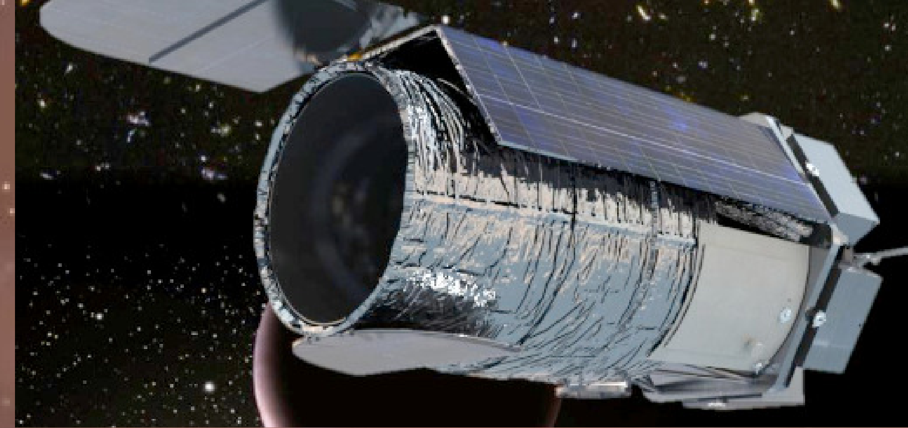


New Worlds Technology Developmen with the AFTA coronagraph

John Trauger
Jet Propulsion Laboratory / Caltech

NRC – AFTA Assessment Committee Review
Washington DC – 13 January 2014

Scope of this presentation

provide an ***assessment of the coronagraph technology*** and how, or if, vould ***advance the technology development goals*** enumerated in VNH. Specifically, the panel would likely be interested in hearing your oughts on if this AFTA coronagraph would strictly add scientific capability, if it would ***also test any of the design/implementation issues*** needed for eventual TPF-like mission?”

Outline

NWNH recommendations for New Worlds Technology Development.

Current state of the critical AFTA coronagraph technologies and AFTA program plans to advance and mature them.

The AFTA coronagraph development is essential preparation for a next-decade exoplanet mission to characterize Earth-like exoplanets.

he ultimate goal is to image rocky planets that lie in the habitable zone – at a
ance from their central star where water can exist in liquid form – and to characteri
 atmospheres. To prepare for this endeavor, the committee recommends a progra
y the technical and scientific foundations for a future space imaging and spectrosc
sion.

n the first part of the decade NASA should support competed technology developn
dvance multiple possible technologies for a next-decade planet imager, and should
elerate measurements of exozodiacal light levels that will determine the size and
plexity of such missions.

f, by mid-decade, a DSIAC review determines that sufficient information has becor
 becoming available on key issues such as planet frequency and exozodiacal dus
ibution, a technology down-select should be made and the level of support increas
nable a mission capable of studying nearby Earth-like planets to be mature for
sideration by the 2020 Decadal survey, with a view to a start early in the 2020 deca
 committee estimates that an additional $100 million will be required for the missio
cific development."

NH p 217:

he committee's proposed program is designed to allow a habitable-exoplanet
ging mission to be well formulated in time for consideration by the 2020 decadal

/NH / EOS Panel Report p 253:

rapid advances in starlight-suppression techniques could enable a moderate-size
ility that could image and characterize giant planets (and perhaps some smaller
es) and investigate the debris and dust disks that are stages in the planet-forming
cess.

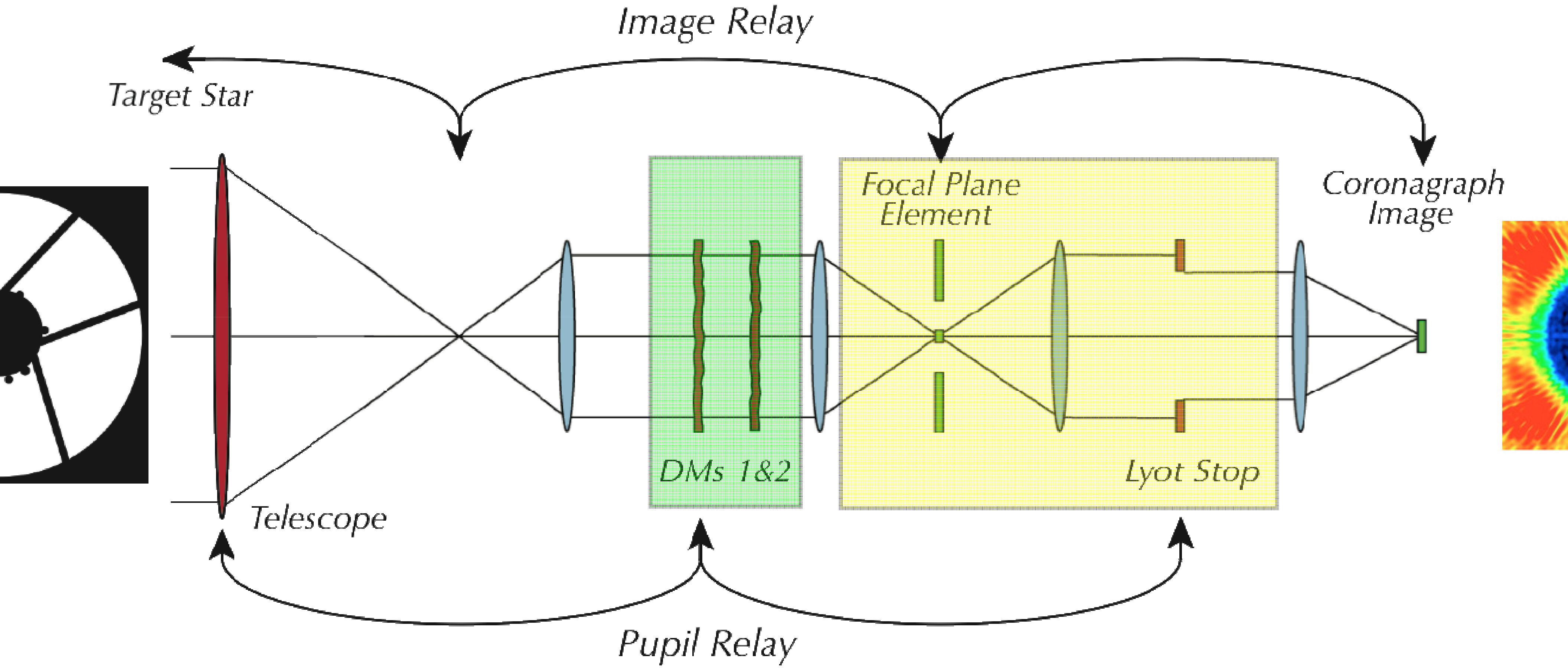
covering even smaller planets and studying their atmospheres with transit
otometry and spectroscopy employ another powerful, rapidly improving technique.

e panel urges increased technology development for these techniques and
ommends that one of these missions, or a yet-to-be-developed approach, be
npetitively selected around mid-decade and, if the budget permits, started before t
d of the decade."

The short answer

urrent and planned future work on the AFTA coronagraph development program pecifically addresses all the Astro2010 recommendations for New Worlds echnology Development.

he AFTA coronagraph development program will rapidly advance the critical nabling technologies for a next-decade exoplanet mission for the direct imaging an pectroscopic characterization of Earth-like exoplanets.



ketch of the essential elements of an ***actively corrected Lyot coronagraph*** *incluc*

e ***sequential pair of deformable mirrors for wavefront control (****common to AF*
imary and backup coronagraph types) and

e ***coronagraph elements*** *(similar diagrams describe the Shaped Pupil and PIAA-*
MC coronagraphs).

agram unfolds the optical system with powered elements as lenses for clarity.
oronagraph elements are highlighted in yellow, wavefront control elements in gree

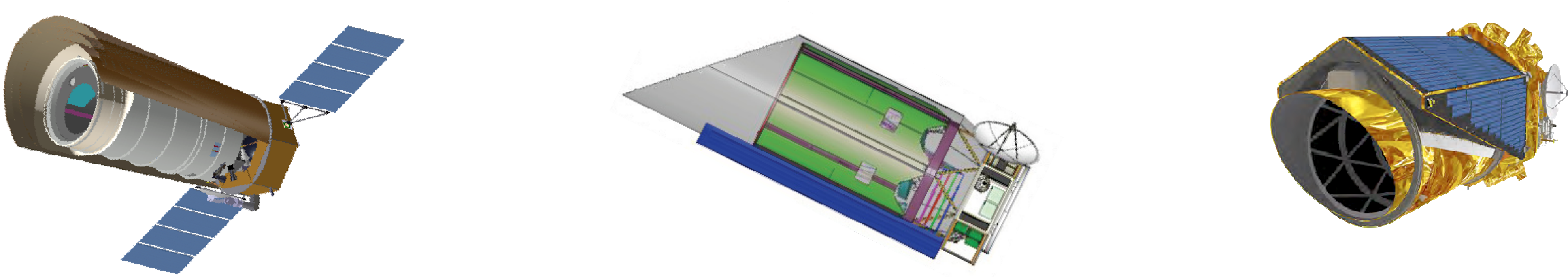
A inherits recent coronagraph technology advance

he AFTA coronagraph development hits the road running – benefiting from NASA
ponsored engineering designs and technology demonstrations:

- Coronagraph mission concept studies (ASMCS/ACCESS/PECO/EPIC, 2009)
- Technology developments (SAT/TDEMs for all coronagraphs, 2010-2013)
- and strategic institutional (IRAD, R&TD) investments.

s a result, most of the critical technologies have been identified and are already po
advance to flight readiness.

FTA investments are accelerating technology readiness, mindful of the lessons lea
nd system engineering from recent ASMCS mission concept and TDEM technolog
udies.



ASMCS/ACCESS (Vortex, Shaped Pupil, PIAA)

ASMCS/PECO (PIAA)

ASMCS/EPIC (VisNuller)

The critical technologies

Coronagraph for starlight suppression

- Theoretical designs and AFTA coronagraph technology selections
- Laboratory demonstrations and performance model validation

High order wavefront control for the creation of high contrast dark field images

- Maturity and performance of the deformable mirror technology
- Wavefront sensing and control algorithms based on DM probes and science
- High order wavefront sensing and control in the presence of pointing jitter

Low order wavefront sensing and correction of telescope jitter and thermal drift

- Requires high fidelity dynamic and thermal models for the telescope
- Definition and demonstration of hardware and sensing and control systems

Post processing image techniques for greater sensitivity

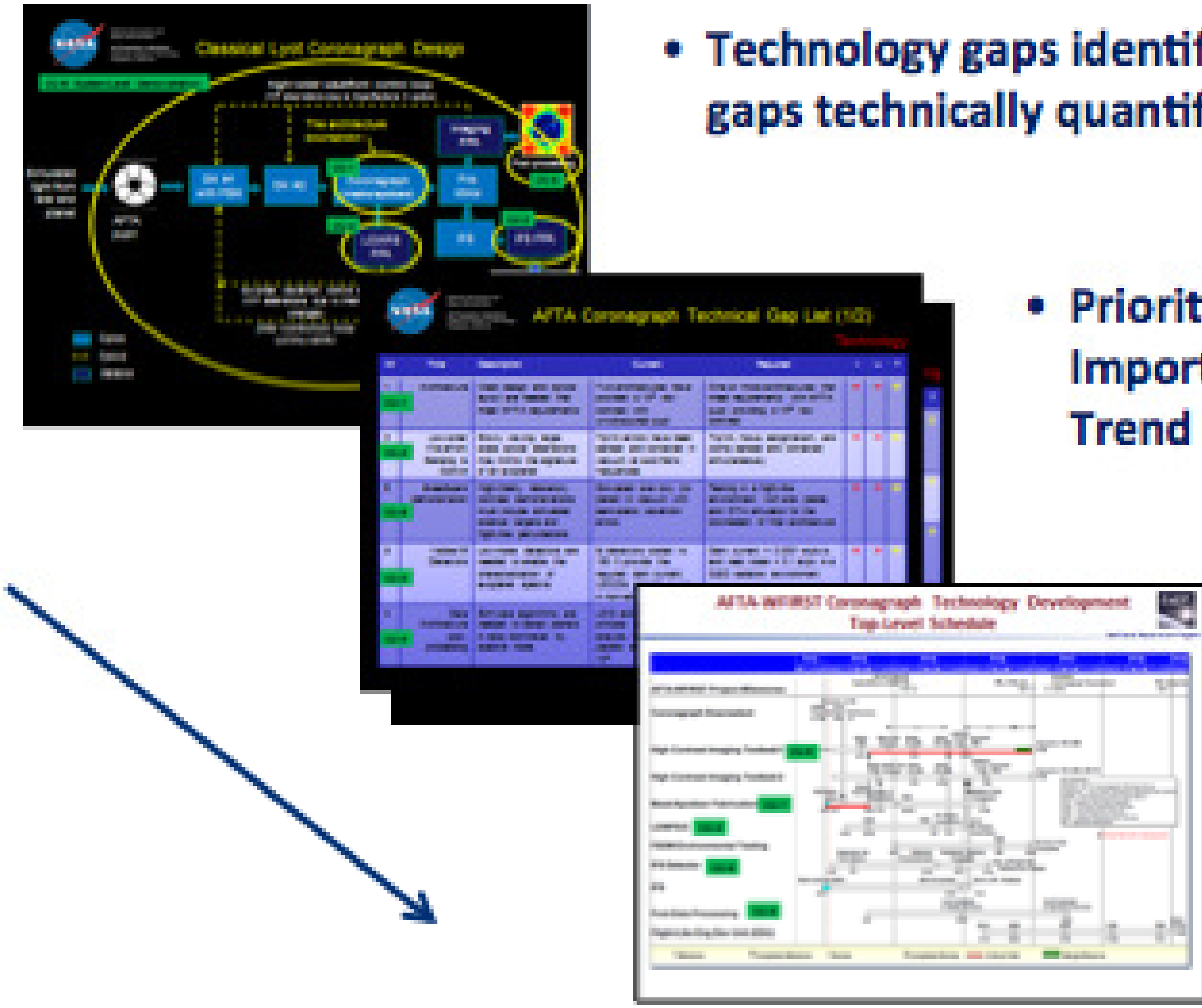
Spectrograph

- Optical design for high throughput, low pixel-to-pixel cross talk, large field of
- Large low read-noise image sensors for R=70 integral field spectroscopy

AFTA coronagraph technology objectives

- Fabrication of the AFTA-configured coronagraph masks.
- Establish flight readiness of the high-order deformable mirrors (DMs).
- Demonstrations of high contrast imaging in the laboratory with a static simulate AFTA pupil.
- Model analysis and prediction of the critical AFTA OTA wavefront characteristics.
- Laboratory demonstrations of high and low order wavefront error sensing and control of a dynamic wavefront (simulated AFTA pointing jitter and low order aberrations) at the breadboard level.
- Demonstrations of post-processing methods for improved sensitivity using dynamic wavefront laboratory data.
- Development and laboratory characterization of the integral field spectrograph (IFS) including low read-noise imaging CCD detectors, overall throughput, and pixel-to-pixel crosstalk.

ExEP Technology Development Process

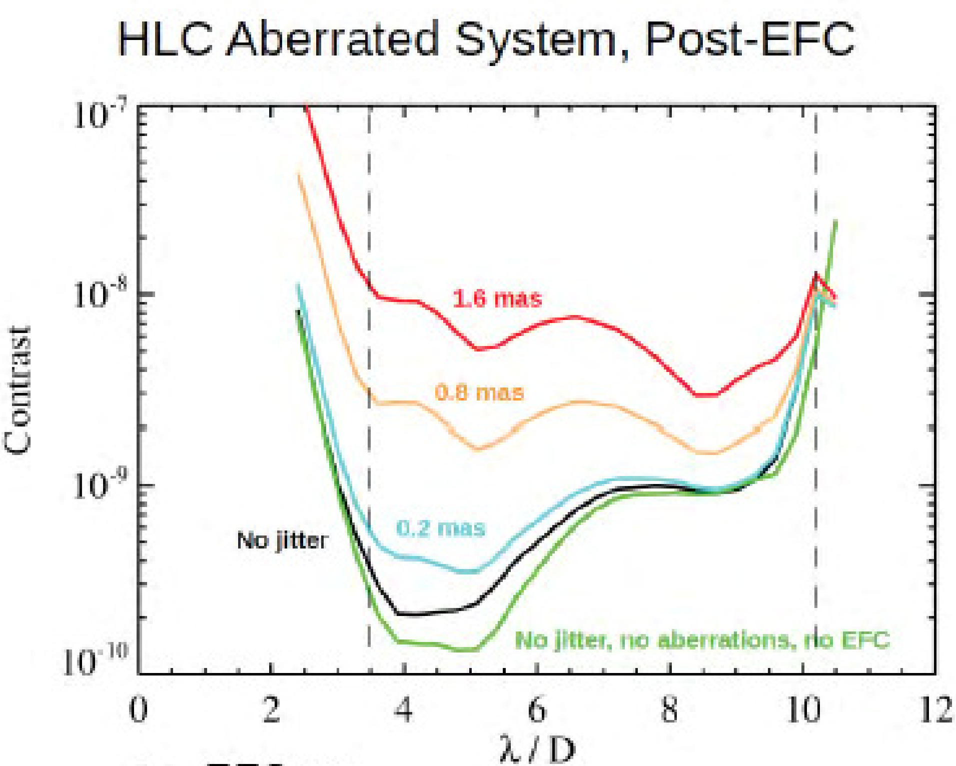


- Technology gaps identified and described, gaps technically quantified
- Prioritized for relative Importance, Urgency, and Trend
- Plans created to retire the top priorities in time

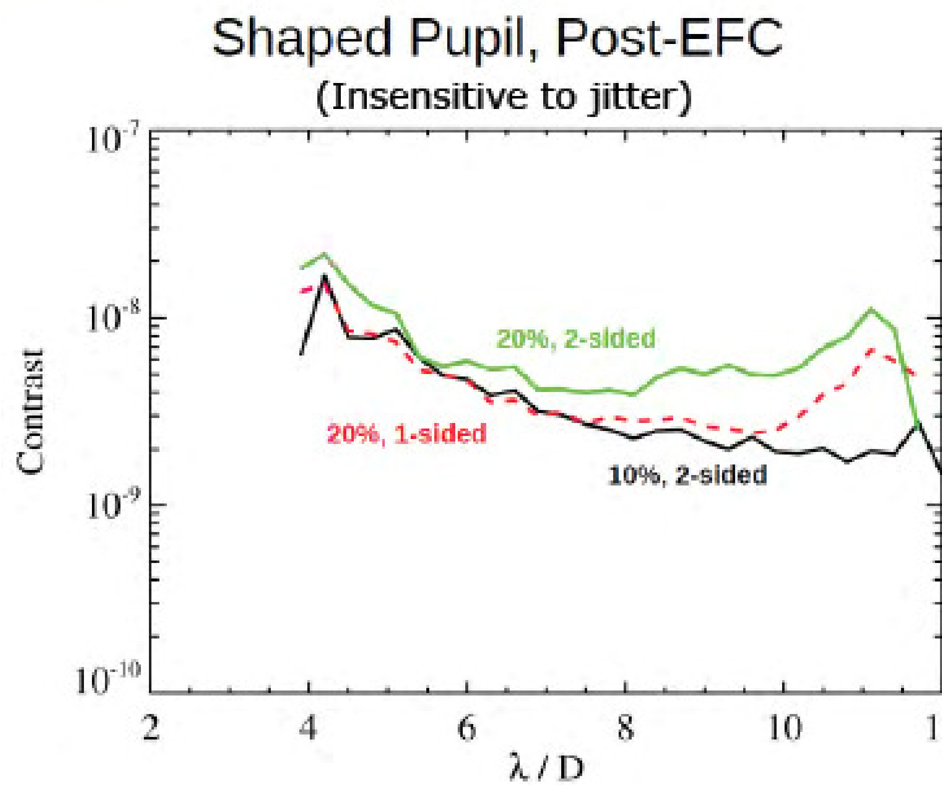
Coronagraph technology plans for AFTA far along; starshade next.

Contrast simulations with AFTA pupil, aberrations and expected range of telescope pointing jitter

- OMC in its "SP mode" provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and "use-as-is" telescope This translates to low cost/schedule risk and a design that has a high probability to pass thru the CATE process.
- In its "HL mode", the OMC affords the potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for most of the RAW speed



λ=550nm

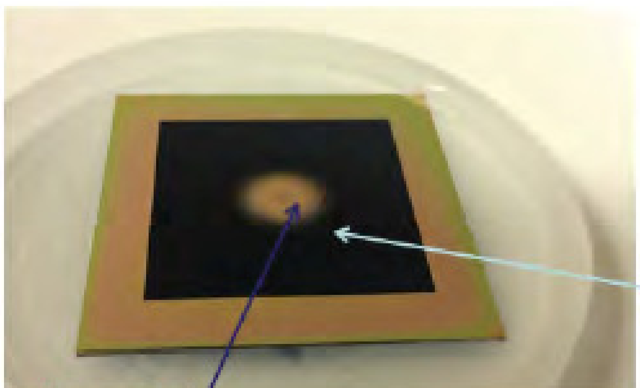


Good balance of science yield and engineering risk

Coronagraph Masks

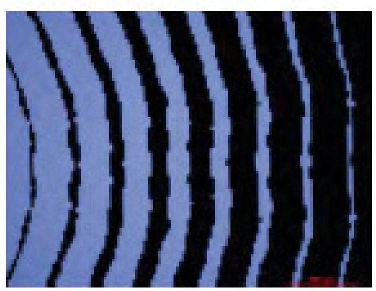
Reflective shaped pupil masks

- Black Si on Al mirror coating demonstrated at JPL/MDL and Caltech/KNI



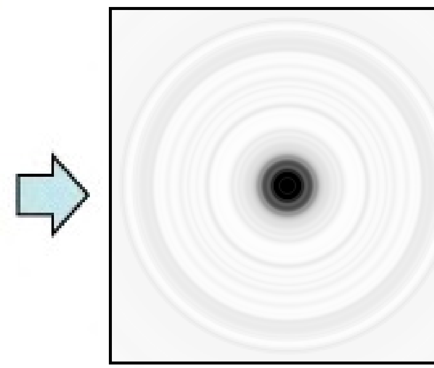
Uniform black achieved with Al + photoresist etch mask

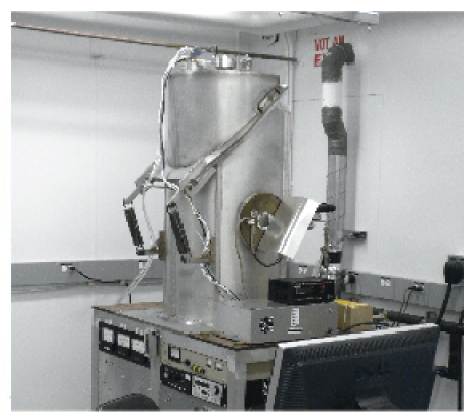
Al covered with photoresist

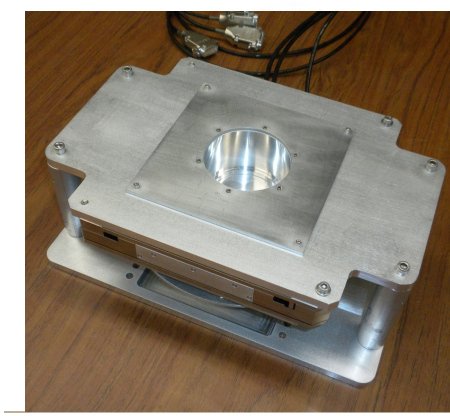


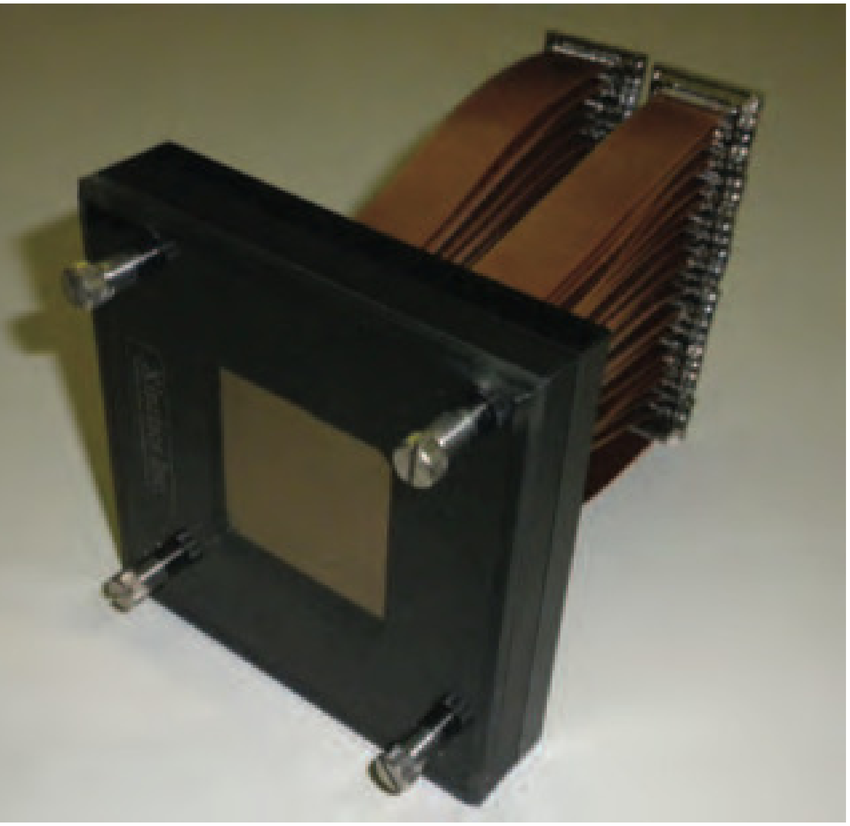
Transmissive hybrid Lyot mask

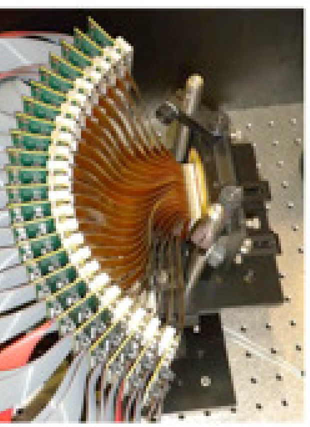
- Profiled Ni layer (amplitude) over coated with profiled MgF2 layer (phase) at JPL Trauger's lab
- Linear mask fabricated and demonstrated 10^{-10} in HCIT for un obscured pupil

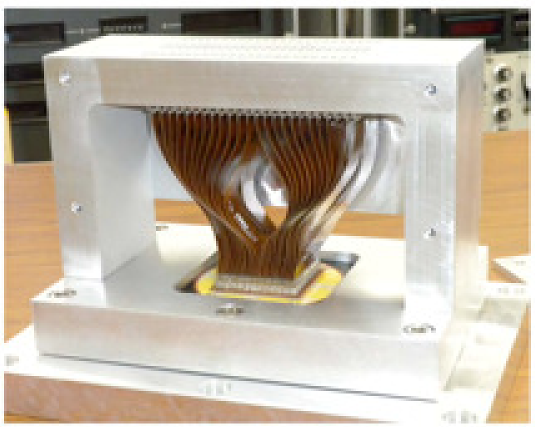








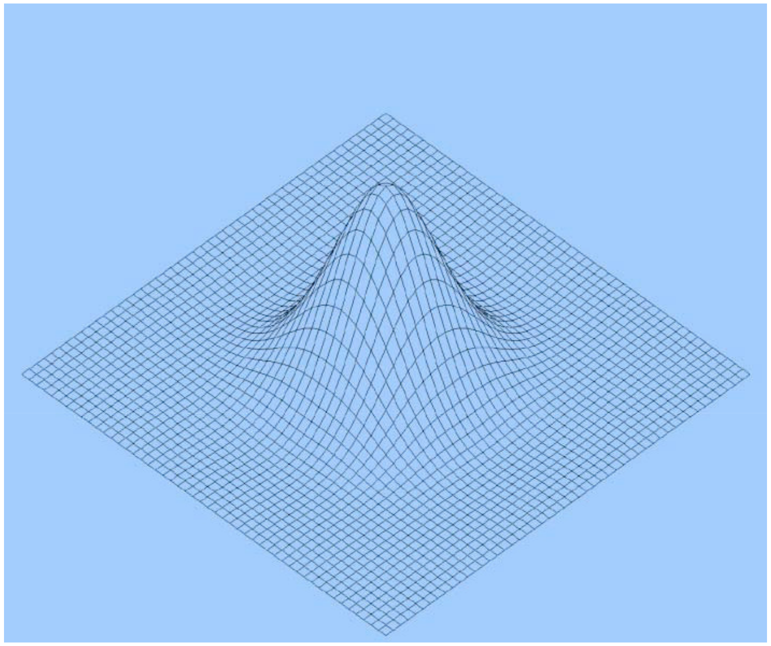
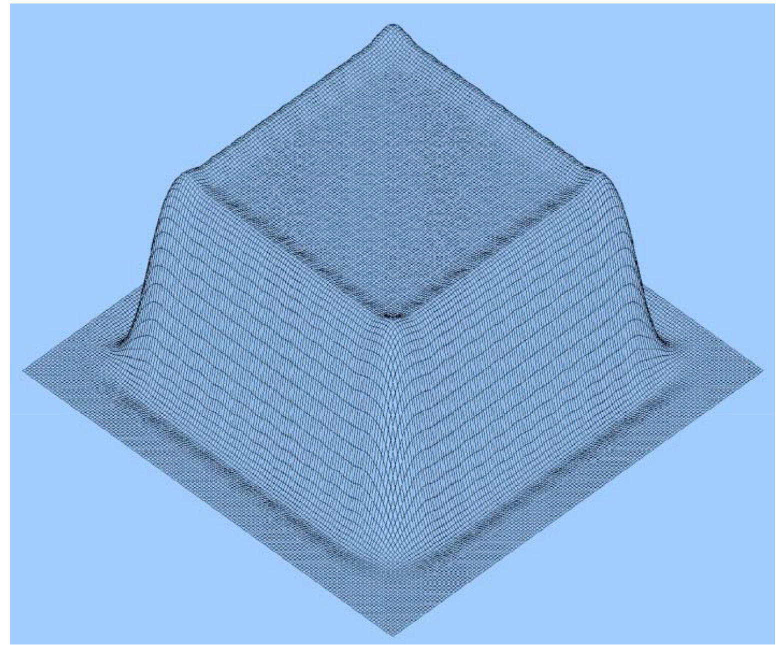




- *Shown is the* ***48x48 actuator*** *PMN electrostrictive deformable mirror.*
- *Manufactured by AOA Xinetics, the outcome of a technology development initiated at the SBIR level in 1997.*
- *High quality DMs of this type have beer active on the HCIT since 2004.*
- *DMs of this type have been used for all HCIT coronagraph demonstrations to date, including TPF Milestones #1,2,3 a all SAT/TDEM demonstrations on the HCIT.*
- *This DM is flight-configured, has completed a* ***protoflight qualification*** *3 axis vibe test to 10.8 grms, DM technol is ~ TRL 5.*

bove, the 48x48 DM is mounted on the Zygo bench for optical tests. Flex bbon cables fan out to the 2304-channel electronic driver system.

bove right, the DM is clamped into its shake table test fixture, with all flex

*ed silica mirror facesheet is flat to **5 nm rms surface** figure in the unpowere e.*

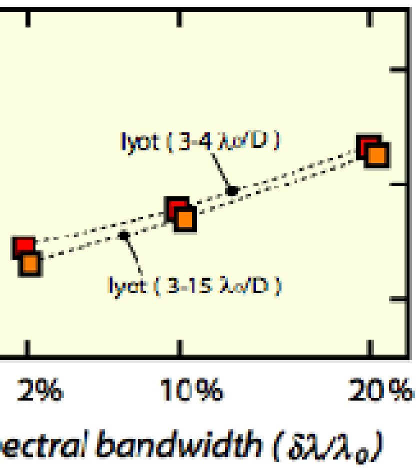
face profile has been measured to accuracies of 25 picometers rms in a vac rferometer with 0.1 x 0.1 mm sample density.

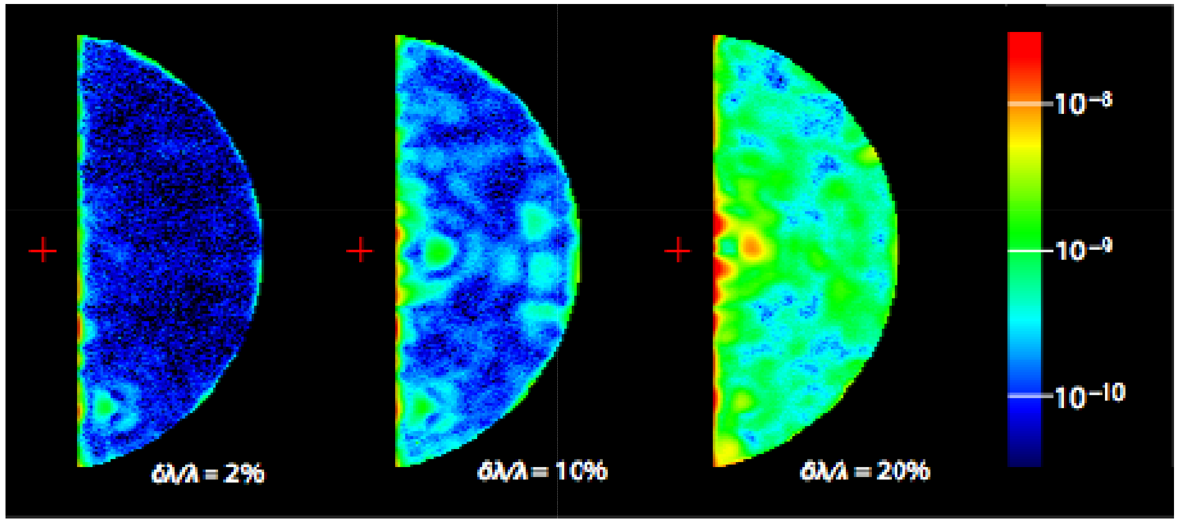
*uated surface deflections are **stable to 0.1 nanometers / 100 hours** in the uum laboratory environment.*

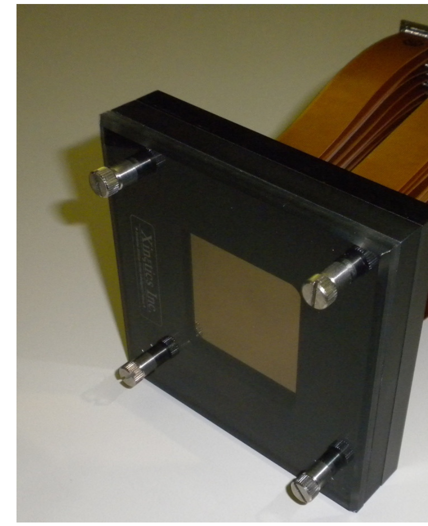
*eft, the **surface influence profile** for a single actuator. Surface displaceme xes typically to 10% of the central displacement at the nearest neighboring uators (1 mm actuator pitch).*

*ght, **linear superposition** of individual influence functions predicts overall ace displacement; shown is the surface figure result for the simple addition*

ective 3: AFTA laboratory performance validations
extension of ASMCS and SAT/TDEM demonstrati







vefront sensing and control *is carried out exclusively with deterministic DI ngs (small surface patterns) and imagery at the science focal plane. The edure is iterative and avoids all non-common-path amplitude and phase err*

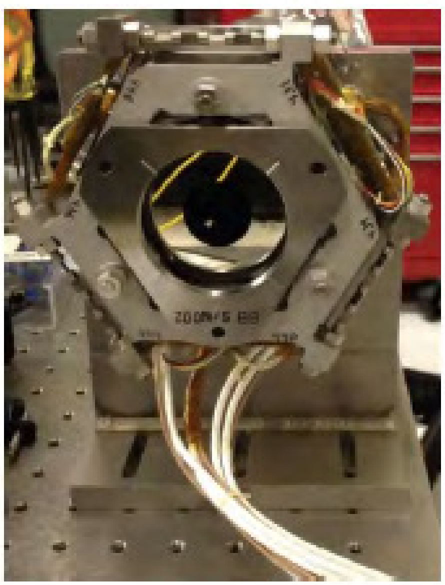
onagraph and wavefront control performance models have been ***validated 2e-10 contrast level*** *in HCIT demonstrations – e.g., as shown for hybrid Ly nagraph with a linear focal plane mask as part of the SAT/TDEM program i l.*

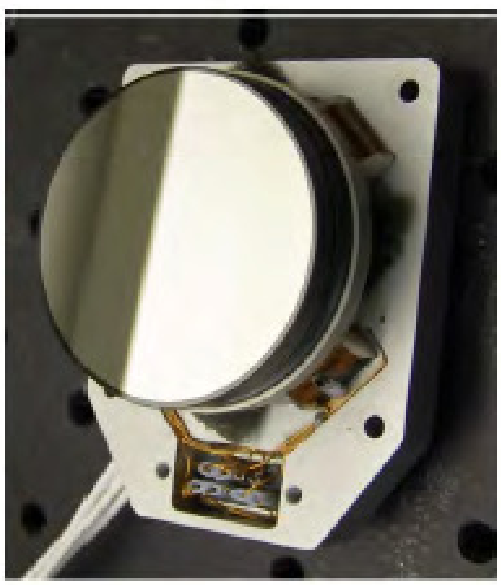
adapt our ***validated coronagraph performance models*** *to the AFTA nagraph*

Active Optics

Fine Steering Mirror (FSM)

- To correct telescope line-of-sight (wavefront tip/tilt) error
- Low risk with rich flight heritage





Deformable Mirror (DM)

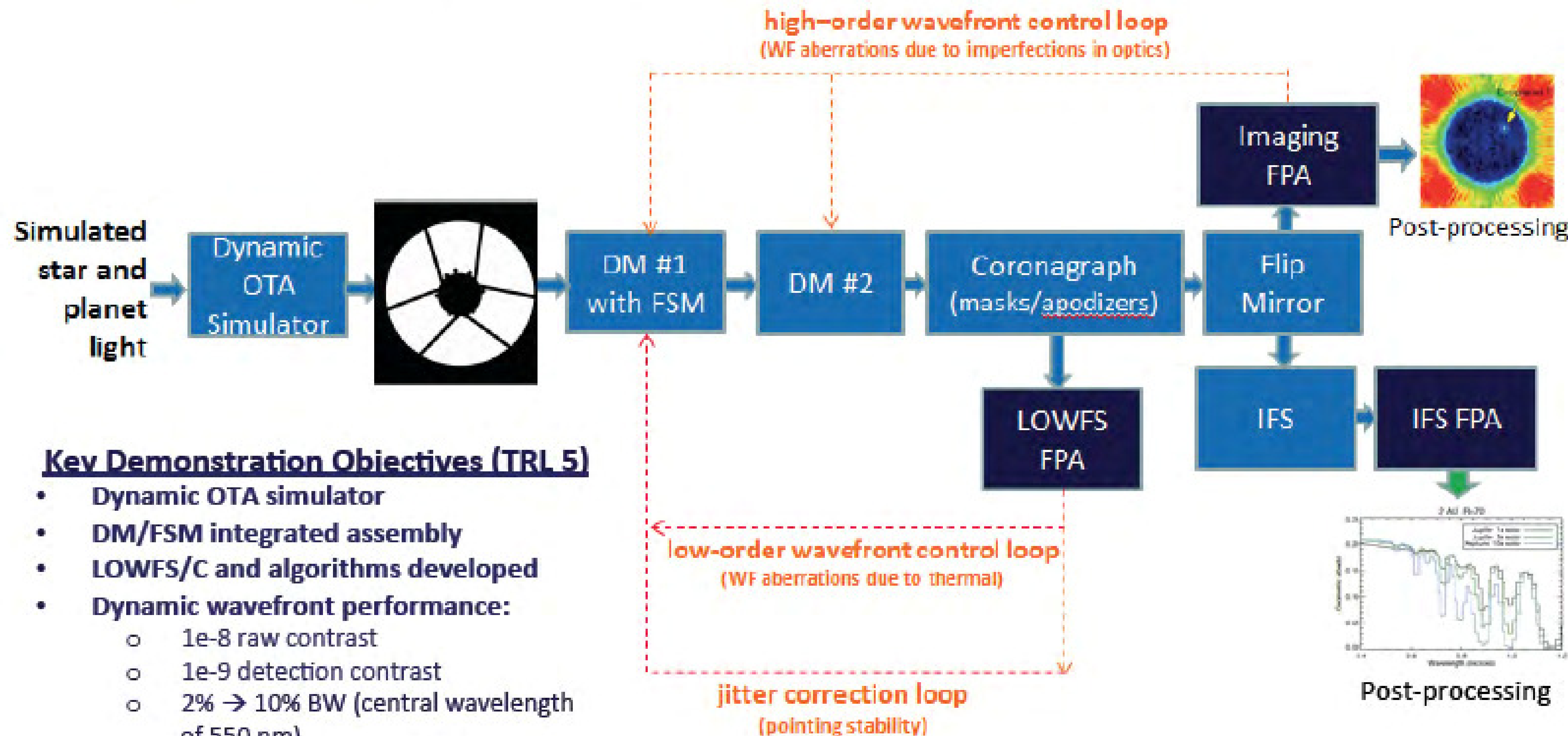
- To correct telescope & instrume optical WFE (static and drift)
- Low risk with good heritage:
  - Flight PMN actuators, driver electron
  - HCIT contrast demonstration to 10^{-10}
  - Assembly passed random vibe test (2012)

Low risk for flight implementation

System-Level Testbed Demonstration
Phase 2: Dynamic Wavefront

Possible Path to Closing Gap

Demonstrate dynamic wavefront performance in fully-assembled coronagraph vacuum testbed with simulated AFTA-WFIRST telescope pupil in a dynamic env't.



Key Demonstration Objectives (TRL 5)

- **Dynamic OTA simulator**
- **DM/FSM integrated assembly**
- **LOWFS/C and algorithms developed**
- **Dynamic wavefront performance:**
  - 1e-8 raw contrast
  - 1e-9 detection contrast
  - 2% → 10% BW (central wavelength of 550 nm)
  - IFS (R~70 TBD) separately
- **Planet simulation and extraction**

Fabrication of the AFTA-configured coronagraph masks ***(underway, to be ready testbed installation by mid 2014)***.

Establish flight readiness of the high-order deformable mirrors (DMs). ***(baseline in house, further environmental tests planned in 2015-6)***

Demonstrations of high contrast imaging in the laboratory with a static simulated AFTA pupil. ***(A straightforward extension of the HCIT tests for SAT/TDEM programs, optical table reconfigurations to be ready by mid 2014)***

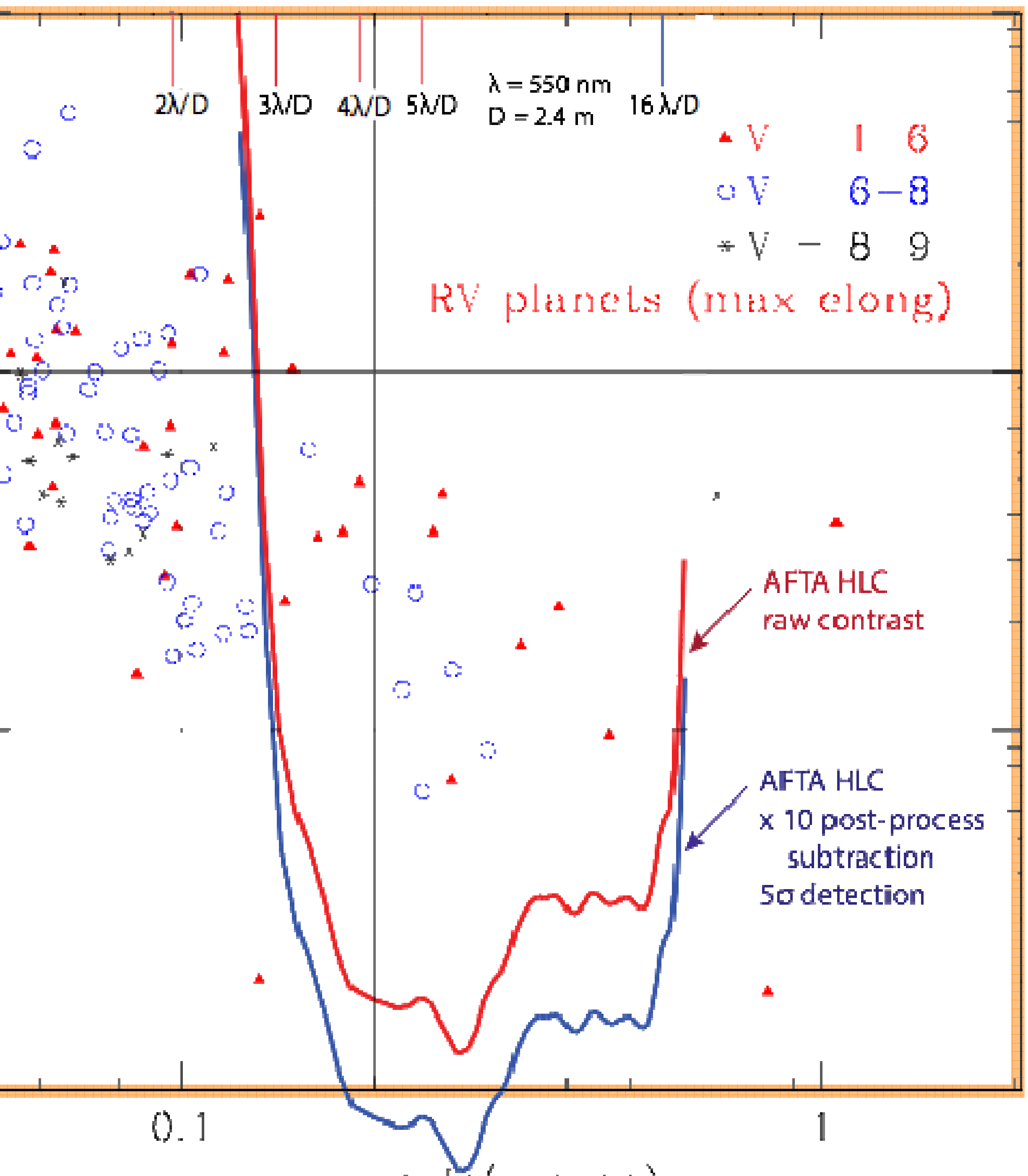
Model analysis and prediction of the critical AFTA OTA wavefront characteristics. ***(underway at GSFC in 2014)***

Laboratory demonstrations of high and low order wavefront error sensing and con of a dynamic wavefront (simulated AFTA pointing jitter and low order aberrations) the breadboard level. ***(model simulations and dynamic testbed elements plan for 2015-6)***.

Demonstrations of post-processing methods for improved sensitivity using dynami wavefront laboratory data. ***(onging parallel efforts)***

Development and laboratory characterization of the integral field spectrograph (IF including low read-noise imaging CCD detectors, overall throughput, and pixel-to-

proaching the Earth-imaging objectives in the NWNH rep



- ***The AFTA coronagraph*** ***up all currently known*** ***planets*** *at elongations be* *λ/D (Traub, AFTA Corona* *Working Group 10/18/13)*
- *Raw contrast curve (red)* *bandwidth, includes AFTA* *wavefront errors, 0.4 mas* *instrument-corrected poin* *jitter.*
- *Post processing curve (b* *represents the 5σ exoplan* *detection threshold follow* *speckle background subt*
- ***AFTA performance is a*** ***fidelity test of NWNH*** ***coronagraph concepts*** ***exoplanet imaging and*** ***spectroscopy.***

AFTA RV Exoplanet Detection Estimates

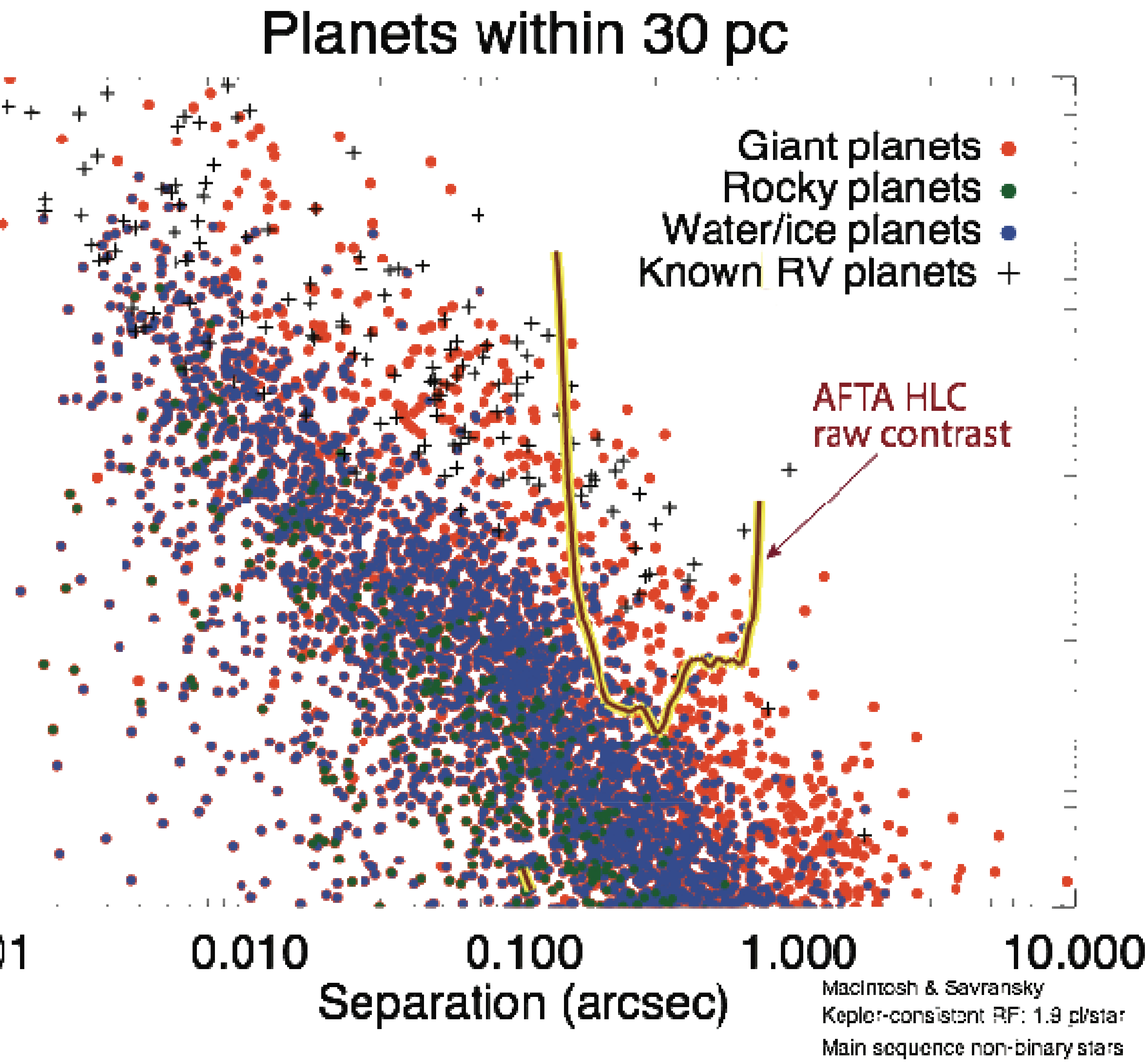
- RV exoplanet detections are estimated based on imaging of radial velocity planets from the current RV catalog

Configuration	Architecture	radial range (arcsec)	median contrast floor for 5σ post-process detections	# RV planets, 550nm band, 6-month campaign	# spectral bands per target, 6-month campaign
Prime (OMC: Occulting Mask Coron.)	Shaped Pupil	0.19 - 0.57	13 x10^{-10}	4	4.3
			4 x10^{-10}	7	4.9
	Hybrid Lyot	0.10 - 0.51	5 x10^{-10}	18	4.3
			1 x10^{-10}	19	4.2
Backup	PIAA	0.09 - 0.63	19 x10^{-10}	23	3.2
			6 x10^{-10}	30	4.3

ote 1. Two rows for contrast and # RV images columns are for cases of
- Current Best Estimate: 0.4 mas RMS jitter & 1 mas star, 10x post-processing factor (slide
- Goal: 0.2 mas RMS jitter & 1 mas star, 30x post-processing factor (slide 5)

ote 2. Spectral bands are 10% wide, centered at 450, 550, 650, 800, 950 nm

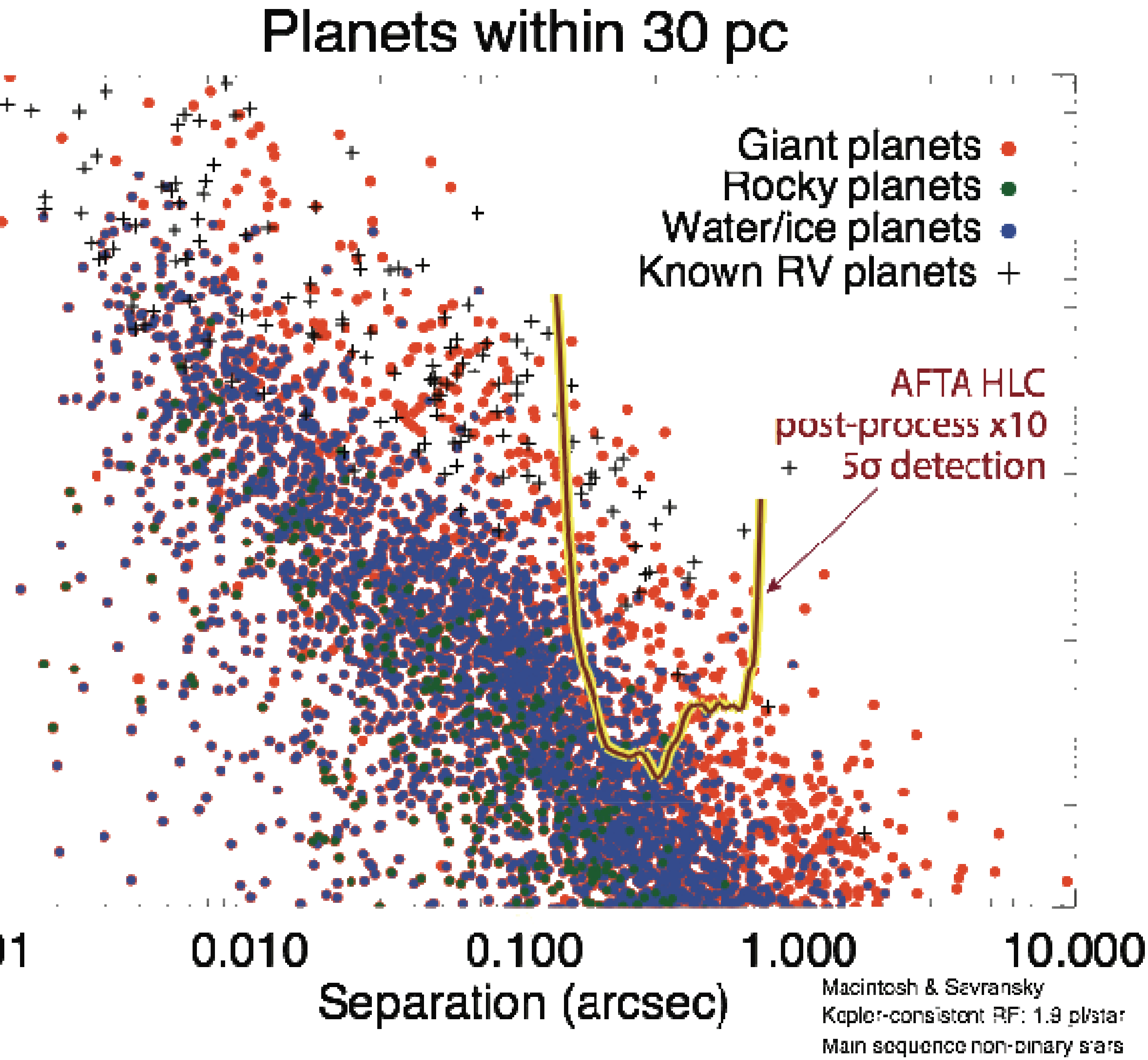
e 5 – AFTA Coronagraph Results Subsequent to primary/backup selection – W. Traub et al



AFTA contra
vs.
a simulated p
populatio

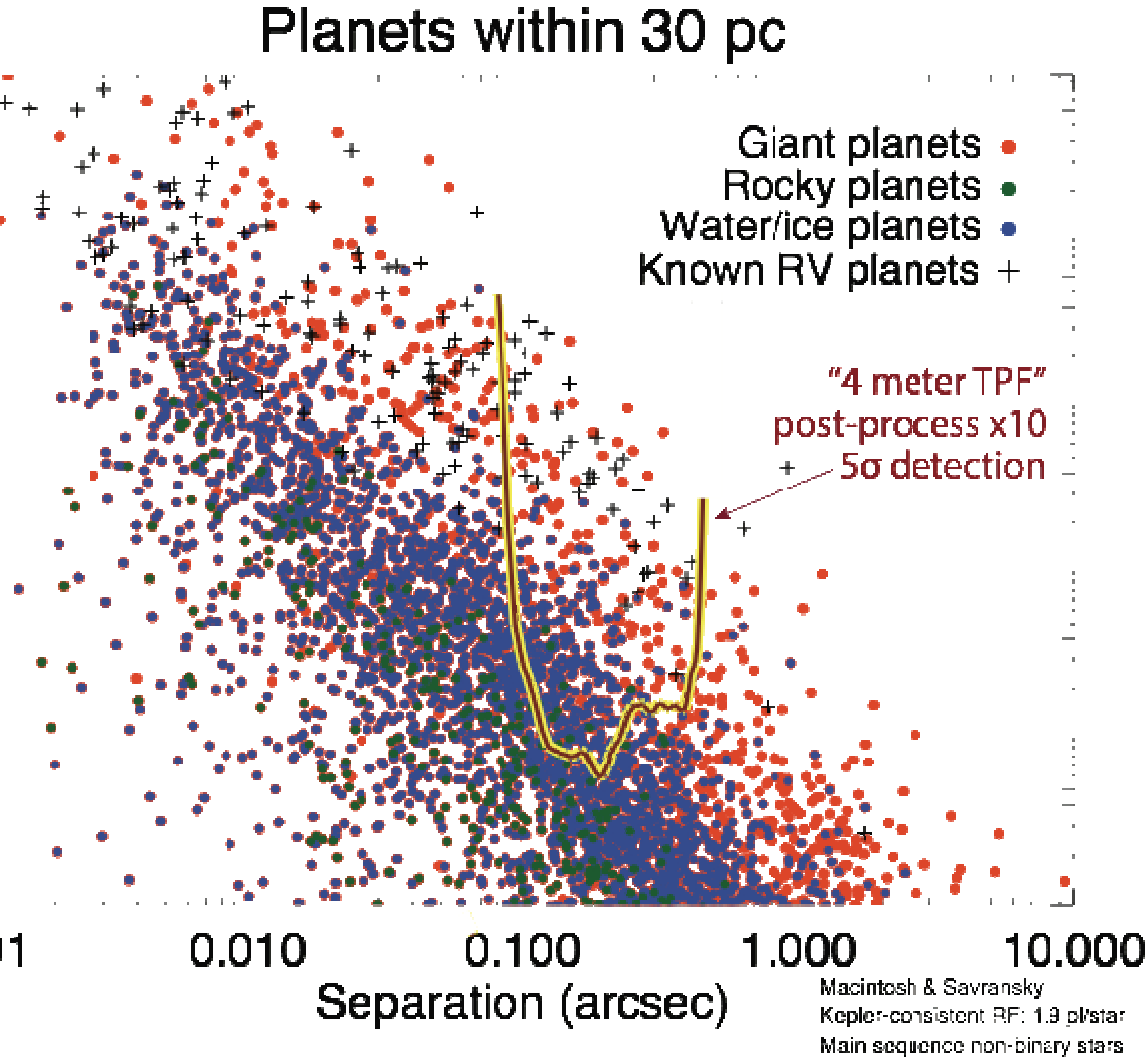
- *Real stars from the of nearby non-bina with a Kepler-cons simulated planet population (Macint Savransky 2013)*
- *Raw contrast curve for 10% bandwidth includes AFTA wav errors, 0.4 mas instrument-correcte pointing jitter.*

AFTA contra
vs.
a simulated pl
population



- Real stars with a si
planet population
(Macintosh & Savra
2013)
- Post processing cu
represents the 5σ e
detection threshold
following x10 speck
background subtrac
- The AFTA coronagr
detect exoplanets w
below the masses a
sizes of the known
planets.

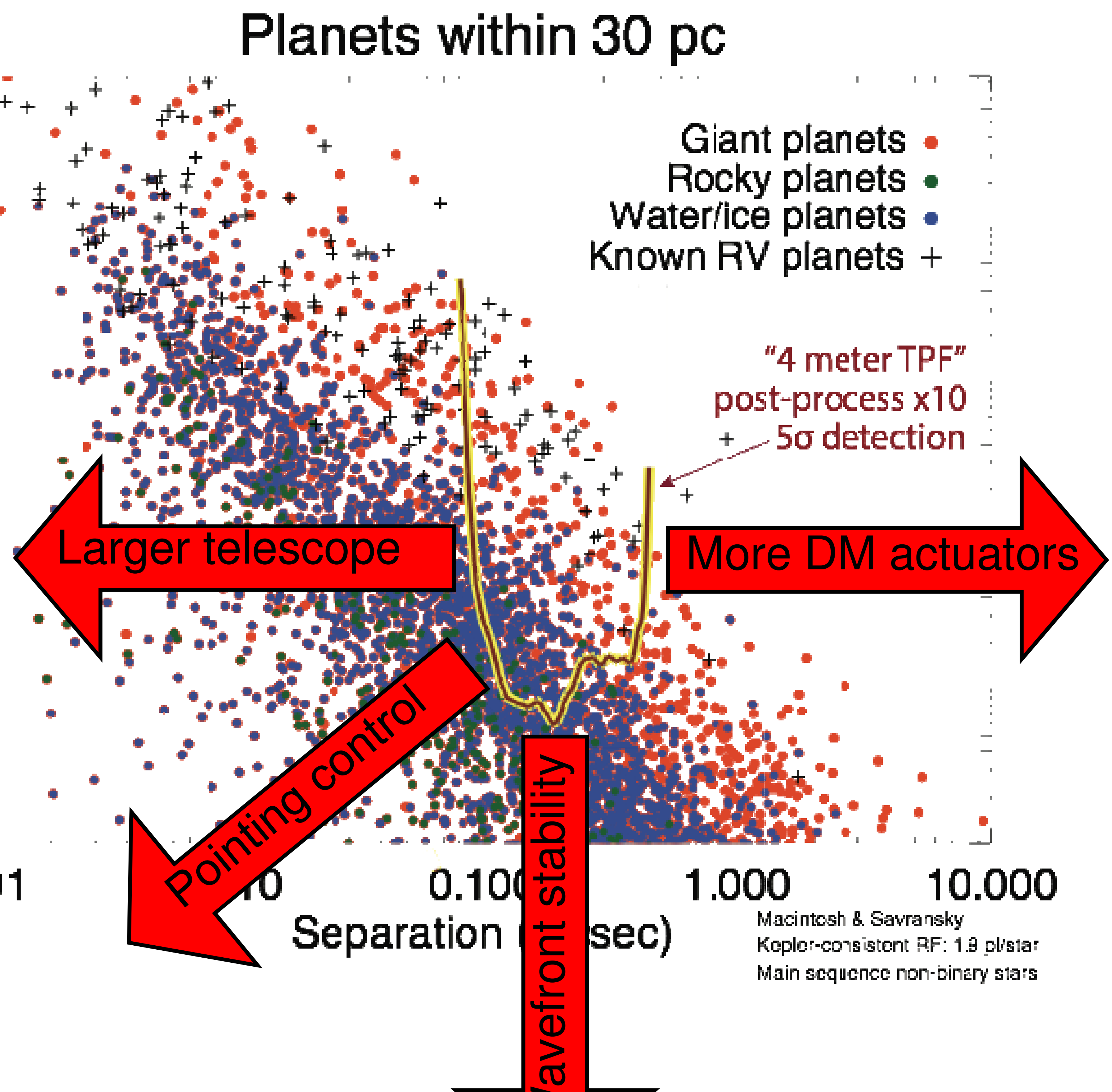
imaging mission



Coronagraph concept
exoplanet mission in t
decade will incorporat

- ***Smaller inner work** **angle** and **better con** using a large unobscu telescope, end-to-end stability, and mature p process speckle subtr methods.*
- ***Tighter PSF** and **be** with a larger telescope extends sensitivity to planets.*
- *E.g., a "**4-meter TP** coronagraph will dete exoplanets well below masses and sizes acc to AFTA, to include Ea exoplanets.*

imaging mission



The AFTA coronag
establishes a footh
pioneering exoplan
science and techno
actualizing the NW
recommendations f
New Worlds Techno
Development Progr

Performance of the
coronagraph illumin
the pathways and
priorities for New W
technology advanc
for the next-decade
exoplanet mission:
telescope size, stab
pointing, wavefront
control, post-proces

Summary

he AFTA candidate architectures were developed over the past decade by groups orking towards future missions. The AFTA selection process specifically scored th chitectures for relevance to future large missions, and those selected got the top ores.

he AFTA coronagraph development program is now organized to refine and emonstrate the fundamental technologies that are critical for a next-decade missio r the direct imaging and spectroscopy of Earth-like exoplanets.

particular, the characteristics and time scales for precision wavefront sensing and ntrol cannot be authoritatively tested in the laboratory – the AFTA space platform ovides critical information, unavailable in the laboratory, that is required for onfidence that a future large space mission is viable.

urrent and planned future work on the AFTA coronagraph development rogram specifically addresses all the Astro2010 recommendations for New orlds Technology Development.

End