Detecting Extra-Solar Earths

Shaped Pupil Coronagraphy for NASA's Terrestrial Planet Finder (TPF-C) Mission

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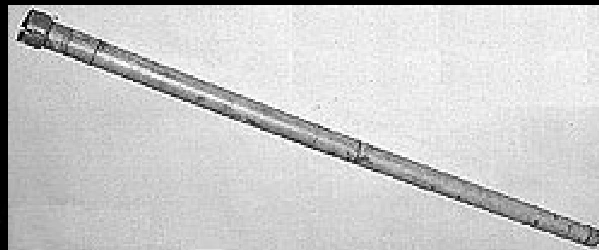
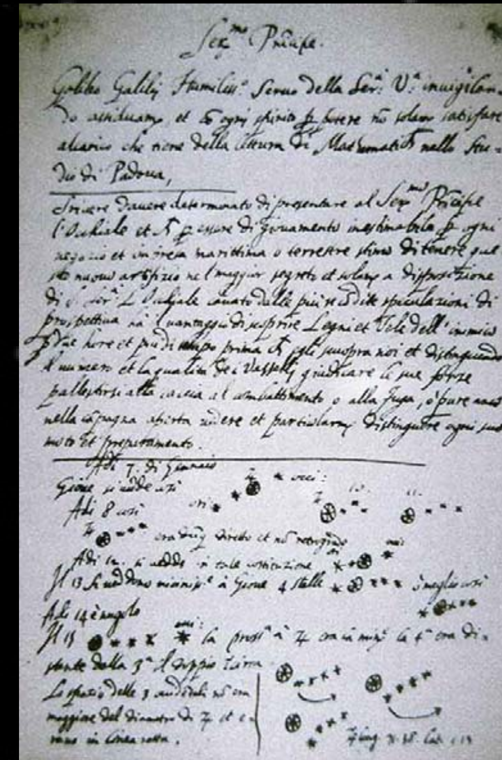
Stanford, April 14 2005





I should disclose and publish to the world the occasion of discovering and observing four Planets, never seen from the beginning of the world up to our own times, their positions, and the observations . . . about their movements and their changes of magnitude; and I summon all astronomers to apply themselves to examine and determine their periodic times. . . .

— Galileo Galilei, March 1610

Is Earth Unique?

- Answer in 2015

- How common are earth-like planets?

- Do they harbor the conditions for life?

"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars."

– A Renewed Spirit of Discovery: The President's Vision for Space Exploration, 2004

Outline

- Background on planet searches and TPF
- The Shaped-Pupil Coronagraph: a solution to planet imaging
- The challenge: wavefront control

The Princeton TPF group

<u>Faculty</u>
N. Jeremy Kasdin (MAE)
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Ed Turner (Astro)
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<u>Staff</u>
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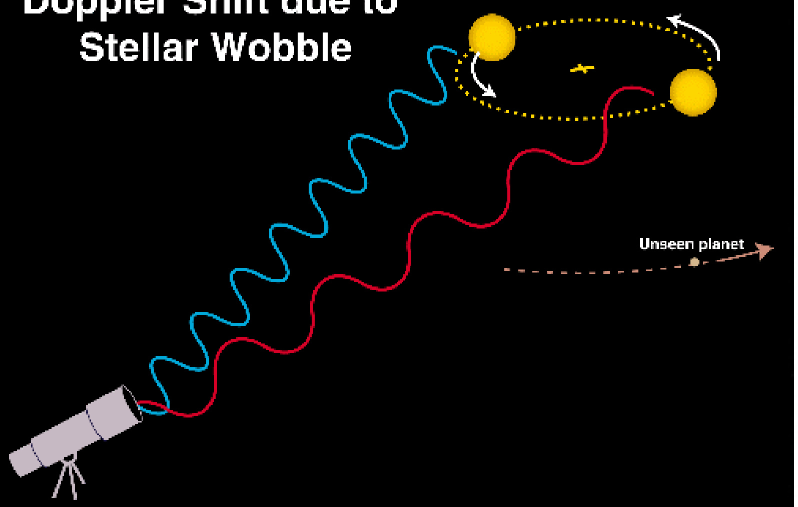
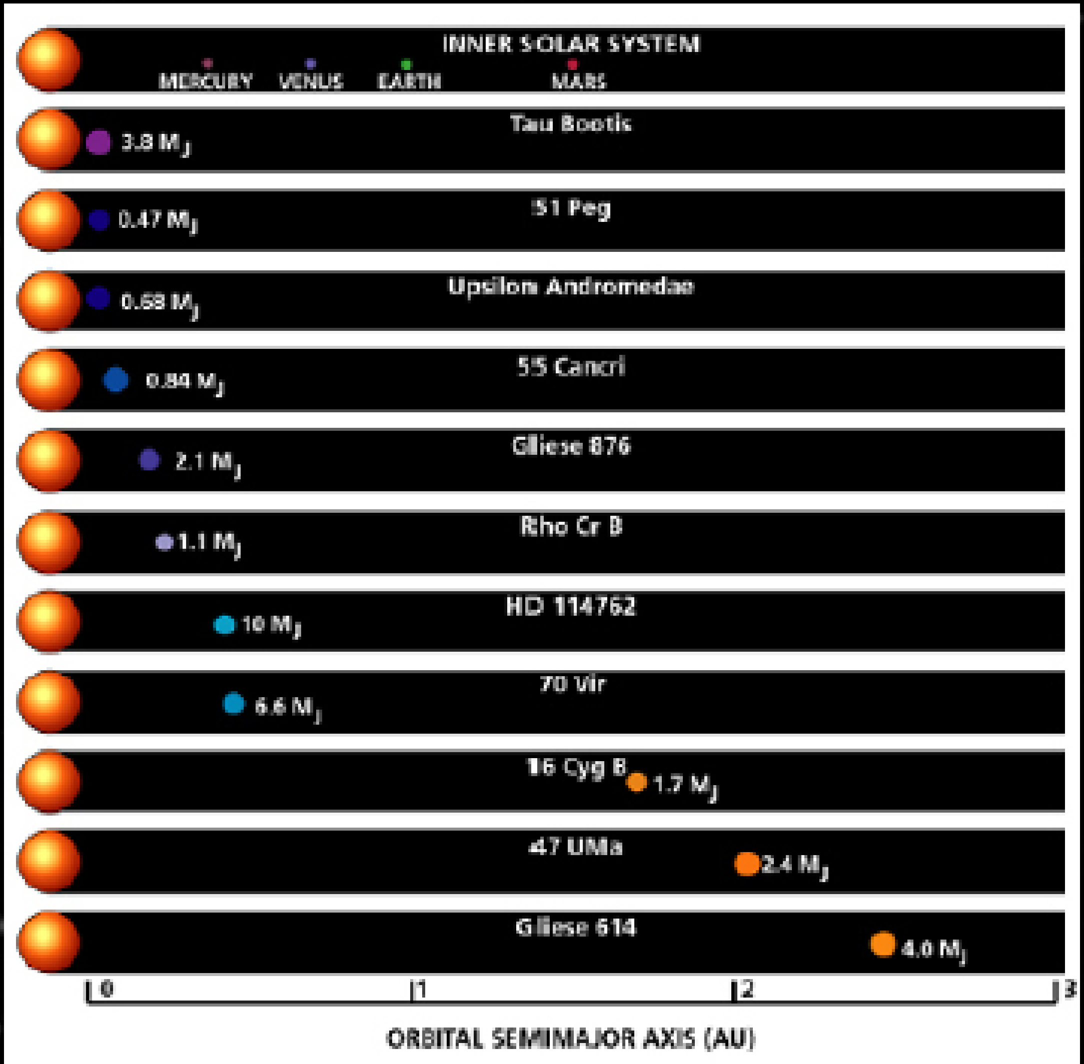
Ruslan Belikov, Ph.D. (MAE)

Discover
Vol. 23, No. 3
March, 2002

Are there any planets out there?

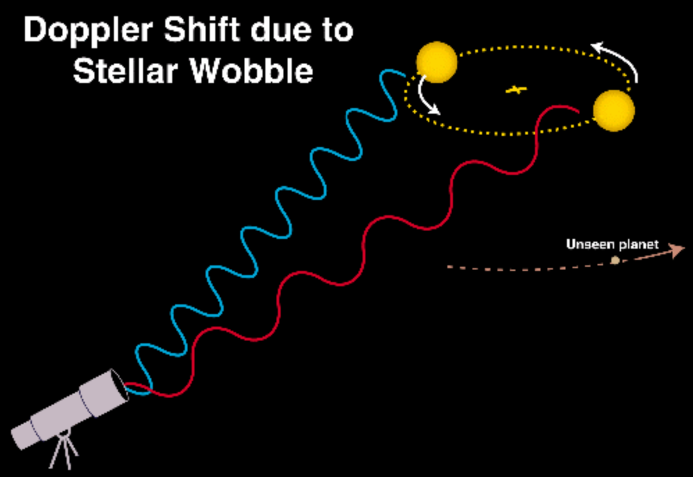
There are at least 145 exoplanets known to date!

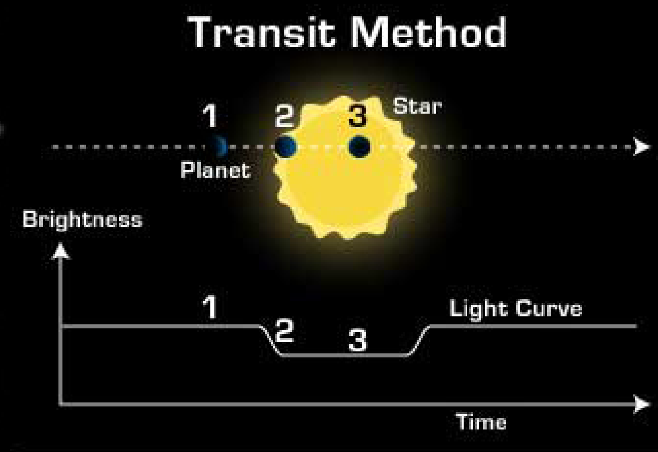


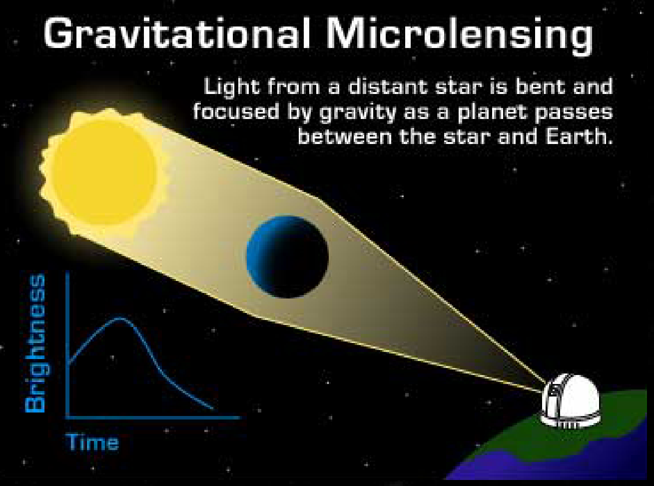


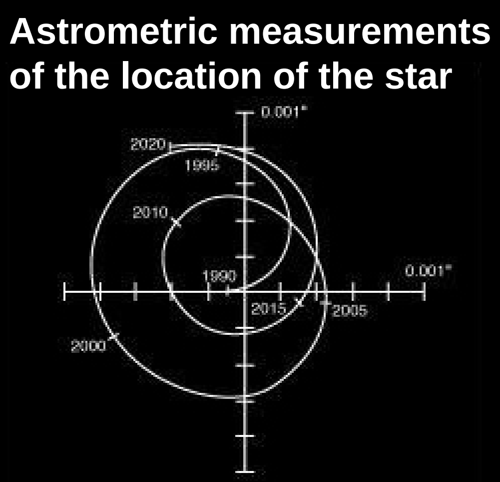
This is an “indirect” detection method

Current detection methods



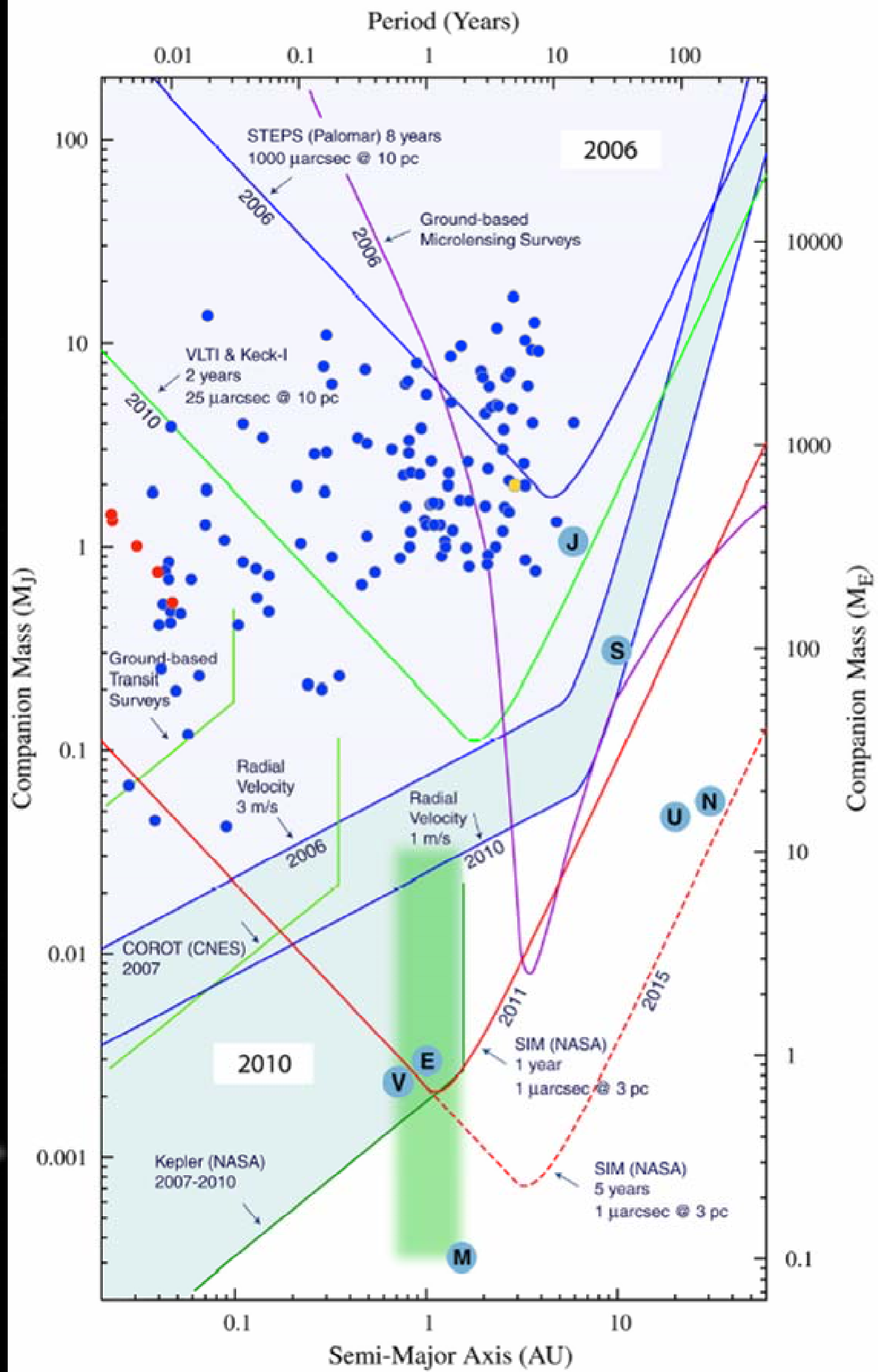






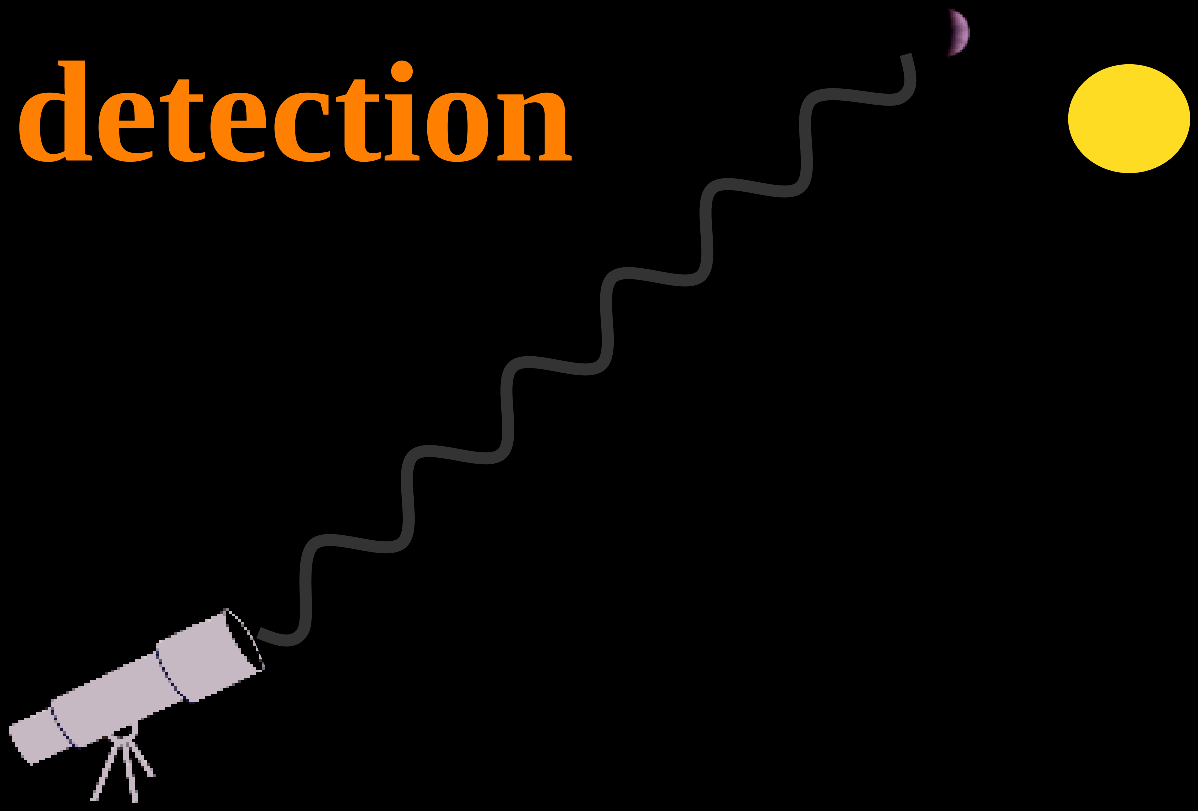
Detected Planets and Mission Sensitivities

- Shown are reported findings up until August 31, 2004.
  - Blue: RV;
  - Red: transits
  - Yellow: microlensing
- 5-σ limits of different techniques shown
- Need direct imaging to detect extra-solar earths



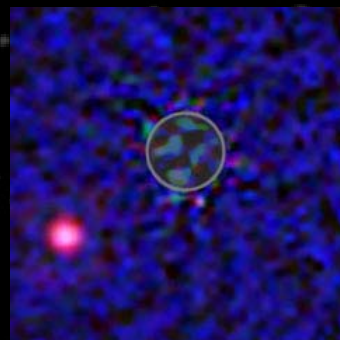
The only way to find terrestrial planets is…

Direct detection

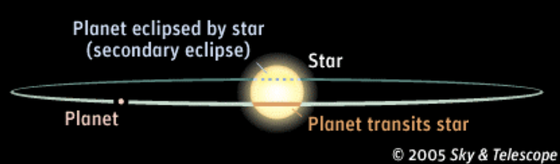


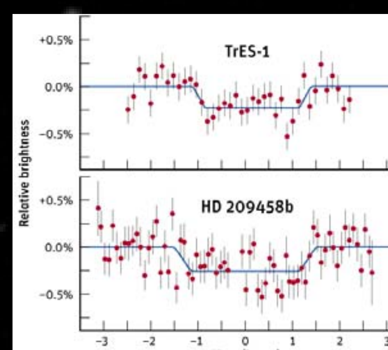
First images of (very large) planets

2M 1207



GQ Lupi



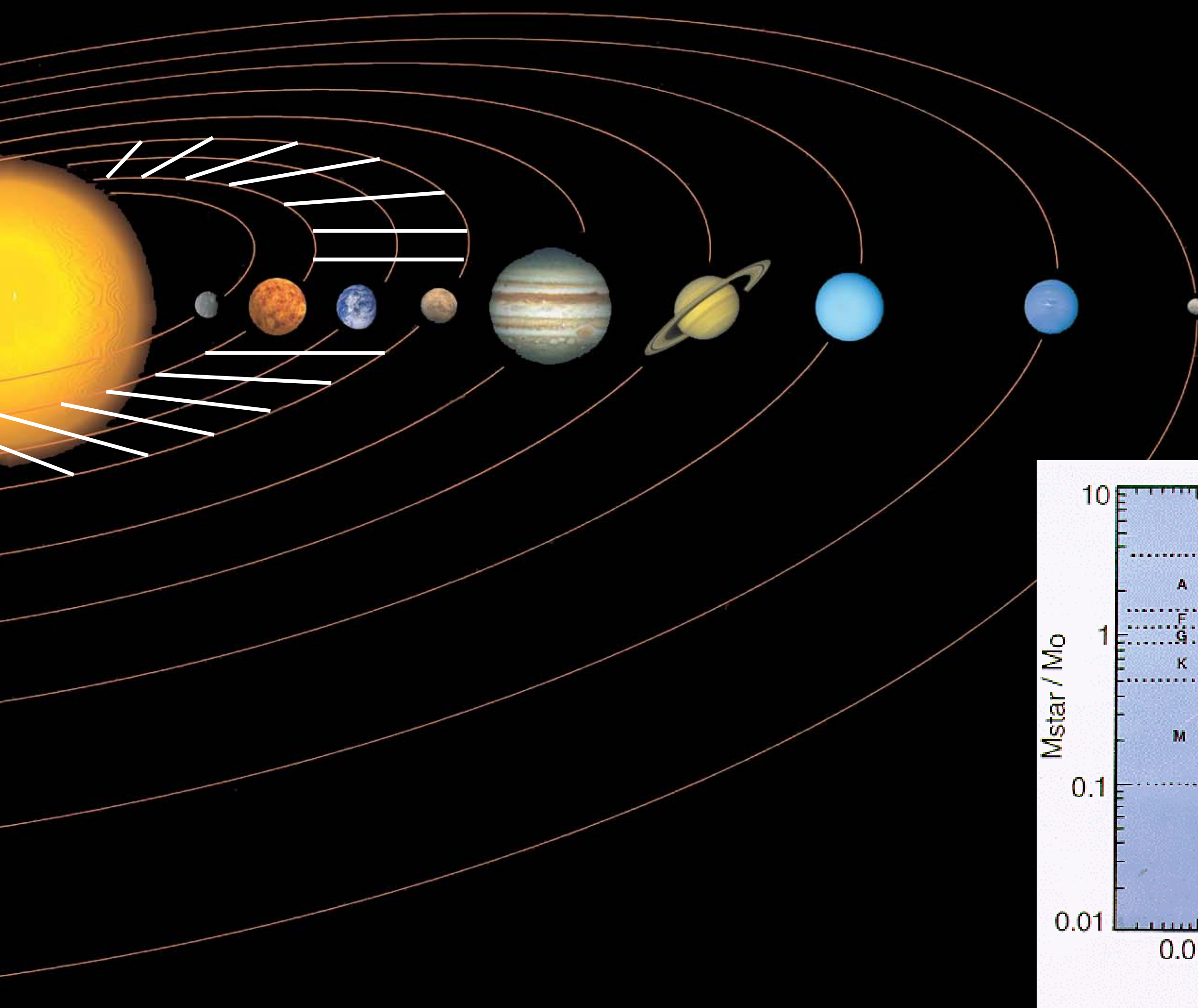


- Left: VLT, IR light with adaptive optics, April 2004. *Courtesy Gael Chauvin / ESO.*
- Right: Hubble, IR light, January 2005. *Courtesy NASA / ESA / Glenn H. Schneider, et al*
- Brown dwarf host, 8 million years, 1000C, 5 Jupiter masses, 54a.u., 2,500 year period

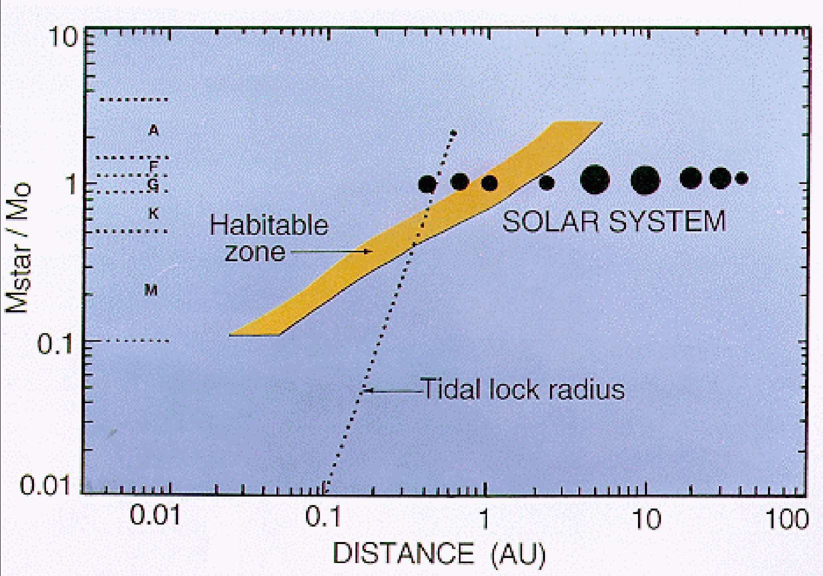
- VLT, NACO adaptive optics infrared camera, March 2005. *Courtesy Ralph Neuhäuser / ESO.*
- few million years, 50a.u., 1200 year period, 2000K, 1-42 Jupiter masses.

- Spitzer’s IR array camera @ 4.5 and 8 microns, October 2004. *Courtesy David Charbonneau (Harvard-Smithsonian Center for Astrophysics)*
- Spitzer's multiband imaging photometer @ 24 microns, December 2004. *Courtesy Drake Deming (NASA/Goddard Space Flight Center)*

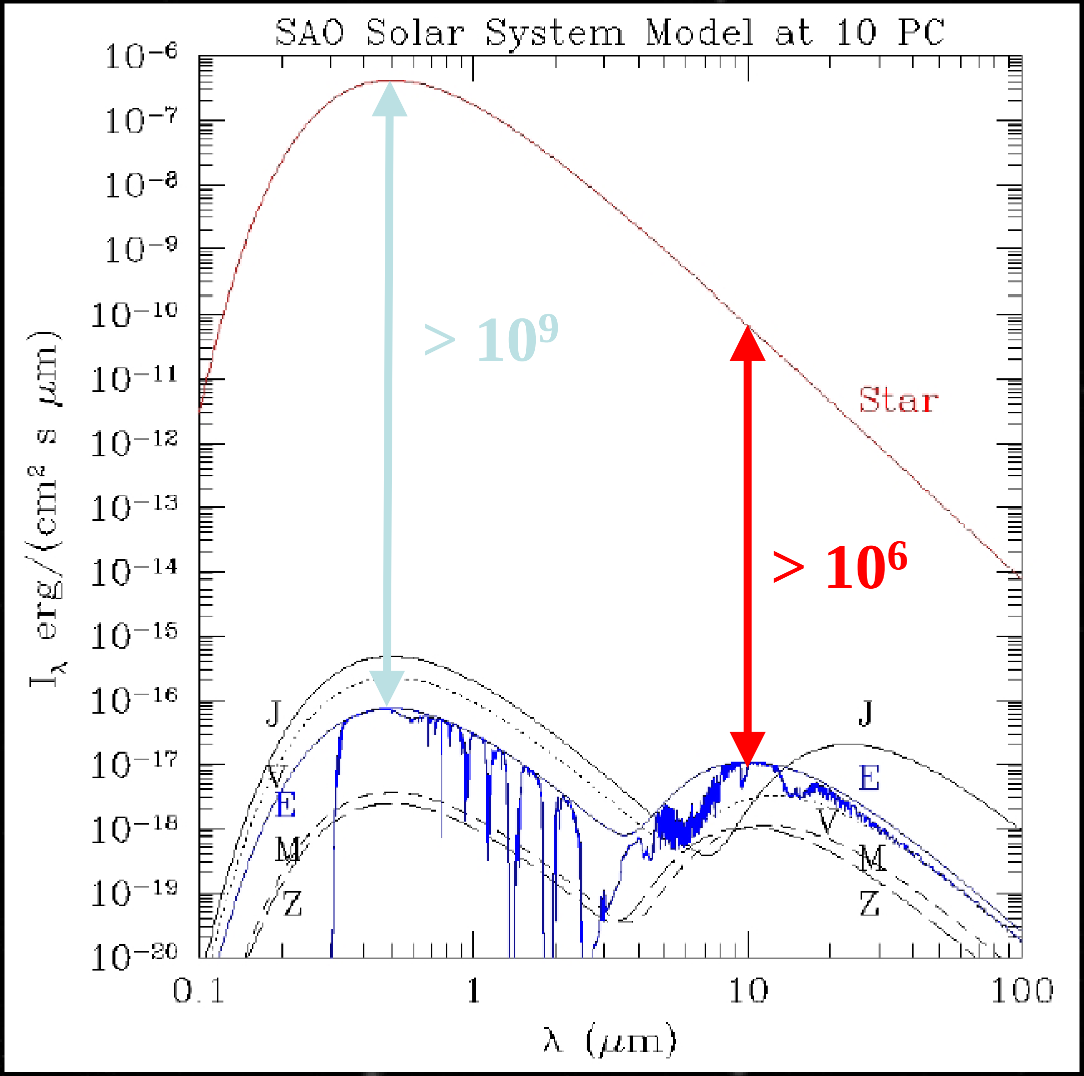
The habitable zone



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



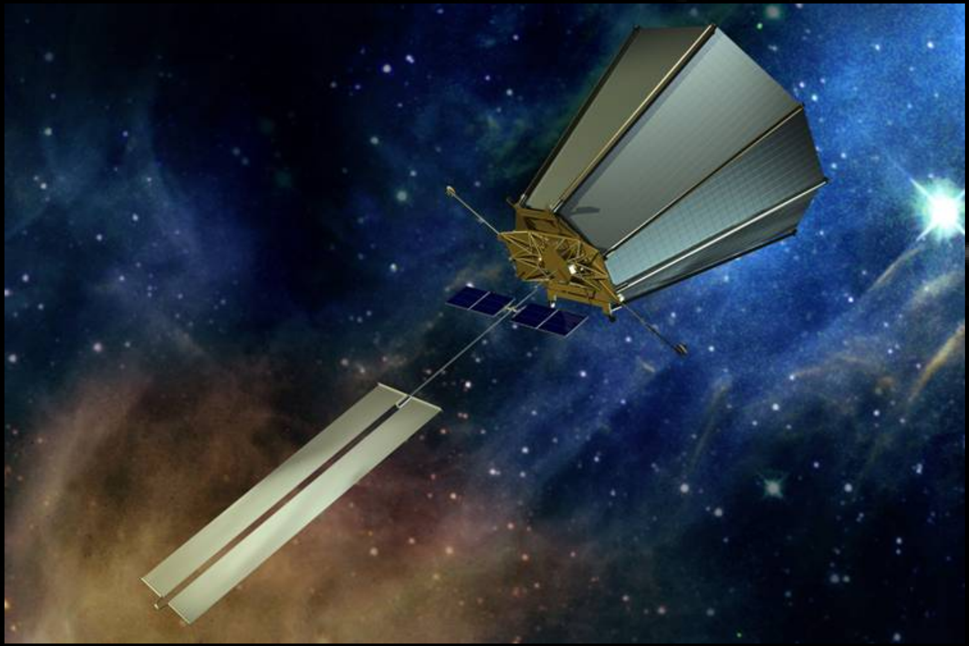
How hard is this really?

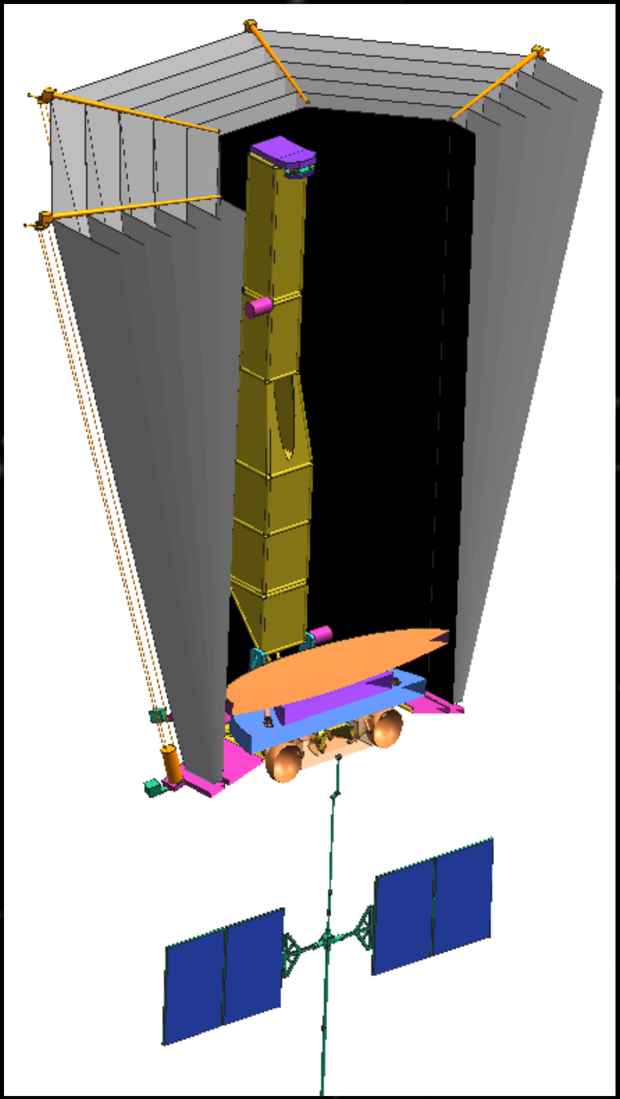


Traub & Jucks

- To minimize glare, image in the infrared. Problems:
  - Much dimmer than visible
  - Much worse resolution than visible
- NASA's conclusion: Do a visible mission first, with very high contrast telescope: the TPF-C.
  - Photon flux and resolution acceptable
  - 10^{10} contrast required

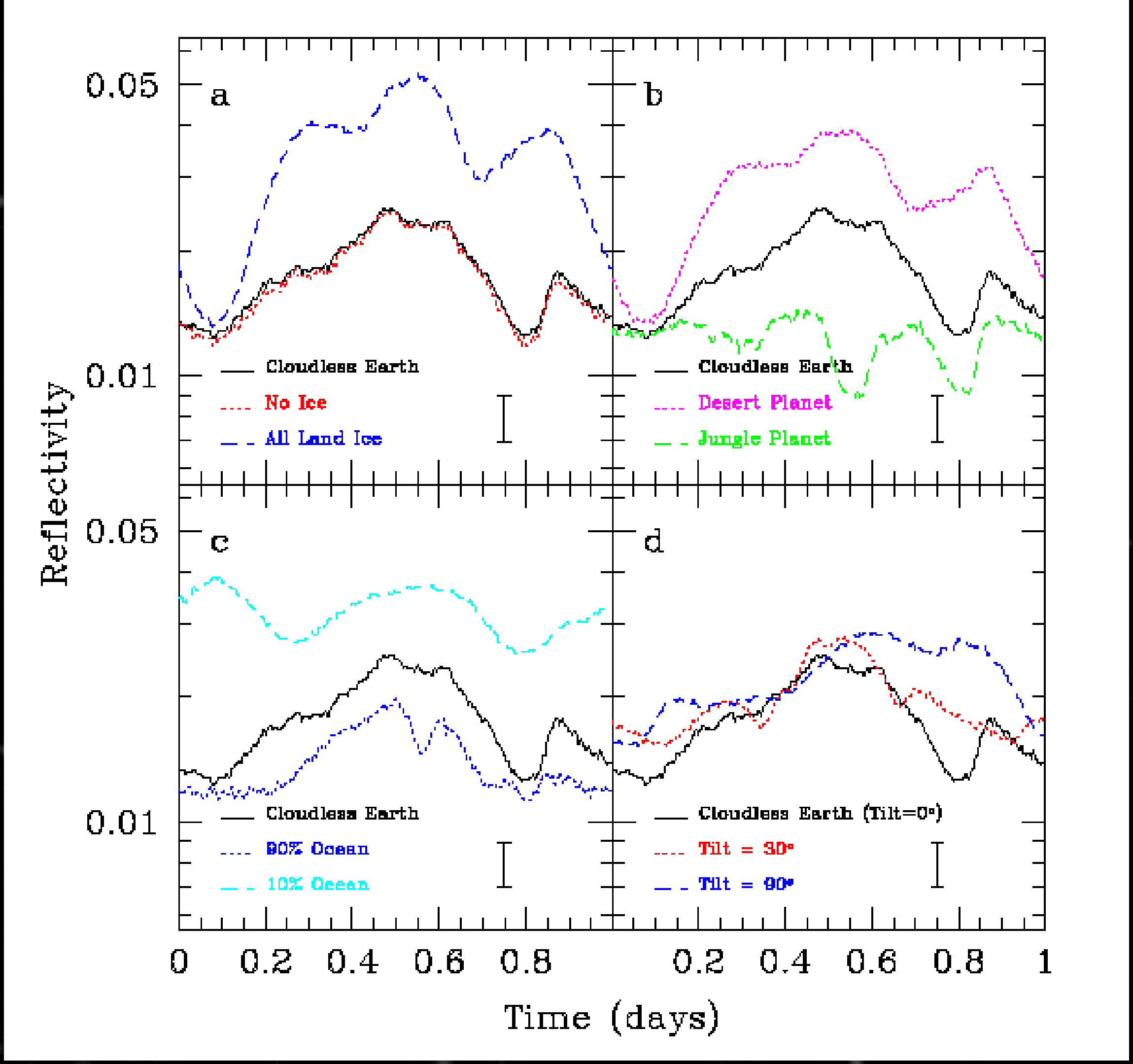
TPF-C





- 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

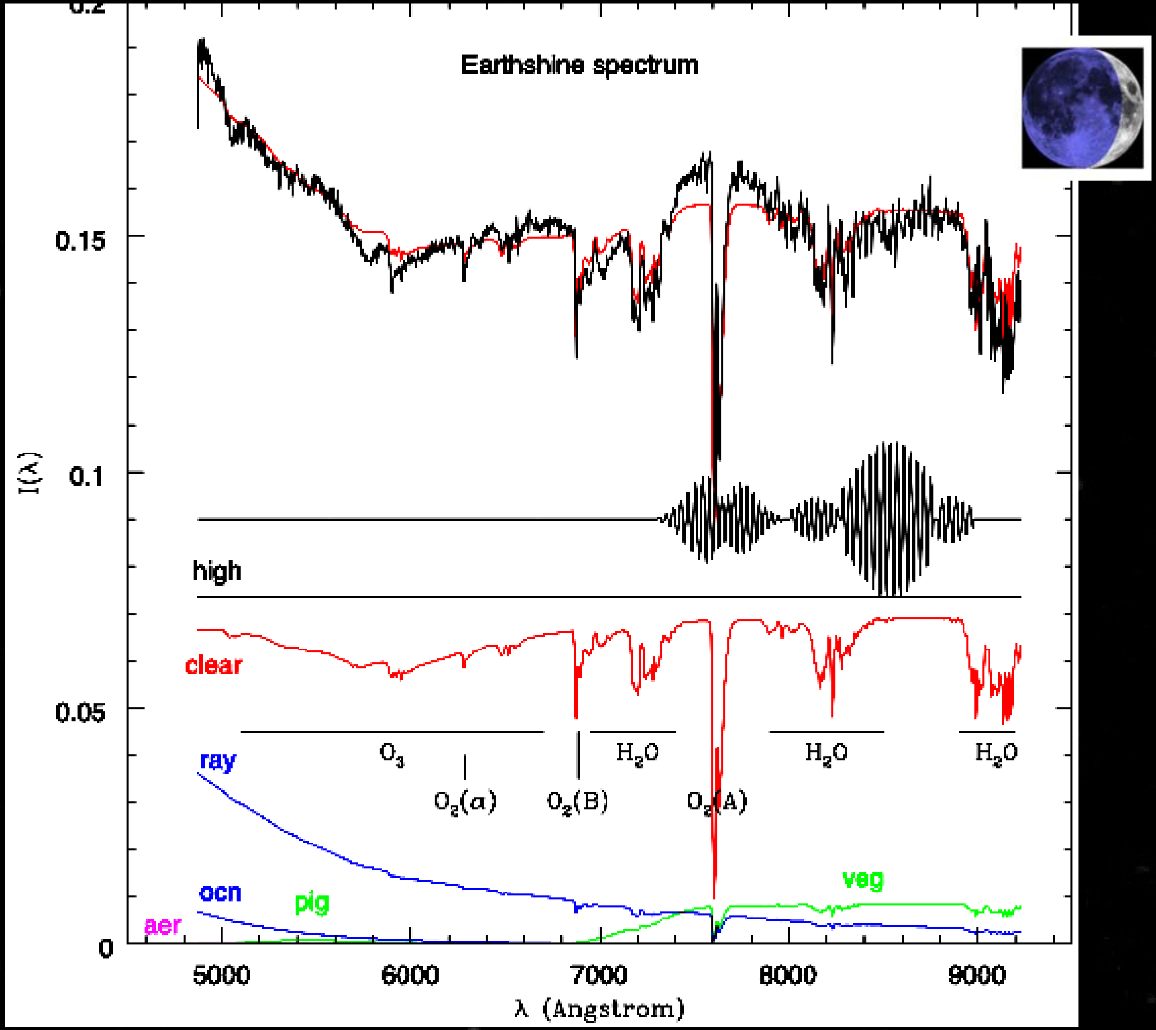
Photometry



Reflectivity
0.05
0.01
a
b
c
d
Cloudless Earth
No Ice
All Land Ice
Desert Planet
Jungle Planet
90% Ocean
10% Ocean
Cloudless Earth (Tilt=0°)
Tilt = 30°
Tilt = 90°
0
0.2
0.4
0.6
0.8
1
Time (days)

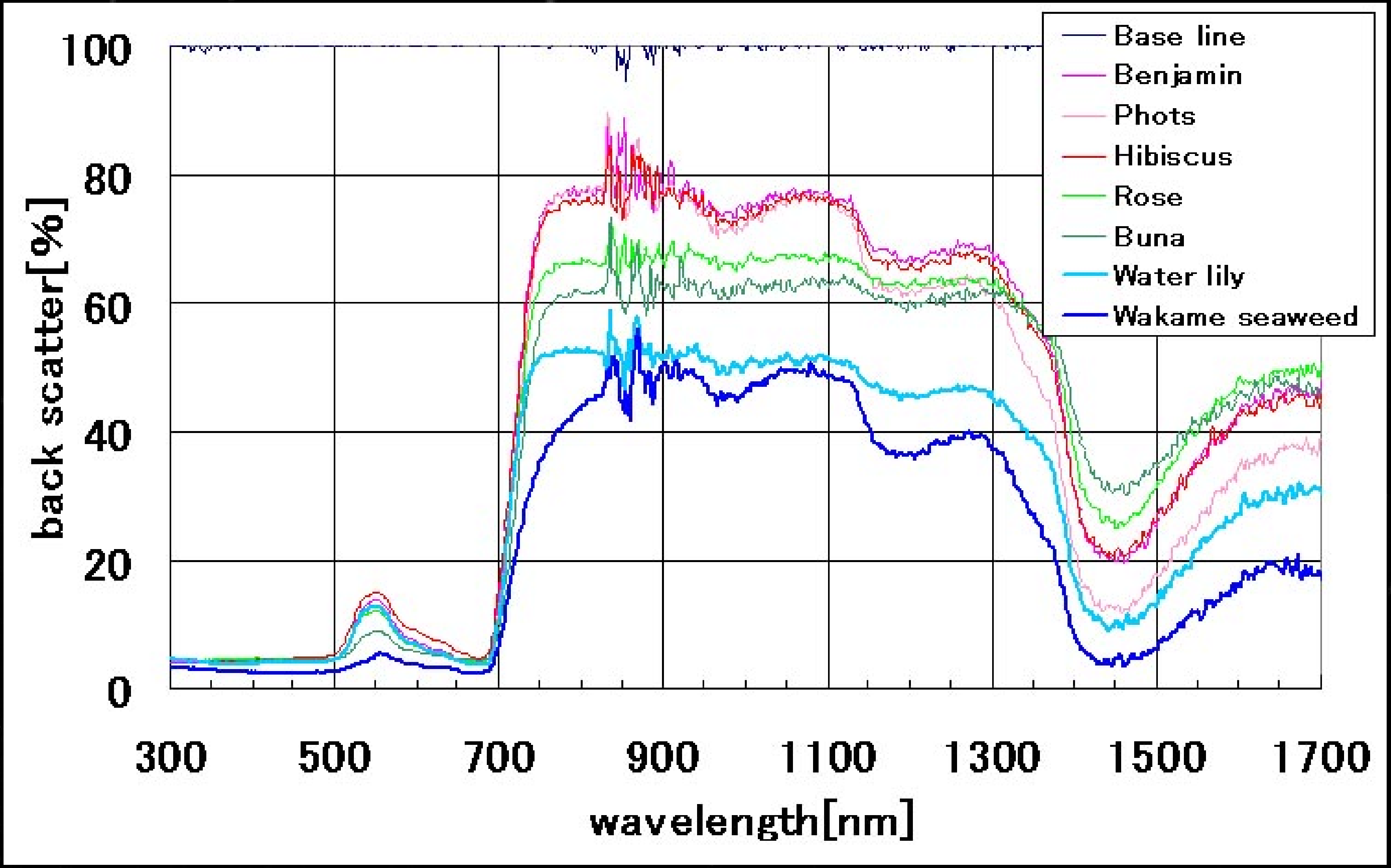
Spectroscopy

Water
Oxygen
Atmospheric Pressure
(Rayleigh Scattering)
Plant Life: Red Edge!

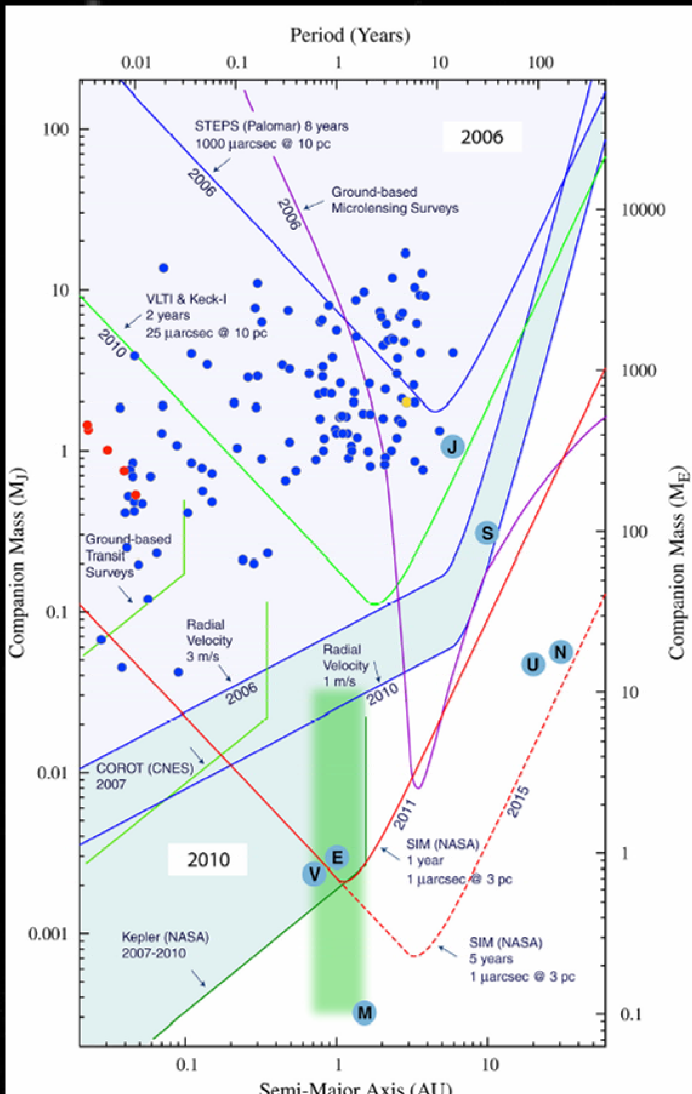


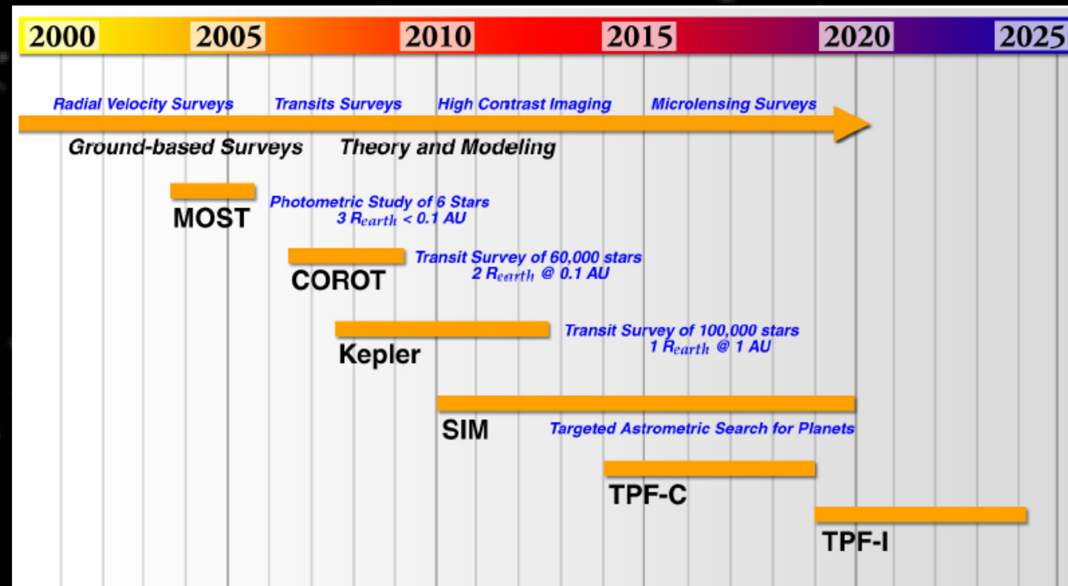
Ref.: Woolf, Smith, Traub, & Jucks, ApJ 2002

Spectra of Plants



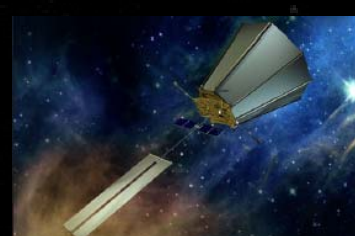
Planet Search Mission Schedule





Kepler

SIM



TPF-C

TPF-I

Outline

- Background on planet searches and TPF
- The Shaped-Pupil Coronagraph: a solution to planet imaging
- The challenge: wavefront control

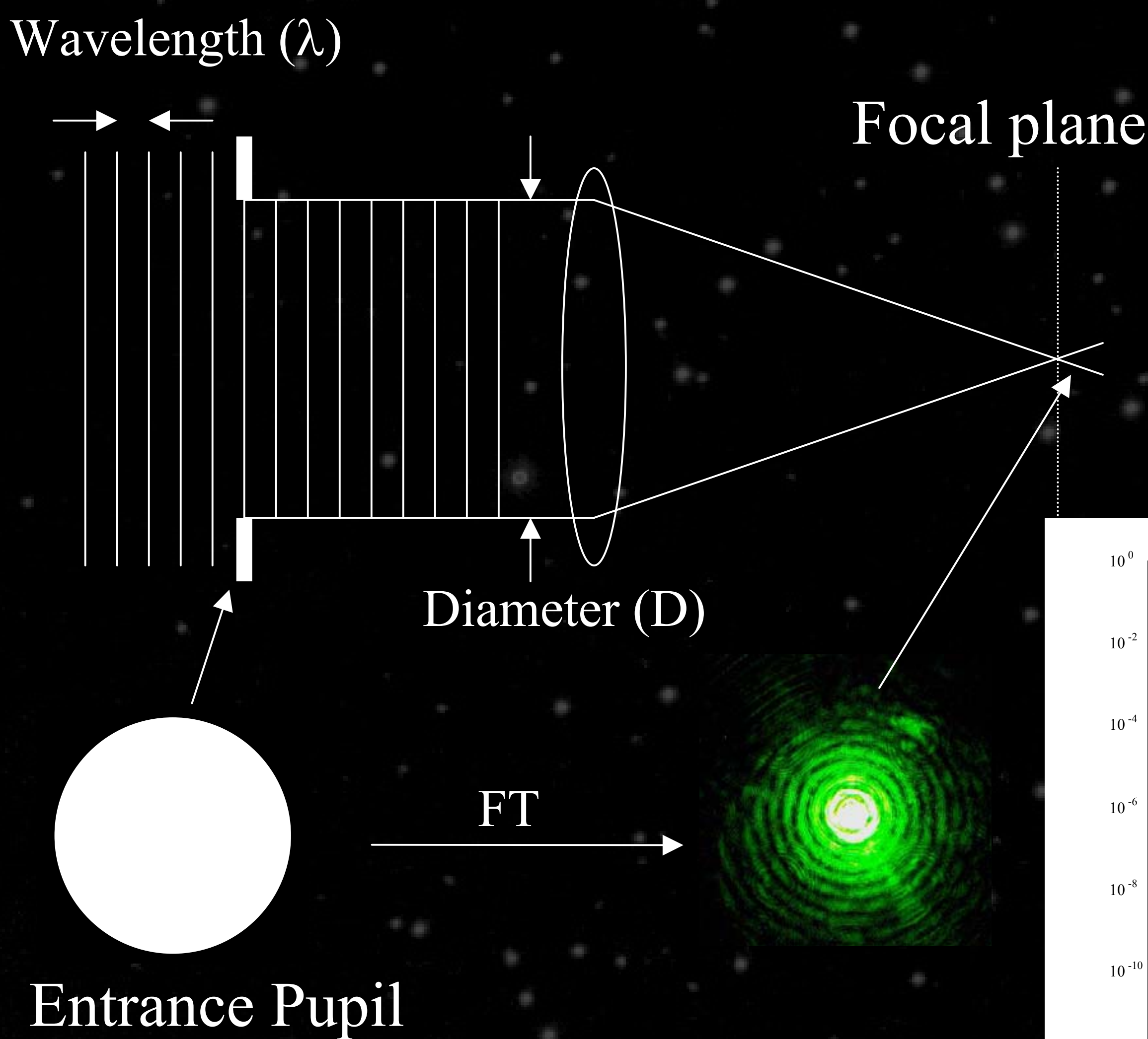
Some Existing Coronagraph Types

- Lyot Coronagraphy
  - Attenuates planet light as well
  - Very hard to manufacture
  - Very sensitive to low order aberrations & pointing

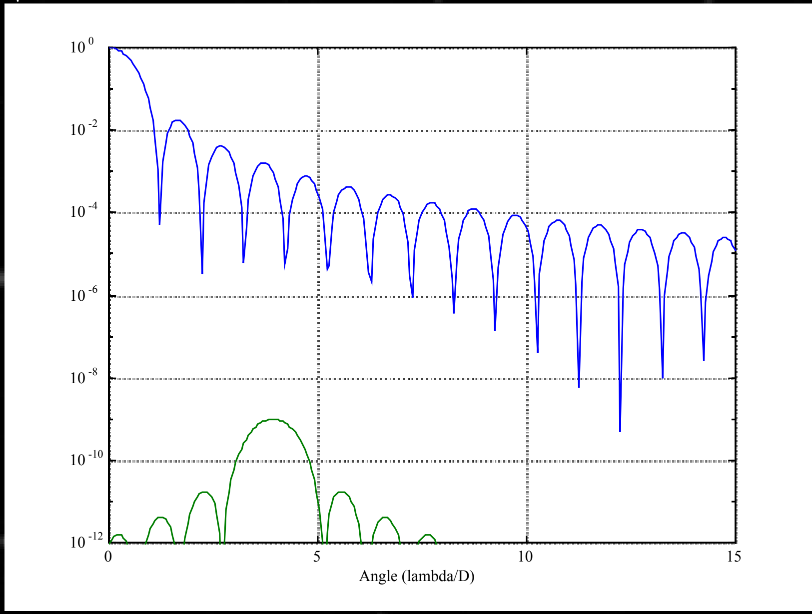
- Apodization
  - Difficult to implement
  - Poor accuracy
  - Low Throughput

- Shaped Pupils & Binary Coronagraphs
  - Our favored solution!!

The Problem: Airy rings (sidelobes)

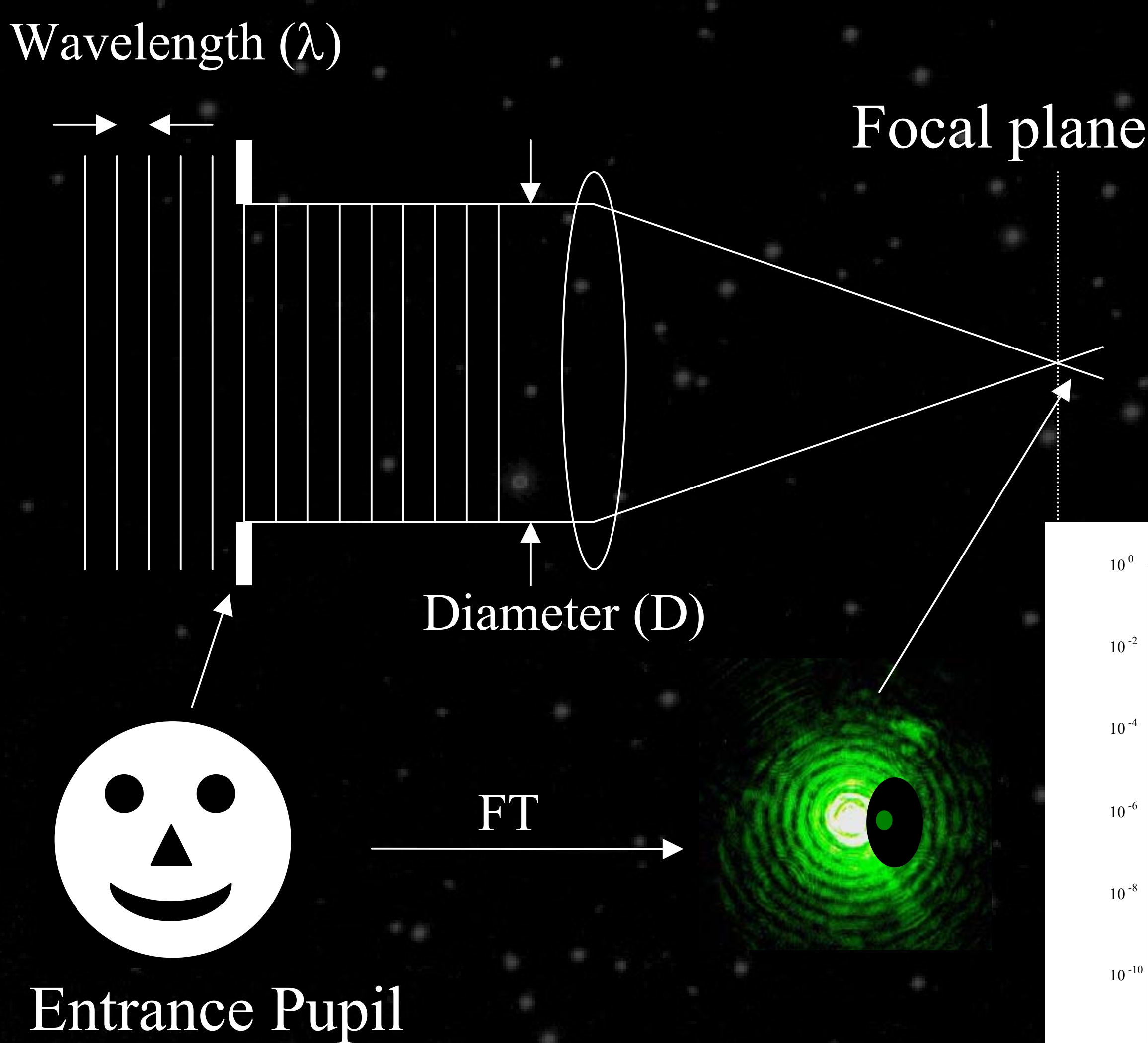


The image in the focal plane is the spatial Fourier transform of the entrance field



Size of Image is a function of Telescope Size and Wavelength

The Soluion: Modify Entrance Pupil



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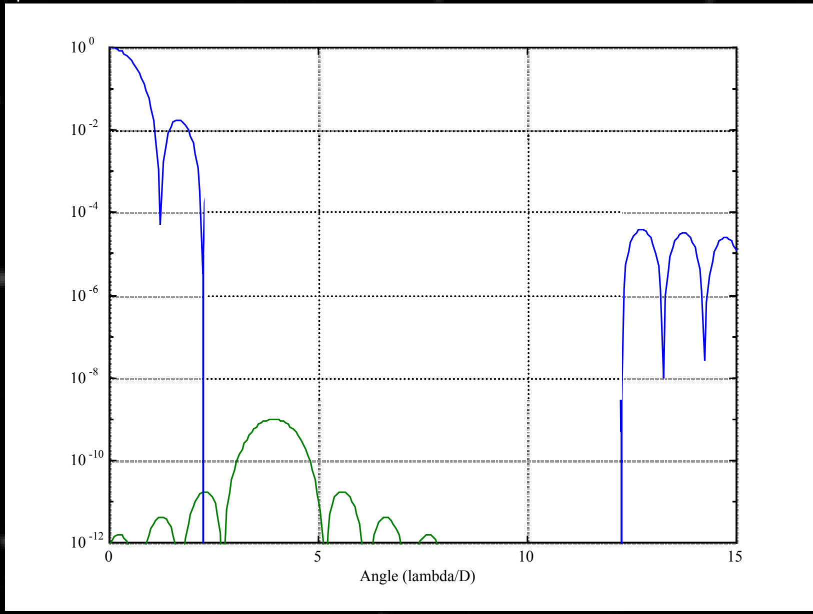


Size of Image is a function of Telescope Size and Wavelength

The optimization problem

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

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

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

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

When we wish to consider binary apodizers (i.e. masks), we also add the constraint that for each opening:

$$A(x,y) = \begin{cases} 1 & |y| \leq a(x) \\ 0 & else \end{cases}$$

We only consider masks that are symmetric with respect to both the x and y axes. Hence, the function *a*() is a nonnegative even function.

Performance metrics

In order to compare the different designs, we use the following metrics:

Size of dark region:

Typically measured using inner and outer working angles: ρ_{iwa} and ρ_{owa}

Contrast:

$$C(\rho) = \frac{E^2(\rho)}{E^2(0)}$$

Airy throughput:

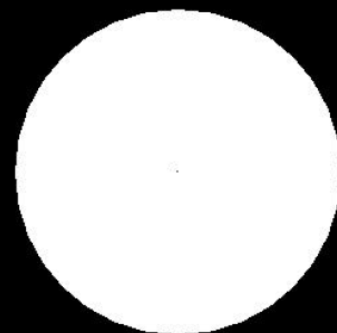
The energy inside the inner working angle divided by the total energy of a clear open aperture:

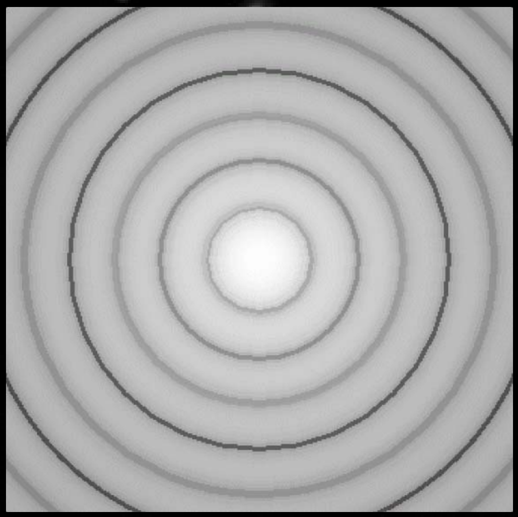
$$\frac{2\pi \int_0^{\rho_{iwa}} E^2(\rho)\rho d\rho}{\pi(1/2)^2} = 8 \int_0^{\rho_{iwa}} E^2(\rho)\rho d\rho$$

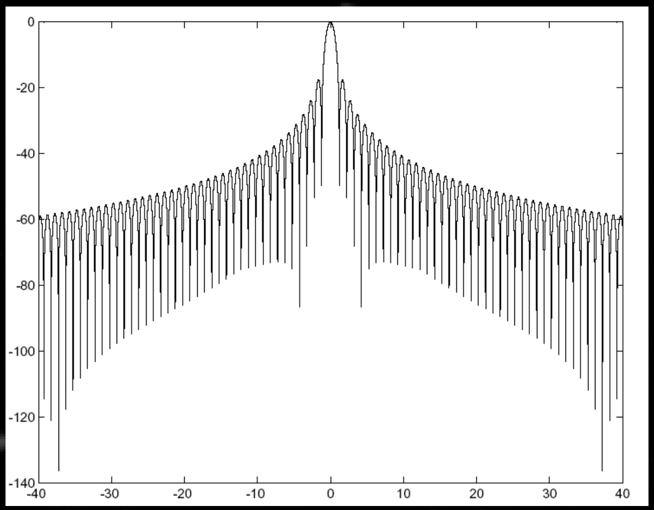
Circular aperture: the Airy pattern

$\rho_{iwa} = 1.24$

$T_{airy} = 84.2\%$





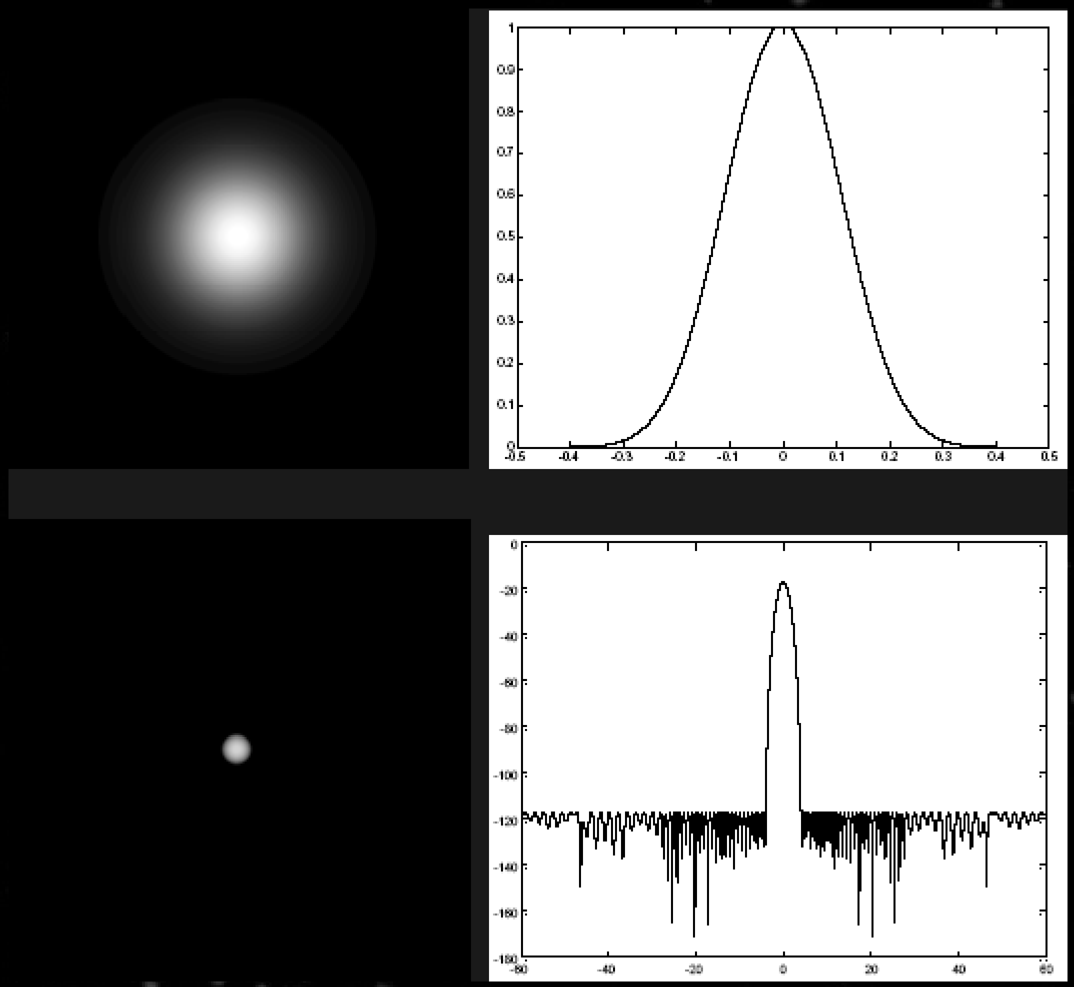


No dark zone

Apodization

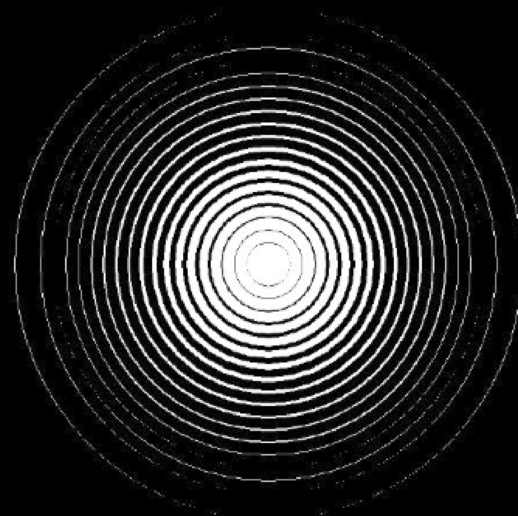
$\rho_{iwa} = 4$

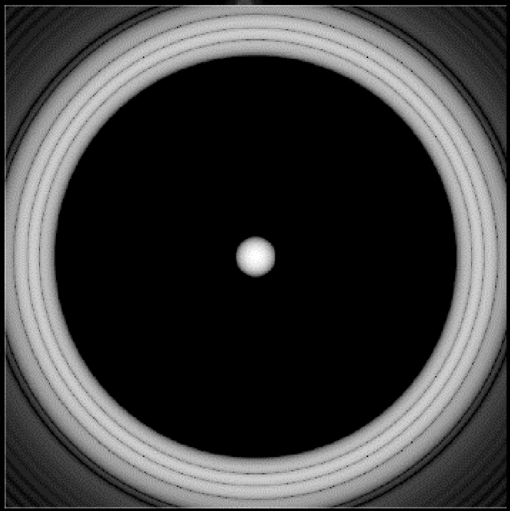
$T_{airy} = 9\%$

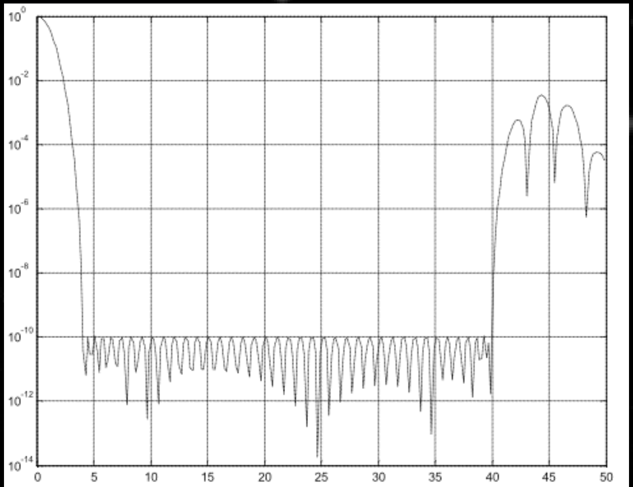


Excellent dark zone **Unmanufacturable**

Binary pupil







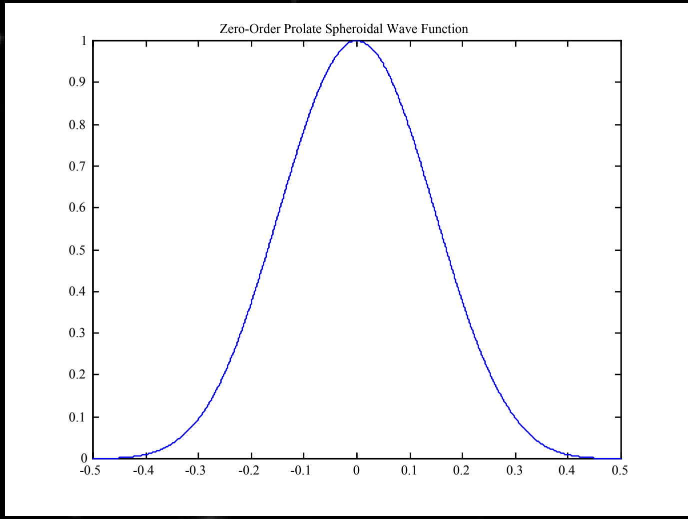
Excellent dark zone

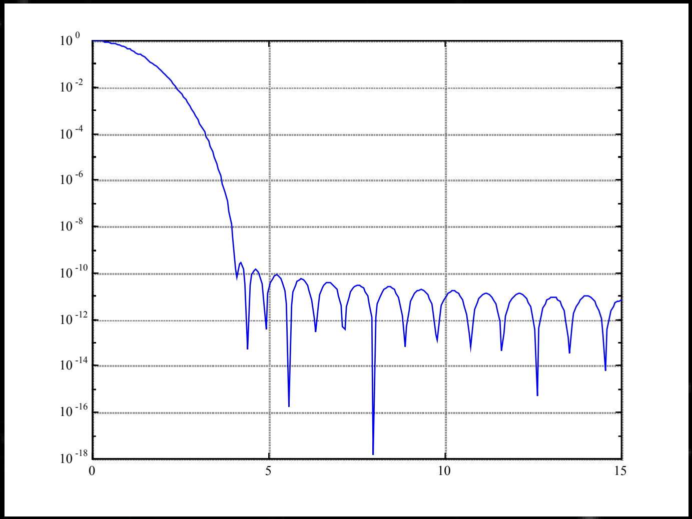
Impossible to manufacture

1D: Prolate Spheroidal (Slepian, 1963)

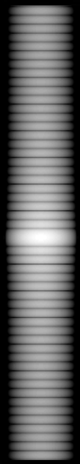
$\rho_{iwa} = 4$

$T_{airy} = 25\%$





Analytic solution via calculus of variations

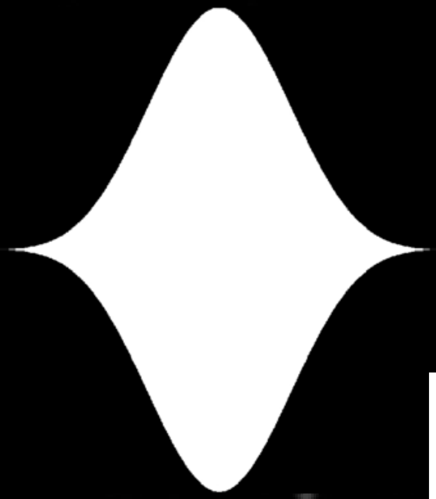


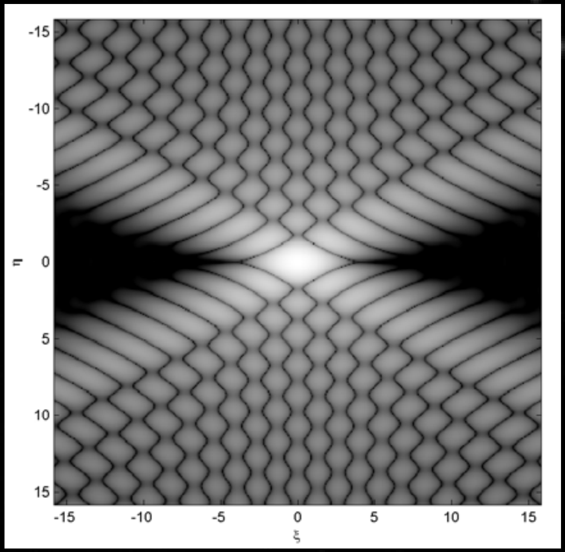
Theoretically optimal for 1-D **Unmanufacturable**

The Spergel-Kasdin pupil

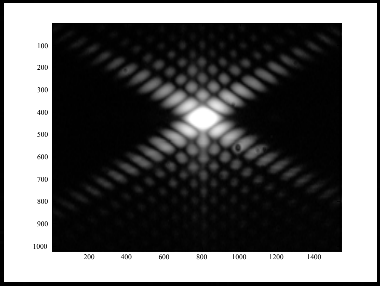
$\rho_{iwa} = 4$

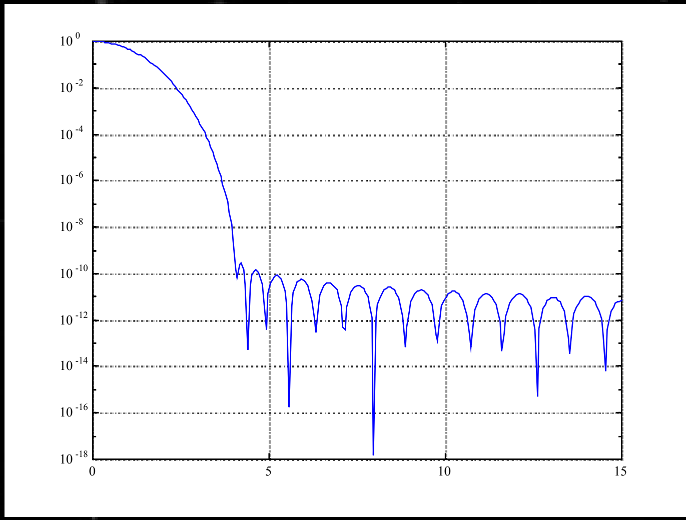
$T_{airy} = 43\%$





Lab image

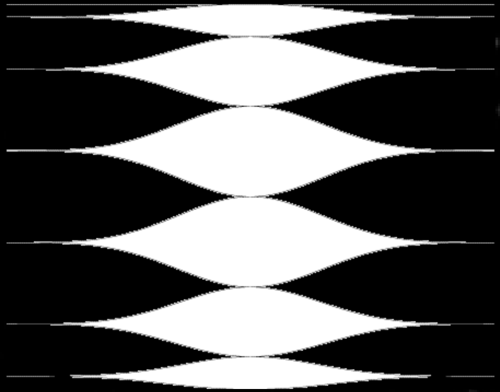
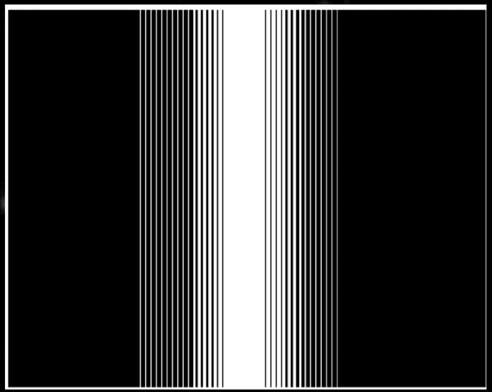
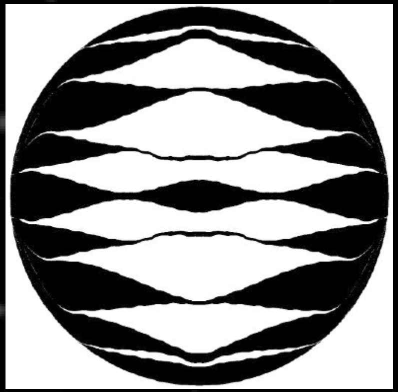
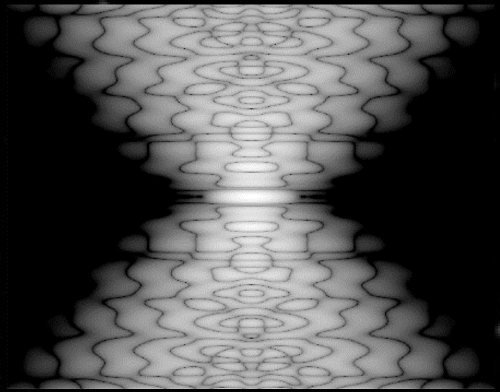
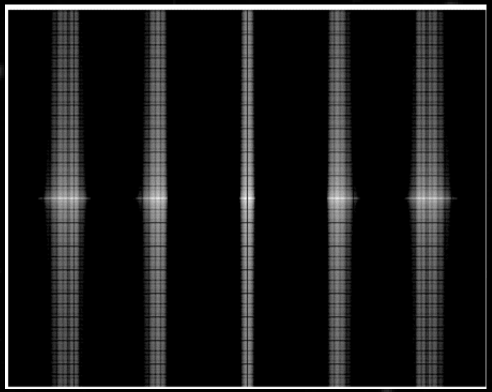
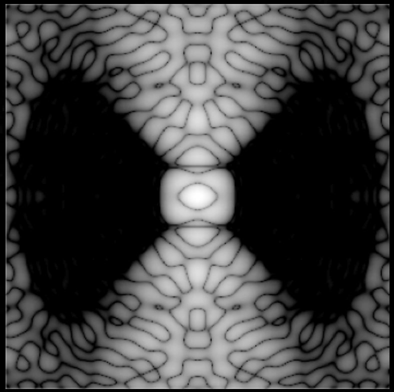




Optimal across x-axis

Very narrow opening

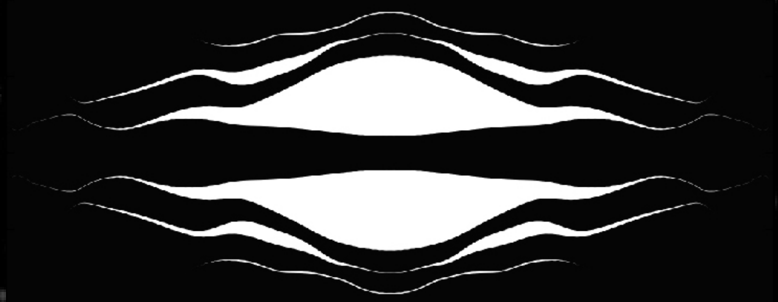
Other designs…

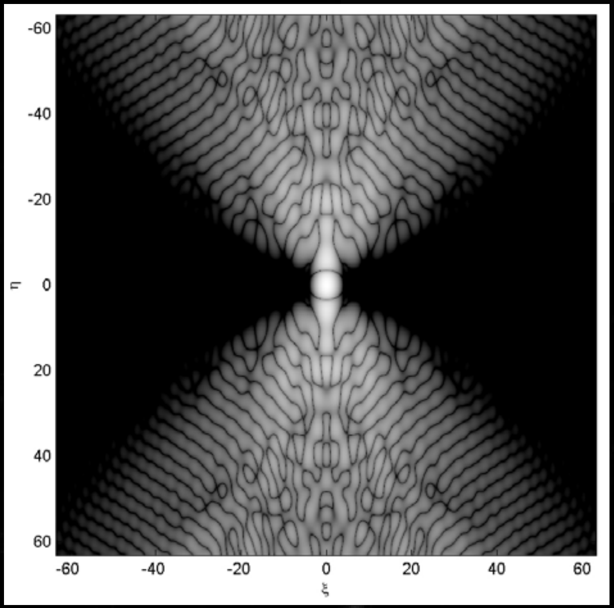







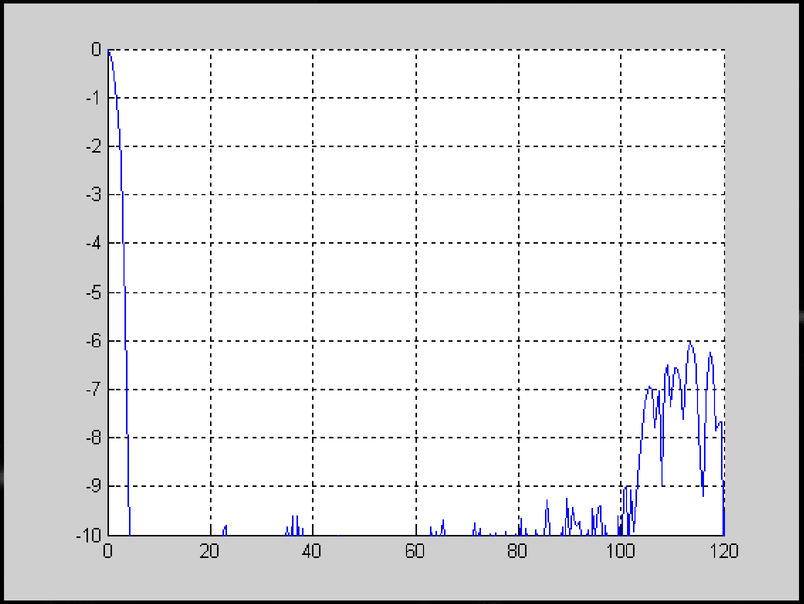
Our favorite…

$\rho_{iwa} = 4$

$T_{airy} = 30\%$







What would a solar system look like?...

Light reflecting off the planet from the star

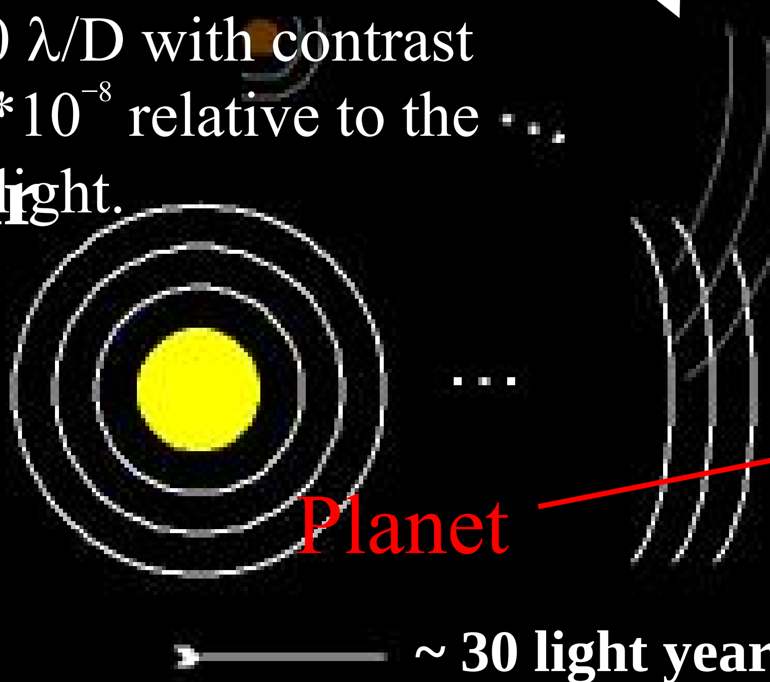
Only star

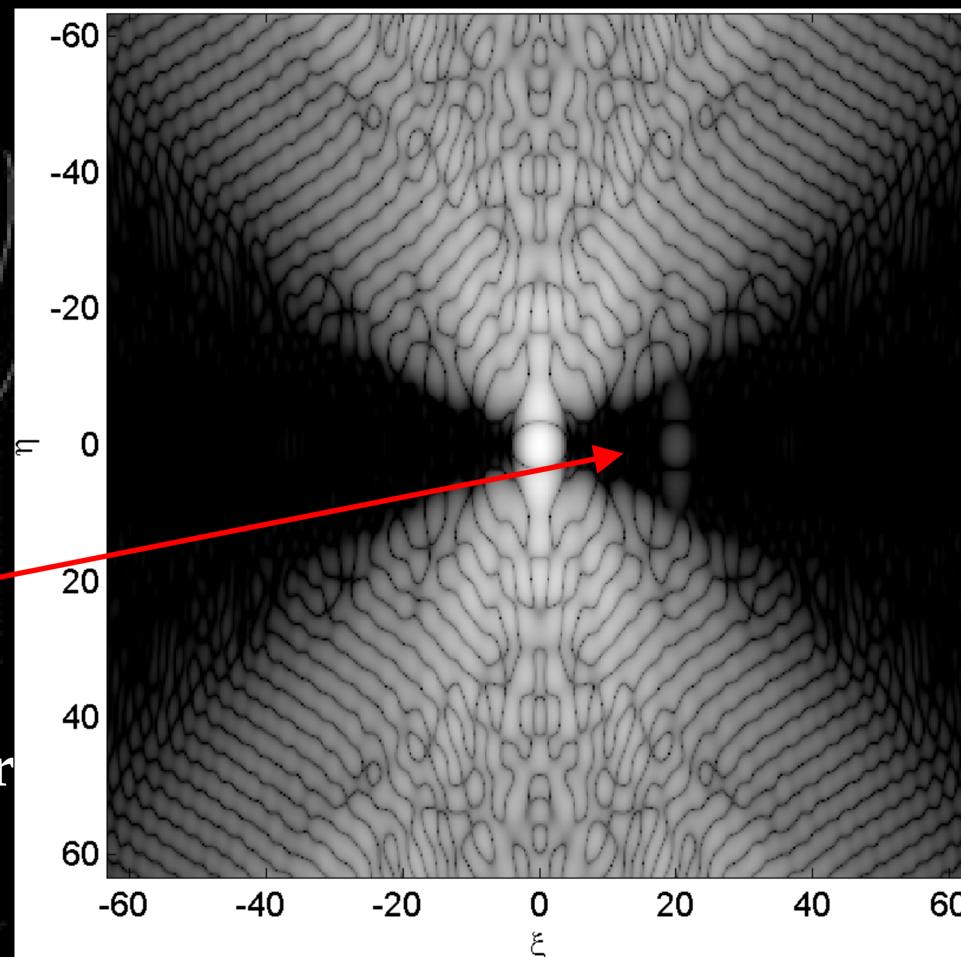
Star+planet

Planet

Simulation of a planet at 20 λ/D with contrast of $5*10^{-8}$ relative to the starlight.

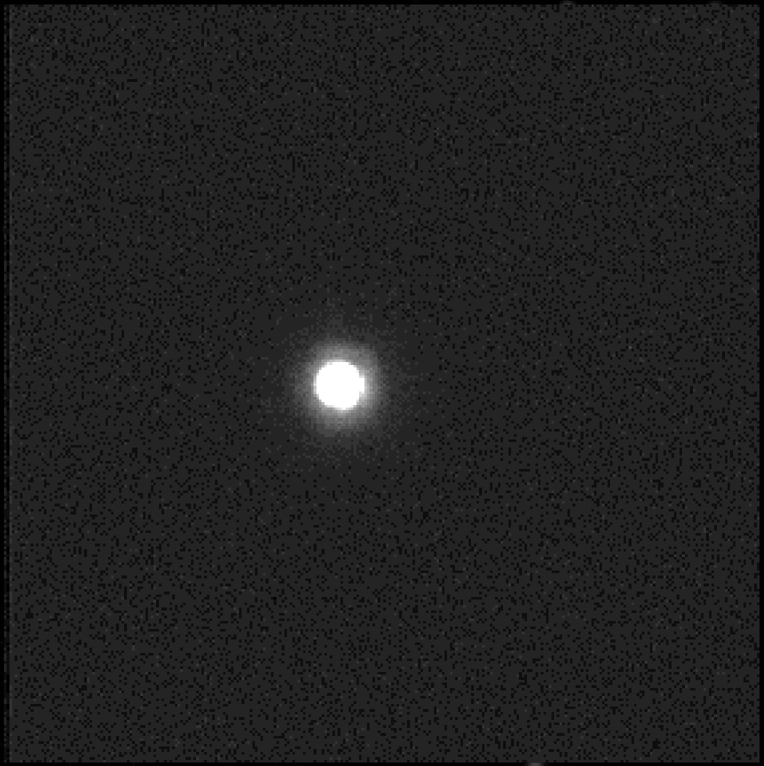
Star

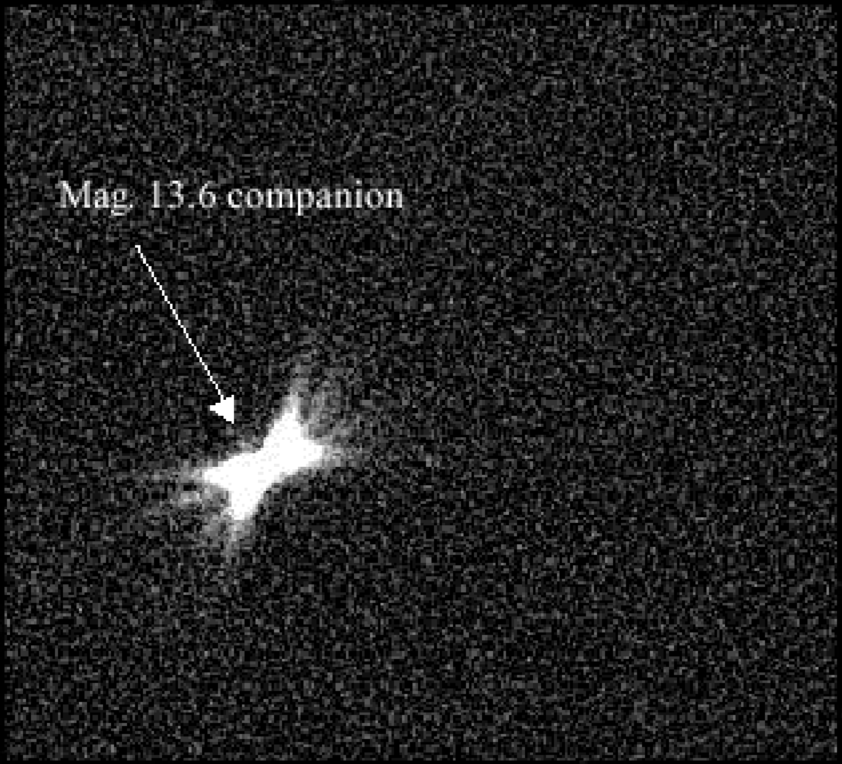




It really works!!

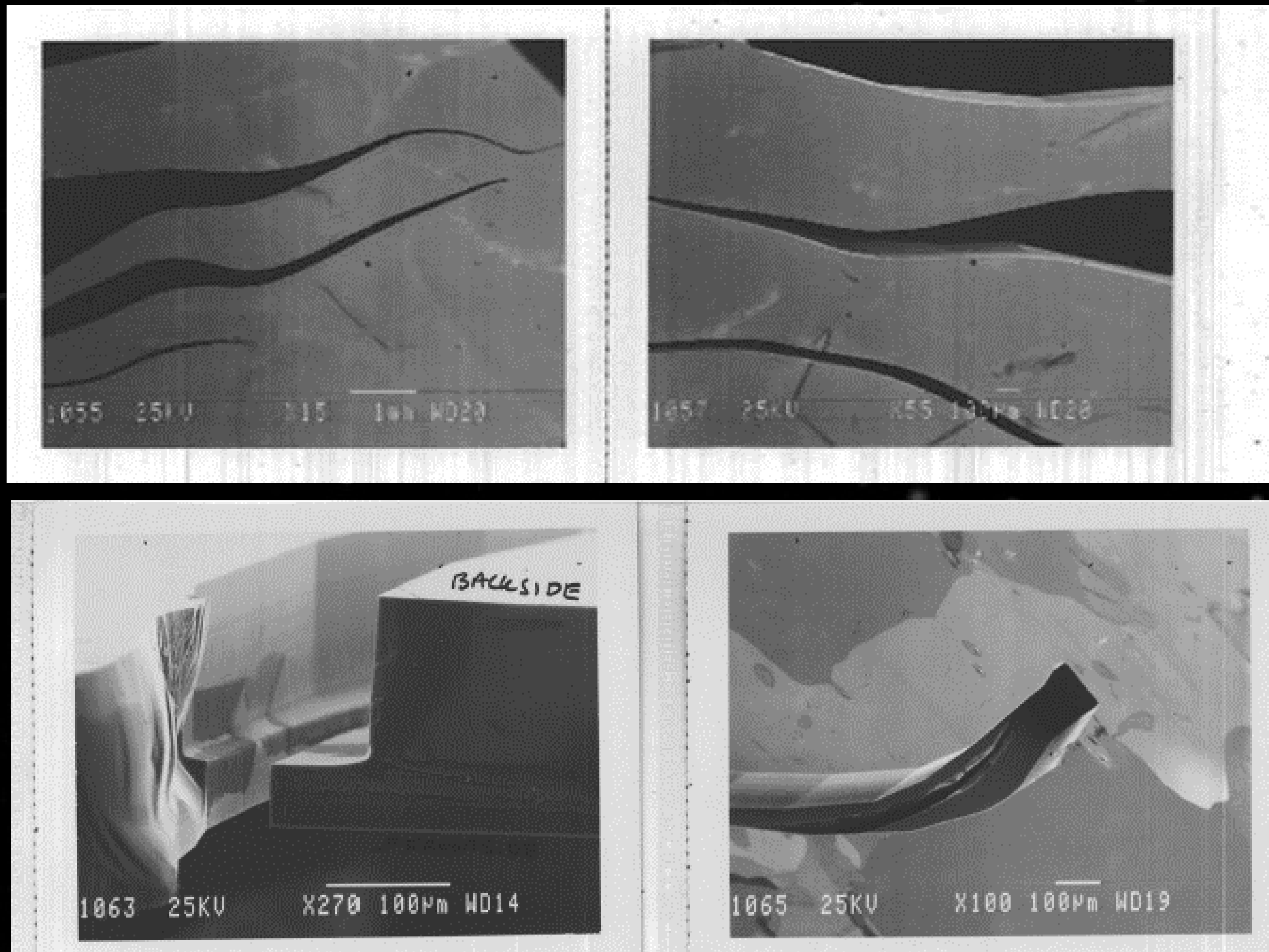
31 Leonis is a dim double with magnitudes 4.37/13.6 and separation 7.9”





Courtesy Prof. Robert Vanderbei

Our mask



Silicon based mask, 200 microns thick (thinned to 50 microns near the openings).

It is all fun and games, until you go to the lab…

Simulated image

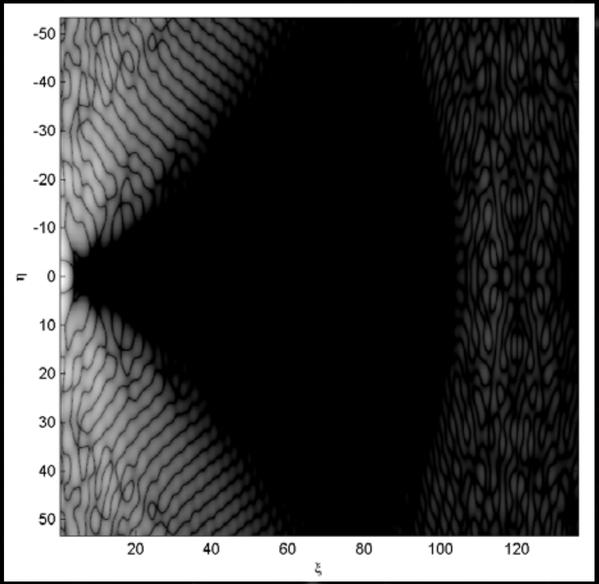
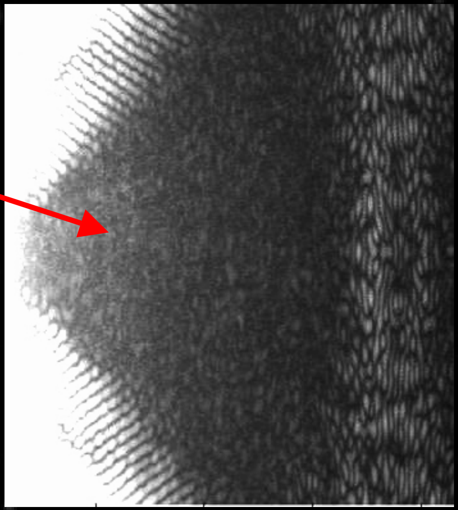
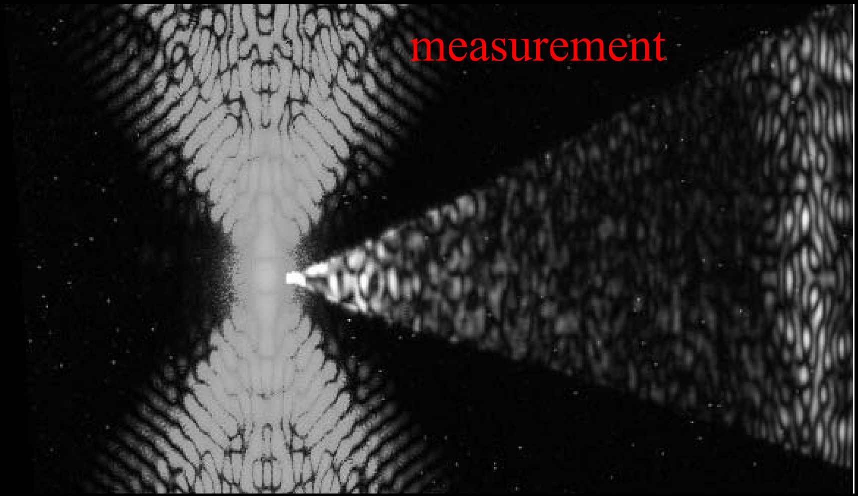


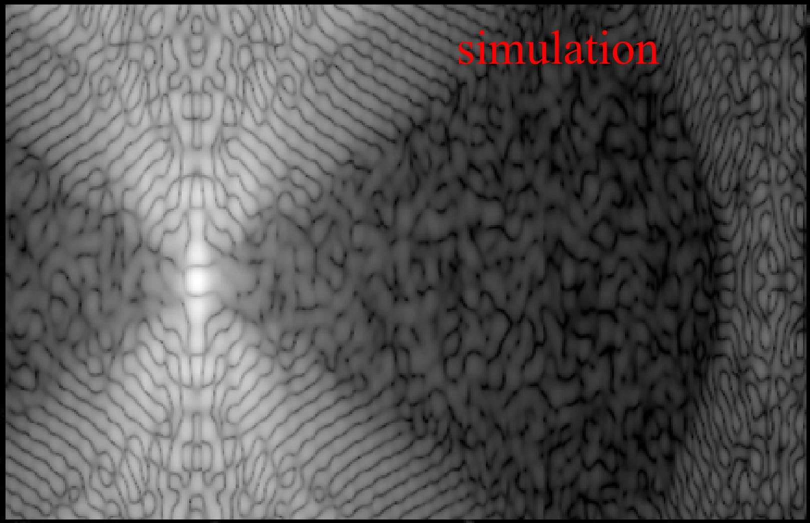
Image measured in the lab

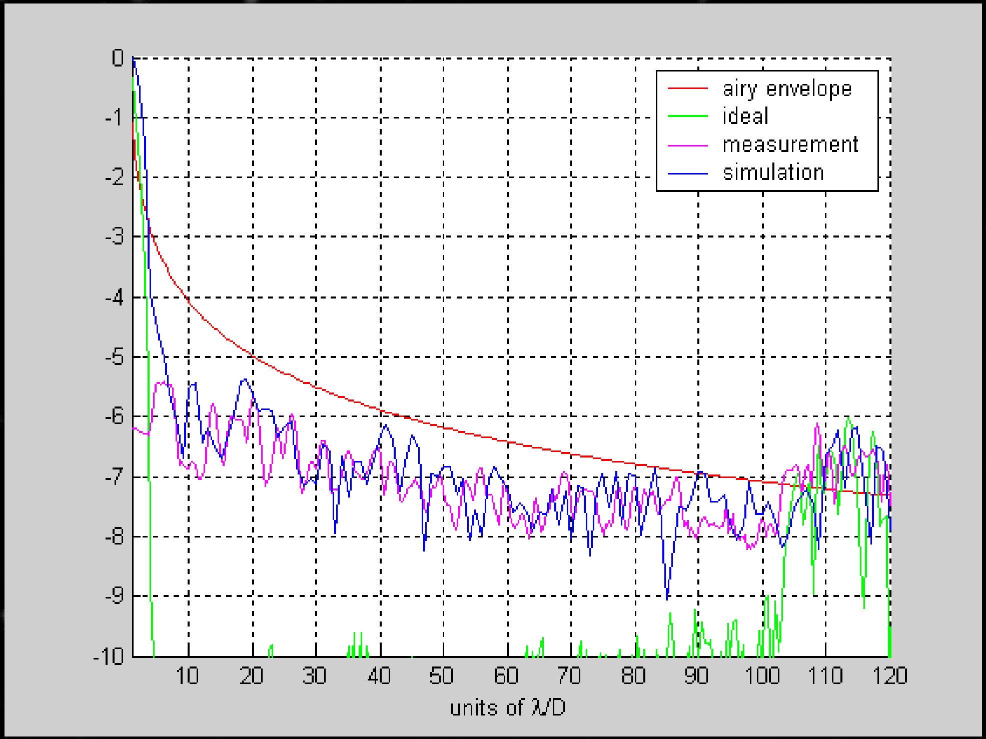
planets???



Our best results to date







Next step: correct aberrations!

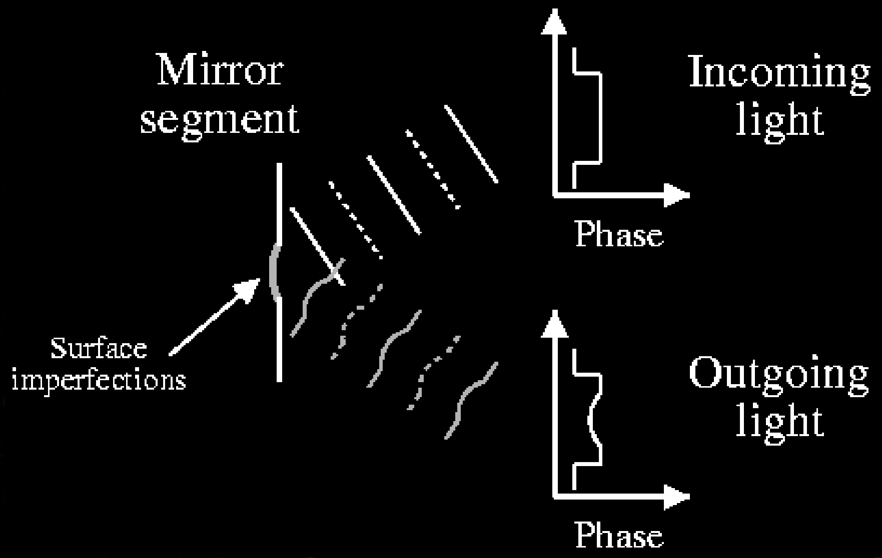
Outline

- Background on planet searches and TPF
- The Shaped-Pupil Coronagraph: a solution to planet imaging
- The challenge: wavefront control

The real challenge:

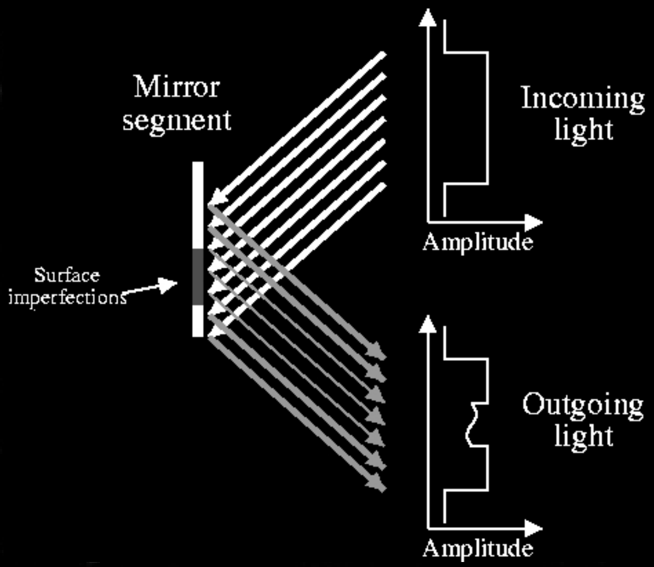
Wavefront control

Phase aberrations



Requirement: $\lambda/10,000$

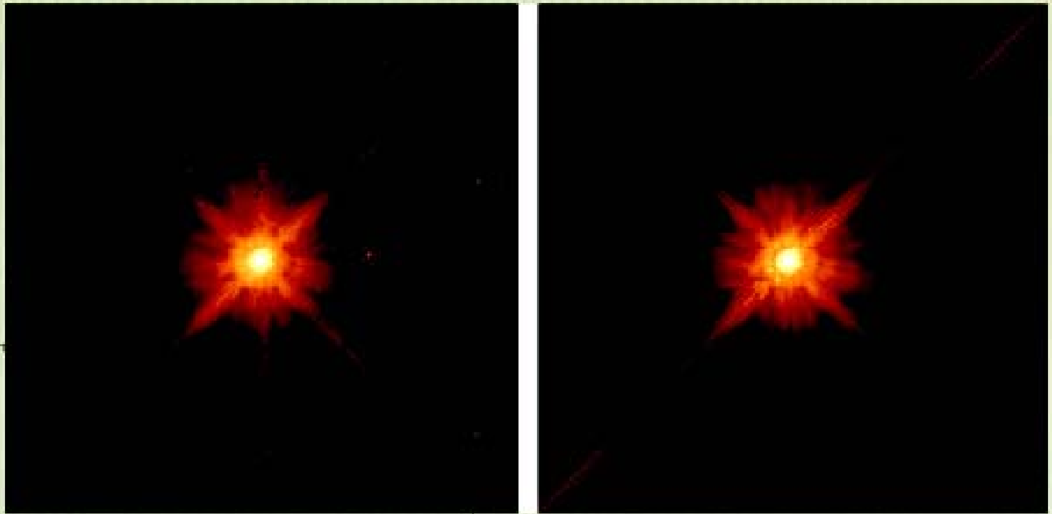
Amplitude aberrations



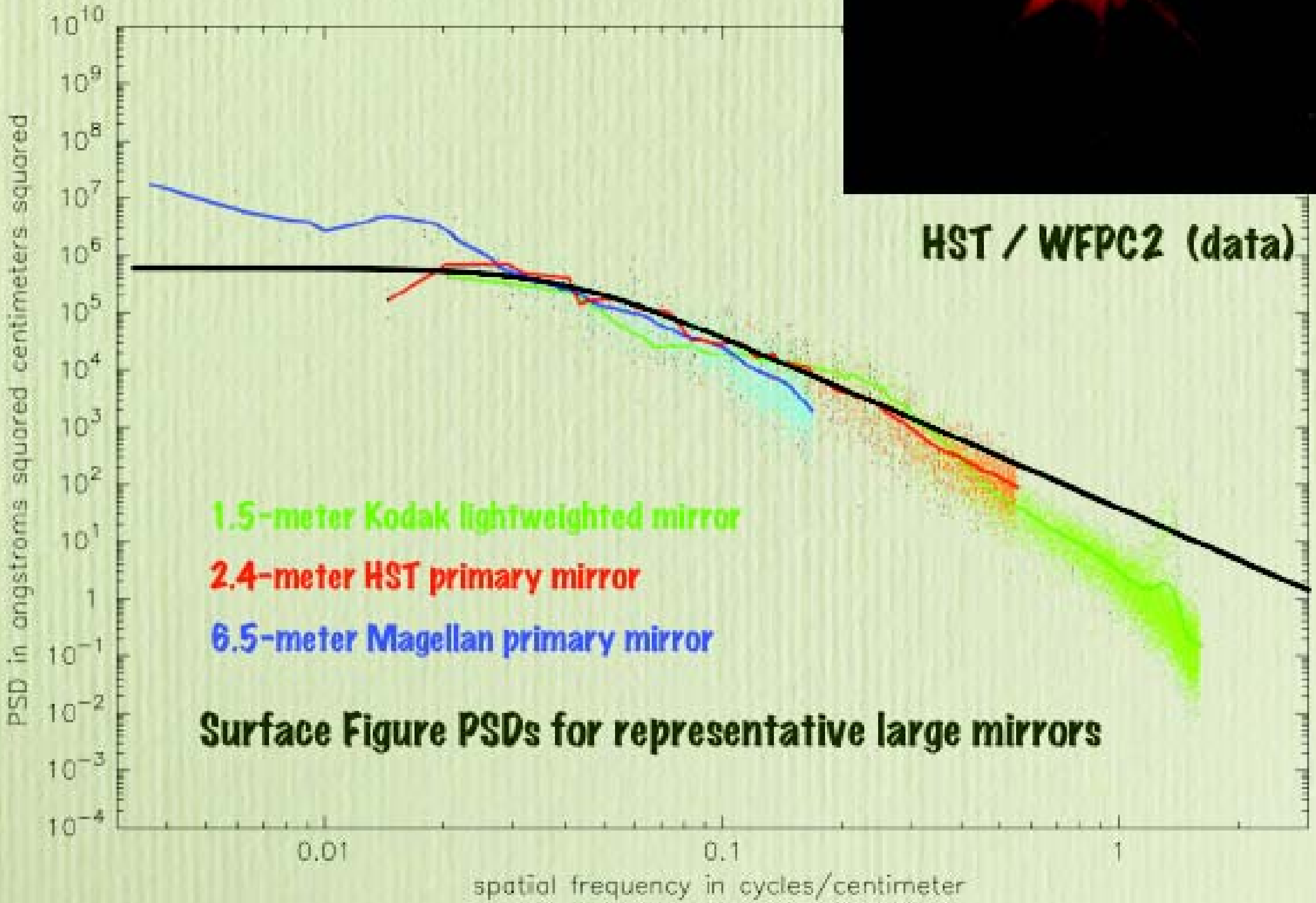
Requirement: 1 / 1,000

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.



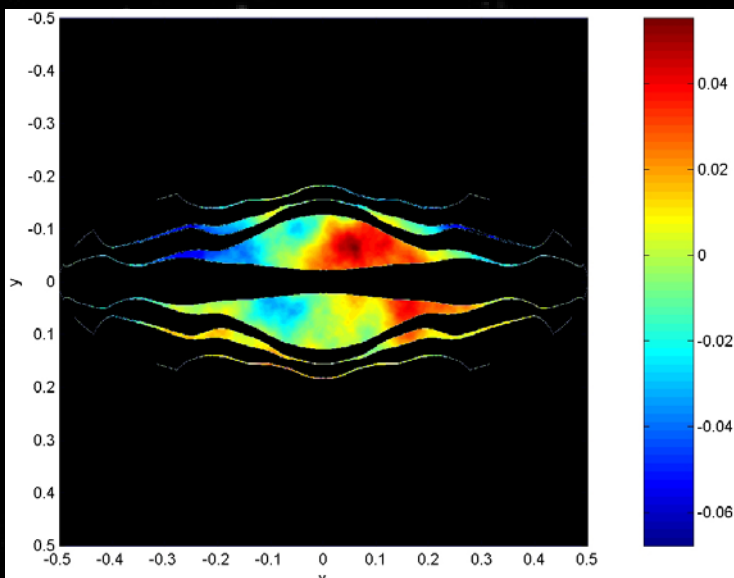
HST / WFPC2 (data) HST / WFPC2 (model)



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.

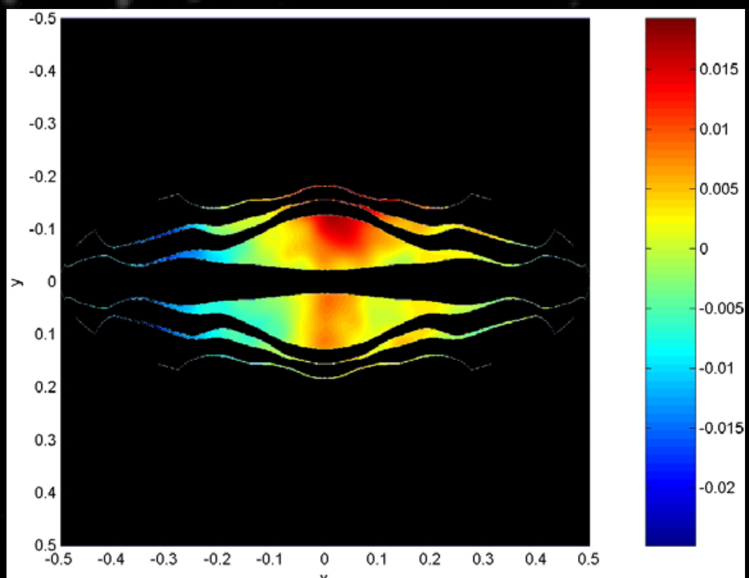
Simulating the aberration

Phase aberrations



RMS = $\lambda/20$
(λ = 632nm, given in units of λ)

Amplitude aberrations

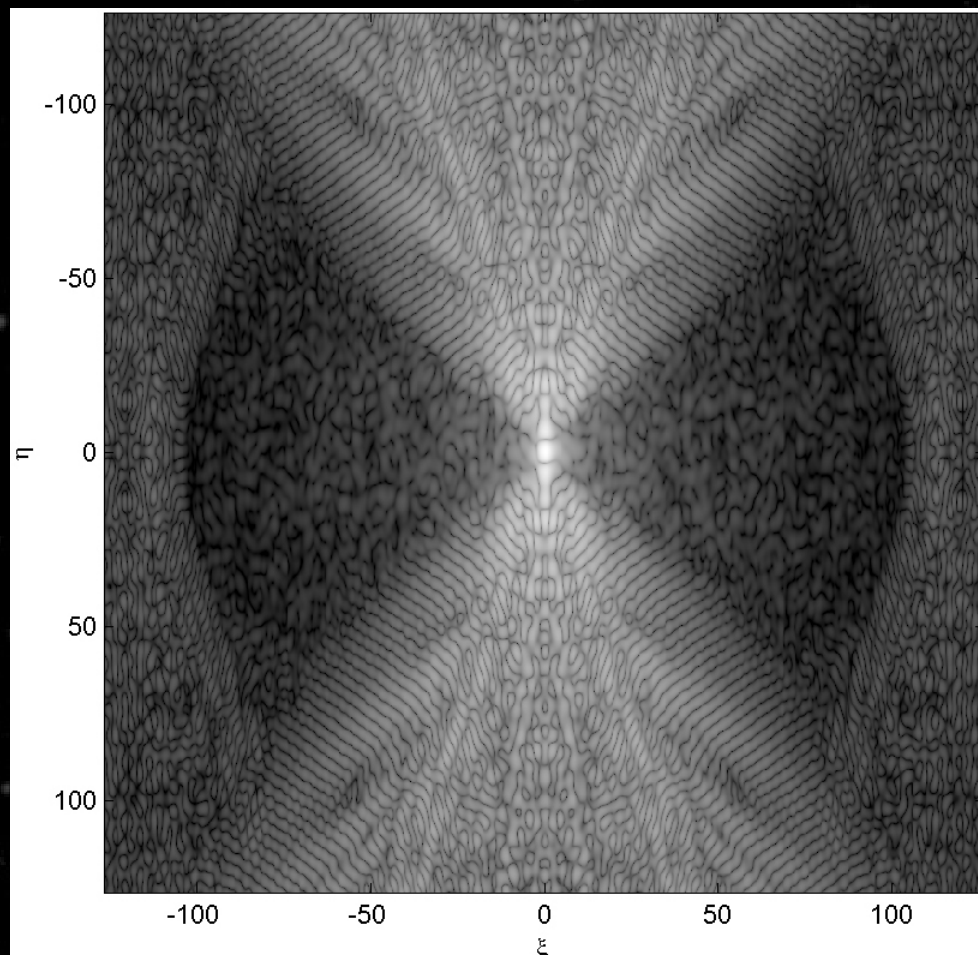


RMS = 0.01

The resulting image

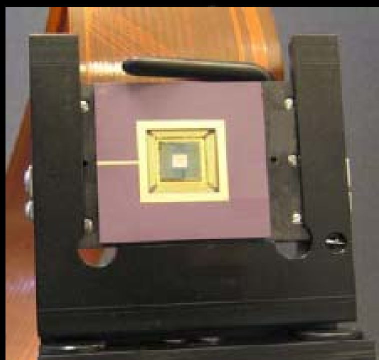
The aberrated image

The ideal image

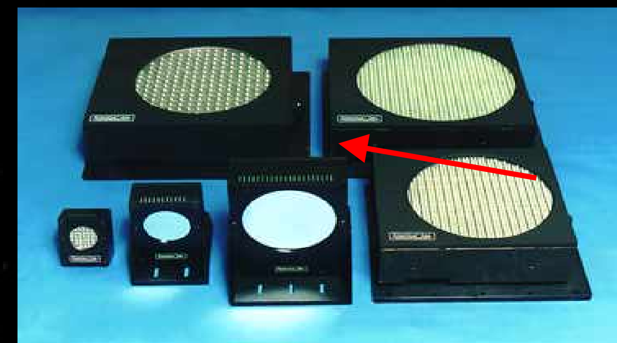


Deformable mirrors

Boston Micromachines

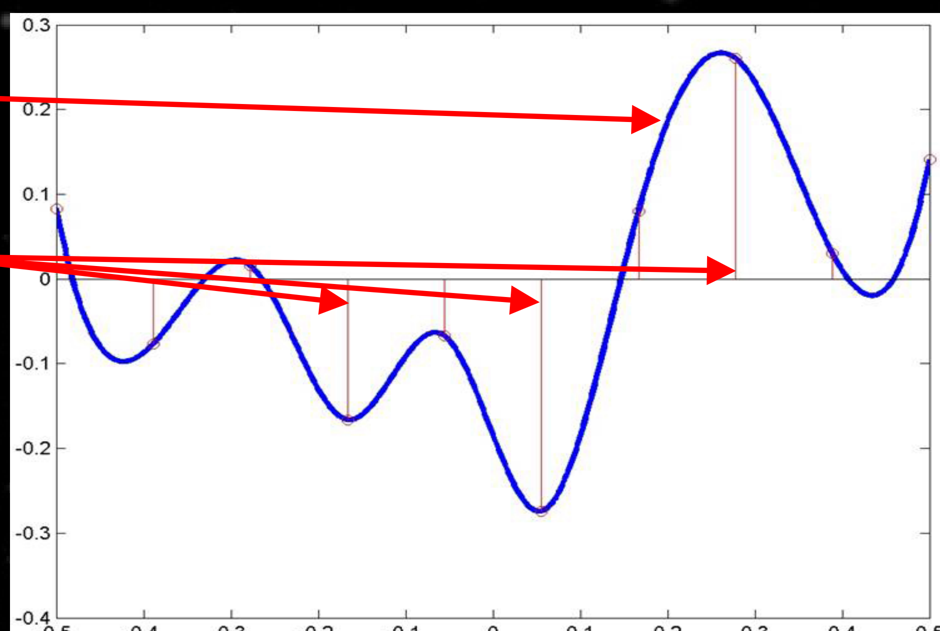


Xinetics



Face-sheet

Actuators



Conventional wavefront estimation and correction

Measurements are taken at the pupil plane

Cannot correct these elements

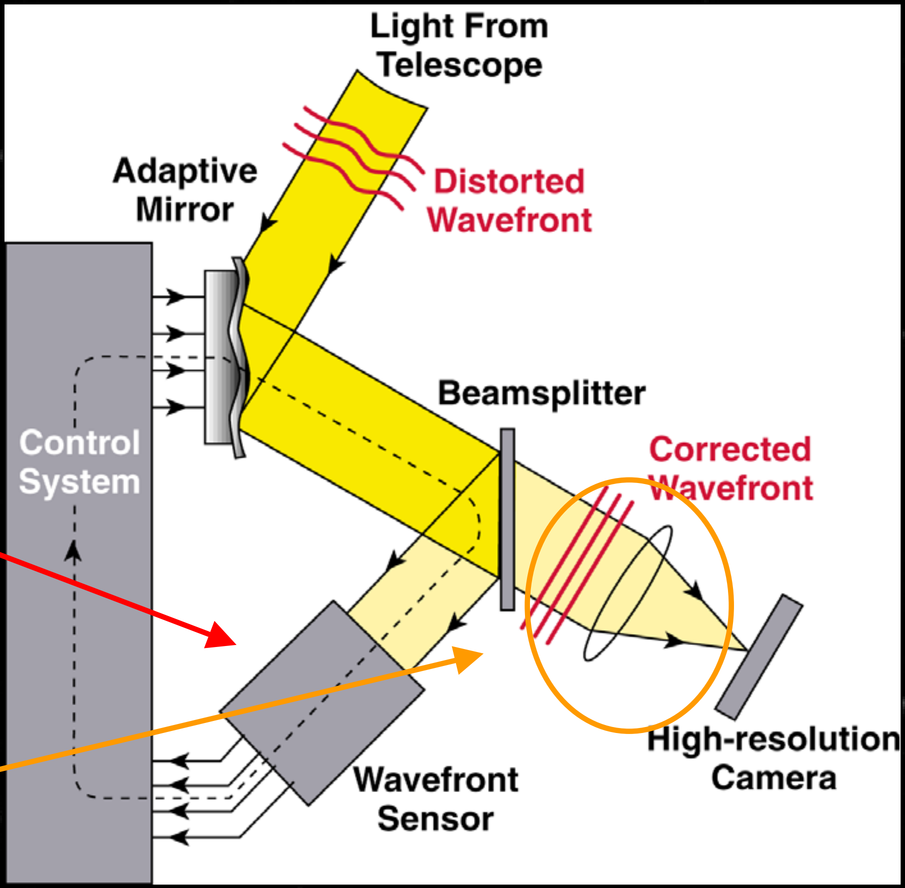
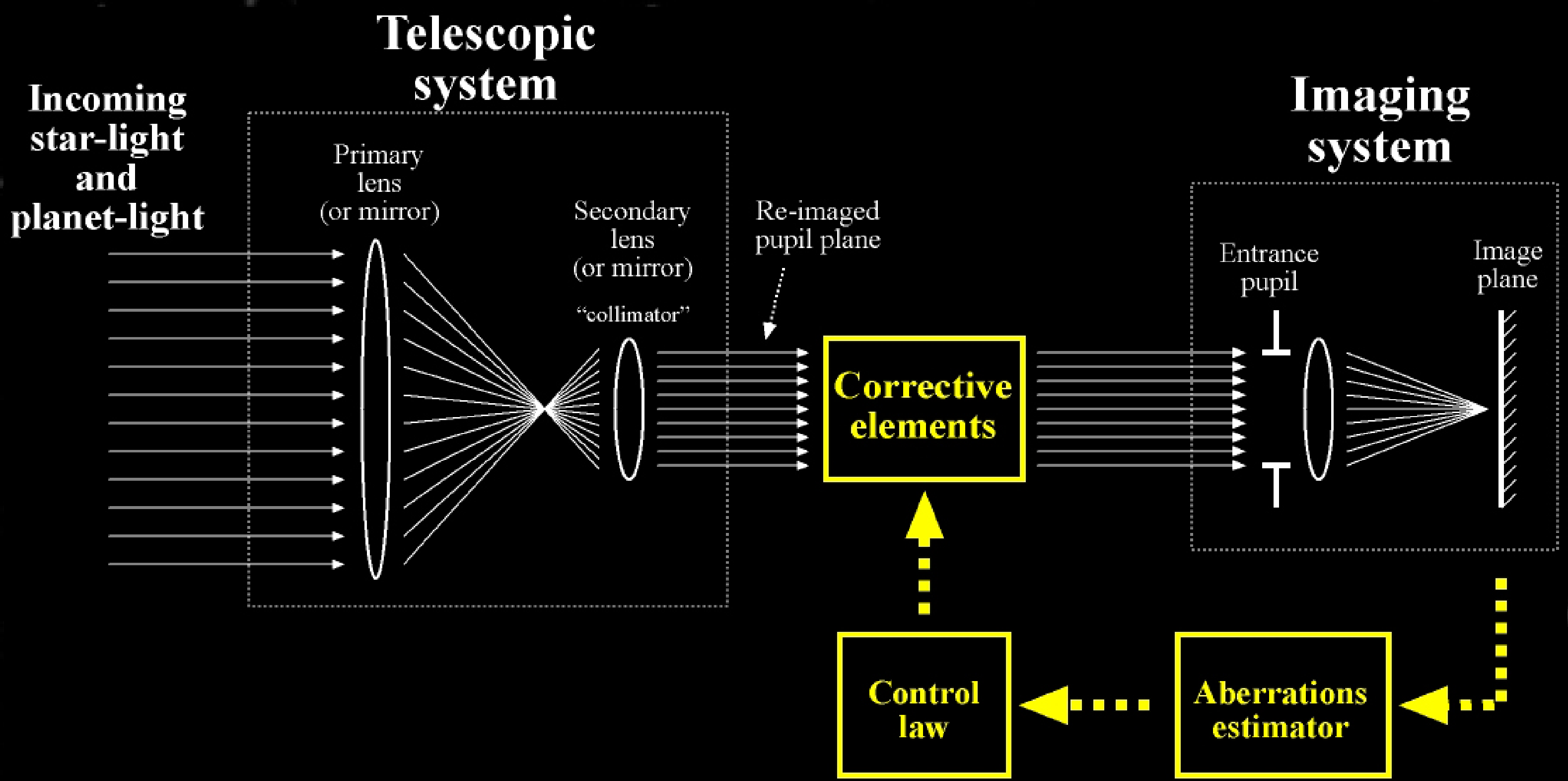


Diagram by Claire Max, UCSC

Image-plane-based wavefront estimation



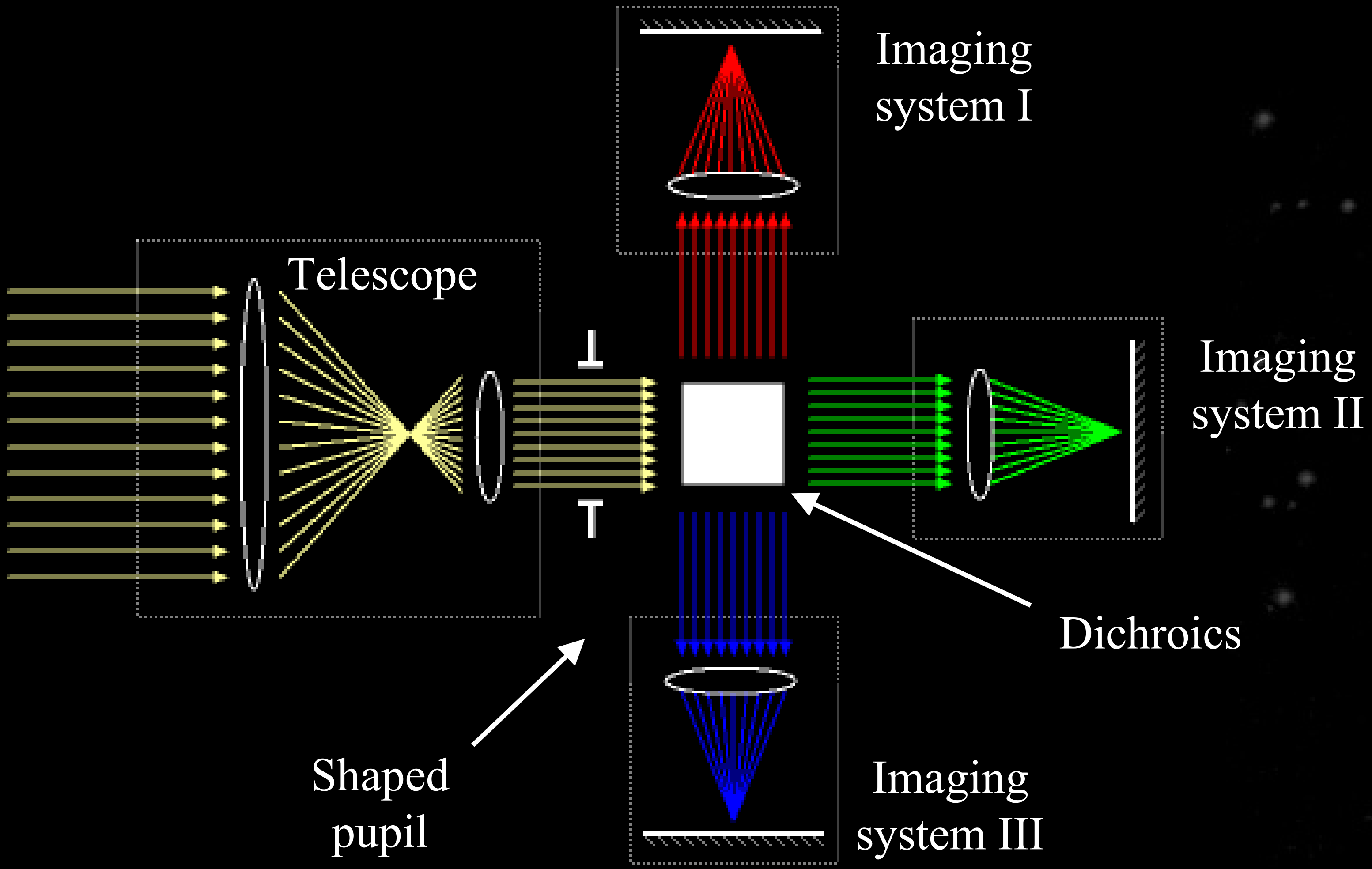
$$I(\xi,\eta)=\left|\iint_A A(x,y)e^{\alpha(x,y)+i\frac{2\pi}{\lambda}\phi(x,y)}e^{i\frac{2\pi}{\lambda}\phi_D(x,y)}e^{-i\frac{2\pi}{\lambda f}(x\xi+y\eta)}dxdy\right|^2$$

Image-plane wavefront estimation techniques:

- Error reduction algorithms (Gerchberg-Saxton)
- Maximum Likelihood techniques
- Optimization-based techniques

Defocus + wavelength diversity

Challenge: getting diversity without sacrificing valuable photons



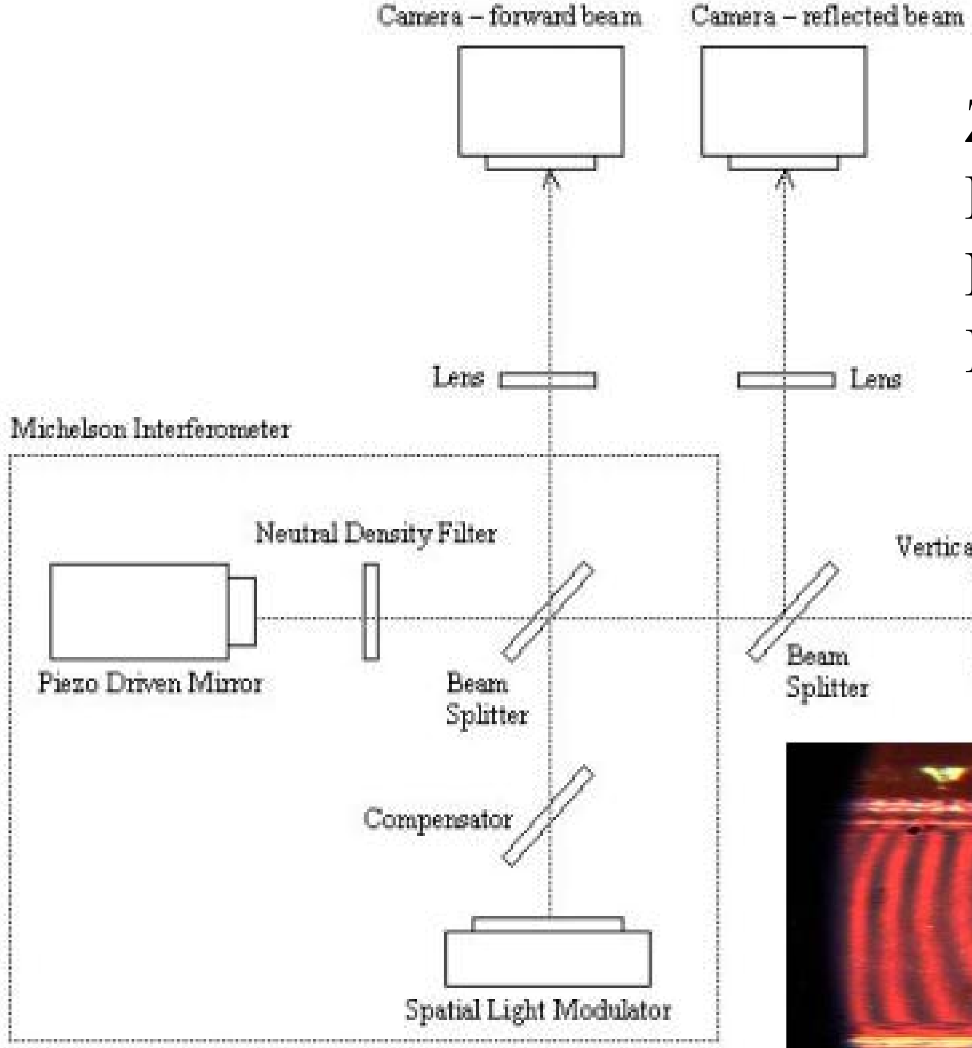
The change in wavelength and the defocus provides the needed diversity without losing any photons

Correction techniques

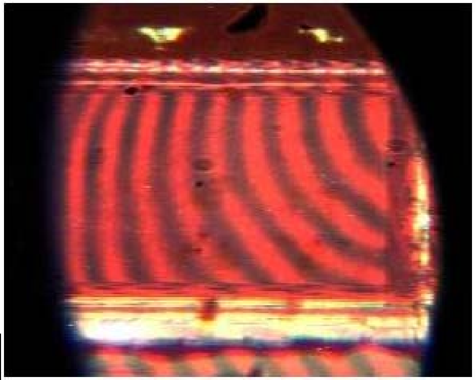
$$I(\xi,\eta)=\left|\iint_A A(x,y)e^{\alpha(x,y)+i\frac{2\pi}{\lambda}\phi(x,y)}e^{i\frac{2\pi}{\lambda}\phi_D(x,y)}e^{-i\frac{2\pi}{\lambda f}(x\xi+y\eta)}dxdy\right|^2$$

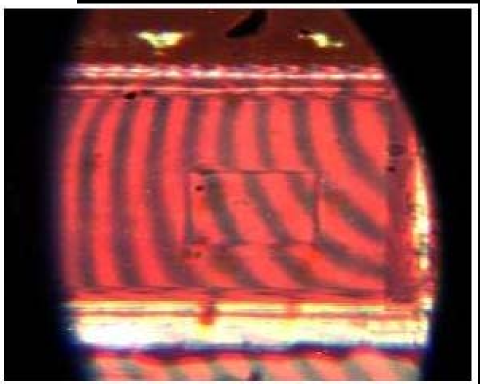
- Conventional phase conjugation
- Global optimization techniques
- Fourier coefficients-based correction

Polychromatic amplitude correction



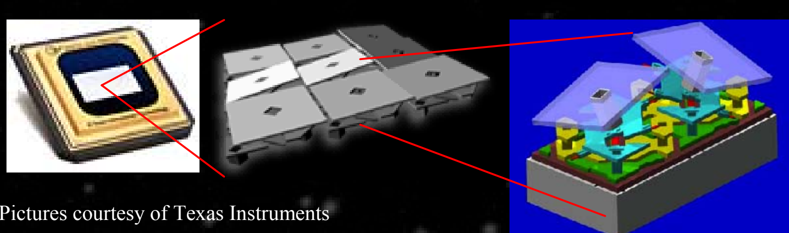
Zero-Path Difference Michelson Interferometer



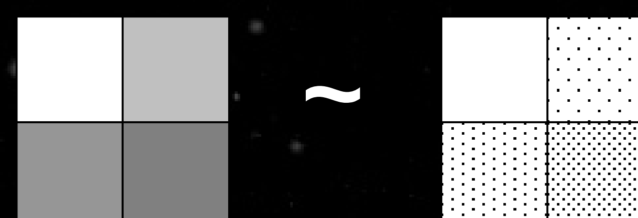


The Challenge: Polychromatic amplitude correction

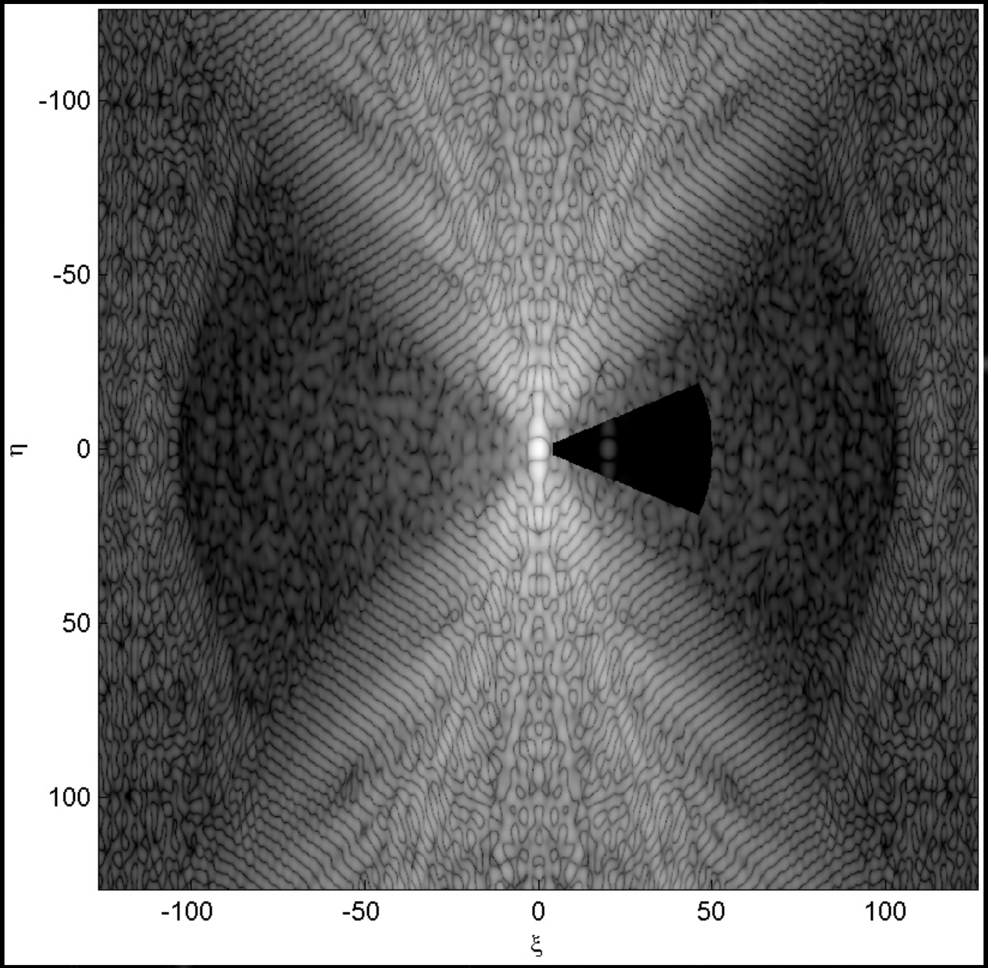
- Phase alone is conceptually easy: use a good DM
- Phase with amplitude is conceptually easy for monochromatic light: use 2 interfering DMs.
- Amplitude polychromatically is difficult
- Proposed solution: use a binary chip like the TI DMD and *dither*



Pictures courtesy of Texas Instruments



Putting it all together…



Future work

- Lab (finally getting deformable mirrors!!)
- Mask designs
- Mask manufacturing
- Estimation techniques
- Correction techniques

Conclusions

- An imaging telescope in the visible is the best approach for earth-like planet detection, but requires 10^{10} contrast.
- The Princeton TPF team has designed the Shaped Pupil Coronagraph as a solution to the high contrast problem
- The main challenge is wavefront control. The TPF group at Princeton is developing methods, algorithms, and significant laboratory capability to correct the wavefront to the required levels
- Within 10 years, we will see the first extrasolar terrestrial planet!


Thank you