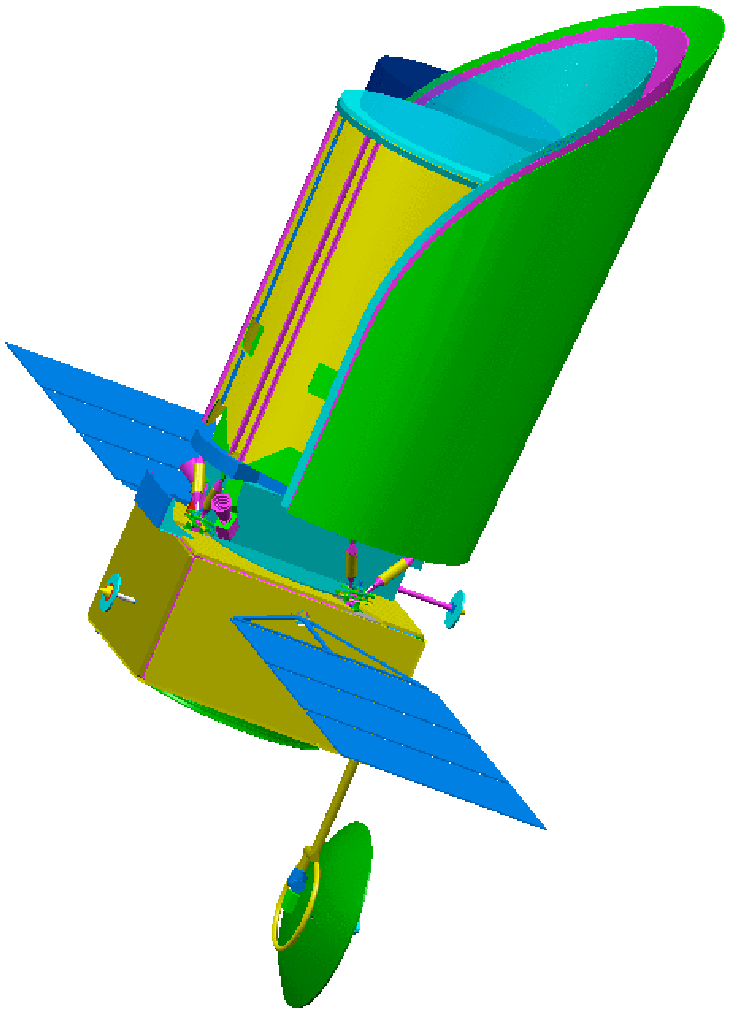
ACCESS -- a science and engineering assessment of space coronagraph concepts for the direct imaging and spectroscopy of exoplanetary systems



John Trauger (Jet Propulsion Laboratory / Caltech)

Solar-Extrasolar Meeting
NASA/Ames -- 6 February 2009

ACCESS Science and Engineering Team

John Trauger, Karl Stapelfeldt, Wesley Traub, John Krist
Dwight Moody, Laurent Pueyo, Stuart Shaklan, Eugene Serabyn
Dimitri Mawet, Curt Henry, Rob Gappinger, Paul Brugarolas, Peggy Park
(Jet Propulsion Laboratory)

Olivier Guyon (University of Arizona & Subaru Telescope)

Jeremy Kasdin, Bob Vanderbei, David Spergel (Princeton University)

Ruslan Belikov (NASA/Ames)

Geoff Marcy (UC Berkeley)

Robert Brown (STScI)

Jean Schneider (Paris Observatory)

Bruce Woodgate (NASA/GSFC)

Gary Matthews, Rob Egerman (ITT)

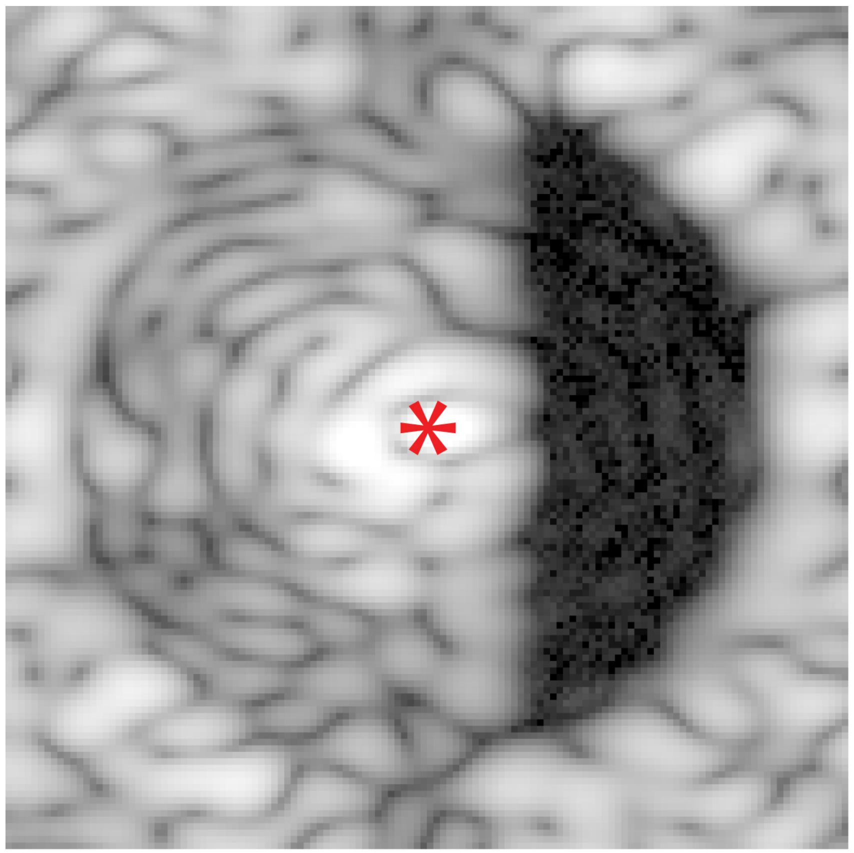
Ron Polidan, Chuck Lillie (NGST)

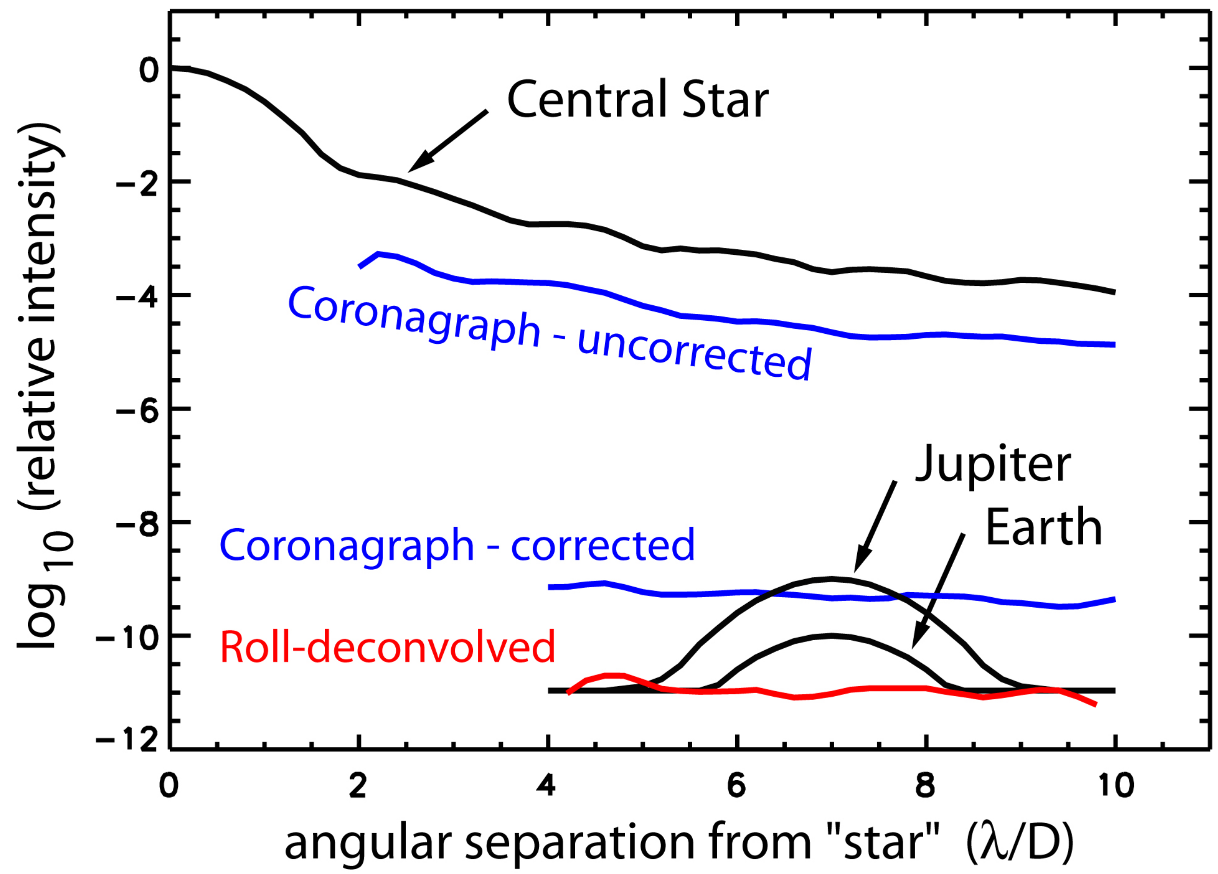
Mark Ealey, Tom Price (NGC/Xinetics)

ACCESS science objectives

- *Direct coronagraphic imaging and low-resolution (R=20) spectroscopy of exoplanet systems in reflected starlight, to include:*
- *Census of nearby known RV planets in orbits beyond ~1AU*
- *Search for mature exoplanet systems beyond the RV survey limits, including giant planets, super-earths, and possibly a dozen earth-mass planets*
- *Observe the life cycle of planetary systems: "dust-to-dust" in the circumstellar environment*
- *Observe Zodi structure as an indicator of unseen planets and planetesimals*
- *Survey Zodi dust as a critical architecture issue for future large life-finding exoplanet missions*

Laboratory coronagraph contrast and stability

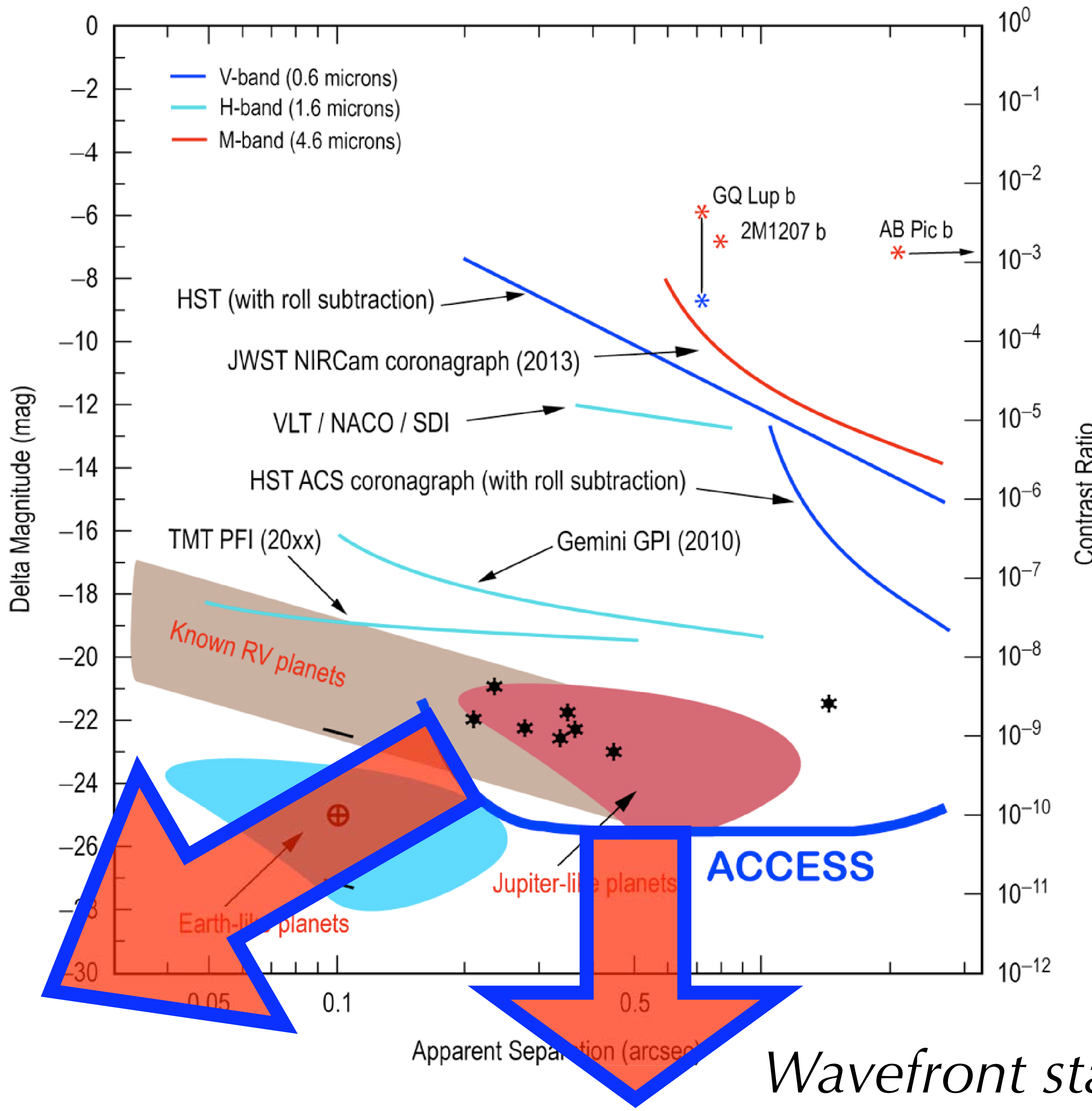




Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (b) the coronagraph field with all DM actuators set to equal voltages; (c) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of 480 consecutive coronagraph images. PSFs of a nominal Earth and Jupiter are also indicated.

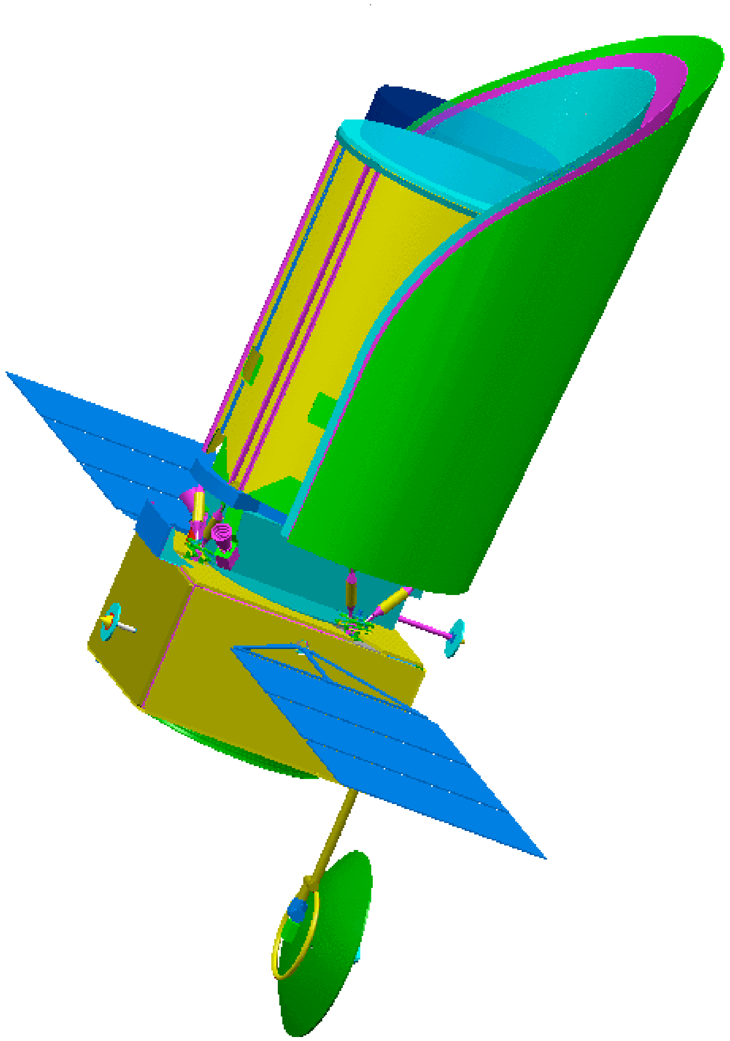
(Trauger & Traub, *Nature*, 12 April 2007, p771)

ACCESS Discovery Space is critically dependent on observatory pointing control and wavefront stability

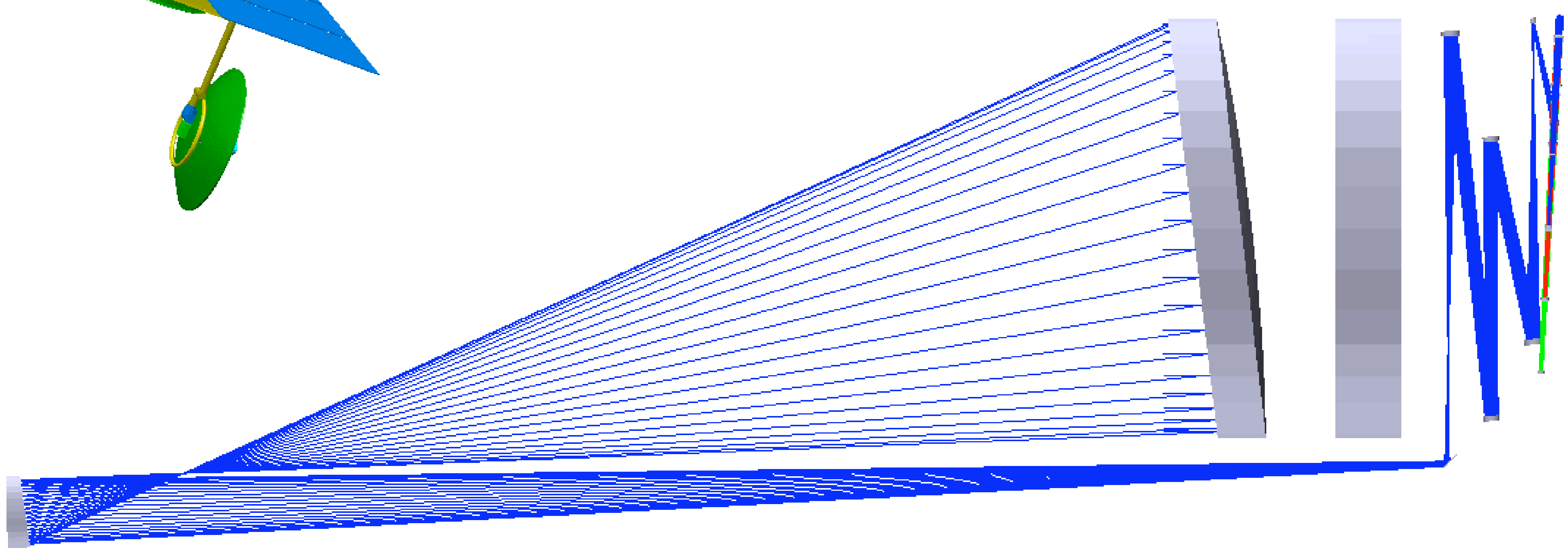


Pointing control and low-order wavefront stability

Wavefront stability



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



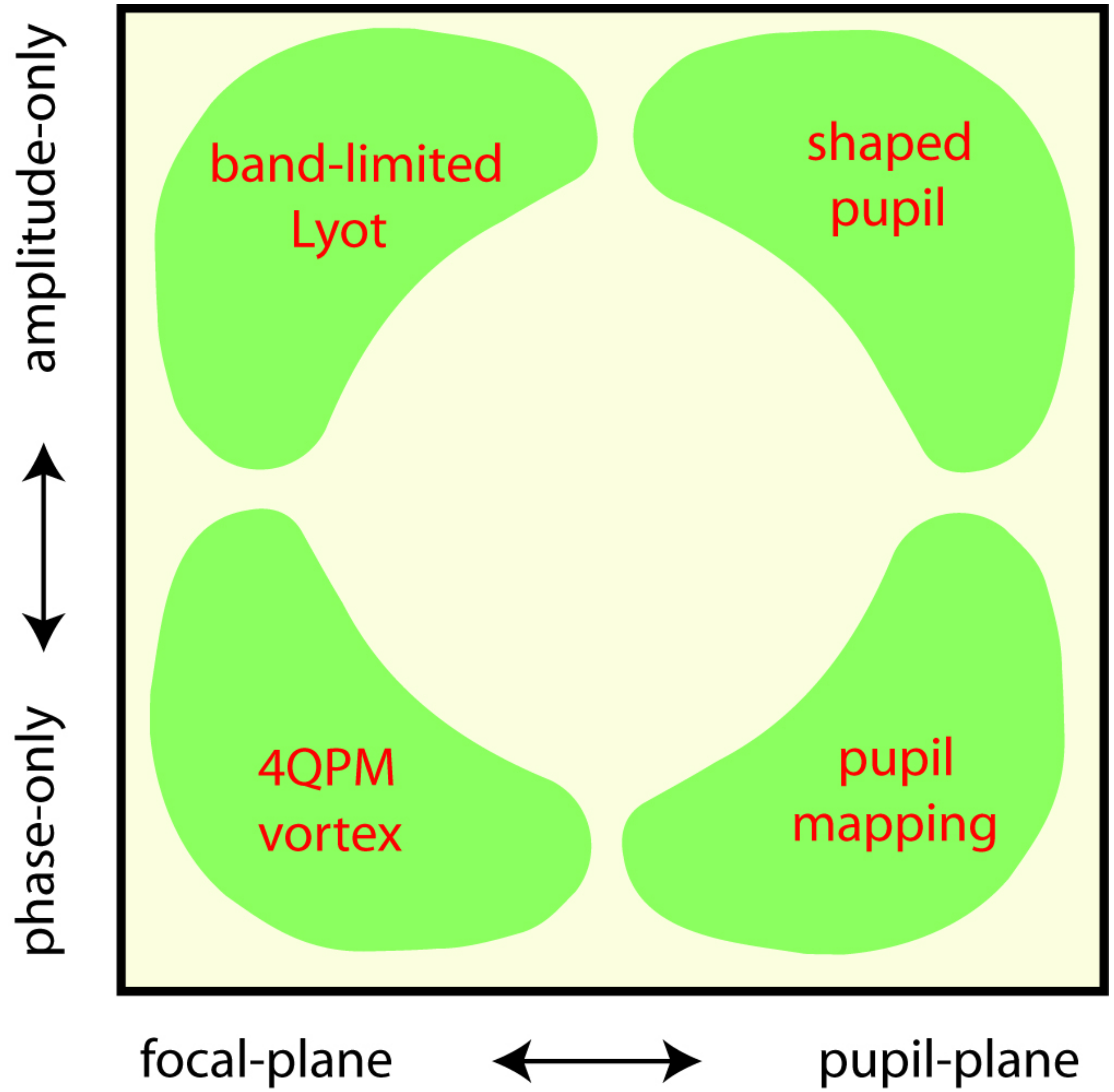
ACCESS observatory

- *Observatory architecture is representative of the "best" available for exoplanet coronagraphy within the scope (cost, risk, schedule) of a NASA medium-class mission*
    - *single spacecraft*
    - *visible wavelengths (500-900 nm)*
- *In particular, all coronagraphs require an observatory system with*
    - *exceptional pointing control*
    - *exceptional wavefront stability and*
    - *active wavefront control*
- *ACCESS requires systems with high technology readiness (TRL6+) for*
    - *reliable estimates of science capabilities and*
    - *reliable determinations of cost and schedule*
- *Baseline observatory architecture defines a capable platform for meaningful comparisons among coronagraph types.*

ACCESS gamut of coronagraph types

Moody,
Trauger,
Traub
C = 1e-9
(3-10 λ/D)
10% bandwidth

Belikov, Pueyo,
Vanderbei,
Kasdin, Spergel
C = 2e-9
(4-10 λ/D)
10% bandwidth

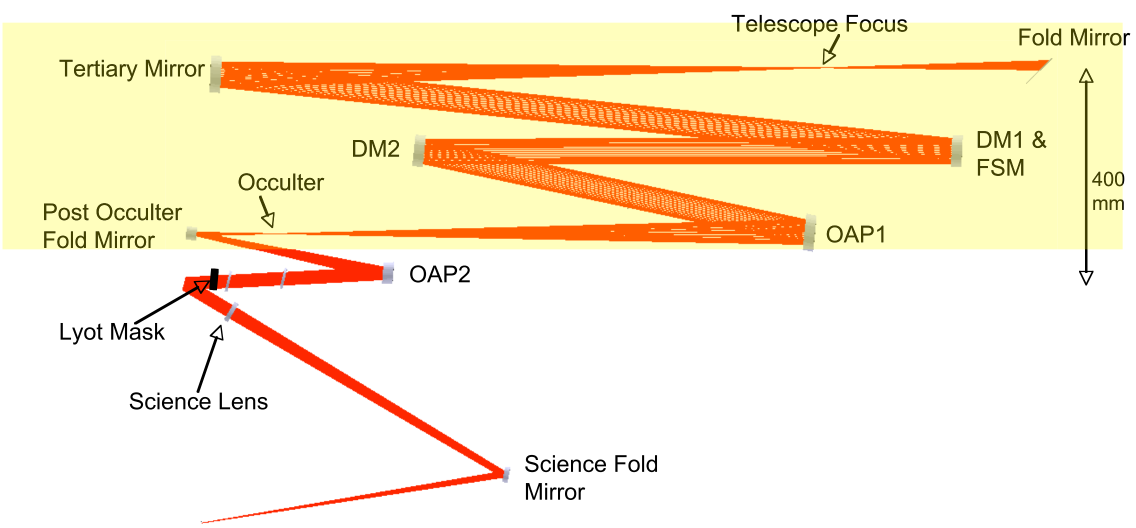


Mawet,
Serabyn,
Schneider
C = 1.5e-6
(3-10 λ/D)
2% bandwidth

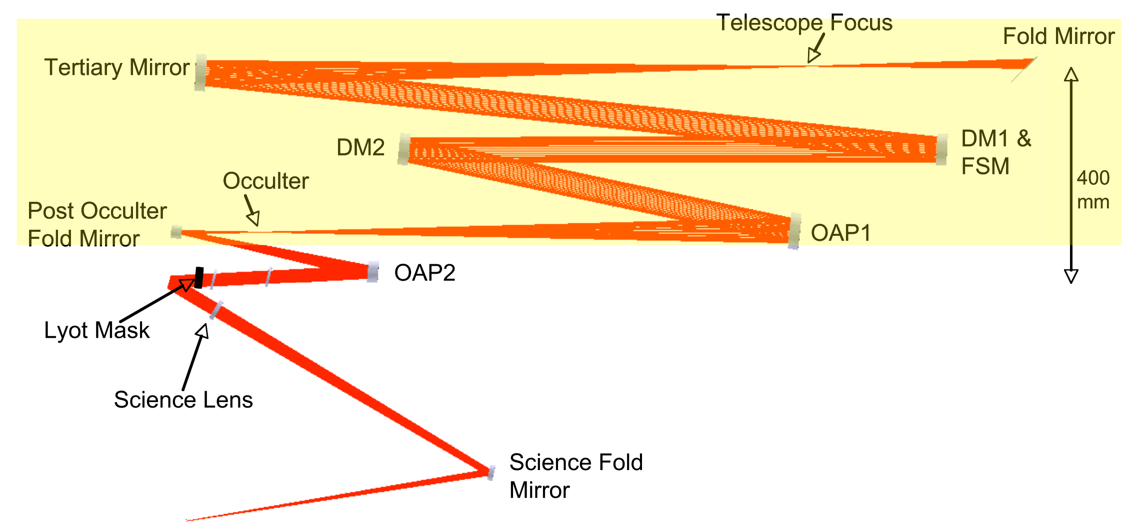
Guyon,
Belikov,
Vanderbei
C = 1e-7
(2-5 λ/D)
monochromatic

ACCESS compares four major coronagraph types

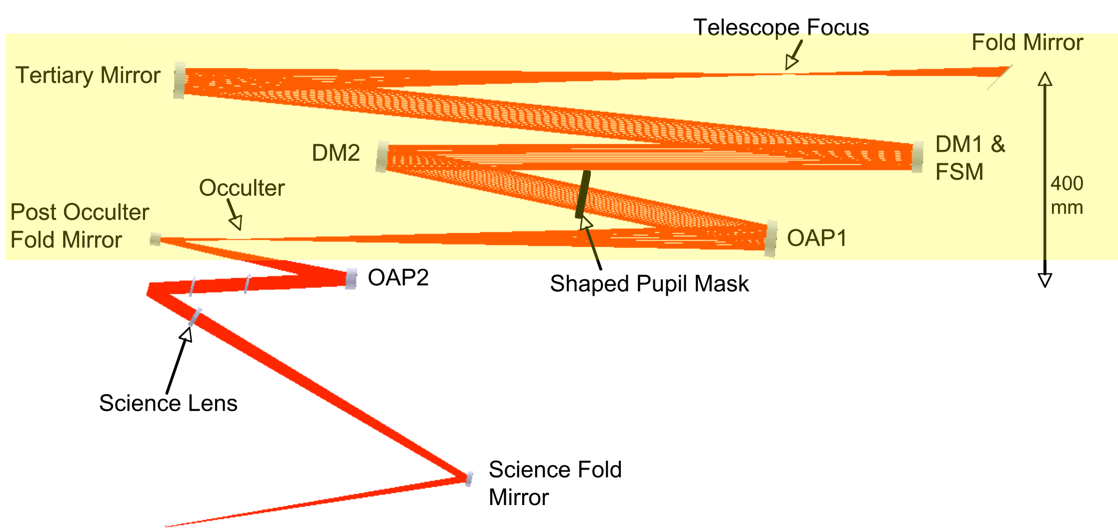
Lyot coronagraph



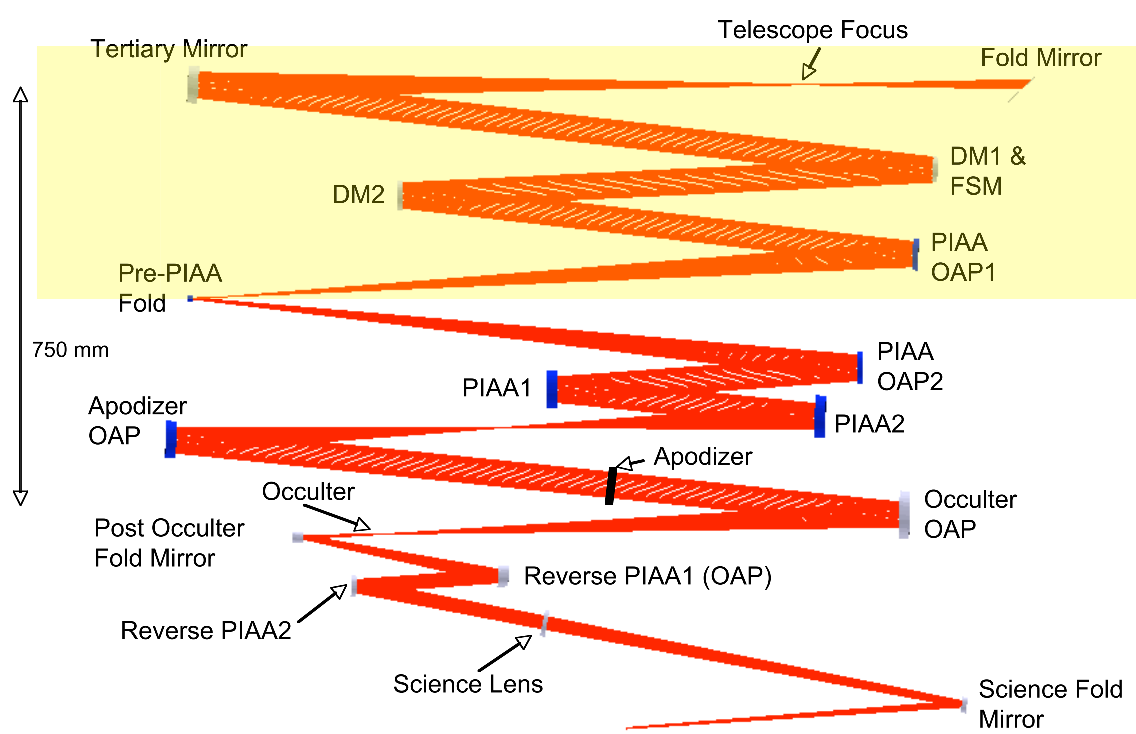
Vortex coronagraph



Shaped pupil coronagraph

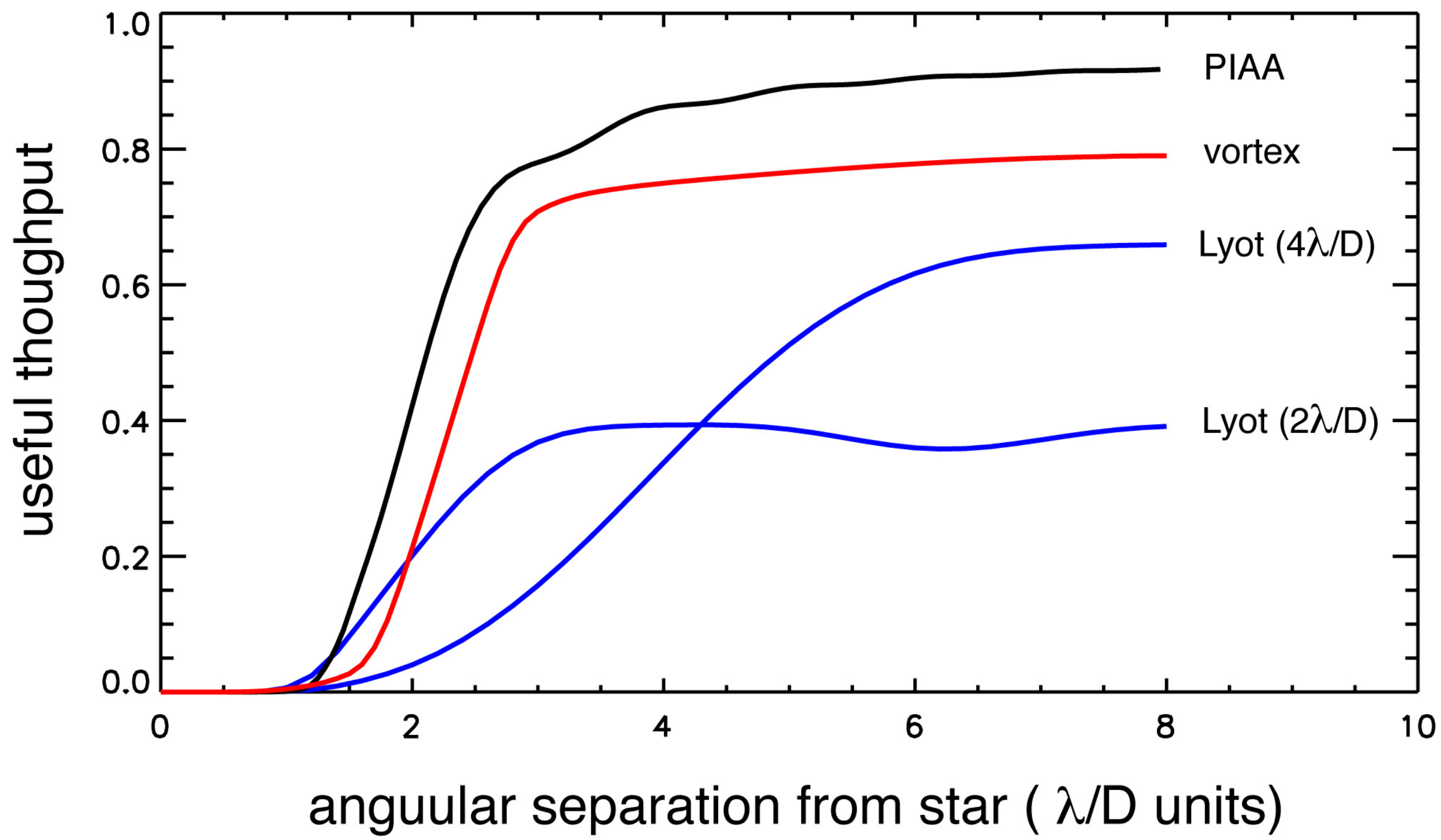


Pupil mapping coronagraph



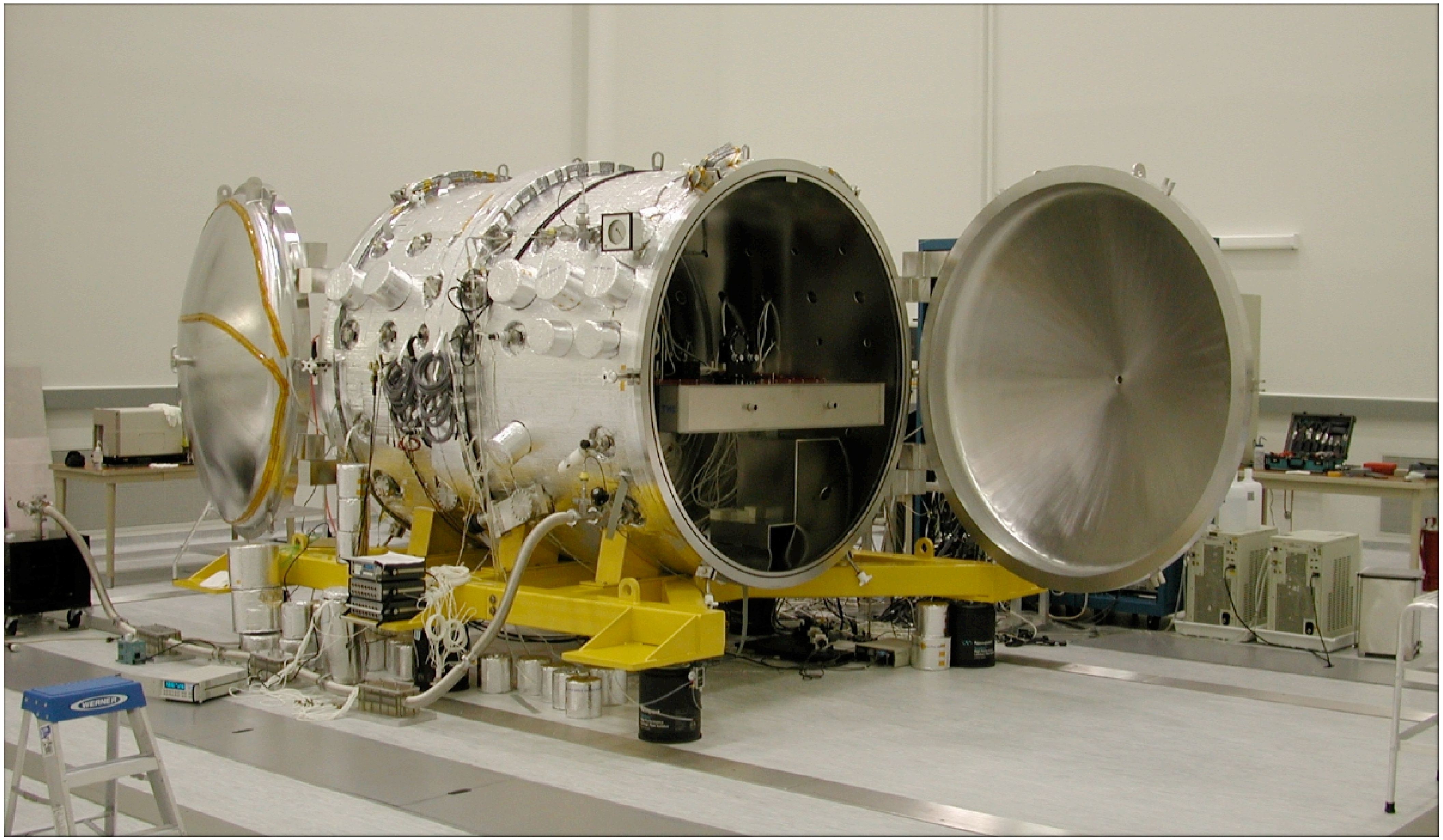
(Note: highlighted elements, including FSM, DMs, and pointing control system, are common to ALL four coronagraph types)

Coronagraph metrics

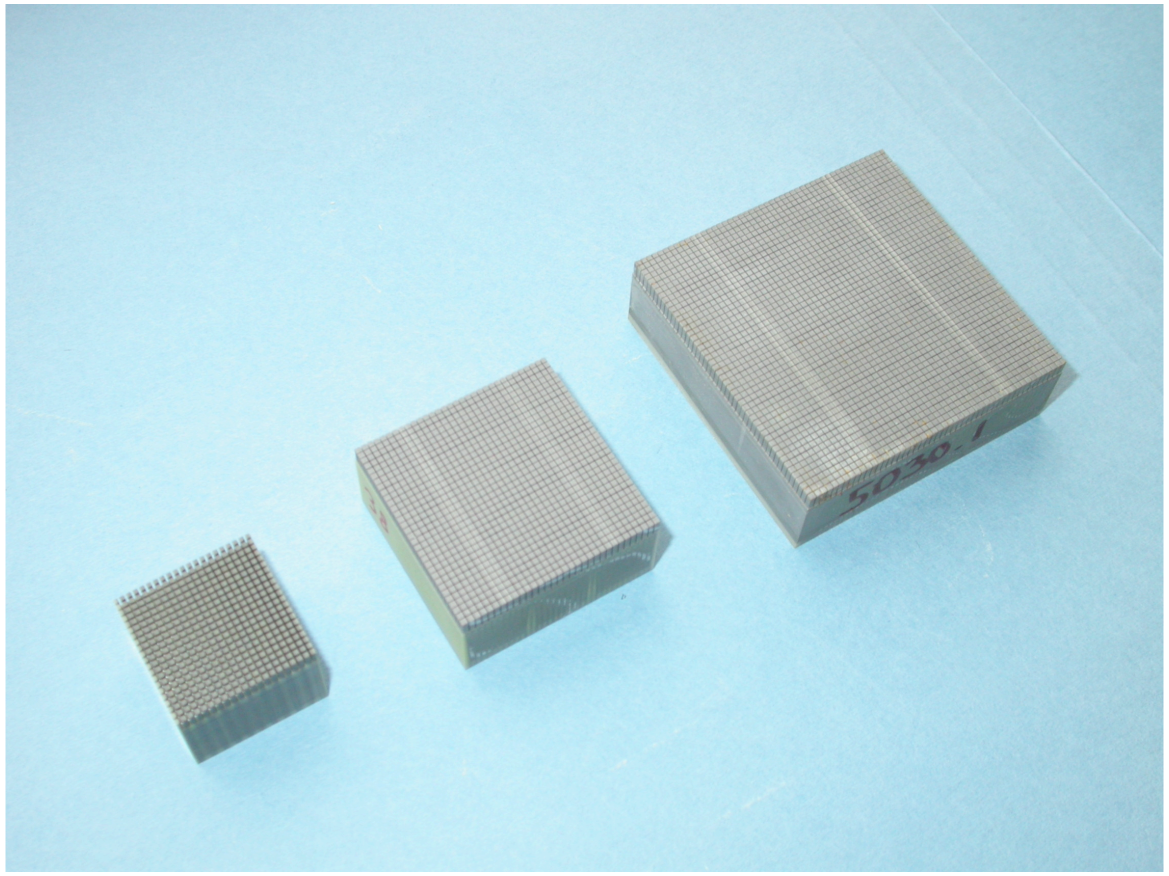


- *A variety of coronagraph types can in principle work with 1e-10 contrast and inner working angles as small as 2 lambda/D.*
- *ACCESS examines the significant performance factors, including PSF shapes, spectral bandwidth, instrument complexity, optical tolerances, and technology readiness..*

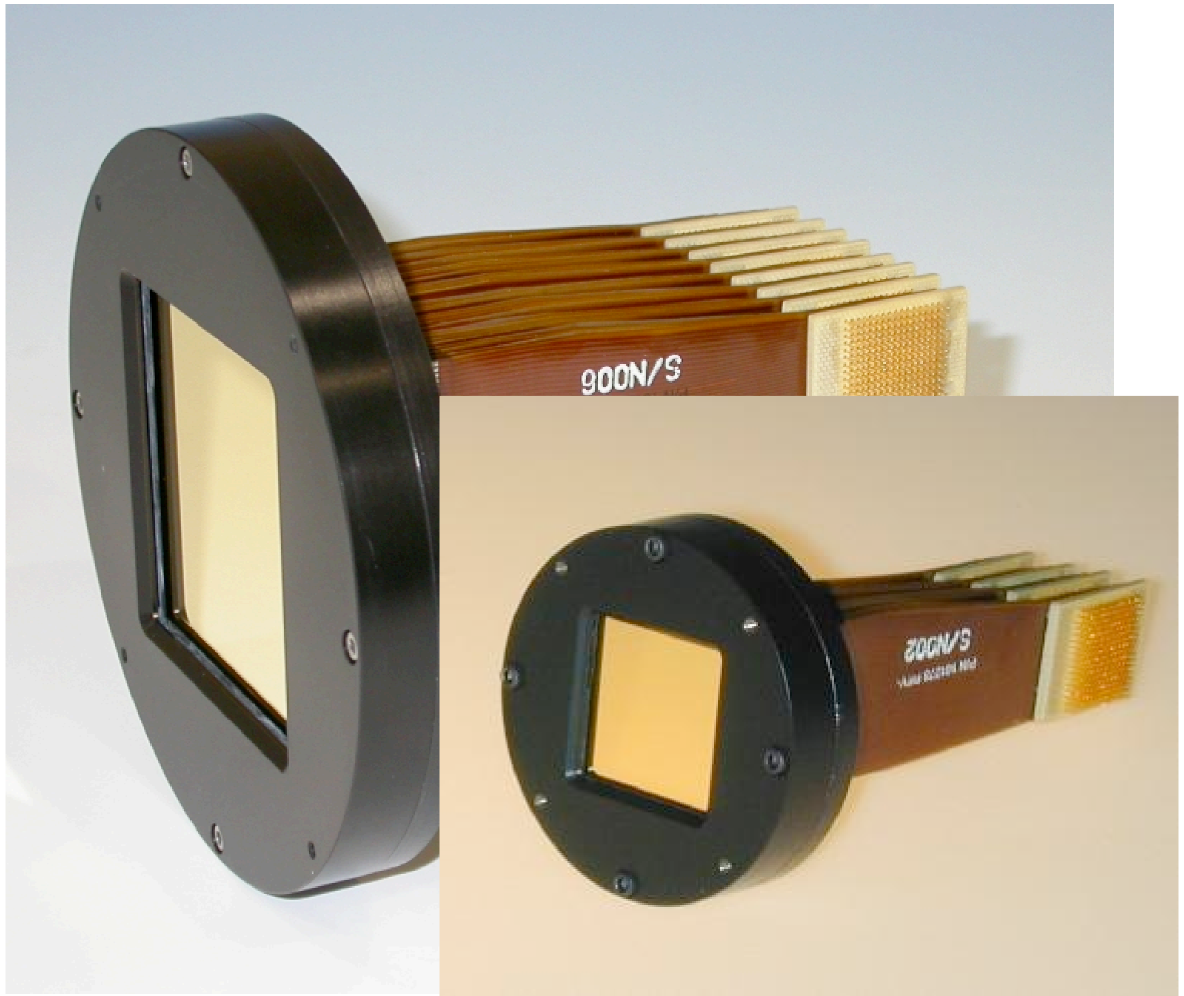
All four coronagraph types are to be tested in JPL's High Contrast Imaging Testbed



Deformable mirror development for HCIT

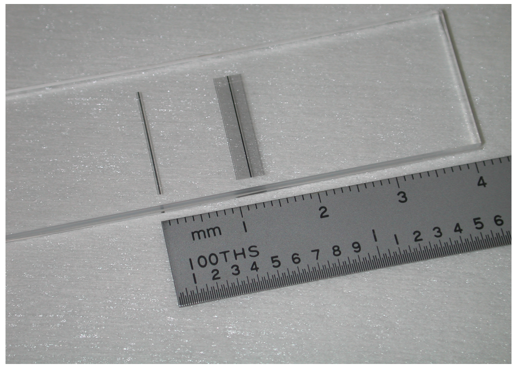


Evolution of monolithic PMN actuator arrays by Xinetics: 21x21, 32x32, and 48x48 arrays.   A fused silica facesheet is bonded to the actuator array (top side). Electrical connections (on the bottom side) complete the DM.



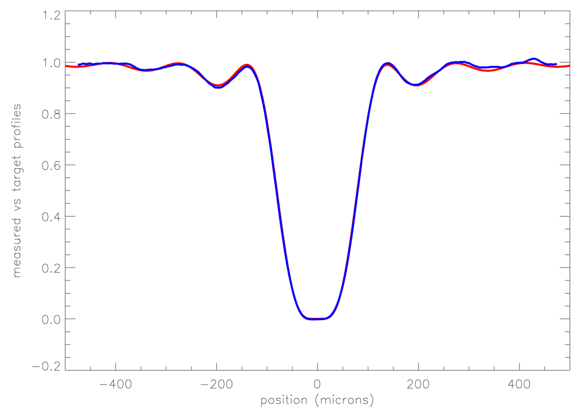
DMs delivered to JPL by Xinetics. Larger arrays are formed by bonding modules together: here a 64x64 array is built up with four 32x32 modules. Mirror surface is polished to $\lambda/100$ rms. Surface figure (open loop) is stable to 0.01 nm rms.

Lyot coronagraph on the HCIT



THICKNESS-PROFILED NICKEL MASK

Nickel mask has been vacuum-deposited on a fused silica substrate. Attenuation profile was built up in a number of passes with a computer-controlled moving slit. The same mechanism will be used to superimpose a dielectric phase layer in future work.



Comparison of the prescribed transmittance profile with the measured profile of the mask pictured at left. Desired profile is the red curve, the measured profile is the blue curve.

Recent contrast demonstrations in the HCIT:

IWA = 3 λ/D, 10% bandwidth, C = 1e-9

IWA = 3.5 λ/D, 20% BW, C = 2 e-9

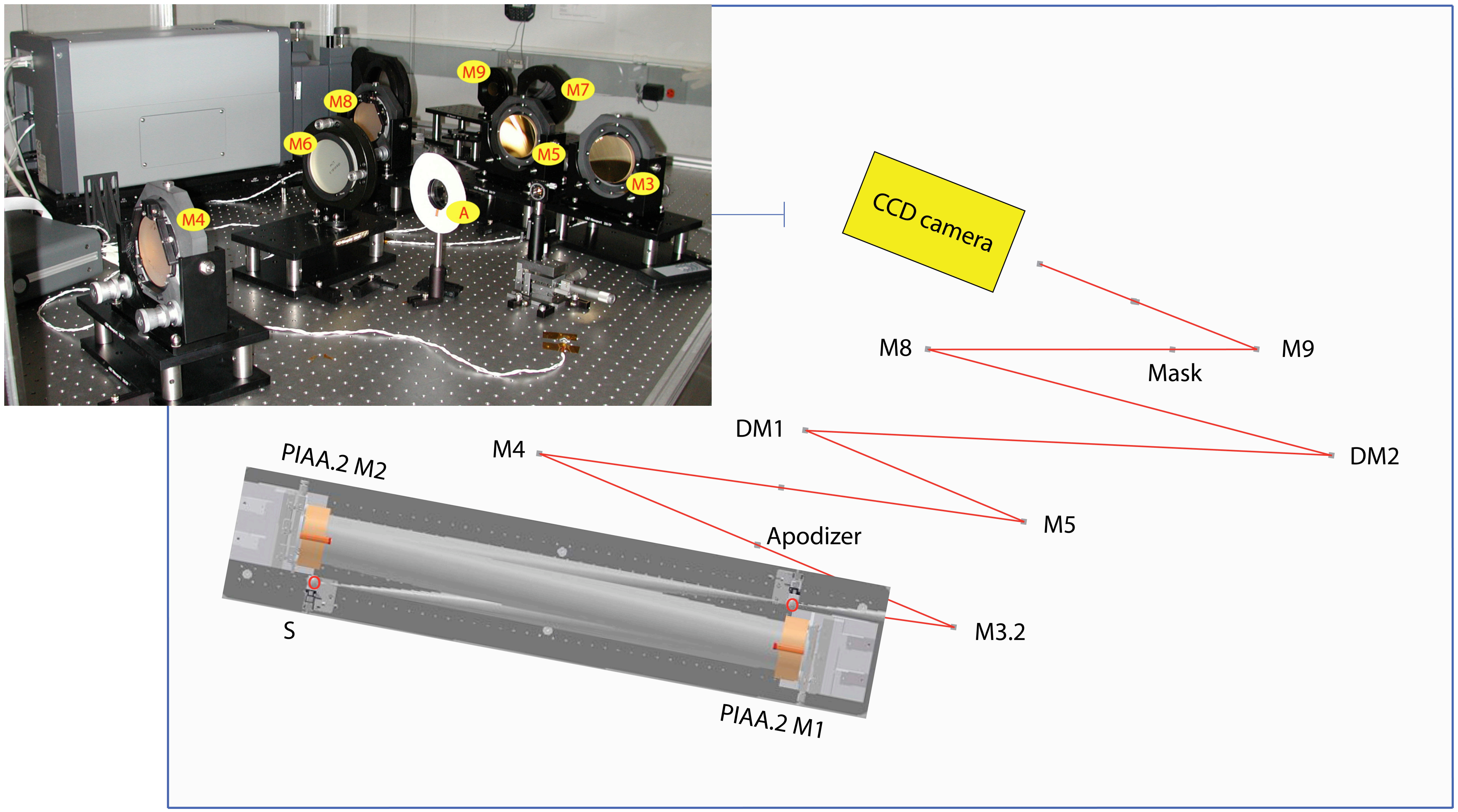
IWA = 4 λ/D, 10% BW, C = 6 e-10,

all with a metal-only 4th-order Lyot mask

Experiments in early 2009 will evaluate hybrid metal-dielectric Lyot masks, manufactured at JPL, which provide improved combinations of inner working angle (IWA), spectral bandwidth (δλ/λ), and throughput efficiency, as indicated in the Table (Moody, Gordon, Trauger 2008).

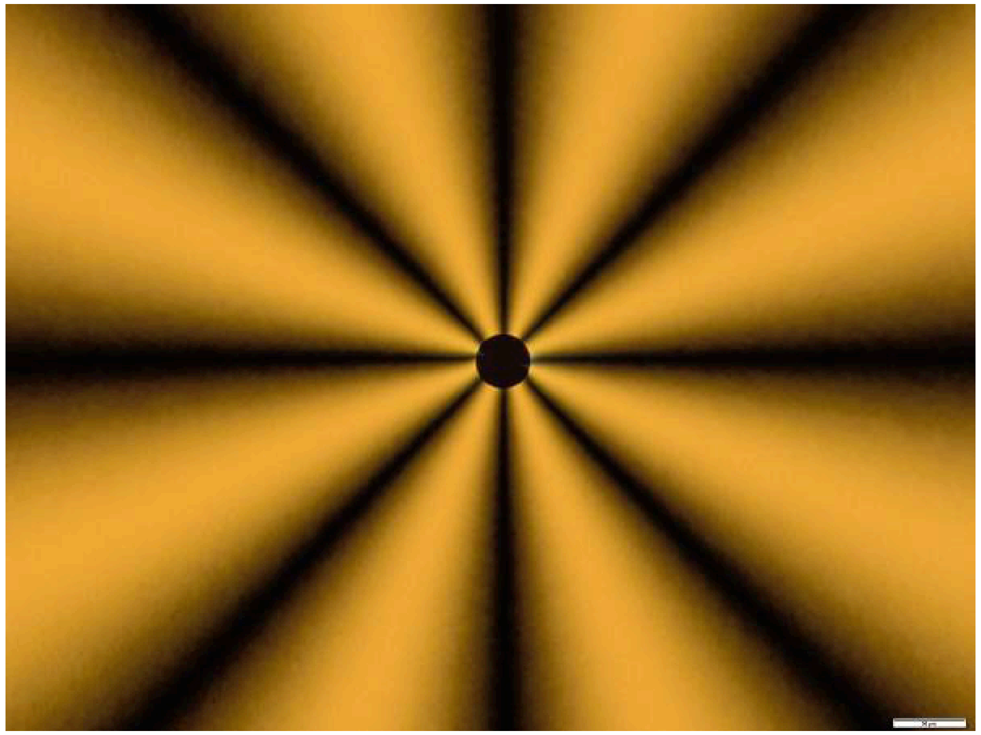
Mask Configuration	Inner Working Angle	Spectral Bandwidth	Inner Contrast (x 10 $^{-10}$)	Outer Contrast (x 10 $^{-10}$)	ε	Lyot Throughput
nickel 4th-order	4 λ/D	10%	1.3 (4 - 5 λ/D)	1.4 (4 - 10 λ/D)	0.36	55%
hybrid 4th-order	4 λ/D	20%	2.1 (4 - 5 λ/D)	3.1 (4 - 10 λ/D)	0.26	67%
hybrid 4th-order	3.5 λ/D	20%	4.5 (3.5 - 4.5 λ/D)	4.5 (3.5 - 10 λ/D)	0.30	63%
hybrid 4th-order	3 λ/D	20%	4.9 (3 - 4 λ/D)	5.0 (3 - 10 λ/D)	0.35	57%
hybrid 4th-order	2.5 λ/D	20%	8.8 (2.5 - 3.5 λ/D)	8.2 (2.5 - 10 λ/D)	0.41	49%

HCIT laboratory setup for PIAA demonstrations



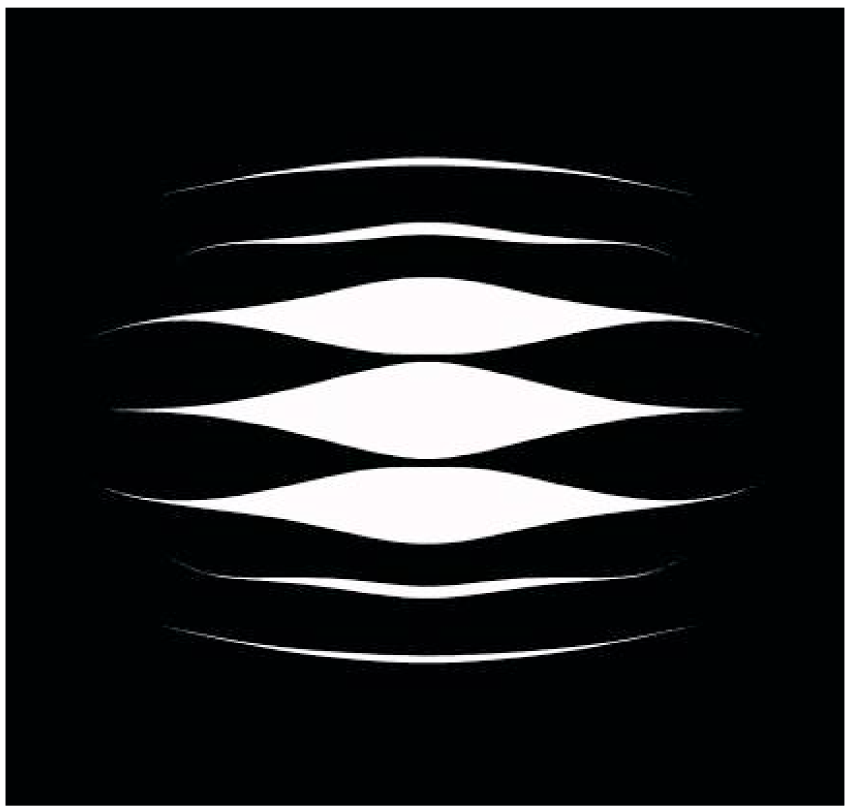
- *Pupil mapping approaches the theoretical maximum for coronagraph throughput.*
- *All optical components for the PIAA experiment are set up at JPL (as of June 2008).*
- *6.5e-7 contrast demonstrated at Subaru in monochromatic light (Guyon 2006)*
- *New PIAA system commissioned by NASA/Ames (Guyon, Belikov, Greene, McKelvey)is nearing completion at Tinsley, with delivery scheduled for 2008.*
- *Tinsley will deliver PIAA system to NASA/Ames and JPL in January 2009, where it will be installed on the new HCIT optical table for ASMCS experiments.*

First vector vortex phase mask for HCIT experiments

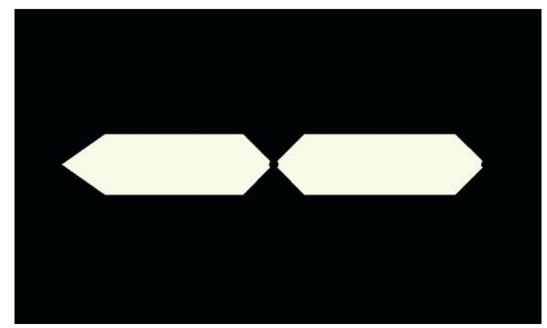


- *Vector vortex approaches the theoretical maximum for coronagraph throughput.*
- *A promising technology for the vector vortex mask is the liquid crystal polymer developed by JDSU (Mawet et al. 2007). A trial mask of this type, with topological charge 4, tuned for monochromatic 0.8 micron light, has been delivered to JPL for ACCESS evaluations on the HCIT.*
- *Image shows the vortex mask illuminated through crossed polarizers. Central circular opaque dot masks the confusion zone at the central singularity*
- *Preliminary tests on the HCIT yield 1.5e-6 contrast at IWA = 3 λ/D in 2% bandwidth light (Jan 2009), and a new EFC procedure is in development.*
- *Vortex mask can be achromatized to 10-20% bandwidths using three polymer layers, as for commercial achromatic half-wave plates. This construction will be attempted this year.*

Shaped pupil coronagraph experiments with HCIT

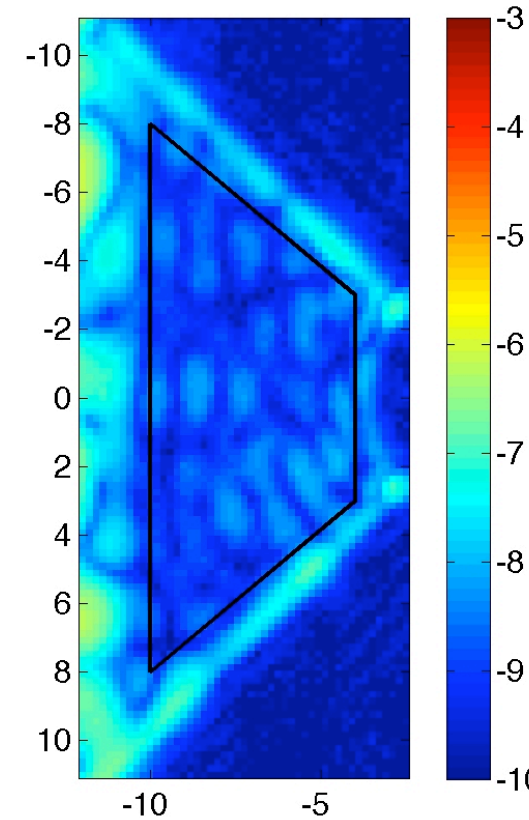


Shaped pupil mask



Focal plane mask

High contrast field



At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear). At center, the corresponding "bowtie" image plane mask. This "Ripple 3" design achieved 2.4e-9 contrast in 10% bandwidth averaged over the 4-10 λ/D dark field (outlined) on the HCIT. (Belikov et al. 2007)

Summary

- *The ACCESS study considers the relative merits and readiness of four major coronagraph types, as well as hybrid combinations*
- *The ACCESS science program is defined in detail in terms of the predicted performance of a TRL6+ mission concept.*
- *The study will also identify specific areas of technology development that would advance the readiness of the major coronagraph types in the coming 5 years.*

End