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Nulling Coronagraph

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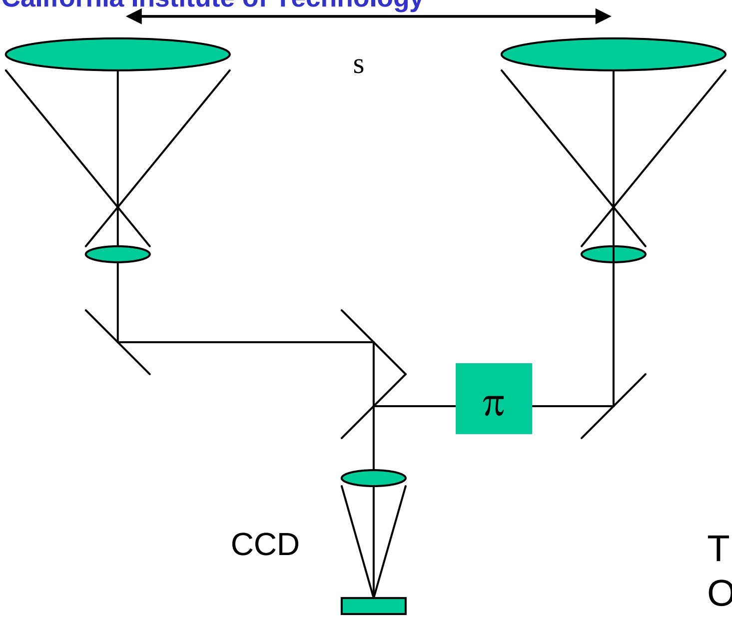
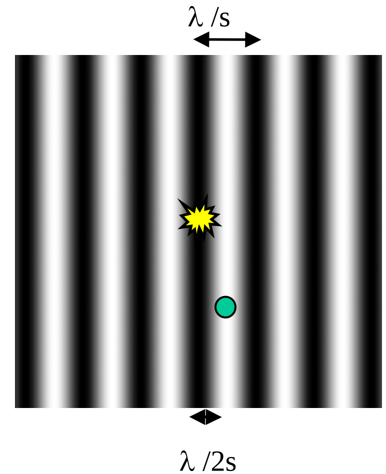
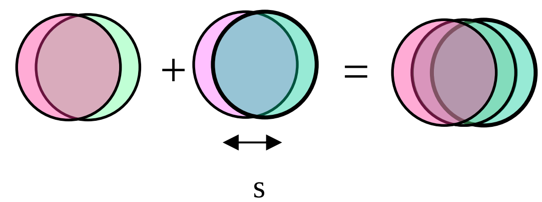
- **A coronagraph based on nulling interferometry, architecture of a nulling coronagraph**
- **Deep nulls, Contrast ≠ starlight suppression**
- **Post coronagraph wavefront sensing and PSF subtraction**

High Contrast imaging with a Nulling Interferometer





Transmission Pattern of Nuller
On the sky. (Star is at the center)



Nulling interferometer when the Shear (baseline) > D (dia of telescope) (eg λ = 10um)

Nulling coronagraph when the Shear (baseline) < D (dia of telescope) (eg λ = 0.5 um)

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2-arm vs. 4-arm Nulling Interferometers

2 arm:

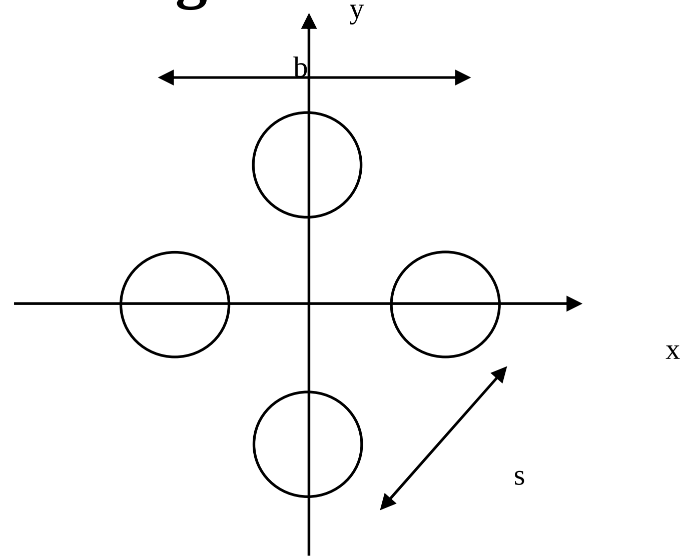
$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} \right|^2$$

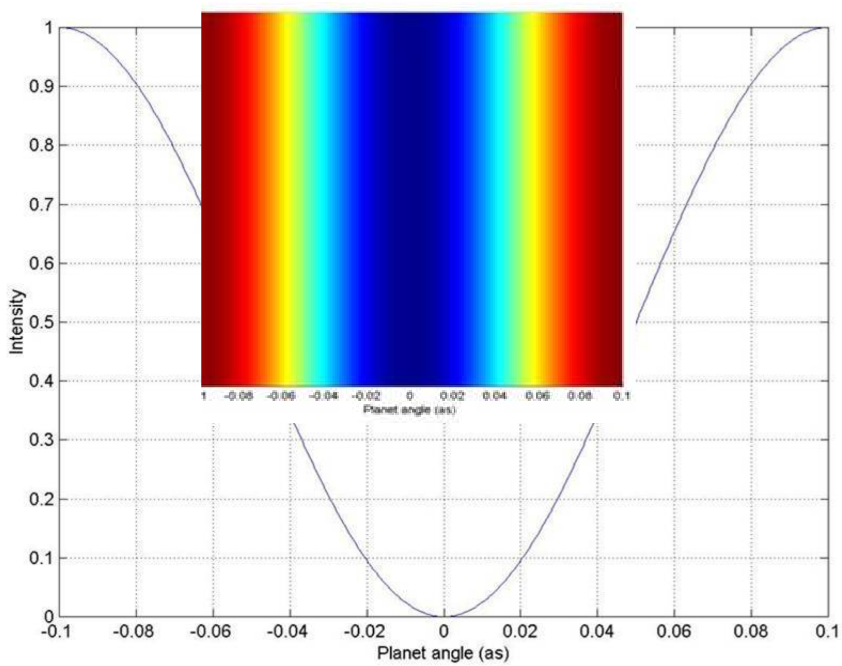
$$\approx I_0 (ks \cos \phi)^2 \theta^2$$

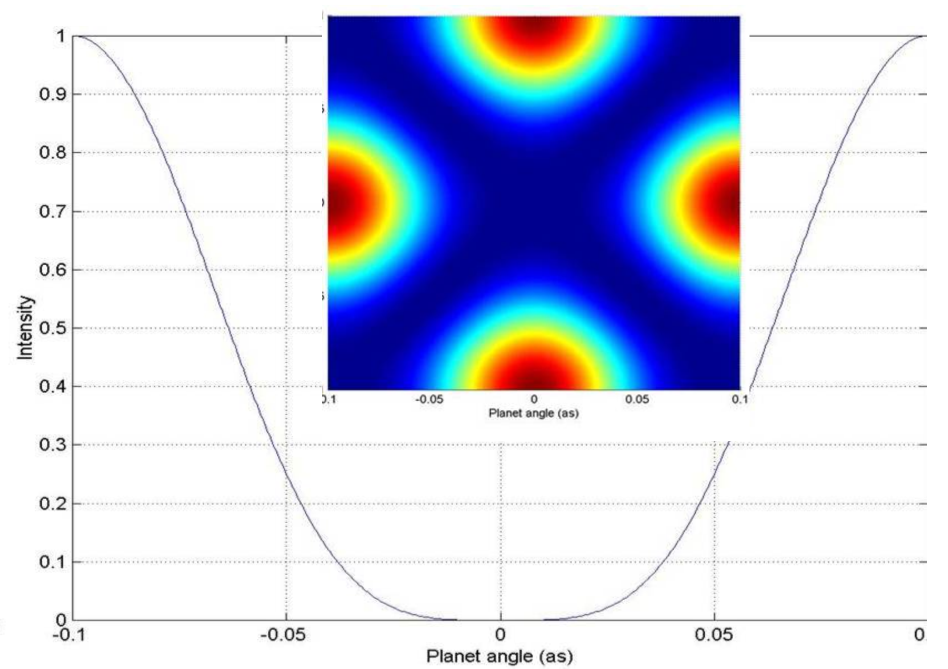
4 arm:

$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} + A_0 e^{i\phi_y} - A_0 e^{-i\phi_y} \right|^2$$

$$\approx I_0 \left(\frac{kb}{2} \right)^4 \cos^2(2\phi)\theta^4$$



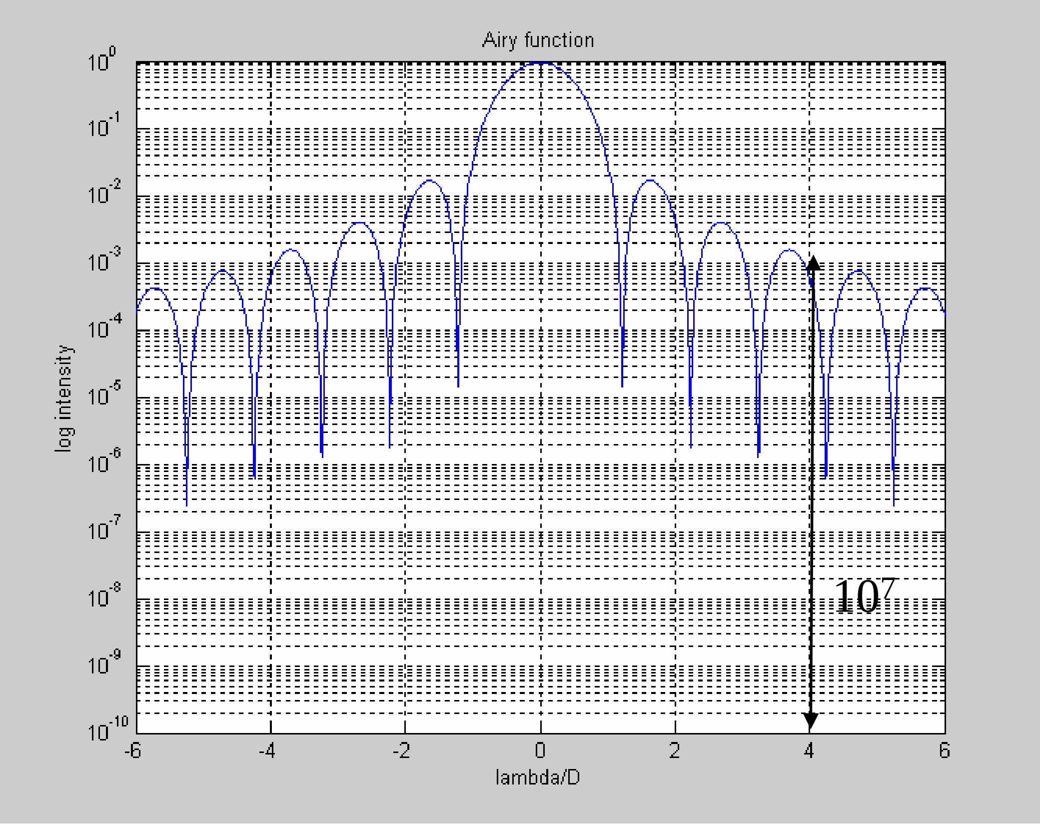




Contrast ≠ Starlight Suppression

- **At ~4 λ/D the airy function is ~ 10^{-3} of the peak**
- **At ~2 λ/D the airy function is ~ 10^{-2} of the peak**

- **Starlight suppression of 10^{-7} will yield a contrast of 10^{-10} @ 4 λ/D**



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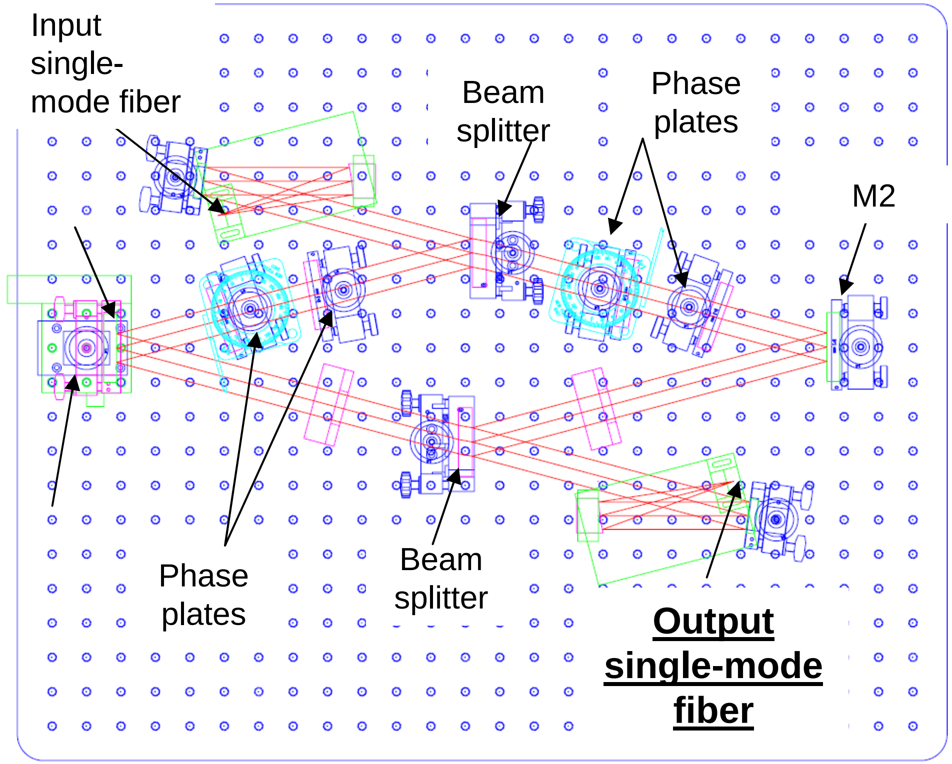
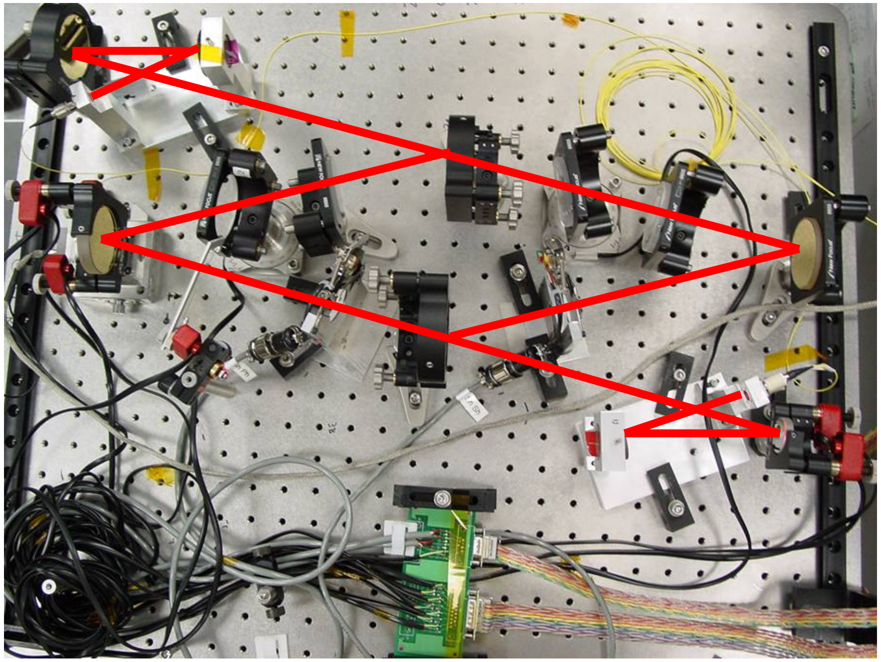
Status of Deep Nulling Experiments

(Symmetric) Nuller Layout





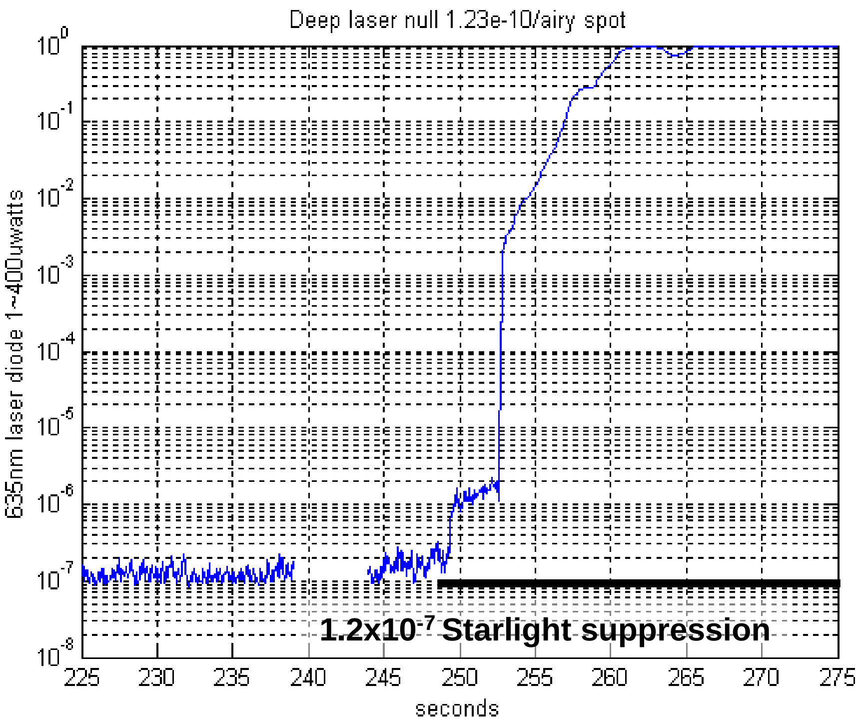
Symmetric nuller

equal # mirror reflections, BS ref, and AR transmission in two arms. Polarization and spectrally balanced

Single mode fiber output

Inside a single mode fiber a **perfect null** can be obtained by controlling just two parameters, **phase and amplitude**

Monochromatic (635nm) Light Nulling



- Laser data:
  - Optical path error of 90 picometer will cause $2x10^{-10}$/airy spot null leakage
  - rms vibration and drift over ~15 sec is ~60pm
- **$1.2x10^{-7}$ suppression ~ $1.2x10^{-10}$ contrast @ 4 λ/D**

Source Null	Pupil Rotation	Intensity Mismatch	Pathlength Fluctuations	Birefringence	Dispersion
Value achieved	0.01 Deg	0.03%	0.06 nm, rms	0.04 nm	NA
Contribution to Null	7.6E-9	2.25E-8	8.73E-8	9.7E-9	
Net Null:	**1.27E-7** (7.9M:1)				
% Contribution	6.0%	17.7%	68.7%	7.6%	

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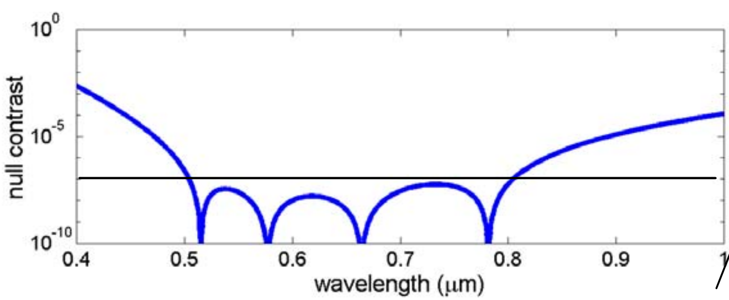
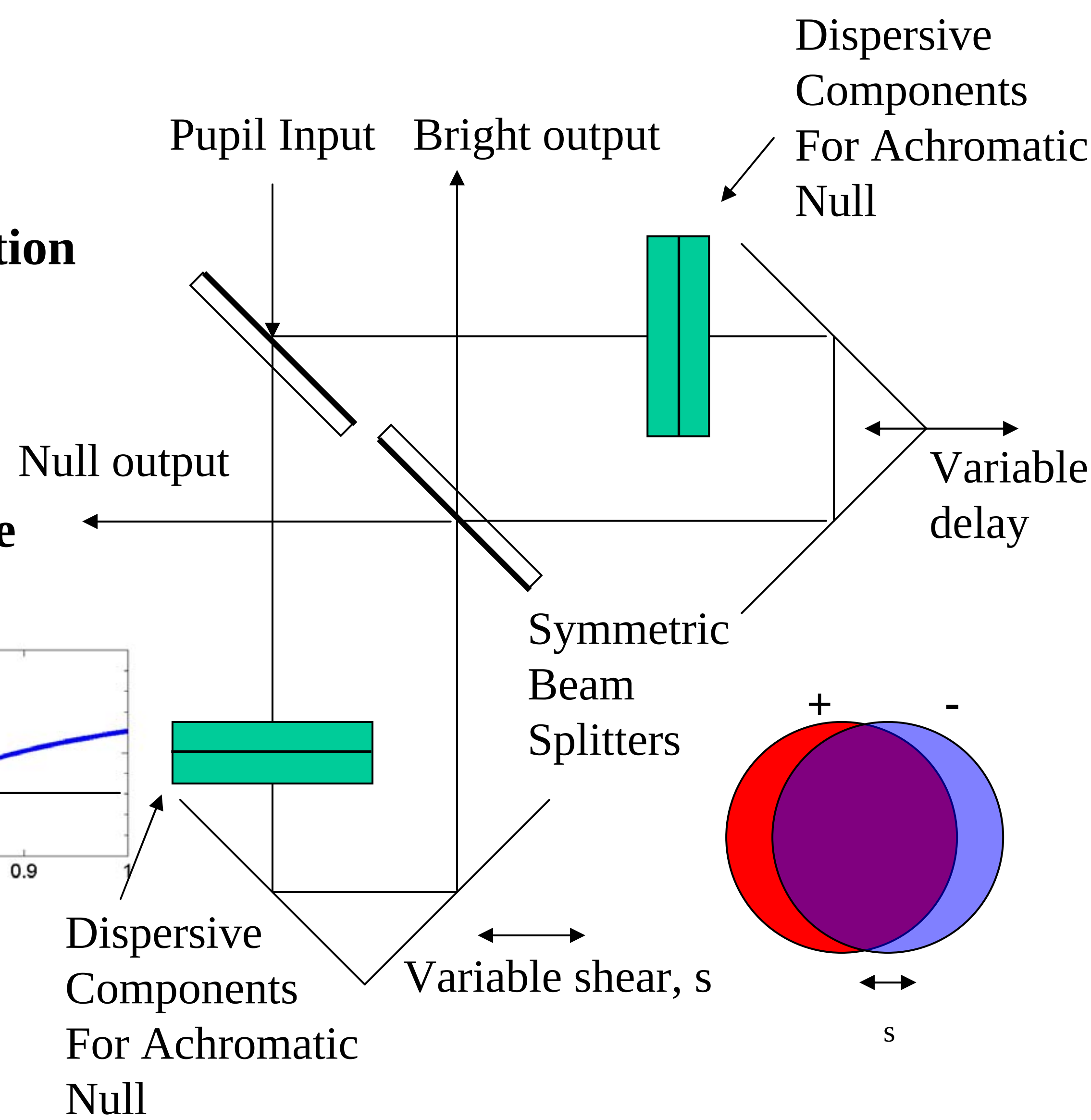
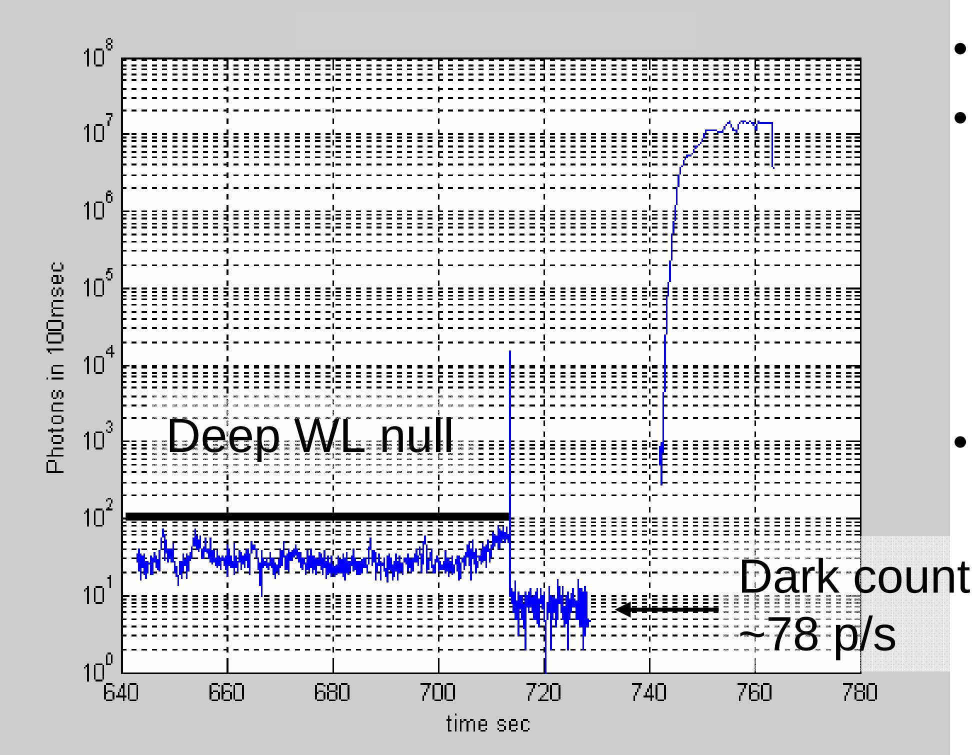
Achromatic Nulling Interferometer

- Single pupil input
- Symmetric design
- Preserves pupil orientation and polarization
- Pupil shear adjustable–variable null baseline
- Dielectric plates provide achromatic null





Broadband Light Nulling Summary



- **Tungsten lamp** (and filter)
- White light data
  - null over 60 sec **~1.1x10^{-9} Contrast**
    - Control of dispersive effect to ~1x10^{-9}
  - **~16% bandwidth** around 650nm.
- 1st order approx null ~ $(\Delta\lambda)^2$ at 2% bandwidth, potentially 64 times better

Data taken @ 10 hz
~ 20 photons/sample @ null
~8 of those photons are dark photons

The deep white light null illustrates a 2nd property of nulling interferometry, the ability to **sense and control** optical path to **10^{-9}** contrast using literally a **handful** of detected **photons** at null.

Nulling interferometry has demonstrated deeper white light suppression than any other coronagraphic approach

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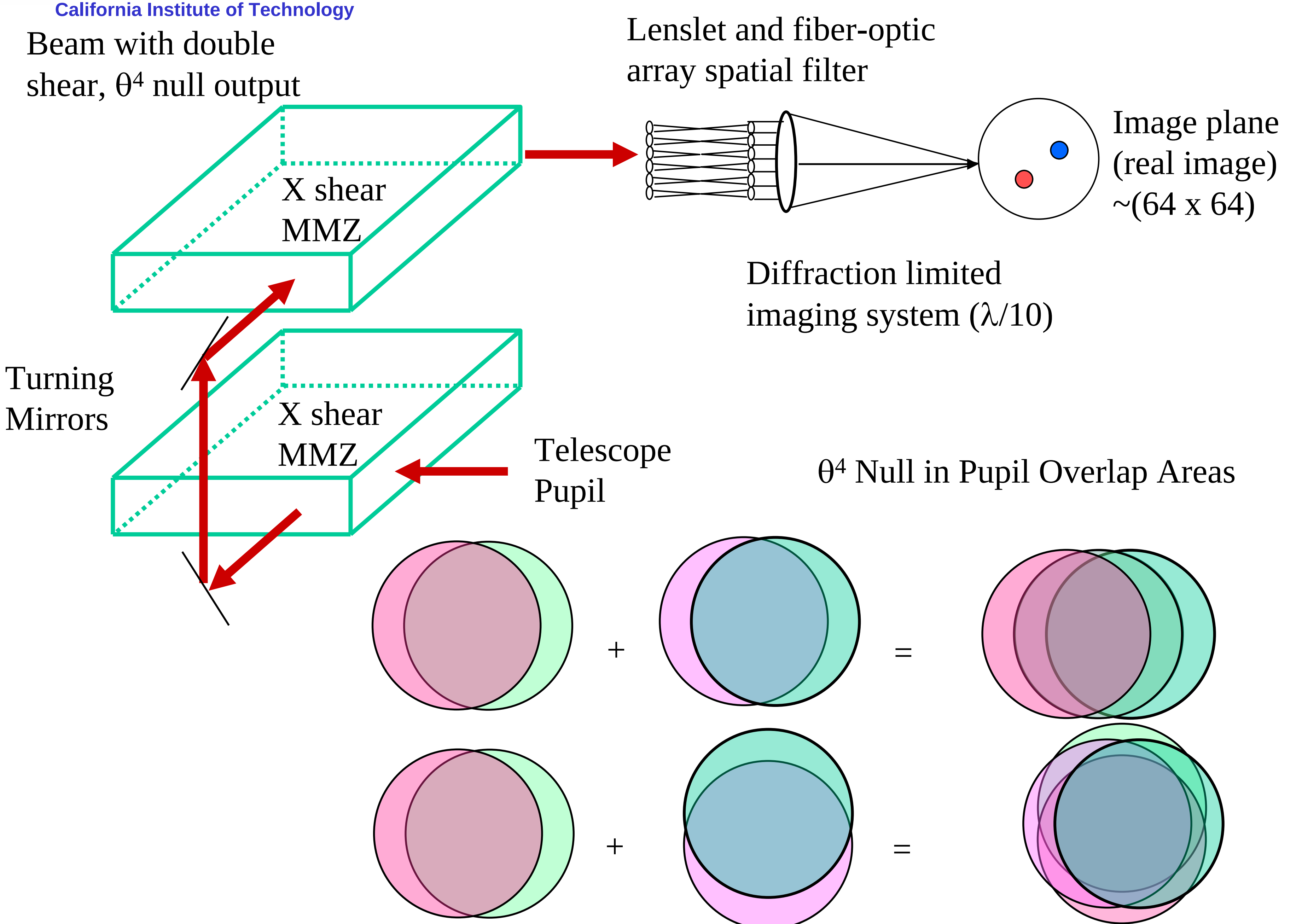
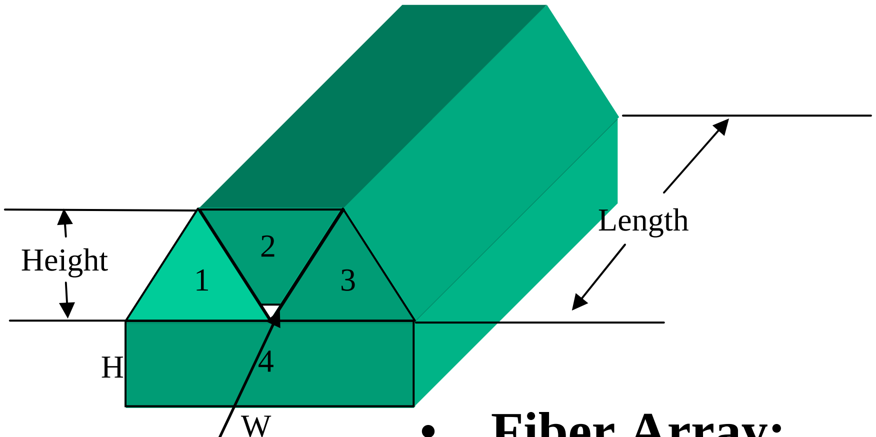
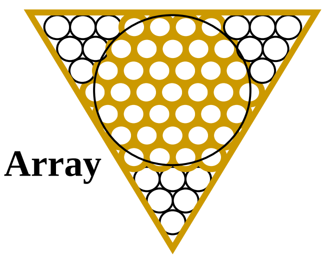
Visible Nulling System Concept

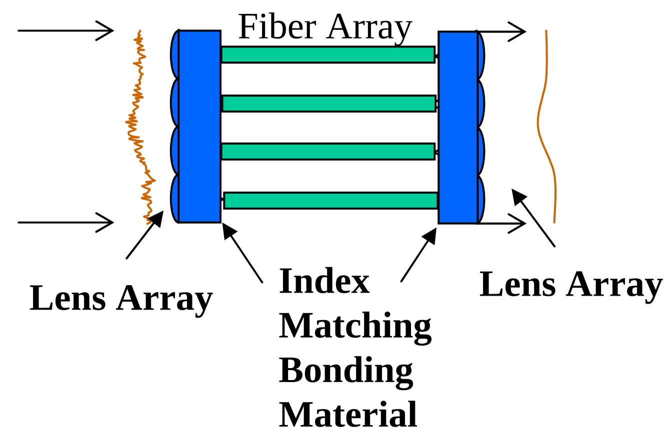


Self Assembly of Fibers in (2nd Generation) Coherent Array



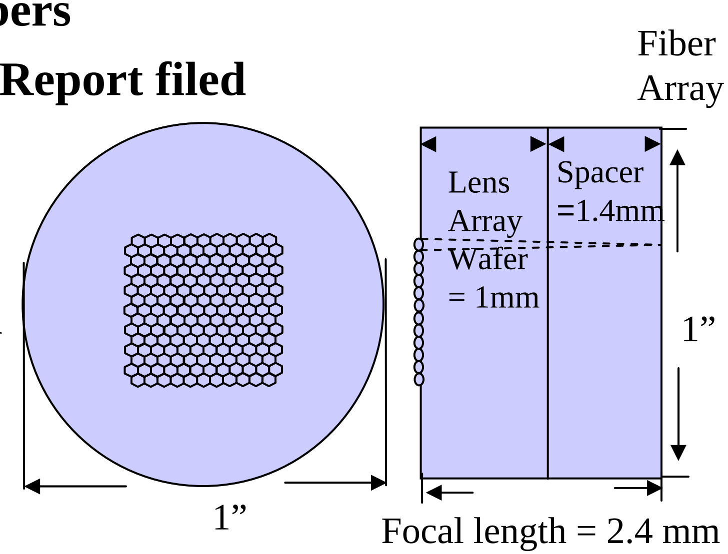


•Fiber Array Detail



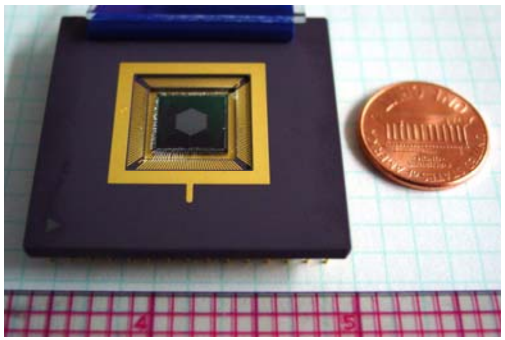
- **Fiber Array:**
  - **3 Dove prisms on rectangular slab**
  - **Prism 2 corner is cut flat to accommodate Fibers**
  - **New Technology Report filed**

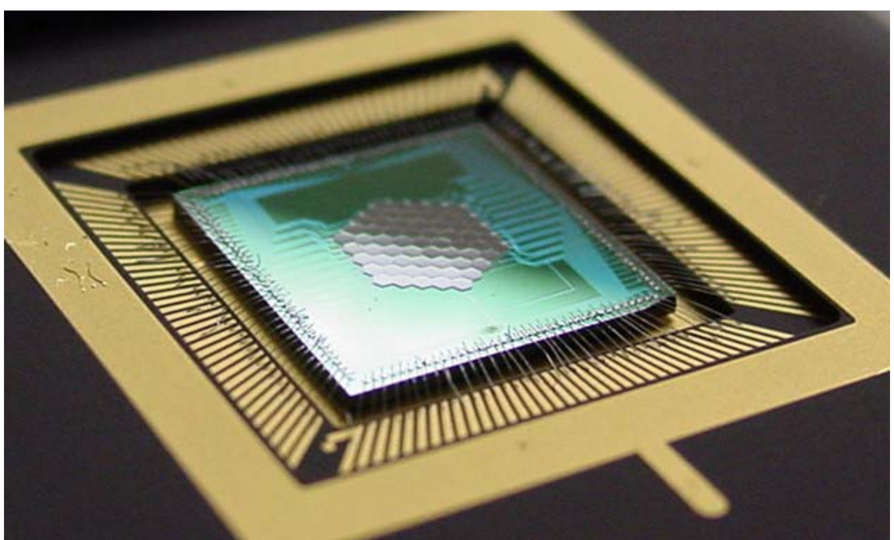
- **Lens Array**
  - Monolithic Lens Array on thin substrate
  - Spacer bonded with thickness = focal length
  - Coating (and pinhole) at focal plane of lenslets, **<u>blocks cladding modes</u>** in fiber



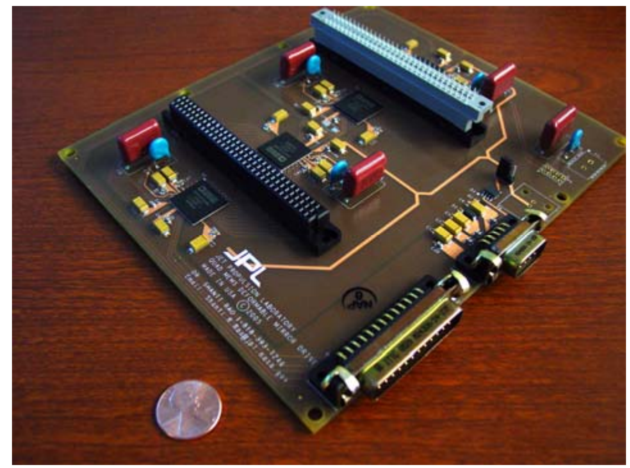
BU DM + JPL Electronics

- **61 channel pathfinder DM**
  - **Boston University**





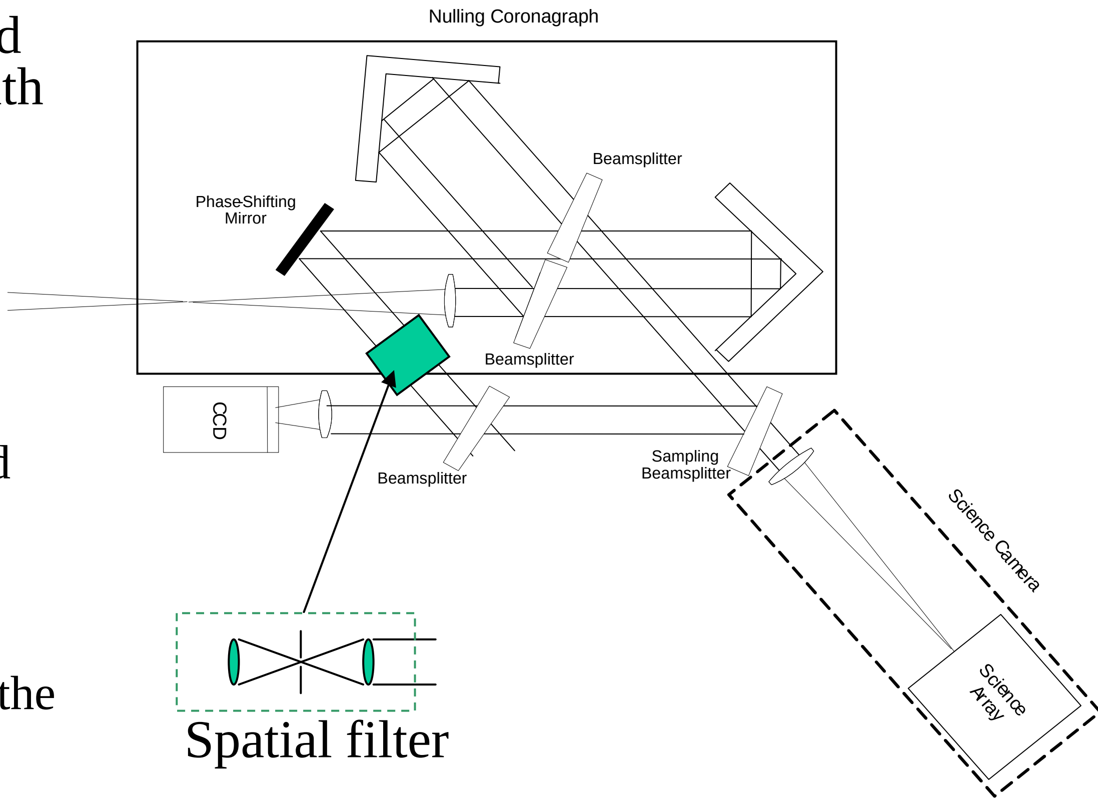
- **128-channel D/A board**



PSF Calibration: Separating the Starlight Speckles from the Planets

- **Even with fibers and deformable mirrors, the starlight suppression will not be perfect.**
  - How can you tell the difference between starlight speckles and planet light?
- Spectral subtraction
- Angular subtraction
- **Coherence of starlight** and property that the star light and planet light are incoherent with each other.

•Spatially filter the starlight from the bright output of the nuller.
•Interfere it with the output from the nuller (after fiber bundle).
  •This measures the amplitude and phase of the light in the speckle pattern.
•The PSF (starlight speckle pattern) is estimated by the Fourier transform of the measured amplitude and phase



Importance of Post Coronagraph Calibration Interferometer

- Post coronagraph wavefront sensor that can produce 10^{-9} contrast with detection of a few dozen photons (per subaperture) that leaks through the coronagraph.
- PSF subtraction based on coherence of light (as opposed to telescope rotation, spectral features, or polarization of source)
  - In space, relaxes the wavefront stability by a few orders of magnitude (over angle diff imaging)
  - Through the atmosphere, can measure quasi-static telescope and non-common path AO errors.
    - Extend contrast from 10^{-3}~10-4 to 10-7~10-8
    - Offer the possibility of atmospheric speckle subtraction

Projects Using these Concepts

- PICTURE (nulling coronagraph and calibration interferometer on a sounding rocket)
- TPF-C Instrument concept study
- EPIC (discovery proposal)
- Gemini Planet Imager (calibration interferometer)
- TMT extreme AO coronagraph concept study. (nuller and calibrator)

Summary

- Nulling interferometry (with single mode fiber) has demonstrated the largest amount of starlight suppression, in laser light, and in white light.
  - White light suppression using realistic photon fluxes. (~100 detected photons/second (16% bandpass) at 10^{-9} constrast)
- Post coronagraph interferometer is a key subsystem for both ground and space based coronagraphs.
  - In space, relaxes stability requirement by orders of magnitude (replace angular differential imaging) for speckle subtraction
  - Through the atmosphere, the calibration system measures the quasistatic AO/telescope errors that produce “pinned speckles” and also offers the possibility of removing residual atmospheric speckles.

Backup slides

2-arm vs. 4-arm Nulling Interferometers

2 arm:

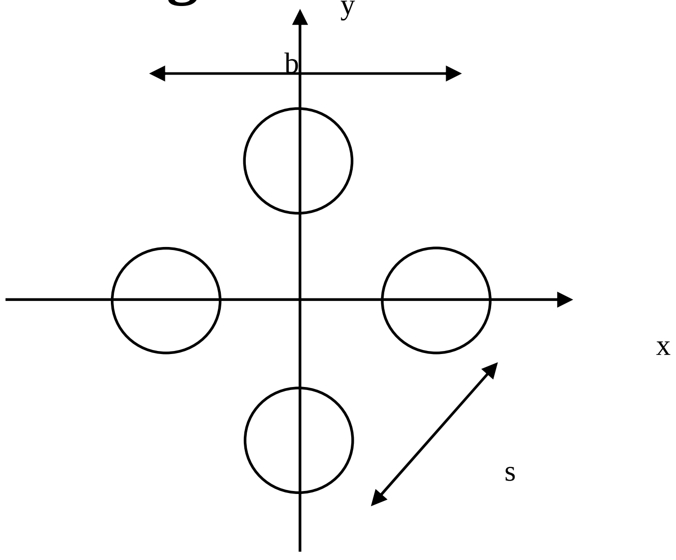
$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} \right|^2$$

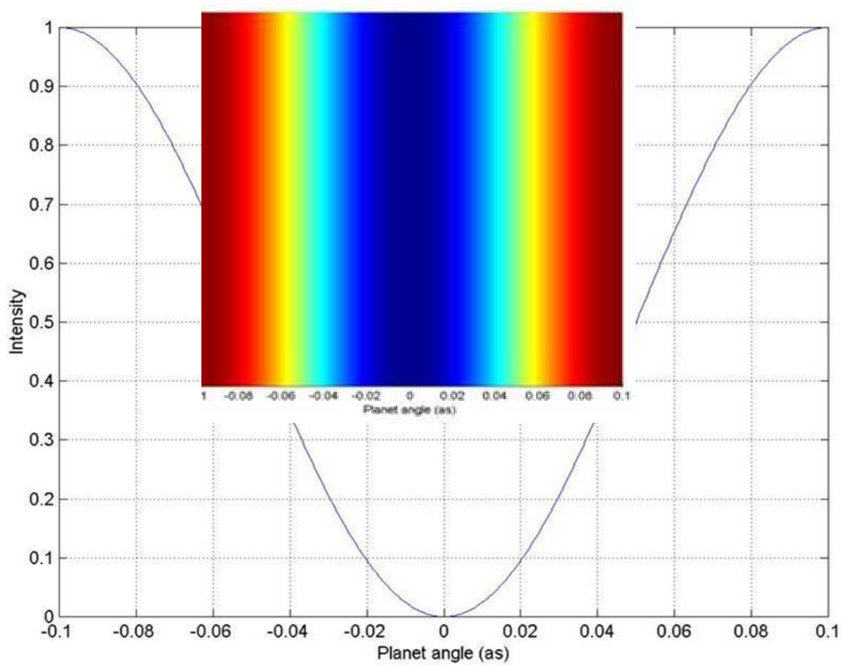
$$\approx I_0 \left(ks \cos \phi \right)^2 \theta^2$$

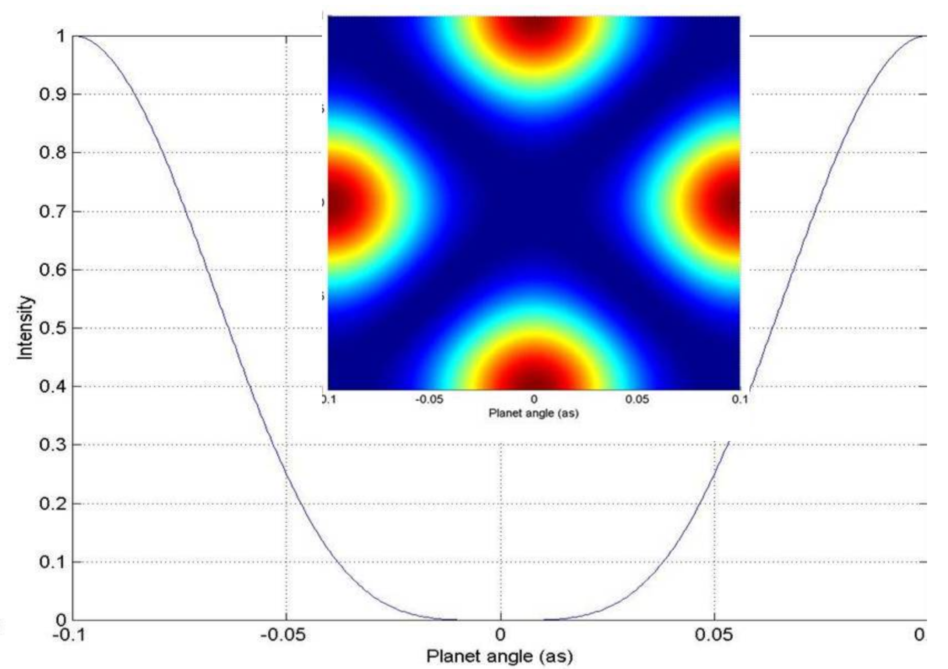
4 arm:

$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} + A_0 e^{i\phi_y} - A_0 e^{-i\phi_y} \right|^2$$

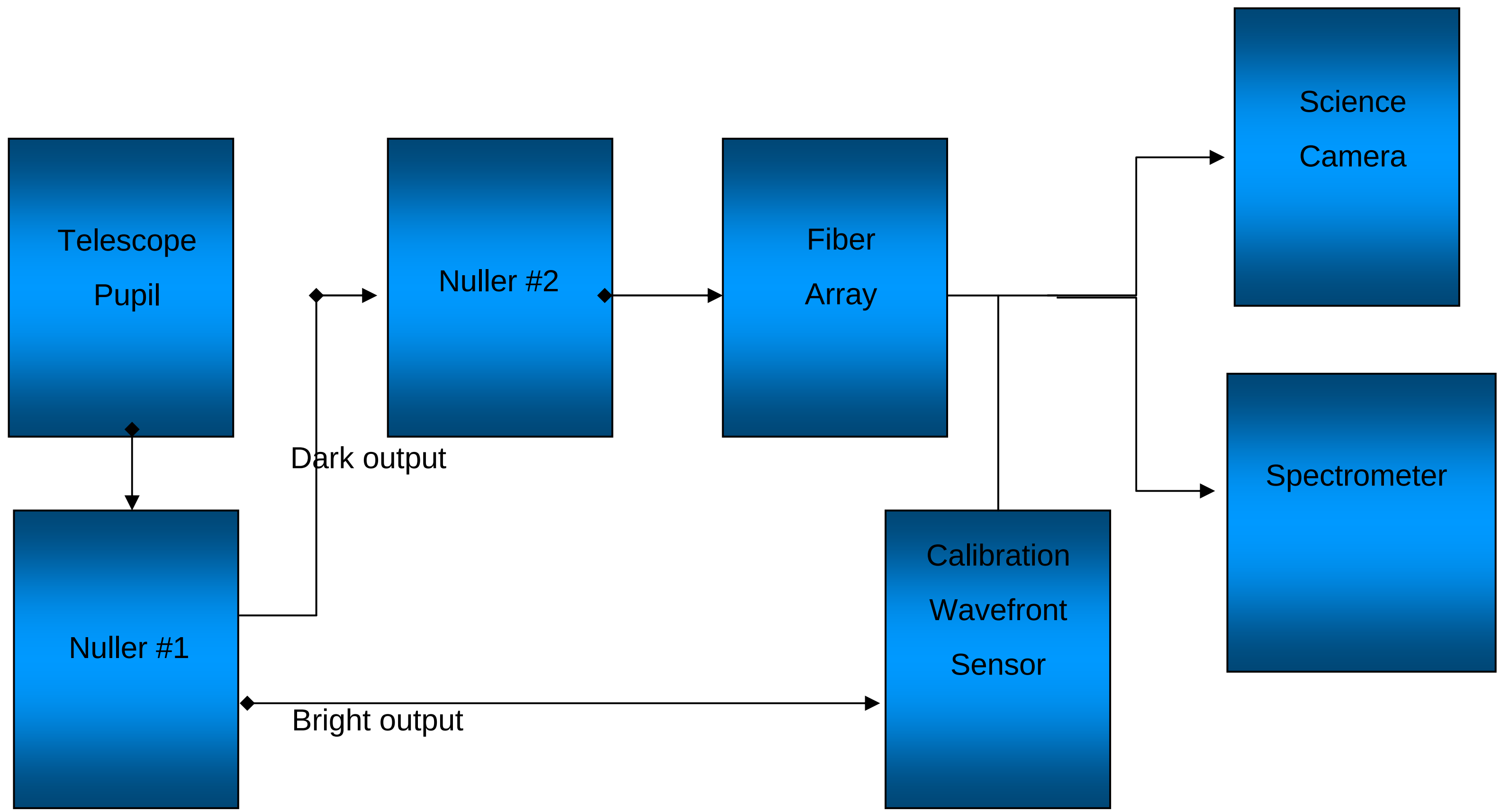
$$\approx I_0 \left(\frac{kb}{2} \right)^4 \cos^2(2\phi)\theta^4$$







Nuller Architecture for Planet Imaging



- Yields θ^4 null

SNR comparison

- Canonical Earth @ 10pc
- Wavelength = 055µm
- $\Delta\lambda$=20% band pass

Telescope	Nuller SNR	Lyot SNR
8.3 x 3m	9.6	5.2
4m	5.9	Not det.

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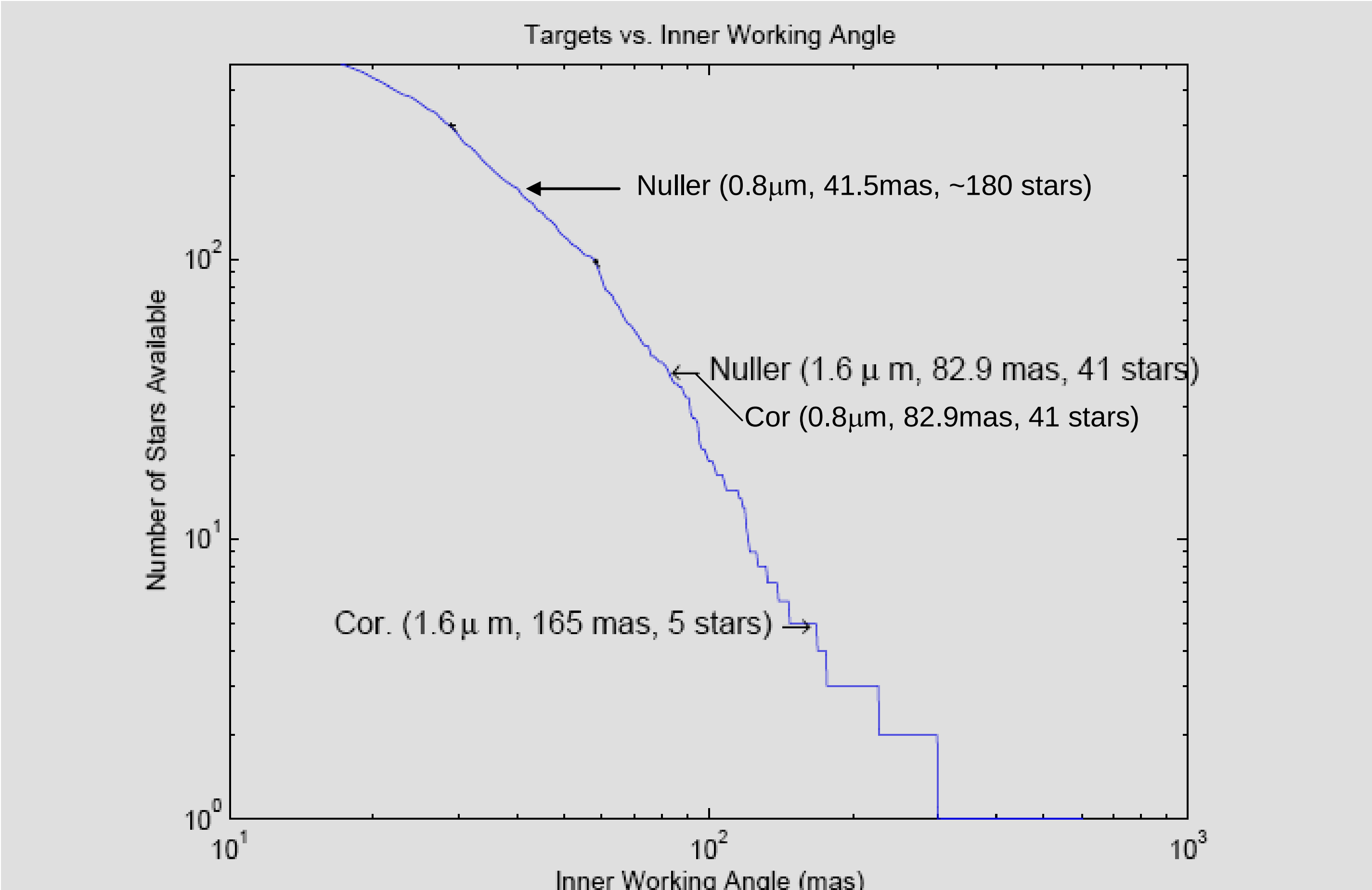
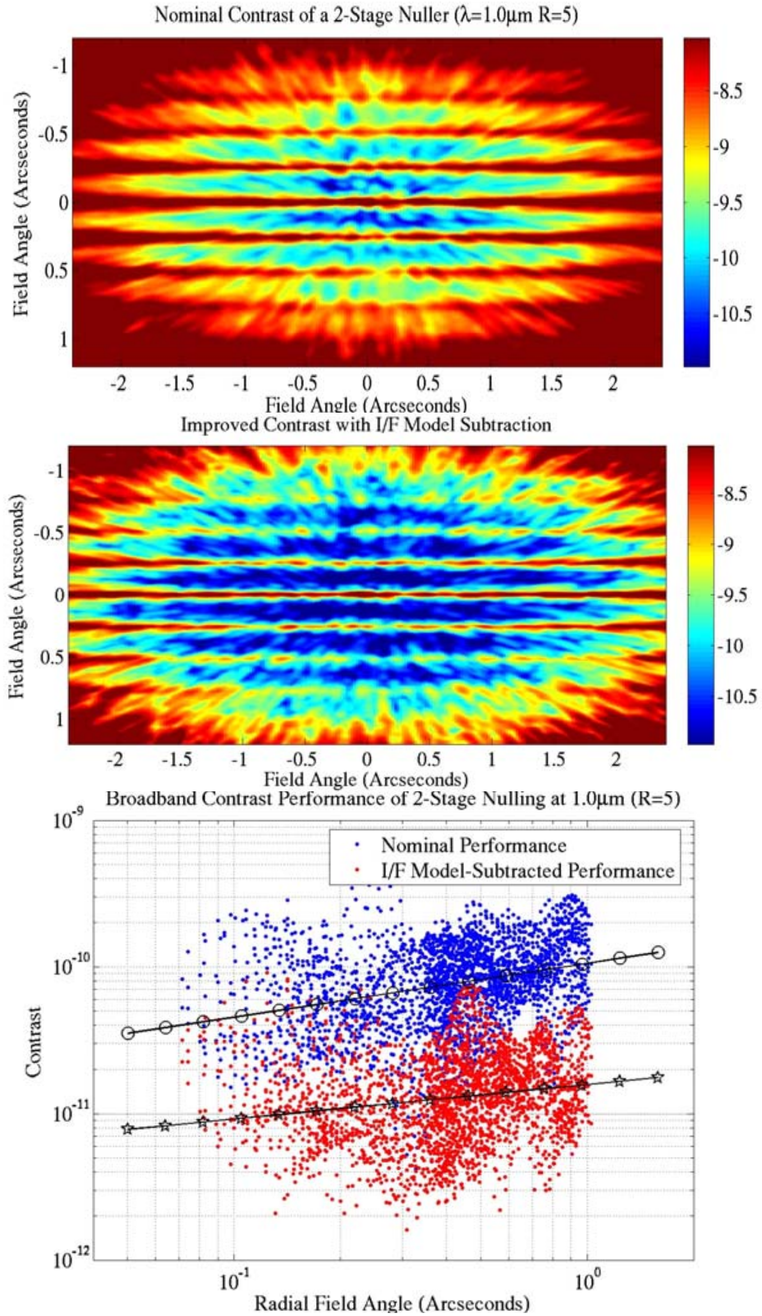
Targets for Characterization



- Spectroscopy @ 0.8um (limitation of 2λ/D vs. 4 λ/D)
- Spectroscopy @ 1.6um
- The target list for spectroscopy will be smaller than detection/discovery because λ is bigger

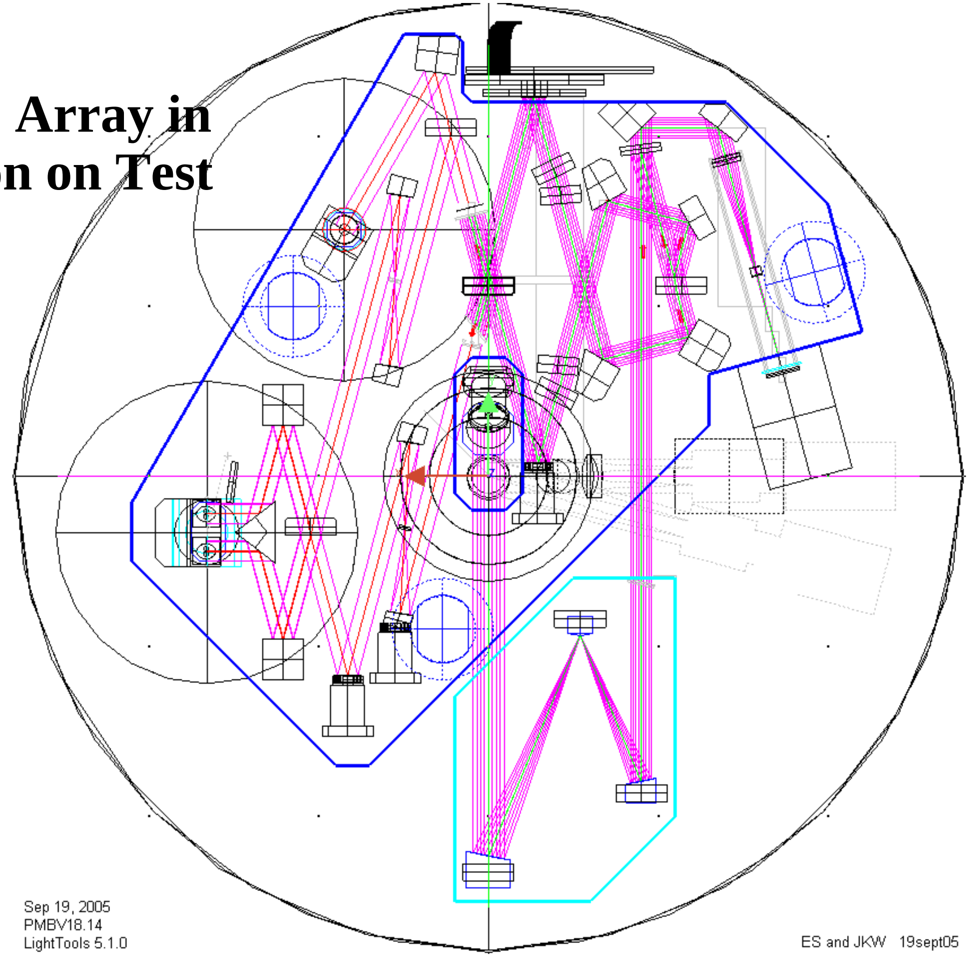
Post Starlight suppression wavefront sensing

- θ^4 nuller
- Shot noise, Detector noise, pixelization included
- Contrast improvement α integration time$^{-1/3}$

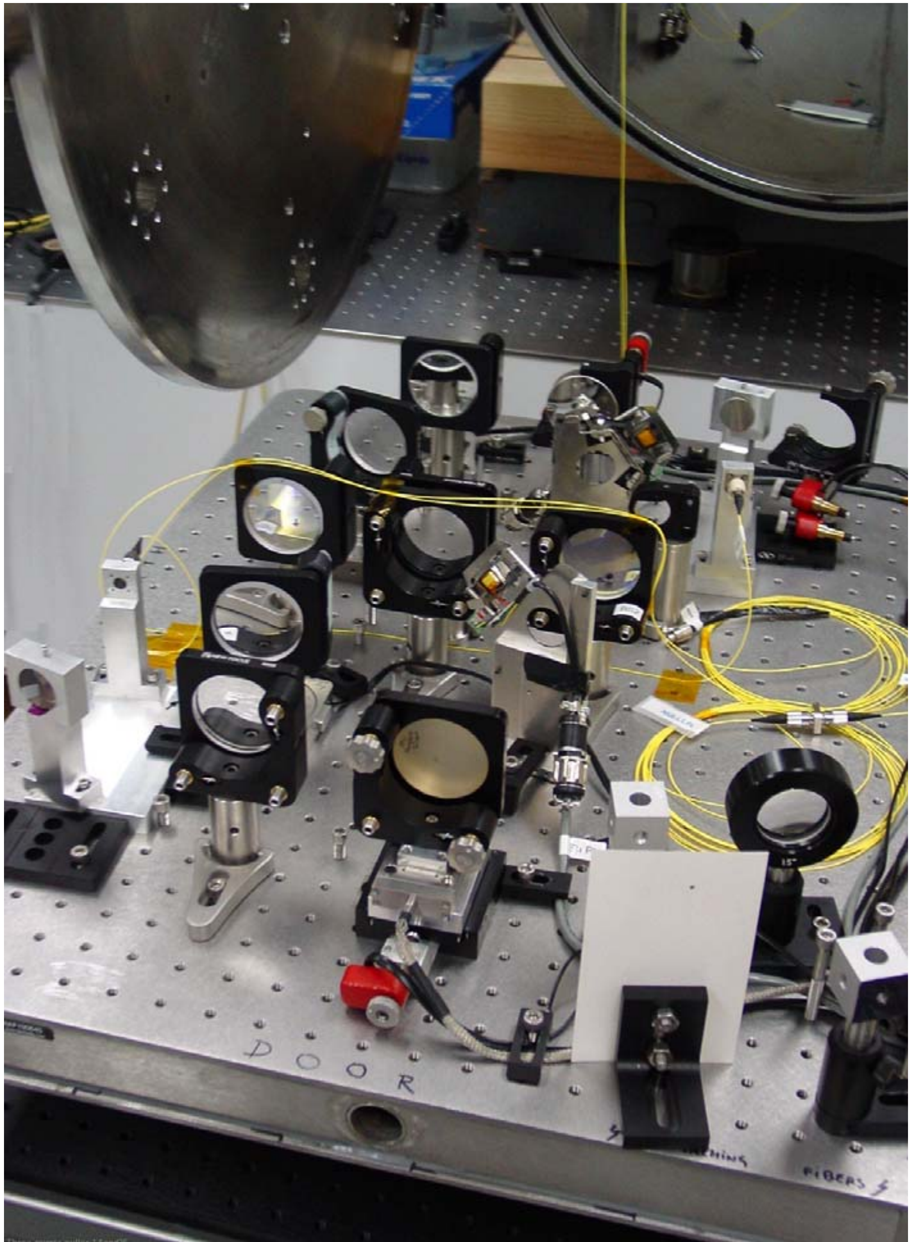


Future Work

- Near Term
  - Advanced Automation of Nuller Experiment
  - Design and Modification of Nuller Test Bed
- Long Term Experiments:
  - Integration of Nuller and SMF Array in Test Bed System Demonstration on Test Bed
    - Integrated nuller and calibration wavefront sensor design
    - Design suitable for a future sounding rocket experiment

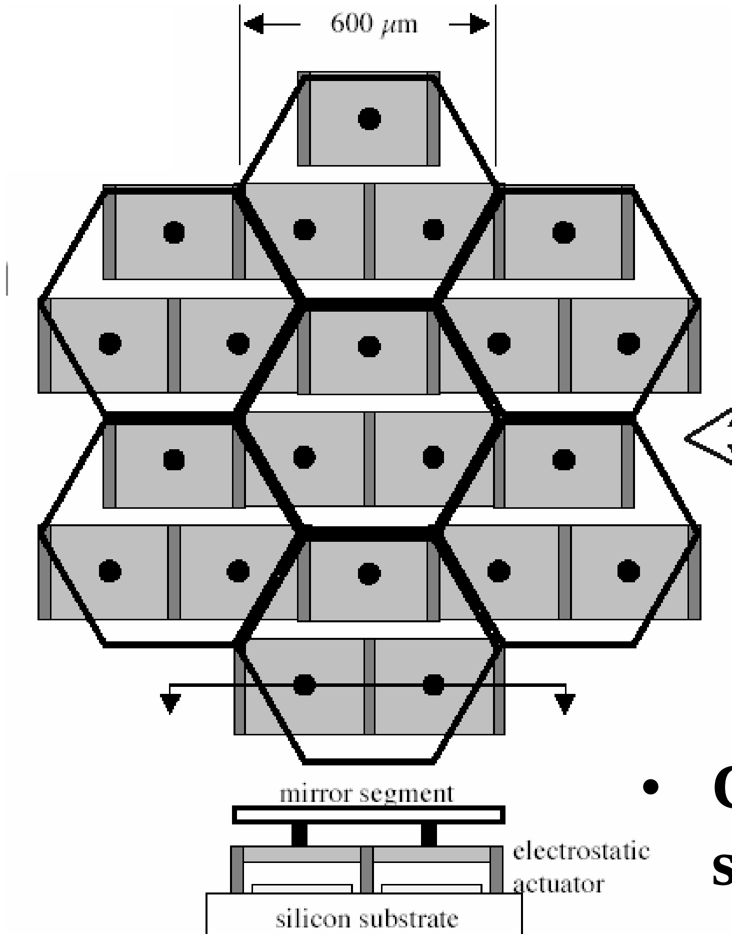


Status of Nulling Experiments

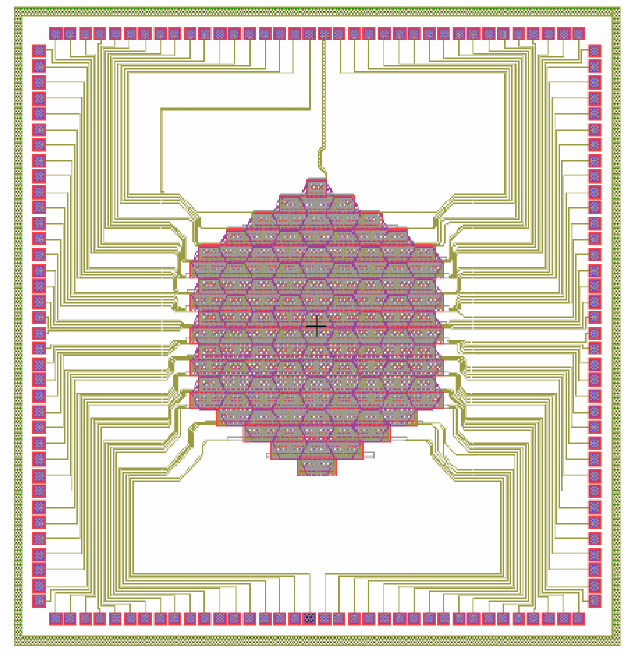


- Prior to 2005, experiment was conducted on an optical table
- Since May nuller moved into the vacuum chamber
- To date, experiments have been run at 1 atm, with the door shut

Boston University MEMS Pathfinder Deformable Mirror



61 Pixel TPF Array



Mask designs complete: Mirror in fabrication now at MEMS silicon foundry

- **Current development is for a 361 segment device**
- **Future development path is for a 1000 segment DM**

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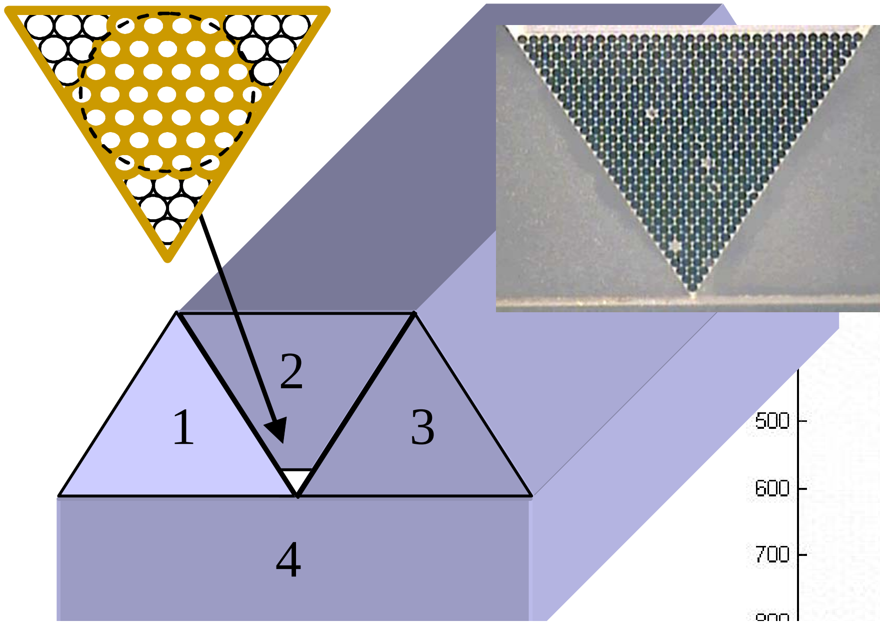
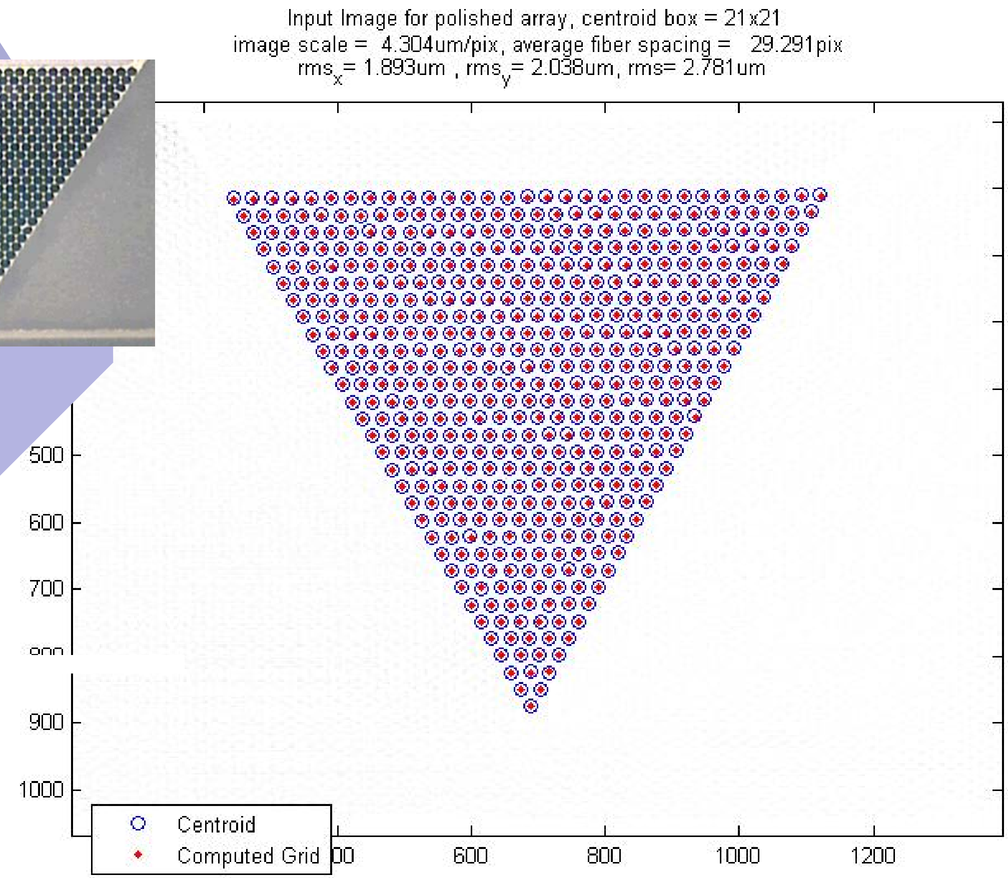
Preliminary Fiber Array Placement Accuracy
500 (331) Fiber Array





- **Measurements show:**
  - **125.75μm fiber spacing**
  - **2.8μm rms position error**
- **Lens arrays to be integrated with Fiber Array**