Perspectives on High Contrast Imaging 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Sentenced rescinded and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

Exoplanets Rising:
Astronomy and Planetary
Science at the Crossroads

Kavli Institute for Theoretical Physics

30 March 2010

Prediction

- Sometime in the next four years, Kepler will announce the detection of significant numbers of Earth-like planets around typical stars.
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"Can we see another Earth?"

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This talk discusses the status for doing it from space.

Prediction

- will

  ical

- h?”

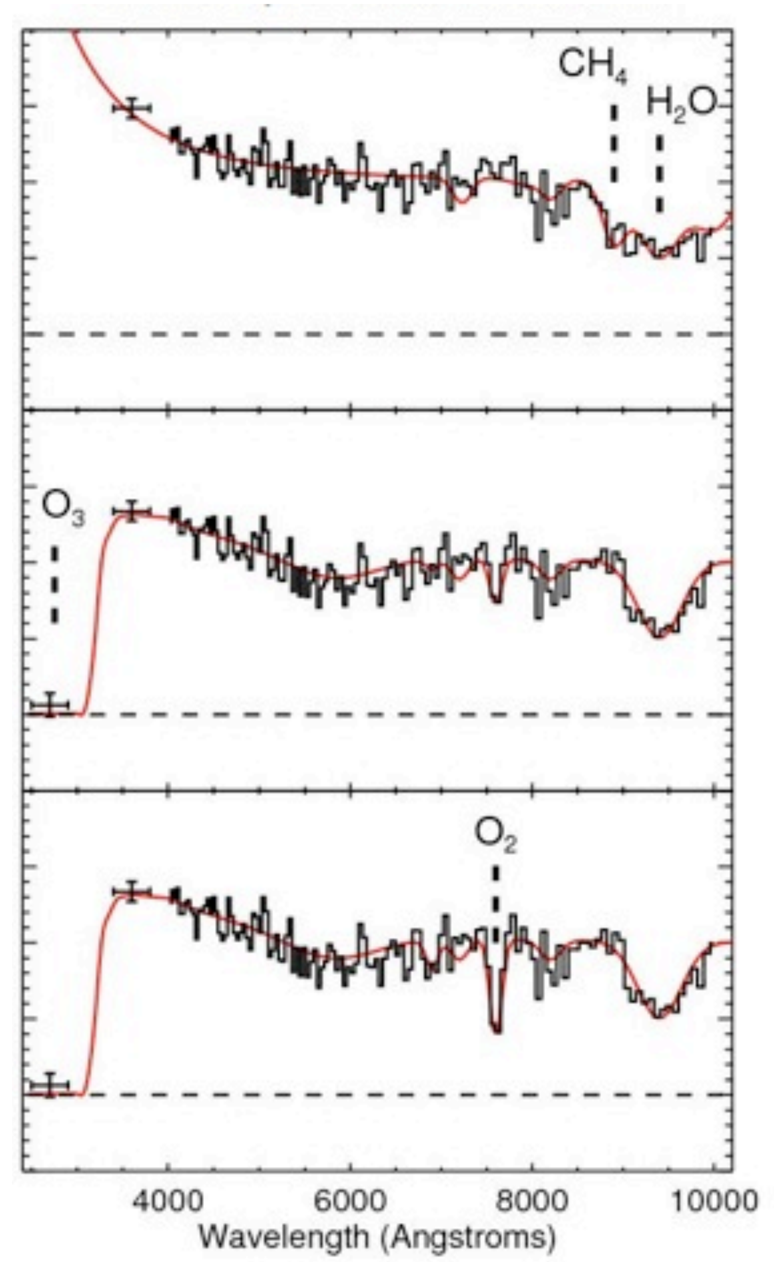
> We choose to . . . do [these] things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend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

This talk discusses the status for doing 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!

Question: What does it take to achieve extremely "High Contrast" in a space telescope?

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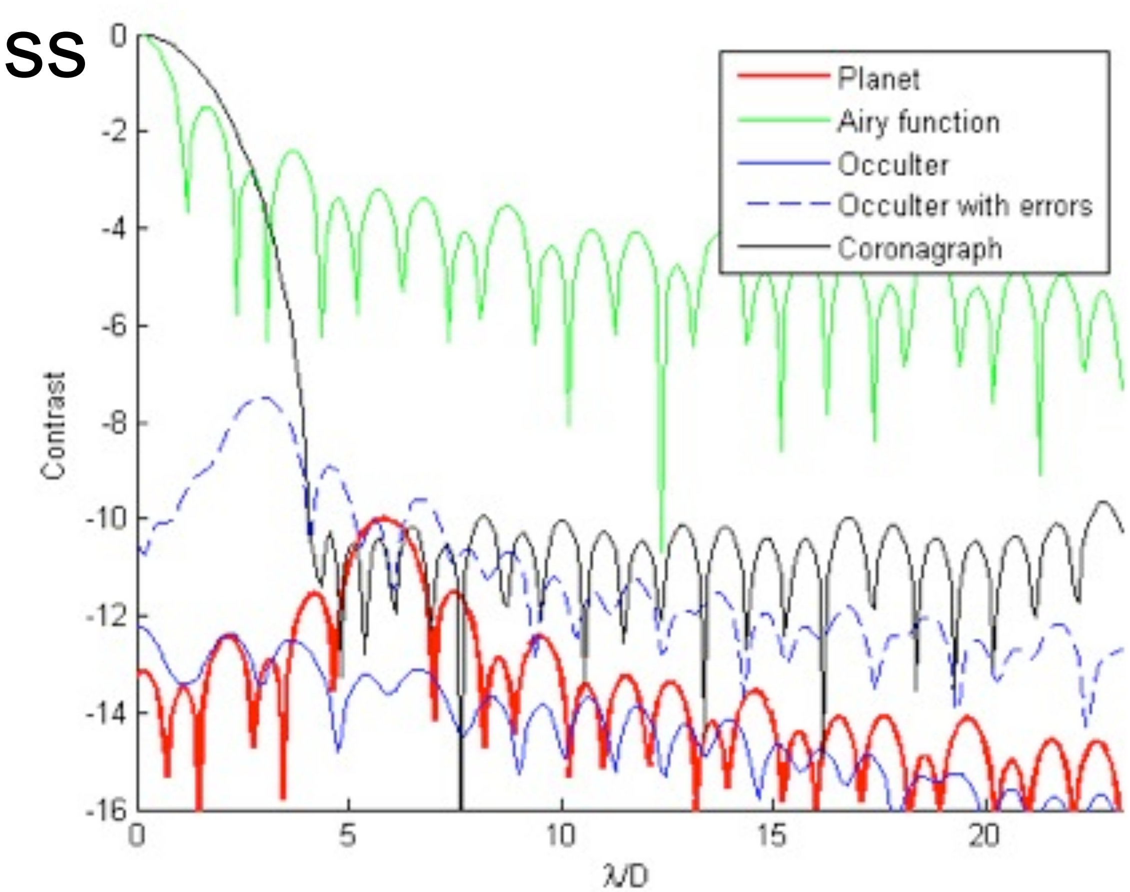
Metrics

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

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.

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REMEMBER: It is all about taking a Fourier Transform!

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Except when it is not!

Phase in Image Plane

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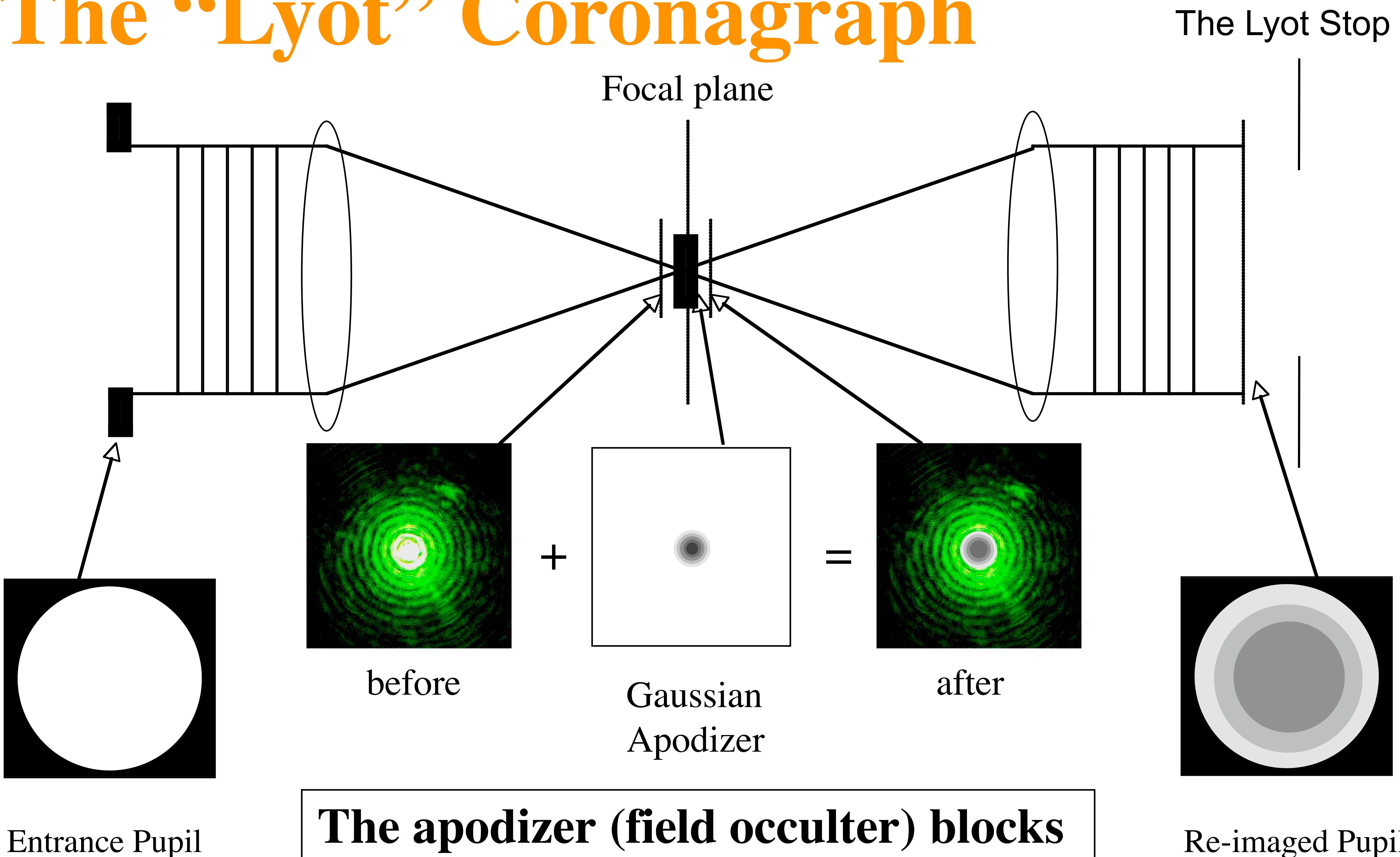
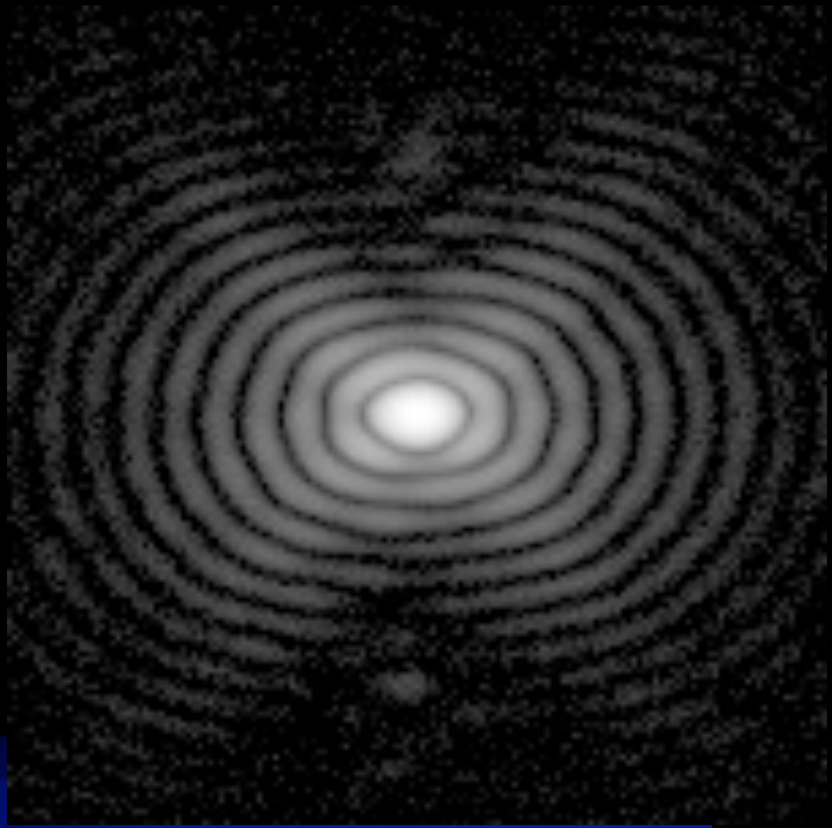
The "Lyot" Coronagraph

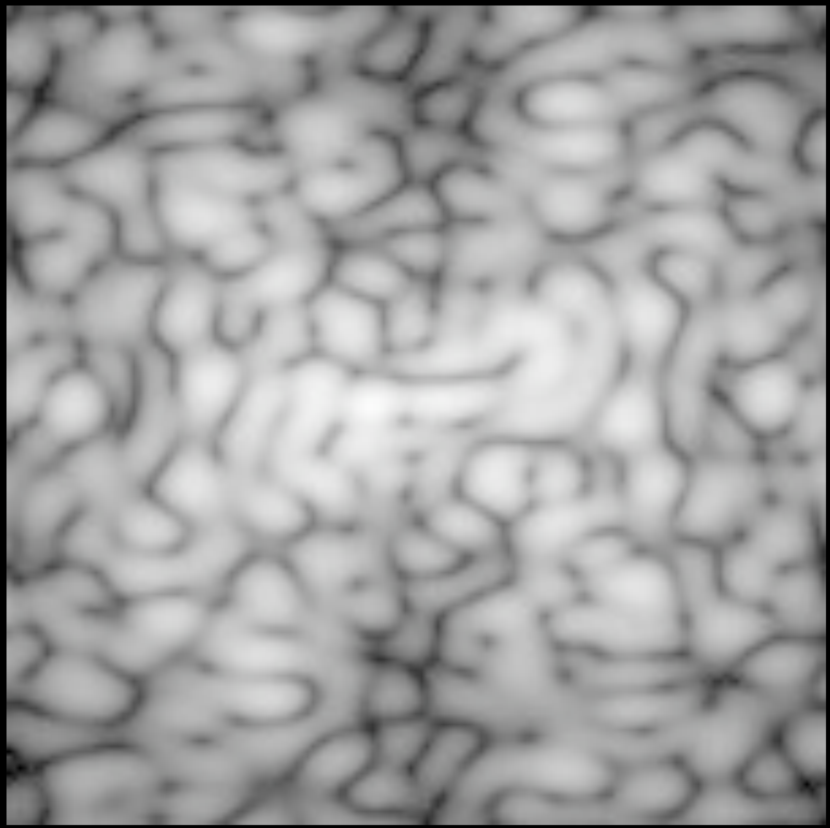


The apodizer (field occulter) blocks most of the light from the star

HCIT Monochromatic Result



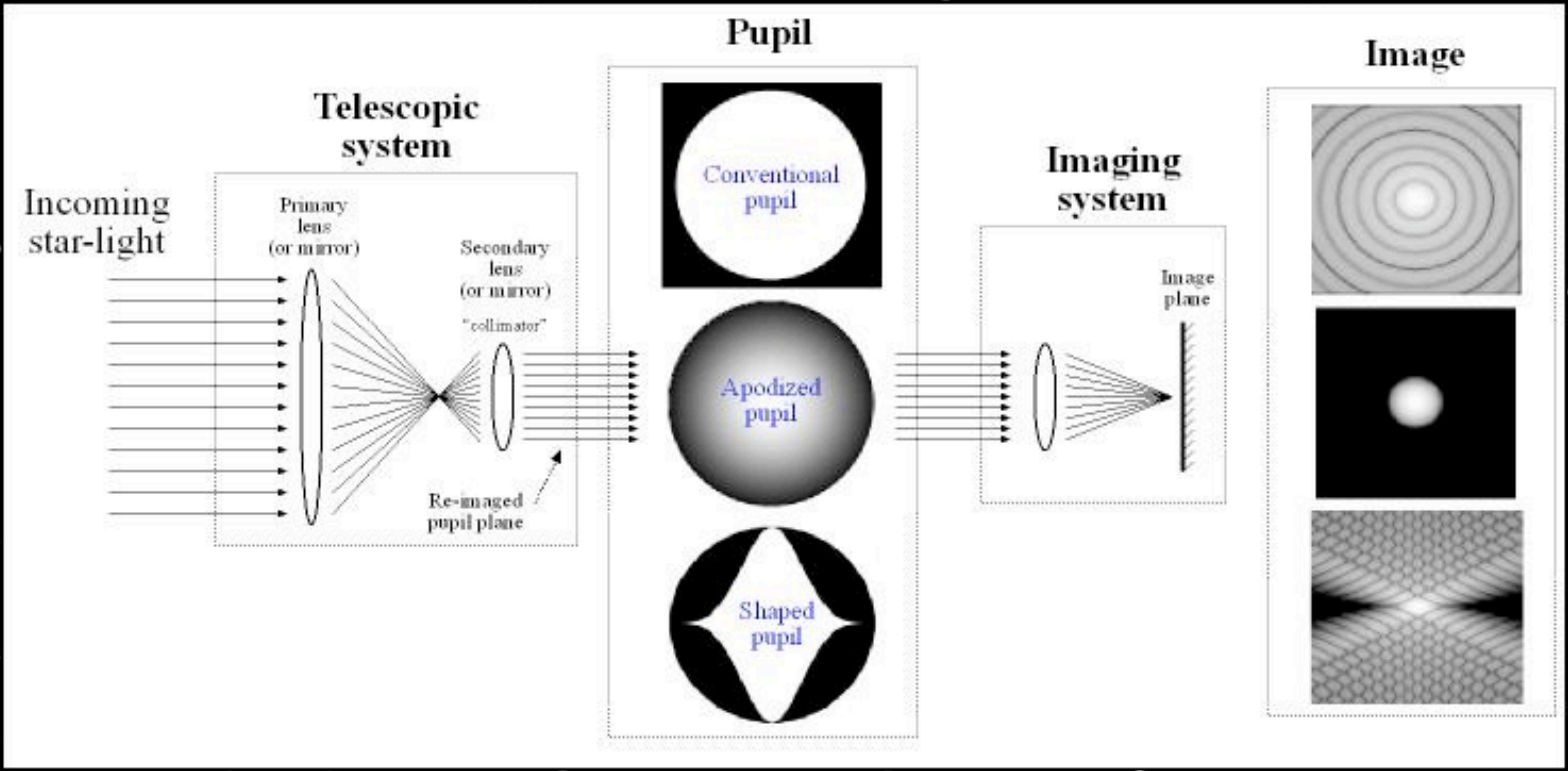
“planet” PSF: occulter moved aside, Lyot in place, narrowband diode laser



coronagraph PSF, DM “flat”, narrowband

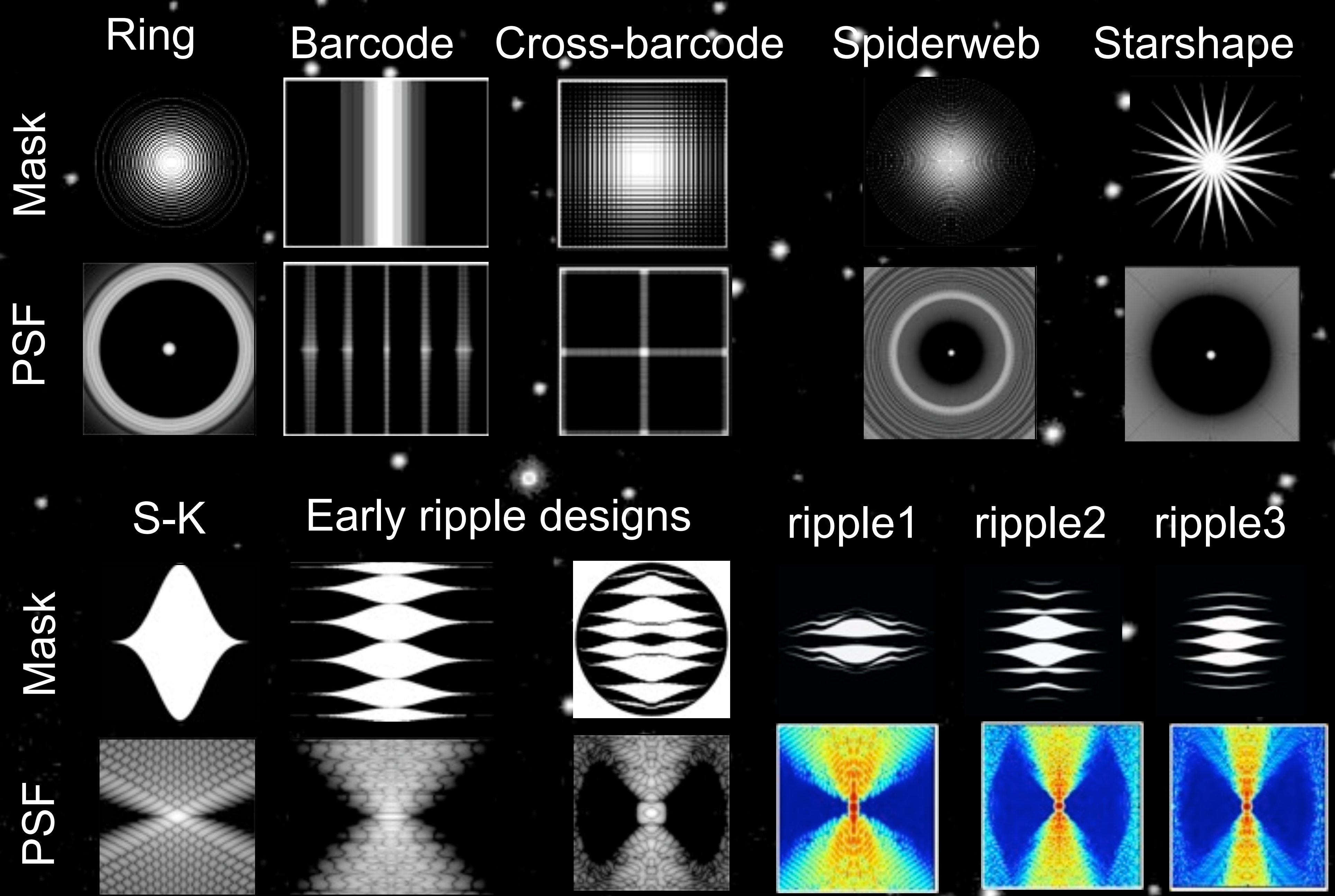
Exquisite experimental design.
Limited by optical quality!

Pupil Apodization to Reshape PSF



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

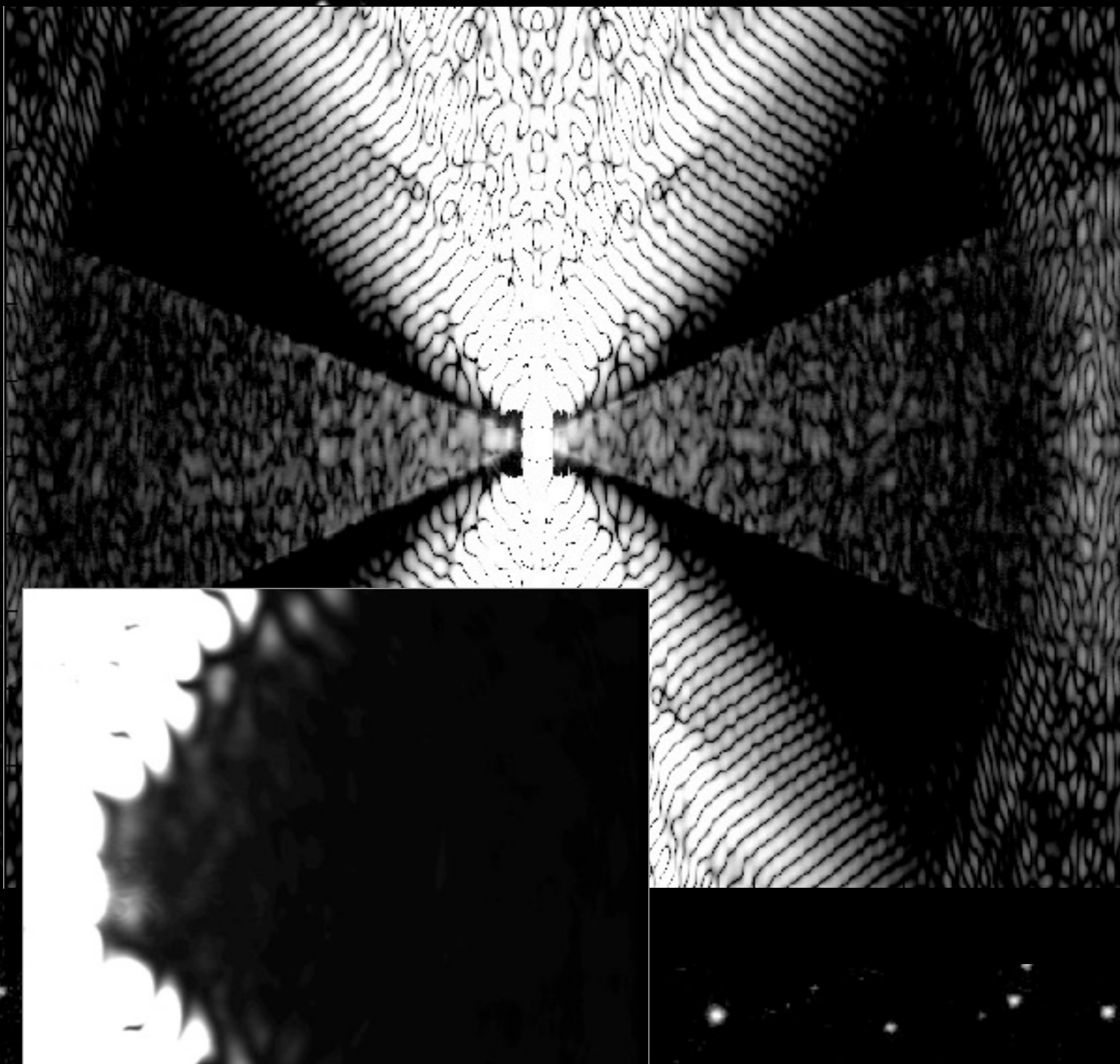
Shaped Pupil Zoo

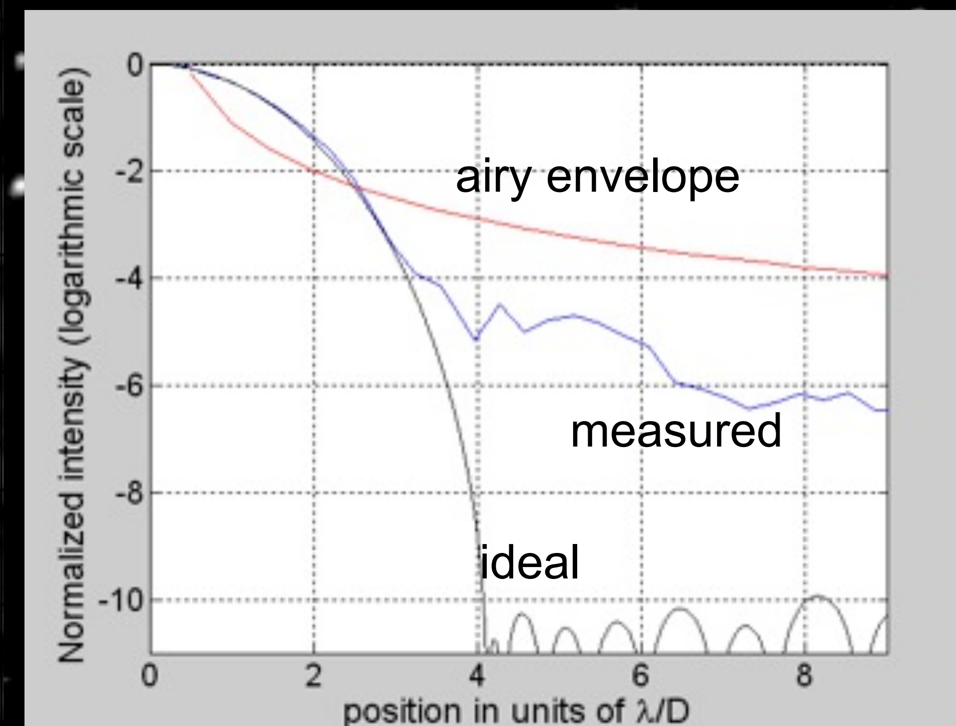


- Shaped pupils: A(x,y) is zero-one valued (holes in masks)
- Advantages:
  - simple to manufacture
  - inherently broadband
  - minimally sensitive to aberrations
  - no off-axis degradation of PSF
- Disadvantages:
  - throughput (though roughly the same as 8th order Lyot coronagraph)
  - IWA (better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

Pupils designed via optimization under certain constraints

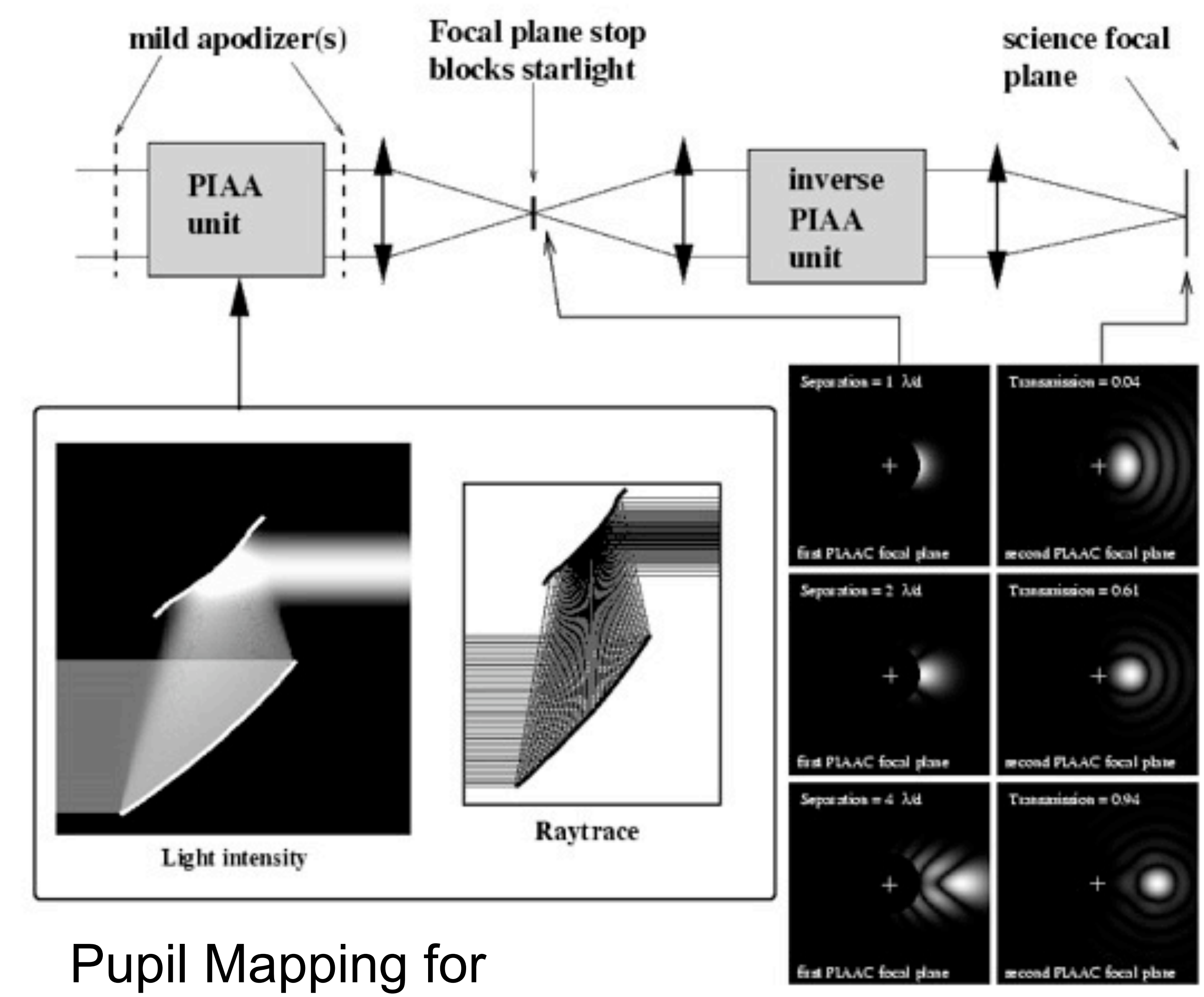
Contrast Measurement at 633nm





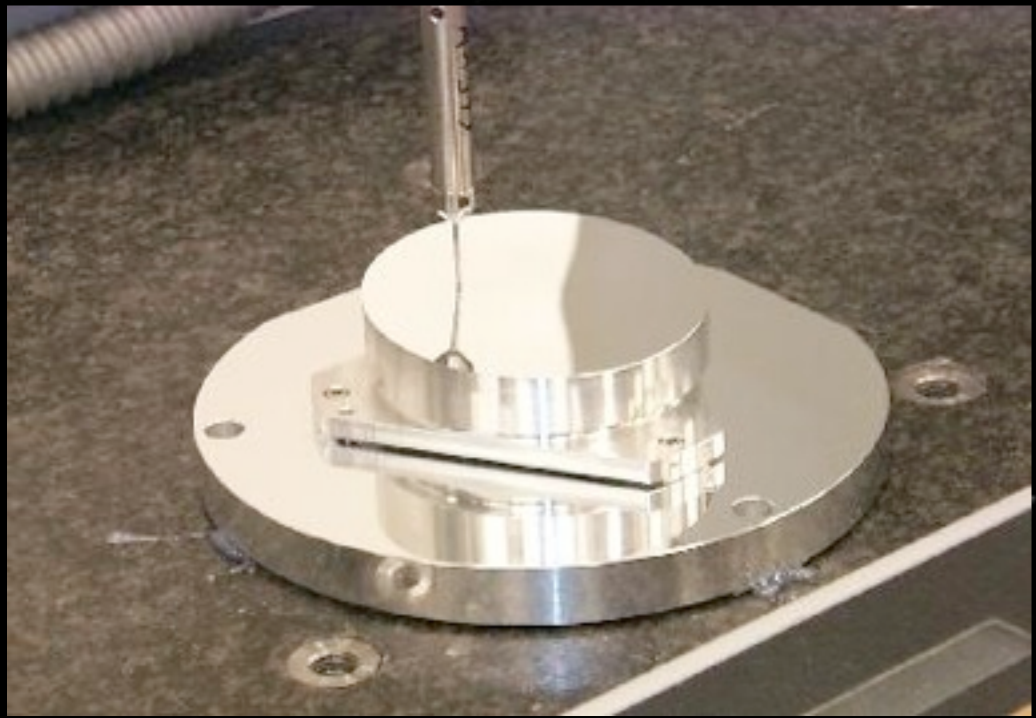
- Contrast:
  - ~10^{-5} @ 4 λ/D
  - <10^{-6} @ 7 λ/D

Phase Induced Amplitude Apodization (PIAA)



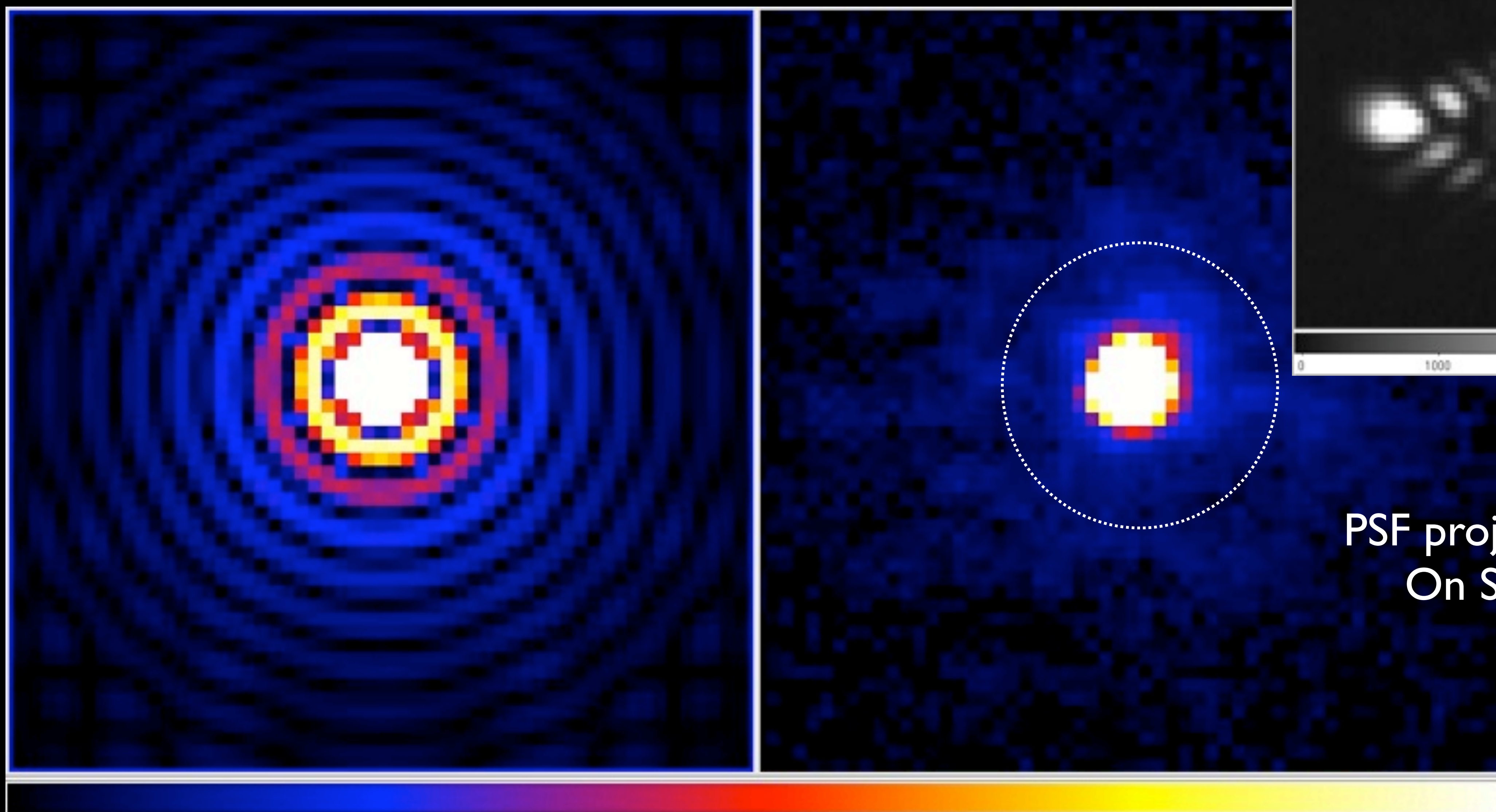
Pupil Mapping for Apodization

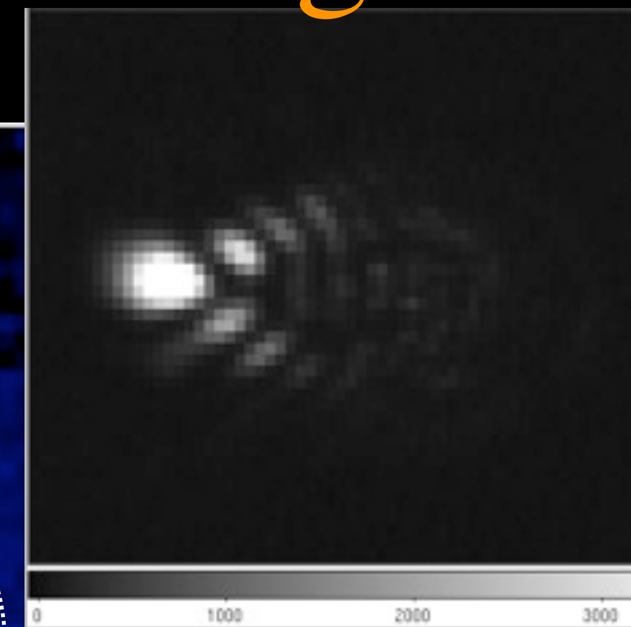
Nearly 100% throughput
100% search area
small (<2 lambda/d) Inner Working Angle



Uncorrected Pupil Remapped Image

Contrast ~6e-4



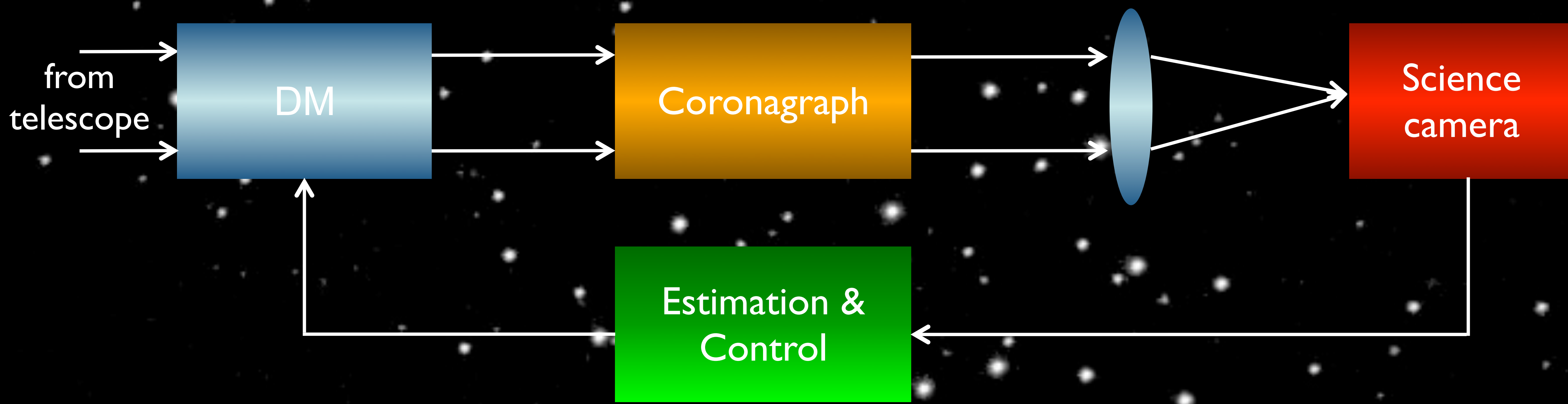


PSF projected
On Sky

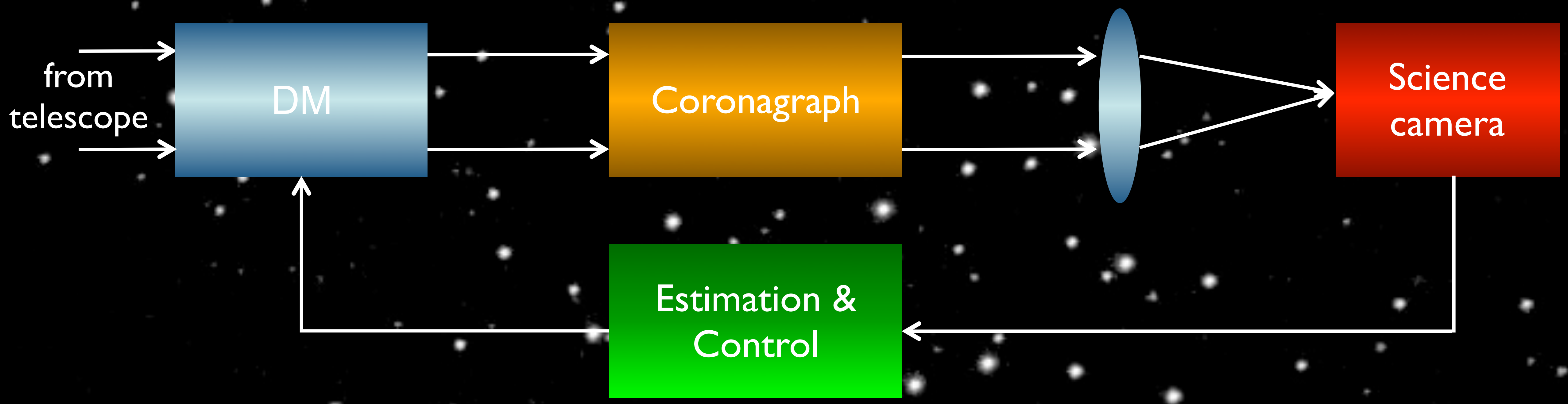
Conventional image (computed)

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.

Wavefront Control



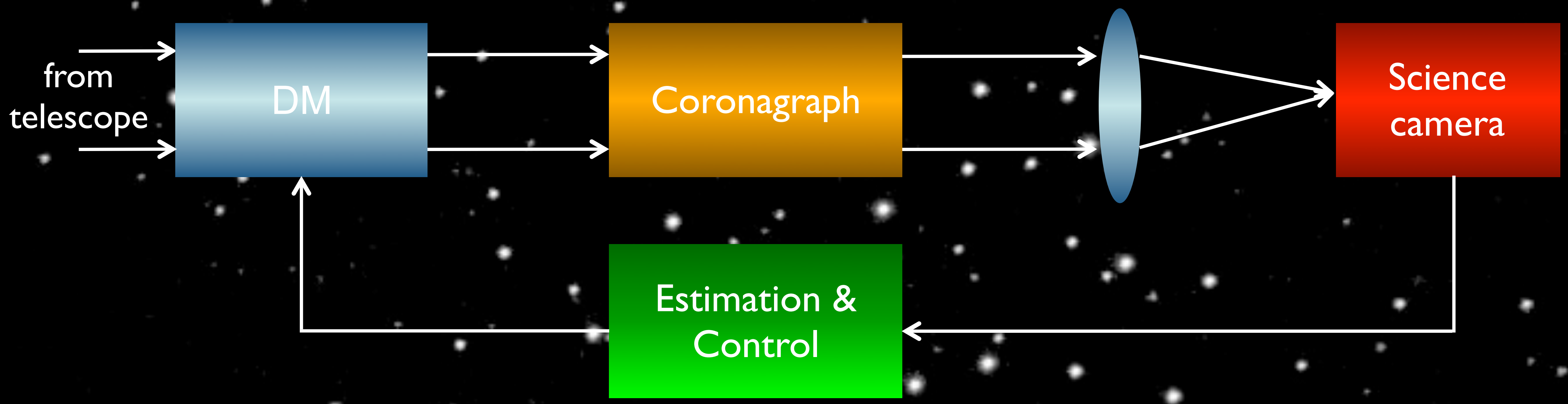
Wavefront Control



<u>Control Algorithms:</u>
Speckle Nulling
Energy Minimization
Electric Field Conjugation
Stroke Minimization

<u>Estimation Algorithms:</u>
DM Diversity
Gerchberg-Saxton

Wavefront Control



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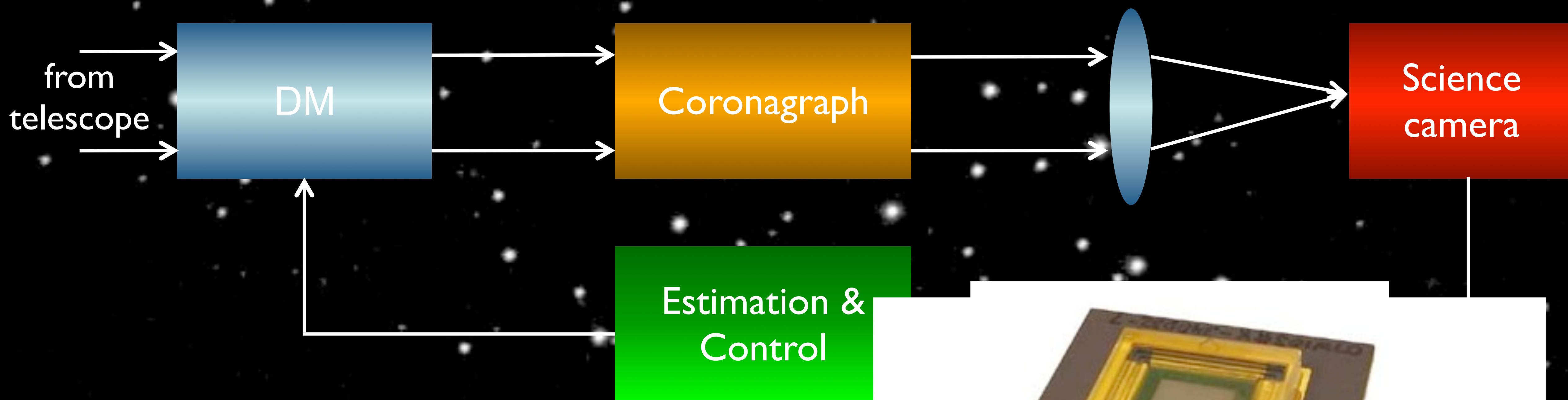
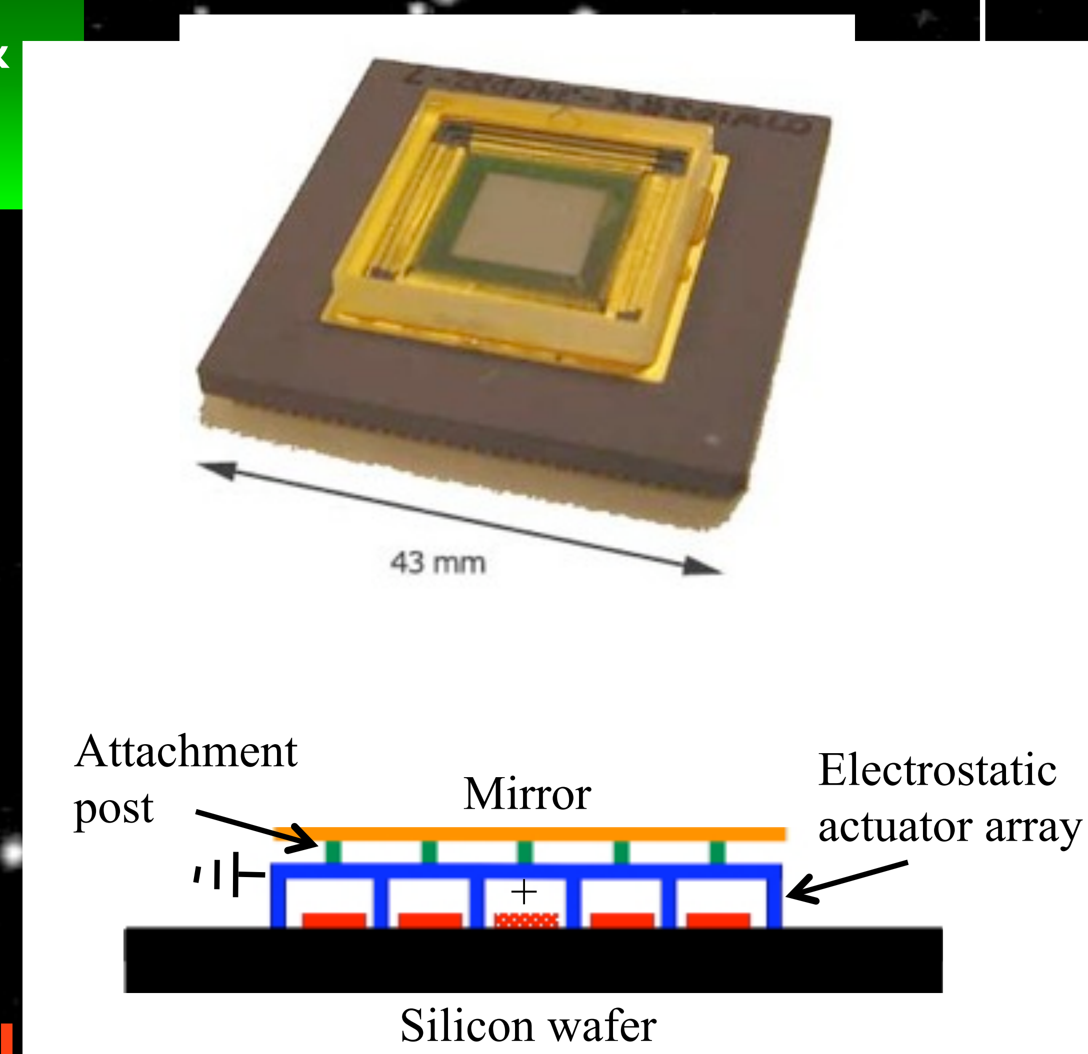
Need to correct both Amplitude & Phase Errors!

Wavefront Control





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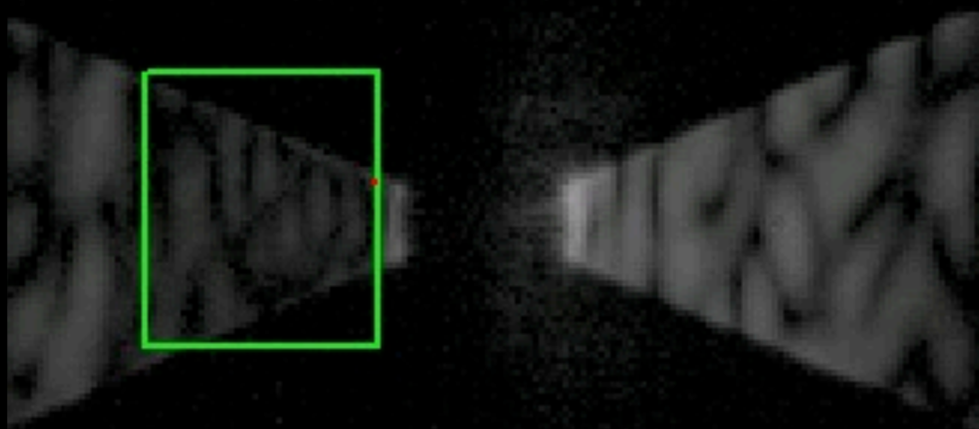
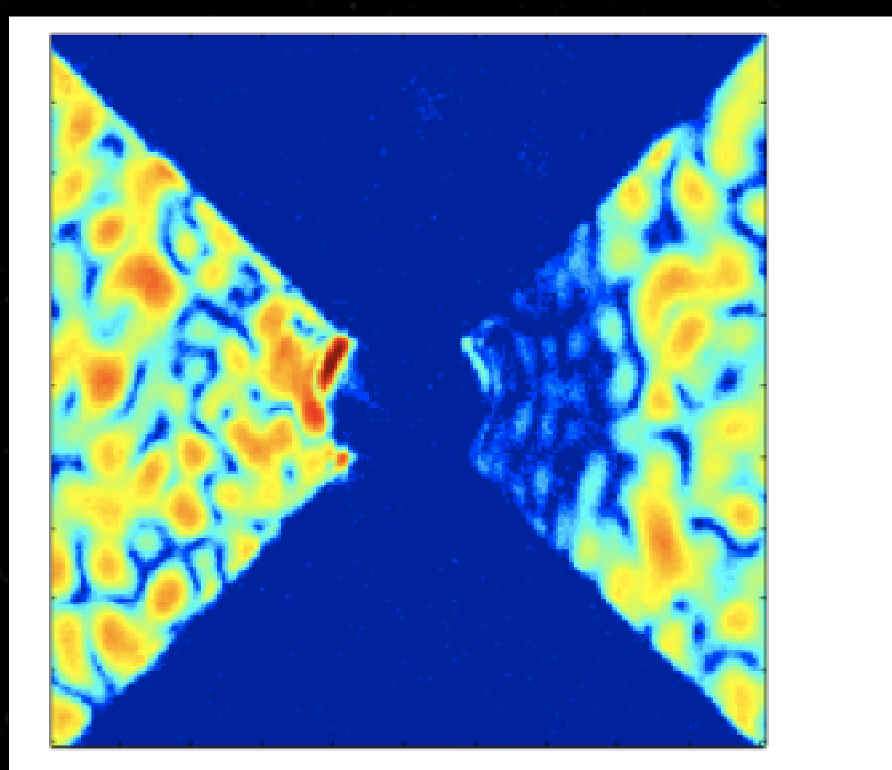
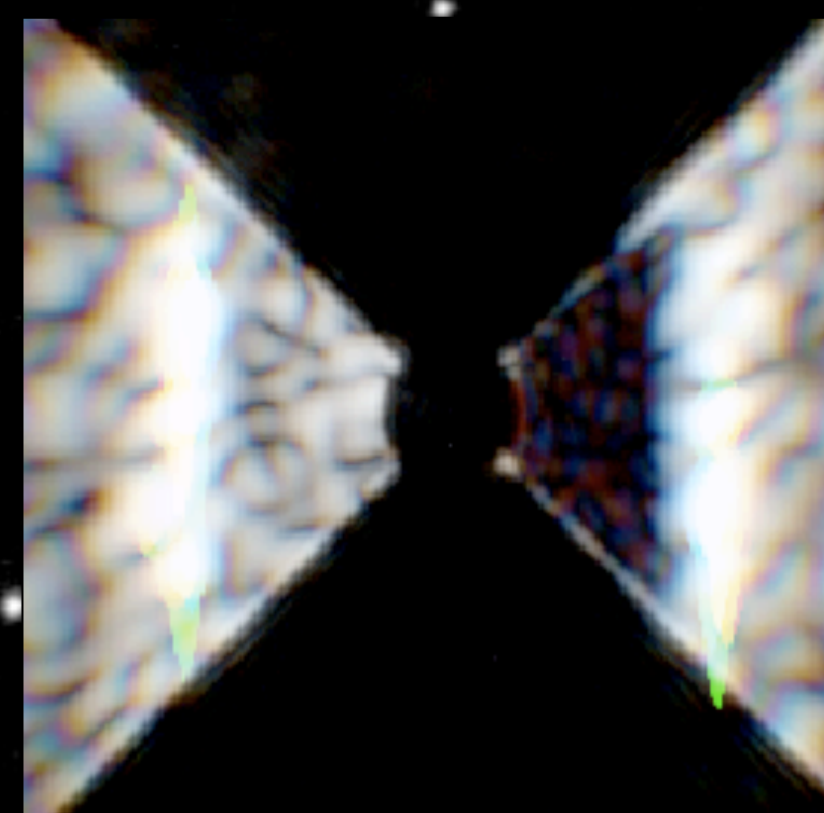
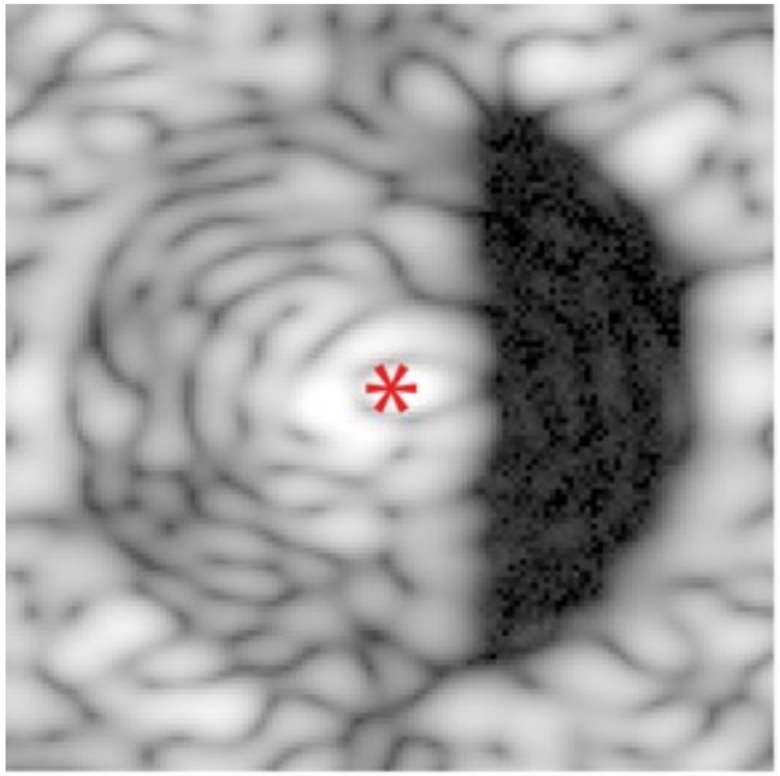
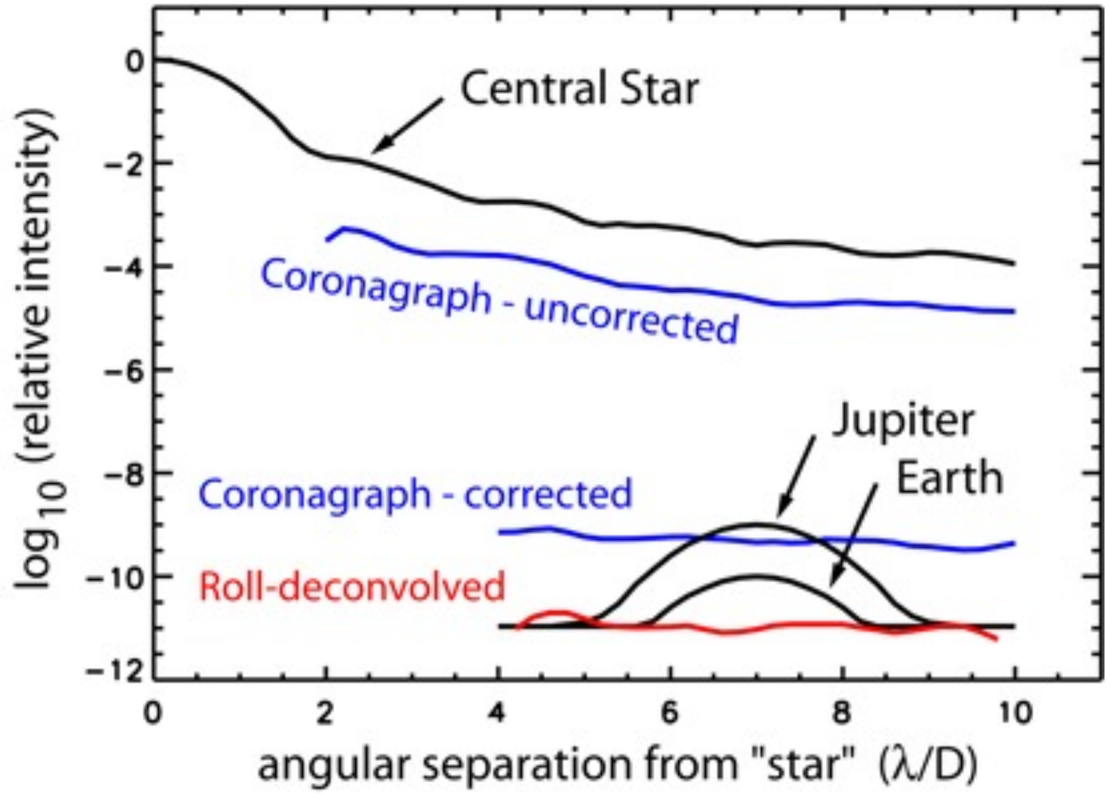
Shaped Pupil Experiments





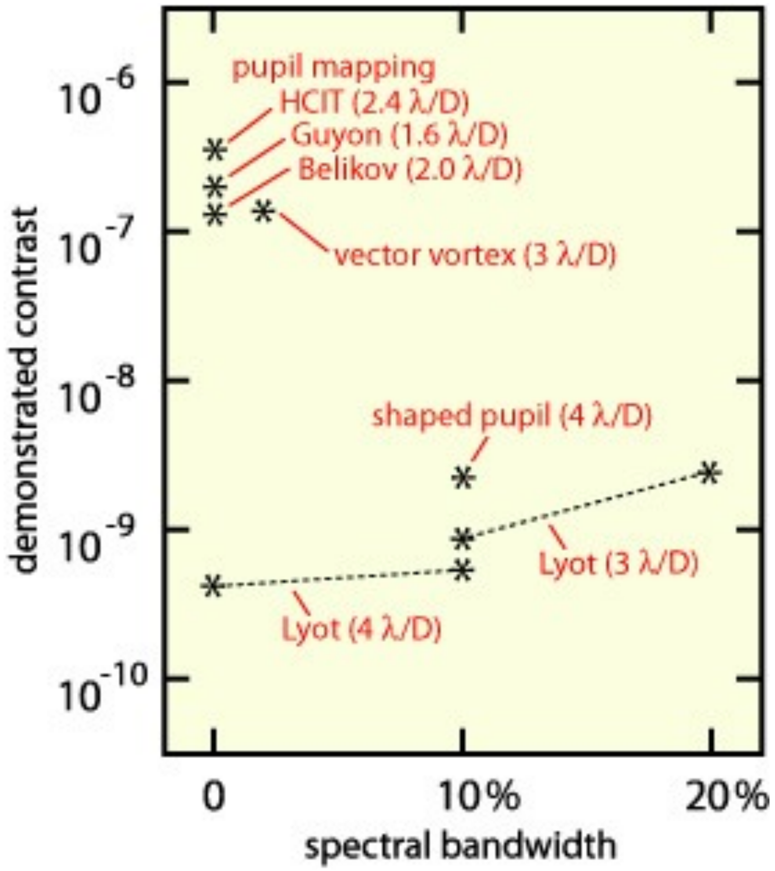






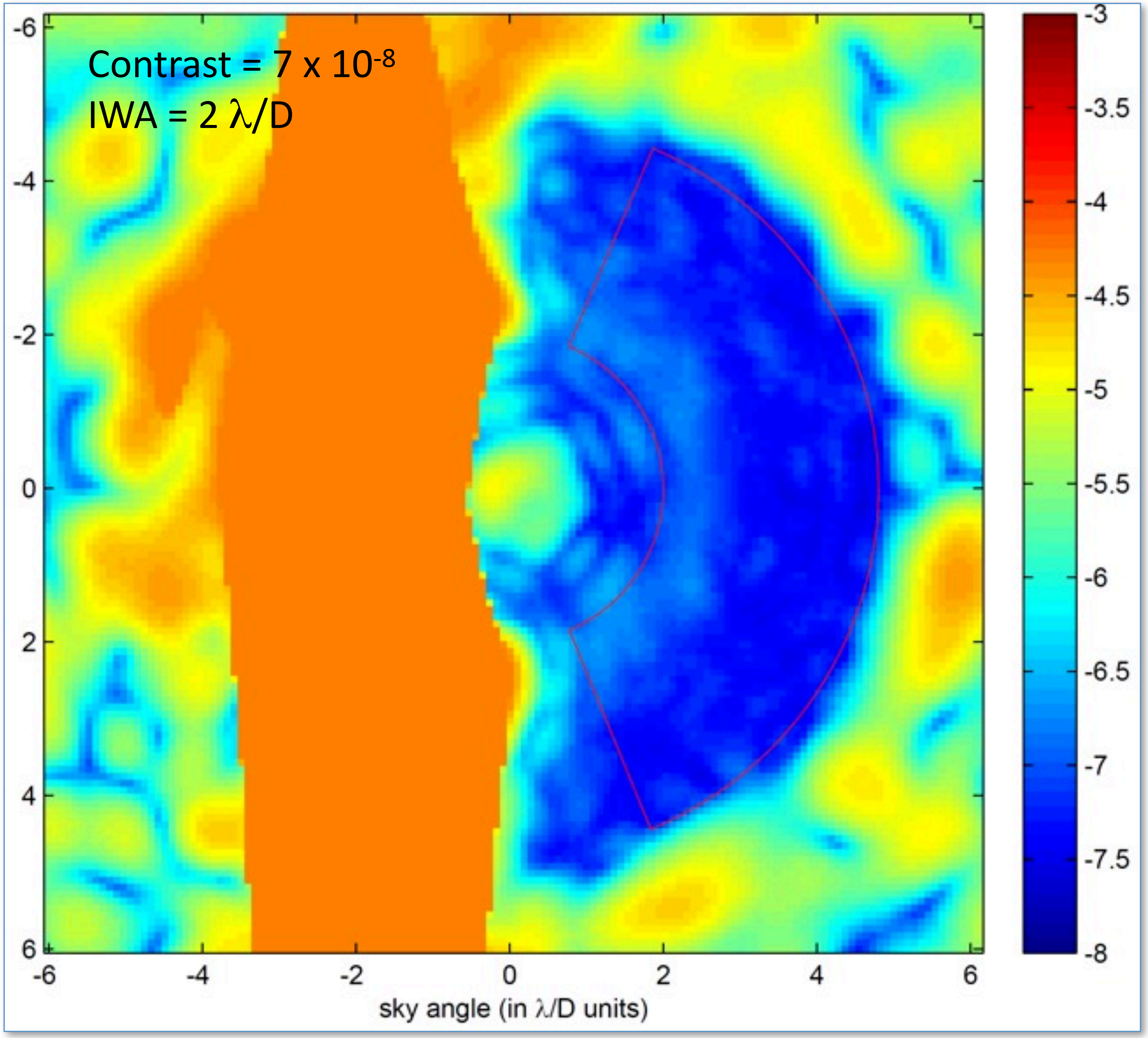
Bandlimited Lyot

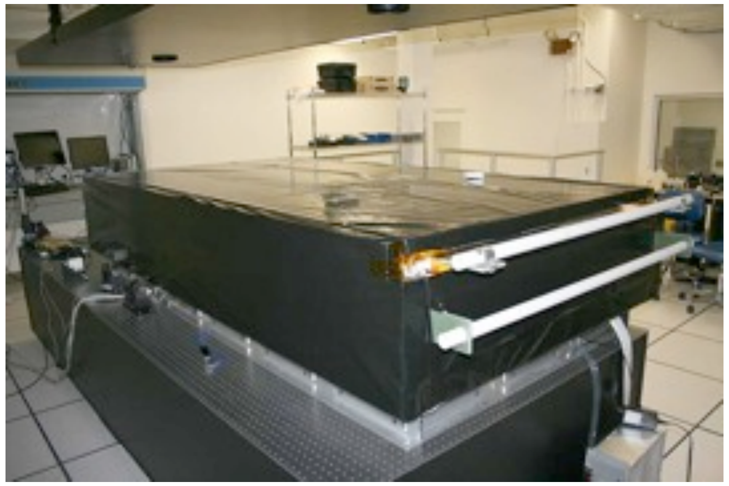
Four coronagraph types have been tested at HCIT

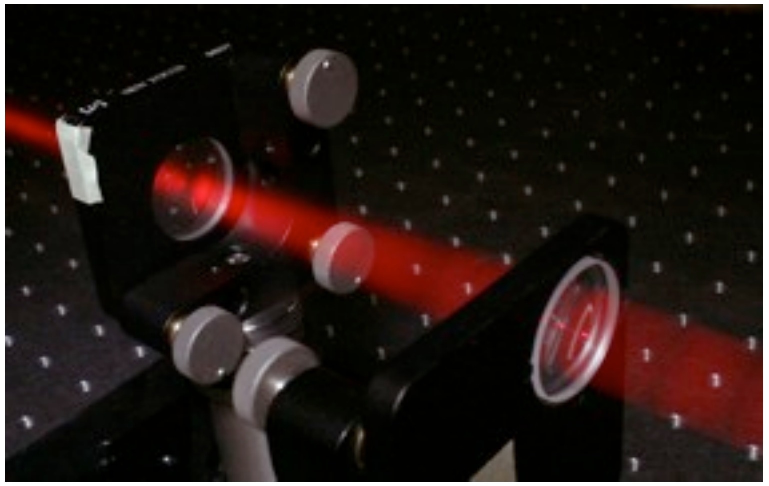


PIAA at Ames

Belikov, et al.

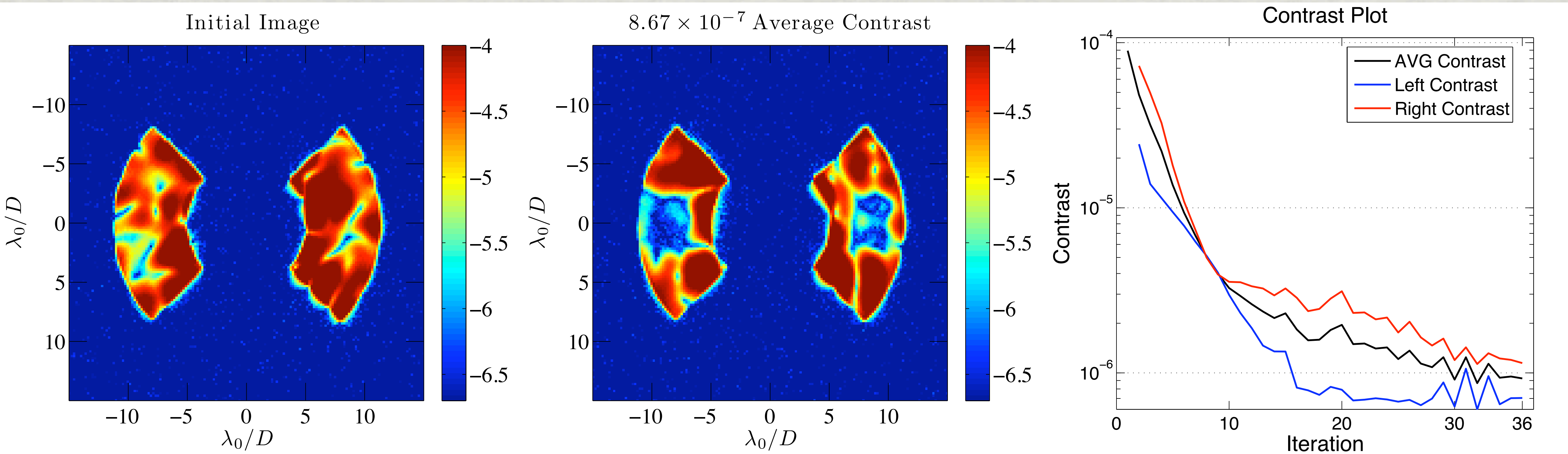




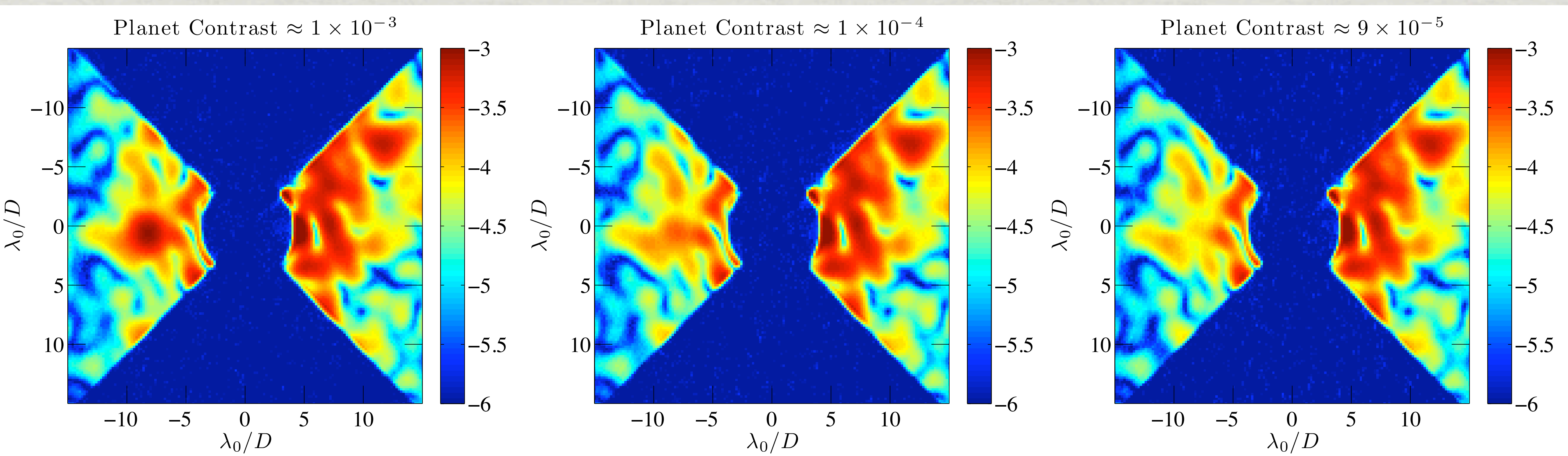


Monochromatic Performance

8.67 x 10^-7 Average Contrast on Both Sides of the Image Plane

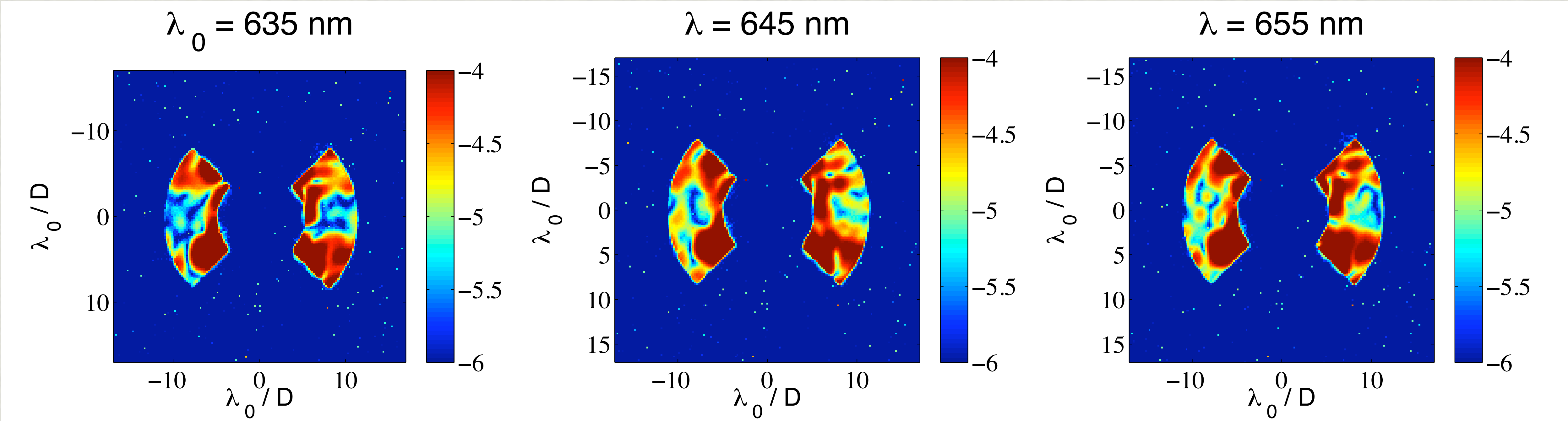


Implementation of variable power artificial planet

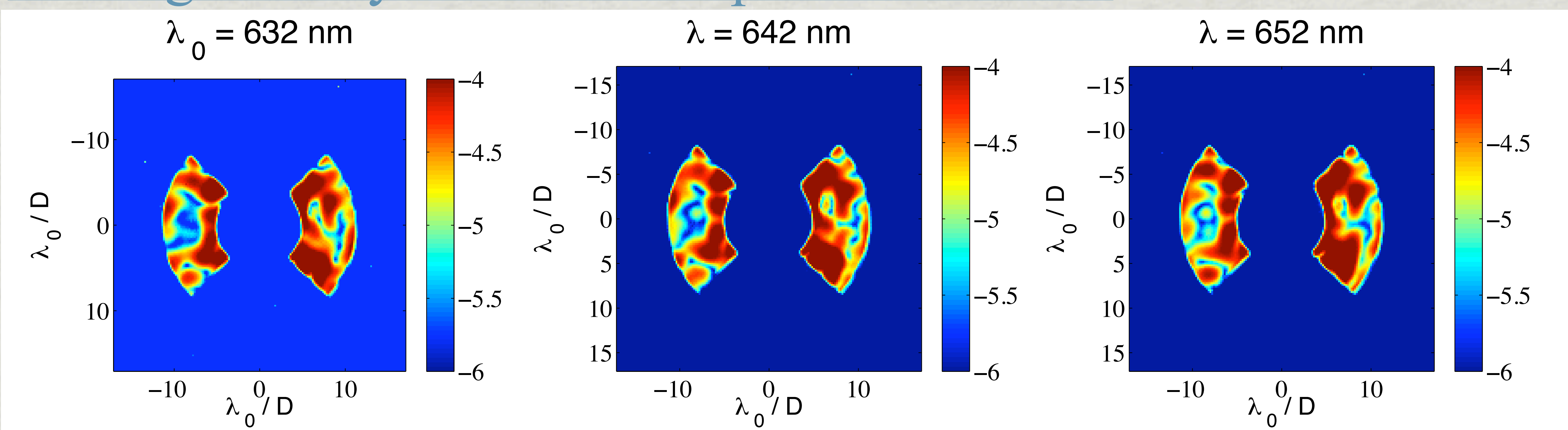


Current Broadband Performance - Images

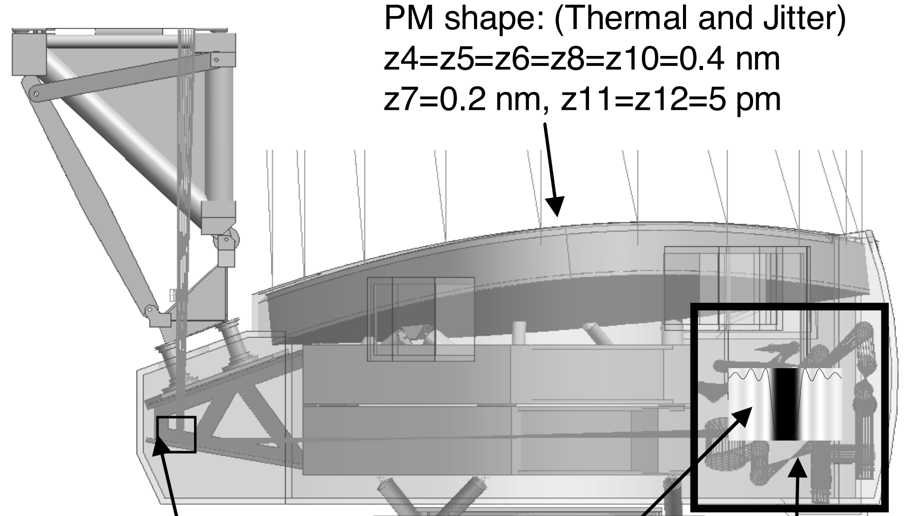
Dividing Energy in Half

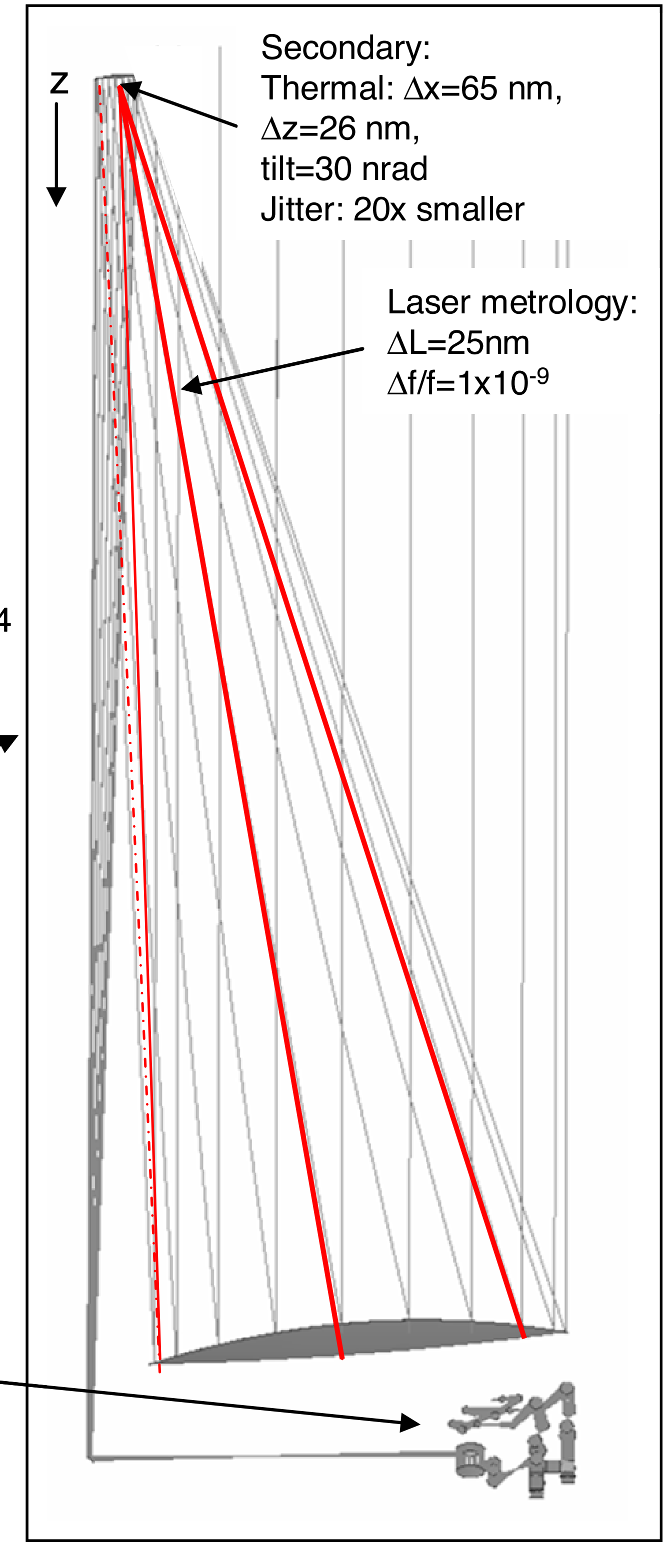


Forcing Anti-Symmetric Component on DM2



Coronagraph Requirement Allocation

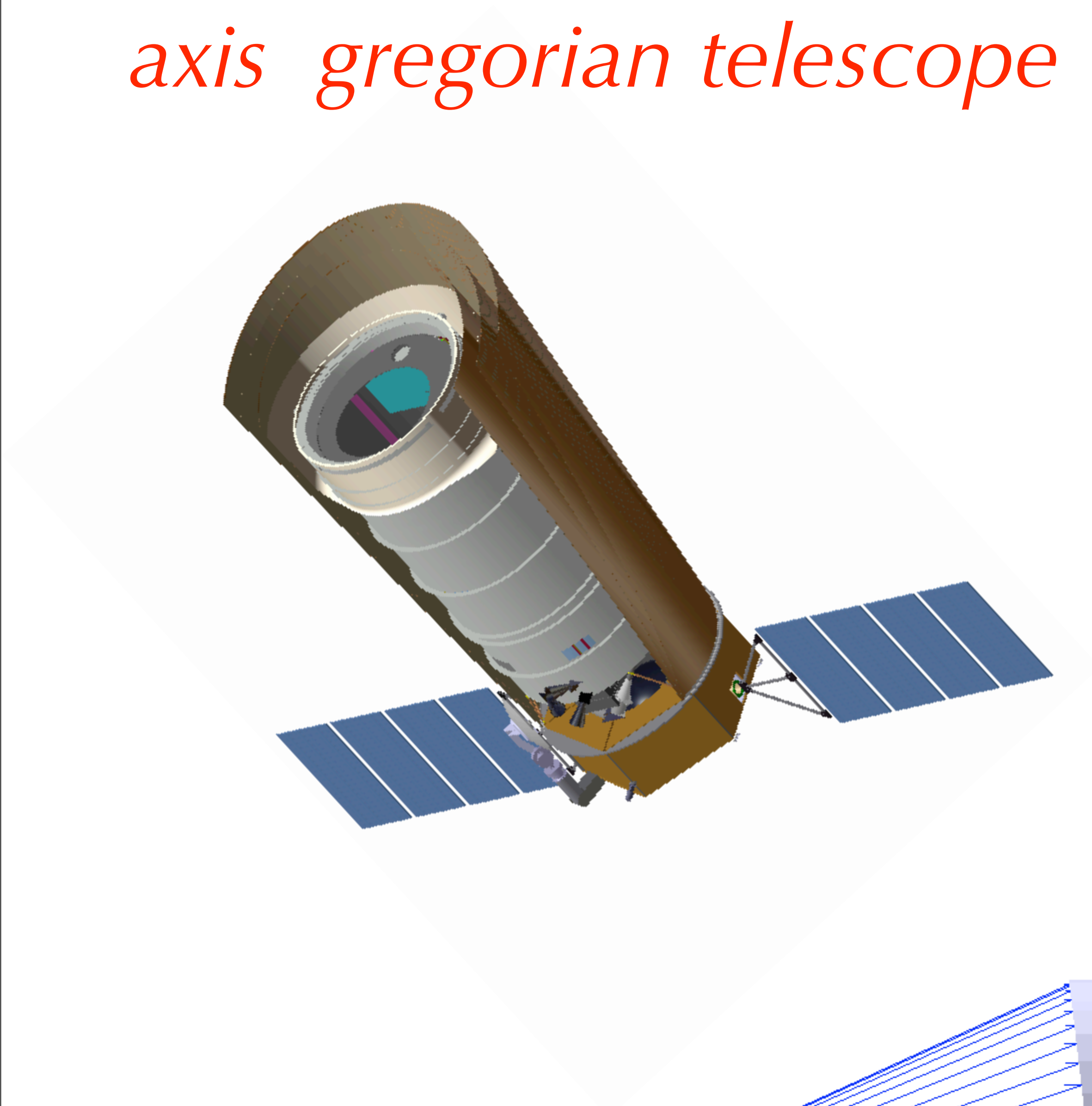


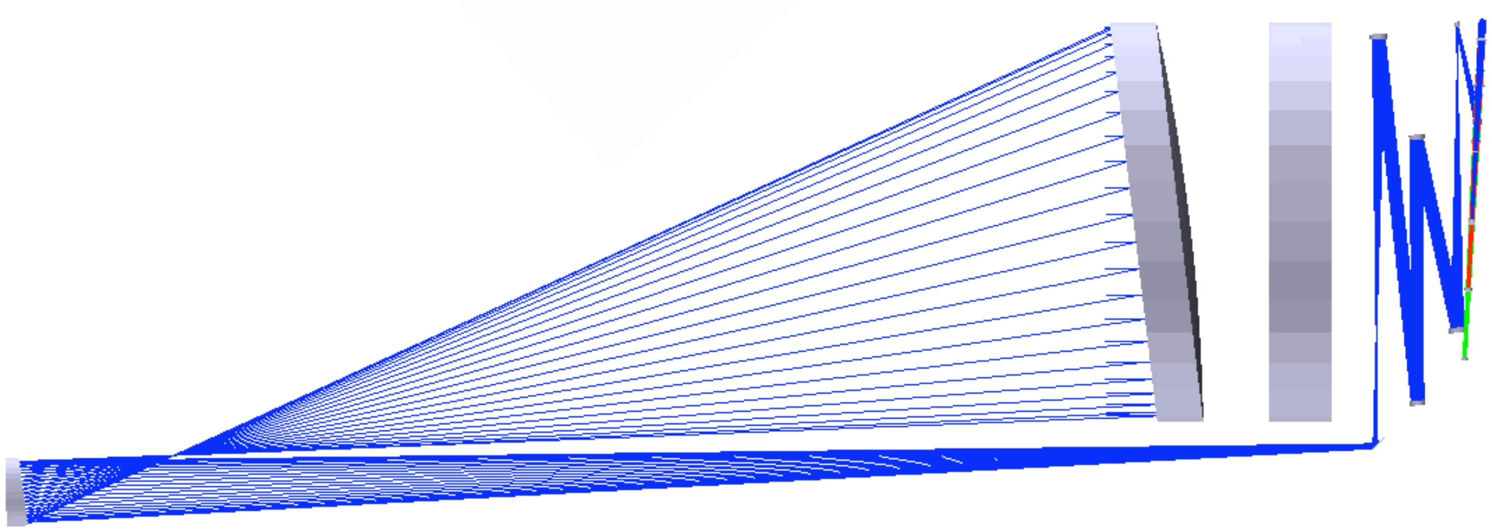


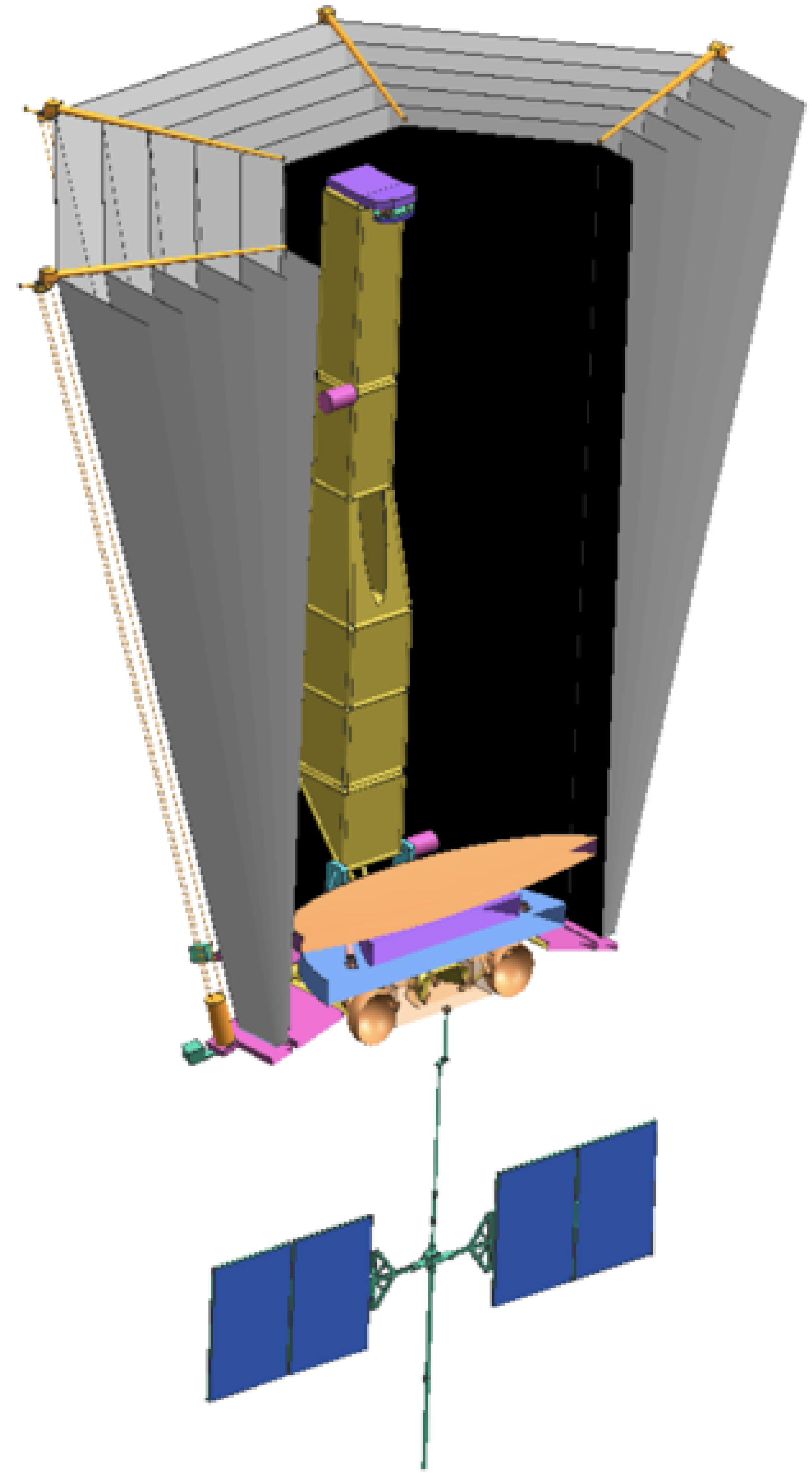
Perturbation	Contributor	Nature	Contrast	Fraction
Structural Defomation	Beam Walk	Thermal	8.29E-13	16.12%
		Jitter	6.33E-13	12.31%
	Aberrations	Thermal	3.28E-14	0.64%
		Jitter	4.43E-17	0.00%
Bending of Optics	Aberrations	Thermal	8.60E-13	16.72%
		Jitter	8.60E-13	16.72%
Pointing	Beam Walk		1.29E-12	25.10%
	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

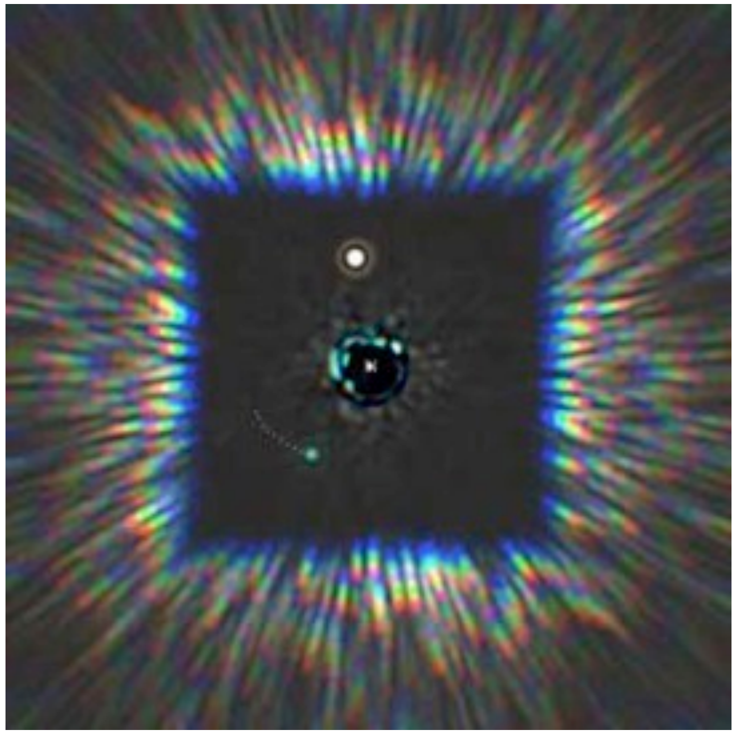






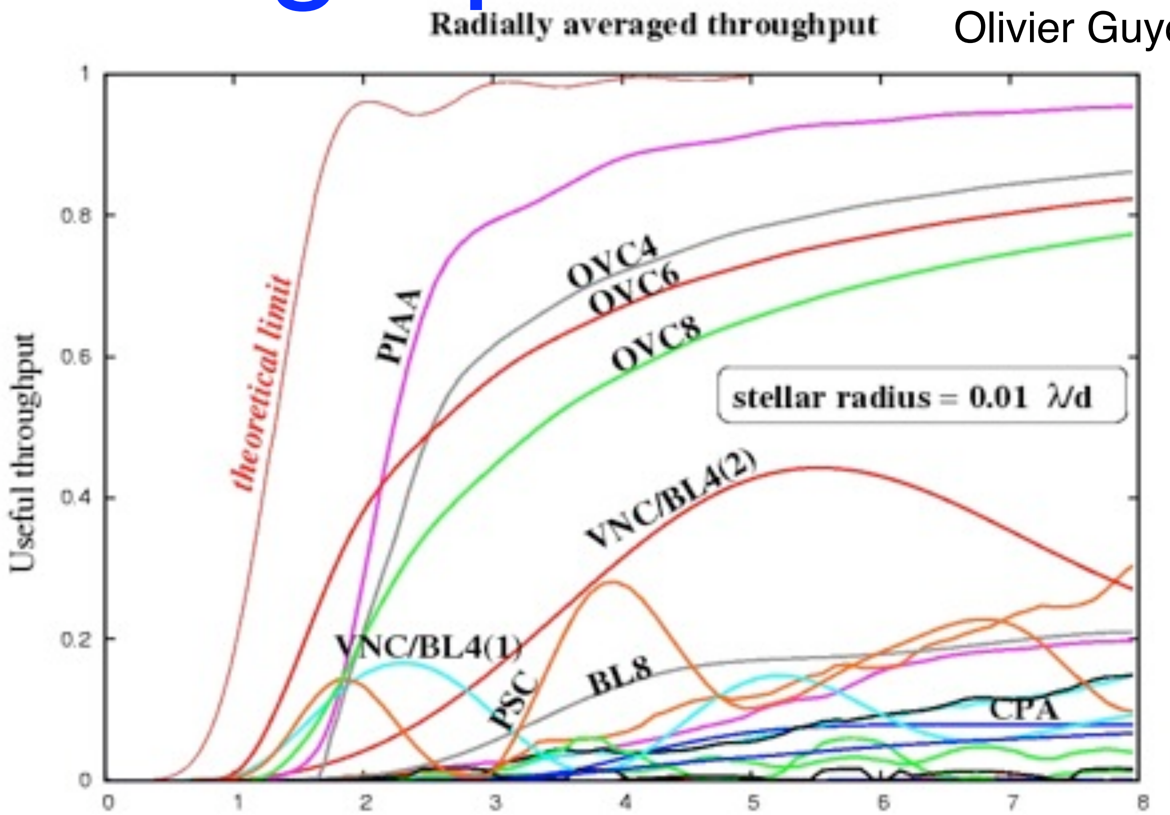
Internal Coronagraphs

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).

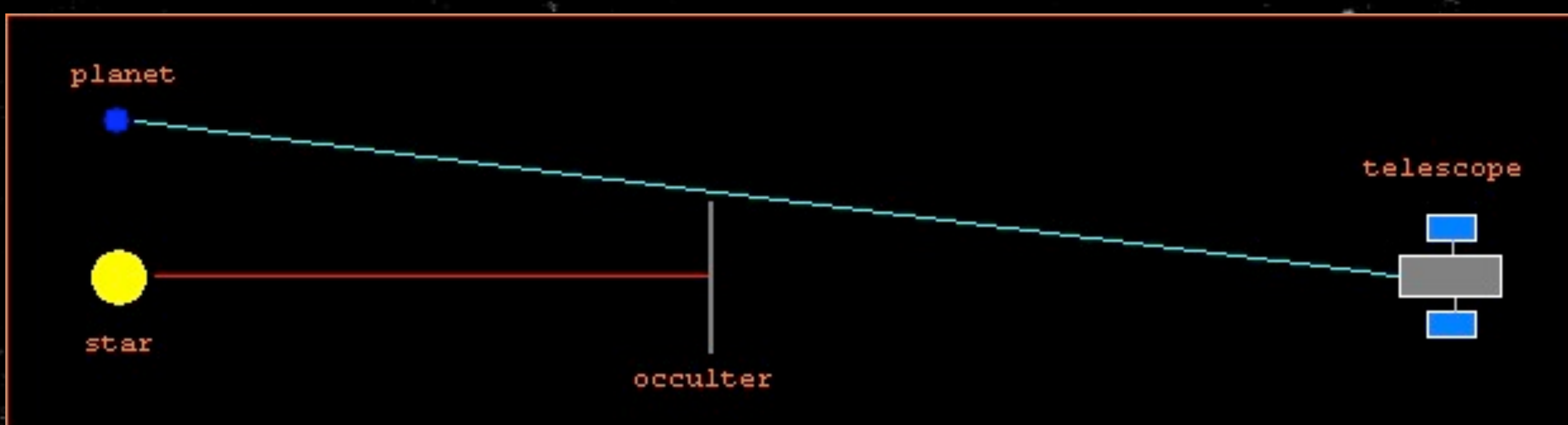
What about mother nature's coronagraph?

Use an external occulter to block the light

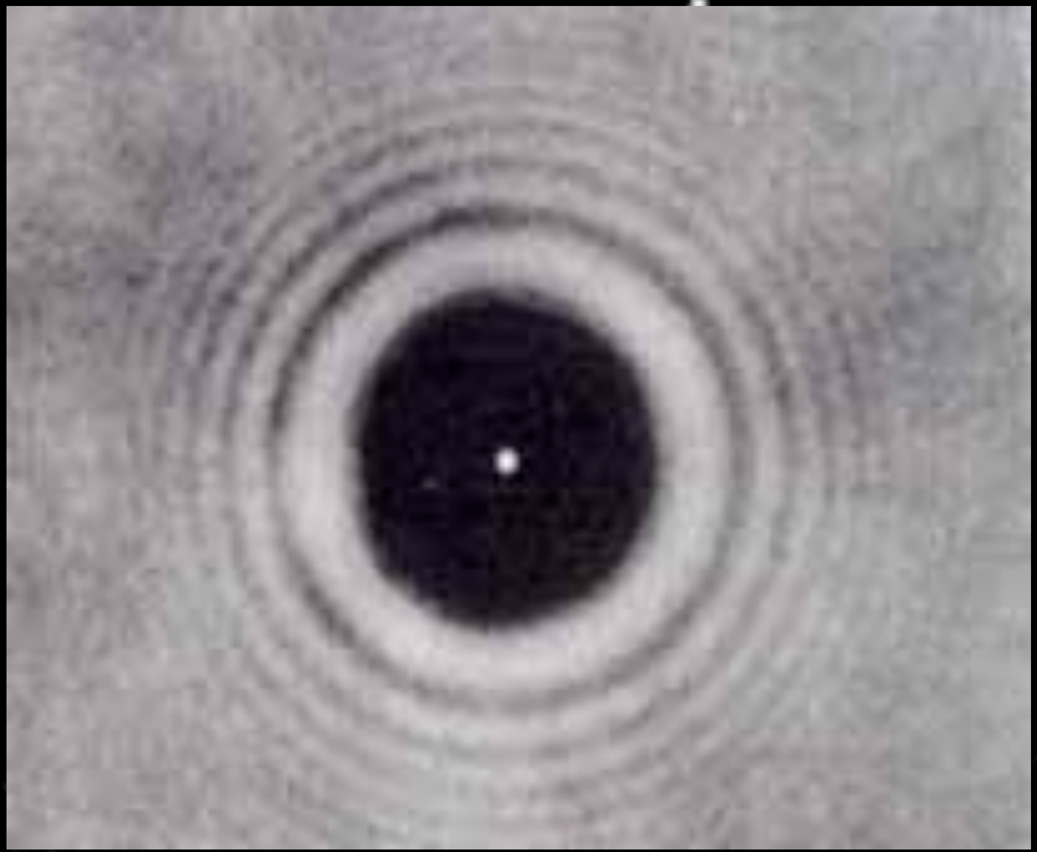
What about mother nature's coronagraph?

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

Electric fields

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

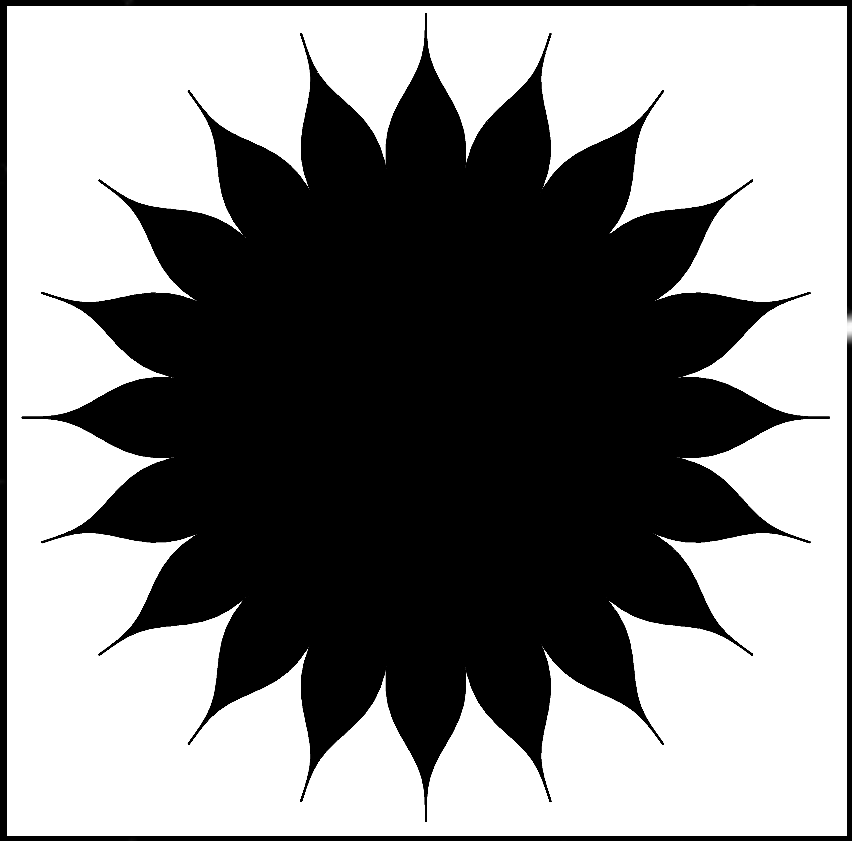
$$E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda Z} \int_0^R A(r) J_0 \left(\frac{2\pi r \rho}{\lambda Z} \right) e^{\frac{\pi i}{\lambda Z}(r^2+\rho^2)} r dr \right)$$

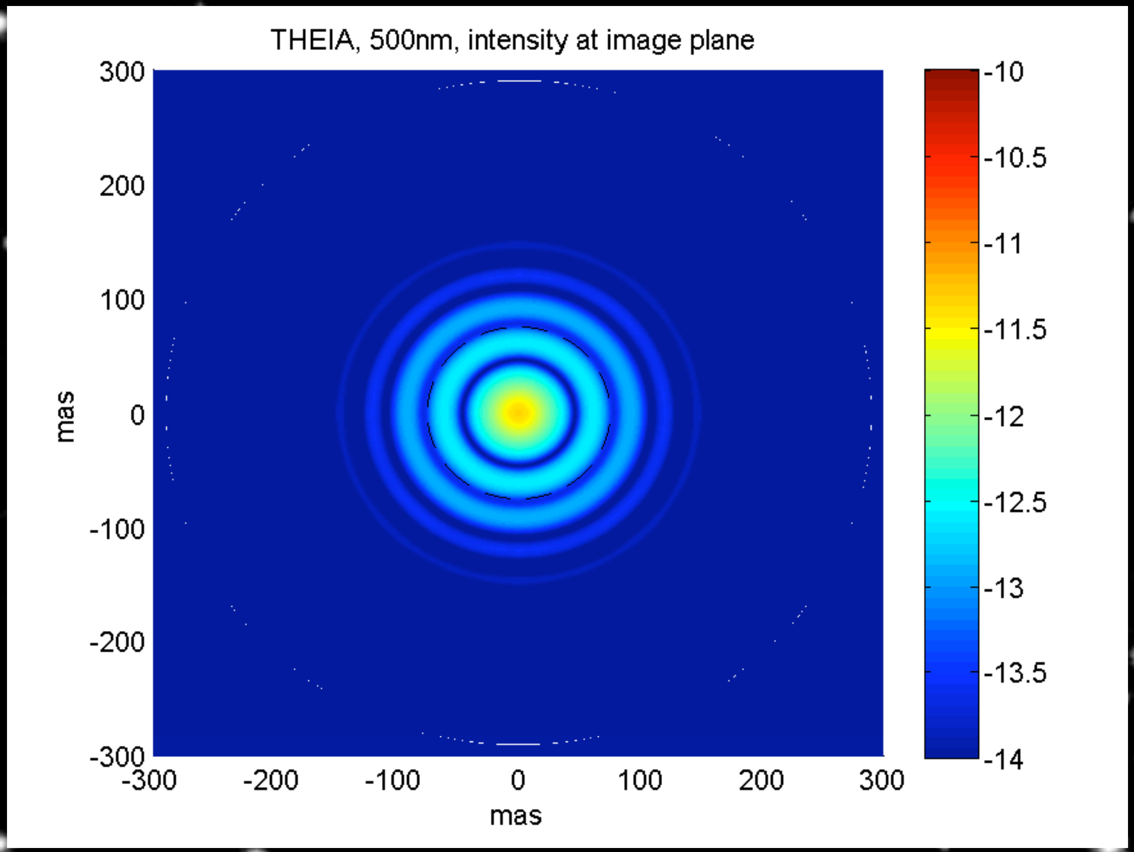
We can use this to calculate the field for a given apodization, A[r], or we can solve an optimization problem to find A[r].

But apodized occulters are really hard to make . . .

Opaque Occulter

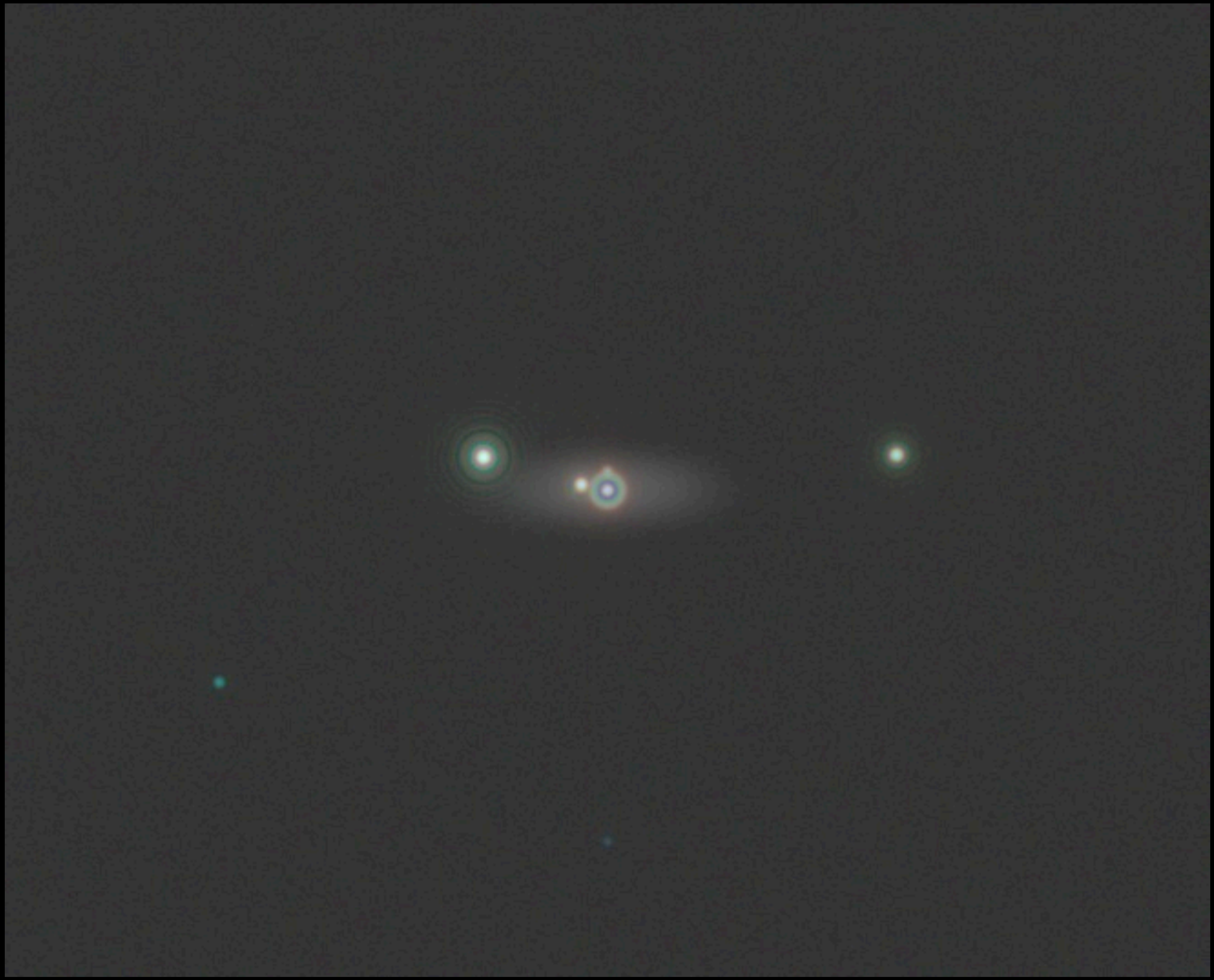
Remember Starshaped Masks?





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

A simulated image of the solar system

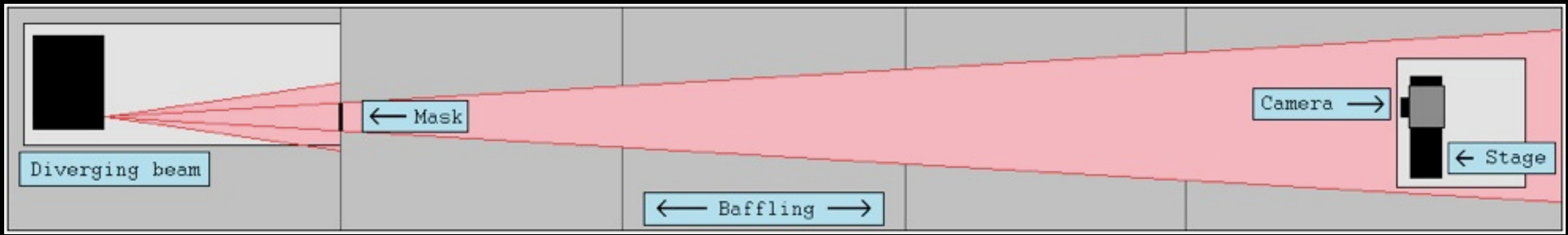


Starshade Requirement Allocation

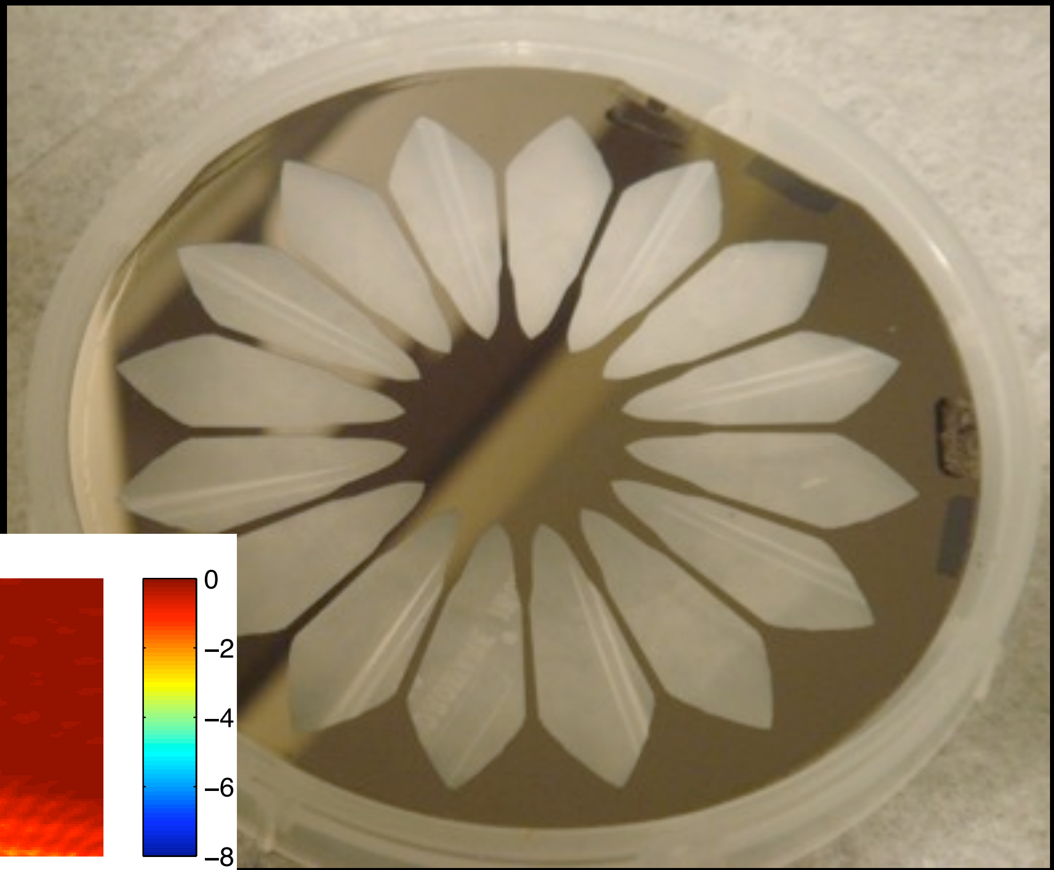
	Manufacture, Deployment, or	amplitude	Notes
1	Petal r.m.s. shape vs design, 1/f^2 power law	100 um	Dominated by low spatial frequencies, p = 10 m at maximum width, decreasing with petal width
2	Petal proportional shape error	80 um	
3	Petal length (clipping at tip)	1 cm	
4	Petal azimuthal position	0.003 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	

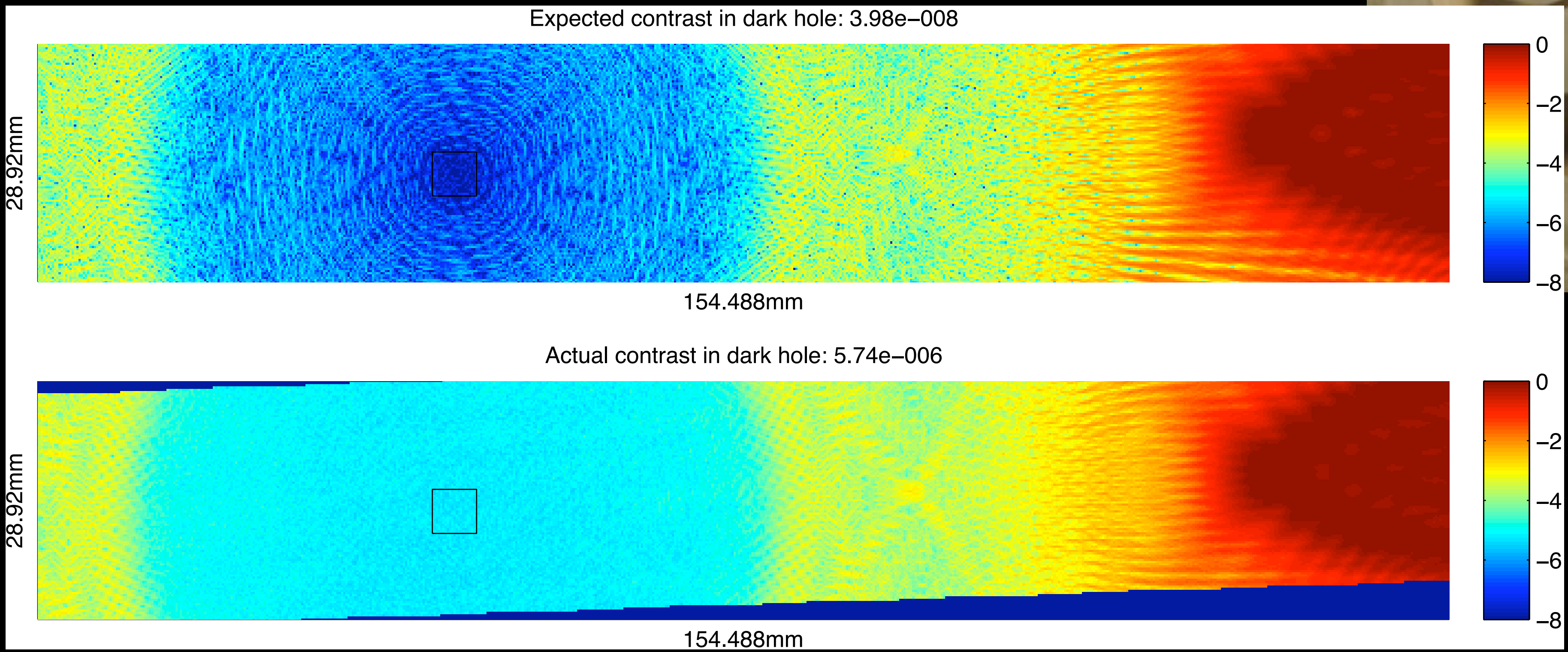
Contrast change below 10^{-12} at 0.6 micron

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 400m wafer at JPL
- Designed for 10^8 contrast

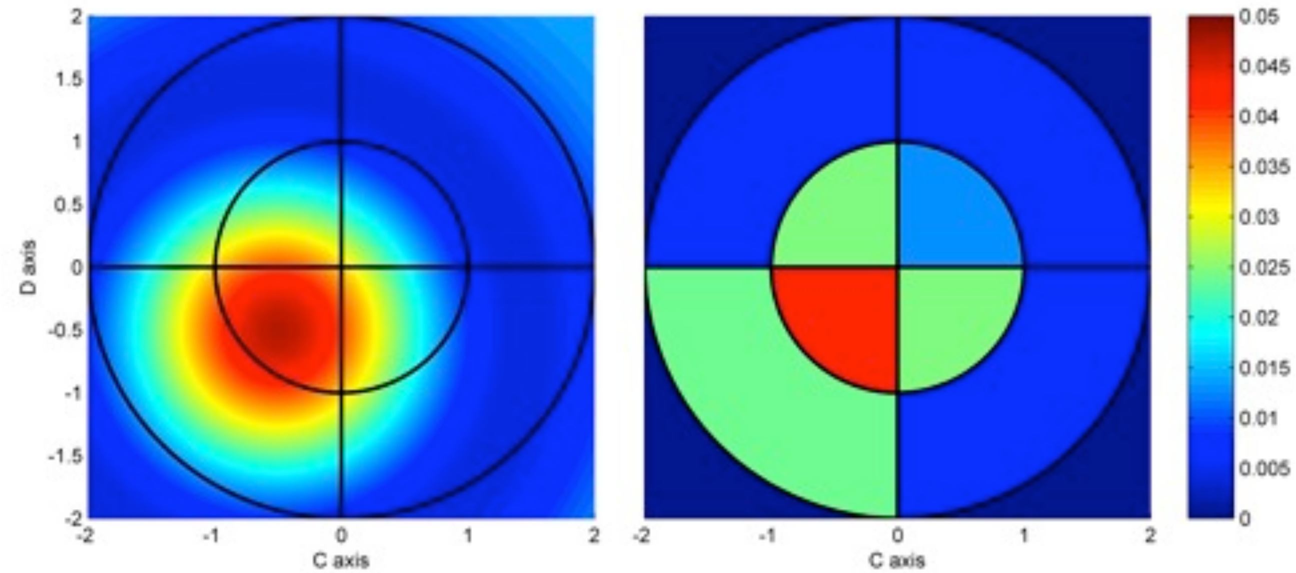


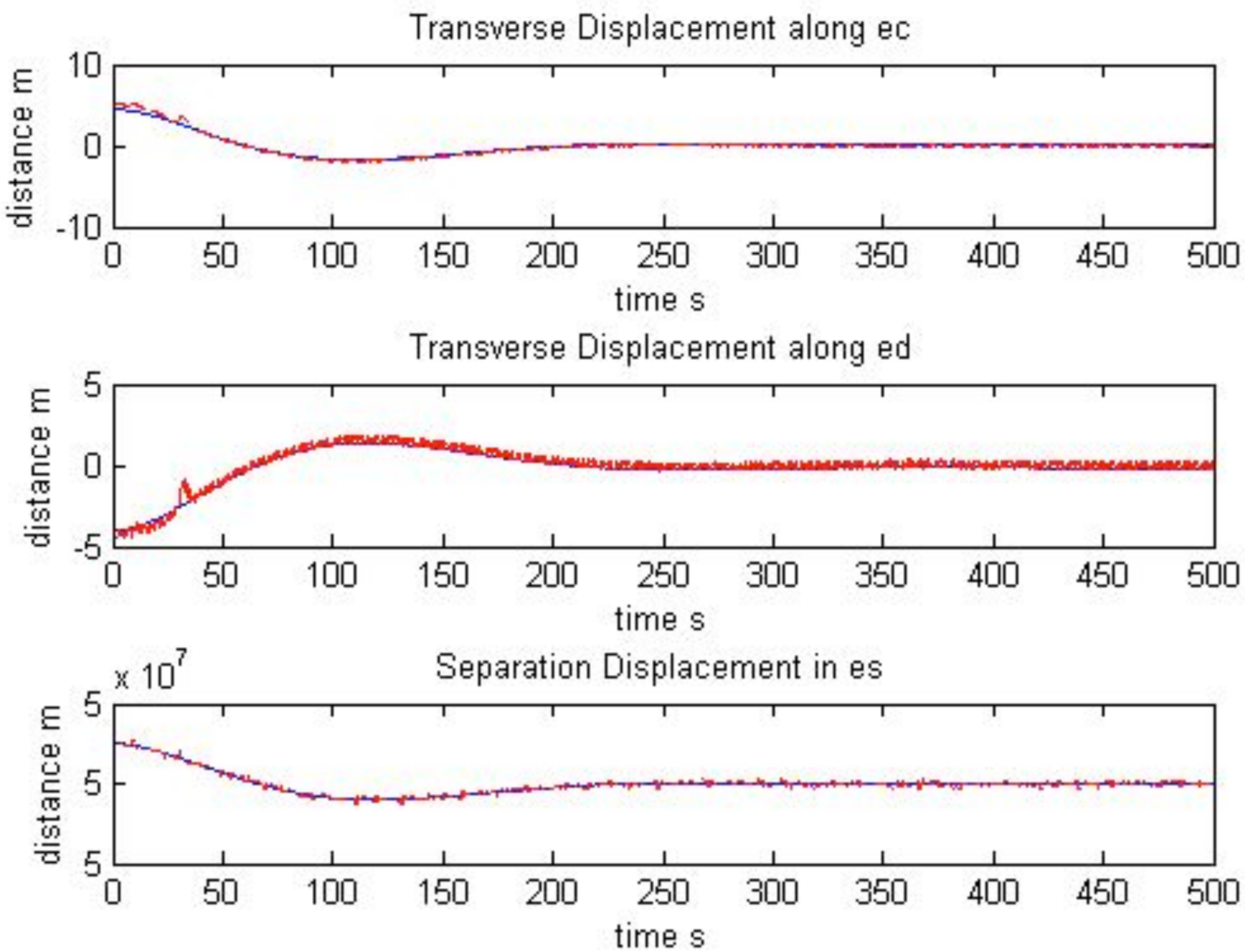


Stationkeeping using Pupil Sensor and Perfect Thrusters

- 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

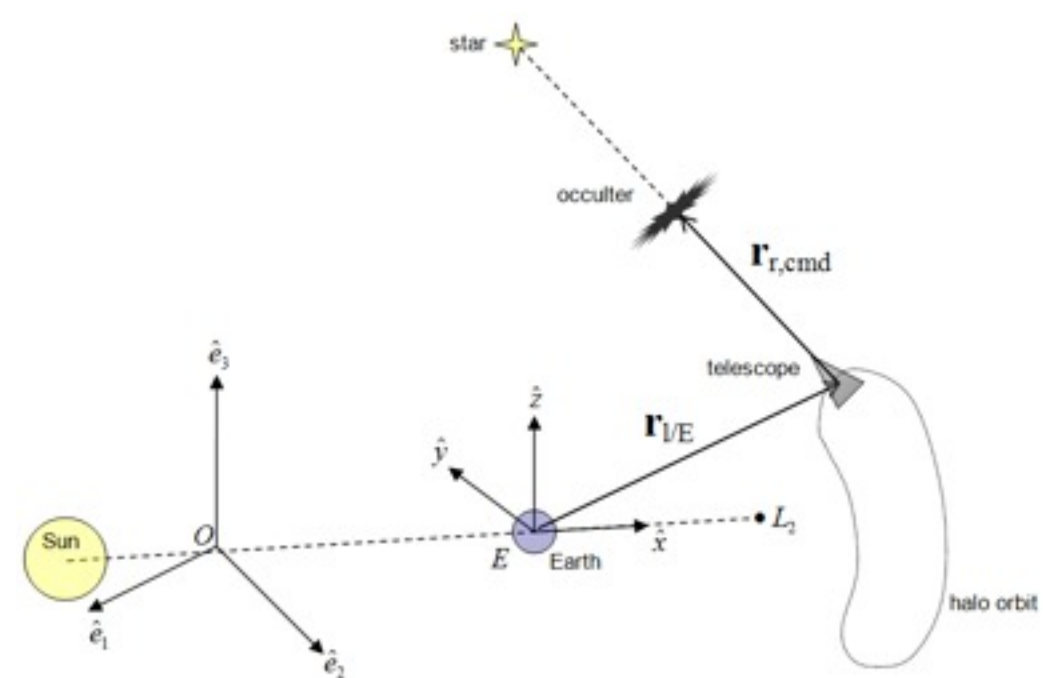
8 Octent Pupil Sensing for Position



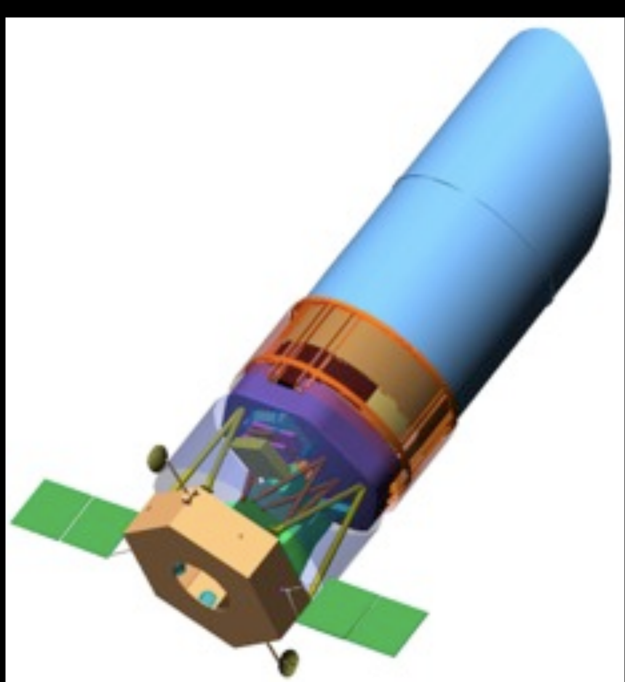


Initial offset = 6.5 m

Initial state error = 10 m



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

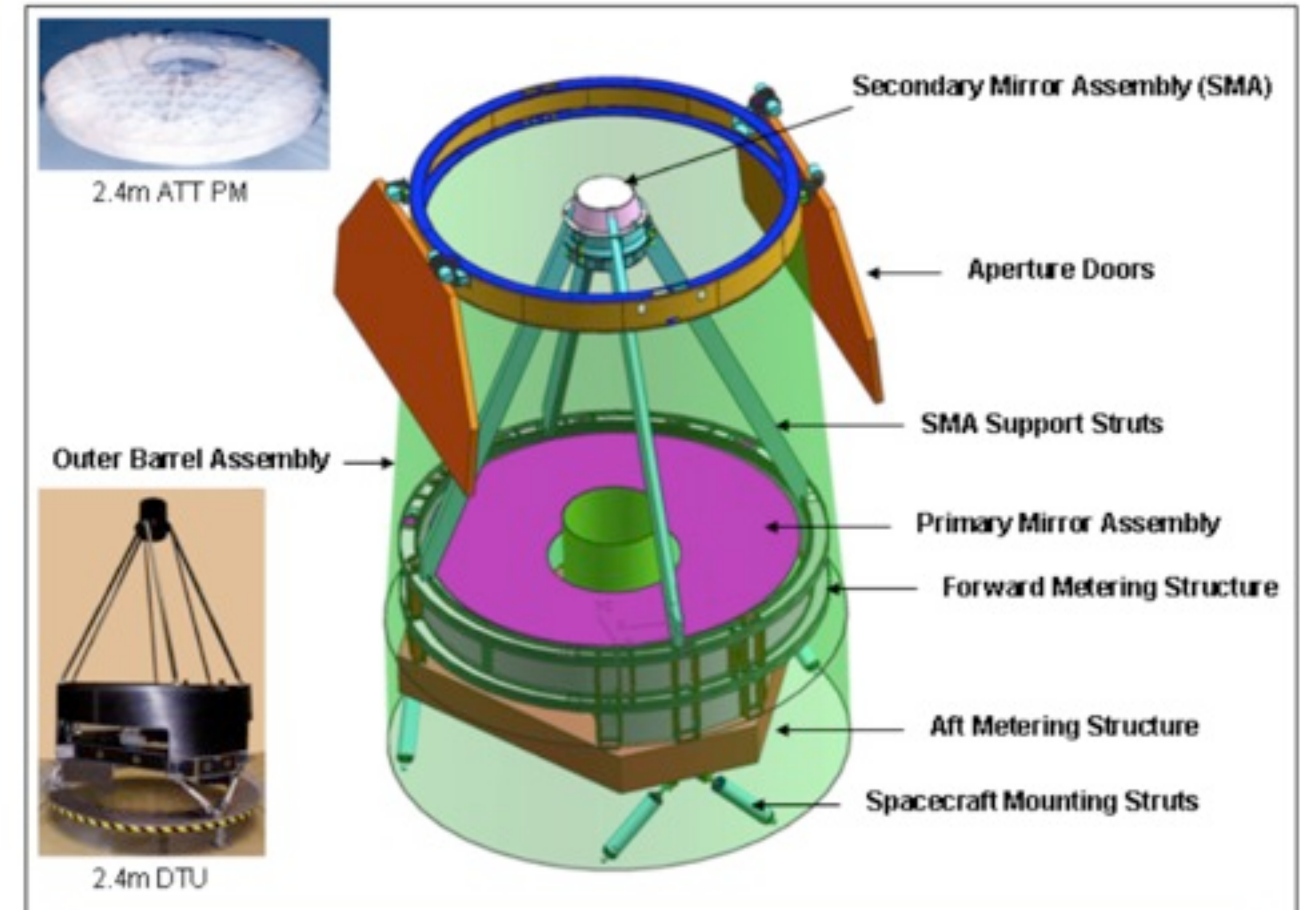
Industry Partners: Lockheed Martin Missiles and Space, ITT Space Systems, LLC, Ball Aerospace

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

Telescope Design

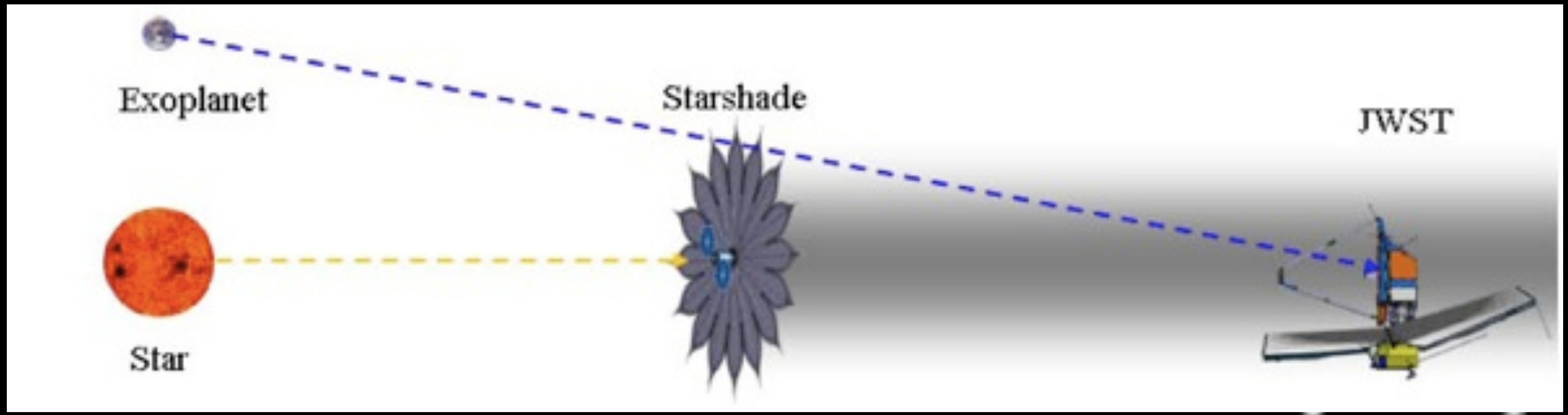
- Three Mirror Astigmat
- Baseline: MgF coatings on primary; LiF on secondary
- Pickoff mirror feeds general astrophysics instruments
- Exoplanet Characterizer;
- Star Formation Camera
- Ultraviolet Spectrograph



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

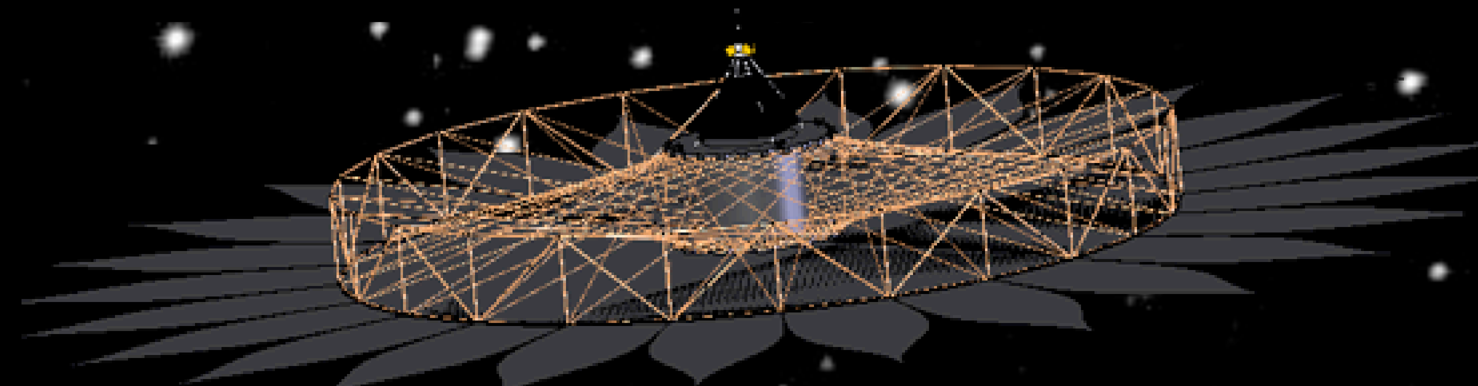
JWST + Occulter

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

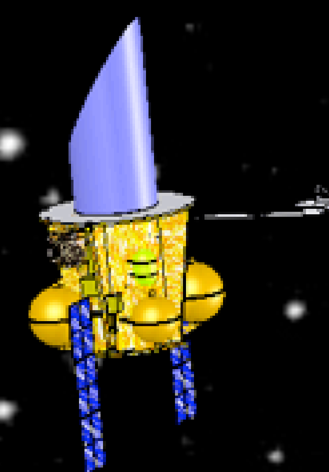


- Disadvantags:
  - Diffraction limited at 2 microns
  - Thrust plume during stationkeeping
  - Limited telescope time
  - Requires adding new filters
  - Requires very large tilted occulter (>60 m tip-to-tip) to increase operating angles
  - Occulter must do acquisition and control as well as move to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

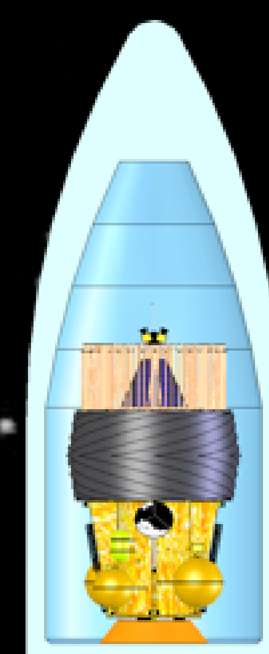
Moderate Telescope + Occulter



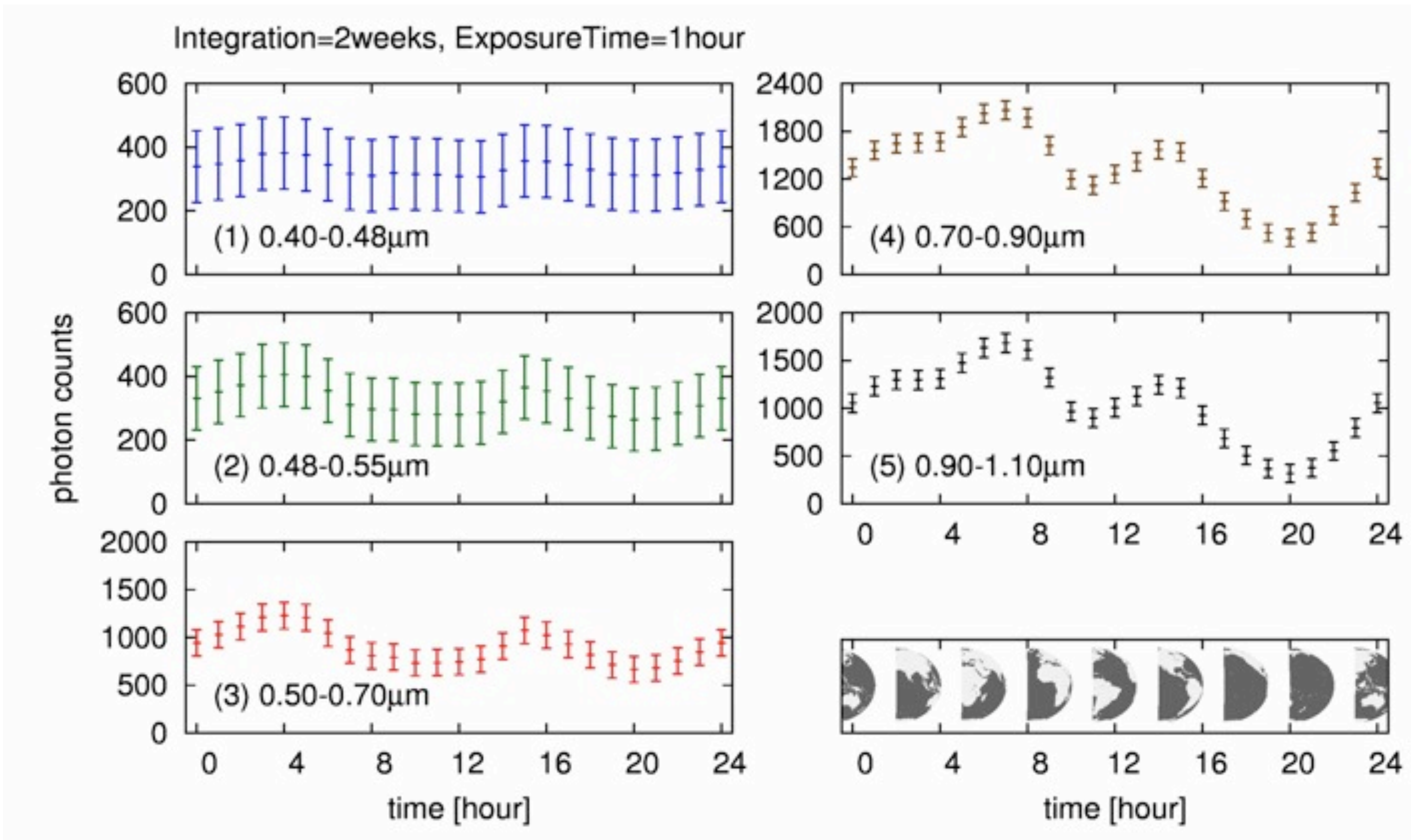
- 1.1 -1.5 meter
  (diffraction limited at 0.3 - 0.5 microns)
- Advantages:
  - Lightweight relatively inexpensive telescope can move, acquire occulter
  - Same resolving power as JWST
  - Can use smaller occulter (< 30 m) with relaxed requirements.
  - Can detect up to 5 Earths with eta = 0.3
  - Can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

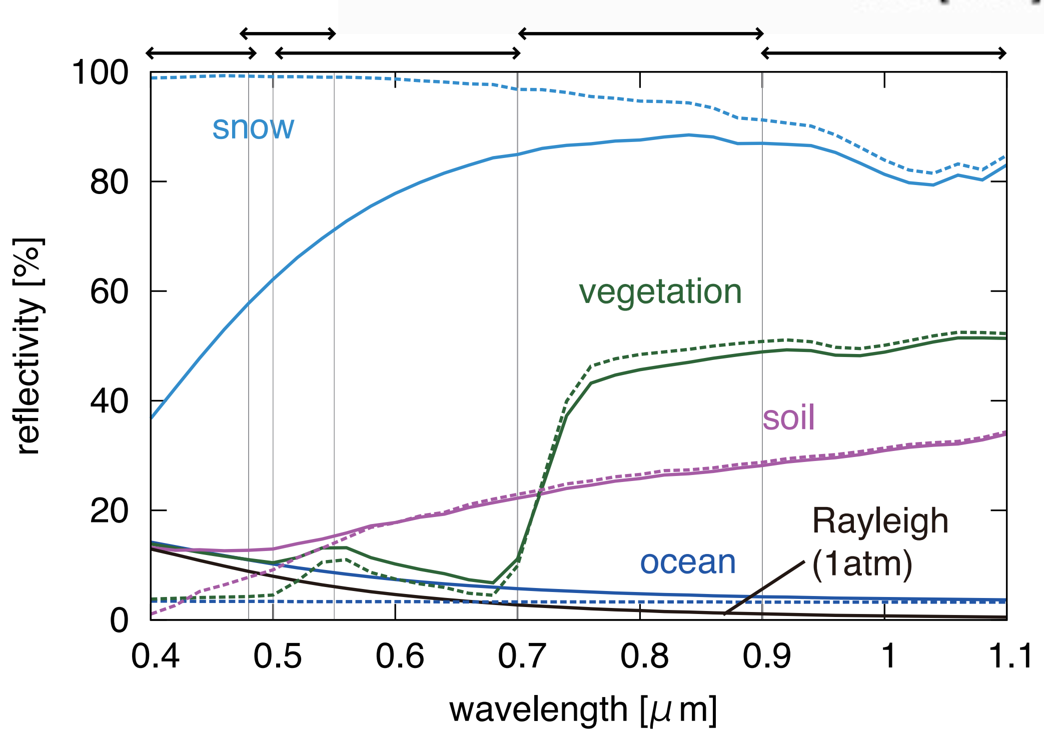


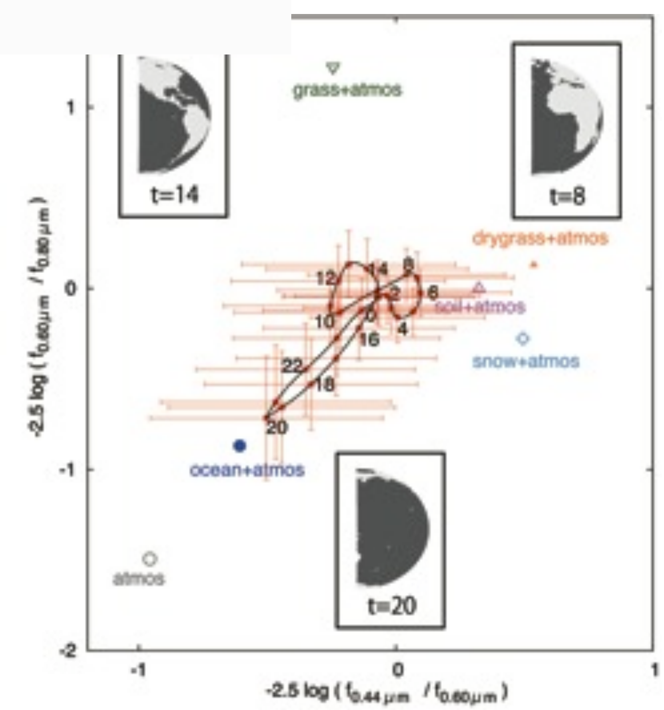
O_3



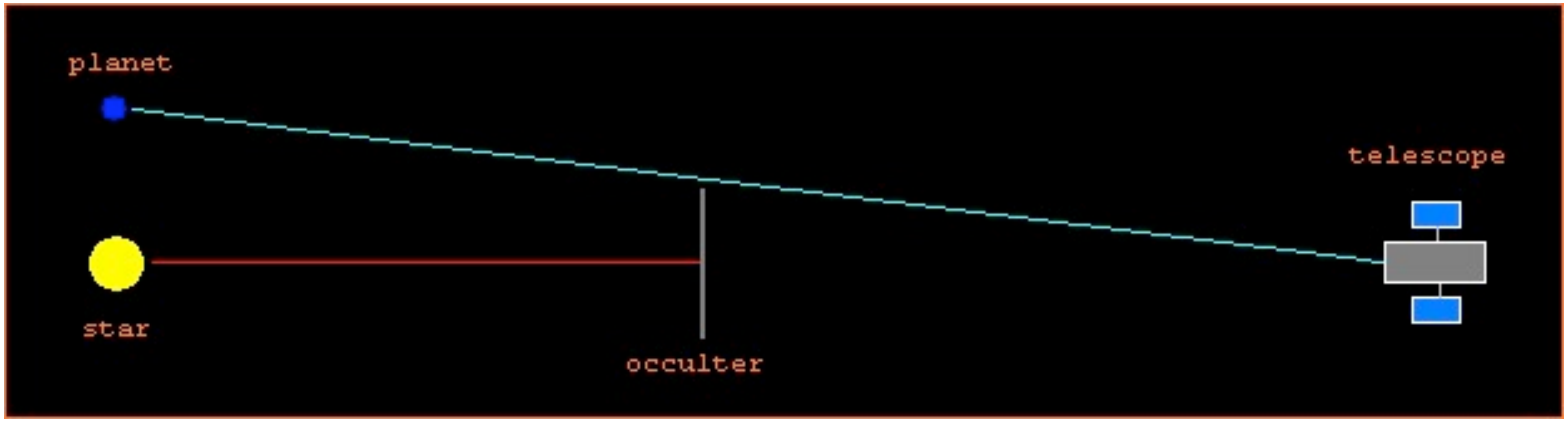
Simulated Observations





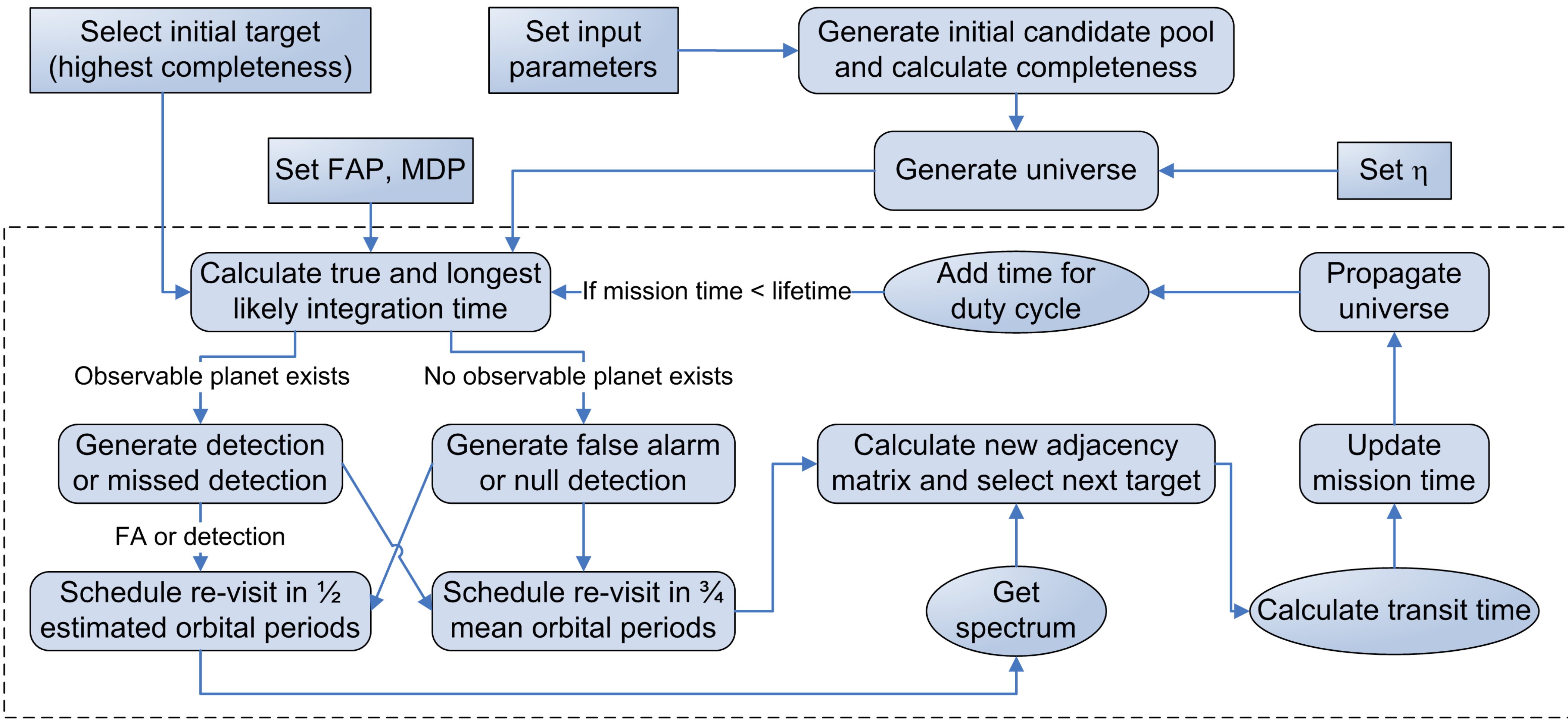


External Occulters



- 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

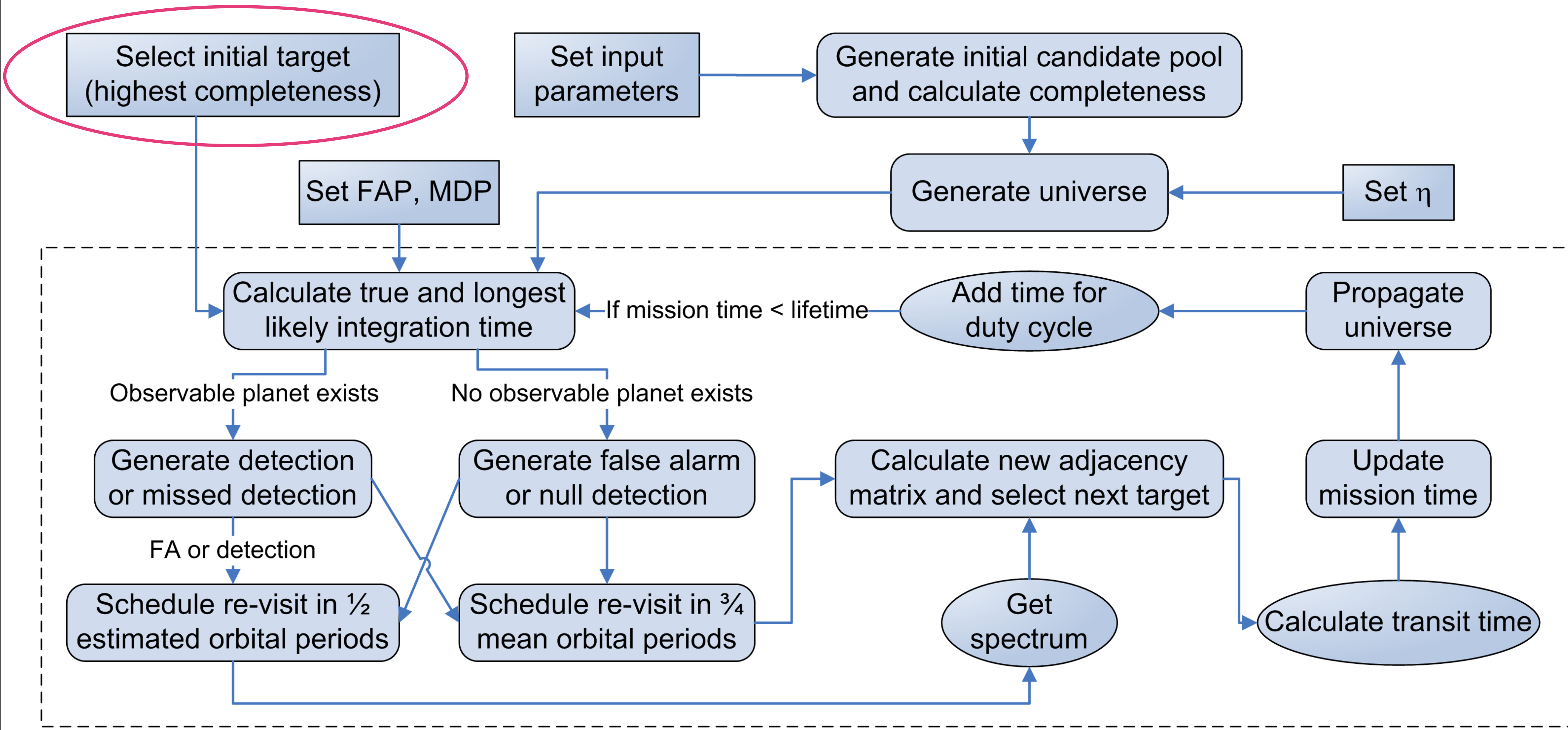
Performance Comparisons



Automated Monte Carlo Mission Generation

How many planets can a mission detect and characterize?

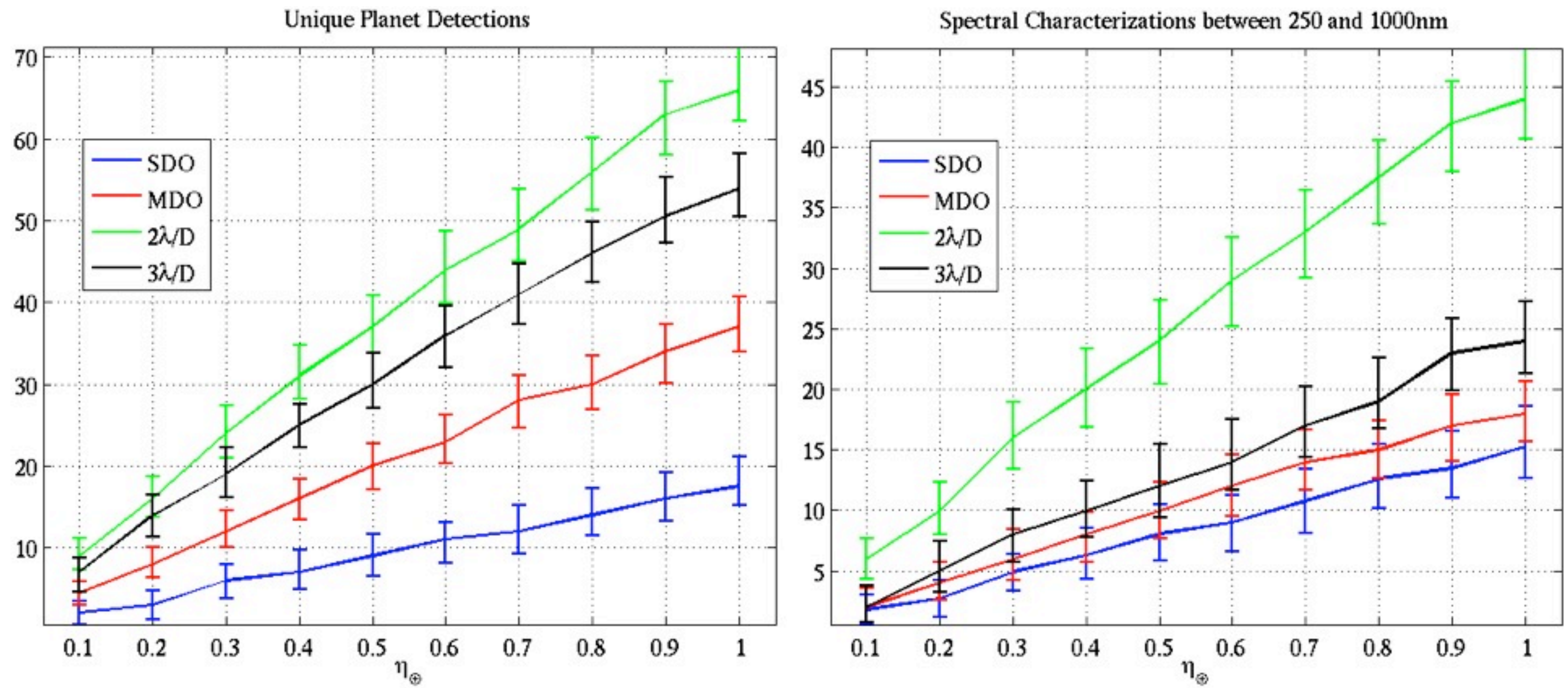
Performance Comparisons



Automated Monte Carlo Mission Generation

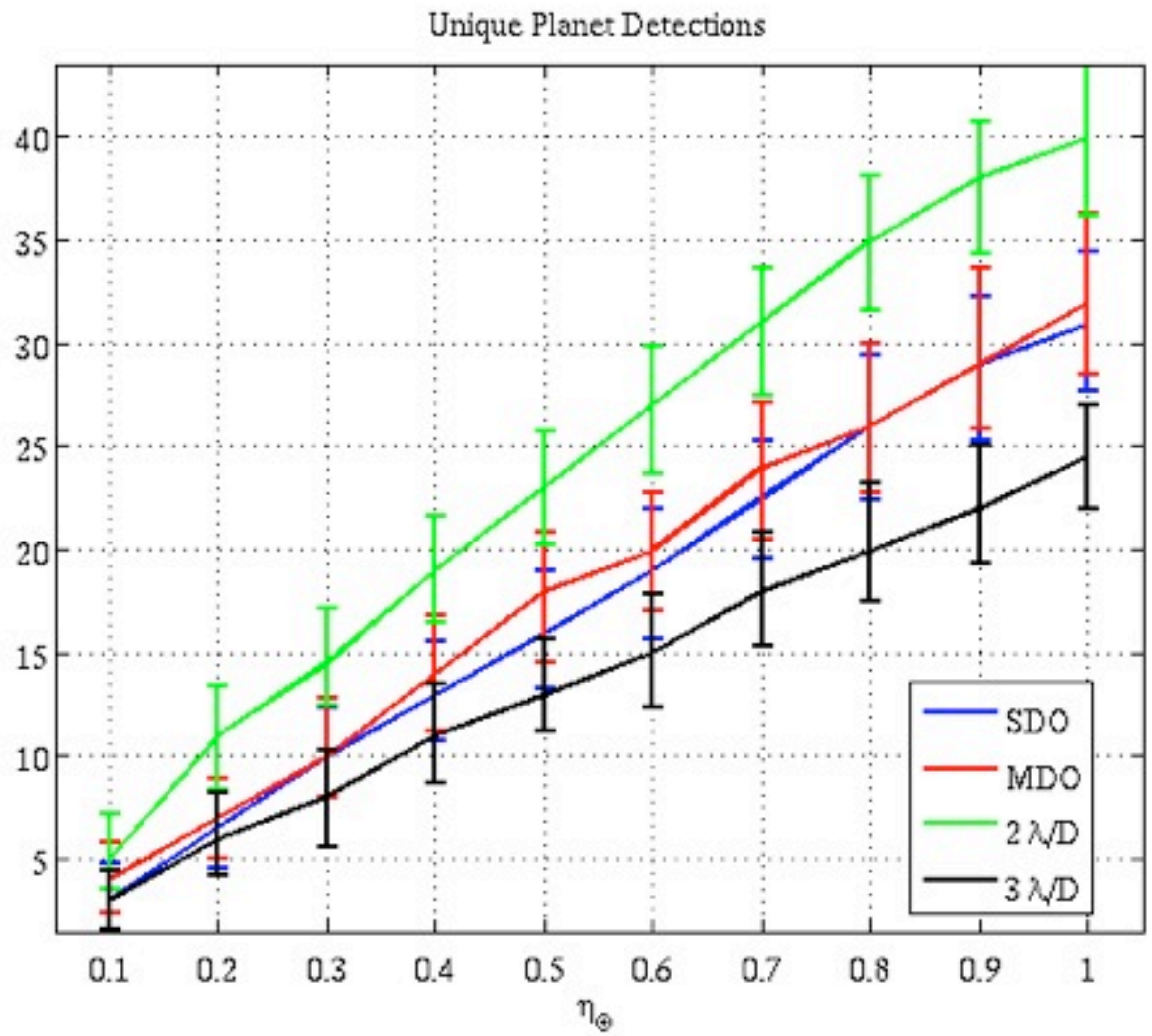
How many planets can a mission detect and characterize?

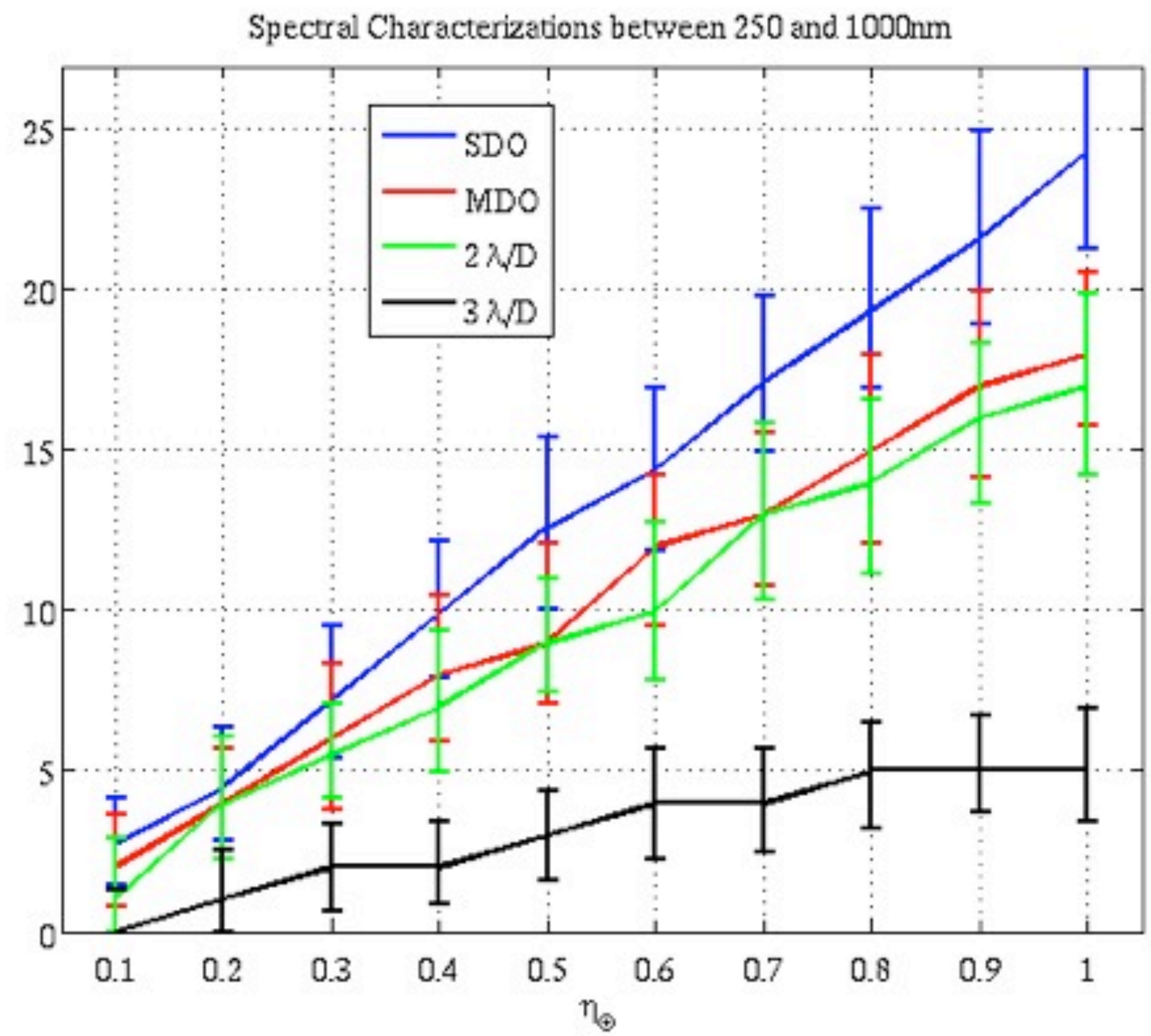
8m Telescope



- 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

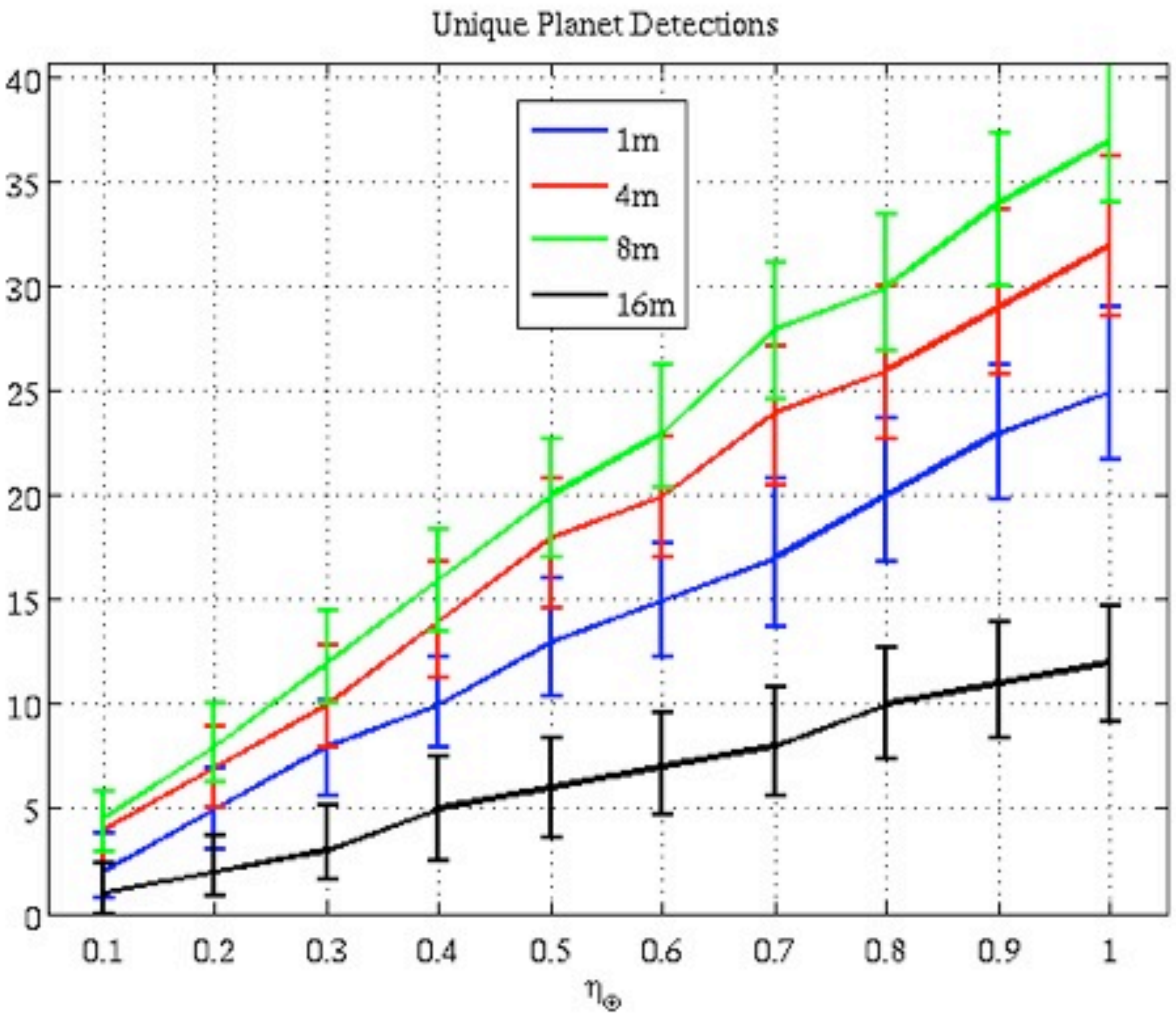
4m Telescope

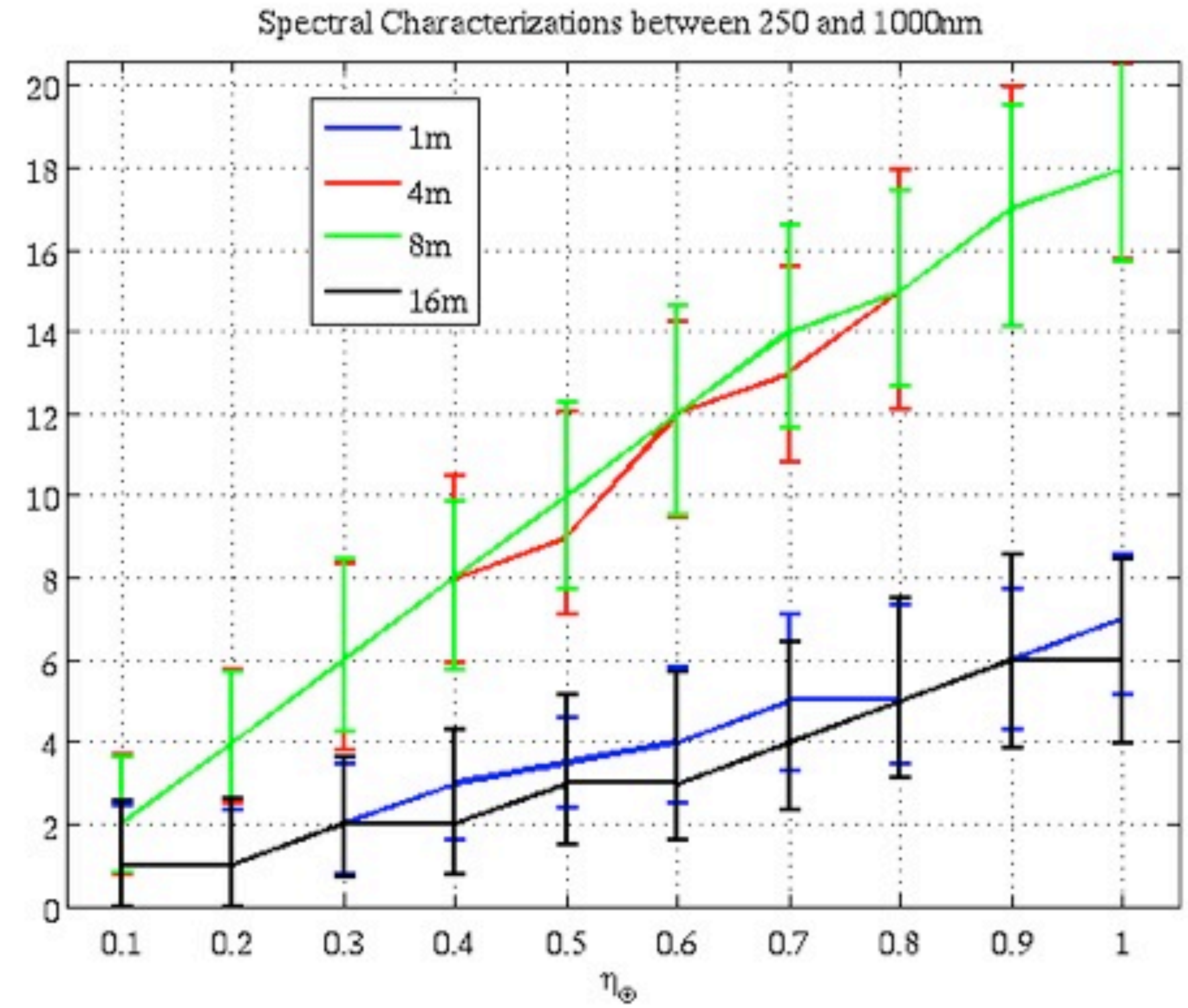




- Almost 40 Earthlike planets detected at eta = 1
- Small variations among approaches (except 3 l/D coronagraph)
- 2 lambda/D coronagraph gets more unique planets and about same number of spectra as MDO
- 3 lambda/D coronagraph gets very few full spectra

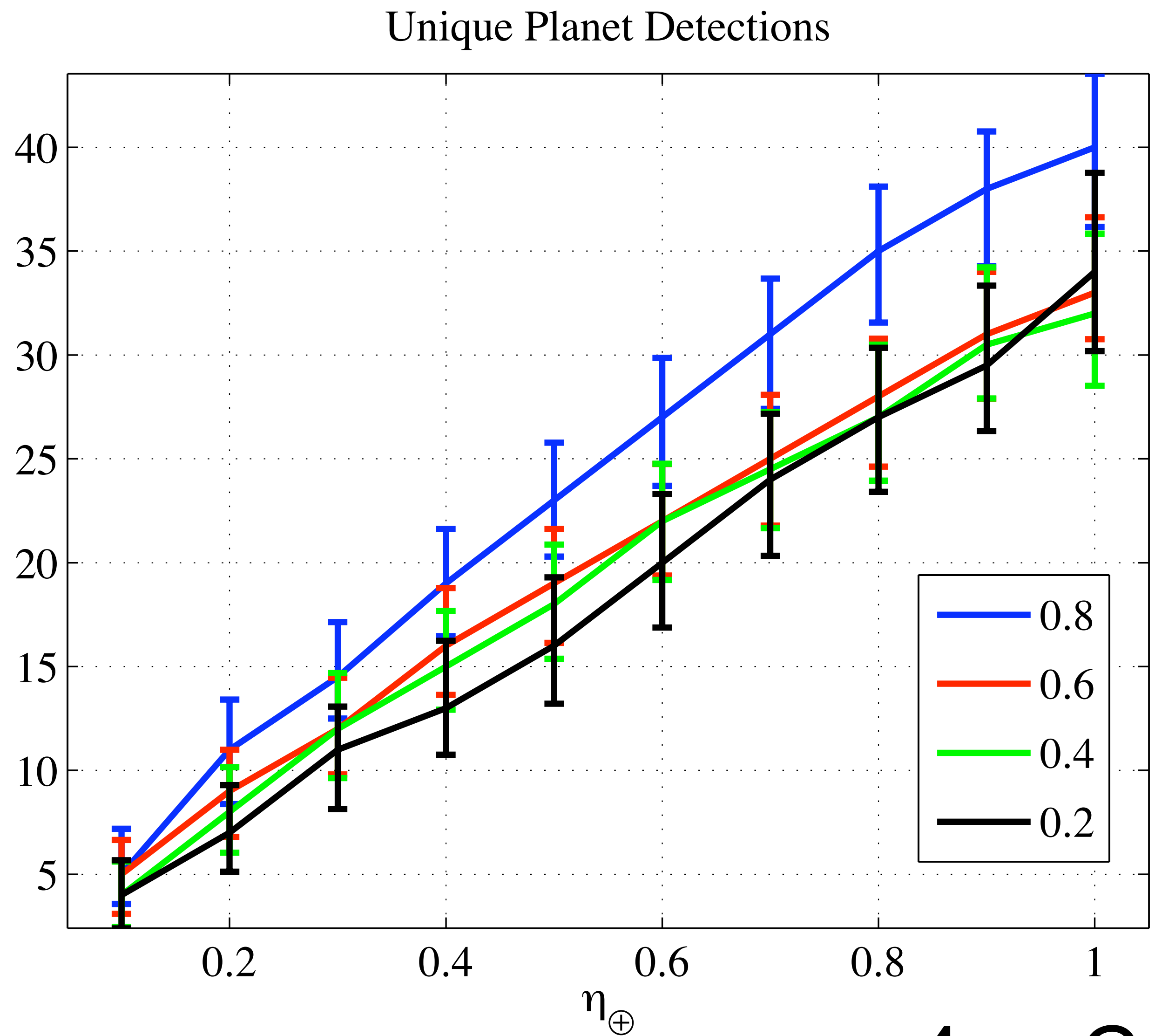
Multiple Distance Occulters

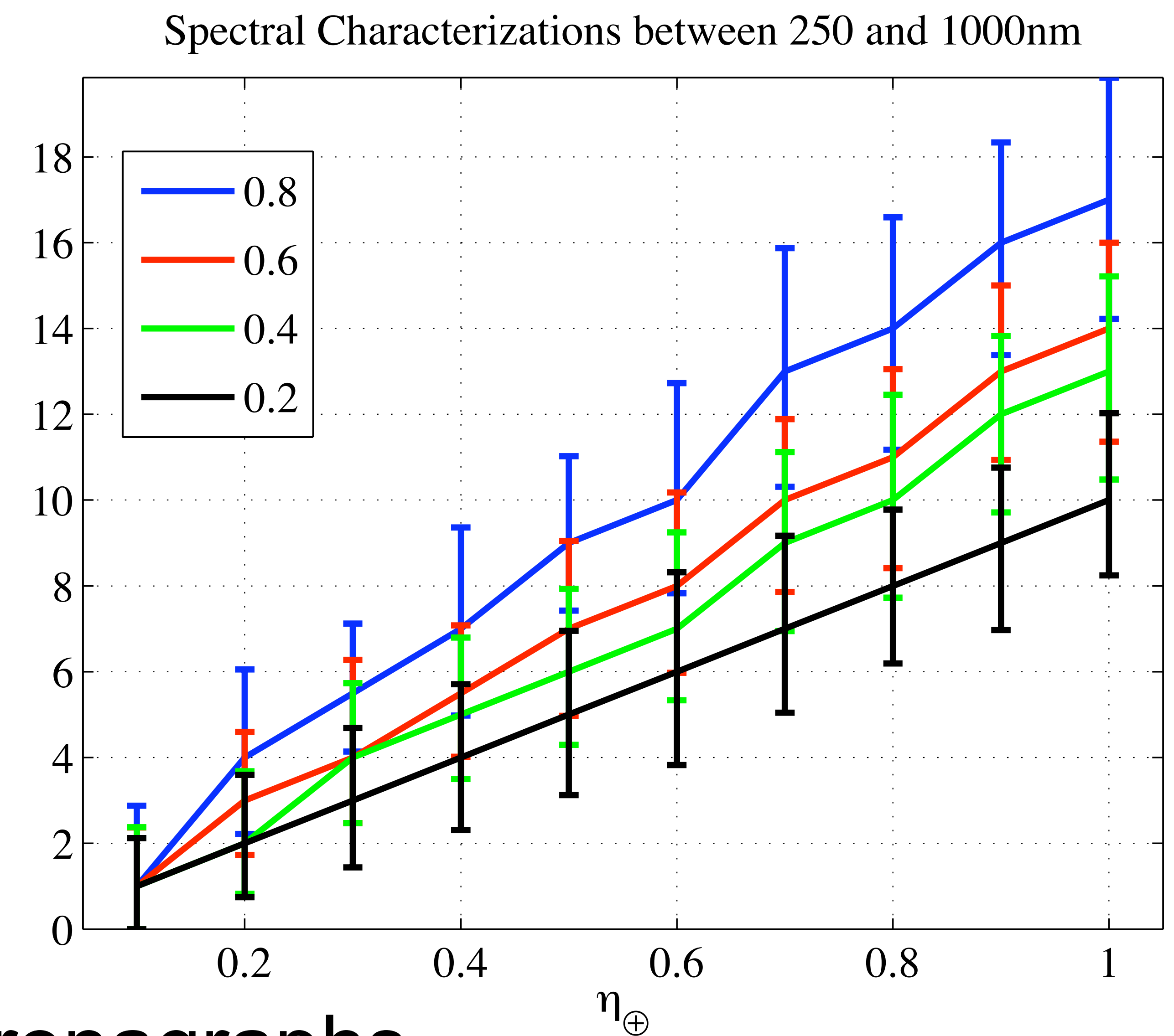




- 4 and 8 m MDO have similar performance
- 16 m MDO has very poor performance compared to coronagraphs
- 1 m MDO does remarkably well (25 Earthlike planets at eta = 1). Only way to get Earths at this scale.

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

Unique Detections

	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

Full Spectra

	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

Some Questions

- At 4 m, is the cost of a starshade less than delta-cost for making an internal coronagraph meet requirements?
- Is one fundamentally harder than the other?
- What is the largest starshade that is practical?
- Would increasing the starshade size to decrease inner working angle help?
- Are better thrusters on the horizon and would they help?
- Is chemical propulsion for stationkeeping ok?
- Can we really get a 2 lambda/D coronagraph?
- Can a coronagraph be made stable enough for long integration times?
- Are we sacrificing UV/Ozone if we opt for a coronagraph?
- Is one architecture better suited to supporting General Astrophysics?
- Can we afford to fly 2 or more starshades (redundancy & efficiency)?
- Can a 1 or 1.5 m telescope resolve a planet out of the background (particularly with large exozodi)?

The Hard Stuff (Coronagraphs)

- Off-axis telescope with exquisite stability
  - thermal
  - jitter
- Large format DMs (96 x 96)
- High reflectivity coatings with minimal polarization
- Demonstrated starlight suppression at small IWA
- Broadband correction across image plane (with large OWA)
- Validated thermal-mechanical-optical modeling
- Photon Counting Detectors out to 1000 nm
- System Level Testing

Many are either demonstrated in the lab or have a path to high TRL.

The Hard Stuff (Starshades)

- Large Telescope (> 4 m)
- Photon Counting Detectors out to 1000 nm
- Precision Starshade Manufacturing, Deployment & Stability
- Validated optical design
- Validated Thermal-Mechanical-Optical Modeling
- Starshade Test Program
- Tight Formation Flying
- Ion or Plasma Electric Propulsion

Much progress on design and analysis with some early lab results in progress.

Pluses and Minuses

Coronagraph Mission

Pluses

- Early detections
- More repeat detections
- Rapid repointing capability
- Complete end-to-end testing
- Large field of regard
- Single launch
- Higher performance for large telescopes

Minuses

- Unlikely UV capability
- Thermo-mechanical stability (telescope)
- Complex optics with wavefront control
- Wavelength and aperture dependent IWA
- Limited discovery region
- Large, off-axis telescope
- More challenging GA instruments

External Occulter Mission

Pluses

- Broadband capability
- No outer working angle limit
- Wavelength and aperture independent IWA
- No wavefront control
- Full resolution
- On-axis telescope
- Richer general astrophysics

Minuses

- Fewer repeat detections
- Thermo-mechanical stability (starshade - scales with size)
- Starshade error budget uncorrectable
- End-to-end optical test impossible
- Limited viewing angles
- Slew time limited

Some Conclusions

- This is a challenge worth pursuing.
- Two viable solutions, but the best approach is not obvious!
- Relative merits depend very much upon scale.
- Technology development, cost and success in the lab is going to be a major factor.
- A ~1.1 m probe with starshade is very intriguing.
- How about both external and internal?

> 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. . . .
>
> --- John F. Kennedy, 1962

Thanks

– Dmitry Savransky
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– Dennis Ebbets
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– Wes Traub
– Rémi Soumer
– Laurent Pueyo
– Sally Heap
– Don Lindler
– Rus Belikov
– NASA HQ, JPL and GSFC
– And many, many, others . . . .

But the mistakes are all mine . . .


Thank You.