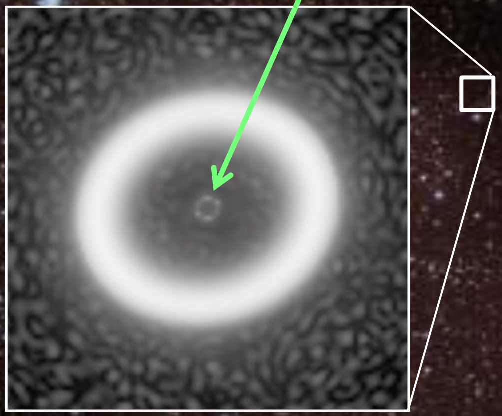
EXCEDE

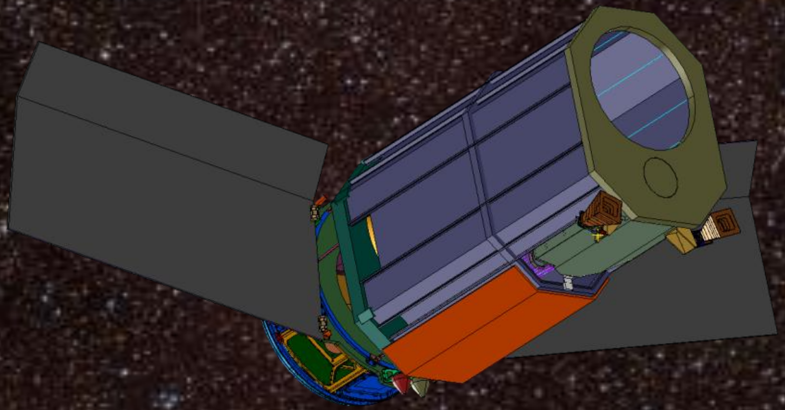
Science, Mission, and Technology Overview

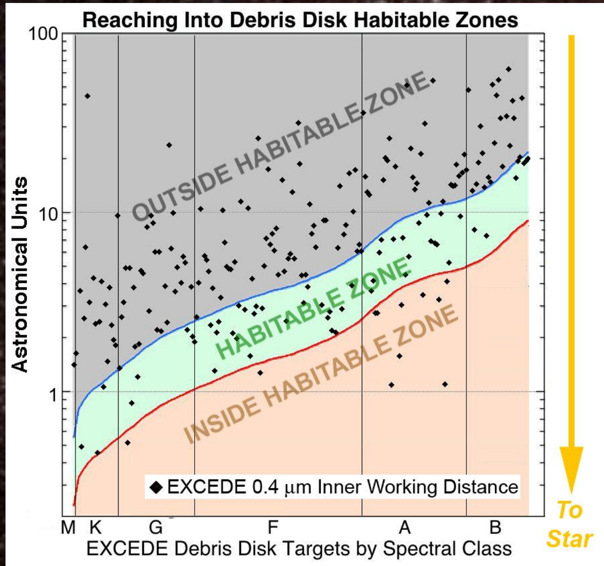
EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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



Dr. Glenn Schneider
Steward Observatory
The University of Arizona





A Response to NASA's 01 Nov 2010 Announcement of Opportunity
NNH11ZDA002O
EXPLORER 2011

This Talk (ExoPAG 5)

Science, Mission, and Technology Overview

- **Mission Overview, Team, Goals**
- **Science Context and Objectives**
- **The Need for *EXCEDE* and Key Enabling Technologies**
- **Science Payload (Key Components & Integrated System)**
  – Phase Induced Amplitude Apodization Coronagraph (PIAA-C)
  – Wavefront Control & Starlight Suppression System (SSS)
  – Science Instrument Module (SIM) and Imaging Polarimeter
  – Performance/Image Simulations
- **Telescope/Spacecraft/Mission Profile (DRM)**
- **Explorer Cat. III Technology Development Program**
  – Direction, Scope, and Focus
  – Test Facilities and Current Status
  – Goals and Milestones
  – Schedule
- **Mission Summary**

Zodiacal Light

Circumsolar Debris Scattering Sunlight in our own Solar System

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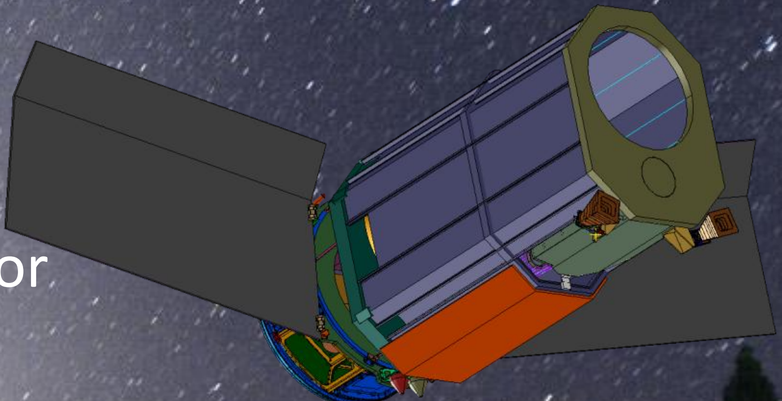


- 0.7 meter off-axis visible-light telescope
- Active Starlight Suppression System:
  – PIAA Coronagraph
  – 2000-Element MEMS Deformable Mirror
  – Low-Order Wavefront Sensor
- Two-band Imaging Polarimeter
- Three-year mission (2000-km LEO Sun-synchronous orbit)
  – Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs.
- Currently approved for two-year Tech. Dev program

Exo-Zodiacal Light

Circumstellar Debris Scattering Starlight in Exoplanetary Systems

EXCEDE

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

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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

SCIENCE TEAM

G. Schneider (PI), UofA	T. Greene, ARC
O. Guyon (IS), UofA	D. Hines (dPI), STScI
R. Angel, UofA	P. Kalas, UC Berk.
L. Close, UofA	M. Kuchner, GSFC
P. Hinz, UofA	A. Weinberger, CIW
G. Rieke, UofA	B. Whitney, U. Wisc.
C. Grady, Eureka Sci.	M. Wyatt, Cambr. U.

PROJECT MANAGEMENT	co-I's & Collaborators
D. Tenerelli (PSM), LM	R. Belikov (TDEV), ARC
G. Prout (PM), UofA	M. Lesser, UofA
J. Mamie (aPM), ARC	C. Stark, CIW

Key TDEV Personnel & Partners

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.

EXCEDE 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 in space enabling future exoplanet imaging missions.

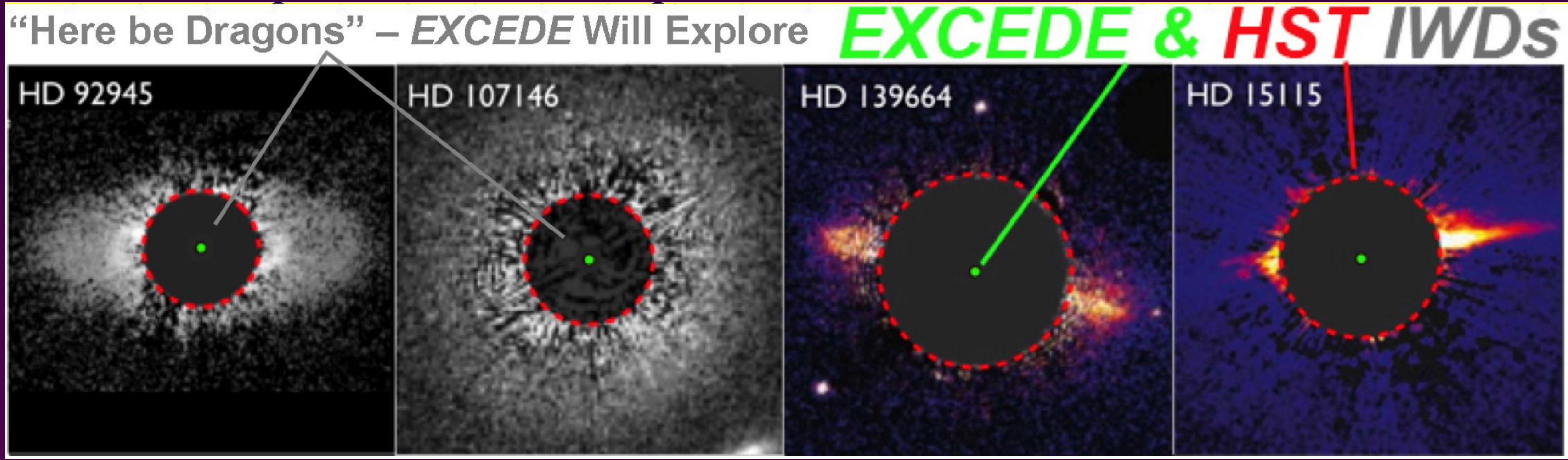
Circumstellar Disks:
Signposts of Planetary Systems & Tracers of Planets

The mere presence of a debris disk is a signpost for some sort of planetary system.

Spatially resolved imaging reveals its structure and traces the presence of massive planets.

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…**
- *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).*
- **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.**



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

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 $L_{disk}/L_{*} \geq 10^{-5}$ and d $\leq$ 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 $\leq$ 150 pc.

3) 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.

4) Radial Velocity Detected Planetary Systems

- $\geq$ 9 stars with RV planets potentially within the reach of EXCEDE.

* (separately, 6 IR-bright DD targets have RV detected planets)

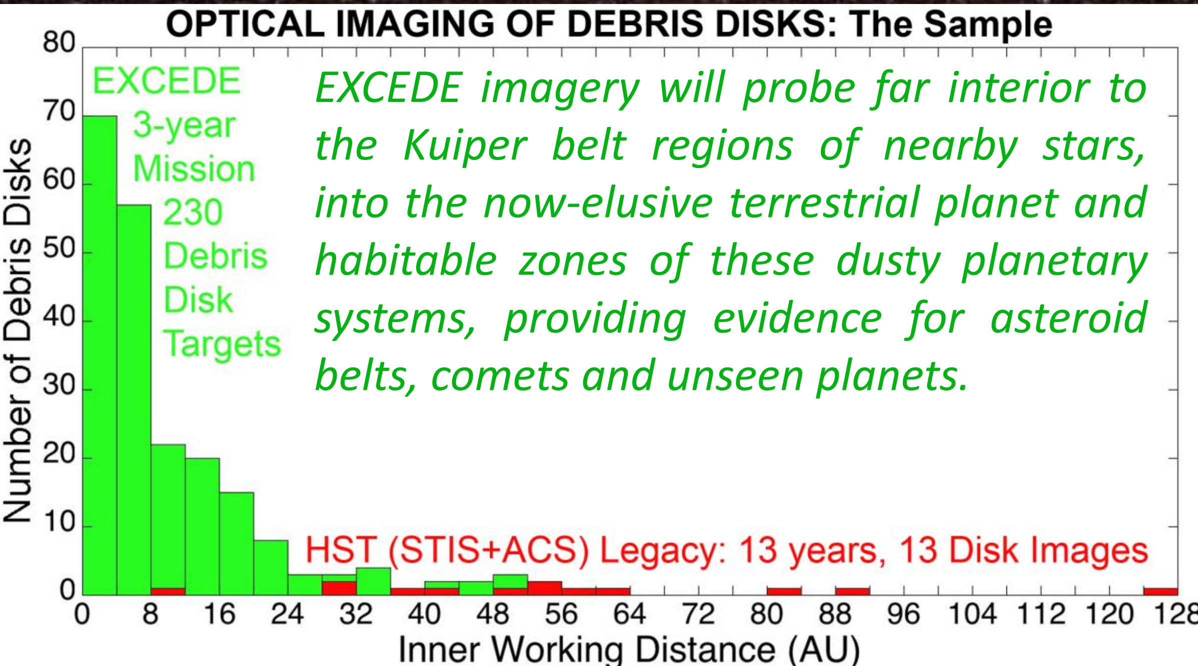
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

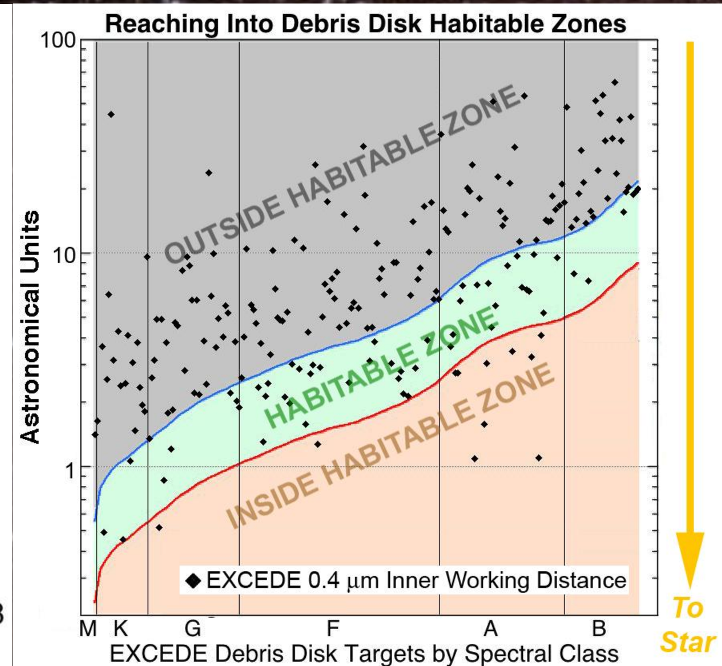
S.O. 1: What are the levels of dust in the HZs of exoplanetary systems?

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.**

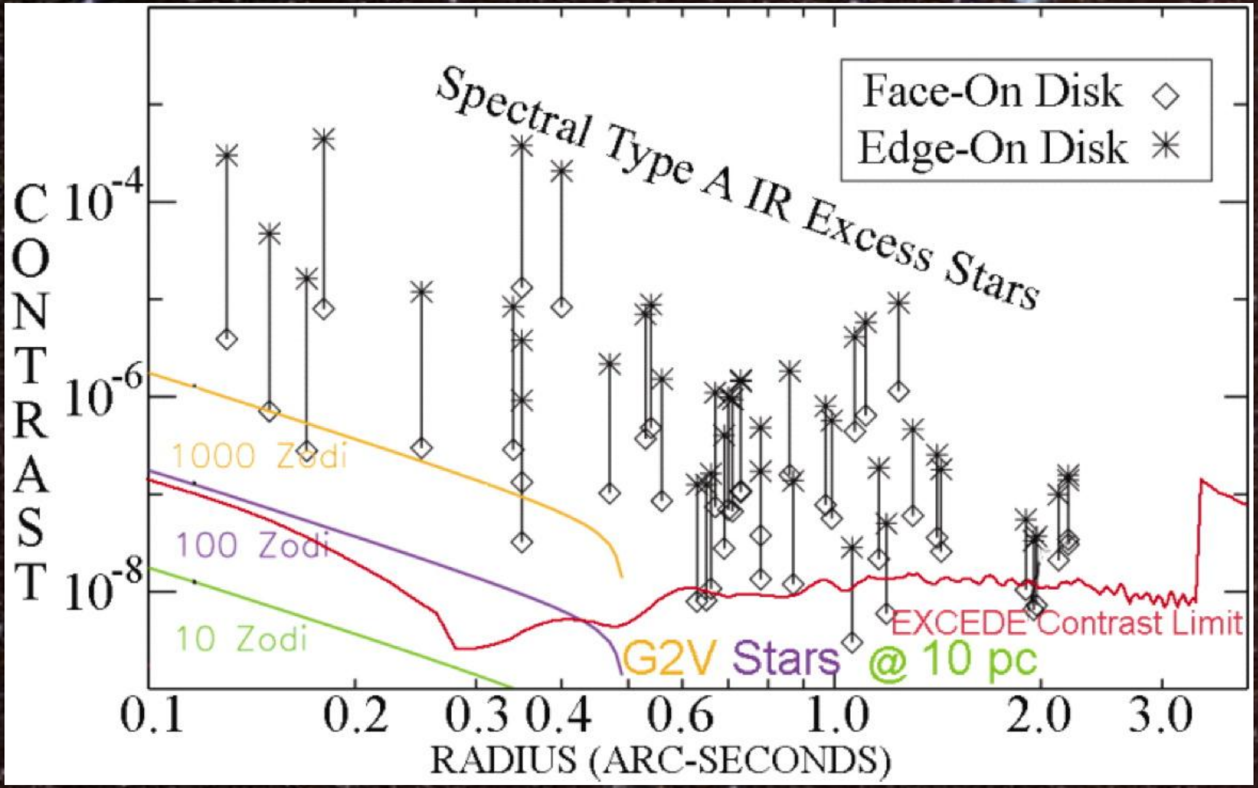
For > ¼ our DD target sample, *EXCEDE*'s 0.14" IWA enables spatially resolved imaging in CS HZs where liquid water can exist on planetary surfaces.





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

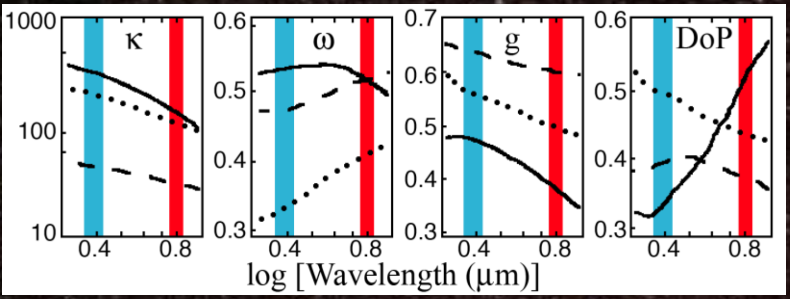
The amount of dust in HZs is key to determining the best strategies to image Earth-like exoplanets — Dust-scattered starlight is the main source of astrophysical "noise" in detecting such faint point sources.

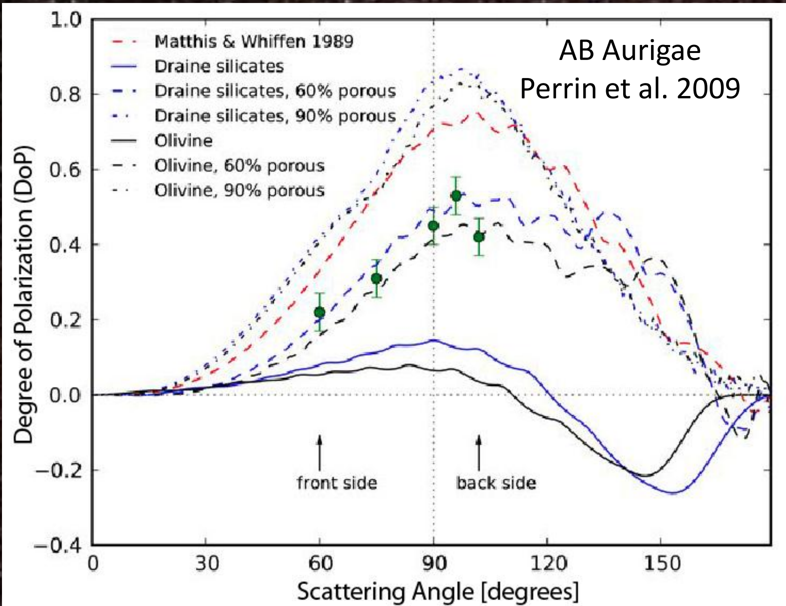


But… It is conceivable that by targeting stars without debris dust, future exoplanet imaging missions may be selecting targets unlikely to have had sufficient initial mass for rich planetary systems (?)

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.



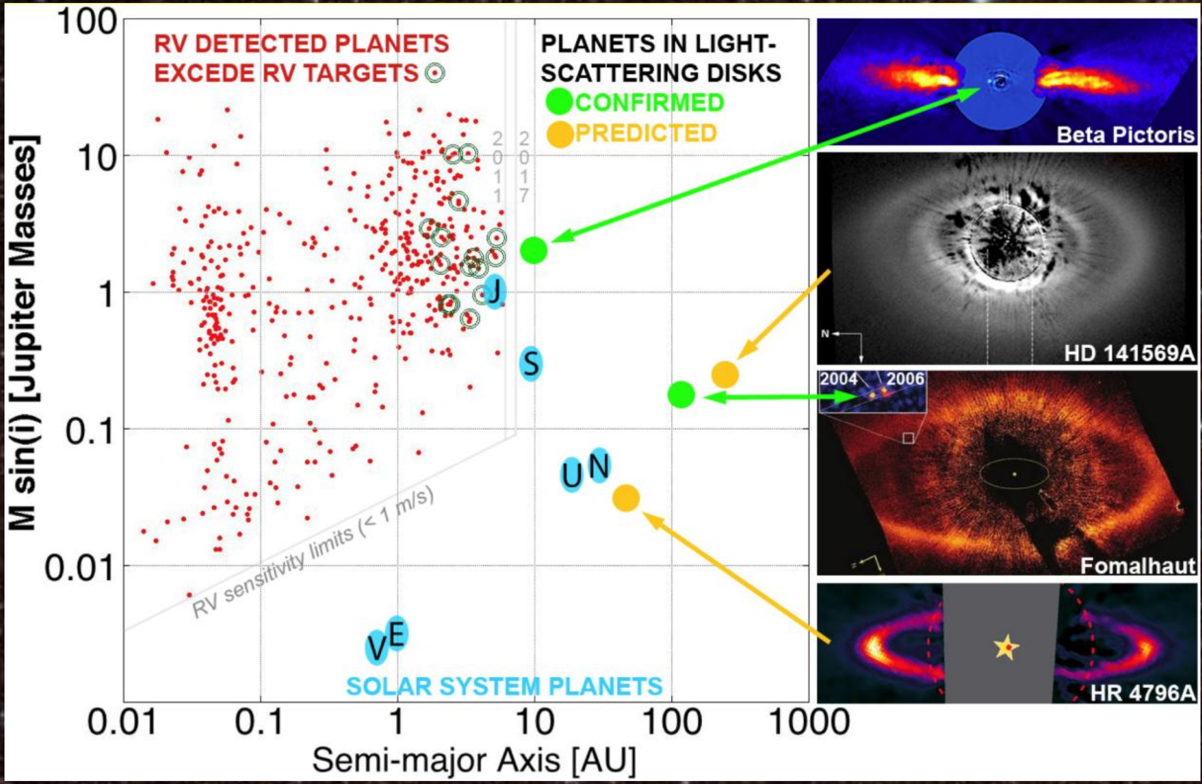


Distinguishing Grain Properties with 2-band Polarimetry

- *Disks may be full of volatile-rich porous grains that carry H_2O 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 dynmaical influences on debris disks.

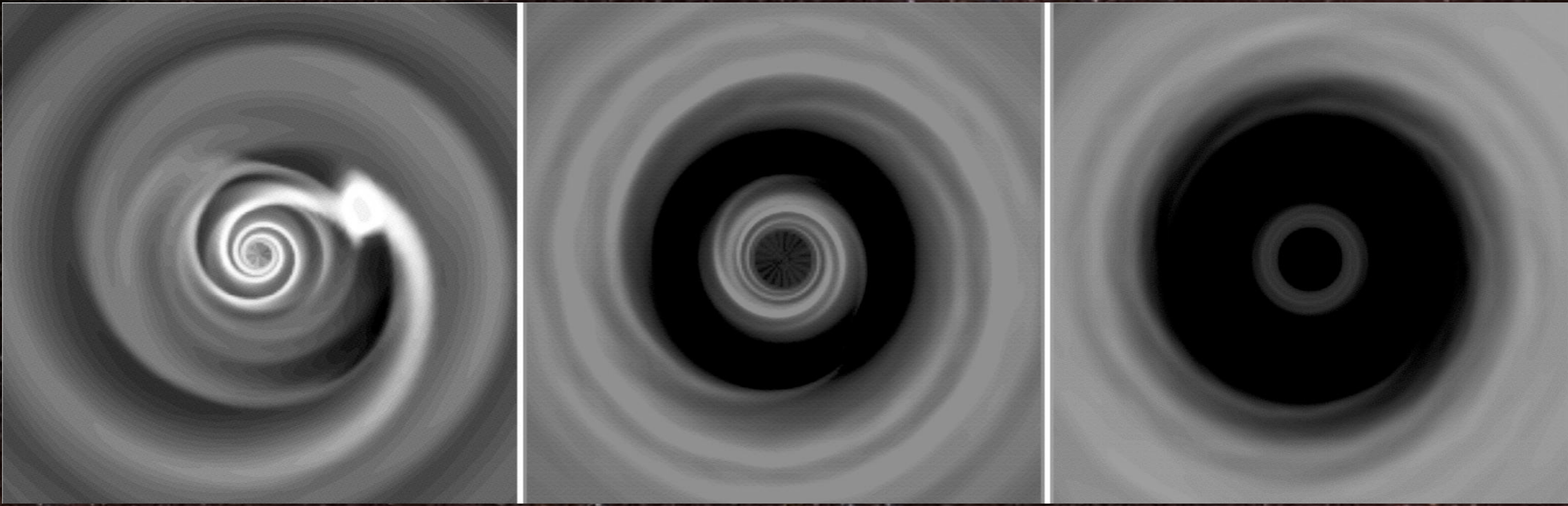


Structure in disks betrays the presence of planetary systems. EXCEDE will reveal the radial locations of planetesimal belts — a powerful indicator of gas-giant and ice-giant planets.

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.

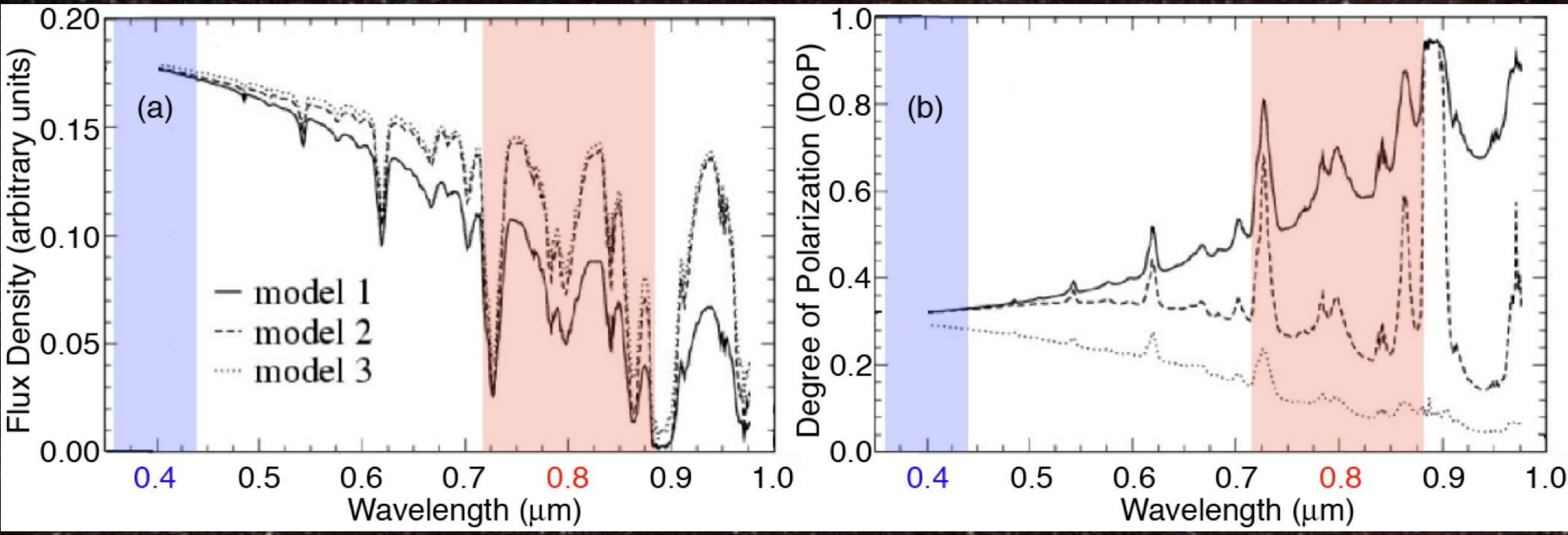


Theoretical models predict material-depleted disk "gaps", observable with *EXCEDE*, evolving over time due to the presence of co-orbiting planets (E.g., above from Bryden et al 1999).

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.

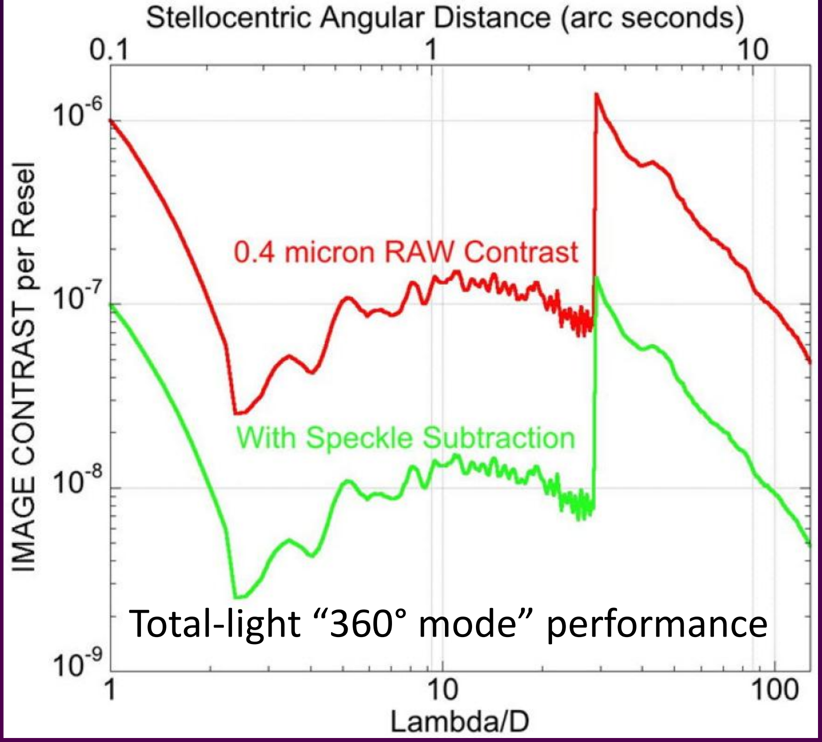
The Need for *EXCEDE*

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 require 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:***
  $10^{-6\,—\,-7}$ resel^{-1} @ 1.2 – 2.0 λ/D
  10^{-7} resel^{-1} @ 2 – ~25 λ/D
- Photon-limited polarized flux contrast augmentation (x10 – 100)



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:

- $10^{-6\,-\,-7}$ 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.

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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.

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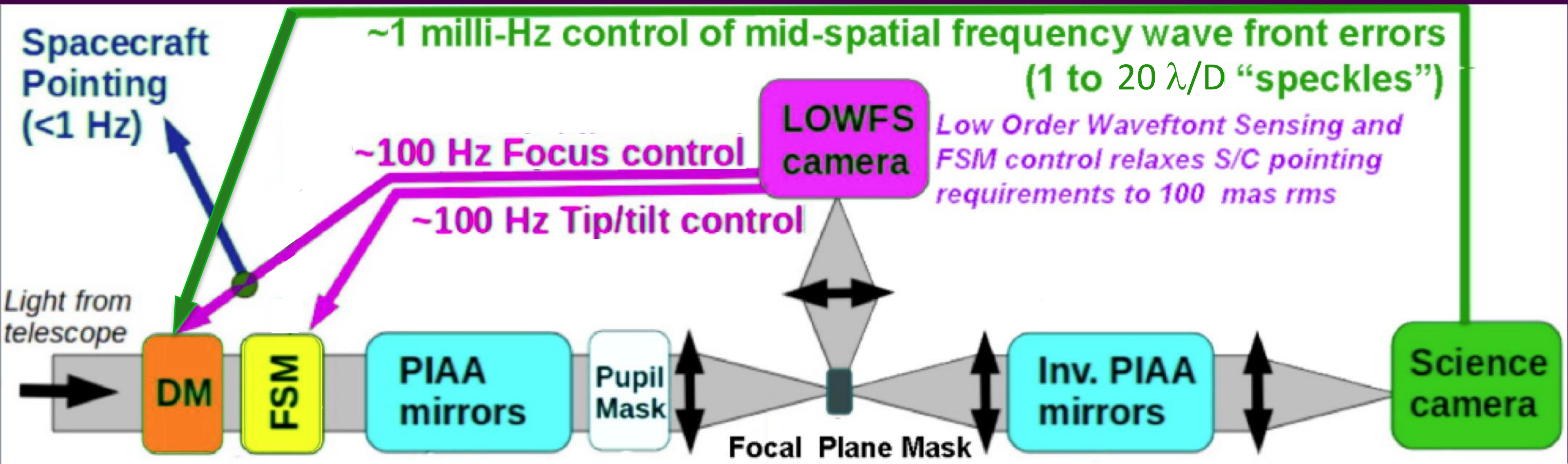
3) ***Well understood calibration methods*** to accurately separate residual starlight from genuine source in science images.

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

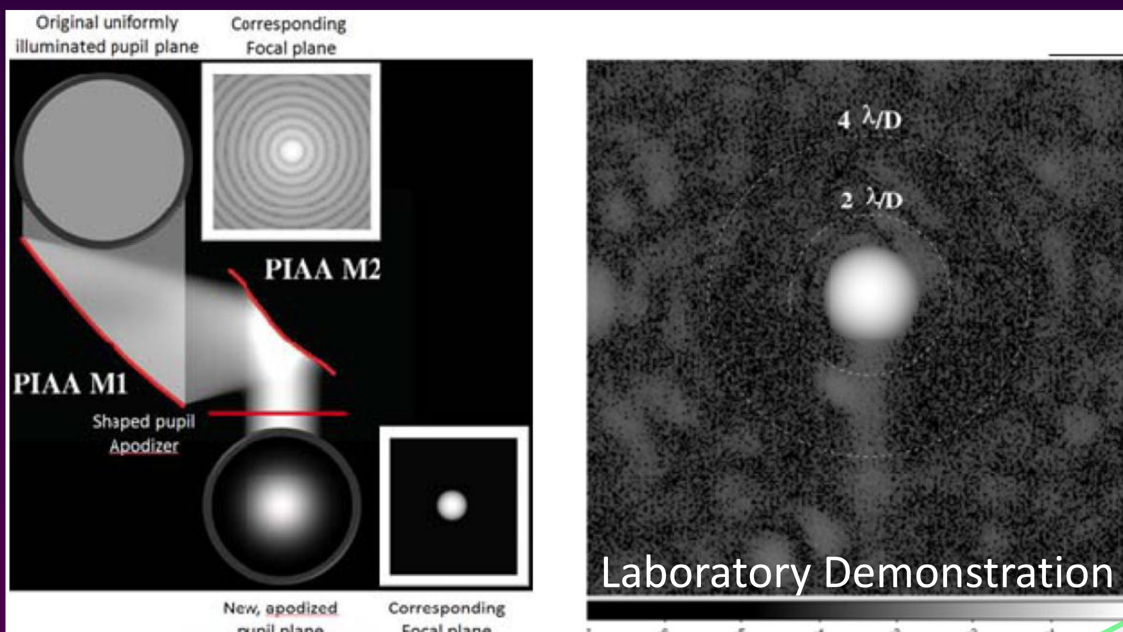
WAVEFRONT CONTROL & STARLIGHT SUPPRESSION



Phase Induced Amplitude Apodization (PIAA) Coronagraphy

— O. Guyon, UofA

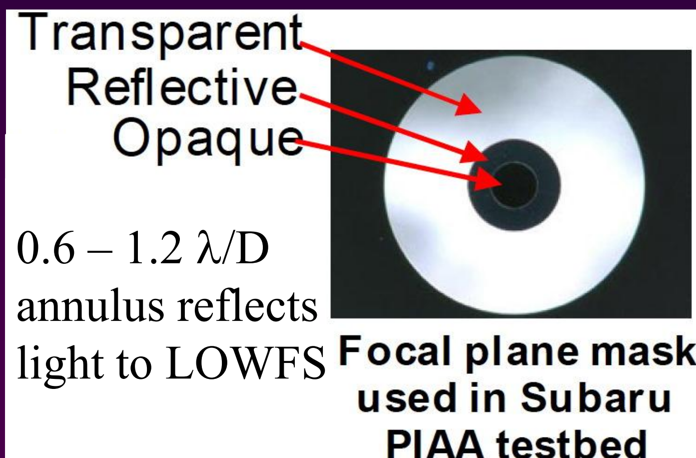
- PIAA is a lossless beam apodization producing a high contrast image of an on-axis point source with no Airy rings! Ideal for coronagraphy.
- PIAA apodizes the pupil by geometric redistibution of light, not by selective masking/absorption, by using (highly) aspheric optics.



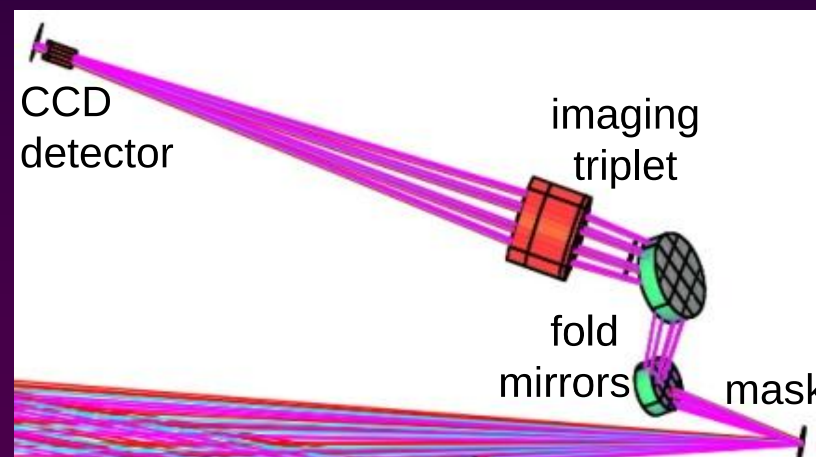
- ***Recently manufactured PIAA mirrors (3.8 nm RMS surface error) exceed the wavefront quality requirements needed for EXCEDE.***

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



Focal plane mask used in Subaru PIAA testbed

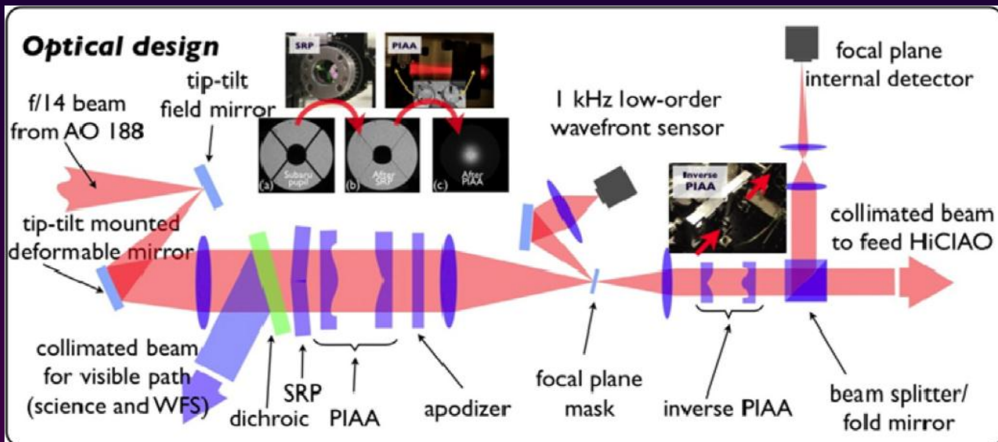


- 10^{-3} λ/D pointing demonstrated with Suburu PIAA testbed (1 Hz)
- Faster (100 Hz) LOWFS now operating in SCExAO instrument

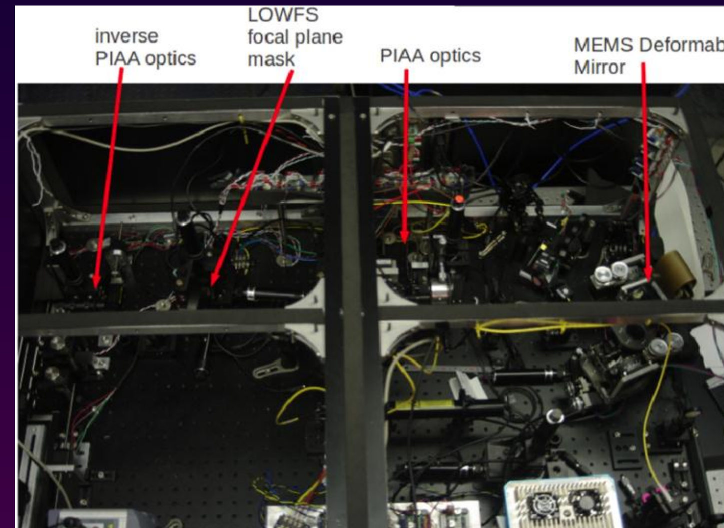
Wavefront Control and Starlight Suppression System (SSS) - Heritage

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

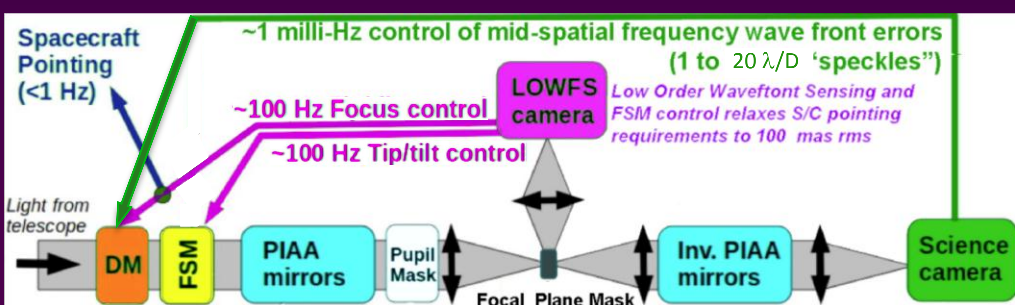
Subaru Coronagraphic EXtreme Adaptive Optics System



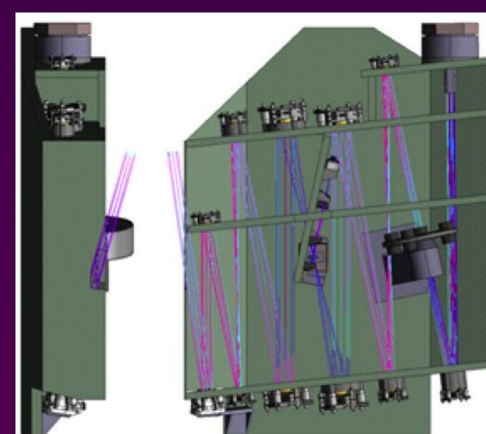
SCExAO is a functioning “testbed” prototype for *EXCEDE*



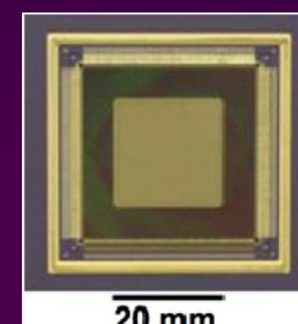
SCExAO implementation with 32^2 BMC MEMS DM



EXCEDE SSS Wavefront Error Control Components



EXCEDE implementation SSS/SIM design using BMC MEMS DM



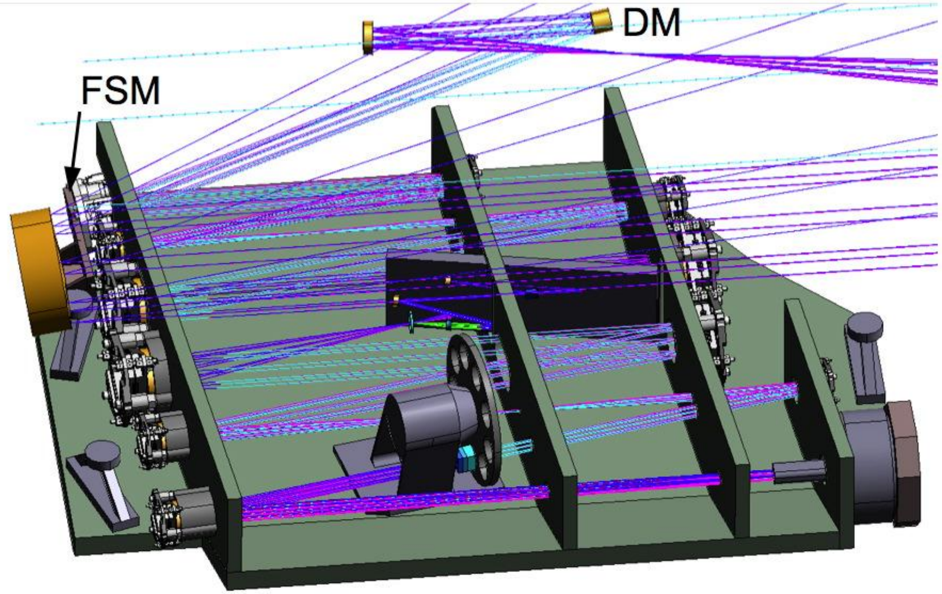
64^2 BMC MEMS DM (similar to GPI)
New 2000-element device under study for *EXCEDE*

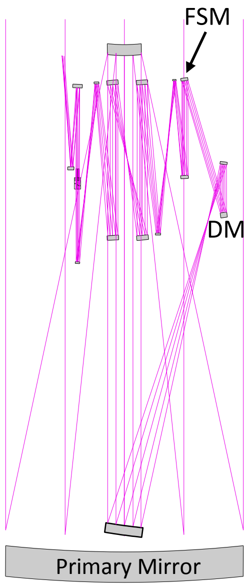
*SCExAO two engineering run on telescope Feb & Sept 2011

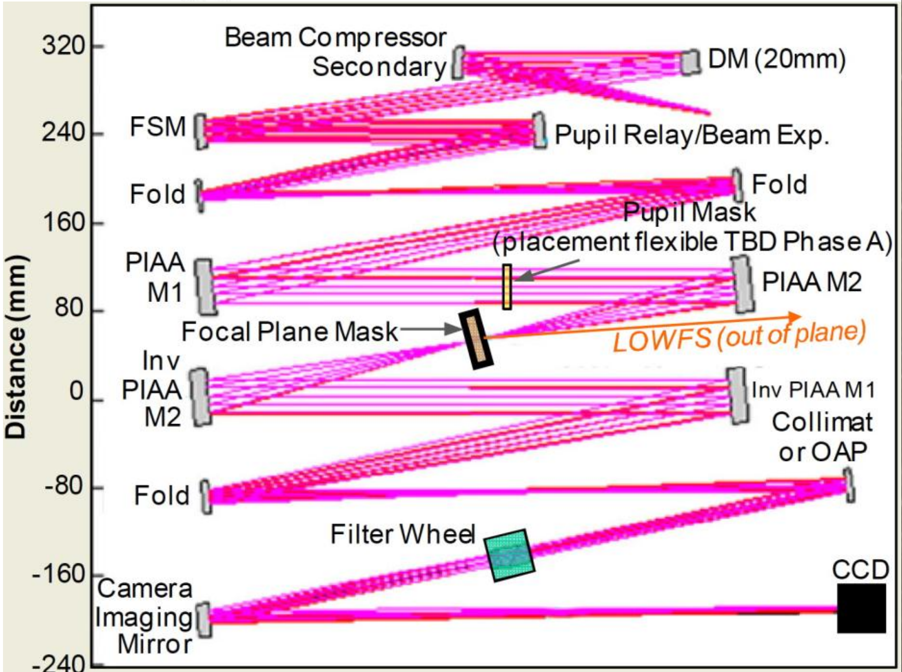
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

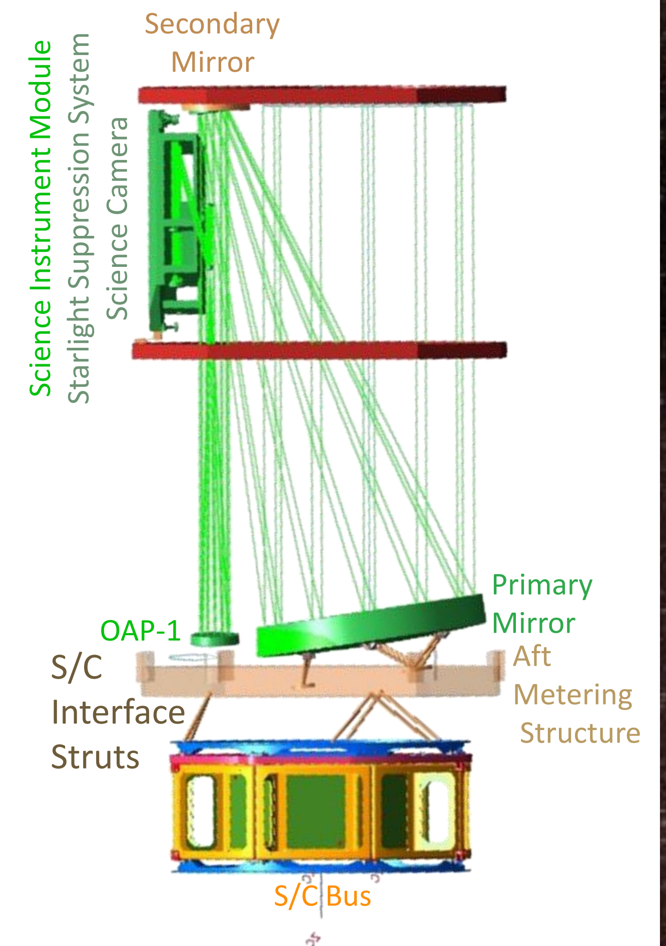
FLIGHT SSS/SCIENCE INSTRUMENT MODULE (SIM) OPTICAL LAYOUT

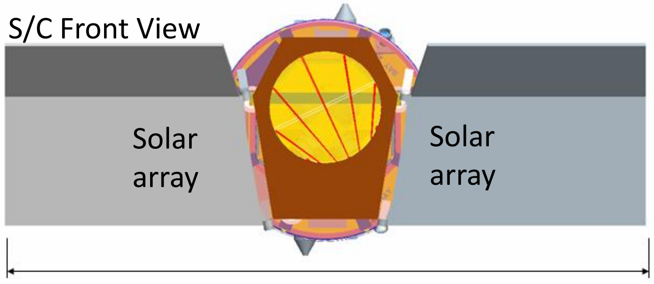
EXCEDE Integratated Science Instrument Module and Starlight Suppression System











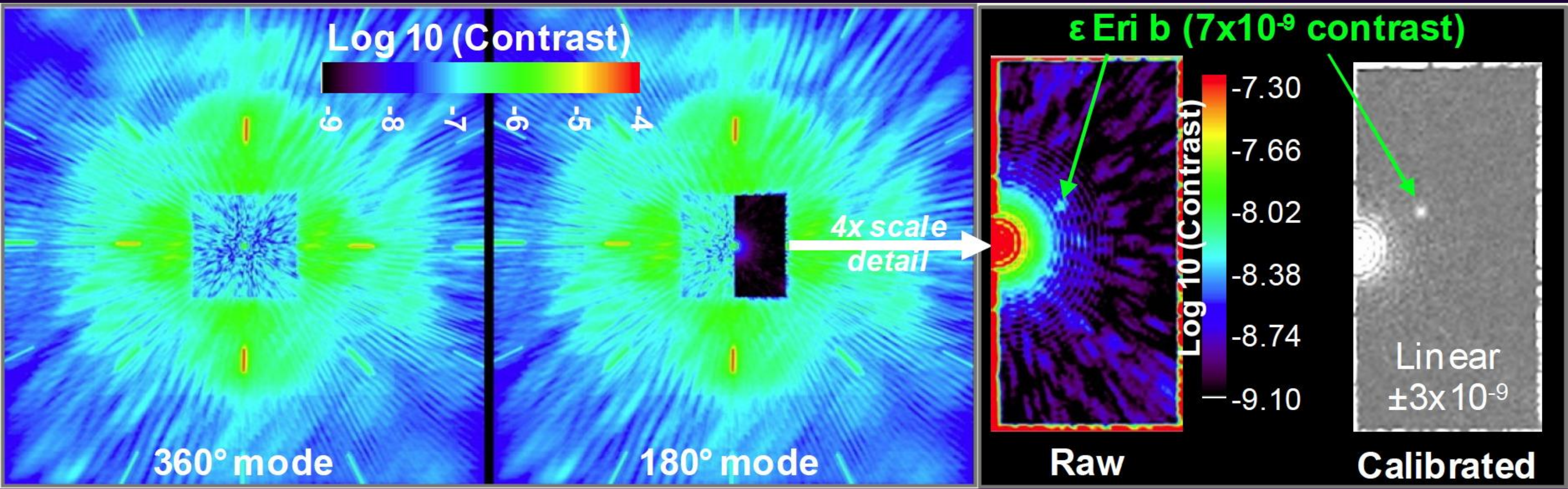
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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

- 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

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



- Image contrasts < 10^{-7} and 10^{-8} are achieved within the DM WF control zone (here 28 λ/D; ~ 7" x 7" FOV @ 0.4 μm with 64^2 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

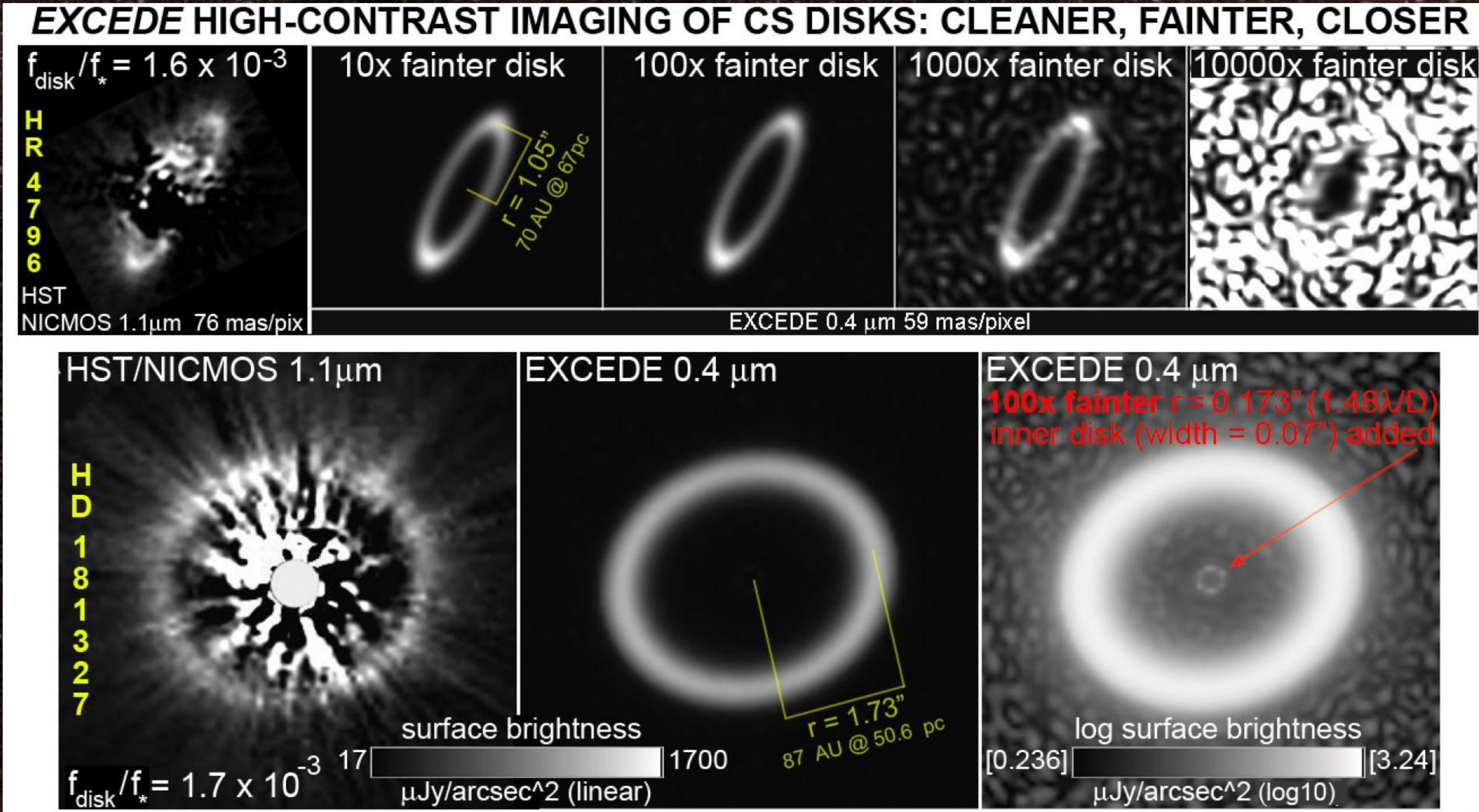
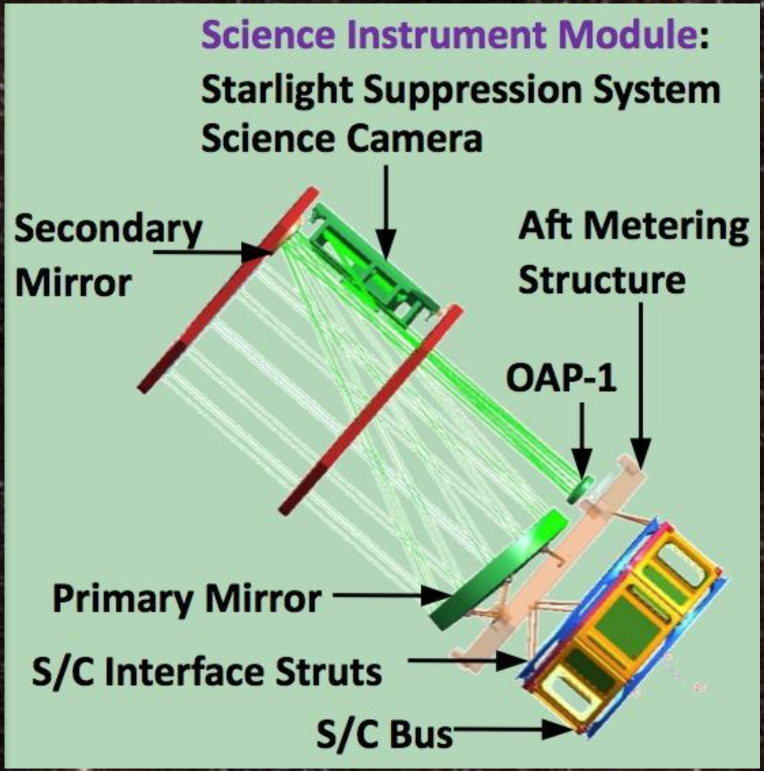
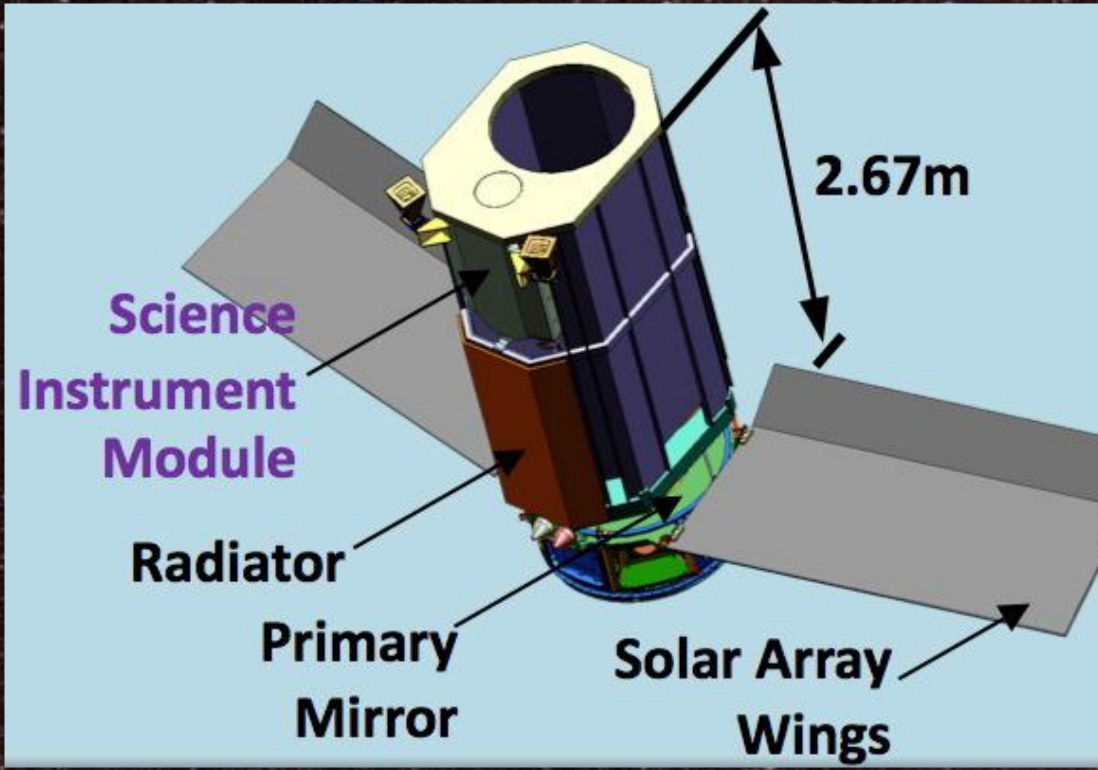


Fig. D.1.10. Pushing *far* beyond the *HST* envelope, *EXCEDE* opens up new observational domains in disk surface brightness and inner working angle. *HST* debris disk images (far left) compared to models of those disks in *EXCEDE* image simulations based on anticipated instrument performance.

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

SIM–TELESCOPE–SPACECRAFT CONCEPT





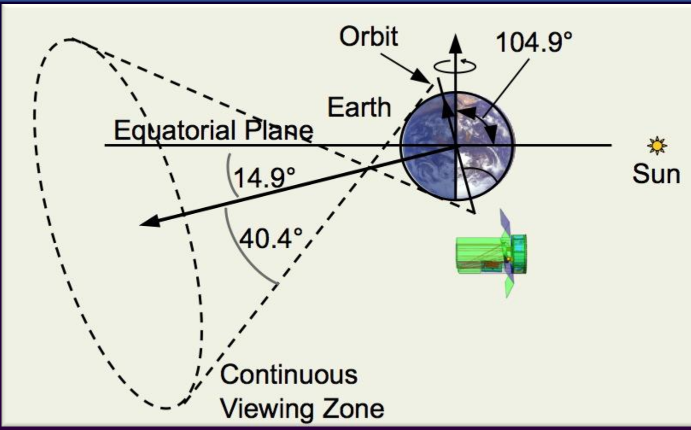
- S/C compatible with current ELV envelopes, mass-to-orbit, etc.
- 2000 km alt. sun-synchronous LEO; 6am asc. node twilight-following orbit: thermal stability, efficient target scheduling, S/C disposal
- 3 year baseline mission after IOC, two SEOs proposed
- Mission Ops: ARC (Sunnyvale), Science Ops: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

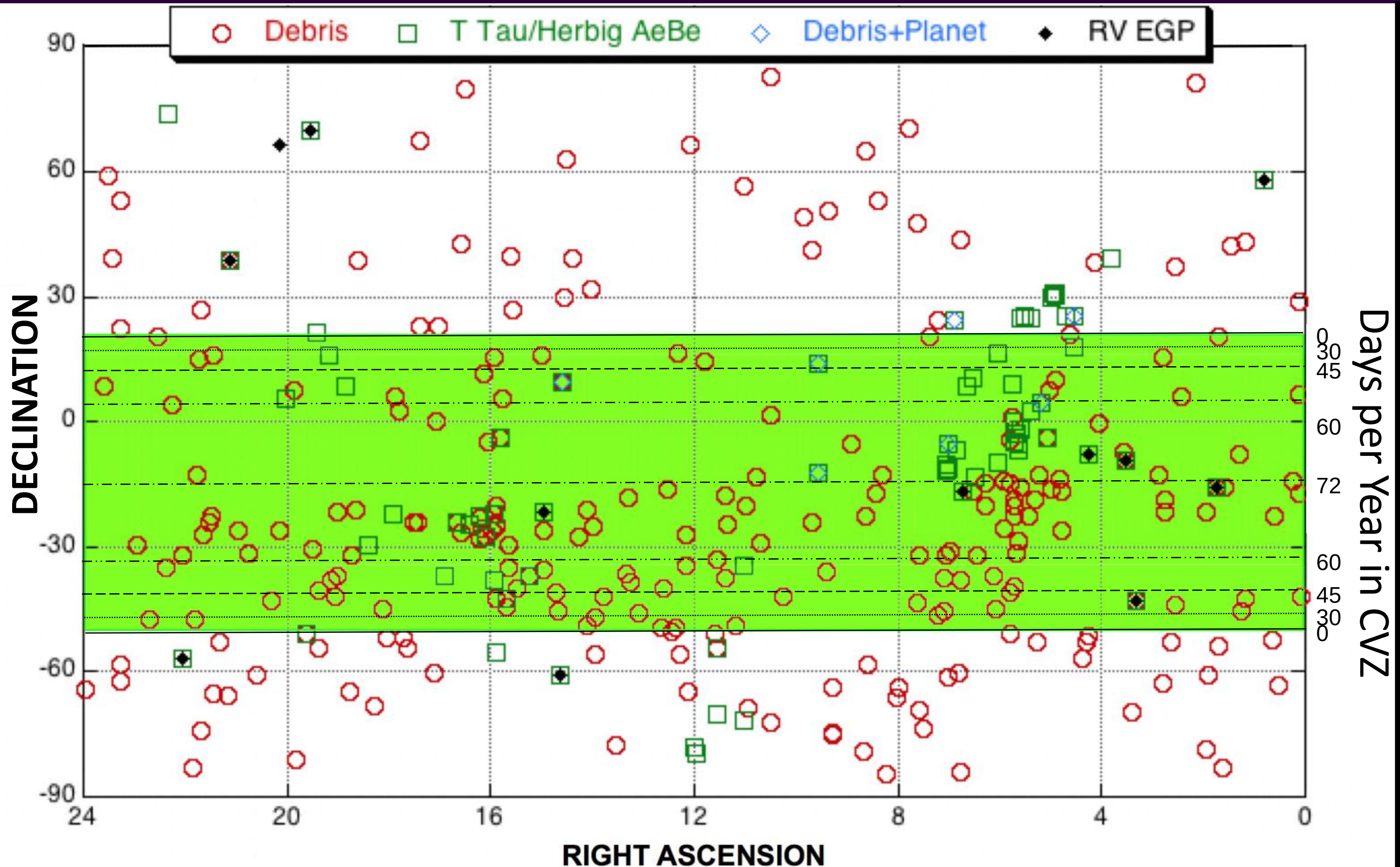
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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: $T_d \sim 10^5$ 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

$-50.3° \leq \delta < +20.5°$

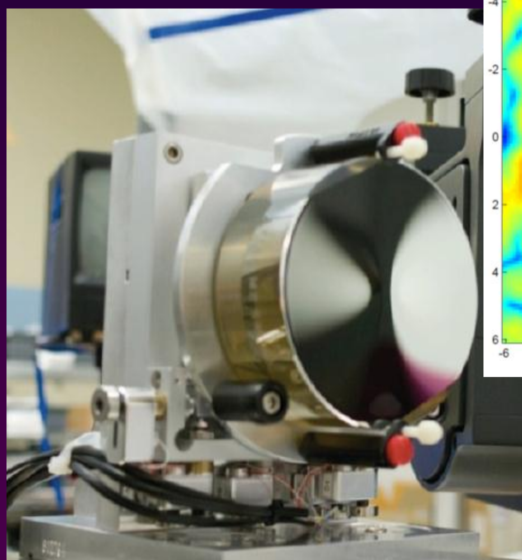
72 day mid-pass

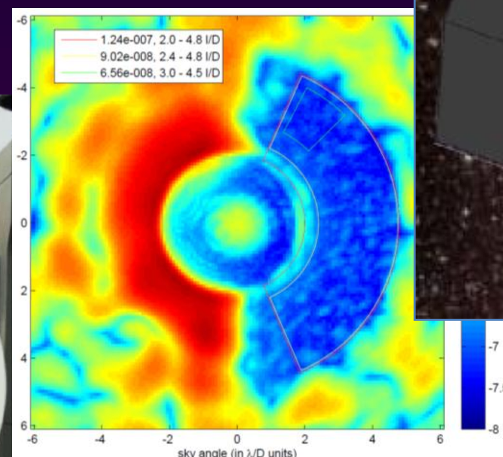
EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

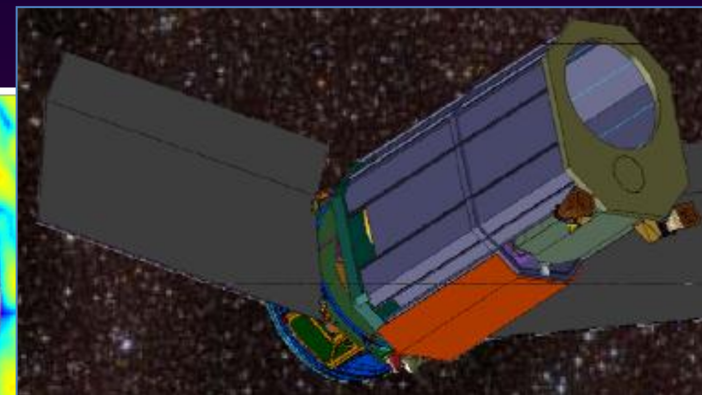
TECHNOLOGY DEVELOPMENT PROGRAM

Two-Year NASA Funded EXPLORER Category III Technology Development Investigation

University of Arizona Lead Investigation
Start: Q1 CY 2012







<u>KEY PARTICIPAING INSTITUTIONS</u>
The University of Arizona
NASA/Ames Research Center
Lockheed-Martin Corp.

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

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

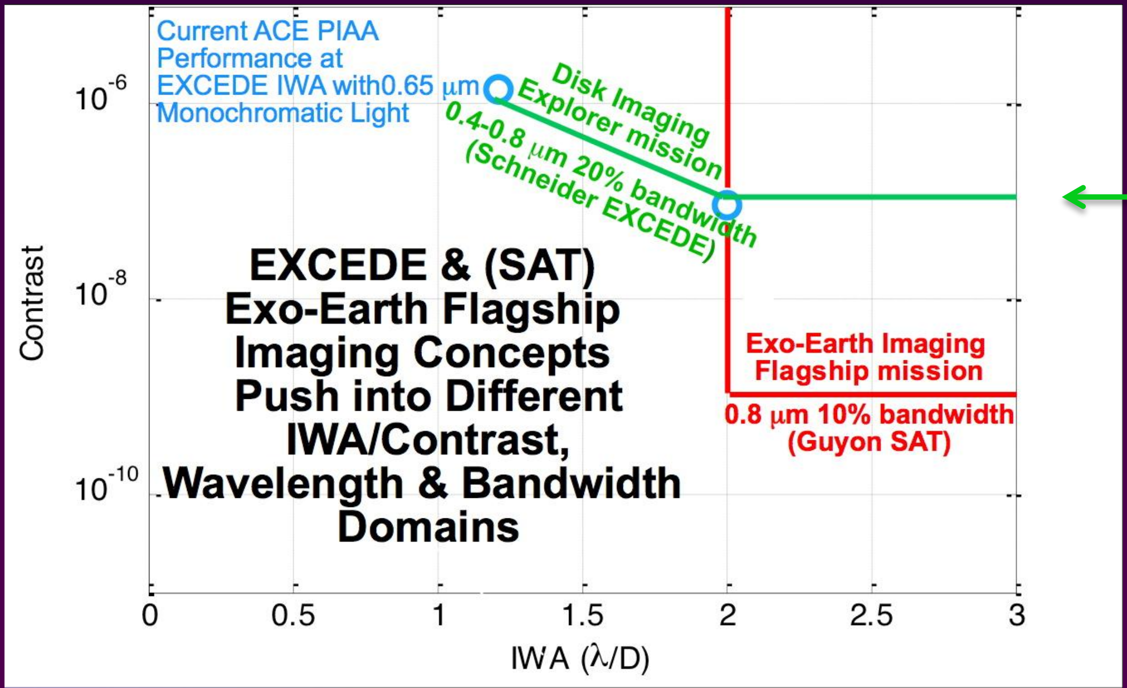
- **PIAA Performance to EXCEDE Requirements in Broadband Light**
- **Demonstrate functionality/operability in vacuum environment**
- **Performance Stability of SSS on observation timescales**

- **Coordinated & Complementary with ROSES-2010 SAT Investigation "Advances in PIAA Coronagraphy" (O. Guyon, PI)**

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 in HZs	Inner: 2 λ/D Outer: No Req. 15 λ/D Demonstration Planned. **Not** Requirement	≤ 10^{-9}	10%	0.8 μm Planned Demonstration, **Not** Requirement

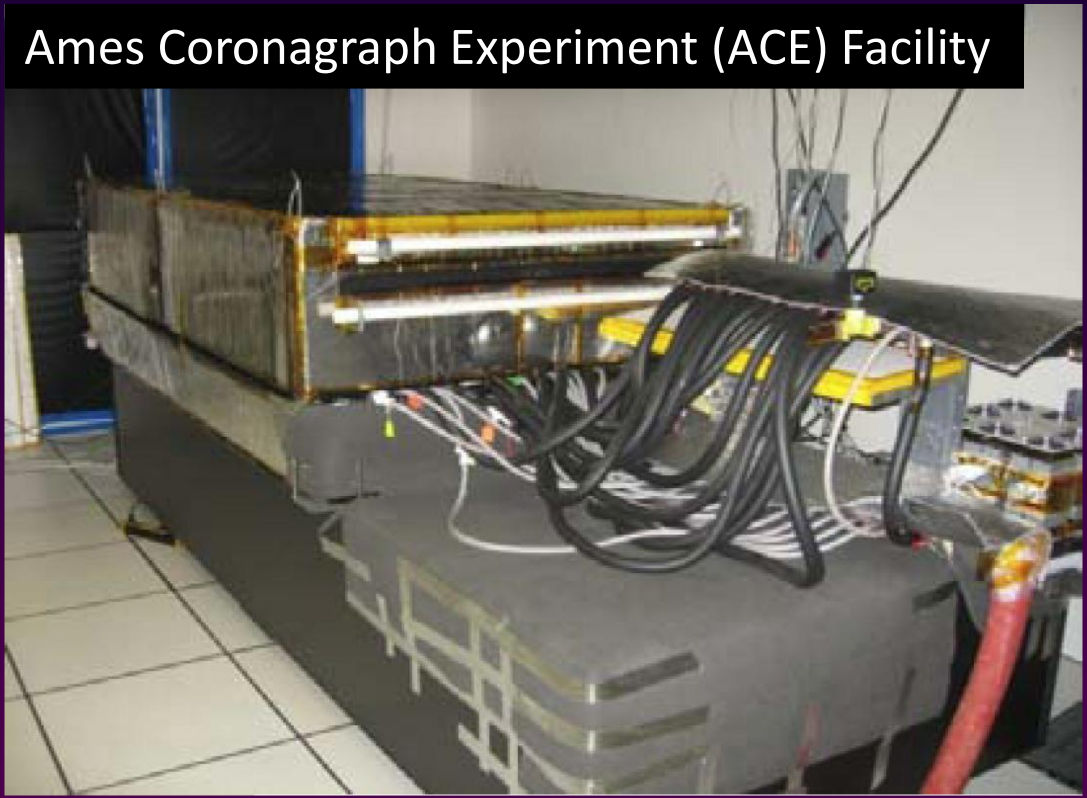


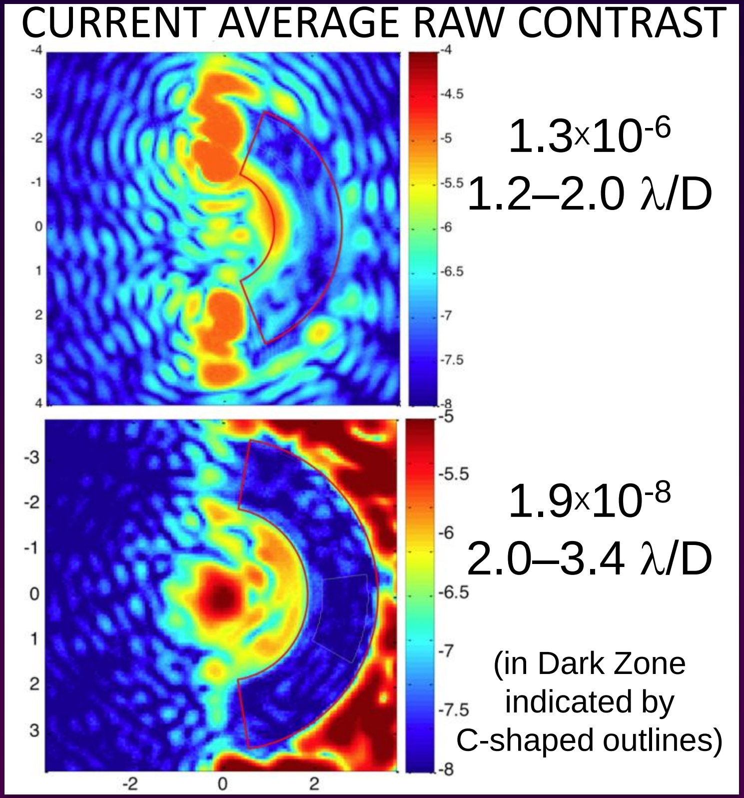
EXCEDE IWA/Contrast requirement is essentially met currently in 0.65 μm monochromatic light

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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 Technology Development Goals & Milestone Summary

(1) Starlight Suppression System:

10^{-6} raw contrast @ 1.2 (IWA) – 2.0 λ/D @ 0.4 μm 20% bandwidth

(2) Starlight Suppression System:

10^{-7} raw contrast @ 2.0 – 20 λ/D @ 0.4 μm 20% bandwidth

Achieve (1) and (2) simultaneously with test configuration defined by:

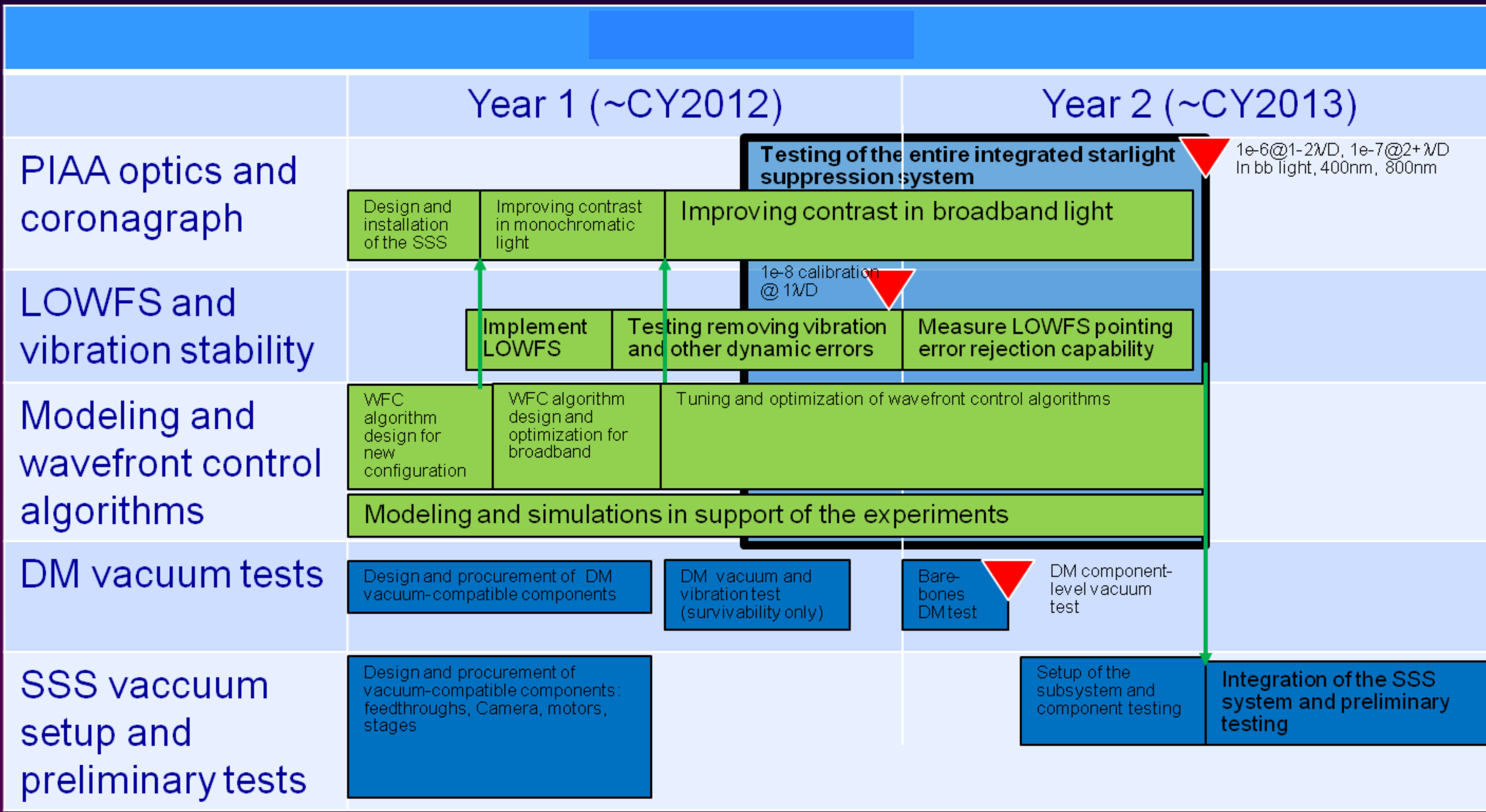
- 160° Field of View "Dark Zone"
- DM ahead of PIAA (per flight configuration) but not necessarily identical in layout to EXCEDE SIM/SSS design
- IWA defined by 50% throughput
- Raw contrast = mean resel^{-1} suppression (w/o 50% IWA throughput compensation

(3) LOWFS: reach performance required for 10^{-7} point source detection @ 1.2 λ/D (part of integrated SSS design to achieve (1) and (2)

(4) Deformable Mirror component-level vacuum/vibration testing

High-Level EXCEDE Technology Development Schedule

- In-air development & testing at Ames Coronagraph Experiment facility
- Vacuum environment testing at Lockheed Martin Thermal-Vacuum facility



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

BACK-UP CHARTS

MISSION GOALS

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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 thier properties."
- Astro2010 – New Worlds New Horizons: " better understanding of the dusty disks surrounding stars."
- Astro2010 – New Worlds New Horizons: " characterize the level of zodiacal light {that} will hamper planet detection."

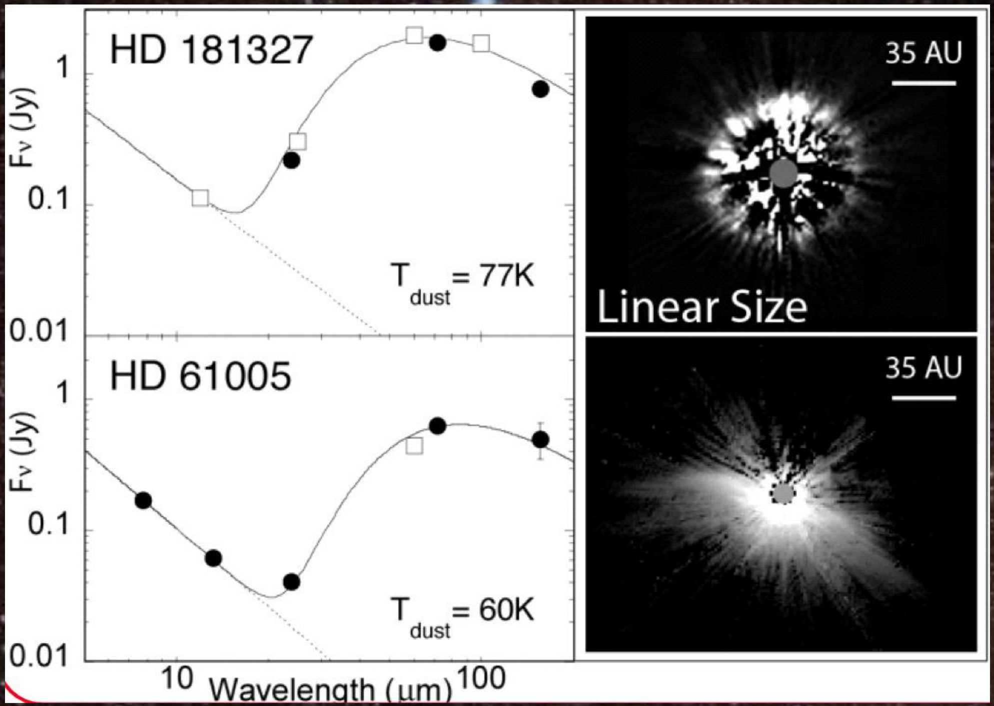
BACK-UP CHARTS

THE NEED FOR EXCEDE

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

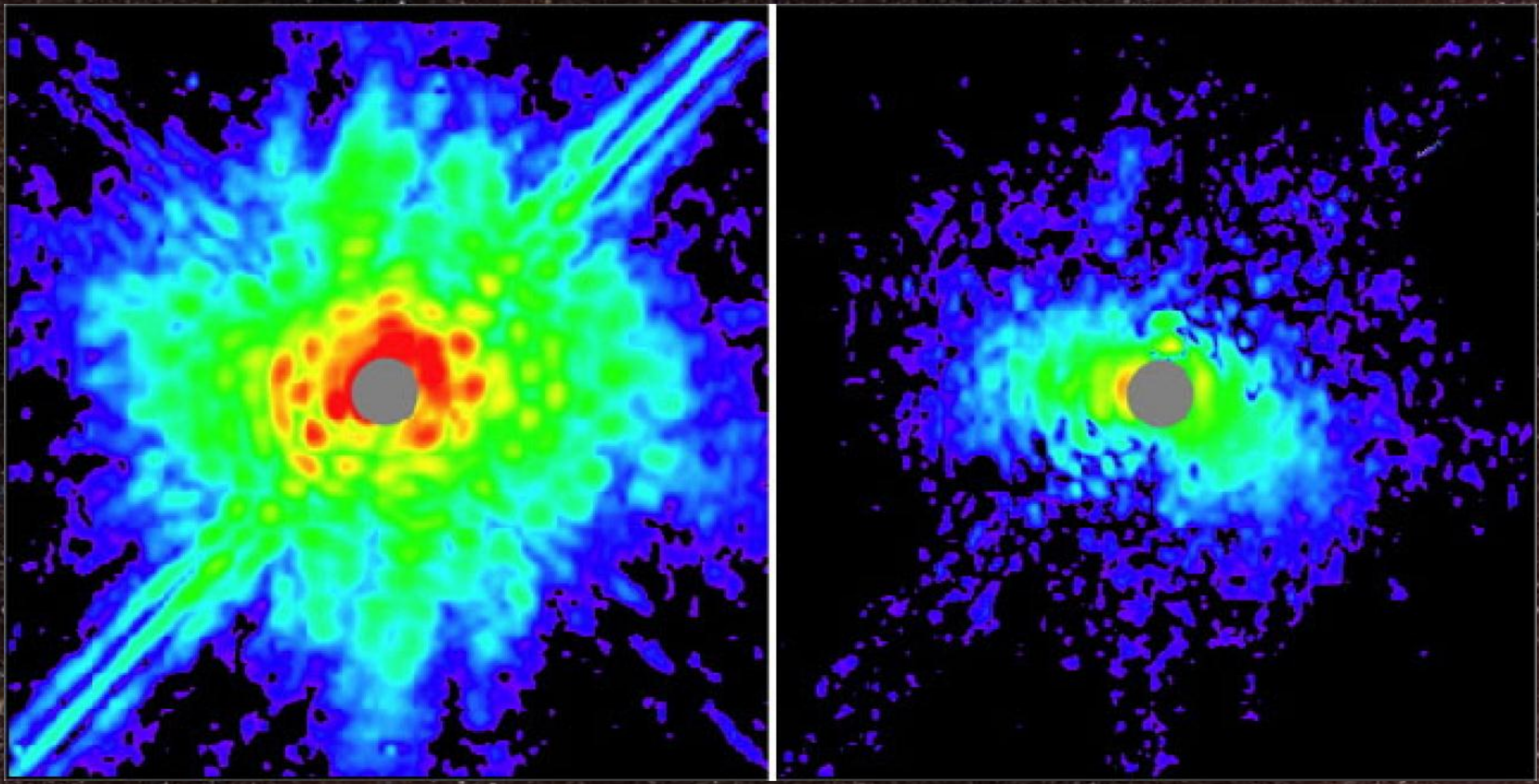
Using Disks to Discover the Diversity of Planetary Systems

- Nearly 400 CS disks have been identified by excess thermal emission.
- Spatially resolved images have been secured for < 5% of these disks.
- The small number of CS disks that have been imaged show a remarkable diversity in disk architechtures.
- Interpreting SEDs without such images provides only ambiguous information about disk structures.
- Spatially resolved images are required to reveal the structures of CS disks and their planetary systems.



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

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 of the residual unpolarized light remaining from the underlying stellar PSF revealing the otherwise undetected circumstellar disk (Schneider & Hines 2007).**

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE is symbiotic with and advances current & planned capabilities

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 ($\lambda^{-\alpha}$, $2 \le \alpha \le 4$). Compared with a 10m AO-augmented telescope observing at H-band, *EXCEDE is two orders of magnitude more sensitive to low surface brightness objects.*

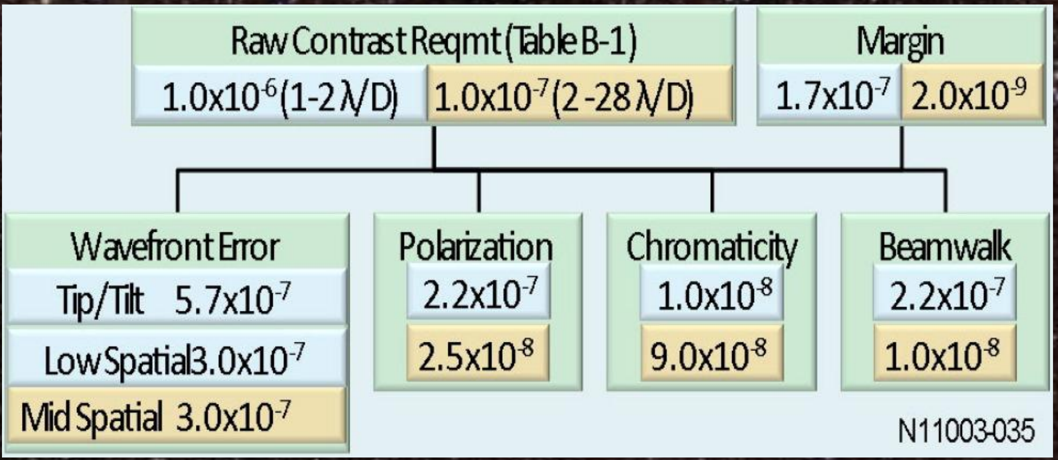
Total-light "360° mode" performance

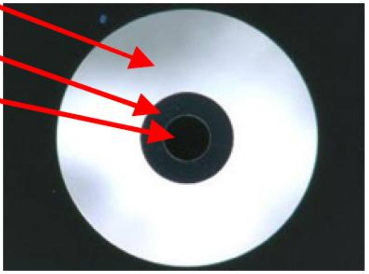
EXCEDE 0.4 μm surface brightness sensitivity (3σ in 10^4 s) = 27.1 mag/arcsec^2 (8.7×10^{-23} W cm^{-2}). ETCs for Lucifer and VLT yield (3σ in 10^4 s) H = 23.7/arcsec^2 (4×10^{-23} W cm^{-2}). *EXCEDE* can detect Rayleigh scattering disks at 3σ with H = 3.4×10^{-25} W cm^{-2}, i.e., *two orders of magnitude fainter than achievable at H band from the ground.*

BACK-UP CHARTS

WAVEFRONT SESNING & CONTROL

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





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

BACK-UP CHARTS

SCIENCE CAMERA

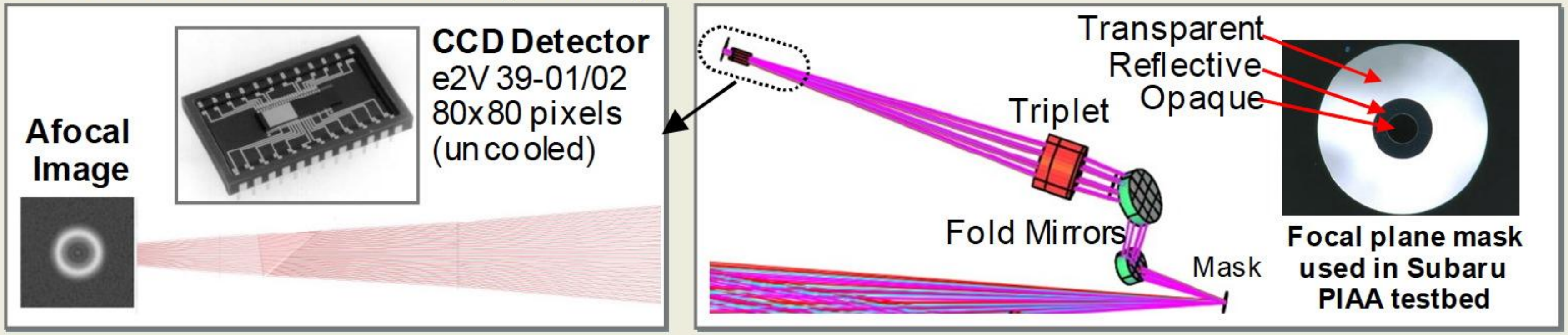
EXCEDE Science Camera

- 1242 x 1152 pixel 3e$^-$ read noise e2V CCD cooled to -108C with 2-stage TEC
- Image Scale: 59 mas/pixel 0.4 μm critically sampled
- 144/288 mas resel at 0.4/0.8 μm, respectively
- Full (DM unontrolled) FOV (~ 10^{-6} contrast): 28” x 28”
- 20% wide “B”/“R” filters and Wollaston polarizers
- Enables full polarimetric analysis: u, q, p, i, θ, DoP and total light imaging

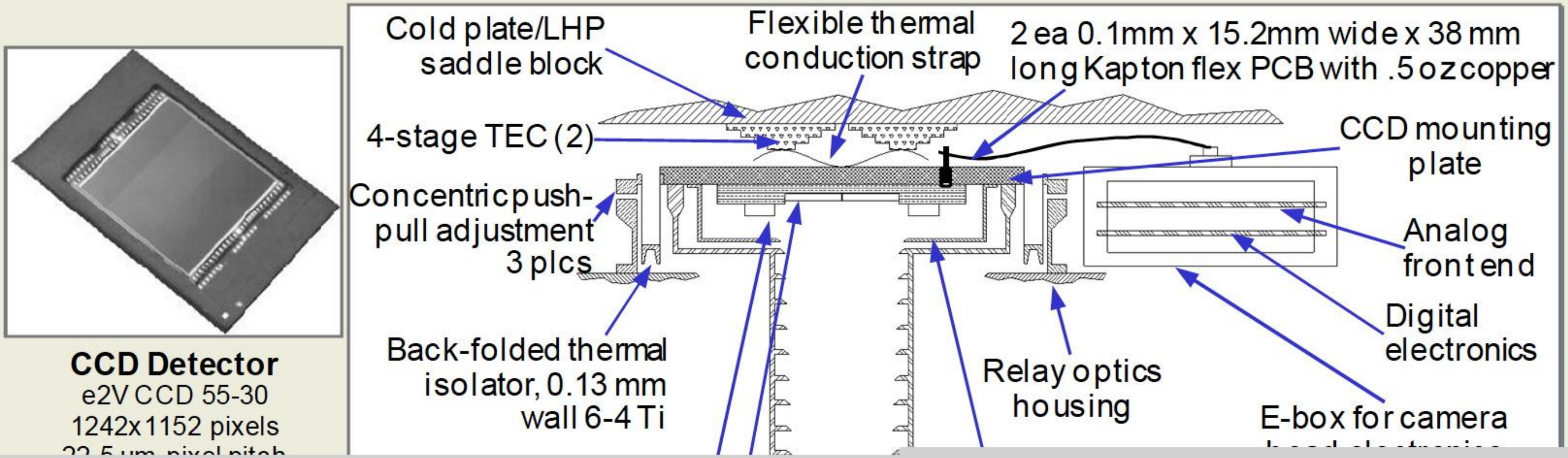
2-Band Imaging Polarimeter

EXCEDE LOWFS and Science Camera Imaging Detectors

2.5 Low Order Wavefront Sensor (LOWFS)



2.6 Science CCD Detector and Camera Head Design

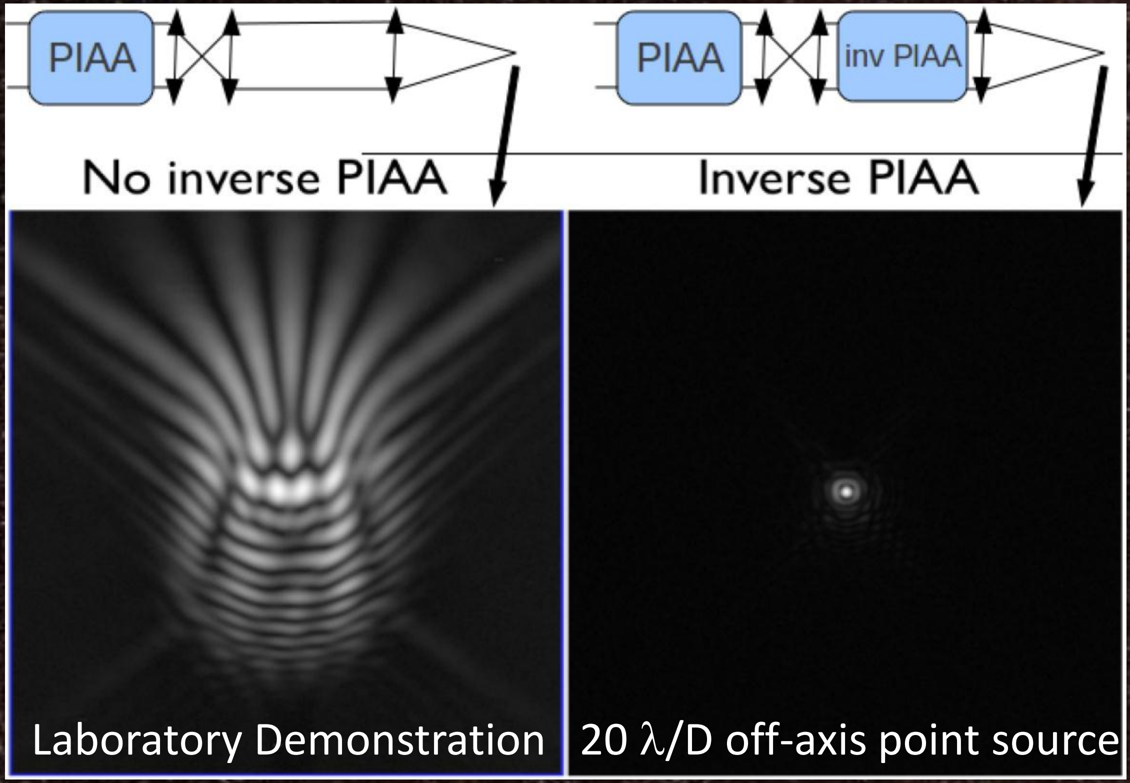


BACK-UP CHARTS

Co-ordination with PIAA SAT

Phase Induced Amplitude Apodization (PIAA) Coronagraphy

- The OFF-AXIS beam is highly abberated by the pupil remapping. But…
- A identical "inverse" PIAA mirror pair exactly "undoes" the PIAA pupil remapping (*after* the PSF core is masked in the image plane).



- INVERSE PIAA mirrors fully restore diffraction-limited off-axis PSFs extending ~ 150 λ/D from the on-axis beam.

Complementarity and Coordination with Guyon SAT Program

ARC/JPL well-established working relationship is aleady 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

Current activities: LOWFS is now being implemented at JPL on PIAA table
Goals are detailed in milestone #2 white paper for Guyon TDEM
Work is done by subcontract to Research Corp. U. Hawaii (PI: Martinache)
- LOWFS also part of Subaru SCExAO system (Closed loop on sky achieved Oct 2011)

For both projects, common S/W &control algorithms are developed and used

We expect LOWFS development work at JPL to be largely completed by March 2012
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

LOWFS plan for EXCEDE: In March 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 period, inter-project communication continues with LOWFS performance optimization*

Coordination with Guyon SAT Program – PIAA MIRRORS

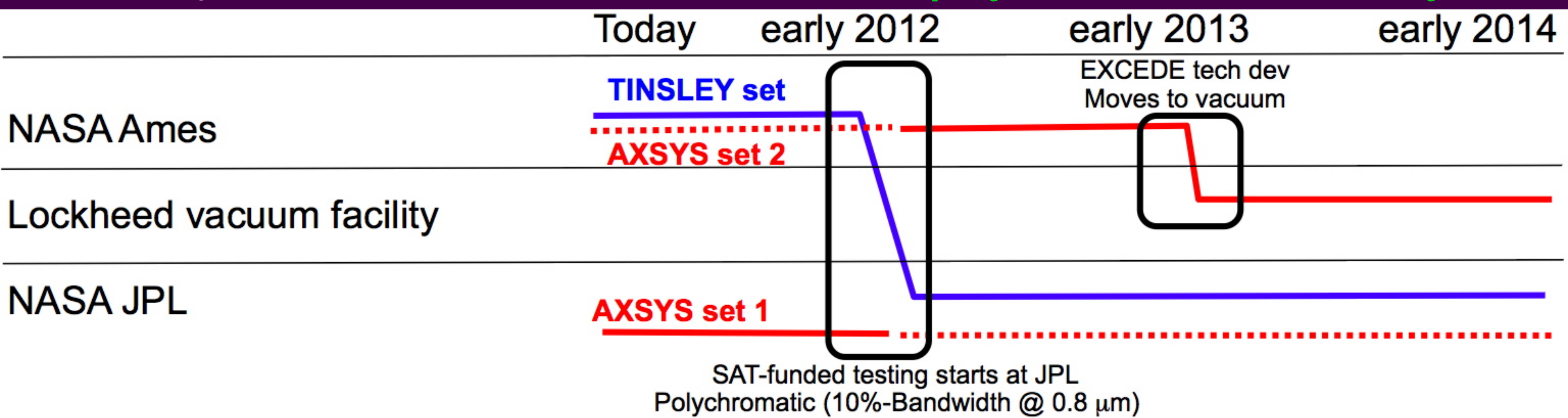
USE EXISTING PIAA MIRROR SETS:

Axsys Technologies sets (2 sets)

First PIAA mirrors made, funded by 1st NASA grant for PIAA dev. (Navigator prog)
Diamond-turned Aluminum, 75mm clear aperture
AXSYS PIAA mirror sets suitable for up to 10^{-7} contrast in broadband light
1st set @ JPL supporting 2-4 λ/D 10^{-9} monochromatic contrast (TDEM) → ***no use after 2012***
2nd is at Ames (now not actively used) → ***will be used for EXCEDE Tech Dev***

Tinsley/L3 set (1 set)

Highest quality PIAA mirrors made so far, funded by ARC
Zerodur substrate, grinding + polishing + narrow beam ion beam figuring
TINSLEY PIAA mirror sets designed to support 10^{-9} contrast in broadband light
Currently in use at A → ***will move to JPL for SAT polychromatic work in early 2012***



BACK-UP CHARTS

ACE/LM-TV TESTING

Technical Considerations for Testing

- 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 our 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