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Towards direct imaging of Exo-planets

Coronagraph Wavefront Correction by Electric Field Conjugation

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Collaborators:

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Are there other Earth-like planets?

The Terrestrial Planet Finder (TPF) Project

The goal of TPF is to survey the habitable zone of the nearest 150 stars (within 20 parsecs away = 66 ly away from Earth) for the existence of terrestrial ("Earth-like") planets.

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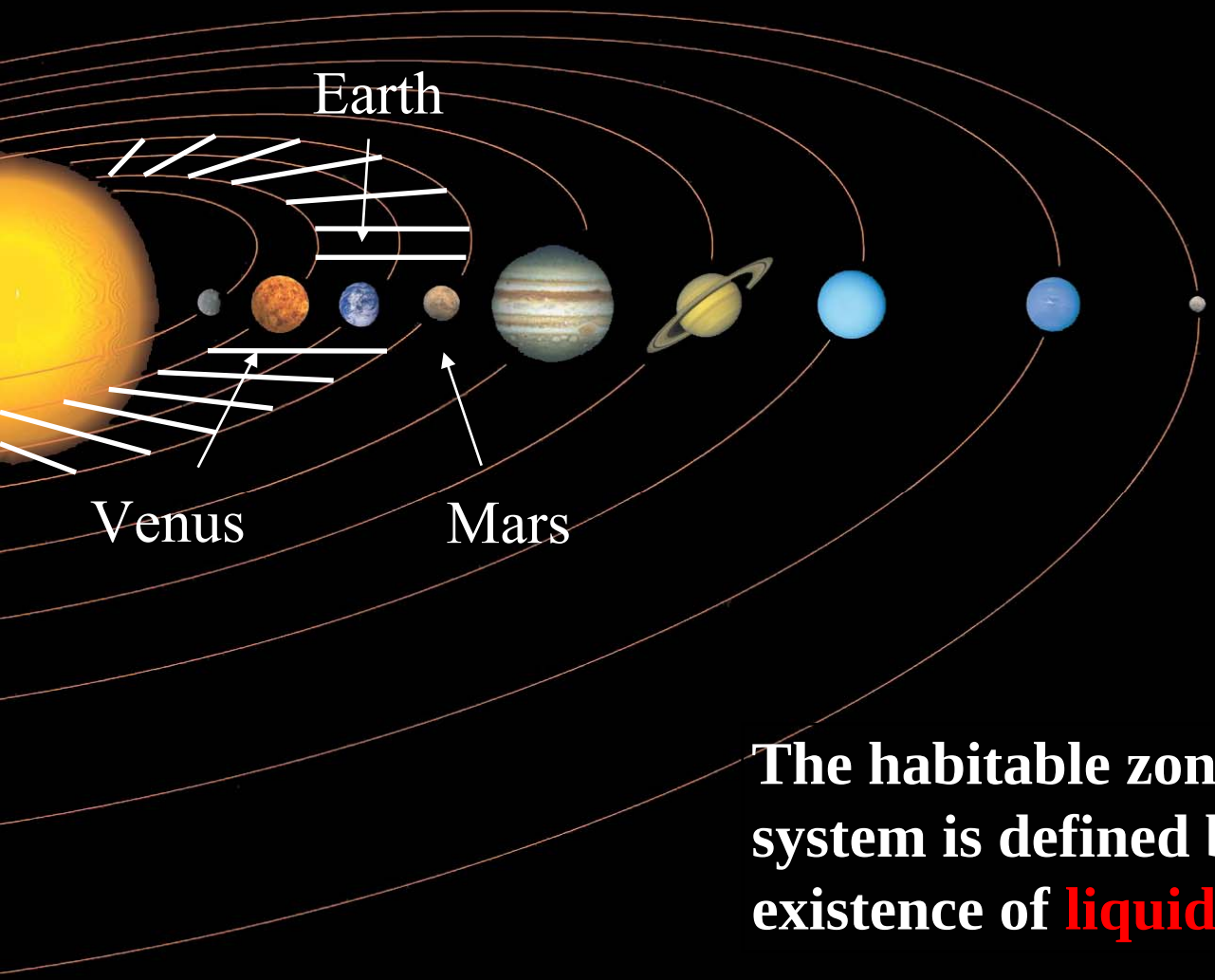
"Earth-like"

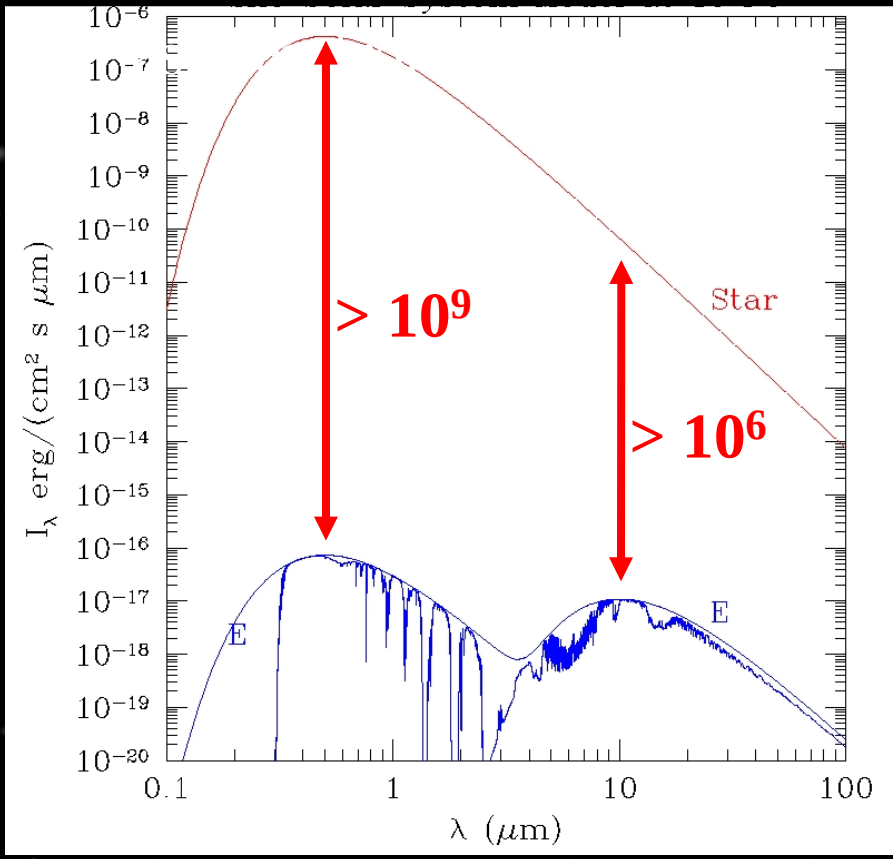


The habitable zone, relative to our solar system is defined by the possibility of the existence of liquid water.

Why is it so hard?

- The planet is 10^{-10} times dimmer than the star.
- A star, 20 parsec (66 ly) away, with a planet 1 AU from the star, the angular separation is 0.05 arcsecond, which is roughly 1/26,000,000 of a complete circle.
- Using a 10m telescope, operating at L=600 nm, a planet and a star, 1 AU apart, would subtend an angle of 2.4241e-007 radians (4 L/D).

Model spectrum of the Sun and Earth



Courtesy of W. Traub, (Sitting over there)

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How challenging is direct imaging of terrestrial planets in visible light?

Imagine looking for a bump 1/100 the thickness of a human hair…

90 microns / 100 = $9*10^{-7}$ m

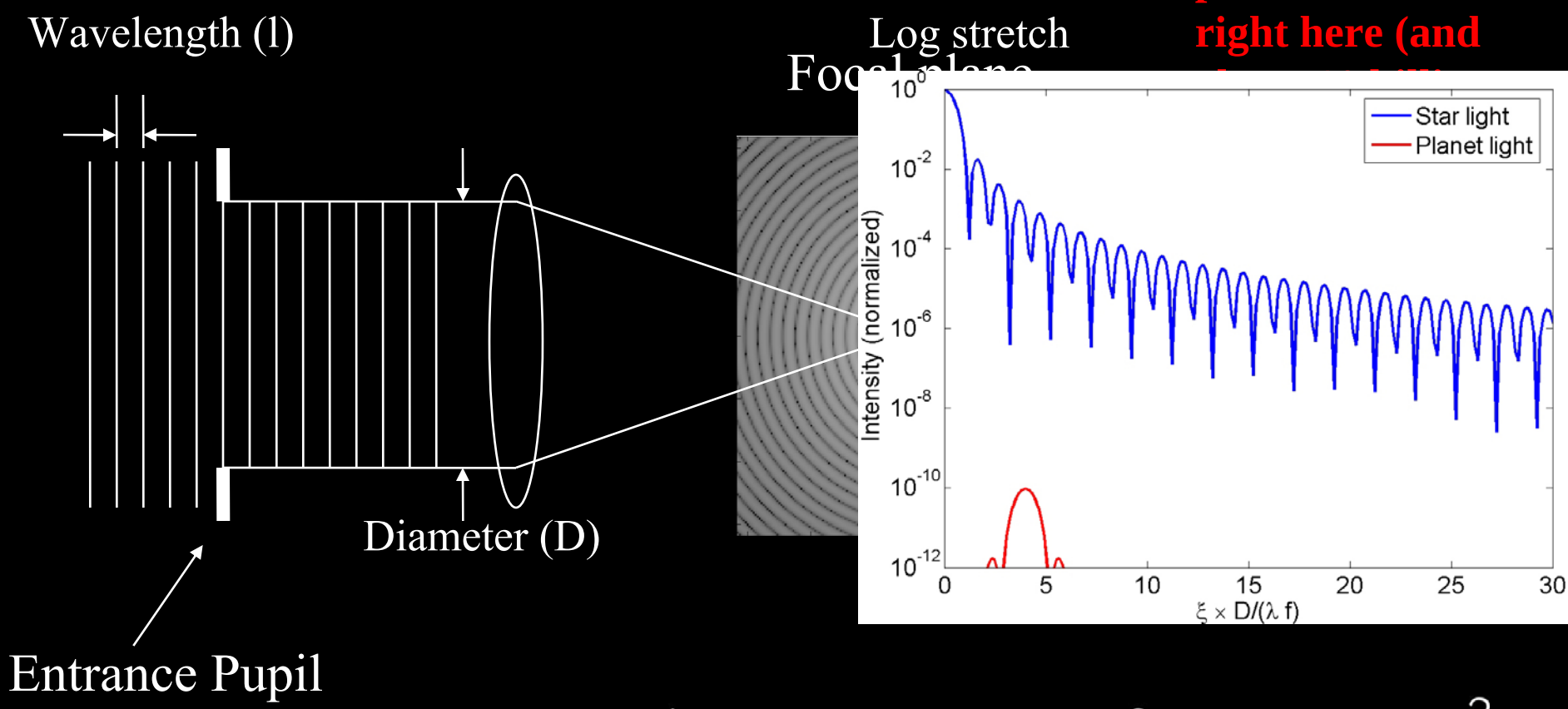
…on the slopes of Mt. Everest!!

9000 m = $9*10^{3}$ m

That's a ratio of 10^{10}, same as Earth to Sun contrast!!

Diffraction

Unfortunately, the planet would be right here (and



$$I(\xi,\eta) = \frac{1}{\lambda^2 f^2}\left|\iint_{-\infty}^{\infty} A(x,y)e^{-i\frac{2\pi}{\lambda f}(x\xi+y\eta)}dxdy\right|^2$$

A

A typical, circular telescope would have to be over a kilometer in diameter in order to detect the Earth-like planet!!

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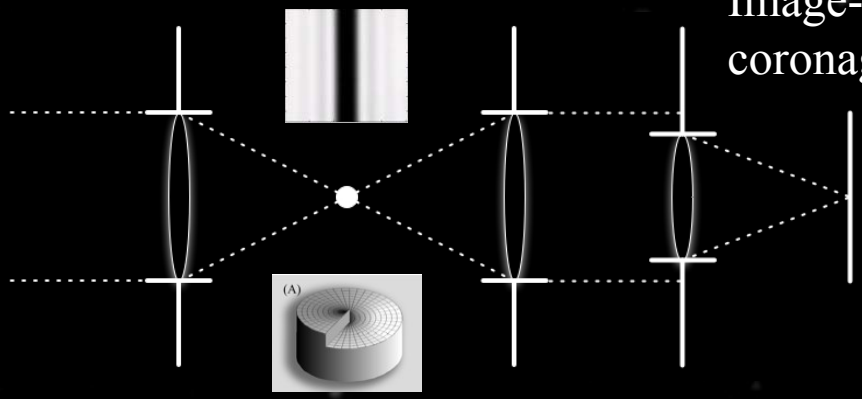
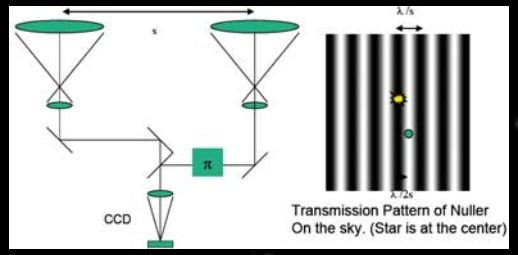
Solutions

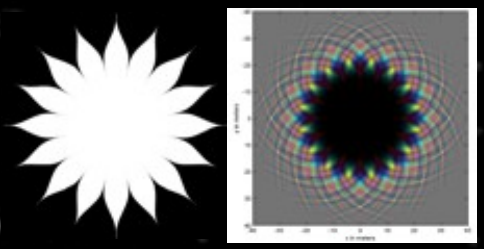
Image-plane occulter coronagraph



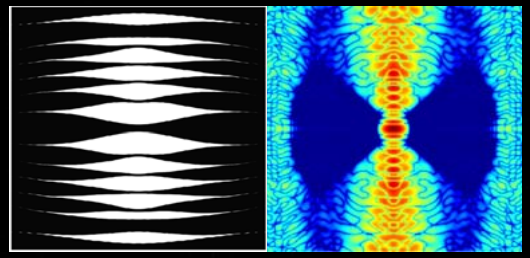
Nulling interferometer



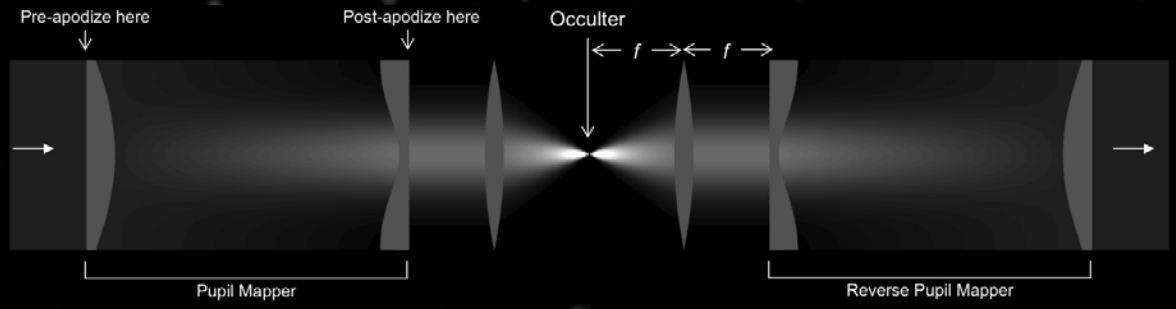
External occulter coronagraph



Shaped pupil coronagraph

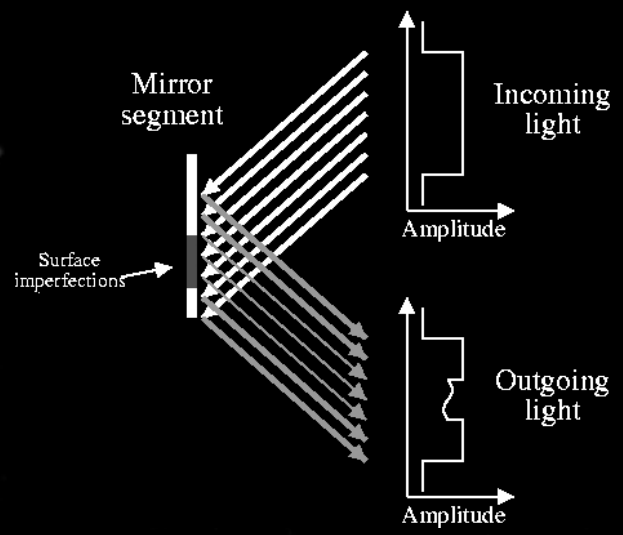


Pupil mapping coronagraph

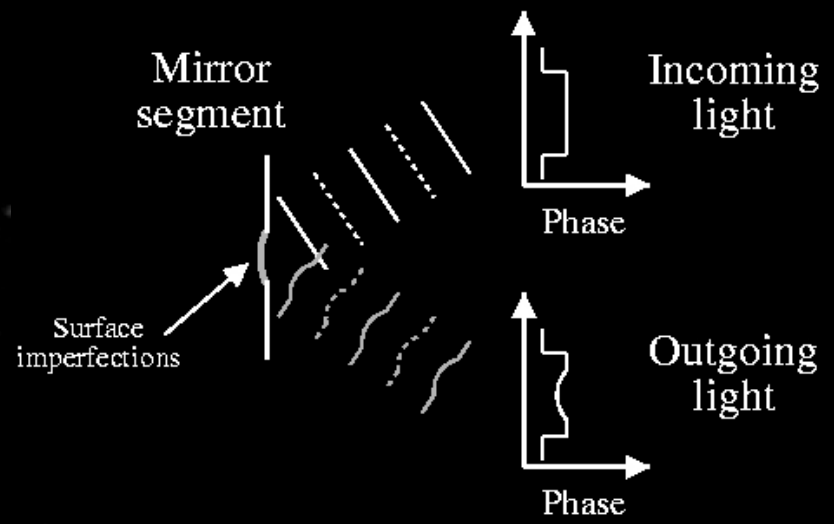


Complex wavefront aberrations

Amplitude aberrations



Phase aberrations



$$I(\xi,\eta) = \frac{1}{\lambda^2 f^2}\left|\iint_{-\infty}^{\infty} A(x,y)e^{\alpha(x,y)+i\frac{2\pi}{\lambda}\beta(x,y)}e^{-i\frac{2\pi}{\lambda f}(x\xi+y\eta)}dxdy\right|^2$$

Wavefront accuracy on the order of $\lambda/10{,}000$ is necessary in order to achieve the desired contrast for Earth-like planet imaging.

Current optical components polishing technology can achieve accuracies between $\lambda/100$ and $\lambda/1000$, depending on the size of the component.

Therefore, a visible light TPF must be equipped with an active wavefront control system

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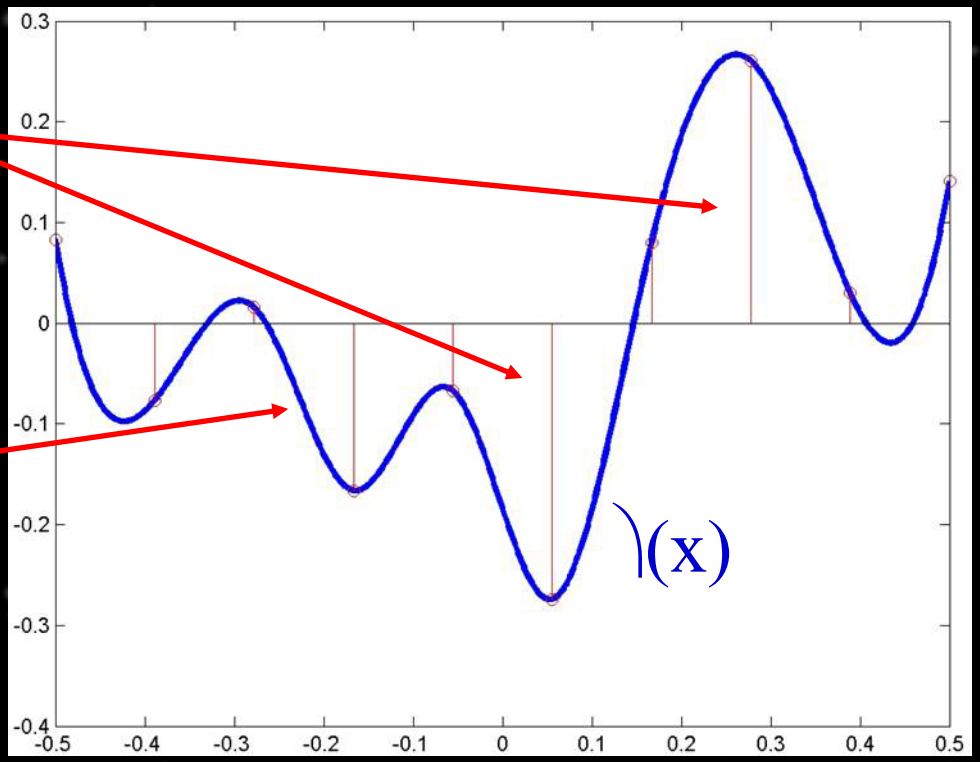
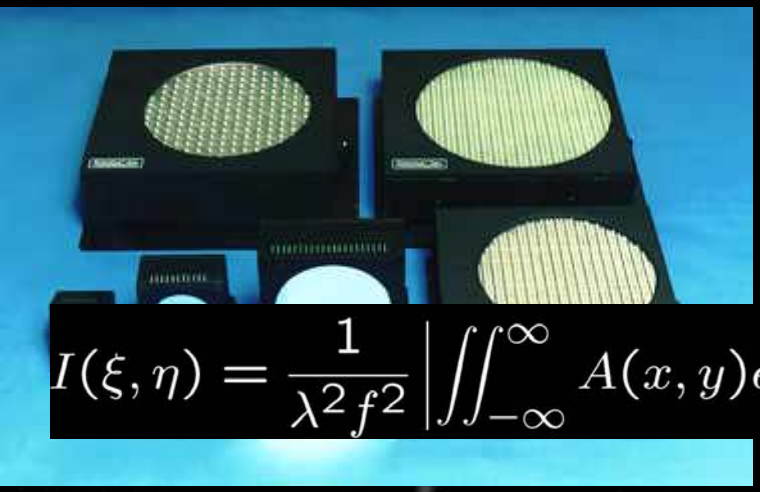
Corrective elements

Deformable mirror model (1D)

Force applied by the actuators on the face-sheet

Reflective face-sheet





$$I(\xi,\eta) = \frac{1}{\lambda^2 f^2}\left|\iint_{-\infty}^{\infty} A(x,y)e^{\alpha(x,y)+i\frac{2\pi}{\lambda}\beta(x,y)}e^{-i\frac{2\pi}{\lambda}\phi(x,y)}e^{-i\frac{2\pi}{\lambda f}(x\xi+y\eta)}dxdy\right|^2$$

Continuous face-sheet DM's, Xinetics product line

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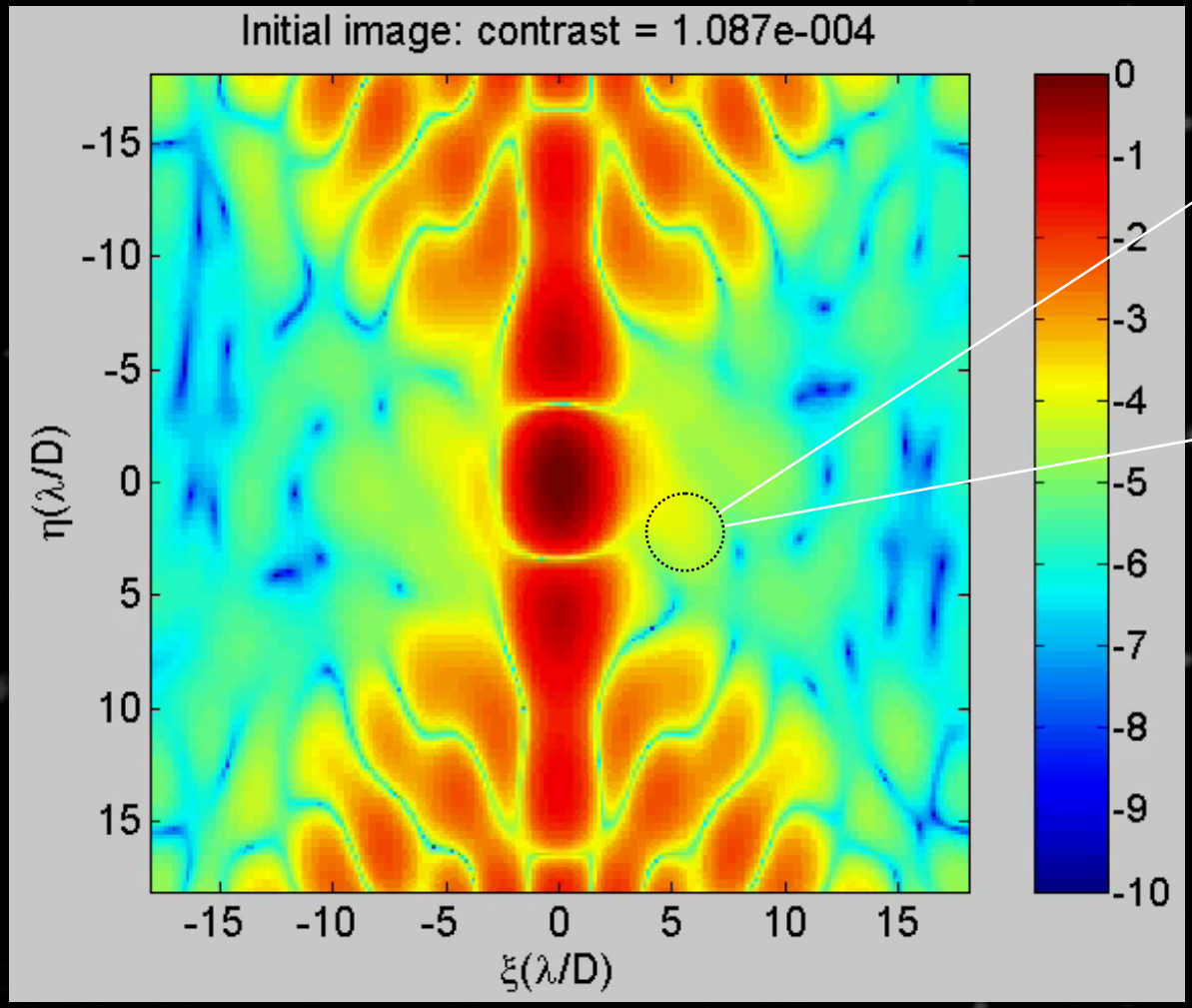
Speckle nulling

Trauger and Burrows (2001-2006)



The location of a "speckle" indicates the spatial frequency of the aberration components that caused it.

The intensity of the speckle indicates the amplitude of the aberration component that cased it.

The spatial phase of the aberration component is determined by testing several shapes on the DM and choosing the best one.

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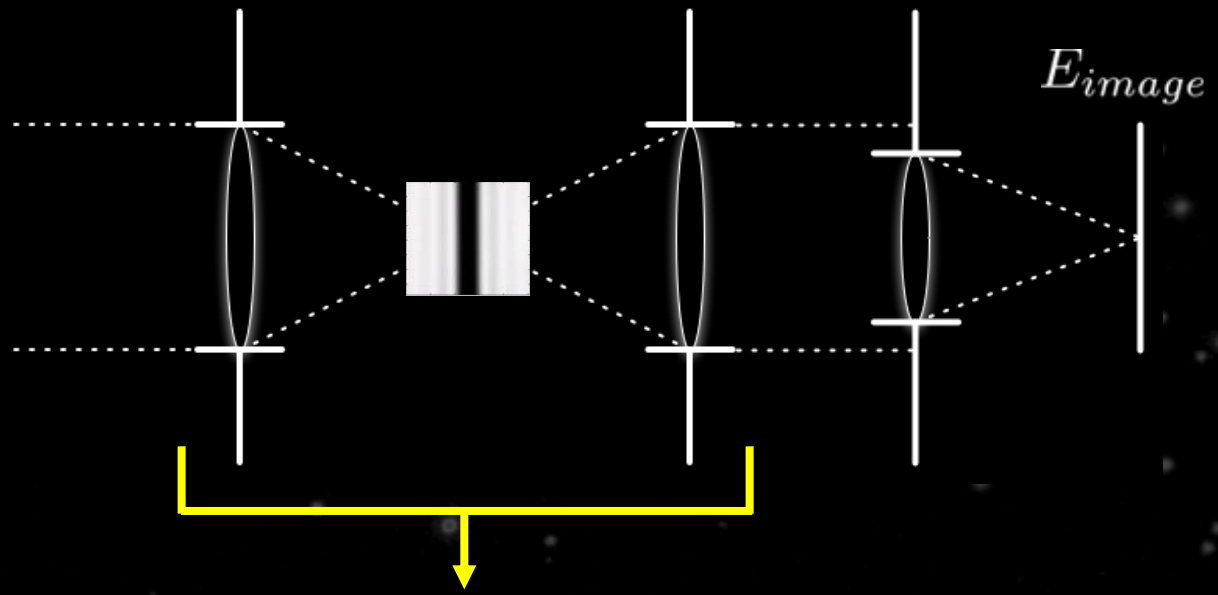
Energy minimization

Borde and Traub (2006)



$$E_{image} = \cancel{E_{ideal}} + E_{abr} + E_{DM}$$

The total energy in the region of interest is given by

$$\mathcal{E} = \left| E_{abr} + E_{DM} \right|^2$$

In order to find the minimum energy, one must solve the set of linear equations that satisfy:

$$\frac{\partial \mathcal{E}}{\partial a_{ij}} = 0$$

Where a_{ij} are the DM's actuators.

All correction algorithms do the same thing...

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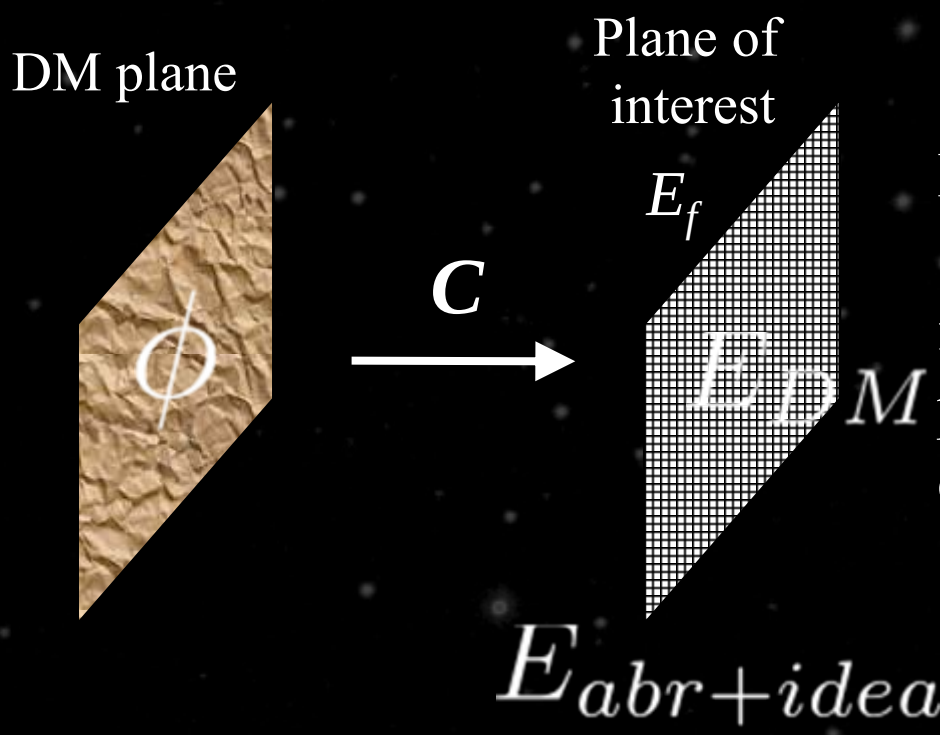
Electric Field Conjugation



EFC finds the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations

$$E_f = \qquad + \qquad = 0$$

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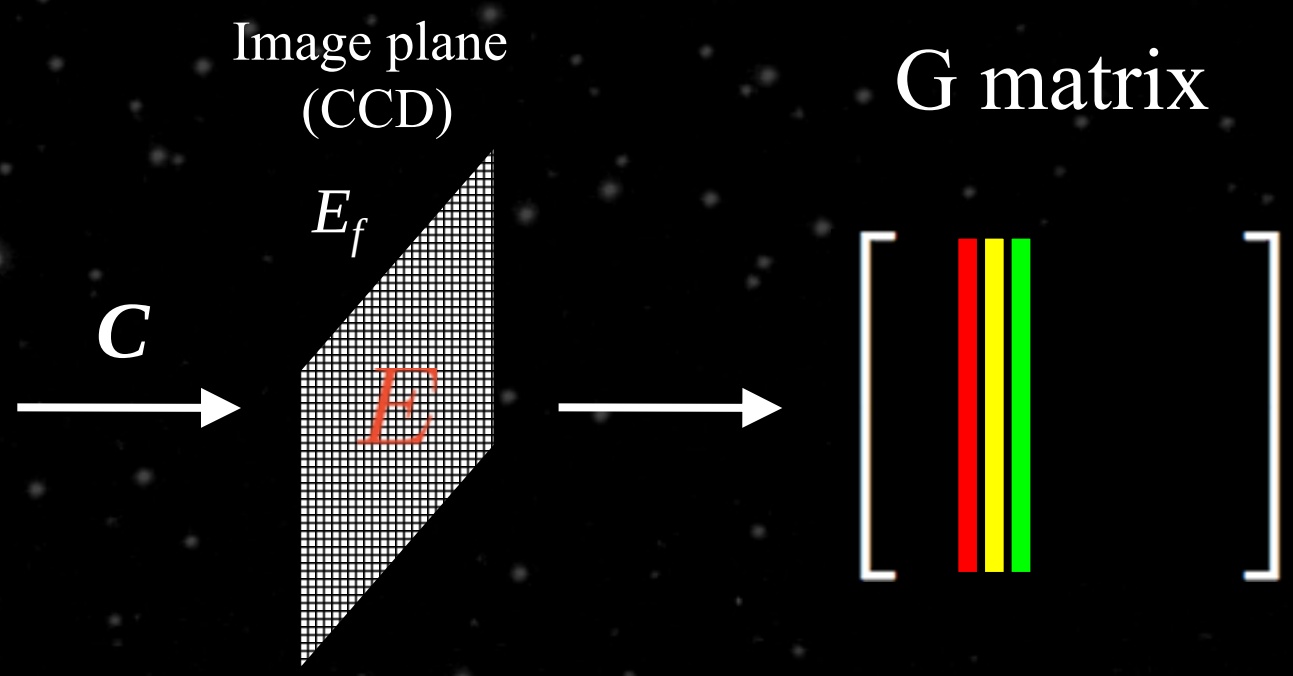
Electric Field Conjugation

How can we linearize the effect of the DM in the image plane?

Assume that the overall effect of the DM in the image plane is the sum of the effects of each of the actuators



The effect of the DM in the image plane will now be Ga, where a are the DM actuator heights.

Electric Field Conjugation

(Extensions)

Extension: Image plane pixels weighting

$$WG\bar{a} = iWE_{ab}$$

If the system model is reduced to a single Fourier transform of an infinite aperture and the weighting function *W* reduces to isolated pixels that change their location according to the brightest peaks in the region of interest, then EFC becomes speckle nulling.

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Electric Field Conjugation

(All extensions)

Multi DM correction

$$\begin{bmatrix} \bar{a} \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{ \quad G \quad \} \\ \cdots \\ \Im\{ \quad G \quad \} \\ \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{i \quad E_{ab} \quad \} \\ \cdots \\ \Im\{i \quad E_{ab} \quad \} \\ \\ \\ \\ \end{bmatrix}$$

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Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

Electric field in the image plane = Electric field due to the system and aberrations + Electric field due to the DM

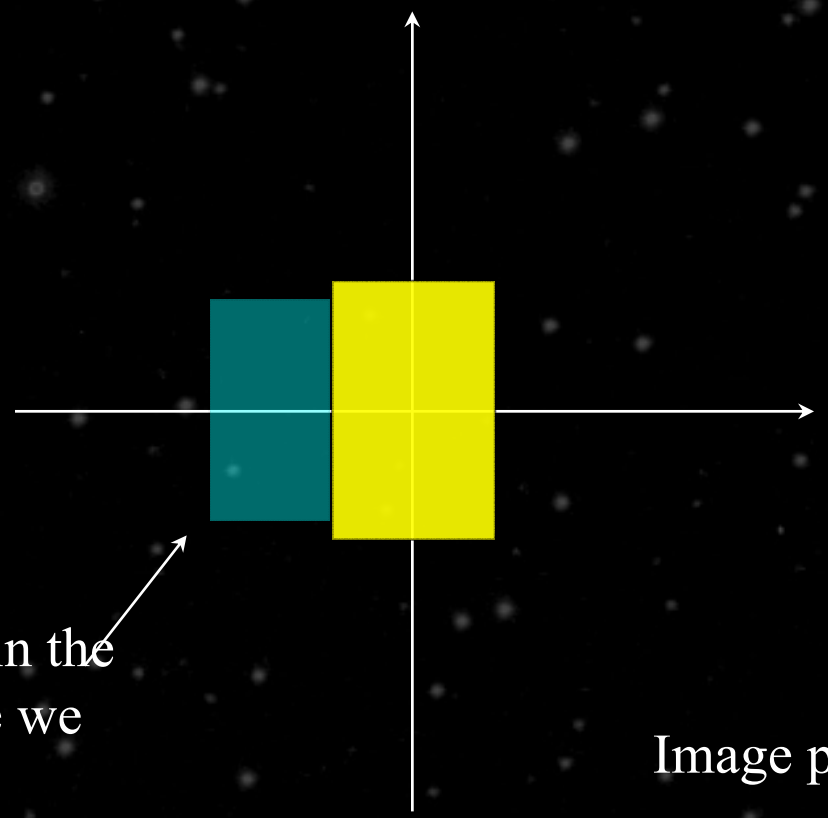
↓

Intensity in the image plane = $\left|\text{Electric field due to the system and aberrations} + \text{Electric field due to the DM}\right|^2$

If we deform the DM in pairs of shapes, ψ_k and $-\psi_k$, then, the difference between the intensity measurements (with at least two pairs) gives enough information to reconstruct the real and imaginary parts of the electric field due to the system and aberrations.

What shapes on the DM should we use for the probes?

$$DM(x, y) = ?$$



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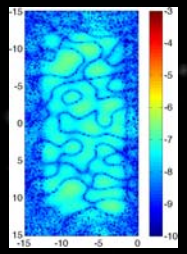
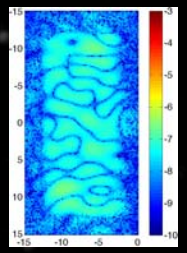
Electric Field Conjugation

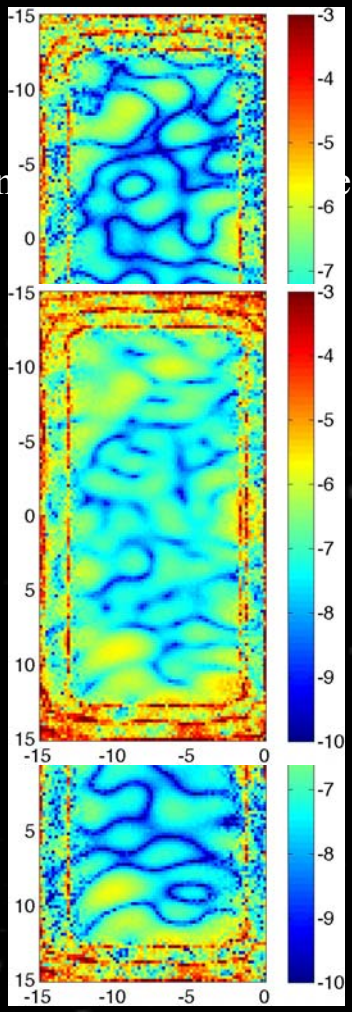
Real and imaginary parts of the estimated Electric field

Difference

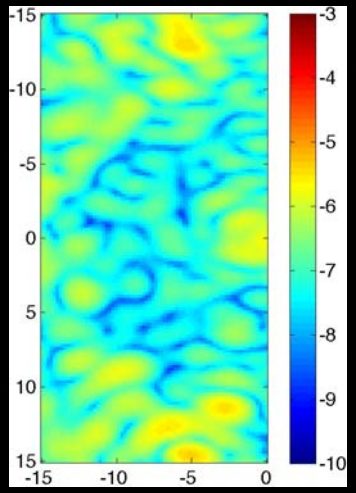


Difference





Measured intensity



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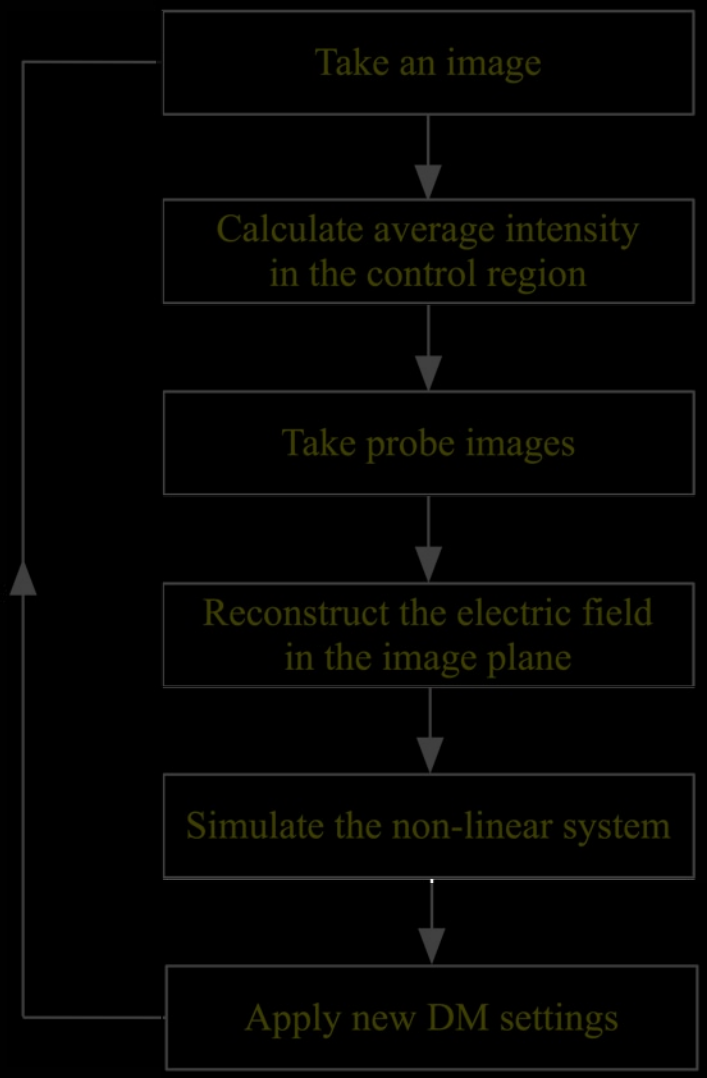
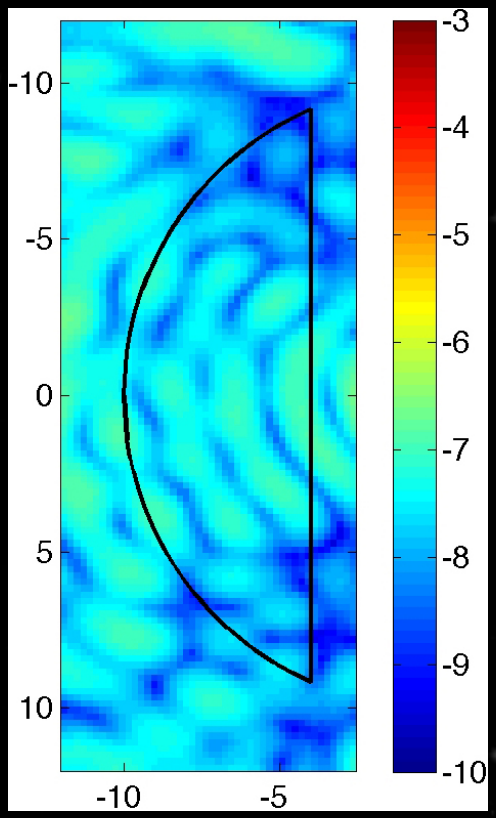
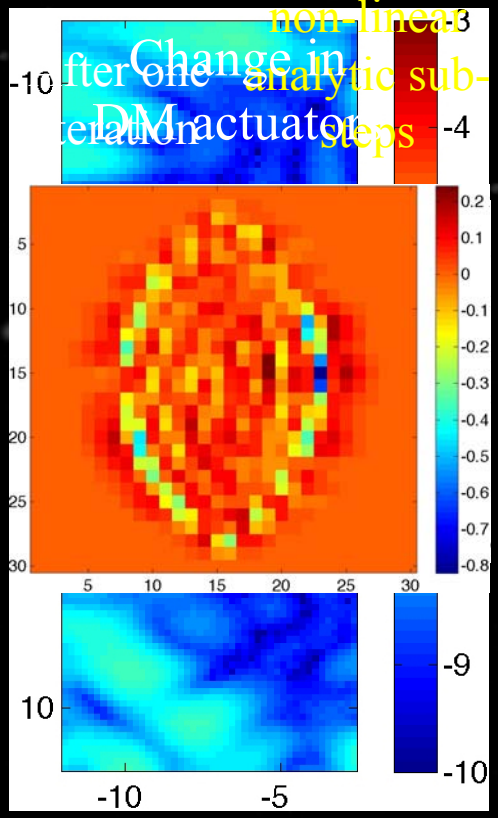
Electric Field Conjugation



Measured image

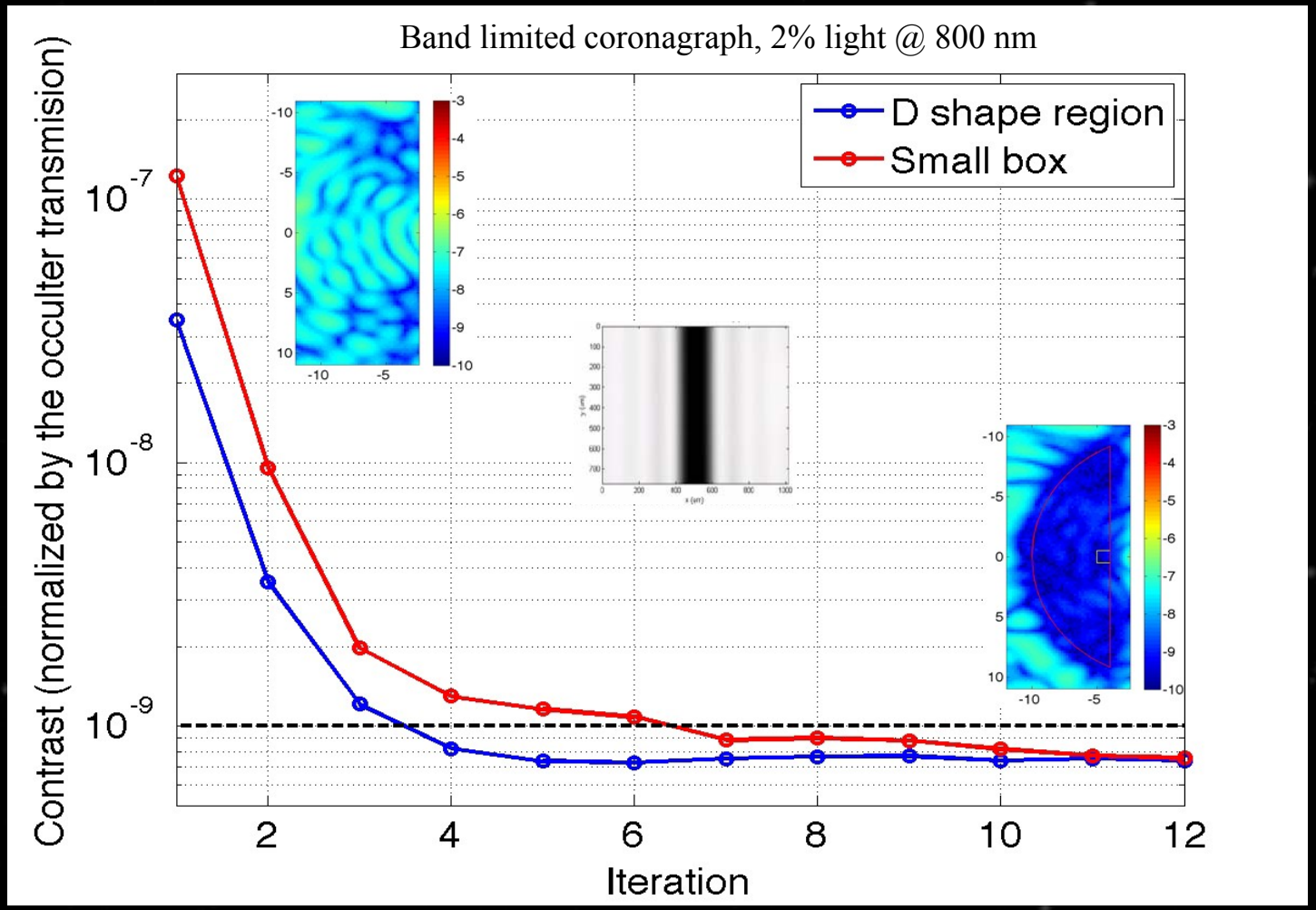
Intensity from Reconstructed Electric Field





Measurements were taken at 2% around 800nm

Band limited coronagraph, 2% light around 800nm



$2.4 * 10^{-10}$ *with monochromatic light*

$4 * 10^{-10}$ *with 2% light*

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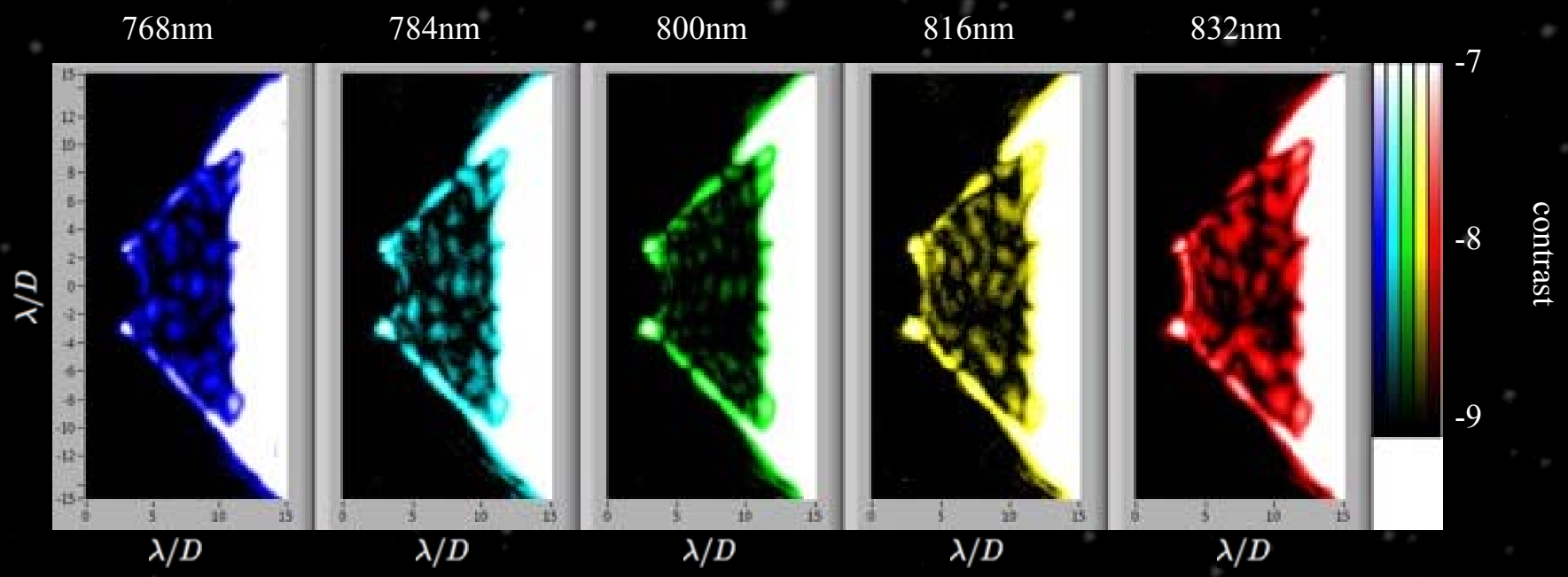
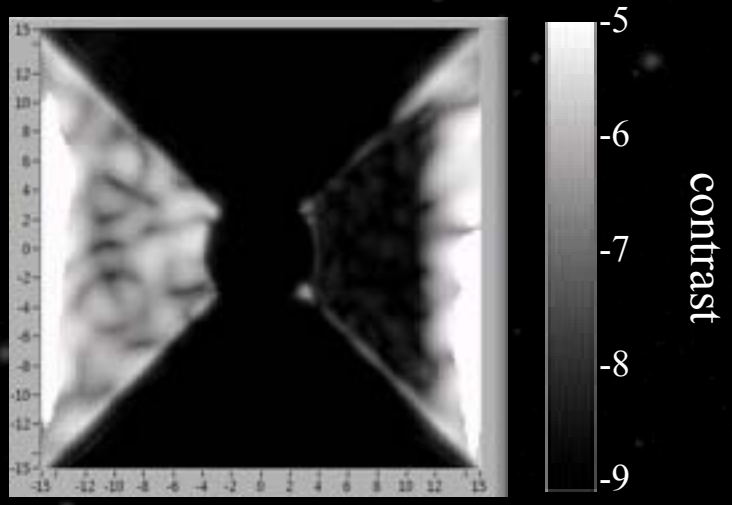
Shaped pupils are achromatic...



Broadband image (10%)
760nm - 840nm



$$Contrast = 2.37 * 10^{-9} \;\; at \;\; 10\% \;\; light$$

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Electric Field Conjugation

(Multi wavelength correction results)

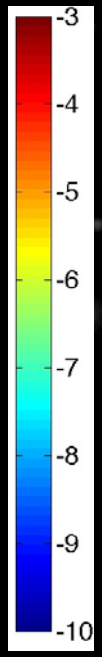
768nm

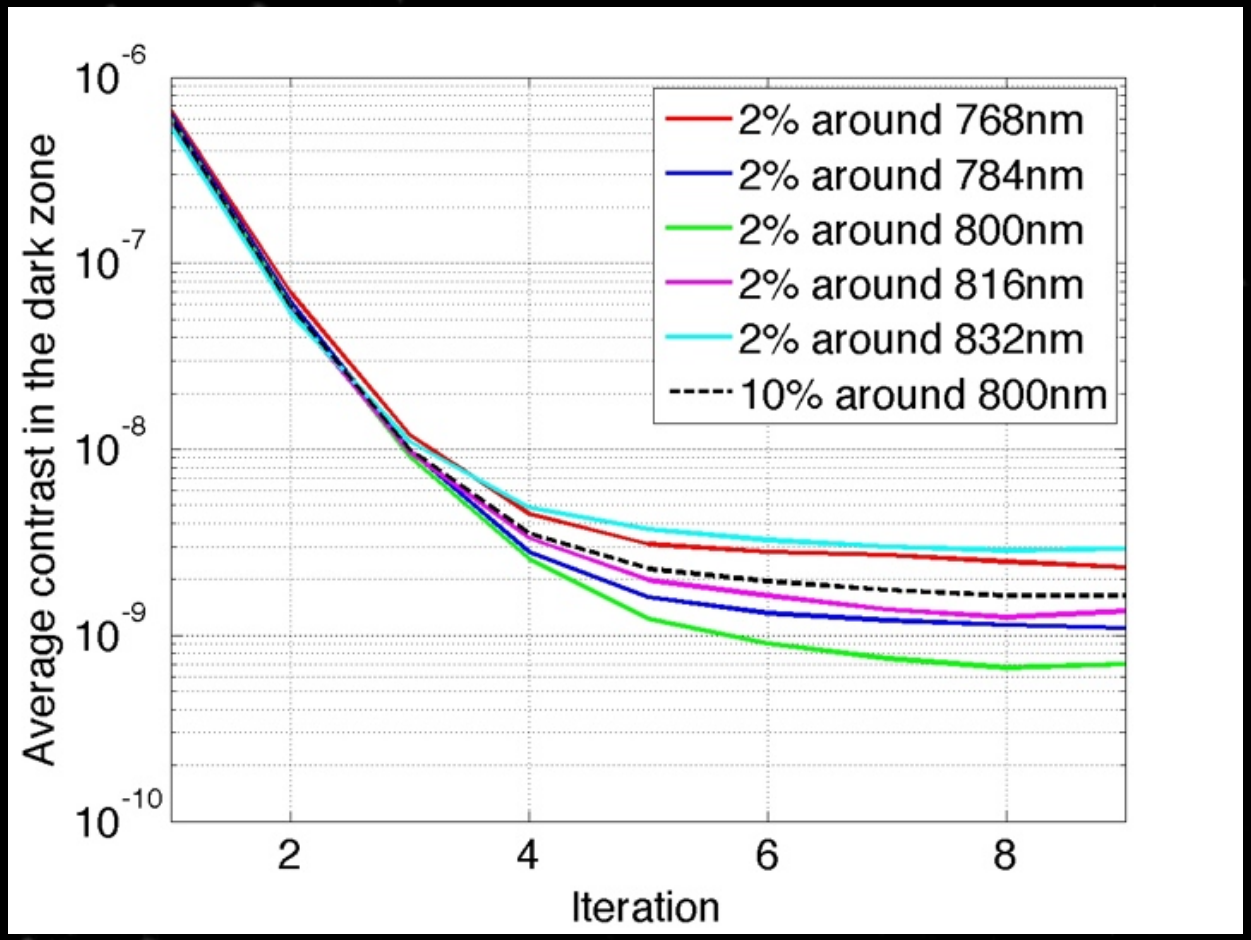
784nm

800nm

816nm

832nm





$$Contrast = 2.3 * 10^{-9} \;\; with \;\; 10\% \;\; broadband \;\; light$$

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HCIT Demonstration of Planet Detection in Broadband Light

The test: Using a band-limited mask, form a dark hole using the Electric Field Conjugation algorithm. Then reset the DM to nominally flat, wait 8 days, and repeat.

Parameters:

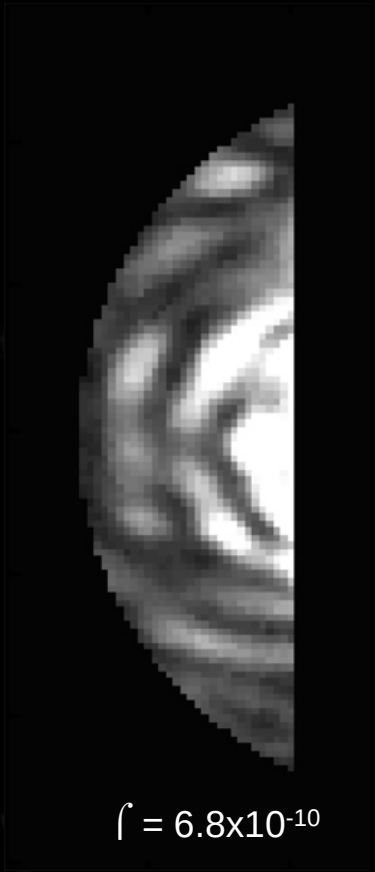
3 filters,
each band 2% wide
Centered around 800, 816, and 832 nm.

Sum together the bands to form composite 6% bandwidth images.

D-shaped dark hole:
IWA = 4 λ/D
OWA = 10 λ/D

Peak contrast = 1e-9

Day 1



∫ = 6.8×10^{-10}

Electric Field Conjugation

Summary

- Contrasts of 1e-9 and better are today's reality. We have demonstrated suppression and repeatability sufficient to detect Jupiters in broadband light.
- The contrasts reported from HCIT are routinely achieved (usually takes a matter of 2-3 hours).
- The world record contrasts are a result of combining a stable vacuum facility, the world's most precise deformable mirrors, a highly dedicated team and the most advanced estimation and correction algorithm.
- The EFC algorithm is flexible, robust and has been used with both the band limited coronagraph and the shaped pupil coronagraph (at HCIT and on the Princeton testbed).
- We are starting now to extend the EFC algorithm to systems with 2 deformable mirrors for broadband full dark hole suppression and will also apply it to the Phased Induced Amplitude Apodization (PIAA) coronagraph.
- We will also implement the algorithm at Palomar to run along side the AO system to correct for quasi-static and static speckles.