Laboratory demonstrations of high-contrast imaging for space coronagraphy

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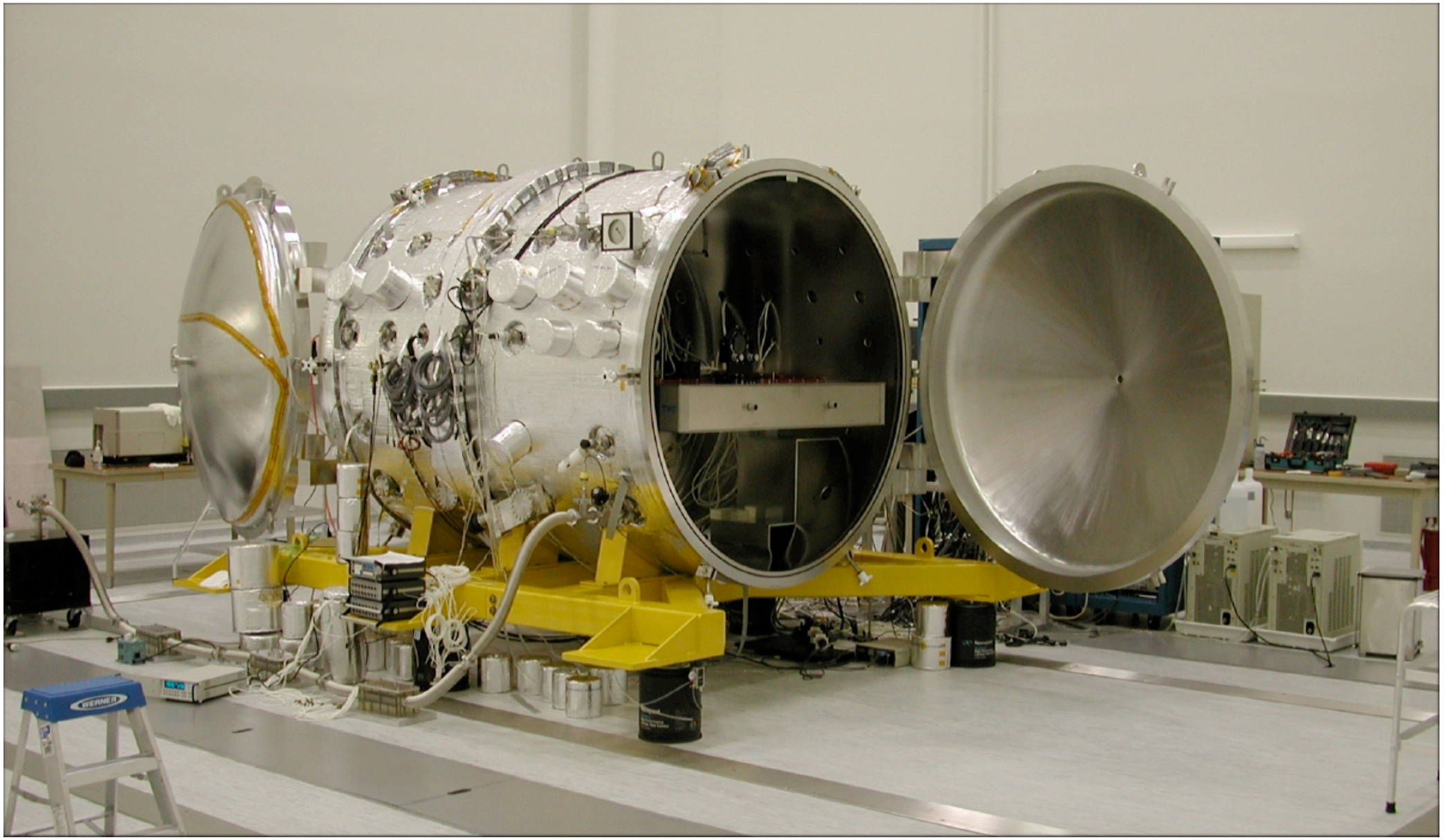
Objectives

The High Contrast Imaging Testbed is intended to:

- Advance the technology readiness of space coronagraph hardware, techniques, algorithms, and predictive models;
- Provide proof-of-concept demonstrations of coronagraph techniques; and
- Support collaborations across the exoplanet community in pursuit of the optimal space coronagraph architecture.

High Contrast Imaging Testbed at JPL



Objectives

- HCIT validates predictive models
  - Simple optical layout, easily modeled
  - Models guide experimentation and coronagraph development
  - Models validated by experiment are needed to support mission design
- HCIT provides wavefront control
  - All coronagraph concepts require active wavefront control
  - DMs, low-power MUX driver, flight-like system
  - Algorithms: MGS, SN, EFC
  - Contrast floor (5e-10) and wavefront stability (1e-11/hours)
  - In progress: new hardware for improved contrast floor (<1e-10)
- HCIT validates coronagraph concepts
  - There is a lot of time/effort/$$ between a good idea (TRL1) and hardware demonstration in a space environment (TRL6)
  - Lyot coronagraph
  - Shaped pupil coronagraph (with Belikov, Kasdin, *et al.* -- Princeton)
  - PIAA coronagraph (with Guyon *et al.* -- Subaru, NASA Ames)
  - Others when ready, such as the optical vortex coronagraph
- New developments for the band-limited coronagraph
  - HEBS, metal masks for 10% bandwidth and 55% throughput
  - Hybrid metal-dielectric masks: 30% bandwidth and 66% throughput
- Goal is to serve the community by helping to advance promising coronagraph concepts to maturity.

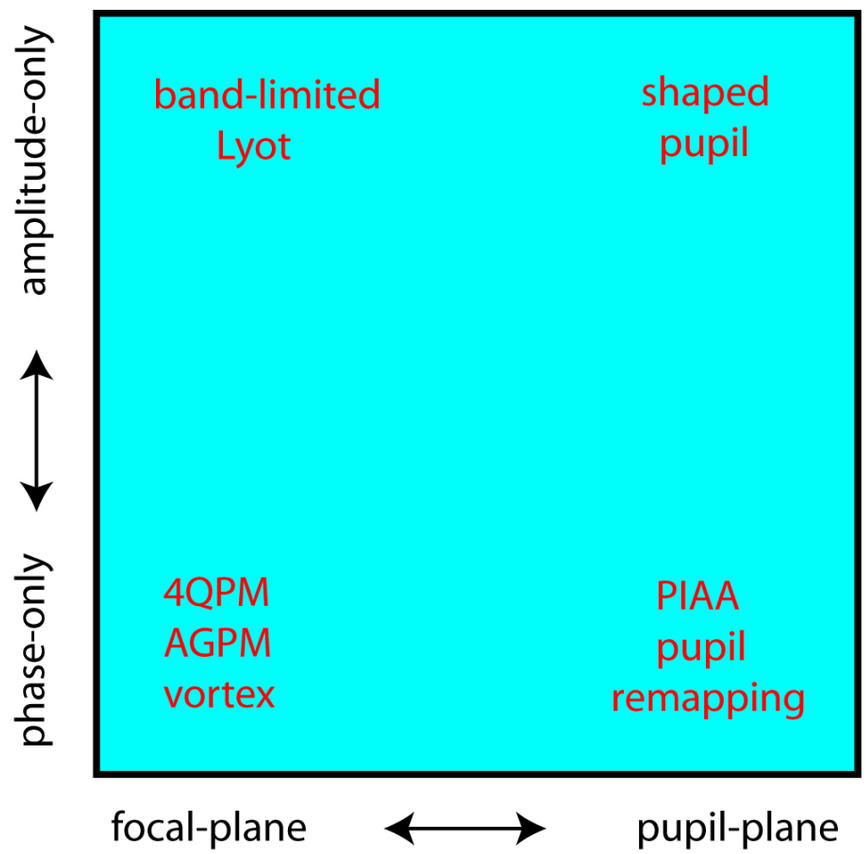
Diverse coronagraph types

Kuchner, Traub,
Crepp, Ge,
Moody, Trauger, ...

C = 5e-10
(4-10 lambda/D)

Spergel, Kasdin,
Vanderbei,
Belikov, Pueyo...

C = 1e-9
(4-10 lambda/D)



Rouan, Riaud,
Mawet, Soummer,
Boccaletti,
Schwarzlander, ...

Guyon,
Vanderbei,
Traub, ...

C = 7e-7
(2-4 lambda/D)

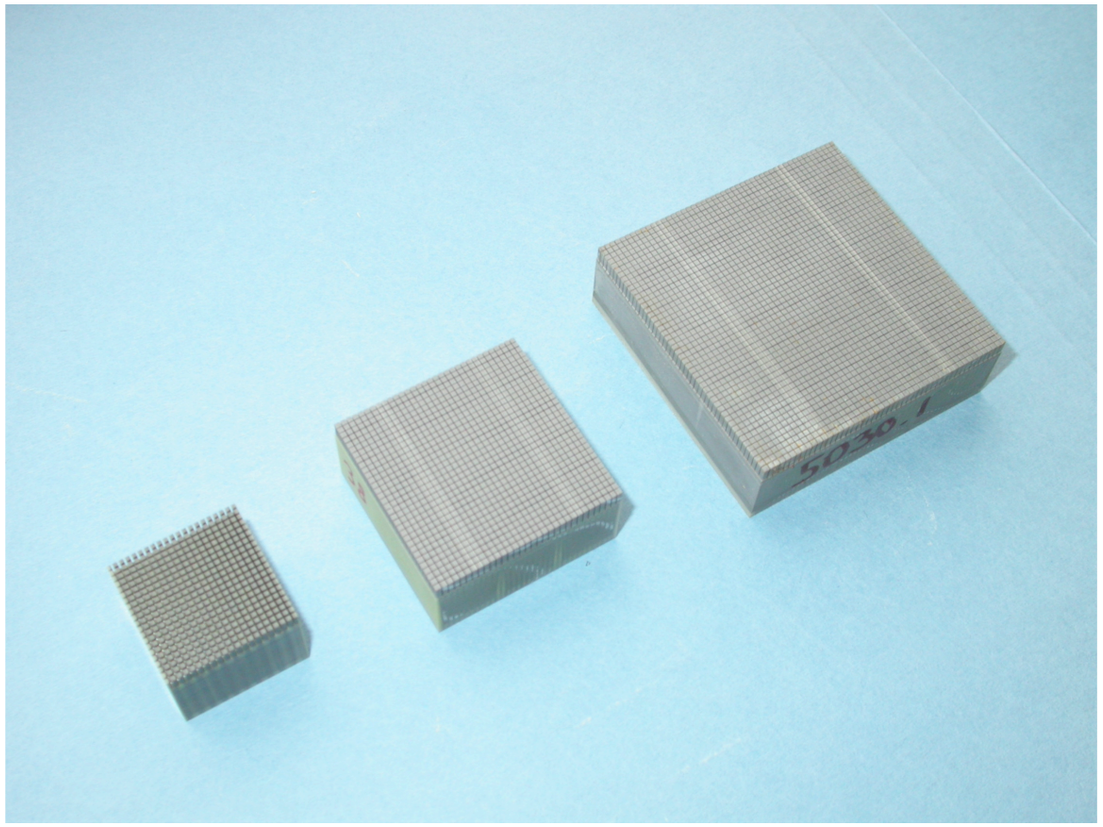
Coronagraphs require active wavefront control

- Coronagraphs are designed to suppress light diffracted by the boundaries of the telescope clear aperture.
- Imperfections in the optical wavefront scatter light and impose a contrast limit for all (internal) coronagraphs
- Theoretical advantages of a given coronagraph architecture will not be realized in practice unless the wavefront errors are controlled.

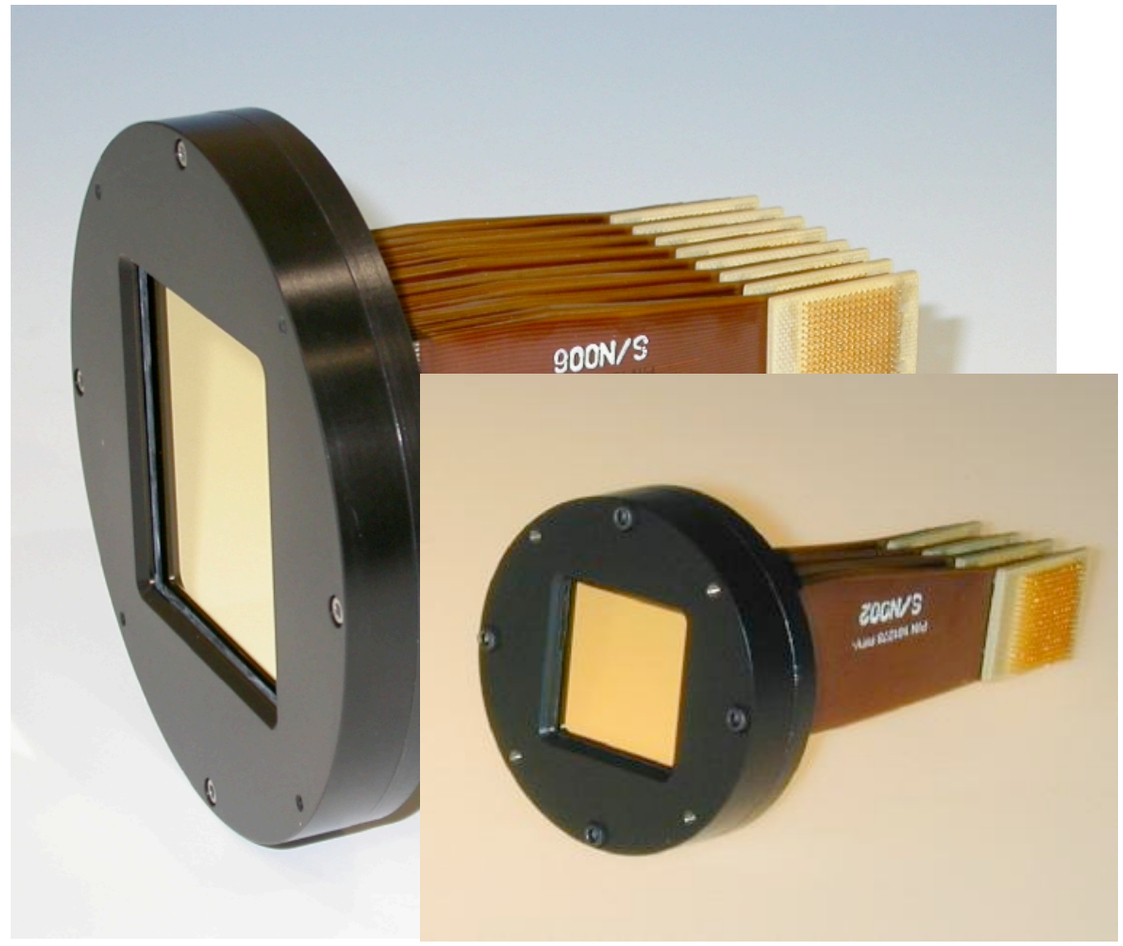
Coronagraphs require active wavefront control

- Real optics: HST-quality primary mirror still requires significant wavefront corrections to image planets with Q = 1.
- Even the best available small-diameter optics (~1 nm rms) for the coronagraph still require order of magnitude improvements in wavefront errors.
- DM phase correction can compensate for imperfections (amplitude and phase) in the coronagraph elements.
- Also, a single deformable mirror can generate a variety of useful amplitude & phase corrections over half of the controllable high-contrast field of view.
- Multiple DMs provide redundancy and additional leverage for correction over the full controllable field of view and increased spectral bandwidth.

Deformable mirror development for HCIT



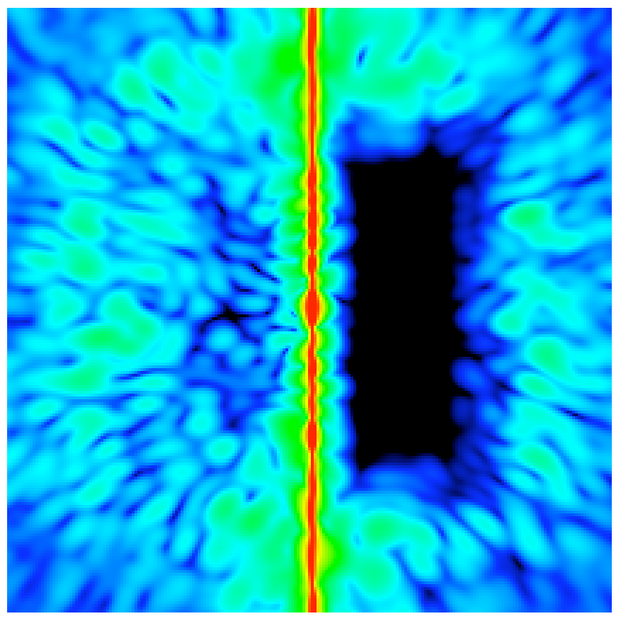
Evolution of monolithic PMN actuator arrays by Xinetics: 21x21, 32x32, and 48x48 arrays. A fused silica facesheet is bonded to the actuator array (top side). Electrical connections (on the bottom side) complete the DM.



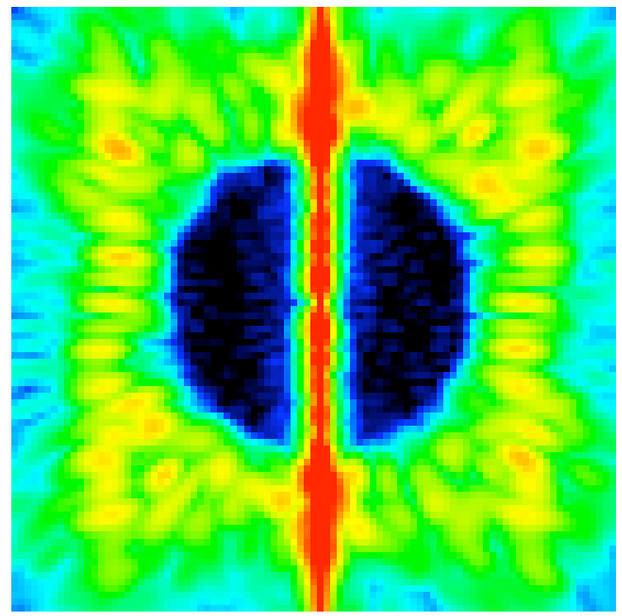
DMs delivered to JPL by Xinetics. Larger arrays are formed by bonding modules together: here a 64x64 array is built up with four 32x32 modules. Mirror surface is polished to λ/100 rms. Surface figure (open loop) is stable to 0.01 nm rms.

Example: predicted contrast over half-fields

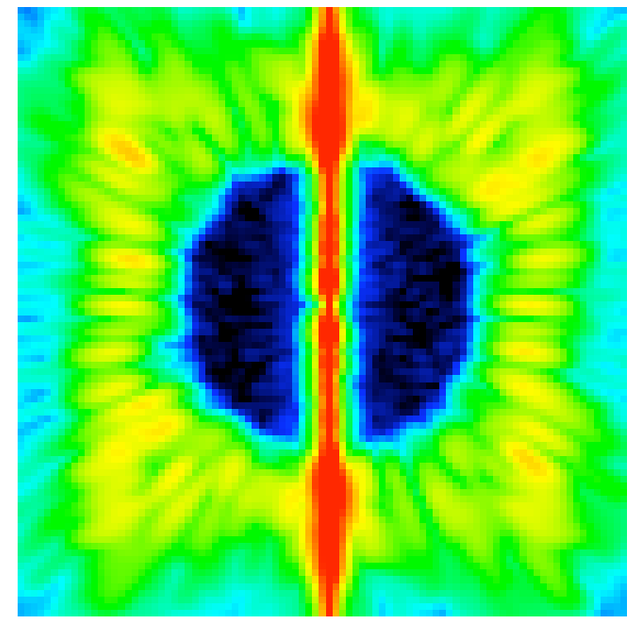
Lyot coronagraph, perfect band-limited occulting mask, single DM



10% bandwidth
760-840 nm
epsilon = 0.32
C = 3e-11
HCIT optics



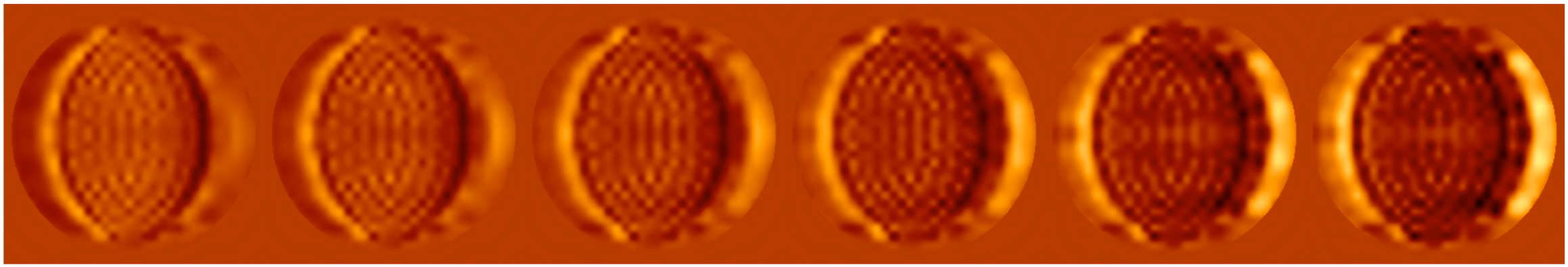
10% bandwidth
746-824 nm
epsilon = 0.32
C = 5e-10
HCIT optics



20% bandwidth
706-864 nm
epsilon = 0.32
C = 7e-10
HCIT optics

(Moody, 2007)

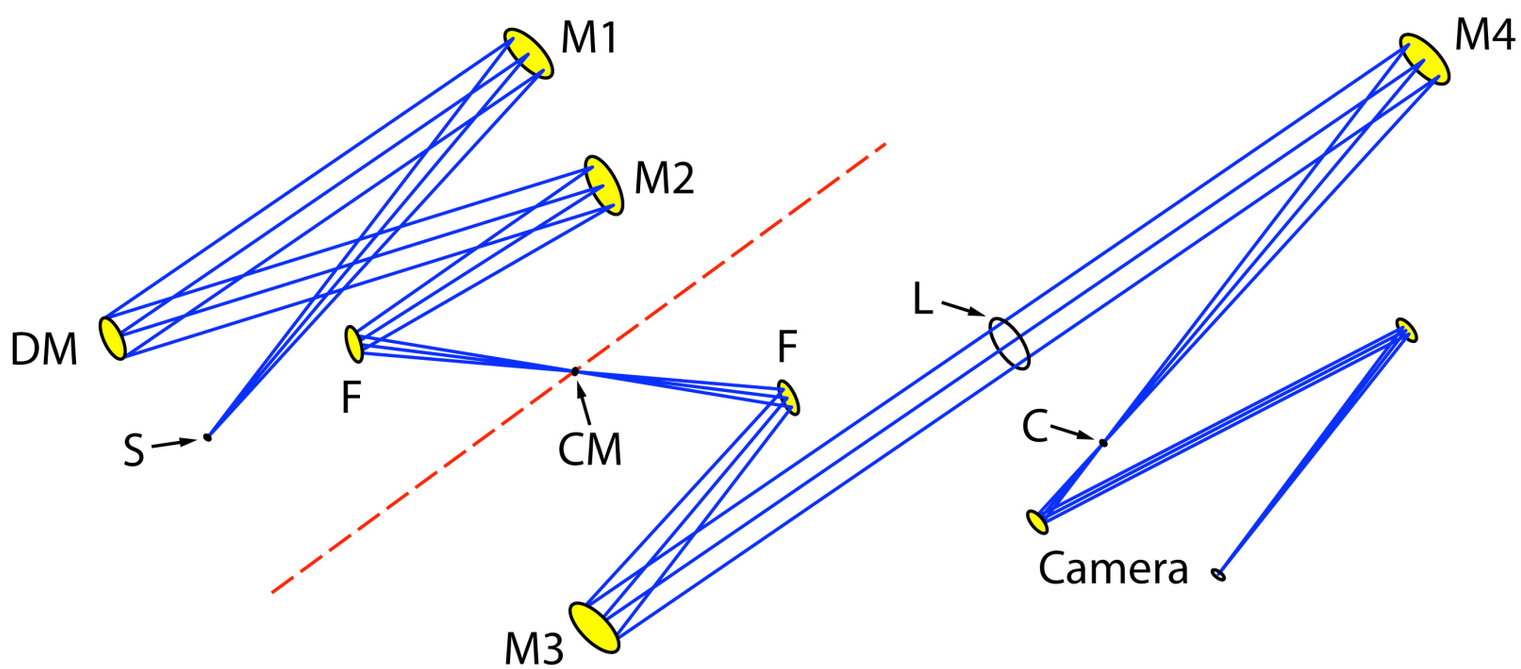
Example:
DM settings compensate for material characteristics

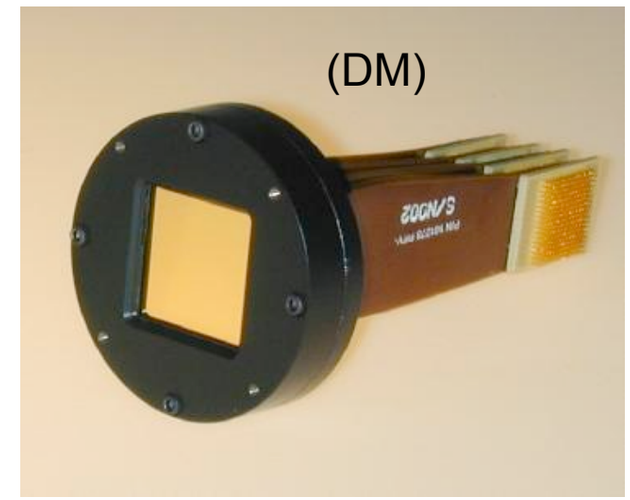


	605 nm	620 nm	635 nm	650nm	665 nm	680 nm
C =	1.9e-10	1.8e-10	2.0e-10	2.5e-10	3.3e-10	4.6e-10

Optimal DM settings for 6% bandwidth, computed for a band-limited occulting mask made of HEBS type IK89 glass (with wavelength-dependent phase-vs-OD characteristics).
Largest deformations are +/- 0.025 wave.

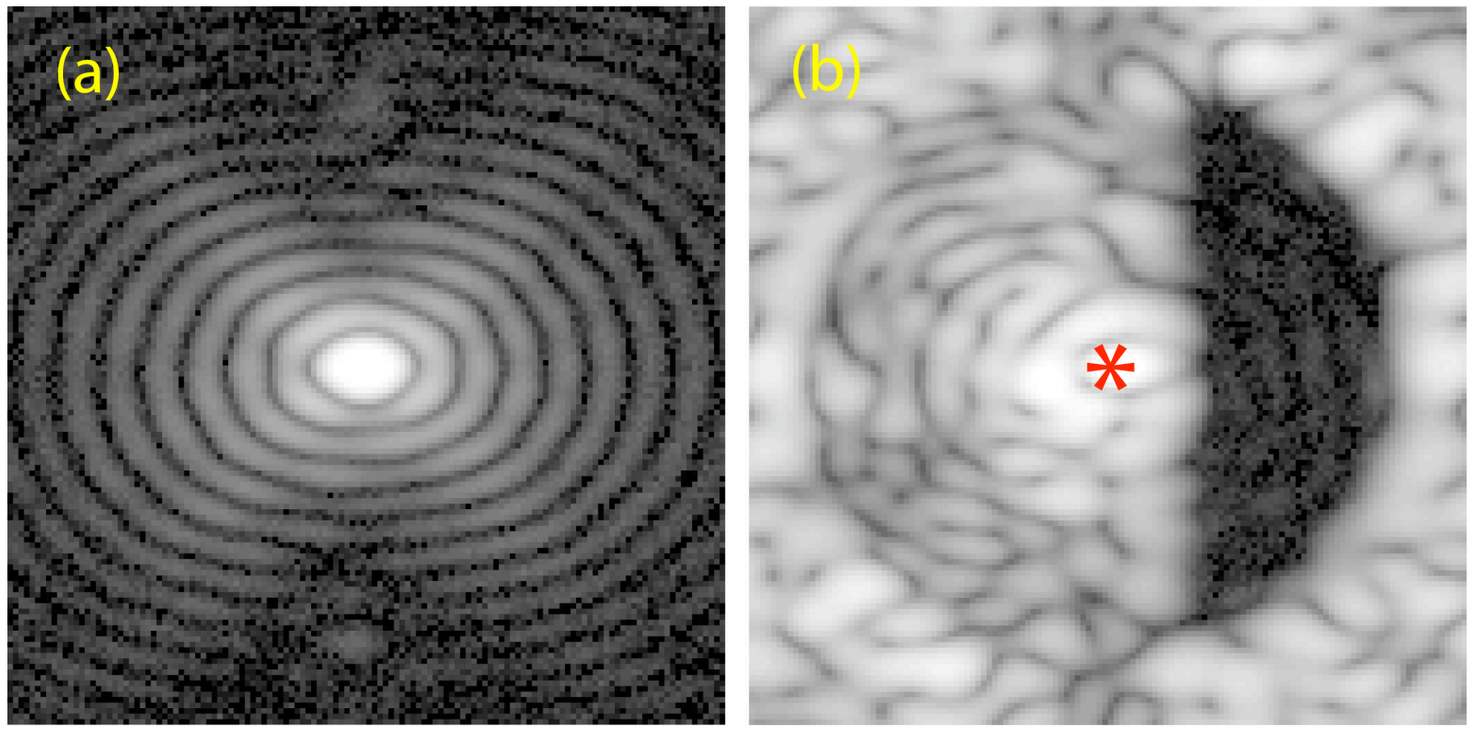
HCIT coronagraph optical layout





- "Star" is a pinhole illuminated by a supercontinuum light source + interference filters
- Off-the-shelf lambda/20 mirrors
- f/25.8 beam illuminates the coronagraph mask (CM)
- Single 32x32 DM, low-power MUX driver
- Coronagraph image is magnified x3 at science CCD to ~4.5 pixels / airy
- Optical table enclosed in a thermally-isolated, vibration-damped vacuum chamber.

Laboratory coronagraph PSF and dark field



Lyot coronagraph PSFs: (a) the star with focal plane mask removed and Lyot mask in place; and (b) the dark half-field with DM voltages set initially by speckle nulling.
Measured contrast values are 6e-10 and 5e-10 averaged over the inner (4-5 lambda/D) and outer (4-10 lambda/D) fields respectively.

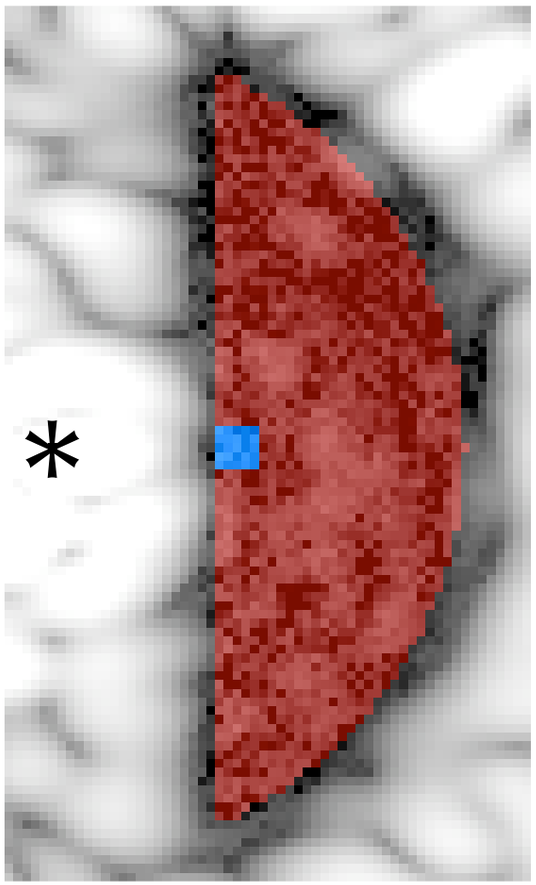
(TPF-C Milestone#1 report, July 2006)

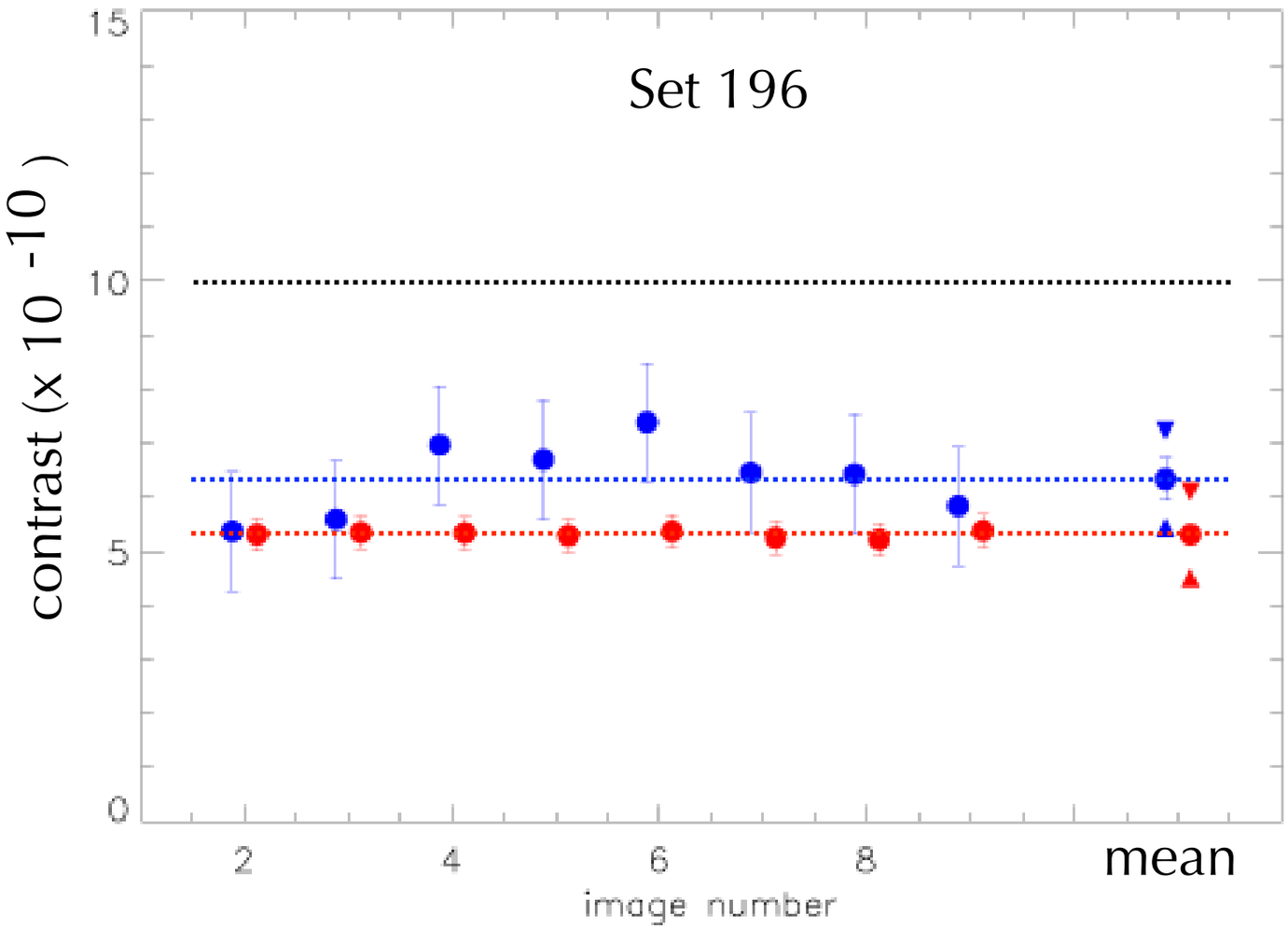
Wavefront sensing and control

- Three algorithms are in general use on the HCIT
  - All wavefront sensing is done at the science CCD focal plane.
- Focus-diversity Gerchberg-Saxton (Krist, 2007):
  - Used to verify optical alignment
  - Defines a flat-wavefront starting point at start of precision nulling.
- Speckle nulling (C. Burrows, 2004):
  - Attacks 20-30% of speckles in the dark field per iteration
  - Robust, requires little knowledge of coronagraph or DM
  - Reaches monochromatic contrast limit of 5e-10
  - Iterative, converges slowly.
- Electric Field Conjugation (Give'on, 2007)
  - Attacks entire dark field in each iteration
  - Requires (and benefits from) detailed knowledge of coronagraph and DM
  - Reaches monochromatic contrast limit of 5e-10
  - Iterative, converges rapidly
  - Can be extended to multiple DMs and simultaneous nulling at multiple wavelengths.

(Give'on *et al.*, *Proc. SPIE*, 6691, paper 07, 2007)

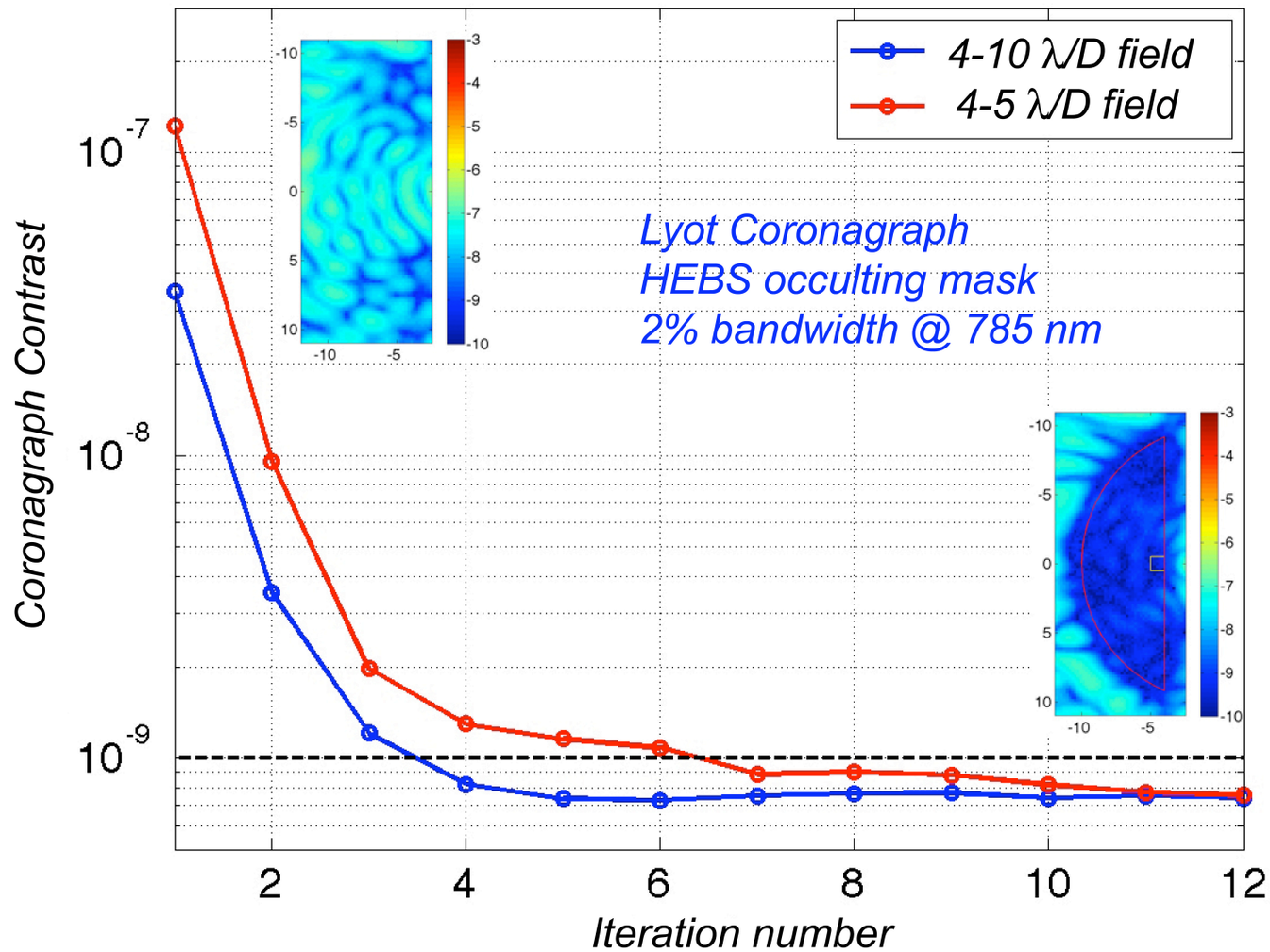
"Classical" speckle nulling with the HCIT





Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. 1-σ error bars indicate the measurement noise estimated from pairwise data.

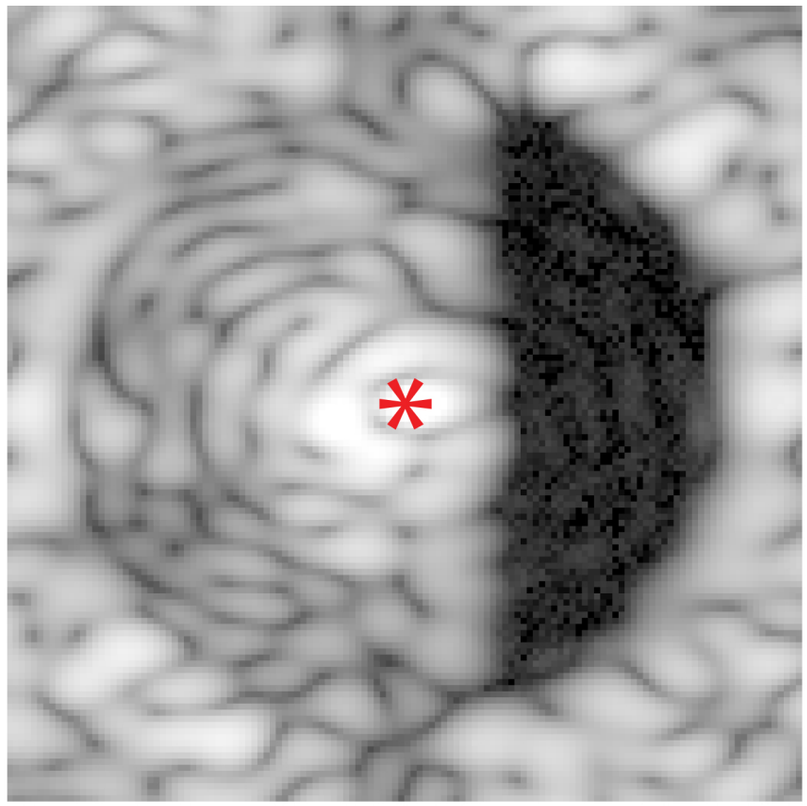
Iterative wavefront sensing and control

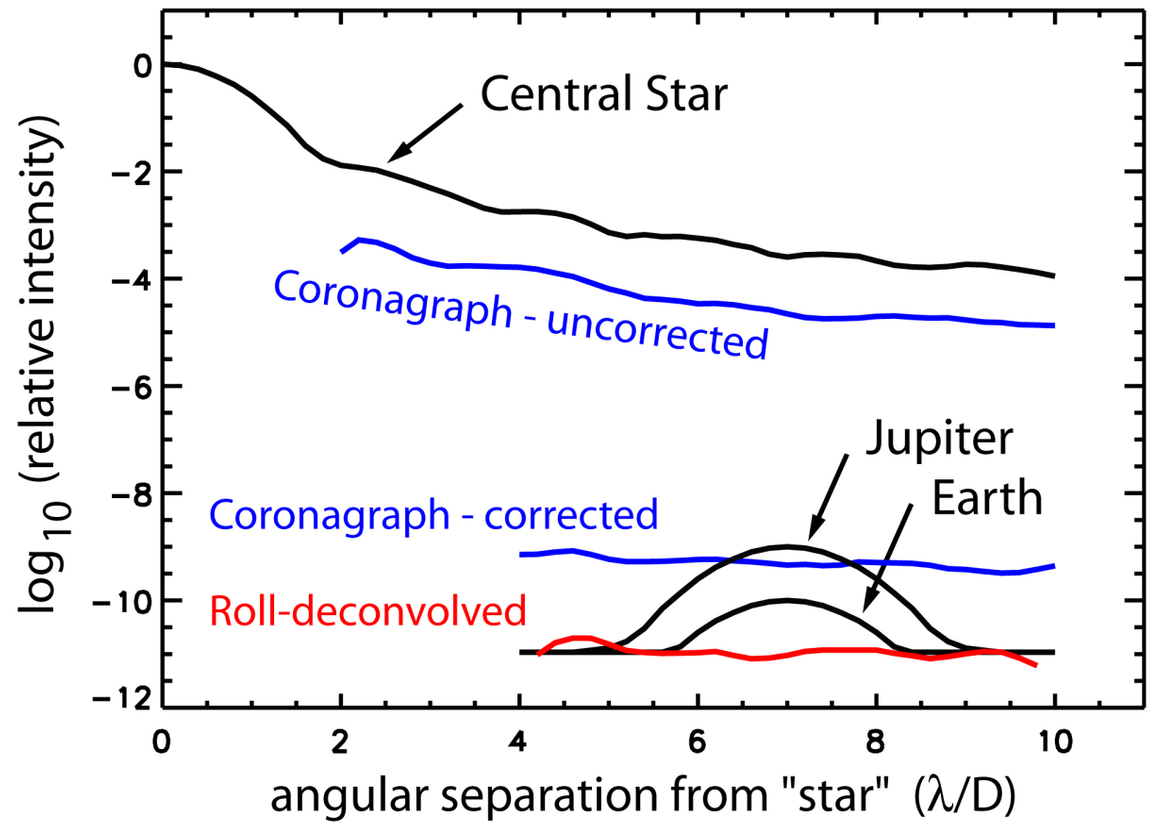


Improved convergence rates demonstrated with the HCIT Lyot coronagraph using the Electric Field Conjugation (EFC) algorithm.

(Give'on *et al.*, *Proc. SPIE*, 6691, paper 07, 2007)

Laboratory coronagraph contrast and stability

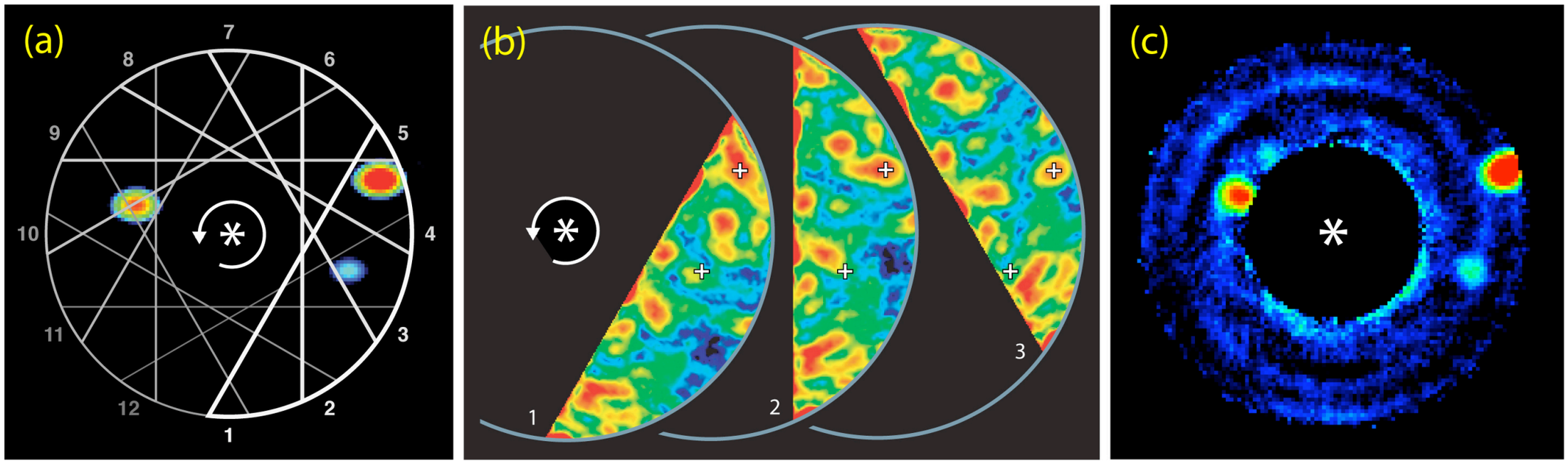




Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (b) the coronagraph field with all DM actuators set to equal voltages; (c) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of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

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

"Roll deconvolution" with HCIT data



Simulation of roll deconvolution with a sequence of 480 consecutive HCIT images taken open-loop over a period of five hours. (a) Three "planets" with the star PSF, but reduced to relative intensities of 10, 5, and 1x10-10. Rotation of the "telescope" and the D-shaped dark field is indicated by the wire grid. (b) Three of the rotated fields are shown, with the simulated planets superimposed (crosses). The 480 images were segregated into 48 sets of 10, and used to construct 48 fields rotated in 7.5 degree increments. (c) The result of roll deconvolution on the set of 48 images by John Krist. The nominal Earth (4 o'clock) and Jupiter (2 o'clock) are clearly seen.

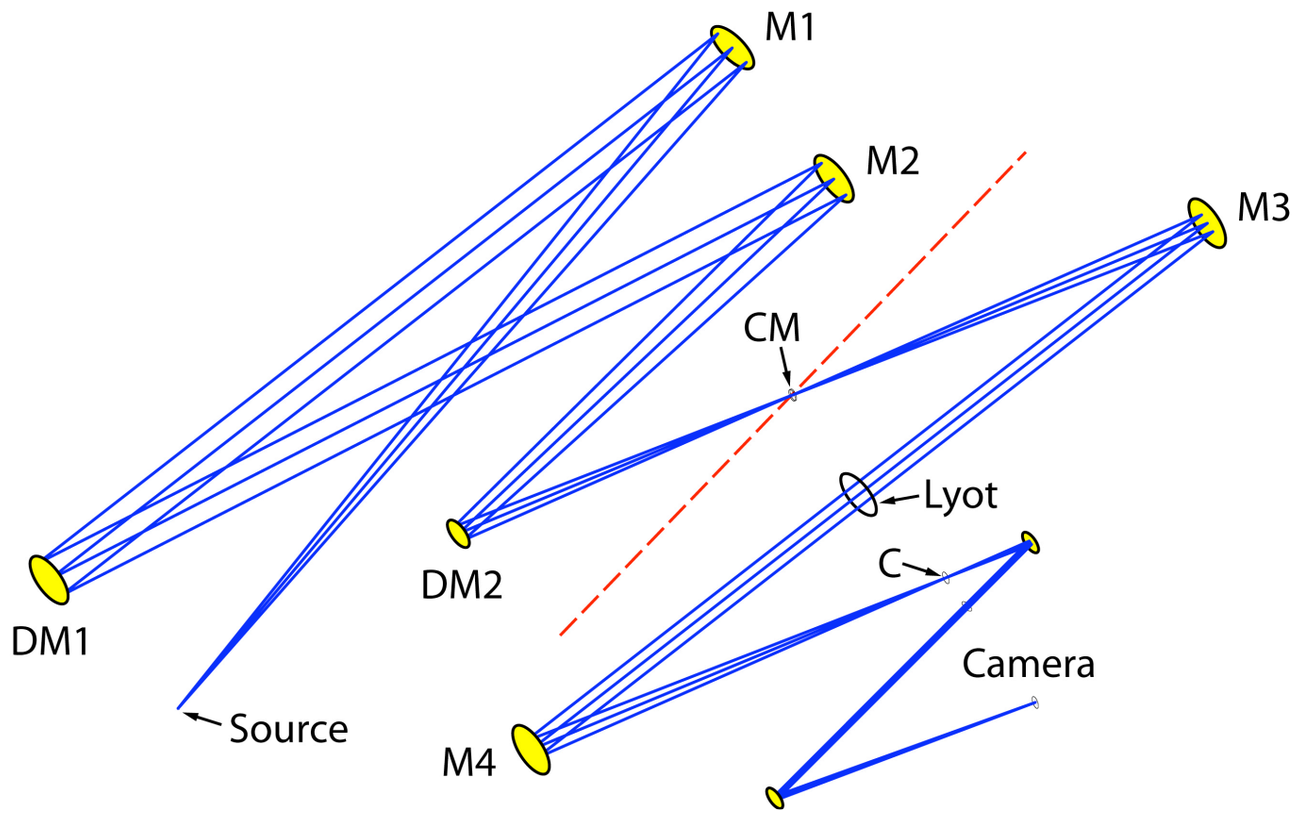
(Trauger & Traub, *Nature*, 12 April 2007, p771)

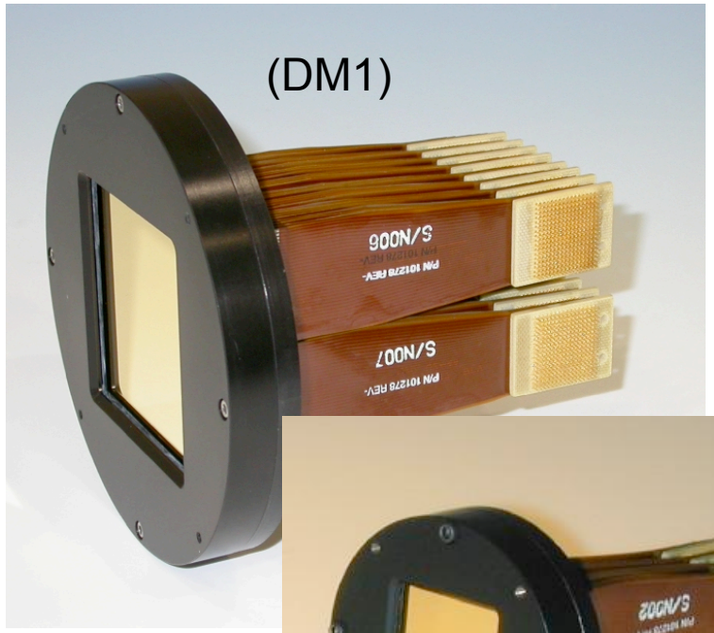
Contrast floor and stability can be traced to DM surface positioning errors:

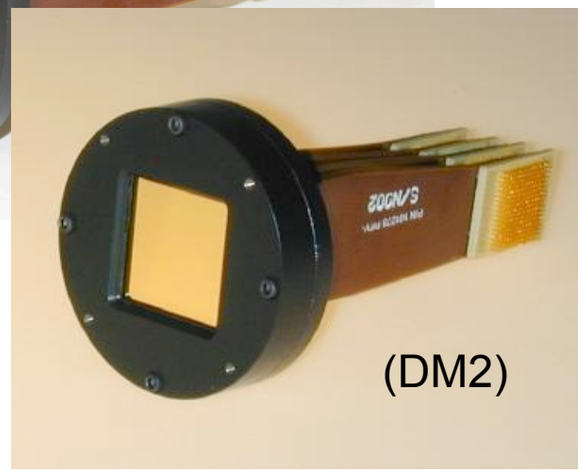
$$C = \pi \left[\frac{2\pi\sigma}{N\lambda} \right]^2$$

- Uncorrelated DM actuator noise produces a flat background of scattered light that places a limit on achievable contrast.
- A consistently-observed contrast of 5e-10 with the HCIT Lyot coronagraph in narrowband light (lambda = 785 nm, N = 30) implies a surface figure noise of 0.05 nm rms.
- Contrast stable to 1e-11 implies a surface figure drift of 0.007 nm rms over periods of 5 hours or more.
- The contrast floor can be improved by:
  - decreasing actuator positioning noise (sigma) or
  - increasing the number (N) of actuators across the diameter
  - both are achievable.

Wavefront control upgrade is in progress

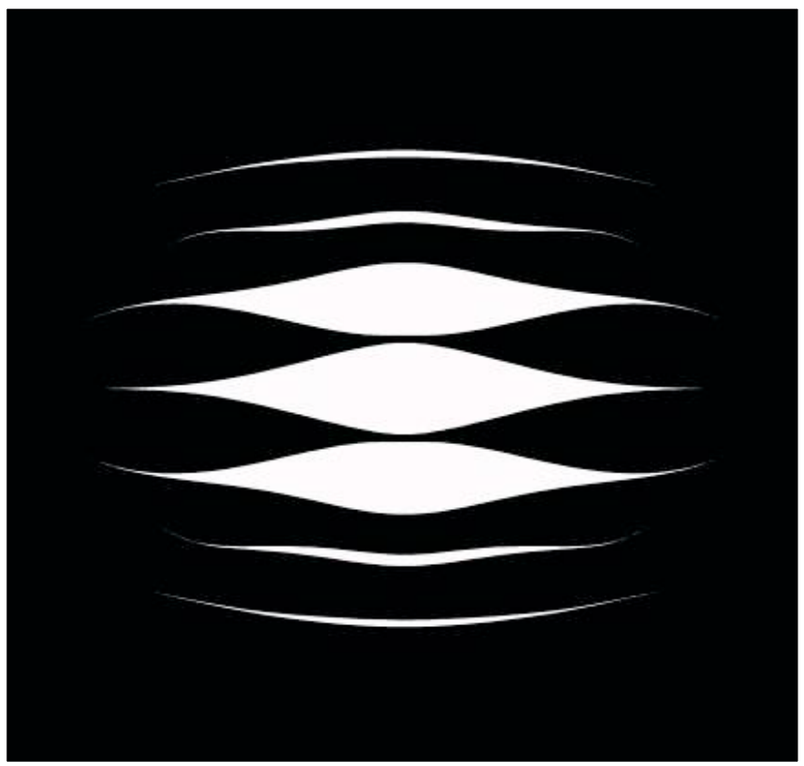




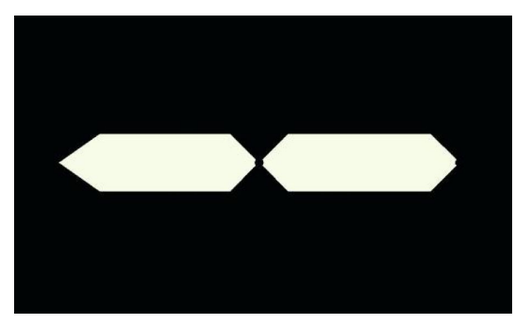


- Monochromatic contrast floor is expected to improve from 5e-10 to better than 1e-10.
- DM1 (64x64 actuators) will reduce contrast floor due to actuator noise by factor of x4
- Improved DM driver system (4x faster MUX refresh rate, design for lower electrical noise, on-board diagnostics) will reduce actuator positioning noise
- DM2 (32x32 actuators) can now be accommodated
- DMs will be calibrated using a two-parameter-per-actuator model.
- All parts (including 64x64 DM, OAPS, driver system) will be ready for installation in the coming months.

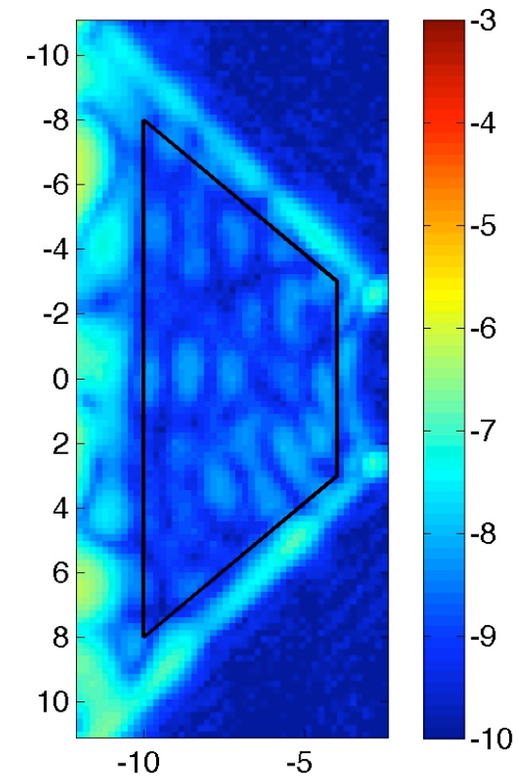
Shaped pupil coronagraph experiments on the HCIT



Shaped pupil mask



Focal plane mask



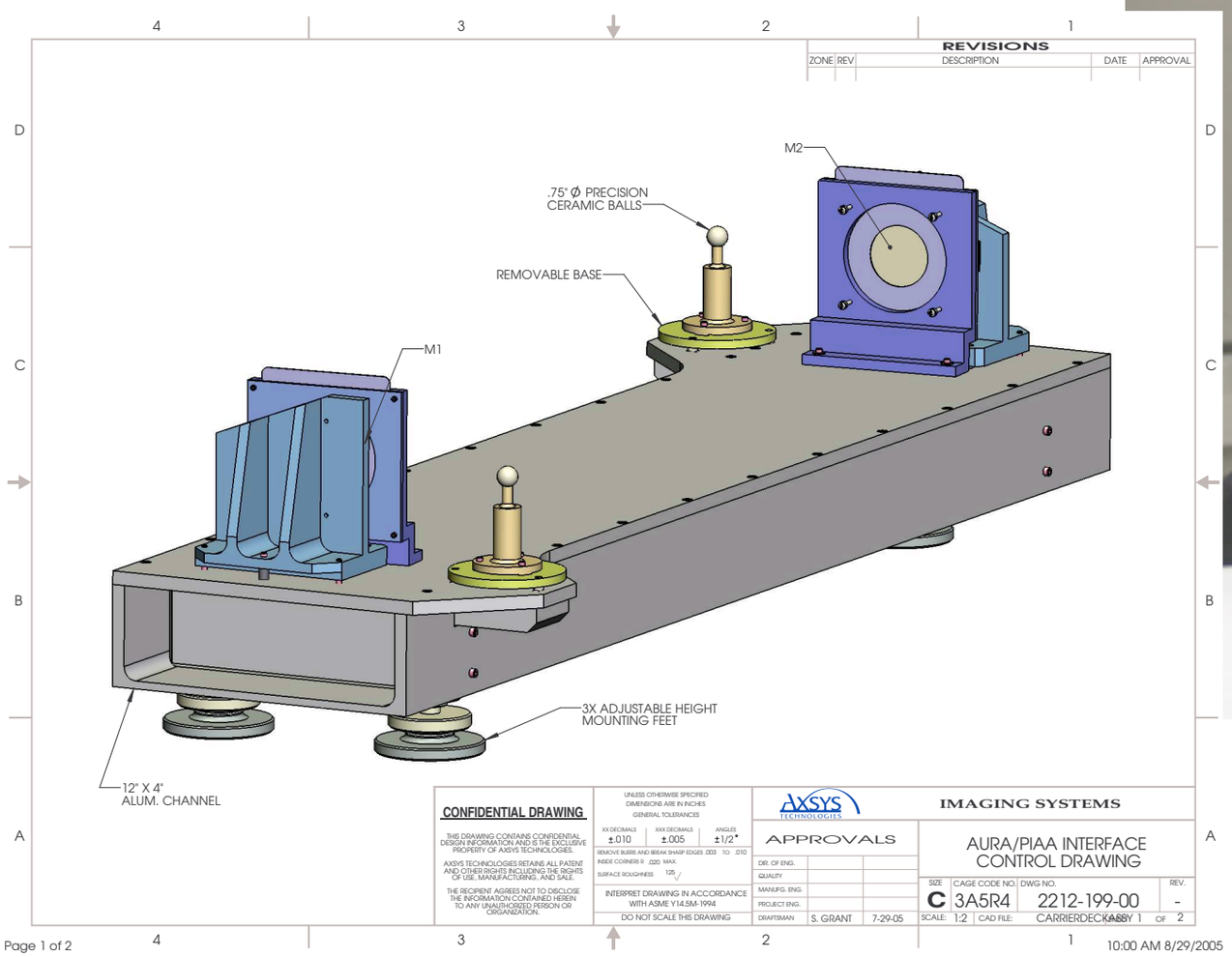
High contrast field

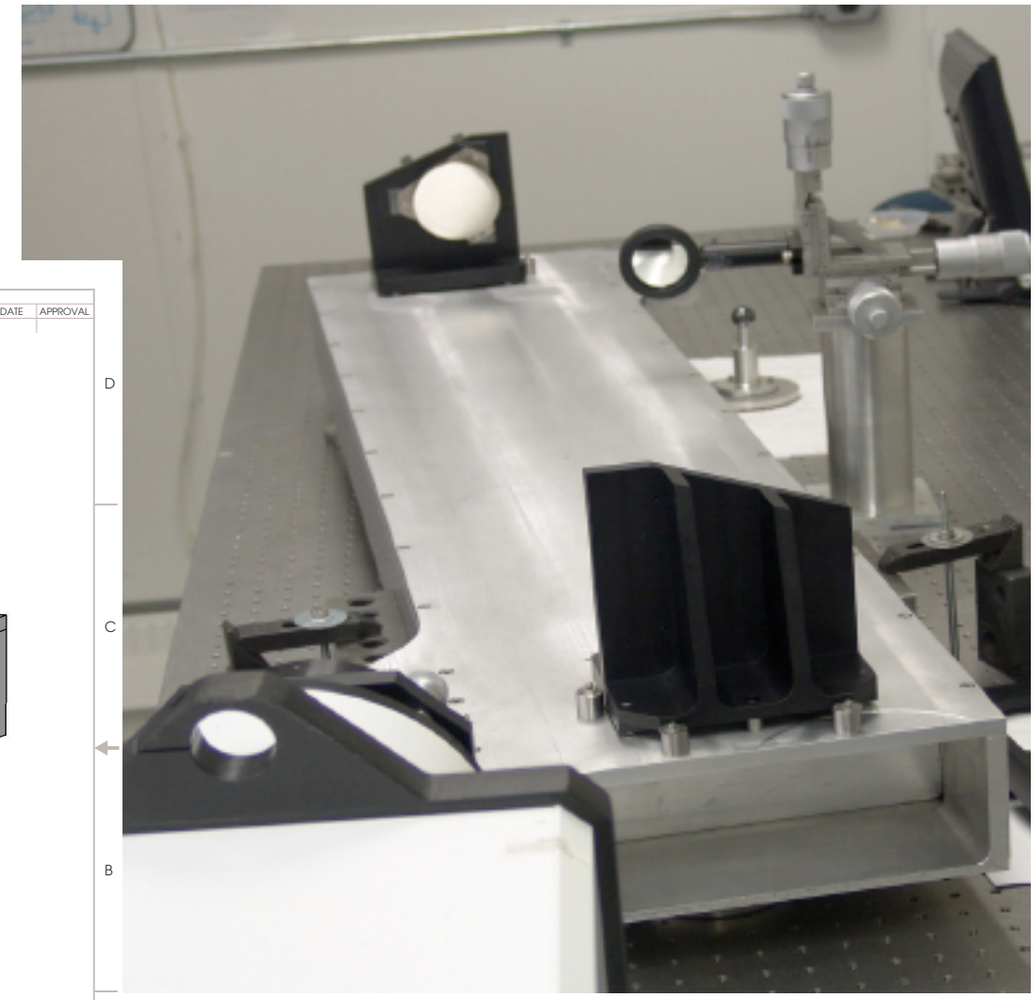
At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear). At center, the corresponding “bowtie” image plane mask. This “Ripple 3” design achieved 2.4e-9 contrast in 10% bandwidth averaged over the 4-10 lambda/D dark field (outlined)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

PIAA experiments

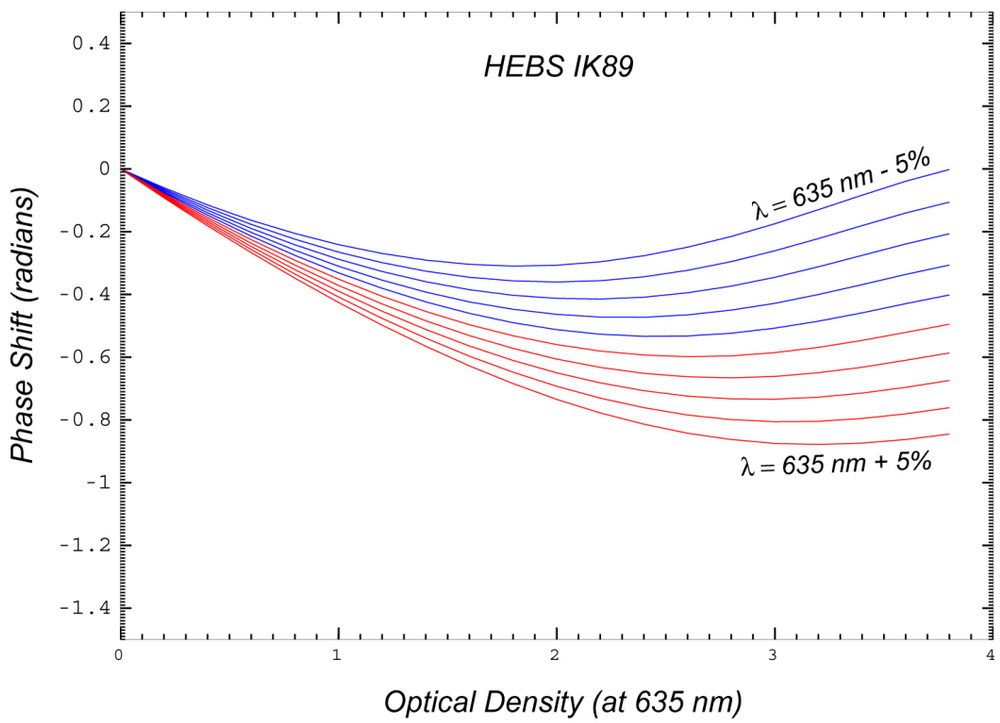
- One of two Subaru PIAA units is at JPL, early planning is underway.
- Overall goal is to learn how to achieve PIAA narrowband contrast better than the current best 7e-7, and to explore broadband (2%, 10%) contrast.
- Post-PIAA pupil apodizer designs are being considered by both Guyon and Vanderbei, to be fabricated at JPL's MDL.
- Preliminary setup and experiments will be carried out in the ambient laboratory (clean room) air, on an optical table within a protective box.
- Initial experiments may have 1 or 2 DMs (Shaklan *et al.*, *Proc. SPIE,* 6693, paper 27, 2007), decision will involve readiness of equipment and algorithms.
- Experiments are coordinated among investigators at Subaru, JPL, and NASA Ames. A second-generation PIAA mirror design by Guyon will be procured by NASA Ames this coming year, will better accomodate spectral bandwidth.

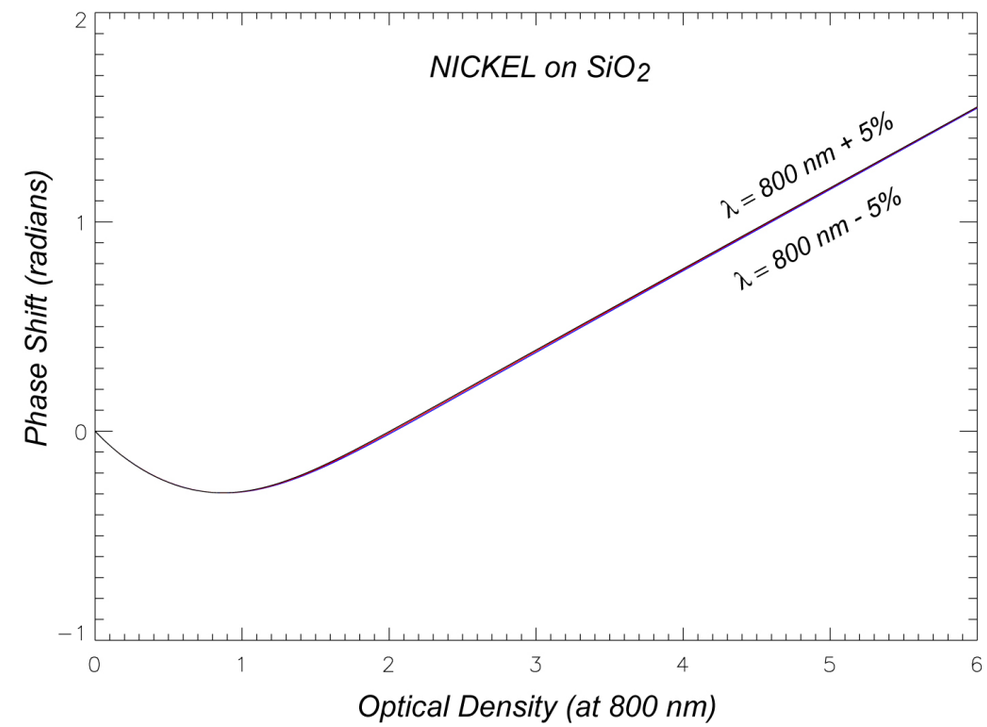
Subaru PIAA unit now at JPL





New masks for the band-limited coronagraph





- HEBS phase vs. OD properties are fixed by the proprietary manufacturing process (Canyon Materials). Dispersion in this relationship limits spectral bandwidth.
- Metals provide a wide range of material properties. Nickel is one convenient choice with considerably less dispersion in phase vs. OD for a deposited film on glass. This subject will be covered by Balasubramanian (this session).

(Moody & Trauger, *Proc. SPIE*, 6693, paper 57, 2007)
(Balasubramanian *et al.*, *Proc. SPIE*, 6693, paper 37, 2007)

Complex profile for the metal+dielectric BL mask

The real and imaginary parts of the complex mask profile are of the following forms:

$$A_{REAL} = \max(10^{-4}, A_S), \text{ where } A_S(x) = 1 - \left(\frac{\sin(\pi x/w)}{(\pi x/w)} \right)^2$$

$$A_{IMAGINARY} = 0.49 \left(\frac{\sin(\pi x/w_1 + \pi)}{(\pi x/w_1 + \pi)} \right) + 0.49 \left(\frac{\sin(\pi x/w_1 - \pi)}{(\pi x/w_1 - \pi)} \right)$$

This complex attenuation profile is decomposed in terms of amplitude and phase.

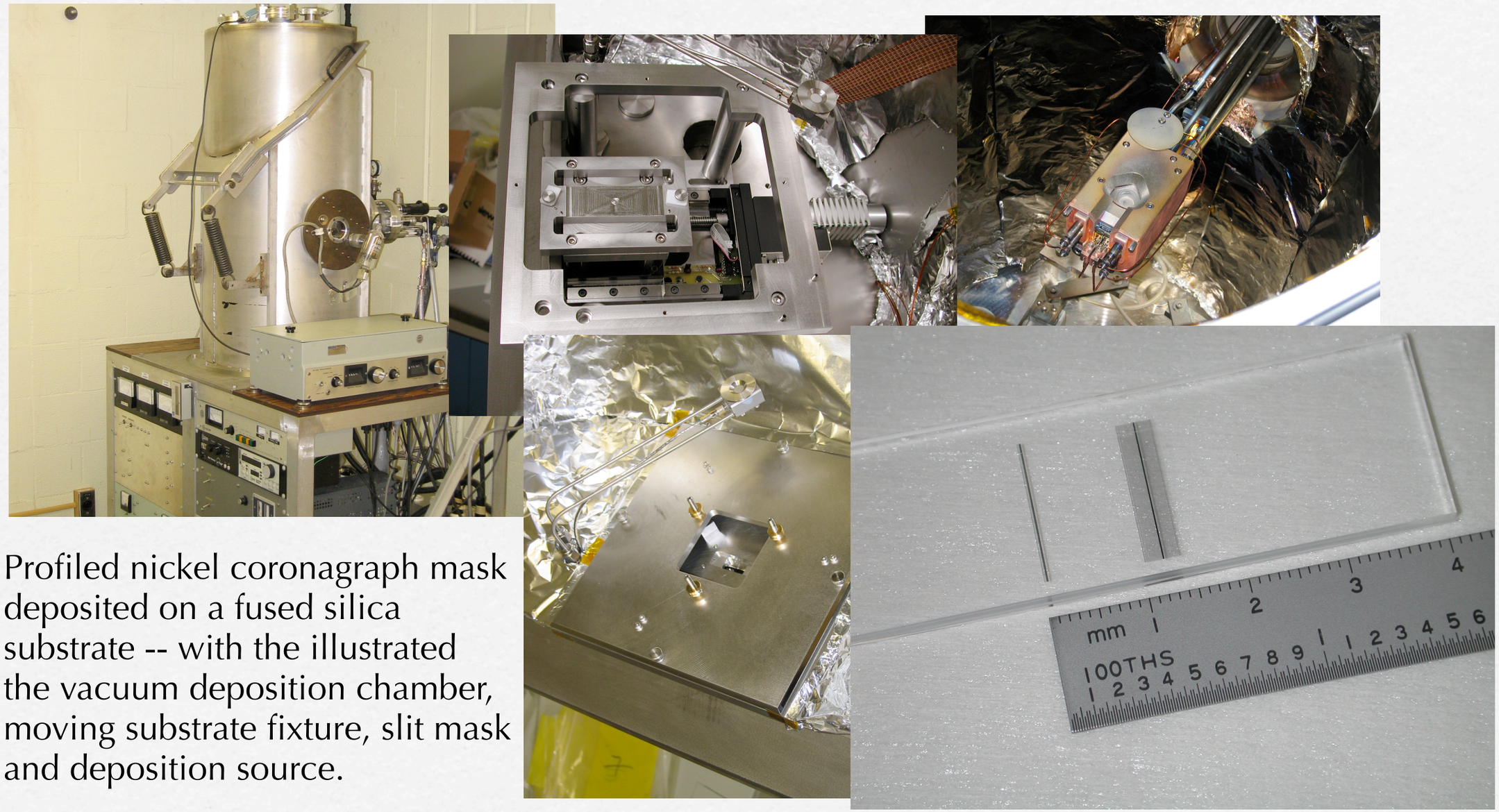
The amplitude defines the optical density profile of the metal film:

$$OD_{metal}(x) = -2 \log_{10} \left\| A_{REAL} - j A_{IMAGINARY} \right\| \otimes \left(a \big/ \sigma\sqrt{2\pi} \right) e^{-(1/2)(x/\sigma)^2}$$

The thickness profile of the dielectric film is adjusted to give the following overall phase shift:

$$\delta\, phase_{metal+dielectric}(x) = phase\left(A_{REAL} - j A_{IMAGINARY} \right)$$

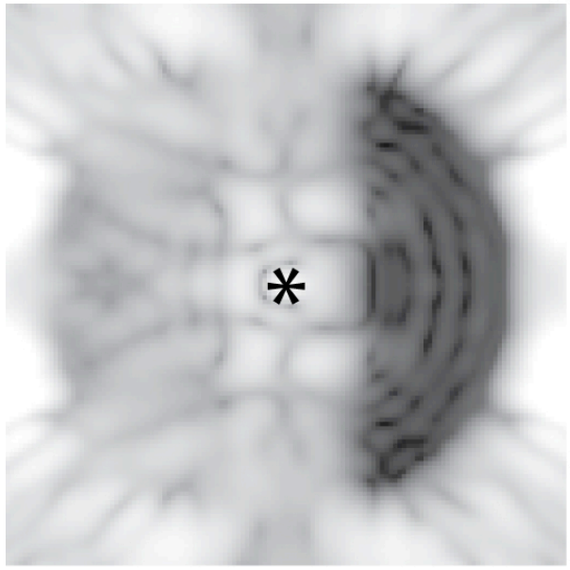
Vacuum deposition chamber for metal+dielectric masks

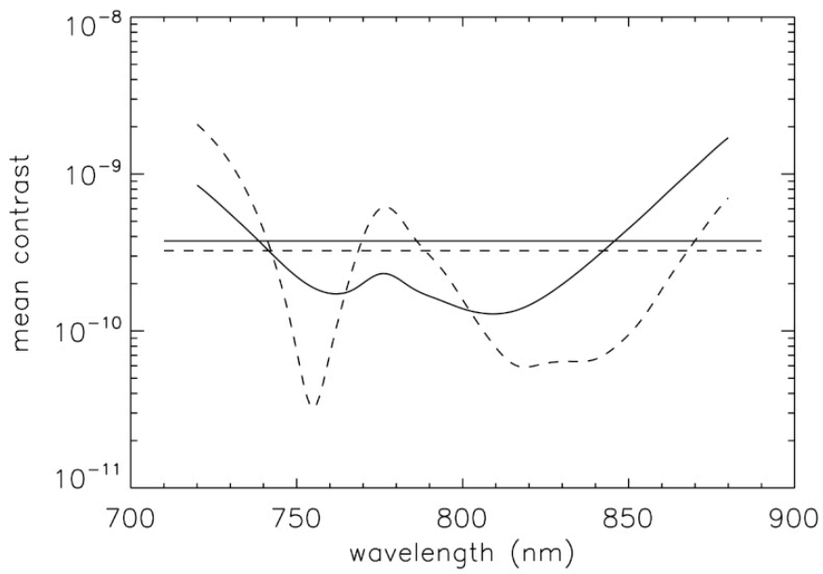


Profiled nickel coronagraph mask deposited on a fused silica substrate -- with the illustrated the vacuum deposition chamber, moving substrate fixture, slit mask and deposition source.

Predicted 20% bandwidth performance

Lyot coronagraph, nickel-dielectric hybrid occulting mask, single DM



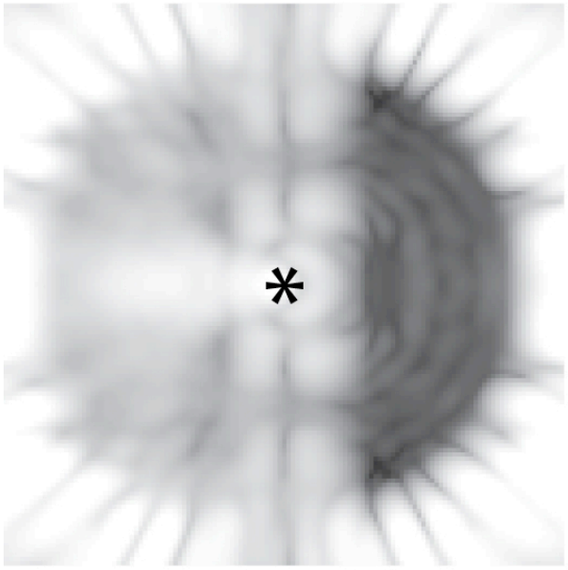


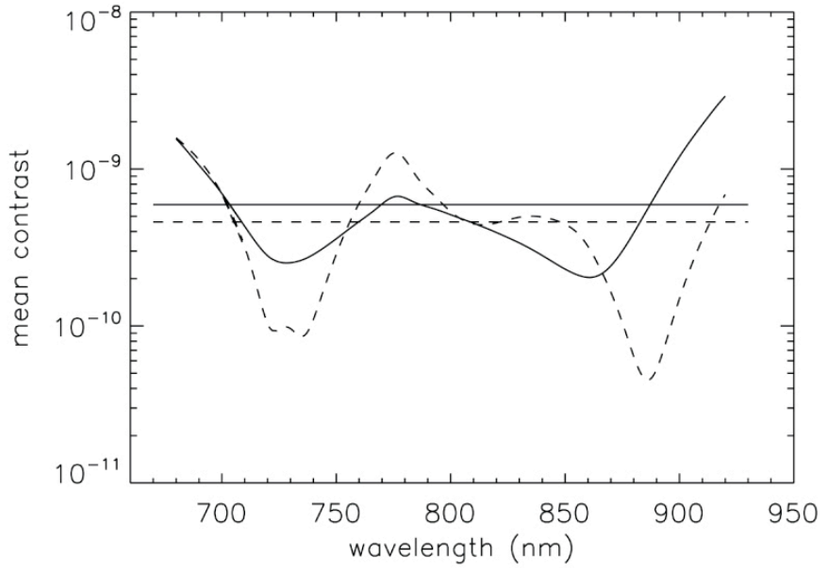
20% bandwidth -- 720-880 nm
Lyot throughput = 67%
C (4-5 lam/D) = 3.7e-10
C (4-10 lam/D) = 3.8e-10

(Moody & Trauger, *Proc. SPIE*, 6693, paper 57, 2007)

Predicted 30% bandwidth performance

Lyot coronagraph, nickel-dielectric hybrid occulting mask, single DM





30% bandwidth -- 680-920 nm
Lyot throughput = 66%
C (4-5 lam/D) = 5e-10
C (4-10 lam/D) = 6e-10

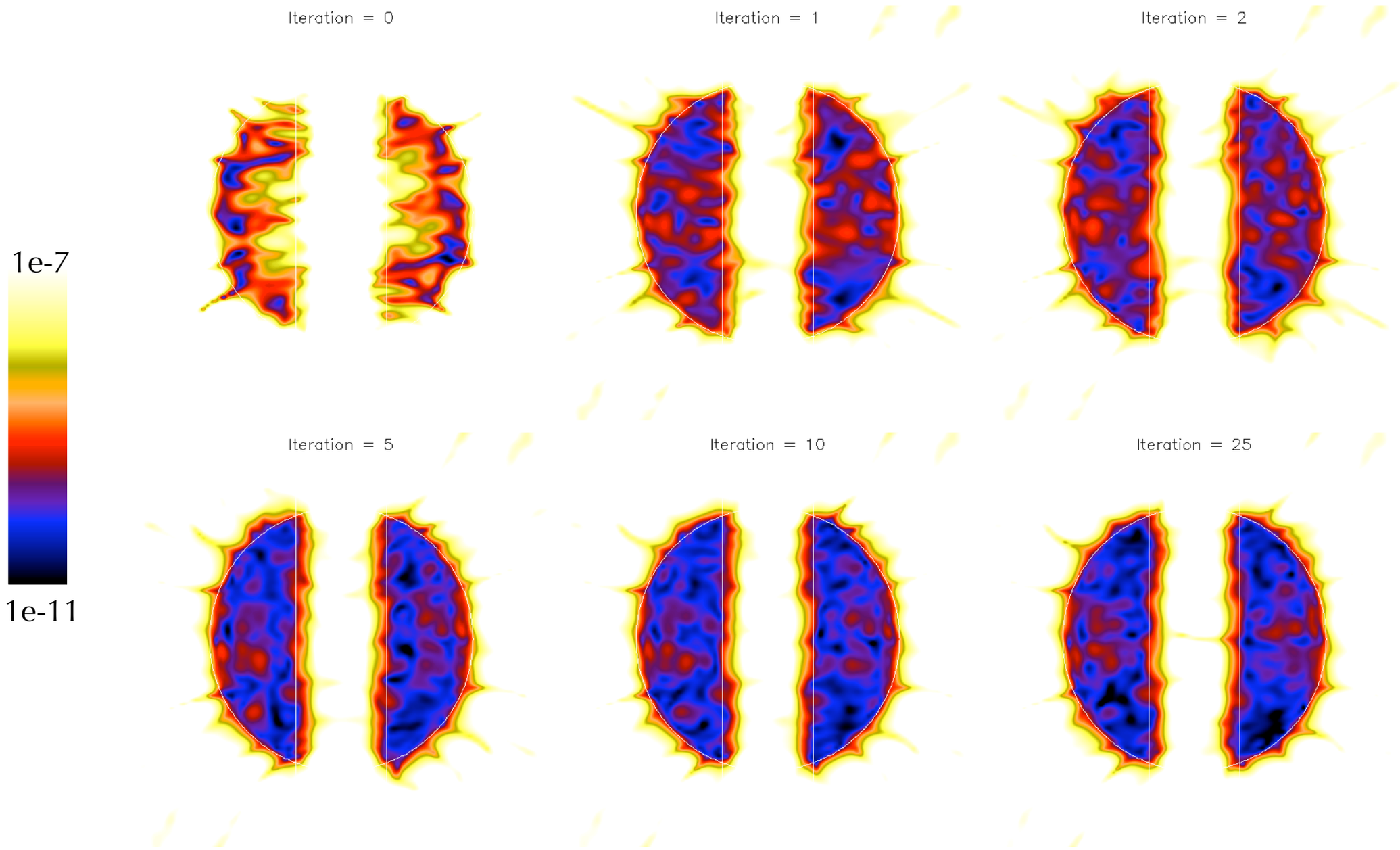
(Moody & Trauger, *Proc. SPIE*, 6693, paper 57, 2007)

Three broadband Lyot masks

Example	Configuration	Bandwidth ($\delta\lambda / \lambda$)	C (4-5 λ/D) $\times 10^{-10}$	C (4-10 λ/D) $\times 10^{-10}$	ε	Lyot throughput
1	HEBS IK89	10%	4.1	1.5	0.47	42.4%
2	Nickel	10%	3.7	1.4	0.36	55.1%
3	Ni + MgF_2	10%	0.38	0.76	0.26	67.2%
4	Ni + MgF_2	20%	3.7	3.8	0.26	67.2%
5	Ni + MgF_2	30%	5.1	6.0	0.27	66.0%

- The first two masks (HEBS and metal-only on glass) are in preparation, with HCIT experiments in 10% bandwidth scheduled to begin this year.
- Fabrication of the third mask (metal+dielectric) and HCIT experiments in 10, 20, and 30% bandwidths to follow.

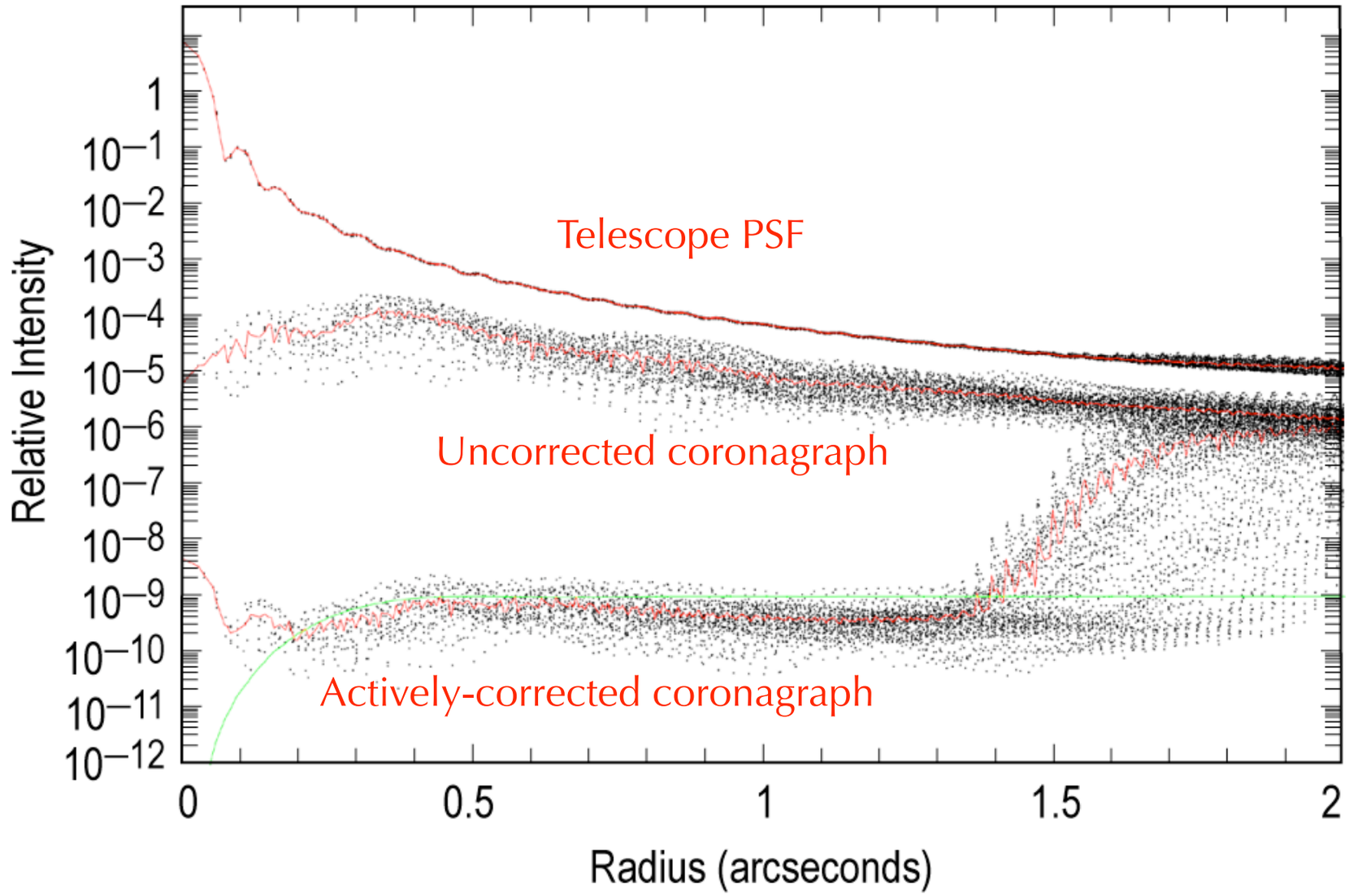
Iterative energy minimization simulation with two DMs: 25% bandwidth (680-880 nm)



Final contrast = 7e-11

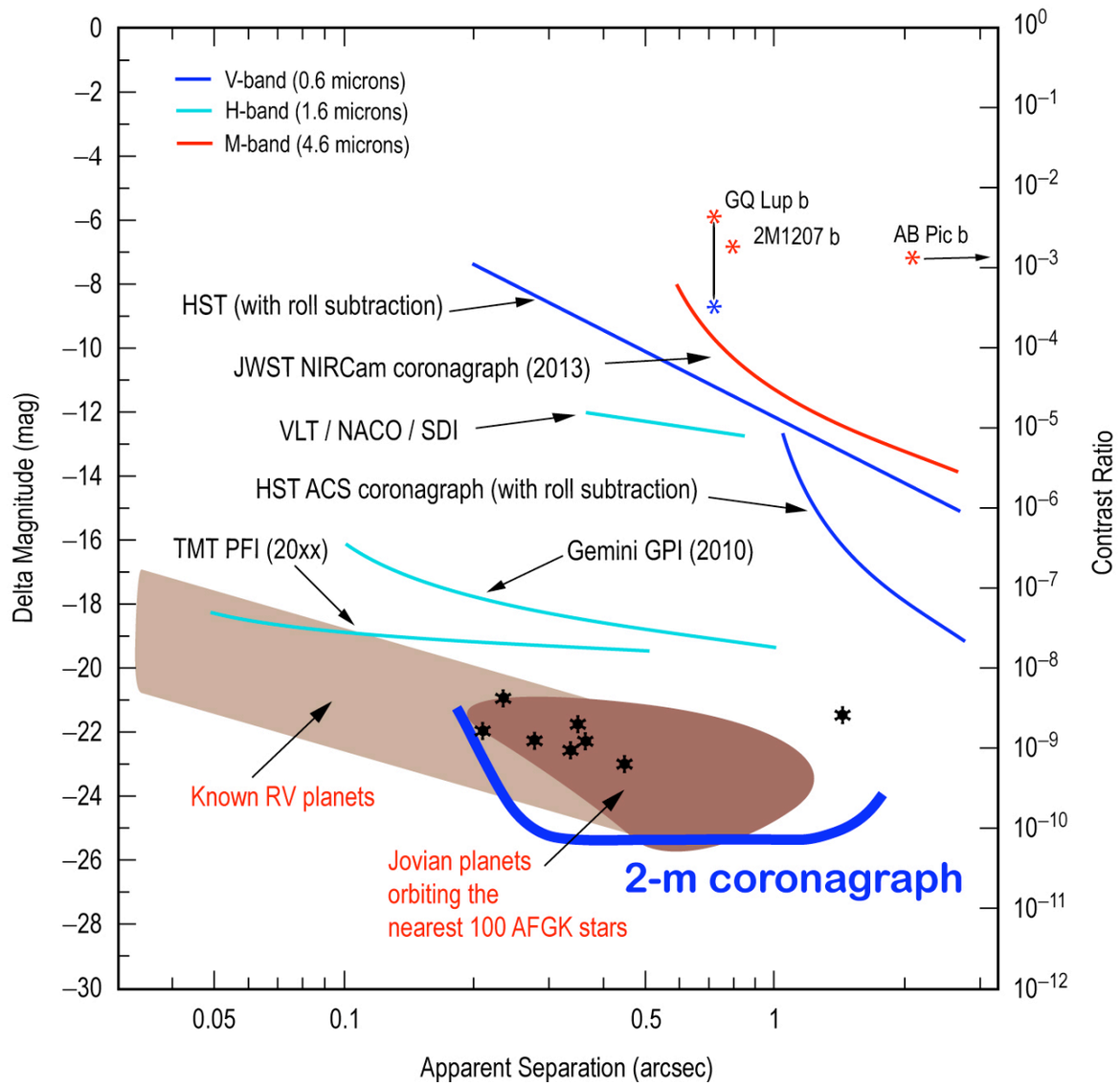
(Krist, 2007)

Validated models provide performance predictions: V-band imaging with a space coronagraph



Plotted are the point spread functions (PSFs) of a 1.8 meter telescope, coronagraph, and coronagraphwith active wavefront correction. Instrument contrast is 1e-9 with an inner working angle of 0.25 arcsec for broadband (20%) visible light.

Discovery space for a "medium-size" mission includes pioneering science



Exoplanet discovery space for a 2-m class coronagraphic telescope, and comparisons with existing and proposed missions and techniques. Known RV planets within reach of the 2-m coronagraph are indicated by the (black) asterisks.

Summary

- HCIT predictive models and algorithms are improving, in support of experiments.
- HCIT validates diverse coronagraph types
  - Lyot coronagraph experiments will continue with 10% bandwidths (and wider).
  - PIAA coronagraph setup has begun and early experiments will begin this year.
  - Shaped pupil coronagraph will be revisited once the wavefront control system is upgraded, or whenever a new shaped pupil is produced.
  - Other coronagraphs, such as the optical vortex, when ready.
- HCIT wavefront control will advance this year
  - Contrast floor due to actuator noise is expected to reach 1e-10 or better.
  - EFC algorithm will be extended to multi-wavelength sensing for 10% bandwidth.
  - Second DM may be added following reconfiguration for the 64x64 DM.
- New developments
  - HEBS, metal masks for 10% bandwidth and 55% throughput
  - Hybrid metal-dielectric masks: 30% bandwidth and 66% throughput
- Goal is to provide a capable, flexible, available development laboratory
  - to advance coronagraph concepts to maturity for flight
  - to provide a basis for comparison of coronagraph concepts.

End