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California Institute of Technology
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NASA’s Exoplanet Program Technology Needs

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Redondo Beach, CA, 1–4 October 2013

Combined-light methods not covered in this talk

- Combined-light methods
  - Radial velocity
  - Transit
  - Microlensing
  - Pulsar timing
  - Astrometry

These techniques do not resolve the planet as separate from the star: telescopes used as "light buckets"

- Starlight suppression methods
  - Coronagraph
  - Starshades
  - Interferometer

Planets resolved as separate objects.

System Requirements

Angular Resolution

Contrast

Inner Working Angle

Angular Resolution: Some numbers to keep in mind

- A 50-cm space telescope equipped with a coronagraph is capable of characterizing the debris disks around ~1 nearby star (epsilon Eridani).

- A 1.5-m space telescope would enable compelling exoplanet science to study planets larger than the Earth – Jupiter and Saturn type planets.

- A space telescope 4-m or more in diameter is needed to survey and detect a reasonable sample of nearby Earth-like planets

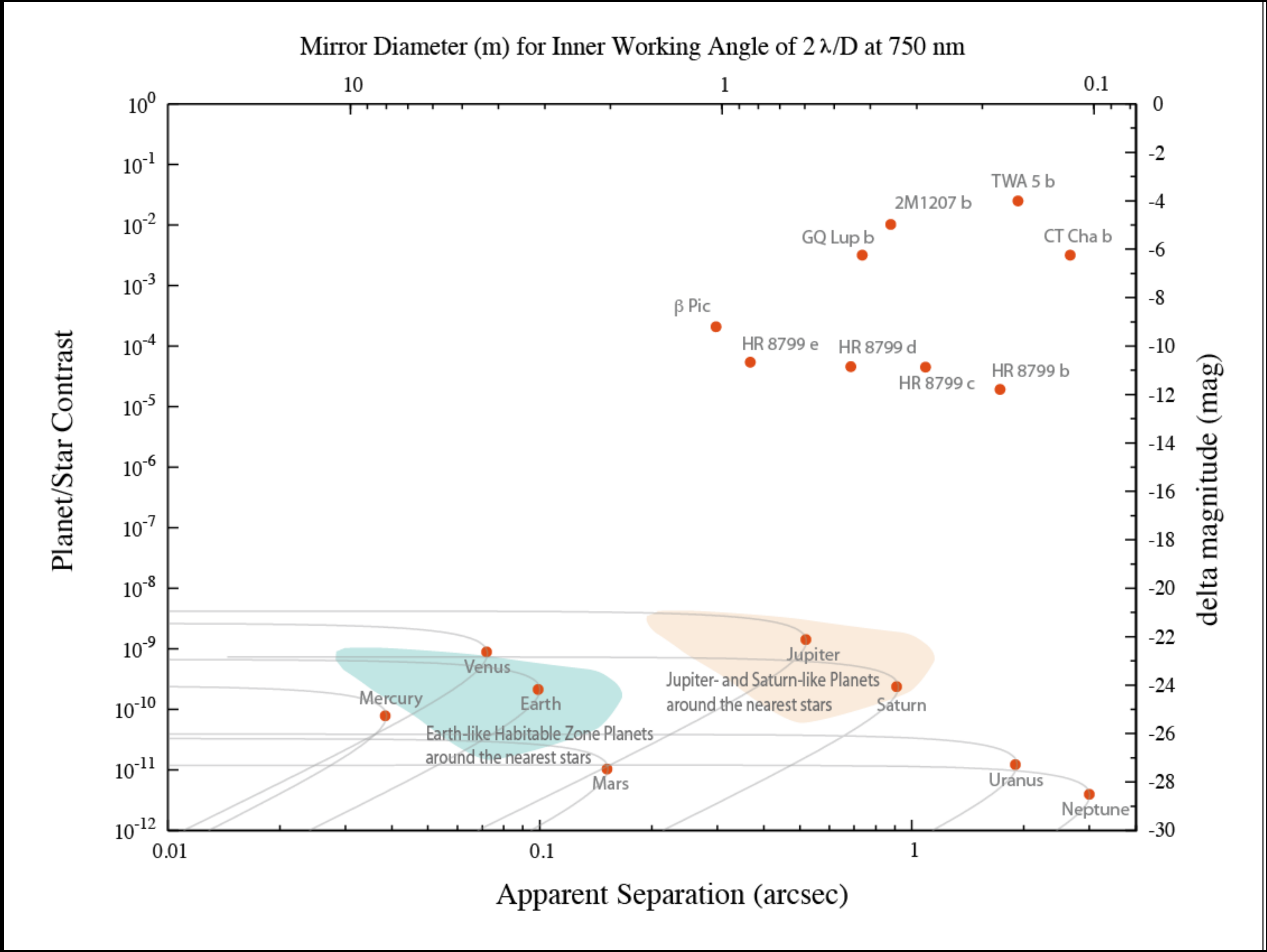
- To image the surface of a planet around a nearby star we would need a telescope ~30 km in diameter.

Contrast: The Spectrum of an Earth-like Exoplanet

At mid-infrared wavelengths, exoplanets shine because they are warm

At visible wavelengths, exoplanets shine in reflected starlight

Imaging Discovery Space



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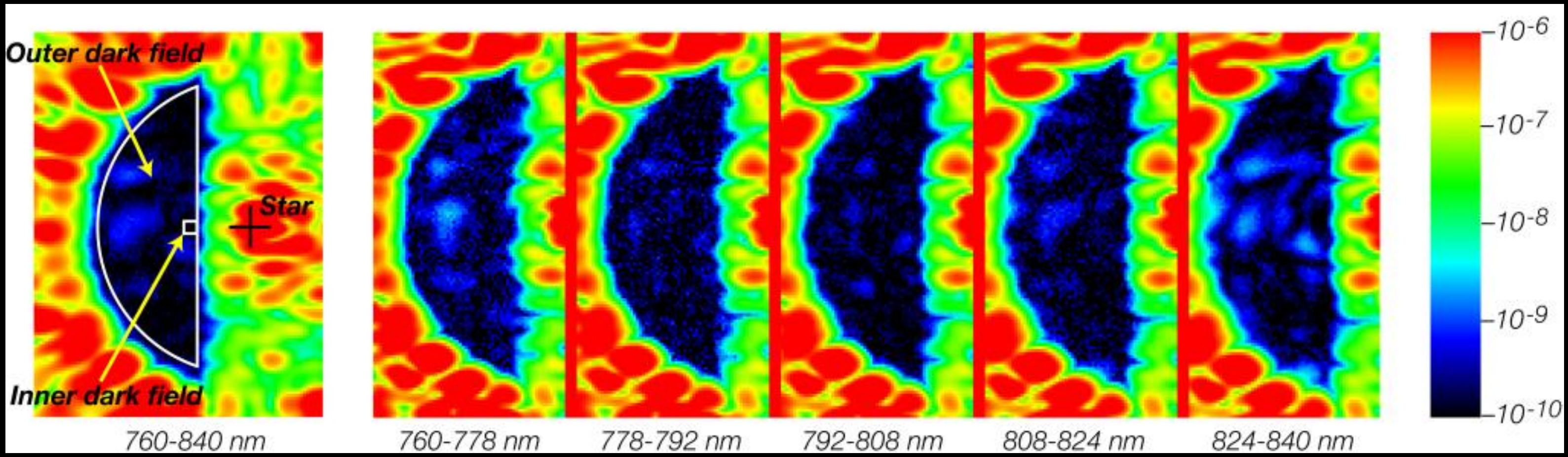
Why is a Space Mission Needed?

Wavefront Errors

Ground-based vs Space-based Imaging



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New Ground-based Exoplanet Instruments 2012-2020

Extreme AO on 8–10-m class telescopes

Palomar P1640

Gemini Planet Imager

ESO VLT-SPHERE

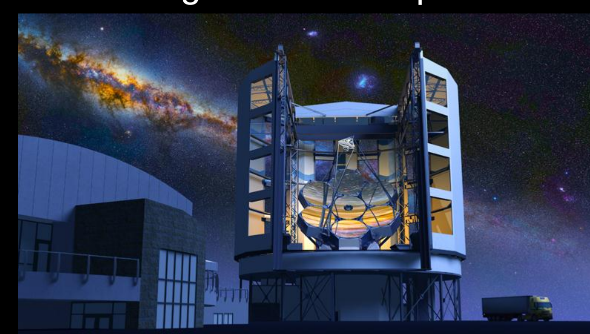
Subaru SCExAO

Extreme AO on Extremely Large Telescopes (30–42m diameter)

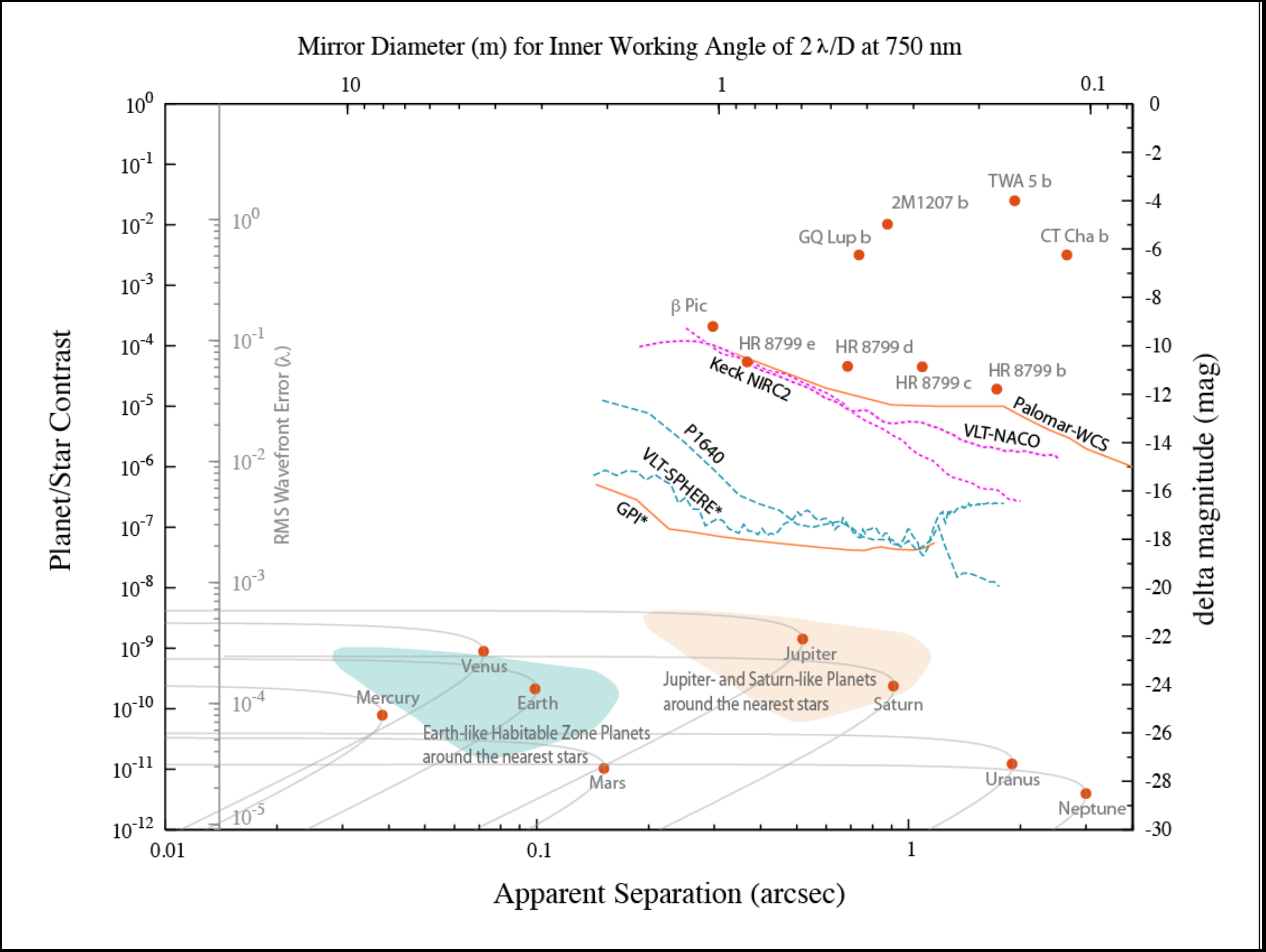
Thirty Meter Telescope

European Extremely Large Telescope

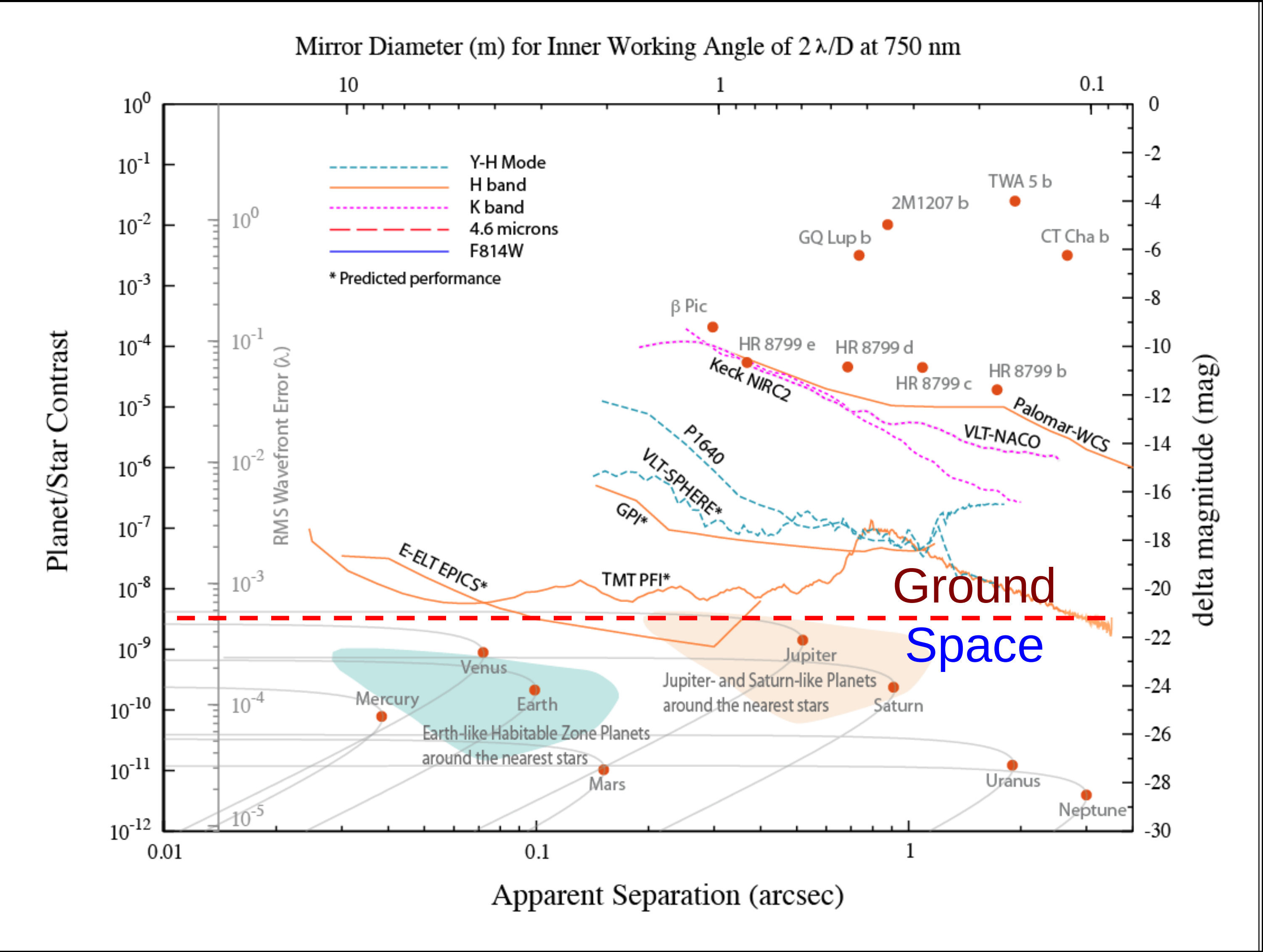
Giant Magellan Telescope



Discovery Space of Existing and Near-term Ground-based Coronagraphs



Discovery Space of Extremely Large Telescopes



Coronagraph Technology Challenges

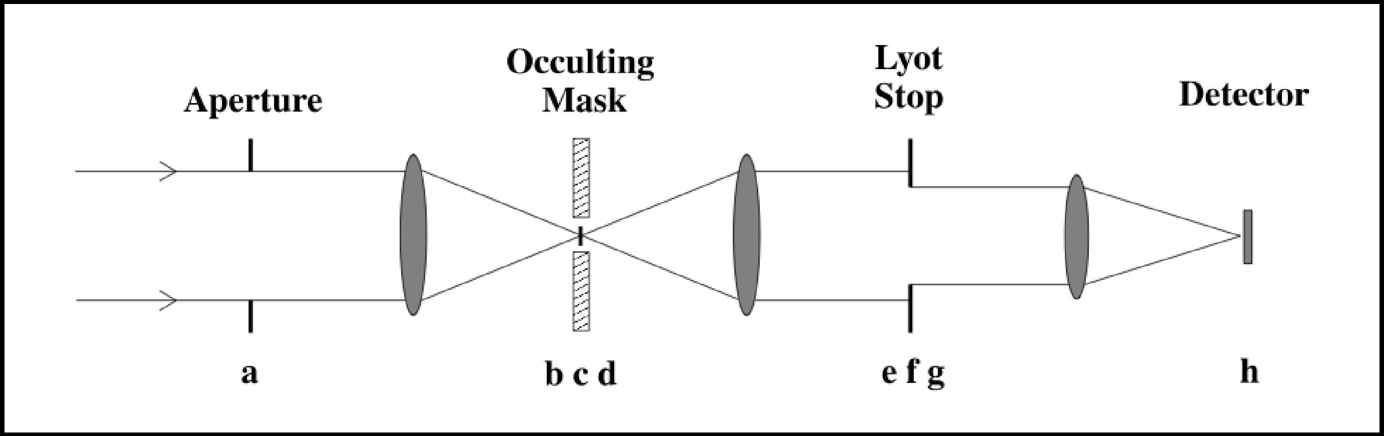
Diffraction Control

Speckle Suppression

Step 1: Diffraction control used to selectively reject starlight

- A diffractive optic is used to remove star-light from the field of view, while allowing the planet light to be detected
  - A fixed optic (does not move)
    - e.g. an image plane mask in a coronagraph, or the occulter of an external coronagraph
  - Mathematically may have perfect performance
  - In practice may have subtle imperfections

- Concepts in Fourier Optics provide a wide variety of possible solutions



Sivaramakrishnan et al. ApJ 552, 397 (2001)

Selected Coronagraph Concepts

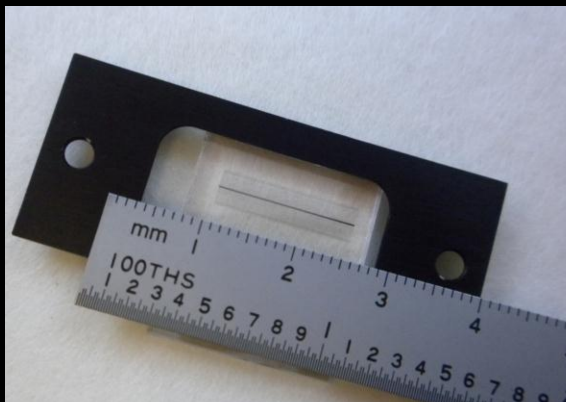


Image Plane Amplitude & Phase Mask (Trauger, JPL)

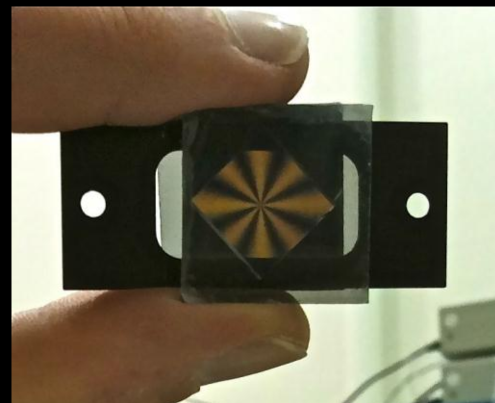
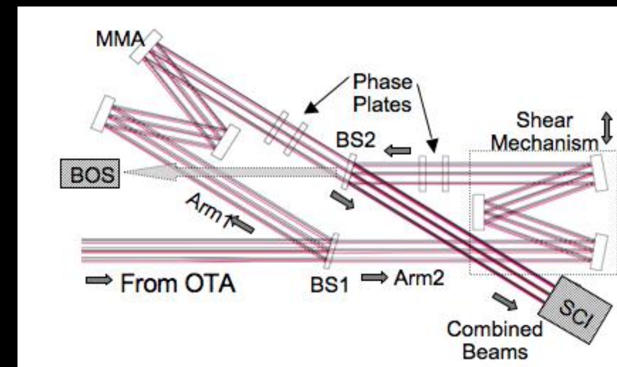
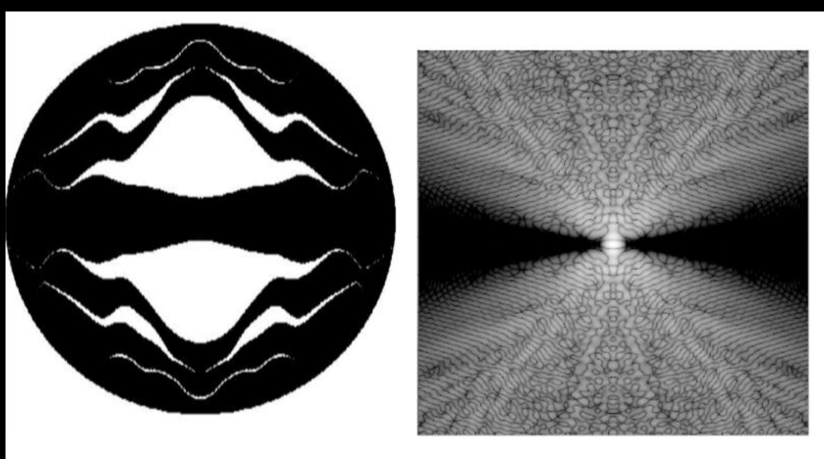


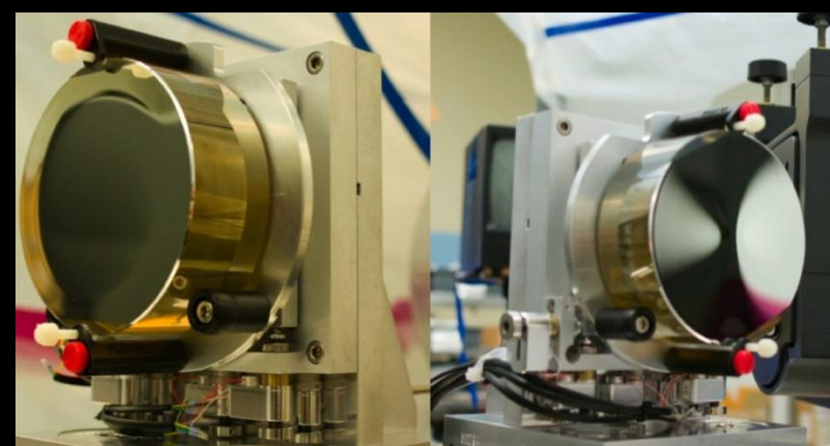
Image Plane
Phase Mask (Serabyn, JPL)



Pupil Shearing
(Clampin, NASA GSFC)



Pupil Masking (Vanderbei, Univ. Princeton)



Pupil Mapping (Guyon, Univ. Arizona)

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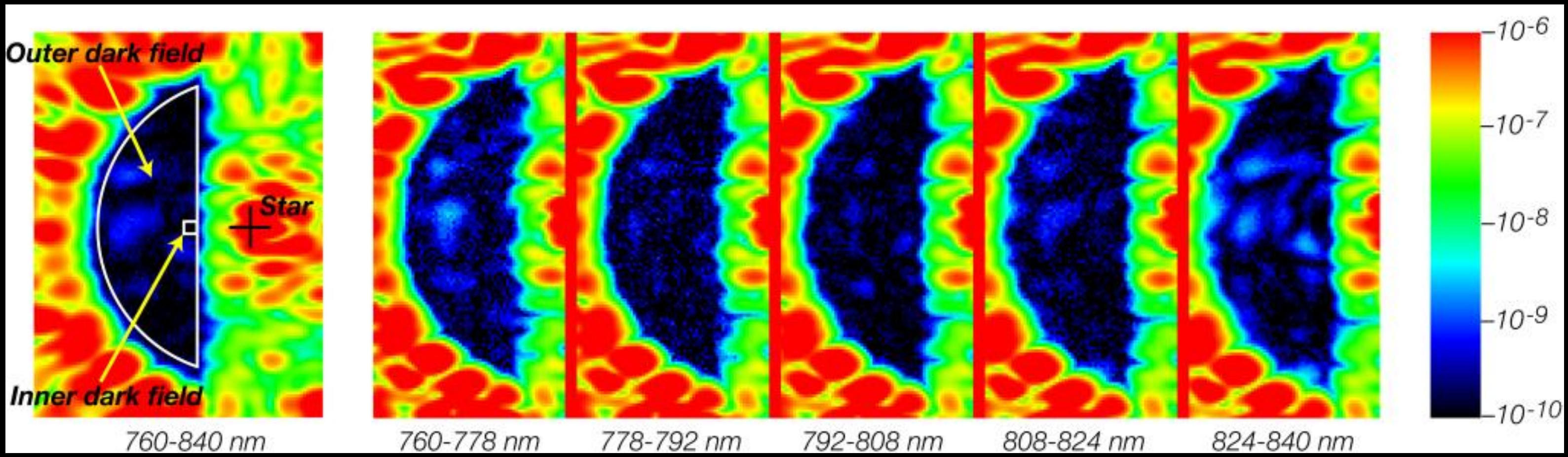
Step 2: Speckle suppression compensates for imperfections in Mask and/or Telescope System

- Wavefront compensation is required, with tolerances set by the desired planet/star contrast
  - Two deformable mirrors are needed for simultaneous phase & amplitude correction over a full field
  - The Talbot effect causes phase errors to give rise to amplitude errors
- Modulation of the wavefront is used to measure and suppress speckles
  - Deformable mirrors are modulated to detect coherent speckles
  - Angular Differential Imaging and Spectral Deconvolution are other forms of modulation that can be used to improve sensitivity in post-processing



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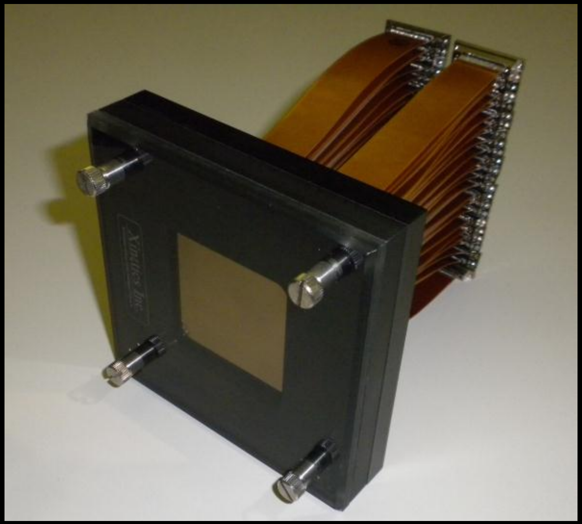
Deformable Mirrors

- Xinetics (NGAS) deformable mirrors have been used to demonstrate contrasts of 2 x 10^{-10}
  - Routinely used in vacuum at HCIT
  - Vibration tested at JPL
- Boston Micromachines (MEMS) deformable mirrors demonstrated contrasts of 10^{-8}
  - Low-power, low mass
  - Flown on PICTURE (Chakrabarti, Boston University)



48x48 Xinetics DM vibration tested at JPL

DMs have not yet been flown but are at a high TRL

Further advances in MEMS DM technology are of great interest

Telescope Engineering Requirements vs λ/D

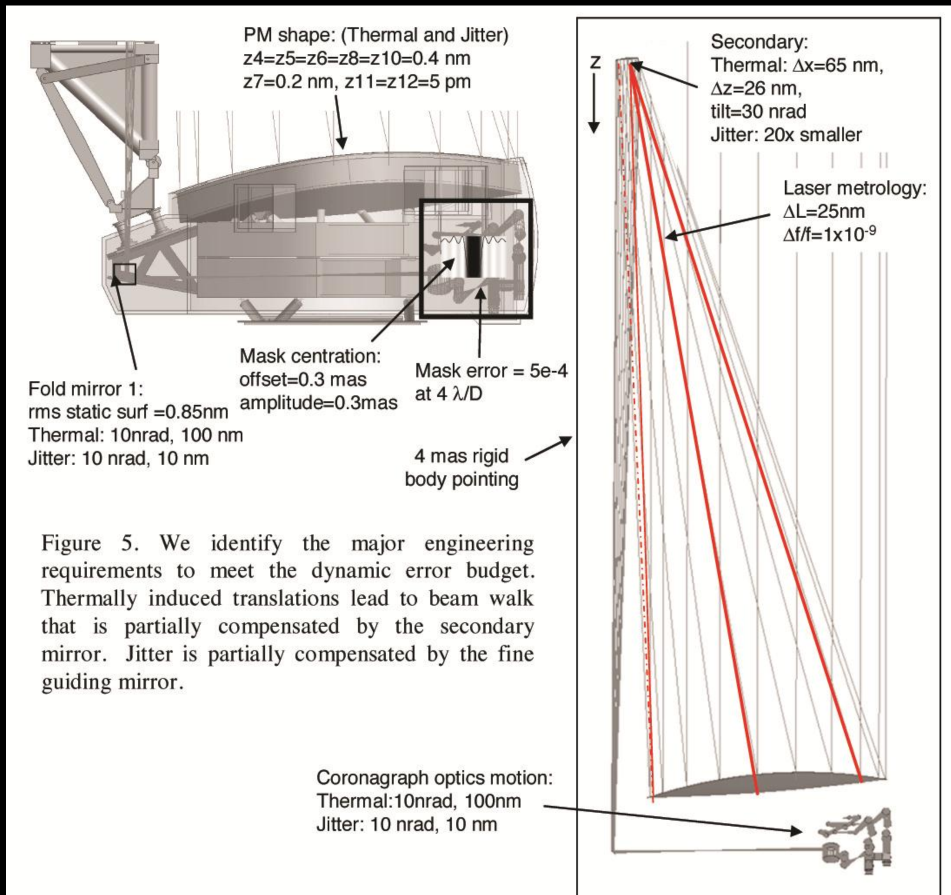


Figure 5. We identify the major engineering requirements to meet the dynamic error budget. Thermally induced translations lead to beam walk that is partially compensated by the secondary mirror. Jitter is partially compensated by the fine guiding mirror.

Laser metrology
required for
sensing and control

Key requirements
1–2 orders of
magnitude tighter
for a 3.8-m telescope
operating at 2λ/D

S. B. Shaklan, L. Marchan, J. J. Green, O. P. Lay, “Terrestrial Planet Finder Coronagraph Dynamics Error Budget,” Proc. SPIE 5905 (2005).

S. B. Shaklan, L. F. Marchan, J. E. Krist, M. Rud, “Stability error budget for an aggressive coronagraph on a 3.8-m telescope,” Proc. SPIE 8151, San Diego, August 2011.

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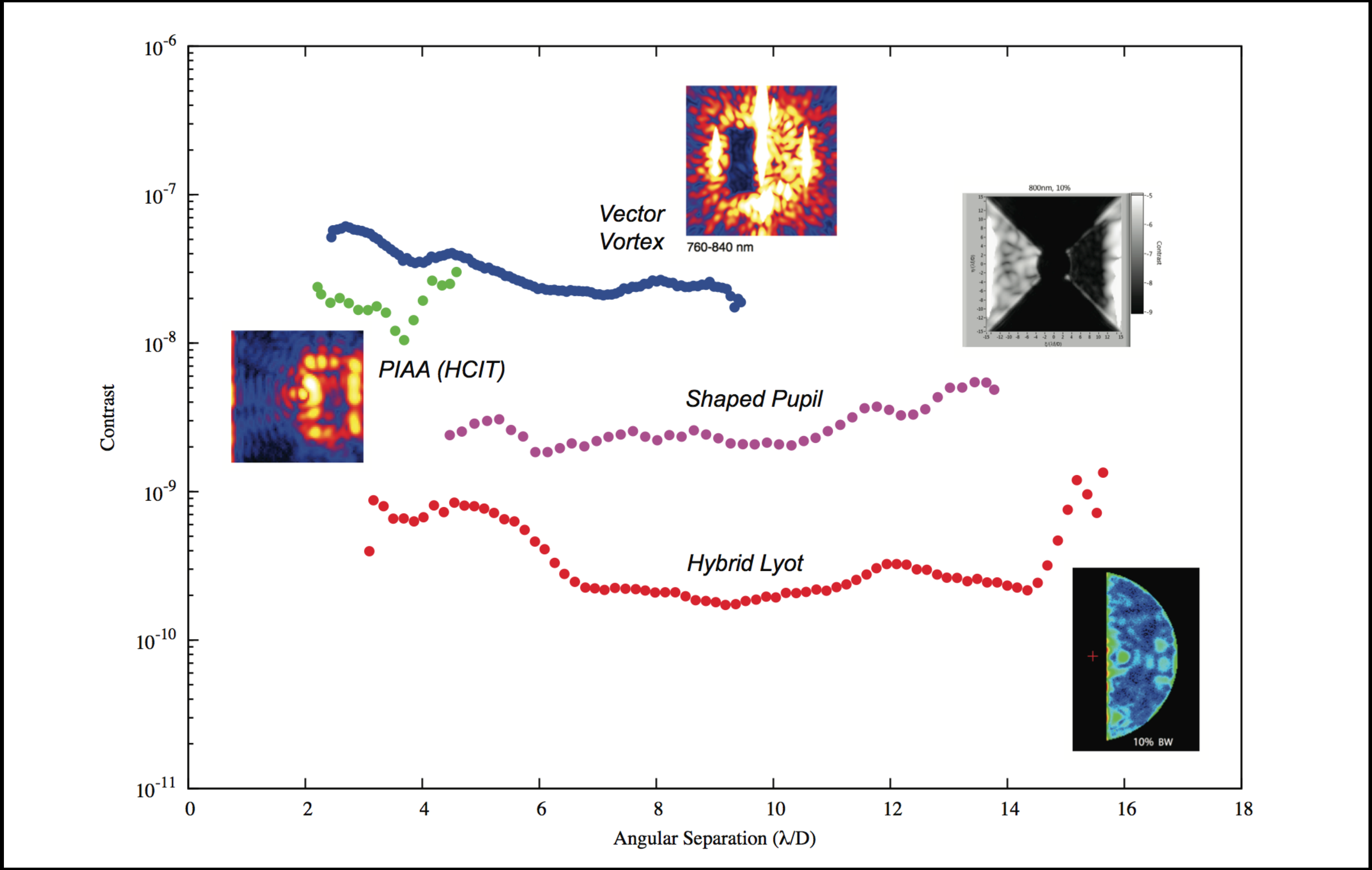
Coronagraph Laboratory Results

Table 1: Coronagraph Laboratory Results

Method	Design	Facility	λ (nm)	$\Delta\lambda$ (%)	Mean Raw Contrast	r_{min} (λ/D)	r_{max} (λ/D)	$\Delta\phi$ (deg)	Hole Shape	Field $(\lambda/D)^2$	Throughput (%)
BLHL	4^{th} order	HCIT	800	2	1.2e-10	3.1	15.6	180	D	283.8	56
BLHL	4^{th} order	HCIT	800	10	3.2e-10	3.1	15.6	180	D	283.8	56
BLHL	4^{th} order	HCIT	800	20	1.3e-09	3.1	15.5	180	D	285.6	56
PIAA	Prolate	ACE	650	0	4.4e-07	1.2	2.0	140	Arc	3.1	46
PIAA	Prolate	HCIT-2	808	0	5.7e-10	1.9	4.7	180	Rect	12.7	46
PIAA	Prolate	HCIT-2	800	10	1.8e-08	2.2	4.6	180	Rect	9.9	46
SPC	Ripple 3	HCIT	800	2	1.2e-09	4.5	13.8	82	Wedge	80.9	10
SPC	Ripple 3	HCIT	800	10	2.5e-09	4.5	13.8	82	Wedge	80.9	10
VNC	$\epsilon = 0.25$	GSFC	633	2	5.3e-09	1.5	2.5	28	Arc	1.0	35
VV	TC4	HCIT	785	0	3.6e-09	2.6	12.2	180	D	173.8	36
VV	TC4	HCIT	800	2	1.7e-08	2.4	9.9	180	Rect.	65.9	43
VV	TC4	HCIT	800	10	2.9e-08	2.4	9.4	180	Rect.	59.8	43
VV	TC4	HCIT	800	20	4.3e-08	2.4	9.1	180	Rect.	55.4	43

State-of-the-Art in Coronagraph Laboratory Experiments with a 10% bandwidth



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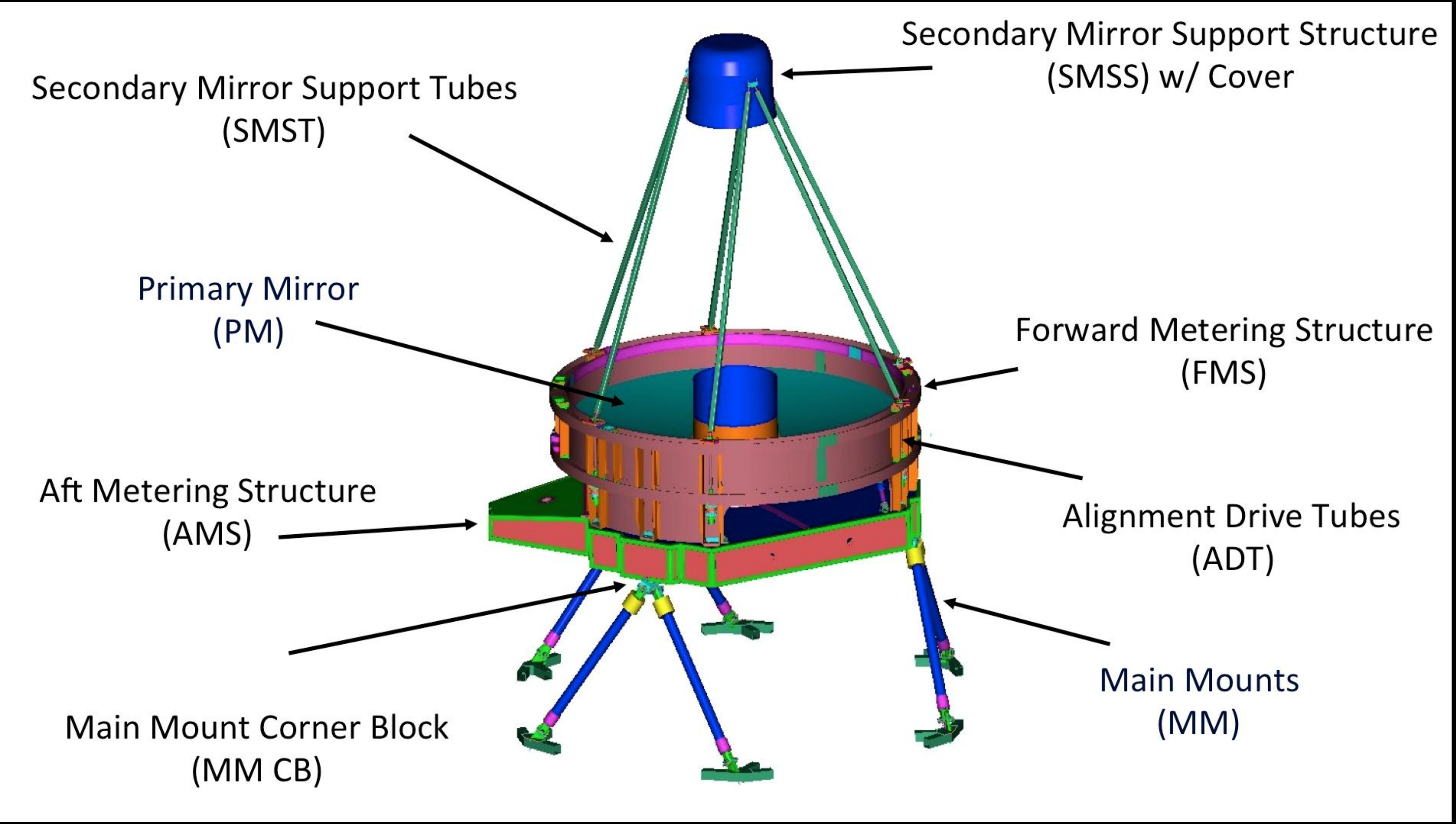
A Coronagraph for an Astrophysics Focused Telescope Asset (AFTA)



The central obscuration and struts make the design of a coronagraph challenging.

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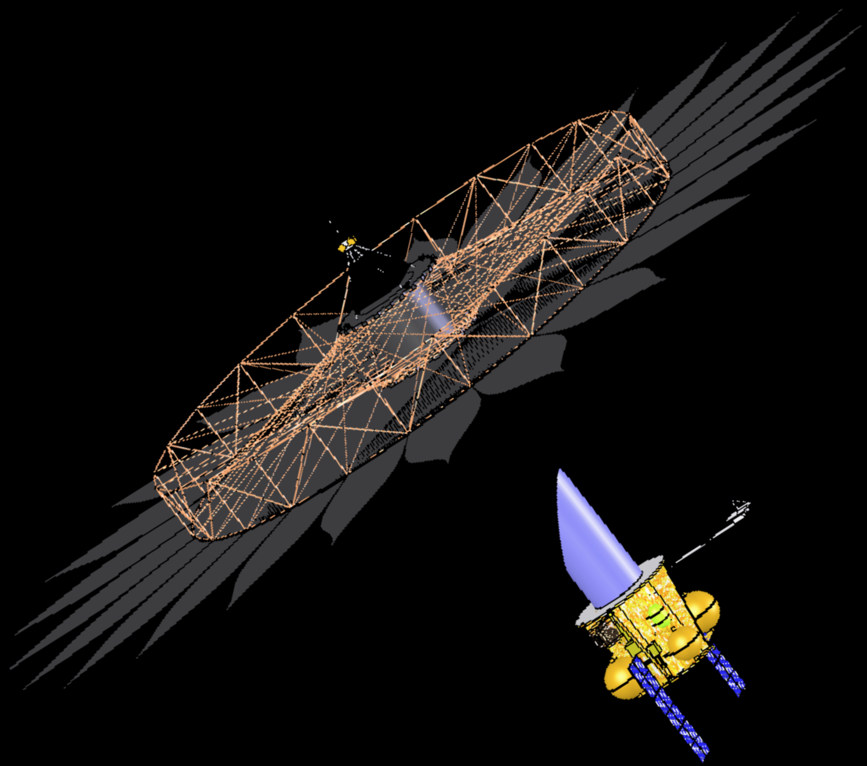
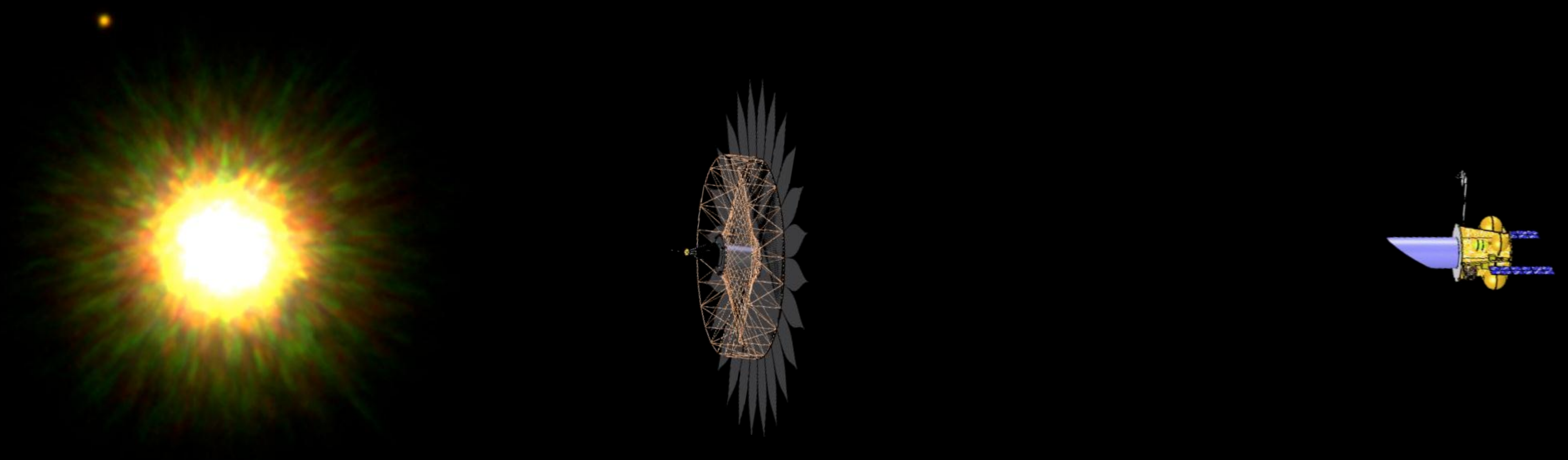
Starshade Technology Challenges



Diffraction Control

Formation Flying

Starshade principle of operation



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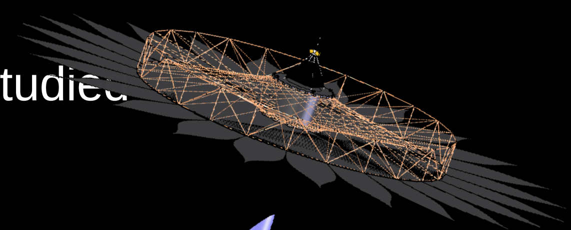
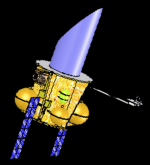
Diffraction control used to shade starlight from the telescope

- Occulter casts a deep shadow on the telescope
  - Starshade is several times larger in diameter than the telescope primary
  - Has a perimeter that diffracts starlight tangentially (thus the petals)
  - Is located far enough away to provide the required inner working angle
  - Formation flying is used to orient and position telescope wrt occulter
- The error budget is concerned only with the profile and orientation of the starshade with respect to the telescope – not the telescope itself
  - The error budget terms are measurable in fractions of millimeters, not fractions of nanometers
- Several different deployment strategies are being studied





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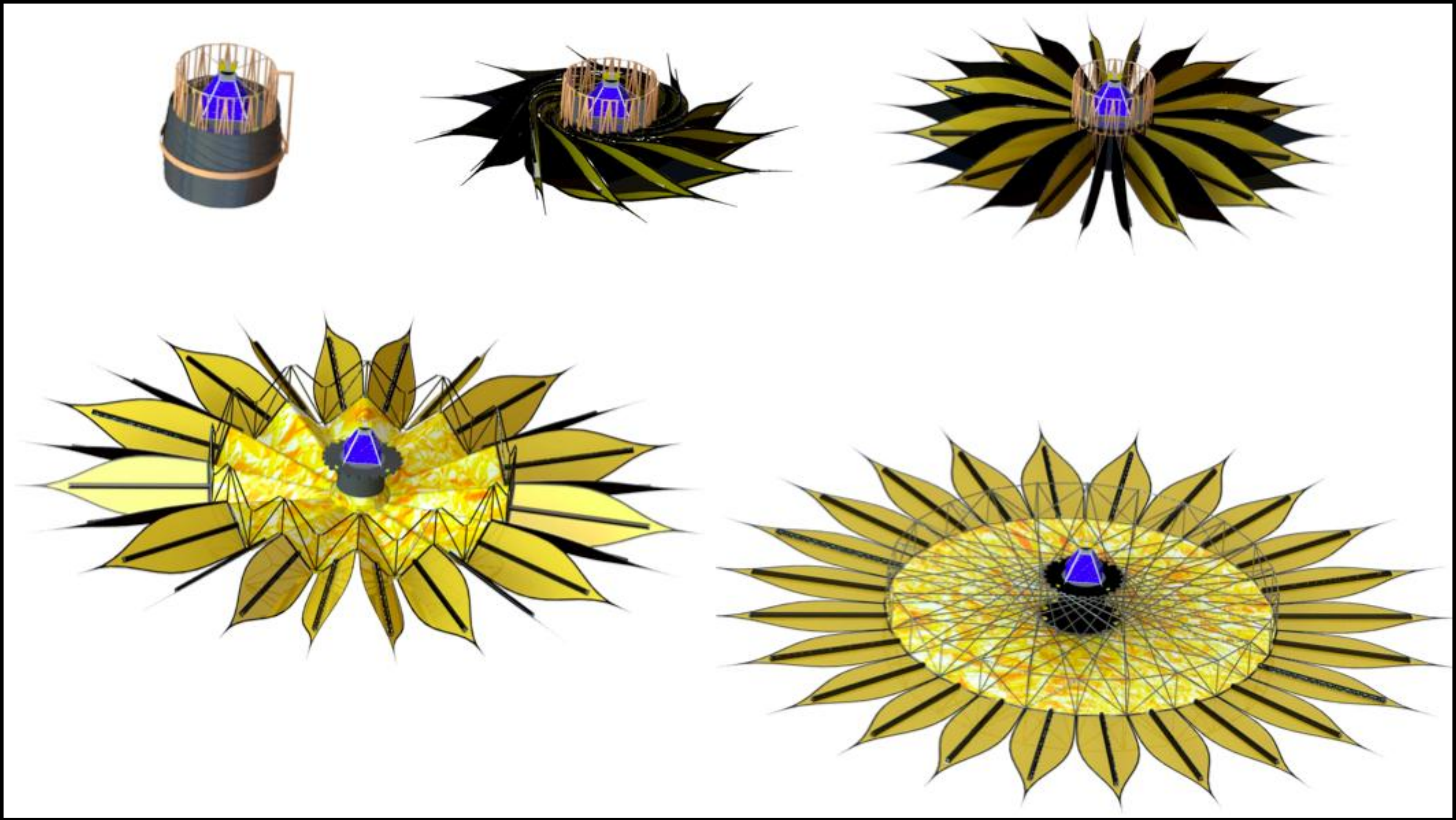
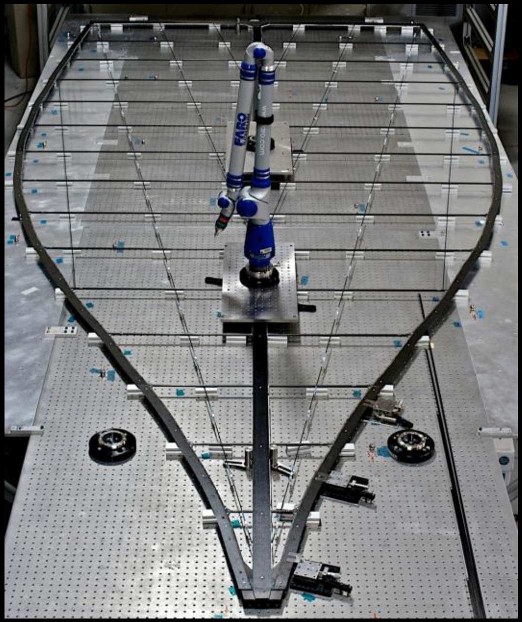
Deployment Concept for Starshade

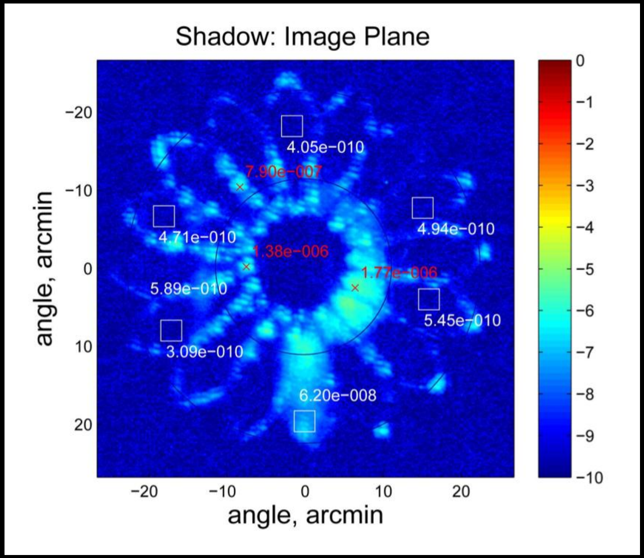


Starshade Development
N. J. Kasdin (Princeton University)

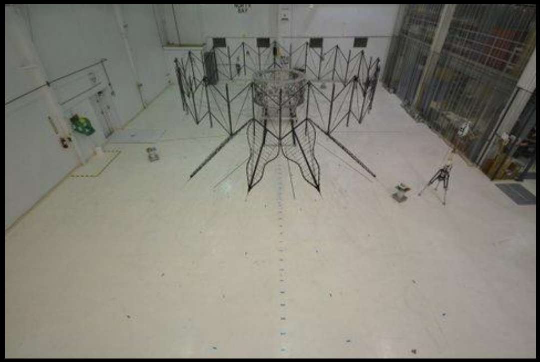


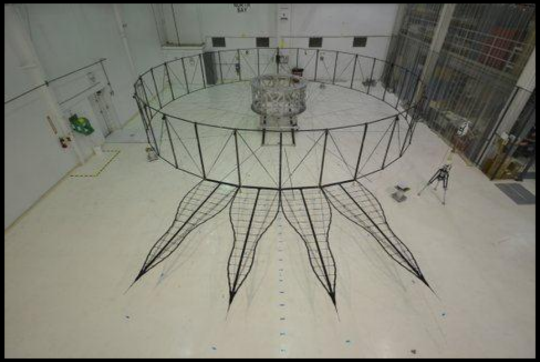
Precision edge Machining

Model validation

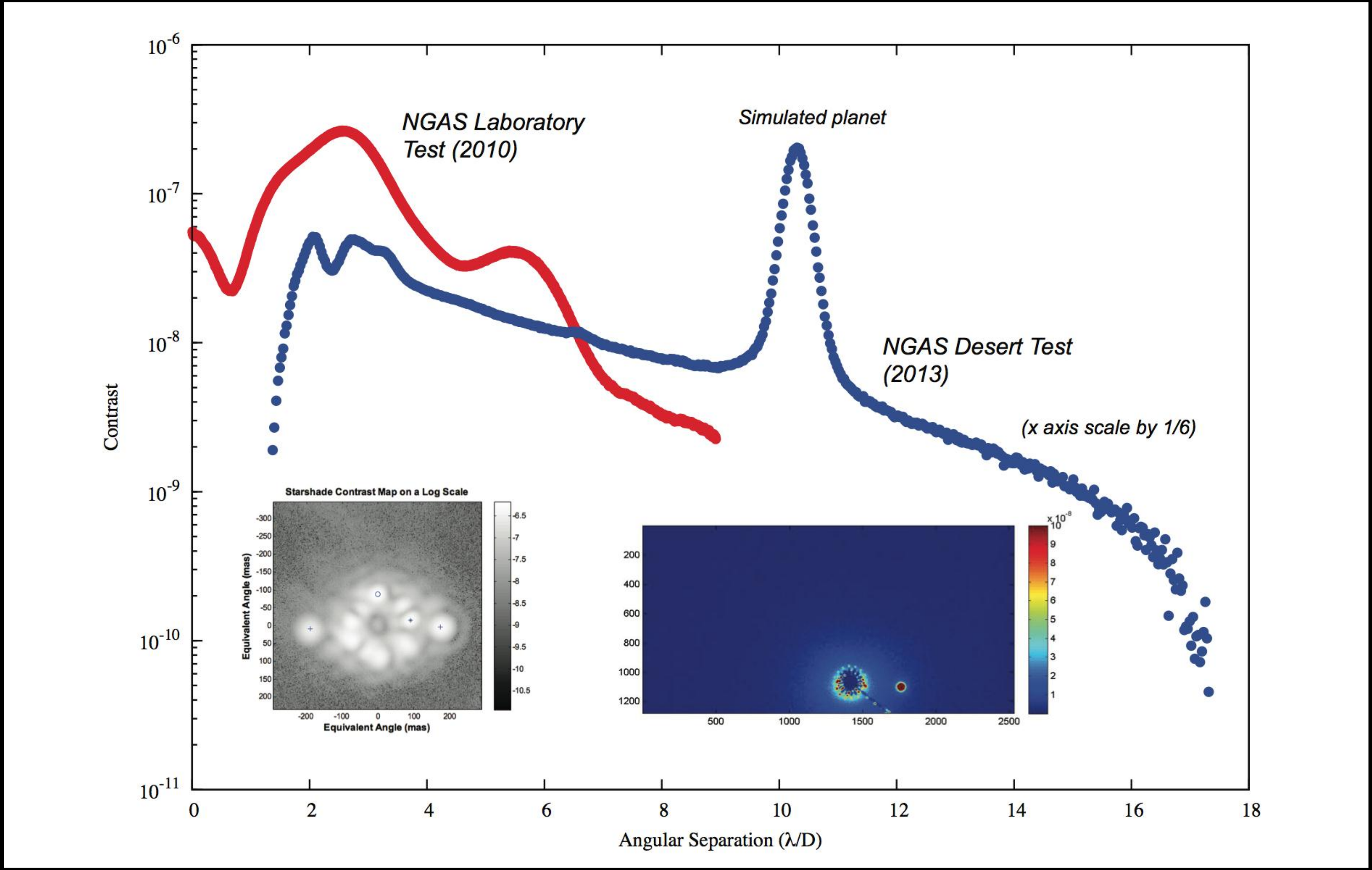


Starshade deployment demonstration





State-of-the-Art in Starshade Experiments with a 50% bandwidth



Summary and Perspective

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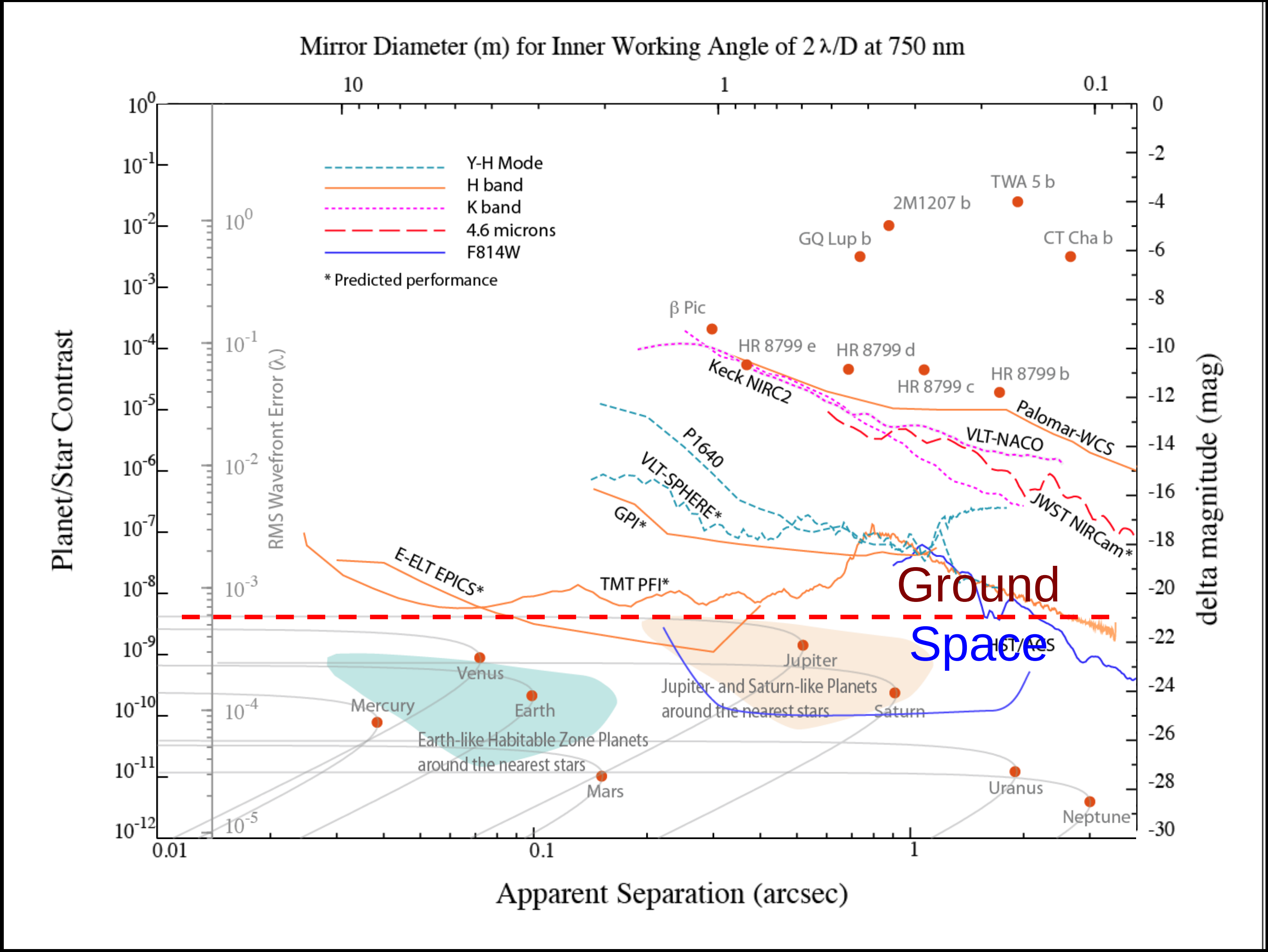
Discovery Space of a Flagship Mission



Further Reading

- W. A. Traub and B. R. Oppenheimer, “Direct Imaging of Exoplanets,” in Exoplanets, S. Seager ed. (University of Arizona Press: Tucson AZ, 2010)

- B. R. Oppenheimer and S. Hinkley, “High-contrast observations in optical and infrared astronomy,” Ann. Rev. Astron. Astrop. 47, 253–289 (2009).

- P. R. Lawson, ed. “Exoplanet Exploration Program Technology Plan Appendix: 2012,” Jet Propulsion Laboratory, JPL Doc 77698
  - http://exep.jpl.nasa.gov/technology/

Acknowledgements

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