Exoplanet Imaging Technology

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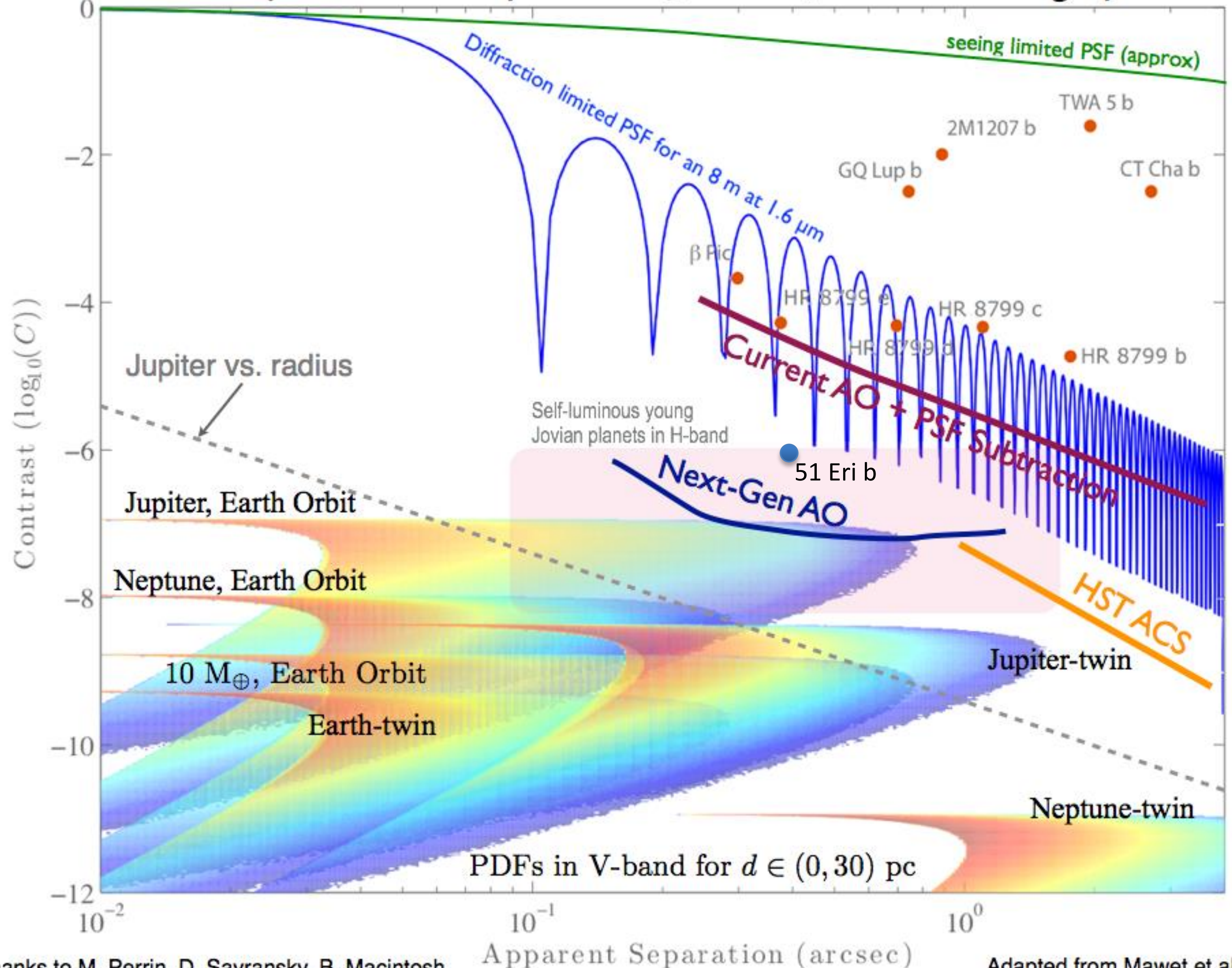
Dec. 13, 2015

Exoplanet Search Space with 3 lambda/D AFTA Coronagraph



Thanks to M. Perrin, D. Savransky, B. Macintosh

Adapted from Mawet et al. 2012

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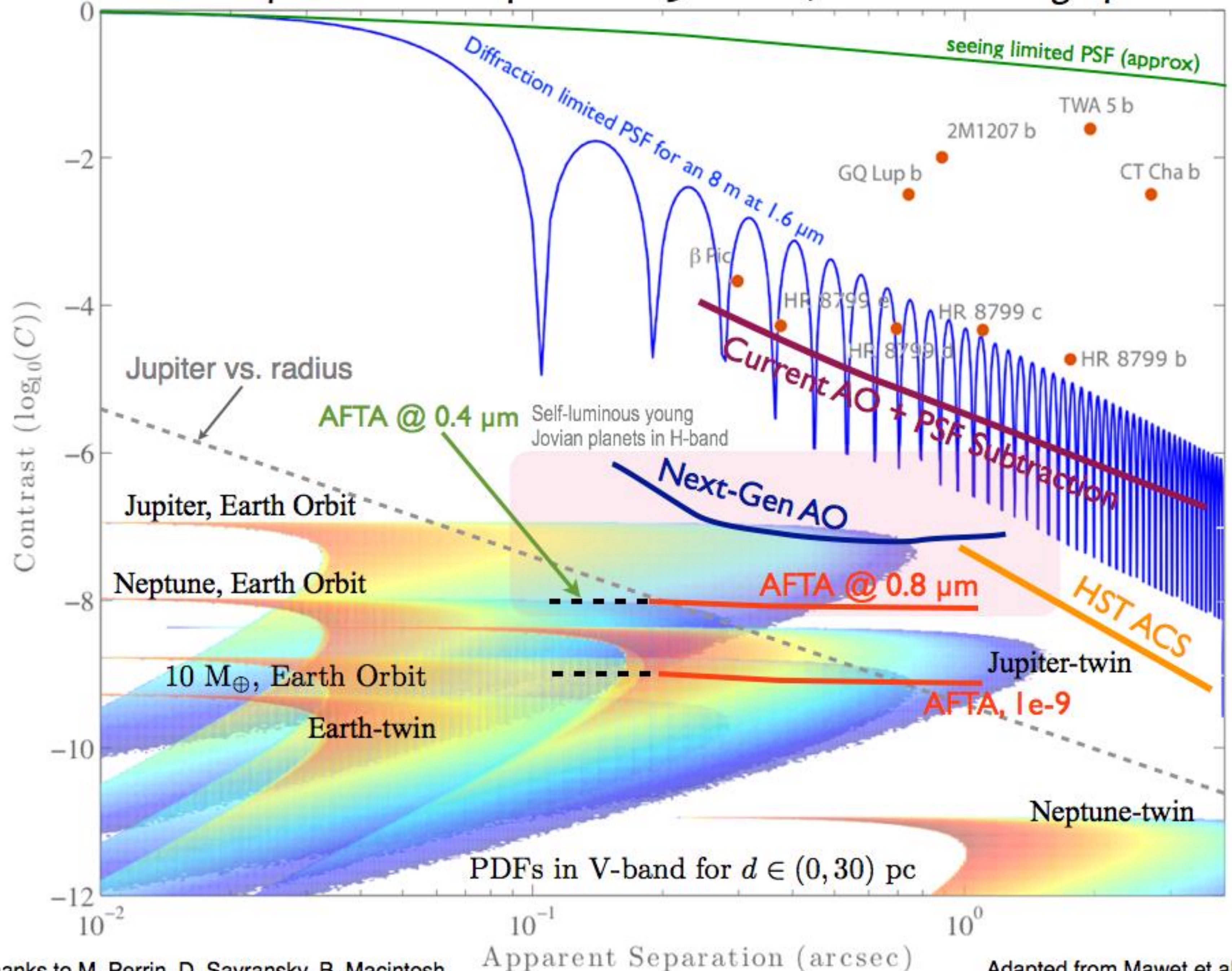

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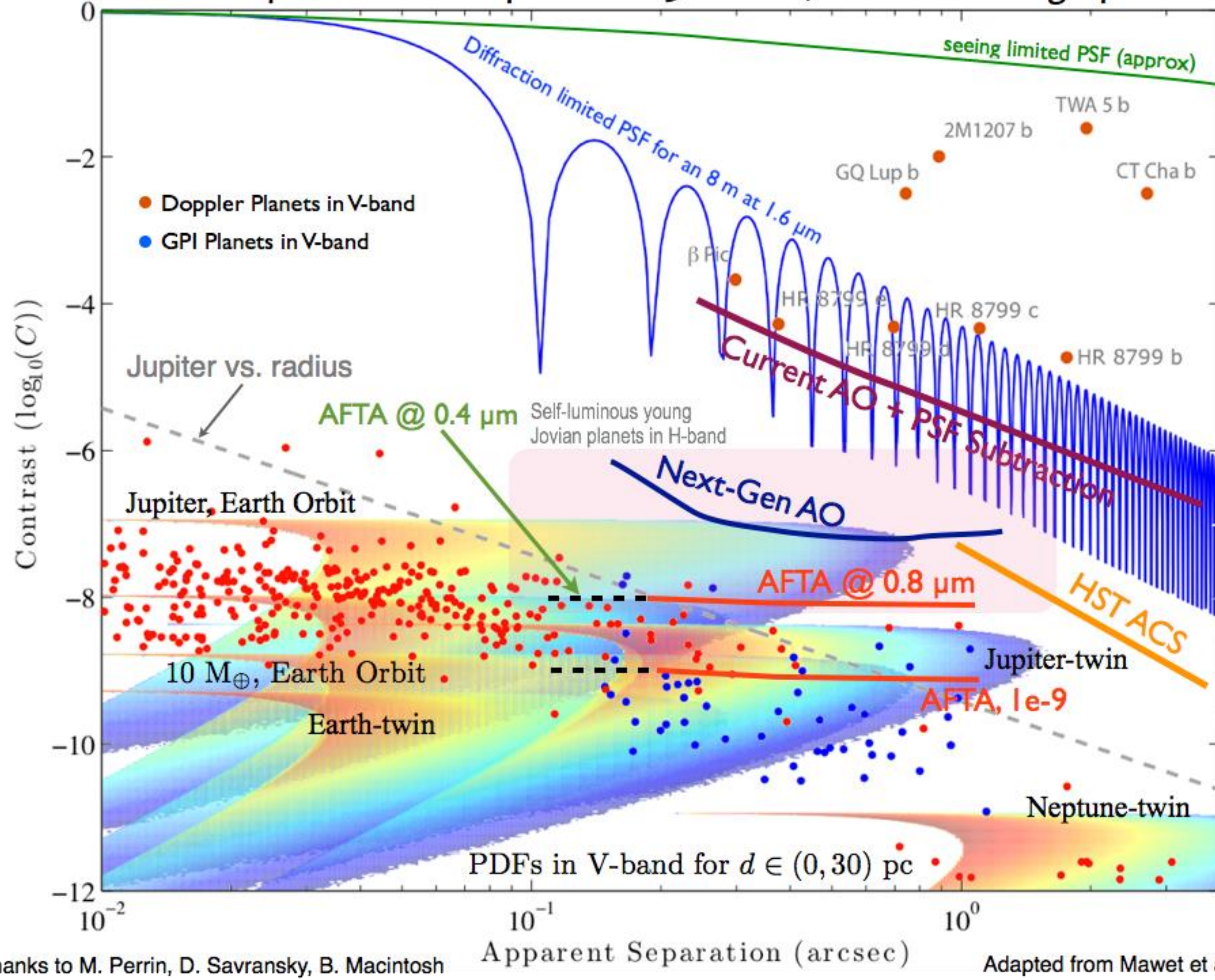

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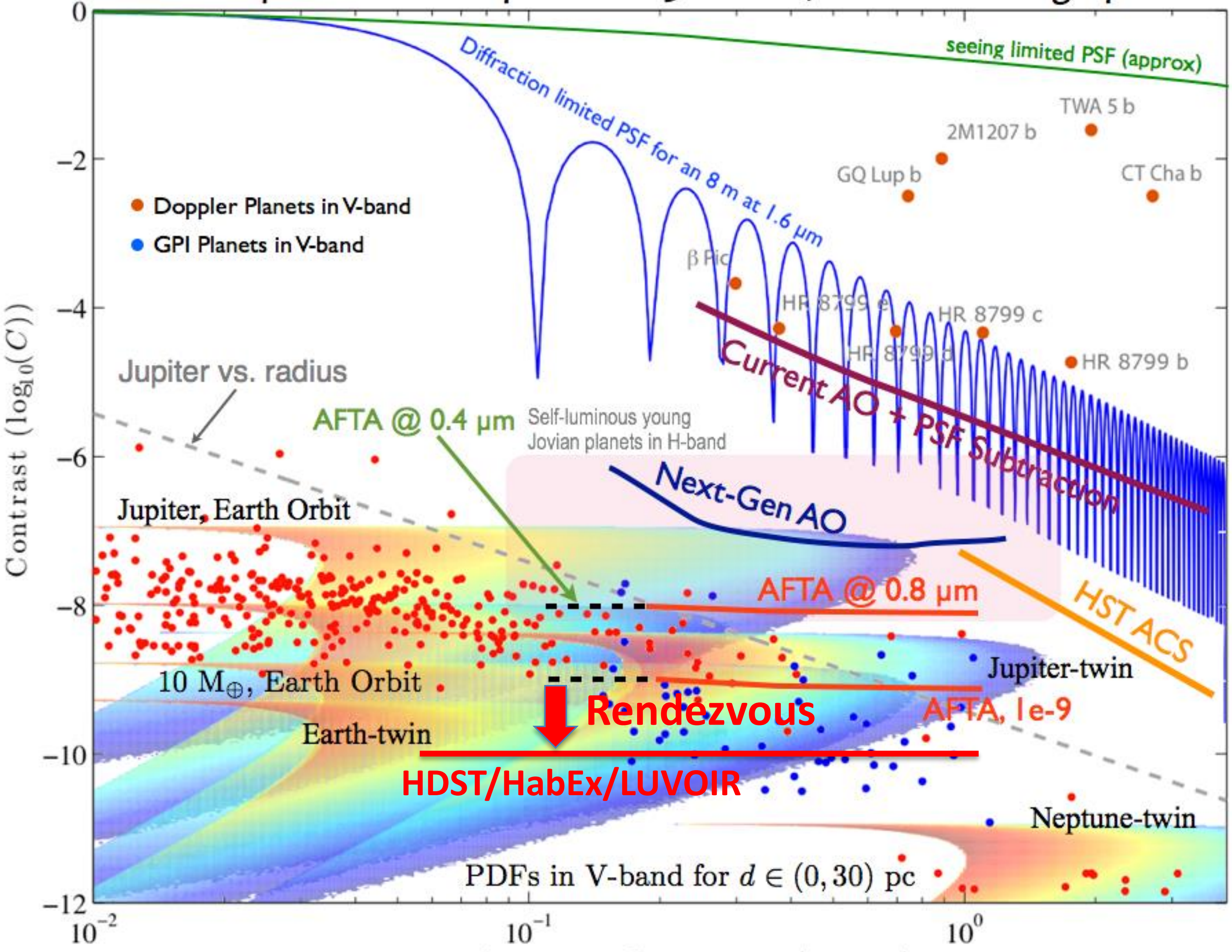

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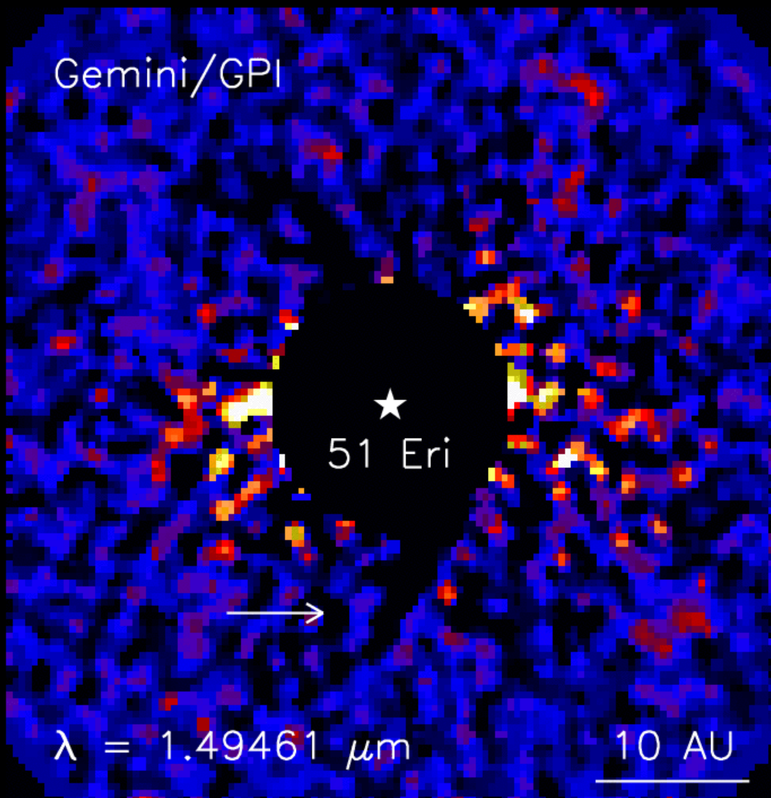
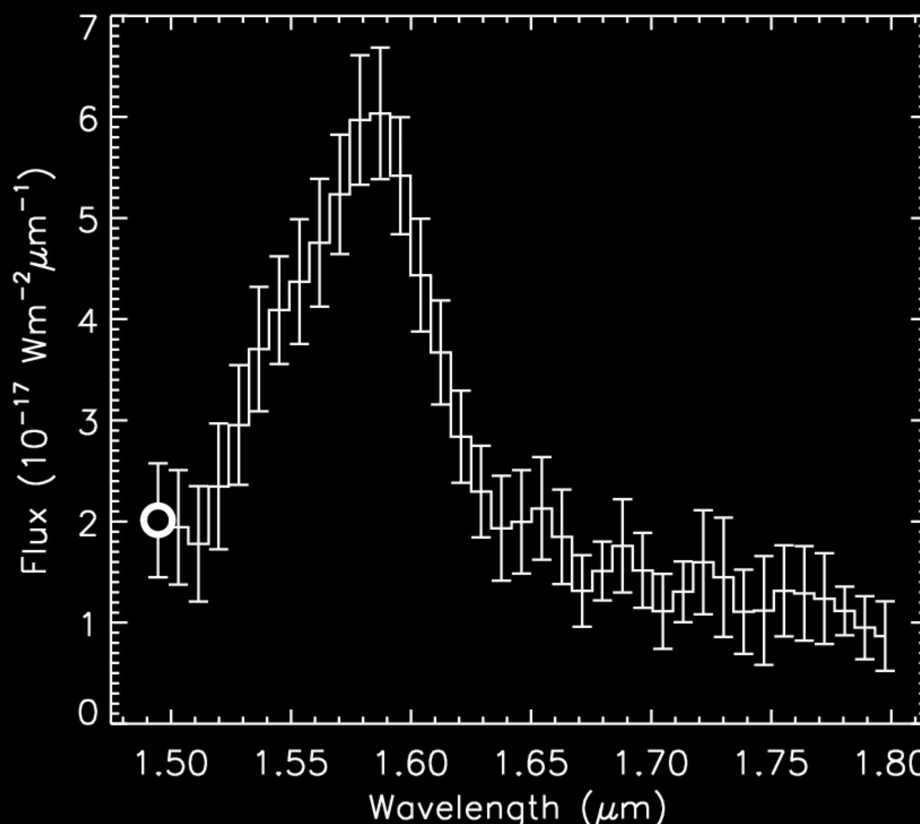
Direct Imaging from the Ground



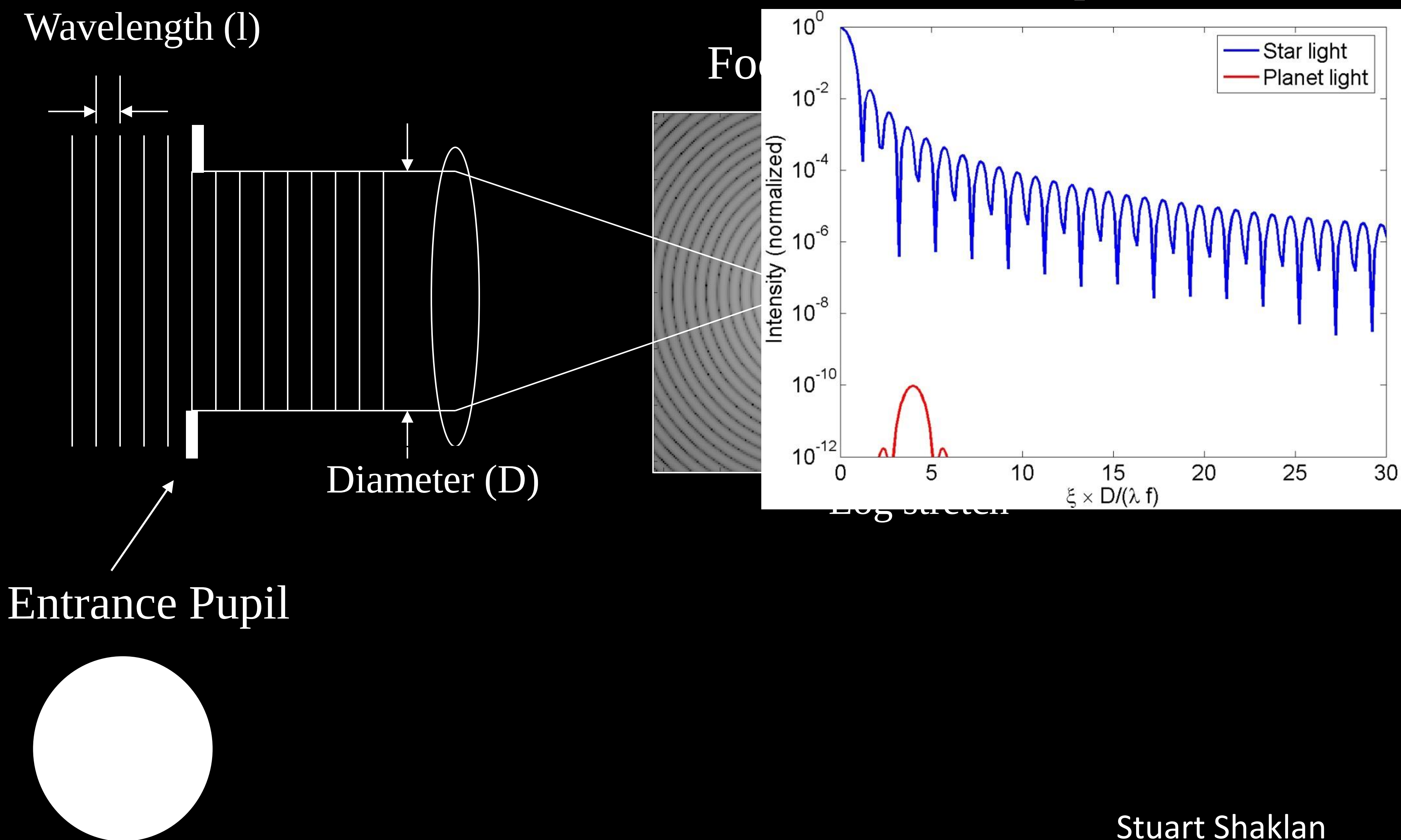


51#Eridani#b#

Bruce Macintosh

Diffraction and the Contrast Problem

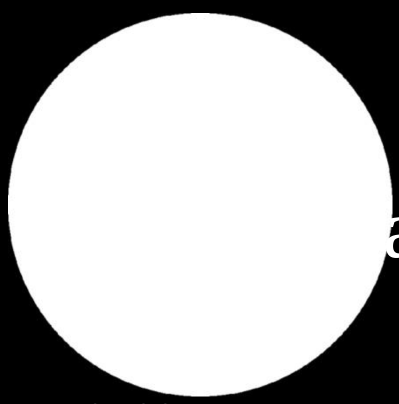
Unfortunately, the planet would be

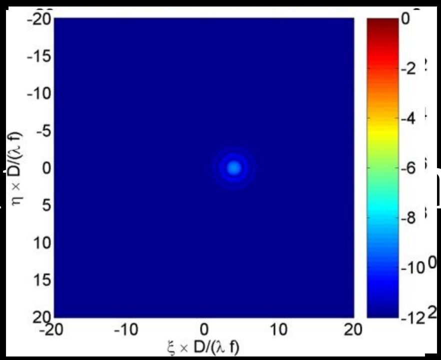


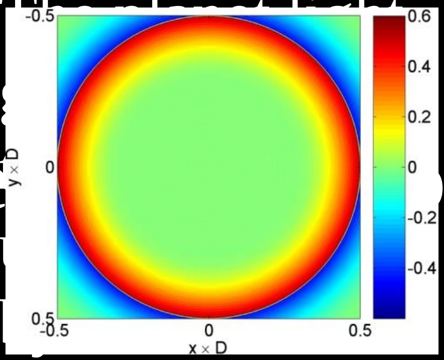
Stuart Shaklan

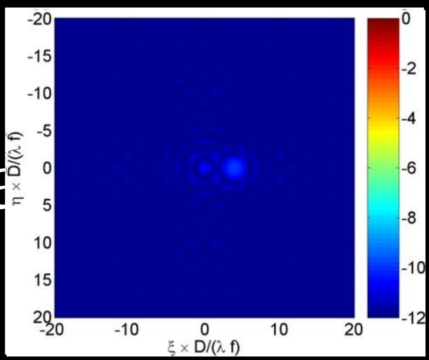
The Lyot Coronagraph

Entrance pupil	Occulter	Lyot stop	Image plane

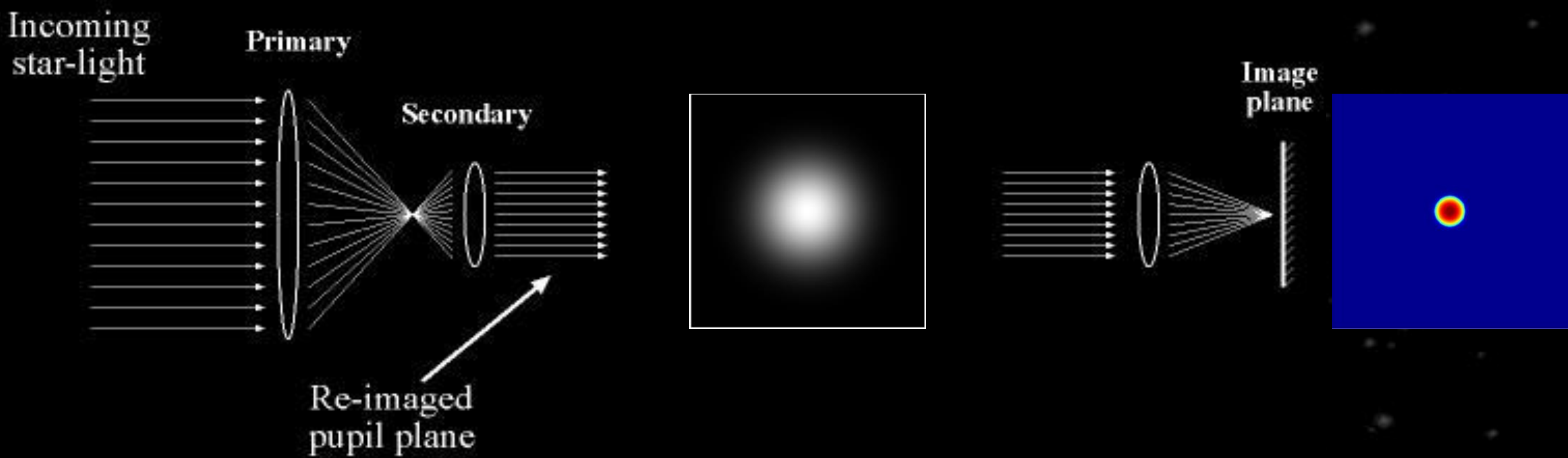








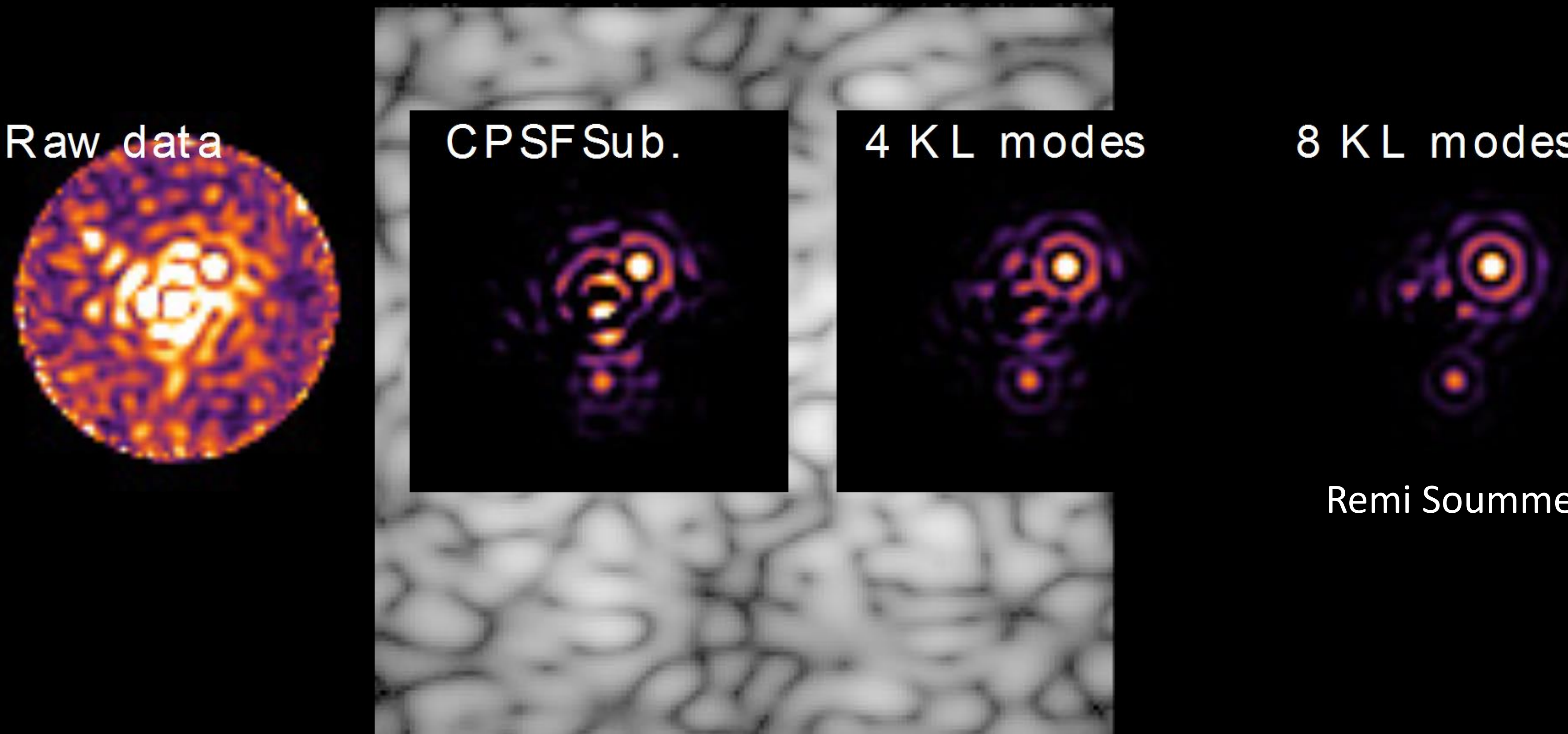
The Apodized Pupil Coronagraph



Stuart Shaklan

Wavefront Error

What's left over
After removing diffraction

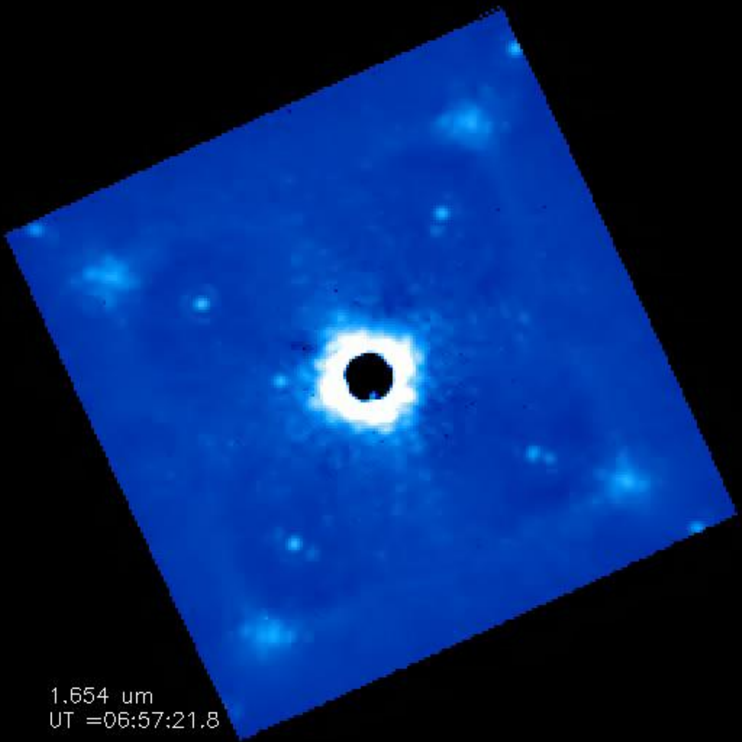


Remi Soummer

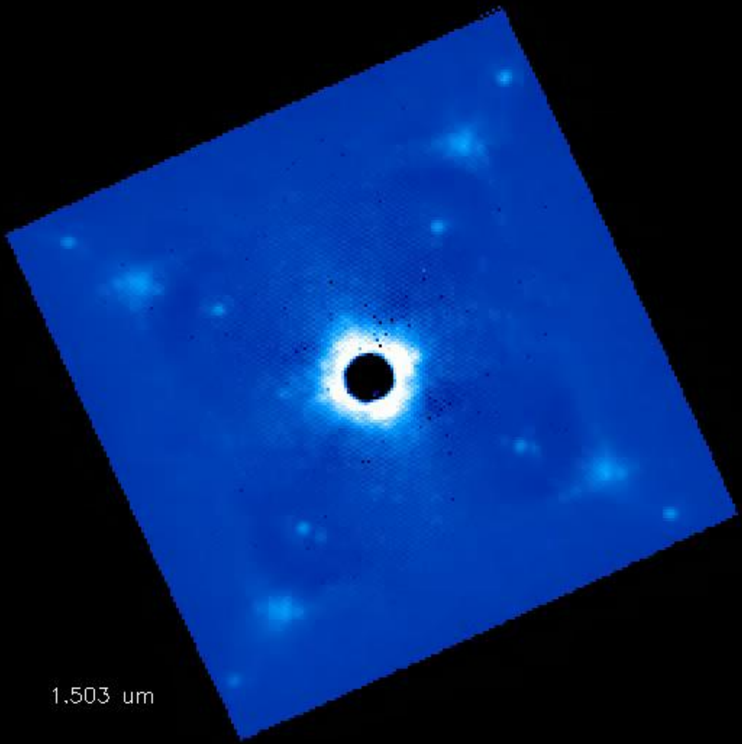
All coronagraphs share a sensitivity to wavefront error and require wavefront control and PSF subtraction

Stuart Shaklan

GPI Image of Beta Pictoris b after Wavefront Control and ADI



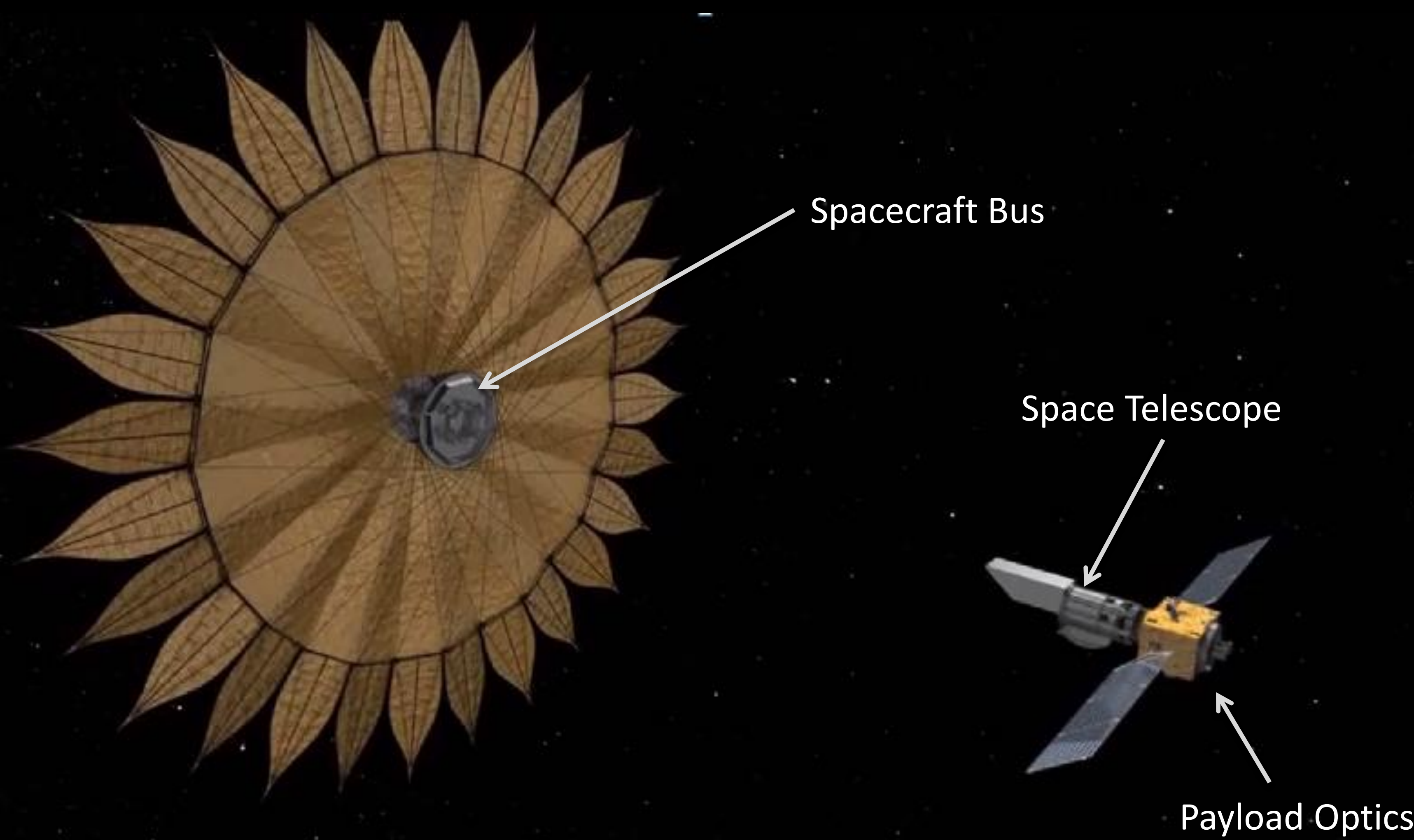
1.654 um
UT =06:57:21.8



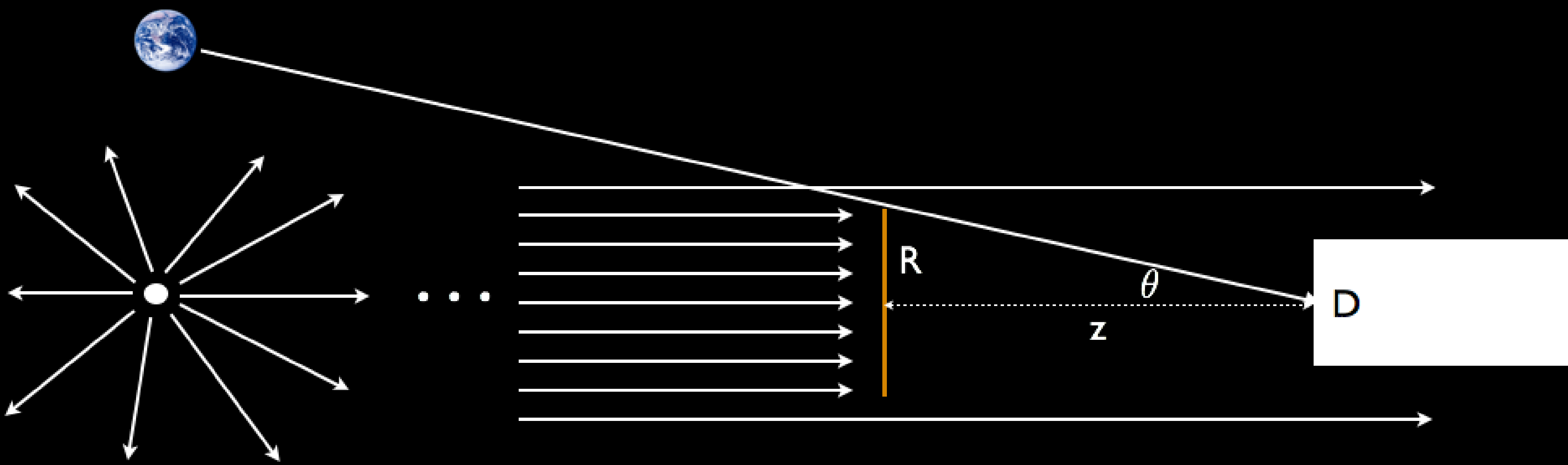
1.503 um

Bruce Macintosh

High-Contrast Imaging with a Starshade



Simple Ray Optics Description

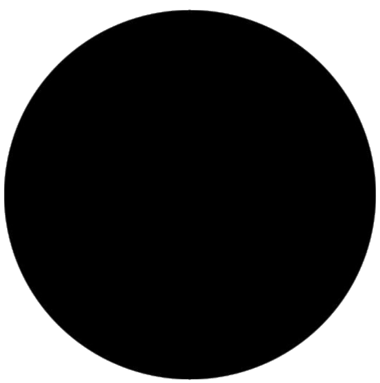


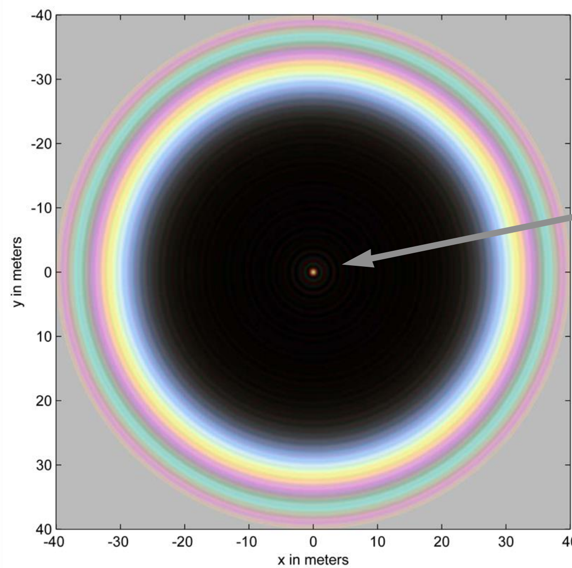
For D = 4 m, R = 3 m, and IWA = 75 mas,
z ~ 10,000 km

This demonstrates the fundamental size and distance scale for the starshade.

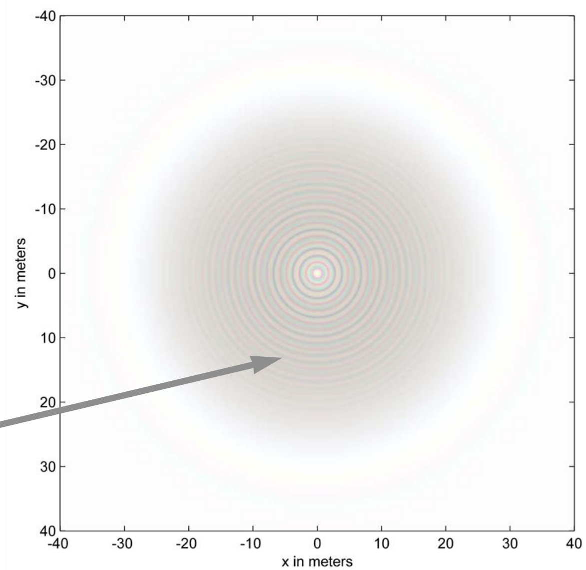
Plain External Occulter (Doesn't Work!)

Circular Occulter

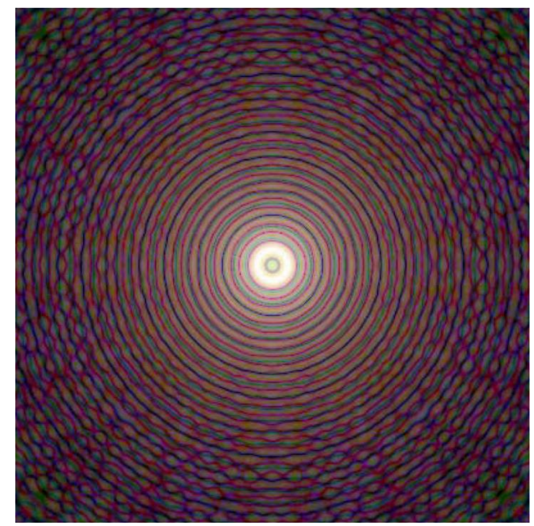




Poisson's Spot!

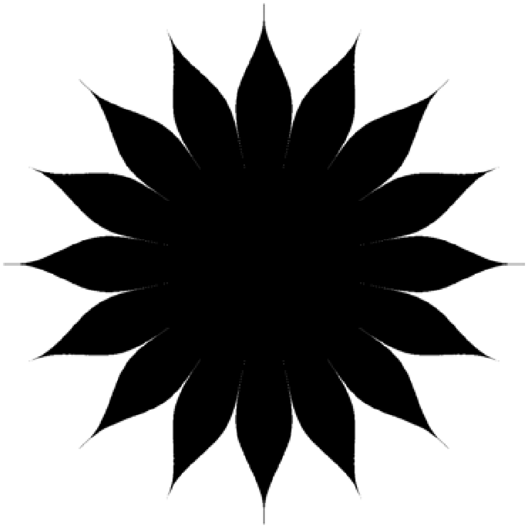


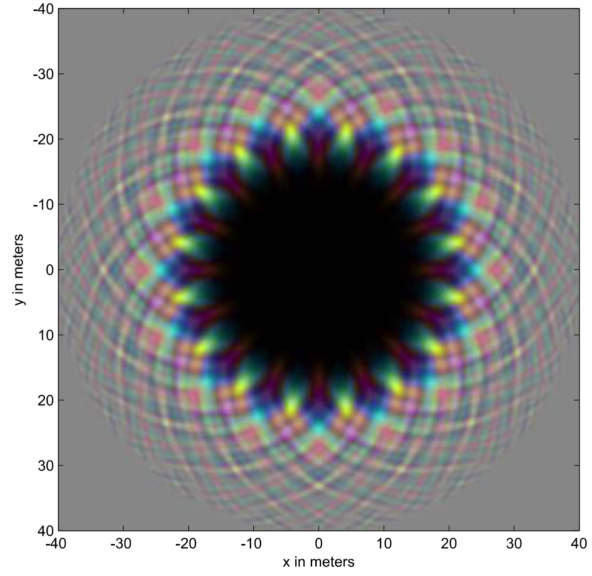
Shadow isn't dark enough

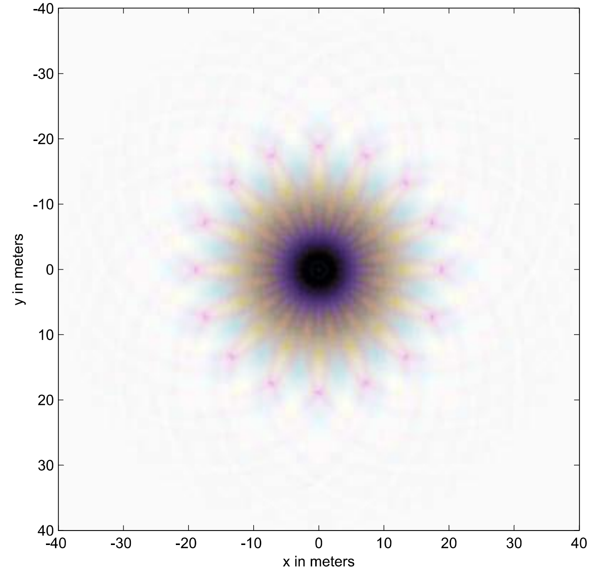


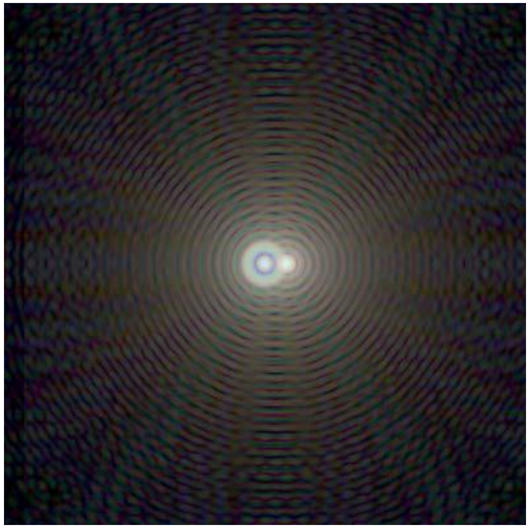
Simulated star/planet image

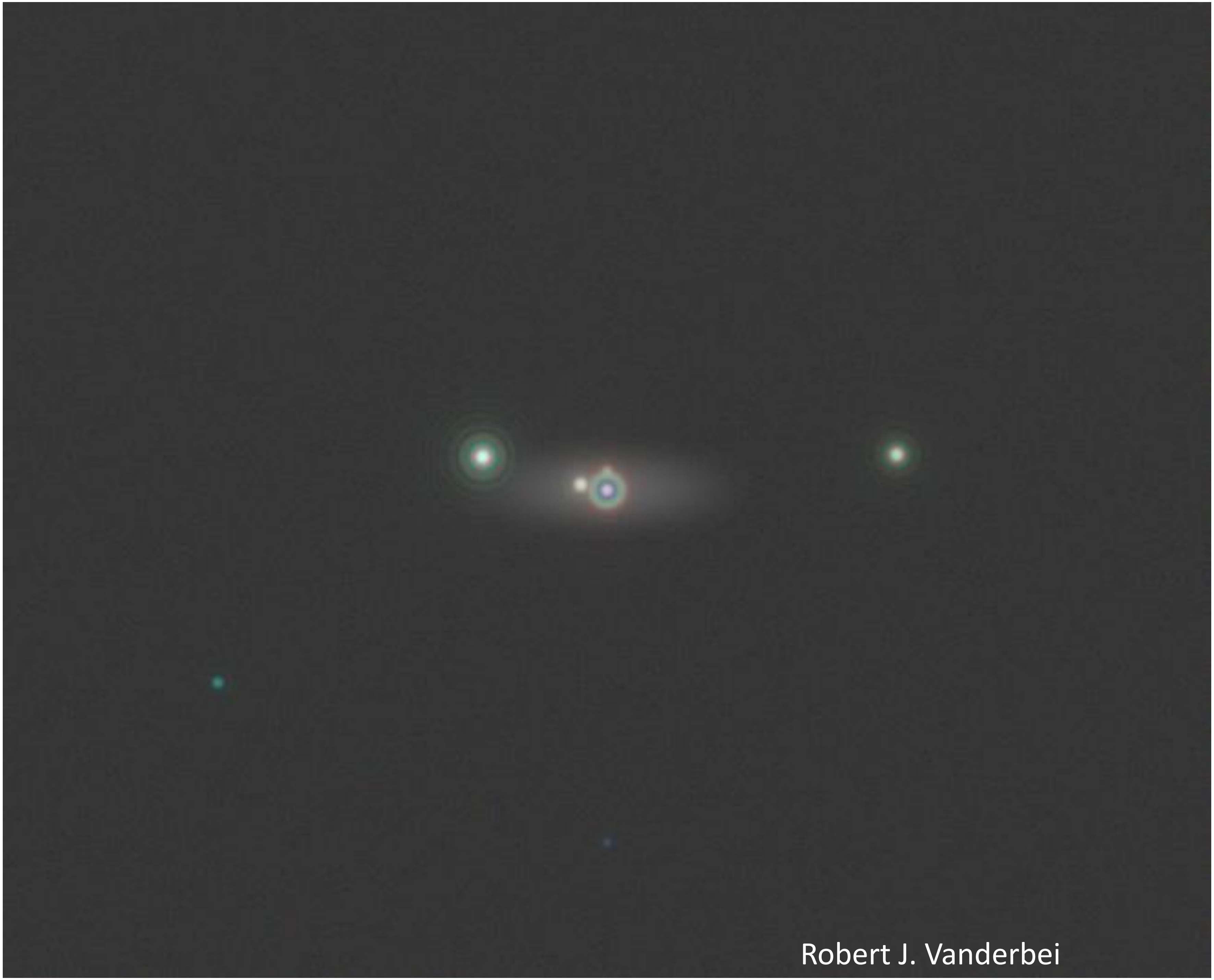
Shaped Occulter











Robert J. Vanderbei

Questions from committee:

- Please report on the status of technology development for exoplanet science.
- With current knowledge, how do coronagraphs and starshades compare and how could they be used in plausible future missions?
- Is the Astro2010 recommendation for a downselect practical or sensible right now?
- Does the WFIRST/AFTA coronagraph make sense as part of a technology development path?
- Will development of other technologies continue to be healthy if the WFIRST/AFTA coronagraph goes forward?

ASTRO 2010

Vision:

"Astronomers are now ready to embark on the next stage in the quest for life beyond the solar system–to search for nearby, habitable, rocky or terrestrial planets with liquid water and oxygen."

Getting There:

"The committee identified a number of high-priority science areas for which mid-term investments are needed beginning early in the decade, including . . . coronagraphs, interferometers, and starshades, leading to a possible late-decade down-selecting."

- Strong funding has been made in critical technologies early in the decade resulting in significant progress on both coronagraphs and starshades (see Paul Hertz presentation)

- The Coronagraph Instrument (CGI) on WFIRST-AFTA represents the most significant and valuable investment NASA can make to mature coronagraph technology for future missions, satisfying the top medium recommendation.

- Modest (<$10M) investment in starshade technology can bring it to TRL 5, or beyond, by the end of the decade. A potential rendezvous mission with WFIRST has enormous potential for both science and technology advancement, and for reducing future risk.

- Continued investments in coronagraphs for future large missions is essential.

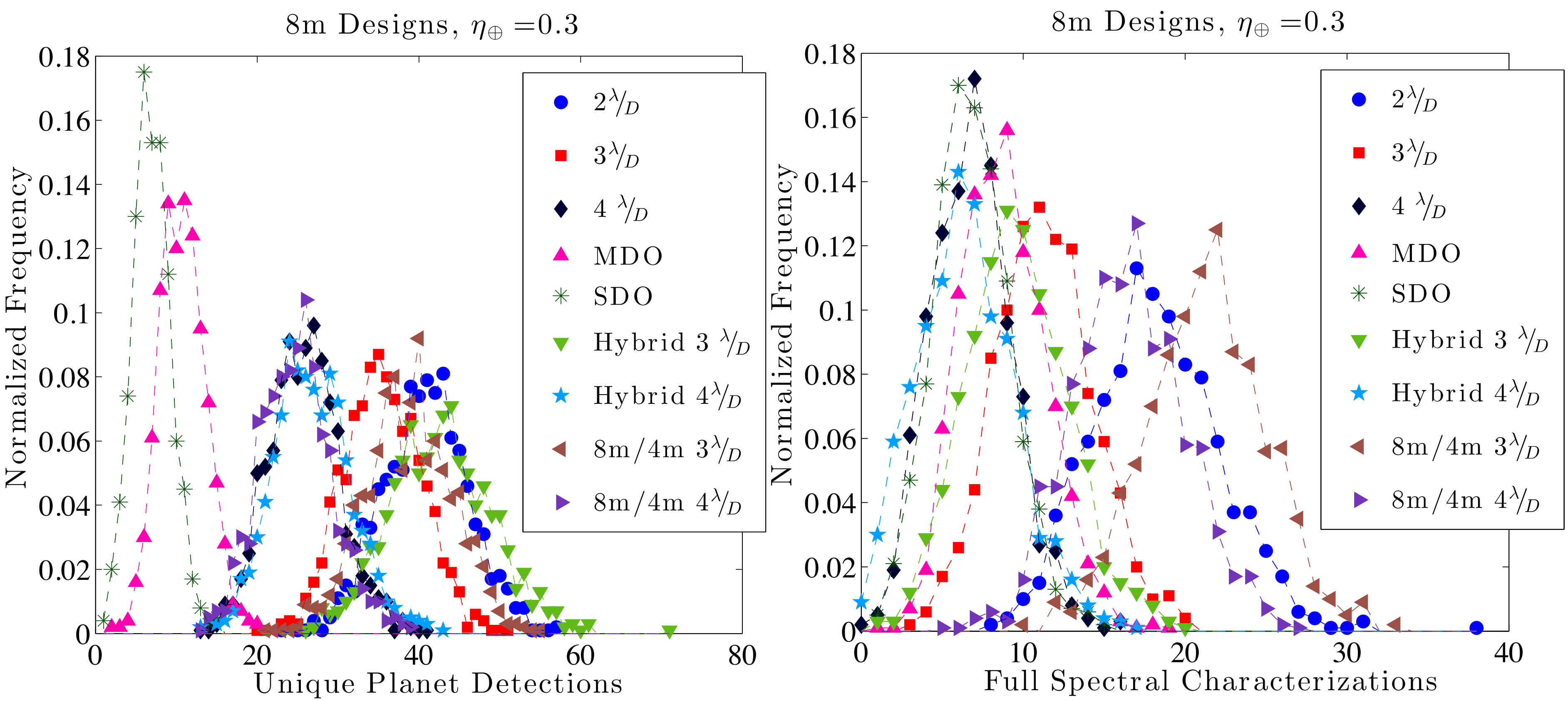
What about a "technology downselect"?

- A choice between starshades and coronagraphs is very mission specific.
- Choosing among coronagraph types is also mission specific, dependent on architecture of telescope and science goals.
- It is premature to make a downselect decision now for a future mission. We have downselected technology for WFIRST and are investing heavily to make it flight ready.
- NASA is poised to increase investments in starshades to raise to TRL 5 or 6.
- A rendezvous mission will both provide unique science early (with potential Earth detection) as well as support starshade technology development.
- The upcoming STDTs will help clarify future mission options and corresponding trade-offs among technology options.
- Continued technology development (particularly for large segmented apertures) will inform eventual decisions for a future mission

Do we have to downselect between starshades and coronagraphs at all?

A hybrid mission including both should be a strong candidate for study by the STDTs. May be most efficient at maximizing science as well as least risky.

For example (from my 2012 talk to the ExoPAG):



Plots courtesy of Dmitry Savransky

These sorts of full mission simulations are still in their infancy, but there is a growing number of approaches (Savransky 2010, Stark 2014, Stark 2015, Turnbull 2012).

Further work is critical for successful future mission design and technology decisions.

Technology Status Overview

Key Coronagraph Technology

Coronagraph Design, Masks and Hardware (varies by type)

– Shaped Pupil (SP), SPLC, Hybrid Lyot, APLC, Vector Vortex, PIAA, PIAA/CMC, 4QPM
– Large central obstruction, spiders, segmented mirrors

Wavefront Estimation and Control (common to all)

Probes and Field estimation, Control Algorithms (EFC & Stroke Minimization), Deformable Mirrors, Broadband control (with and without IFS), Low-Order Wavefront Sensing and Control (LOWFSC)

Data Analysis and Planet Identification

PFS Subtraction (LOCI, ADI, KLIP), IFS data cube, Spectral Characterization

Mission Modeling and DRMs

Engineering and Instrumentation

Optical design, polarization, IFS, calibration and test, operations

Error Analysis

Polarization, finite stellar size, stability, thermal bending (low-order aberrations)

Does the WFIRST/AFTA coronagraph make sense as part of a technology development path?

Coronagraph Design, Masks and Hardware (varies by type)

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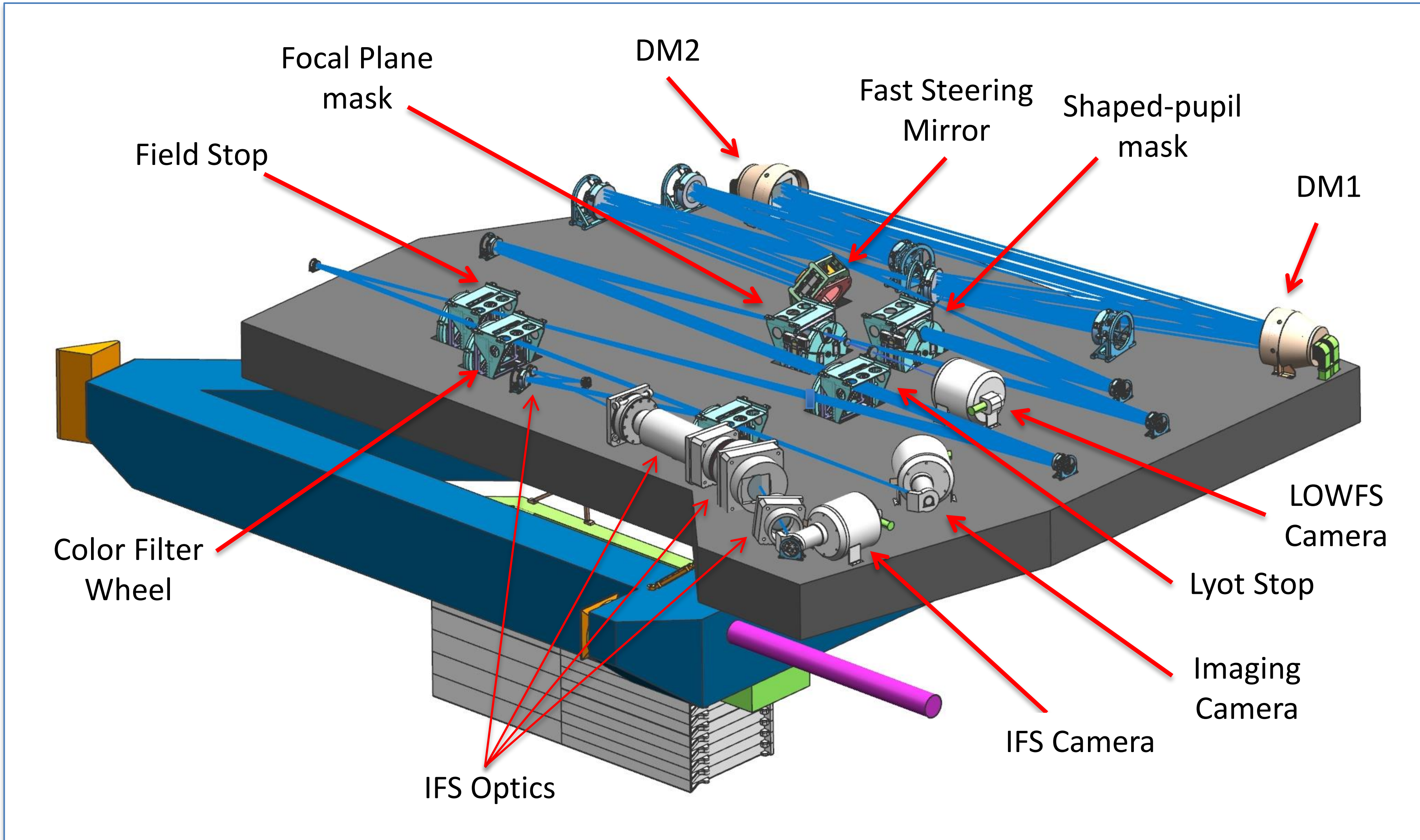
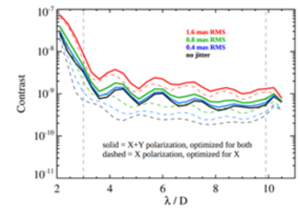
Coronagraph Technology Status

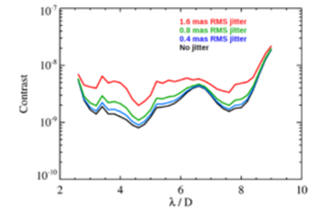
The most significant developments have occurred in the CGI project for WFIRST



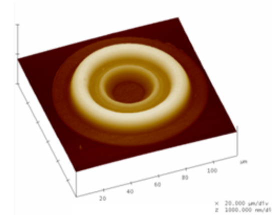
Technology Development Sequence

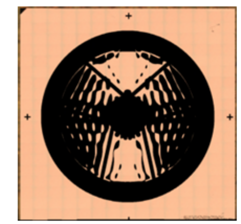
Coronagraph Designs Work with AFTA Telescope "as is" (Computer Model)



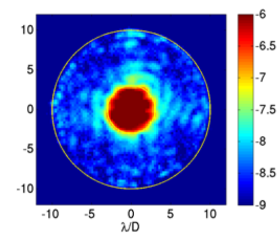


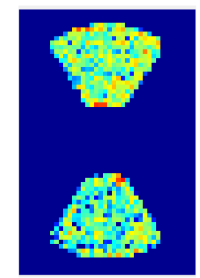
Demonstrate Fabrication of Key Starlight Suppression Components





Demonstrate Starlight Suppression in Narrowband Light

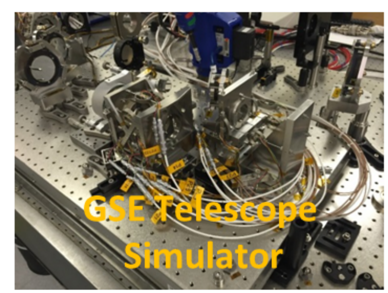




in progress

Demonstrate Starlight Suppression in Broadband Light

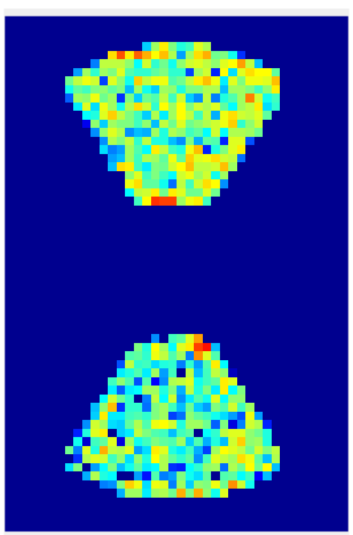
Demonstrate Starlight Suppression in Broadband Light, with Simulated Jitter and Drift from "as-is" Telescope

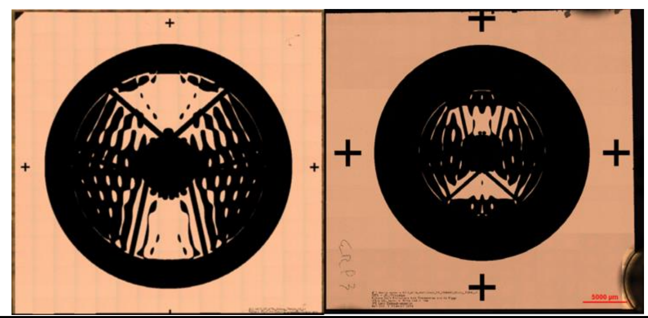


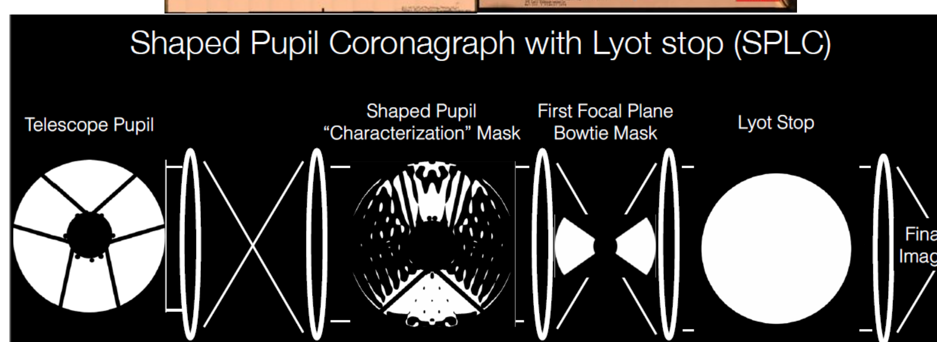
Ilya Proberezhskiy

Shaped Pupil Coronagraph Status

- Mastered making reflective shaped pupil masks at JPL (Bala)
- Milestone 2 result from fall 2014:
  - 6×10^{-9} narrowband contrast across a 4.4-11 λ/D
  - SPC Gen 1, 1 DM -> 1-sided wedge-shaped dark hole
- Since then, adopted Princeton's Gen 2 design w/ Lyot stop (SPLC)
  - Increased throughput, decreased IWA to 2.8 λ/D
  - Added 2nd DM for double-sided dark hole



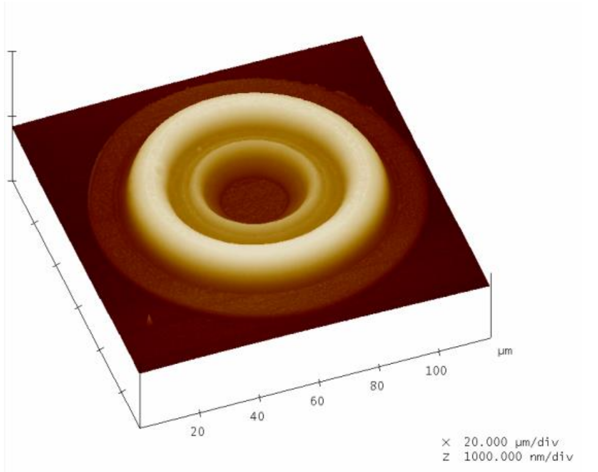


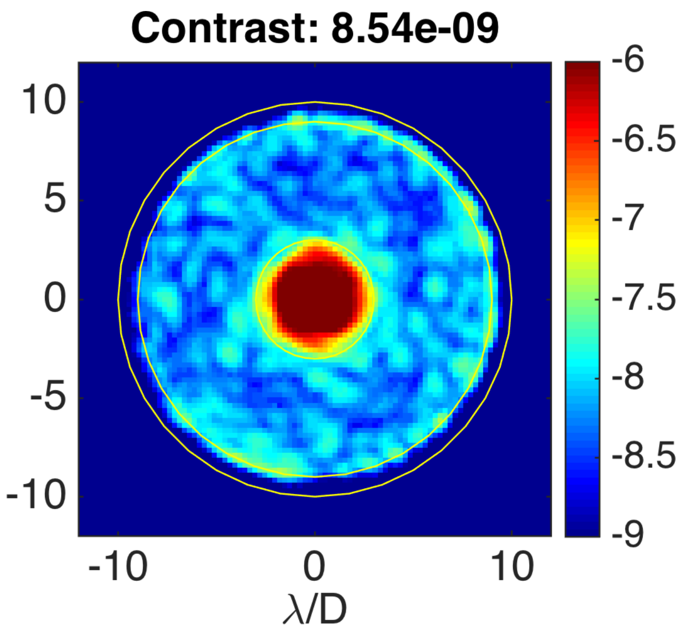


Ilya Proberezhskiy

Hybrid Lyot Coronagraph Status

- Making circular HLC occulters
- Milestone #4 passed TAC review on 3/13/2015
- Demonstrated ~7×10^{-9} contrast with AFTA pupil, 2 DMs, 360 deg dark hole, 3-9 lambda/D, narrowband
- Performing 10% broadband nulling toward Milestone #5 due 9/15/2015
- Mask dielectric radiation testing

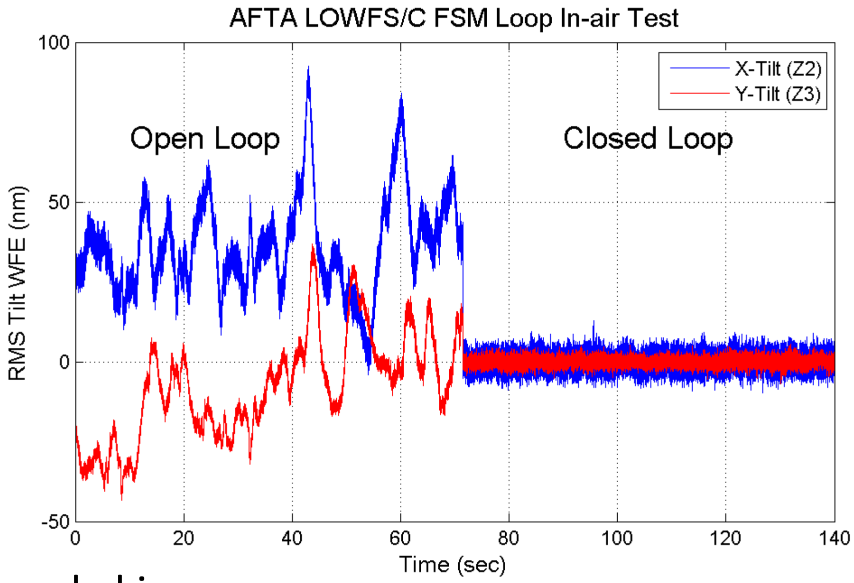


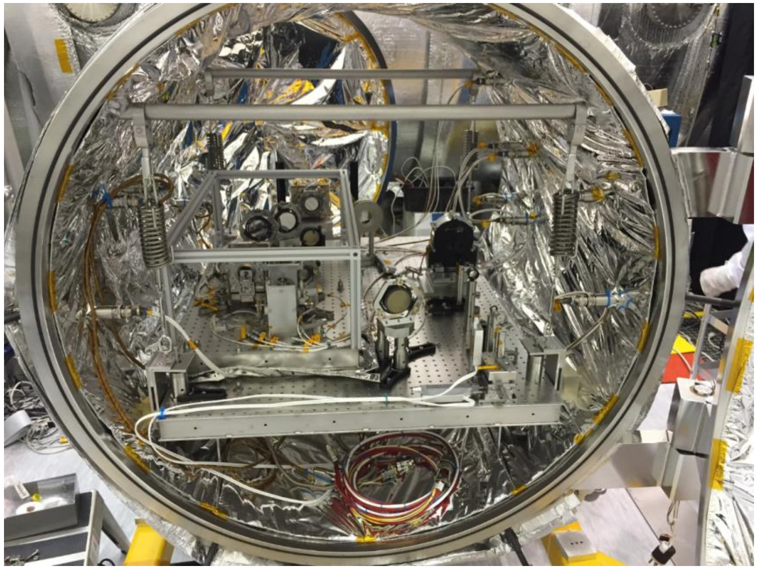


Ilya Proberezhskiy

LOWFS/C Status

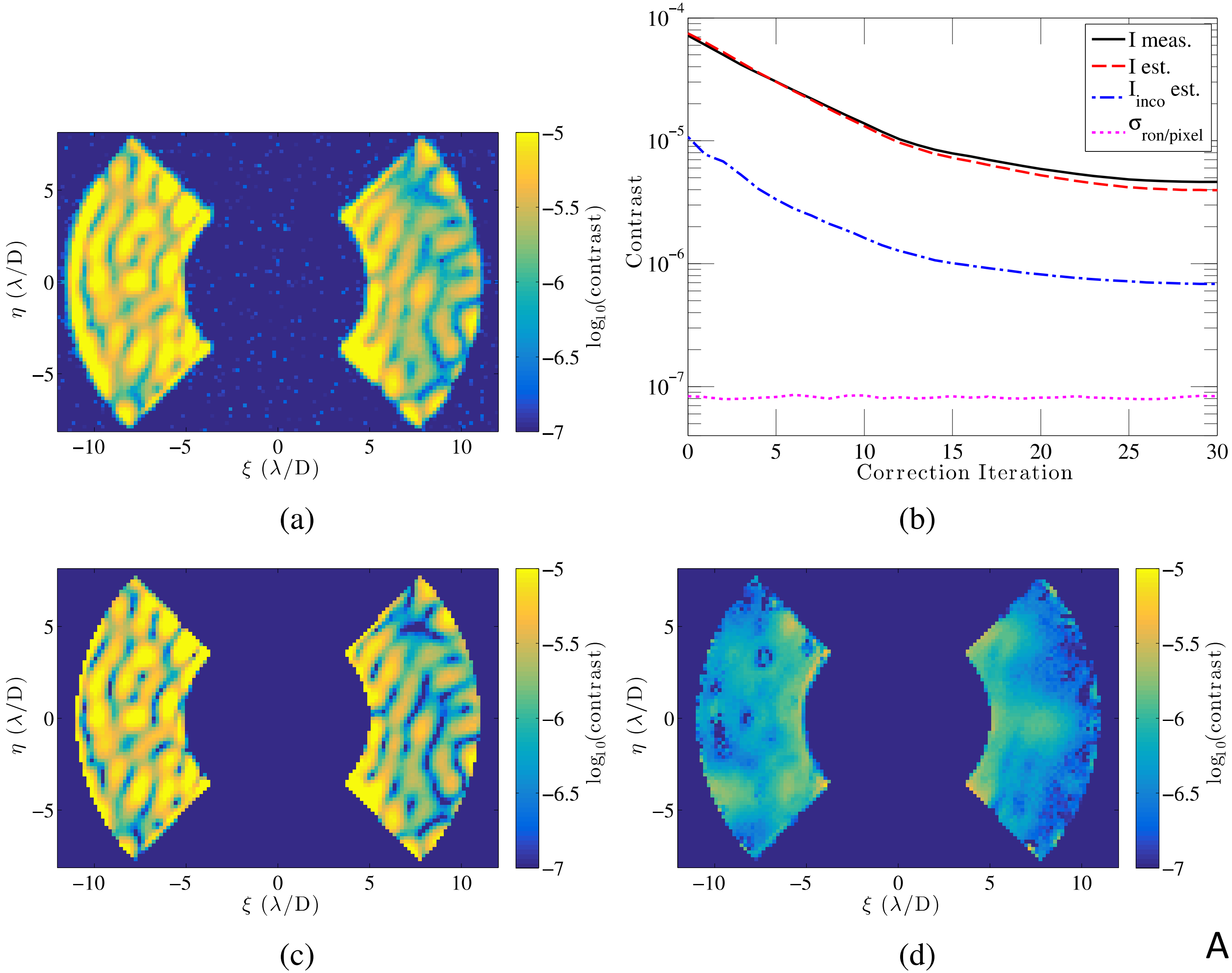
- Selected Zernike WFS after extensive performance modeling, tolerancing
  - Uses rejected starlight reflected by HLC and SPC coronagraph occulters
- Designed, built, aligned and calibrated LOWFS/C testbed (OTA simulator + LOWFS/C hardware)
  - Inject and then correct fast pointing error, slow wavefront errors up to Z11
- Demonstrated sensing functionality in air (seeing limited), closed loop tip/tilt control in air
- Started LOWFS/C characterization in vacuum toward Milestone 6





Ilya Poberezhskiy

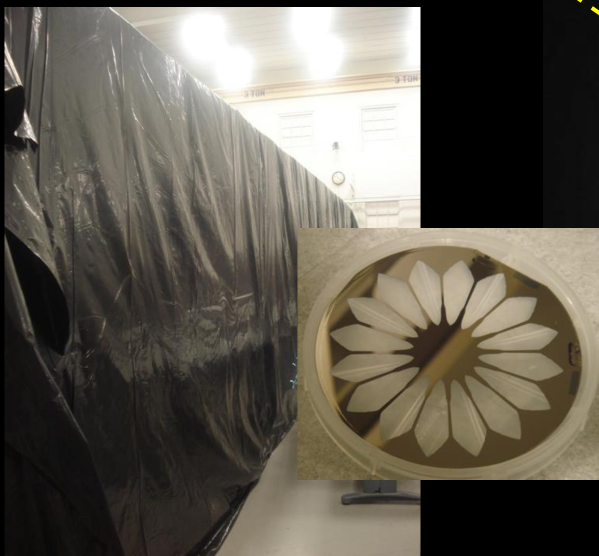
Princeton Result with Injected Planet

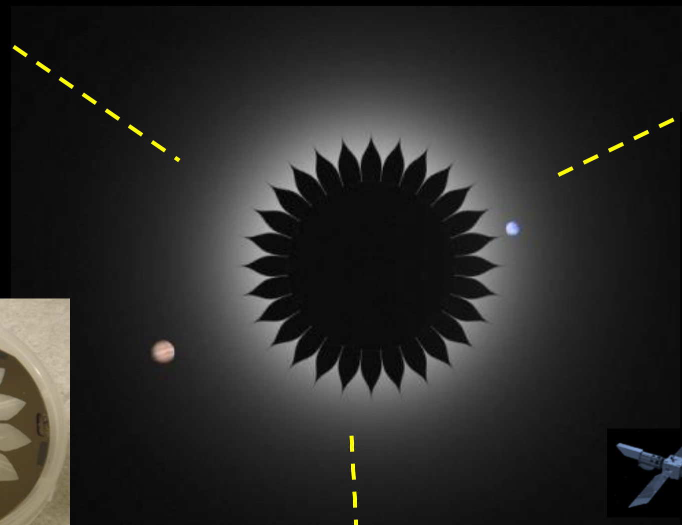


A J Riggs

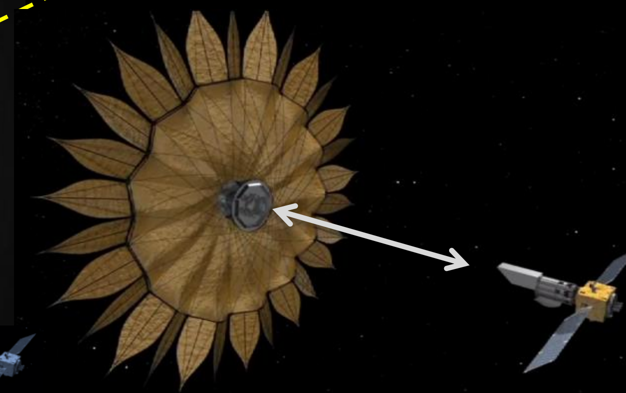
Starshade Technology Status

Diffraction and Scattered Light Control

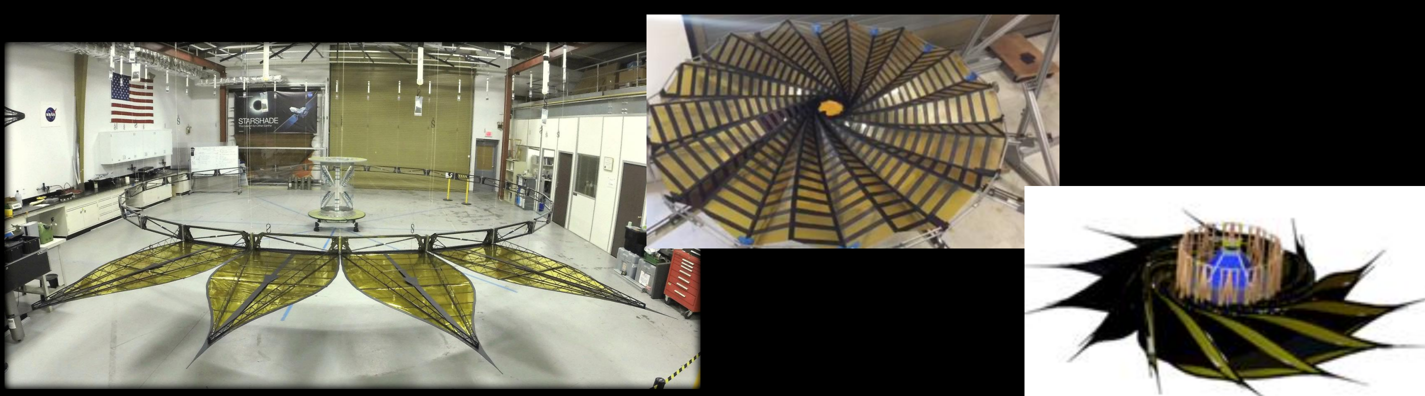




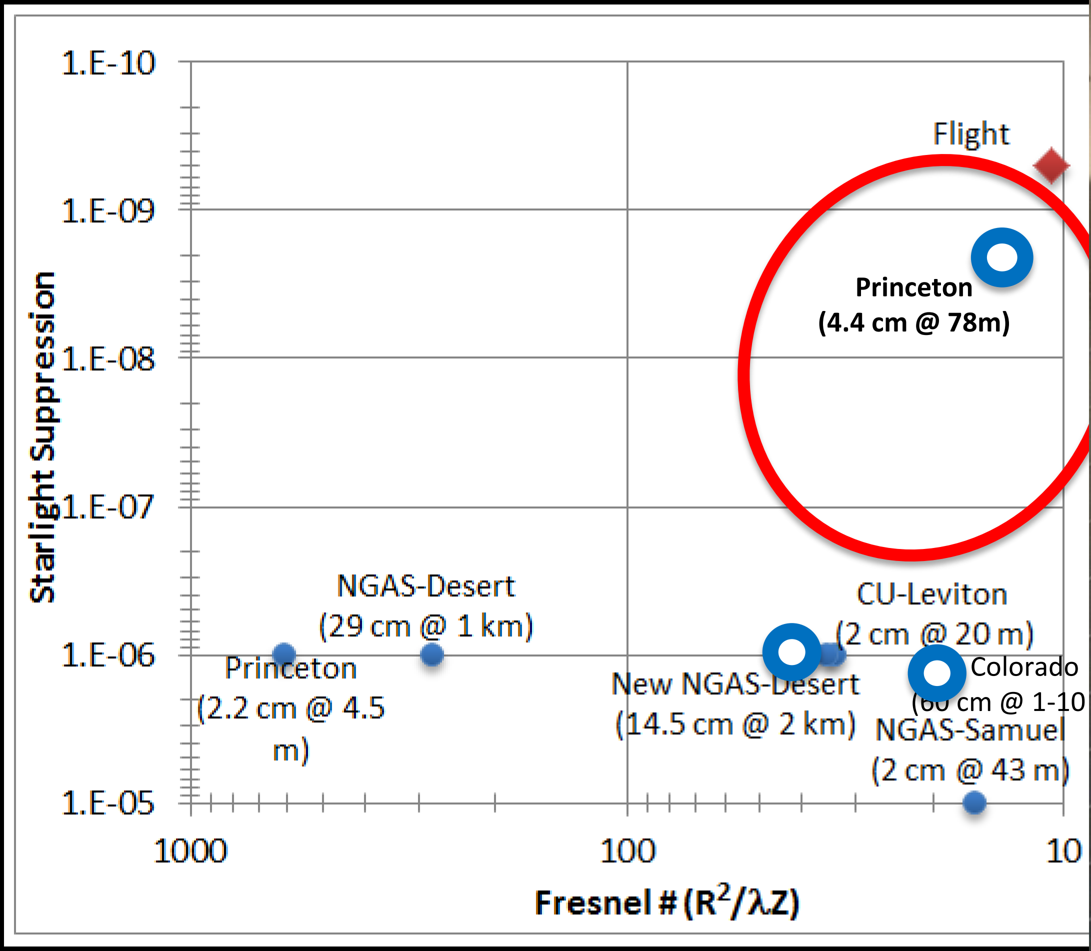
Lateral Formation Flying Sensing



Large Deployable Structures



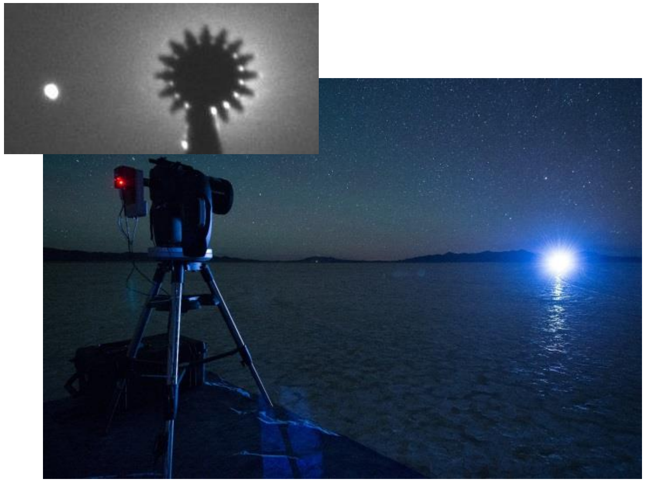
Optical Performance Technology Gap



Scheduled demos

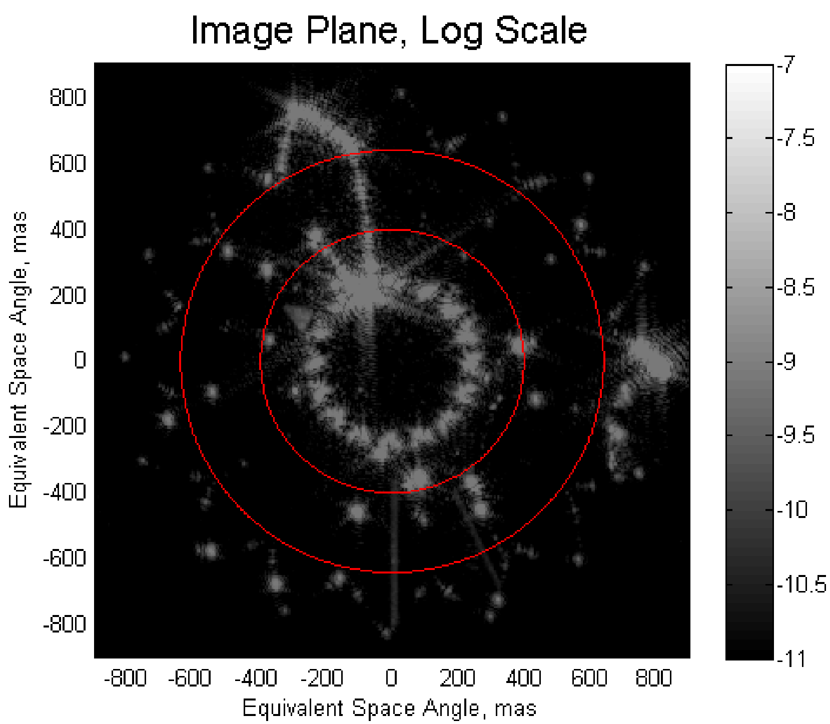
Past demos

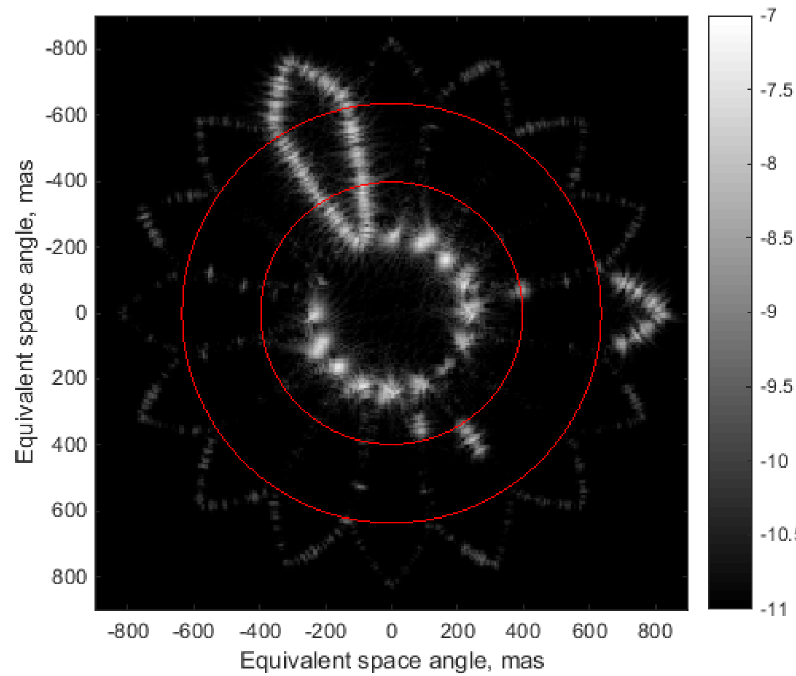
Goal



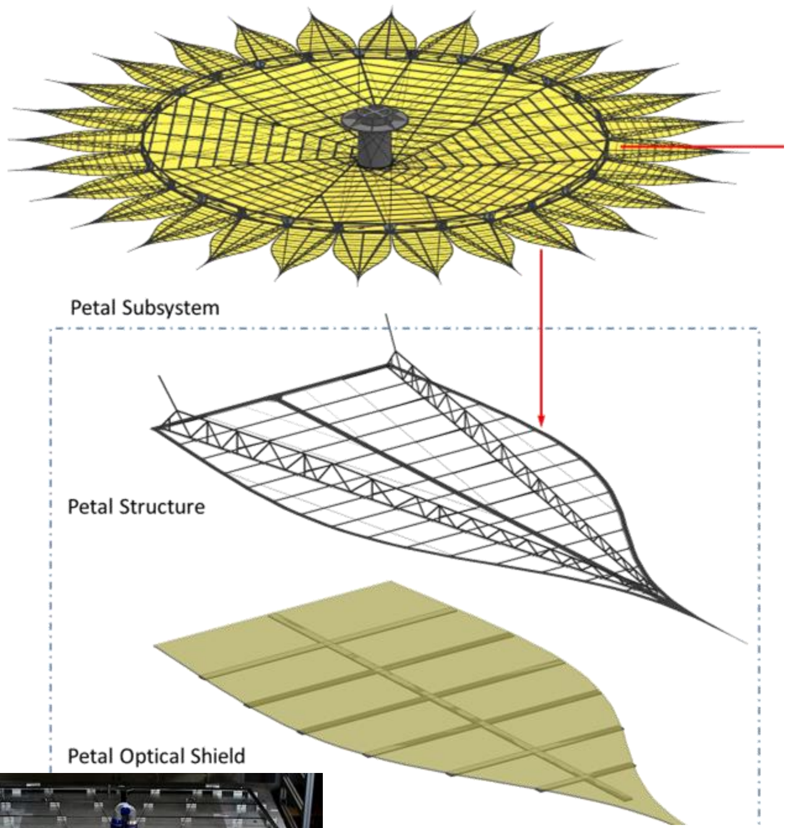
Northrop Grumman Desert Testing

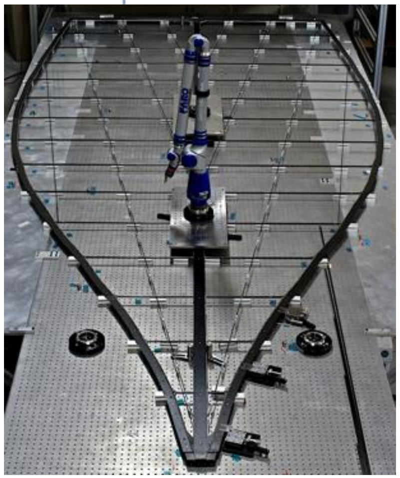
Princeton Lab Tests





Petal Fabrication Activities





Status

- Design of 7m petal with flight-like materials completed *(Princeton and JPL TDEM-10)*

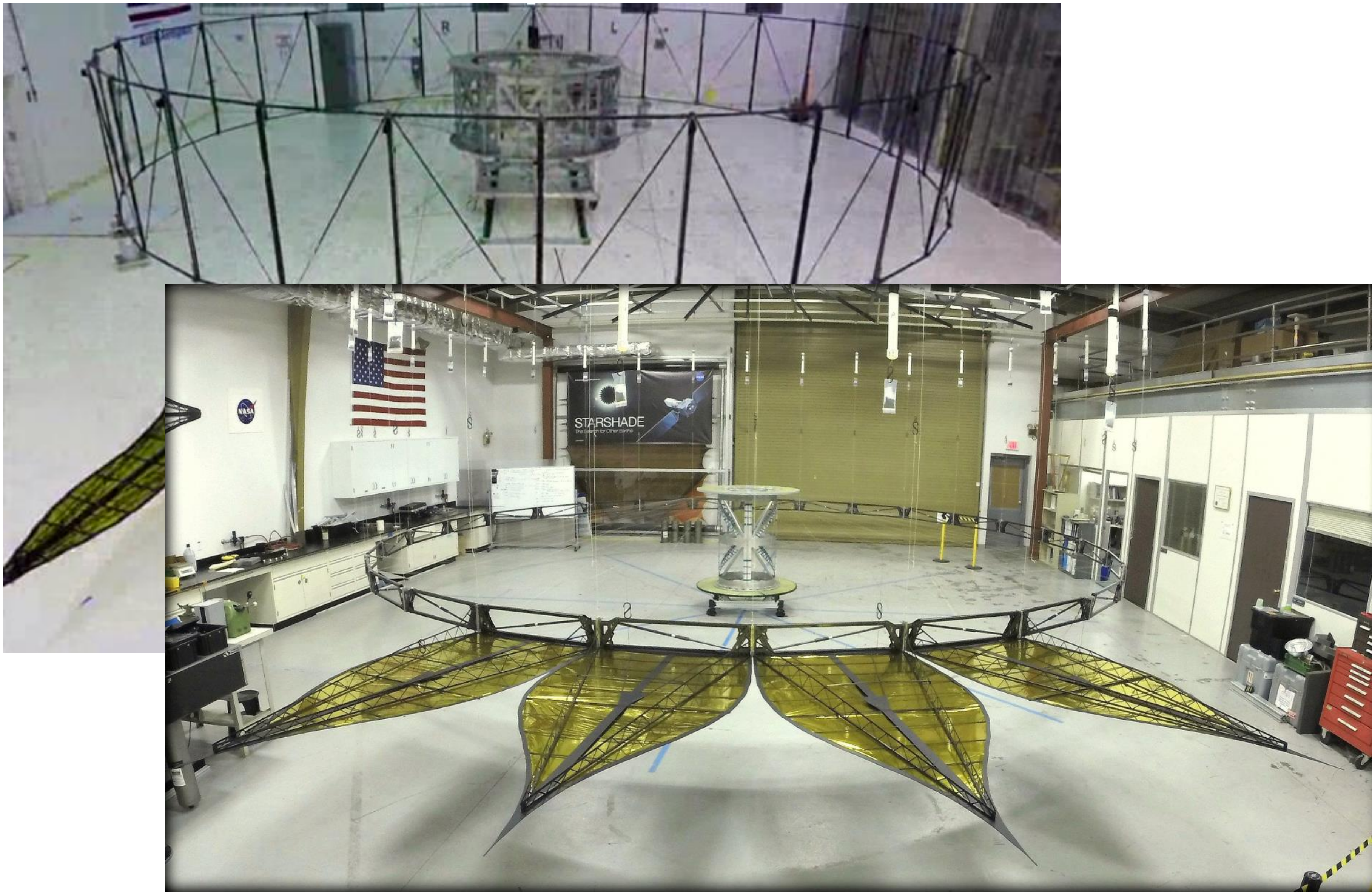
- Designing flight-like interfaces to integrate petal to overall structure
  - Base hinges
  - Launch tie downs
  - Petal unfurling mechanism
  - Optical edge and tip interfaces

Planned

- Fabricate a full-scale petal with optical edges and optical shield *(Princeton and JPL TDEM-12)*

- Demonstrate stowing and unfurling the full-scale petal to verify shape tolerance requirements *(Princeton and JPL TDEM-12)*

Thuraya → Starshade

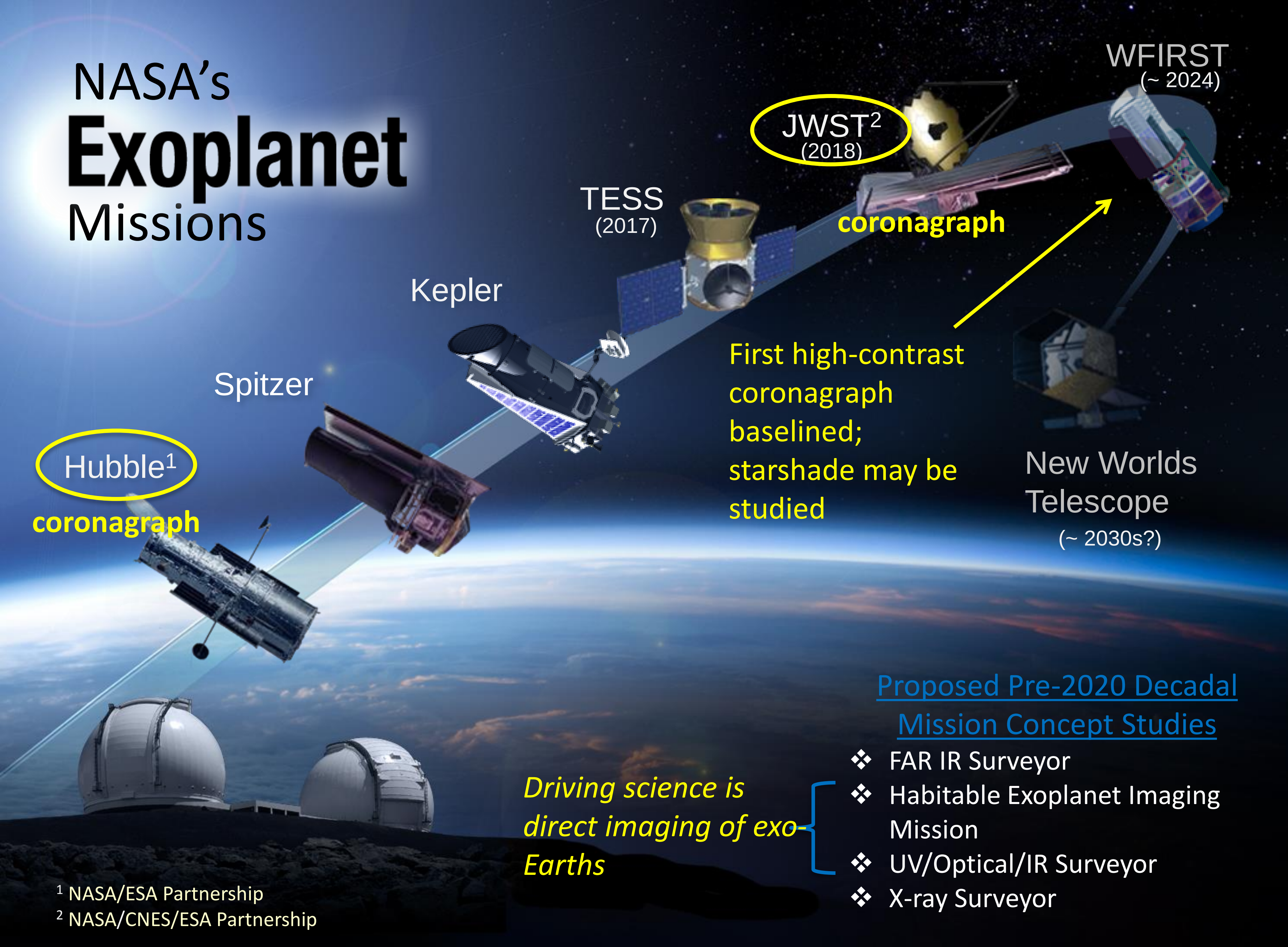


With current knowledge, how do coronagraphs and starshades compare and how could they be used in plausible future missions?

This is extremely mission specific and depends upon scale. Several studies have begun to study architectures; upcoming STDTs will be essential for addressing this. Science from probe studies was comparable.

Current research directed at making mission level comparisons (Stark 2015 in process, Savransky and Turnbull preparatory science projects)

Little to nothing has been done so far on DRM modeling of combined missions.


NASA's
Exoplanet
Missions
Hubble[1]
coronagraph
Spitzer
Kepler
TESS
(2017)
JWST[2]
(2018)
coronagraph
WFIRST
(~ 2024)
First high-contrast coronagraph baselined; starshade may be studied
New Worlds Telescope
(~ 2030s?)
Proposed Pre-2020 Decadal Mission Concept Studies
❖ FAR IR Surveyor
❖ Habitable Exoplanet Imaging Mission
❖ UV/Optical/IR Surveyor
❖ X-ray Surveyor
Driving science is direct imaging of exo-Earths
[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership

With current knowledge, how do coronagraphs and starshades compare and how could they be used in plausible future missions?

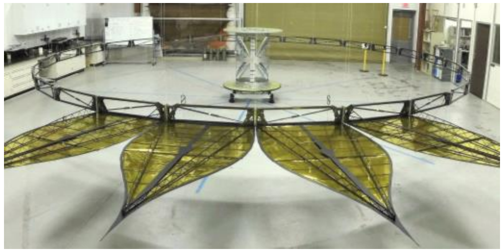
This is extremely mission specific and depends upon scale. Several studies have begun to study architectures; upcoming STDTs will be essential for addressing this. Science from probe studies was comparable.

We do know that adding a starshade to rendezvous with WFIRST provides complementary science and critical technology development!

Starshade Rendezvous Missions with WFIRST
Range of Scenarios under Study

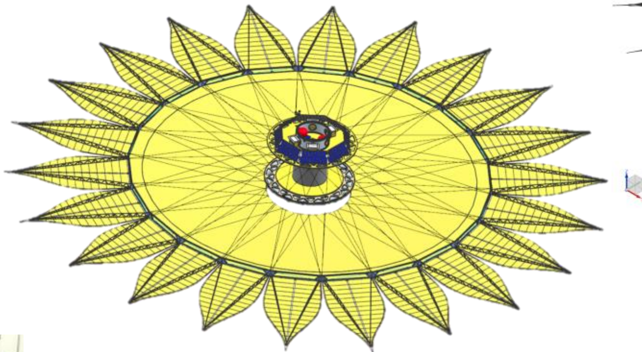
All missions launch on Falcon-9 to Earth-Sun L2 & use AFTA coronagraph as instrument, with masks removed

Tech Demo
20m Starshade
(current prototype size)
Retarget with Biprop Propulsion



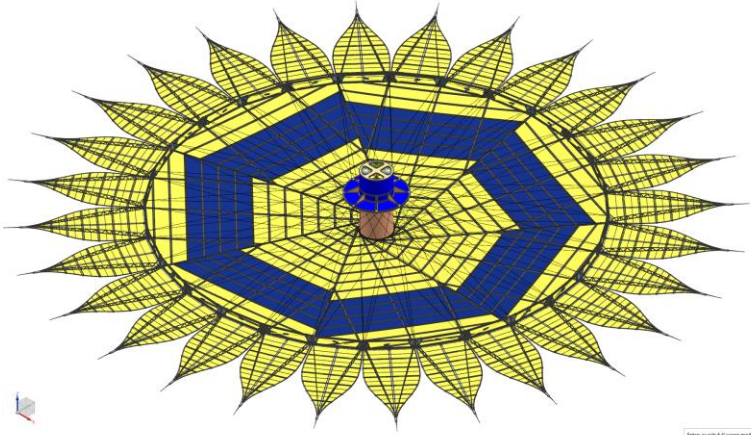
In 1 year, can:
Detect ~12 Known Gas Giants

Exo-S Case Study
34m Starshade
Retarget with Biprop Propulsion



In years 1 & 2, can:
Characterize ~12 Known Giants &
Search ~12 Cum. HZs for exo-Earths
Year 3 can be Reserved for Revisits

Earth-Finder
40m Starshade
Retarget with Solar Electric Propulsion
with power by thin-film cells on starshade



In 5 years, can:
Search ~50 Cum. HZs for exo-Earths

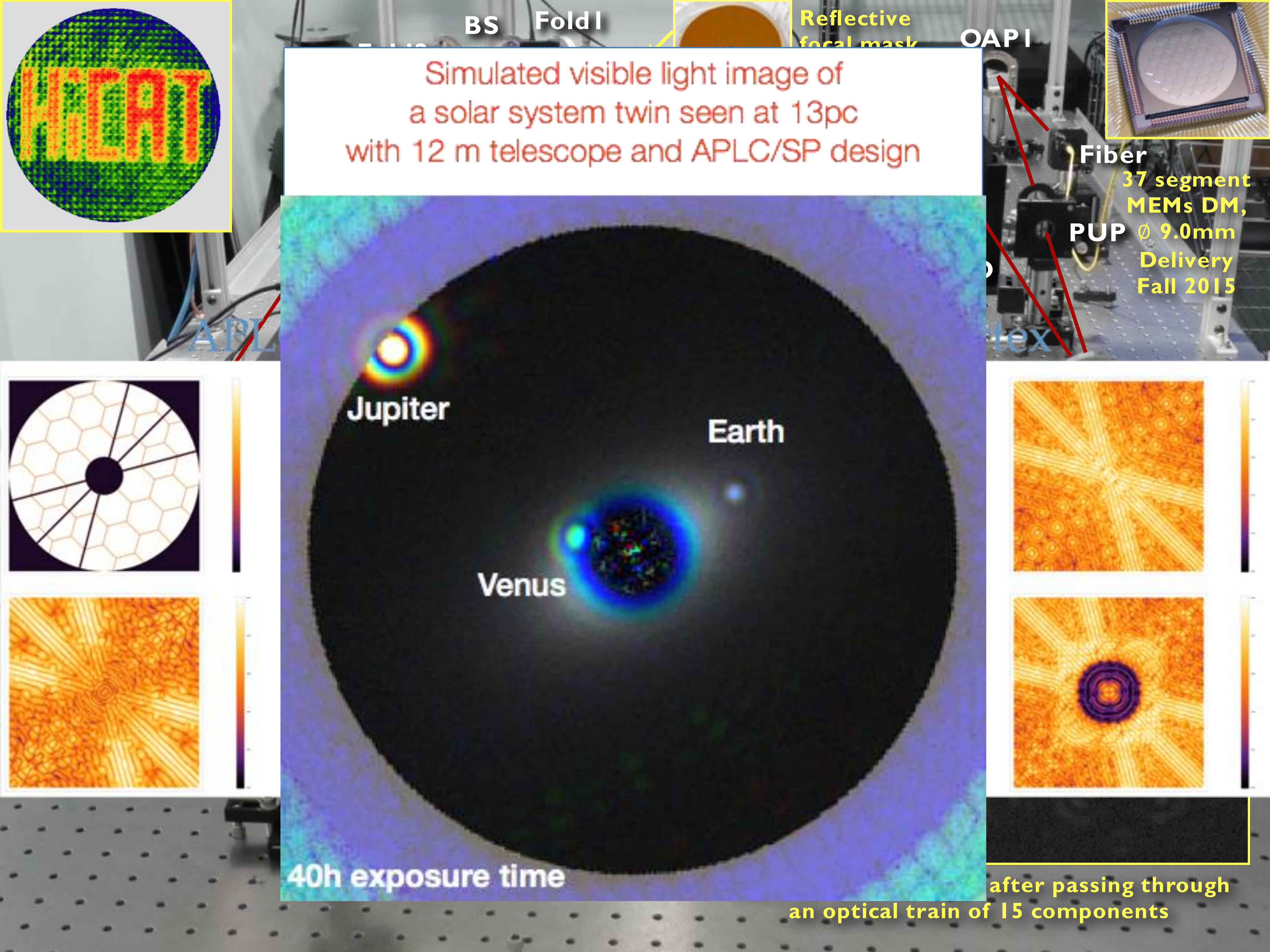
WFIRST launches starshade-ready, including:
- ***Filters for starshade bandpass***
- ***Proximity radio wih 2-way ranging***
- ***Sun-target angles including 40 to 83 deg***

Will development of other technologies continue to be healthy if the WFIRST/AFTA coronagraph goes forward?

YES!

<u>These fall into three categories:</u>

- Modest increase in funding (< $10M) to bring starshade to TRL 5 by end of decade (plus support for making WFIRST CGI “starshade ready”).
- APRA & TDEM support for coronagraph and wavefront control technology for complex apertures and segmented mirrors to prepare for future large mission (HDST, LUVOIR, HabEx)
- Potential explorer class demonstrations


BS
Fold1
Reflective
OAP1
Fiber
37 segment MEMs DM,
PUP Ø 9.0mm
Delivery Fall 2015
Simulated visible light image of
a solar system twin seen at 13pc
with 12 m telescope and APLC/SP design
Jupiter
Earth
Venus
40h exposure time
after passing through
an optical train of 15 components

Thank You!

And many thanks to the folks who supplied slides or information and otherwise helped me prepare this talk:

Stuart Shaklan, Doug Lisman, Rick Demers, Nick Siegler, Ilya Proberezhskiy, Remi Soummer, Olivier Guyon, Rus Belikov, Sara Seager, the Exo-S team

Sincere apologies to anyone I inadvertently missed and for anything left out.