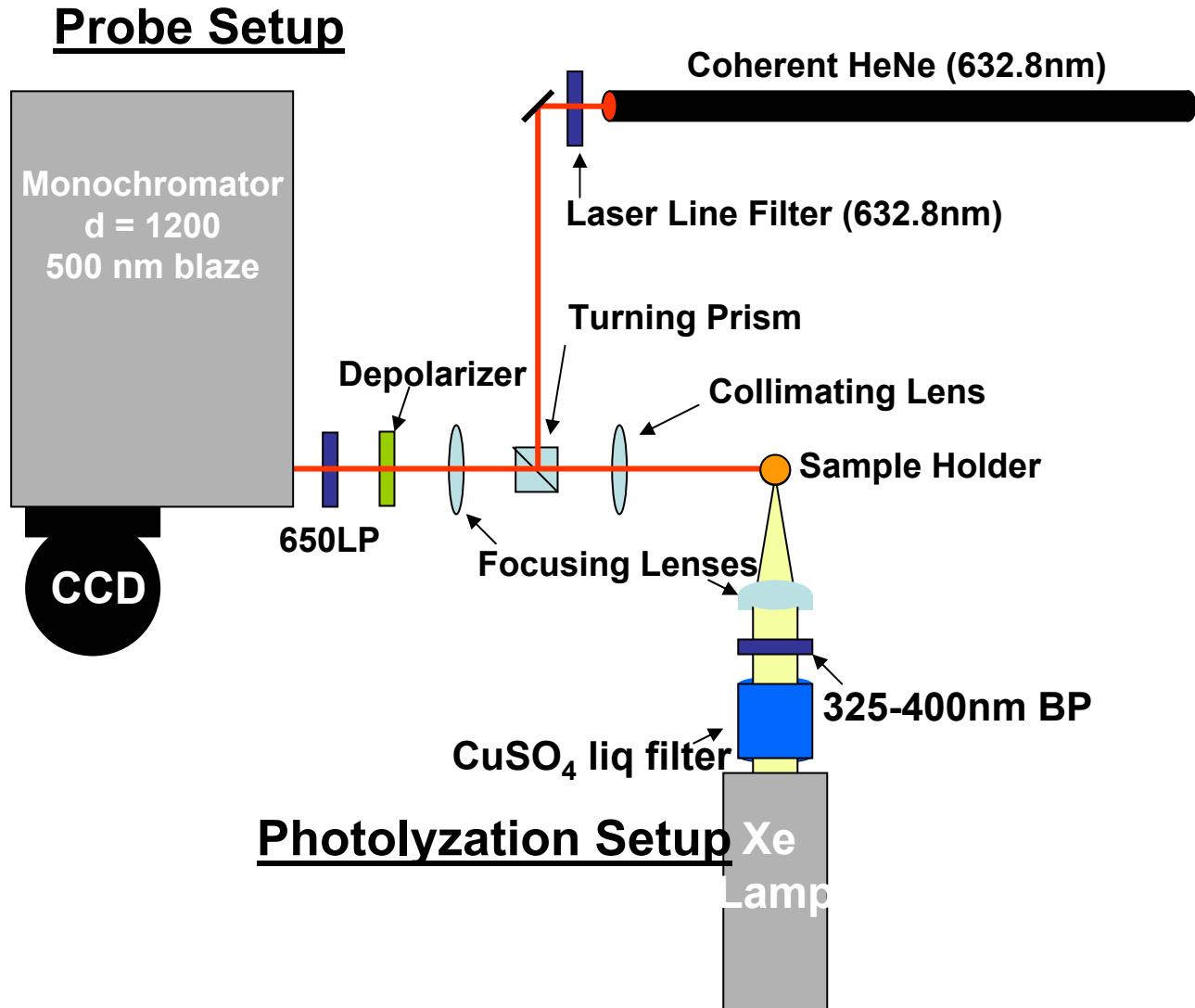


- Theoretical frequencies slightly different than experimental

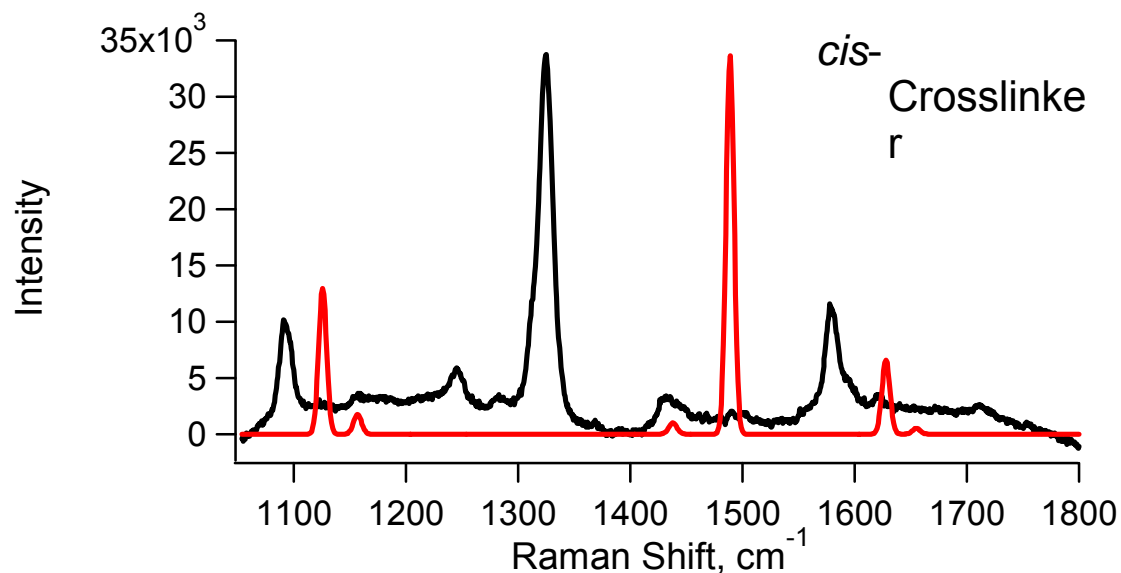
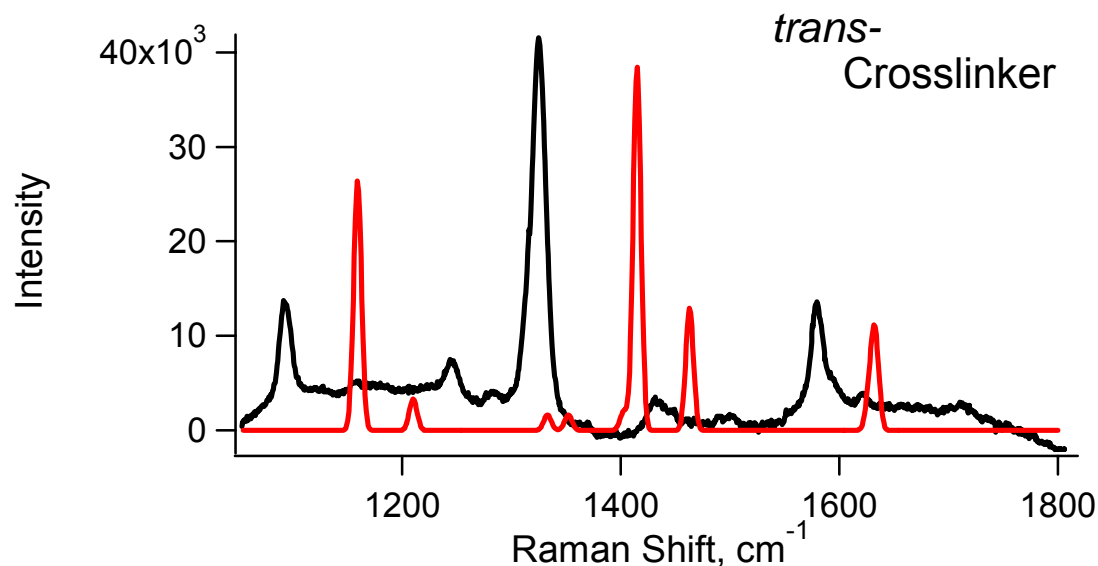
- Crosslinker: major peak in experimental spectrum not predicted ( $1343 \text{ cm}^{-1}$ )



# Raman Experimental Setup

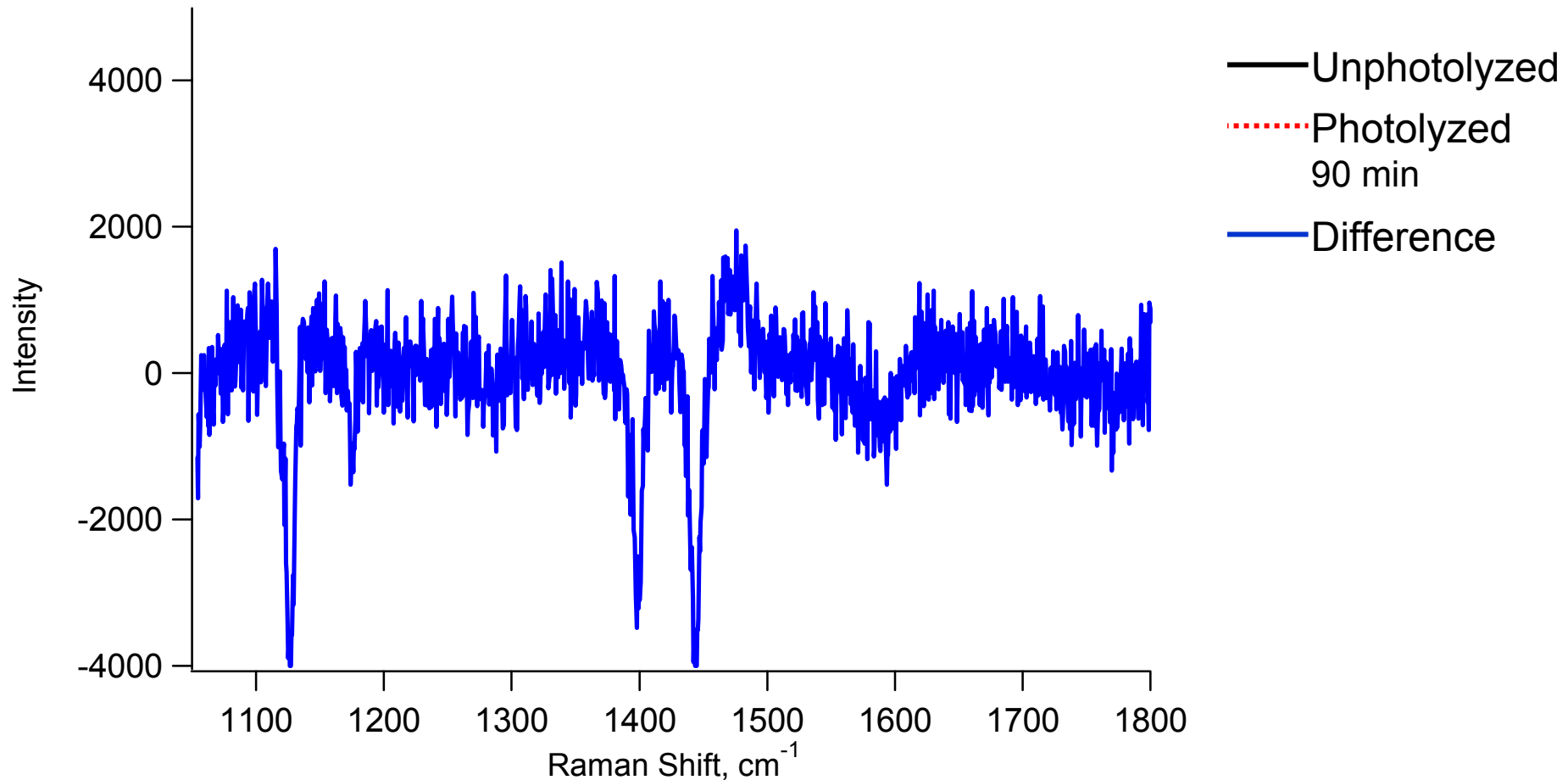


# Experimental vs. Theoretical – Raman



- *trans* spectra for monomer 2 show many similarities between experimental and theoretical values
- Again, theoretical frequencies are slightly greater than experimental values
- Experimental spectrum after photoisomerization indicates little change; theoretical *cis* spectrum predicts shift in major peak
- Slight decrease in peak intensity is observed

# Photolyzed Raman: Polymer 2



1. Unphotolyzed spectrum characteristic of *trans* isomer; major peaks identified
2. Upon photoisomerization, the intensity of characteristic *trans* peaks decreases
3. Grow-in peak observed near 1474 cm<sup>-1</sup>, better identified in difference spectrum

**Summary: IF we can do it-**

## **What's in it for NIAC and the Scientific Community?**

**Large membrane optics can enable innovative missions for imaging the cosmos, resolving spectral and spatial details of exosolar planets and searching for life, including evidence of Earth's Origins, while substantially reducing mass, launch and fabrication costs.**

## **Specific Grand Challenges Addressed Will Be:**

- **Innovative methods for understanding and imaging the cosmos**
- **Novel searches for life—including evidence of Earth's Origins**
- **Lightweight construction and fabrication of space systems**
- **Missions such as Terrestrial Planet Imager require lightweight mirrors with minimum diameters of 20 to 40 meters.**
- **Missions like TPI will be feasible.**

**•U factor**

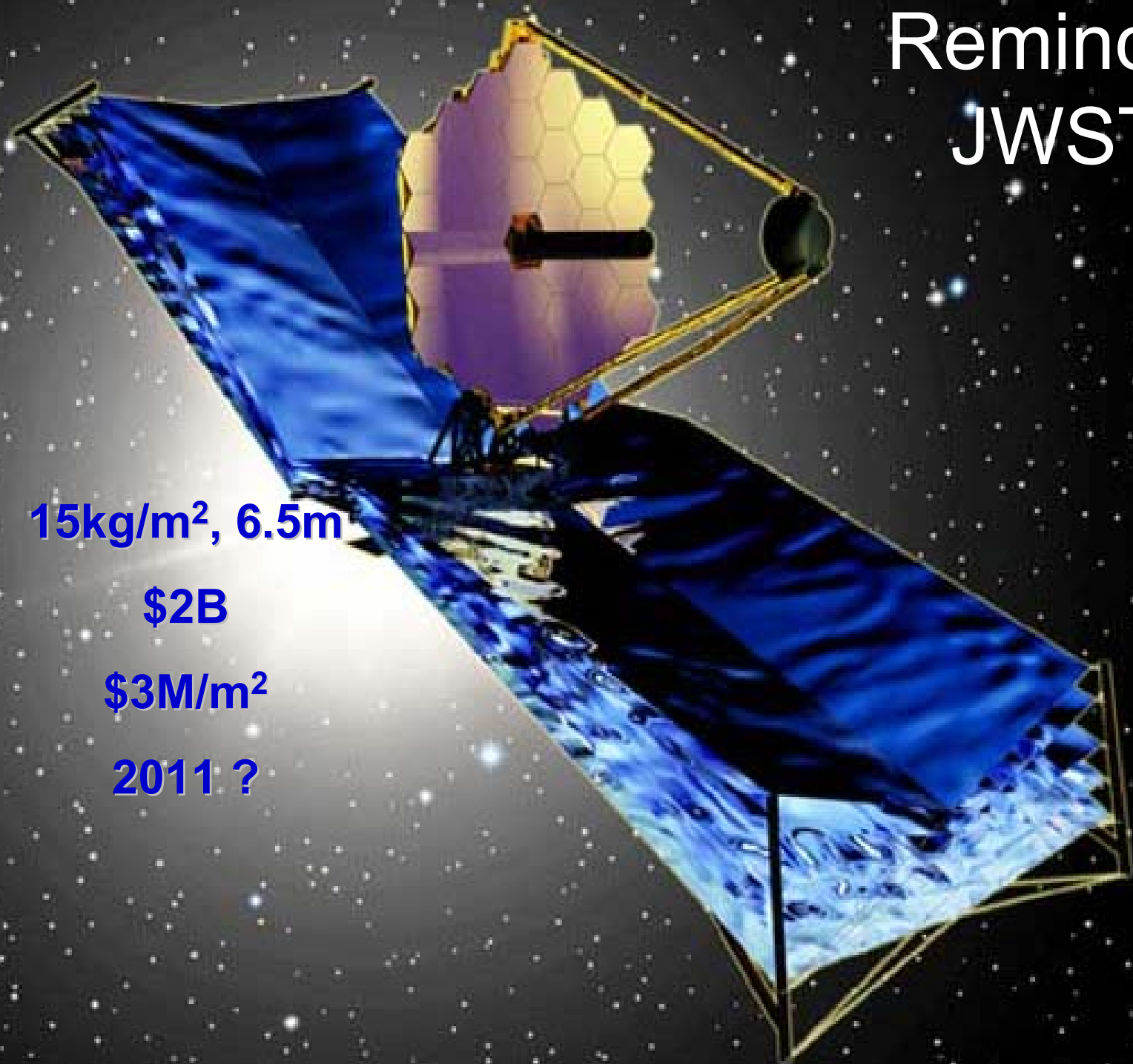
# Reminder JWST

**15kg/m<sup>2</sup>, 6.5m**

**\$2B**

**\$3M/m<sup>2</sup>**

**2011 ?**



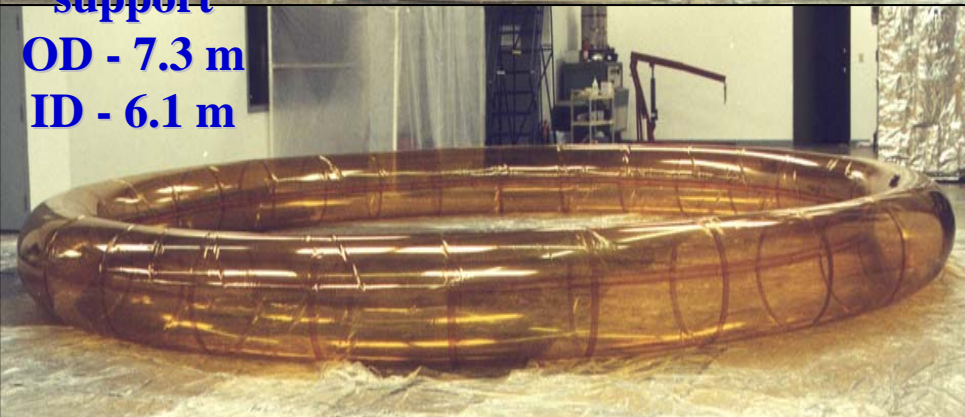


# NIAC Phase III Telescope?

**Vision:** to make a 6 meter diameter *active* mirror that weighs 3 kilograms not 500 kilos and costs 1% of current technology



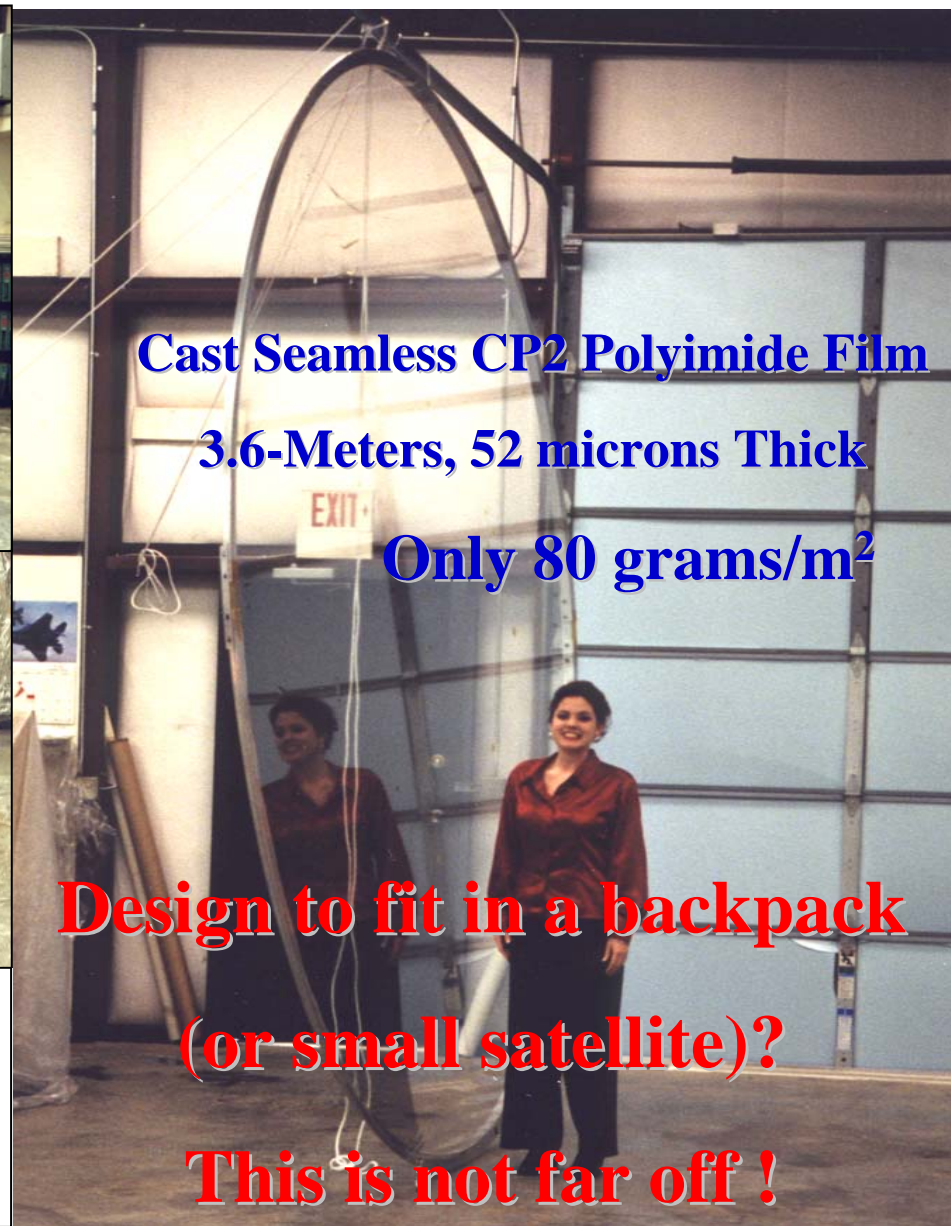
**Toroidal  
support**



**OD - 7.3 m  
ID - 6.1 m**



**Same size as  
NASA  
JWST  
Telescope**



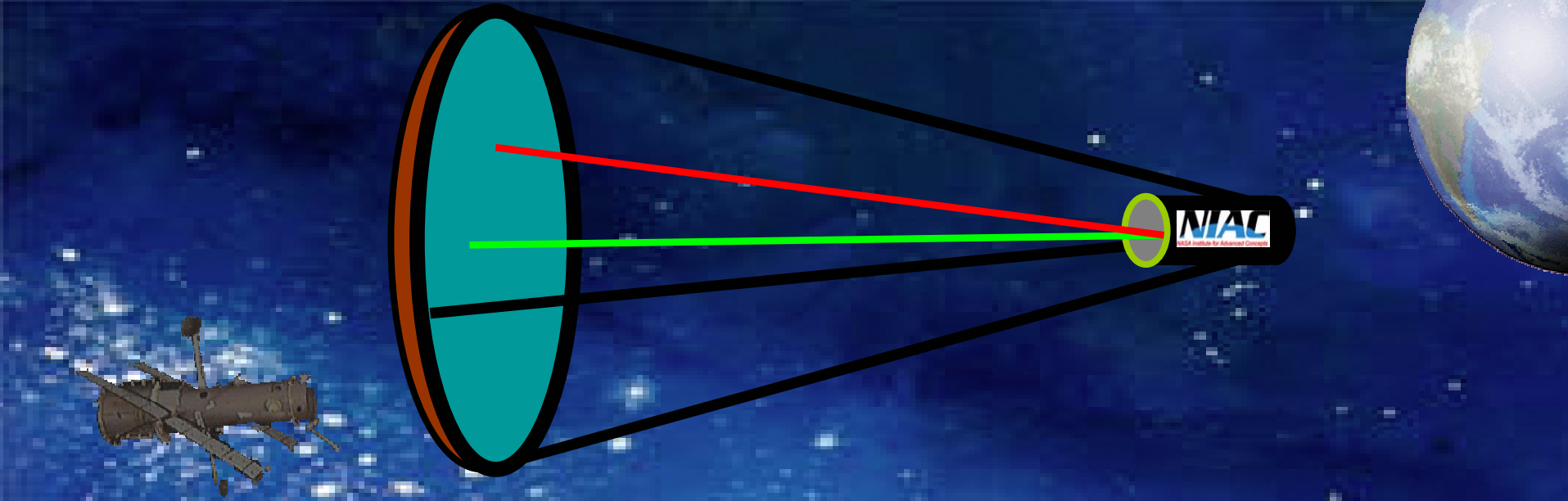
**Cast Seamless CP2 Polyimide Film**

**3.6-Meters, 52 microns Thick**

**Only 80 grams/m<sup>2</sup>**

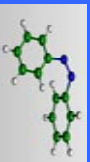
**Design to fit in a backpack  
(or small satellite)?**

**This is not far off !**



**We have made progress in engineering, synthesizing, fabricating and understanding several new materials, and on metrology design and testing**

**We have results which indicate our goals to provide optically controlled corrected active mirrors (OCCAM) may be achievable**



**I am grateful to NIAC for funding this work. Thank you.**

**PI Contact: Joe Ritter      University of Hawaii Institute for Astronomy  
4761 Lower Kula Road, Kula, HI, 96790   Joe.Ritter@yahoo.com   808-268-2622**

# Can we do better?

## Ideas for New Materials

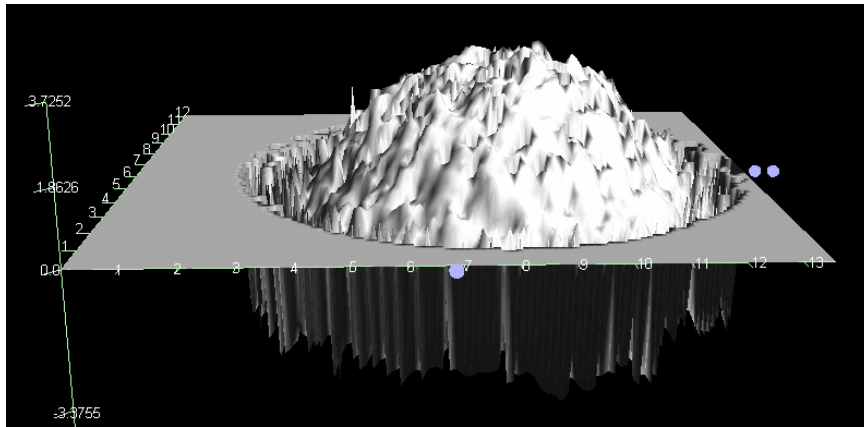
**Design, synthesize, optimize and test hybrid electrically and optically actuated active substrates which use**

- 1) Combined Cis-Trans/Twisted Intermolecular Charge Transfer (CT-TICT) materials (EPP1)**
- 2) Optoelectronically modulated bending crystal conducting polymers: bending crystal rhodium-quinones in conducting substrate (EPP2)**
- 3) UV resistant APPO based azo polymer?**

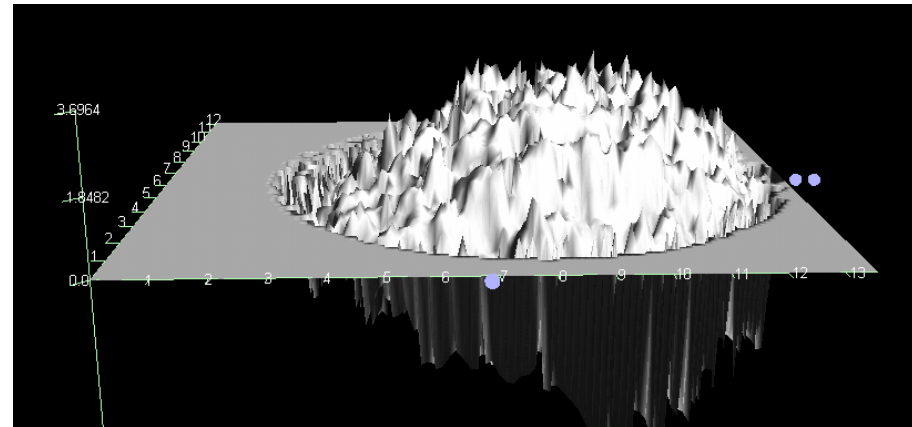
**Goal:** Understand and harness electro-optically induced molecular forces and distortions to create the first hybrid high pixel density dual mode electro-optically addressable active optic.



# OPD reconstructed with and without illumination for actuation



Illuminated Unpolarized



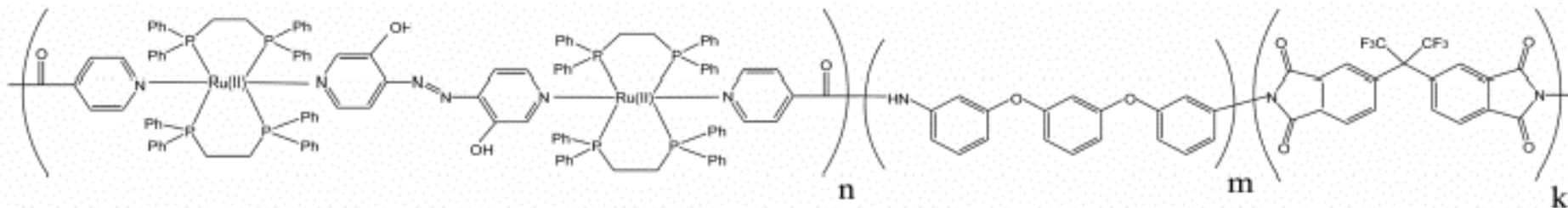
Not Illuminated

# Hybrid Membrane optics

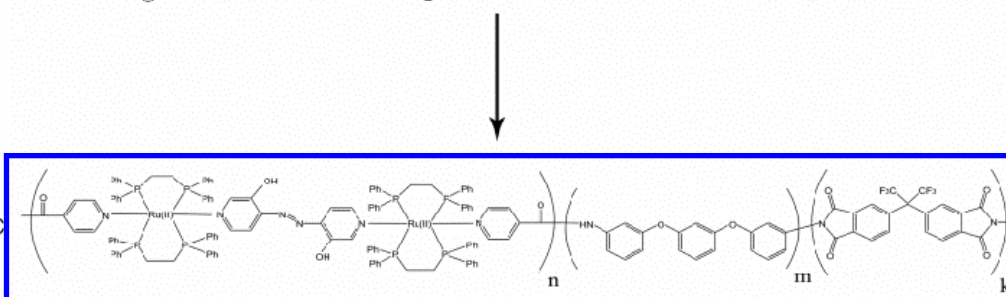
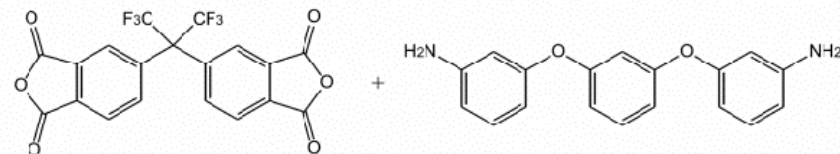
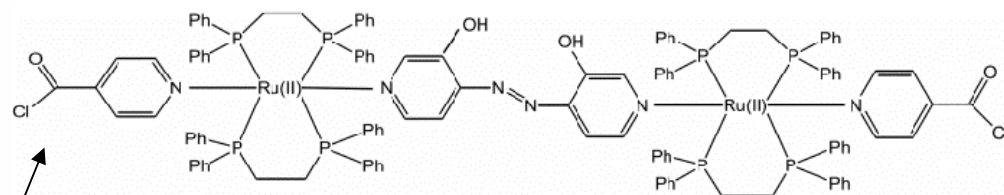
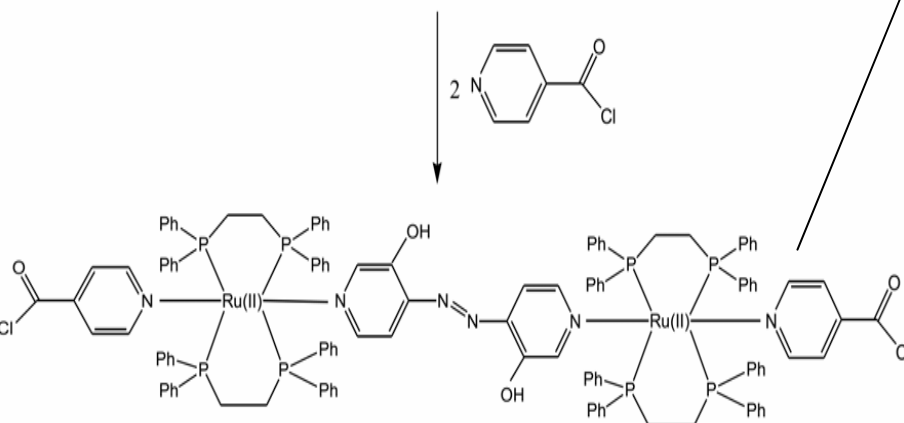
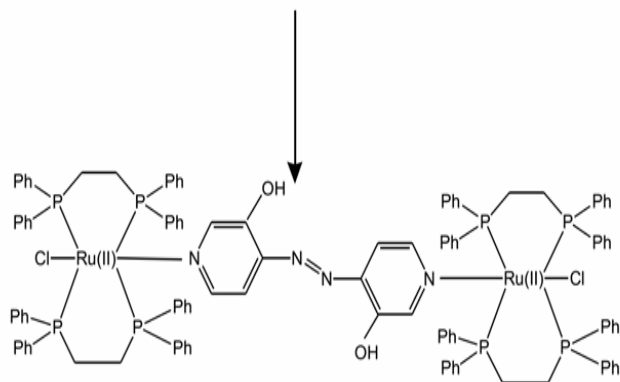
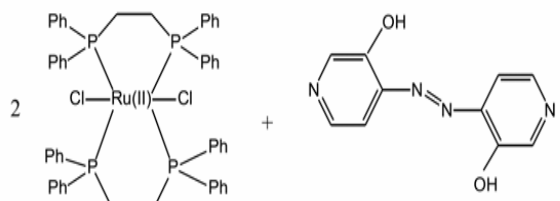
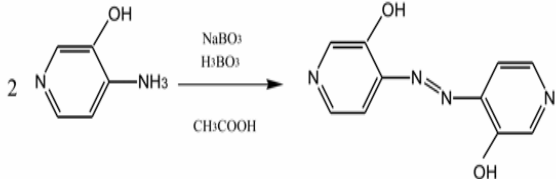
- **CT-TICT**

**(Cis Trans with Twisted Intermolecular Charge Transfer)**

- Approach : combine the switchability of a cis-trans isomerization with the electrostatic “power stroke” involved in a TICT.
- A double bond in the ground state of the molecule is broken in the excited state and the molecule is able to rotate freely between the cis and trans states.
- As the moiety relaxes back to the ground state the molecule decays back to the ground state the double bond is reformed locking the polymer into a set geometric configuration.



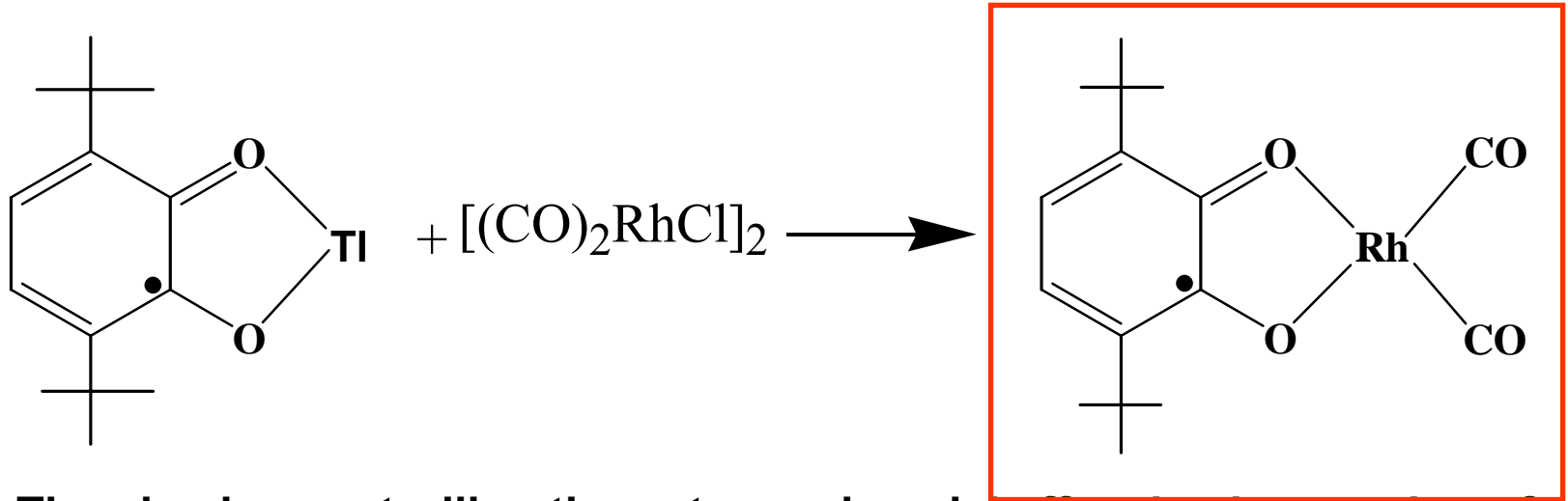
# Synthesis of the photomechanical Combined Cis – Trans/TICT moiety



# Optoelectronically Modulated Bending Crystalline Membrane Active Optics

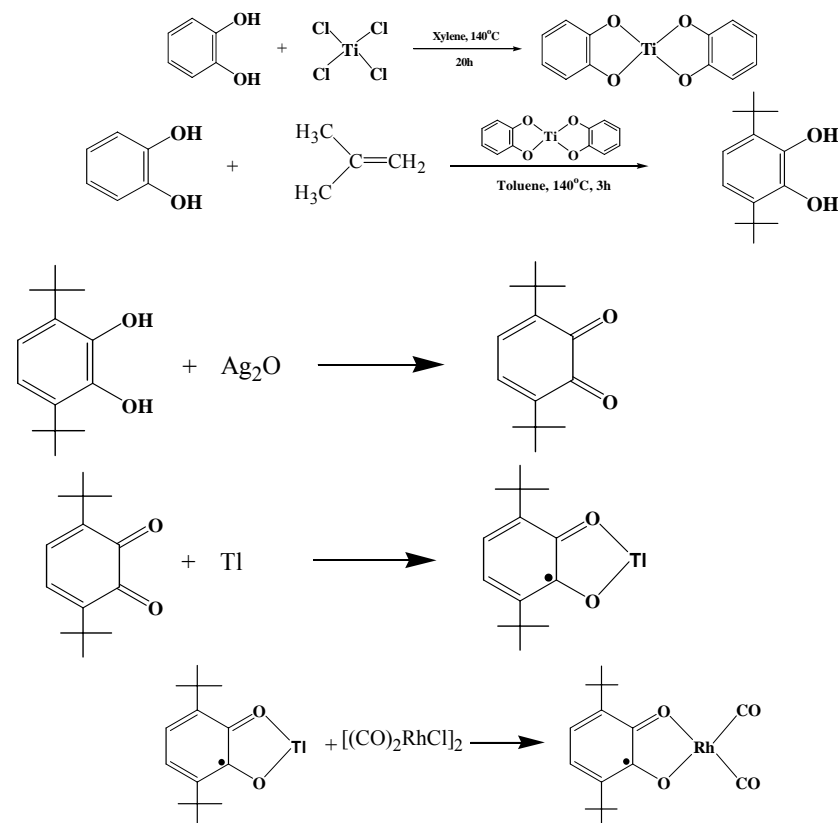
## • Rhodium Quinones

- Linear stacks of Rh(3,6-di-*tert*-butyl-semiquinone)(CO)<sub>2</sub> bend reversibly when exposed to near-IR radiation.

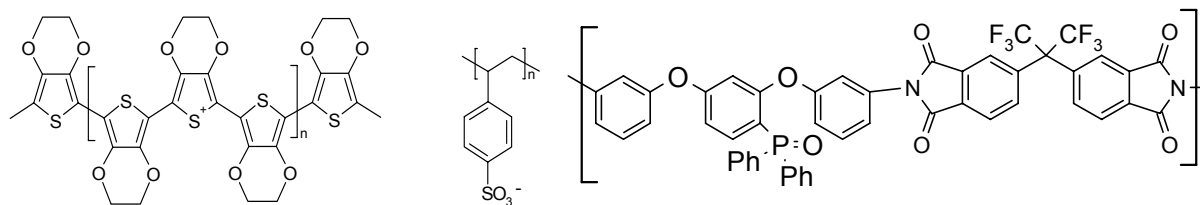


- The physics controlling the opto-mechanical effect is the creation of electron/ hole pair excitons in the backbone of the chain causing an elongation of the rhodium semiquinone bond and a contraction between rhodium centers.
- It is likely that such a physical property can be actuated electrically as well as optically
- We propose to optically and electrically actuate the bending effect seen in these materials by combining them with a conductive polymer which has been optimized for space based applications.

# Synthesis of the Electro-Photomechanical Complex



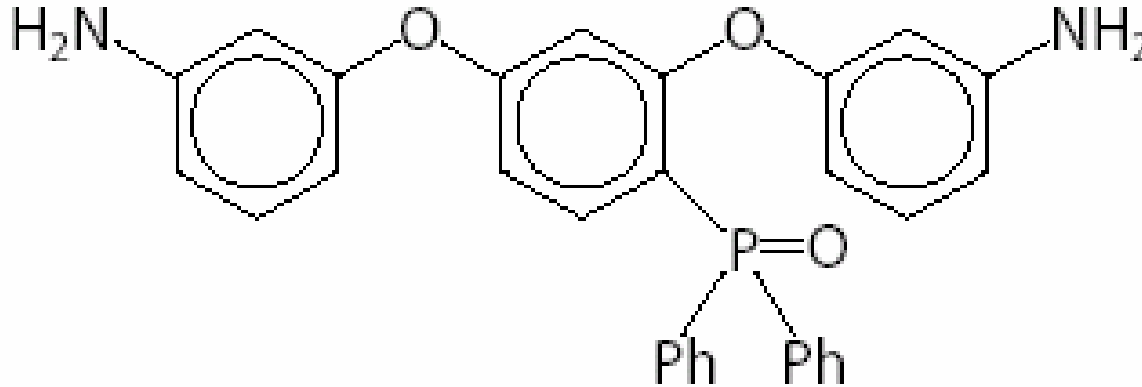
**Total synthesis of the photomechanical complex  $\text{Rh}(\text{CO})_2(3,6\text{-DBSQ})$**



**Eleflex (left) and TOR-NC (right) provide the matrix for the Rhodium quinones**

# UV resistance?

## Synthesis based on APPO



### TOR-NC

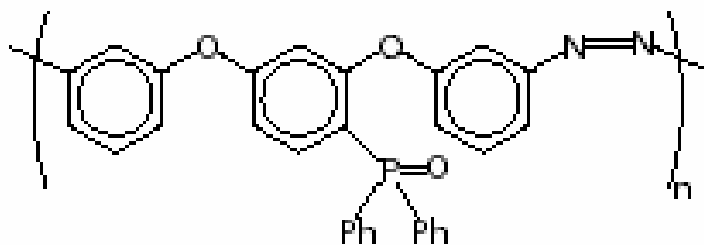
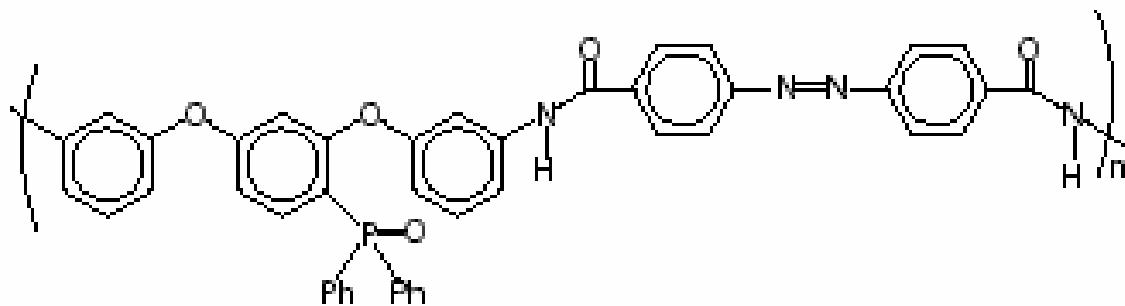
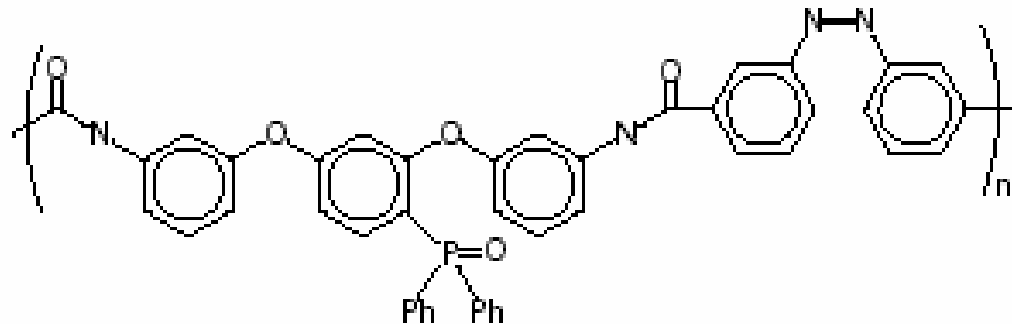
**Compared to Kapton (a standard polymer used in space) it is 3.5x more resistant to AO.**

**AO degrades the TorNC and reacts with it creating a inorganic Phosphene oxide layer which protects the rest of the material**

**This was originally develop by John Connell at NASA LaRC Composites and Polymers Branch and is licensed to Triton.**

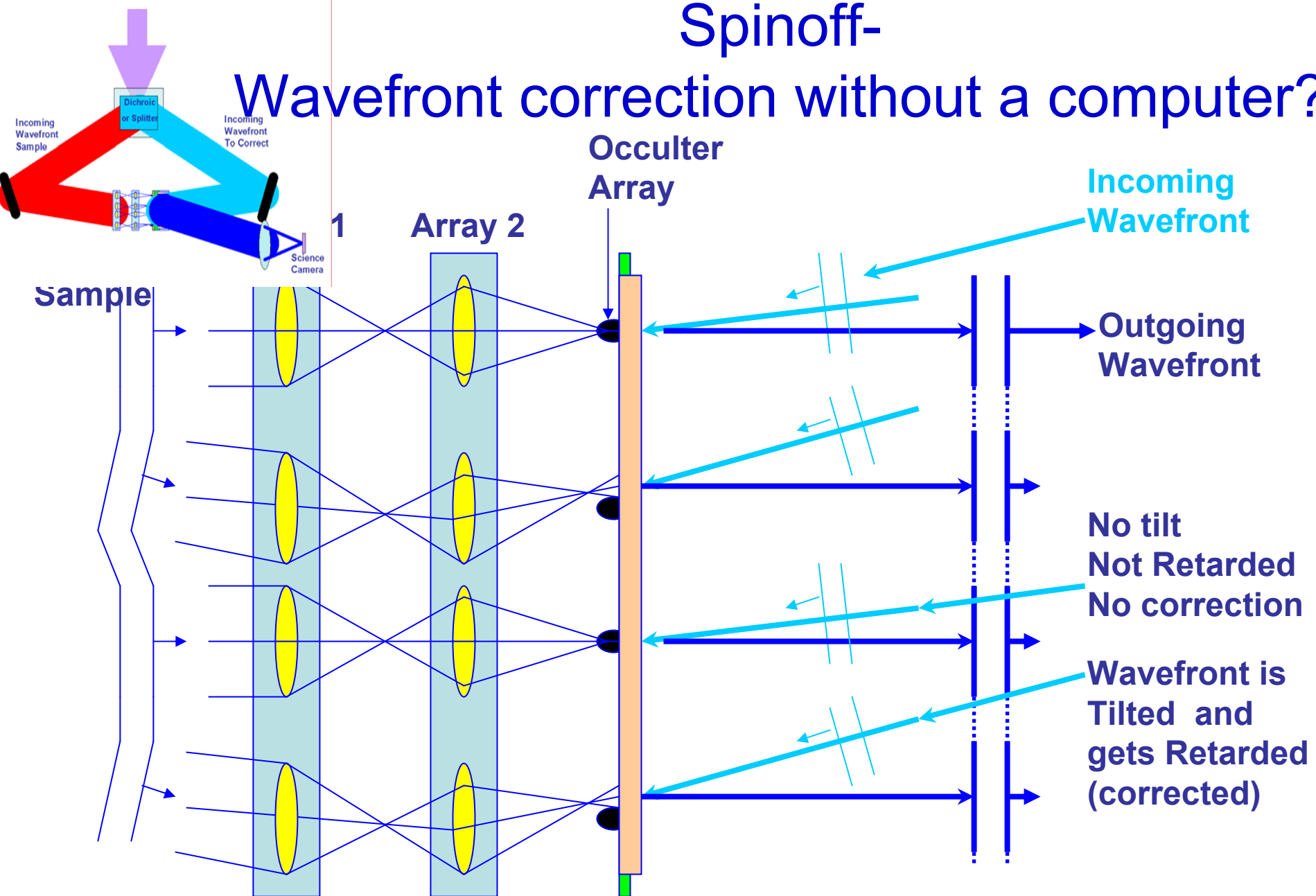


# 3 possible AZO APPO polymers



# Spinoff-

## Wavefront correction without a computer?



# Modified SH Array with OASLM

