The WFIRST Coronagraph Instrument – An update

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Jet Propulsion Laboratory
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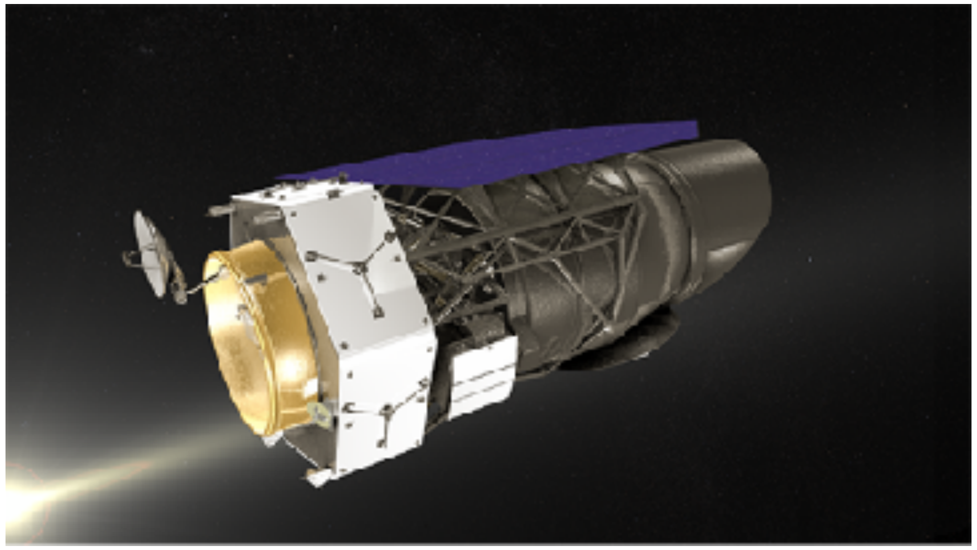
The decision to implement the WFIRST mission will not be finalized until NASA completes the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

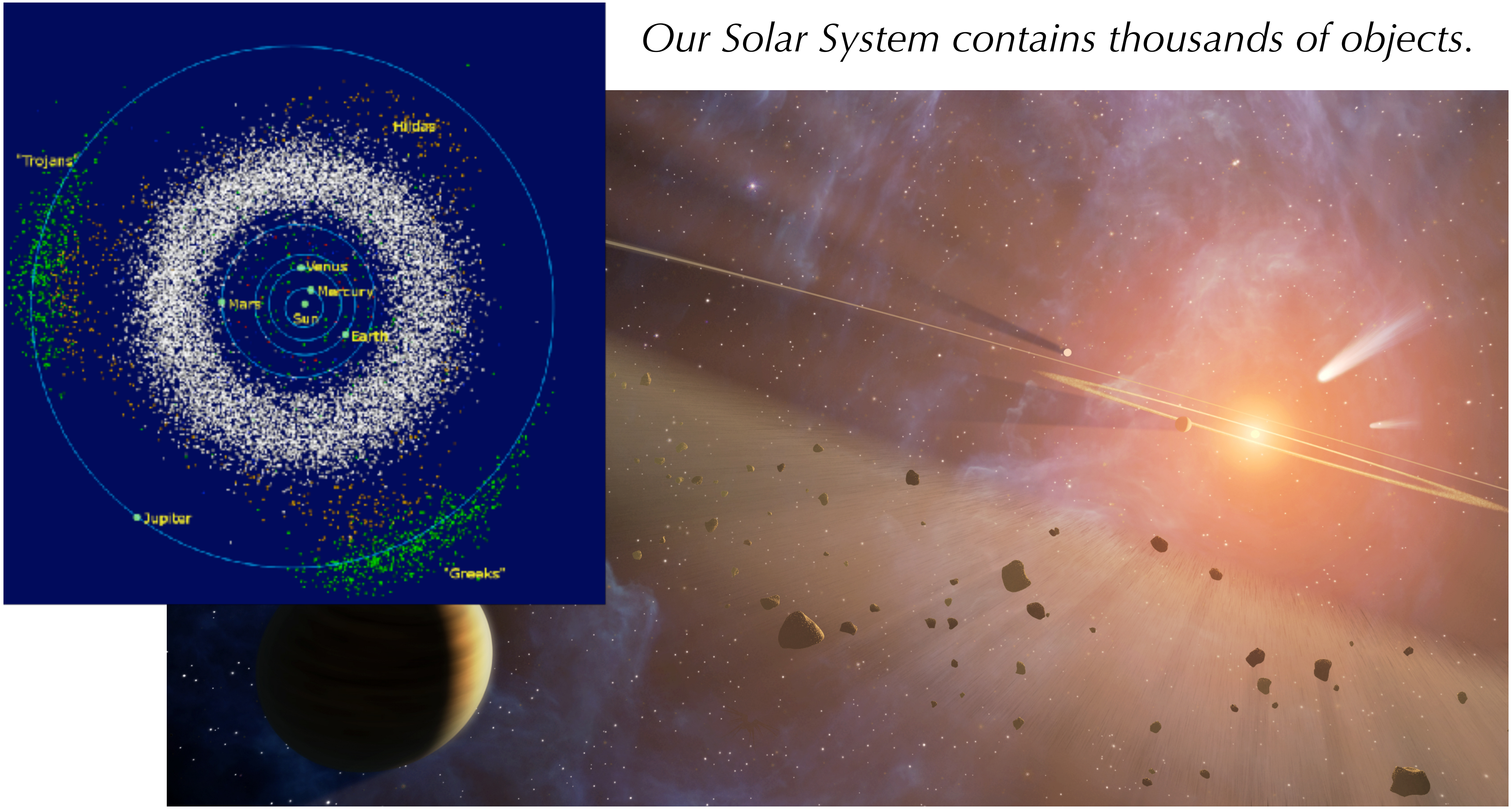
The WFIRST Coronagraph Instrument is designed for the direct imaging of exoplanet systems



- WFIRST hosts two instruments: the Wide Field Imager (WFI) emphasizing dark energy investigations, and the coronagraph instrument (CGI) to advance the technologies for ***extreme high contrast imaging*** and spectroscopy from space.
- Paves the way for ***future exo-Earth flagship missions*** now envisioned as the HabEx and LUVOIR concepts.
- Mature planets are seen in ***reflected starlight***, and will be ***faint*** and ***close to the star*** (relative intensities are parts per billion, separations are tenths of an arcsecond).
- CGI advances the essential technologies for control of the ***complex (amplitude and phase) optical wavefront to picometer levels*** with the WFIRST 2.4 meter space telescope.
- WFIRST, scheduled for launch in 2025, is now progressing from Phase A to Phase B.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Objective is imaging observations of exoplanet systems



Our Solar System contains thousands of objects.

Direct imaging adds a critical dimension to the exploration of exoplanet systems that are likely to be equally complex.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

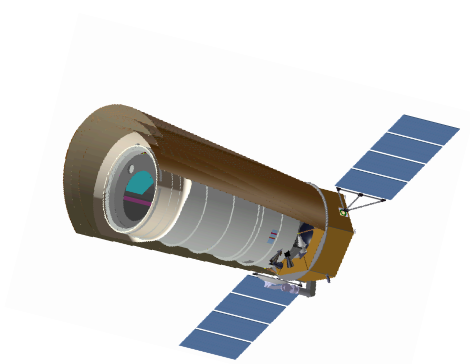
CGI inherits recent coronagraph technology developments

- ***WFIRST CGI is intended to advance observatory performance models and validate them against actual on-orbit performance.***

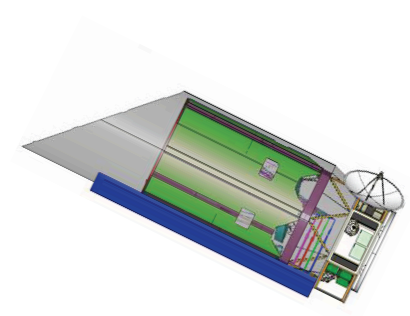
- The ***CGI design benefits from knowledge gained*** from the past decade of science mission concept studies and ground-based experience.
  - Space mission studies for groundbreaking exoplanet science (Astrophysics Strategic Mission Concept Studies/ACCESS, PECO, EPIC, 2009) and the Exo-C mission concept study (2015).
  - Technology developments (NASA/SAT/TDEMs for space coronagraphs)
  - Direct imaging experience (GPI, SPHERE, SCExAO/CHARIS) from ground-based observatories.

- The ***CGI establishes a pioneering foothold*** in direct imaging of exoplanet systems, validating science performance predictions while providing a science baseline for future exoplanet mission planning.

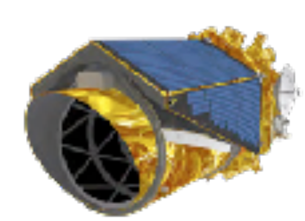
Ground Observatories



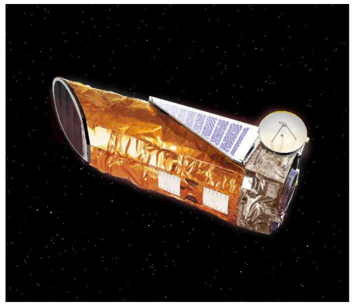
Concept studies: ASMCS/ACCESS



ASMCS/PECO



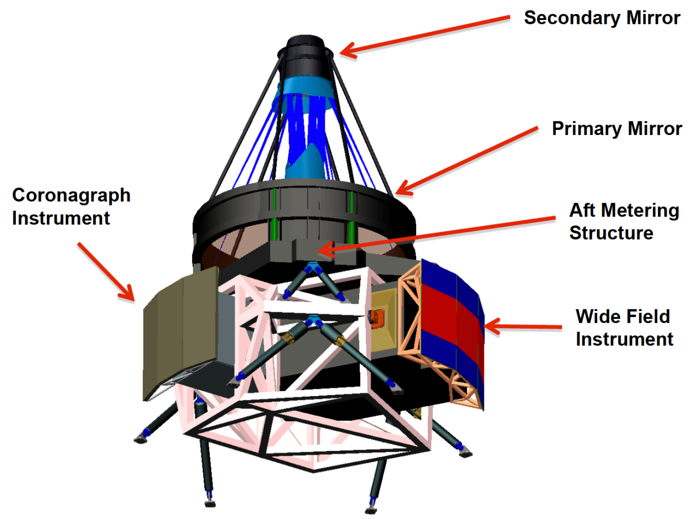
ASMCS/EPIC

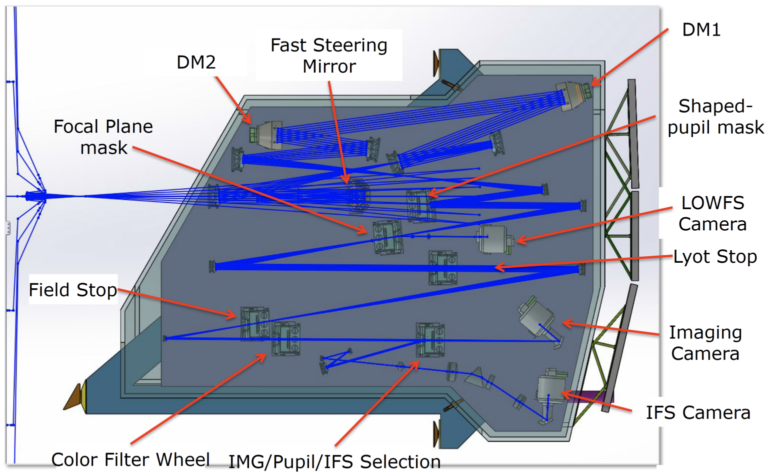


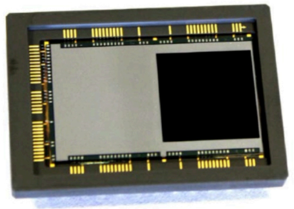
Exo-C

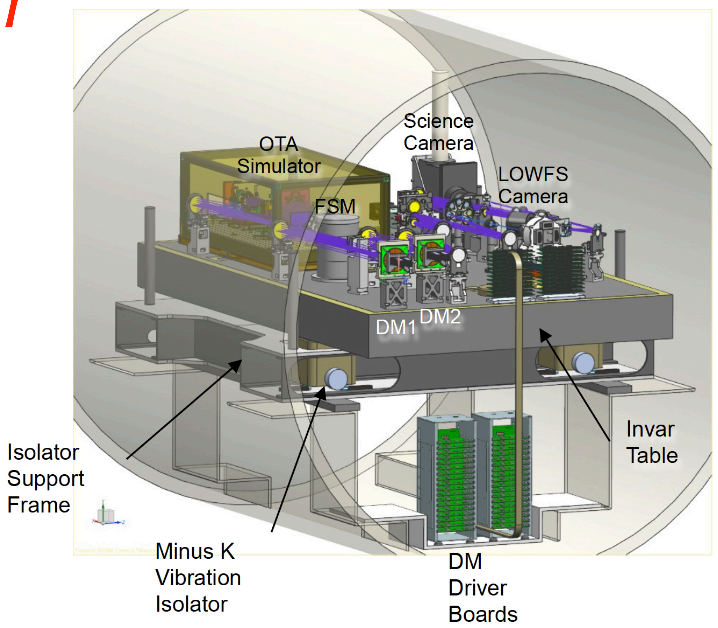
(J. Trauger, Mirror Tech Workshop, 11/16/2017)

CGI is a technology pathfinder

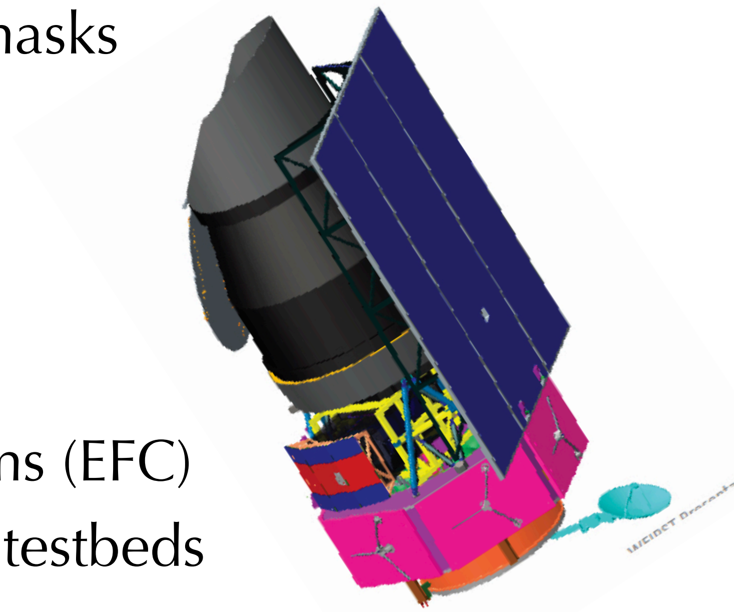






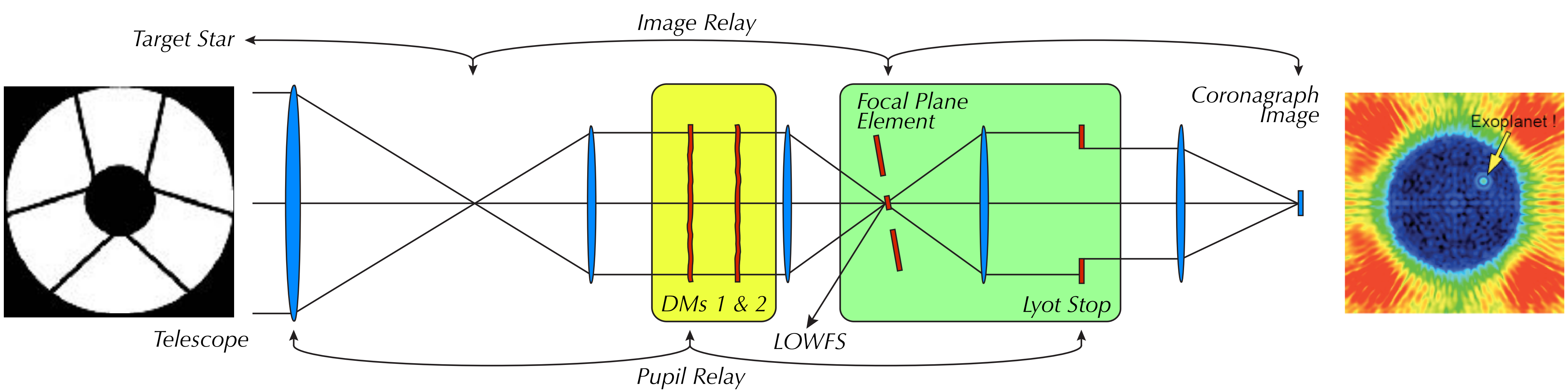


- Opto-mechanical design of the CGI instrument
- Integrated modeling of the end-to-end telescope-instrument optical system
- Design and fabrication of coronagraph focal plane and pupil plane masks
- High-order precision wavefront sensing at the science focal plane
- Low order Zernike wavefront sensing
- Low order wavefront control with the deformable mirror
- DM actuator calibration and operational strategies for best stability
- Laboratory development of high-contrast dark field creation algorithms (EFC)
- Validation of static and dynamic wavefront control on the laboratory testbeds
- Jitter control with a momentum-compensated fast steering mirror
- Low-noise EMCCD development and laboratory validations
- Tolerance analysis of the coronagraph components
- Exoplanet science yield calculations based on end-to-end observatory models



(J. Trauger, Mirror Tech Workshop, 11/16/2017)

CGI is an actively corrected coronagraph



- Sketch of the essential elements of an ***actively corrected Lyot coronagraph*** includes
  - the ***pair of deformable mirrors for control of the complex wavefront*** to create the high contrast dark field of view, to correct for telescope static wavefront errors, to compensate for thermal drift in the telescope optics, and …
  - the ***coronagraph elements to suppress starlight diffracted by the telescope*** (Hybrid Lyot coronagraph shown here – a comparable diagram describes the Shaped Pupil coronagraph).
- Coronagraph ***design is matched to our current best knowledge of the WFIRST telescope***. Refinements to the design continue as we learn more about the WFIRST static and dynamic wavefront characteristics.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

WFIRST CGI wavefront control

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

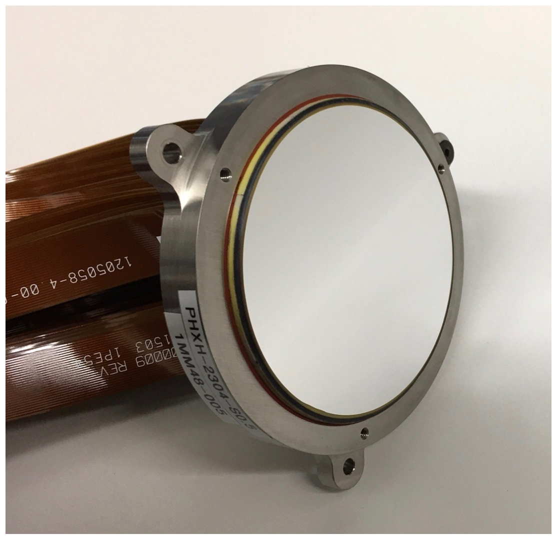
- ***High-order wavefront control*** is implemented with a pair of DMs, using wavefront phase and amplitude information sensed at the science focal plane.

- ***Pointing control and jitter:*** (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.

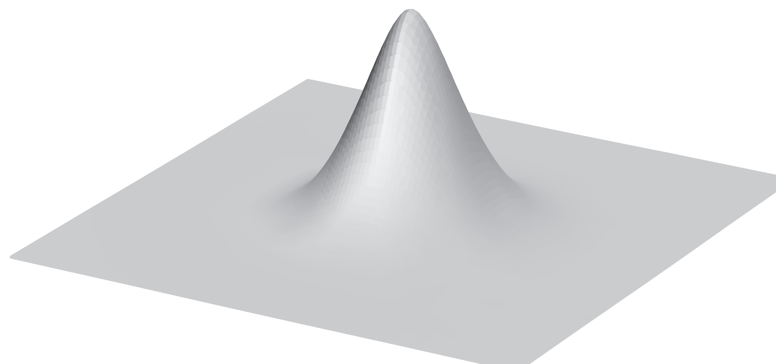
- ***Low order wavefront drift:*** (1) coronagraph design to minimize sensitivities to low order wavefront errors, where possible, (2) the low order Zernike wavefront sensing technique enabled by shaping the reflective phase of the focal plane mask, and (3) correction of low order WF drift using one of the DMs with a tight budget for open-loop DM surface control.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

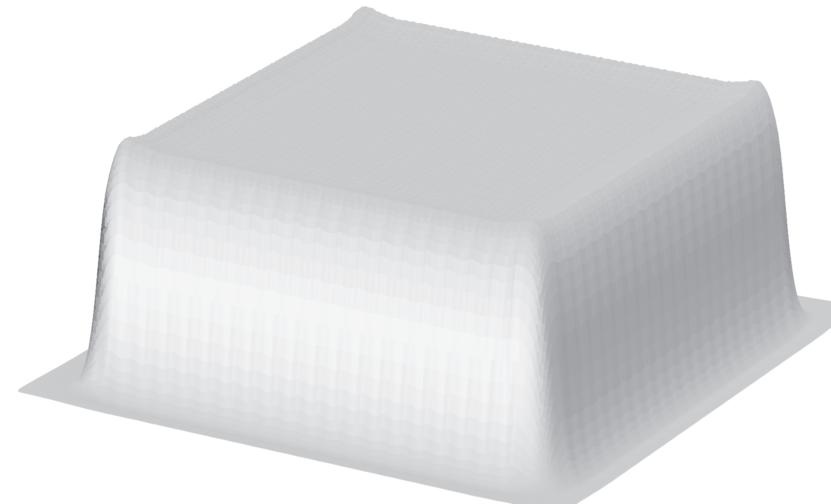
High-order wavefront control with deformable mirrors



Xinetics 48x48 DM
(2304 actuators on a 1x1-mm pitch)



Single actuator influence profile



A 20x20 array of these profiles sums to a flat surface

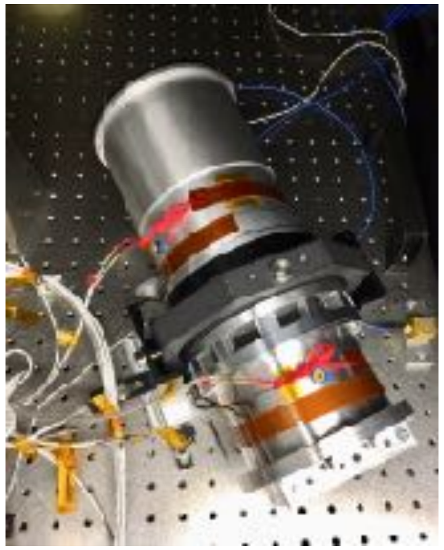
- WFIRST coronagraph design incorporates a ***pair of 48x48-actuator deformable mirrors (DMs).***
- Developments of DM hardware and control algorithms over the past decade have enabled ***high-contrast demonstrations*** in the laboratory, as recorded by NASA-sponsored ASMCS, TDEM, TPF-C, and recent WFIRST coronagraph milestones.
- WFIRST CGI program is intended to advance the flight DM technology to Technology Readiness Level TRL9.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Characterization of the deformable mirrors

- Laboratory ***Vacuum Surface Gauge (VSG)*** is an imaging interferometer mounted within a vibration-isolated vacuum chamber.
- VSG images the DM surface with 250 pixels / mm^2, measures individual actuator surface motions to 50 pm rms with background/parasitic signals < 1%.
- It is being used to ***characterize flight-like 48x48 Xinetics DMs***. Our objectives are:
  - Measure surface influence profiles and calibrate surface .
  - Characterize stability, drift, and hysteresis to picometer rms levels.
  - Develop DM surface control algorithms to match flight operational requirements.

VSG is certified for JPL critical items.



VSG fixture for tests of the 48x48 DM

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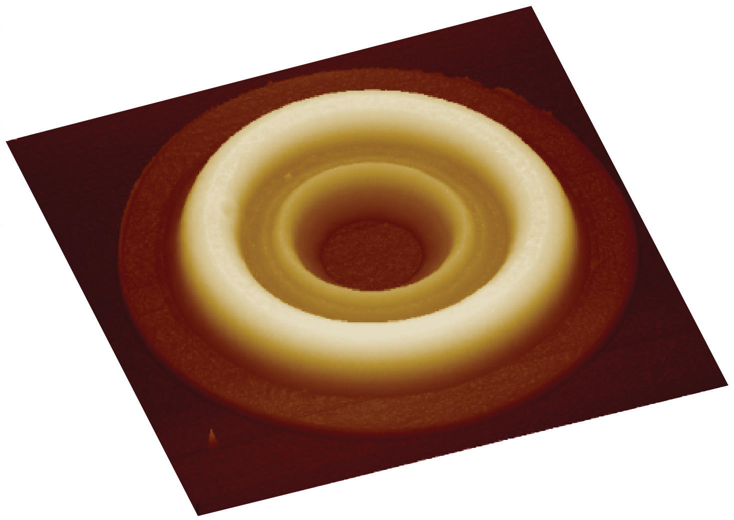
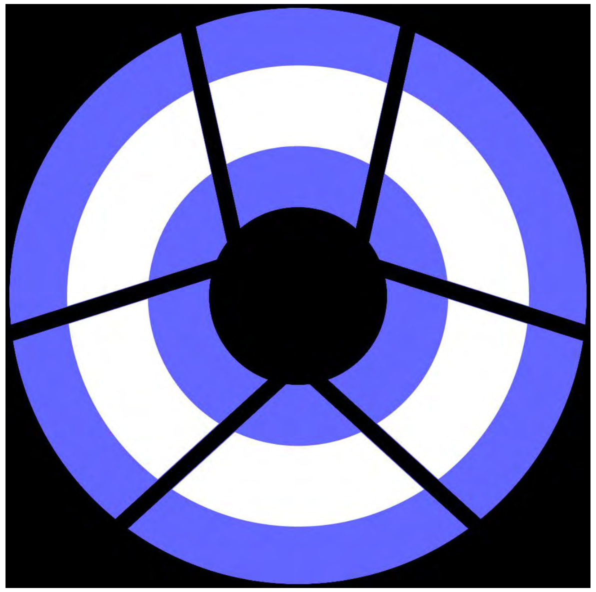
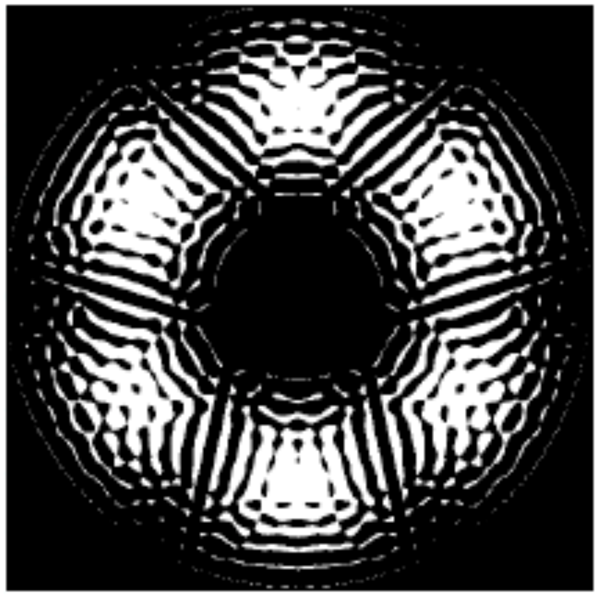
CGI coronagraph masks



HCL metal-dielectric mask (100 micron dia)



HLC Lyot stop

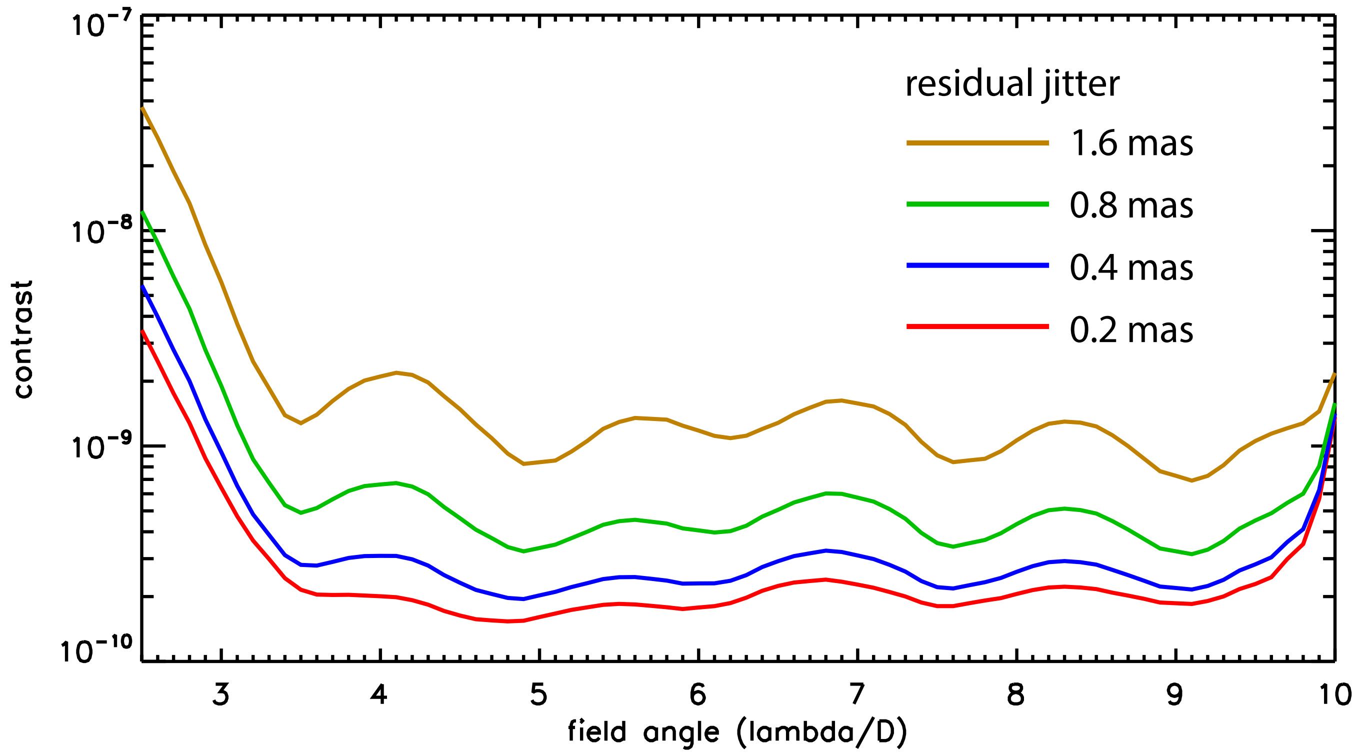


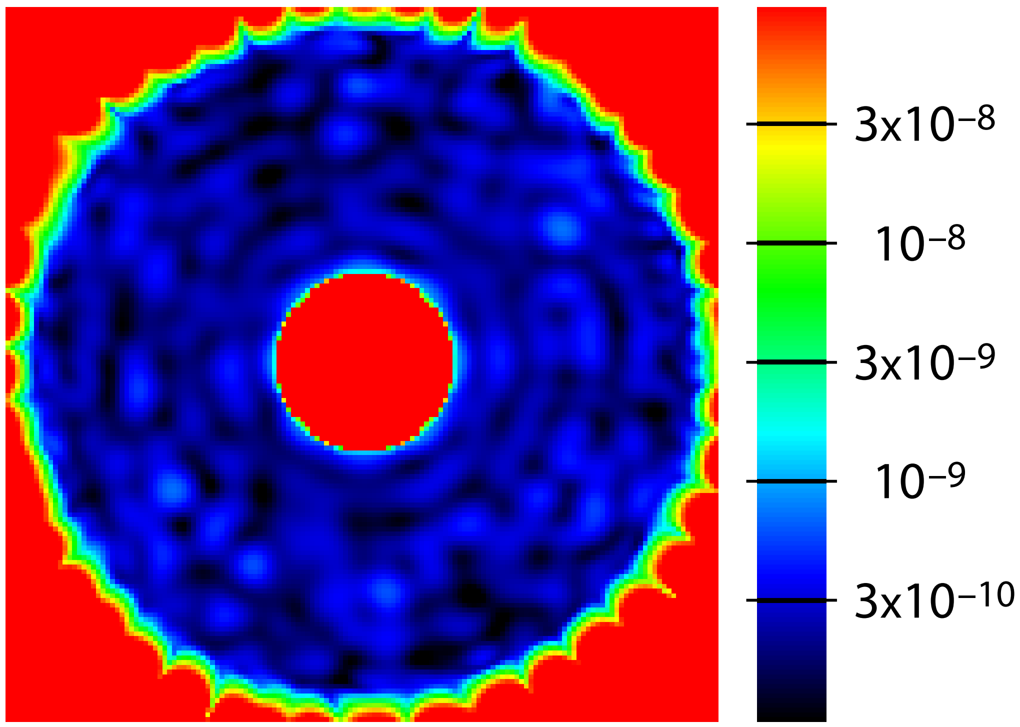
Shaped pupil mask for disk science

- These are examples of focal plane and pupil plane elements for the hybrid Lyot (HLC) and shaped Pupil (SPC) coronagraph modes.
- HLC focal plane mask is comprised of two layers – one metal and one dielectric – to provide leverage over both the amplitude and phase (real and imaginary parts) of the incoming stellar PSF. It is fabricated by JPL's MicroDevices Laboratory.
- At center, superimposed in blue on a silhouette of the WFIRST pupil, the Lyot stop completes the HLC coronagraph.
- At right, one of several SPC masks, inserted into the optical path upstream of an opaque focal plane occulting mask. It is also fabricated by JPL's MicroDevices Laboratory.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph high-contrast dark field of view

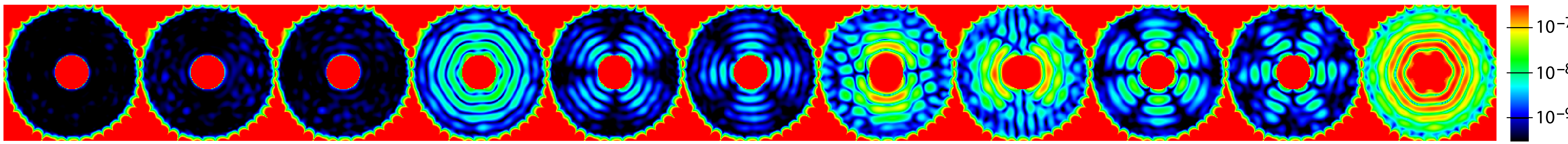




- HLC design optimization utilizes the ***focal plane mask, Lyot stop, and DM settings as free parameters.***
- High contrast dark field extends from ***2.8 to 10 λ/D in radius*** with ***10% spectral bandwidth*** centered on 550 nm.
- ***Full 360° field*** is optimal for initial imaging of RV planets and blind searches for new planets, where the orbital parameters are yet unknown.
- Design anticipates the expected range of ***residual pointing jitter*** in the WFIRST coronagraph. (Figure does not include other sources of wavefront error.)

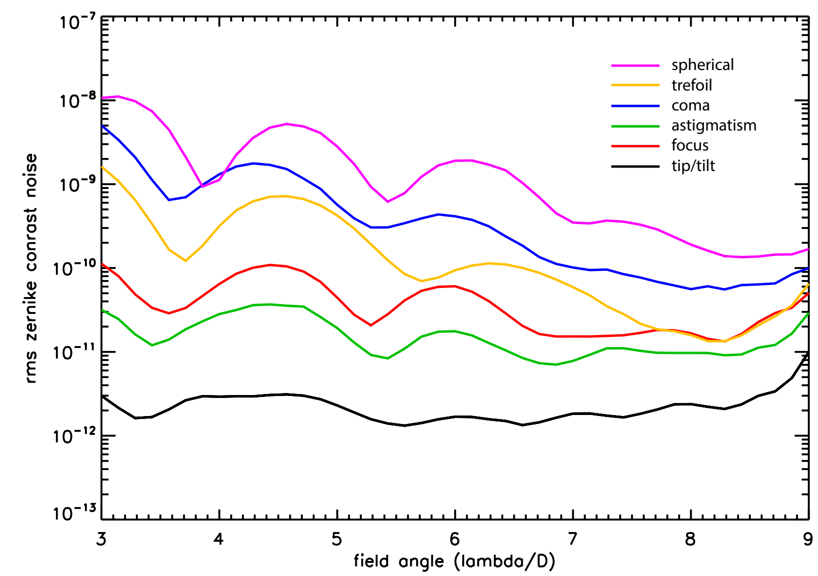
(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph contrast sensitivity to wavefront drift



nominal PSF | tip | tilt | defocus | oblique astig | vertical astig | vertical coma | horizontal coma | vertical trefoil | oblique trefoil | spherical

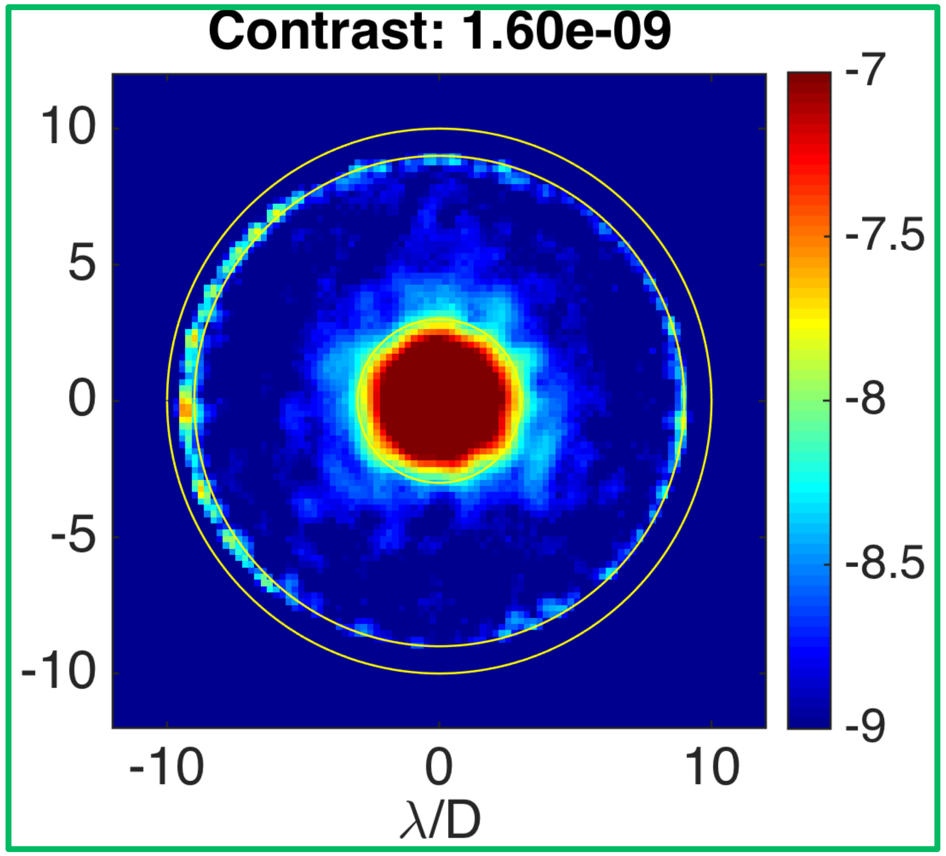
- Coronagraph design is tolerant to jitter, but sensitive to low order wavefront drift.
- Above, the appearance of dark fields (10% bandwidth, 0.4 mas rms jitter, 1 mas diameter star) in response to individual zernike wavefront errors of 100 pm rms introduced at the WFIRST primary mirror.

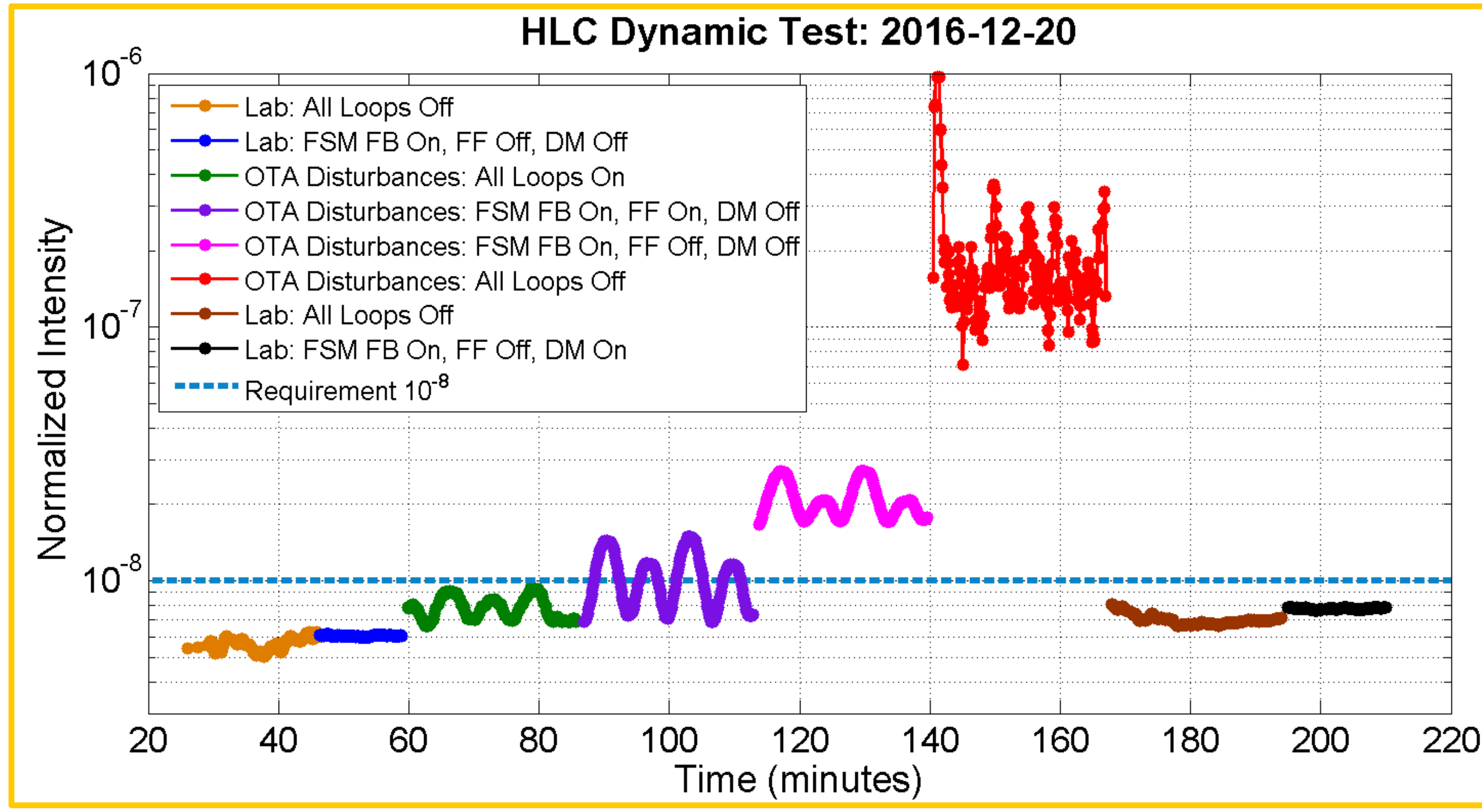


- Plotted are the rms azimuthal variations between aberrated and nominal PSFs vs. radial separation for each zernike term.
- Coronagraph will compensate for low order wavefront drift with a low order wavefront sensing and control (LOWFS&C) system.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph contrast demonstrations

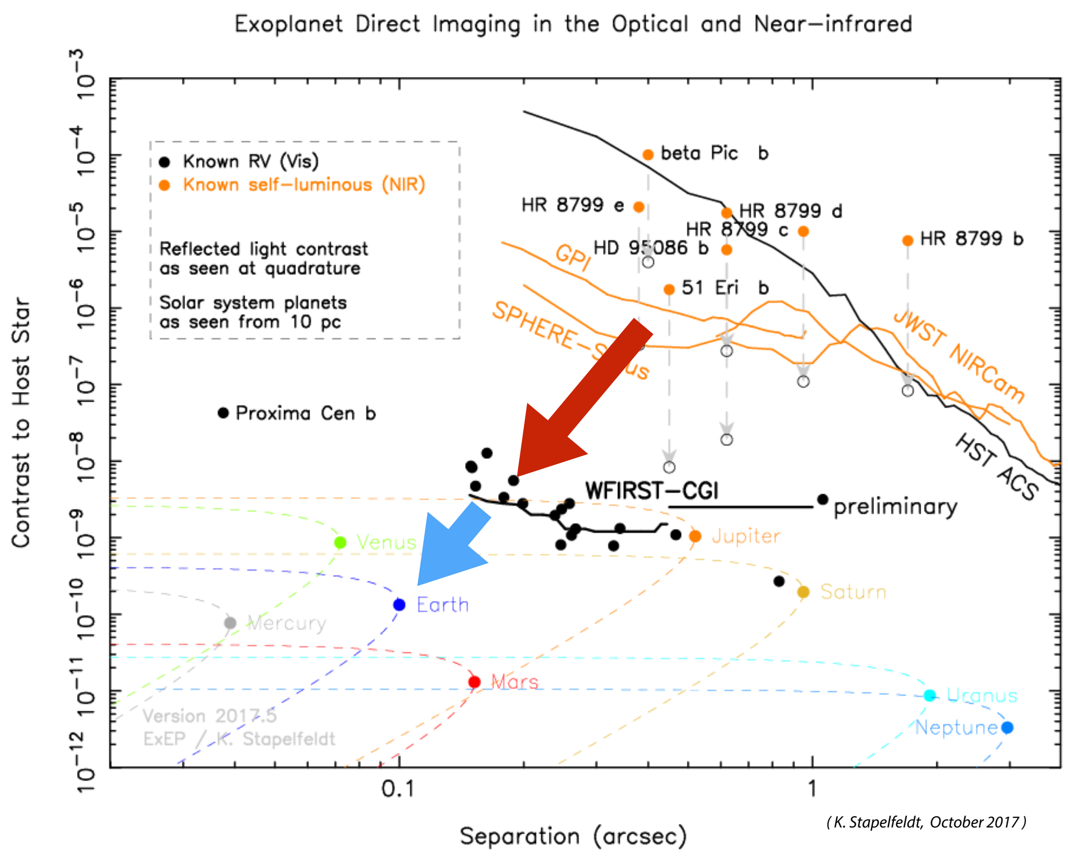


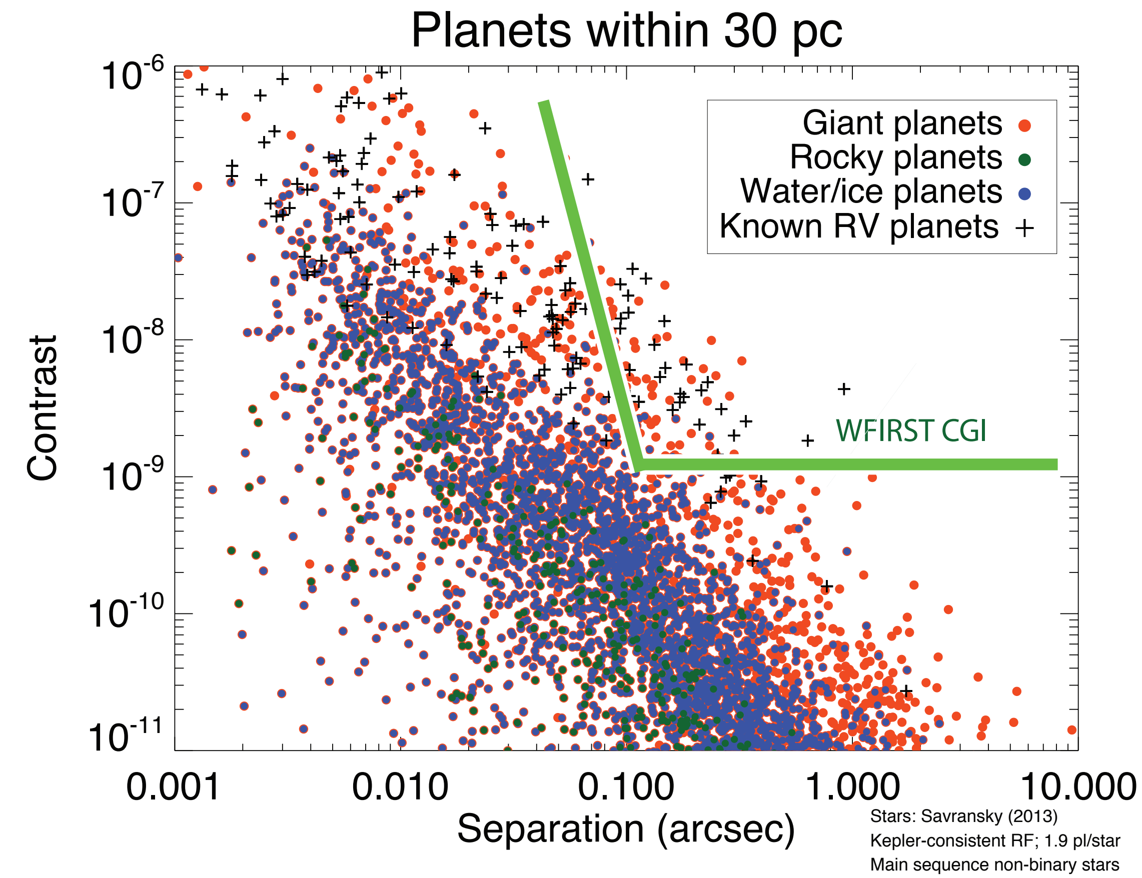


- HLC contrast laboratory demonstration on the WFIRST MCB testbed: 10% spectral bandwidth centered at 550 nm.
- At left, a ***demonstration of 1.6×10^{-9} contrast*** in the static testbed environment (J. Seo, 12/2016).
- At right, ***contrast in the dynamic testbed environment*** simulating on-orbit pointing and focus disturbances, and LOWFS&C sensing and rejection (F. Shi, 12/2016):
  - 14 mas rms pointing drift plus estimated WFIRST jitter corrected with a fast steering mirror,
  - 2 nm PV focus disturbance (4x worst than WFIRST expectations) corrected with the DM.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

WFIRST Coronagraph Instrument is a pathfinder for a next-decade exo-Earth imaging mission





- The WFIRST Coronagraph Instrument actualizes the Astro2010 Decadal recommendations for a ***New Worlds Technology Development*** program and establishes a foothold in pioneering exoplanet science and technology.
- Performance of the WFIRST coronagraph illuminates the pathways for the design of the ***next-decade exoplanet mission***: telescope size, stability, pointing, wavefront control, post-processing, etc.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Summary

- The WFIRST Coronagraph Instrument (CGI) actualizes the NRC Astro2010 decadal recommendations for the development of technologies for high-contrast direct imaging of exoplanet systems from space, leading to the first direct observations of mature exoplanets in reflected starlight.
- CGI hardware developments and strategies for precision wavefront control advances many of the enabling technologies for future flagship exoplanet missions, now envisioned as HabEx and LUVOIR.
- The WFIRST mission is scheduled to enter Phase B in 2018, on the path to launch in September 2025.

"I'll tell you something else I think. I think there are other bowls somewhere out there with intelligent life just like ours."

Frank Modell – The New Yorker – 11/2/1987

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

End