Technology Demonstration Milestone #1 for the EXoplanetary Circumstellar Environments and Disk Explorer (*EXCEDE*) — II. Science Drivers and Implications.

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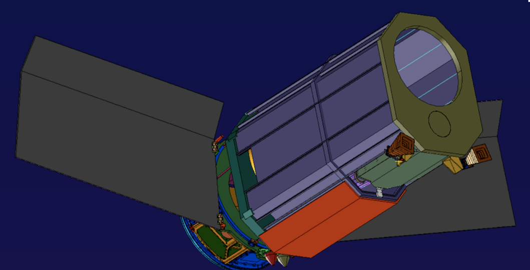


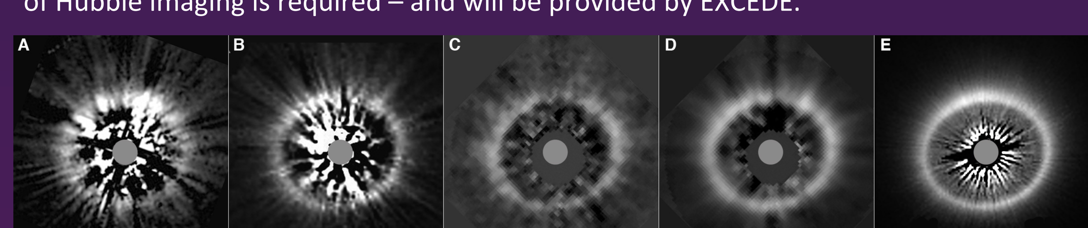
EXCEDE

ABSTRACT

The **EXoplanetary Circumstellar Environments and Disk Explorer (EXCEDE)** is an EX class Explorer mission proposed to study the formation, evolution, architectures, and diversity of exoplanetary systems by characterizing suspected planet-hosting circumstellar (CS) environments into and beyond host-star habitable zones using a small (0.7 m diameter) off-axis telescope. EXCEDE was selected by NASA (as a Category III Explorer program) for technology demonstration and maturation to advance key elements of its proposed starlight suppression system (SSS) combining the use of a Phase Induced Amplitude Apodized (PIAA) coronagraph, Micro-Electro Mechanical Systems (MEMS) Deformable Mirror (DM), closed-loop Low-Order Wavefront Sensing (LOWFS) and Control, and mid-spatial frequency wavefront error correction and control using the science camera for electric field conjugation and speckle suppression for image contrast enhancement. To meet the science goals of the EXCEDE mission, the SSS must simultaneously, repeatably, and stably, deliver disk-to-starlight *raw* image contrast per resel of 10^{-6} from 1.2 to 2.0 λ/D, and 10^{-7} beyond 2.0 λ/D in optical light, which has now been laboratory demonstrated for monochromatic light in an in-air environment (see paper I. by Belikov et al, session 109.02). This level of performance when extended to 10% – 20% broadband light (technology demonstration milestone #2 to be pursued over the next year) will enable the EXCEDE mission. Here we discuss the applicability of these performance metrics to studying the current "here be dragons" regions of light-scattering CS debris disks, including those now well-observed as revealed at larger stellocentric angular distances with the Hubble Space Telescope (HST) Imaging Spectrograph's (STIS) coronagraph with multiple-roll PSF-template subtracted coronagraphy as imaged in **HST GO program 12228**, in the context of the EXCEDE science mission goals. This investigation is funded in part by NASA grant NNX12AH39G, and STScI grant GO-12228, with partnership contributions by the University of Arizona, the NASA Ames Research Center, and the Lockheed-Martin Corporation.

The HUBBLE LEGACY and the NEED FOR EXCEDE

Since 1990, HST instruments have included five coronagraphs (three commissioned for investigatory science) that, with a significant investment of HST orbits, have yielded an astrophysically compelling, but small-sample, "Rosetta stone" of (the brightest) CS debris systems within its technical capabilities. To date, space-based coronagraphy (uniquely with HST) has delivered spatially resolved, photometrically calibrated, images in optical/near-IR light of ~ 20 light-scattering CS debris systems greatly contributing to our understanding (thus far) of planetary system formation, evolution, architectures, and diversity. Over time, the development and adoption of increasingly aggressive (and robust) observation methods and reduction techniques have improved the image quality and dust-detection sensitivity of CS debris by HST coronagraphy, resulting in this current sample. HST imaging, however, is ultimately limited in stellocentric (i.e., "inner working angle") contrast, by its imperfect, incomplete, and temporally and spatially variable starlight suppression, arising from uncontrolled instabilities in the point spread function delivered to its instruments by it's optical telescope assembly. As a result, as exceptionally valuable and informative as these images have been, they are intrinsically limited in depth, image quality, and dust-detection sensitivity, in particular in the innermost regions of these exoplanetary debris systems where unseen planets may dominate disk dynamics, planet building/ migration, and systemic evolution. A space-based next-generation coronagraphic system, with *active* wavefront error control, designed to meet the goals of exoplanetary science through studies CS of debris systems as informed by the legacy of Hubble imaging is required – and will be provided by EXCEDE.

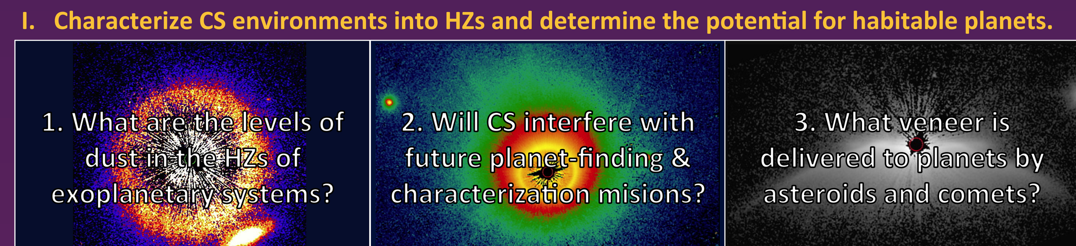


Representative improvements in HST PSF-subtraction coronagraphy: HD 181327 debris ring. (A–D) derived from the same raw data (NICMOS 1.1 μm imagery) and (E) STIS 6 roll (6R) contemporaneous observationally matched-PSF template subtracted coronagraphy (PSFTSC; Schneider et al 2014, AJ in prep). A: Discovery image using two (of ten) non-contemporaneously observed PSF template stars (Schneider et al 2006, ApJ 651 414; GO program 10177). B: "LAPLACE" (HST AR program 11279) re-processing and globally optimized re-reduction with PSF-matching and down-selected 53 template ensemble (Schneider et al 2010, Proc. HST Calib. Workshop). C: LOCI re-processing (without regularization) with a 232 LAPLACE recalibrated PSF template library. D: KLIP re-processing (35 coefficients) using same PSF template library as (C) with regularization. C & D from Soummer, Pueyo, and Larkin 2012 (ApJ 755 28; HST AR program 12652). E: STIS 6R-PSFTSC (GO program 12228). Gray circle marks location and size of the NICMOS r = 0.3" coronagraphic circular obscuration.

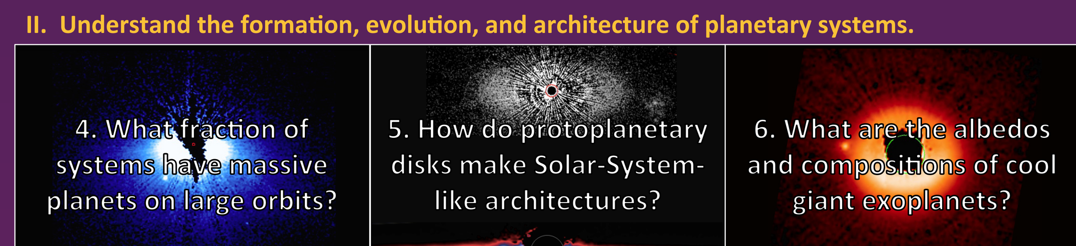
EXCEDE SCIENCE OBJECTIVES

EXCEDE WILL UTILIZE OBSERVATIONS OF DUSTY CS DISKS TO:

I. Characterize CS environments into HZs and determine the potential for habitable planets.



II. Understand the formation, evolution, and architecture of planetary systems.



III. Develop & demonstrate advanced coronagraphy in space for use in future major missions.

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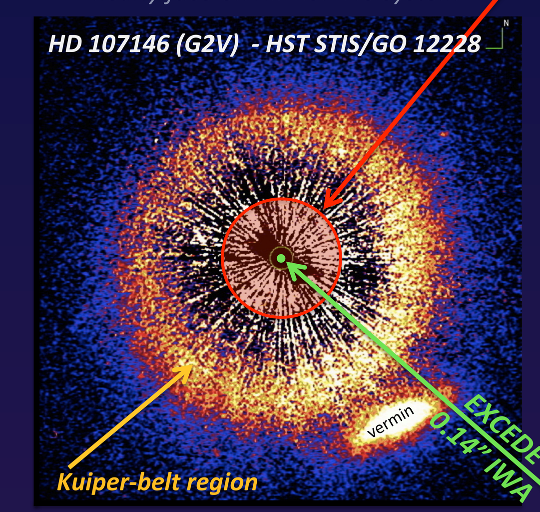
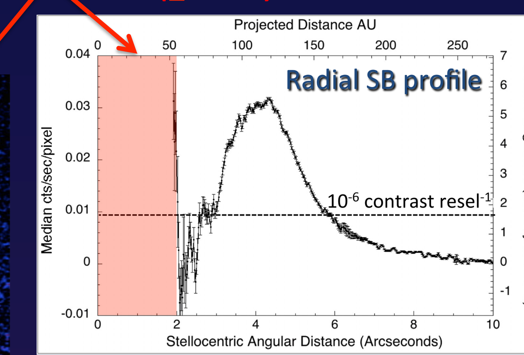
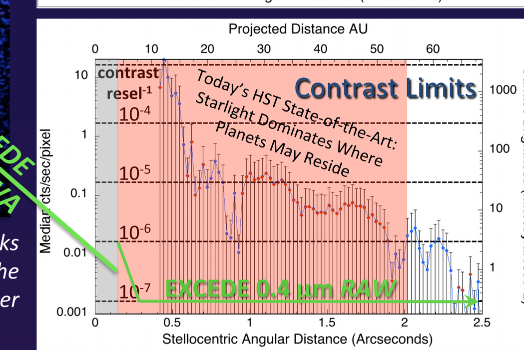
STATE-OF-THE ART HST SPACE CORONAGRAPHY TODAY

Looking "in" from the outside: CS debris scattering starlight in the nearly face-on HD 107146 System

HERE (≤ 55 AU) BE HST DRAGONS!







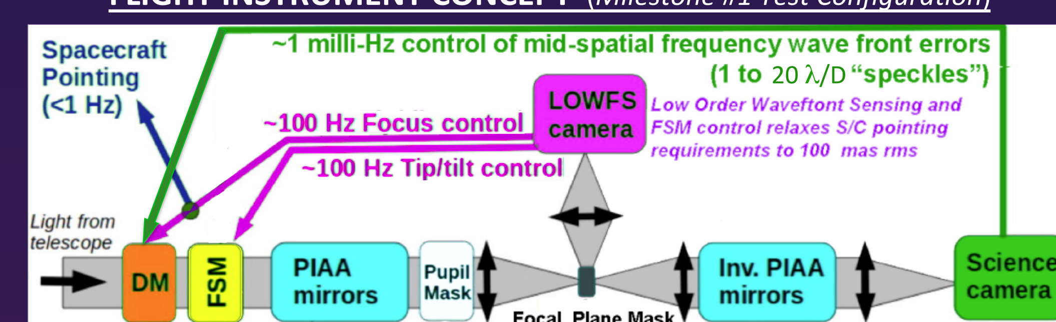
Dynamical interactions between planets and disks are predicted to play vital roles in generating the architectures of planetary systems, but the inner regions of such systems, today, remain obscured.

EXCEDE TECHNOLOGY DEMONSTRATION MILESTONE #1

MONOCHROMATIC CONTRAST DEMONSTRATION: "Demonstrate, using Phase-Induced Amplitude Apodization, a raw contrast median level 10^{-6} between a 1.2 λ/D inner working angle and 2.0 λ/D, simultaneously with a median level of 10^{-7} between 2.0 λ/D and 4.0 λ/D, *in monochromatic light* at any single wavelength in the range of 400 nm ≤ λ ≤ 900 nm over a single-sided dark zone." **– JPL Document D-75787**

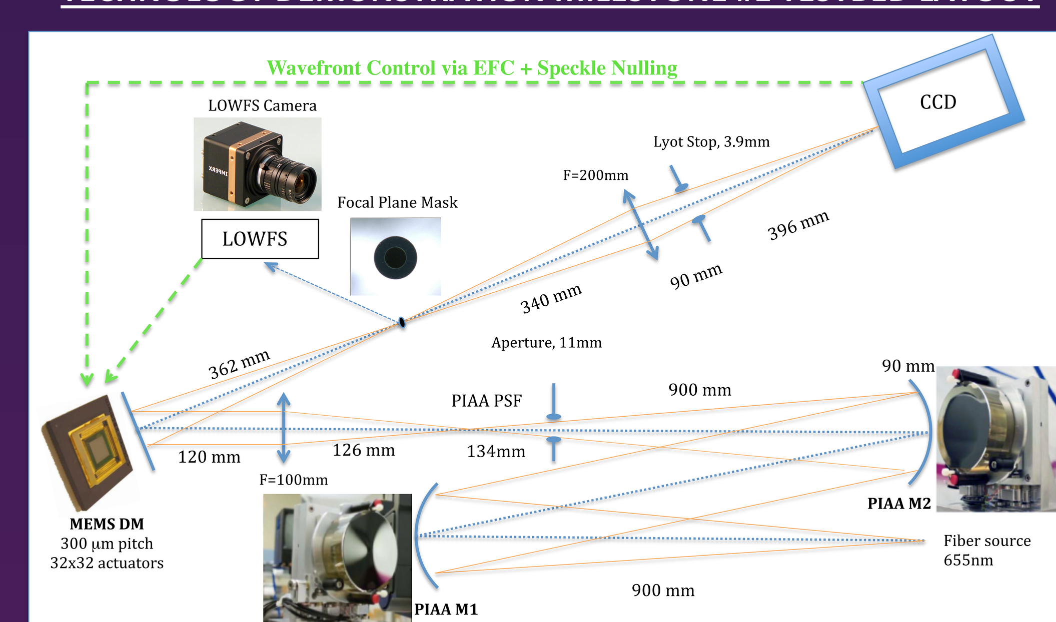
EXCEDE WAVEFRONT ERROR CONTROL & STARLIGHT SUPPRESSION

FLIGHT INSTRUMENT CONCEPT *(Milestone #1 Test Configuration)*



- 70 cm unobscured aperture off-axis telescope (*Input fiber on XYZ stage*)
- Fine Steering Mirror for high precision pointing control (*Replaced by DM*)
- Low Order Wave Front Sensor for focus & tip-tilt control
- MEMS Deformable Mirror for wave front error control (*32x32 actuators*)
- Phase Induced Amplitude Apodization optics (*forward PIAA mirror set only*)
- Two-band Nyquist-sampled imaging polarimeter (*650 nm imaging CCD*)

TECHNOLOGY DEMONSTRATION MILESTONE #1 TESTBED LAYOUT



LABORATORY TEST FACILITY

In-Air Key Component and Integrated, Wavefront Control and Starlight Suppression Testing

- ***The NASA Ames Research Center's Coronagraph Experiment (ACE) Laboratory is being used for all in-air testing, and calibration of EXCEDE key components and sub-systems.***
- ***The ACE facility provides a thermally controlled, vibration isolated, in-air environment specifically designed for the needs of high-contrast optical systems testing.***

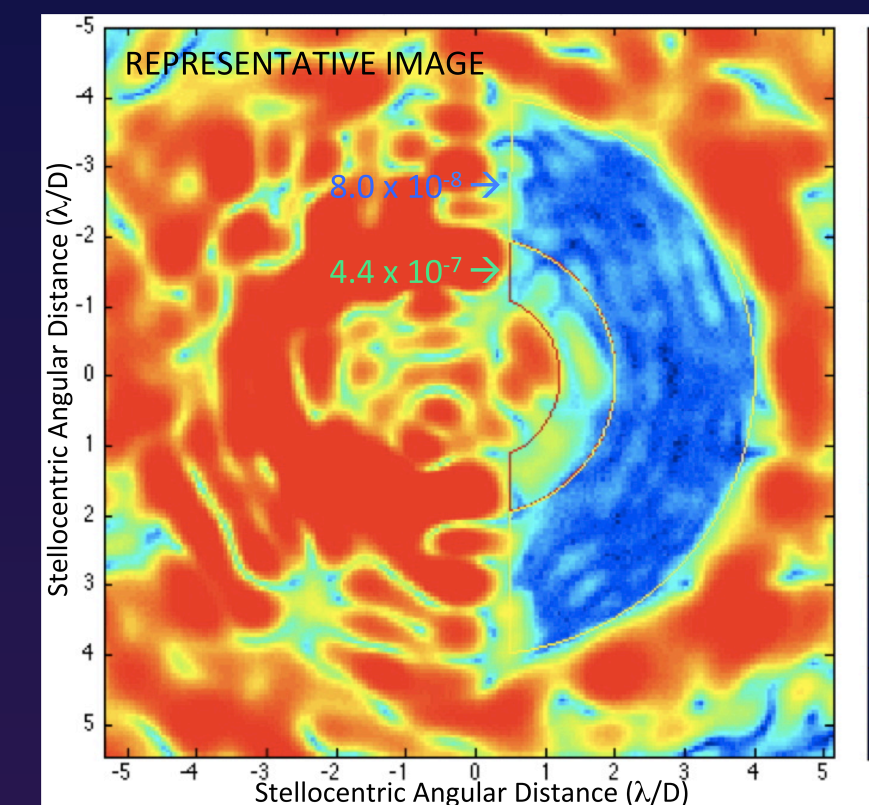
Following unit testing of key EXCEDE optical components, the fully-integrated EXCEDE Milestone #1 test bench was installed, configured, tested, calibrated and SUCCESSFULLY operated at ACE, fulfilling all Milestone #1 requirments. With Milestone #1 now met, the test bench will be reconfigured for the Miletone #2 (broadband) demonstration planned as ongoing into Q1CY15.

POLARIMETRIC CORONAGRAPHY: THE CONTRAST TURBO-CHARGER

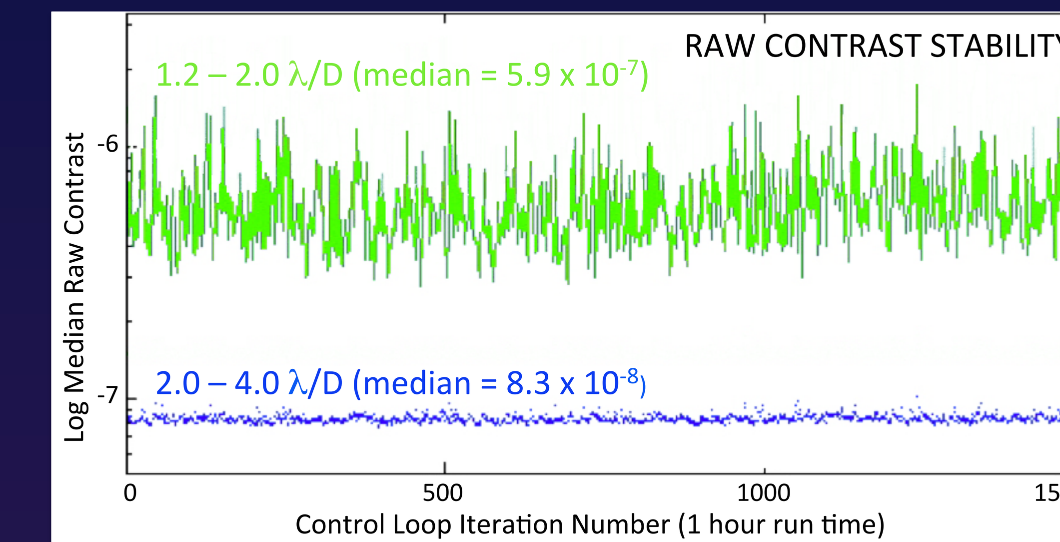
The EXCEDE *flight instrument* science camera concept (not undergoing current laboratory testing) incorporates a two-band imaging polarimeter in concert with science objectives 3, 5, and 6 that, importantly, *also* provides order-of-magnitude contrast augmentation in imaging polarizing dust grains (typically ~ tens of percent polarization for CS debris). With full Stokes imaging, coronagraphic residuals (e.g., "speckles") from the (largely) unpolarized PSF halo can be suppressed (in principal to the limit of the photon noise for a fully unpolarized star). This method was successfully tested on-orbit with HST (NICMOS) coronagraphic polarimetry of the GM Aur CS disk (HST GO program 10852; G. Schneider, PI), and works independent of, and multiplicatively with, other starlight/speckle suppression methods.

LABORATORY DEMONSTRATION RESULTS – TECHNOLOGY DEMONSTRATION MILESTONE #1 SUCCESSFULLY COMPLETED

CONTRAST FIELD



TEMPORAL STABILITY

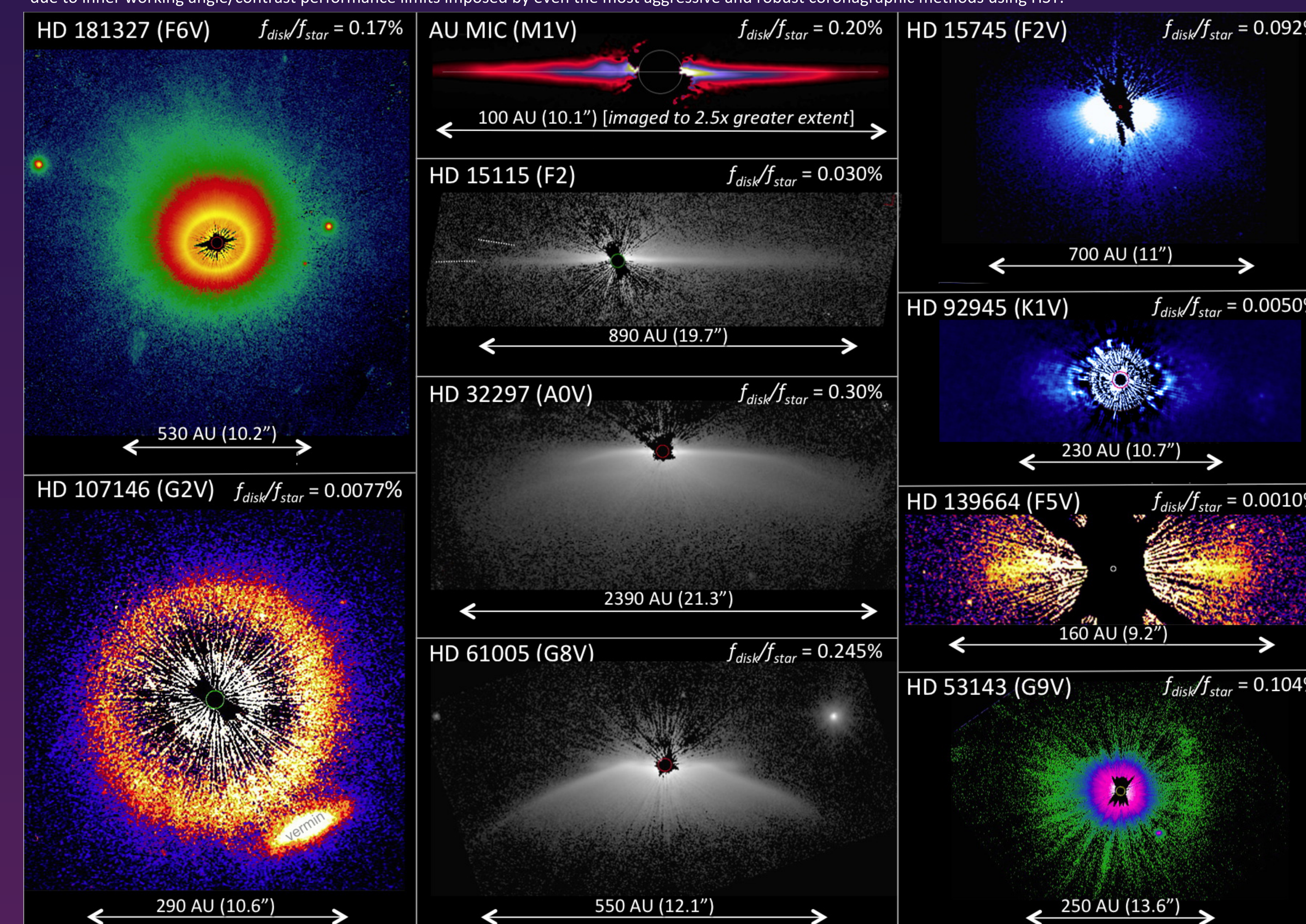


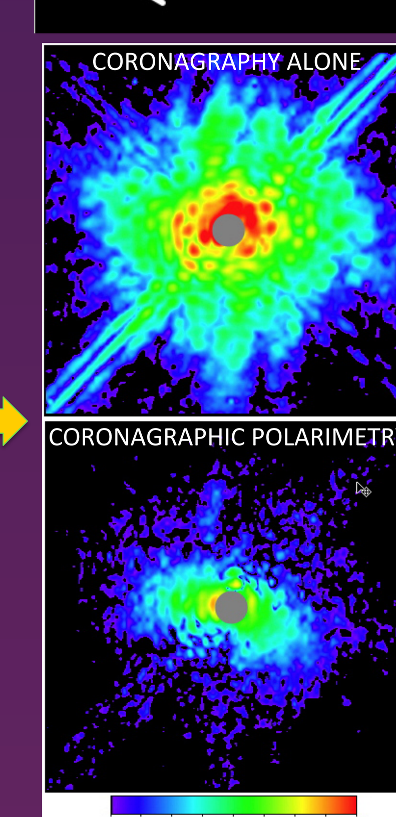
- **Median Raw Contrasts better than Milestone #1 Requirment**
- **Temporal Stability on 1 Hour Timescale**
- **Repeatability in 3 Independent Trails**
- **Re-application of MEMS map after +1 day**

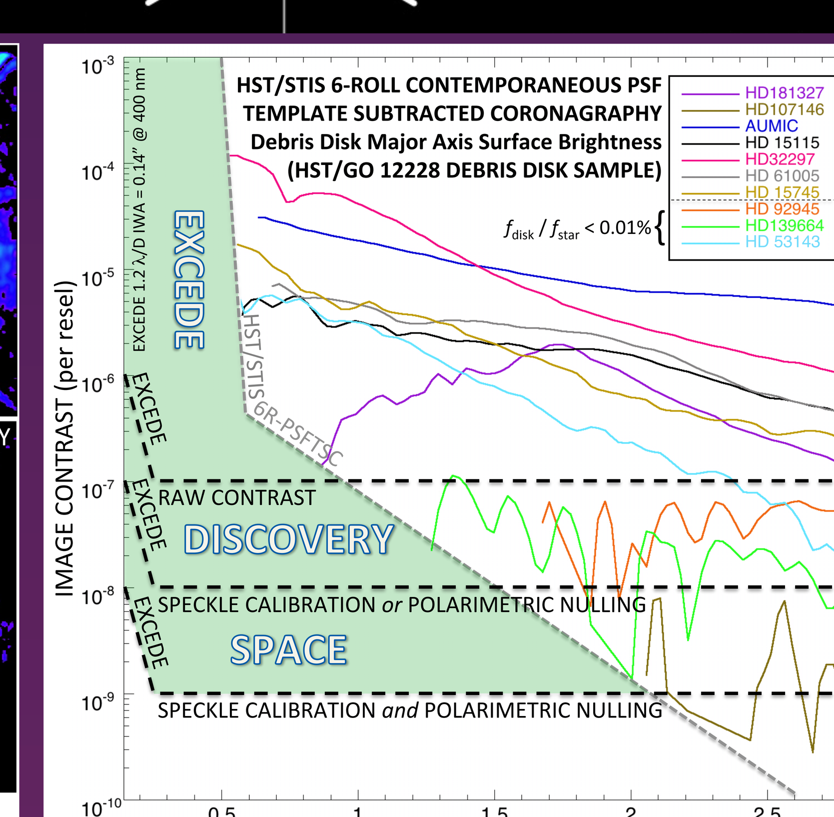
➔ Results Reproducable ± ~ 10%

BUILDING ON THE HST GO/12228 DEBRIS DISK IMAGING LEGACY

In HST/GO program 12228, utilizing 80 spacecraft orbits, we successfully observed half of the then-known, previously discovered, light-scattering debris disks using 6-roll STIS PSF template subtracted coronagraphy (PSFTSC) with precursor science goals symbiotic to those of EXCEDE (Schneider et al 2014, AJ, in prep). The resulting highly diverse images uniquely provide a legacy data set with an unprecedented combination of image quality (fidelity by rejection of optical artifacts), inner working angle, spatial resolution, sensitivity to light-scattering debris, photometric efficacy, and stellocentric spatial extent. As astrophysically important and powerfully diagnostic as these images are, they represent only the "low hanging fruit" from amongst the many hundreds of debris disks known (but yet unimaged in scattered light) through their thermal infra-red emission – due to inner working angle/contrast performance limits imposed by even the most aggressive and robust coronagraphic methods using HST.







BEYOND HST

*EXCEDE*ing TODAY'S STATE-OF-THE-ART LIMITS

HST coronagraphy, *augmented* with aggressive PSF matching/subtraction techniques, has proven effective for detecting and resolving light-scattering debris disks, and mapping debris disk sub-structures, robustly as close as ~ ½ arcsecond from their host stars – for the brightest and least contrast-challenging disks. E.g., see (left) the GO 12228 debris disk sample surface brightnesses (corresponding to the above images) along the disk major axes expressed in contrast units: 10^{-4} to 10^{-6} per resel at ~ 0.5" < r < 2.0" for the intrinsically brightest disks

Fainter (f_{disk}/f_{star} < 0.01%) disks are detectable only at larger stellocentric angular distances (e.g., beyond ~ 1" – 2"), but at greatly reduced efficacy and SNR. E.g., radial *variations* in SB on ≤ 0.2" scales measured for the three f_{disk}/f_{star} < 0.01% disks observed with STIS 6R-PSFTSC are due to "pollution" from (still) incomplete-to-dominant PSF-subtraction residuals in the > 1.2" – 2.7" stellocentric zones, and should *not* be over-interpreted as spatially-resolvable sub-structure intrinsic to the disks.

The EXCEDE instrument design enables two *independent* methods of contrast augmentation: (1) Speckle Calibration, and (2) Polarimetric Nulling – extending it's contrast-limited sensitivity separately by one, or combined, by two orders of magnitude (to the level of the photon noise).