EXCEDE: The Exoplanetary Circumstellar Environments And Disk Explorer

Utilizing A Phase Induced Amplitude Apodized Coronagraphic Telescope For High Contrast Imaging Of Circumstellar Planet-forming Environments

Glenn Schneider and the EXCEDE Science and Mission Team

Abstract

We describe the Exoplanetary Circumstellar Environments and Disk Explorer (EXCEDE) SMEX mission to directly image starlight-scattering circumstellar material in the planet-forming regions of stars exhibiting thermal infrared emission above their stellar photospheric levels (a signpost of planetary systems in formation). EXCEDE will provide contrast-limited scattered-light detection sensitivities 100 to 1000 times more sensitive than the HST and JWST coronagraphs at a smaller inner working angle, enabling the exploration and characterization of exoplanetary circumstellar disk systems in currently inaccessible observational domains. Utilizing a laboratory-demonstrated high-performance Phase Induced Amplitude Apodized Coronagraph (PIAA-C), integrated with a 50 cm diameter unobscured aperture visible-light telescope, EXCEDE will provide an unrivaled disk-to-star imaging contrast of $\leq 10^{-7}$ and a 1 λ/d inner working angle of 0.2" with 0.2" spatial resolution at 0.4 μm. Such unprecedented spatially-resolved circumstellar disk images will enable determinations of disk characteristics (mass, geometry, surface brightness, grain properties) for stars over a wide range of stellar mass and age, providing a unique and comprehensive dataset to understand the formation and evolution of extrasolar planetary systems. Concomitantly, EXCEDE will provide unparalleled imagery of those rare debris disks previously resolved with inferior capabilities. These "Rosetta stones" are the basis of our current understanding of planetary disk systems and EXCEDE observations will overcome current limitations that thus-far have resulted in significant model degeneracies. EXCEDE will also directly image and characterize extrasolar giant planets with orbital distances as small as 1.5 AU and disk sub-structures influenced by co-orbiting planets - for the first time within the terrestrial planet zone (< 5 AU) around the nearest stars. EXCEDE is a science-driven technology pathfinder and demonstrator for subsequent planet-finding and characterization missions that will also provide future missions (e.g., JWST & TPF-C) well-honed targets sets for follow-on and multi-wavelength investigations.

Science Objectives

Discovery Science:

- Obtain a compendium of scattered light images of solar systems in formation
- Probe dust-scattered starlight within the inner (terrestrial) habitable zones of exoplanetary systems
- Reveal the presence of previously undetected planets by measuring asymmetries in disk structures

Characterization Science:

- Directly image Jupiter-like planets in nearby exoplanetary systems
- Determine physical and geometrical properties of dust grains within circumstellar environments over a range of stellar ages
- Assess the growth of primordial dust grains into planetesimals by comparing dust properties of young planet-forming CS environments over the epoch of planet formation

Relevance to NASA Science Programs

- Strategic Plan subgoal 3b: *"conduct advanced telescopic searches for Earth-like planets and habitable environments around other stars"*
- Science Plan – Strategic Goals and Decadal Outcomes: *"understand … the formation of planetary systems"* and *"create a census of extrasolar planets and measure their properties"*
- Science Plan – Targeted Outcomes: *"study the birth of … planetary systems,"* and *"determine what properties of a star… are most strongly correlated with the presence of habitable Earth-like planets*

EXCEDE Science Team

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- Mark Kuchner (NASA/GSFC)
- Alycia Weinberger (Carnegie Inst Wash.)
- Carol Grady (Eureka Scientific)
- Mark Wyatt (Cambridge University)
- Paul Kalas (Univ. Ca., Berkeley
- Barbara Whitney (Space Science Institute)

NASA Center Partnership & Management

- NASA Ames Research Center

Lead Industrial Partner

- Lockheed-Martin

Data Archive and Distribution Center

- Multimission Archive at STScI

Mission Objectives

- Enable high spatial resolution optical imaging in the planet-forming zones of circumstellar environments with unprecedented $\leq 10^{-7}$ contrast
- Survey selected stars with IR excesses indicative of thermally emissive orbiting dust from a > 300 high priority target pool to image circumstellar protoplanetary, transitional, and debris disks and disk sub-structures with an anticipated yield of approximately 100%
- Survey selected stars nearest Earth with radial velocity detected giant planets to directly image EGPs into terrestrial planet zones
- Provide two-band optical polarimetry, a key diagnostic tool for disk grain properties, also enhancing instrumental sensitivity to dust (or planet) scattered starlight by an additional factor of ≥ 100 (i.e. 10^{-9} inner working angle contrast)
- 2 year survey of ~ 250 high priority target

Mission Characteristics

- Type: Small Explorer/Astrophysics
- Launch Vehicle: Pegasus XL
- Launch Date: unconstrained $\geq$ January 2012
- Orbit: Sun-synchronous, 950 km, e=0, i=99°, LEO
- Duration: 2 yr after IOC + 1 yr SEOs

Science Payload

- 50 cm diameter unobscured aperture off-axis telescope
- Passive optic for wavefront error correction
- Phase Induced Amplitude Apodized Coronagraph
- 1 λ/D image plane masks
- Two-band polarimetric imager

Instrument Characteristics

- Spectral passbands: 0.4, 0.8 μm (20% FWHM)
- Coronagraph inner working angle: 0.2" at 0.4 μm, 0.4" at 0.8 μm
- Raw/augmented IWA image contrast: point-source: 10^{-6}, azimuthal median: 10^{-7}
- Spatial resolution: 200 mas at 0.4μm
- Linear Polarimetry with Wollaston prisms
- Coronagraphic Polarimetry IWA contrast: down to 10^{-9} for strongly polarizing dust around bright unpolarized stars
- Full Polarimetric Field of View: 40" x 40"
- Image scale: 83 mas pixel^{-1} (PSF critically sampled at 0.4 μm)
- Image data format: 2 x (512 x 512) pixels
- Science detector: low noise, high QE, high dynamic range CCD
- Guiding array: low noise CCD to produce target derived optical FES with NEA $\leq$ 2 mas to PCS

Spacecraft

- Mass (SC + Payload): 149 kg
- Power (SC + Payload): 214 W
- Pointing Control: 3-axis stabilized
- Pointing authority: 2 mas using closed-loop optically derived fine error signal from instrument using target star

Raw Science Data Downlink

- 512x512 16-bit images
- 280 images per day
- 312 Mbytes/day
- 2 data dumps/day

High Level Data Products

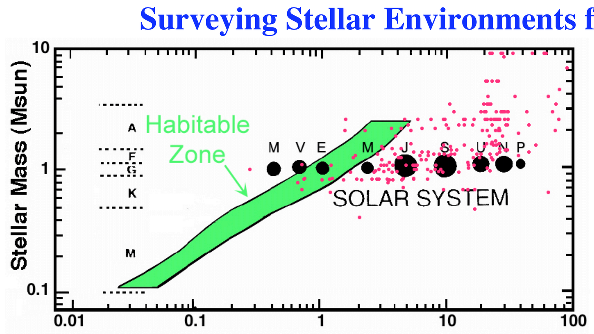
- 0.4 μm & 0.8 μm surface brightness maps
- 0.4 μm & 0.8 μm flux density limits
- Polarimetric Stokes u, q images
- 2D Polarization state vector maps (polarization fraction, orientation)
- Polarized and total intensity images
- Quantitative estimation on all products

Mission Timeline (dates w.r.t. launch)

- Launch: $\geq$ January 2012
- Initial On-Orbit Checkout: January–February 2012
- Baseline Mission: February 2012– February 2014
- Science Extension Option: Mar 2014–Mar 2015

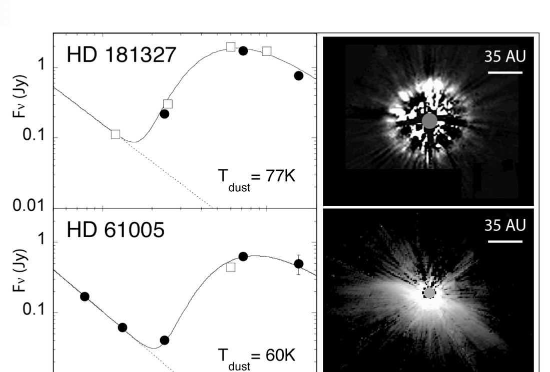
SCIENCE with EXCEDE

Surveying Stellar Environments for Scattered Light Disks

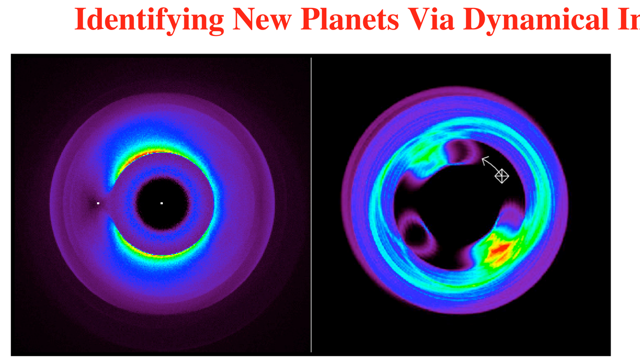


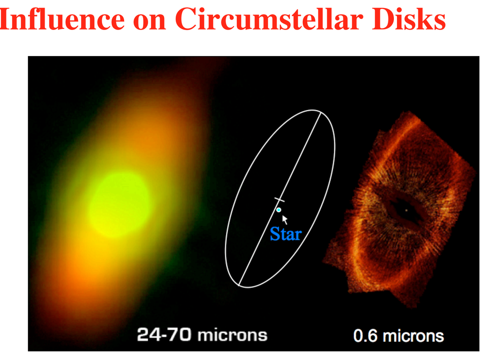
Reaching into Stellar Habitable Zones (left): (adapted from Kasting et al. 1993) EXCEDE will survey nearby stars to image debris structures within their planetary systems. The 0.2" inner working angle at 0.4 μm for our sample in AU is shown (red dots). For ~10% of the sample, EXCEDE will probe into the stellar "habitable zones" (red dots in green region), where temperatures allow for the existence of liquid water in the circumstellar environment.

Removing Model Degeneracies with Scattered-Light Imaging (right): Disk geometries and morphologies cannot be determined by thermal IR excess alone. Small grains radiate less efficiently than large grains. Therefore, at a given equilibrium temperature, small grains reside farther from their central stars than large grains. E.g., IR-excesses measured by *IRAS* (squares) and *Spitzer* (dots) for the dominant grain populations around HD 181327 (top) and HD 61005 (right) indicate similar temperatures, but drastically different disk morphologies as revealed with scattered light imaging (*HST*/NICMOS; Schneider et al 2006, Hines et al 2007).



Identifying New Planets Via Dynamical Influence on Circumstellar Disks

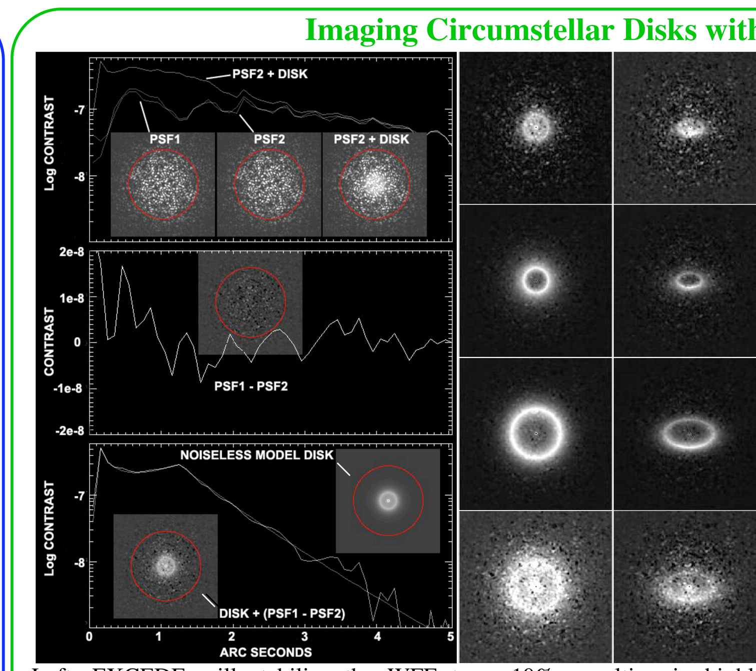




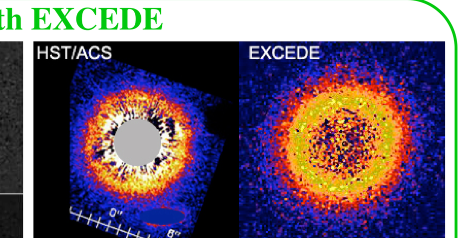
Embedded Planets Influencing Circumstellar Material: Scattered light surface brightness distributions for debris disks under the dynamical influence of a co-orbiting planet. Left: Type I (Kuchner & Holmes 2003) debris disk model with a one earth-mass planet orbiting at 1 AU (Kuchner et al. 2007). Right: Type IV debris disk model for the Vega system, an archetype for EXCEDE exoplanetary debris disk targets. The clumpy structure in Vega's debris disk has been used to infer the presence of a Neptune mass planet at 65 AU that migrated outward from 40 AU over ~50 Myr (Wyatt 2003).

Fomalhaut: One of the very few debris systems resolved with both *Spitzer*/MIPS (left; Stapelfeldt et al. 2004) and *HST*/ACS (right; Kalas et al. 2005). The 70 μm thermal emission and scattered optical light trace an inclined dust belt ~140 AU distant, but de-centering from, the central star indicative of the presence of an unseen massive planet. EXCEDE will image the inner hot debris that is detected (but unresolved) by *Spitzer* at 24 μm, but is un-observable with *HST*.

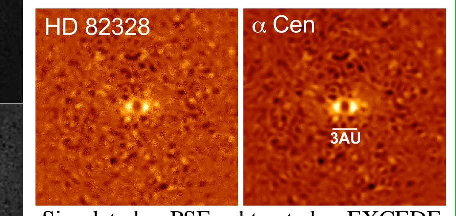
Imaging Circumstellar Disks with EXCEDE



Left: EXCEDE will stabilize the WFE to $\leq$ 10%, resulting in highly repeatable coronagraphic PSFs (top) yielding photon limited azimuthally medianed contrasts $\leq 10^{-8}$ at $\geq$ 2 λ/D (middle) revealing detailed structures in low SB disks (e.g., bottom). Right: Simulated images of 1" and 2" radius ring-like disks with 10^{-7} per resolution element disk:star contrast at 2 λ/D.

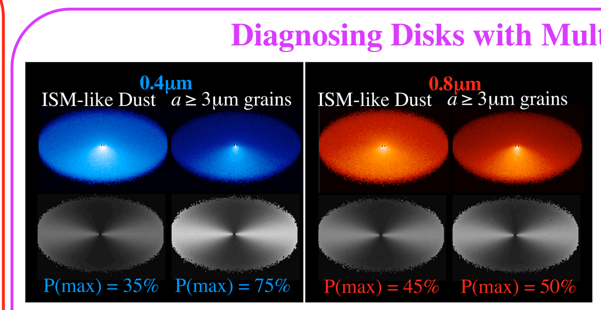


EXCEDE will reveal the inner regions of circumstellar debris disks otherwise lost in the glare of the central stars. E.g., HD 107146: r $\leq$ 60 AU (gray circle) unseen with HST/ACS (left; Ardila et al 2004).

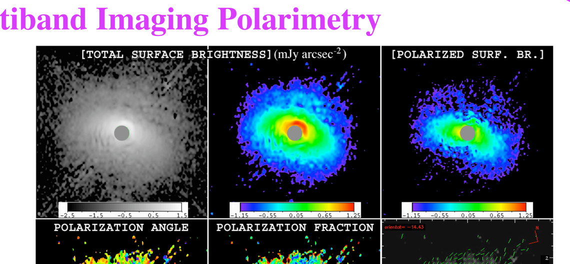


Simulated PSF-subtracted EXCEDE images of hypothetical 100 "zodi" SB(r) ~ $r^{-2.4}$ zodiacal debris systems about nearby sun-like stars. With polarimetric "speckle nulling", EXCEDE's reach will further extend to 10-20 zodi debris systems with strongly polarizing dust.

Diagnosing Disks with Multiband Imaging Polarimetry



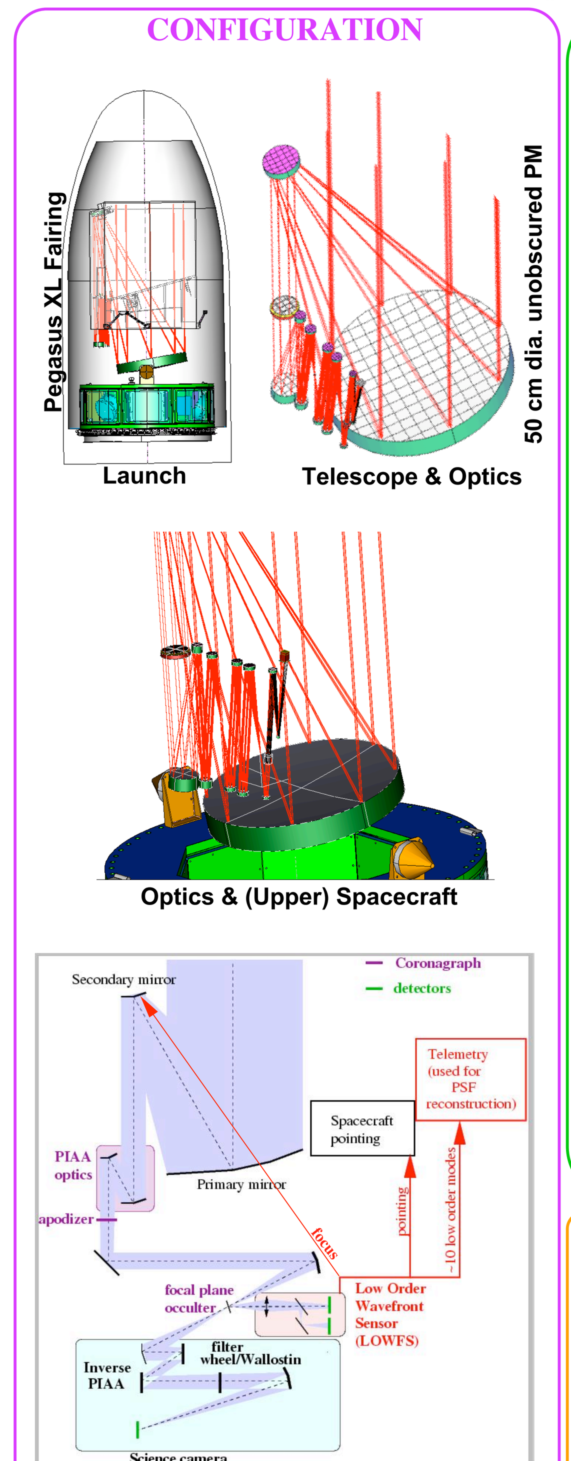
Monte-Carlo Scattering Models: (top) Example total intensity images for a circumstellar disk with a surface density ~ 1/r. Larger grains show a stronger forward *vs.* backward scattering asymmetry, which is greater at shorter wavelengths. (bottom) Percentage polarization maps of the same disks (linear stretched black = 0%, white = 100%). In both spectral bands, larger grains produce higher linear polarization, but large grains polarize light much more efficiently than smaller grains. Thus two-band imaging polarimetry provides a powerful diagnostic to constrain grain size distributions.



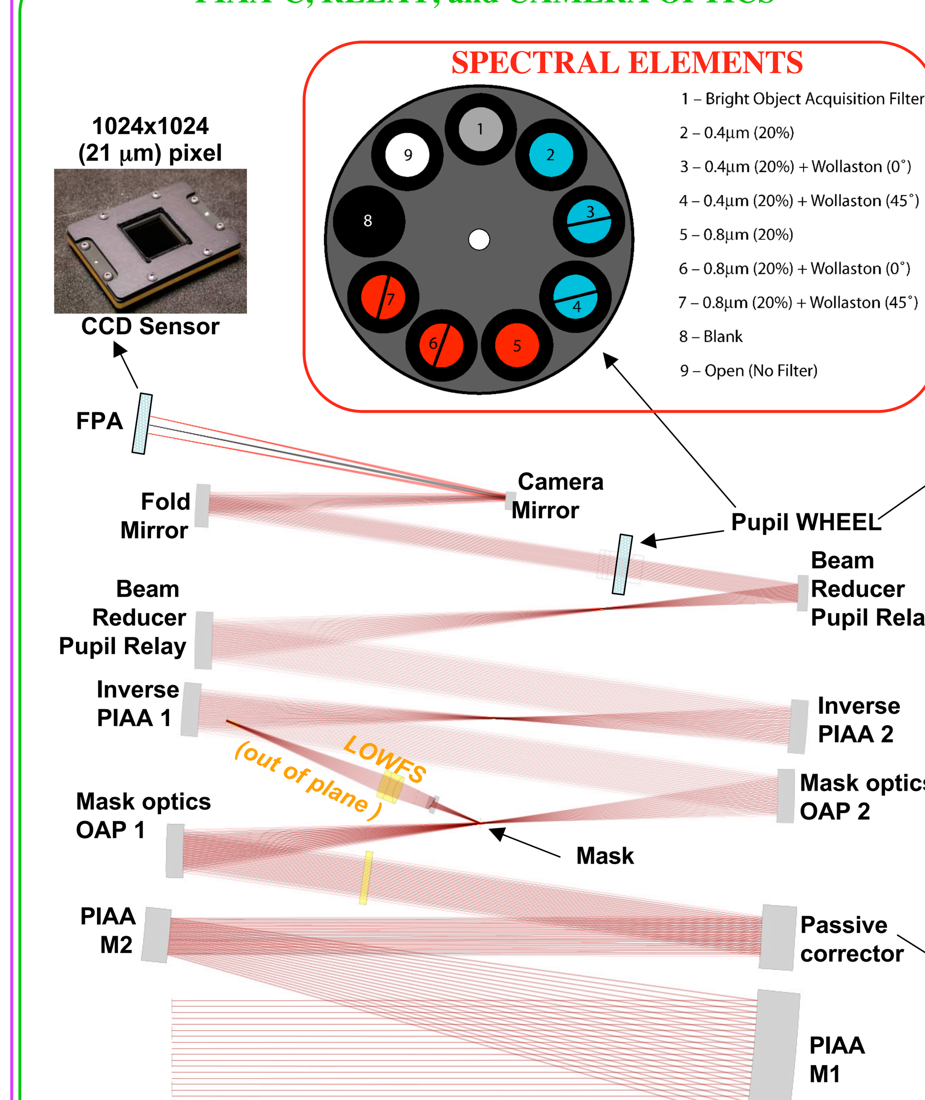
Polarimetric analysis of the protoplanetary disk around the T Tauri star GM Aur (Schneider et al. 2007), analogously enabled with EXCEDE's two Wollaston polarimeter for much more contrast-challenging sources, provides complete spatially resolved polarimetric state vector information while fully recovering physical flux density measurements (Hines et. al 2000) – crucial in constraining disk models to elucidate grain properties.

EXCEDE TELESCOPE & INSTRUMENT

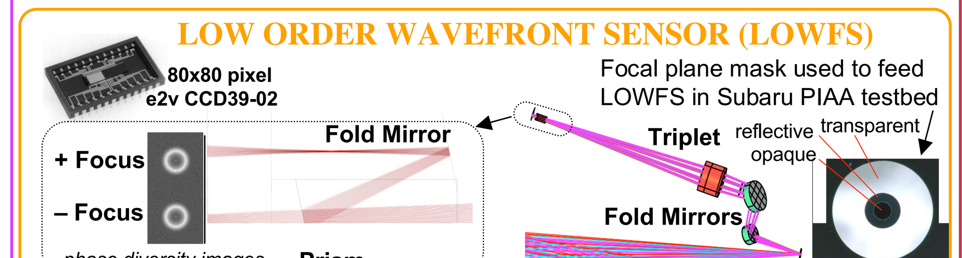
CONFIGURATION



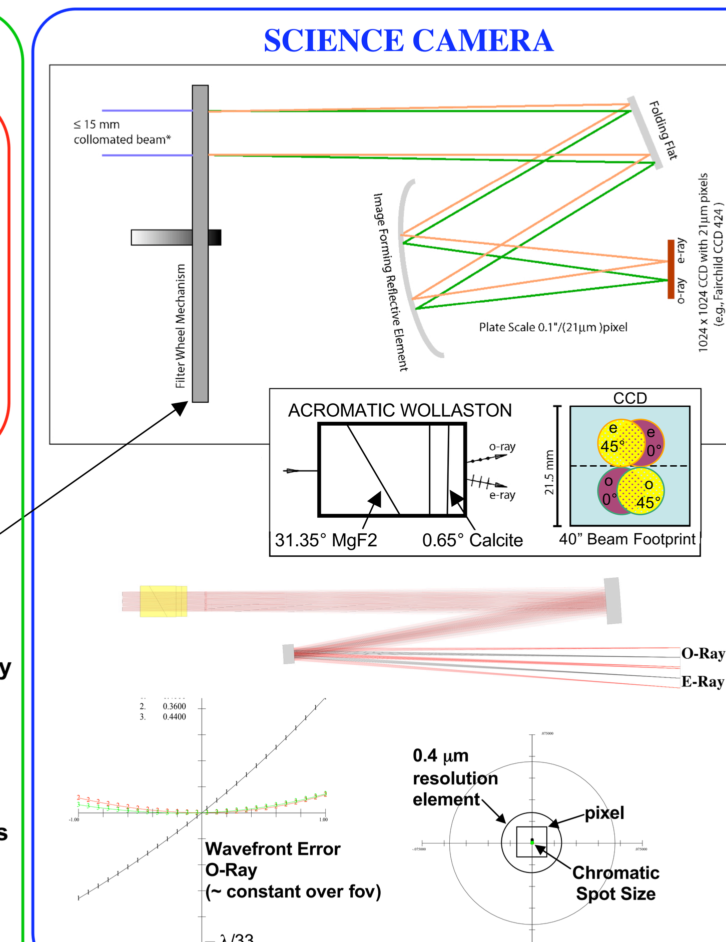
PIAA-C, RELAY, and CAMERA OPTICS



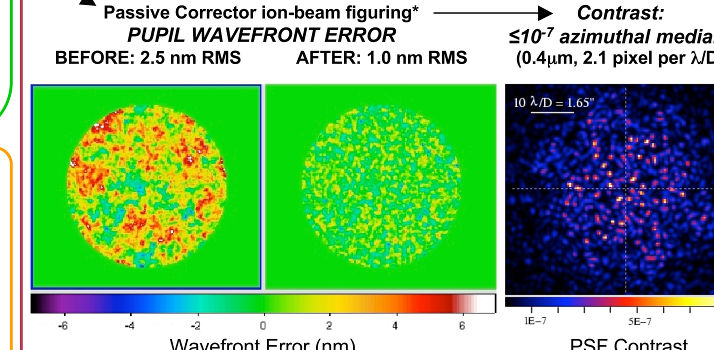
LOW ORDER WAVEFRONT SENSOR (LOWFS)



SCIENCE CAMERA



WAVEFRONT CONTROL & CONTRAST



*Ion beam size = 1/40 pupil diameter
15% measurement+figuring calibration error

†At all radii > 2λ/D
Peak speckle contrast ≤ 10^{-6}