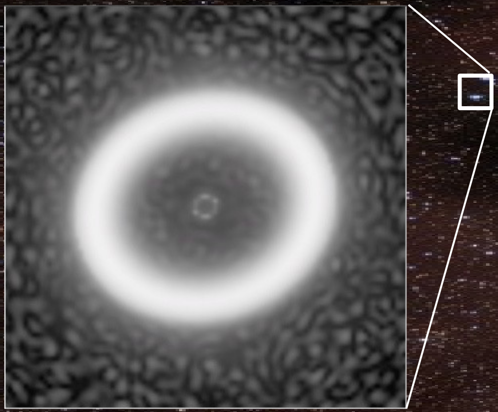
EXCEDE

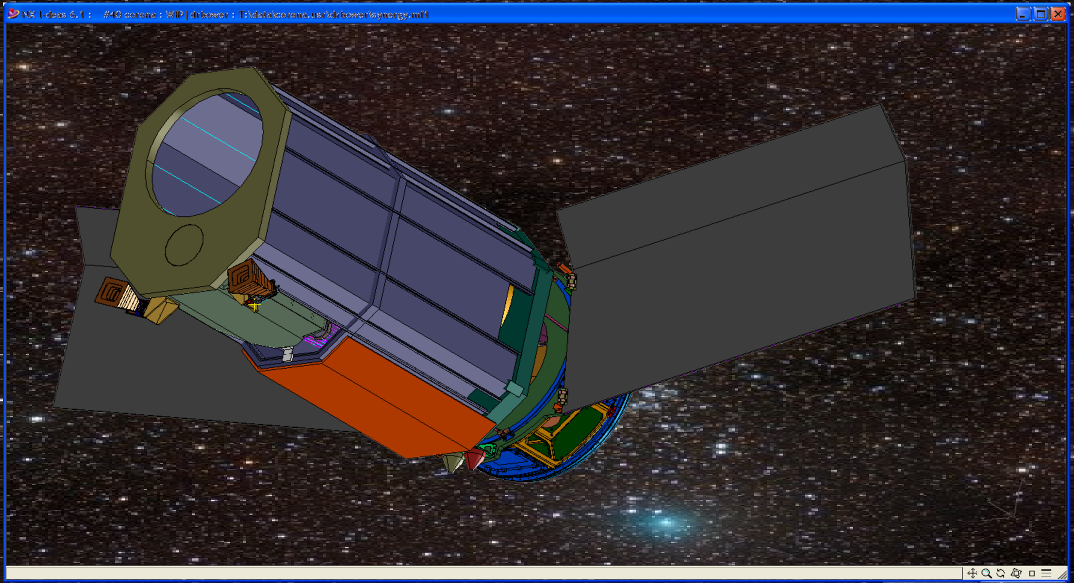
Science, Mission, and Technology Development Overview

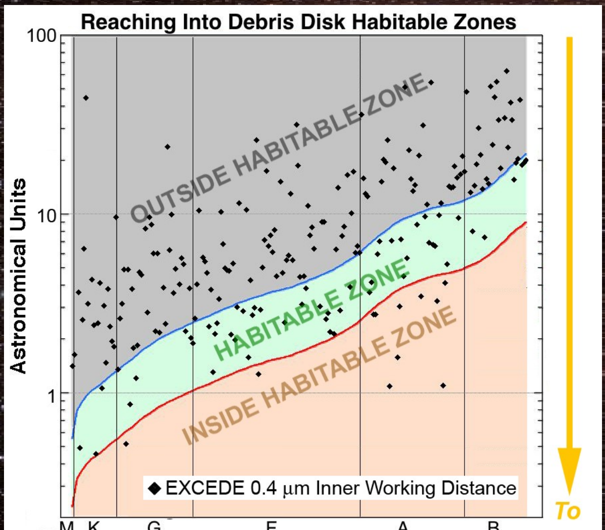
EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.

Dr. Glenn Schneider (PI)
Dr. Olivier Guyon (IS)
Steward Observatory
The University of Arizona





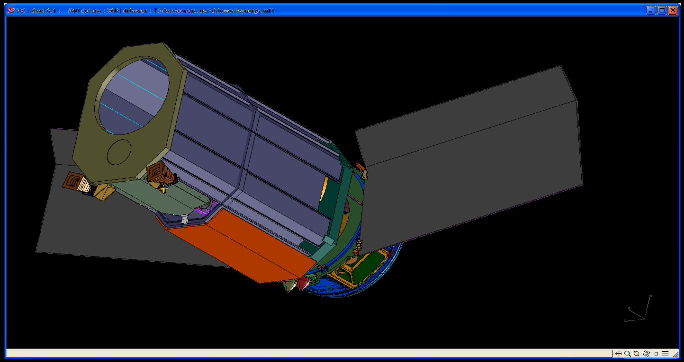


EXCEDE

Mission Overview

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.



- 0.7 meter off-axis visible-light telescope
- Active Starlight Suppression System:
  - PIAA Coronagraph (~1 l/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor
- Two-band Imaging Polarimeter
- Three-year mission (2000-km LEO Sun-synchronous orbit)
  - Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs
- Newly NASA-funded 2-year Tech. Dev program
  - Partnership contributions from UofA, Lockheed-Martin, NASA/AMES

PRESENTATION BY R. BELIKOV 8842-182

EXCEDE

Selected by NASA for Two-Year Category III Technology Development Program

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

SCIENCE TEAM

G. Schneider (PI), UofA
O. Guyon (IS), UofA
R. Angel, UofA
L. Close, UofA
P. Hinz, UofA
G. Rieke, UofA
C. Grady, Eureka Sci.

T. Greene, ARC
D. Hines (dPI), STScI
P. Kalas, UC Berk.
M. Kuchner, GSFC
A. Weinberger, CIW
B. Whitney, U. Wisc.
M. Wyatt, Cambr. U.

PROJECT MANAGEMENT co-I's & Collaborators

D. Tenerelli (PSM), LM
G. Prout (PM), UofA
J. Mamie (aPM), ARC

R. Belikov (TDEV), ARC
M. Lesser, UofA
C. Stark, CIW

KEY PARTICIPATING INSTITUTIONS

Academic

The University of Arizona
Eureka Scientific
Space Telescope Science Institute
University of California, Berkeley
Carnegie Institute of Washington
Cambridge University

NASA Centers

NASA/Ames Research Center
NASA/Goddard Space Flight Center

Industry

Lockheed-Martin Space Systems (prime)
ITT Corp.
Boston Micromachines Corp.
Broad Reach Engineering Co

Key TDEV Personnel & Partners

Zodiacal Light
Circumsolar Debris Scattering Sunlight in our own Solar System

MISSION GOALS

To **characterize circumstellar environments**, reaching into habitable zones (HZs), to assess the potential for planets.

To **understand the formation, evolution, and architecture of planetary systems**.

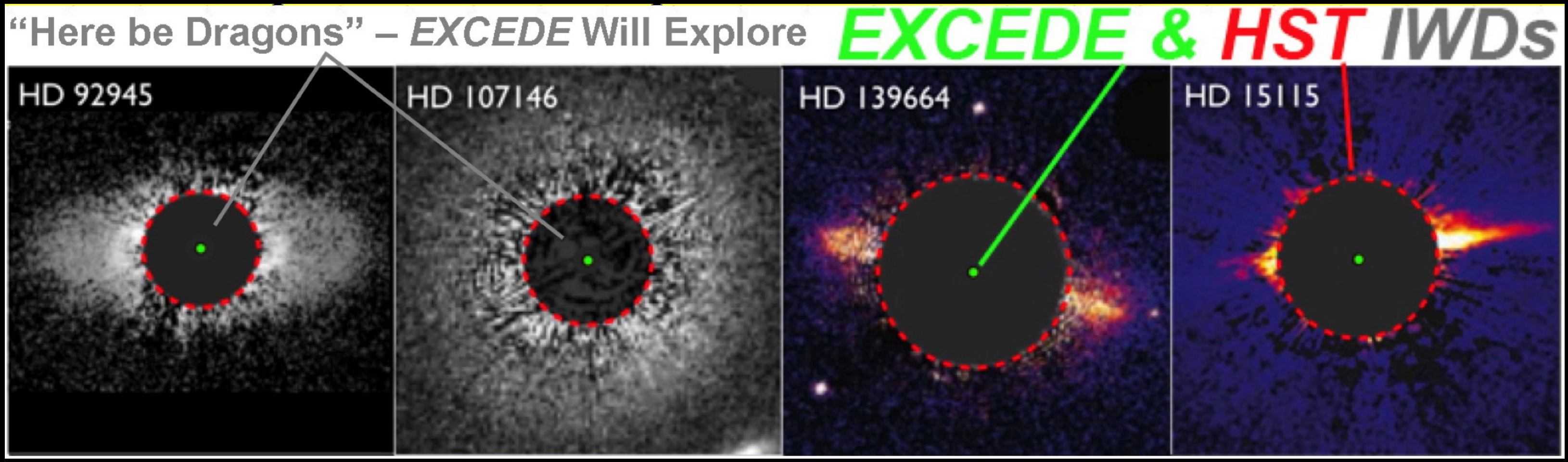
To **develop & demonstrate advanced coronagraphy for space**, enabling future exoplanet imaging missions.

Using Disks to Discover the Diversity of Planetary Systems

- **Scattered-light images provide the greatest insights because they trace dust at a wide range of stellocentric distances, but…**

- **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.

No existing coronagraphs have sufficiently small inner working angles and disk-to-star image contrast sensitivity to probe CS disk systems. in their habitable zones (where the Earth resides in our solar system).



HST optical images of CS Disks. *EXCEDE will image ~ 1000x fainter in contrast and at least 3x closer to their stars and at spatial resolutions comparable to the best JWST will deliver.*

SCIENCE OBJECTIVES

EXCEDE WILL UTILIZE OBSERVATIONS OF DUSTY CS DISKS TO:

1. **Explore the amount of dust in Habitable Zones** (where dust indirectly traces the level of terrestrial planet bombardment by asteroids and meteorids).

2. Help determine **if this dust will interfere with future planet-finding missions.**

3. Constrain the **composition of material delivered to planets**.

4. Investigate what **fraction of systems have massive planets on large orbits.**

5. Observe **how protoplanetary disks make Solar System-like architectures**.

6. Measure the **reflectivity of giant planets and constrain their compositions**.

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

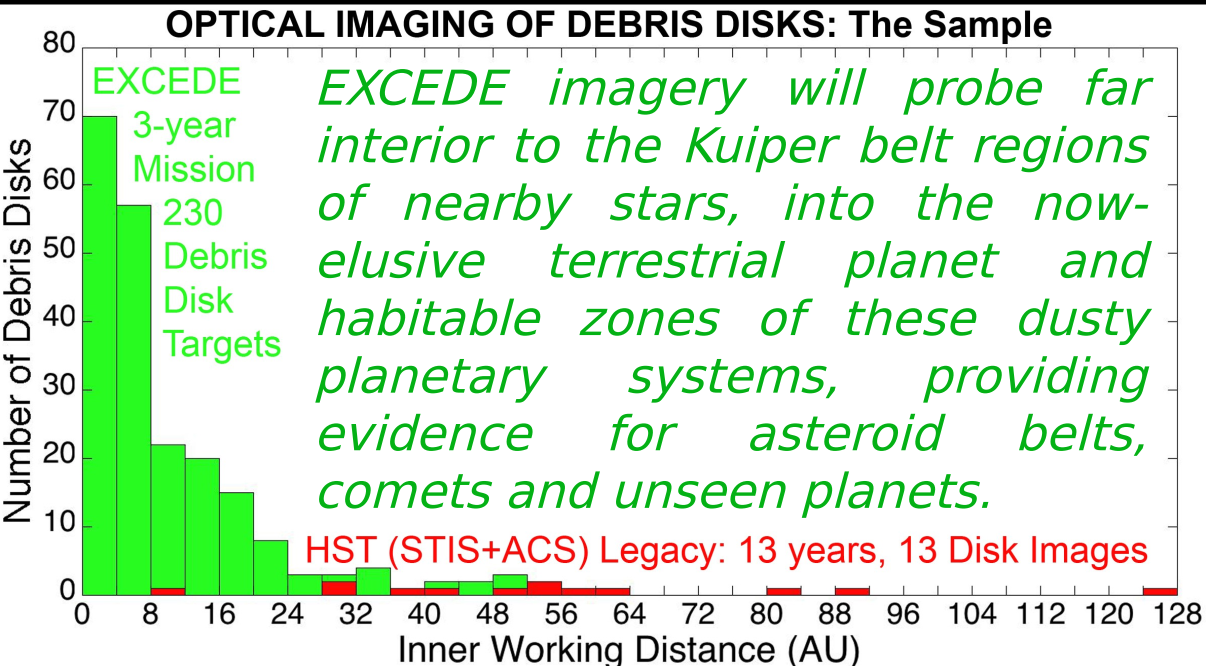
S.O. 1: What are the levels of dust in the HZs of exoplanetary systems?

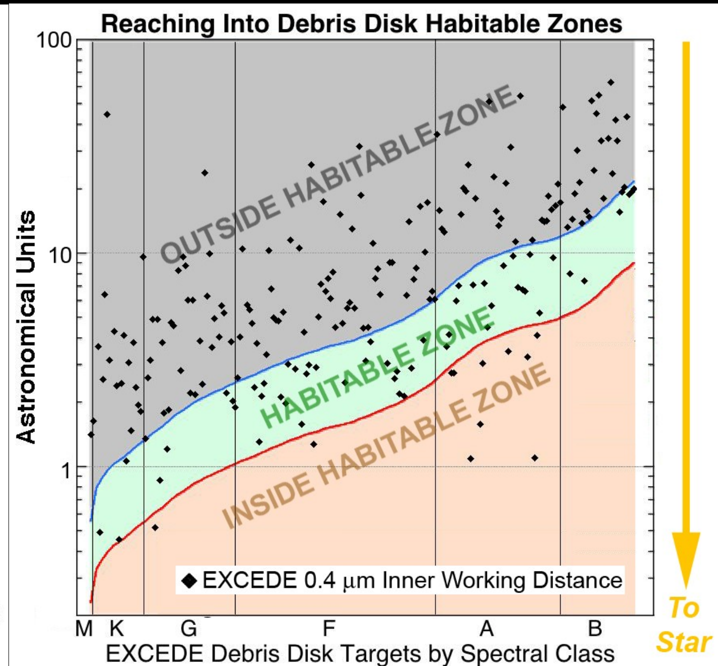
EXCEDE will provide direct images of scattered light debris disks around a sample of ~ 230 nearby (≤ 100 pc) stars revealing the levels of zodiacal light (ZL) present in these systems. ZL is a proxy for the:

— richness of planetesimal belts and their degree of gravitational stirring.

— indirect indication of the level of bombardment that might be experienced by terrestrial planets in these systems.

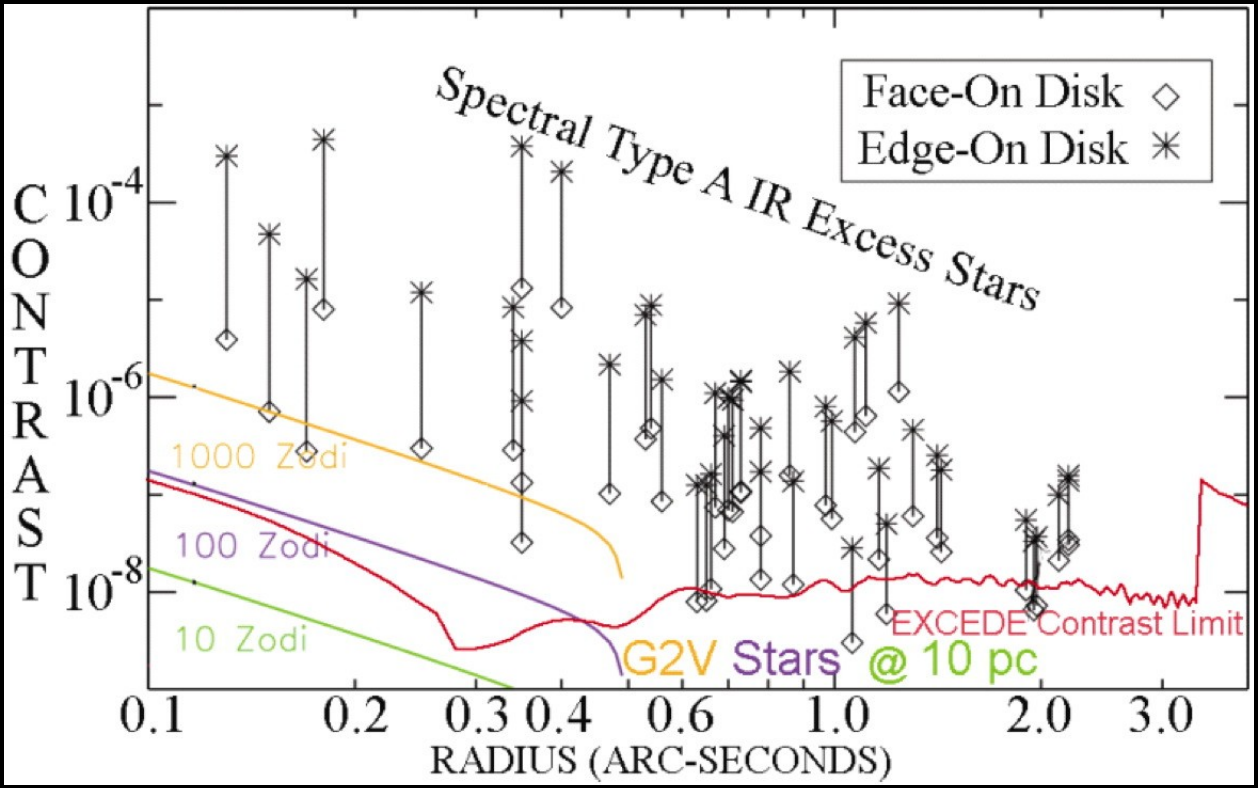
For > ¼ our DD target sample, *EXCEDE*'s 0.14" IWA enables spatially resolved imaging in CS HZs where liquid water can exist on planetary surfaces.





S.O. 2: Will dust in the HZs interfere with planet-finding?

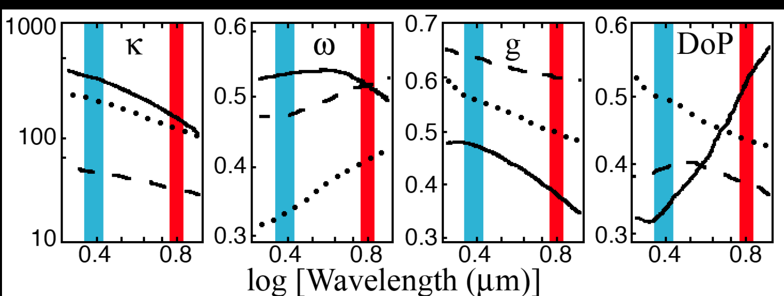
The amount of dust in HZs is key to determining the best strategies to image Earth-like exoplanets — Dust-scattered starlight is the main source of astrophysical "noise" in detecting such faint point sources.

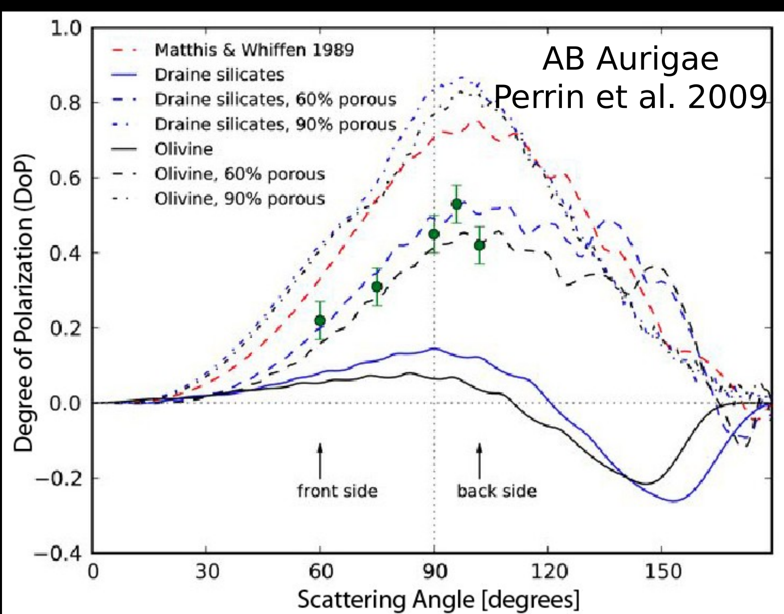


But… It is conceivable that by targeting stars without debris dust, future exoplanet imaging missions may be selecting targets unlikely to have had sufficient initial mass for rich planetary systems (?)

S.O. 3: What veneer is delivered to planets by asteroids and comets?

Identifying the presence of icy and organic-rich disk grains will give the first clues to the presence of volatiles important for life. EXCEDE's two-band imaging polarimeter is crucial to disentangling the dynamical and compositional history of disks.





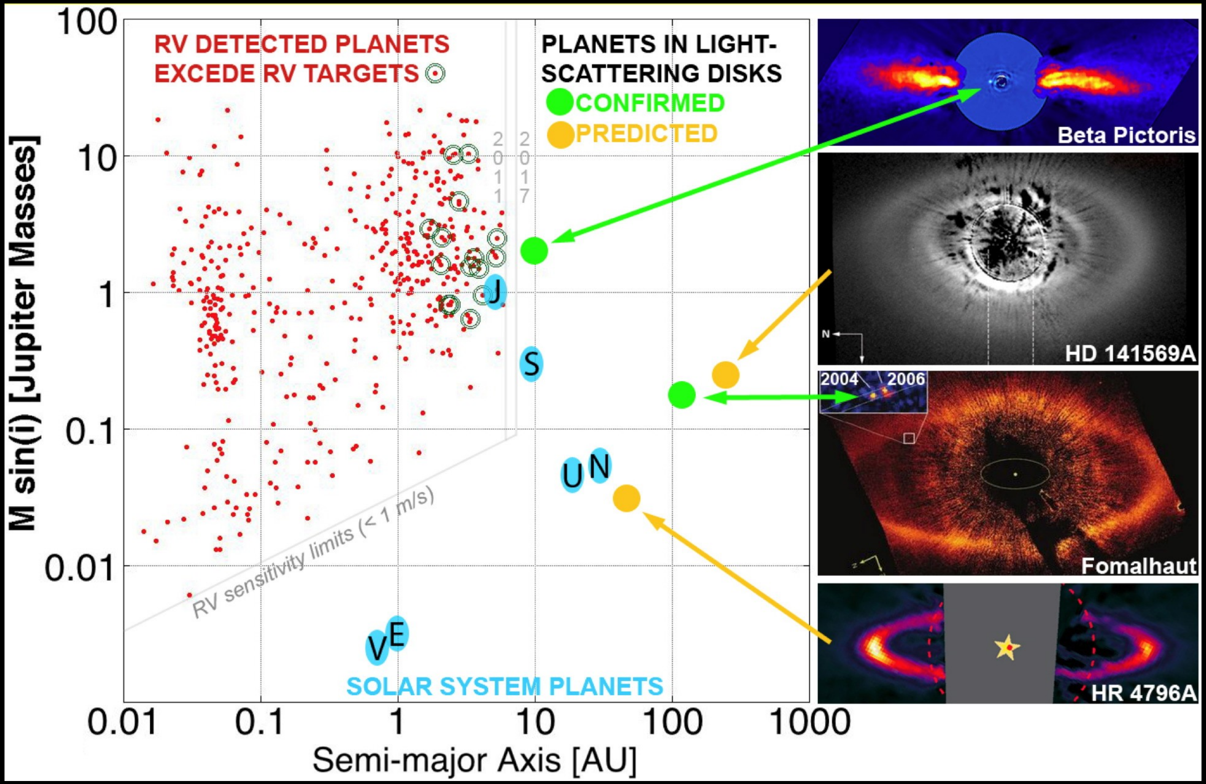
Distinguishing Grain Properties with 2-band Polarimetry

• ***Disks may be full of volatile-rich porous grains that carry H2O and C to planet surfaces, or compact and bone-dry spherules***. **Different grains have different λ dependent absorption (κ) and scattering efficiencies (ω), directional profiles (g) and degree of polarization (DoP). Examples show compact ISM-like grains (solid lines), moderate-sized fluffy grains (dotted) and larger grains (dashed) as in some PP disks.**

• ***EXCEDE measures the DoP of dust-scattered starlight as a stellocentric function of azimuthal angle***. ***HST*** **prototype coronagraphic polarimetry observations of the *very* bright AB Aur CS disk (accessible at *HST* contrasts) place tight constraints on the likely composition of the light-scattering dust in this system. *EXCEDE* will probe *many* more CS disks in this way.**

S.O. 4: How many systems have massive planets on large orbits?

EXCEDE's image contrast and 144 mas spatial resolution (e.g., 144 mas at 10 pc) will vastly increase the number of Neptune-analogs discovered from dynamical influences on debris disks.

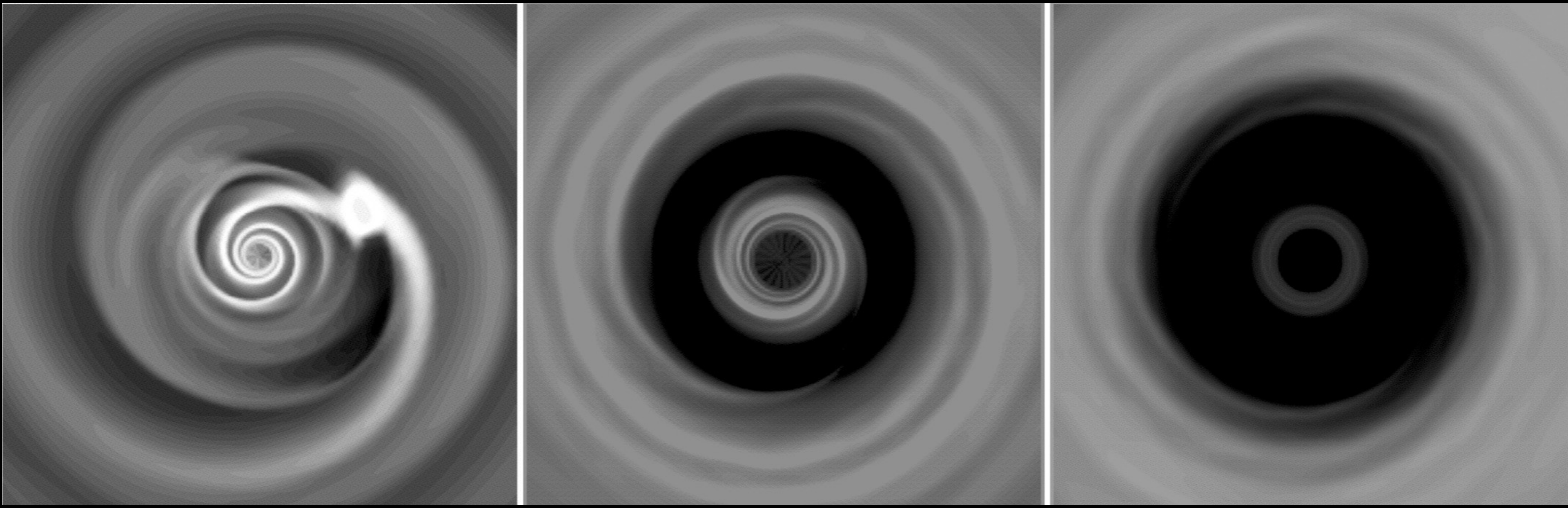


Structure in disks betrays the presence of planetary systems. EXCEDE will reveal the radial locations of planetesimal belts — a powerful indicator of gas-giant and ice-giant planets.

S.O. 5: How do PP disks make Solar-System-like architectures?

EXCEDE images will reveal disk sub-structures including large (> 20 AU) cavities and gaps associated with young Jovian-mass images.

EXCEDE will observationally test models that predict gaps opening in CS disks as a result of tidal interactions with giant planets..

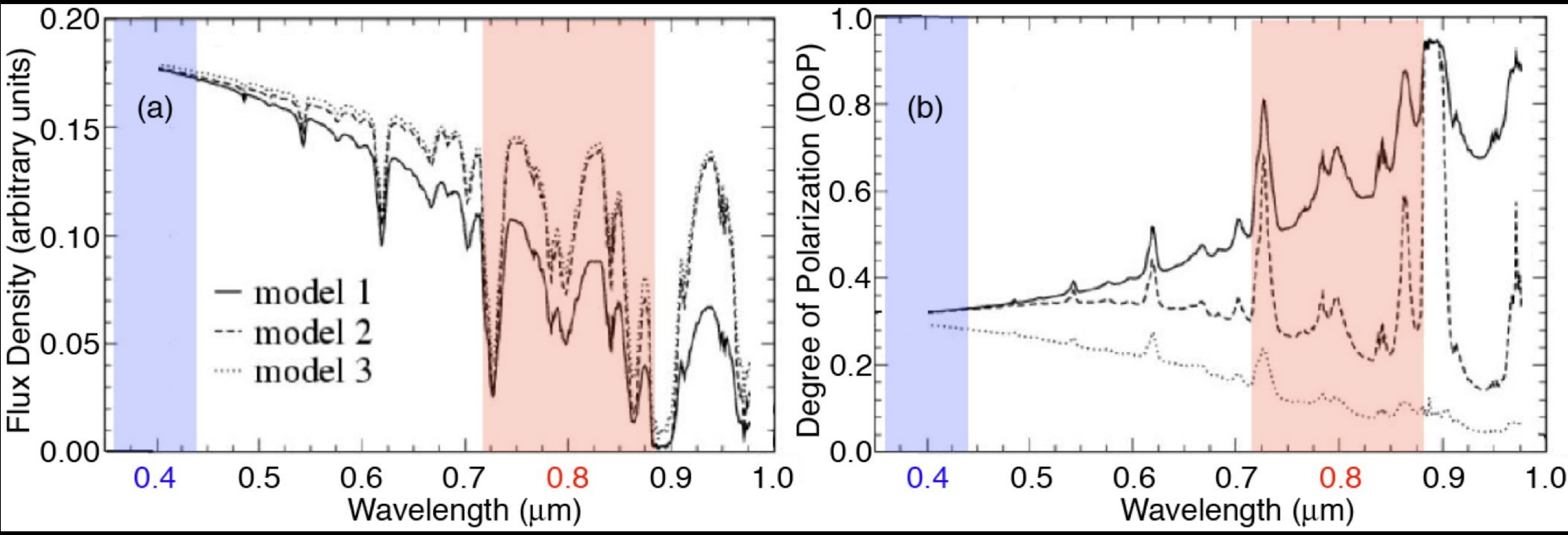


Theoretical models predict material-depleted disk "gaps", observable with *EXCEDE*, evolving over time due to the presence of co-orbiting planets (E.g., above from Bryden et al 1999).

S.O. 6: What are the albedos & compositions of cool giant exoplanets?

EXCEDE will produce the 1st images of extrasolar planets in the inner (0.5 < a < 7 AU) regions of mature planetary systems like our own.

Simultaneous measurements of DoP, color, and total brightness will probe the atmospheric compositions of cool EGPs for the 1st time.



Model planetary atmospheres with flux and DoP affected by molecular photochemestry (solid line), tropospheric clouds (dashed line) and stratospheric haze (dotted line). EXCEDE will inform and arbitrate.

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EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE TARGETS (4 classes oversubscribing a 3-year DRM by ~ 25%)

- **Screened against stellar binarity that would degrade image contrast.**
- **Span ages from ~ 1 My to several Gyr and spectral types M – B.**
- **Stellar brightness sufficient for LOWFS & DM WF error control.**
- **Sample sufficiently large to diffuse uncertainties in age estimations.**

1) ***IR Detected Debris Disk (DD) Systems***

• 230 targets* with Ldisk/L* ≥ 10-5 and d ≤ 100 pc (in most cases)
– will re-image the ~ 20 DDs previously resolved by HST.

2) ***Protoplanetary (PP) Disk Systems***

• 54 optically-thick PP & transition disks around T Tau & Herbig Ae/Be stars at d ≤ 150 pc.

5) ***The Nearest Stars out to 7 pc***

• 49 stars in the immediate solar neighborhood for which EXCEDE is capable of imaging zodiacal dust in HZs as faint as tens of zodis.

7) ***Radial Velocity Detected Planetary Systems***

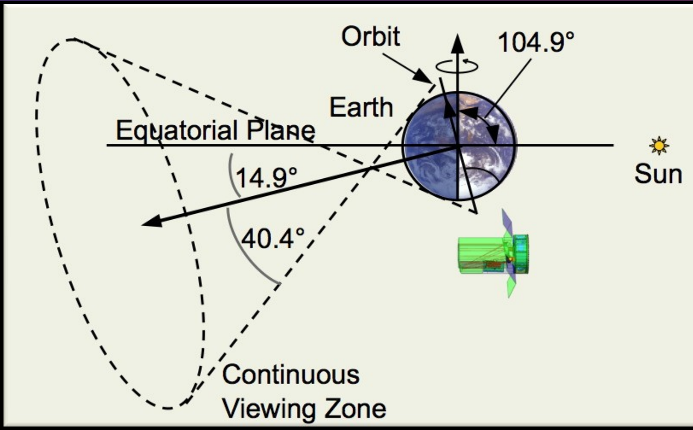
• ≥ 9 stars with RV planets potentially within the reach of EXCEDE.
* (separately, 6 IR-bright DD targets have RV detected planets)

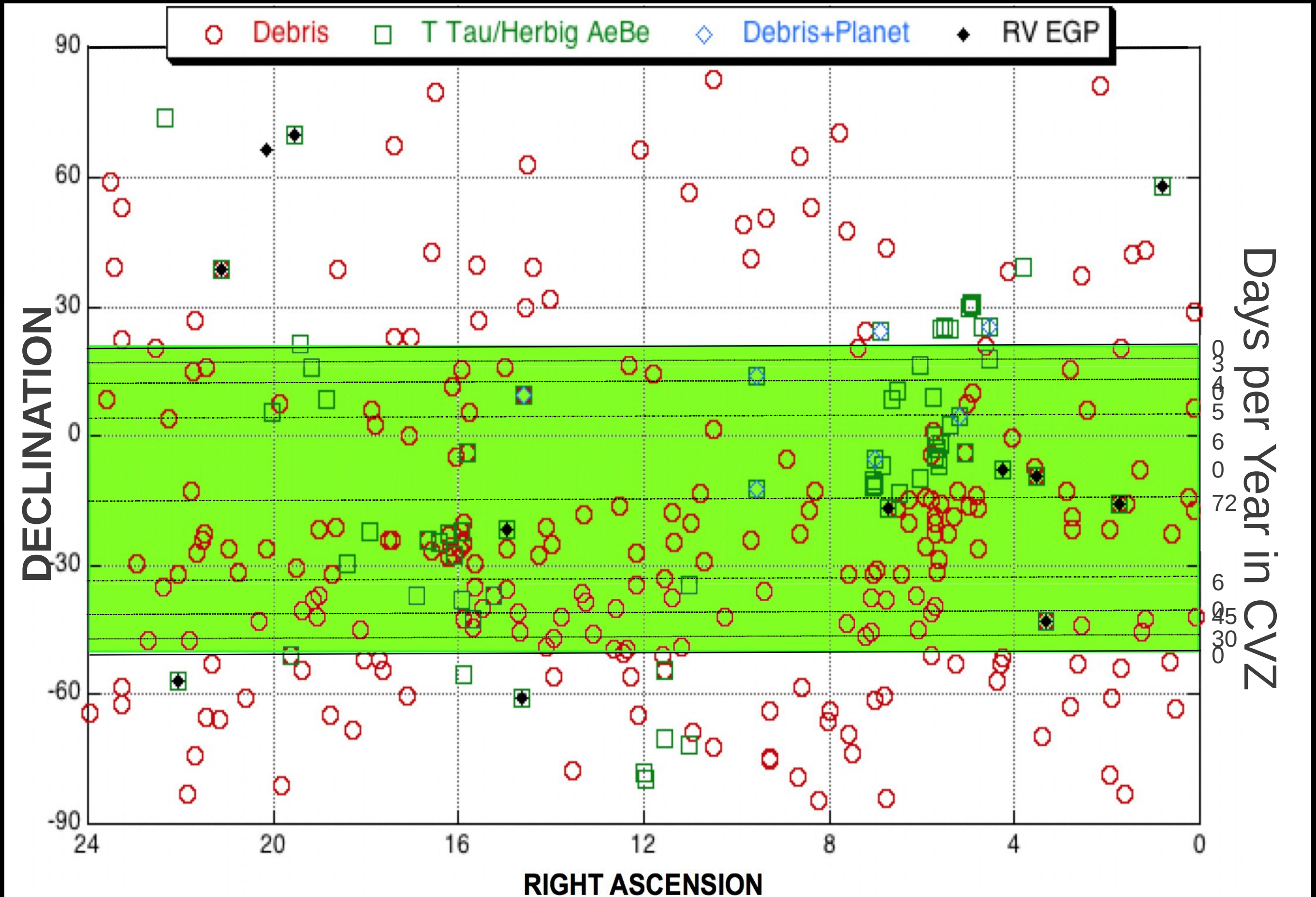
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE TARGETS & Orbital Considerations

Selected Orbit Provides:

- Large CVZ (efficient scheduling of most targets)
- Thermal Stability ("follows" terminator)
- Allows (multiple) ONR ad non-CVZ observations
- Mitigation of SC disposal propulsion: Td ~ 105 yr





EXCEDE ORBIT

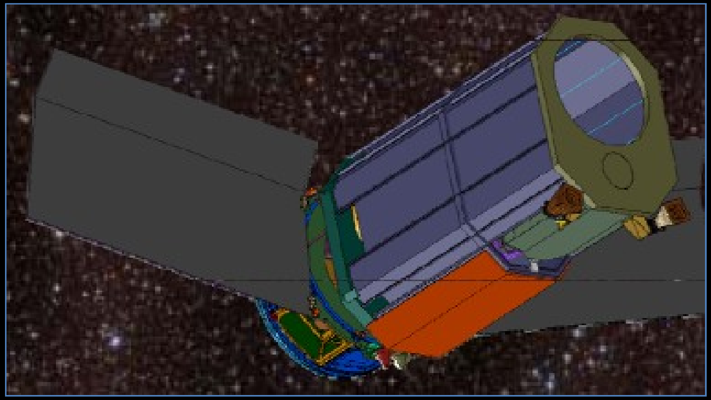
Circular LEO
2000 km altitude
Sun-synchronous
6 AM asc. Node
105° inclination
127 min period
antisun pointed

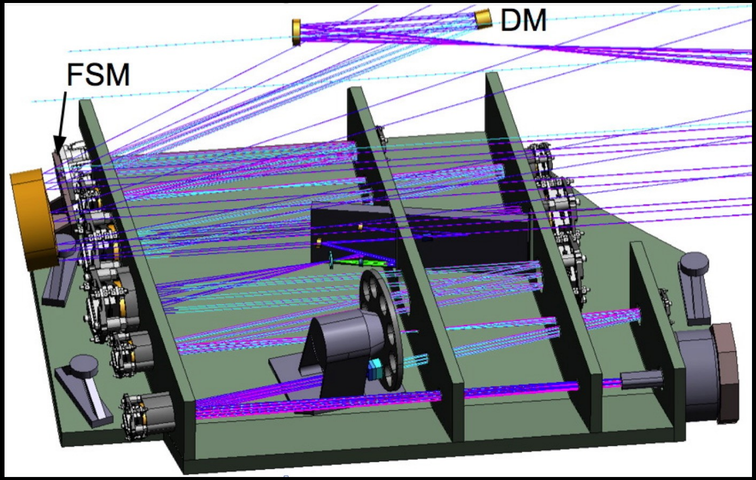
EXCEDE CVZ

assuming 5° BEA
$-50.3° \leq \delta < +20.5$
72 day mid-pass

FLIGHT INSTRUMENT CONCEPT

- Small (0.7 m) TMA optical telescope (fully unobscured pupil)
- Highly-efficient PIAA coronagraph
- Active/Closed-loop Wavefront-Error (WFE) Control System
- Two-Band Diffraction-Limited Imaging Polarimeter





How *EXCEDE* Will Succeed — Three Key Enabling Technologies

1) ***A highly efficient (PIAA) coronagraph*** to block central starlight while imaging the surrounding field to an IWA equal to the diffraction limit.

High-performance Phase Induced Amplitude Apodized (PIAA) coronagraph with *raw* "background"-to-peak contrast ratios:

- 10^{-6} — 10^{-7} $resel^{-1}$ from 1 – 2 λ/D with a 1.2 λ/D IWA* (*50% throughput)
- $\leq$ 10-7 resel-1 with $\geq$ 90% throughput everywhere beyond a 1 resel annulus (to $\geq$ 22 λ/D = 2.6" at 0.4 μm, 5.2" at 0.8 μm) circum-scribing a 1.2 λ/D coronagraphic mask.

2) ***A robust wavefront (WF) control system*** to deliver a high-quality, stable, WF to the coronagraph.

- 2000-element centrally actuated Micro Electro-Mechanical Systems (MEMS) Deformable Mirror (DM) *using the science detector* to measure & correct mid-spatial frequency WFEs (e.g., manifested as "speckles").
- Low Order Wavefront Sensor (LOWFS) using central starlight and Fast Steering Mirror (FSM) to measure/correct Tip/tilt & Focus.

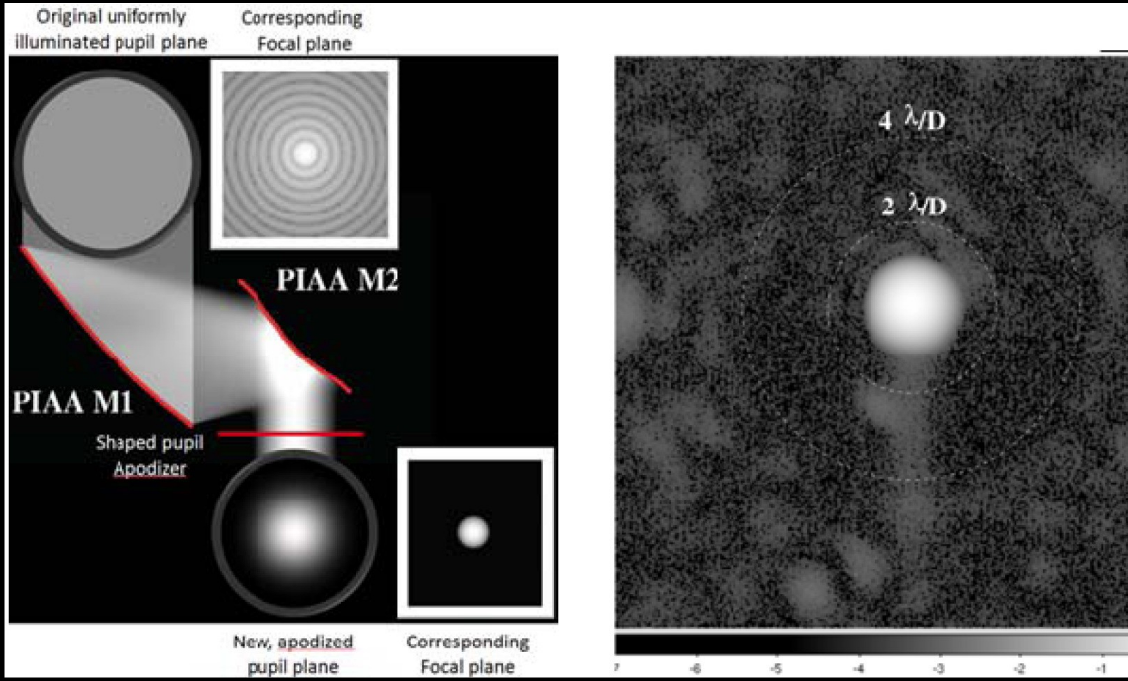
3) ***Well understood calibration methods*** to accurately separate residual starlight from genuine source in science images.

Phase Induced Amplitude Apodization (PIAA) Coronagraphy

PIAA is a lossless beam apodization producing a high contrast image of an on-axis point source with no Airy rings! Ideal for coronagraphy.

PIAA apodizes the pupil by geometric redistibution of light, not by selective masking/absorption, by using (highly) aspheric optics → full throughput

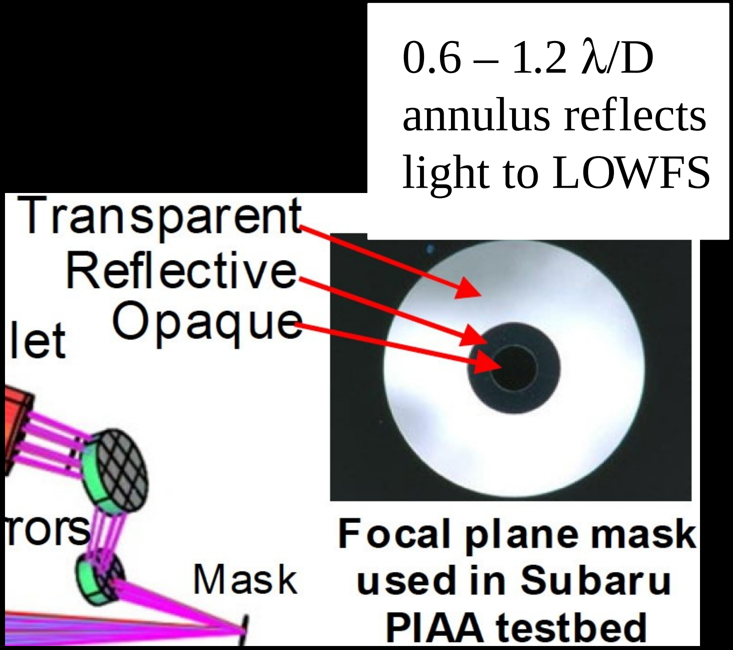
- PIAA technique validated in lab to 4e-9 contrast level at 2 l/D, and to ~1e-6 level at 1 l/D (NASA JPL, AMES, Subaru)

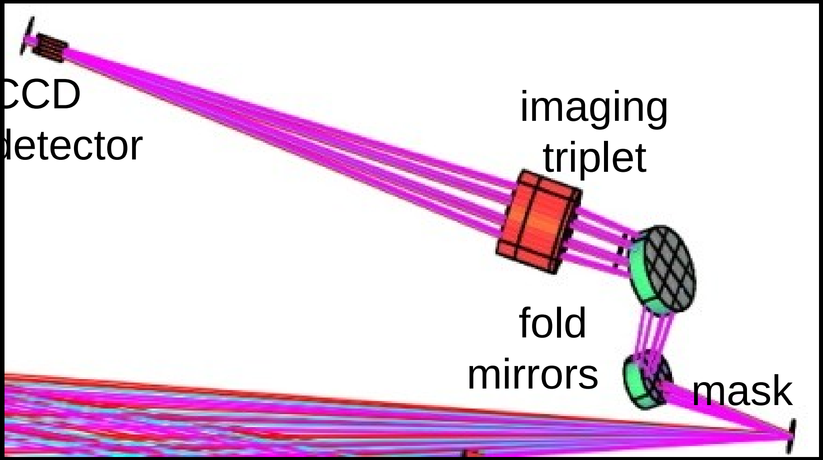


Recently manufactured PIAA mirrors (3.8 nm RMS surface error) exceed the wavefront quality requirements needed for EXCEDE.

Low-Order Wavefront Sensor (LOWFS)

- Provides Active Tip/Tilt and Focus Control with Fast Steering Mirror
  - relieves S/C of highest levels of fine body-pointing control
- Measures (telemeters) residual astigmatism
- Uses broadband light from reflective 0.6 – 1.2 λ/D annulus on FPM
- Sufficient light for V ≤ 10 targets for 1% λ/D accuracy in ~ 3.5 ms





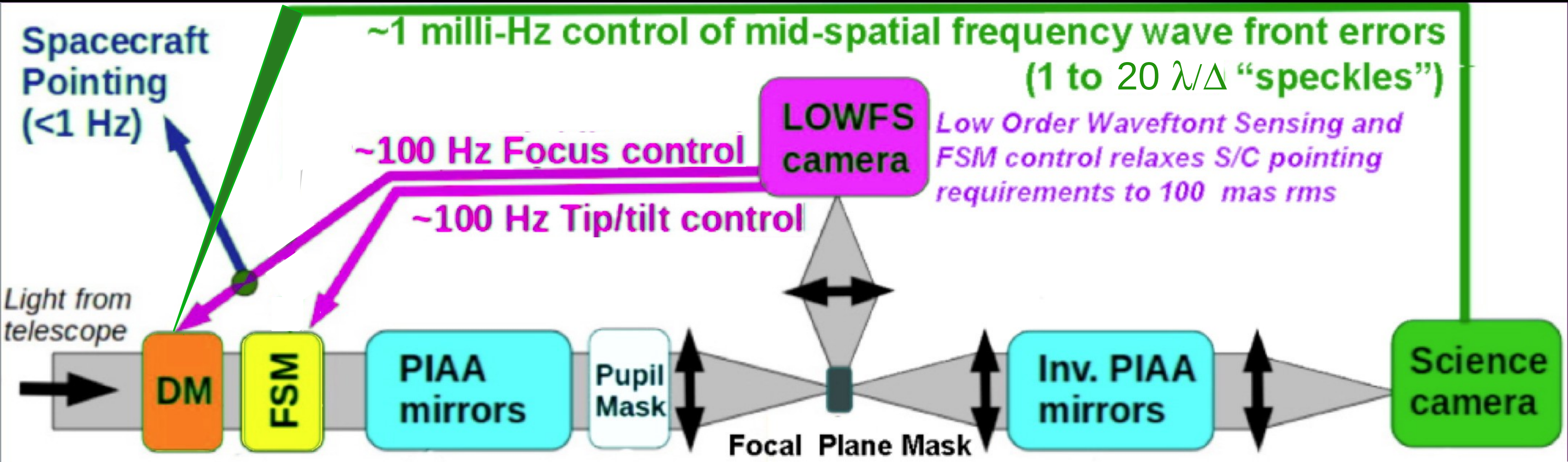
- 1e-3 λ/D pointing demonstrated with Subaru PIAA testbed (1 Hz)
- Faster (70 Hz) LOWFS now operating in SCExAO instrument

3e-4 λ/D pointing demonstrated with JPL PIAA testbed (0.1 Hz)

EXCEDE Science Payload Description

- 70 cm unobscured aperture off-axis telescope
- Fine Steering Mirror for high precision pointing control
- Low Order Wave Front Sensor for focus & tip/tilt control
- MEMS Deformable Mirror for wave front error control
- Phase Induced Amplitude Apodization coronagraph
- Two-band Nyquist-sampled imaging polarimeter

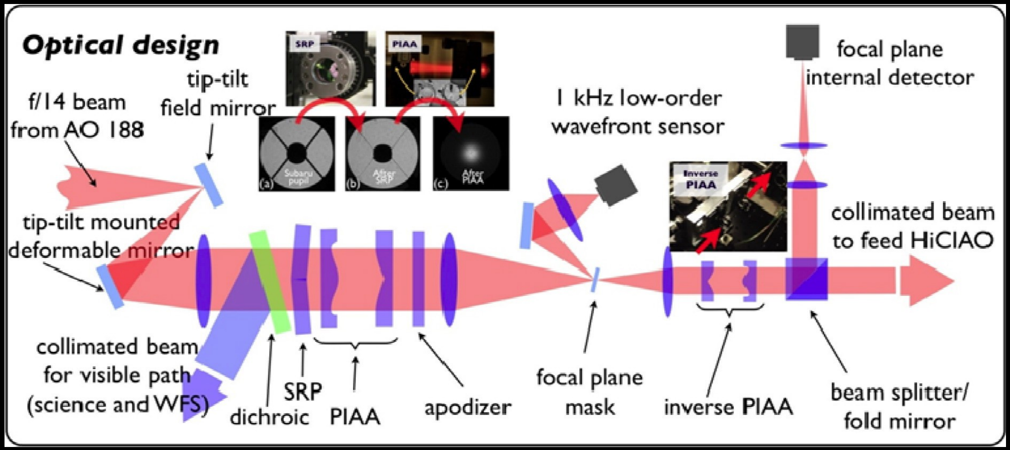
WAVEFRONT CONTROL & STARLIGHT SUPPRESSION

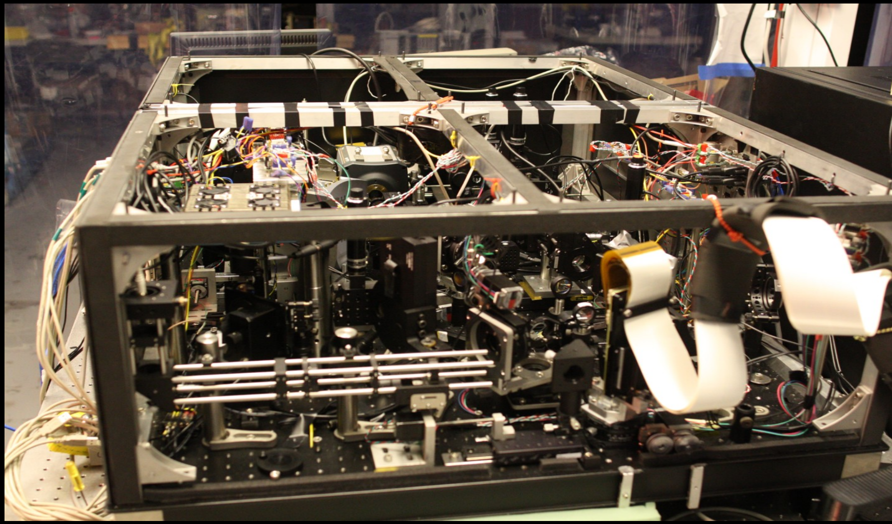


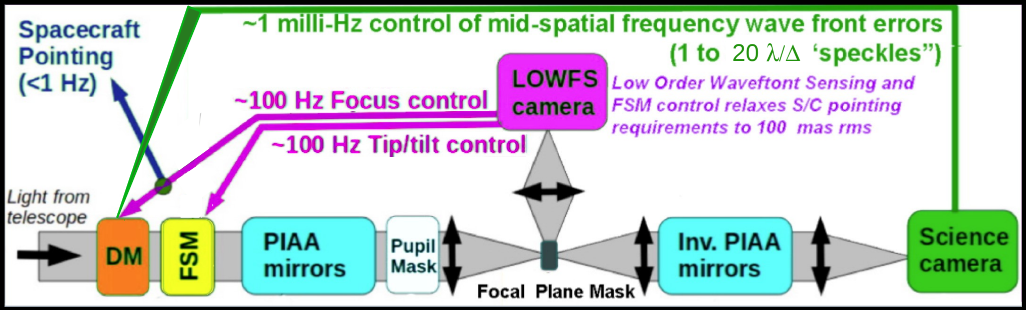
Wavefront Control and Starlight Suppression System (SSS) - Heritage

- Key elements in *EXCEDE* SSS similar to demonstrated SCExAO*

Subaru Coronagraphic EXtreme Adaptive Optics System



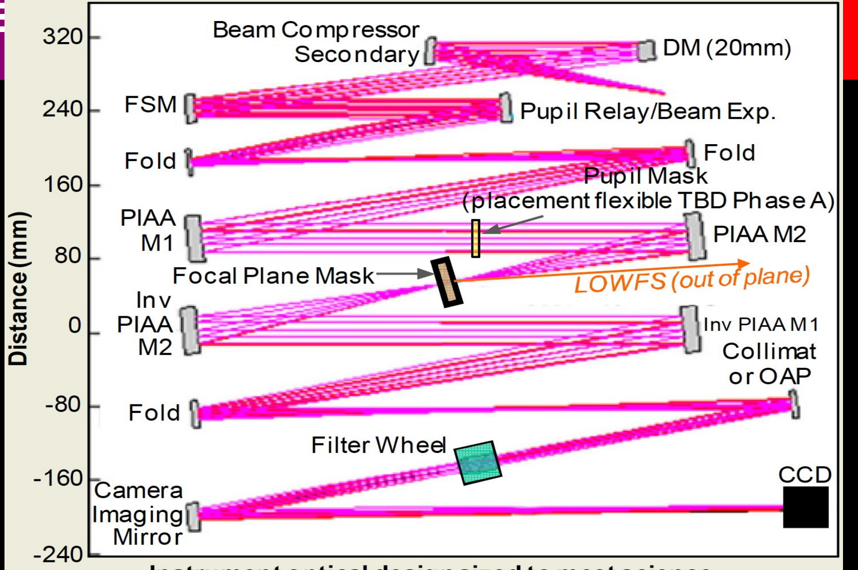




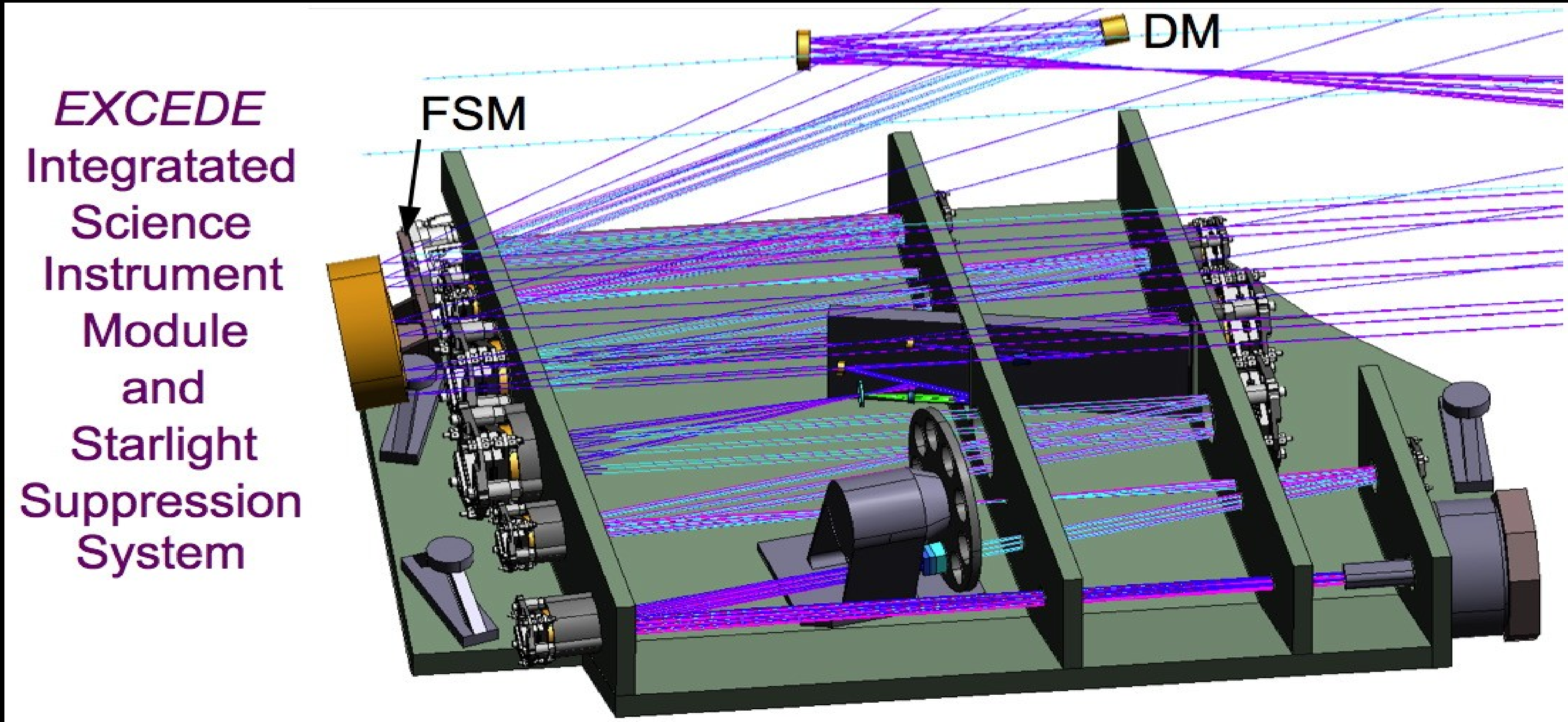
EXCEDE SSS Wavefront Error Control

SCExAO presentation
F. Martinache
8447-70
Thu 16:10pm

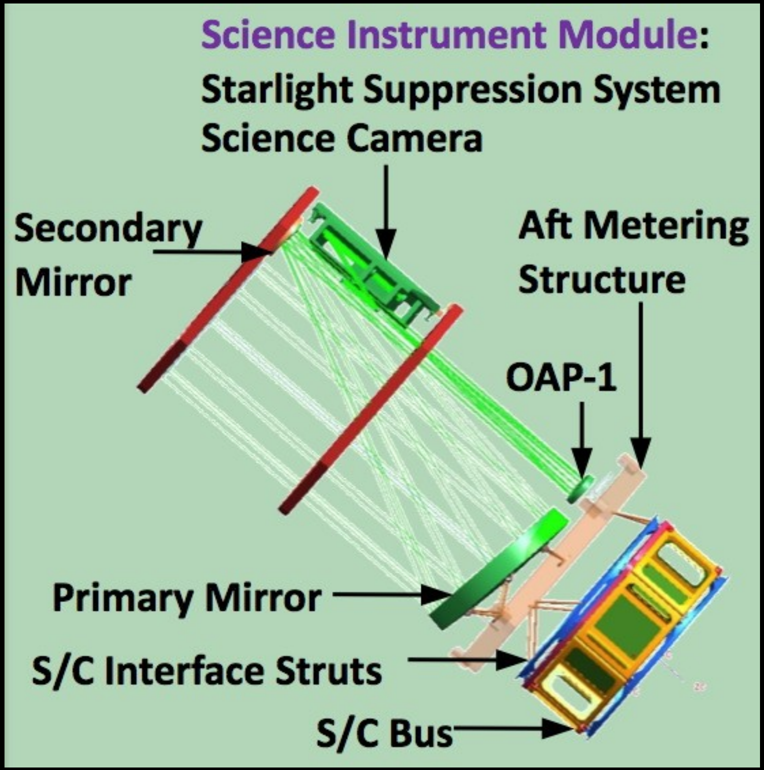
FLIGHT SSS/SCIENCE INSTRUMENT MODULE (SIM) FLIGHT CONCEPT

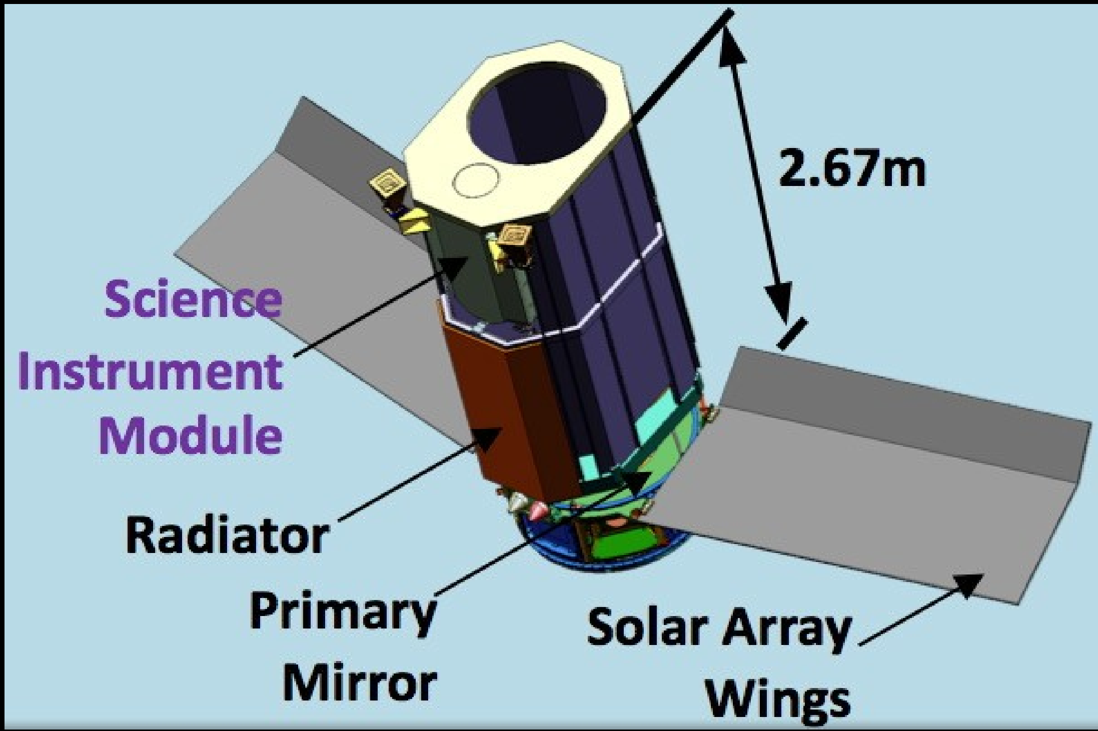


Instrument optical design sized to meet science requirements within volume constraints



SIM–TELESCOPE–SPACECRAFT CONCEPT





- S/C compatible with current ELV envelopes, mass-to-orbit, etc.
- 2000 km alt. sun-synchronous LEO; 6am asc. node twilight-following orbit: thermal stability, efficient target scheduling, S/C disposal
- 3 year baseline mission after IOC, two SEOs proposed
- Mission Ops: ARC (Sunnyvale), Science Ops: UofA (Tucson)

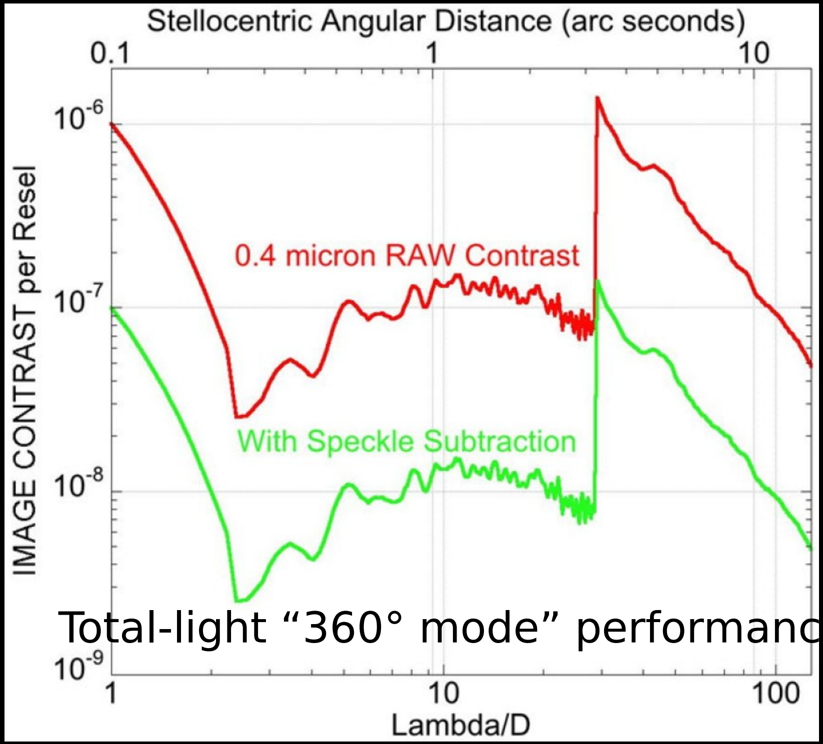
The Need for *EXCEDE*

EXCEDE fulfills the capability currently lacking in NASA's mission portfolio to achieve today's key exoplanetary science goals.

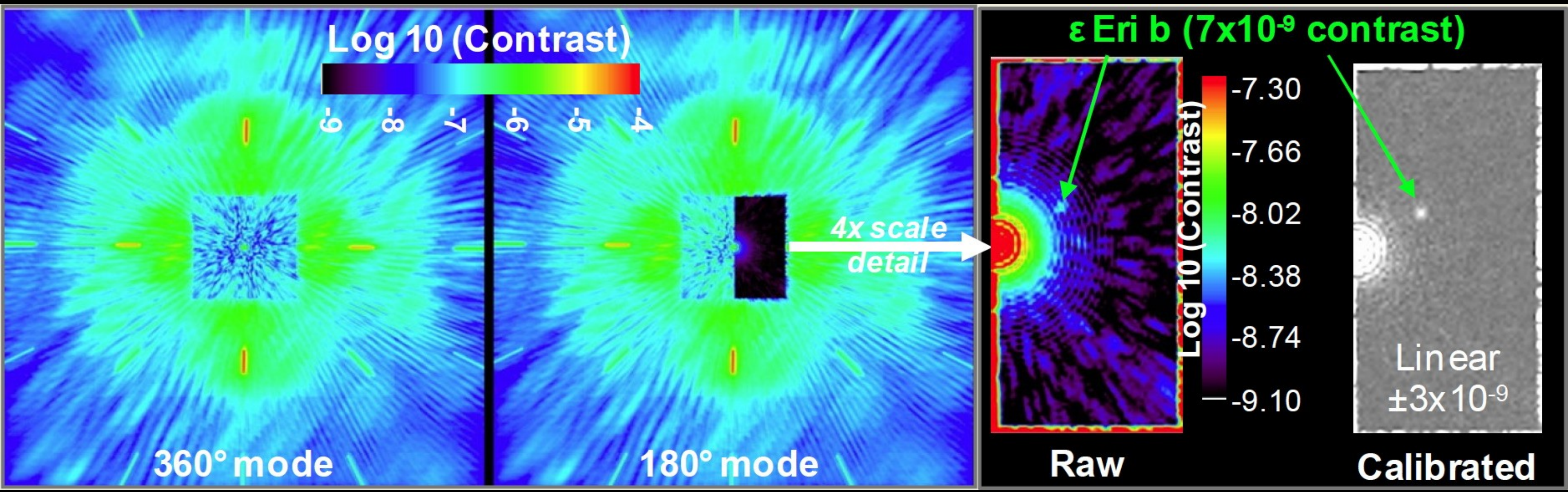
A large aperture telescope is not required to meet EXCEDE's scientific objectives. Imaging CS dust at small IWA is a contrast, not photon, limited problem.

Imaging Sensitivity to ~ 10 zodi disks & mature EGPs

- Diffraction-limited polarimetric & total light ***imaging in 2-bands: 0.4 & 0.8 μm*** *(spatial resolution 0.14" and 0.28")*
- ***Very Small Inner Working Angle (0.14") (0.7 Astronomical Units at 5 pc.)***
- ***Raw Image contrasts for science goals:***
  1e-6 — -7 resel-1 @ 1.2 – 2.0 λ/D
  10e-7 resel-1 @ 2 – ~25 λ/D
- Photon-limited polarized flux contrast augmentation (x10 – 100)



EXCEDE STARLIGHT SUPPRESSION (SIMULATION) with PIAA Coronagraph & DM WF Control



- Image contrasts < 1e-7 and 1e-8 are achieved within the DM WF control zone (here 28 λ/D; ~ 7" x 7" FOV @ 0.4 μm with 642 DM) in 360° (disk survey) and 180° (faint-disk follow-up and planet imaging) modes.

- Simulated PSFs shown with 1 mas target mis-centering error and 10 inoperable DM actuators (worse than GPI yield).

- ε Eri b @ 3.3 AU (9 λ/D) in *single* 3 hr simulated raw and calibrated images (90% speckle subtraction, photon, and 1.4% flat field noise).

EXCEDE DISK IMAGE SIMULATIONS

EXCEDE HIGH-CONTRAST IMAGING OF CS DISKS: CLEANER, FAINTER, CLOSER

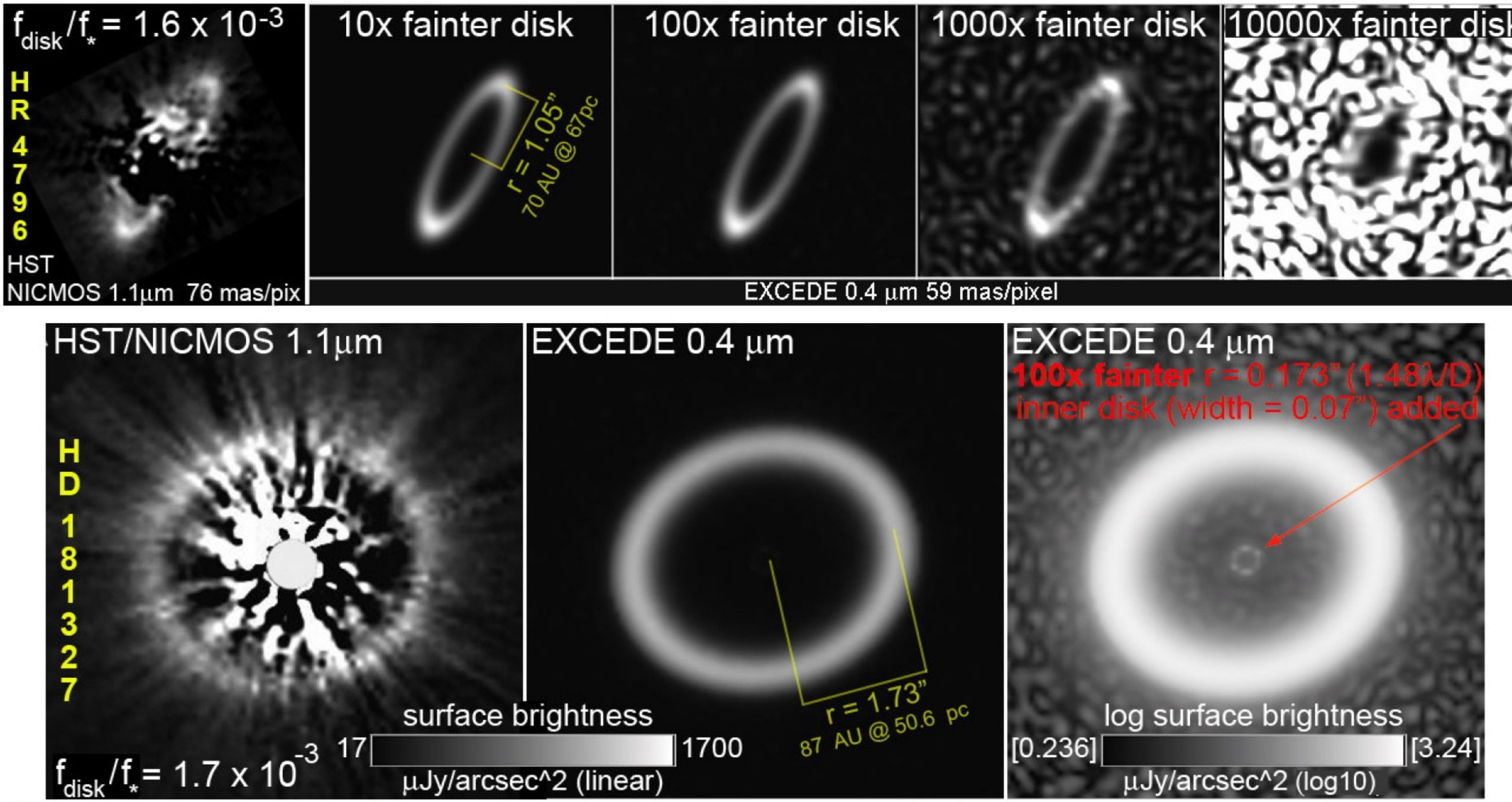
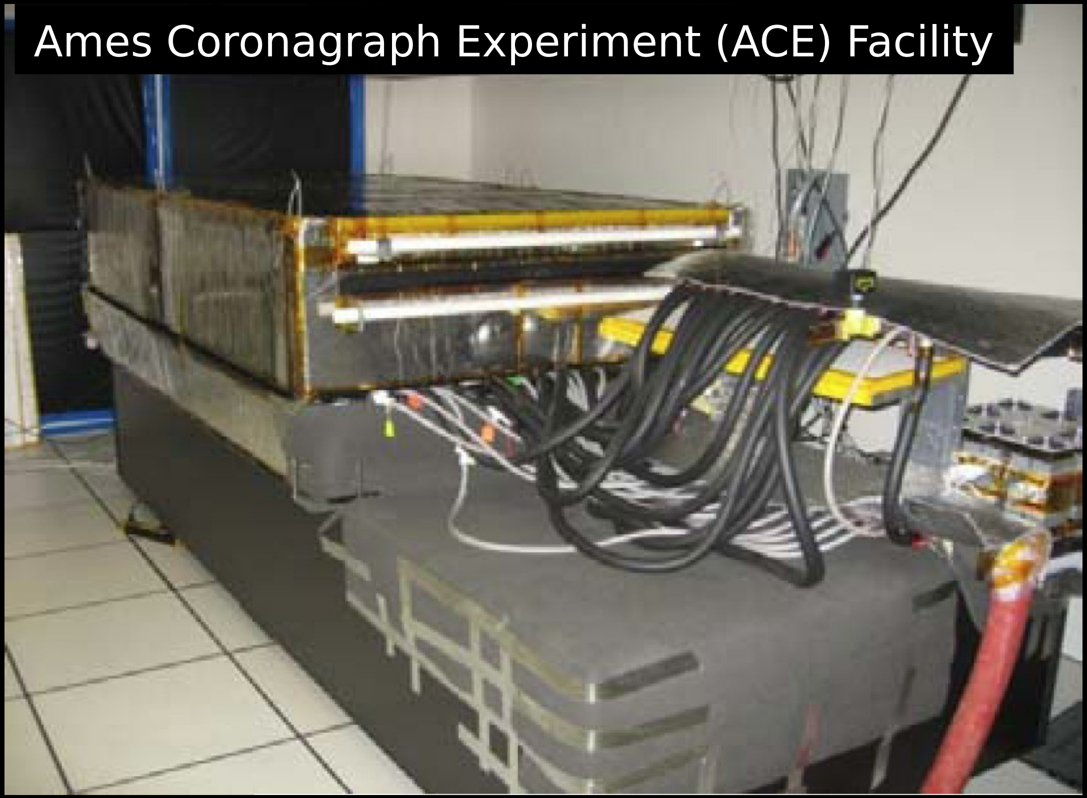
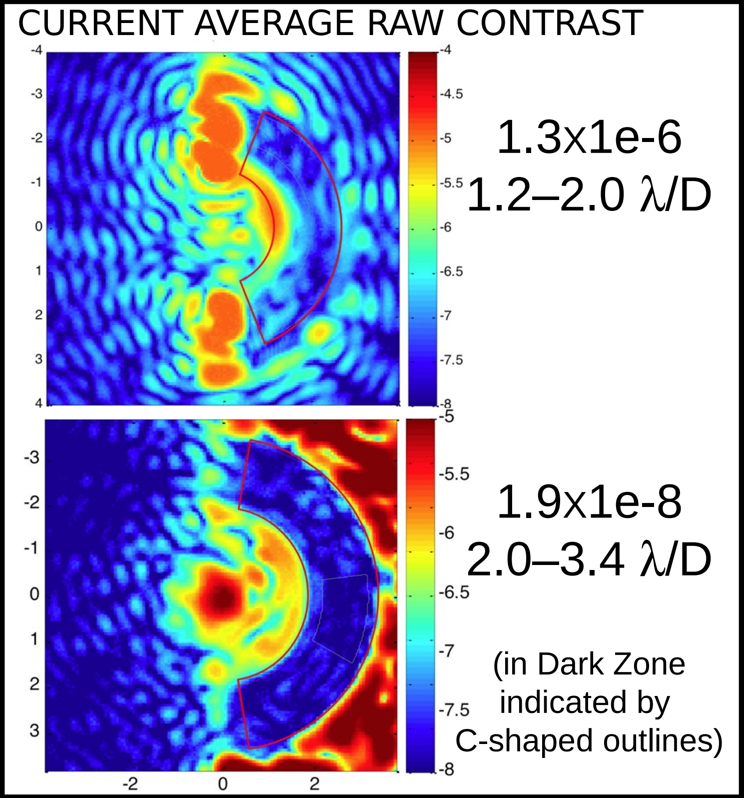


Fig. D.1.10. Pushing *far* beyond the *HST* envelope, *EXCEDE* opens up new observational domains in disk surface brightness and inner working angle. *HST* debris disk images (far left) compared to models of those disks in *EXCEDE* image simulations based on anticipated instrument performance.

Wavefront Control and Starlight Suppression System (SSS) – Testing

The NASA/Ames Coronagraph Testbed will be used to advance the EXCEDE sub-system and SSS Technology Readiness Level as a Category III Explorer Investigation





PIAA + DM contrast/IWA performance required for *EXCEDE* has been closely demonstrated in 0.65 μm monochromatic light at the ACE facility
Category III Technology Development Goal: 20% Bandwidth @ 0.4 μm

EXCEDE Mission Summary

- **Survey of ~ 350 "nearby" exoplanetary disk systems:**

  – High spatial resolution **optical imaging polarimetry into HZs** in CS environments with unprecedented IWA/image contrasts.

  – Survey selected IR-excess stars to image protoplanetary, transition, and debris disks and disk sub-structures over the epochs of **disk/planet formation, evolution & history.**

  – **Directly image known radial velocity-detected extrasolar giant** planets orbiting in terrestrial planet zones.

  – Study **disk grain properties** via 2-band optical polarimetry, while additionally enhancing dusty disk contrast to the photon noise limit**.**

- **"EXPLORER 2011" Two-year Category III Technology Development Program (CY 2012/2013 – 2013/2014)**

- **Science and Technology Pathfinder for Future Exo-Earth Imaging and Characterization Missions**

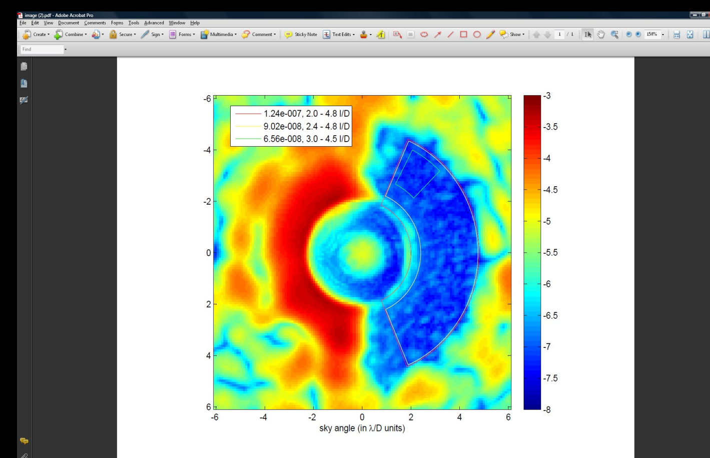
BACK-UP CHARTS

TECHNOLOGY DEVELOPMENT PROGRAM

Two-Year NASA Funded EXPLORER Category III Technology Development Investigation

EXCEDE TECHNOLOGY DEVELOPMENT FOCUS

- **PIAA Performance to EXCEDE Requirements in Broadband Light**
- **Demonstrate functionality/operability in vacuum environment**
- **Performance Stability of SSS on observation timescales**



KEY PERSONNEL

Glenn Schneider (UofA) – Principal Investigator
Olivier Guyon (UofA) – Instrument Scientist; PIAA-Coronagraph
Ruslan Belikov (ARC) – ACE Technical Director
Domenick Tenerelli (LM) – T&V Manager

KEY PARTICIPAING INSTITUTIONS

The University of Arizona
NASA/Ames Research Center
Lockheed-Martin Corp.

EXCEDE Science Camera (in concert with S.O.'s 1–6)

- Flight: 1242 x 1152 pixel e2V CCD cooled to -108C with 2-stage TEC
  - 3e- read noise, noise from dark current ~ 3 e-/pix in 1000 s
  - High (~ 70%, TBS) QE in both spectral bands

- ***20% wide "B"/"R" spectral bands*** and filtered Wollaston polarizers
  - ***0.36 to 0.44 μm and 0.72 to 0.88 μm*** (plus 1% wide "acq" filter)

- Image Scale: 59 mas/pixel, critically sampled @ 0.4 μm
  - Spatial resolution 144/mas @ 0.4 μm, 288/mas @ 0.8 μm

- ***Field-of-View (Working Angle Ranges)***
  - ***IWA @ 0.4 μm resolution limit***
  - DM controlled: 6" x 6" @ 0.4 μm , 7" x 7" @ 0.8 μm
  - DM uncontrolled: 28" x 28" (~ 10-6 contrast @ control zone limit)

- Two-band Polarimetric Imaging*
  - Enables full polarimetric analysis: u, q, p, i, θ, DoP
  - Total light and fractional polarization (DoP) imaging

- *simultaneous U/Q with four (0°, 45°, 90°, 135°) pol angle sampling in each band

NASA EXPLORER CATAGORY III INVESTIGATION: DIRECTION & SCOPE

- **To further mature … elements of the EXCEDE {SSS} technologies:**
  - **Phase Induced Amplitude Apodization Coronagraph Optics**
  - **Deformable Mirror**
  - **Low Order Wavefront Sensor**
  - **Wavefront Control Algorithms**
  - **SSS technologies and WF control integration**

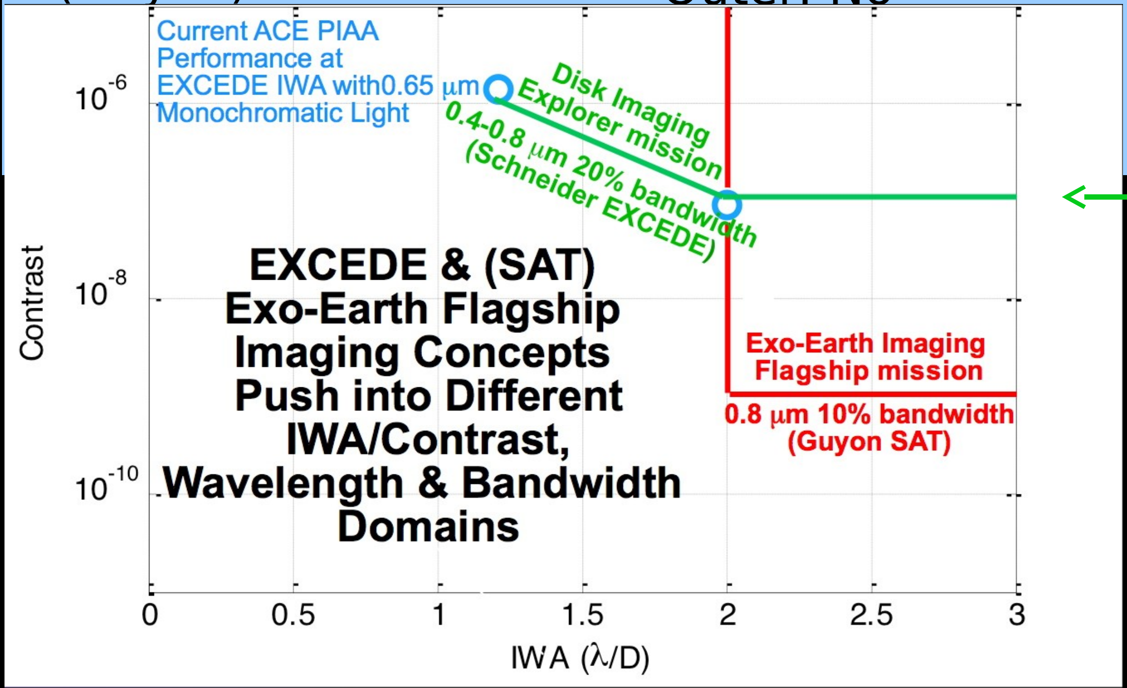
EXCEDE TECHNOLOGY DEVELOPMENT FOCUS

- **PIAA Performance to EXCEDE Requirements in Broadband Light**
- **Demonstrate functionality/operability in vacuum environment**
- **Performance Stability of SSS on observation timescales**

Complementarity and Coordination with SAT/PIAA Program

Technical Requirements for Different Science Goals

Mission	Science Goals	Working Angle	RAW Contrast	Bandwidth	Wavelength
EXCEDE (Schneider)	CS Disks in HZs	Inner: 1.2 λ/D Outer: ≥ 20 λ/D	10-6–7	20%	0.4 & 0.8 µm
SAT/PIAA (Guyon)	Exo-Earths	Inner: 2 λ/D Outer: No	≤ 10-9	10%	0.8 µm Planned Demonstration, **Not** Requirement



EXCEDE IWA/Contrast requirement is essentially met currently in 0.65 µm monochromatic light

Complementarity and Coordination with Guyon SAT Program

ARC/JPL well-established working relationship is already in place, with weekly meetings and coordinated problem-solving

Technology Design and Hardware Flow-Down to EXCEDE

(1) Low Order Wavefront Sensor Design and Control Algorithms (S/W)

(2) PIAA Mirrors (MOU process started for use of existing mirrors)

Broader complementarity of EXCEDE & SAT programs to other JPL coronagraph developments; *different coronagraph designs push different areas in performance space*

Coordination with Guyon SAT Program - LOWFS

Early demonstration: LOWFS 1st developed for PIAA on Subaru PIAA testbed
→ demonstrated 10-3 λ/D pointing control in air
→ demonstrated simultaneous sensing of tip, tilt, focus, remapped tip, remapped tilt

JPL: LOWFS implemented at JPL on PIAA table, development completed Q1 2012
Goals are detailed in milestone #2 white paper for Guyon TDEM
Work done by subcontract to Research Corp. U. Hawaii (PI: Martinache)

Subaru: LOWFS also part of SCExAO system (Closed loop on sky achieved Oct 2011)
Subaru LOWFS work ongoing, with continuous improvements:

- Better control algorithms (modal control, optimal noise filtering)
- Improvements in calibration (faster calibration)
- Ability to dial fixed offsets during closed loop

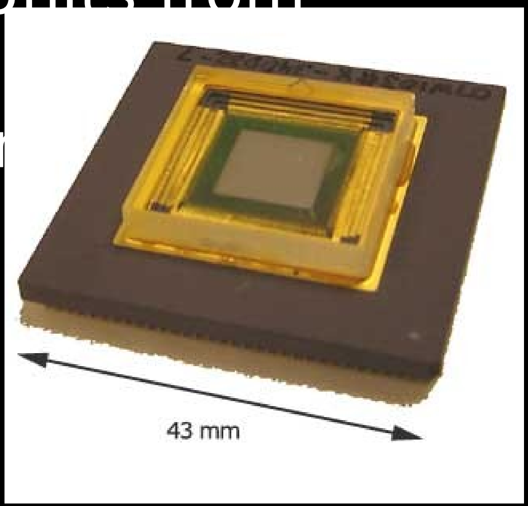
SAT/EXCEDE projects: common S/W & control algorithms are developed and used

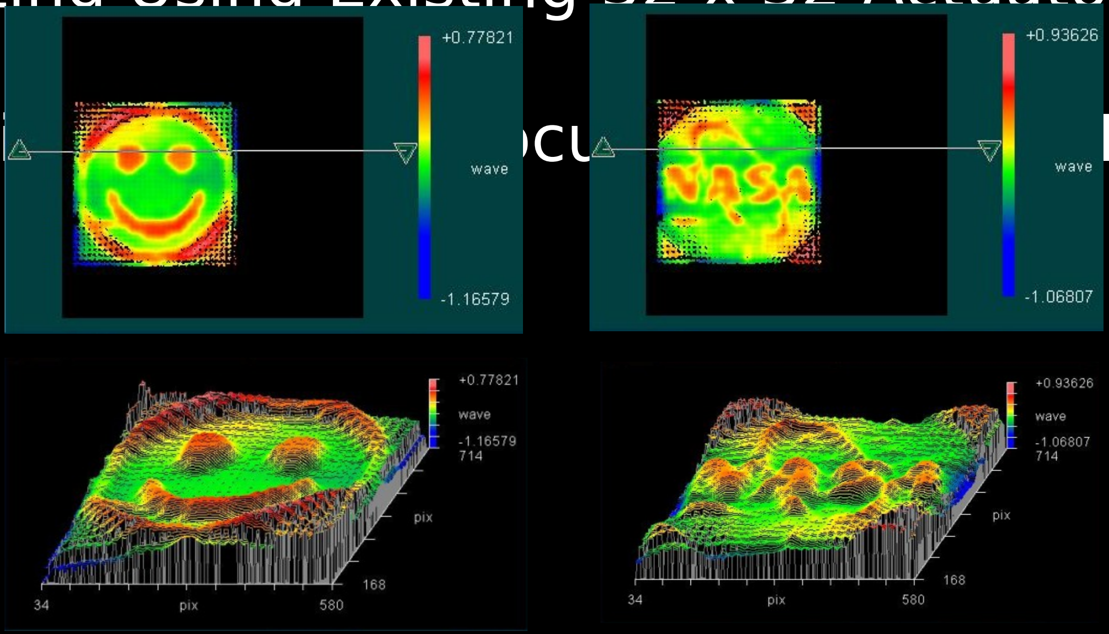
LOWFS plan for EXCEDE: In Q2/Q3 2012, LOWFS implementation completed at JPL
→ ideal time to transfer knowledge gained at JPL/Subaru (SAT) to ACE (EXCEDE)

– allows rapid implementation of LOWFS (2-3 months) at ACE
– after this, inter-project communication continues with performance optimization
– UofA deploys optical scientist at ACE (June 2012) for EXCEDE LOWFS implementation, SSS integration and test.

Micro-Electro-Mechanical Systems (MEMS) Deformable Mirror (DM)

- ACE & Vacuum Testing Using Existing 32 x 32 Actuator Units from
  chi ocu ll
  i



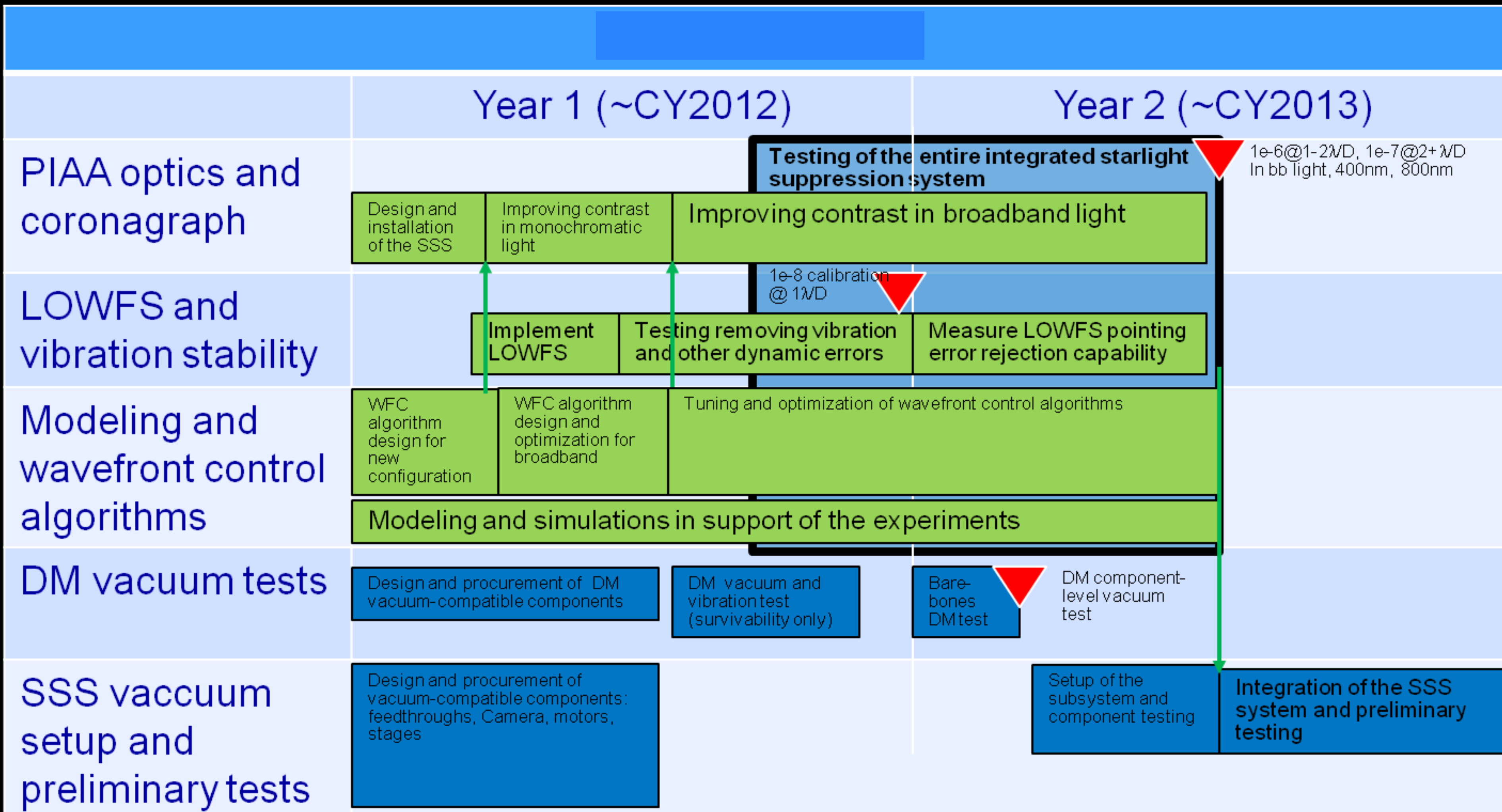


- Flight: 2000 element circular area actuated unit under

High-Level EXCEDE Technology Development Schedule

air development & testing at Ames Coronagraph Experiment facil

cuum environment testing at Lockheed Martin Thermal-Vacuum fa



EXCEDE Mission Goals

- To characterize circumstellar environments in habitable zones (HZs) to assess the potential for planets.
- To understand the formation, evolution, and architecture of planetary systems.
- To develop & demonstrate advanced coronagraphy in space enabling future exoplanet imaging missions

Broad Impact and Direct Applicability to Exoplanet Astrophysics

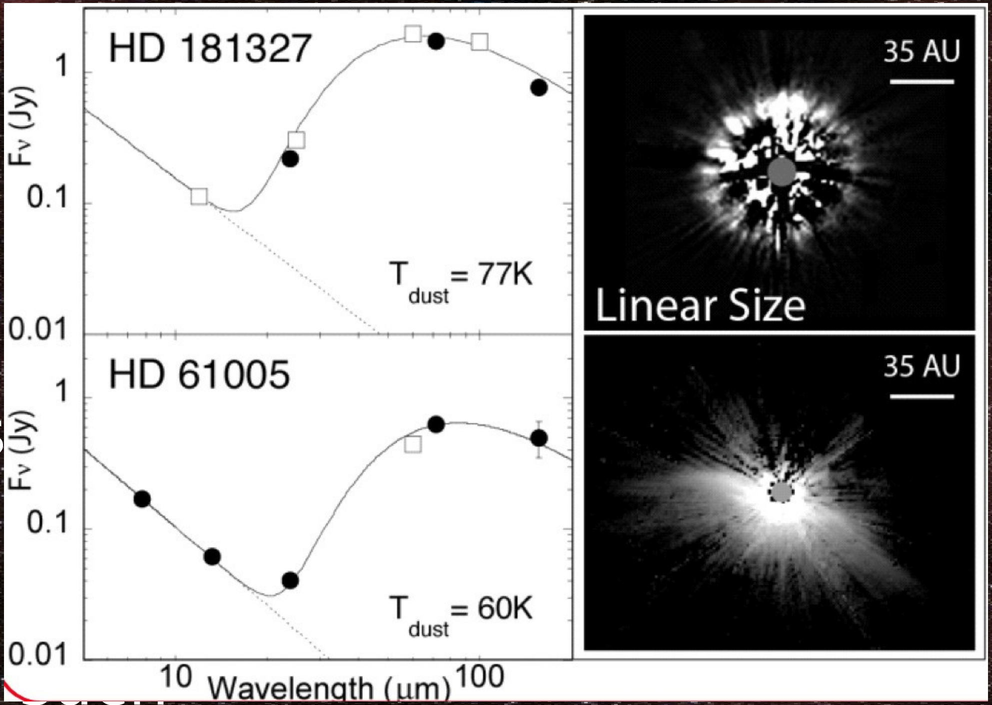
- NASA SCIENCE PLAN: "How do planets... originate?"
- NASA STRATEGIC PLAN: "progress in creating a census of extra-solar planets and measuring their properties."
- Astro2010 – New Worlds New Horizons: " better understanding of the dusty disks surrounding stars."

Using Disks to Discover the Diversity of Planetary Systems

Nearly 400 CS disks have been identified by excess thermal emission.

Spatially resolved images f these disks.

The small number of CS d that have been imaged s remarkable diversity in d architectures.

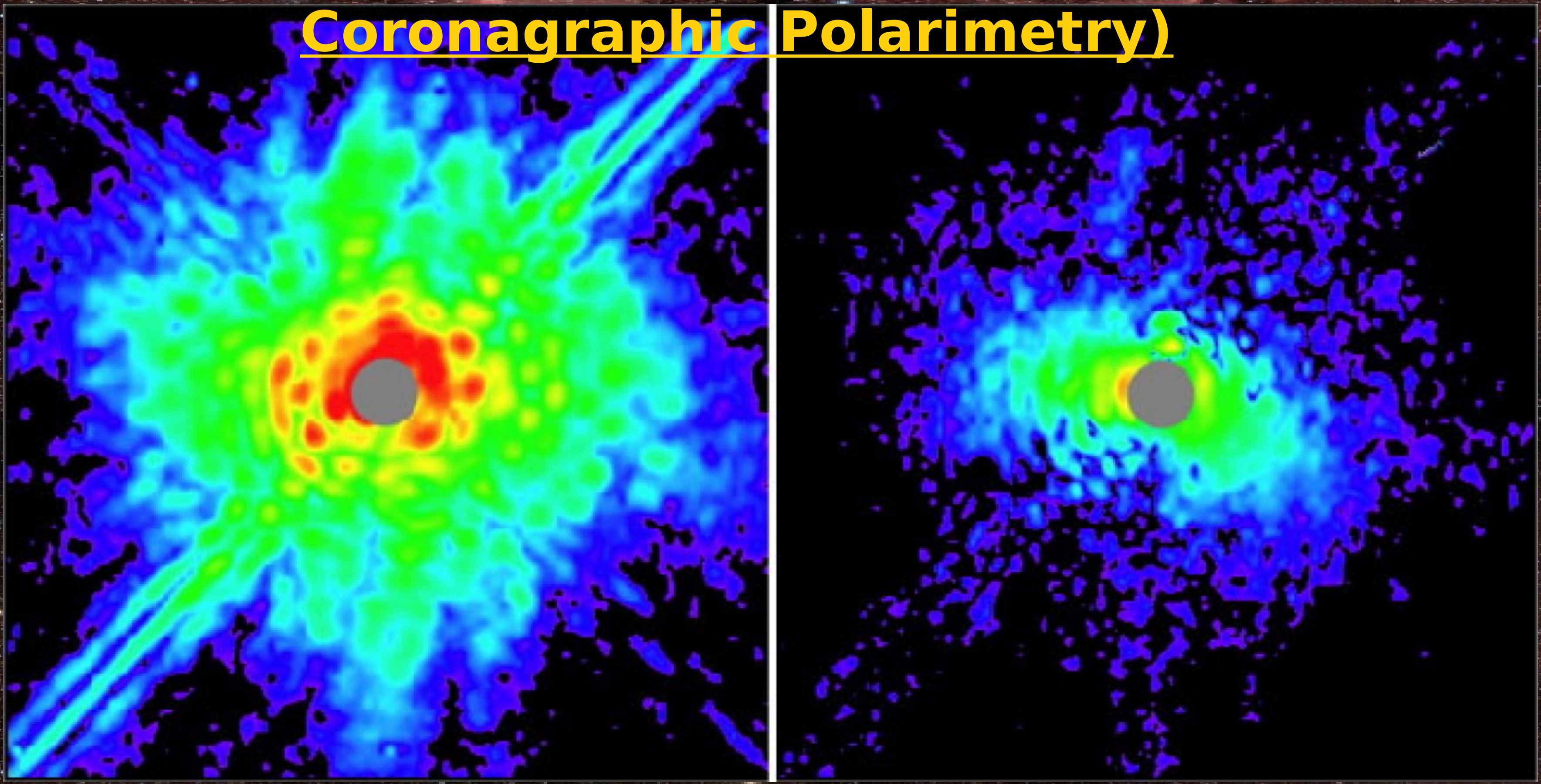


Interpreting SEDs without such images provides only ambiguous information about disk structures.

- Similar SEDs but very different image morphol
- Small grains radiate less efficiently than large.
- At a given equilibrium temperature, small grai reside at greater stellocentric distances.

Spatially resolved images are

GM AURIGAE – "Proof of Concept" (HST Coronagraphic Polarimetry)



LEFT: The GM Aurigae CS disk remains hidden against the incompletely suppressed starlight with "raw" HST coronagraphy alone. ***RIGHT:*** Polarimetric coronagraphy eliminates most

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE is symbiotic with and advances current &

Table 1 - Comparison[a] to Space- and Ground Based Optical/Near-IR Stellar Coronagraphs

	HST ACS	HST NICMOS	**EXCEDE**	JWST NIRCam[b]	GPI[f] (1.65μm) "expected"
Raw IWA Cntrst	N/A [(c)]	10^{-3} @ 0.3"	**10^{-6} @ 0.14"**	7×10^{-5} @ 0.58" [(d)]	---
Aug.[e] IWA Cntrst	N/A [(c)]	10^{-4} @ 0.3"	**10^{-7} @ 0.14"**	7×10^{-6} @ 0.58" [(d)]	3×10^{-6} — 5×10^{-7} @ 0.14"
Aug.[e] 2xIWA Cntrst	N/A [(c)]	2×10^{-5} @ 0.3"	**10^{-8} @ 0.28"**	9×10^{-6} @ 1.16" [(d)]	2×10^{-6} — 8×10^{-8} @ 0.28"
mask radius[d] arcec	0.9" / 1.8"	0.3"	**0.12" / 0.24"**	0.4" / 0.27"	0.123" (H-band)
IWA (λ/d)	13 / 26	3.2	**1.2**	6 / 4	3
Clear Aperture	50%	85%	**100%**	19%	---
λ (μm)	0.4 — 0.8	1.1 — 2.0	**0.4, 0.8**	2.1 – 4.8	Y to K2 bands available
Resolution (mas)	42 — 84	115 — 210	**144, 288**	103–236	50 mas

[a] Comparative metric λs: ACS 0.4 μm, NICMOS 1.1 μm, *EXCEDE* 0.4 μm, NIRCAM 4.6μm; [b] See Krist et al 2007
[c] The smallest ACS IWA is 13λ/D, so contrast comparison to *EXCEDE* is not meaningful
[d] NIRCAM 4λ/D wedge occulter; contrast measure excludes low contrast wedge area
[e] With PSF subtraction for space coronagraphs, with speckle subtraction + ADI + Spectral Differencing for GPI
[f] GPI: stellar I mag dependent contrast; range 9 > I > 5. http://planetimager.org/pages/gpi_tech_contrast.html

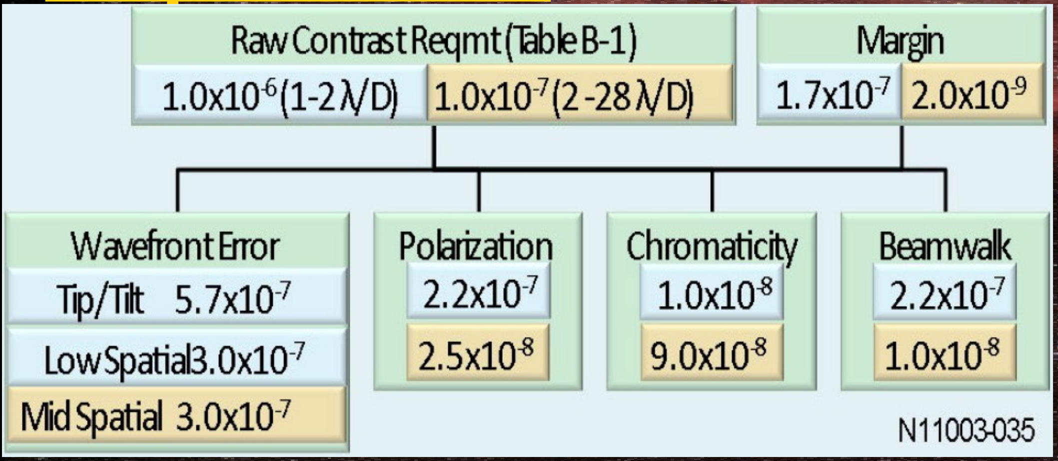
N.B.: By observing in the blue (0.4 μm), *EXCEDE* gains in sensitivity over even the largest ground-based telescopes because scattered-light from small grains is highly λ-dependent ($\lambda^{-\alpha}$, $2 \leq \alpha \leq 4$). Compared with a 10m AO-augmented telescope observing at H-band, *EXCEDE is two orders of magnitude more sensitive to low surface brightness objects.*

Total light "360° mode" performance

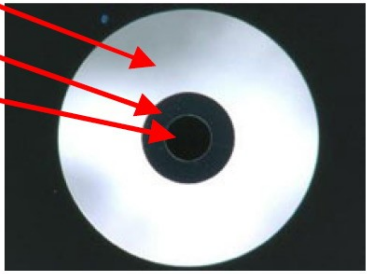
EXCEDE 0.4 μm surface brightness sensitivity (3σ in 104 s) = 27.1 mag/arcsec2 (6.7x10-23 W cm-2). ETCs for Lucifer and VLT yield (3σ in 104 s) H = 23.7/arcsec2 (4x10-23 W cm-2). *EXCEDE* can detect Rayleigh scattering disks at 3σ with H = 3.4x10-25 W cm-2, i.e., *two orders of magnitude fainter than achievable at H band from the ground.*

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

How *EXCEDE* Will Succeed — WF Sensing & Control Requirements



Transparent
Reflective
Opaque



0.6 – 1.2 λ/D annulus reflects light to LOWFS

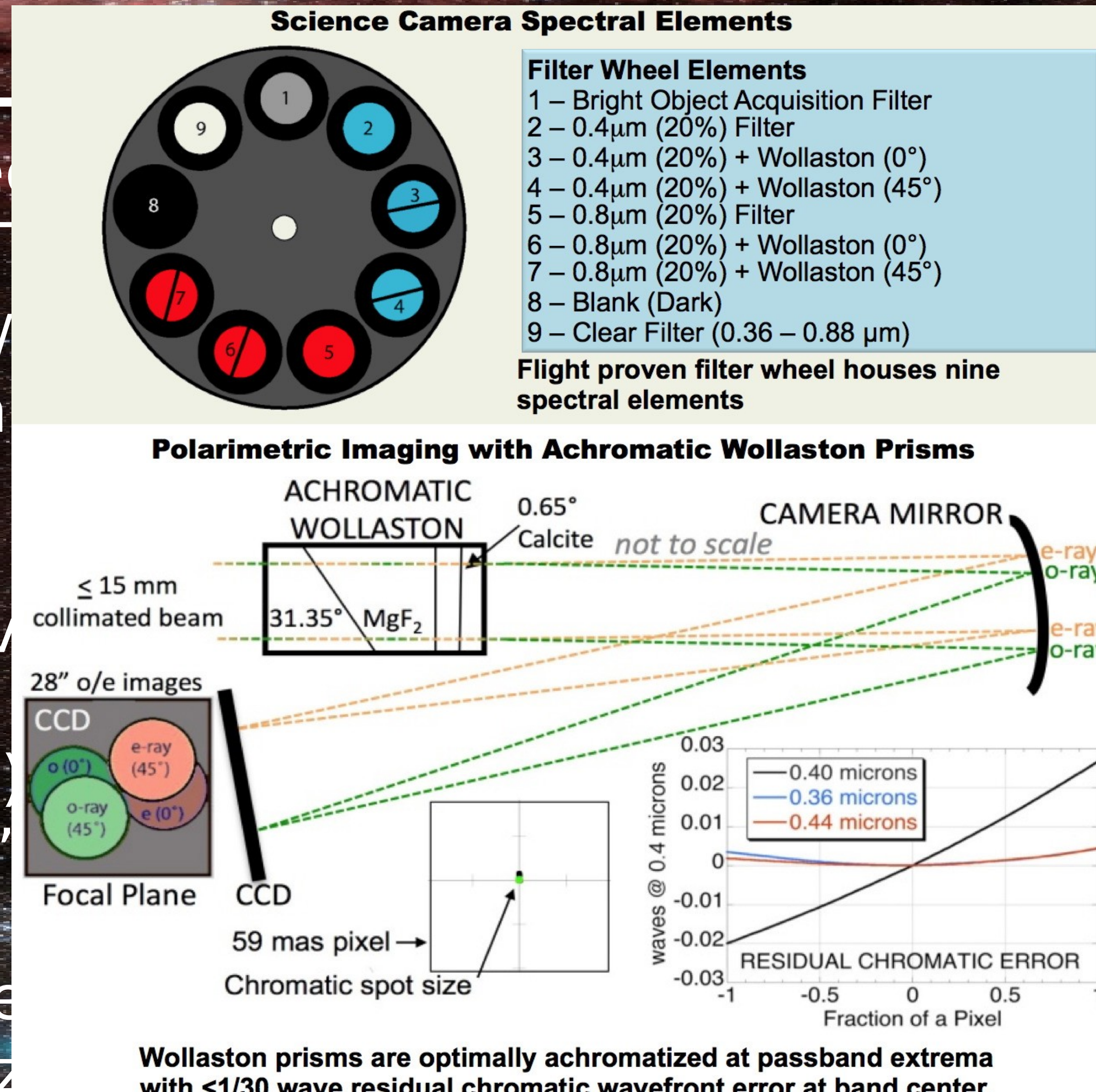
Focal plane mask used in Subaru PIAA testbed

Table 2 — EXCEDE Wavefront Quality Requirements/Goals.

	EXCEDE raw contrast req'mts	Sensing during observation		Control	Pre-launch validation	On orbit verification
Tip/Tilt	0.01 waves RMS **21 mas RMS** mech. tilt at FSM	LOWFS SNR=1 for V =10	~400 Hz update, 1 mas accuracy	Slow offload: S/C pointing. Fast: Instrument FSM	Validate LOWFS sensitivity + S/C disturbance model	LOWFS
Focus	**0.2 nm RMS on WF**		~10 Hz update, 0.1 nm RMS	DM actuation		
Mid spatial frequencies (< 30 λ/D)	0.1 nm per mode	Science camera, used with small DM dithers		DM actuation	PSF Contrast	PSF Contrast

EXCEDE Science Camera 2-Band Imaging Polarimeter

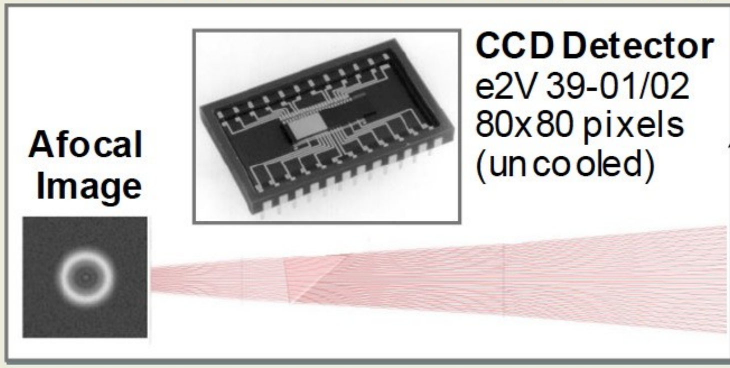
- 1242 x 1152 pixel 3e-
  noise e2V CCD coolec
  -108C with 2-stage T
- Image Scale: 59 mas/
  0.4 μm critically sam
- 144/288 mas resel at
  0.4/0.8 μm, respectiv
- Full (DM uncontrolled)
  (~ 10-6 contrast): 28"
- 20% wide "B"/"R" filte
  and Wollaston polariz

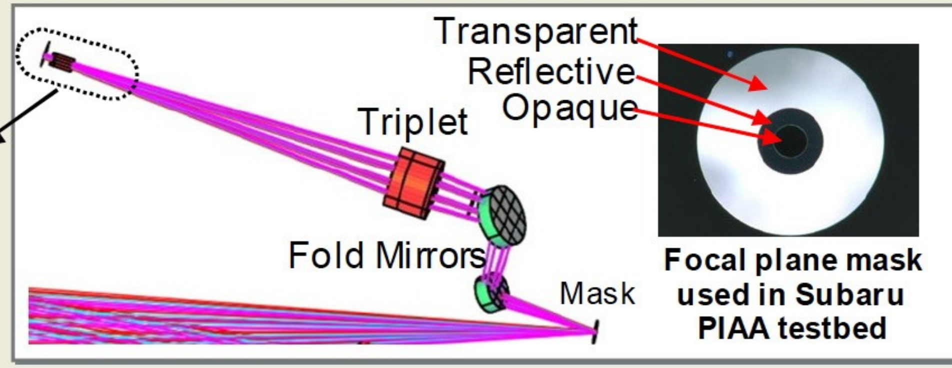


EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE LOWFS and Science Camera Imaging

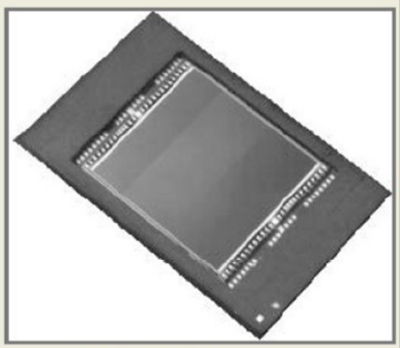
2.5 Low Order Wavefront Sensor (LOWFS)



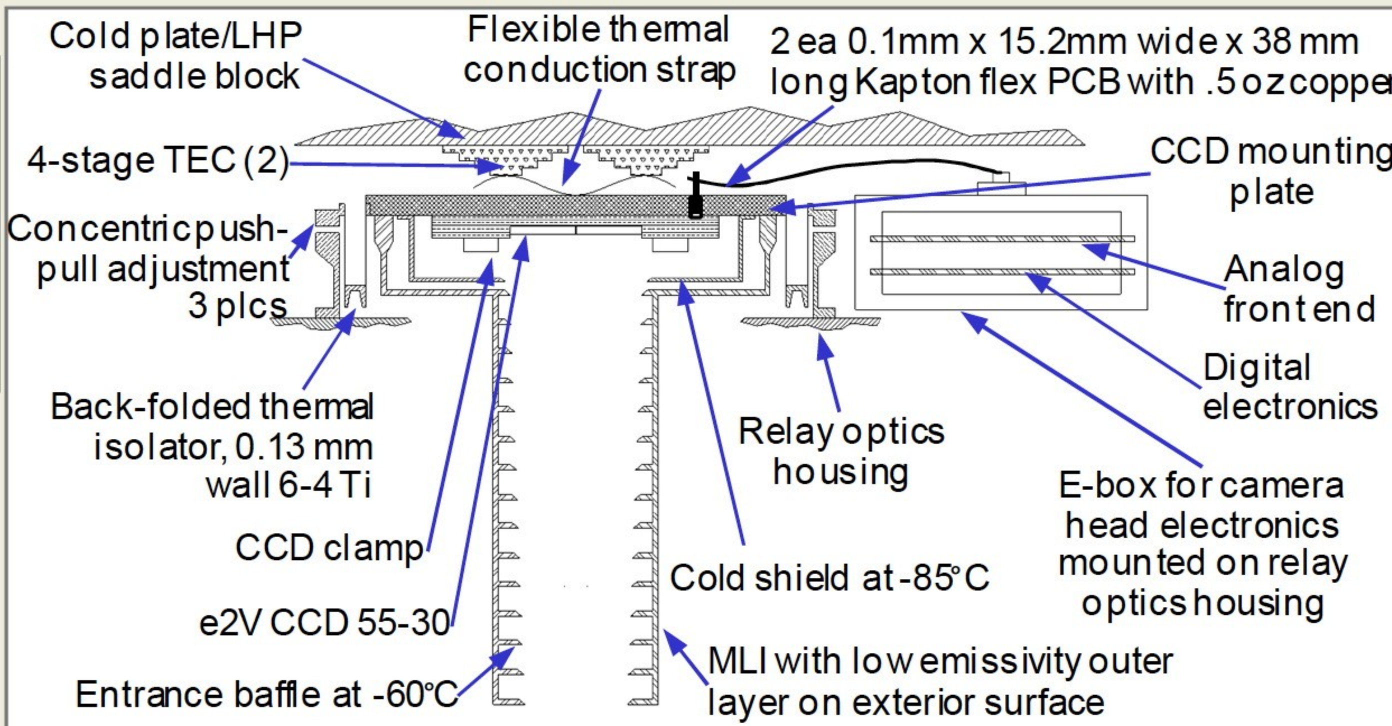


Focal plane mask used in Subaru PIAA testbed

2.6 Science CCD Detector and Camera Head Design

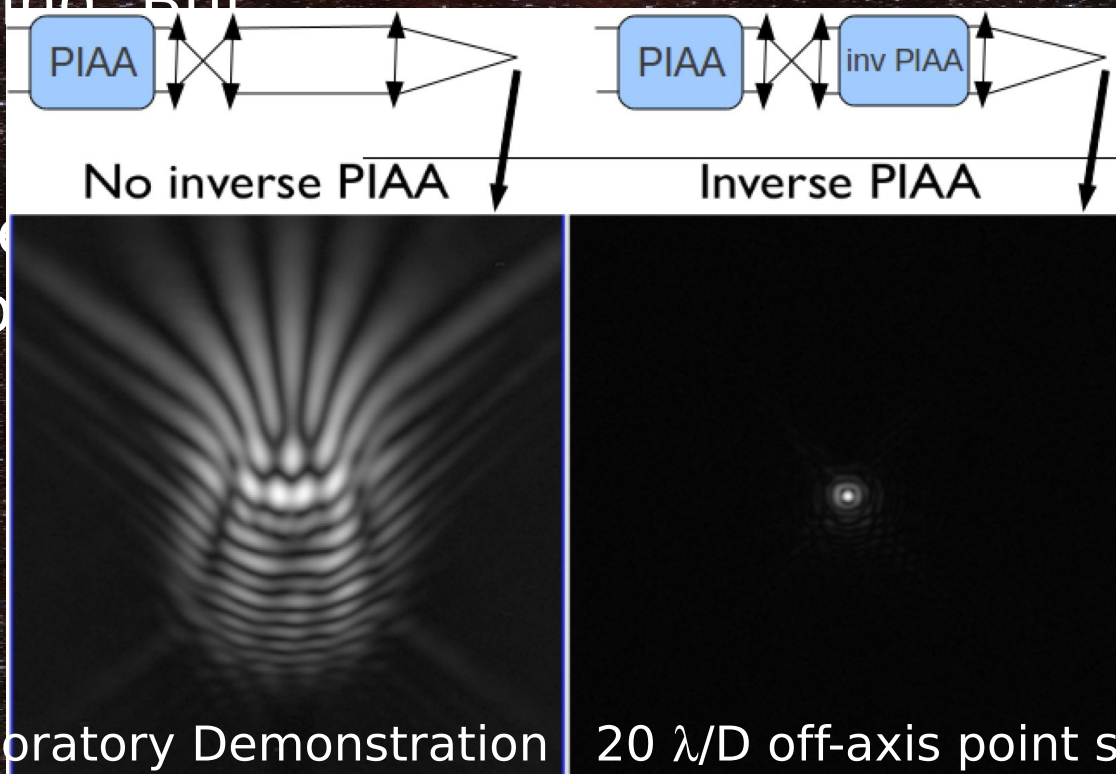


CCD Detector
e2V CCD 55-30
1242x1152 pixels
22.5 µm pixel pitch
3e- read noise
QE ~ 70% 0.4 µm



Phase Induced Amplitude Apodization (PIAA) Coronagraphy

- The OFF-AXIS beam is highly abberated by the pupil remapping. But
- A ident tly “undoes” th PIAA
  pupil r sked in the image p



Laboratory Demonstration   20 λ/D off-axis point source

- Laser spectrum cutoff is at ~460 nm (may produce sufficient power density to 400 nm with different fiber; TBD)
  - Operate with 20% bandwidth as blue as fiber coupling allows
  - Operate at **400–440 nm and use a monochromatic laser at 360 nm**
- Use one of two existing 32x32 DMs in ACE lab
  - 32x32 device will demonstrate performance for key science objectives of EXCEDE
  - BMC developing 2K device -- anticipated availability in April 2013
  - Electronics for 32x32 device electronics upgradeable for 2K device
- DM electronics will be outside the LM test chamber, with cables feeding in.
  - LM already worked with high-density ribbon cables