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Managing the Wavefront for High Contrast Imaging from Space

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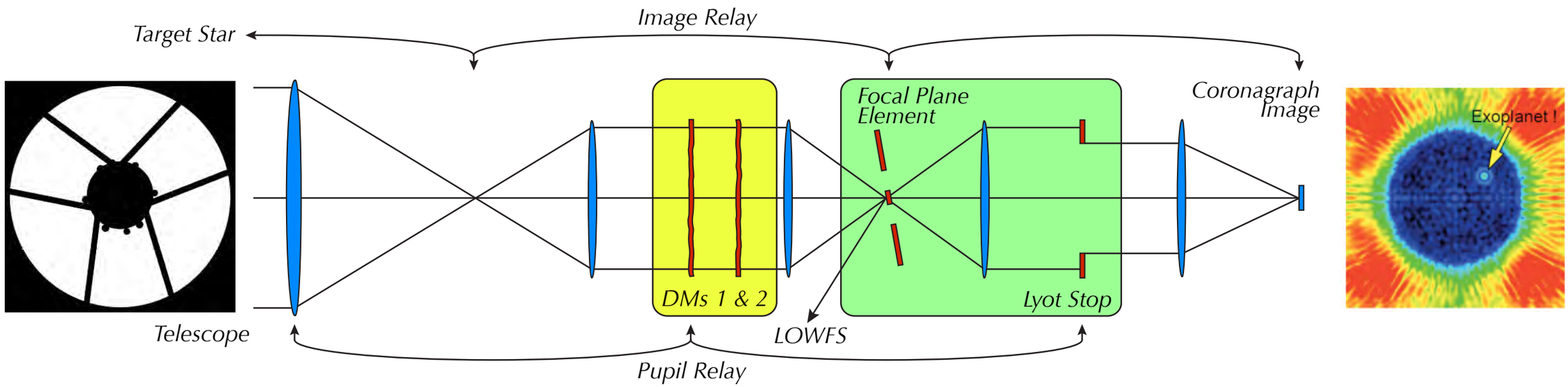
The AFTA Coronagraph breaks new ground in the characterization of exoplanet systems

- AFTA mission will ***enable, for the first time, the science*** of direct imaging and spectroscopy of cool mature planets from space, while ***responding to new engineering challenges***
- Planets will be seen in ***reflected starlight***
- Planets will be ***faint and close to the star***
- High contrast imaging requires ***complex (amplitude and phase) wavefront correction***
- High contrast imaging requires ***unprecedented telescope wavefront stability***
- Must ***anticipate the "unknown unknowns"*** of the technology before launch
- Must ***devise comprehensive (yet practical) system level tests*** for critical requirements
- Must of course stay ***within budget and schedule*** while controlling risk
- Mission will ***meet science expectations "out of the box" as launched***, on the first try, with performance margins where possible, and no prospects for upgrades or repairs after launch.

An actively corrected coronagraph



- Sketch of the essential elements of an ***actively corrected Lyot coronagraph*** includes
  - the ***sequential pair of deformable mirrors for control of the complex wavefront*** to create the high contrast dark field, correct for telescope static wavefront errors, compensate for thermal drift in the telescope optics, and
  - the ***coronagraph elements to suppress starlight diffracted by the telescope*** (HLC shown here, comparable diagrams describe the Shaped Pupil and PIAACMC coronagraphs).
- Coronagraph ***designs are matched to our current knowledge of the AFTA telescope***, have evolved (and continue to evolve) as we learn more about the AFTA static and dynamic wavefront characteristics.

AFTA coronagraph wavefront control

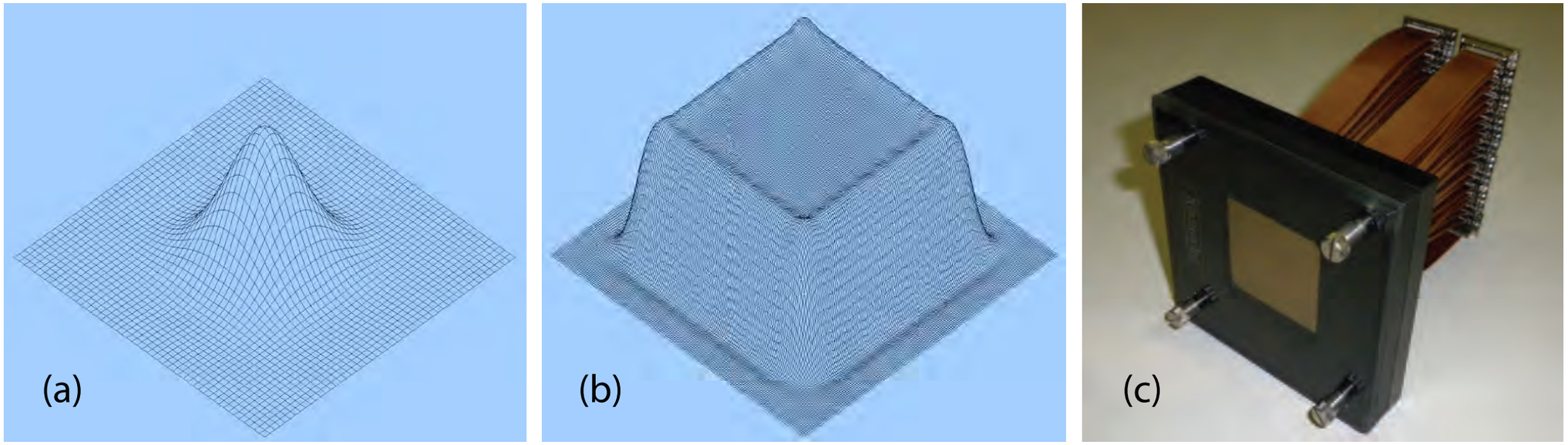
- Wavefront stability requirements exceed those of the WFIRST observatory, therefore ***sensing and correction of jitter and drift*** are implemented within the AFTA coronagraph.

- ***Response to pointing control requirements*** includes (1) coronagraph design for minimum sensitivity to pointing jitter, (2) guide camera using the starlight reflected directly from the focal plane mask without positional bias, and (3) pointing correction with a dedicated fast/fine steering mirror control loop within the coronagraph instrument.

- ***Response to low order wavefront jitter and drift*** includes (1) coronagraph design to minimize low order wavefront error sensitivities, where possible, (2) enable Zernike low order wavefront sensing by shaping the reflective phase of the focal plane mask, and (3) superimposing low order WF corrections on the settings for one of the DMs with a tight budget for open-loop DM surface control.

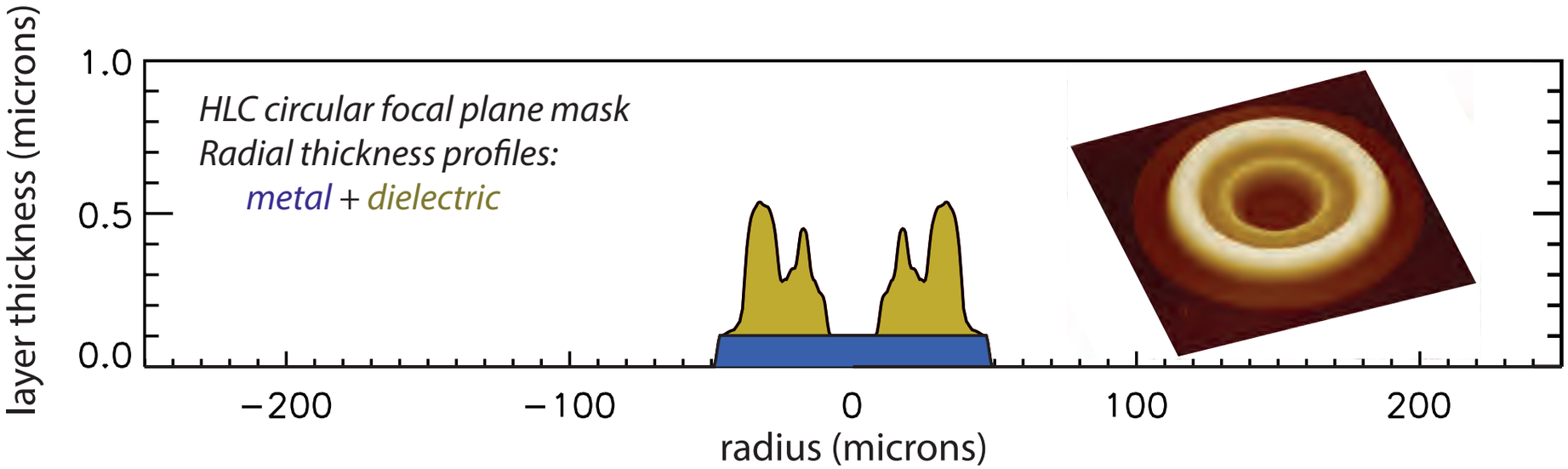
- AFTA challenge is to validate and demonstrate wavefront control at the required levels, which translates to ***10s of picometers rms***!

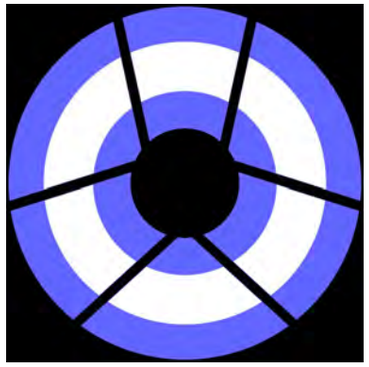
Wavefront control with deformable mirrors



- Xinetics DMs have been the ***workhorse for high contrast demonstrations*** over the past decade.
- AFTA coronagraph design incorporates a ***pair of 48x48 actuator DMs.***
- AFTA program ***will extend past developments*** by refining the manufacturing processes, carrying out a flight qualification environmental test program, and carrying out detailed calibrations.
- Fused silica mirror facesheet is flat to ***5 nm rms surface figure*** in the unpowered state.
- Surface profile has been ***measured to accuracies of 25 picometers rms*** in a vacuum interferometer with 0.1 x 0.1 mm sample density.
- Actuated surface deflections are ***stable to 0.1 nanometers / 100 hours*** in the vacuum laboratory environment.

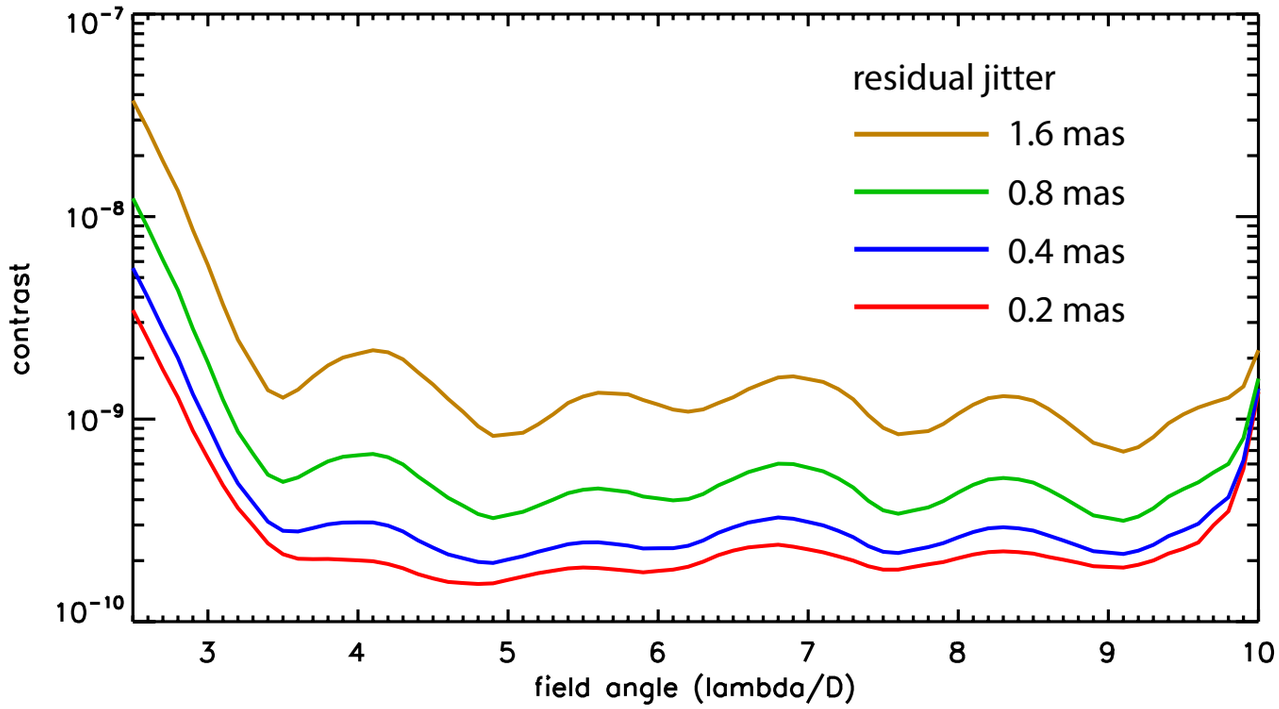
HLC coronagraph mode

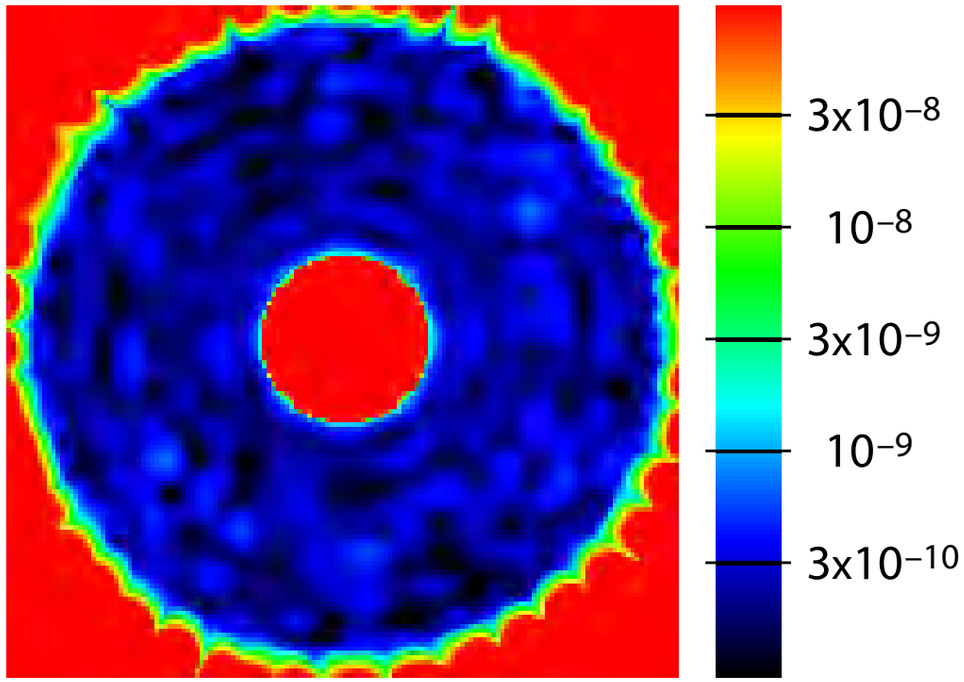




- These are the focal plane and pupil plane elements for the hybrid Lyot coronagraph instrument mode.
- Circular focal plane mask is comprised of two elements – one metal and one dielectric – to provide leverage over both the amplitude and phase (real and imaginary parts) of the incoming stellar PSF. At left, a plot of the radial thickness profiles of the metal and dielectric, and an AFM image of the manufactured mask.
- Central "phase dimple" shifts the starlight reflected from the central λ/D diameter by a quarter wave, providing both pointing control and low-order wavefront information to the AFTA zernike wavefront sensing system.
- Two manufacturing methods have been demonstrated for the focal plane mask.
- Shown at right, superimposed in blue on a silhouette of the AFTA pupil, the Lyot stop completes the HLC coronagraph.

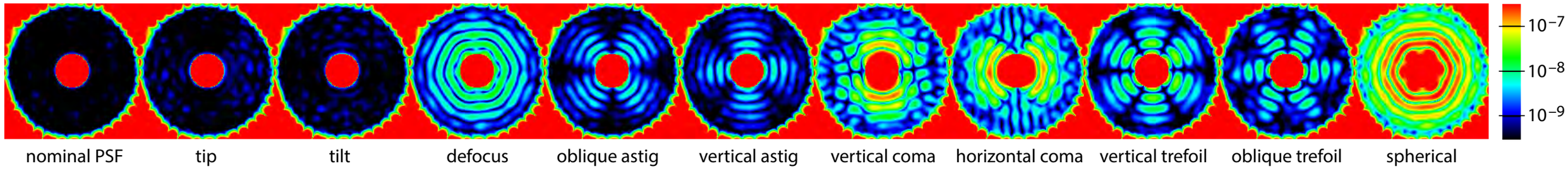
Coronagraph contrast sensitivity to pointing jitter



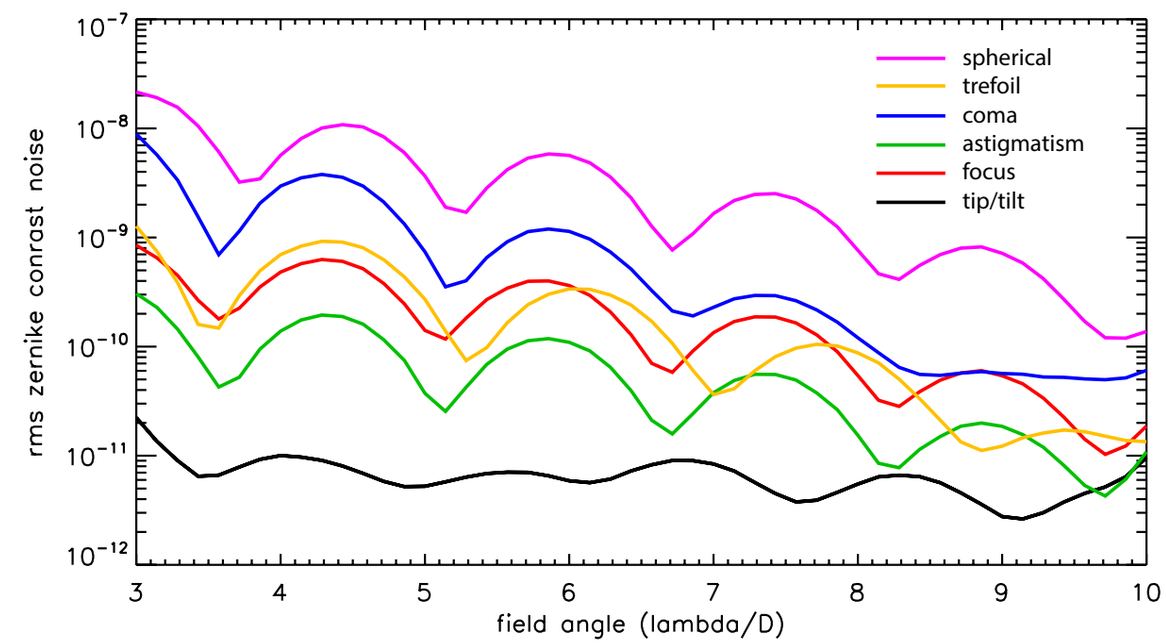


- Coronagraph design, utilizing the coronagraph elements and DM settings as free parameters, accommodates the expected range of residual pointing jitter in the AFTA coronagraph.
- High contrast dark field extends from 2.5 to 10 λ/D in radius, with spectral bandwidth of 10% centered on 550 nm, and with contrast vs. residual jitter as shown.

Coronagraph contrast sensitivity to low order wavefront jitter and drift

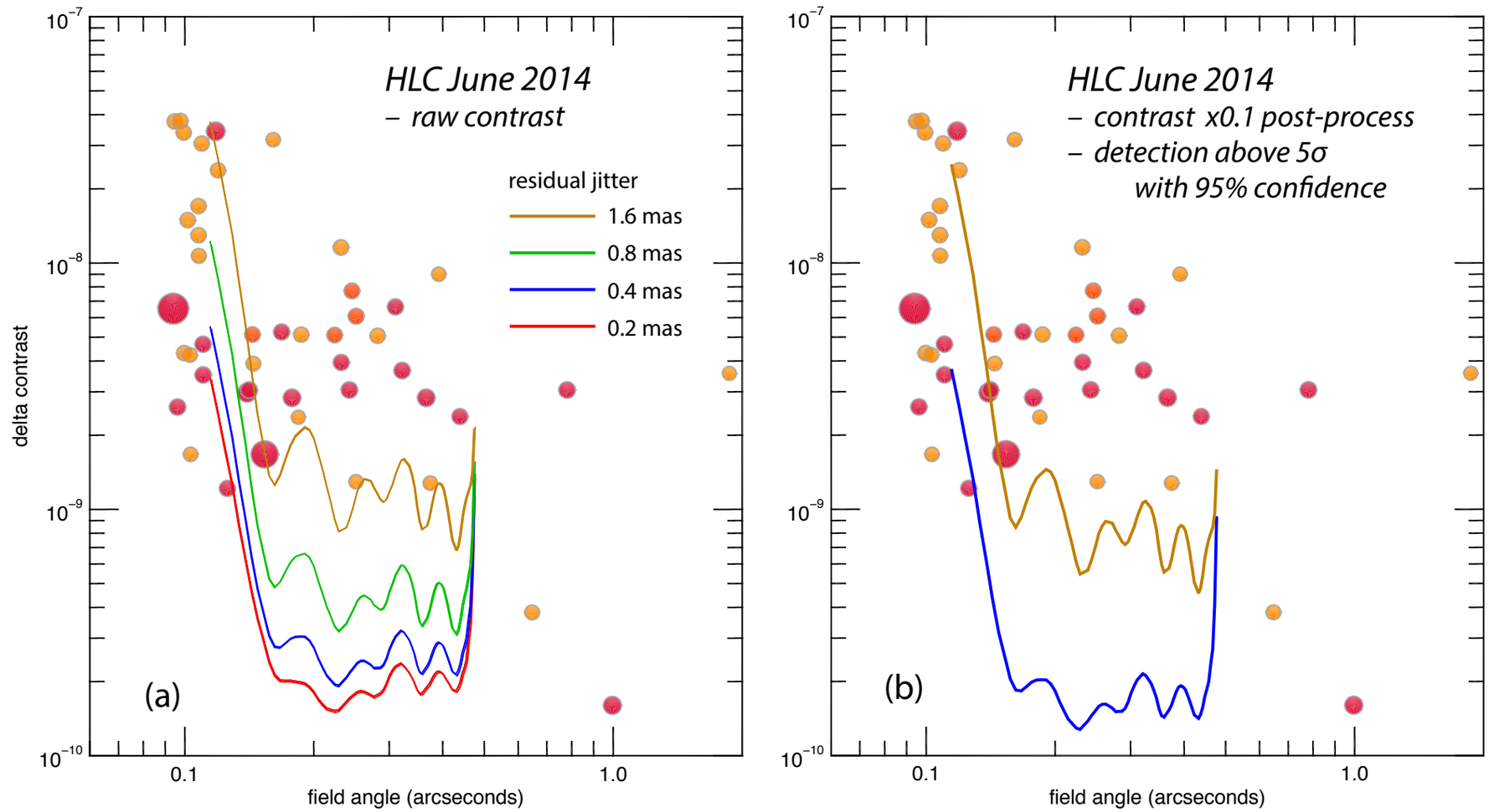


- Coronagraph design is tolerant to jitter, but sensitive to low order wavefront jitter and drift.
- Above, the appearance of dark fields (10% bandwidth, 0.4 mas rms jitter, 1 mas diameter star) in response to individual zernike wavefront errors of 100 pm rms introduced at the AFTA primary mirror.



- Plotted at right are the rms azimuthal variations between aberrated and nominal PSFs vs. radial separation for each zernike term.
- AFTA coronagraph will compensate for low order wavefront drift with a low order wavefront sensing and control (LOWFS&C) system.

Coronagraph design objective is greatest science yield



- Coronagraph contrast superimposed on a delta-magnitude plot of the known RV planets with maximum separations of 100 mas or larger. Raw contrast at left, representative post processing result at right.
- Contrast, IWA, OWA, spectral bandwidth are all balanced for greatest science yield.
- Refinements to the coronagraph designs continue, as ongoing engineering analyses provide improved knowledge of the AFTA telescope performance.

Post-processing

- ***ADI (Angular Difference Imaging)? RDI (Reference PSF Difference Imaging)? SDI (Spectral Difference Imaging)?*** It all all depends on wavefront stability.

- ***ADI Pro:*** we expect that telescope roll maneuvers will provide the shortest time delays and minimum WF drift, so knowledge of thermal evolution during roll on a given star may be the most accurate among the observing scenarios. ***Con:*** AFTA limitation to ±15 degree rolls likely limits the IWA to ~3 λ/D or larger

- ***RDI Pro:*** IWA restriction is relaxed. ***Con:*** expect larger WF drift due to longer time delays for slew and stabilization on reference star, RDI comparison involves two (or more) star PSFs with different colors, stellar diameters, zodi, background objects, and different solar illumination of the observatory.

- ***SDI is not viable*** for 10-9 dark holes, since the spectral character of the high contrast dark field is a complex equipartition of phase and amplitude, and working angles are just a few λ/Ds.

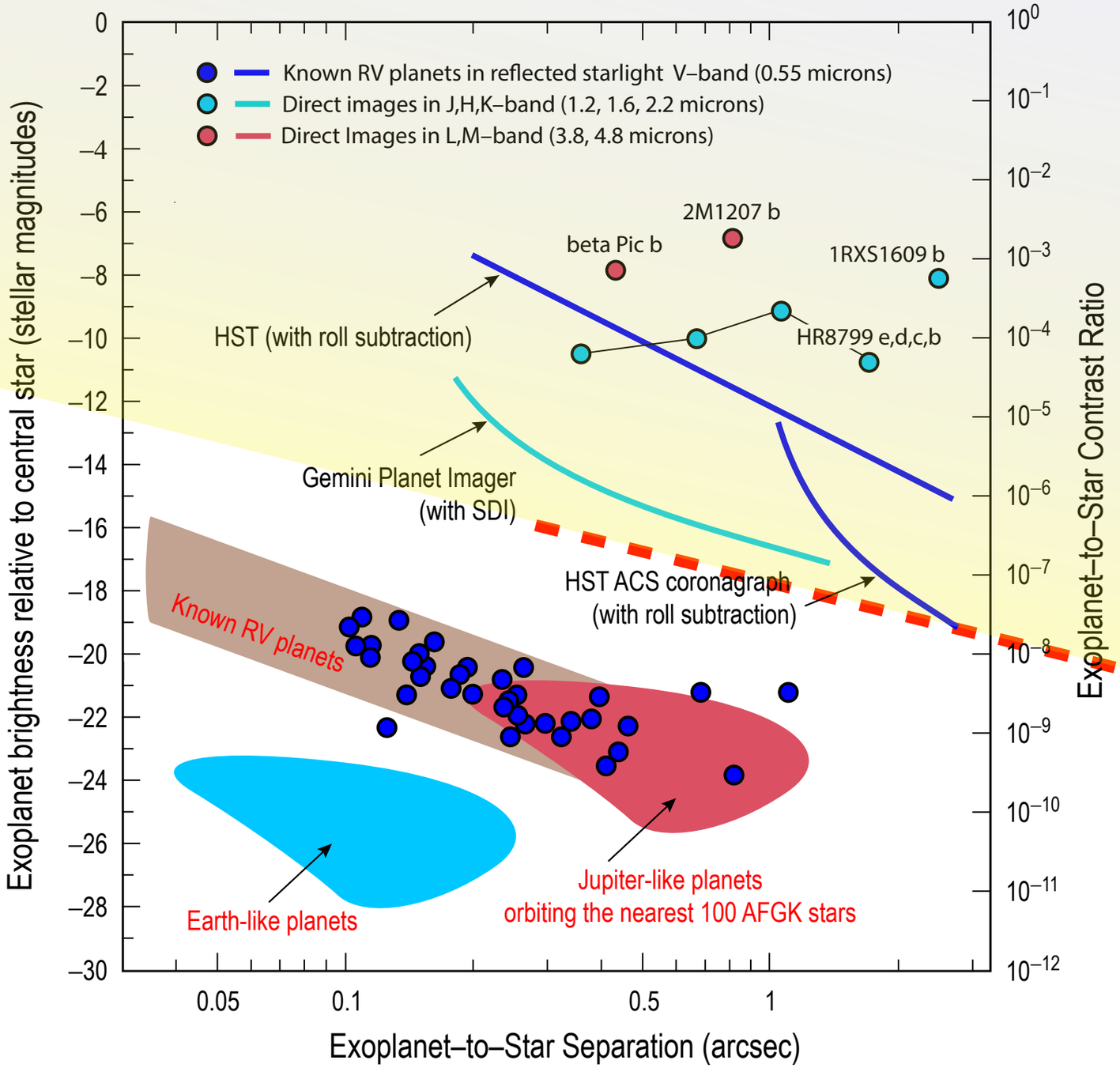
- Can we count on ***post-processing to improve contrast*** by factors of 10? 30? Post-processing studies are already underway at the STScI and JPL.

Summary

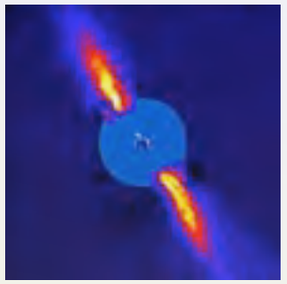
- AFTA coronagraph design and post processing strategies will be matched to our best knowledge of the AFTA telescope.
- Wavefront stability and control is our greatest technical challenge.
- The AFTA coronagraph will provide our first images of mature exoplanets in reflected starlight, and its technology development specifically addresses the Astro2010 recommendations for New Worlds Technology Development.

Backup

Wavefront control defines the contrast limits and science domains for space and ground based observatories

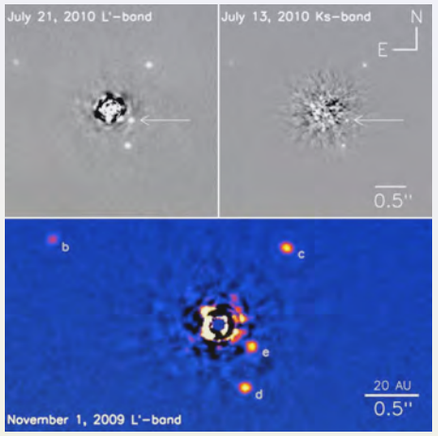


beta Pic b



Lagrange et al. 2010

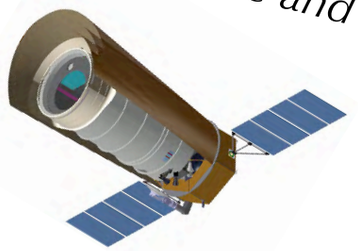
HR8799 b,c,d,e



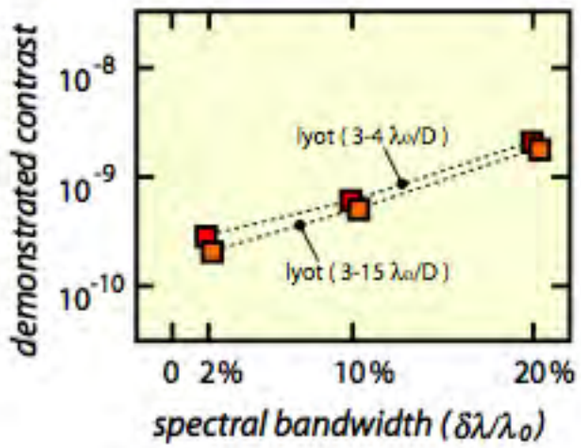
Marois et al. 2010

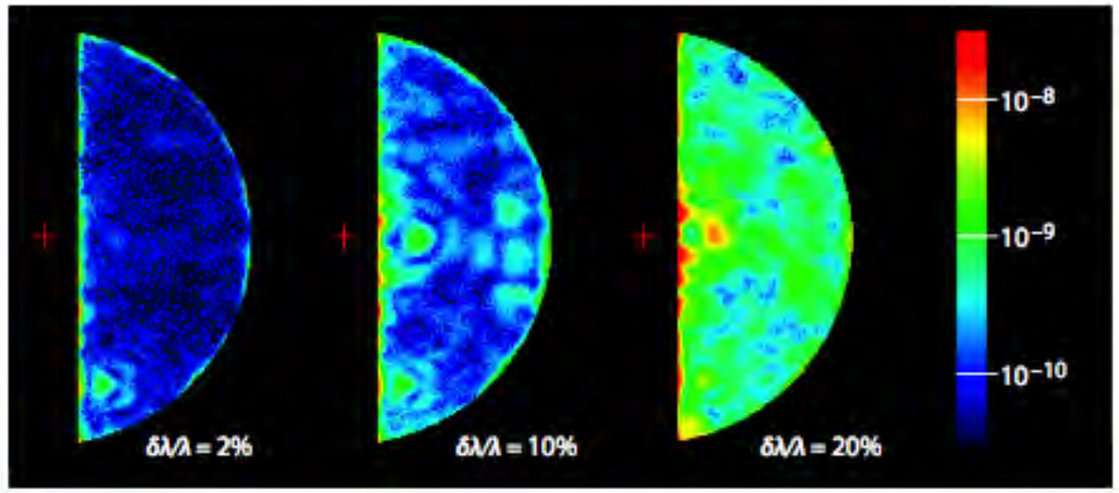
Phase-dominated wavefront errors

Equipartition of phase and amplitude errors



AFTA coronagraph performance validations are an extension of ASMCS and SAT/TDEM laboratory demonstrations



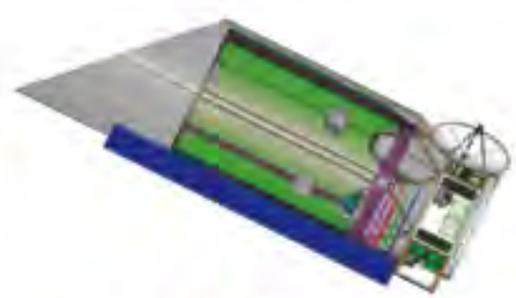


- ***Wavefront sensing and control*** *is carried out exclusively with deterministic DM settings (small surface patterns) and imagery at the science focal plane. The procedure is iterative and avoids all non-common-path amplitude and phase errors.*
- *Coronagraph and wavefront control performance models have been* ***validated to the 2e-10 contrast level*** *in HCIT demonstrations – e.g., as shown for hybrid Lyot coronagraph with a linear focal plane mask as part of the SAT/TDEM program in July 2011.*
- *We adapt our* ***validated coronagraph performance models*** *to the AFTA coronagraph.*

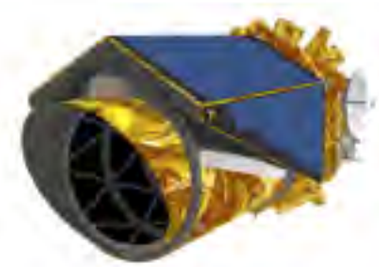
AFTA inherits recent coronagraph technology advancements

- *The AFTA coronagraph development hits the road running – benefiting from NASA sponsored 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.*
- *As a result, most of the critical technologies have been identified and are already poised to advance to flight readiness.*
- *AFTA investments are accelerating technology readiness, mindful of the lessons learned and system engineering from recent ASMCS mission concept and TDEM technology studies.*

ASMCS/ACCESS
(Lyot, Vortex, Shaped Pupil, PIAA)

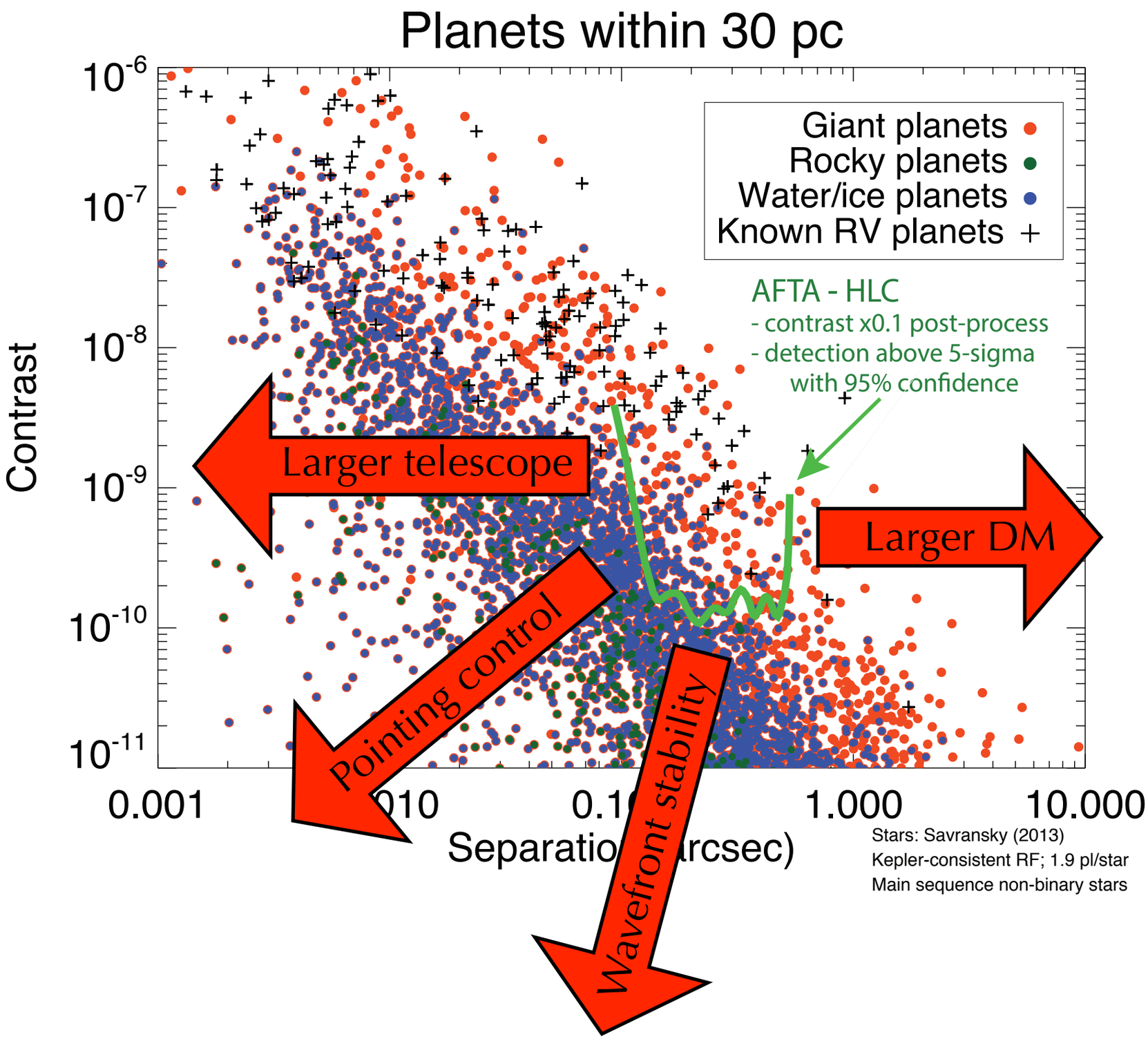


ASMCS/PECO
(PIAA)



ASMCS/EPIC
(VisNuller)

AFTA coronagraph is a pathfinder for a next-decade exoplanet imaging mission



The AFTA coronagraph establishes a foothold in pioneering exoplanet science and technology – actualizing the NWNH recommendations for a New Worlds Technology Development Program.

Performance of the AFTA coronagraph illuminates the pathways and priorities for New Worlds technology advancement for the next-decade exoplanet mission: telescope size, stability, pointing, wavefront control, post-processing, etc.

End