Towards 10^{10} Contrast for Terrestrial Exoplanet Detection:

Coronography Lab Results and Wavefront Control Methods

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National Institute of Standards and Technology

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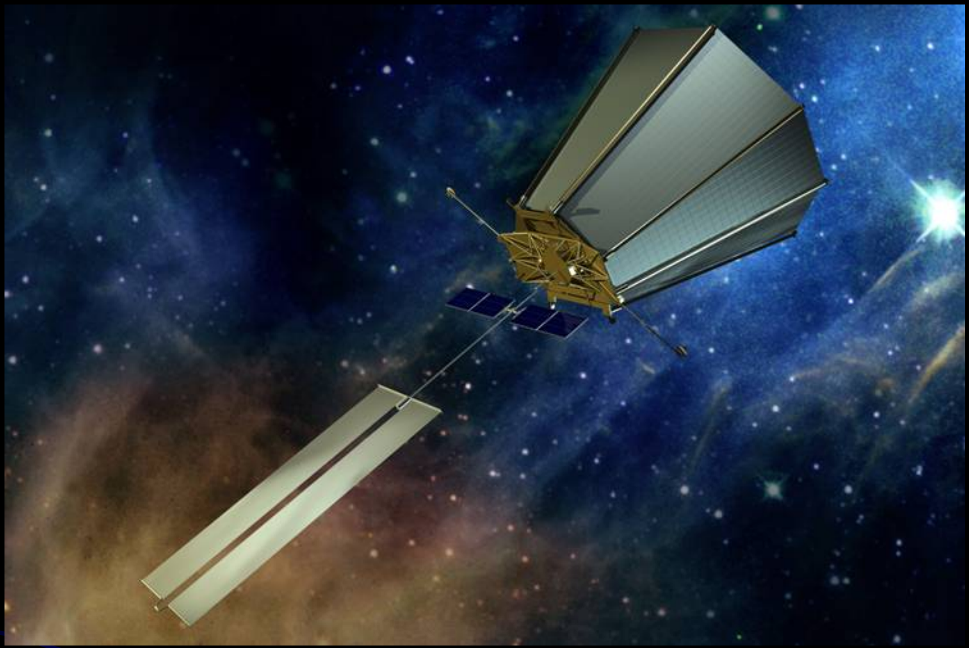
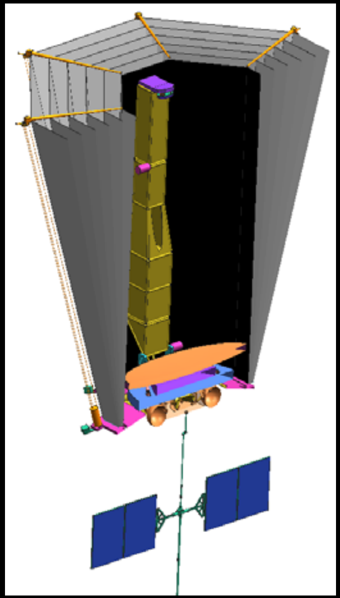
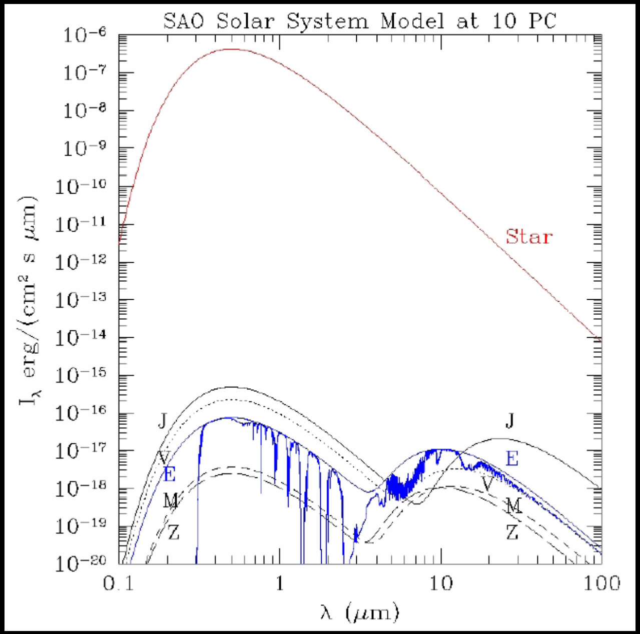
TPF-C





- 2015-2020 ??
- Detection
  - 35 core nearby stars (150 extended mission)
  - Distance from star: 0.7-1.5 a.u.
  - Surface area: 0.5 of Earth and greater
- Characterization
  - Orbit, distance
  - Photometry: size, rotation
  - Spectroscopy: atmosphere, water
  - Life
- General Astrophysics



Outline

- Pupil apodization methods
  - Shaped Pupils
  - Phase-Induced Amplitude Apodization
- Laboratory results and simulations
- The real challenge: broadband wavefront control in phase and amplitude

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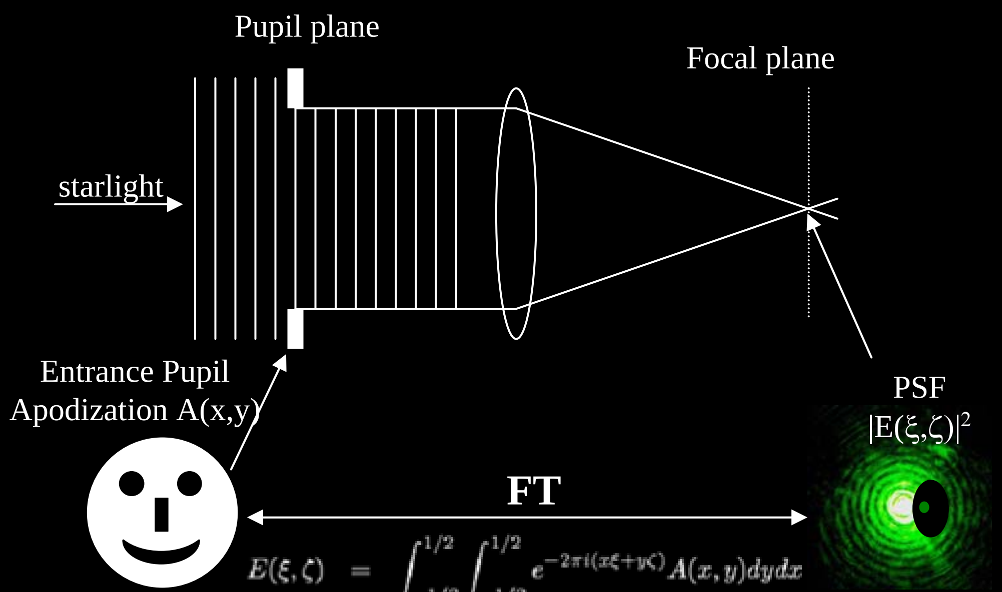
Pupil Apodization Overview



$$E(\xi,\zeta) = \int_{-1/2}^{1/2}\int_{-1/2}^{1/2} e^{-2\pi i(x\xi+y\zeta)} A(x,y)\,dy\,dx$$

$$\vdots$$

$$E(\rho) = 2\pi \int_{0}^{1/2} J_0(2\pi r\rho) A(r)\, r\, dr,$$

- Main selling points:
  - Performance competitive with more conventional Lyot-style coronagraphs
  - Simple to manufacture
  - Inherently broadband
  - Minimally sensitive to aberrations
  - No off-axis degradation of PSF

The Optimization Problem

Find an apodization function *A(r)* that solves:

$$maximize \quad E(0) = \int_0^{\frac{1}{2}} A(r) 2\pi r dr$$

$$subject\ to \quad -10^{-5} E(0) \le E(\rho) \le 10^{-5} E(0), \quad \rho_{iwa} \le \rho \le \rho_{owa}$$

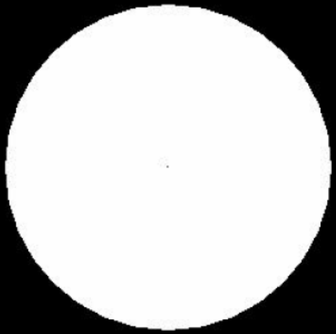
$$0 \le A(r) \le 1 \qquad\qquad 0 \le r \le 1/2$$

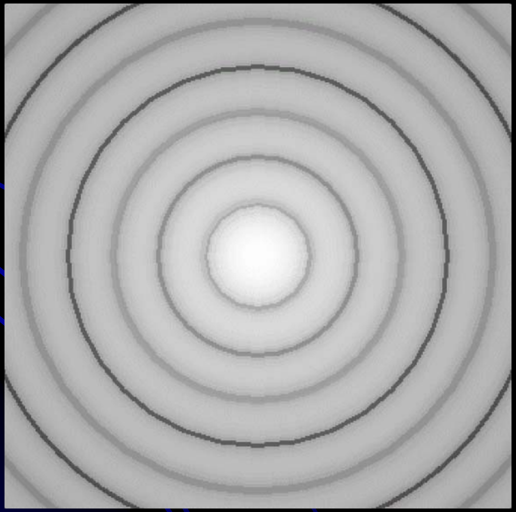
- Performance metrics
  - Size of dark region, i.e. inner/outer working angles ρ_{iwa} and ρ_{owa}
  - Contrast $C(\rho) = \frac{E^2(\rho)}{E^2(0)}$
  - Airy throughput $\frac{2\pi \int_0^{\rho_{iwa}} E^2(\rho)\rho d\rho}{\pi(1/2)^2} = 8 \int_0^{\rho_{iwa}} E^2(\rho)\rho d\rho$

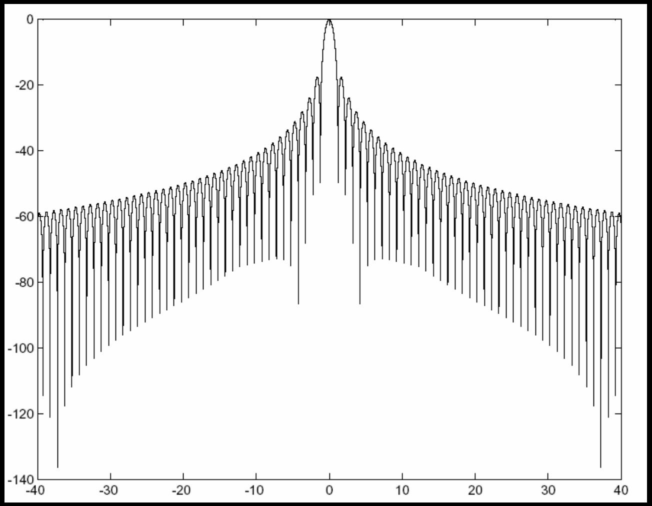
Clear Aperture: The Airy Pattern

$\rho_{iwa} = 1.24$

$T_{airy} = 84.2\%$





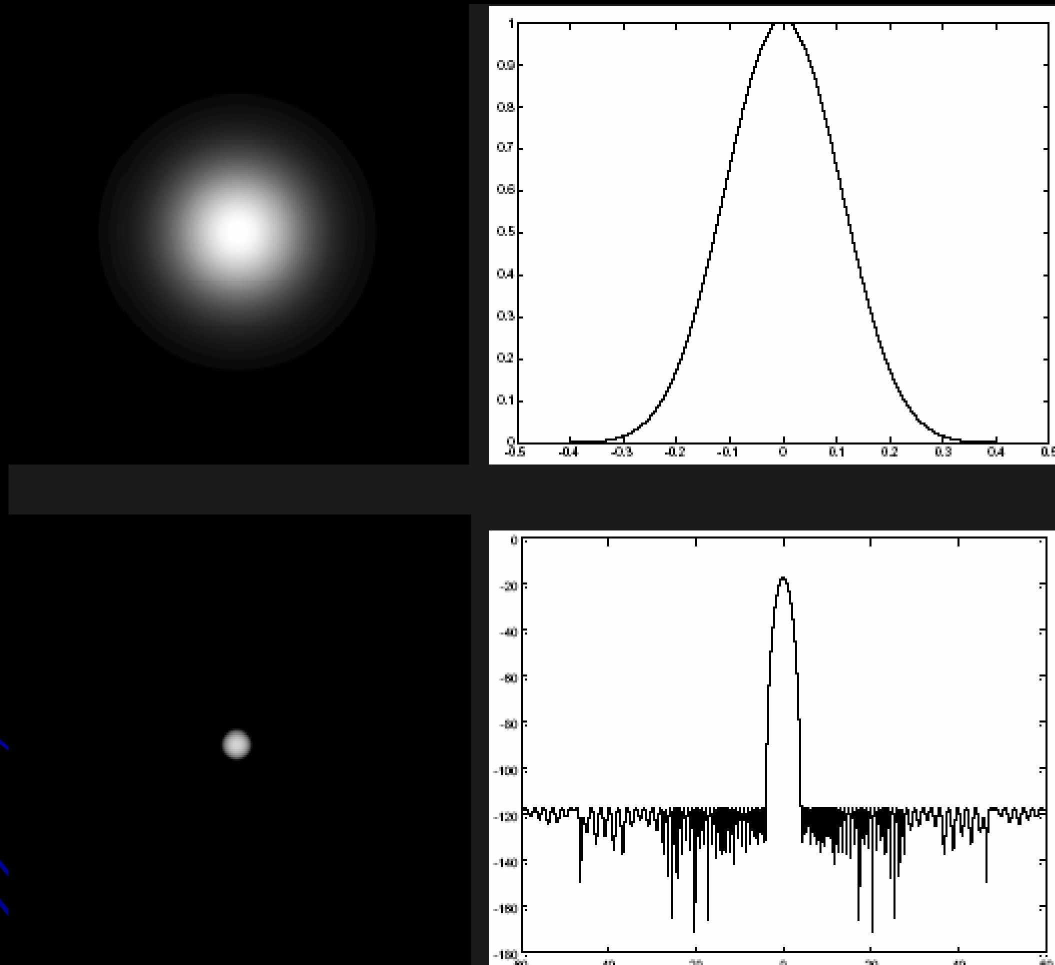


No dark zone

Apodization

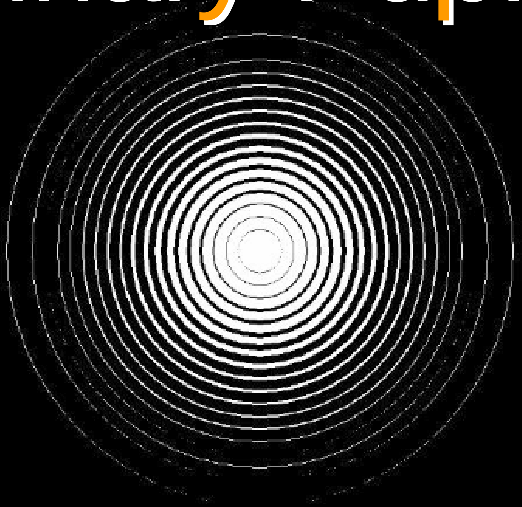
$\rho_{iwa} = 4$

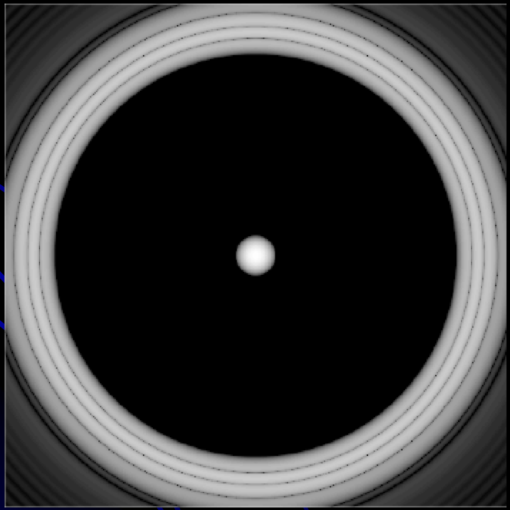
$T_{airy} = 9\%$

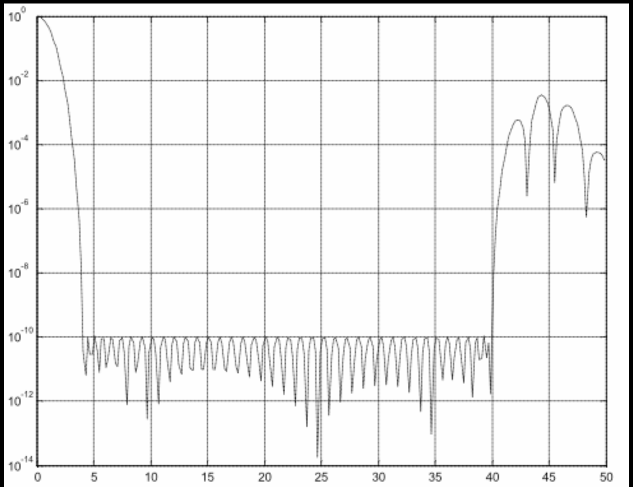


Excellent dark zone **Unmanufacturable**

Binary Pupil







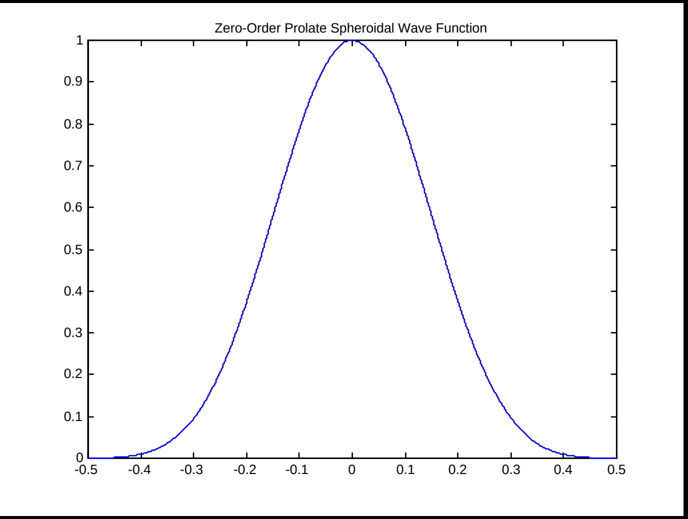
Excellent dark zone

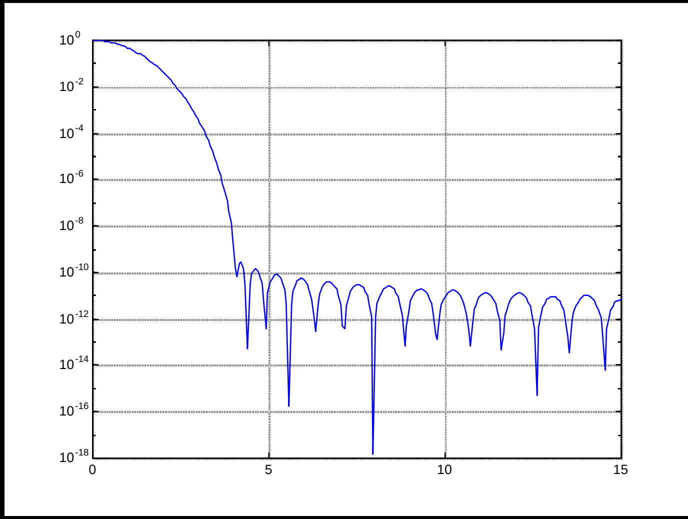
Impossible to manufacture

1-D Prolate Spheroidal (Slepian 1963)

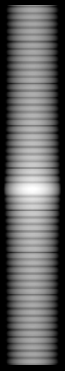
$\rho_{iwa} = 4$

$T_{airy} = 25\%$





Analytic solution via calculus of variations

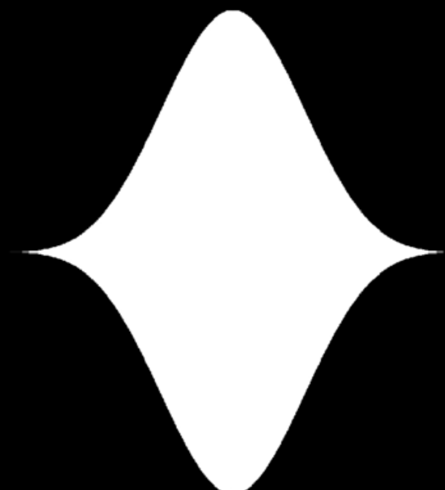


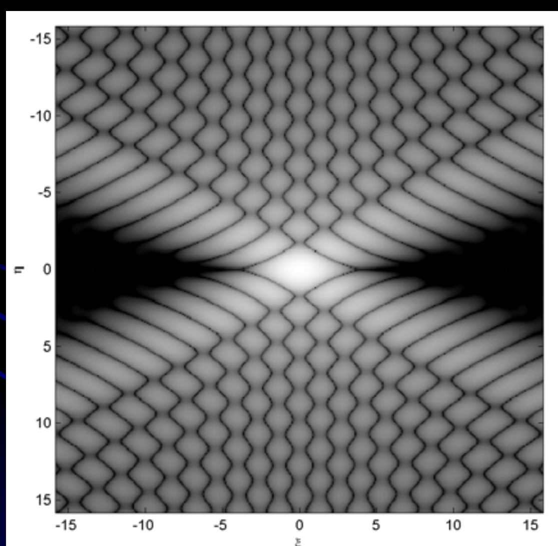
Theoretically optimal for 1-D **Unmanufacturable**

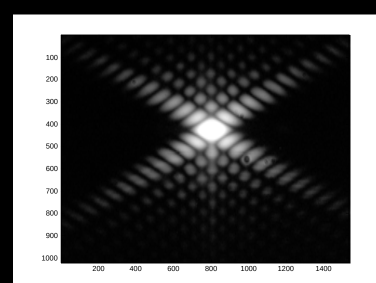
The Spergel-Kasdin Pupil

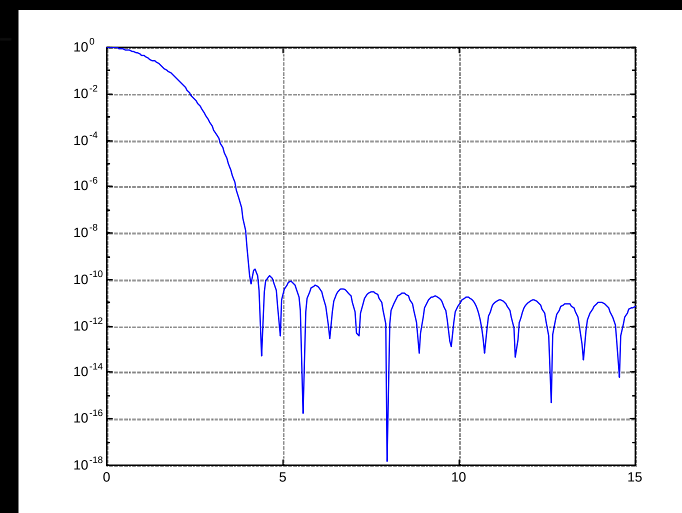
$\rho_{iwa} = 4$

$T_{airy} = 43\%$



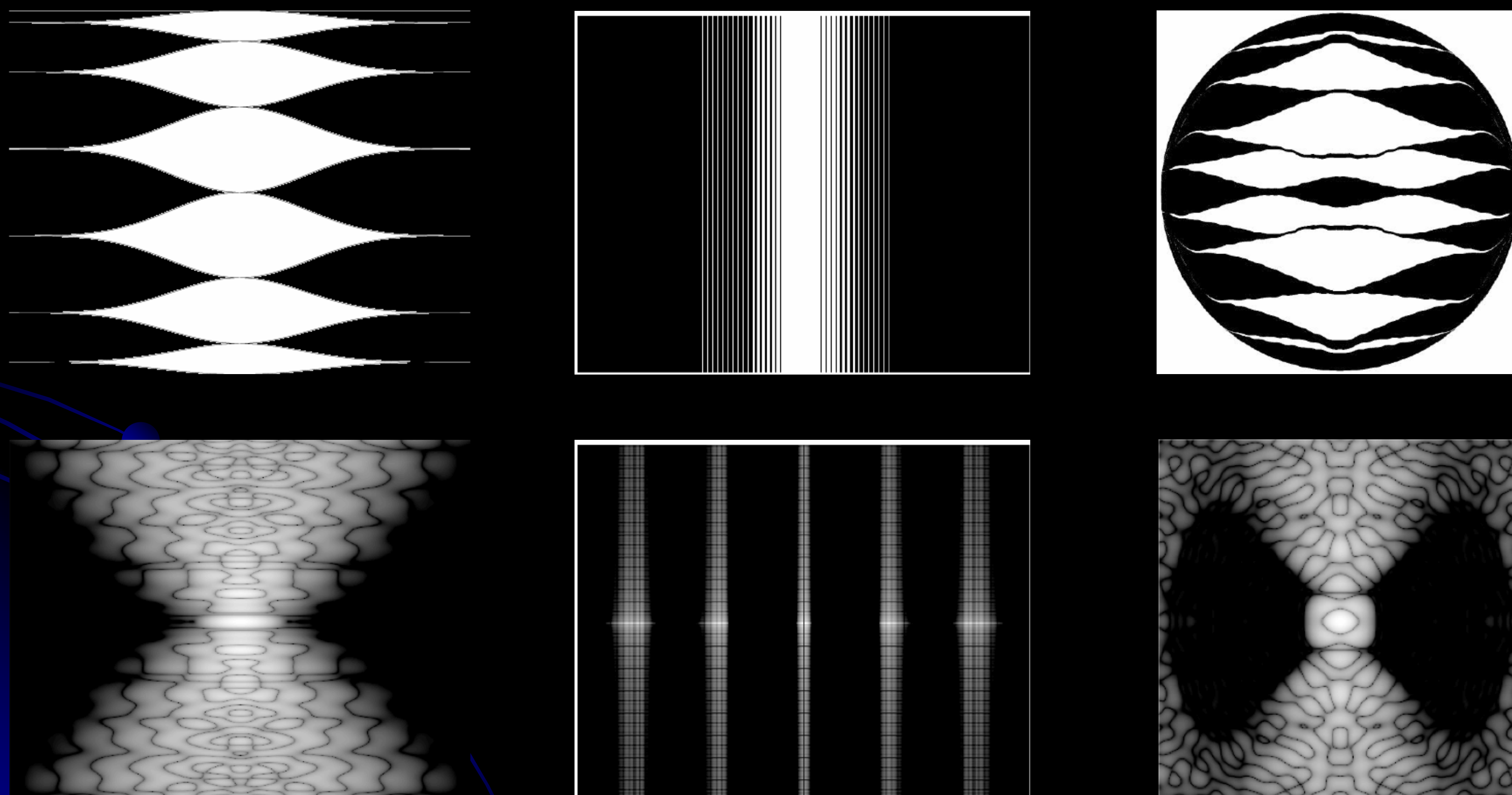






Optimal across x-axis **Very narrow opening**

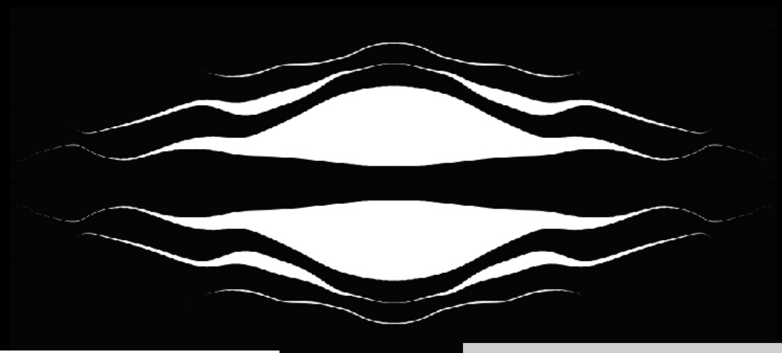
Other Designs

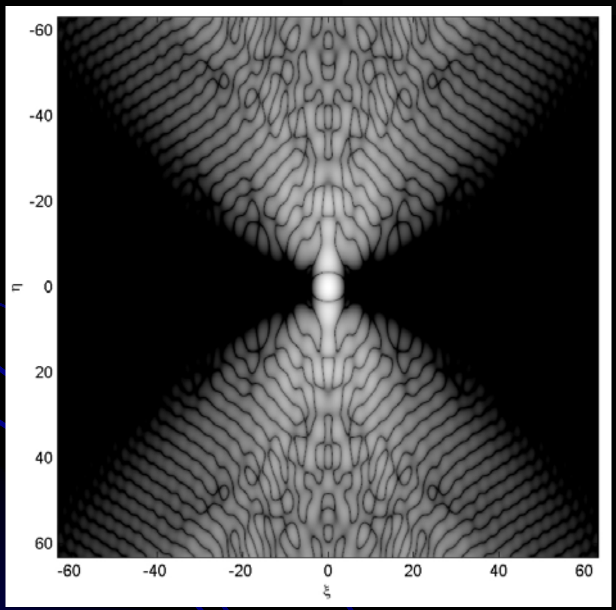


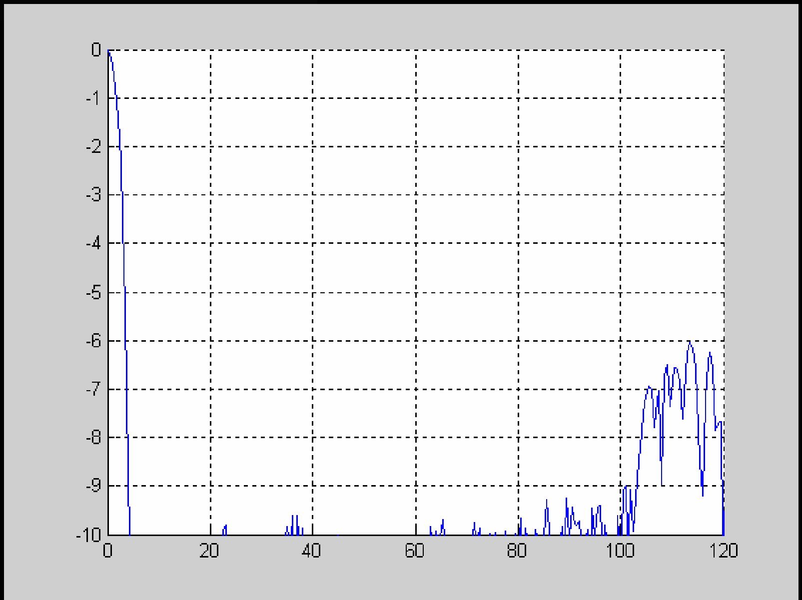
Our Current Favorite

$\rho_{iwa} = 4$

$T_{airy} = 30\%$

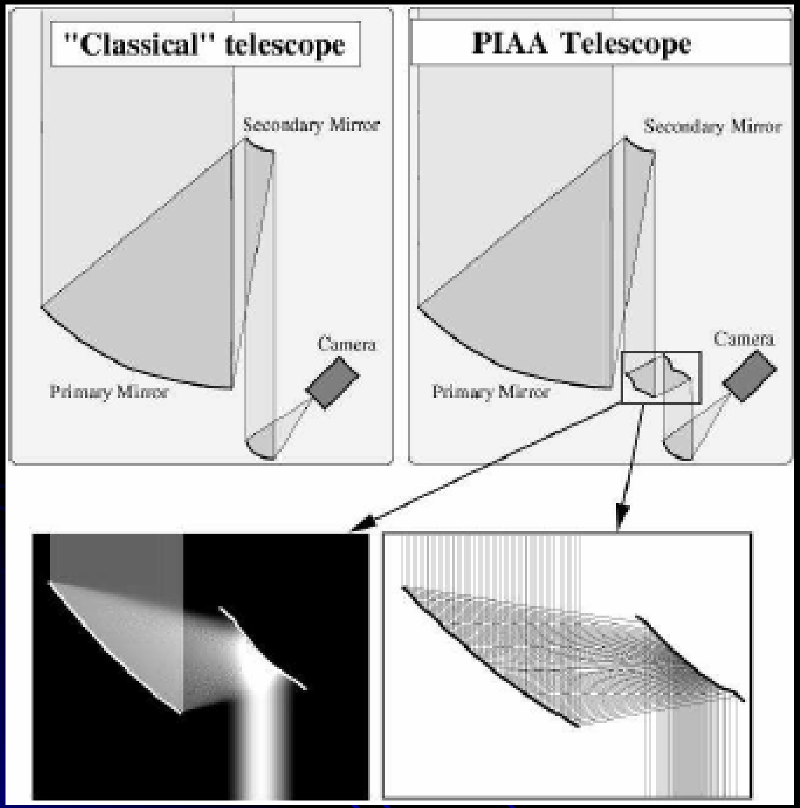




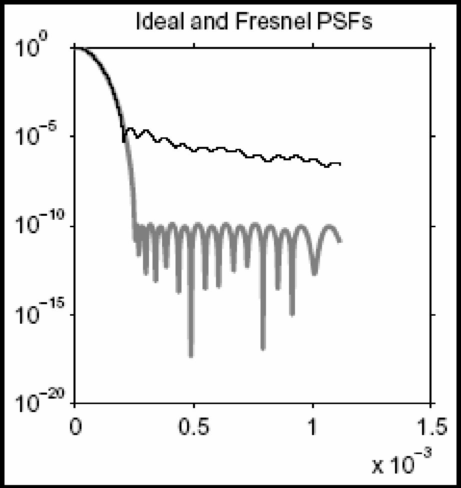


- Simpler to manufacture and less polarization sensitivity than e.g. masks with a lot of openings
- Central obstruction can be used for secondary

Alternative: Phase Induced Amplitude Apodization



Olivier Guyon, astro-ph/0412179v1, 2005



Robert Vanderbei, 2005

- Unproven and somewhat controversial method
- High risk, high reward
- Main advantage: very little light loss
- Potential problems:
  - Fresnel effects
  - Off-axis degradation
  - Difficulty in manufacture
  - Polychromatic corrections

Outline

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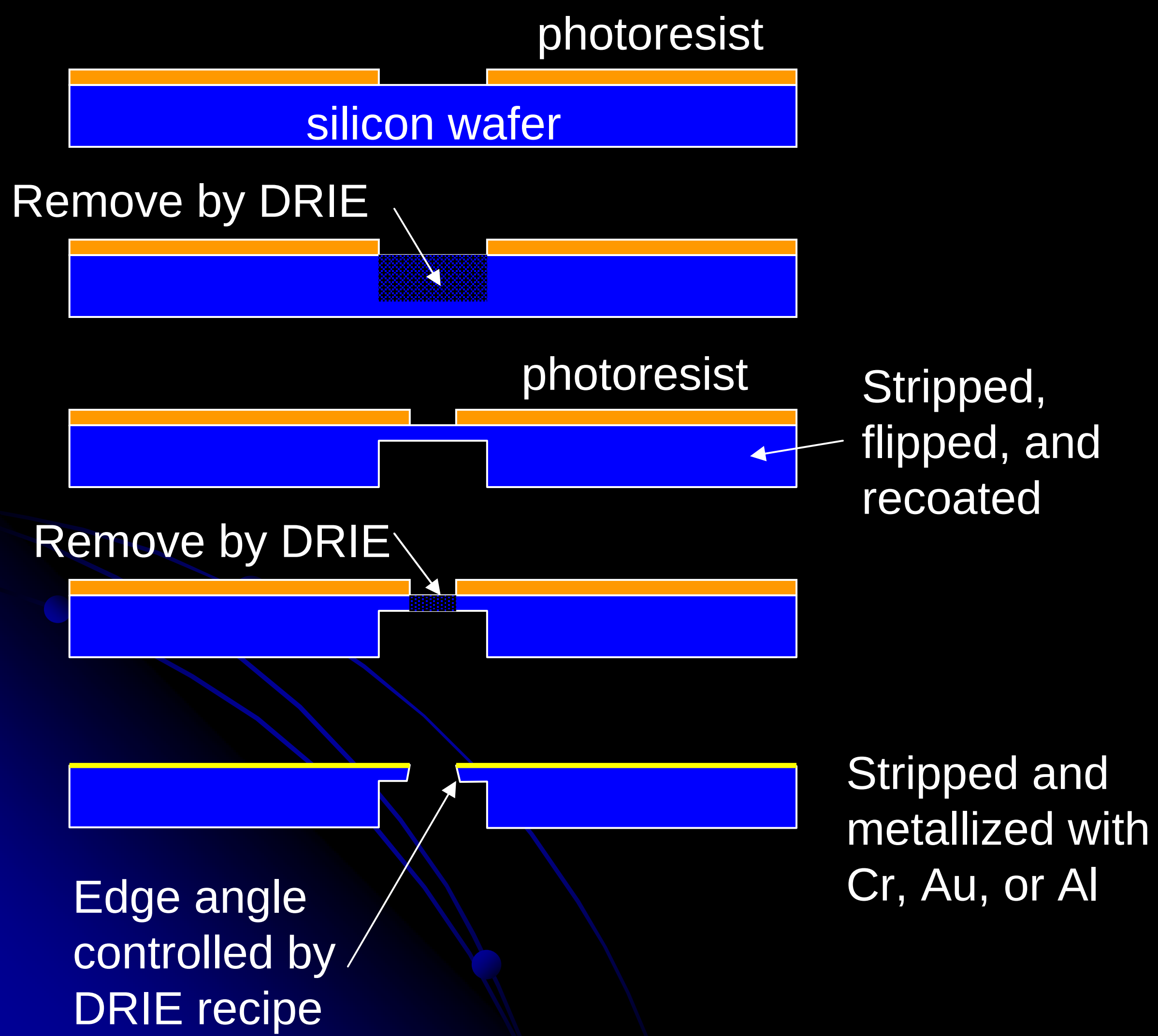
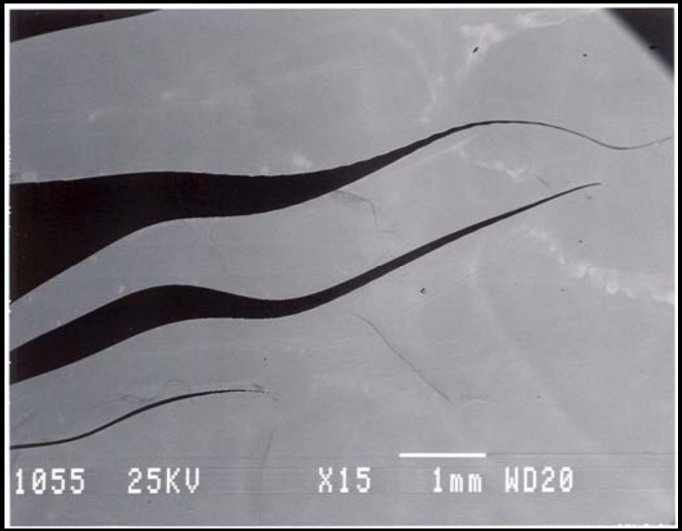
Elliptical Mask Manufacturing

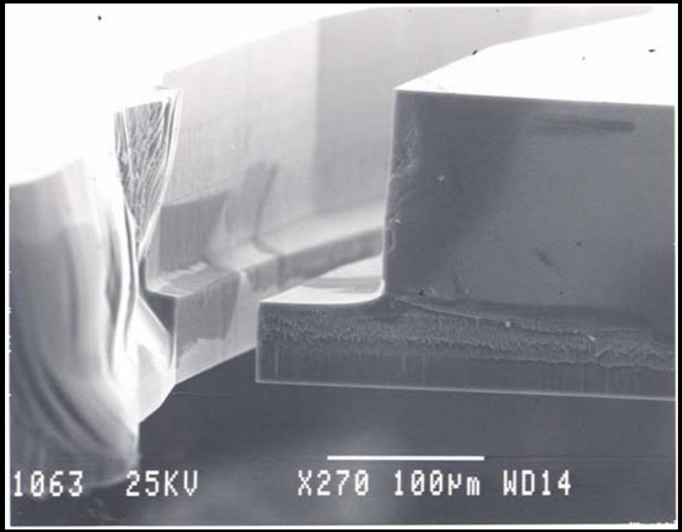


- Manufactured by NIST
- Commercial Si wafer
  - 76 mm diamter
  - 320 micron thick
  - 1-10 ohm cm, p-type, B doped
  - <1-0-0> oriented
- Double-sided Deep Reactive Ion Etch (DRIE) to make holes
  - First etch: wafer thinned to 50 micron thickness around openings
  - Second etch: through etch to complete holes

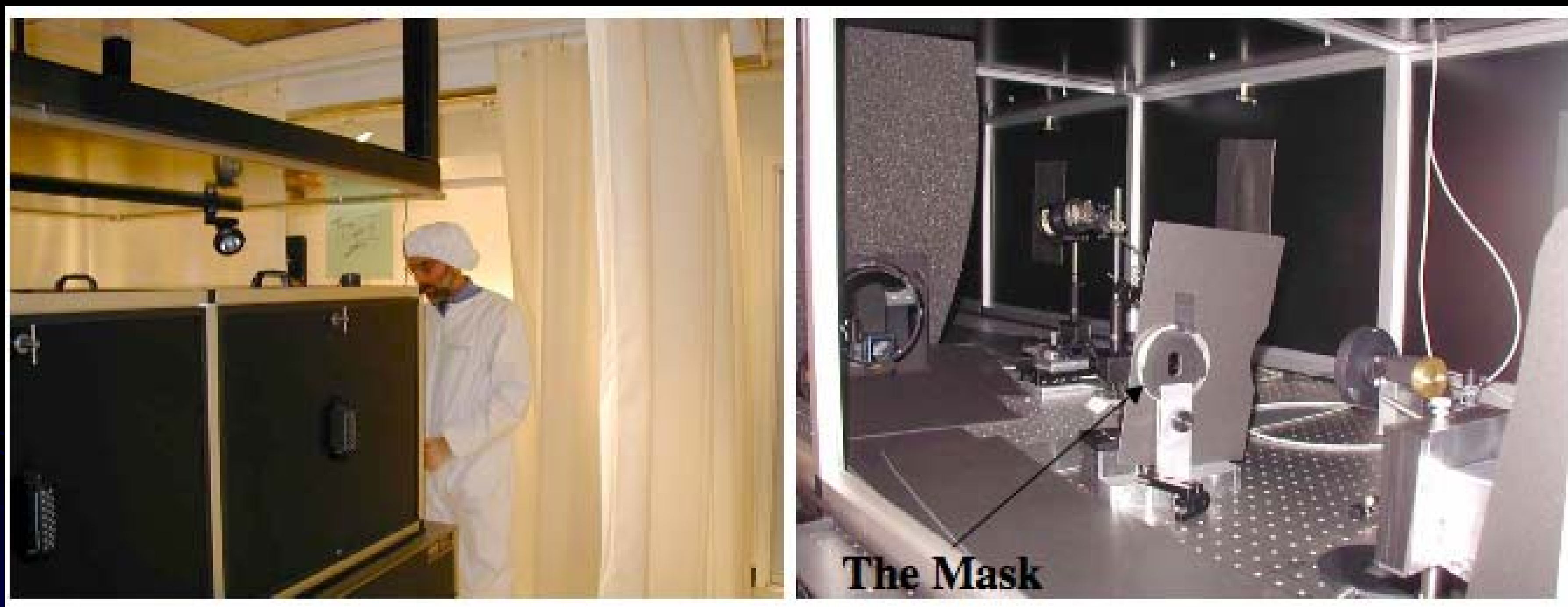
Laboratory Mask



- Mask made to flight quality (precision < 1 micron)
- Efficient, repeatable process
- Future masks will feature metalized coating and undercut edges.

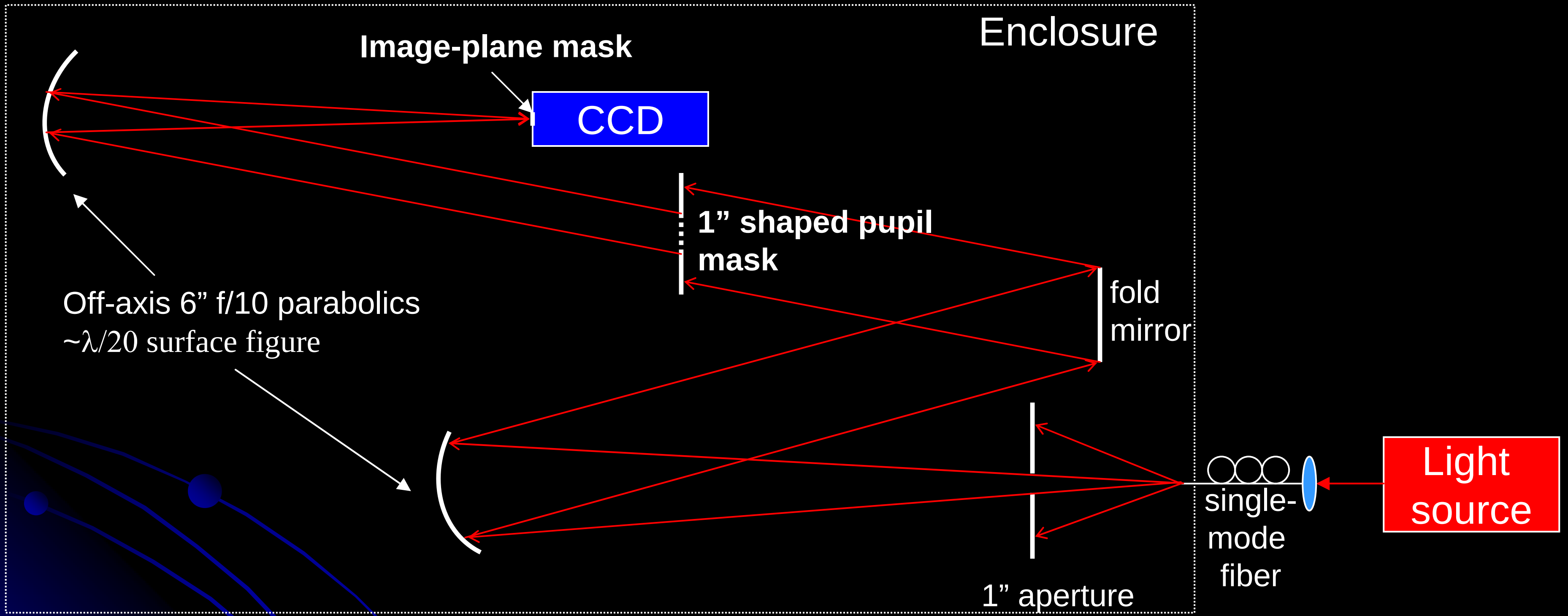


Our Recently Completed Laboratory



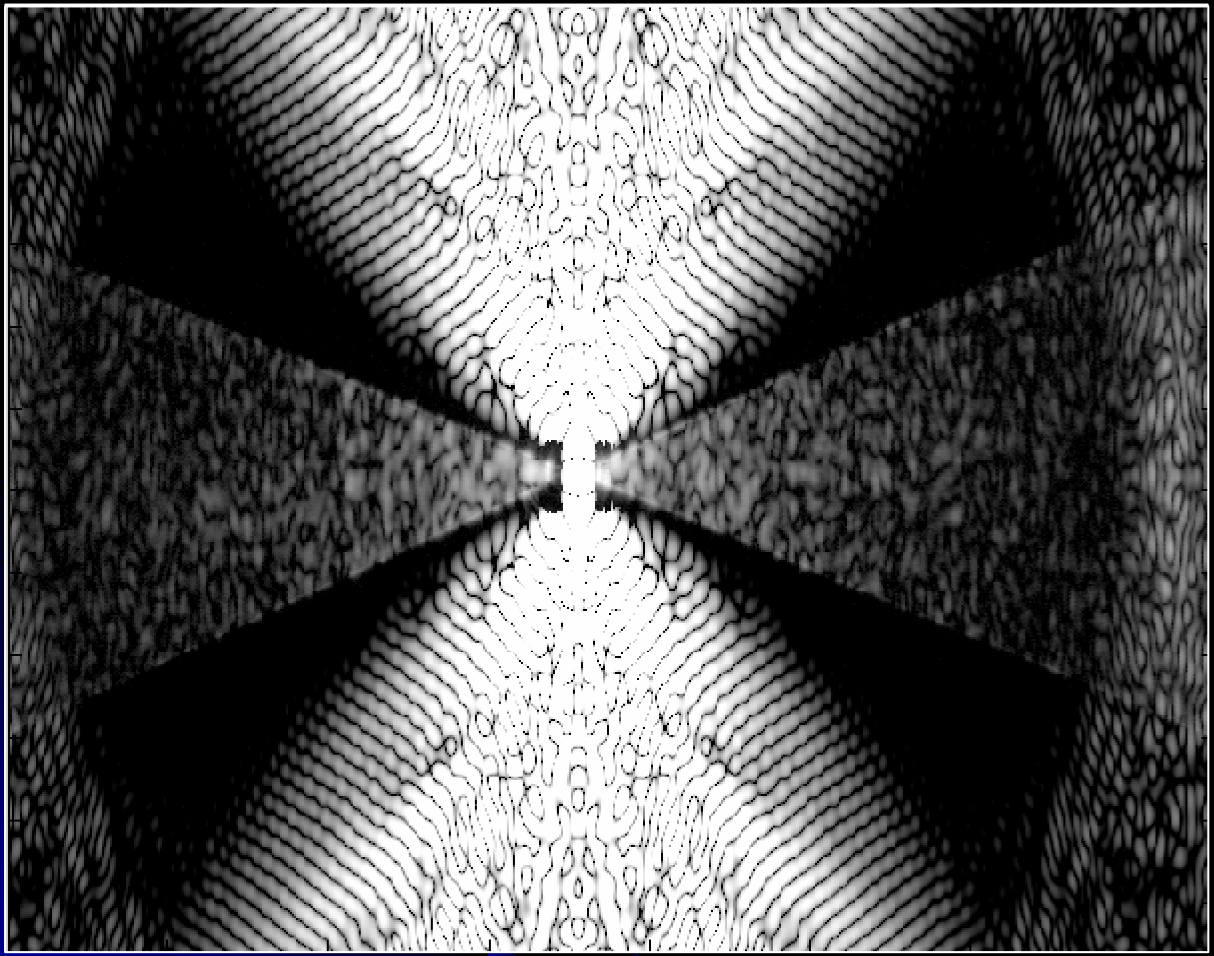
- Clean room
- 1.2 x 5 m vibration-isolated optical bench
- Enclosure to eliminate thermal convection, air turbulence, particulate contamination, and stray light

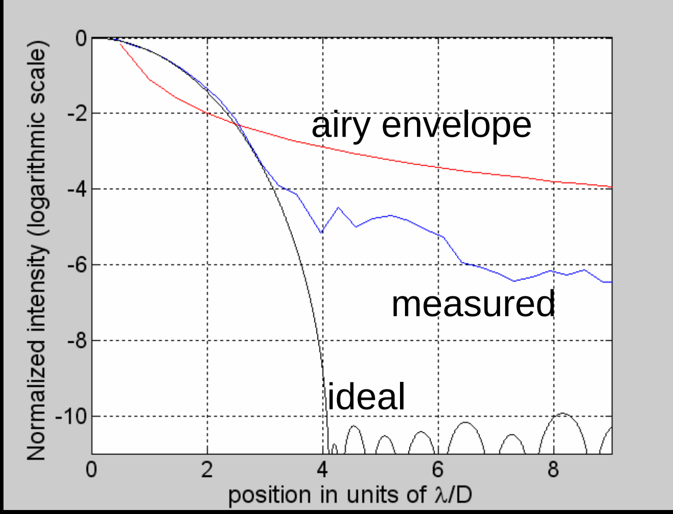
Optical Layout



- Shaped pupil mask illuminated by simulated starlight
- CCD placed at first focus (f/60)
- Image-plane mask (bowtie mask) placed on CCD chip.

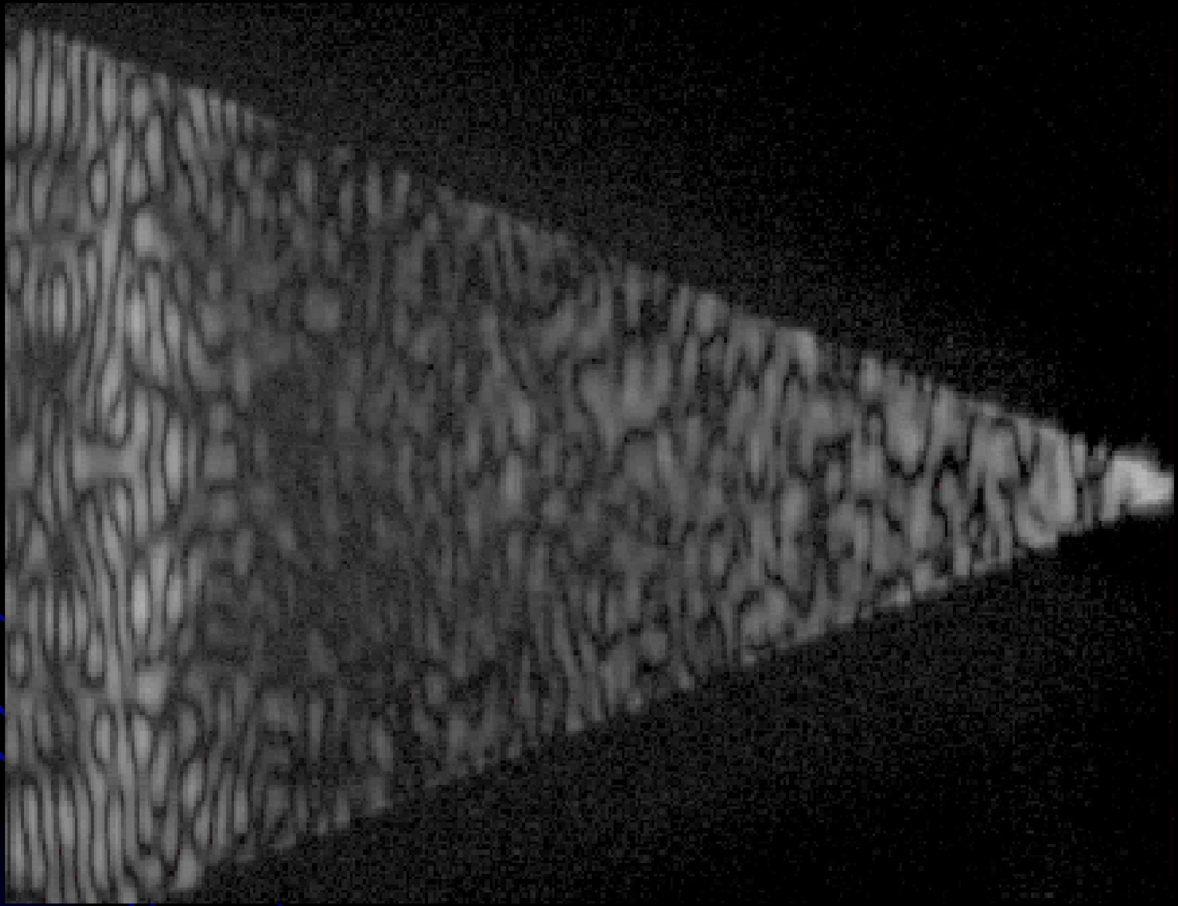
Contrast Measurement at 633nm





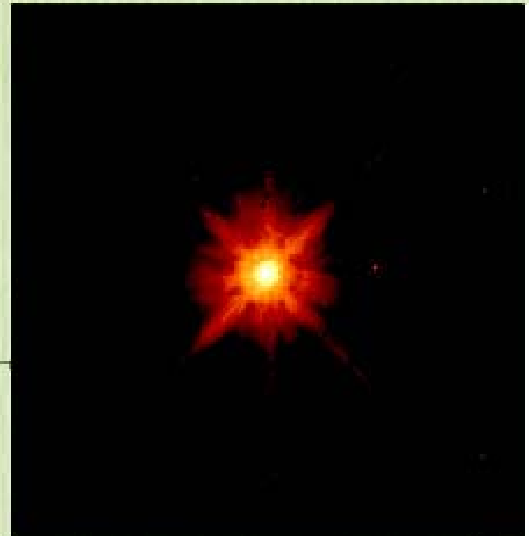
- Contrast:
  - $\sim 10^{-5}$ @ 4 λ/D
  - $< 10^{-6}$ @ 7 λ/D

Cause of Speckle: Mirror Aberrations

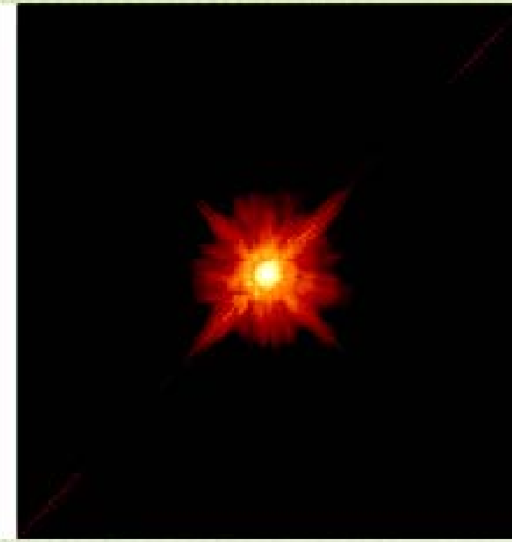


Surface Figure on Large Telescope Optics

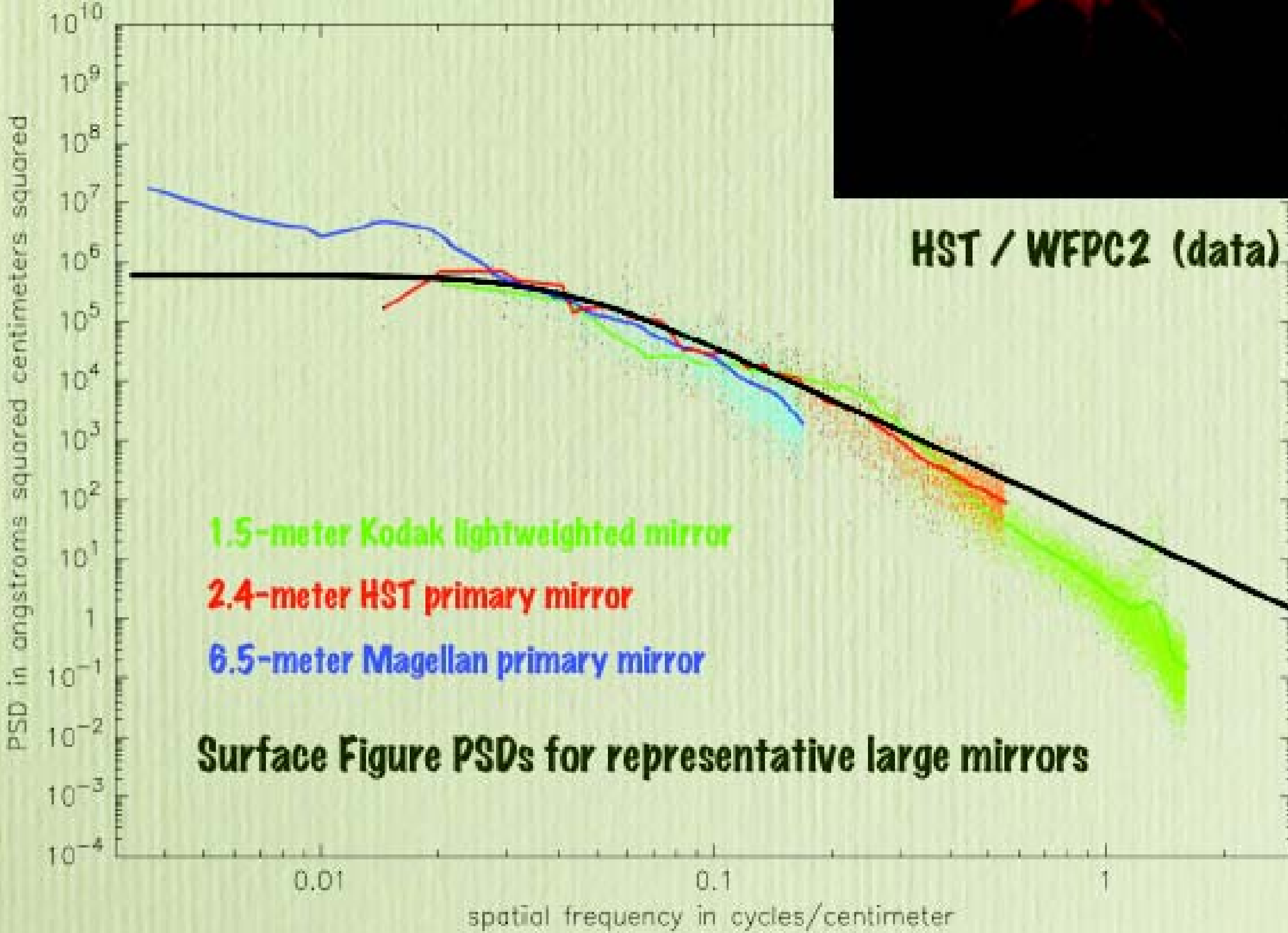
At right: Control of optical scatter due to surface figure errors on large telescope mirrors with dimensions is the dominant engineering issue for high contrast imaging applications.



HST / WFPC2 (data)

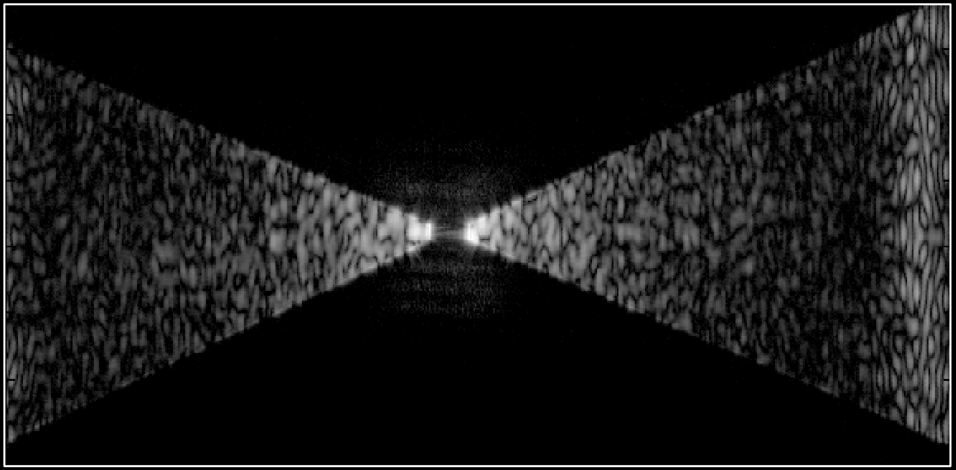


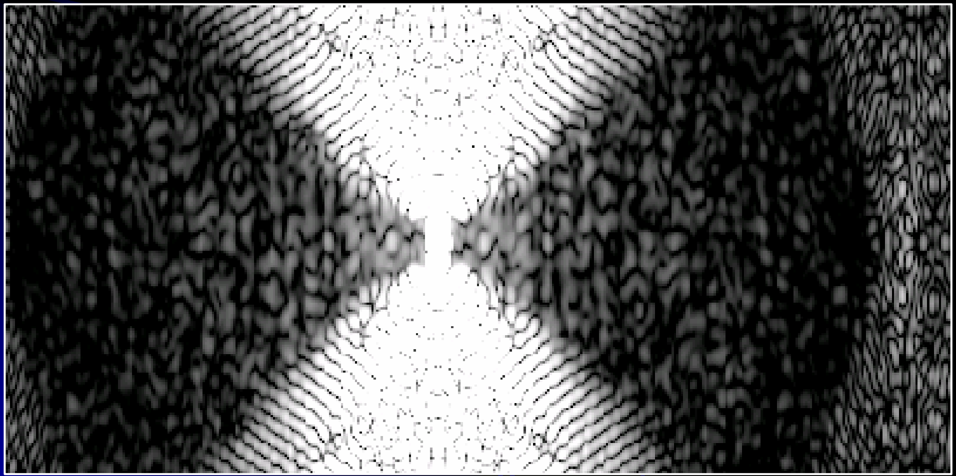
HST / WFPC2 (model)

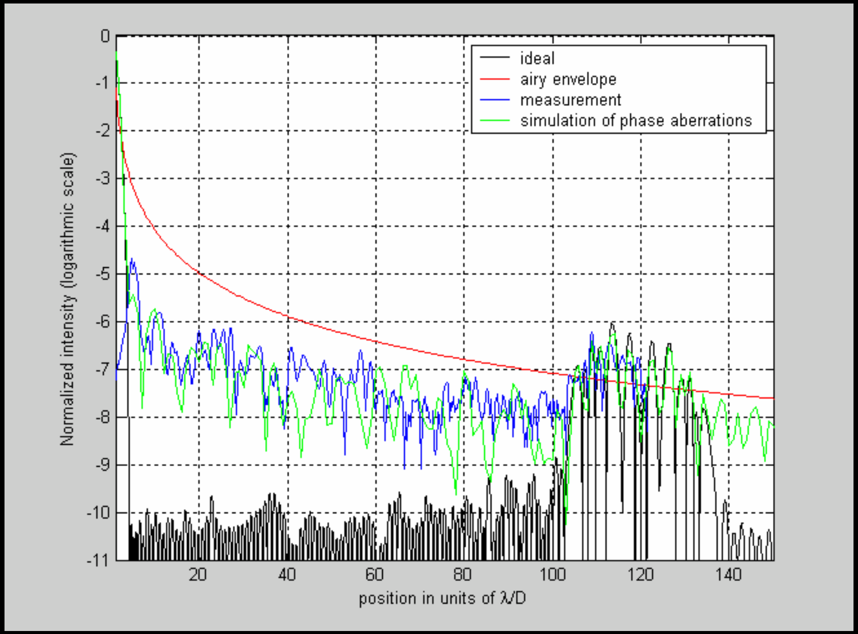


At left: State of the art for surface figure errors at the critical spatial frequencies has changed little since HST despite advances in mirror construction and modern polishing technologies.

Simulation of Phase Aberrations

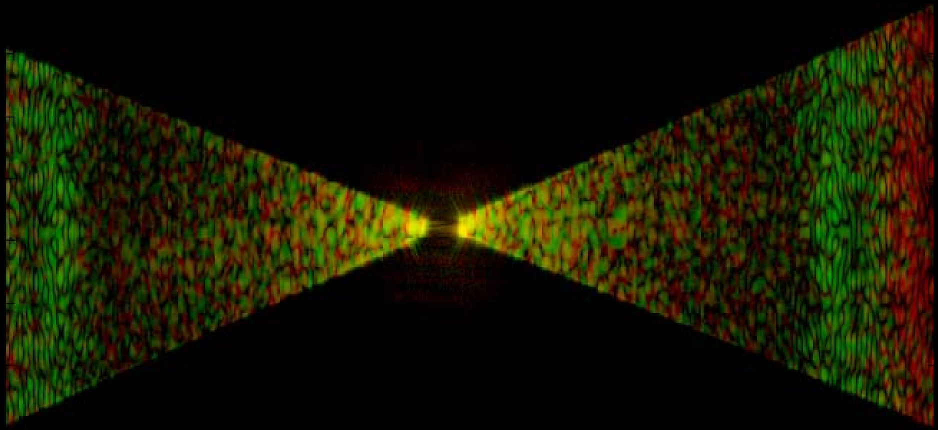

measurement


simulation

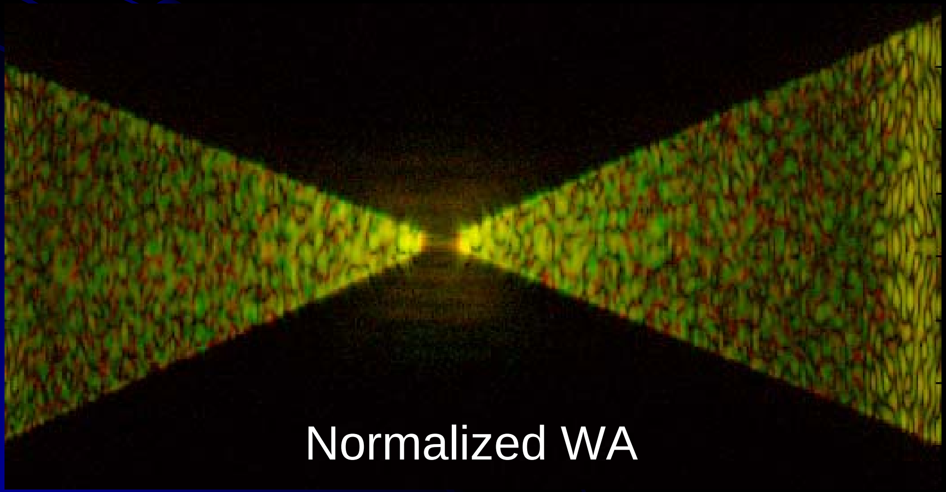


- Simulation based on 1/f random-noise phase aberrations for $\lambda/20$ mirrors
- Confirms mirror phase aberrations are dominant cause of our speckle

Contrast Measurements for Red (633nm) and Green (532nm)



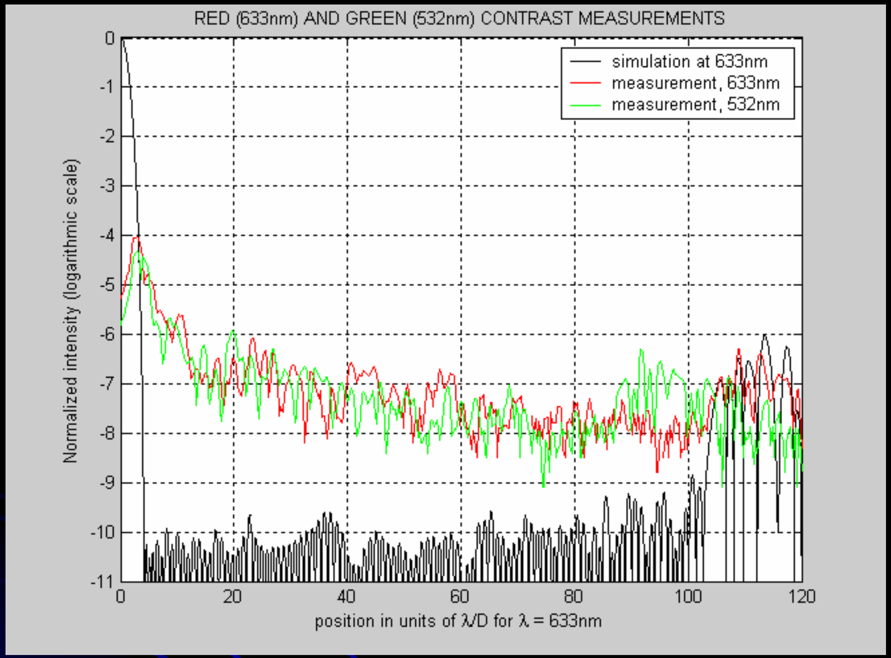
Physical scale



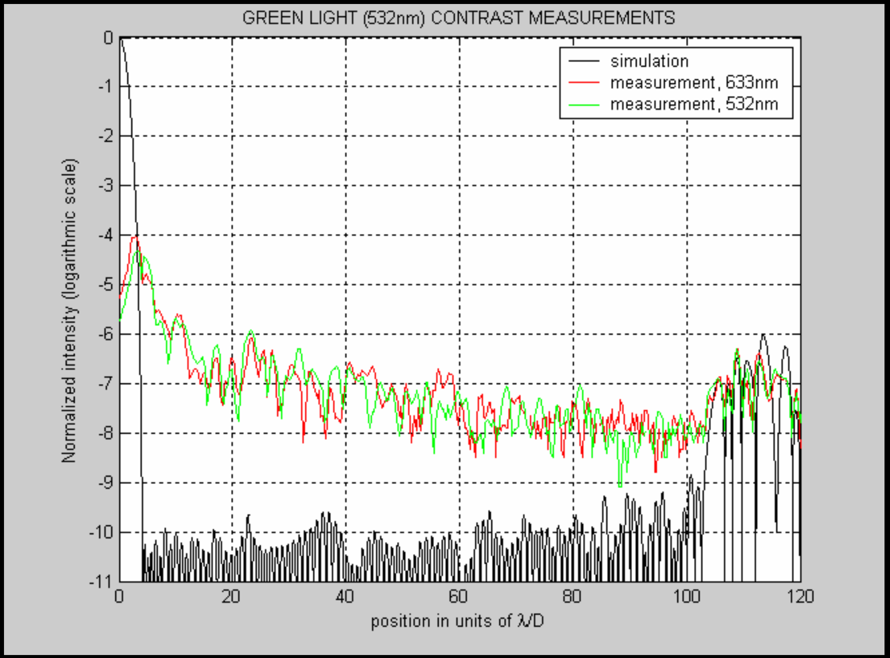
Normalized WA

- Focal plane color image
  - Green image contracted with respect to red, by exactly the correct factor
- Green image stretched to match λ/D scale of red image (normalized WA).
  - Speckle pattern similar for low IWA for the 2 wavelengths

Comparison of Red and Green Contrast



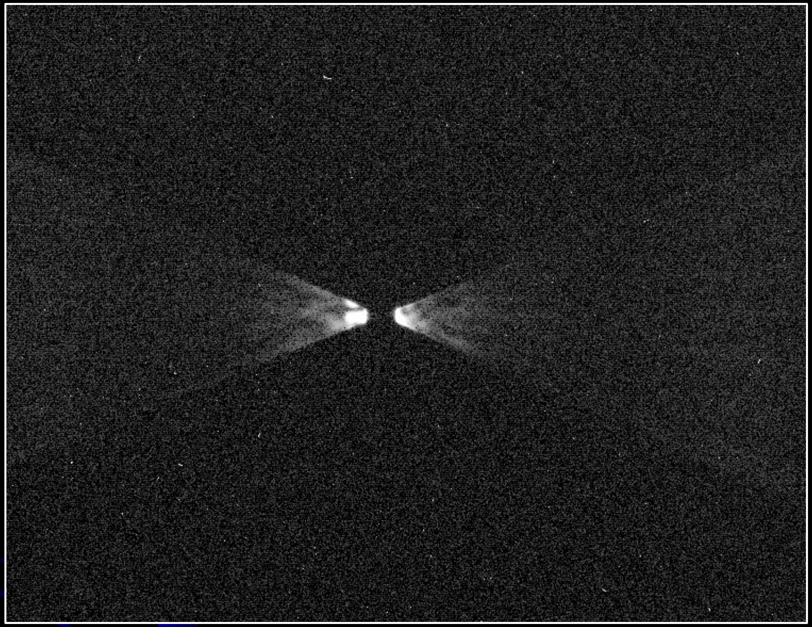
Physical scale

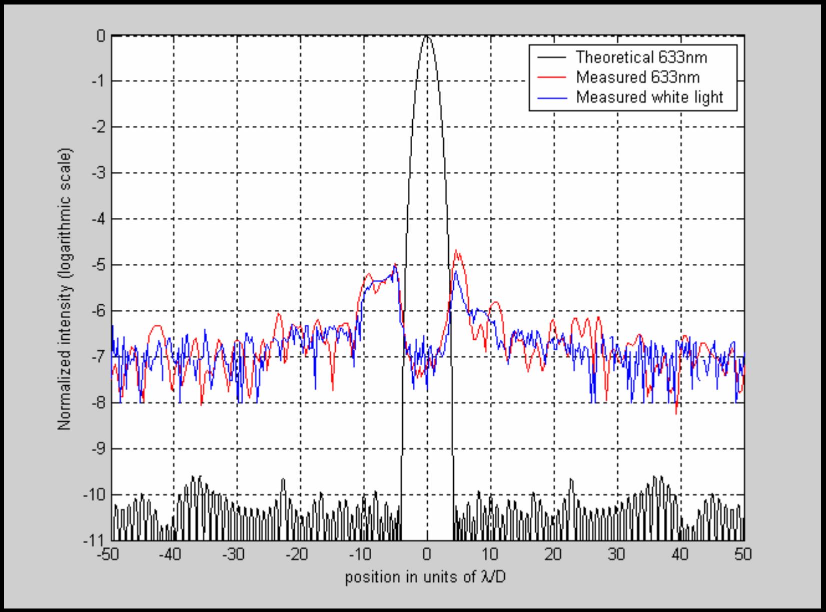


Normalized WA scale

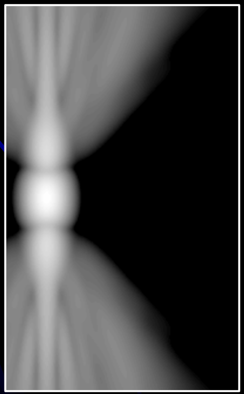
- Contrast levels in red and green are the same
- Speckle pattern is similar for small WA

White Light Results





measured PSF



theoretical PSF

- Shaped Pupils are Broadband
- Contrast in white light is roughly the same as for monochromatic
- Speckle structure is similar to monochromatic case for low IWA

Outline

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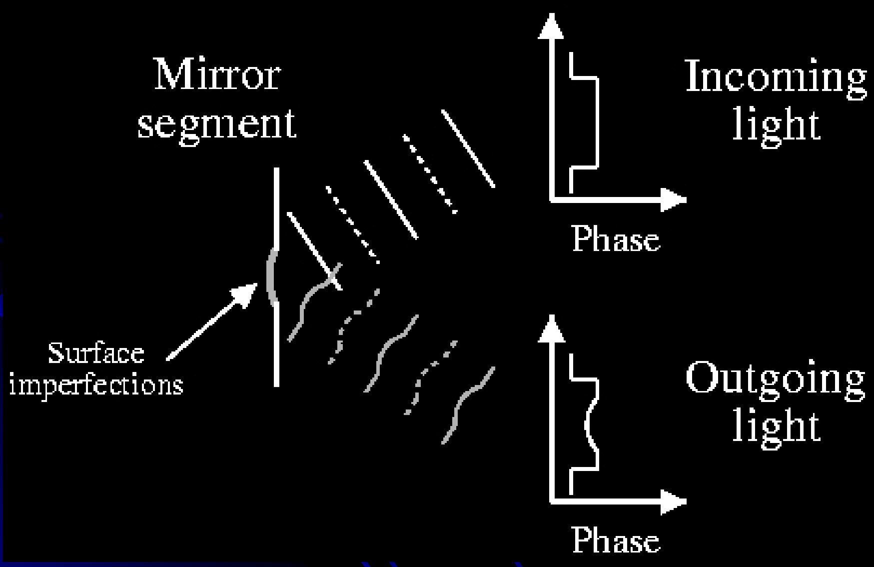
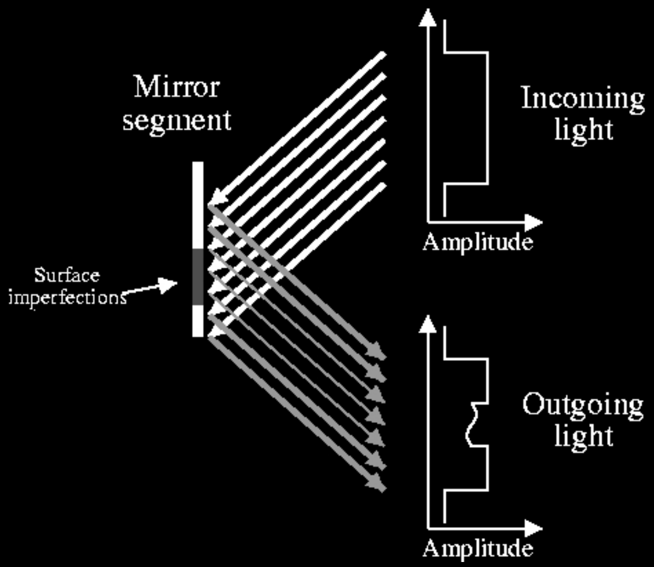
The Real Challenge: Wavefront Control

Phase aberrations



Requirement: λ/10,000

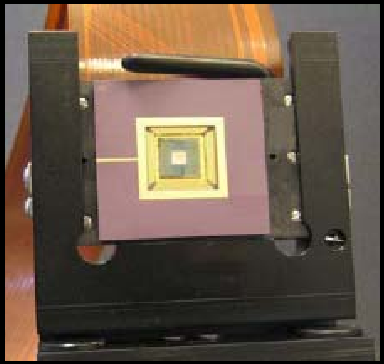
Amplitude aberrations



Requirement: 1 / 1,000

Deformable Mirrors

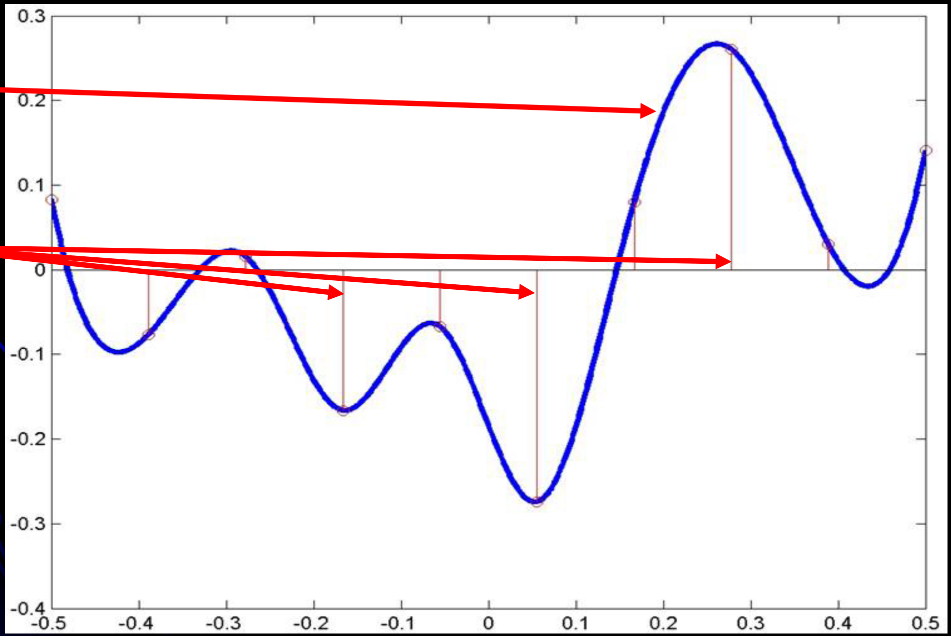
Boston Micromachines



Xinetics

Face-sheet

Actuators

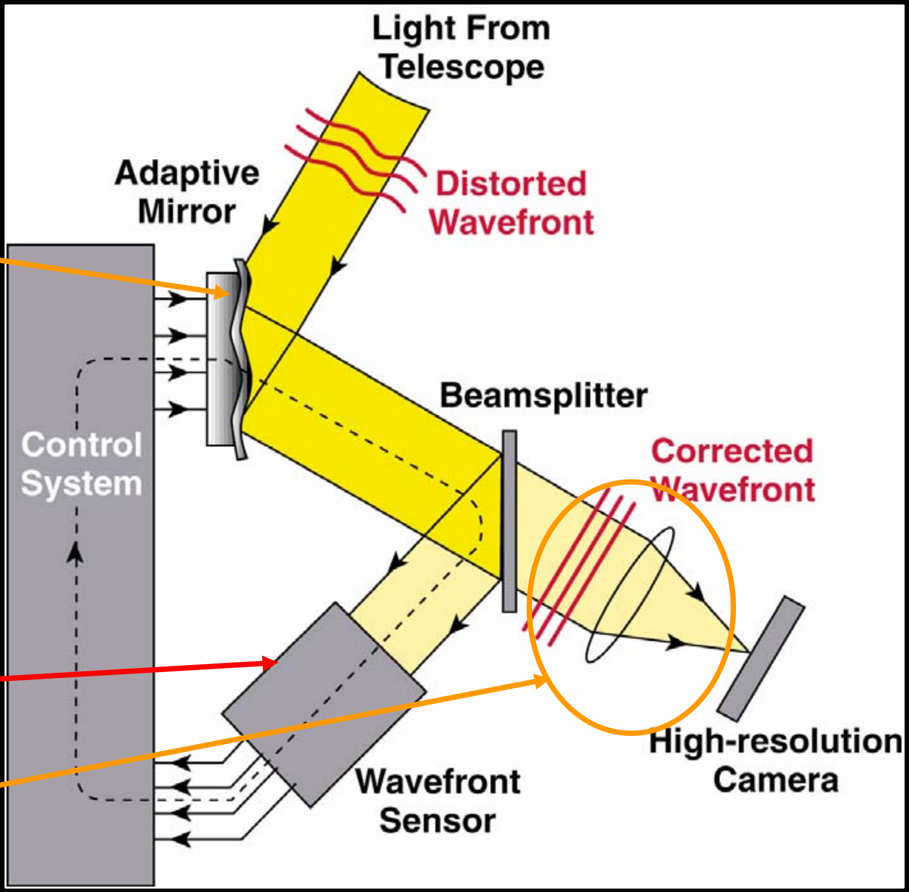


Conventional Wavefront Estimation and Correction

Does not correct amplitude distortions

Measurements are taken at the pupil plane

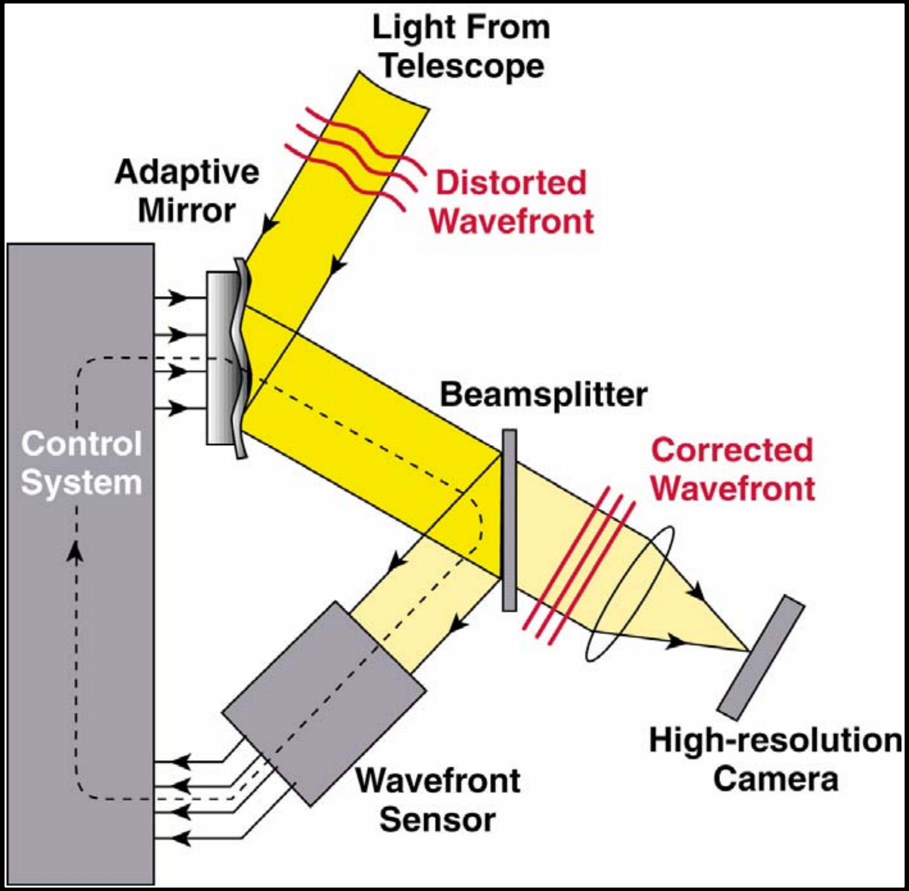
Cannot correct these elements



Courtesy Claire Max, CfAO

Types of Amplitude Errors

- Reflectivity nonuniformity of mirrors (grey)
- Mask errors (grey)
- Phase induced amplitude error (chromatic)
- Unmodeled physics (polarization effects, fresnel and vector diffraction, etc.)



Courtesy Claire Max, CfAO

λ–Dependent (Chromatic) Amplitude Errors

- Proposed solutions
  - Place DMs at each conjugate location
  - Operate in multiple narrow bands (Roger Angel)
  - Put shaped pupil in front of the primary and actuate primary and secondary mirrors (Roger Angel)
  - Live with it and use difference imaging techniques to subtract speckle

Conclusions

- The Princeton TPF team has designed the Shaped Pupil Coronagraph as a solution to the high contrast problem
- Investigating the PIAA approach
- Experimental demonstration of high contrast limited only by quality of optics
- The main challenge is wavefront control, phase *and* amplitude in white light. The TPF group at Princeton is developing methods, algorithms, and significant laboratory capability to do wavefront estimation and correction to the required levels