Coronagraphs and Starshades for Imaging Planets from Space

"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

(convicted of heresy, 1633
House arrest until his death.
Sentenced rescinded and
public regret, October, 1992)

N. Jeremy Kasdin
Princeton University

2009 Sagan Symposium

Pasadena, CA   12 November, 2009

Are we Alone?

- How do planetary systems form and evolve
  - So far, we have only observed the "tip of the iceberg", need to detect lower mass planets and **zodiacal light**
- What are the properties of planets?
  - Are there novel types of planets not seen in our solar system (e.g., water planets)?
- Are there other habitable planets?
  - Detection of **science of life**

Only the **direct imaging** of planets can address all of these questions!

Prediction

- Sometime in the next four years, Kepler will announce the detection of significant numbers of Earth-like planets around typical stars.
- Astronomers and the public will ask:

"Can we see another Earth?"

Prediction

- Sometime in the next four years, Kepler will announce the detection of significant numbers of Earth-like planets around typical stars.
- Astronomers and the public will ask:

"Can we see another Earth?"

We are going to focus today on how to do it from space.

Prediction

- will
  ical
- h?”

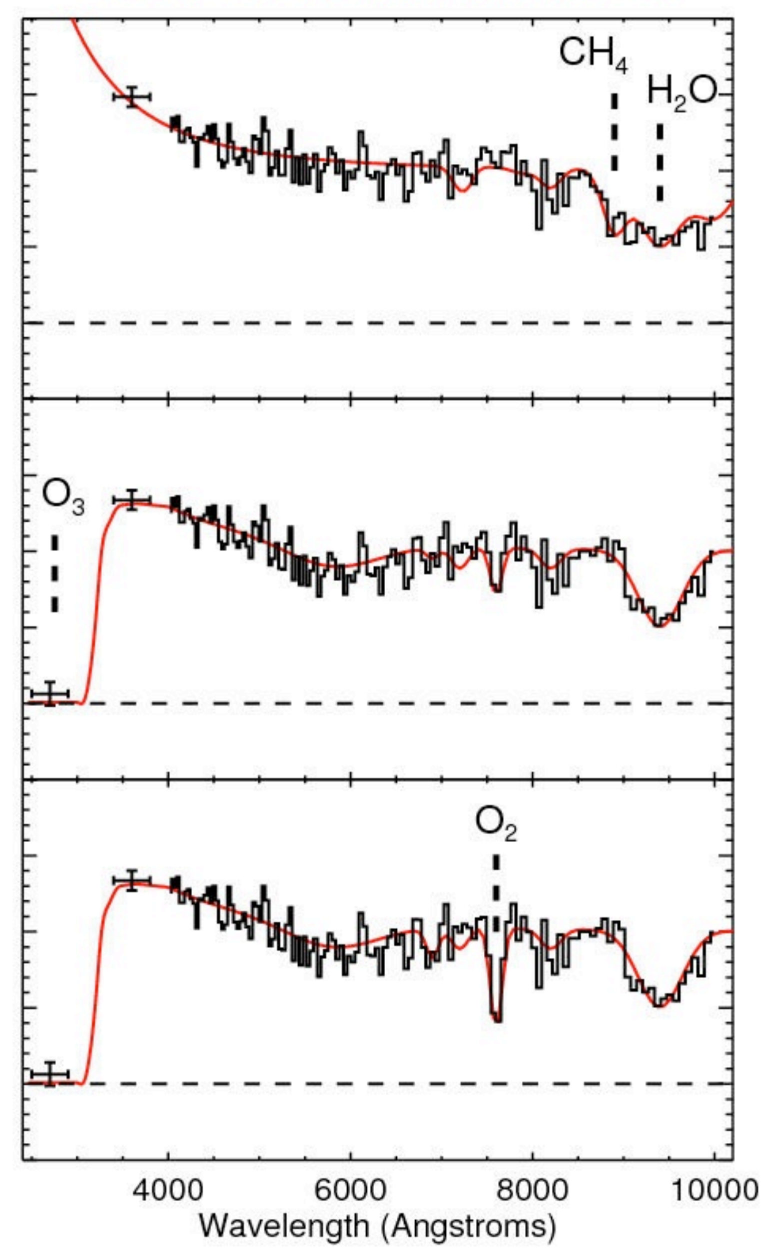
> We choose to . . . do [these] things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.
>
> John F. Kennedy
> Rice University, 1962

We are going to focus today on how to do it from space.

Direct Imaging Exoplanet Science

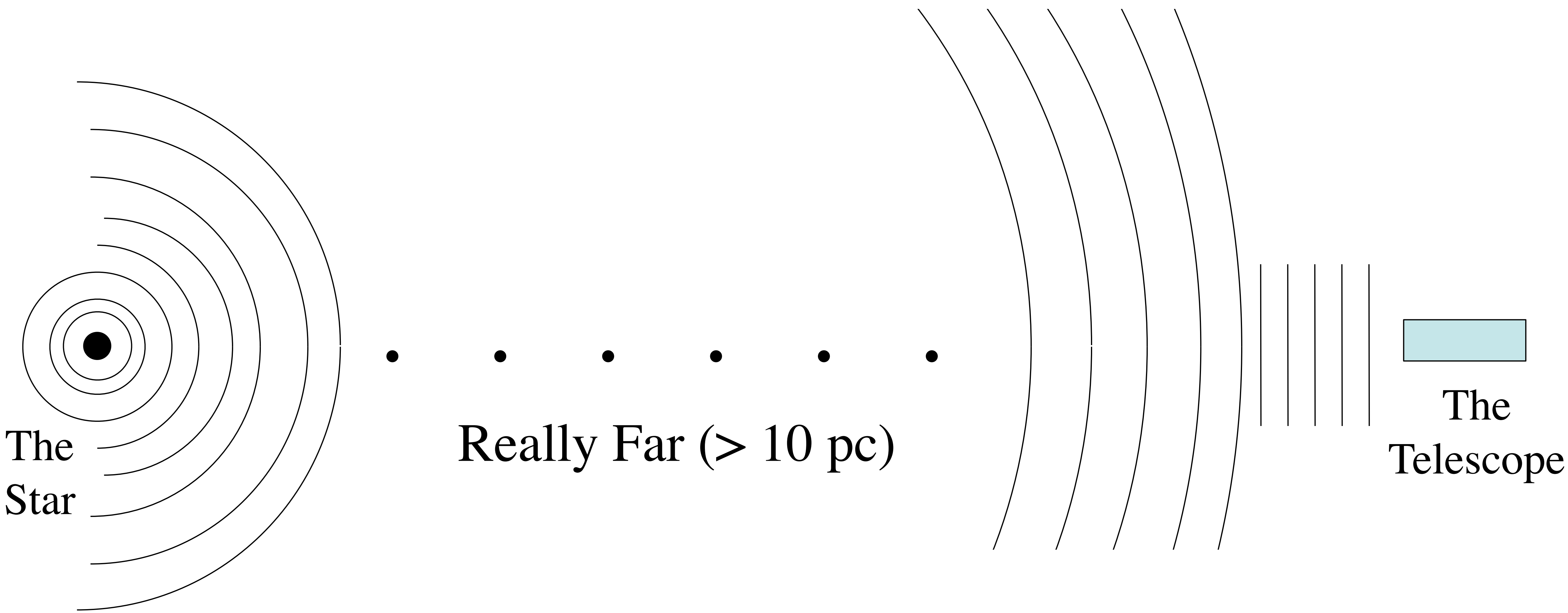
Can we find life if it exists?

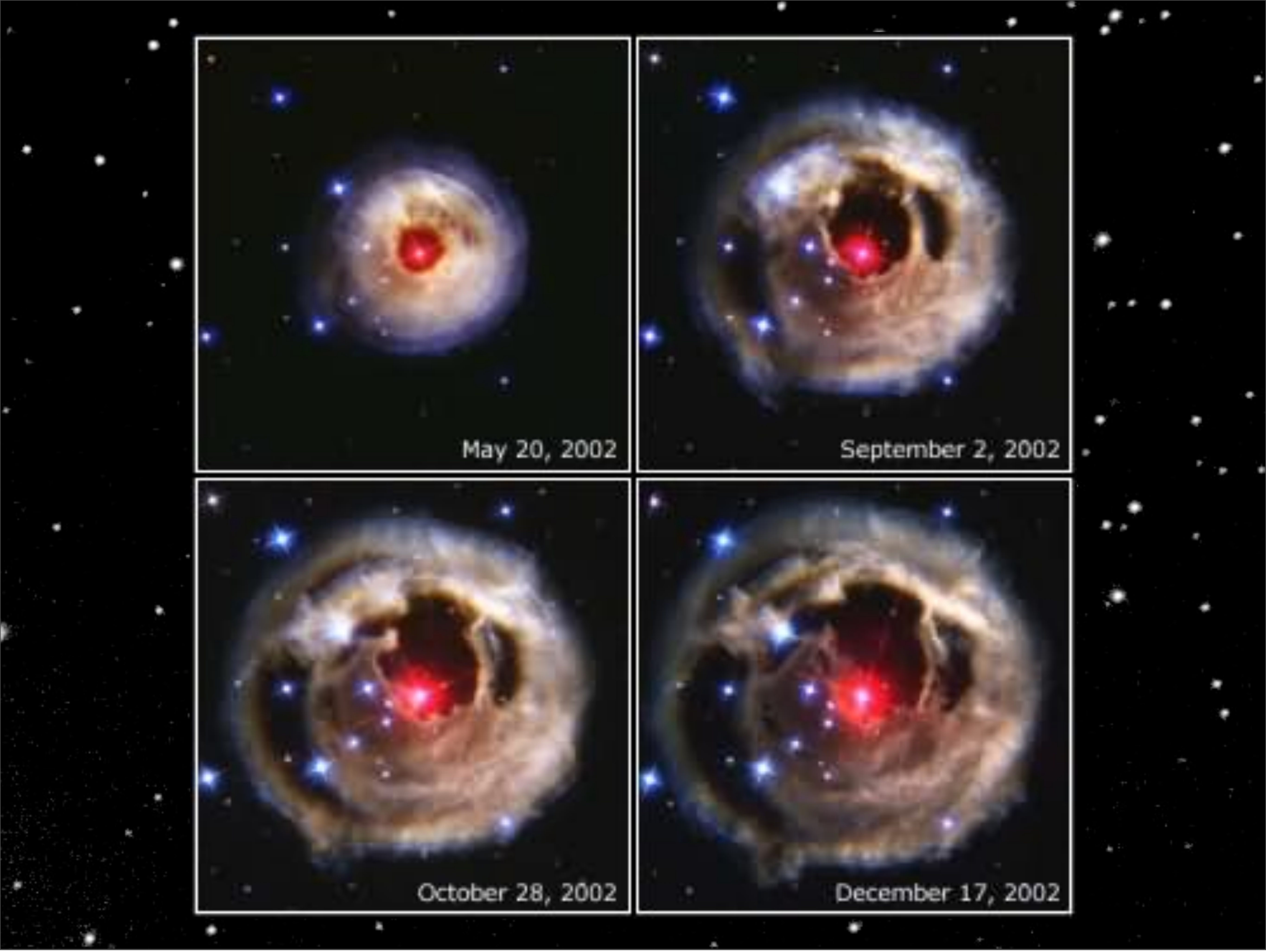
- Detect Earthlike planets in the habitable zone (as many as possible)
- Characterize their spectra from 250 - 1000 nm
- Revisit to characterize orbits and detect seasonal variations
- Characterize gas giants and outer RV planets
- Characterize circumstellar disks and dust
- Mass and radius?



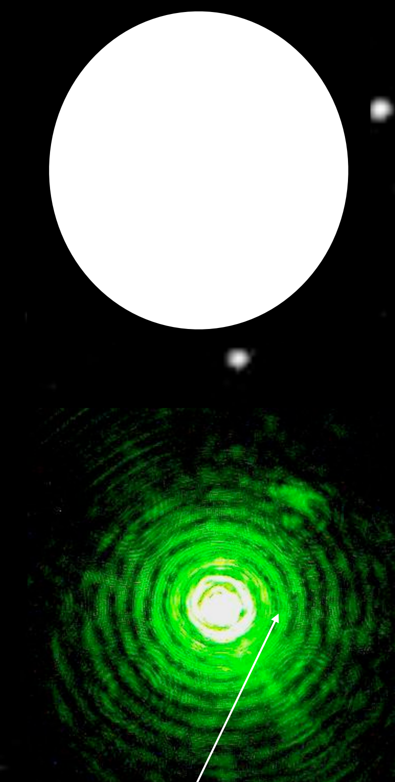
And it would be nice to do a rich collection of astrophysics!

How We See The Stars



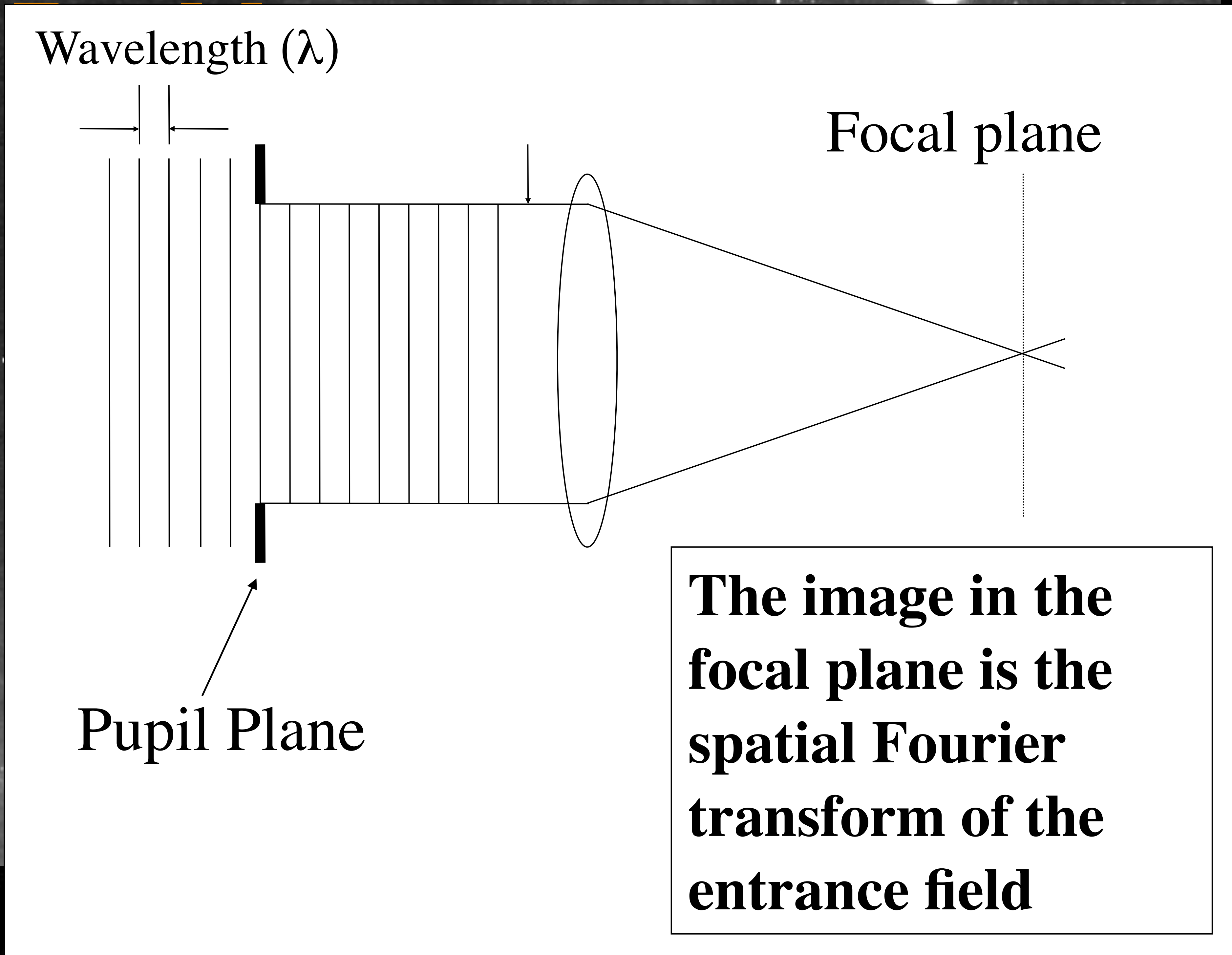

May 20, 2002
September 2, 2002
October 28, 2002
December 17, 2002

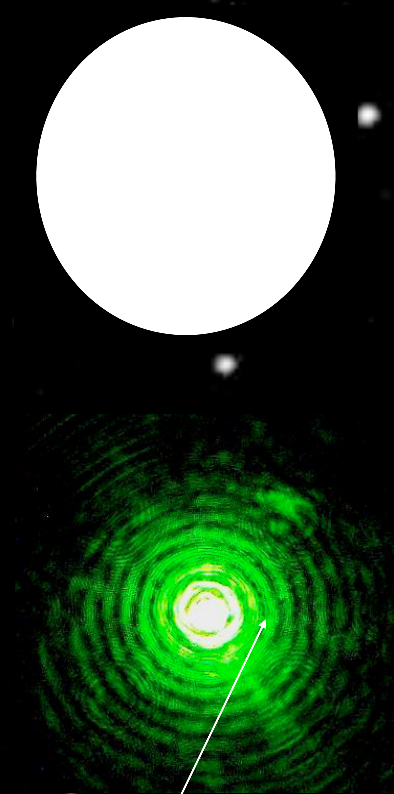
Airy Rings – The Diffraction Problem



Unfortunately, the planet would be right here (and about 10 billion times dimmer in visible light)

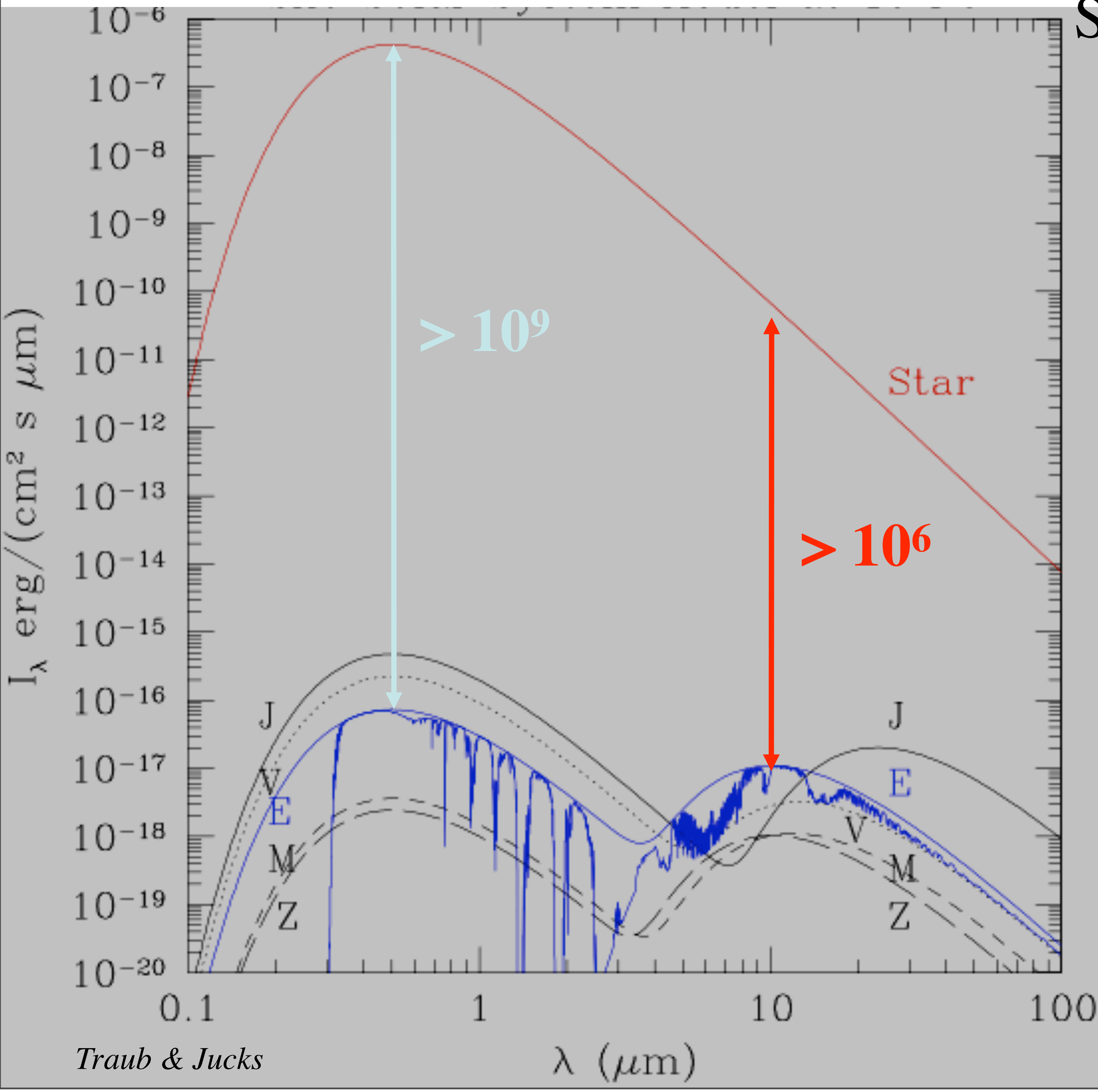
Airy Rings – The Diffraction

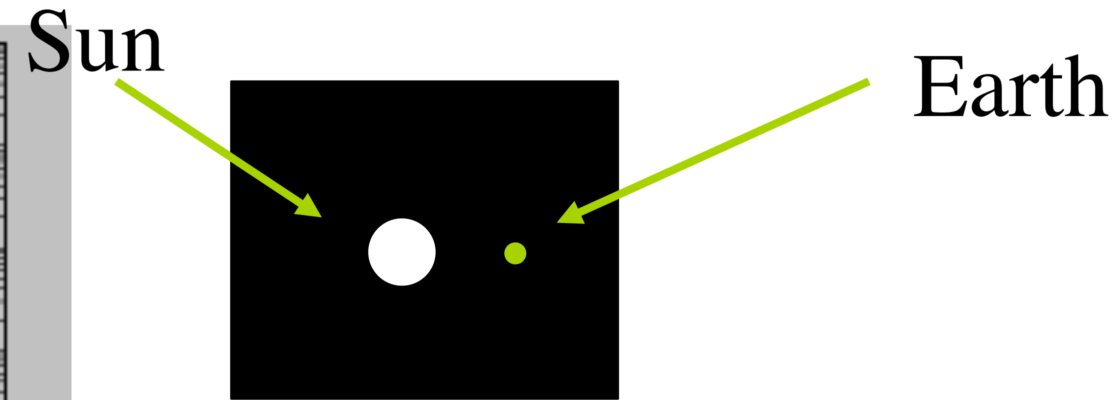




Unfortunately, the planet would be right here (and about 10 billion times dimmer in visible light)

The Contrast Ratio Problem

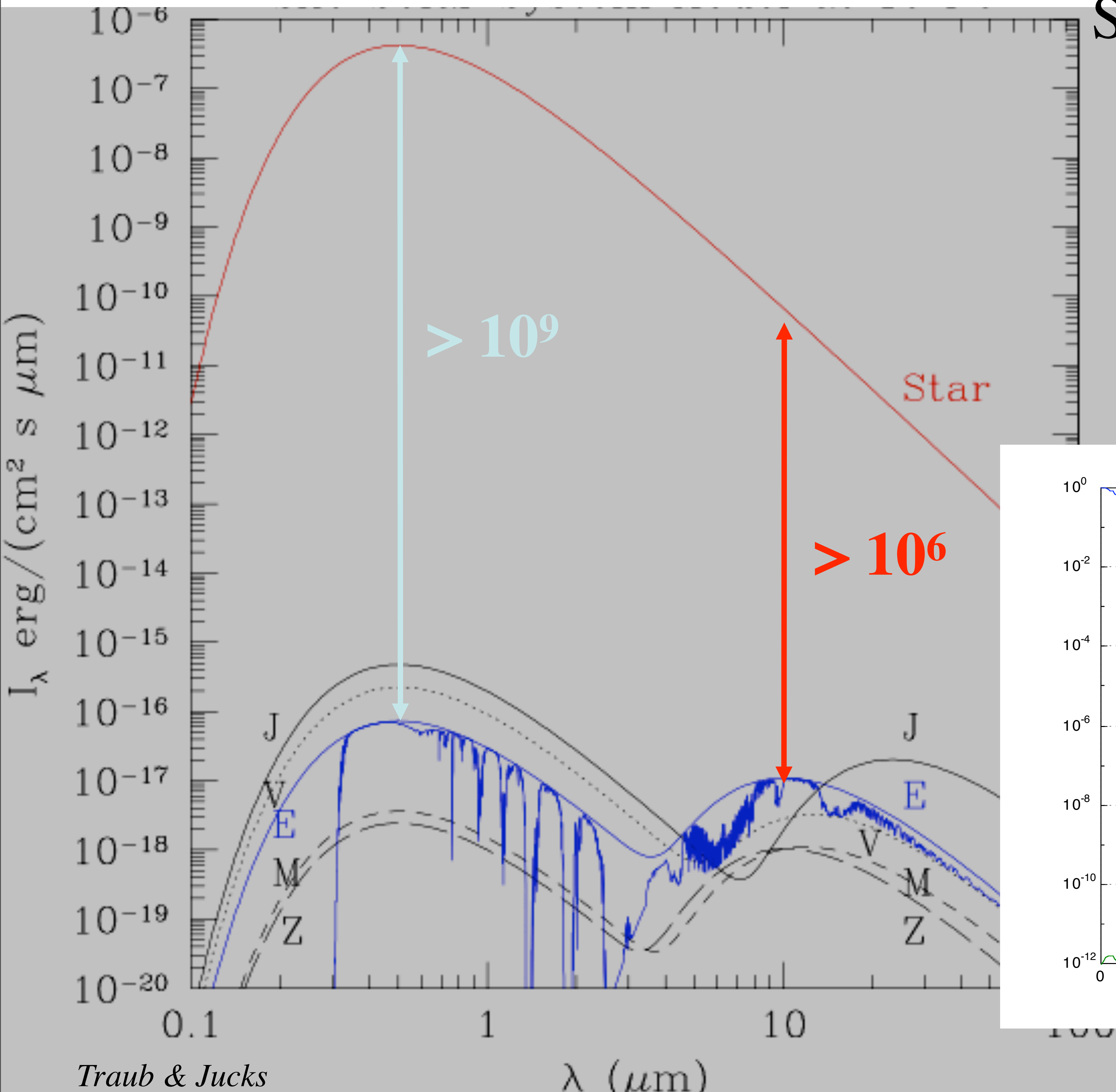




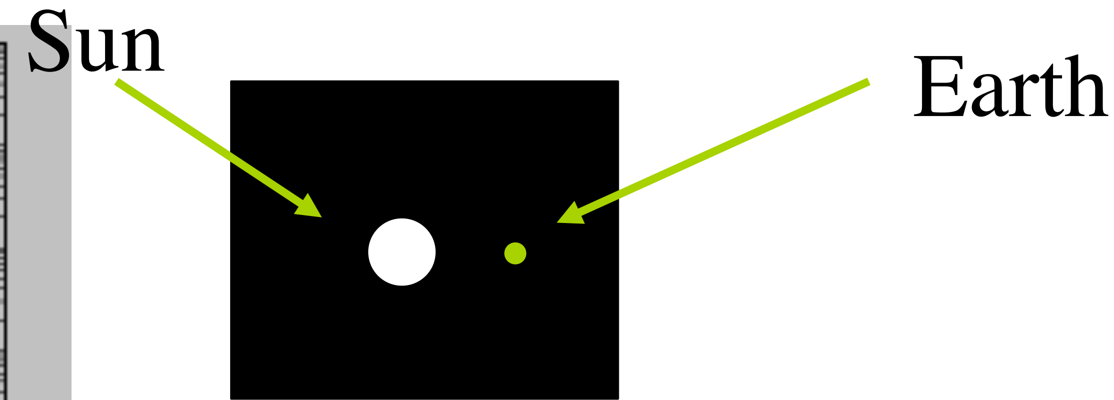
At 10 pc, angular separation is 100 marcsec

- **Visible**
  - **Earth/sun ~ 10^{-10}**
  - **Zodi small**
- **Infrared**
  - **Earth/sun ~ 10^{-7}**
  - **Zodi large**

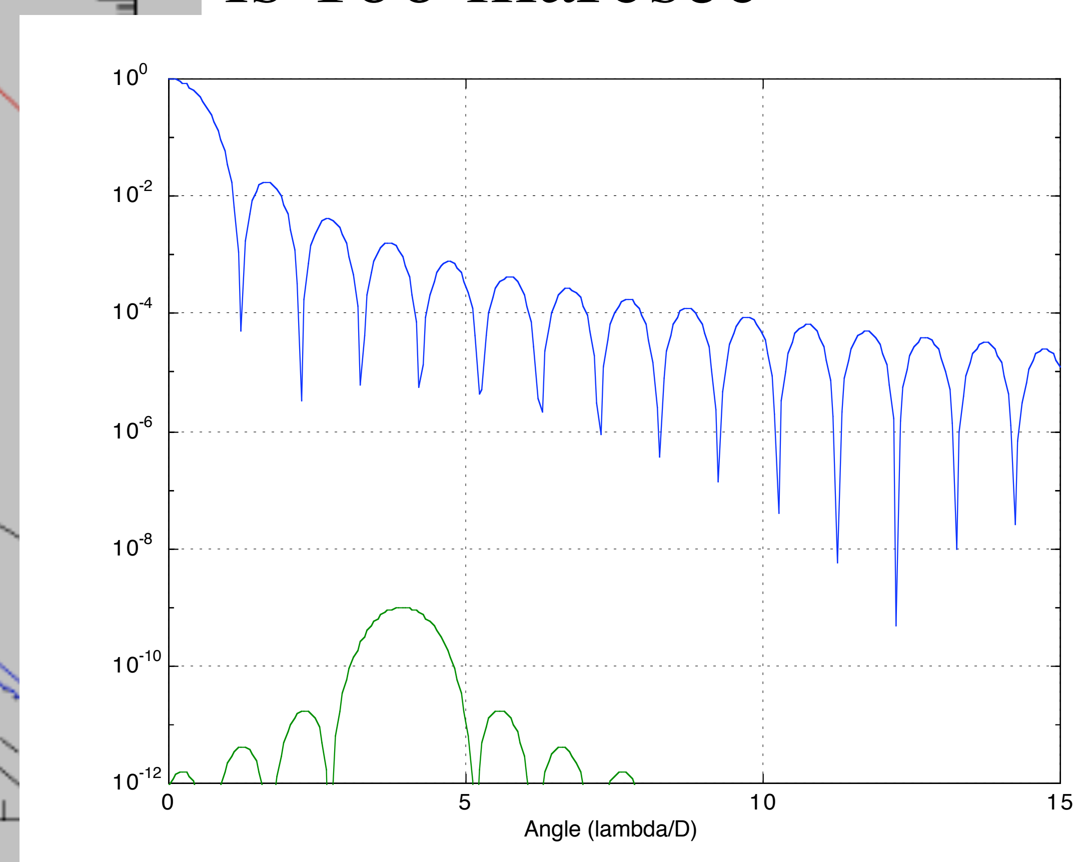
The Contrast Ratio Problem



Traub & Jucks



At 10 pc, angular separation is 100 marcsec

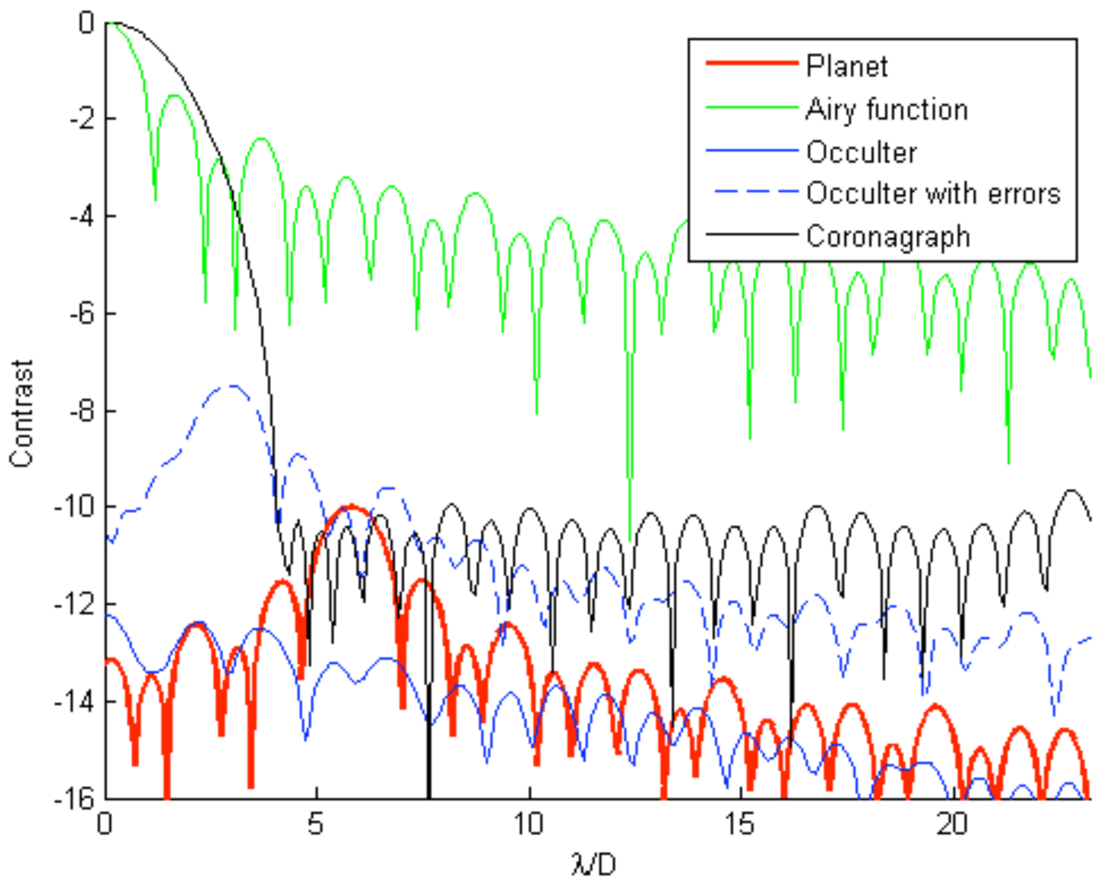


Solution: **Change the optical path of the starlight to create "High Contrast" in final image.**

Solution: Change the optical path of the starlight to create "High Contrast" in final image.

Metrics

- ~~Contrast~~ => Residual Q (planet / background)
- Inner and Outer working angle
- Throughput (absolute and relative)
- Observing Season
- Maximum integration time / Limiting Delta-mag
- Speckle stability
- Zodi Confusion

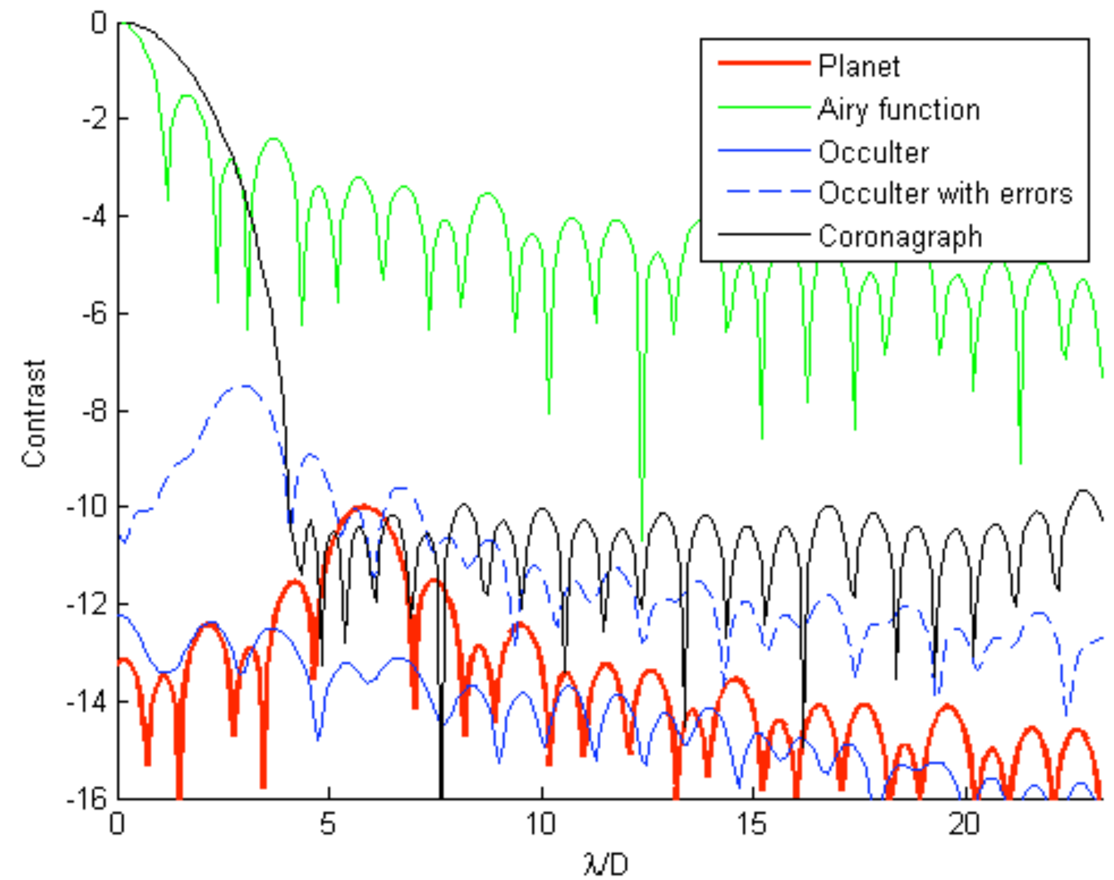


Solution: Change the optical path of the starlight to create "High Contrast" in final image.

Metrics

- ~~Contrast~~ => Residual Q (planet / background)
- Inner and Outer working angle
- Throughput (absolute and relative)
- Observing Season
- Maximum integration time / Limiting Delta-mag
- Speckle stability
- Zodi Confusion

A careful error allocation is necessary to ensure the residual background is comparable to the planet.



Three Classes of Solutions

- Nulling Interferometers
- Internal Coronagraphs
- External Occulters

Internal Coronagraphs

Block starlight or modify PSF internal to telescope

Amplitude in Image Plane

- Lyot coronagraph
- Bandlimited Lyot

Amplitude in Pupil Plane

- Apodized Pupil
- Shaped Pupils
- APLC
- PIAA

Phase in Image Plane

- Four quadrant phase mask
- Vector Vortex coronagraph
- Achromatic interference coronagraph

Phase in Pupil Plane

- Visible nuller

This list is not comprehensive.

Internal Coronagraphs

Block starlight or modify PSF internal to telescope

Amplitude in Image Plane

- Lyot coronagraph
- Bandlimited Lyot

Amplitude in Pupil Plane

- Apodized Pupil
- Shaped Pupils

REMEMBER: It is all about taking a Fourier Transform!

Phase in Image Plane

- Four quadrant phase mask
- Vector Vortex coronagraph
- Achromatic interference coronagraph

Phase in Pupil Plane

- Visible nuller

This list is not comprehensive.

Which means . . .

Which means . . .

You can’t beat the uncertainty principle

Which means . . .

You can't beat the uncertainty principle

which limits your resolution (and inner working angle)

Which means . . .

You can't beat the uncertainty principle

which limits your resolution (and inner working angle)

And it depends upon wavelength

Which means . . .

You can’t beat the uncertainty principle

which limits your resolution (and inner working angle)

And it depends upon wavelength

which limits your bandwidth

Which means . . .

You can't beat the uncertainty principle

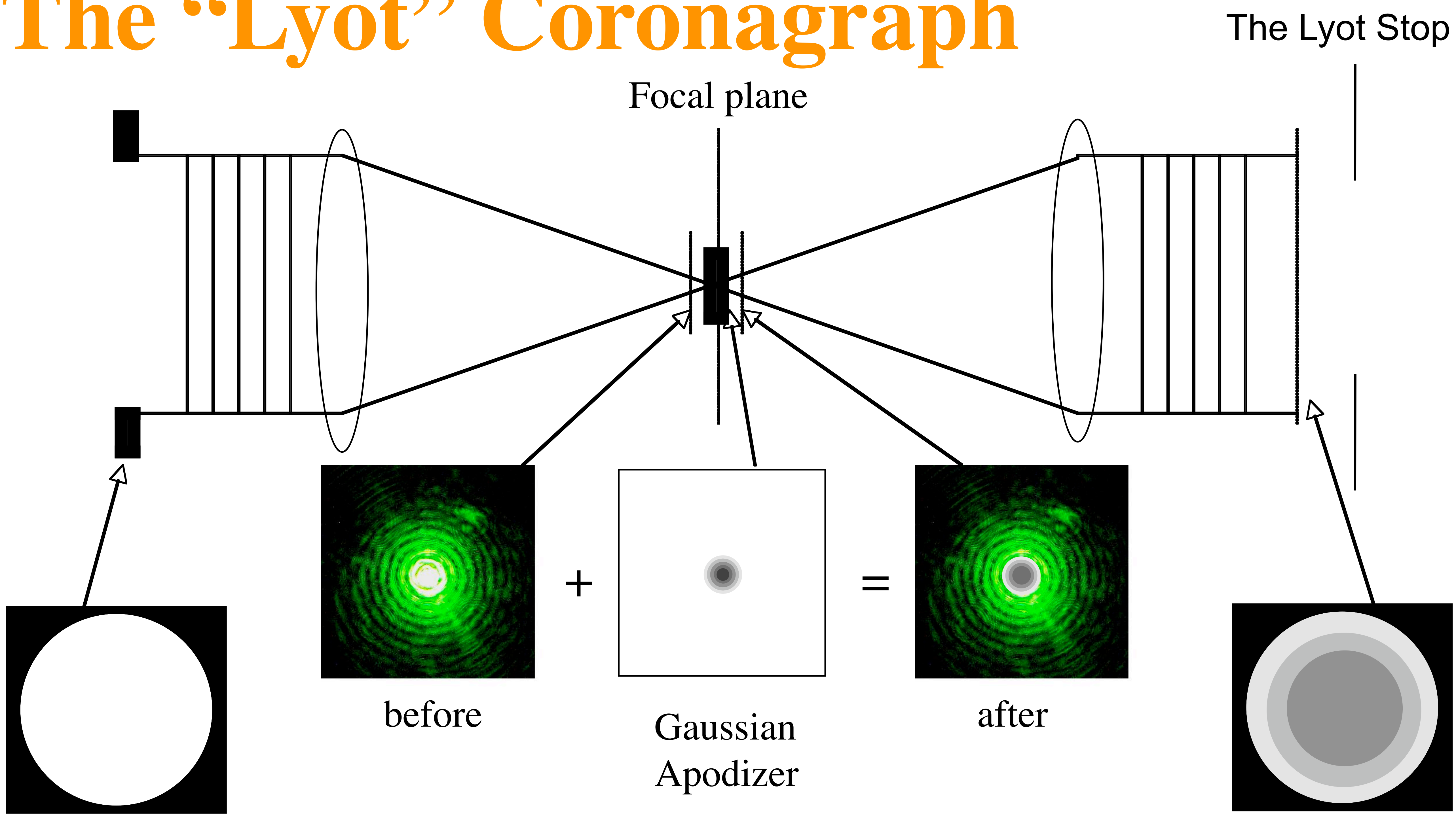
which limits your resolution (and inner working angle)

And it depends upon wavelength

which limits your bandwidth

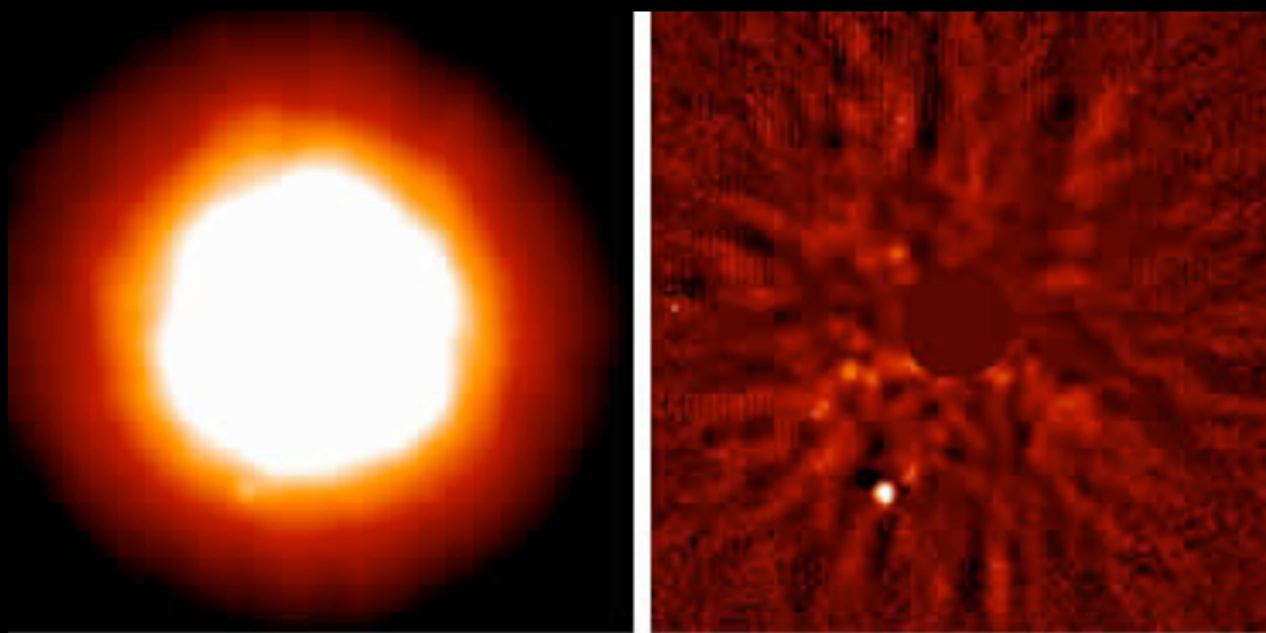
And getting enough photons would be nice!

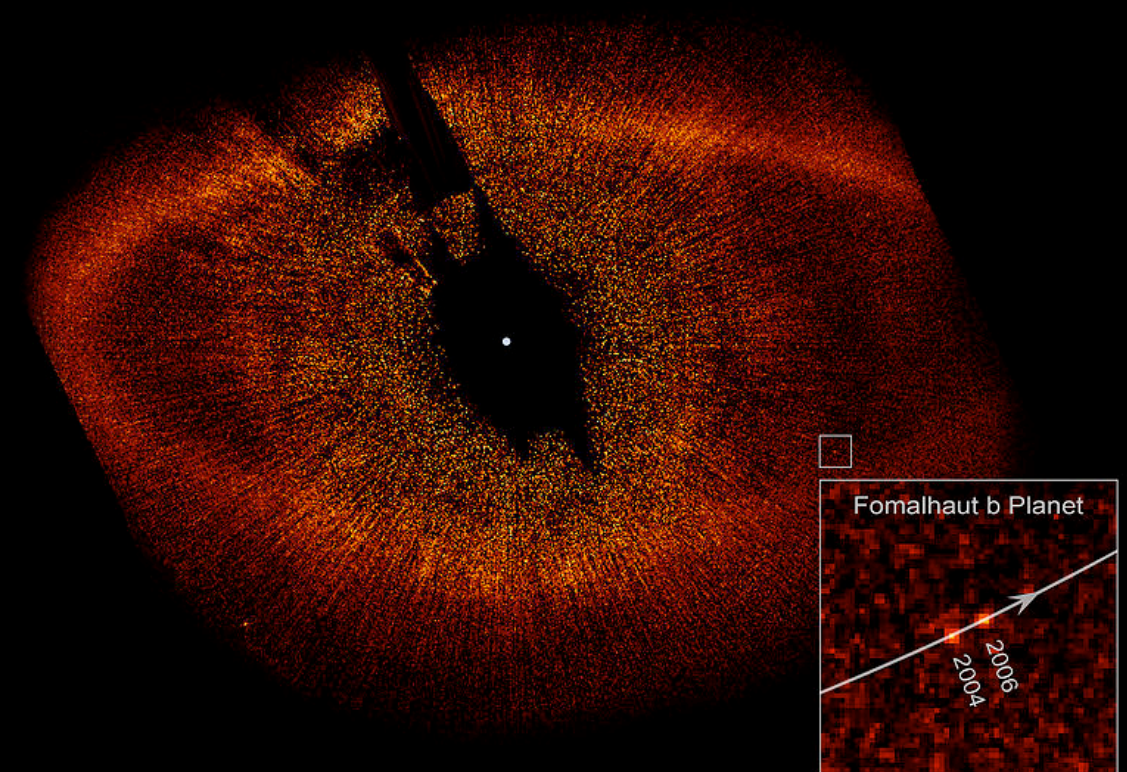
The “Lyot” Coronagraph



The apodizer (field occulter) blocks most of the light from the star

Two Discoveries

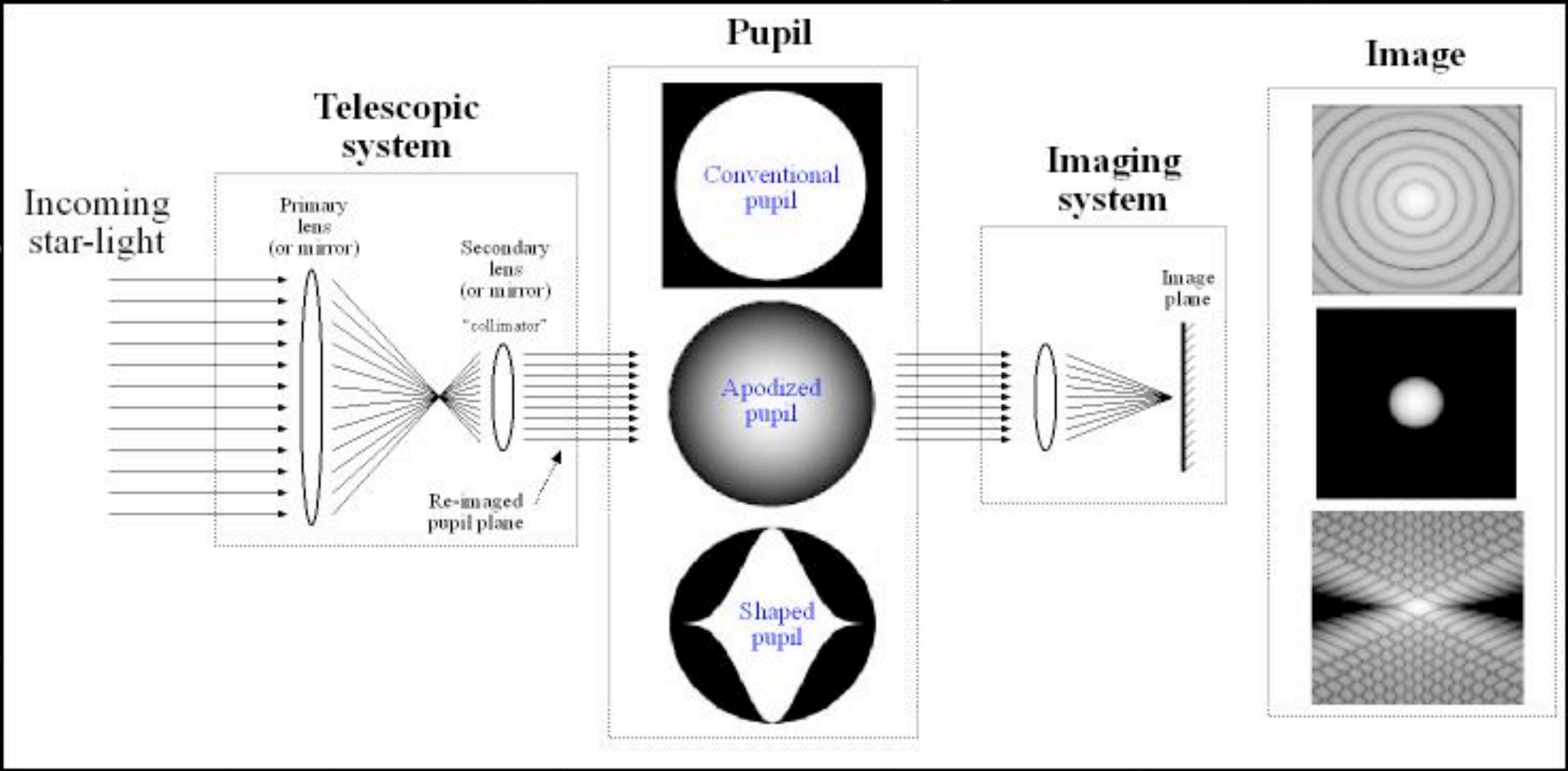




A suspected Brown Dwarf orbiting 15 Sge. Image taken at Gemini Observatory/University of Hawaii

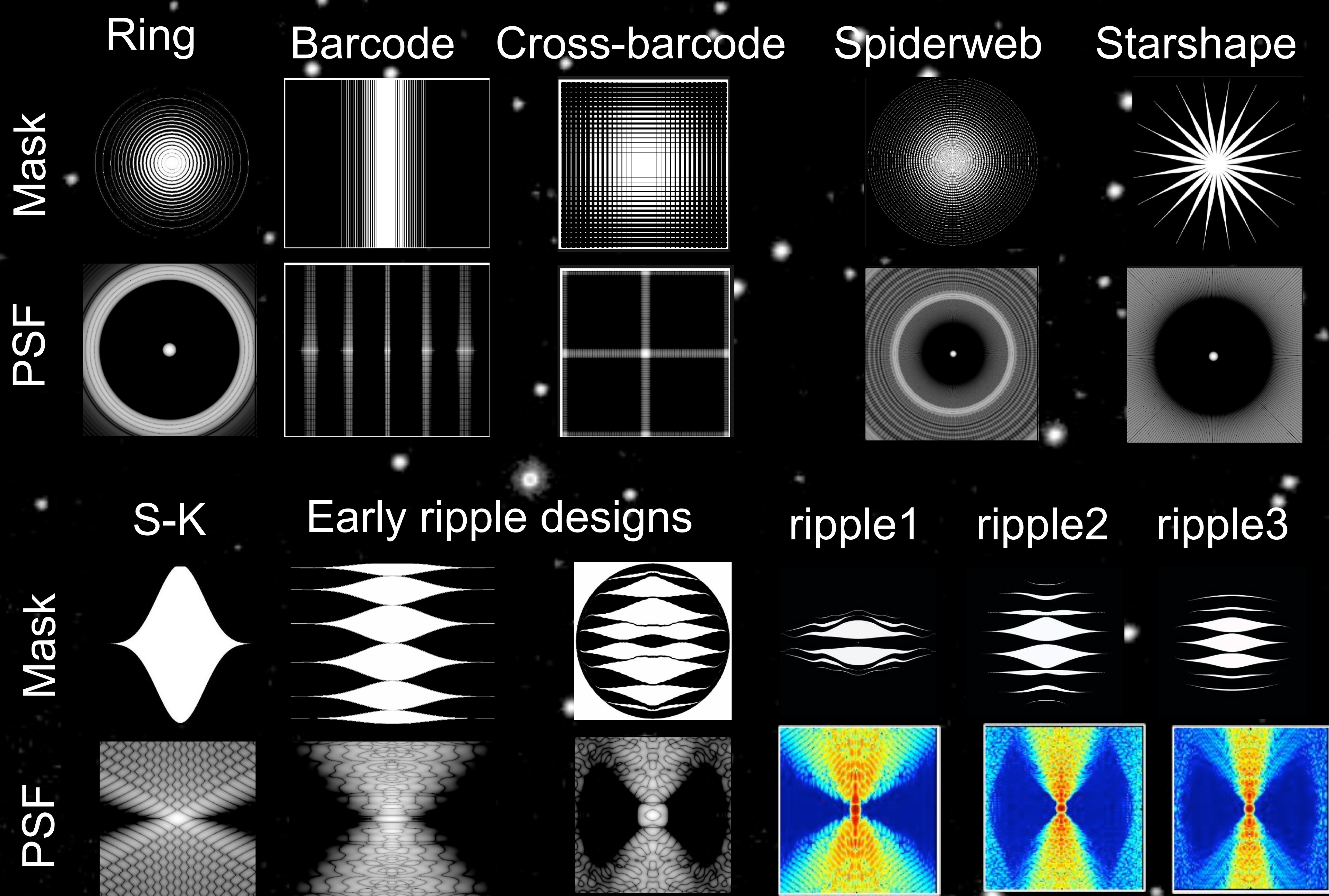
Fomalhaut b, the first imaged planet (taken from the Hubble Space Telescope)

Pupil Apodization to Reshape PSF



$$E(\xi,\zeta) = \int\int e^{i(x\xi + y\zeta)} A(x,y)\,dy\,dx$$

Shaped Pupil Zoo

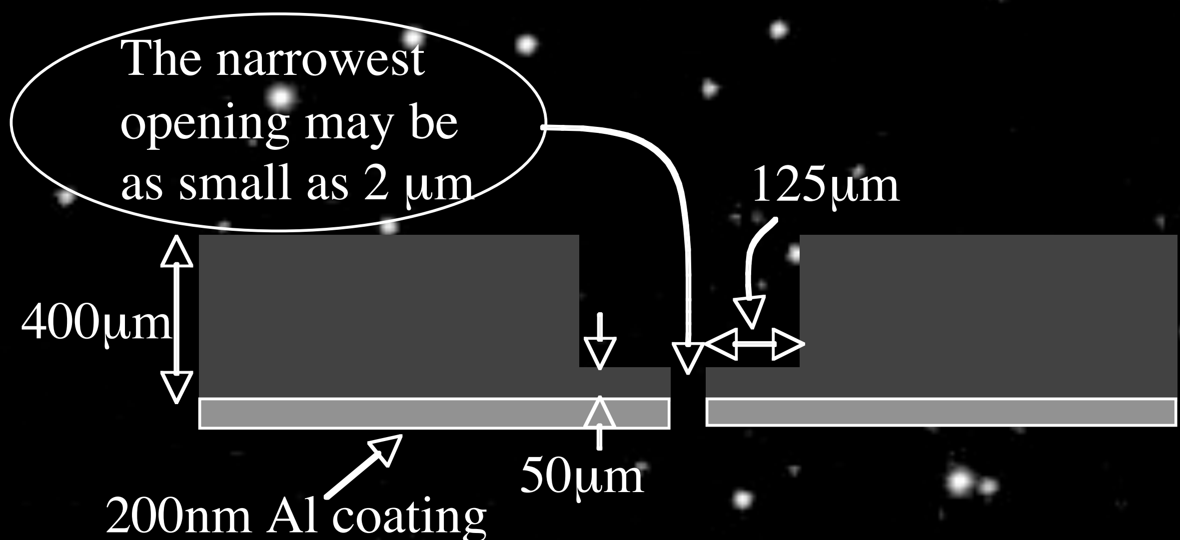


- Shaped pupils: A(x,y) is zero-one valued (holes in masks)
- Advantages:
  - simple to manufacture
  - inherently broadband
  - minimally sensitive to aberrations
  - no off-axis degradation of PSF
- Disadvantages:
  - throughput (though roughly the same as 8th order Lyot coronagraph)
  - IWA (better IWA can be achieved through less discovery space or greater simplicity)

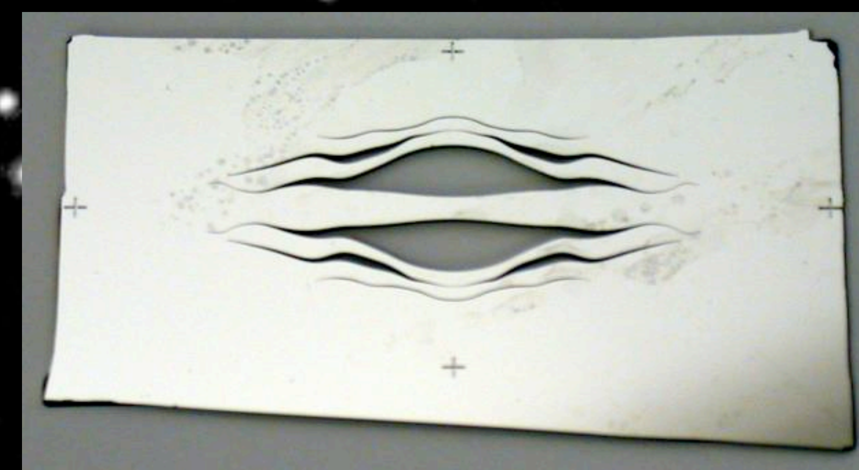
Pupils designed via optimization under certain constraints

One of Ripple1s

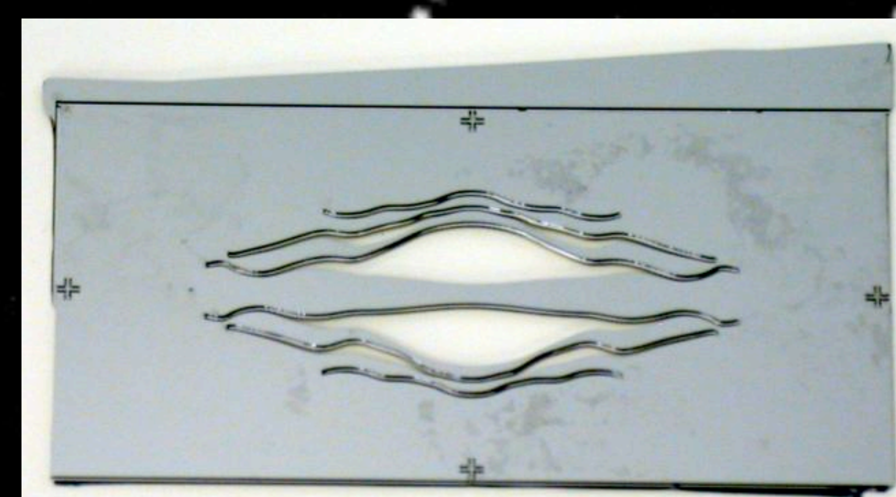
Design



Optical images

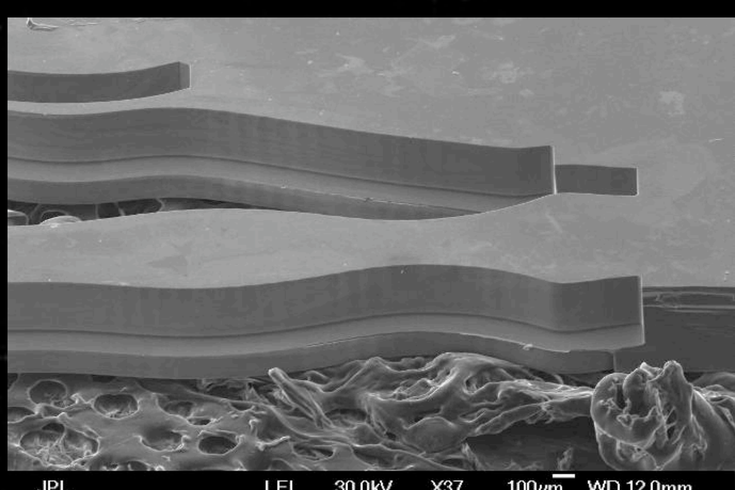


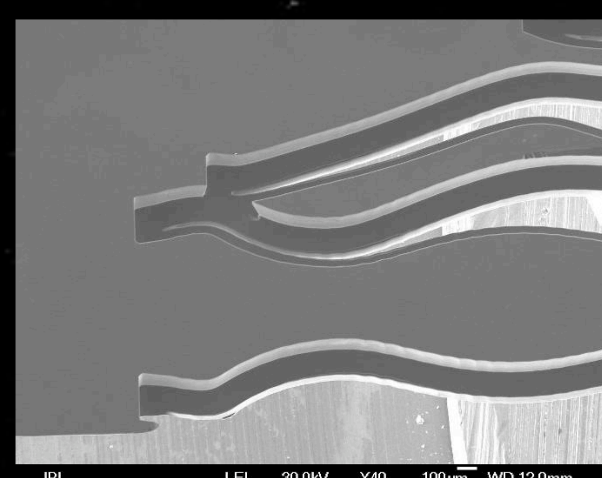
Aluminum coated side



uncoated side

SEM images

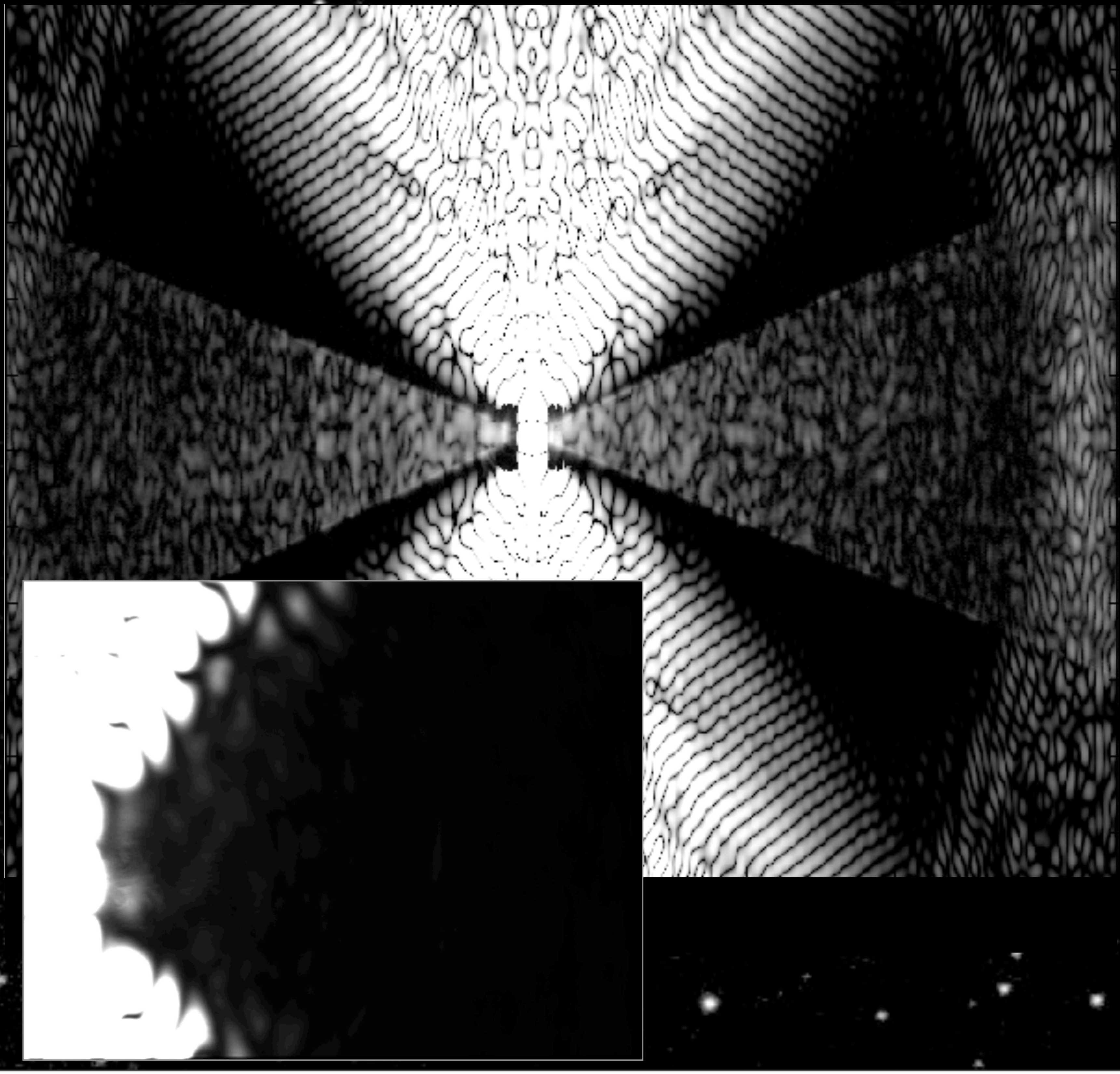


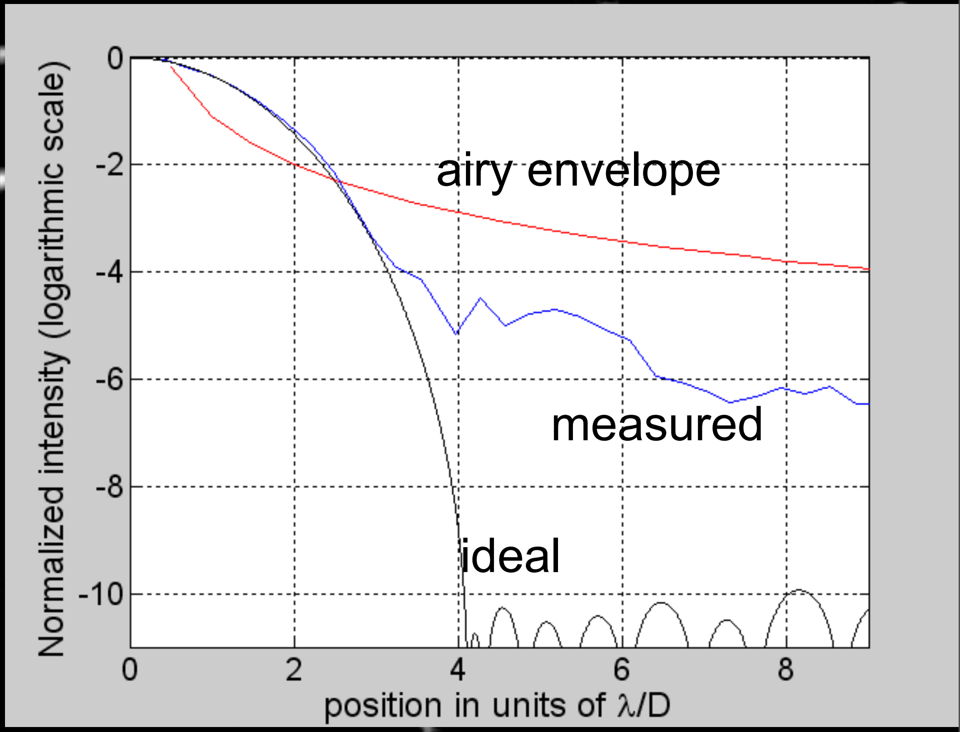


Made via Deep Reactive Ion Etching (DRIE)

Courtesy of K. Balasubramanian (6265-130)

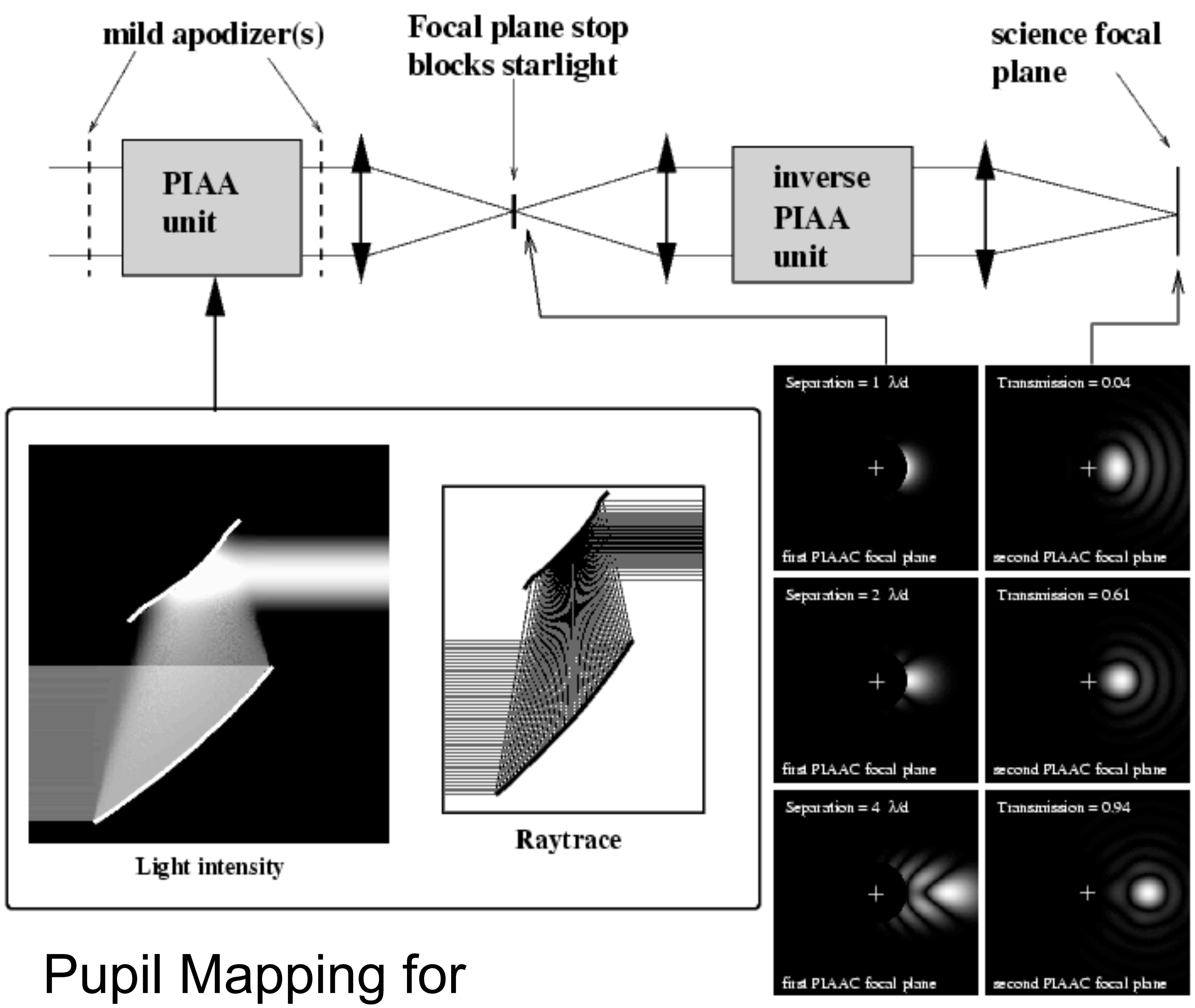
Contrast Measurement at 633nm





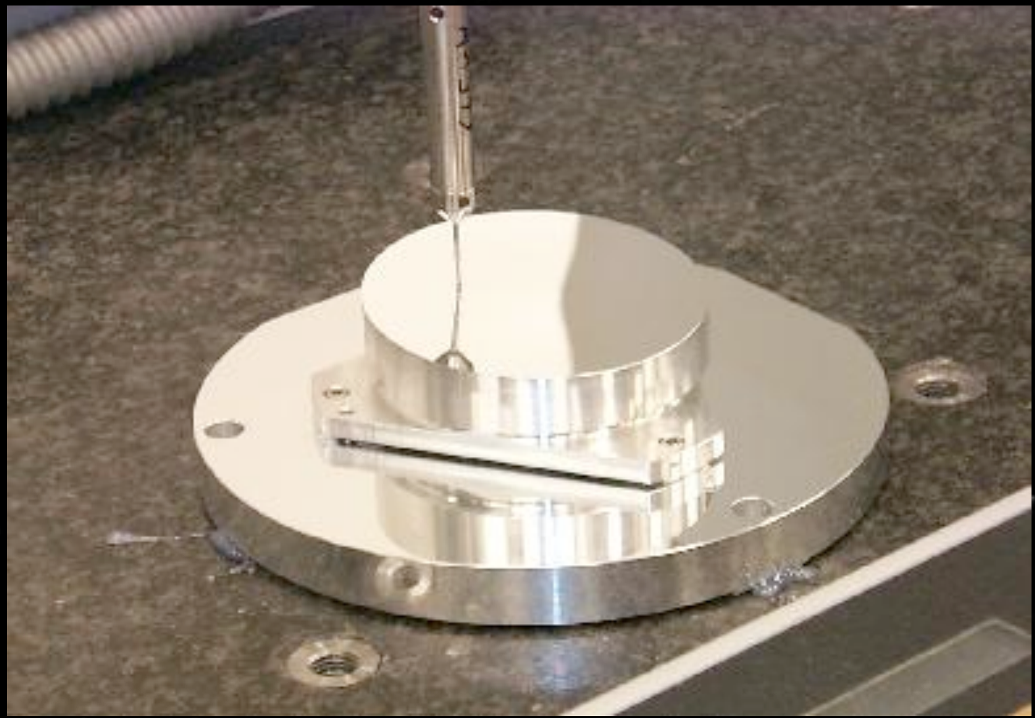
- Contrast:
  - ~10^{-5} @ 4 λ/D
  - <10^{-6} @ 7 λ/D

Phase Induced Amplitude Apodization (PIAA)

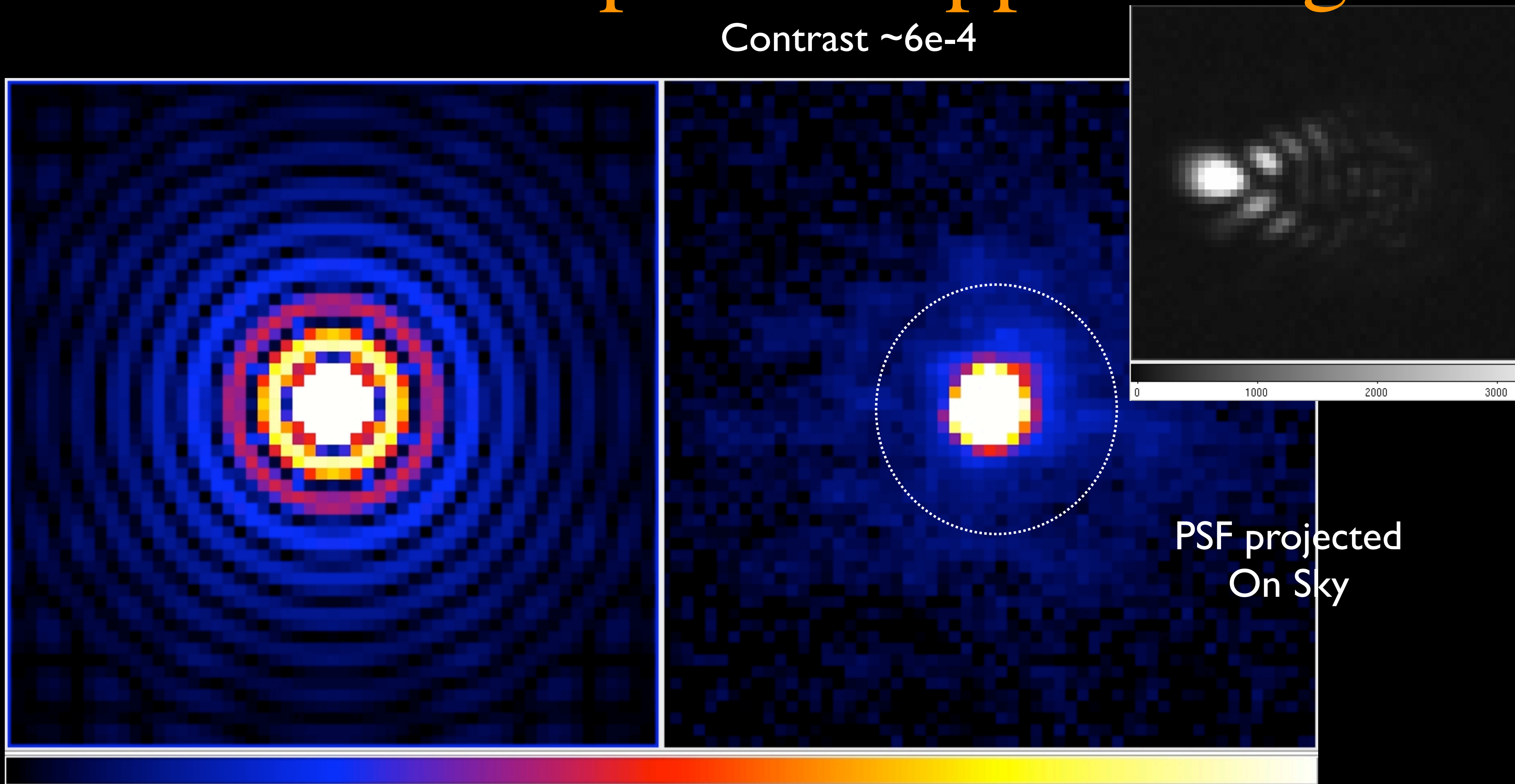


Pupil Mapping for Apodization

Nearly 100% throughput
100% search area
small (<2 lambda/d) Inner Working Angle



Uncorrected Pupil Remapped Image

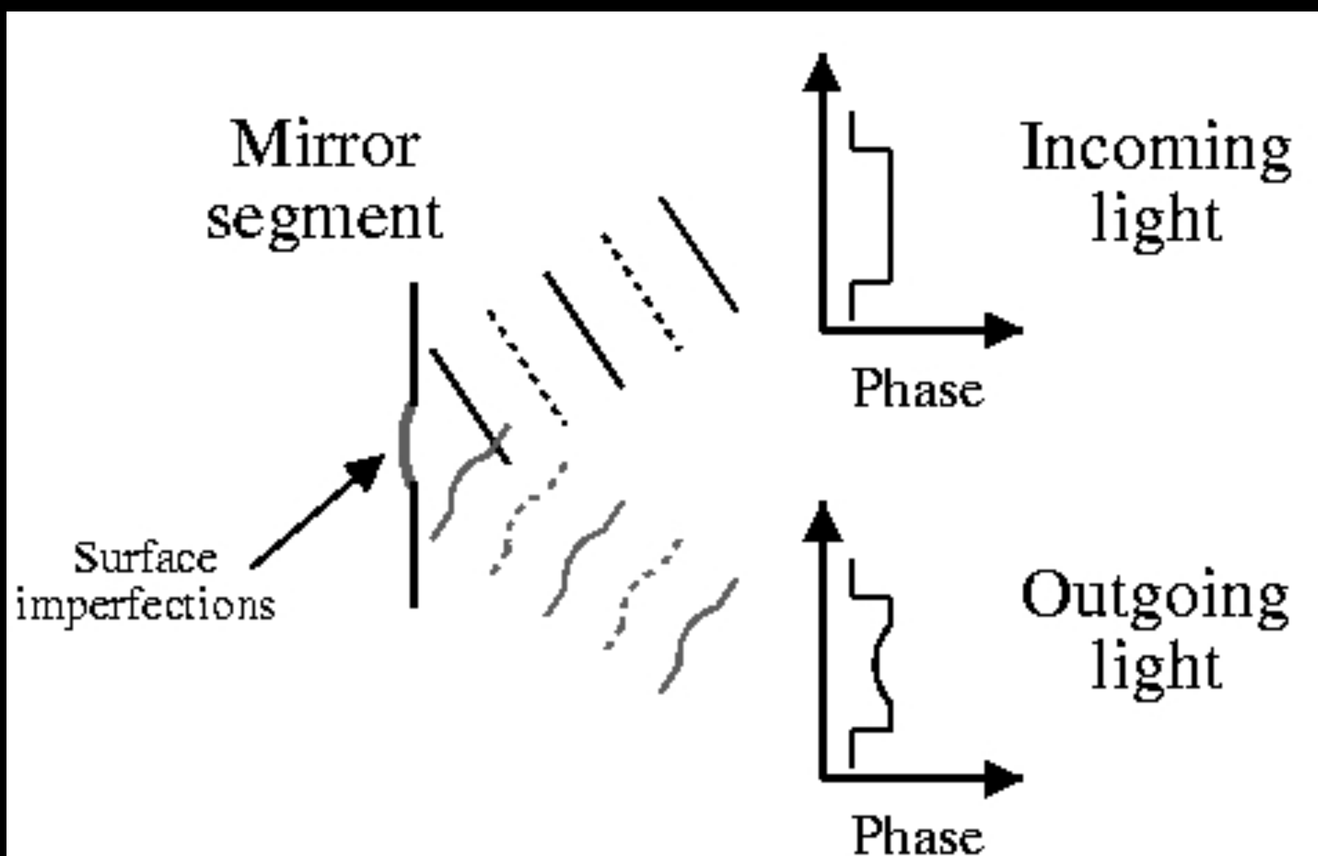


Conventional image (computed)

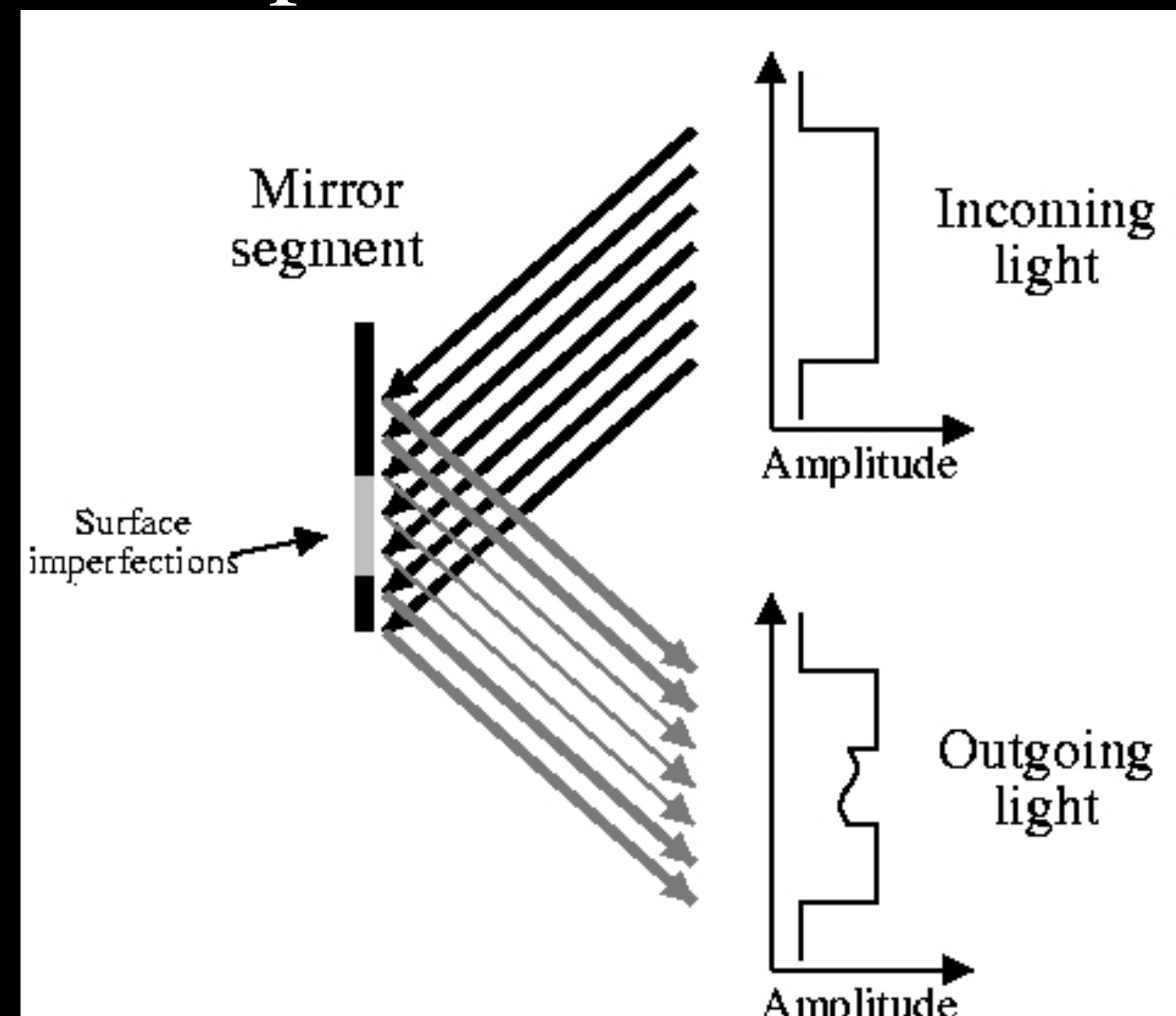
PIAA image (obtained in the lab). White circle shows the area of the image that would be lost if we had done our apodization with a mask.

What is the biggest problem?
Wavefront Error

Phase Aberrations



Amplitude Aberrations



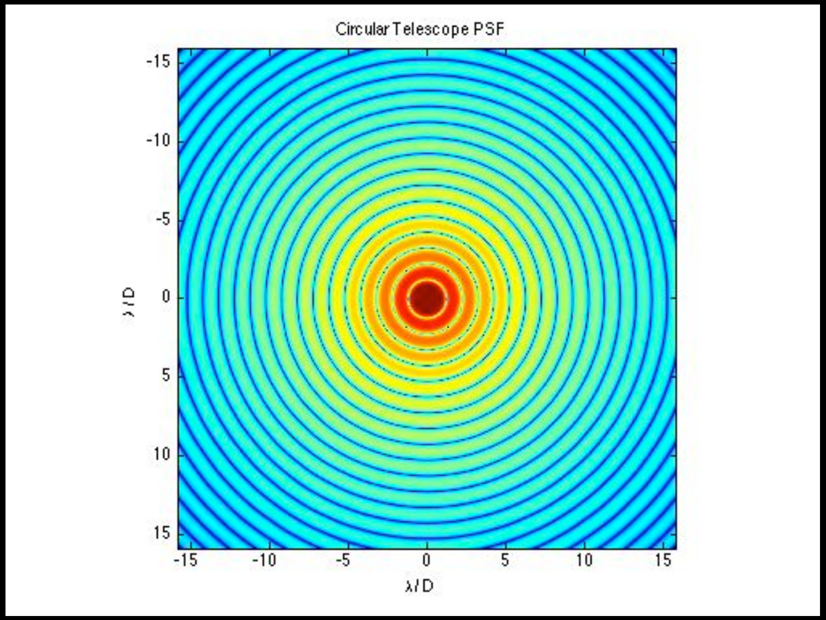
$$I(\xi,\eta) = \left| \mathcal{F}\left\{ [1-\beta(x,y)]\, A(x,y) e^{i\phi(x,y)} \right\} \right|^2$$

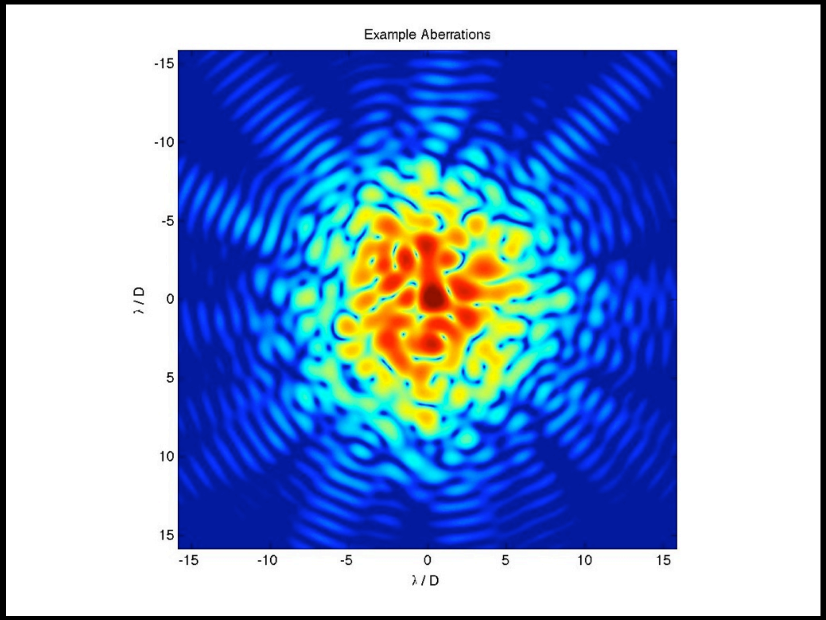
Amplitude aberration: $[1-\beta(x,y)]$

Phase aberration: $e^{i\phi(x,y)}$

What is the biggest problem?
Wavefront Error

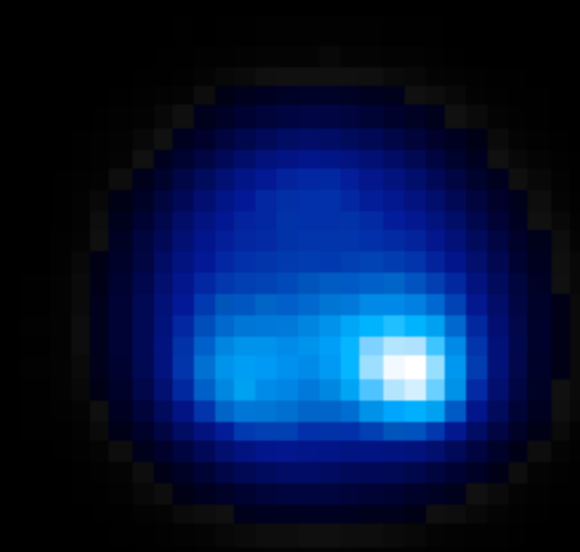
Effects of the Atmosphere





Because of the atmosphere, big telescopes don't resolve any better than small ones!

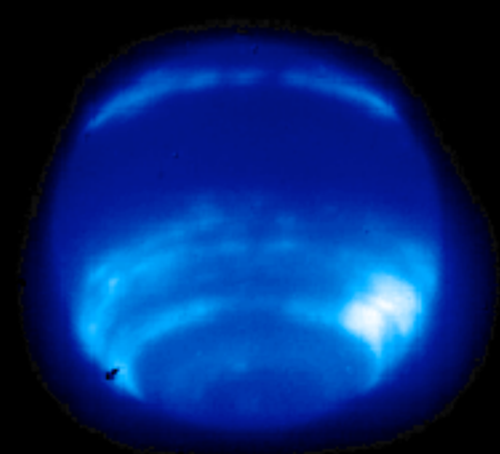
Current & Future Ground Telescopes use AO



Without Adaptive Optics

Neptune

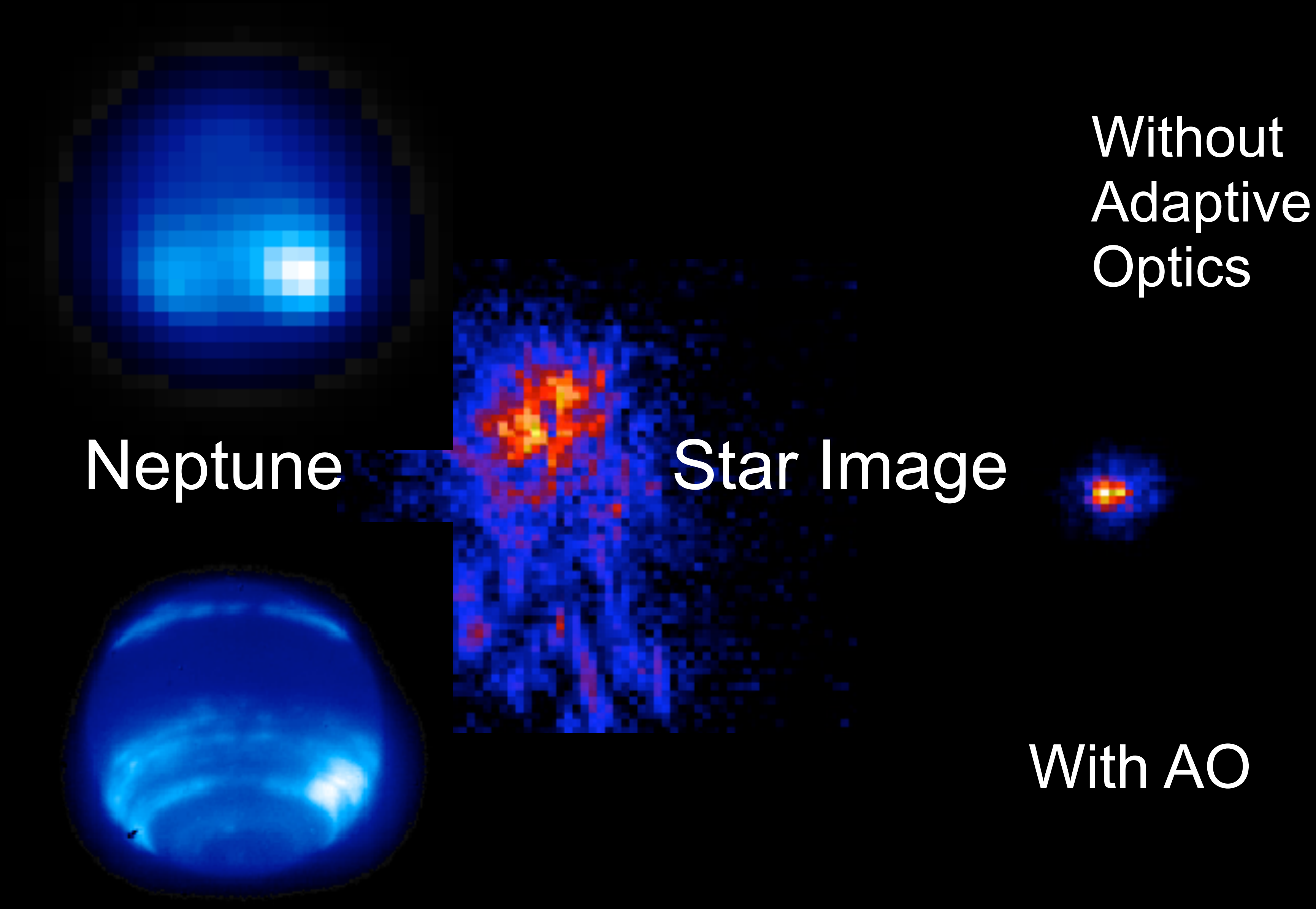
Star Image



With AO

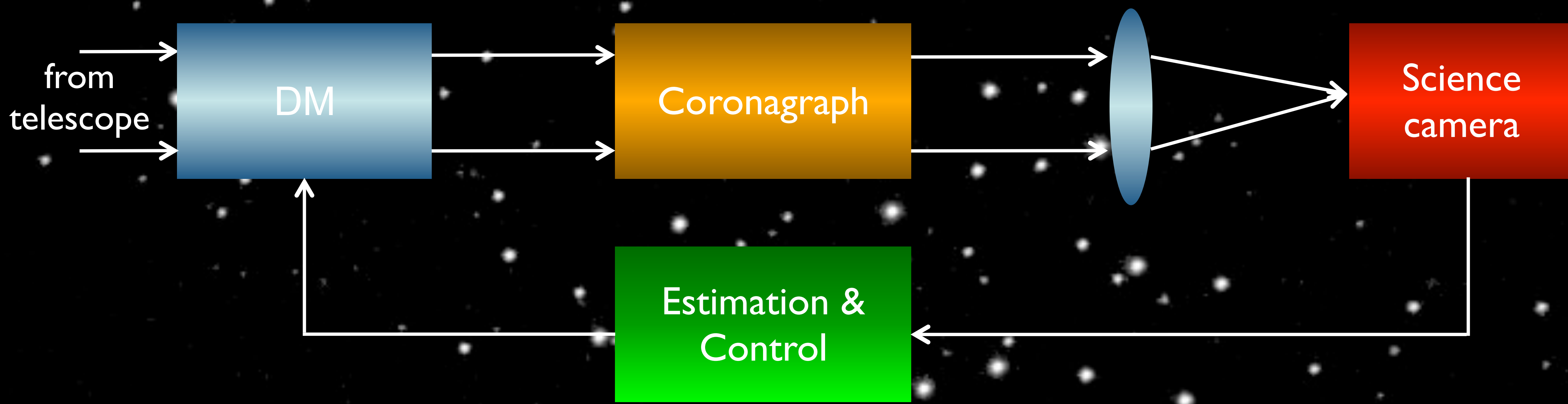
Images and Video from UC Santa Cruz Adaptive Optics course.

Current & Future Ground Telescopes use AO



Images and Video from UC Santa Cruz Adaptive Optics course.

Wavefront Control

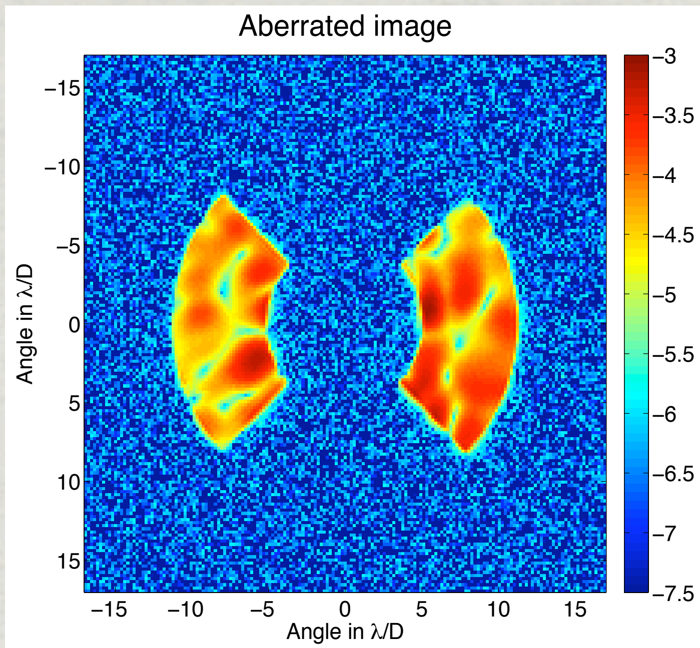


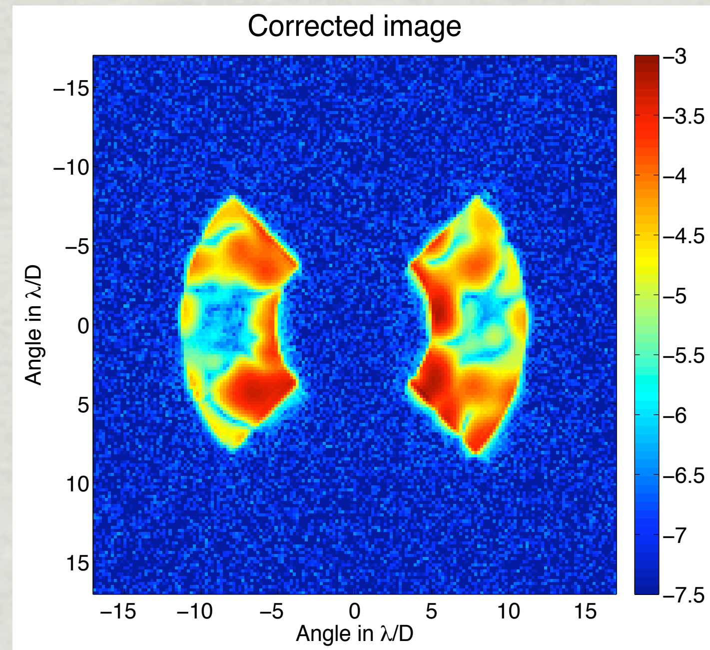
Control Algorithms:
Speckle Nulling
Energy Minimization
Electric Field Conjugation
Stroke Minimization

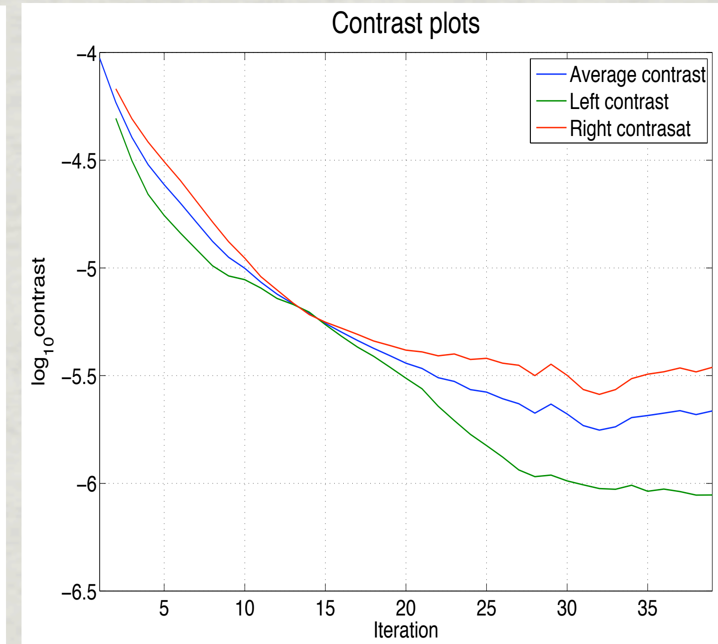
Estimation Algorithms:
DM Diversity
Gerchberg-Saxton

Experimental Results: Symmetric Dark Holes

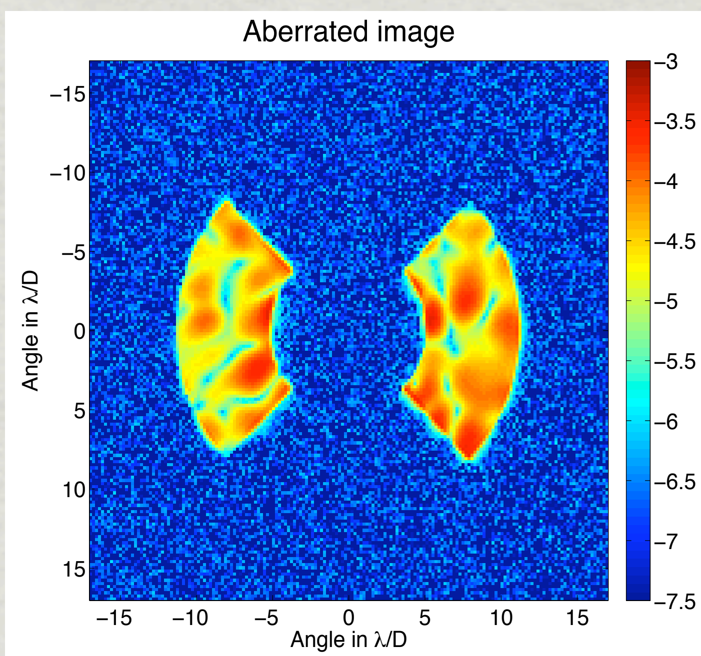
DM Diversity:

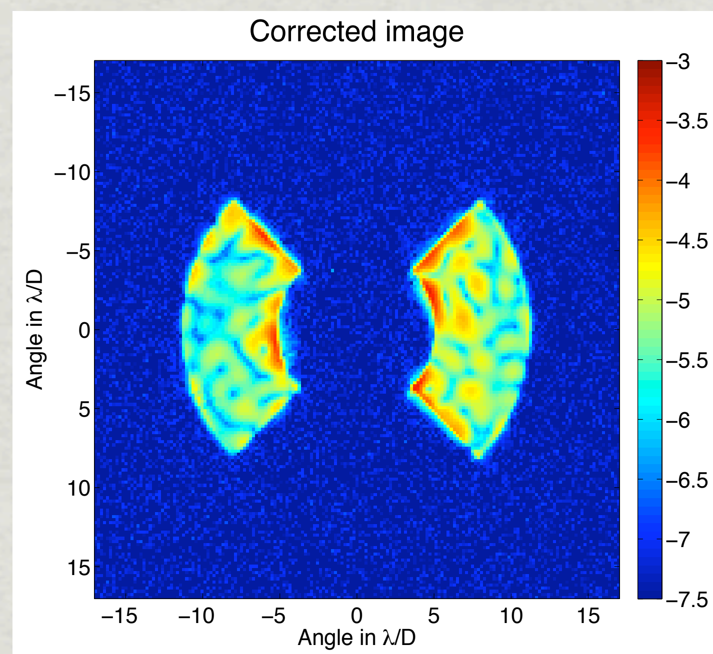


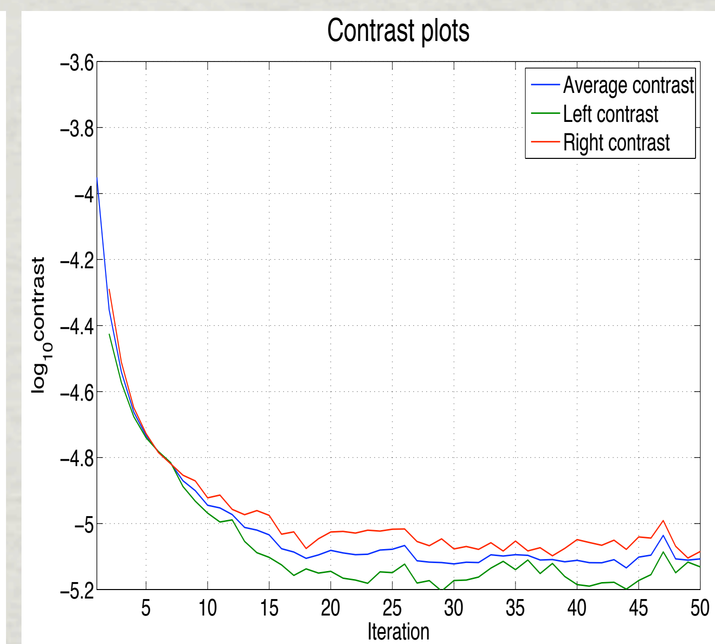




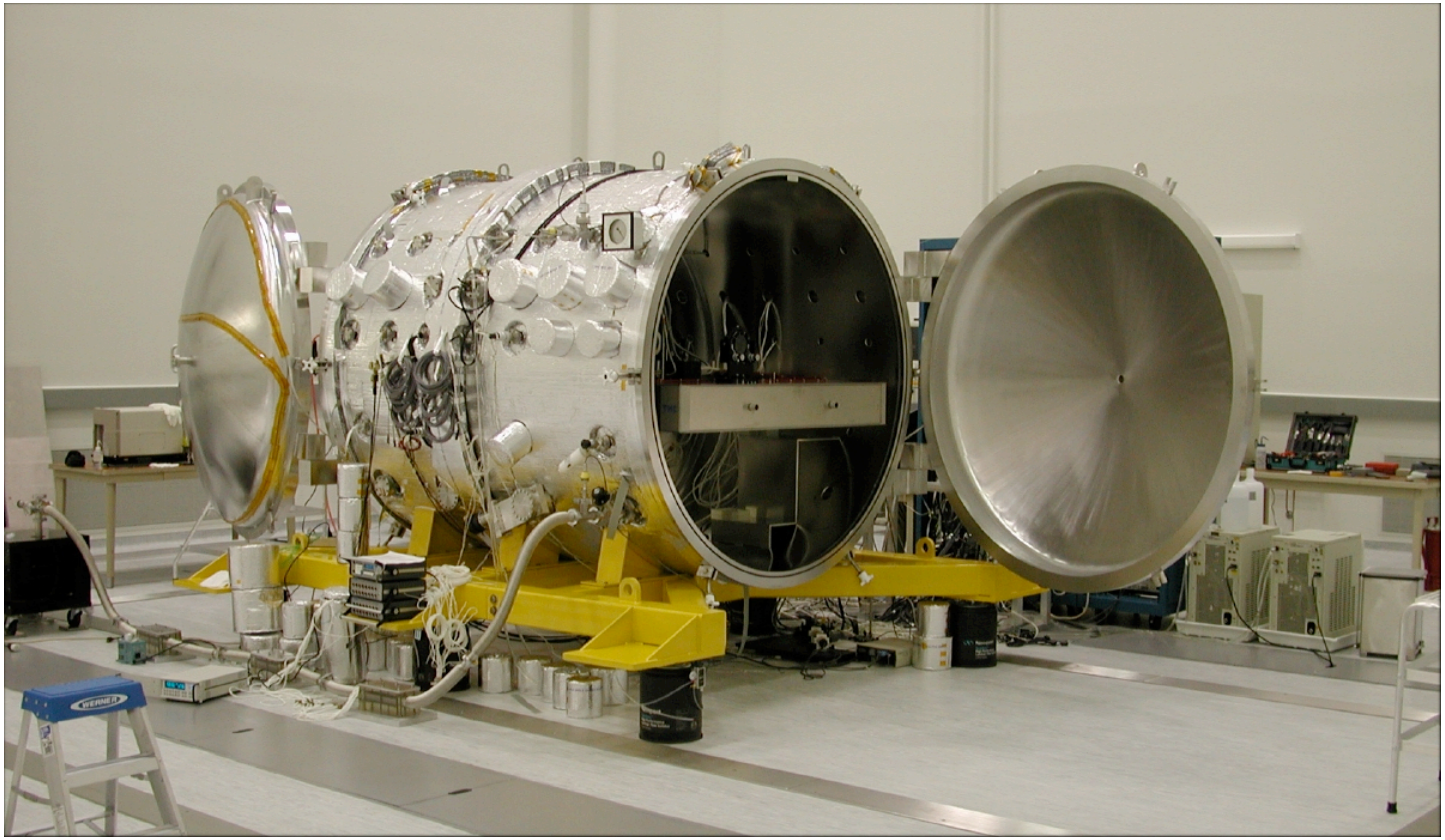
Two-Camera:



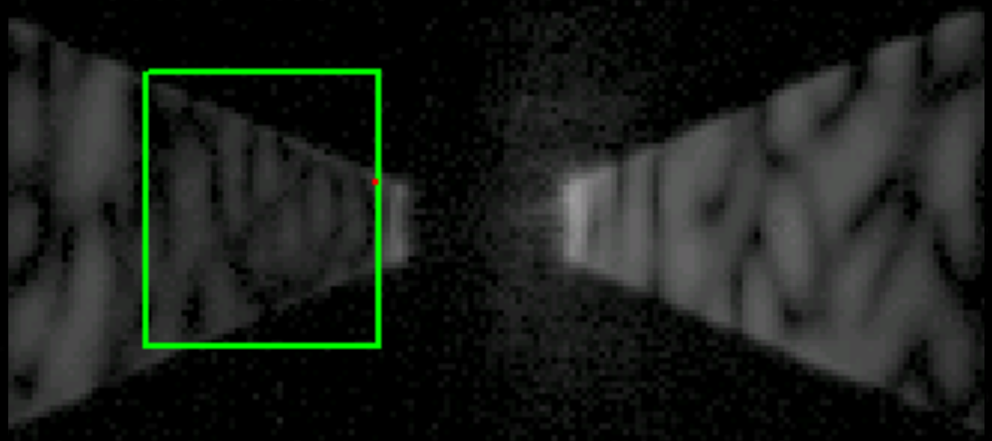


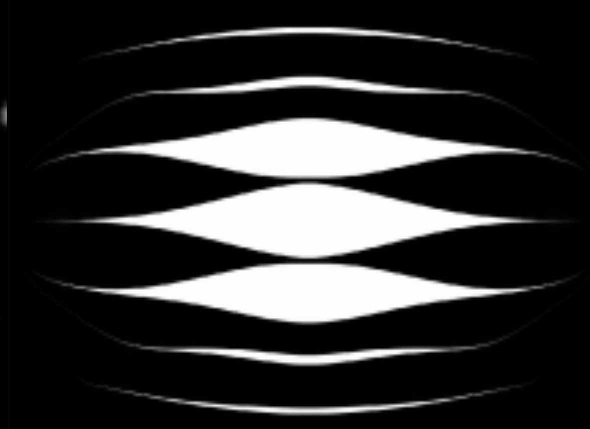


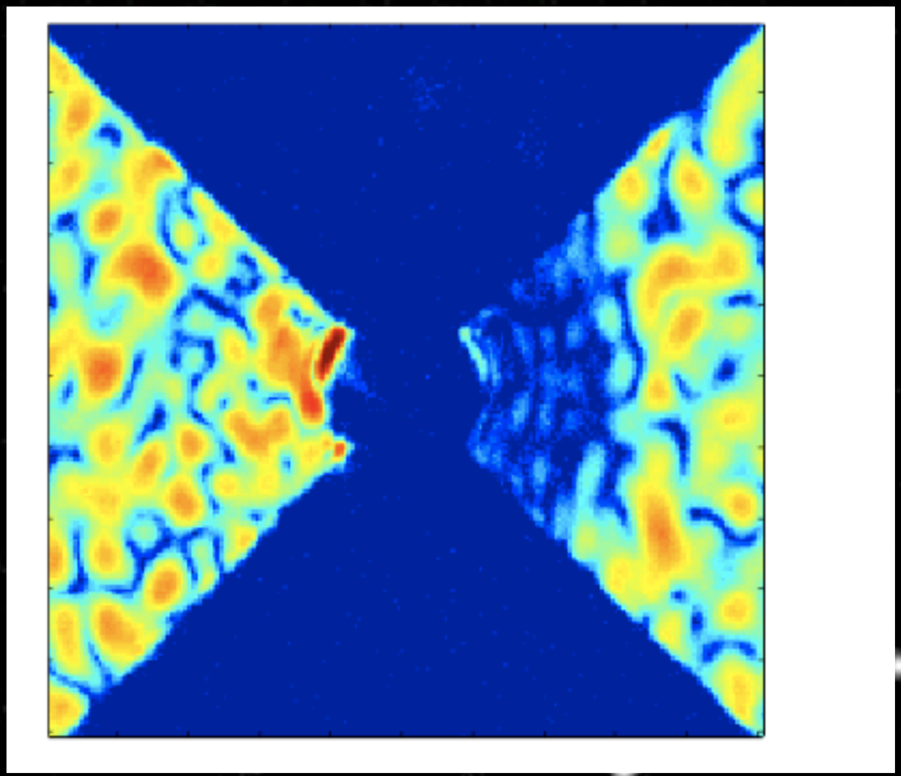
All four coronagraph types have been tested in JPL's High Contrast Imaging Testbed

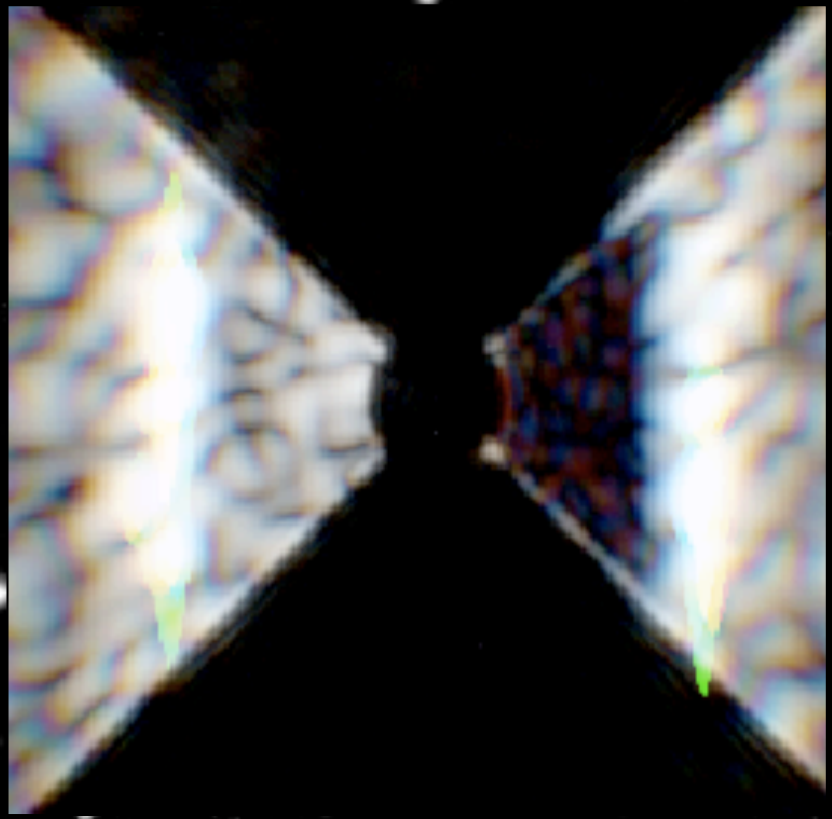


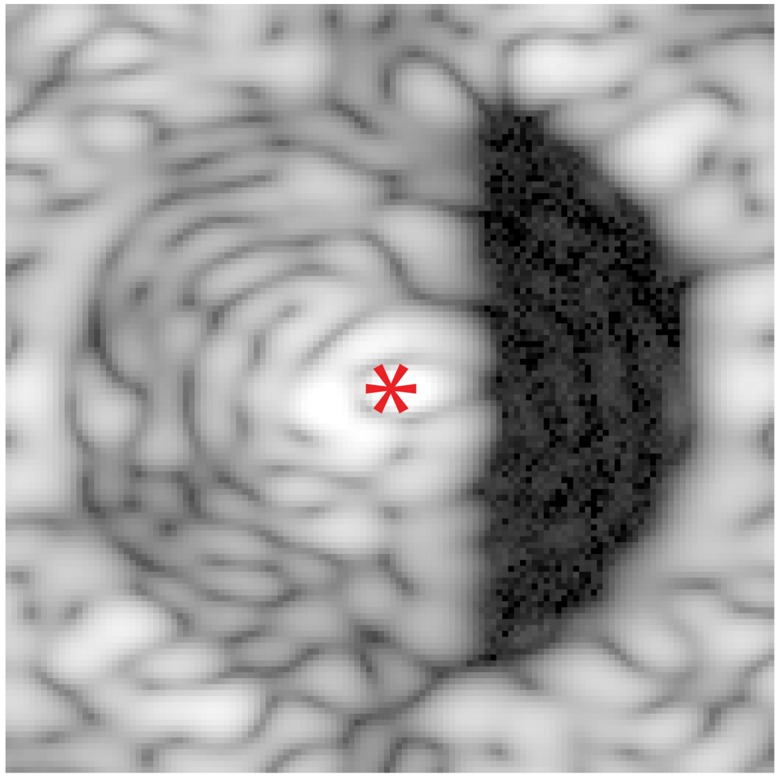
Shaped Pupil Experiments



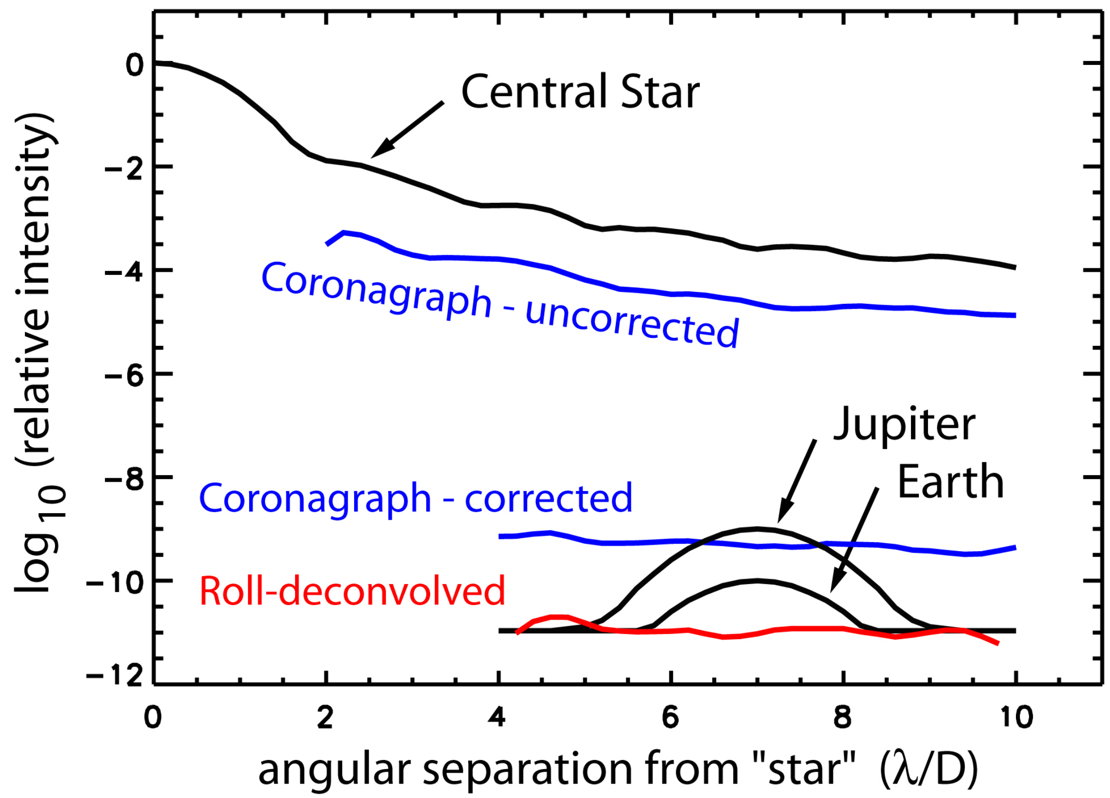




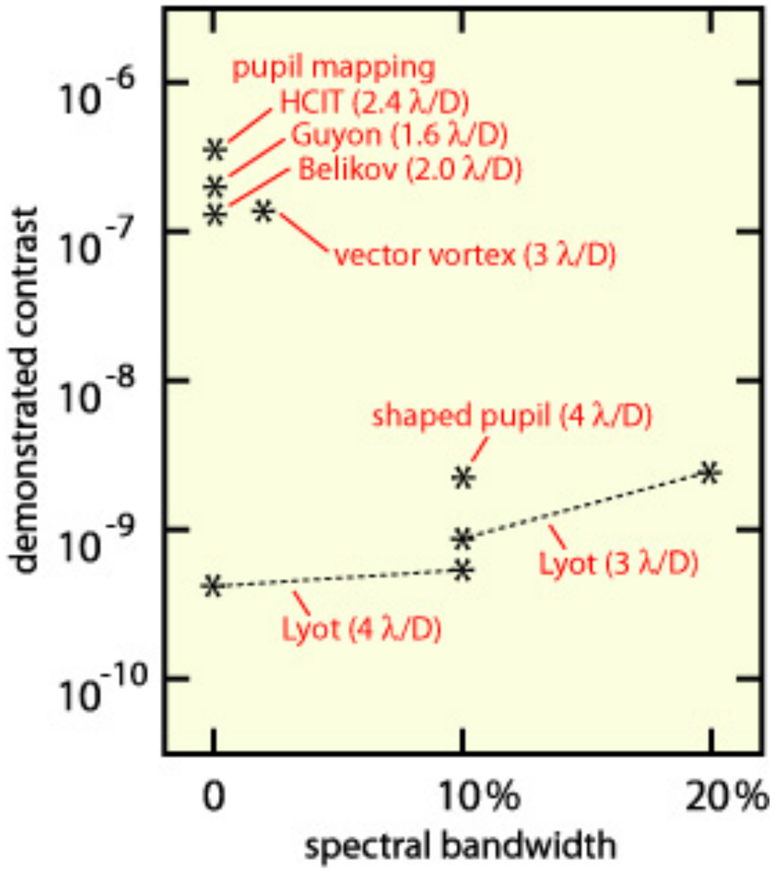




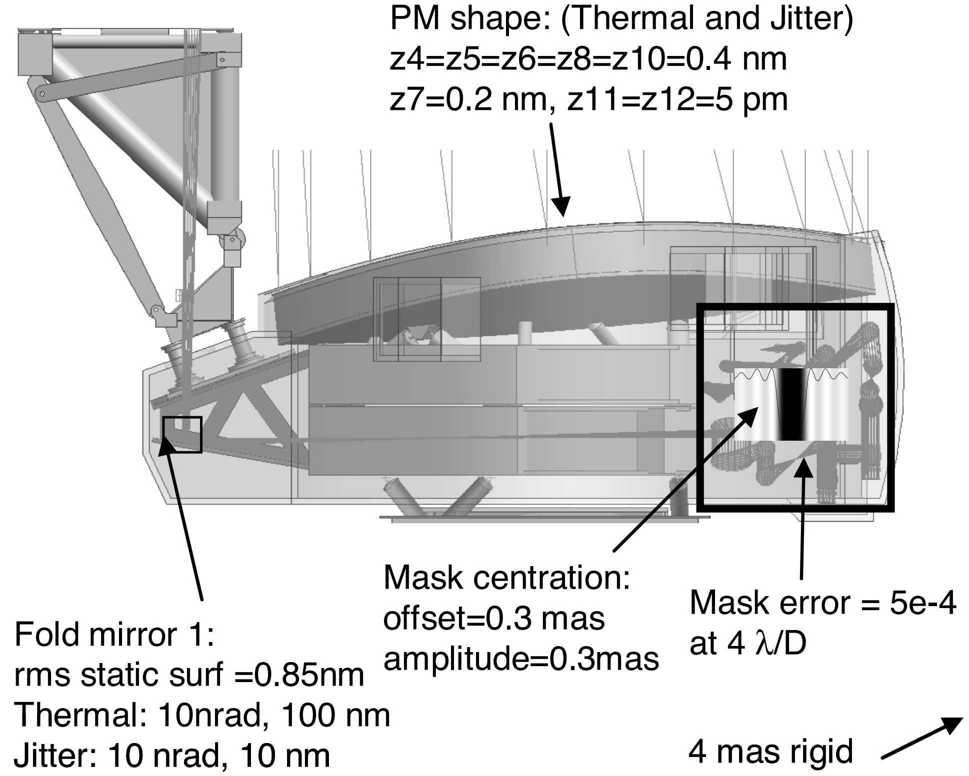
Bandlimited Lyot

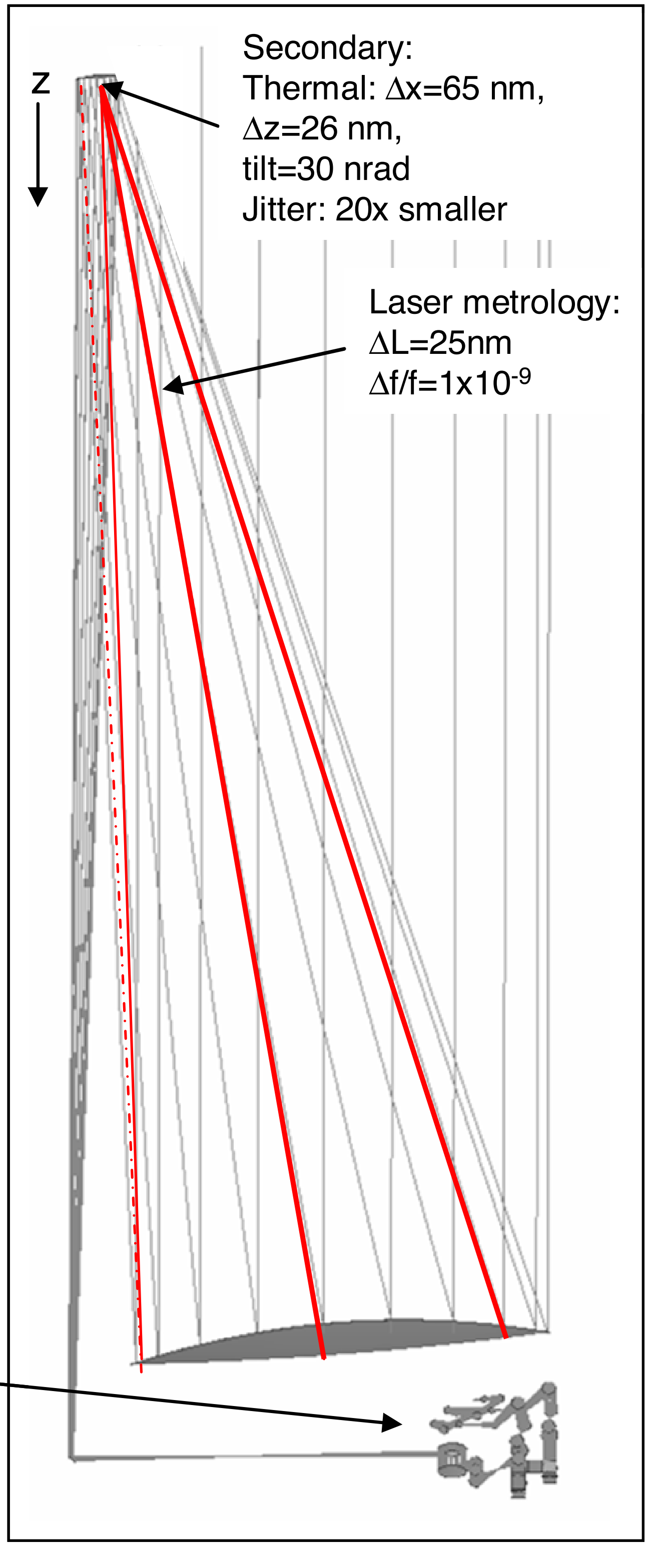


Four coronagraph types have been tested at HCIT



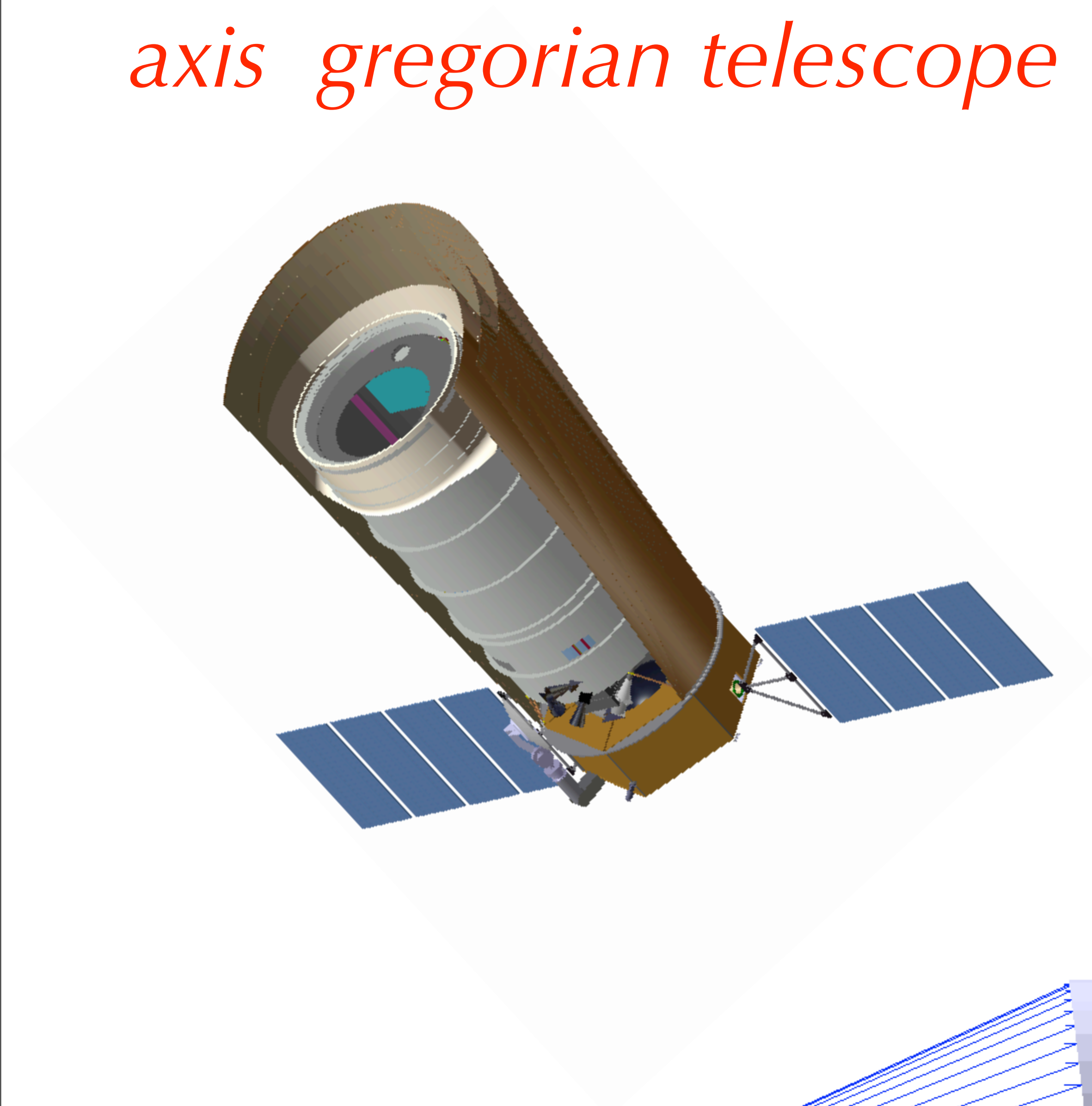
Coronagraph Requirement Allocation

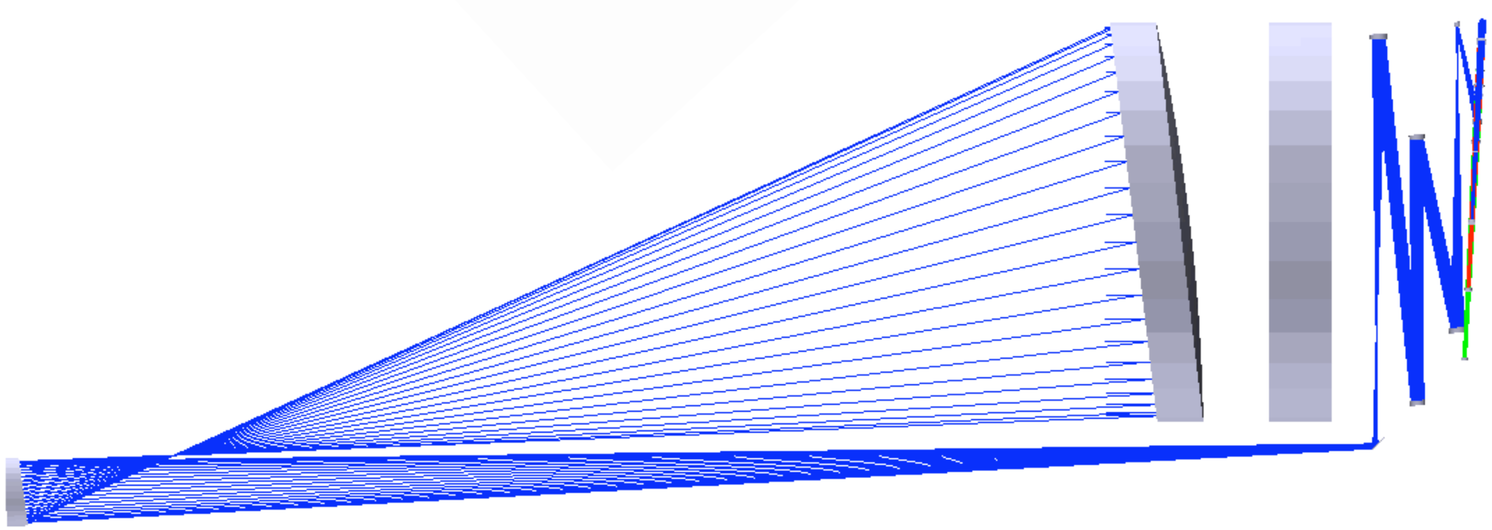




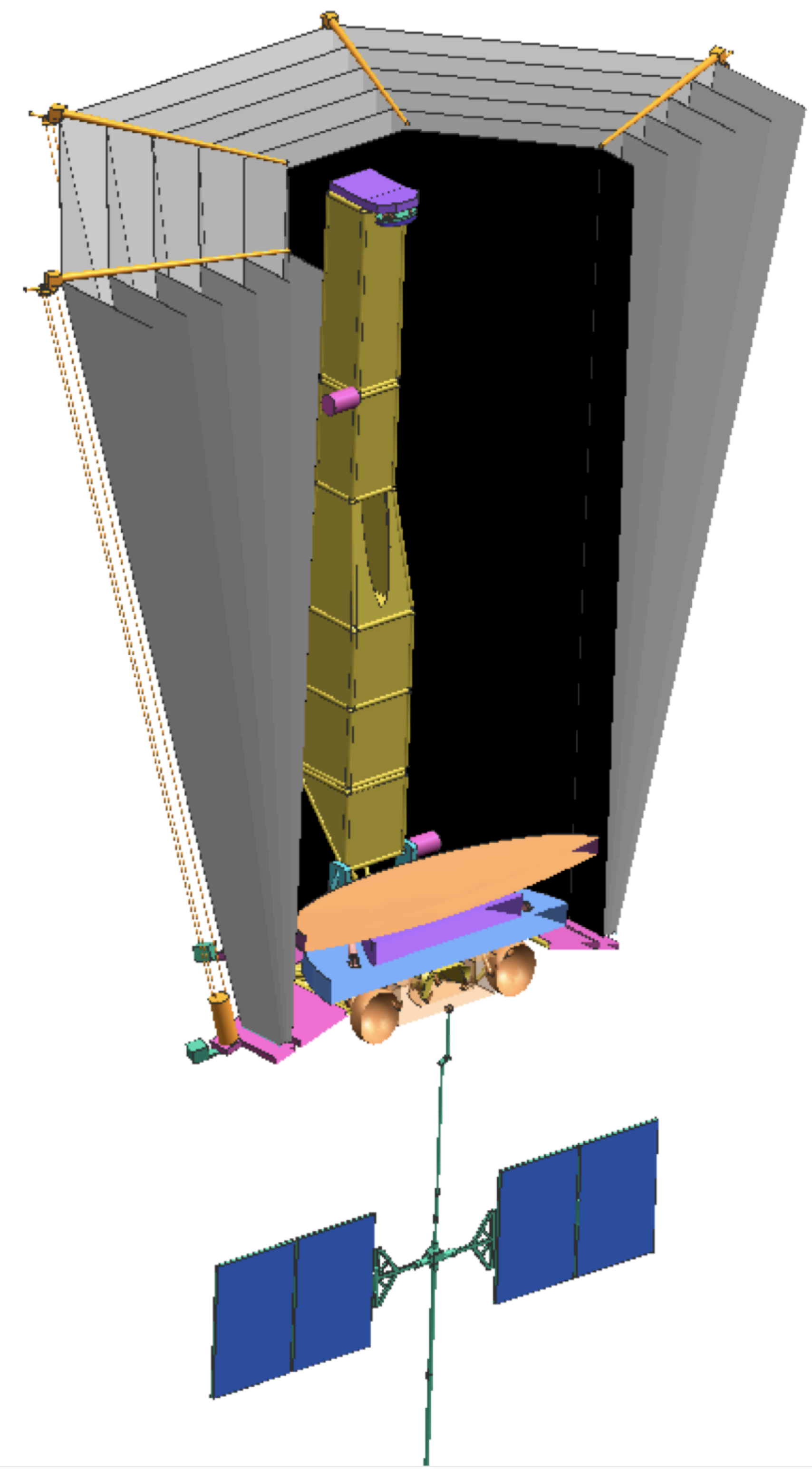
Perturbation	Contributor	Nature	Contrast	Fraction
Structural Defomation	Beam Walk	Thermal	8.29E-13	16.12%
		Jitter	6.33E-13	12.31%
	Aberrations	Thermal	3.28E-14	0.64%
		Jitter	4.43E-17	0.00%
Bending of Optics	Aberrations	Thermal	8.60E-13	16.72%
		Jitter	8.60E-13	16.72%
Pointing	Beam Walk		1.29E-12	25.10%
	Image Motion		9.04E-14	1.76%
	Mask Error		5.46E-13	10.63%
SUM			5.14E-12	

ACCESS observatory:
1.5 meter - unobscured off-axis gregorian telescope



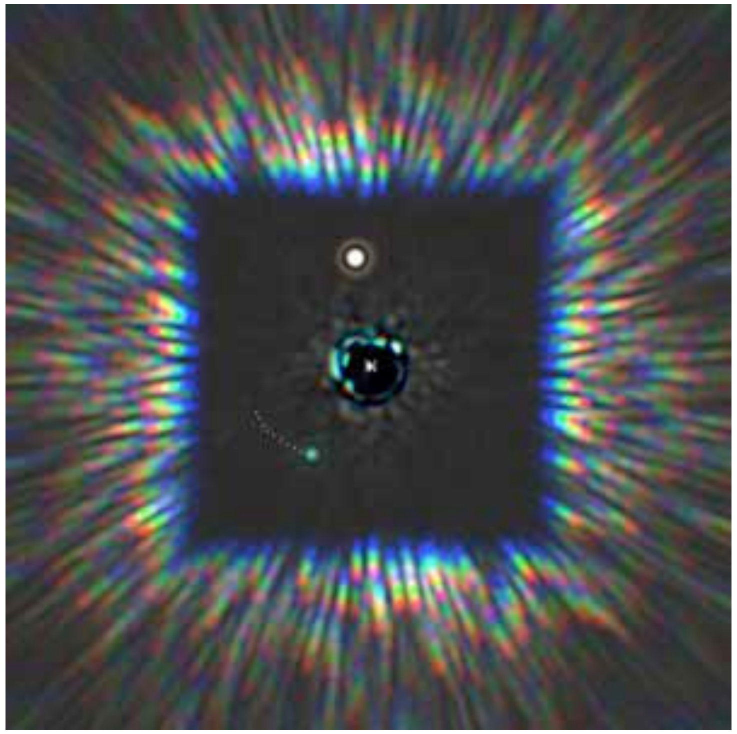


TPF-C:
8 meter - unobscured, eliptical off-axis telescope



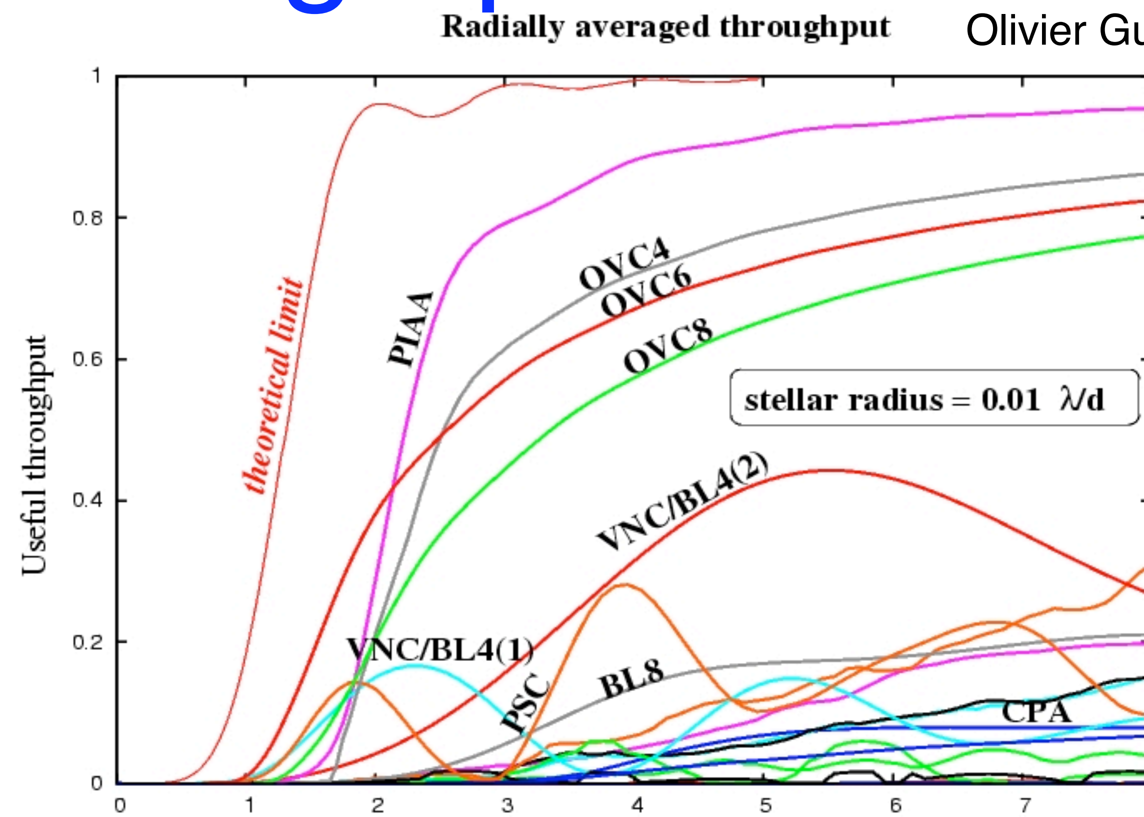
Internal Coronagraphs

Christian Marois



Simulated GPI Image

Olivier Guyon

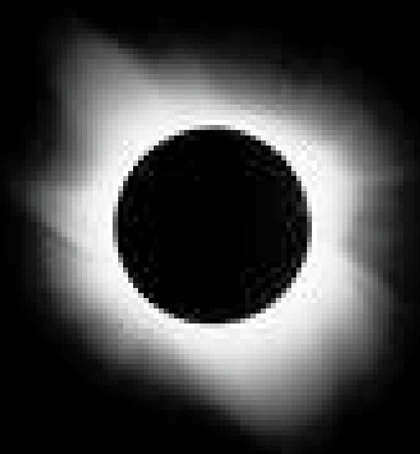


- Inner working angle depends on wavelength and aperture.
- Most require off-axis telescope and monolithic mirror.
- Most have lower throughput.
- All require active wavefront control and stable telescope.
- Limited outer working angle.
- Bandwidth limited by wavefront control system.
- Rapid retargeting.
- Large sky angles.
- Little or no UV capability (unlikely to get ozone cutoff).

What about mother nature's coronagraph?

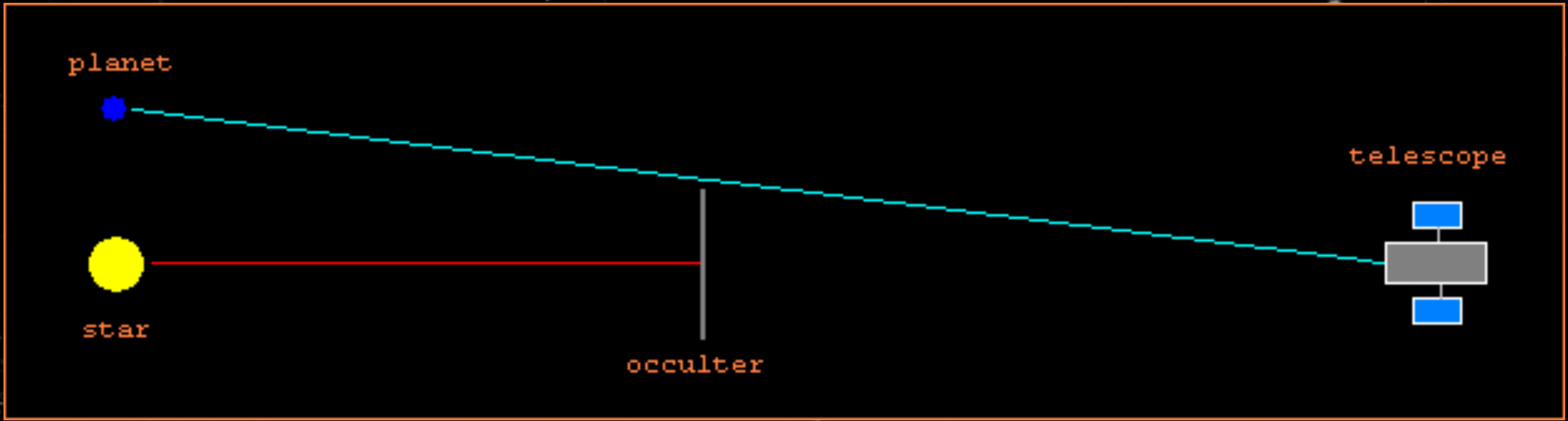
Use an external occulter to block the light

What about mother nature's coronagraph?

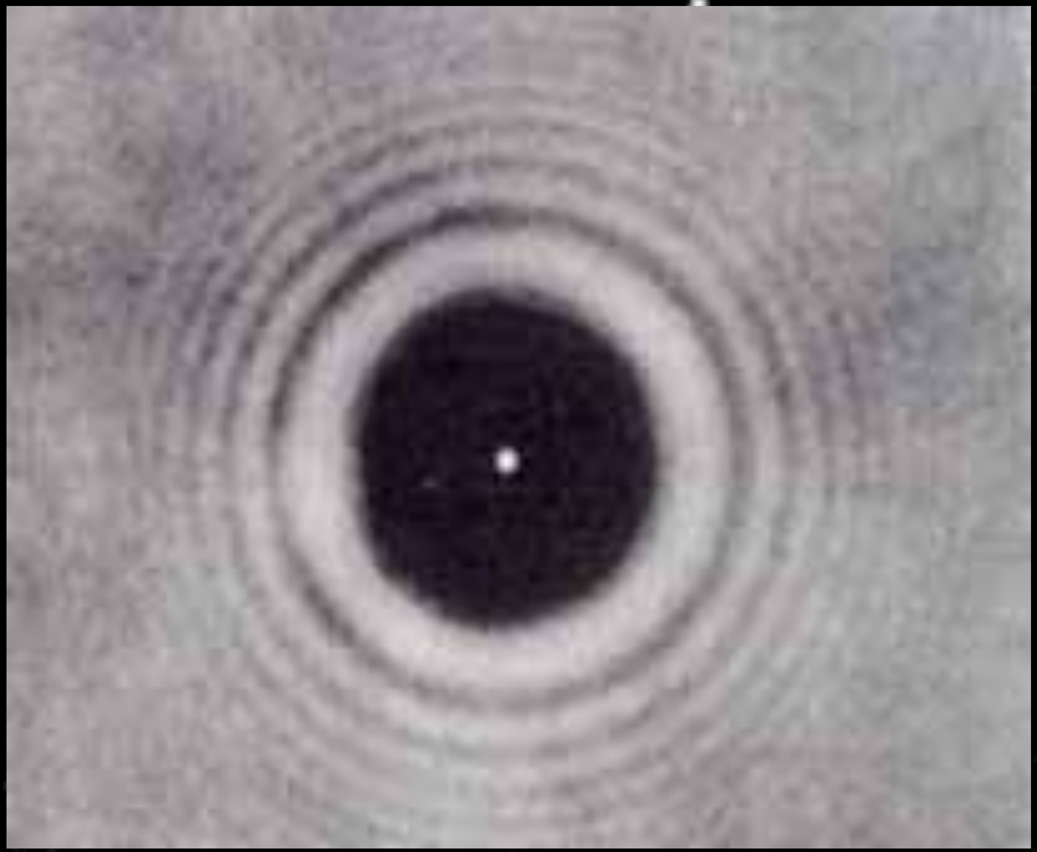


Use an external occulter to block the light

- In 1962, Lyman Spitzer at Princeton first proposed high contrast imaging with an artificial external occulter



Unfortunately, the diffraction problem is still there



Poisson's Spot

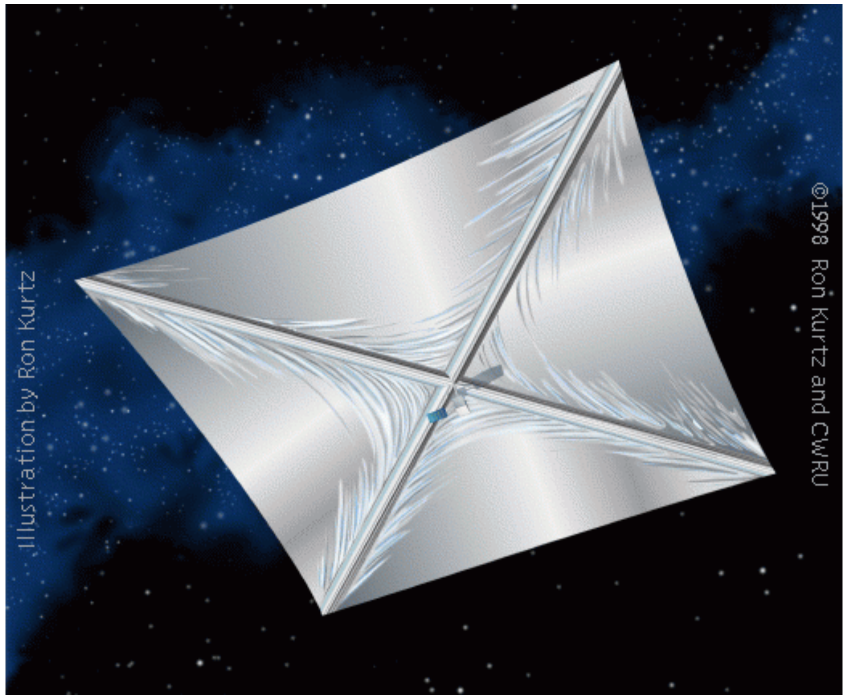
Unfortunately, the diffraction problem is still there

ANSWER: Apodize the occulter!

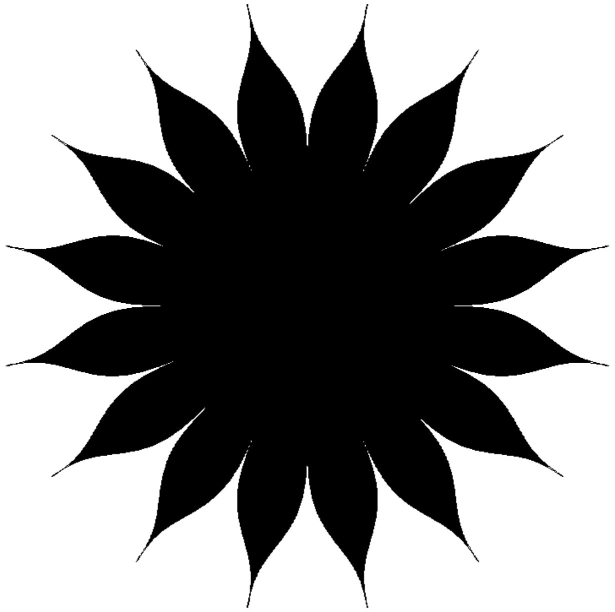
Poisson's Spot

External Occulters

- Spitzer (1962) first proposed using an apodized starshade.
- Others followed, Boss (Copi & Starkman (2000)), Umbras (Schultz (2003))
- Copi & Starkman found general solution to Fresnel integral on axis.
- Vanderbei et al. (2007) found optimal apodization functions.
- Spitzer & later Marchal (1985) first suggested using a *shaped* starshade.
- Simmons (2005) suggested occulters as complements to shaped pupils.
- Cash (2006) proposed a starshaped starshade.



BOSS



NWO, THEIA

UMBRAS

Electric fields

Using Babinet's principle, the field due to a transmissive occulter is:

$$E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda Z} \int_0^R A(r) J_0\left(\frac{2\pi r\rho}{\lambda Z}\right) e^{\frac{\pi i}{\lambda Z}(r^2+\rho^2)} r dr\right)$$

We can use this to calculate the field for a given apodization, A[r], or we can solve an optimization problem to find A[r].

Electric fields

Using Babinet's principle, the field due to a transmissive occulter is:

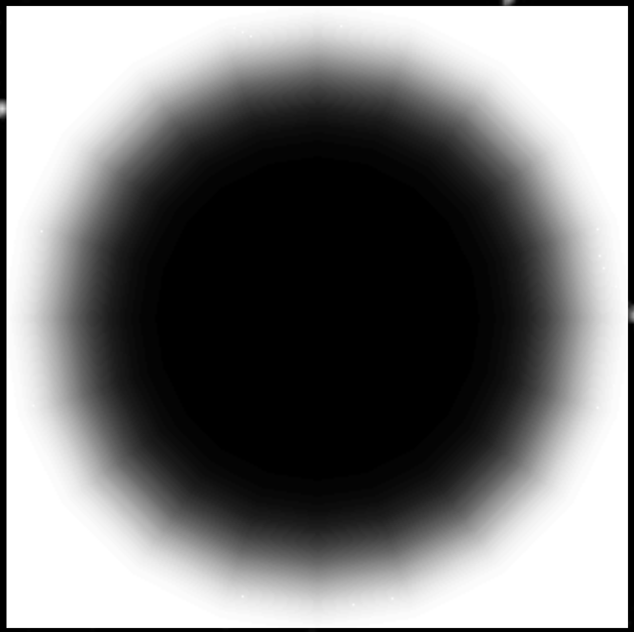
$$E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda Z} \int_0^R A(r) J_0 \left(\frac{2\pi r \rho}{\lambda Z} \right) e^{\frac{\pi i}{\lambda Z}(r^2+\rho^2)} r dr \right)$$

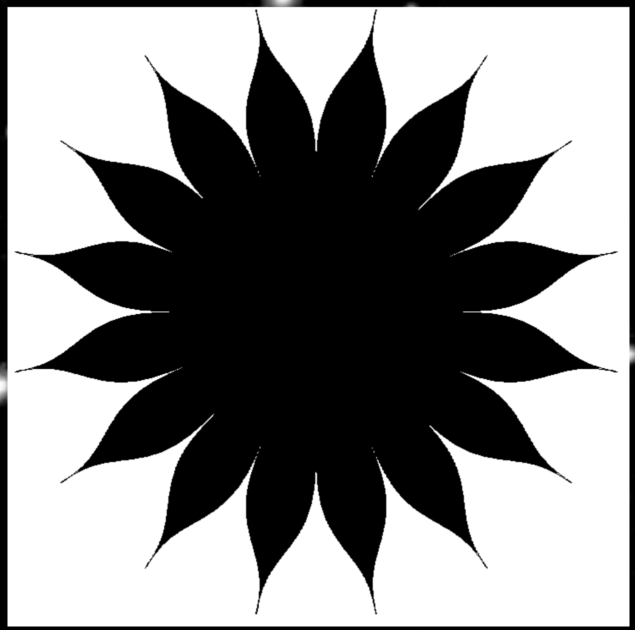
We can use this to calculate the field for a given apodization, A[r], or we can solve an optimization problem to find A[r].

But apodized occulters are really hard to make . . .

Opaque Occulter

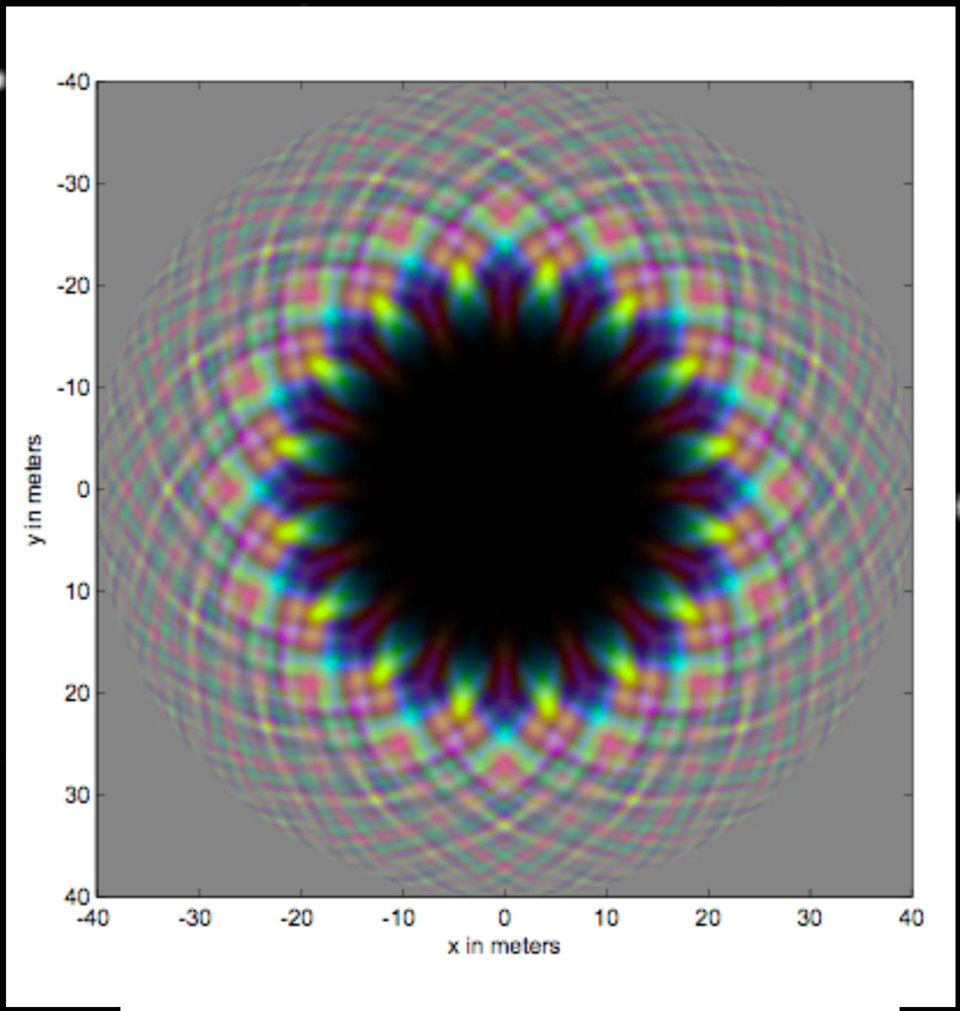
Remember Starshaped Masks?

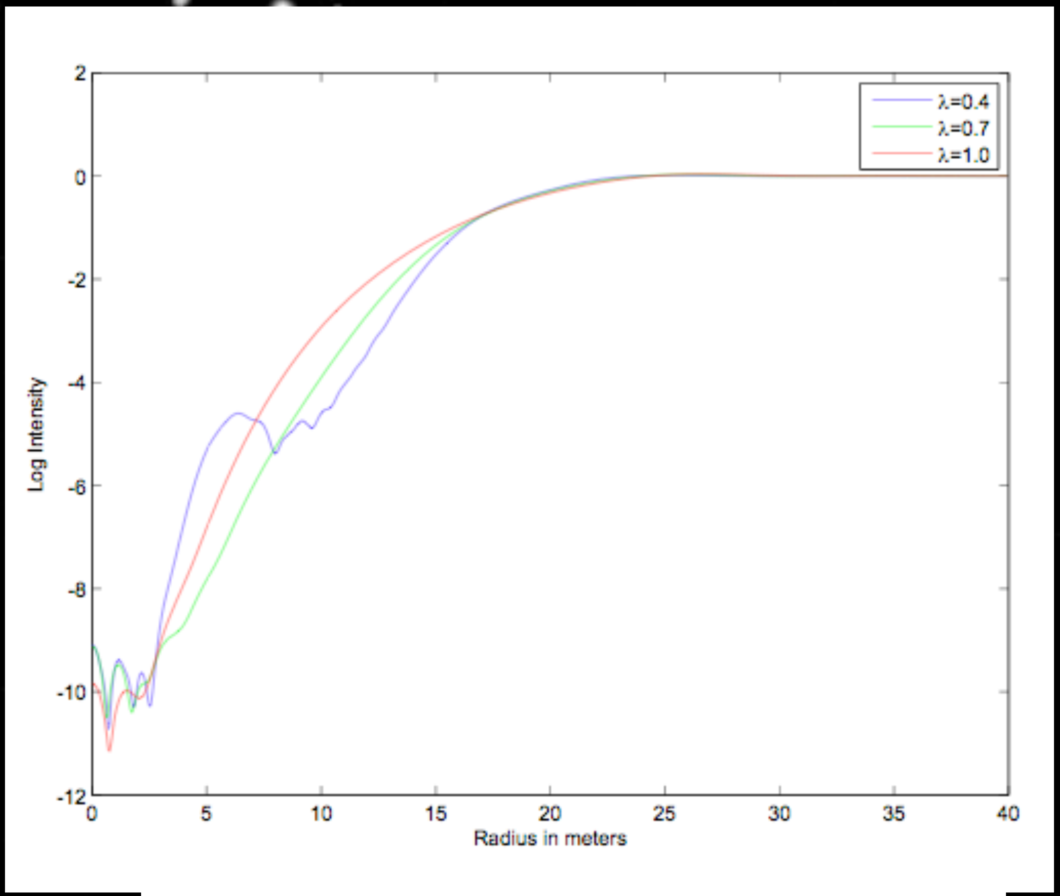


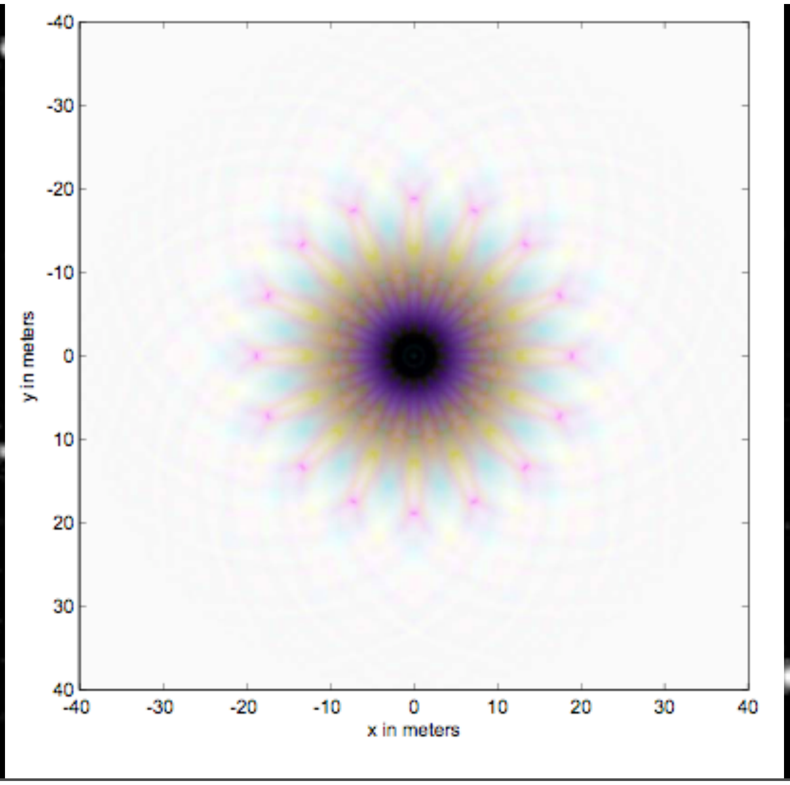


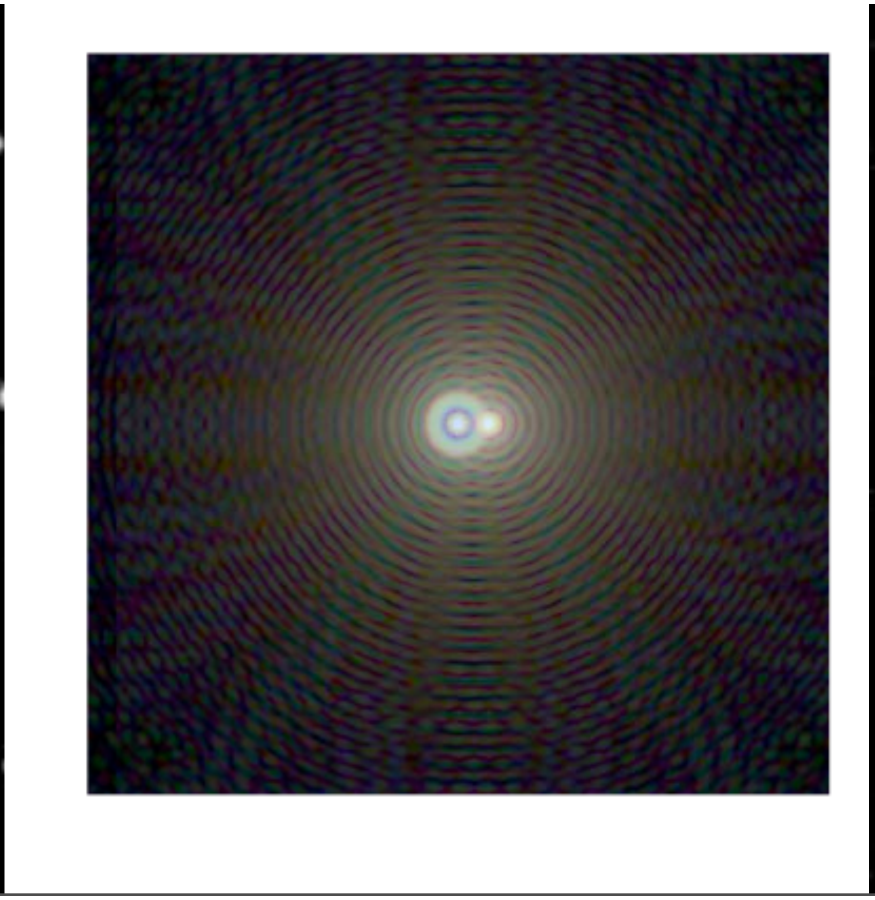
$$
\begin{aligned}
E_{o,\mathrm{petal}}(\rho,\phi) &= E_{o,\mathrm{apod}}(\rho) \\
&\quad -E_0 e^{\frac{2\pi i z}{\lambda}} \sum_{j=1}^{\infty} \frac{2\pi(-1)^j}{i\lambda z} \left(\int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_{jN}\left(\frac{2\pi r \rho}{\lambda z}\right) \frac{\sin\left(j\pi A(r)\right)}{j\pi} r\,dr \right) \\
&\quad \times \left(2\cos\left(jN(\phi-\pi/2)\right)\right)
\end{aligned}
$$

An Optimal 16-Petal Design

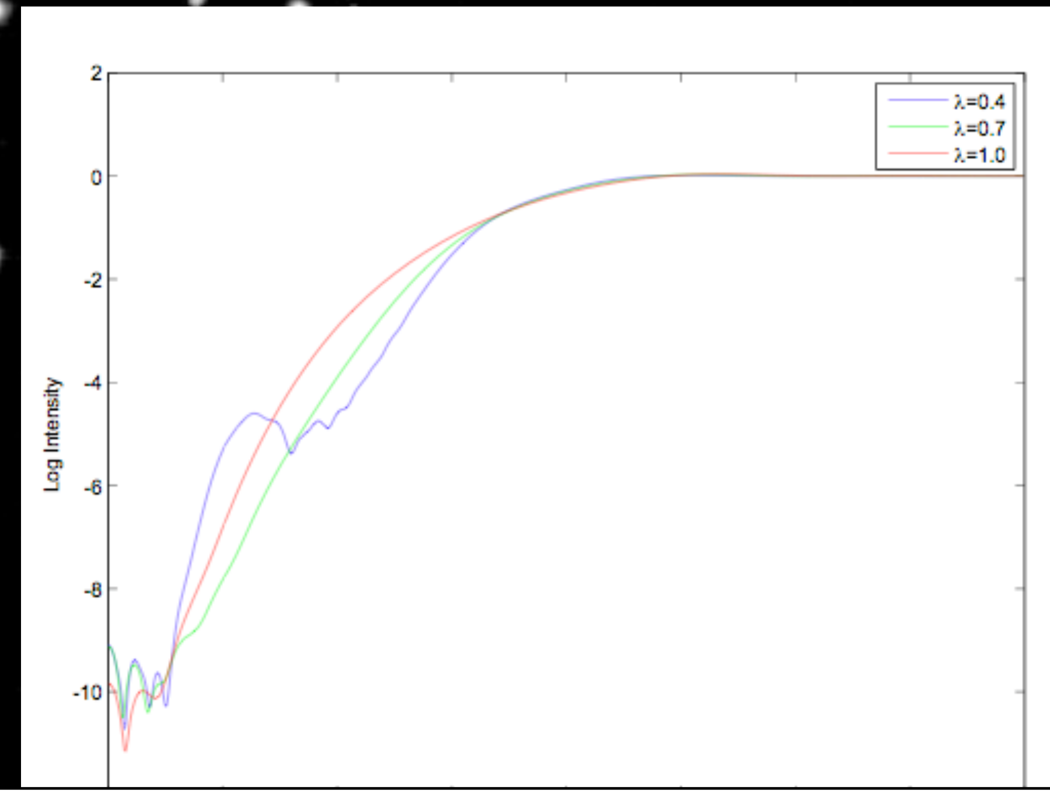




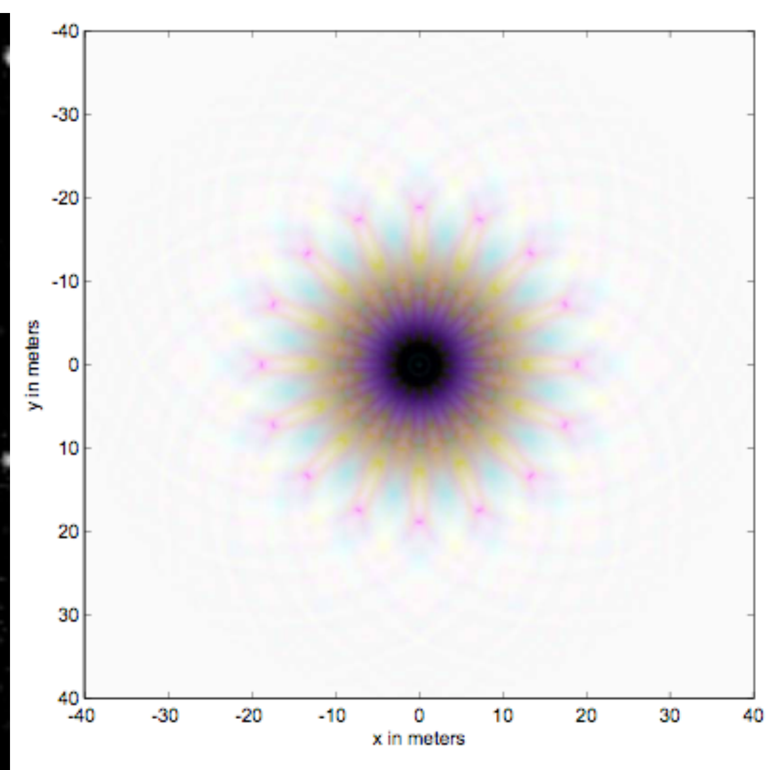


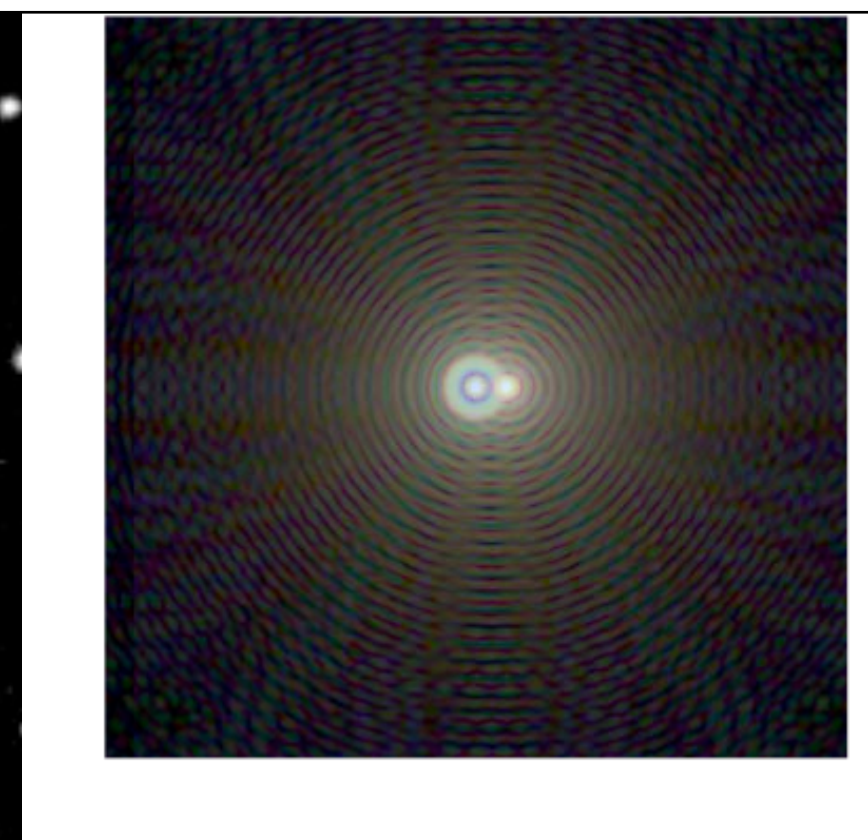


An Optimal 16-Petal Design



They're actually still pretty hard to make . . .





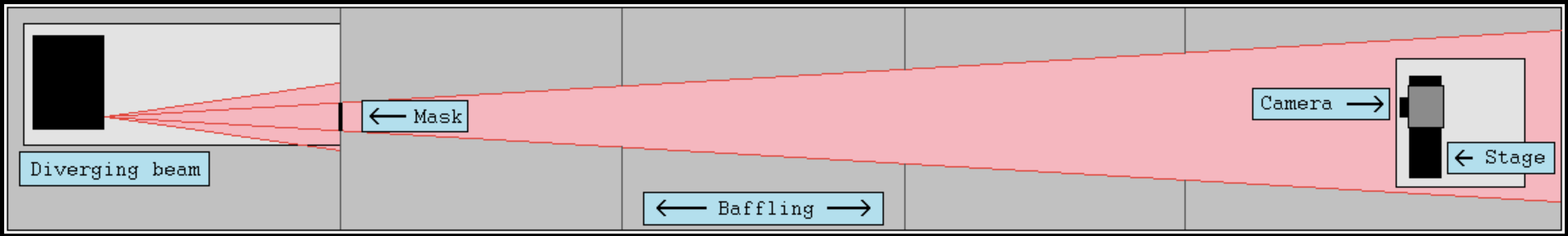
Starshade Requirement Allocation

	Manufacture, Deployment, or	amplitude	Notes
1	Petal r.m.s. shape vs design, 1/f^2 power law	100 um	Dominated by low spatial frequencies, p = 10 m at maximum width, decreasing with petal width
2	Petal proportional shape error	80 um	
3	Petal length (clipping at tip)	1 cm	
4	Petal azimuthal position	0.003 deg	1 mm at petal tip
5	Petal radial position	1 mm	
6	In-plane rotation about base	0.06 deg	1 cm at petal tip
7	Petal bend with r^2 deviation	5 cm	
8	Out of plane petal bending, r^2 deviation	>50 cm	
9	The cross-track (telescope/occulter alignment)	75 cm	

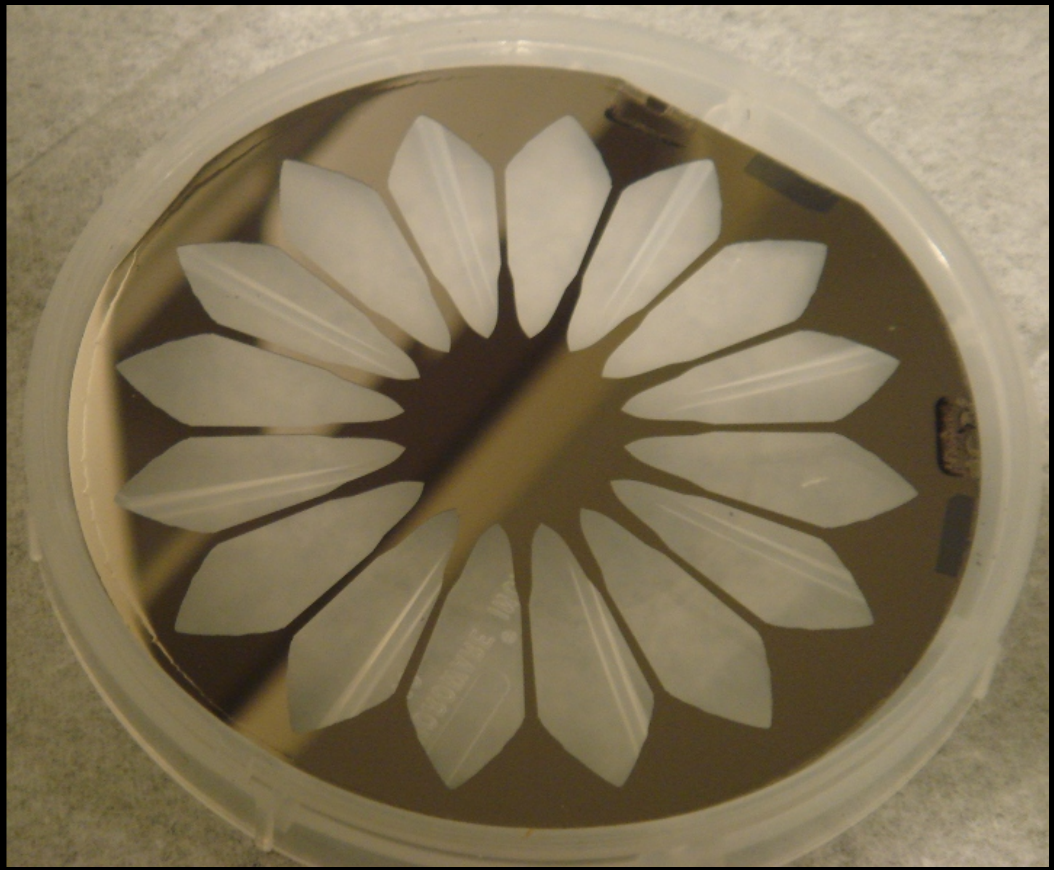
Contrast change below 10^{-12} at 0.6 micron

A simulated image of the solar system

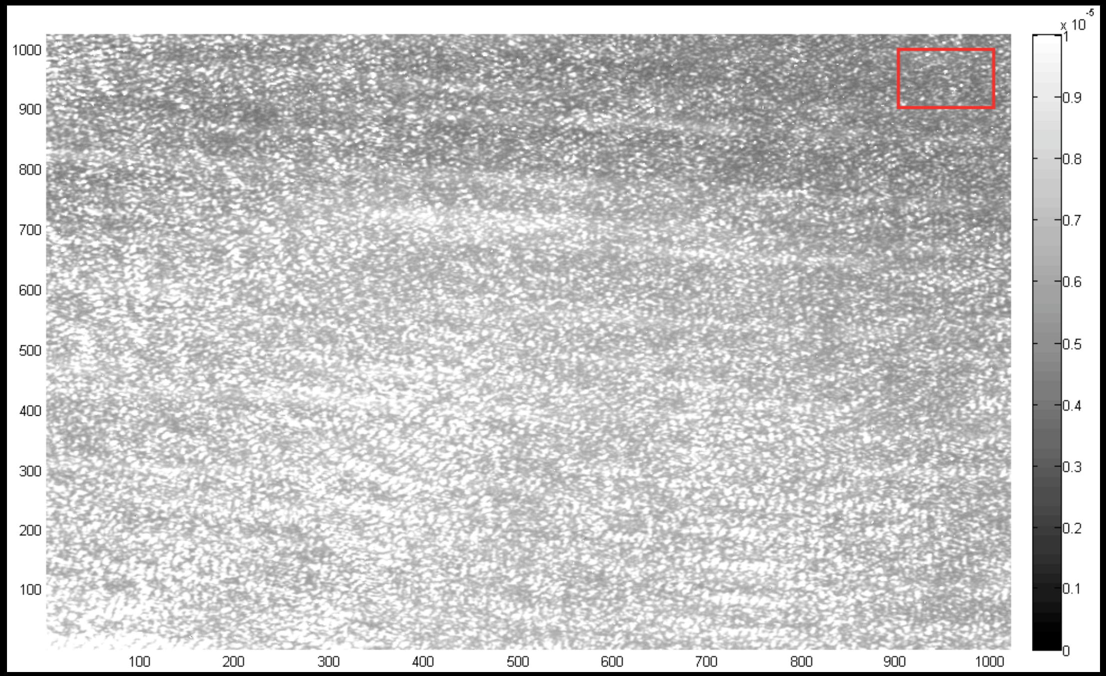
Occulter Experiments



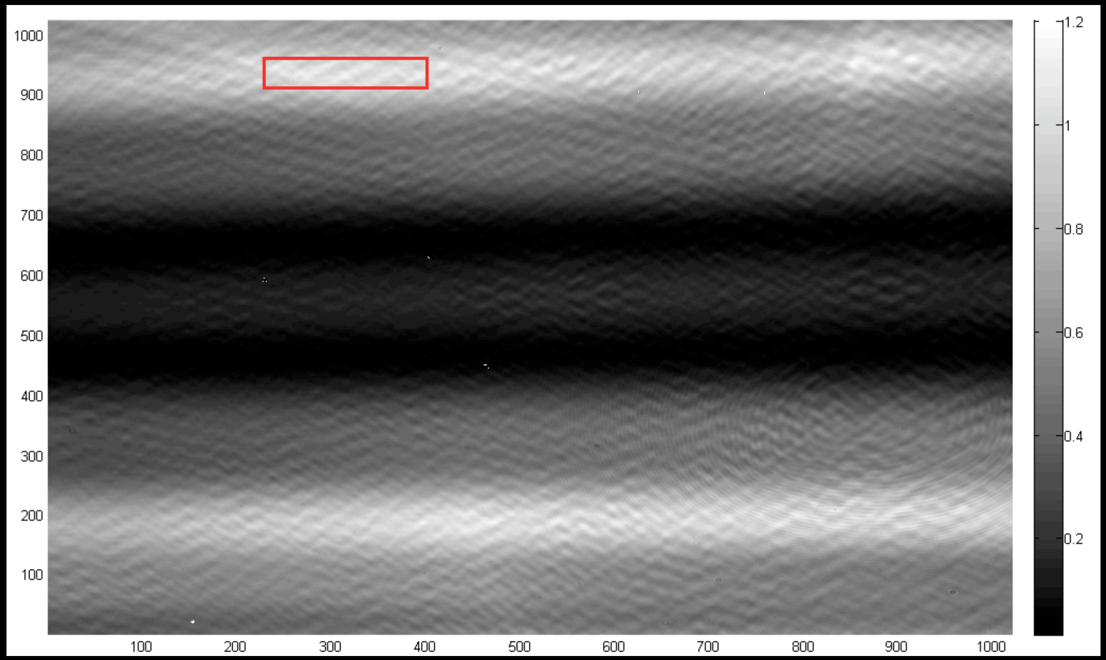
- Inside 40' x 8' x 4' enclosure to isolate from environment
- No optics between pinhole and mask
- No optics (currently) between mask and camera
- 4" diameter, occulter is inner 2"
- Etched from 400!m wafer at JPL
- Designed for 10^8 contrast



First Results

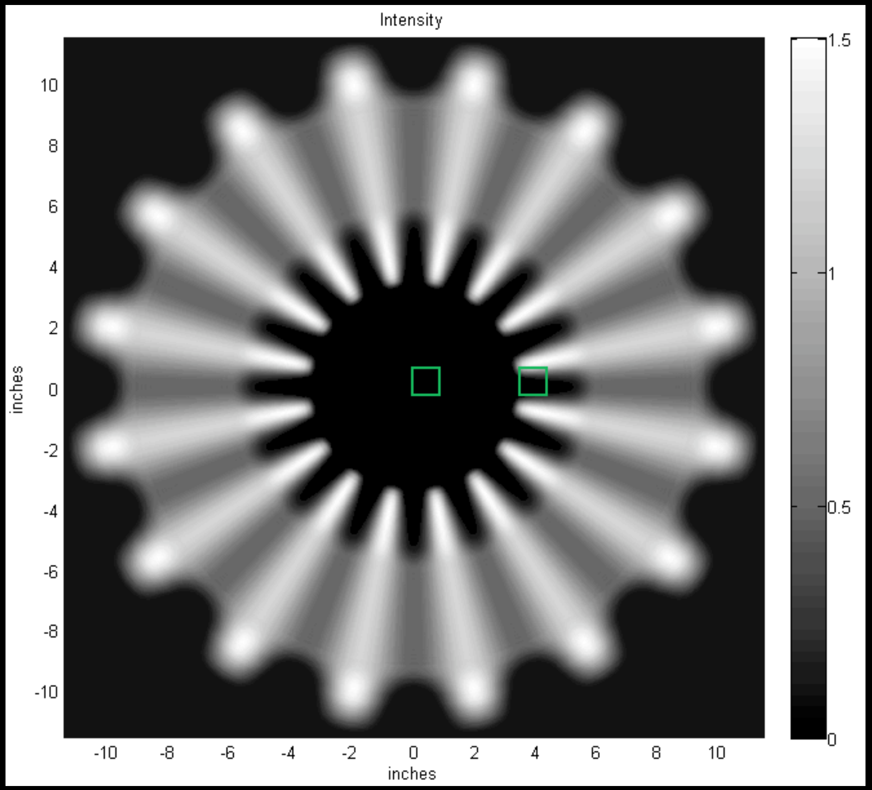


900s exposure, median intensity in box 4.9 x 10^{-6}

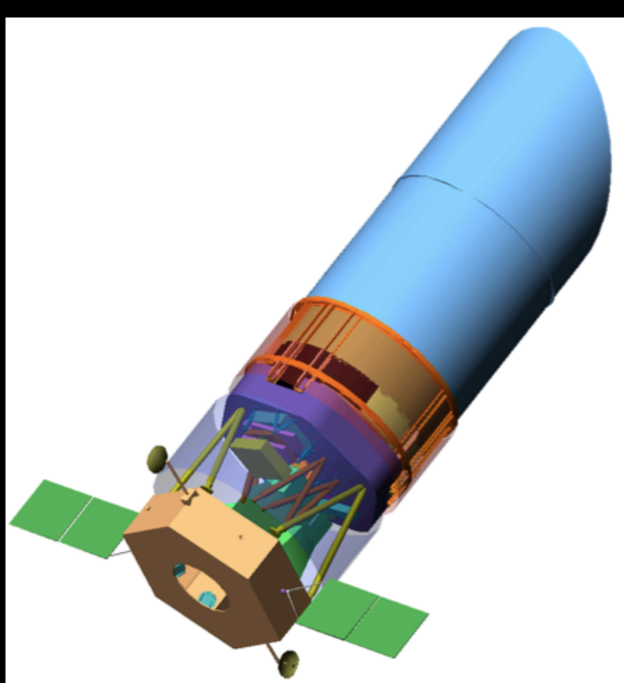


0.06s exposure, scaled to median intensity 1 in box

Approximate locations shown in green on simulated image at right.



Telescope for Habitable Earths and Interstellar/Intergalactic Astronomy (THEIA)



PI: Jeremy Kasdin/David Spergel

Co-Investigators

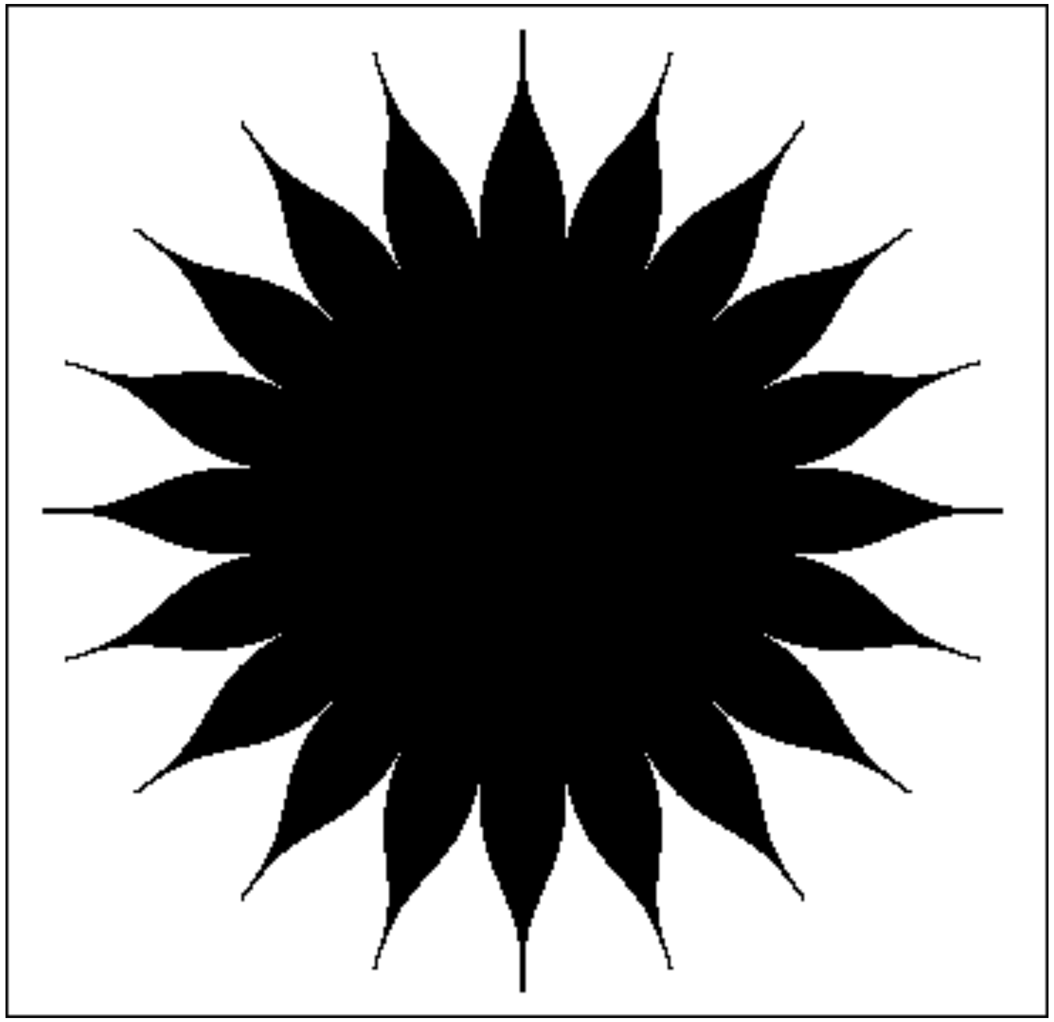
Paul Atcheson, Matt Beasley, Rus Belikov, Morley Blouke, Eric Cady, Daniela Calzetti, Craig Copi, Steve Desch, Phil Dumont, Dennis Ebbets, Rob Egerman, Alex Fullerton, Jay Gallagher, Jim Green, Olivier Guyon, Sally Heap, Rolf Jansen, Ed Jenkins, Jim Kasting, Ritva Keski-Kuha, Marc Kuchner, Roger Lee, Don J. Lindler, Roger Linfield, Doug Lisman, Rick Lyon, John MacKenty, Sangeeta Malhotra, Mark McCaughrean, Gary Mathews, Matt Mountain, Shouleh Nikzad, Bob O'Connell, William Oegerle, Sally Oey, Debbie Padgett, Behzad A Parvin, Xavier Prochaska, James Rhoads, Aki Roberge, Babak Saif, Dmitry Savransky, Paul Scowen, Sara Seager, Bernie Seery, Kenneth Sembach, Stuart Shaklan, Mike Shull, Oswald Siegmund, Nathan Smith, Remi Soummer, Phil Stahl, Glenn Starkman, Daniel K Stern, Domenick Tenerelli, Wesley A. Traub, John Trauger, Jason Tumlinson, Ed Turner, Bob Vanderbei, Roger Windhorst, Bruce Woodgate, Bob Woodruff

Industry Partners: Lockheed Martin Missiles and Space, ITT Space Systems, LLC, Ball Aerospace

NASA Partners: Jet Propulsion Laboratory/Caltech, Goddard Space Flight Center, Ames Research Center, Marshall Space Flight Center

University Partners: Arizona State University, Caltech, Case Western Reserve University, University of Colorado, John Hopkins University, University of Massachusetts, University of Michigan, MIT, Penn State, Princeton University, Space Telescope Science Institute, University of California-Santa Barbara, University of California-Berkeley, University of Virginia, University of Wisconsin, Yale University

	1-dist. Occulter	2-dist. Occulter
Occulter distance (km)	70400	55000
Occulter IWA (mas)	75	75
Occulter spectral band (nm)	250-1000	250-700
Second occulter distance (km)	-	35000
Second occulter IWA (mas)	-	118
Second occulter spectral band (nm)	-	700-1000
Occulter radius (m)	25.6	20
Number of petals	20	20
Petal length (m)	19	10
Minimum gap between petals (mm)	0.12	1.0
Minimum width of petal tip (mm)	1.62	1.0

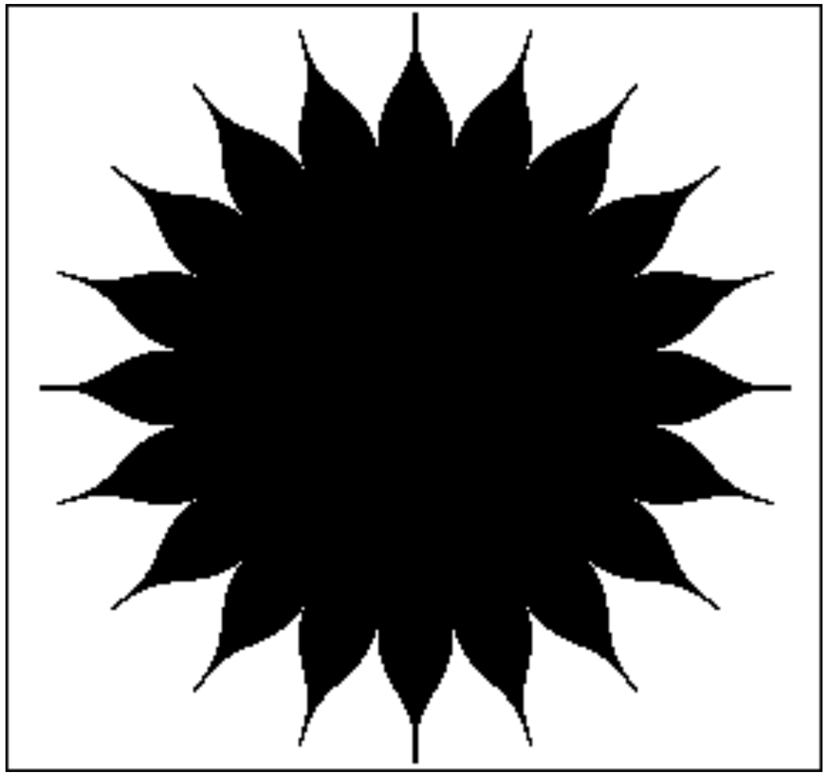


To scale:

Left: single distance occulter

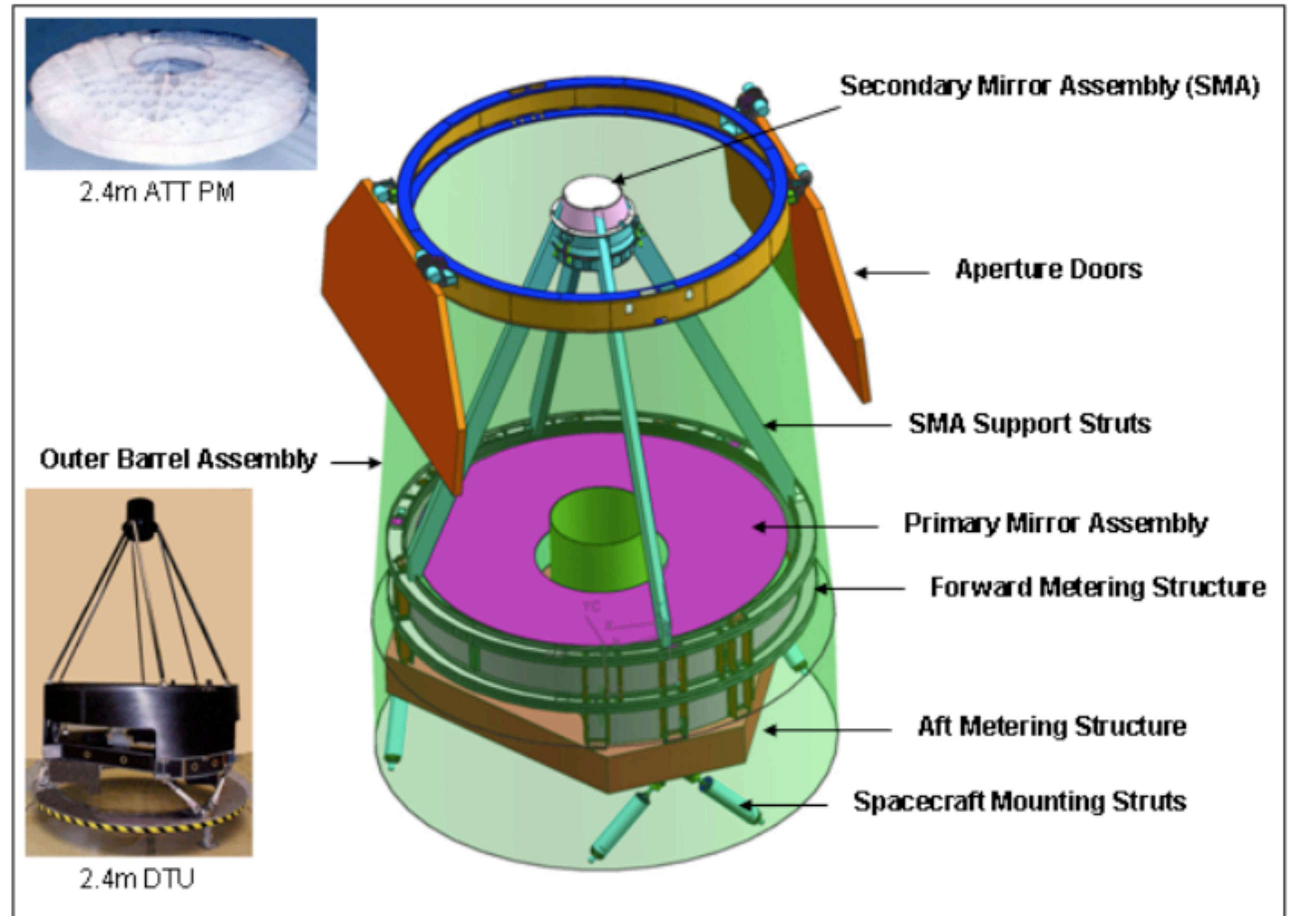
Right: two-distance occulter

Optimal designs for a 4 meter telescope



Telescope Design

- Three Mirror Astigmat
- Baseline: MgF coatings on primary; LiF on secondary
- Pickoff mirror feeds general astrophysics instruments
- Exoplanet Characterizer;
- Star Formation Camera
- Ultraviolet Spectrograph

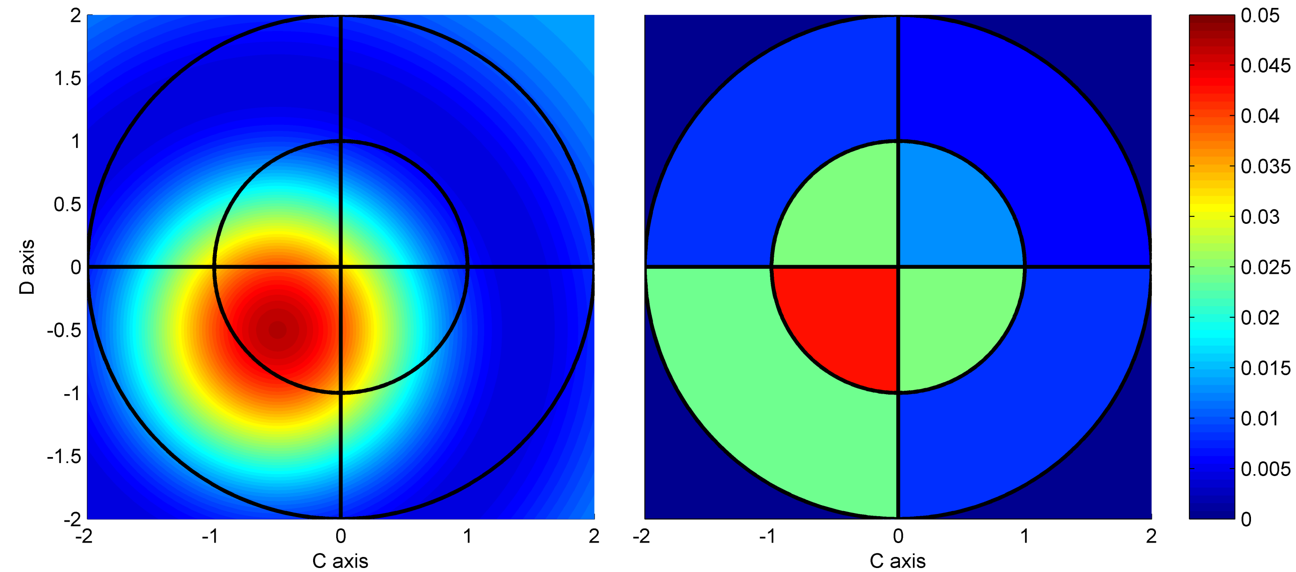


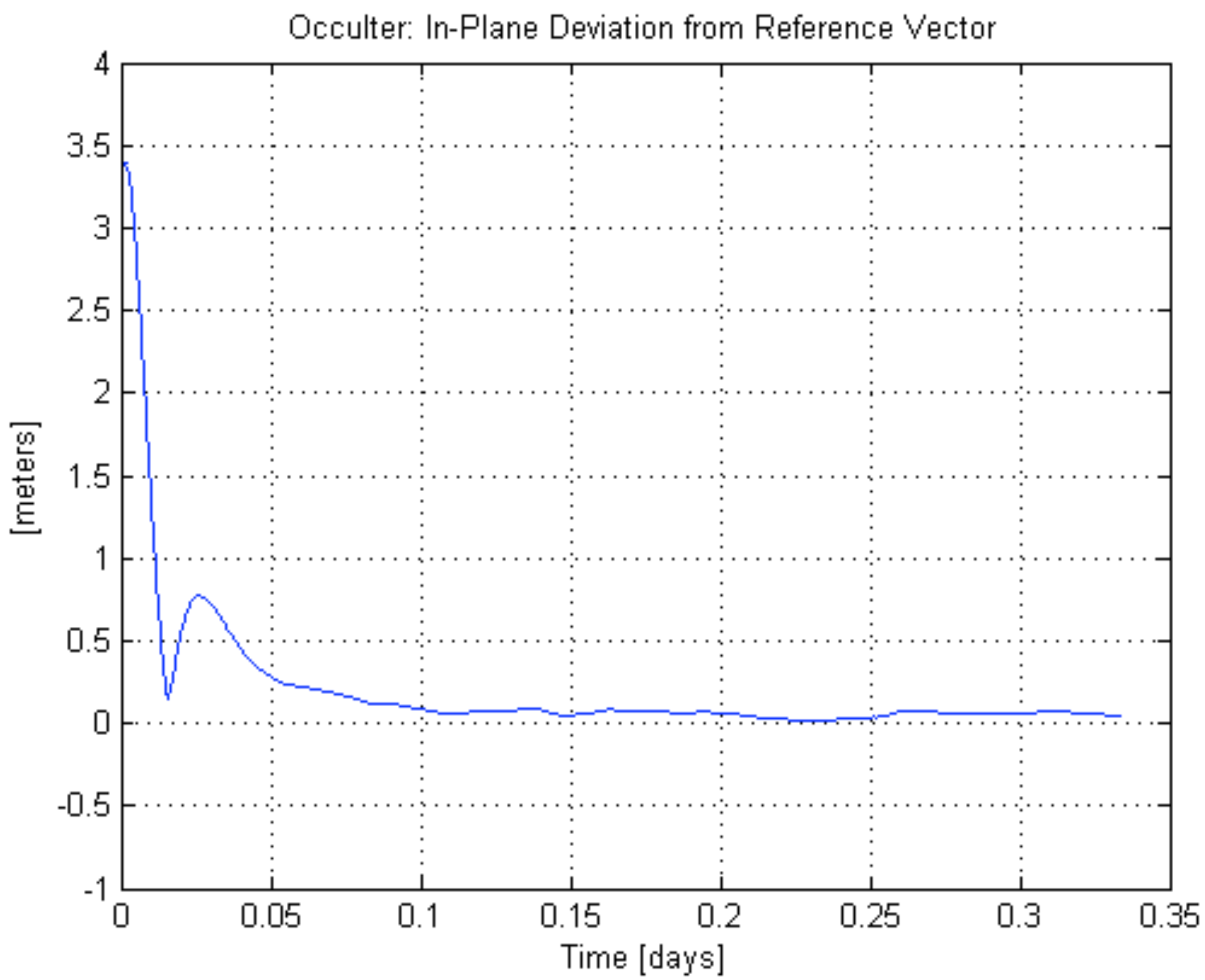
Telescope concept for a 4-meter aperture on-axis design that can be build using technology developed by ITT Space systems Division

Stationkeeping using Pupil Sensor and Perfect Thrusters

- Full Nonlinear Dynamic Model
- Discrete Measurements and Kalman Filter for position information
- Continuous Thrusters plus noise
- Gravity gradient and solar pressure disturbances
- Feed forward control plus feedback linearization

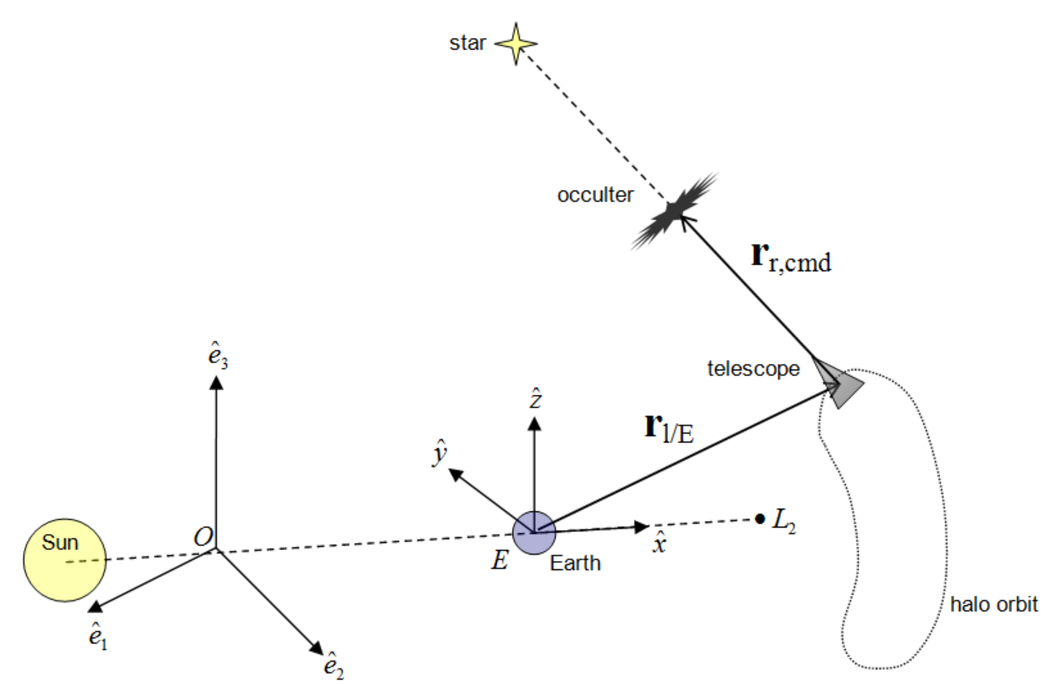
8 Octent Pupil Sensing for Position



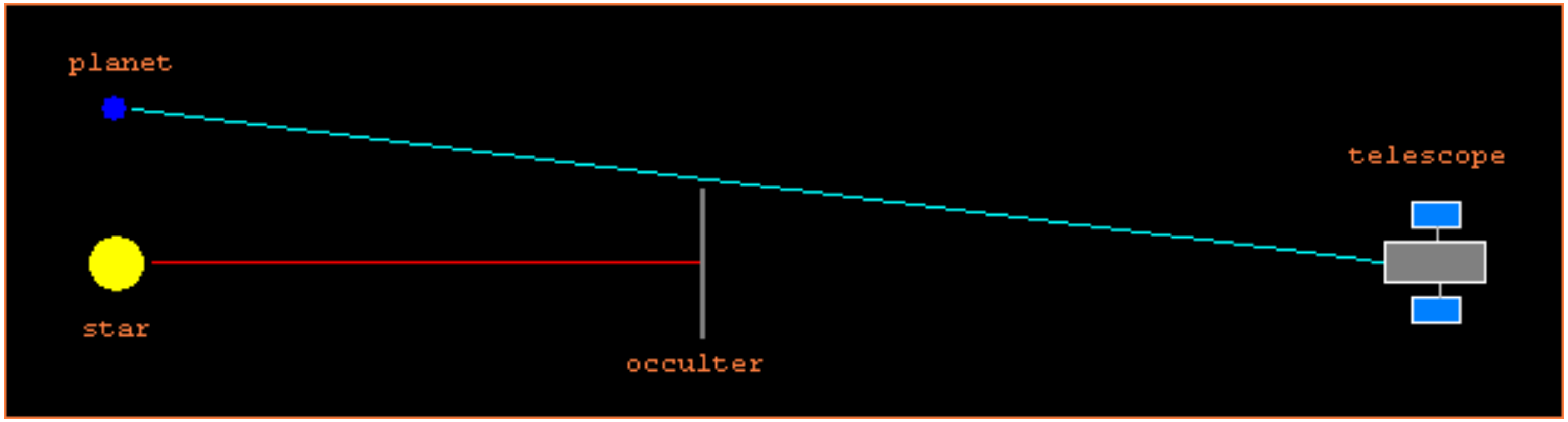


Initial offset = 6.5 m

Initial state error = 10 m



External Occulters



- Geometric iwa given by size and distance of starshade (100 m at 100,000 km gives 100 mas).
- Full throughput outside geometric IWA.
- Throughput decays smoothly (& rapidly) inside geometric IWA.
- Unlimited outer working angle.
- Size increases with wavelength.
- Starshade must slew from target to target.
- Limited viewing angles due to Sun reflection off starshade.
- Challenging to manufacture and control

Summary Comparison

Internal Coronagraph

- Variable Inner Working Angle
- Limited Outer Working Angle
- Fixed, rapid repointing
- Large viewing angles
- Optics/Detector Limited Bandwidth
- Relatively Low throughput
- Technology/Cost Drivers
  - Off-axis, diffraction limited telescope
  - Telescope Stability
  - Wavefront Control
  - Small IWA Coronagraph (2 λ/D)

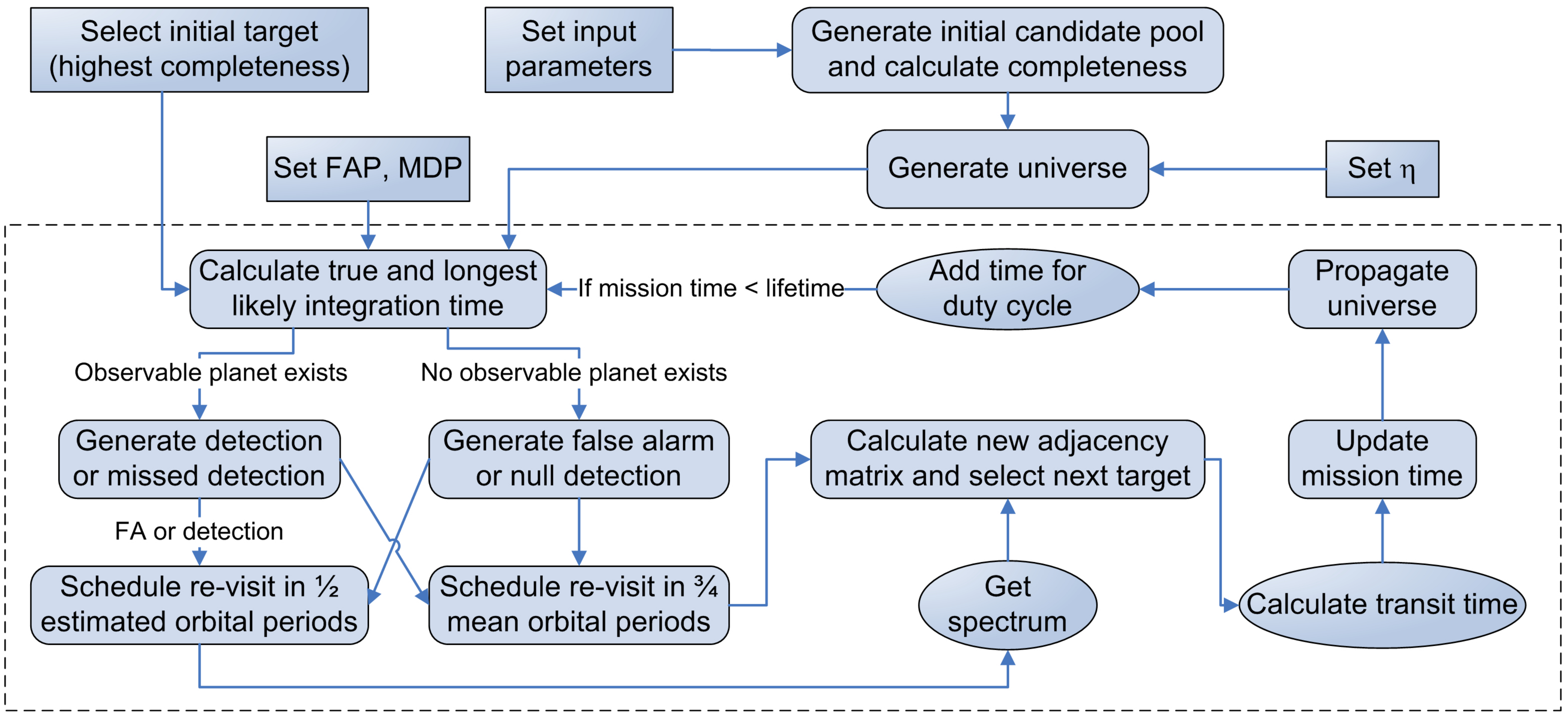
External Occulter

- Fixed Inner Working Angle
- Wide Outer Working Angle
- Variable Slew Time
- Small field of regard
- Variable BW (depends on size)
- High throughput
- Technology/Cost Drivers
  - Size & Distance
  - Positioning Control & Slewing
  - Manufacturing & Deployment Accuracy
  - Starshade Stability

Notes:

- Hybrid design was not tenable but complimentary suppression might make sense
- Premium placed on small/nearby starshade with small petals (lower mass, easier deployment, fits into fairing, lower fuel use, more rapid slews, easier to test, looser tolerances)

Performance Comparisons



Automated Monte Carlo Mission Generation

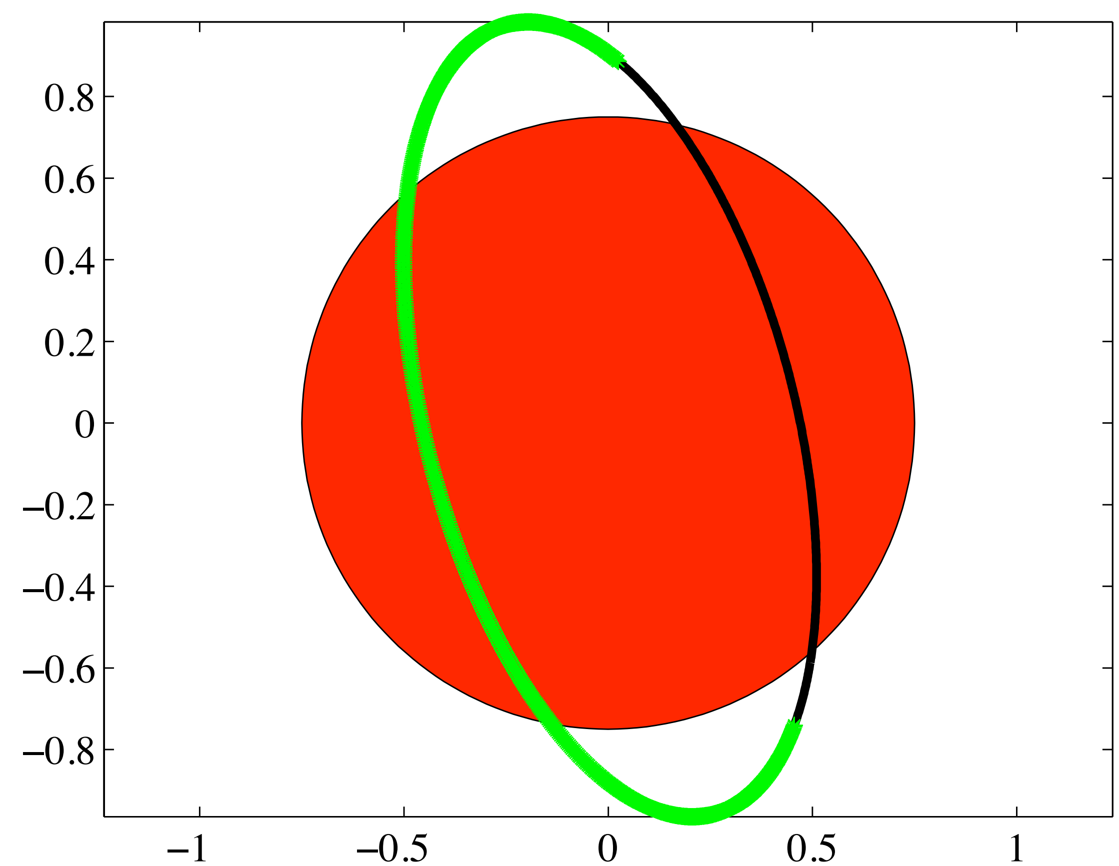
How many planets can a mission detect and characterize?

Completeness

A direct detection can be parametrized by two values:

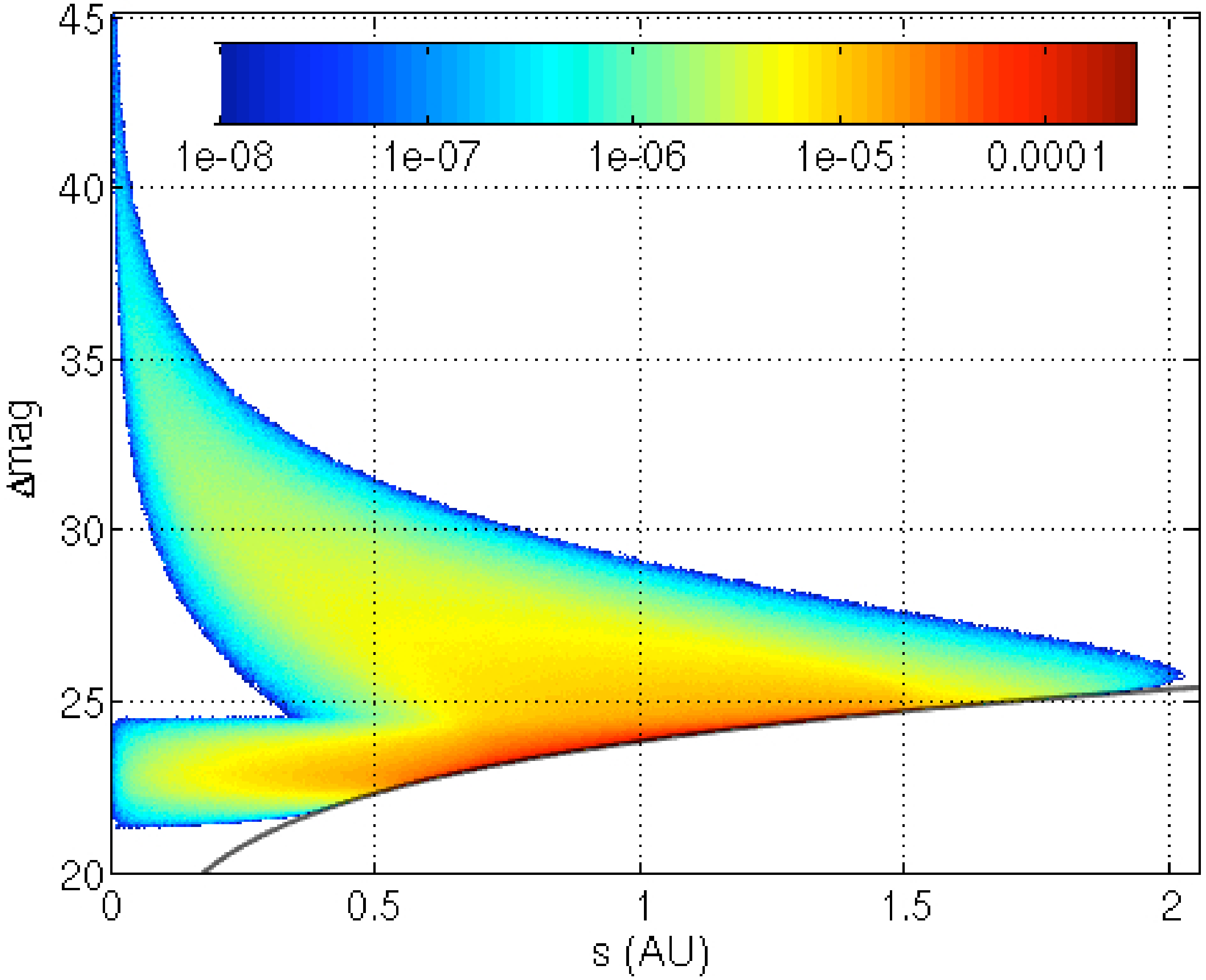
- Difference in brightness between star and planet (Δmag)
- Angular separation between star and planet (s)

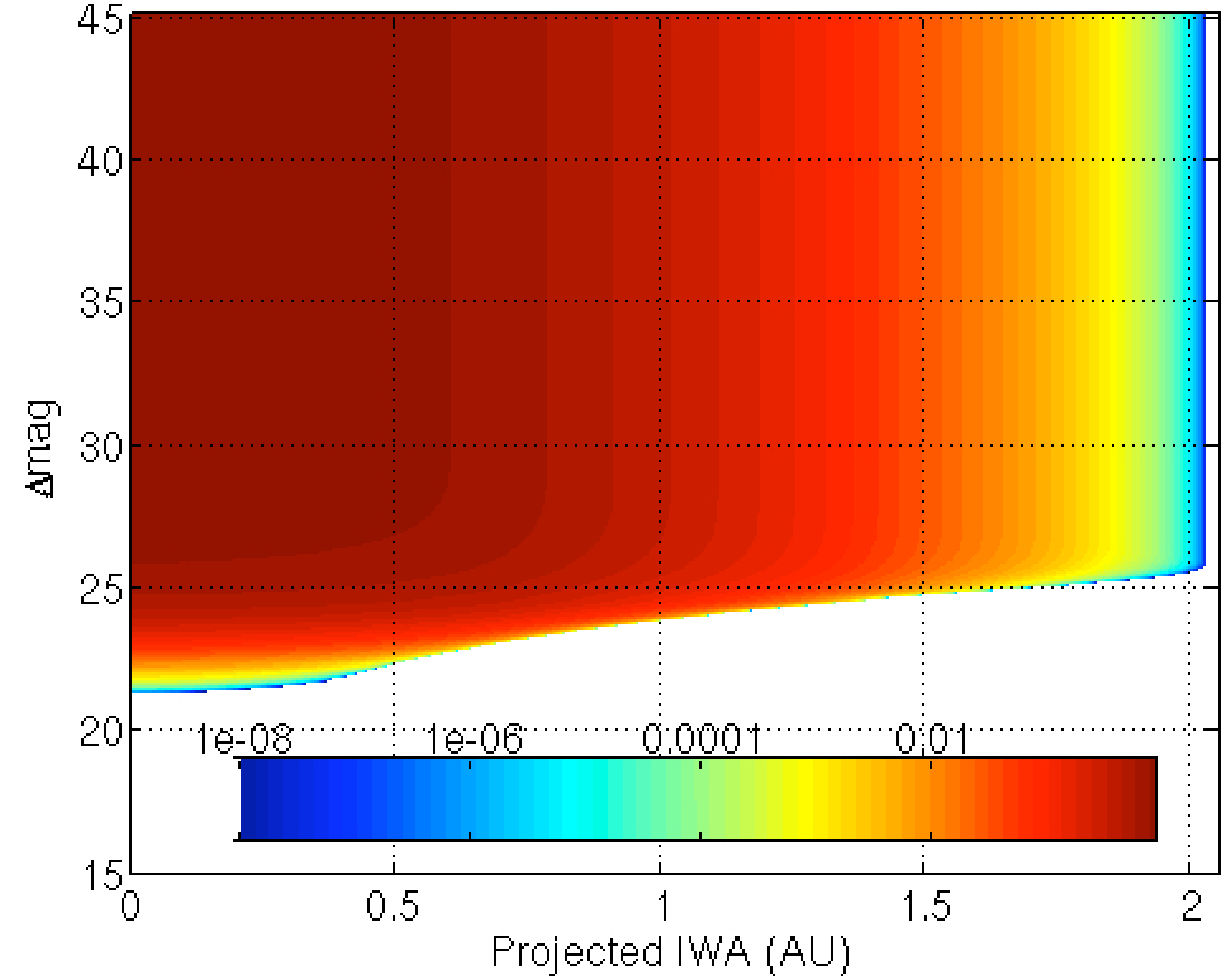
For detection, the angular separation must be greater than the instrument's inner working angle (IWA) and the Δmag must be greater than the limiting Δmag



Projection of a planetary orbit. The planet is sufficiently illuminated for detection on the green portion of the orbit, but cannot be seen within the projected IWA represented by the red circle

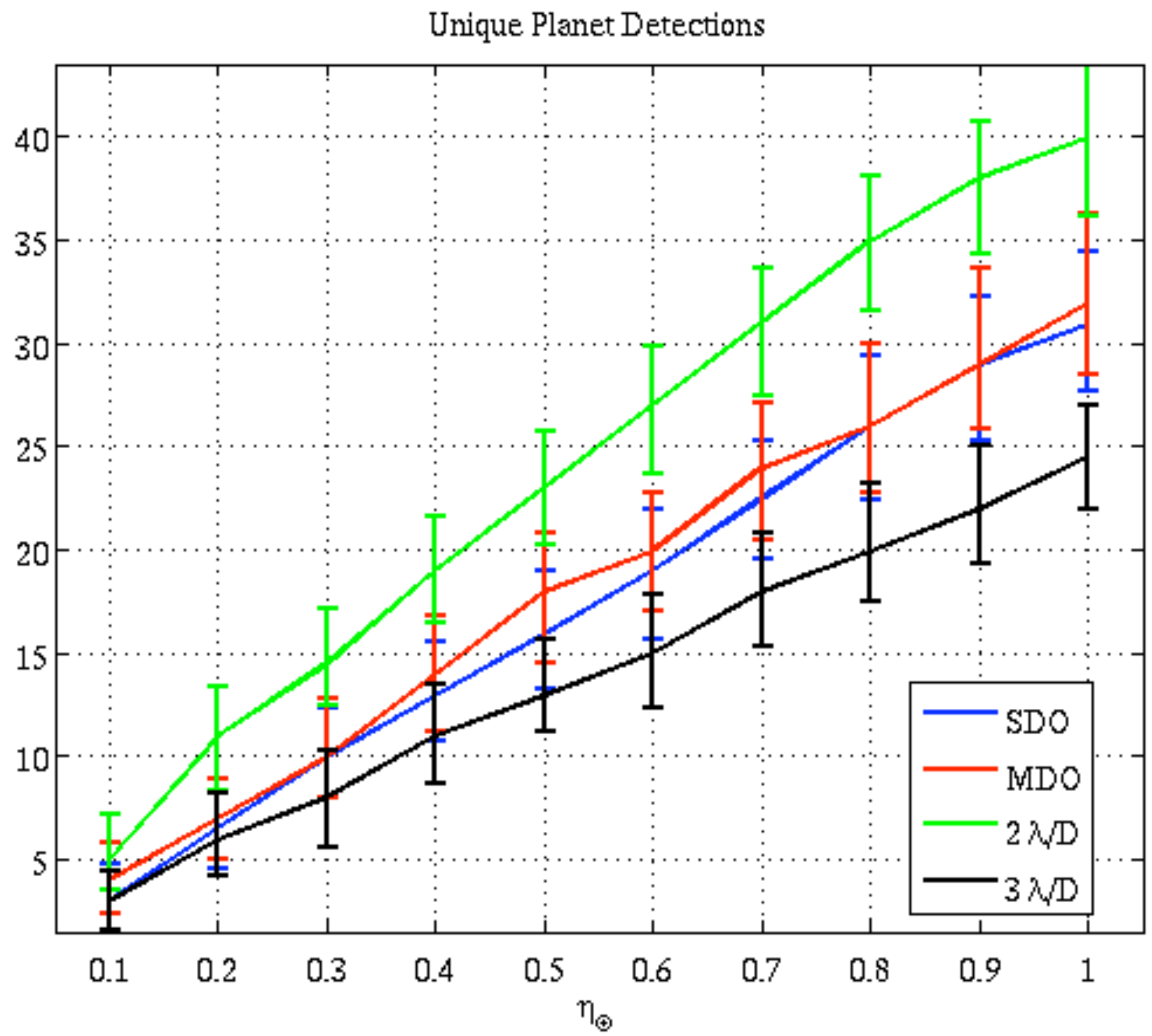
Completeness

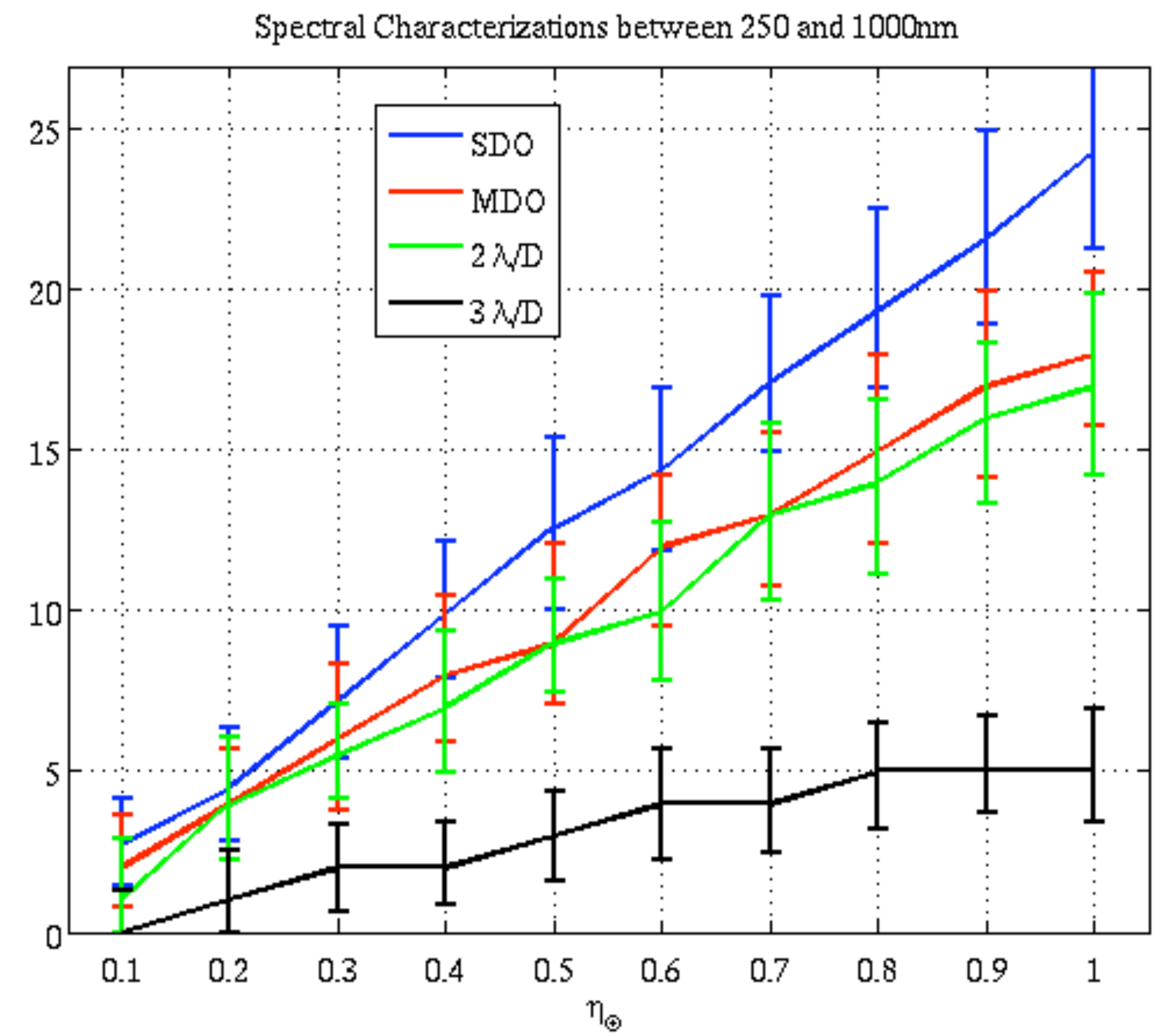




- For a given population of planets you can calculate the joint probability density function of s and Δmag (left image)
- The cumulative distribution of this PDF tells you the probability of detecting a planet (given one exists) for a specified IWA and limiting Δmag (right image) - this is the star's completeness

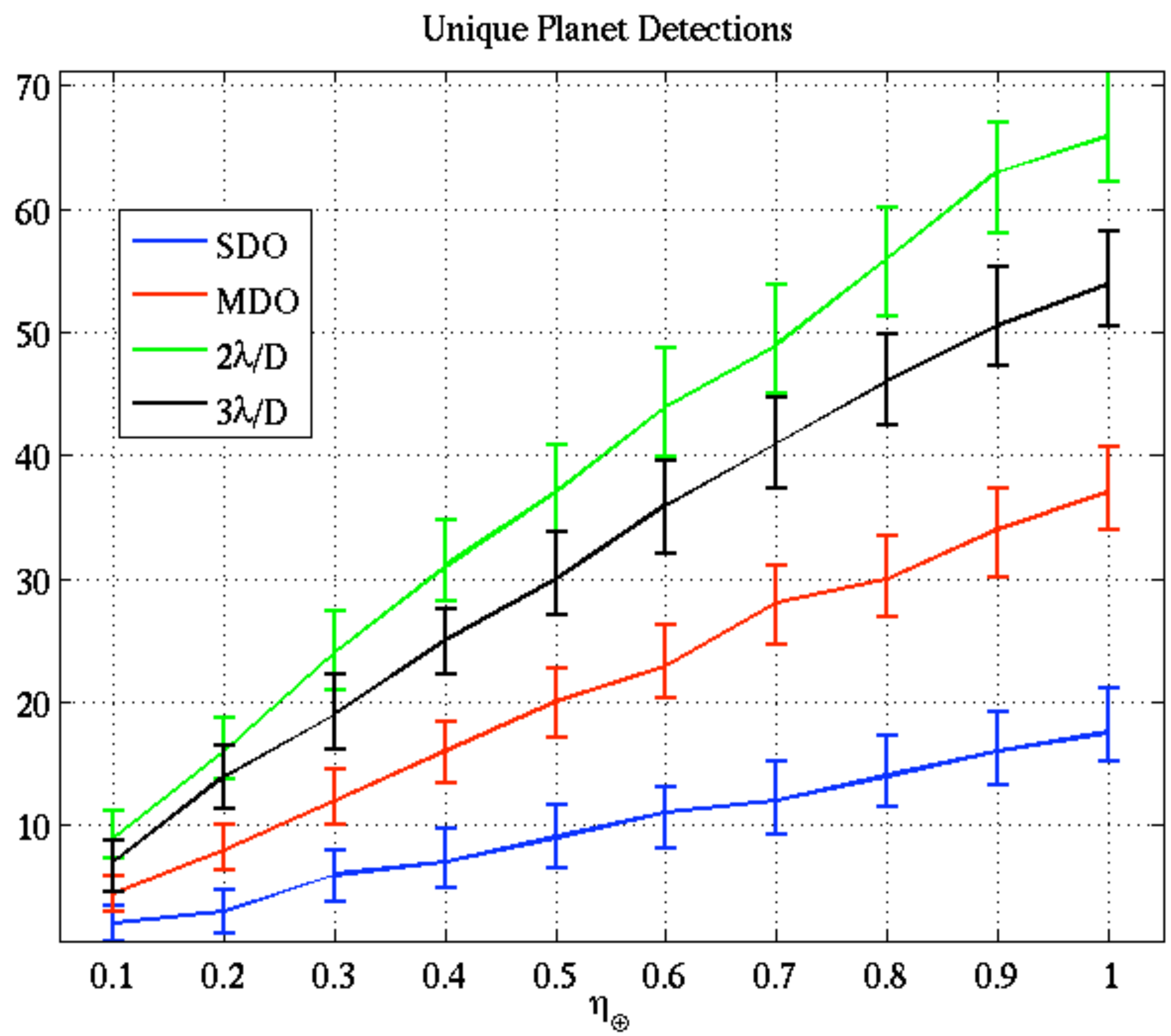
4m Telescope

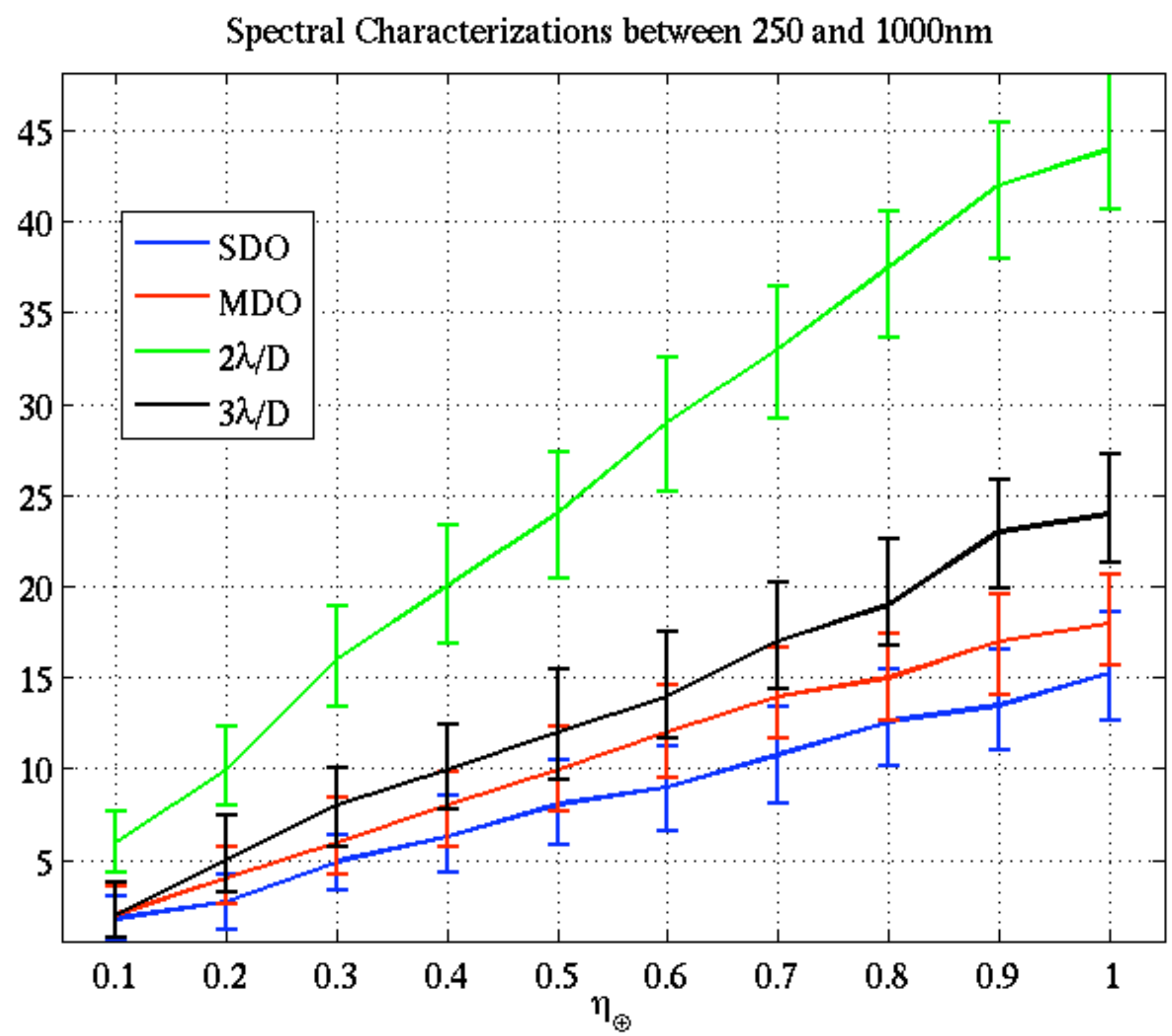




- Almost 40 Earthlike planets detected at eta = 1
- Small variations among approaches (except 3 l/D coronagraph)
- 2 lambda/D coronagraph gets more unique planets and about same number of spectra as MDO
- 3 lambda/D coronagraph gets very few full spectra

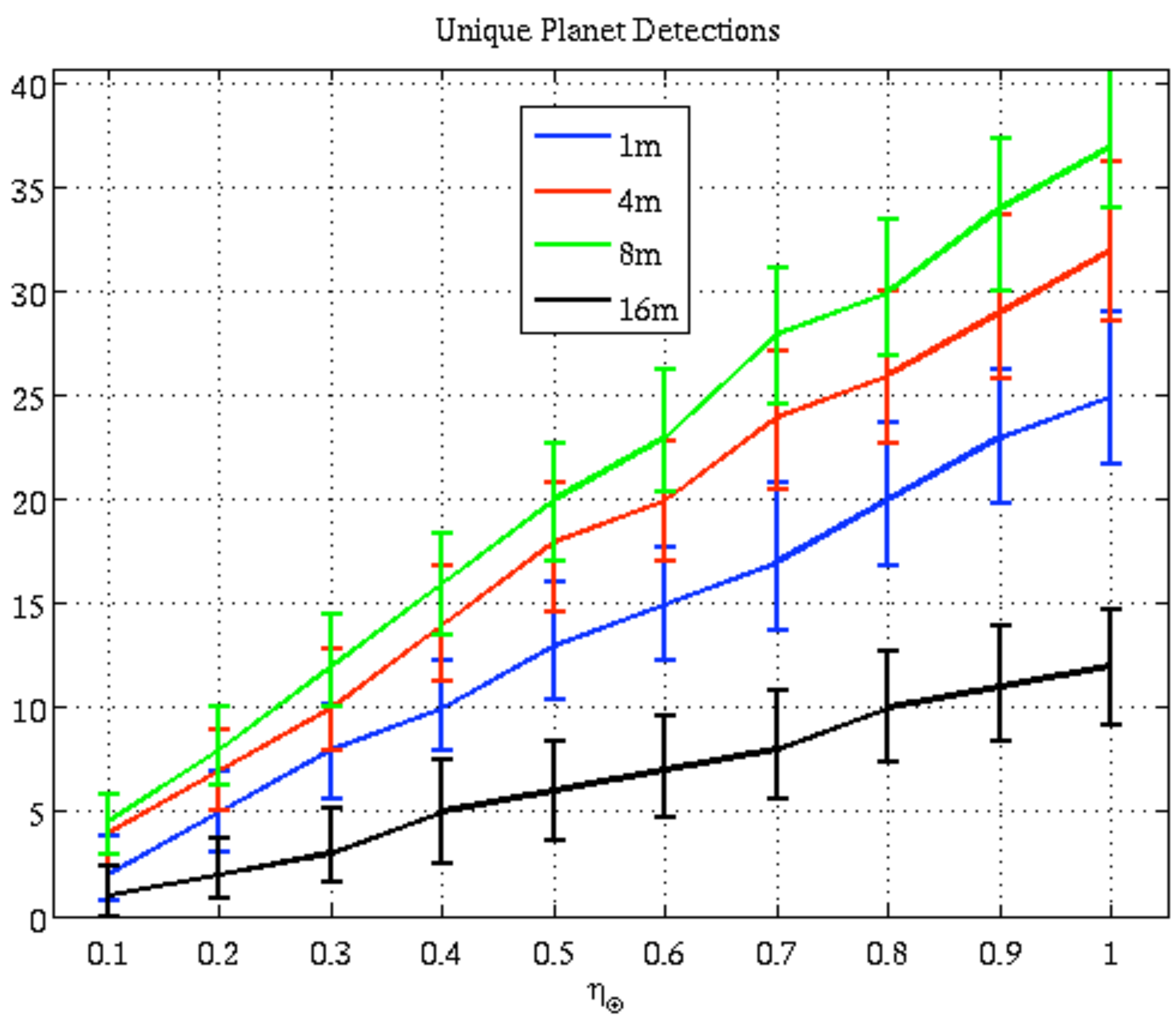
8m Telescope

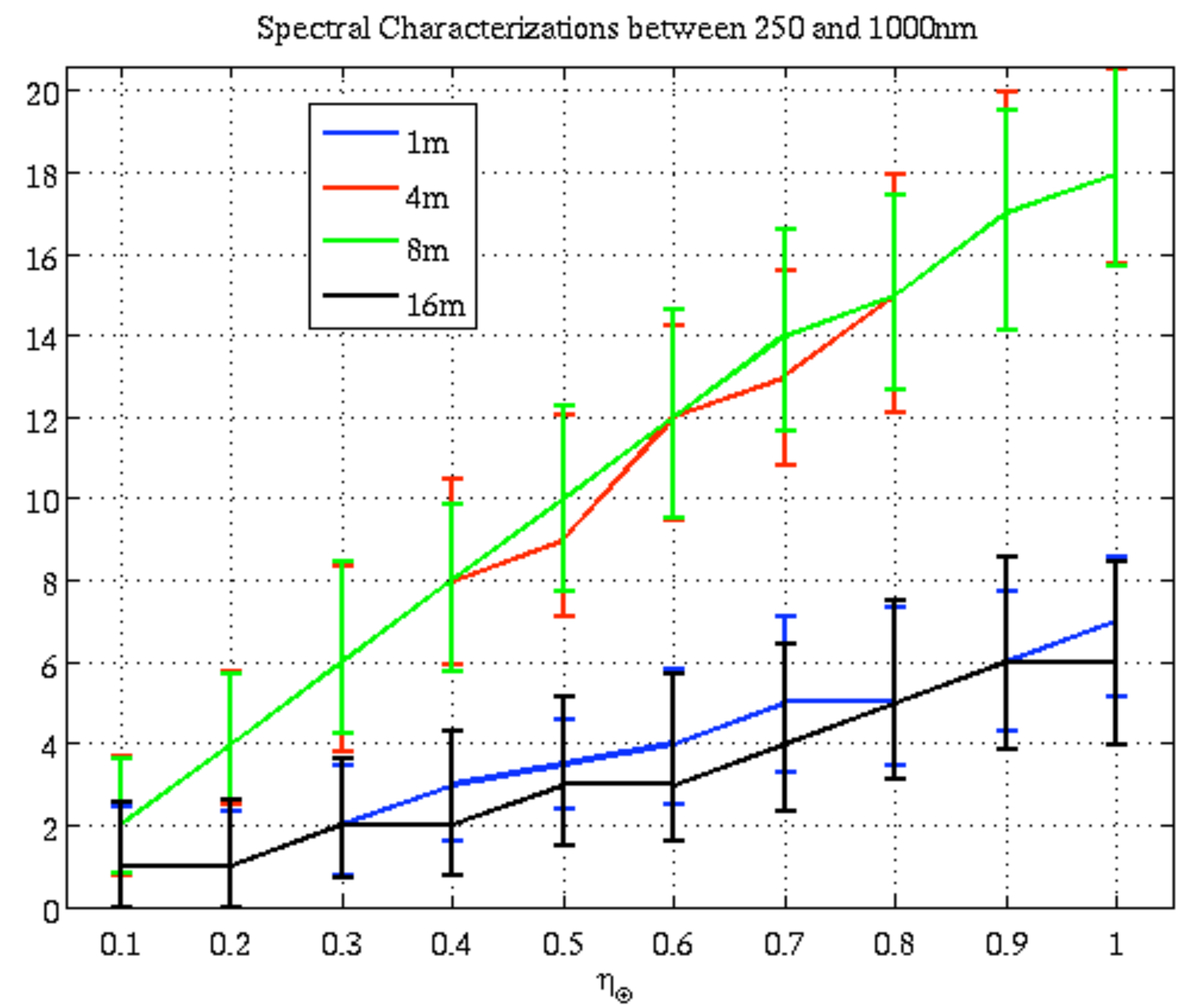




- Over 50 Earth like planets detected at eta = 1
- Same thrusters as 4 m
- 3 lambda/D still IWA limited, but better relative performance than 4 m
- For telescopes ≥ 8 m, coronagraphs outperform occulters

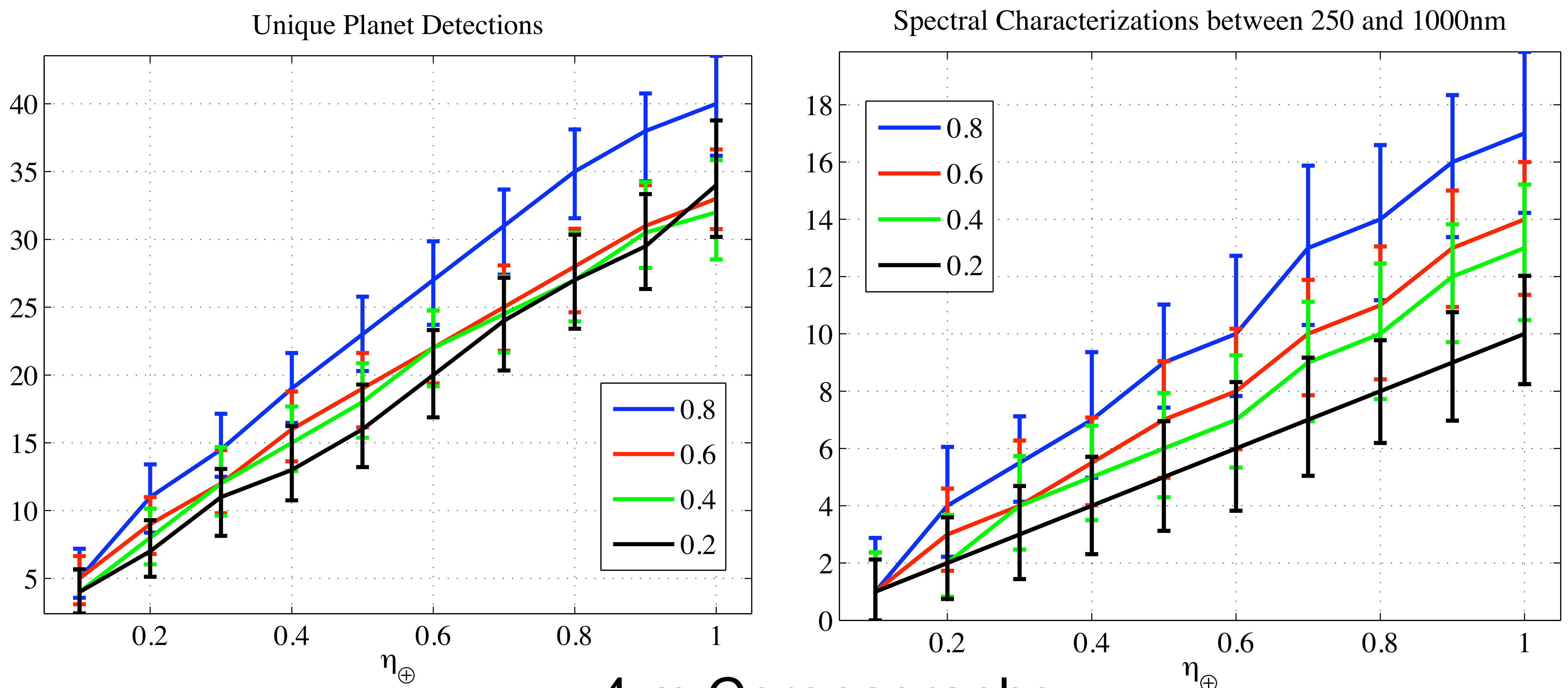
Multiple Distance Occulters





- 4 and 8 m MDO have similar performance
- 16 m MDO has very poor performance compared to coronagraphs
- 1 m MDO does remarkably well (25 Earthlike planets at eta = 1). May be a good choice for a lower cost (probe) mission. Only way to get Earths at this scale.

How Optimistic is Coronagraph Result?



4 m Coronagraphs

- Small variations for wide range of coronagraph throughputs
- Assumes long integration times are viable

Summary

Unique Detections $\eta_{Earth} = 1$ Full Spectra

	SDO	MDO	2 λ/D	3 λ/D
1 m	X	25	X	X
4 m	31	32	40	25
8 m	18	37	66	54
16 m	X	12	102	99

	SDO	MDO	2 λ/D	3 λ/D
1 m	X	7	X	X
4 m	24	18	17	5
8 m	15	18	44	24
16 m	X	6	95	80

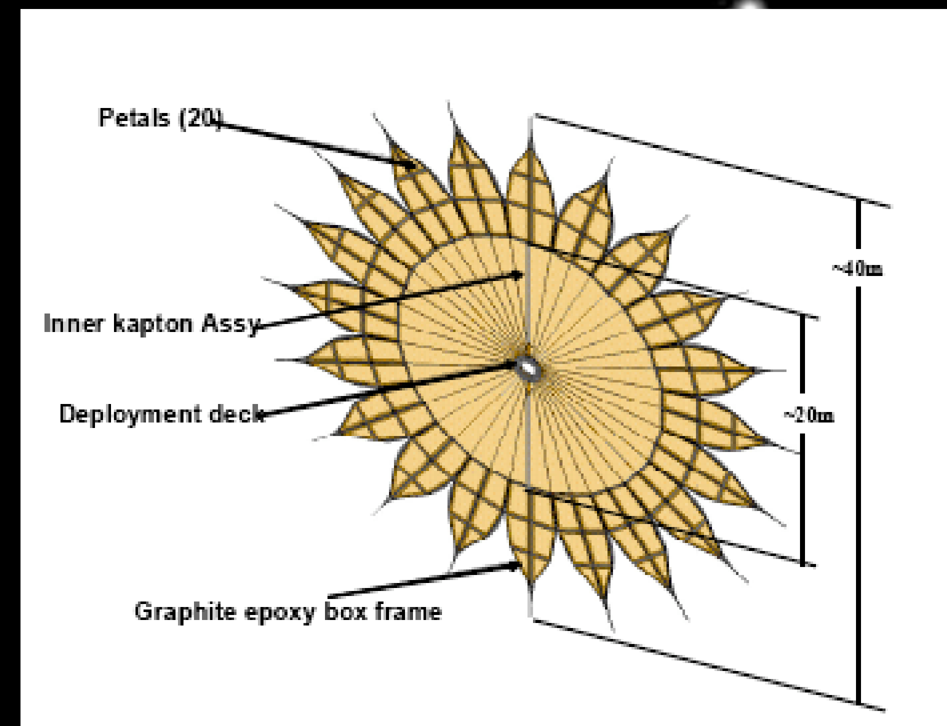
- At 4 m, little difference among architectures (except 3 lambda/D coronagraph) with some optimism
- Choice driven by technology and cost
- 1 m & 4 m MDO get similar numbers of detections!
- Starshades offer diminishing returns above 8 m without significant improvements in thrust/Isp

Are there less expensive options we can do sooner?

Can they get Earths?

JWST + Occulter

- Remi Soummer, Web Cash, et al.
- Advantages:
  - JWST will soon launch
  - 6 meter telescope
  - NirSpec



- Disadvantags:
  - Diffraction limited at 2 microns
  - Limited telescope time
  - Requires adding new filters
  - Requires very large tilted occulter (>60 m tip-to-tip) to increase operating angles
  - Occulter must do acquisition and control as well as move to targets.
  - Complexities of interfacing with major mission

Moderate Telescope + Occulter

- 1.1 -1.5 meter telescope (diffraction limited at 0.3 - 0.5 microns)
- Advantages:
  - Lightweight relatively inexpensive telescope can move, acquire occulter
  - Same resolving power as JWST
  - Can use smaller occulter (< 30 m) with relaxed requirements.
  - Can detect up to 5 Earths with eta = 0.3
  - Can repeat visits for orbits
  - Can detect ozone
  - Opportunities for general astrophysics


Thank You.