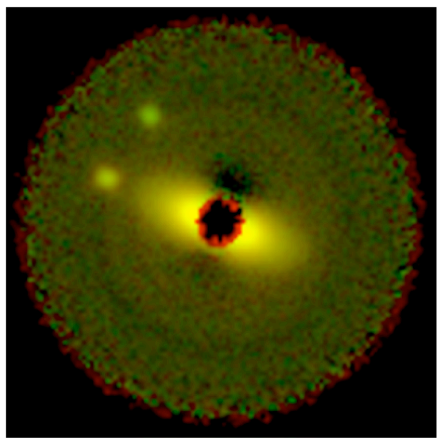
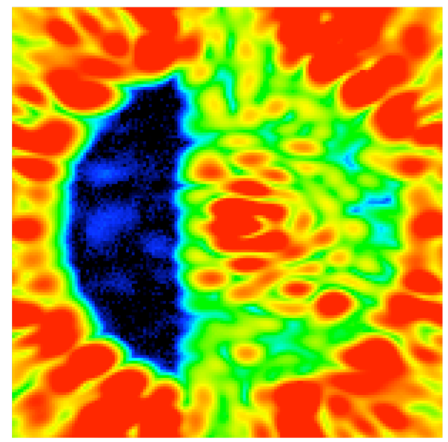
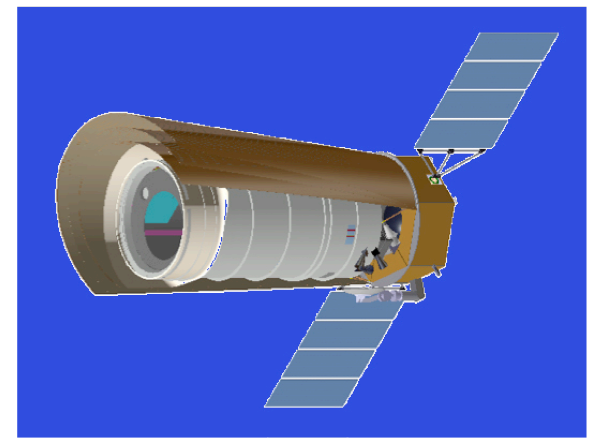
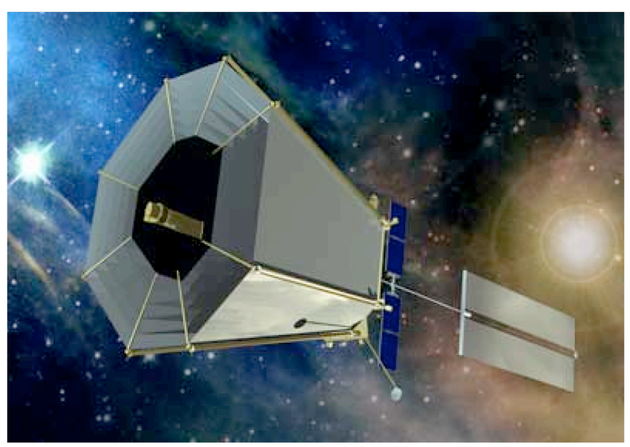
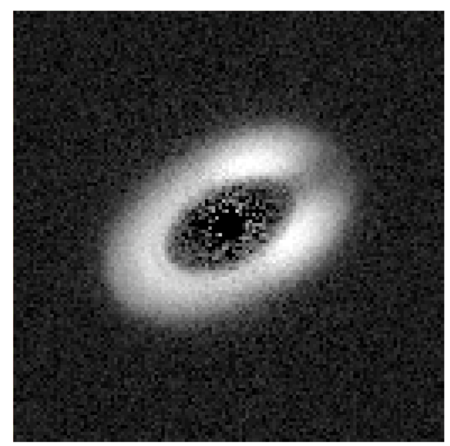
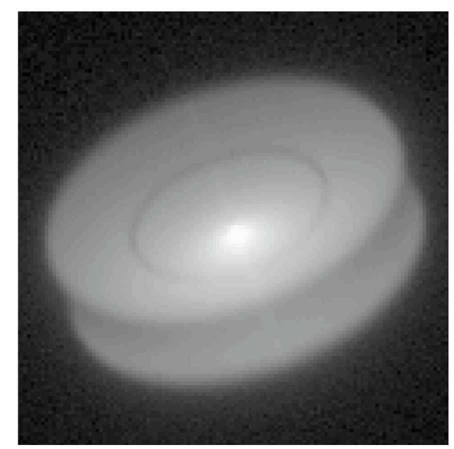
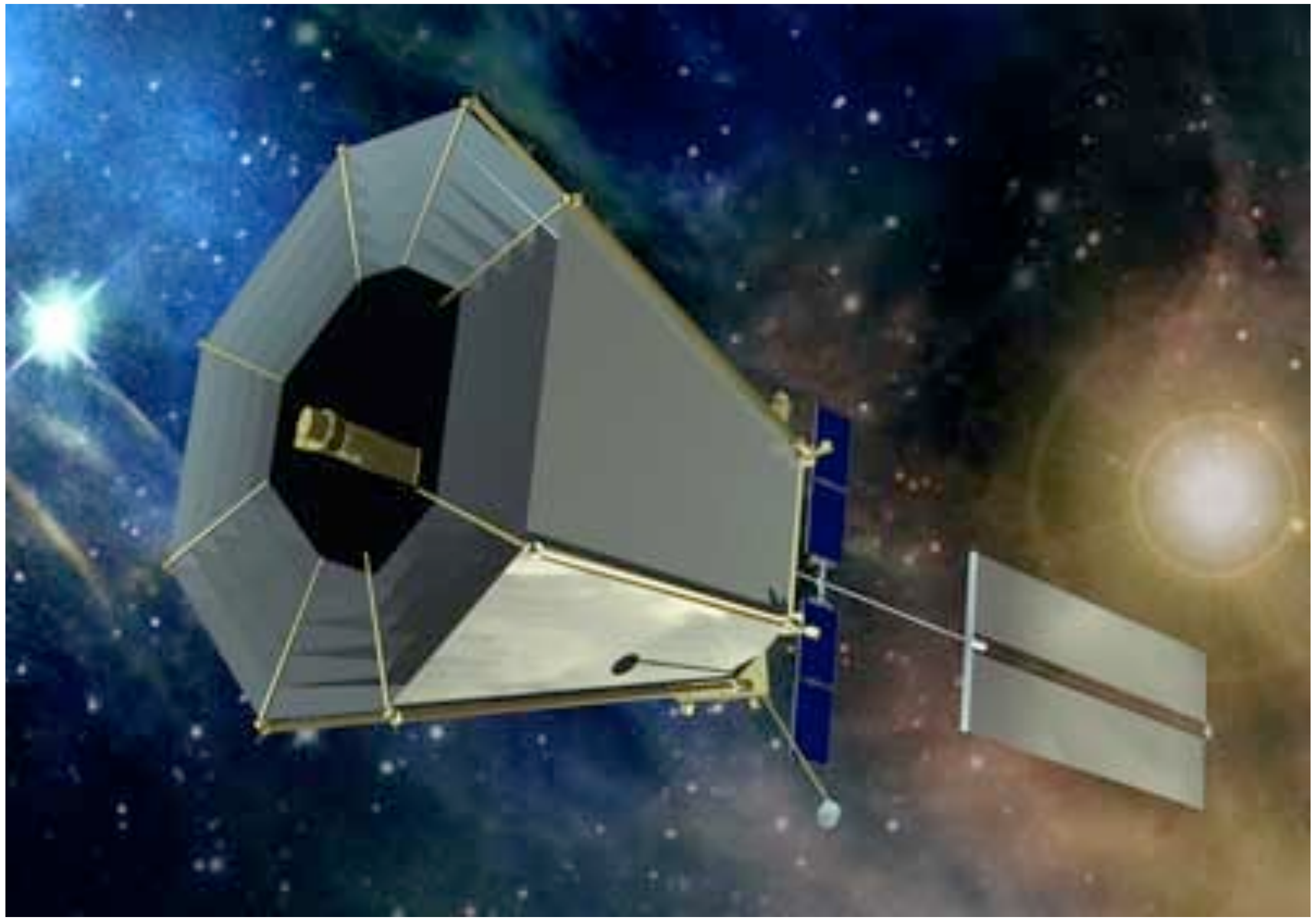
Coronagraphic Observatory Concepts for the Direct Imaging of Nearby Planetary Systems From Space

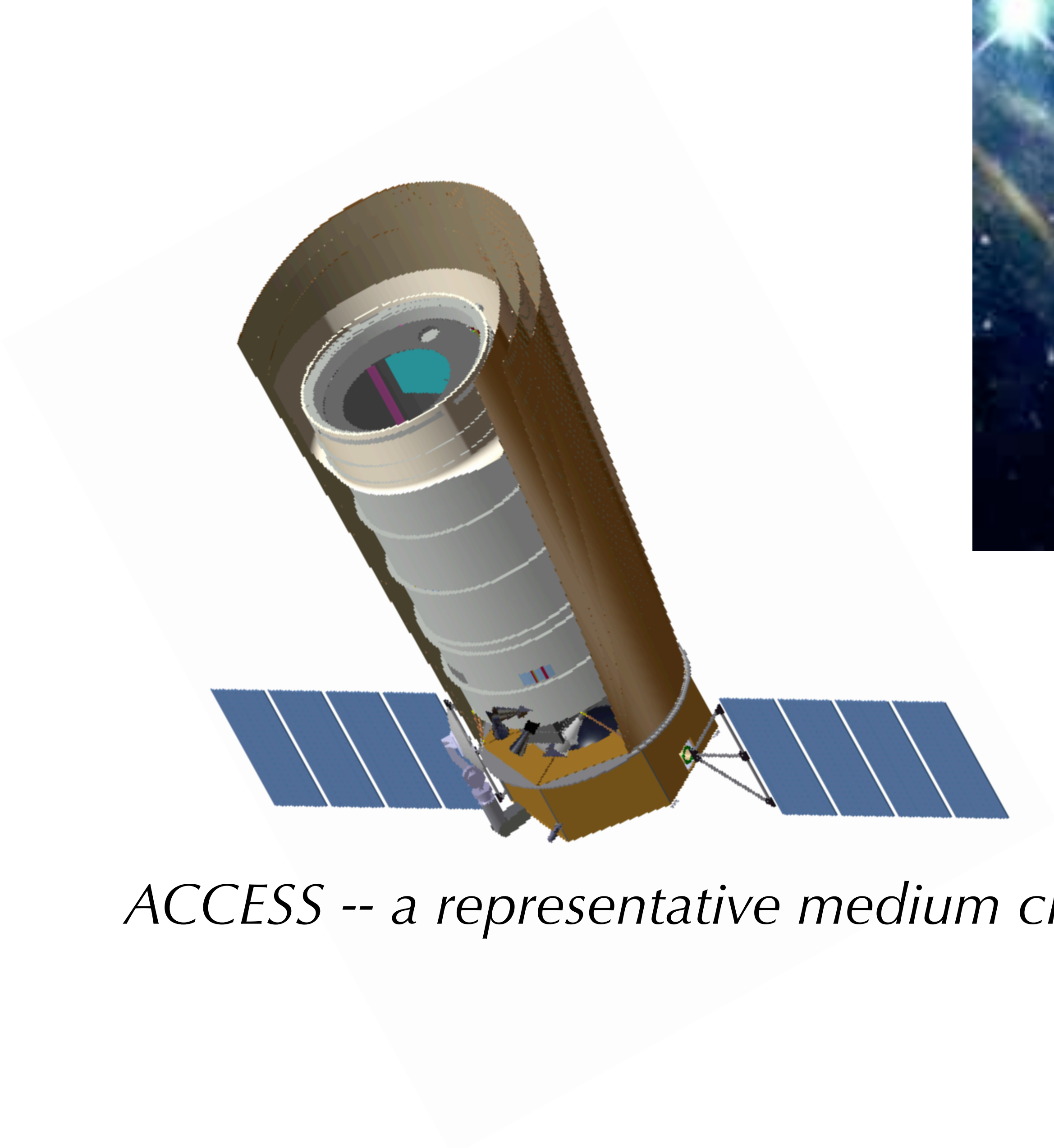







John Trauger, JPL / Caltech

Sagan Summer Workshop
Beckman Institute / Caltech -- 20 July 2009

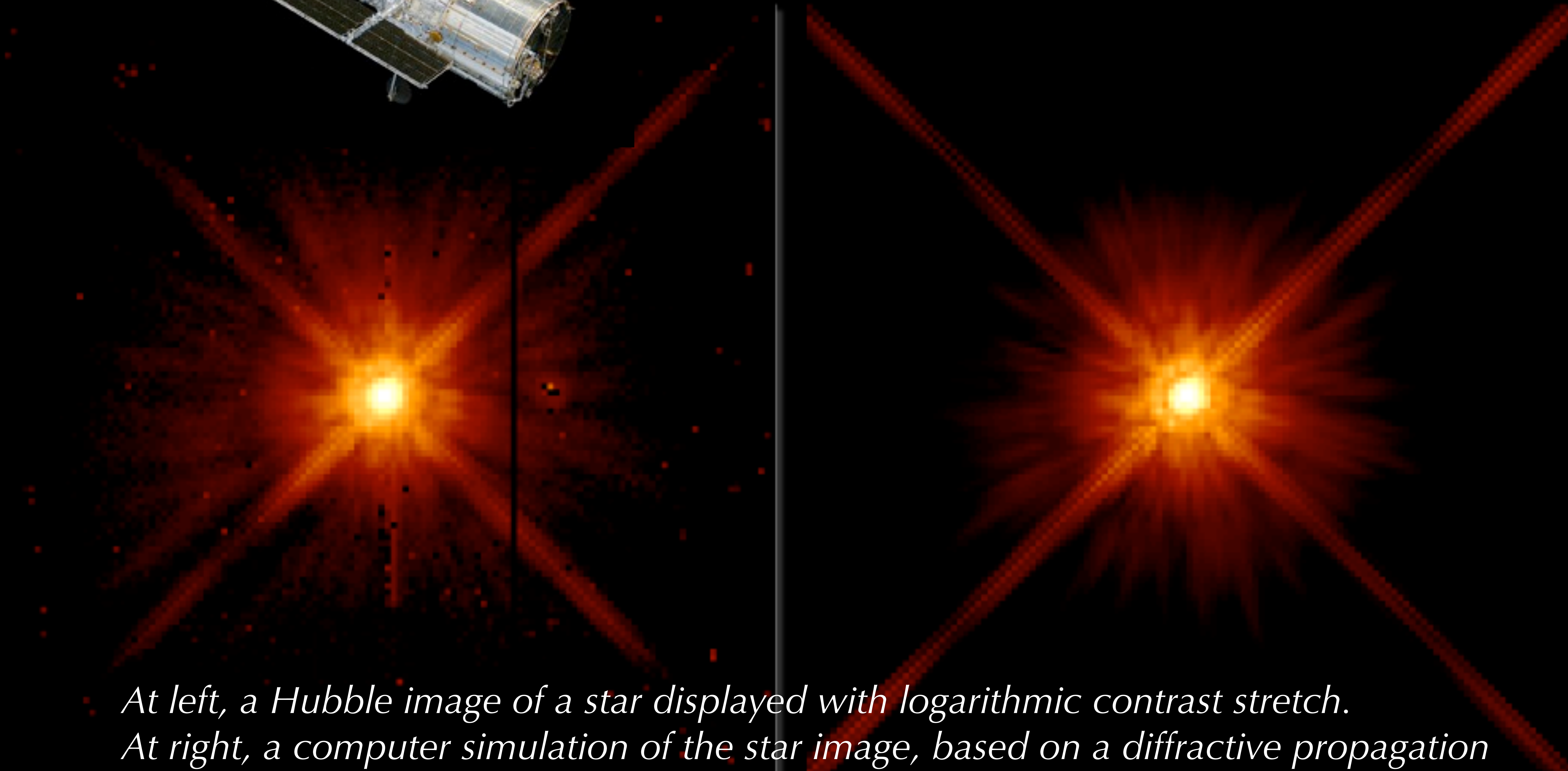
TPF-C -- a representative flagship class coronagraphic mission





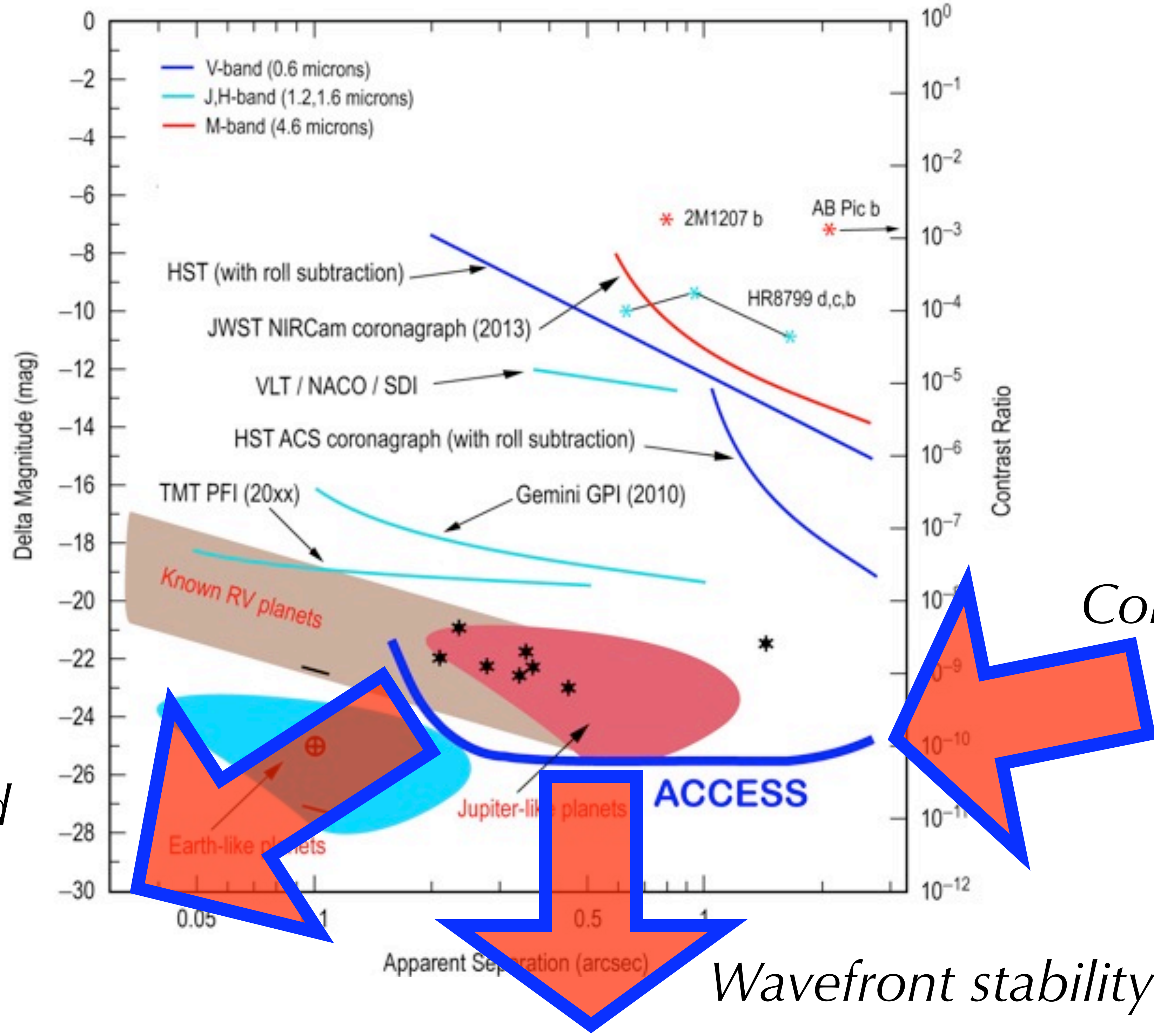
ACCESS -- a representative medium class coronagraphic mission concept

A coronagraph is needed for high-contrast imaging of planetary systems



At left, a Hubble image of a star displayed with logarithmic contrast stretch. At right, a computer simulation of the star image, based on a diffractive propagation model validated by the Hubble data. The model uses the important characteristics of the as-built optical system to predict image performance.

Coronagraph Discovery Space is critically dependent on coronagraph design, observatory pointing control, and optical wavefront stability

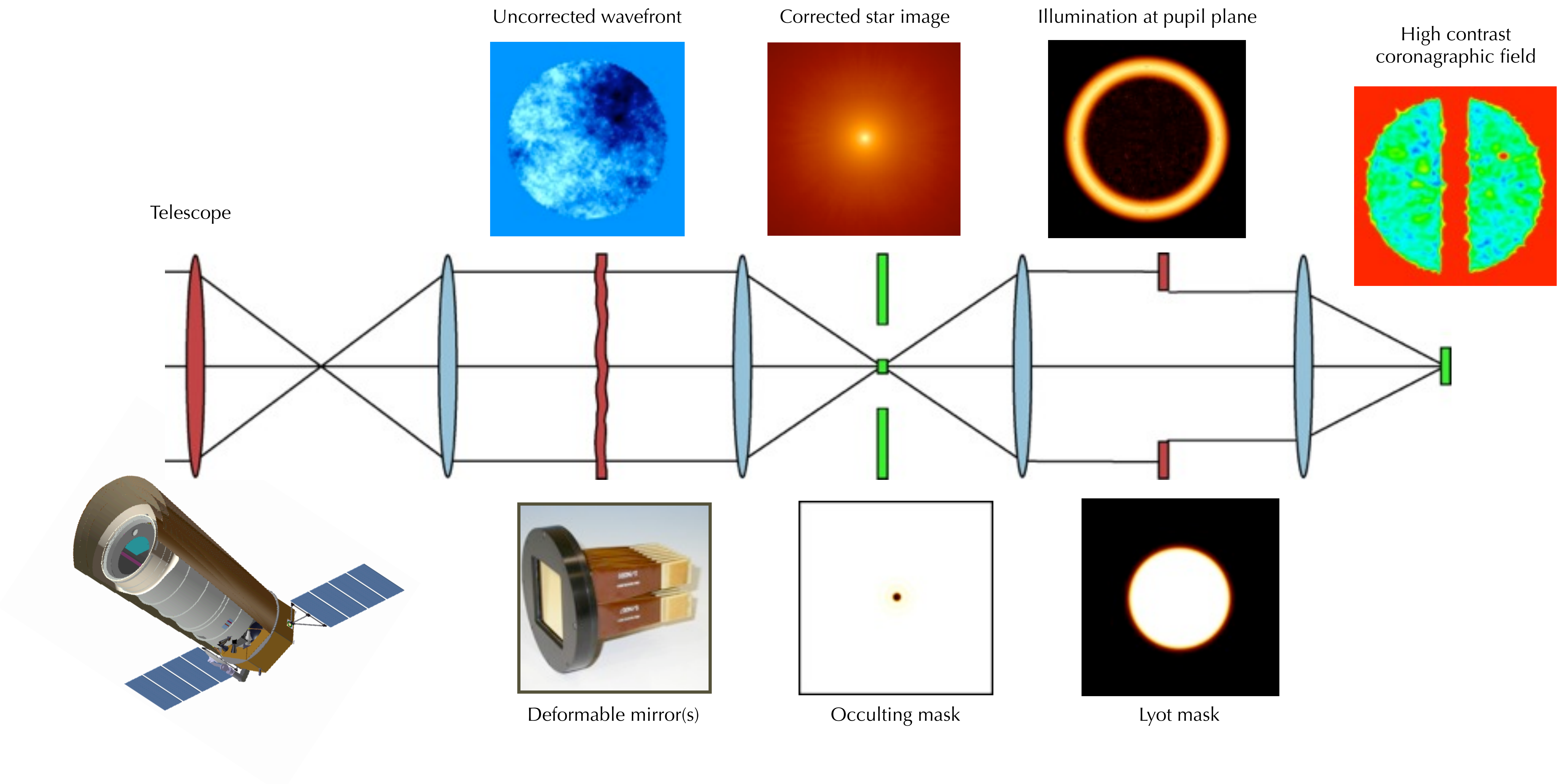


Pointing control and low-order wavefront stability

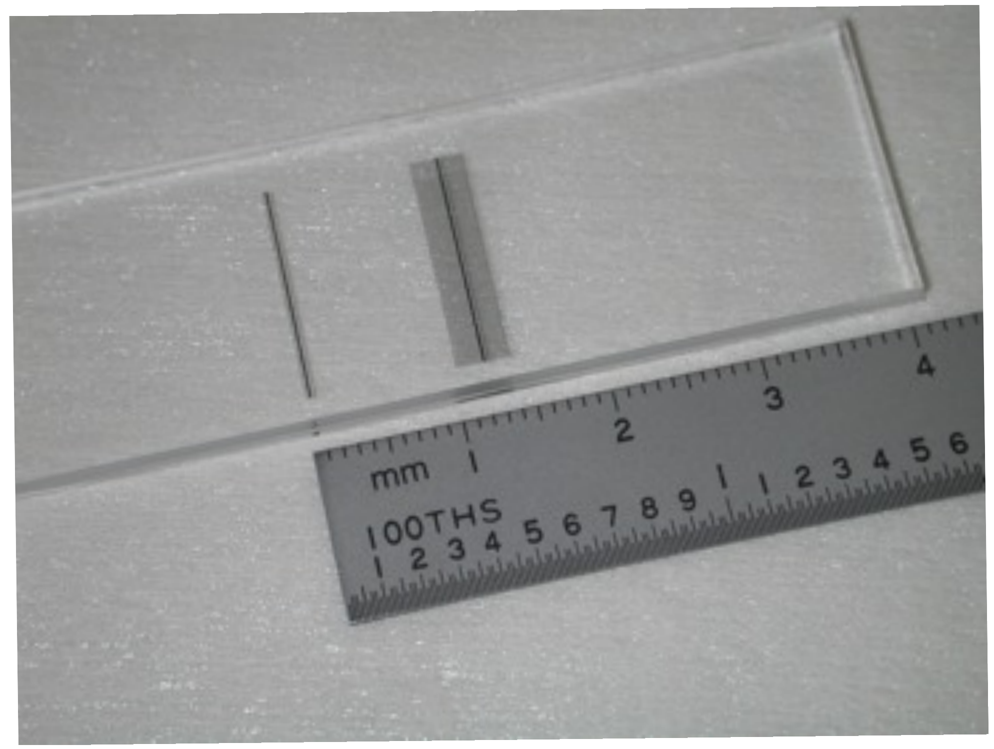
Coronagraph design

Wavefront stability

Here are the essential elements of a space coronagraph



The occulting element



The star image falls on the occulting element, blocking the image of the star, while not blocking the surrounding planets.

A simple opaque spot or bar would work.

An apodized occulting element works better (Kuchner and Traub 2002).

Refinements in the design of this occulting element have been made at JPL and used to demonstrate extremely high contrast imaging at contrast levels better than billion-to-one.

The Lyot element

The Lyot element trims away the diffracted light that passes around the occulting element.

This principle was first described by Bernard Lyot in 1930.

It is a simple thin metal disk with a hole, placed at a pupil following the occulting element, completes the coronagraph.

This coronagraph could, in principle, completely suppress all unwanted starlight -- if the mirrors in the telescope and instrument could be manufactured without the slightest errors!

The deformable mirror

Real telescopes, even the "best money can buy", have imperfections significant enough to require optical correction.

The residual "scattered light" that remains in the image can be corrected with a deformable mirror, shown here.

The deformable mirror clears a "dark field", where high contrast imaging of planets can be carried out.

This principle was first described by Malbet, Yu, and Shao in 1995.

Accuracy of deformable mirror surface positioning set limits on the achievable contrast:

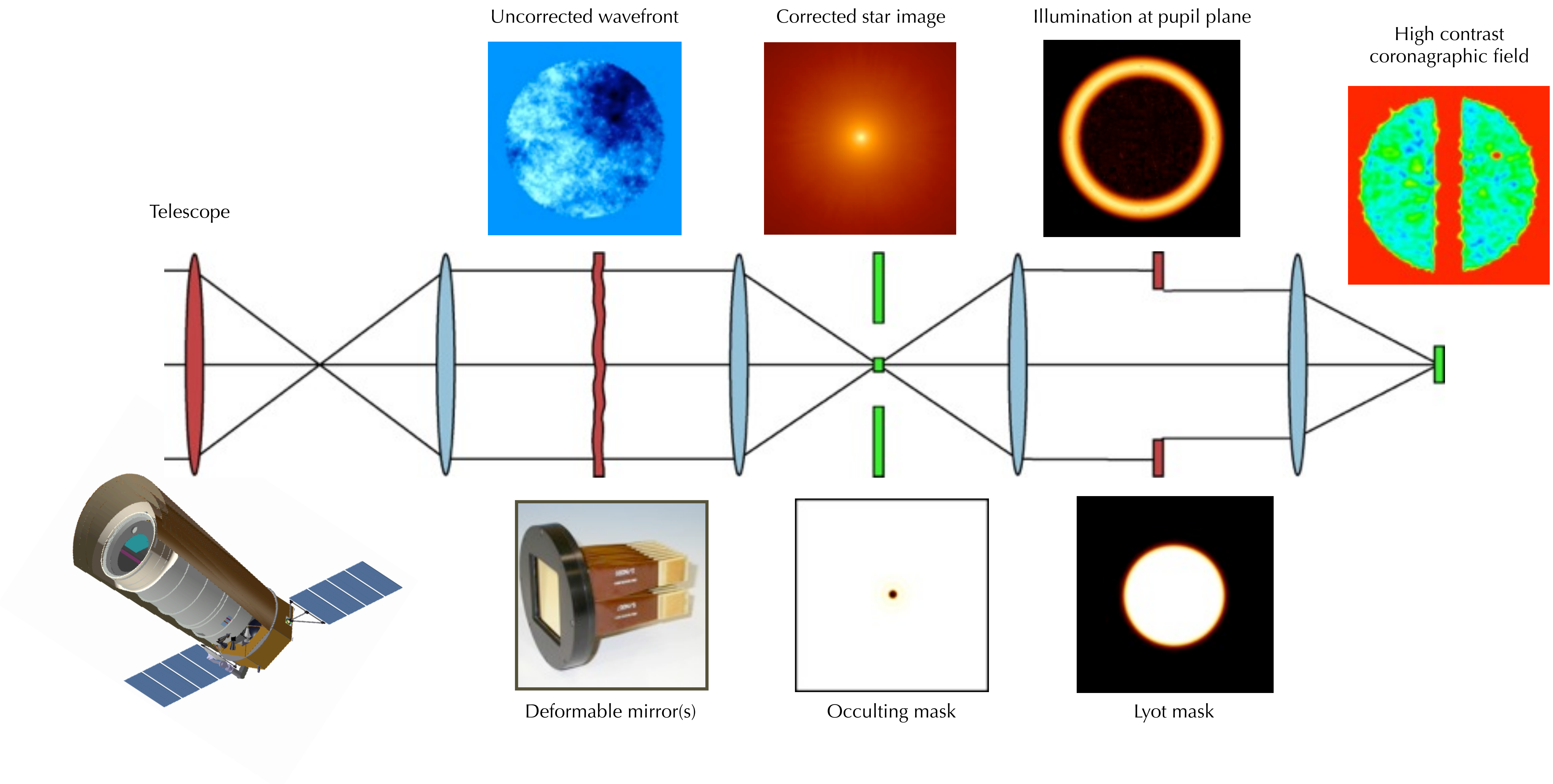
$$C = \pi \left[\frac{2\pi\sigma}{N\lambda} \right]^2$$

- *Uncorrelated DM actuator noise generates a uniform background of scattered light that places a limit on achievable contrast (C). A consistently-observed contrast C = 5e-10 with the HCIT Lyot coronagraph (with λ = 800 nm and N = 30) implies a surface figure noise of 0.05 nm rms.*
- *Contrast stable to 1e-11 over periods of 5 hours or more demonstrate an open-loop surface figure drift of 0.007 nm rms or less over extended periods.*

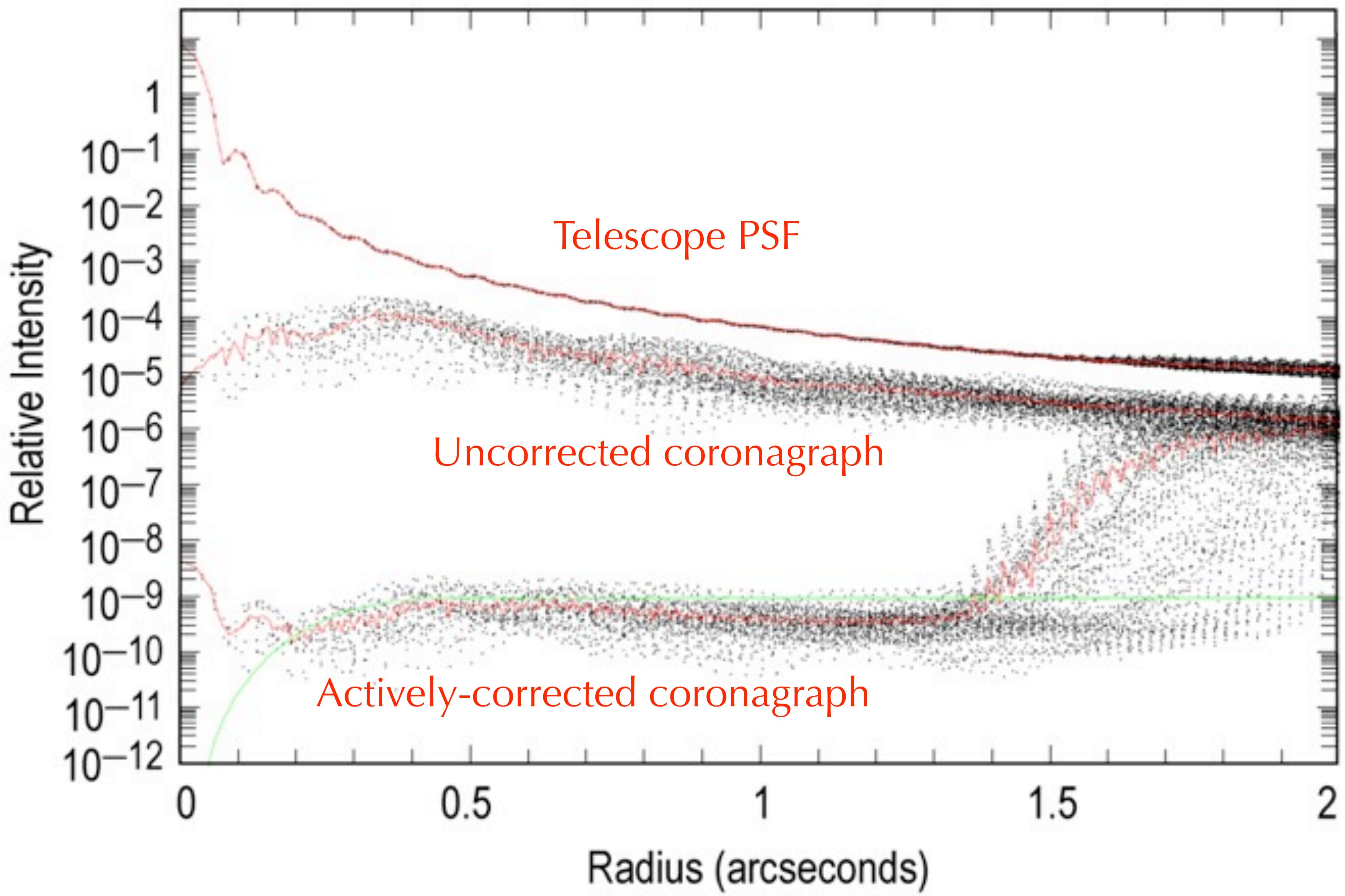
$$Q = \left[\frac{2\pi\varepsilon}{\lambda} \right]^2$$

- *Ability to create a sinusoidal ripple $\varepsilon \sin x$ on the DM is indicated by the appearance of a 1st-order speckle with relative intensity Q. Speckle nulling generates discernable speckles at the 5e-10 level, demonstrating a surface figure sinusoid of amplitude 0.003 nm.*

Here are the essential elements of a space coronagraph

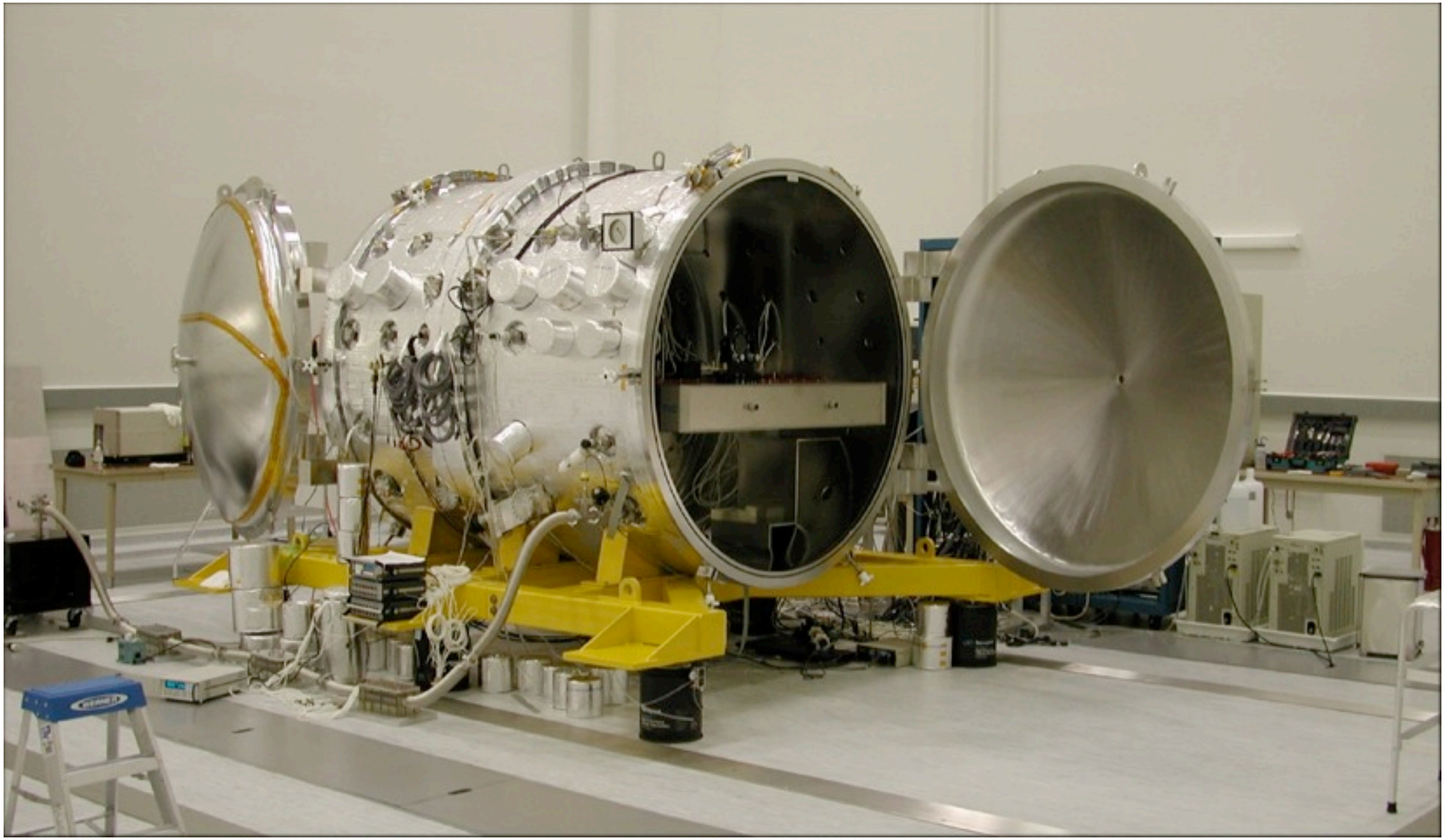


Experiments validate models -- models provide performance predictions: V-band imaging with a space coronagraph



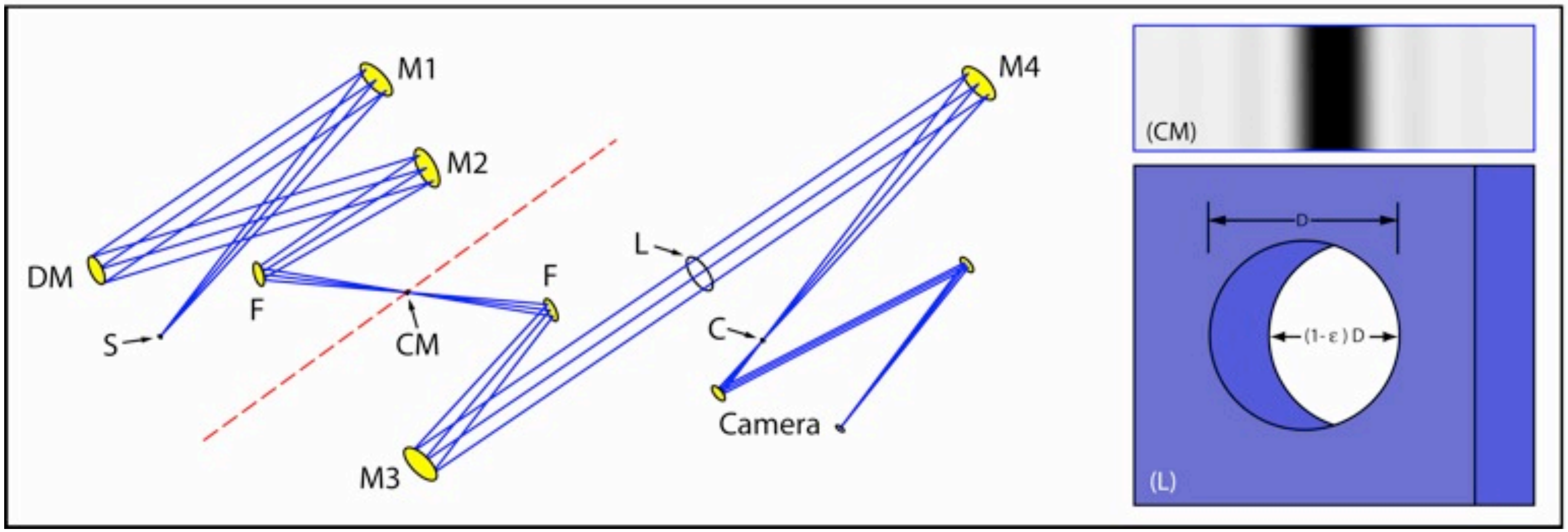
Plotted are the point spread functions (PSFs) of a 1.8 meter telescope, coronagraph, and coronagraph with active wavefront correction. Instrument contrast is better than 1e-9 with an inner working angle of 0.25 arcsec for broadband (20%) visible light.

Model validation and technology development takes place on the High Contrast Imaging Testbed at JPL

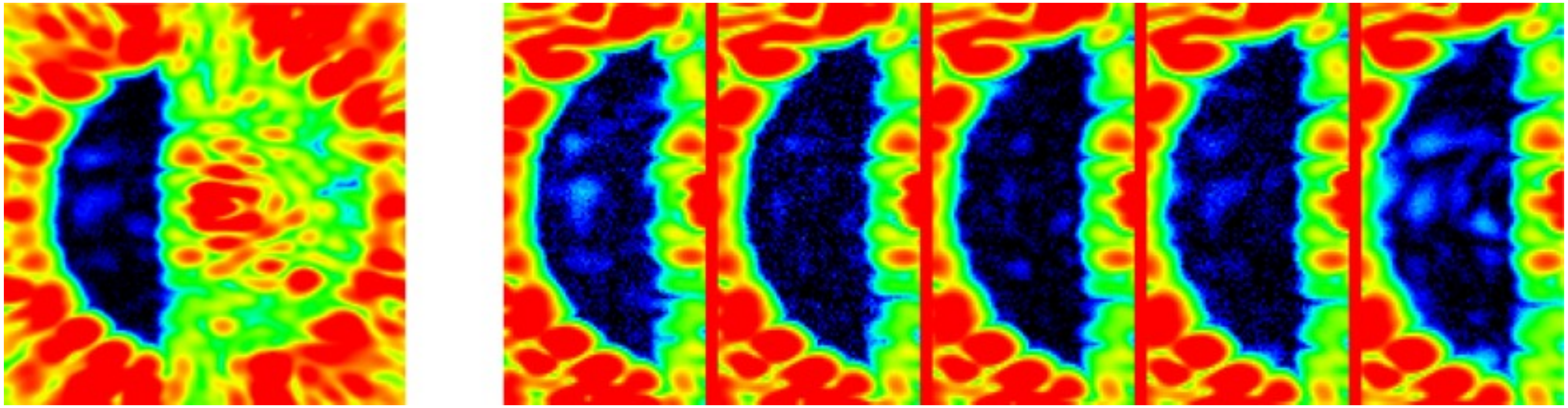


Accurate optical models of the coronagraph have been validated in detail on the High Contrast Imaging Testbed at JPL.

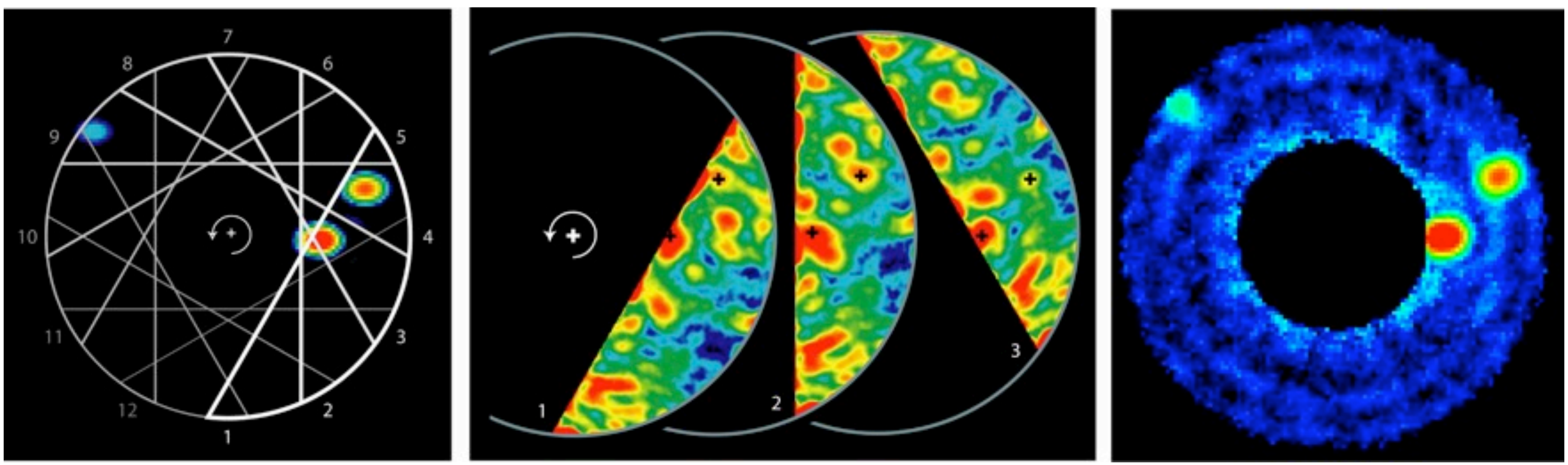
HCIT Lyot coronagraph layout



Elements of the HCIT Lyot coronagraph: the light source (S) is a 5 micron pinhole illuminated by light relayed from a fiber; four identical off-axis paraboloidal mirrors (M1, 2, 3, 4); two flat fold mirrors (F), the band-limited focal plane mask (CM); the Lyot mask (L); the high-contrast coronagraph field appears at (C); and the CCD camera with a pair of OAP mirrors for 3x magnification.

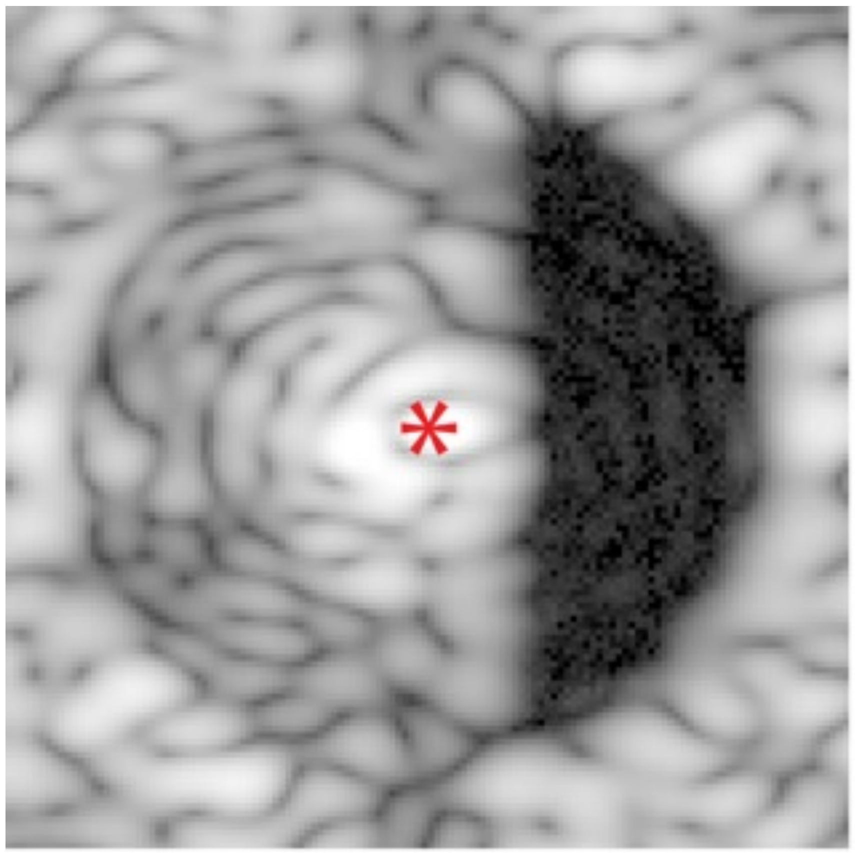


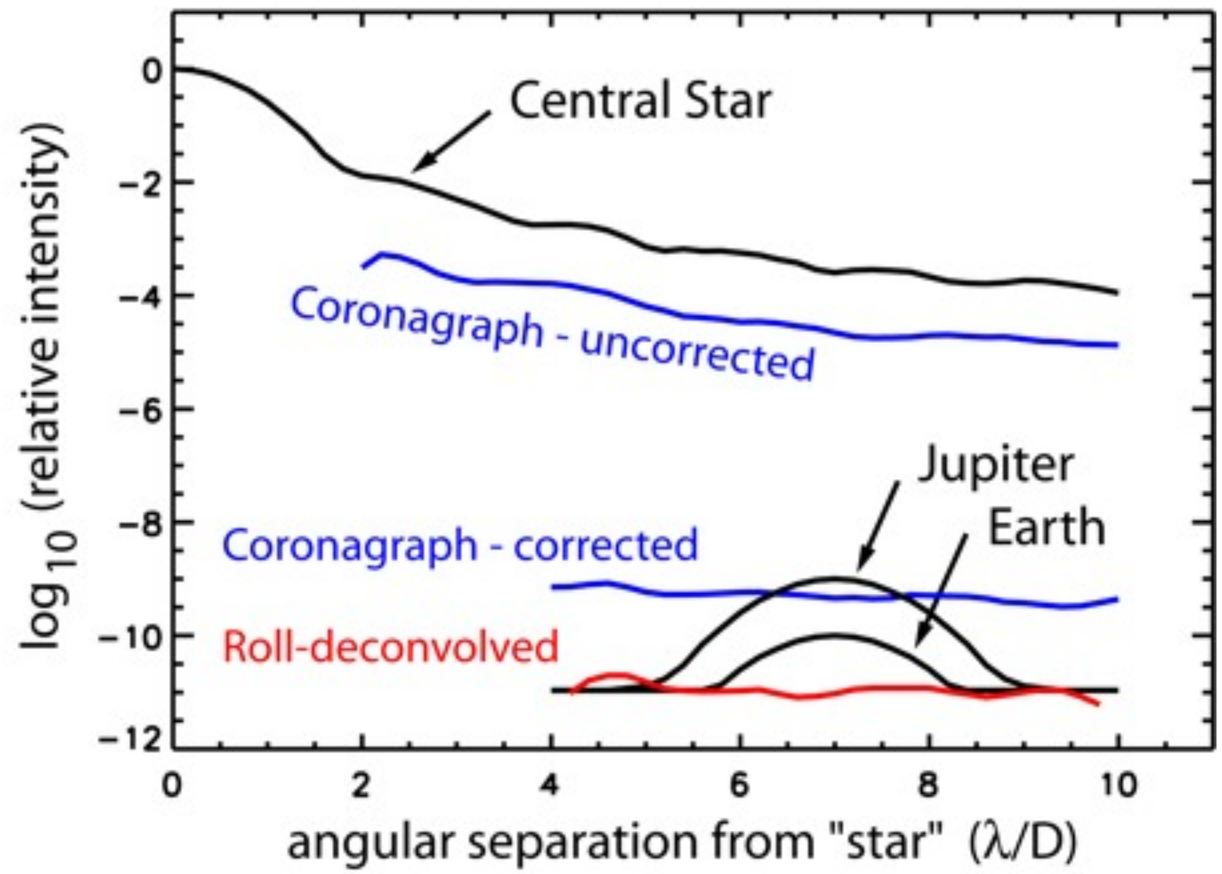
Laboratory demonstrations of high-contrast coronagraph dark fields, demonstrating "starlight" suppression to levels beyond billion-to-one (2008).



Simulations of coronagraph data processing, with laboratory data, illustrate one method to distinguish Earth-like planets from the glare of the central star.

Laboratory demonstrations of coronagraph contrast and stability



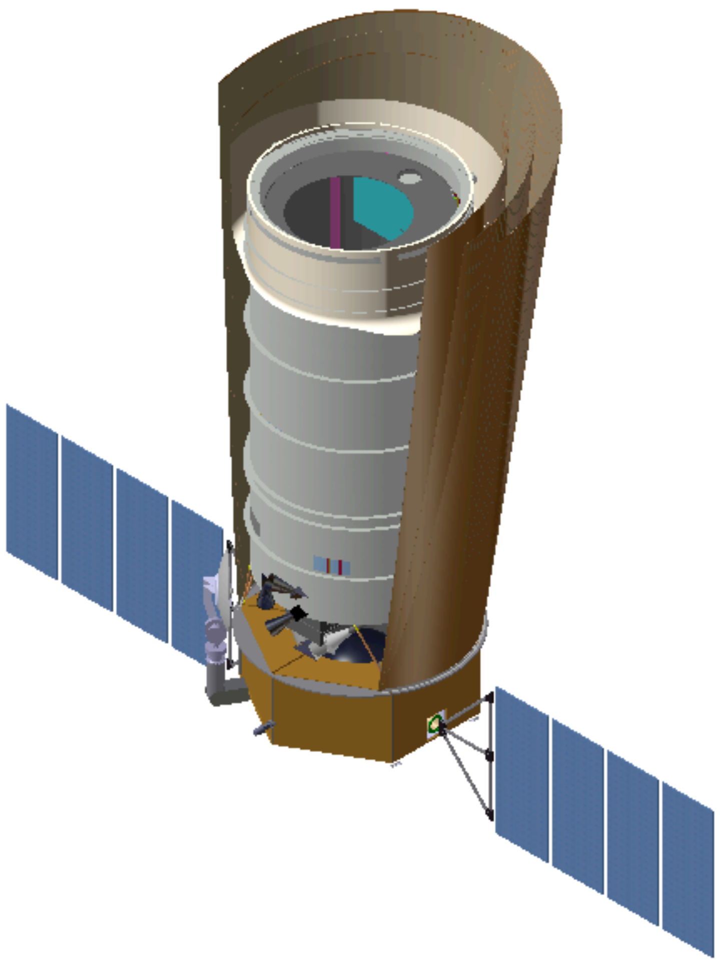


Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (b) the coronagraph field with all DM actuators set to equal voltages; (c) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of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

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

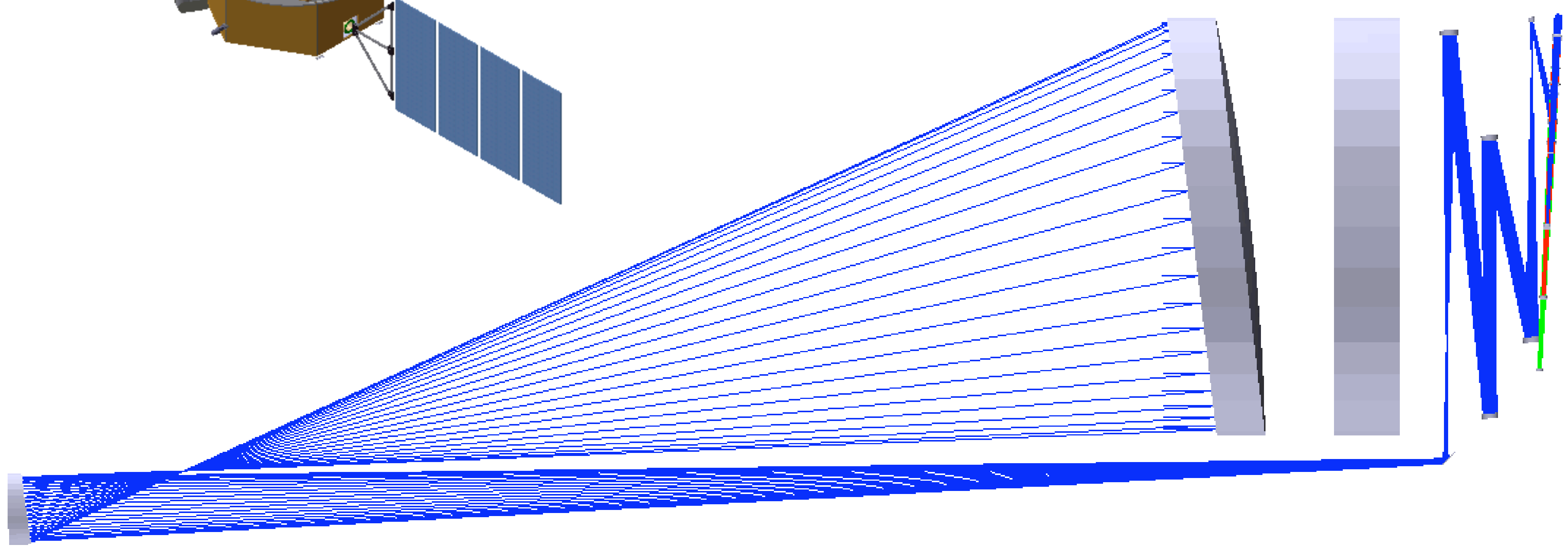
A medium-class space coronagraph, provides access to nearby planetary systems

- *Imaging and spectroscopy of known radial velocity planets*
  - *Nine nearby stars host RV planets with apastron distances > 0.25 arcsec*
  - *Existing ephemerides provide timing for maximum visibility*
  - *Measure colors, take spectra, resolve sin(i) ambiguity in mass*
- *Discovery of new giant planet companions*
  - *RV surveys are incomplete for orbital periods > 8 years, early F and hotter stars lacking strong metallic lines, stars with high chromospheric activity, and face-on systems*
  - *Potential to discover mature 5-10 AU Jovian planets orbiting as many as 200 nearby stars*
  - *Among these, 30 stars within 25 pc harbor close-in RV planets*
- *Debris disks and exozodiacal dust*
  - *1000 times more sensitive than HST, to reach as faint as Kuiper Belt analogs*
  - *Direct evidence of ongoing collisions between unseen small bodies*
  - *Unseen planets impress dynamical signatures in the debris structures, including rings, gaps, warps, and asymmetries*
- *Terrestrial planets*
  - *Potential to detect Earth-sized planets orbiting a 5-10 nearby stars*

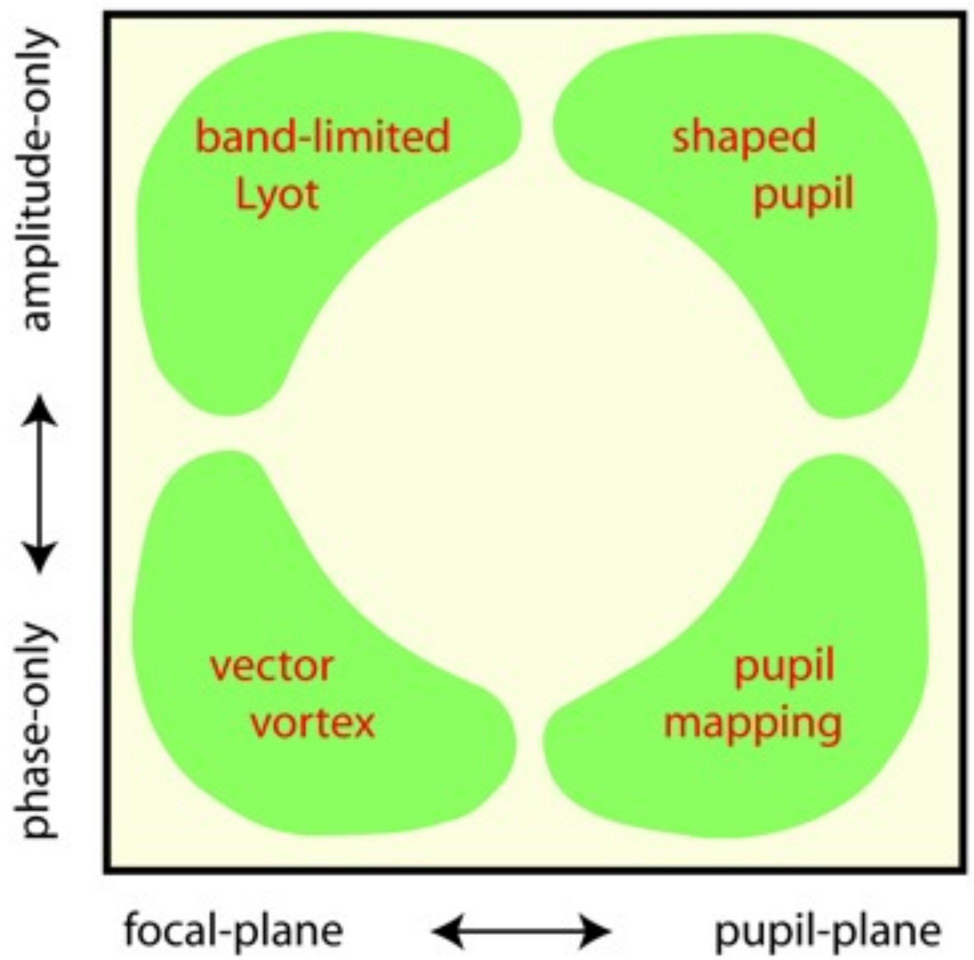


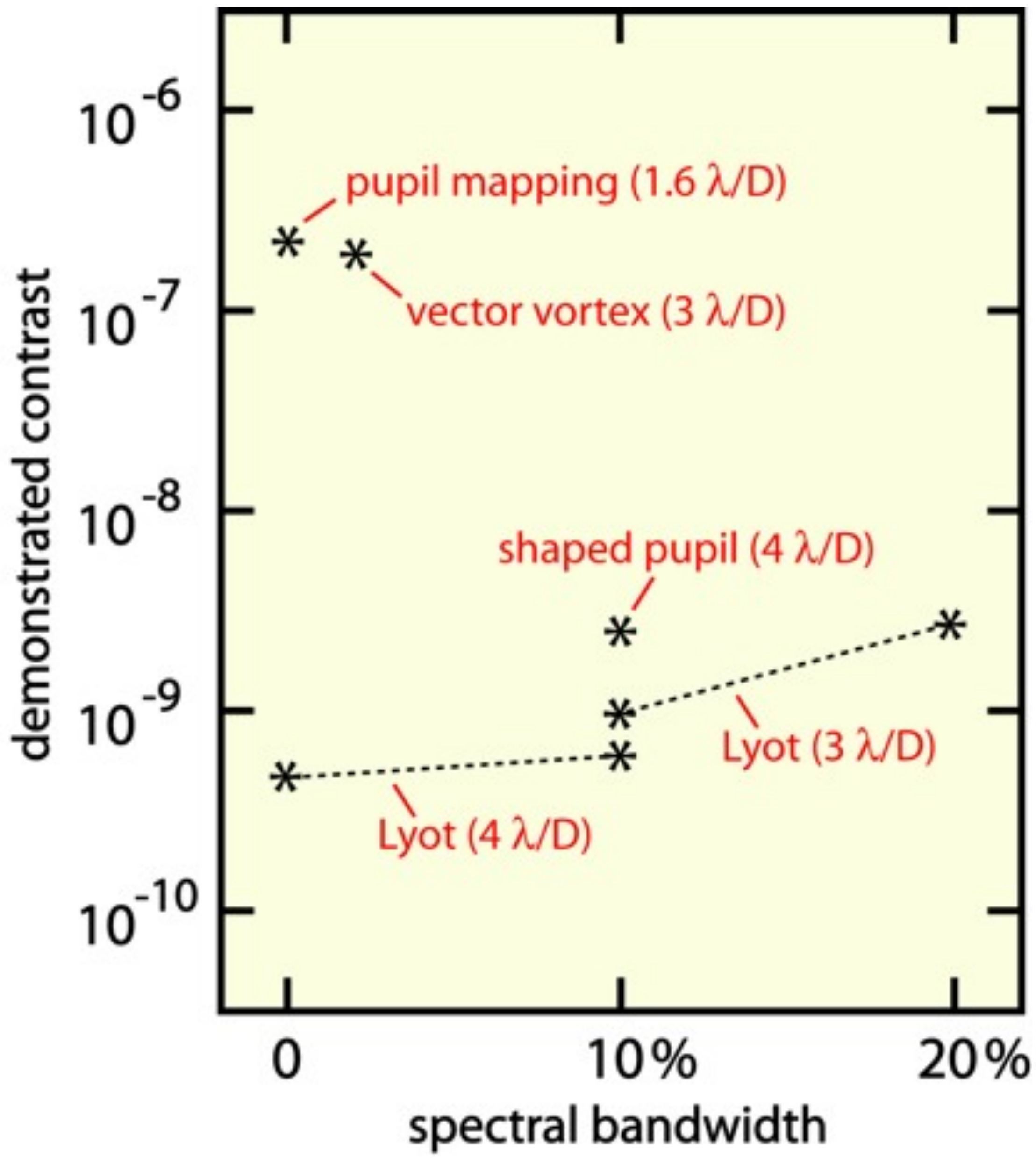
The ACCESS observatory platform is the same for the four coronagraph types included in the study.

Telescope is a1.5-meter unobscured off-axis Gregorian



ACCESS gamut of coronagraph types





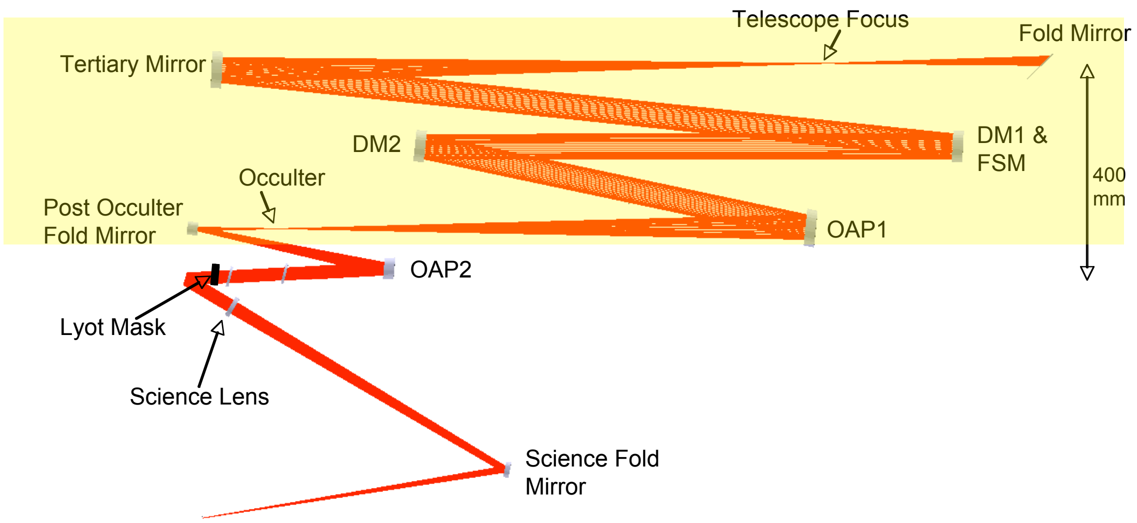
The four major coronagraph types perform starlight rejection with combinations of phase and amplitude elements placed in focal and pupil planes. Best demonstrated laboratory contrast to date (July 2009) are indicated at right. Significant improvements are expected in the coming year as an outcome of active laboratory developments with well-understood technologies.

Medium-class coronagraphic space observatory

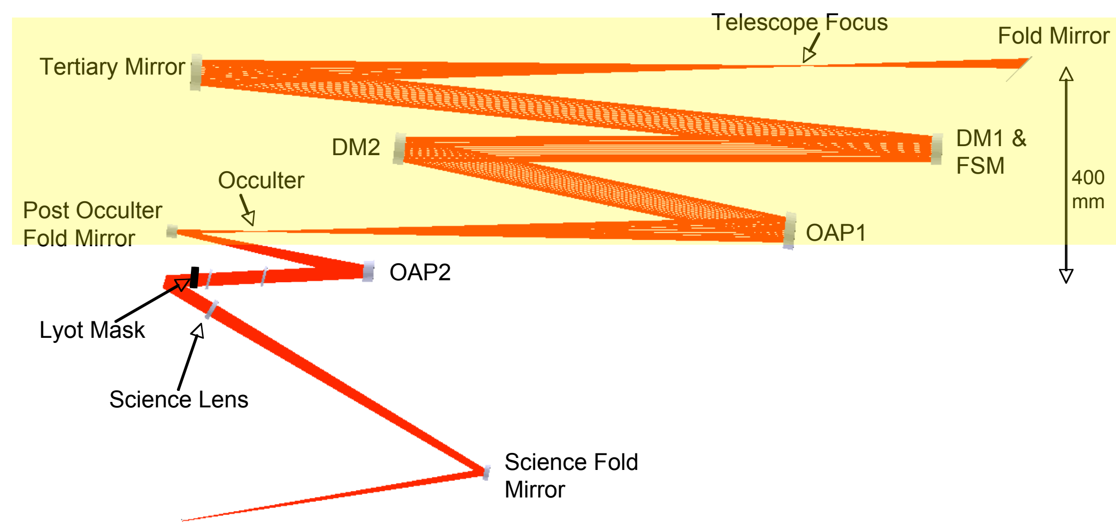
- *Observatory architecture is intended to represent the "best" available for exoplanet coronagraphy, within the scope (cost, risk, schedule) of a NASA medium-class mission*
  - *visible wavelengths (500-900 nm) for smaller λ/D and better IWA*
  - *single spacecraft (external occulter + telescope exceeds medium cost)*
- *In particular, all coronagraphs require an observatory system with*
  - *exceptional pointing control*
  - *exceptional wavefront stability and*
  - *active (deformable mirrors) wavefront control*
- *Successful concept 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 evaluation of the concept and meaningful comparisons among coronagraph types.*

ACCESS compares four major coronagraph types

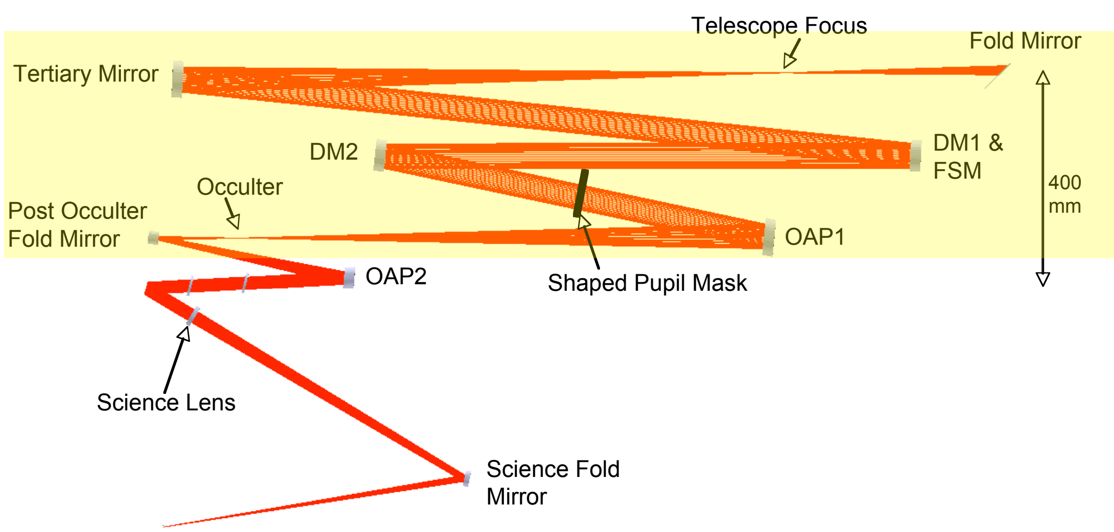
Lyot coronagraph



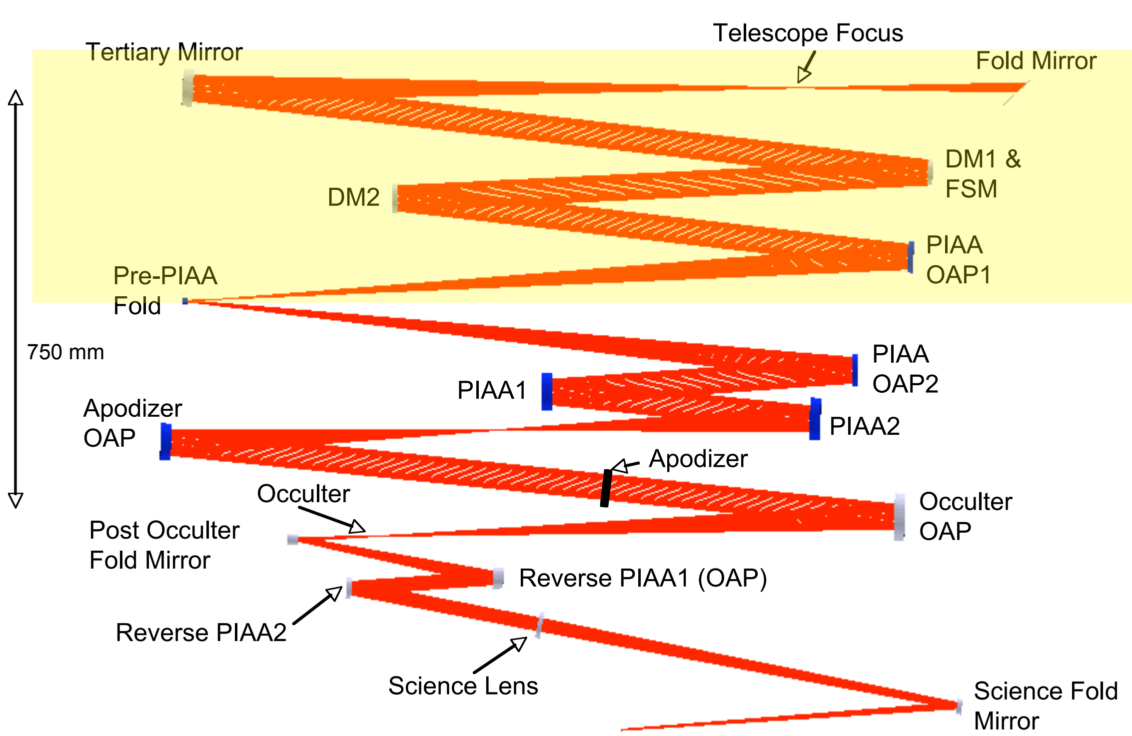
Vortex coronagraph



Shaped pupil coronagraph

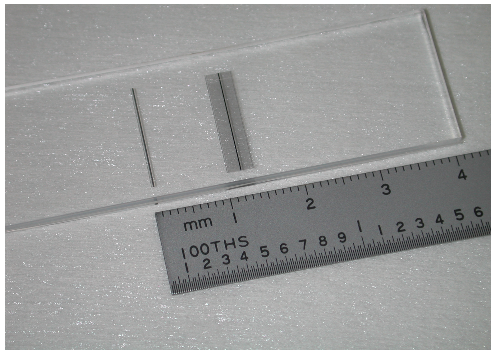


Pupil mapping coronagraph



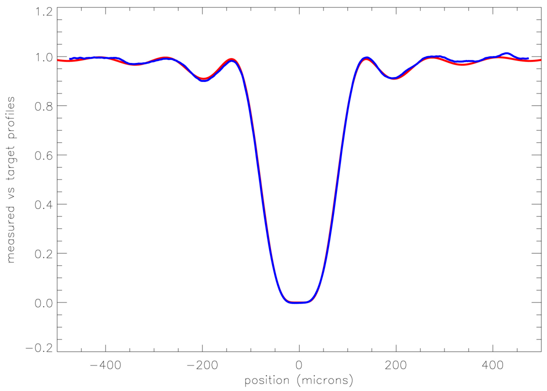
(Note: highlighted elements, including FSM, DMs, and pointing control system, are common to ALL four coronagraph types)

Lyot coronagraph demonstrations 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.

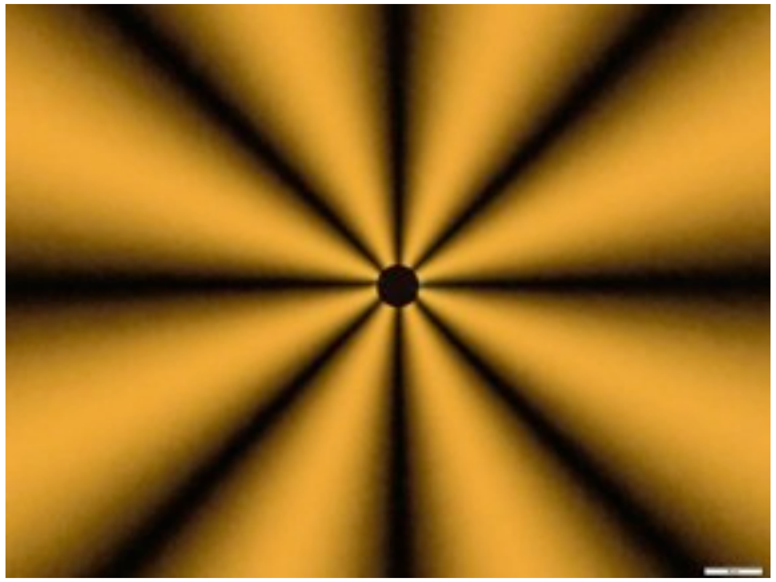
Recent contrast demonstrations in the HCIT:
IWA = 3 λ/D, 10% bandwidth, C = 1.2 e-9
IWA = 3 λ/D, 20% BW, C = 2.7 e-9
IWA = 4 λ/D, 10% BW, C = 6 e-10,
with linear metal-only or metal+dielectric 4th-order Lyot masks. All Lyot masks have been manufactured at JPL.

Prospects and Risks

- *Contrast predictions based on end-to-end Fresnel propagation models and component properties have been validated (to within 20%) by HCIT experiments.*
- *New 2.5 λ/D Lyot masks are being manufactured for HCIT tests in Fall 2009, with a predicted contrast better than 1e-9 over 20% bandwidth with 50% throughput.*
- *Extensive tests (including HCIT) demonstrate that metal-dielectric masks are TRL 6 components*

Vector vortex coronagraph mask for HCIT experiments

Recent contrast demonstrations in the HCIT:
IWA = 3 λ/D, 2% bandwidth, C = 2.0 e-7
with the first-ever charge-4 liquid crystal polymer vortex mask from JDSU (seen at left through crossed polarizers). Measured IWA is 1.8 λ/D with 90% throughput in unpolarized light.

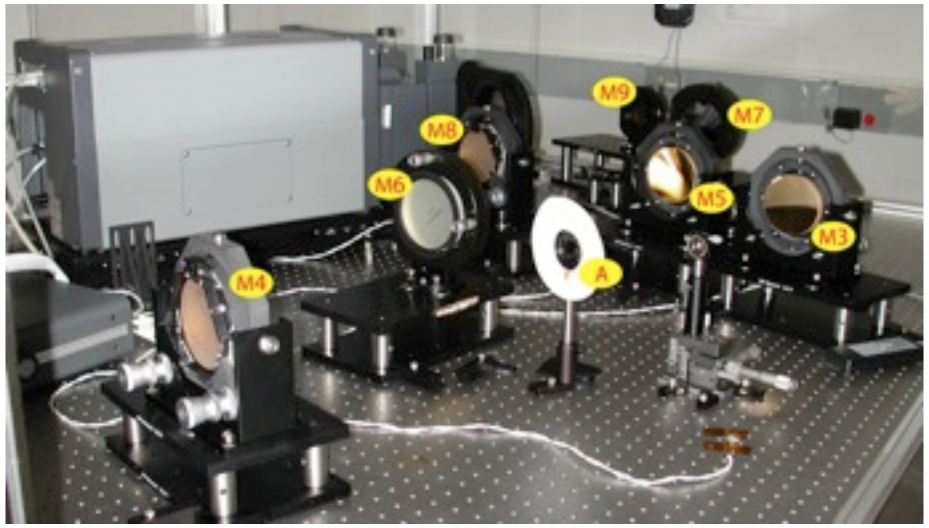


Prospects and Risks

- *Contrast predictions based on end-to-end Fresnel propagation models and component properties have been validated (to within 20%) by HCIT experiments.*
- *Models predict that reduction of internal reflections will lead to contrast ~1e-9 with a 2% bandwidth; new component is on order from JDSU for delivery this summer.*
- *Models predict that a three-layer achromatization will lead to contrast ~1e-9 with a 20% bandwidth; new component is on order from JDSU for delivery this summer.*

Pupil mapping demonstrations on the HCIT

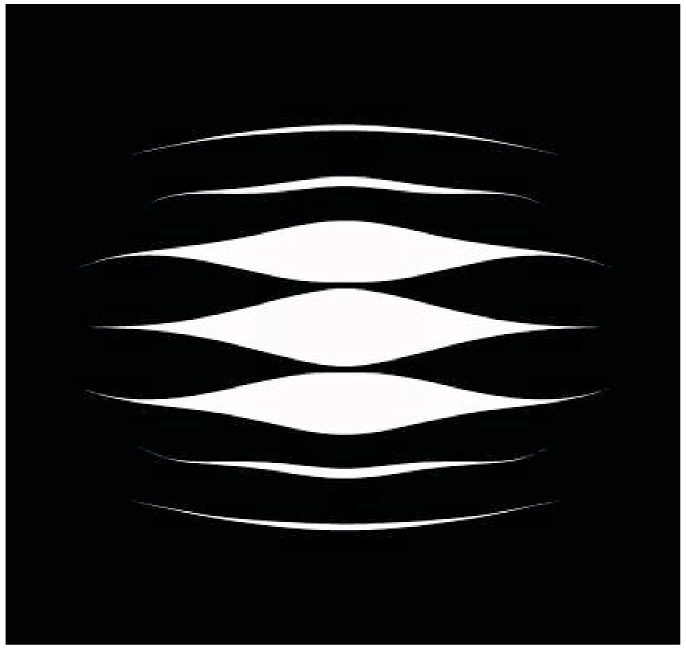
To date, the best contrast result for a pupil mapping (PIAA) coronagraph:
IWA = 1.6 λ/D, monochromatic, C = 2.2e-7
was achieved by Guyon (2009) at the Subaru Observatory laboratories. A new PIAA system, commissioned by NASA/Ames and manufactured by Tinsley, is now mounted in the HCIT for its first experiments in a vacuum environment.



Prospects and Risks

- *Predictions of system response to DM wavefront control, and predictions of achievable contrast, are both hampered by lack of an efficient computational technique that includes diffractive effects in a pupil mapping system with imperfect optics.*
- *Manufacturing and metrology of the PIAA apodizing mirror #1 are challenging, may require an advancement in polishing and metrology.*
- *New PIAA system is presently installed in the HCIT, undergoing two months of tests.*

Shaped pupil coronagraph experiments with HCIT



At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque). This "Ripple 3" design achieved:
IWA = 4 λ/D, 10% bandwidth, C = 2.4 e-9
on the HCIT (Belikov et al. 2007).

Prospects and Risks

- *Contrast predictions based on end-to-end Fresnel propagation models and component properties have been validated (to within 20%) by HCIT experiments.*
- *Smaller inner working angles are possible in principle with the use of a pair of DMs.*
- *Note that a shaped pupil with a pair of deeply actuated DMs shares parameter space with the pupil mapping approach.*
- *No further HCIT experiments are planned for shaped pupils at this time.*

“Suggested” medium-class coronagraphic observatory

- *Telescope -- 1.5 meter diameter primary mirror, unobscured off-axis gregorian, with a stable metering structure;*
- *Spacecraft configured for L2 orbit;*
- *Pointing control system designed end-to-end to include telescope and spacecraft dynamics, active vibration damping, and pointing knowledge and fine correction with reference to the bright central star;*
- *Active thermal control system, including V-groove solar shield, for stability of the optical wavefront;*
- *Pair of deformable mirrors in the instrument for active wavefront control;*
- *Focal plane wavefront error sensing and control algorithms;*
- *CCD imaging and integral field spectroscopy of the science field;*
- *End-to-end optical (Fresnel diffraction) propagation models with realistic element characteristics (mirror surface PSDs, etc) for sensitivity analysis and tolerancing.*

Suggestion -- Keep the concept simple!

- *Control mission cost with a minimal yet capable system.*
- *Minimize the number of optical elements -- each element needs to be specified, manufactured, mounted, aligned, tested.*
- *Simplify end-to-end system modeling and tolerancing -- modeling must keep track of N elements and NxN interactions.*
- *Limit the buildup of wavefront errors -- additional elements lead to tighter specifications on all elements, as well as specifications on alignments, pointing, beam walk, spectral bandwidth, polarization.*
- *Reduce scattered light -- each additional element is an additional source of scattering, especially those near focal planes.*
- *Improve efficiency -- high system throughput argues for a minimum of elements.*
- *Strive for a minimum of moving parts -- they are expensive.*
- *Test the system end-to-end on the ground -- elements will be tested individually, but system-level testing is also essential prior to launch.*
- *Reduce risk of mission degradation or failure -- each critical element has the potential for mission delays, cost overruns, performance degradation over time, and mission failure.*

Pioneering science is the objective

- *Direct imaging and spectroscopy of the nearby exo-planetary systems is compelling space astronomy, even for a medium-sized mission.*
- *Science is well-served by a sequence of achievable missions -- success in an initial medium-size mission opens the portal for pioneering exoplanet science today, which in turn provides the case for well-designed missions in the future.*
- *"Something today" vs. "Something better tomorrow" -- we can be futurists, but compelling missions are within our grasp today.*
- *"Better is the enemy of good enough" -- old NASA proverb*
- *Demonstrated capability (a bird in the hand) vs. promising technology developments for the coming years (the bird in the bush) -- beware: inventing the future takes time.*
- *The exoplanet community (that's us) is one of the fastest growing areas of astrophysics -- let's find a way to initiate the development of a mission that can happen in our lifetime.*

“Pitch” for a medium-class coronagraphic observatory

A viable mission for the direct coronagraphic imaging of the nearby planetary systems could be implemented now, with known methods that have been validated in the laboratory, using technologies available today.

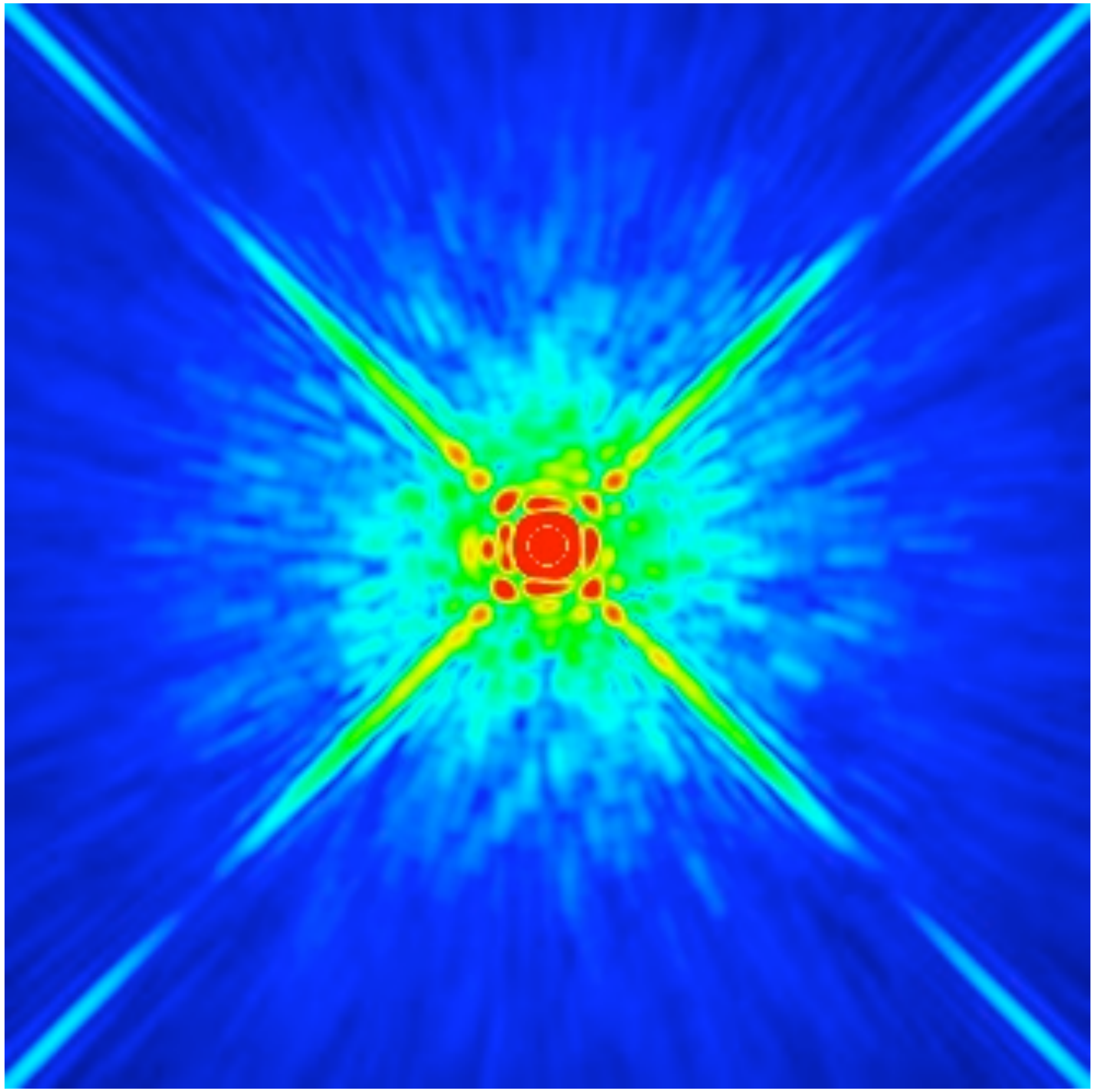
The Astro2010 Decadal Survey by the National Academies is now evaluating astronomy program priorities for the coming decade, with a report to be released next year. A high priority for a medium-class exoplanet mission in the coming decade is one possible outcome.

As we await the Astro2010 recommendations, NASA has announced a competitive program for the advancement of planet-finding technologies.

We expect significant advancements and opportunities for the exploration of other planetary systems in the coming years.

Backup

Toy Coronagraph



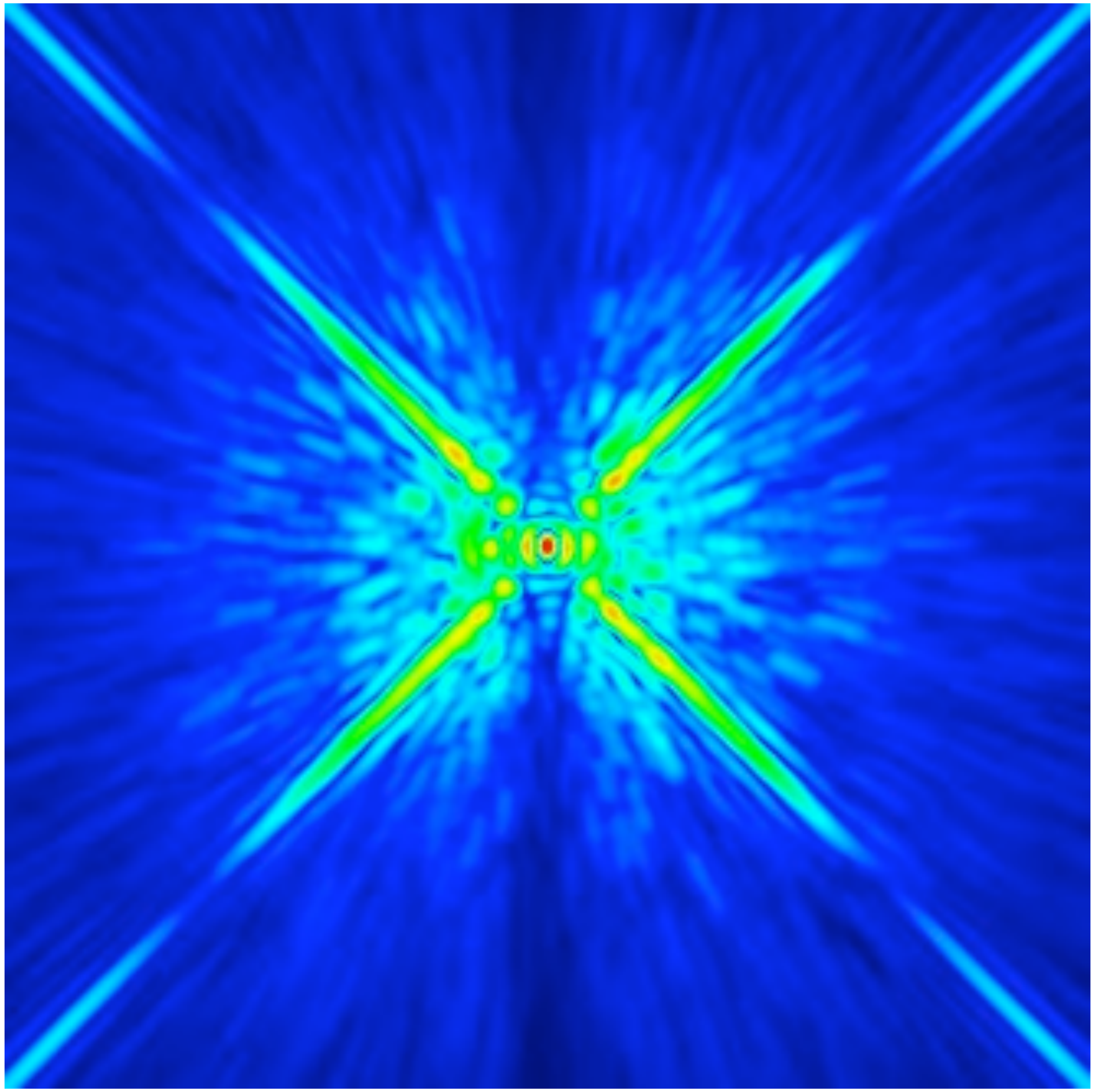
~~Occulting Element~~

~~Lyot Element~~

~~Deformable Mirror(s)~~

~~Look Deeper~~

Toy Coronagraph



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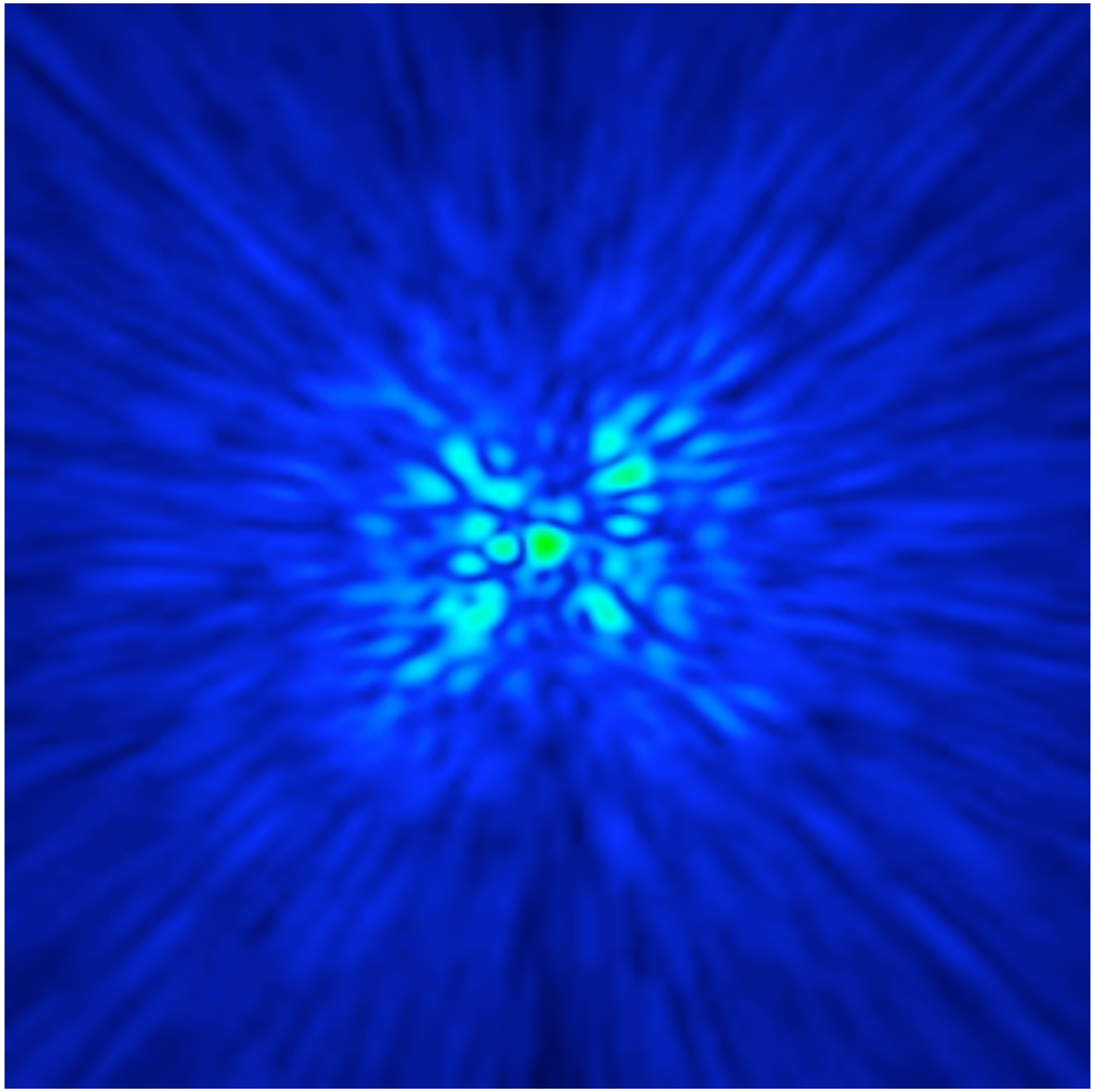

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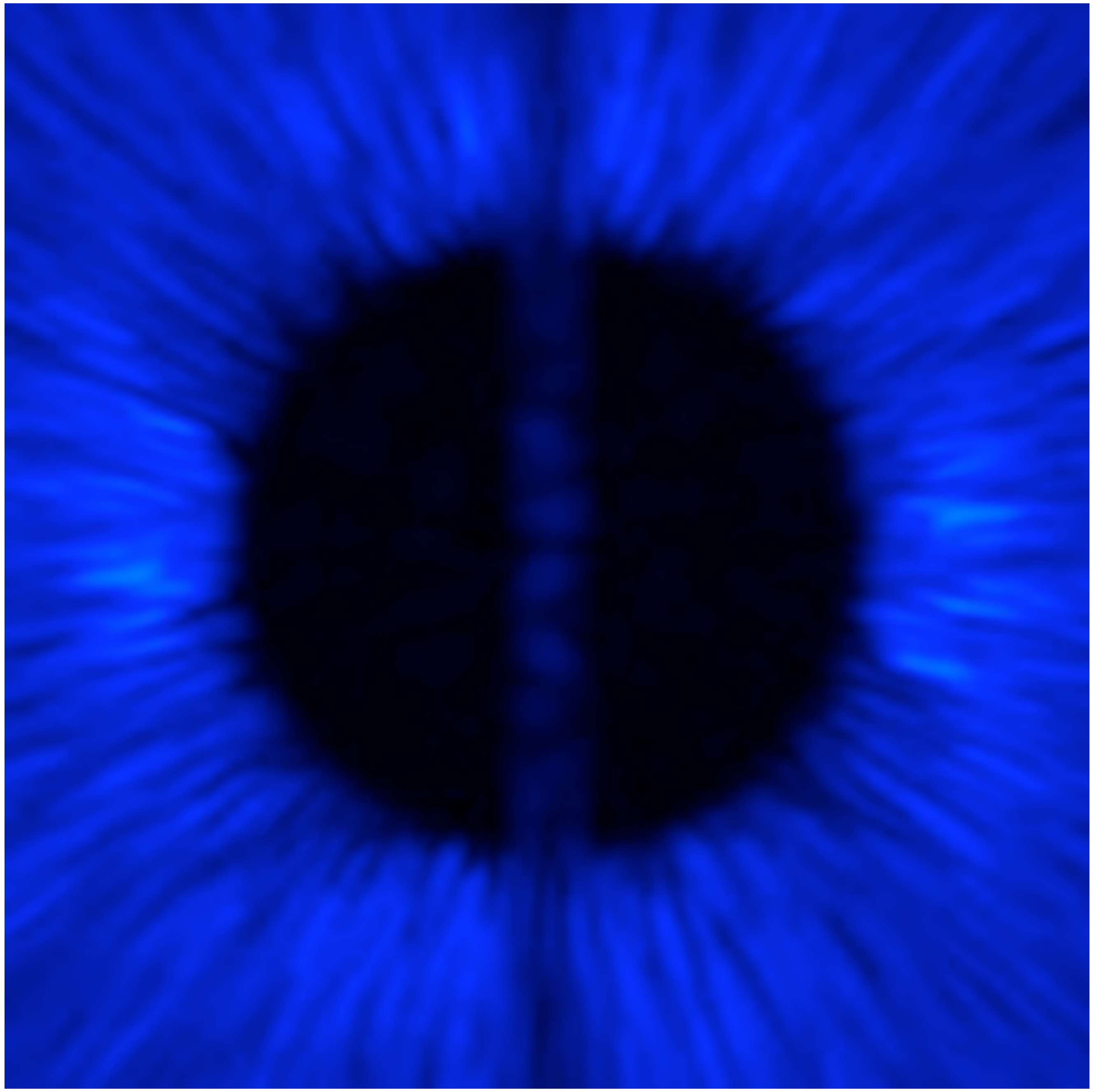

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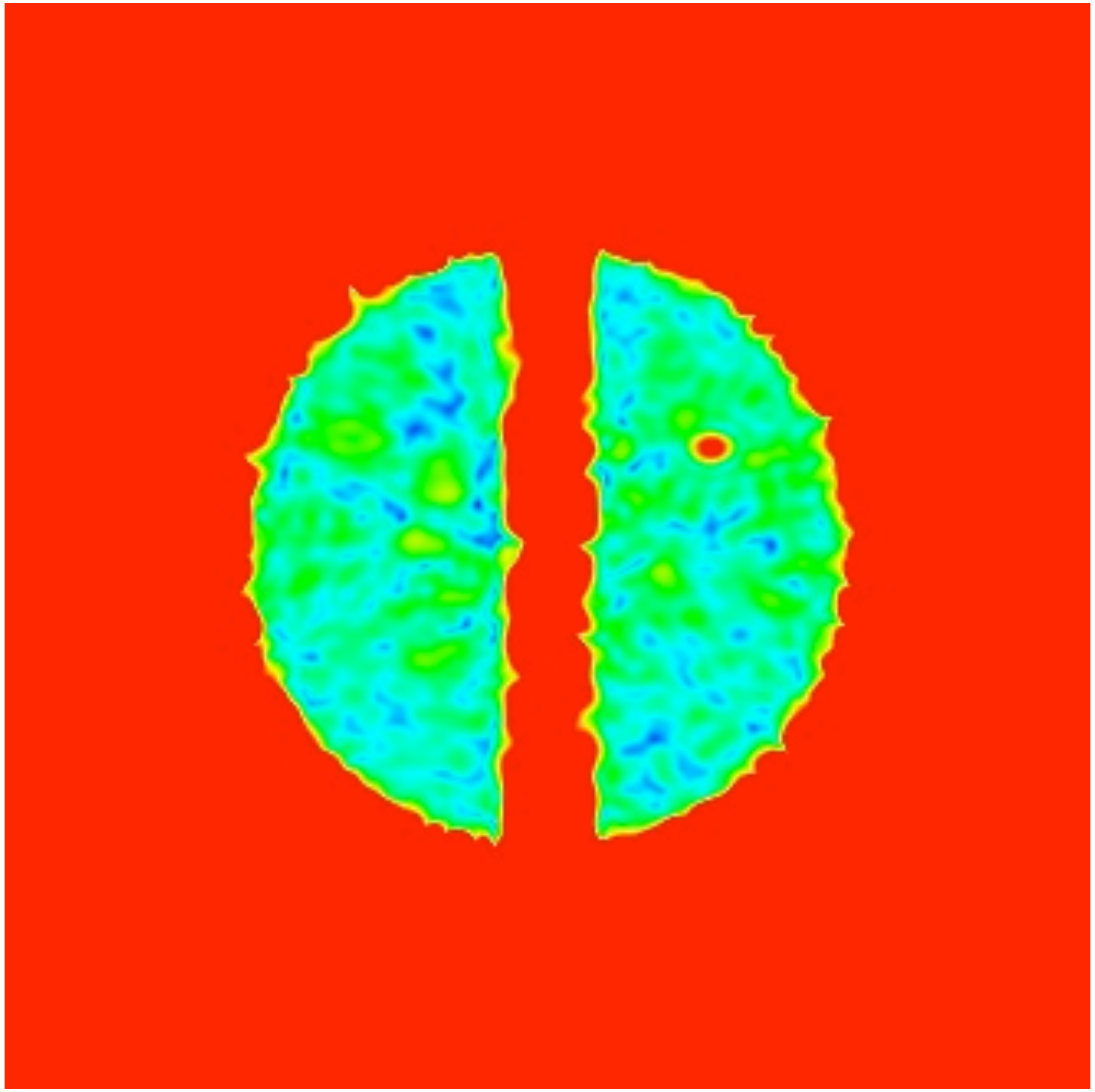

Occulting Element

Lyot Element

Deformable Mirror(s)

Look Deeper

End