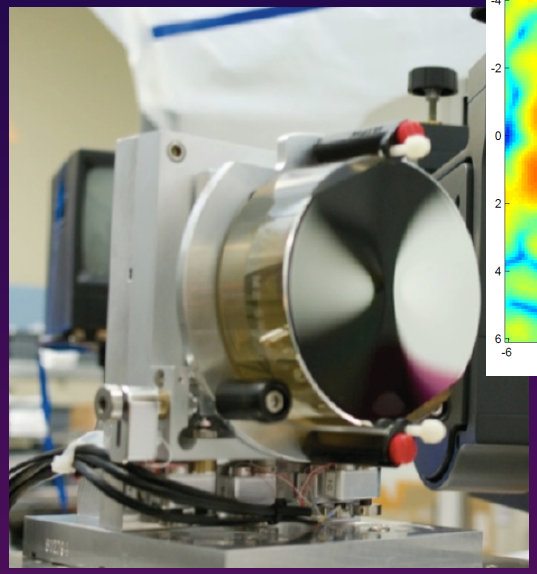
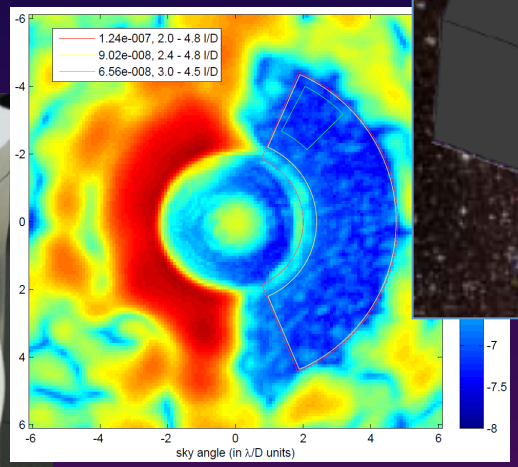
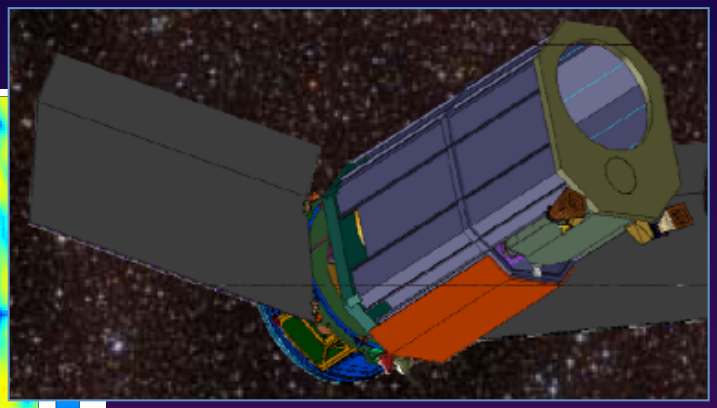
TECHNOLOGY DEVELOPMENT

NASA Funded EXPLORER Category III Technology Development Investigation

University of Arizona Lead Investigation
CY's 2012 - 2014







KEY PARTICIPAING INSTITUTIONS

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

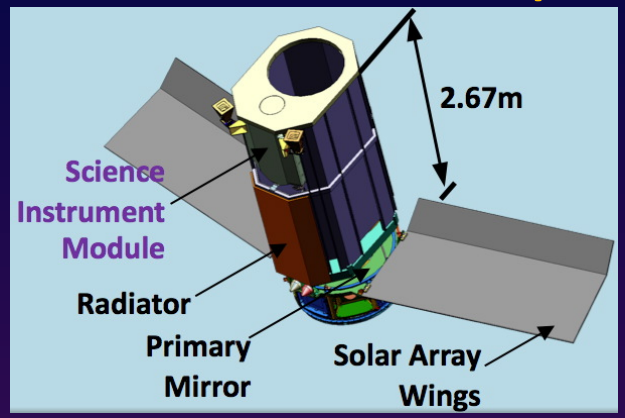
KEY PERSONNEL

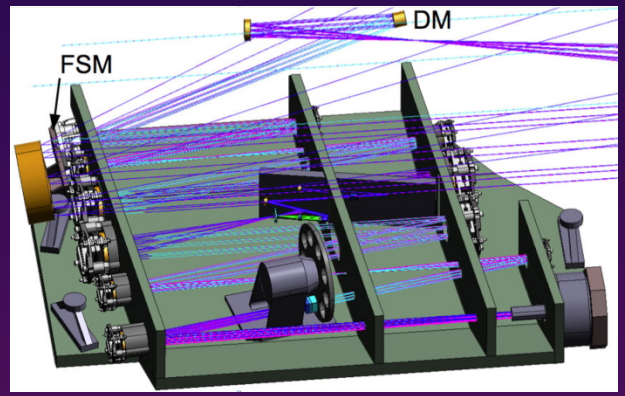
Glenn Schneider (UofA) – Principal Investigator
Olivier Guyon (UofA) – Instrument Scientist; PIAA-Coronagraph
Ruslan Belikov (ARC) – Ames Coronagraph Experiment Technical Director
Rick Kendrick (LM) – Vacuum Test/Validation Project Manager

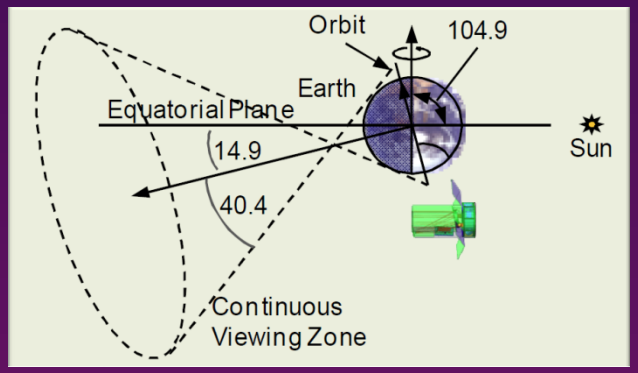
Outline

- Overview of the EXCEDE hardware
- ACE testbed and results
- Coronagraph performance limits at small IWAs

Telescope and mission overview

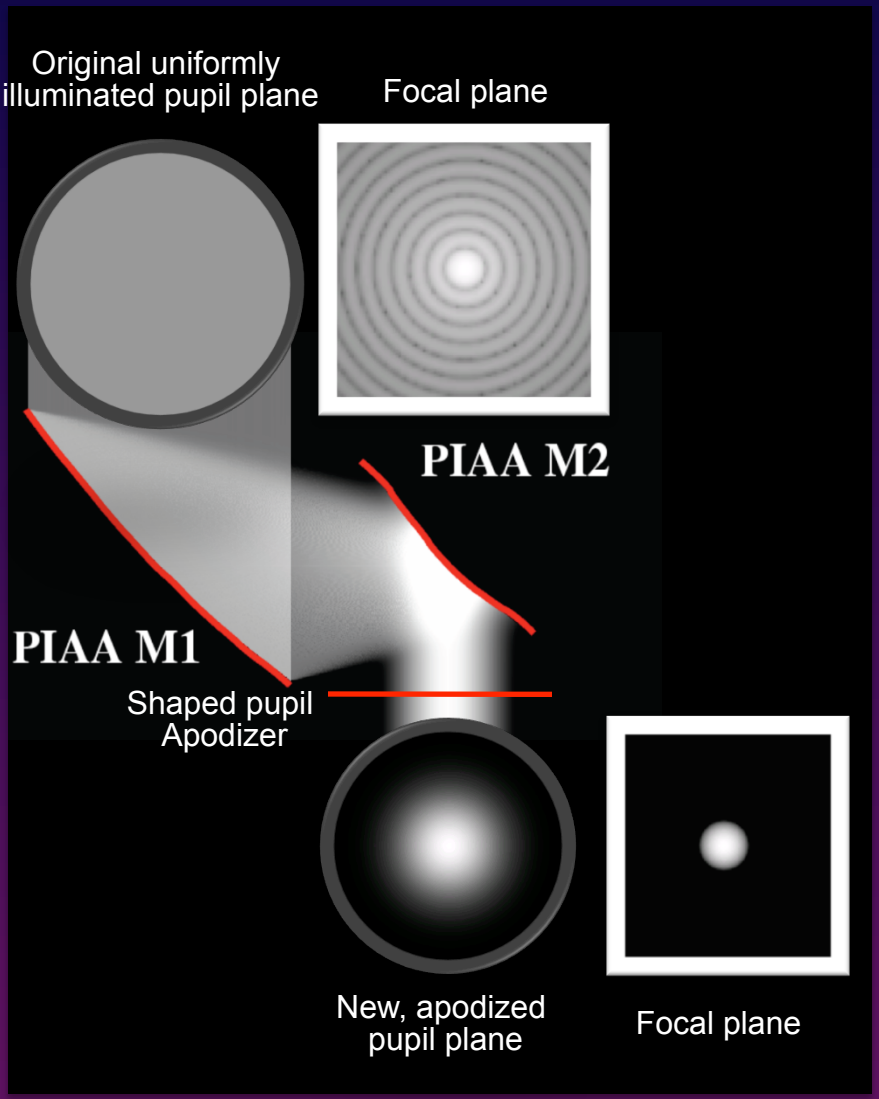






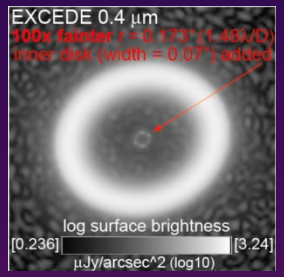
- Technical specs:
  - 0.7m primary, TMA unobstructed optical telescope
  - Active Starlight Suppression System
    - PIAA Coronagraph
    - 2000-element MEMS Deformable Mirror
    - Low-Order Wavefront Sensor
    - 10^{-6} raw contrast between 1.2 and 2.0 λ/D
    - 10^{-7} raw contrast between 2 and 22 λ/D
  - Two-band Imaging Polarimeter (20% bands at 0.4 and 0.8 μm)
- Mission overview
  - ~$200M (EX class Explorer)
  - Orbit: sun synchronous 2000km, 6am "dawn/dusk" anti-sun conic viewing
  - 3 year mission (after IOC)
  - Survey of ~ 350 nearby exoplanetary systems
- Newly NASA-funded 2-year technology development program (with partnership contributions from UofA, Lockheed-Martin, NASA/ARC)

PIAA (phase-induced amplitude apodization)

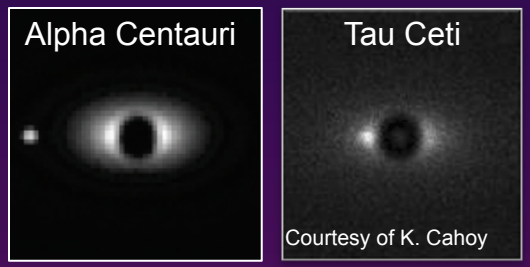


Mission concepts using PIAA

EXCEDE (0.7m) (Schneider et. al.) | PECO (1.4m) (Guyon et. al.) | EXACT/ExEC (2.4m) (Guyon et. al. / Belikov et. al.) | WFCT (4m) (Angel et. al.



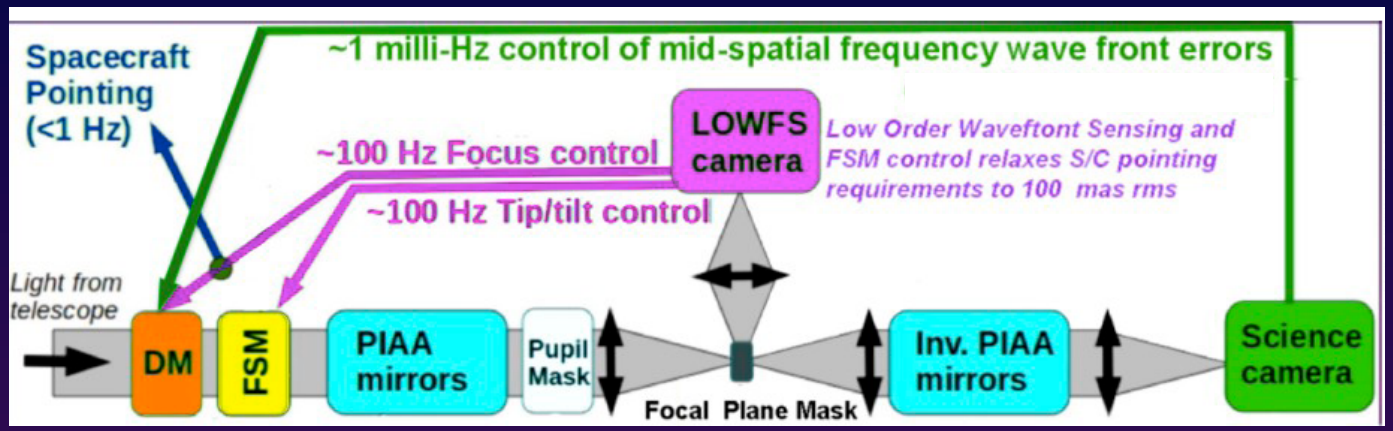
HZ disk simulation (small inside disk)



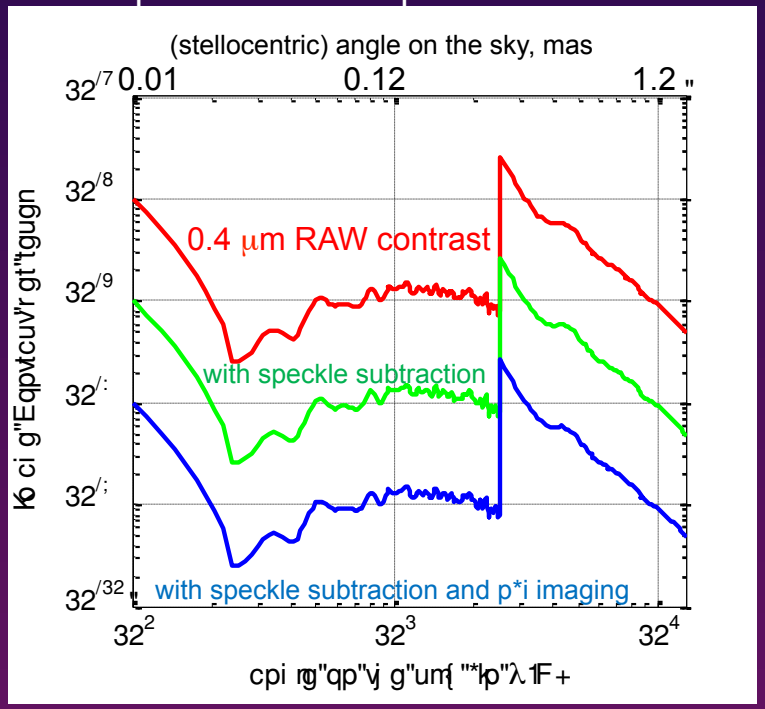
ExoEarth direct image simulations

- PIAA invented by Olivier Guyon with significant contributions by Bob Vanderbei, Wesley Traub
- High-throughput (almost 100%)
- Aggressive IWA (1.2 λ/D)
- Track record of successful hardware development and testing

Starlight Suppression System

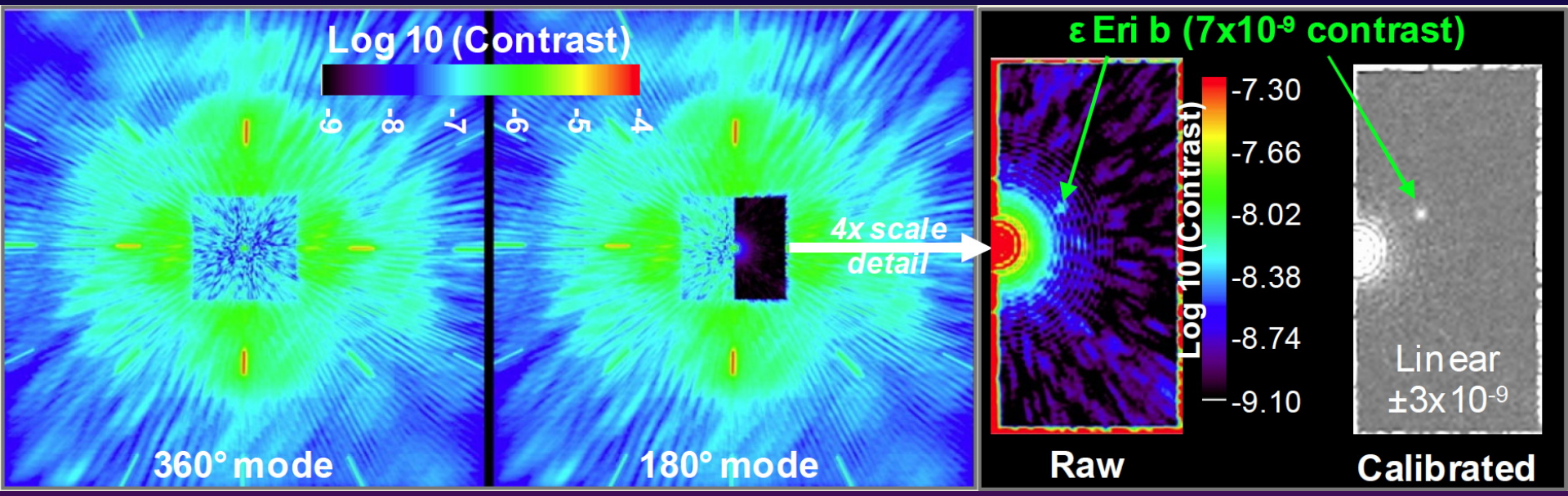


Expected contrast performance



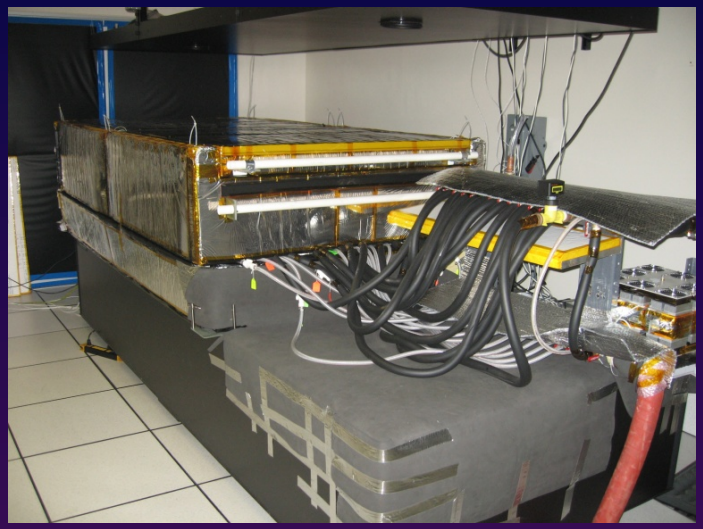
- 1.2-2.0 λ/D: limited by residual low order errors (tip/tilt, defocus)
- 2.0-25 λ/D: limited by amplitude errors and residual chromaticity (with 1 DM).
- >25 λ/D: limited by measured surface quality of the DM.

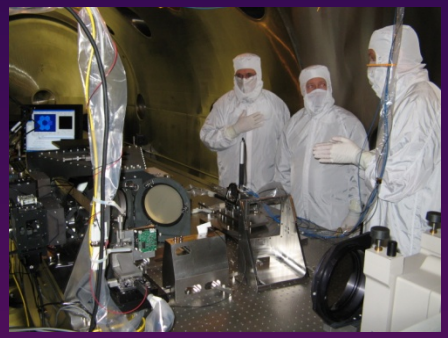
EXCEDE STARLIGHT SUPPRESSION (SIMULATION) with PIAA Coronagraph & DM WF Control

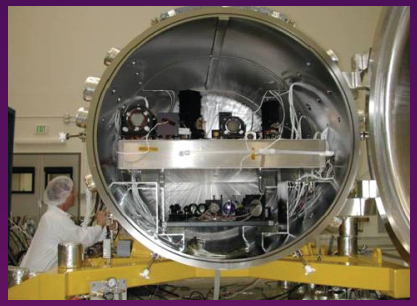


- Image contrasts < 10^{-7} and 10^{-8} are achieved within the DM WF control zone
  - 360°mode (disk survey)
  - 180°mode (faint-disk follow-up and planet imaging)
  - Simulated PSFs shown with 1 mas target mis-centering error and 10 inoperable DM actuators (worse than GPI yield).
  - Simulation based on old 64x64 DM (28 λ/D; ~ 7" x 7" FOV @ 0.4 μm) . Currently baselining "2K" DM with OWA of ~ 25 λ/D (does not alter simulations much)
- 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).

Ames Coronagraph Experiment (ACE) testbed







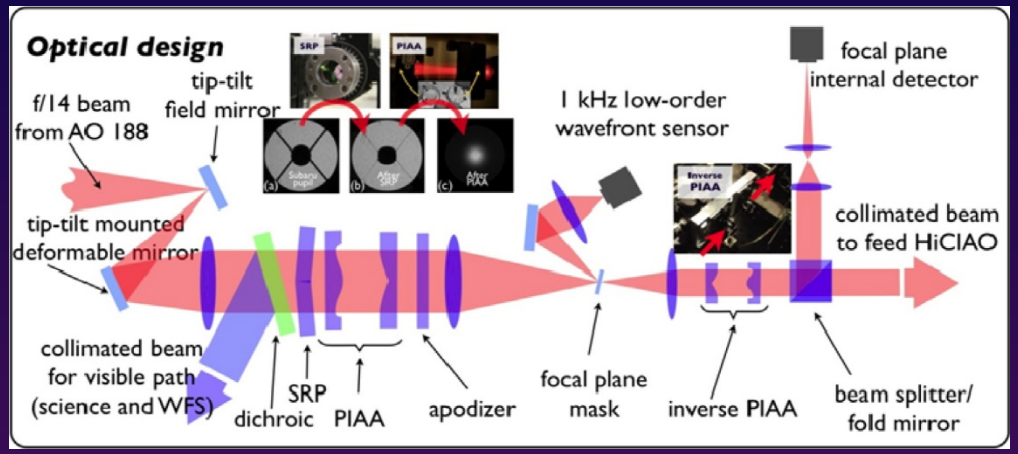
- ACE testbed
  - Dedicated to testing PIAA and related technologies
  - In temperature-stabilized air
  - Flexible, rapidly reconfigurable
  - Initial validation (TRL 1-4) of PIAA and related technologies
    - MEMS DMs
    - Wavefront Control
    - Alternative masks/occulters
  - PIAAgen2 mirror manufacture
- Lockheed Martin
  - New testbed coming online soon
  - Focused on EXCEDE vacuum demonstration
- JPL HCIT and MAM chambers
  - TRL 4+ validation (including vacuum)
  - testing a variety of coronagraphs

Also collaborating with JPL's coronagraph tech dev efforts (outside EXCEDE)

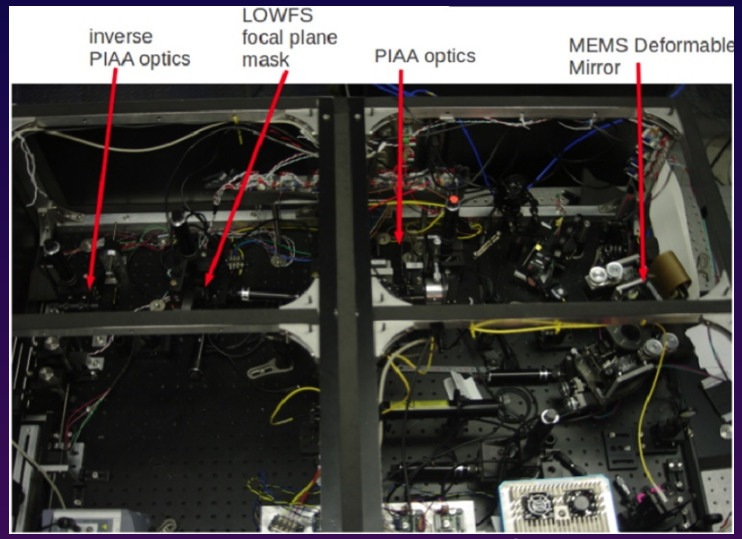
Collaboration with SCExAO: PIAA Coronagraph on the sky

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

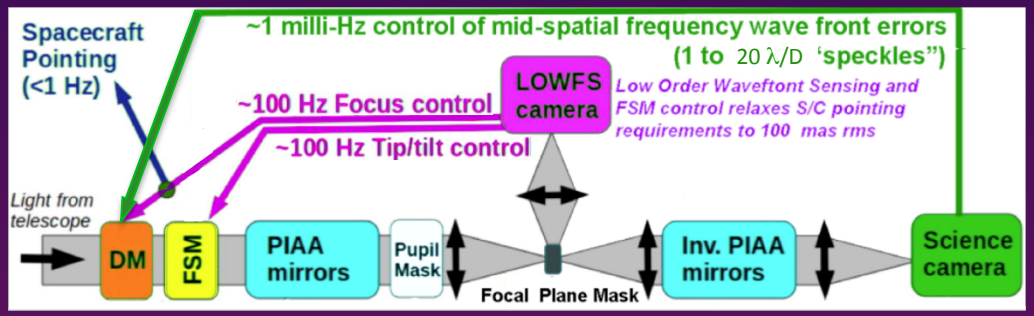
Subaru Coronagraphic EXtreme Adaptive Optics System



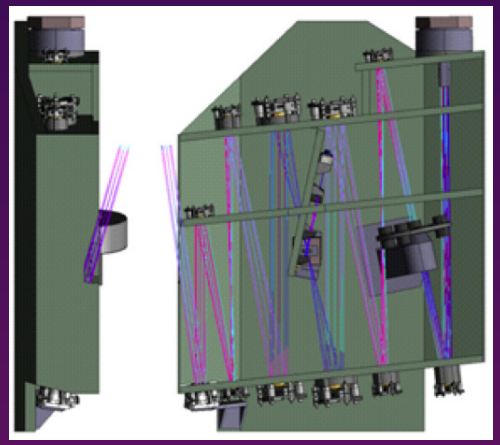
SCExAO is a functioning "testbed" prototype for *EXCEDE*



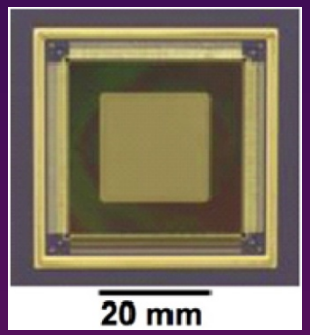
SCExAO implementation with 32^2 BMC MEMS DM



EXCEDE SSS Wavefront Error Control Components



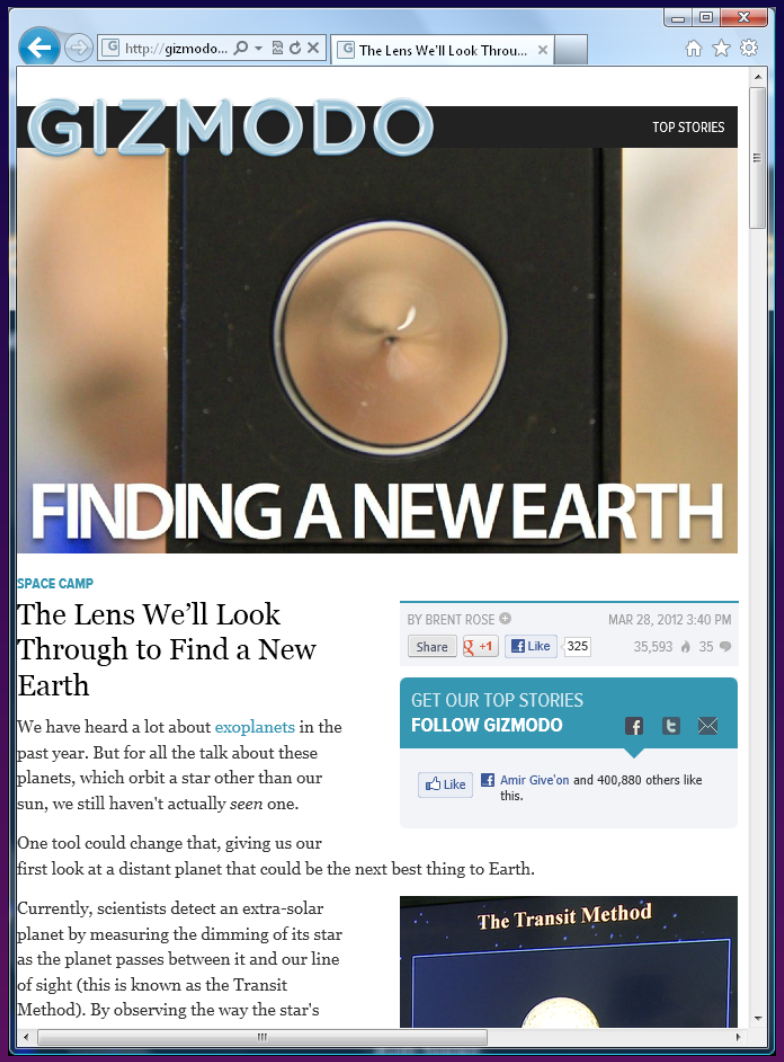
EXCEDE implementation SSS/SIM design using BMC MEMS DM



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

* EXCEDE's starlight suppression architecture (PIAA + LOWFS + inverse PIAA + speckle nulling) was successfully demonstrated on sky in 2012

Recent press coverage of ACE



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SPACE CAMP

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BY BRENT ROSE MAR 28, 2012 3:40 PM

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We have heard a lot about exoplanets in the past year. But for all the talk about these planets, which orbit a star other than our sun, we still haven't actually *seen* one.

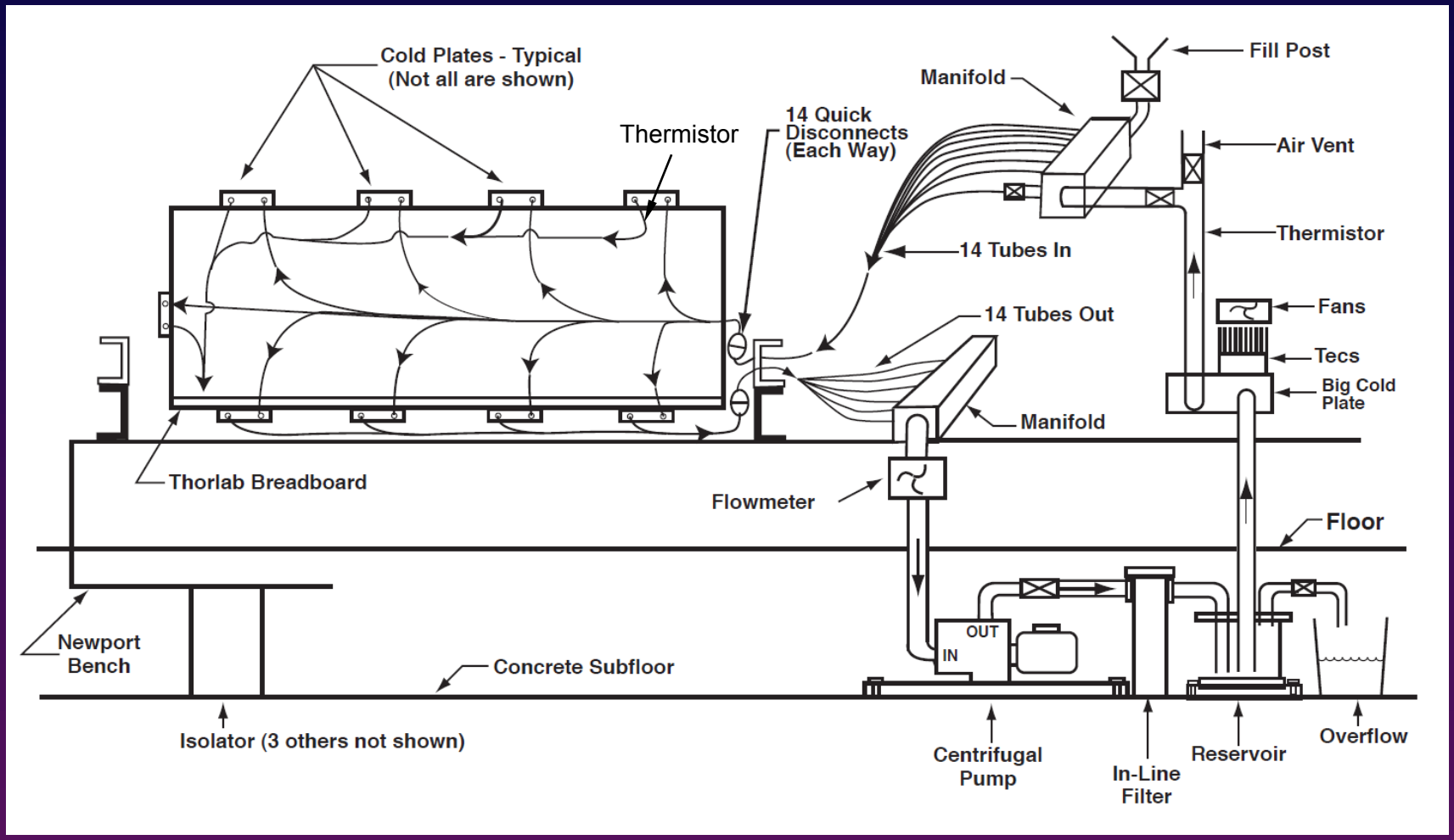
One tool could change that, giving us our first look at a distant planet that could be the next best thing to Earth.

Currently, scientists detect an extra-solar planet by measuring the dimming of its star as the planet passes between it and our line of sight (this is known as the Transit Method). By observing the way the star's

The Transit Method

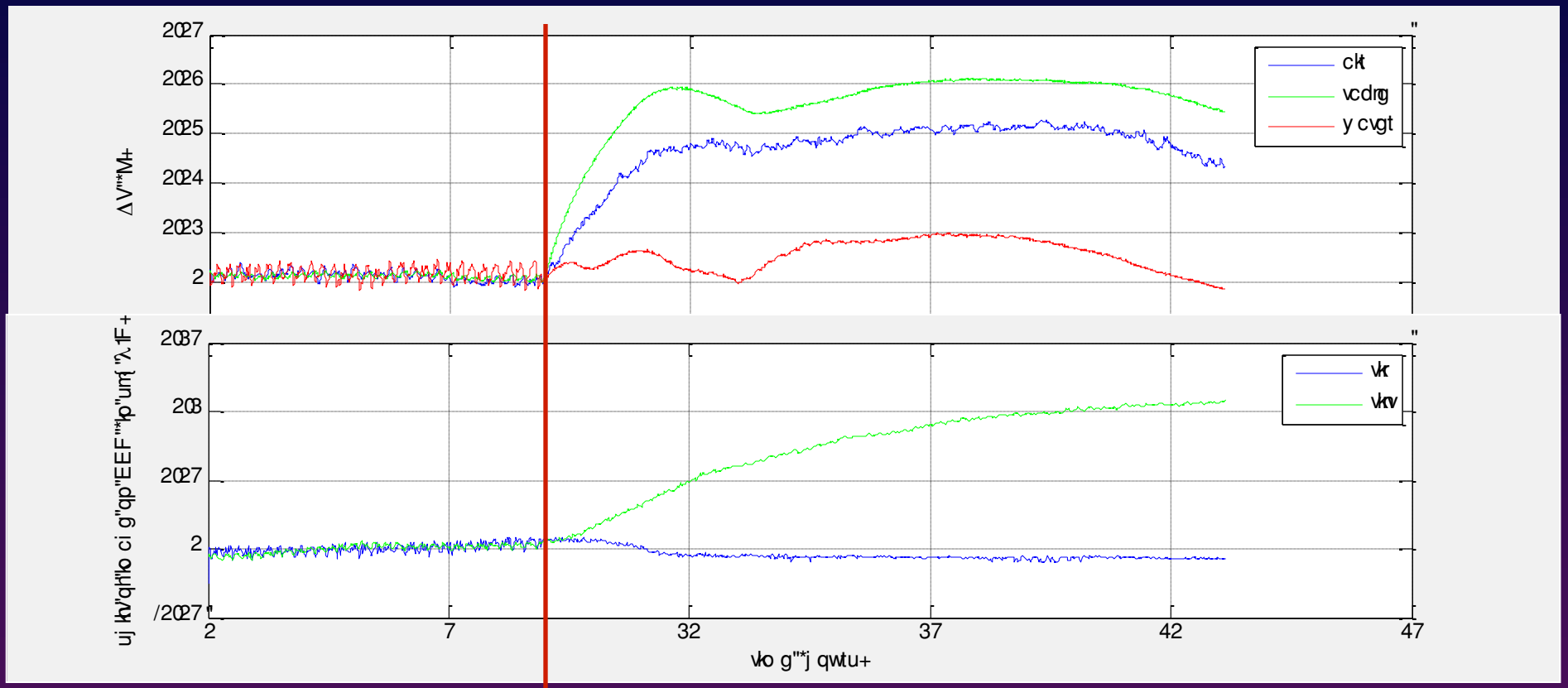
http://gizmodo.com/5896588/the-lens-well-look-through-to-find-a-new-earth

Active thermal control system



- Often observe < 0.5mK stability over 1hr (based on a measurement independent of control system input)

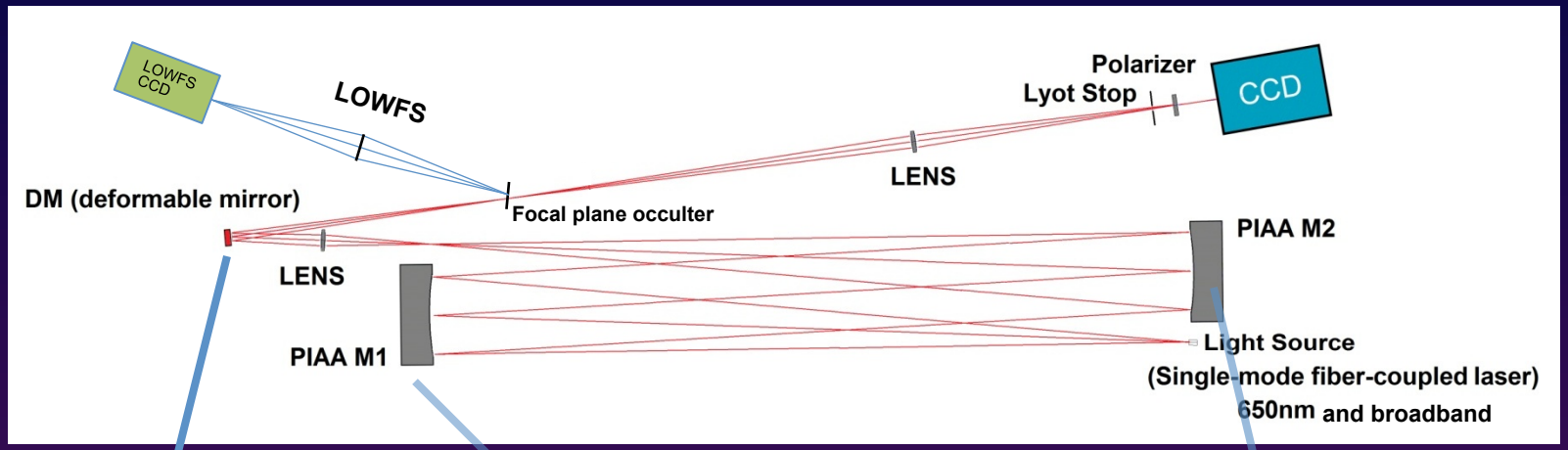
Temperature Stability

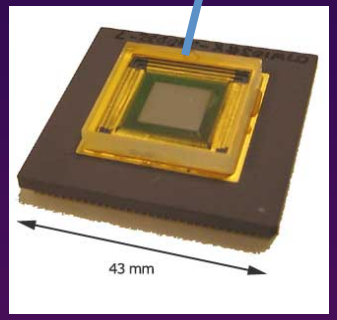


Active thermal control ON ← | → Active thermal control OFF

- Outside the enclosure, temperature varies by ~ 0.5K.
- Inside the enclosure (active thermal control OFF), temperatures vary by ~ 50mK, causing tip/tilt errors of about 0.1 λ/D
- With ATC ON, can sustain the following root mean square values:
  - Air T: 0.9mK
  - Table: 0.4mK
  - Water: 1.3mK
  - Tip/tilt: 4.8e-3 λ/D (limited by insufficient tuning of the ATC algorithm)
  - According to simulations, such tip/tilt will limit contrast to ~1e-9 at 2 λ/D

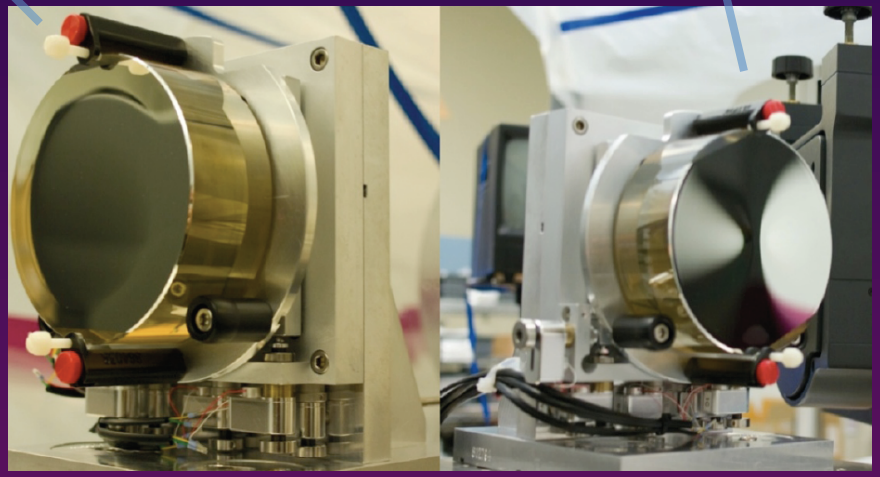
ACE Optical Layout





Boston Micromachines
Deformable mirror (32x32)

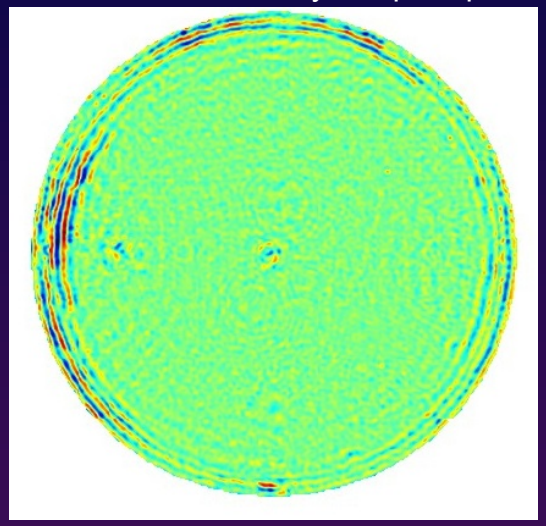
Wavefront control uses
a combination of
EFC (Give'on et al. 2007)
and Speckle Nulling



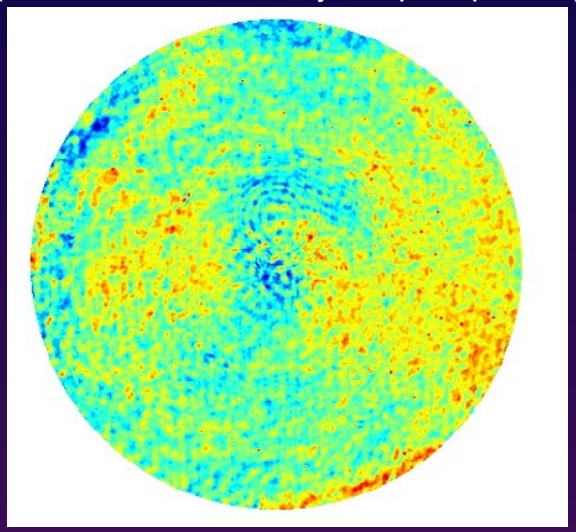
Broadband-capable PIAA mirrors
made by L-3 Tinsley

State of the art Tinsley PIAA Mirrors

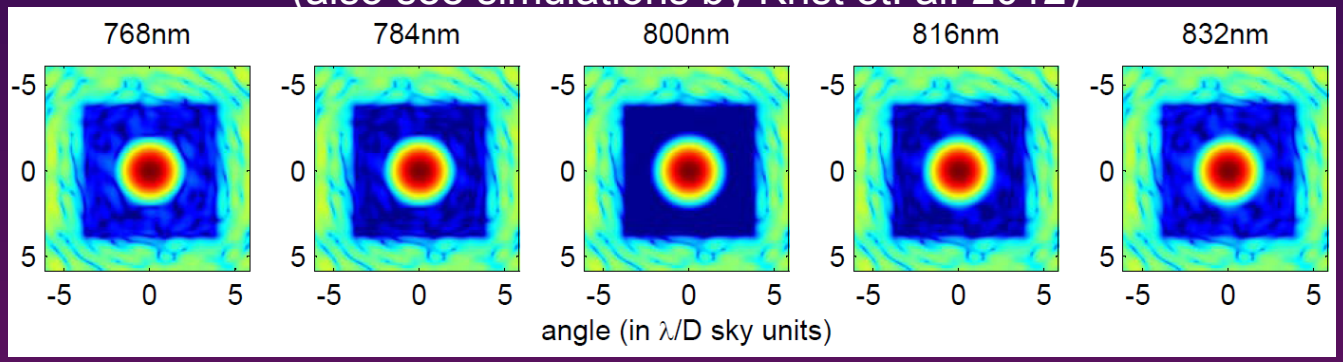
PIAA M1 error map
(4.65nm RMS for 0-90 cycles per aperture)



PIAA M2 error map
(3.8nm RMS for 0-90 cycles per aperture)

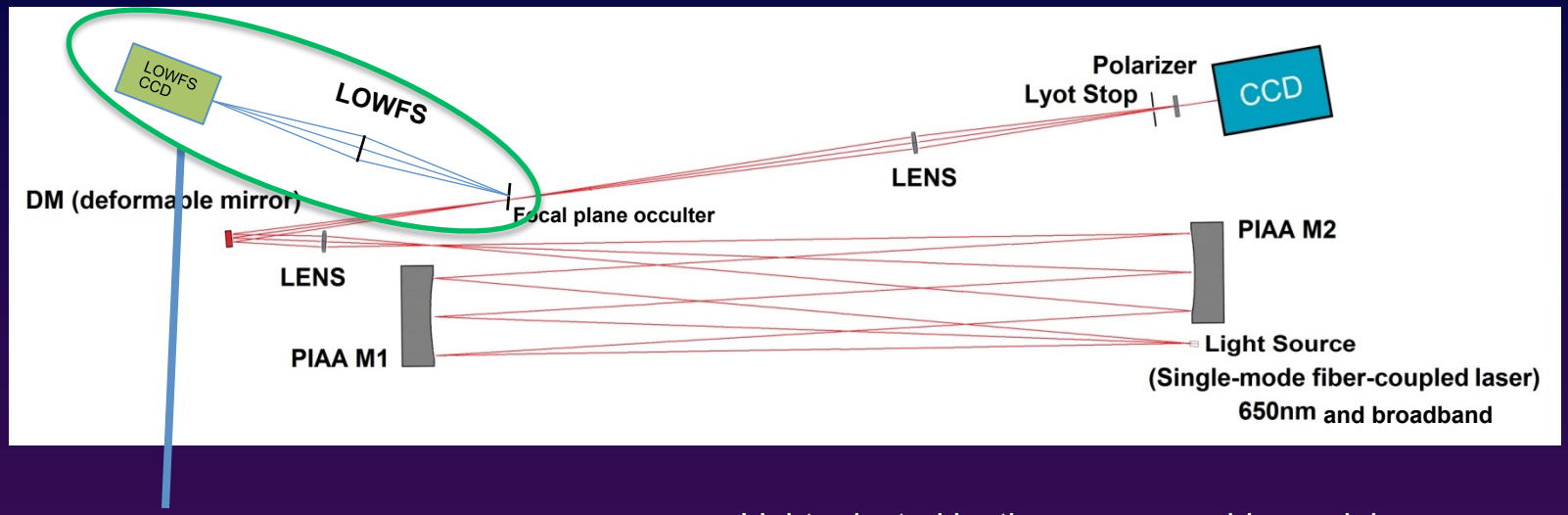


Simulation of 2DM broadband wavefront control
(contrast better than 1e-9 in a 10% band around 800nm)
(also see simulations by Krist et. al. 2012)



Mirrors designed for 1e-9 contrast at 2 λ/D, but can be adopted to 1e-6 at 1 λ/D
Several other sets (by Axsys) are available as well

Architecture of the LOWFS

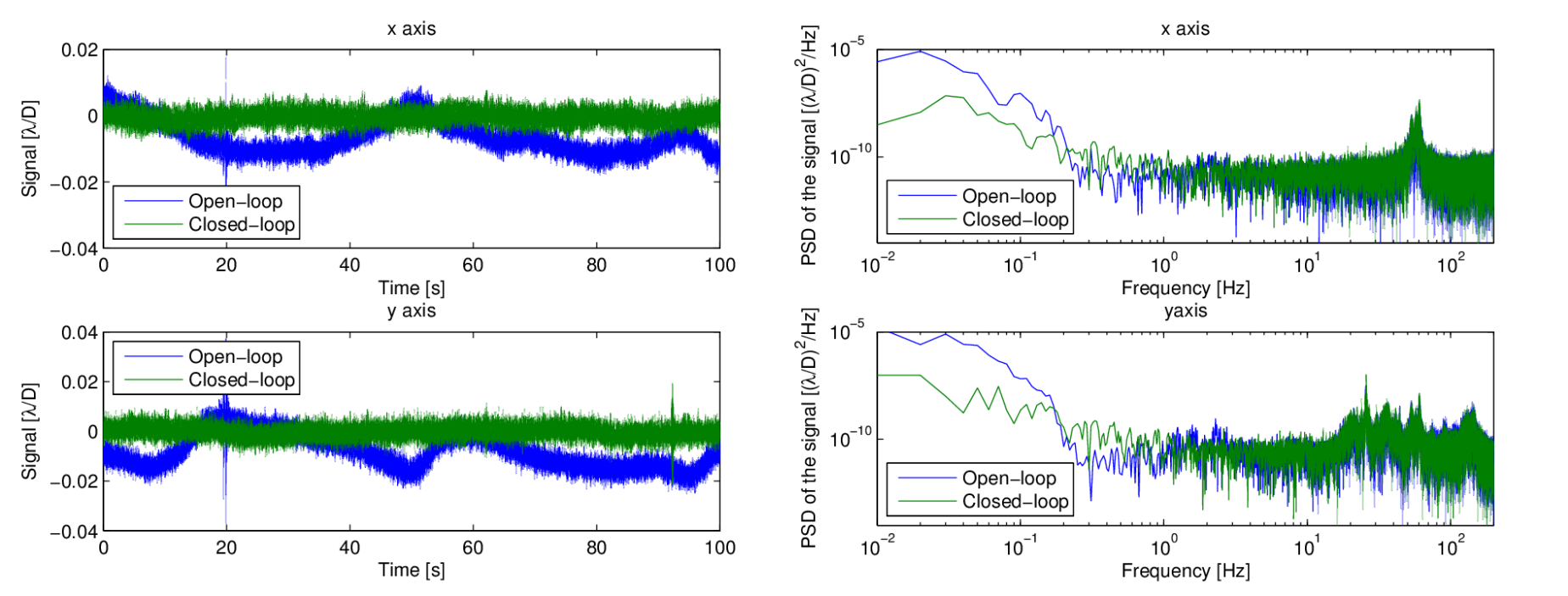


Fast camera
1100 Hz maximum
14 bits/pixel
Low noise

- Light rejected by the coronagraphic mask is collected for the LOWFS
- A lens reimages the PSF on a fast camera
- A controller grabs images, calculates modes (tip/tilt upstream and downstream the PIAA, focus, …)
- Commands are send to actuators (tip/tilt mirrors, piezo stages, …)
- Correction of 2 modes: tip/tilt upstream the PIAA
- 2 actuators: X and Y translation of the source with piezos
- Real-time controller
  - 450 Hz maximum frequency in closed-loop
  - 1100 Hz in open-loop (vibration analysis)

- Work led by Julien Lozi (see his Dissertation talk 328.03D)

Performance of the LOWFS



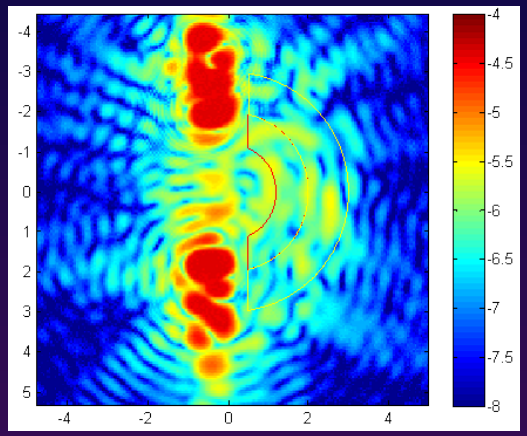
- The vibration analysis, coupled with accelerometers, helped us to identify contributors
- The controller removes mostly residual turbulence below 1 Hz
- We will try to reduce vibrations, especially on the y axis, between 10 and 150 Hz

- Residue:
  - Open-loop: 6×10^{-3} λ/D
  - Closed-loop: **2.5×10^{-3} λ/D**

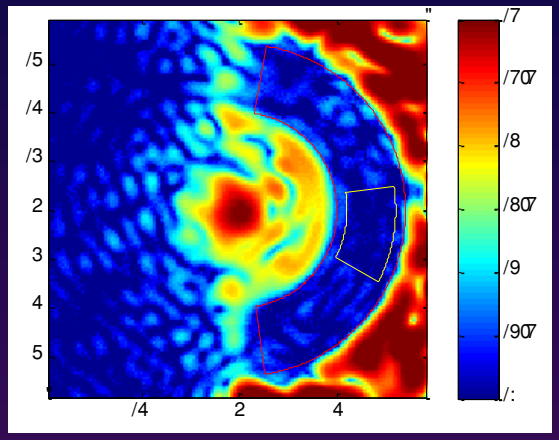
➔ Since we installed the LOWFS, the contrast improved by a decade

Results (ACE air testbed)

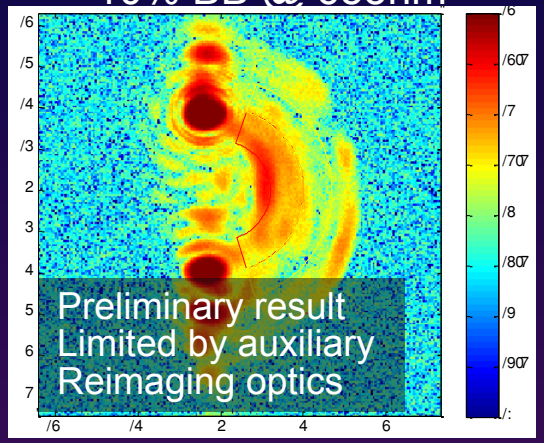
~8e-7, 1.2-2.0 λ/D
655nm

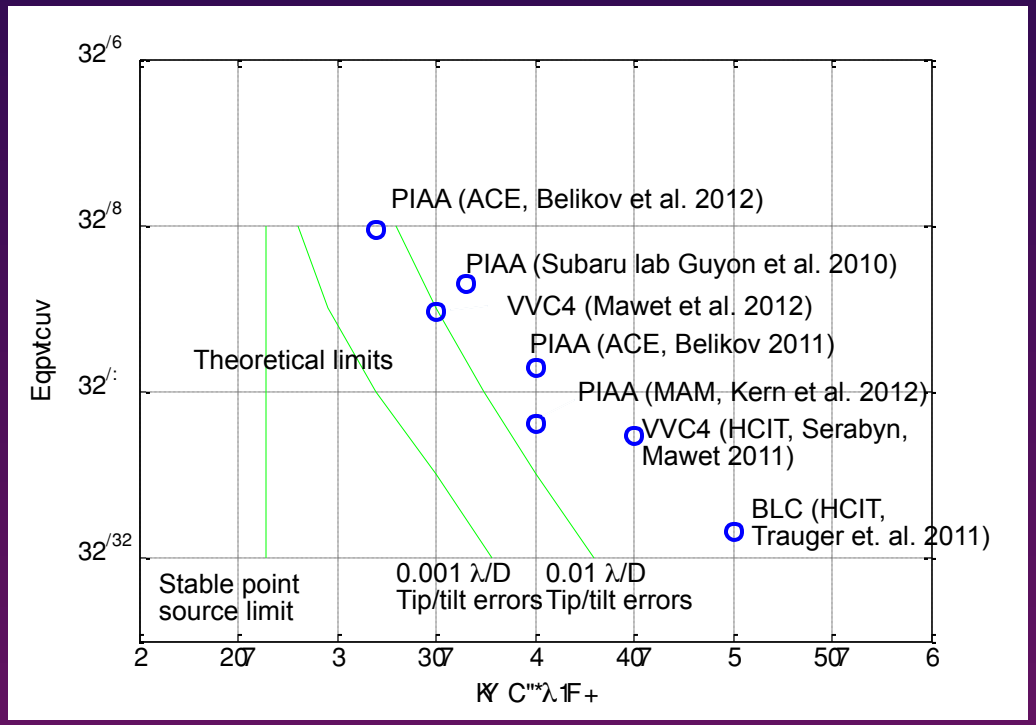


1.9e-8, 2.0-3.4 λ/D
655nm



6e-6, 1.2-2.0 λ/D
10% BB @ 655nm

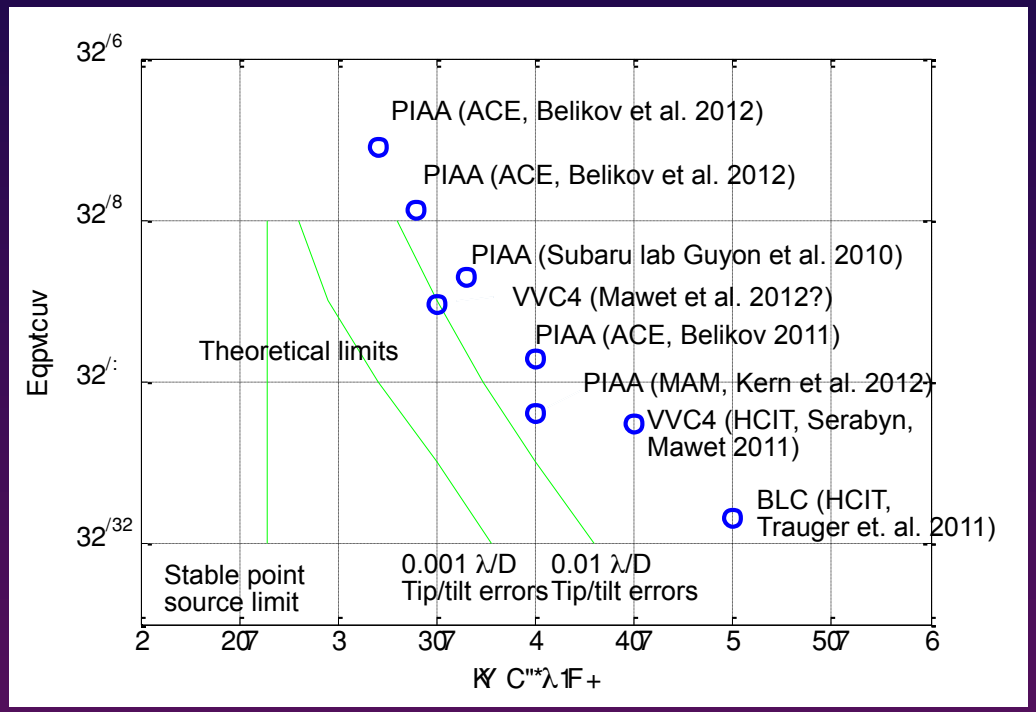




Ruslan Belikov, NASA Ames Coronagraph Laboratory

Aside: Observations and conjectures on importance of coronagraph type

Raw conrast lab demonstrations
(in monochromatic or narrowband light)



- All the leading coronagraph concepts designed to the same IWA will have roughly the same (i.e. theoretically optimal) sensitivity to low-order aberrations
- In leading lab coronagraph demonstrations, coronagraph performance is a function of
  - (a) design specs (especially IWA)
  - (b) external factors (e.g. stability, facility)
  - NOT coronagraph type
- There is no single "best" coronagraph (although different regions of design space may favor different coronagraph types)
- The real challenge is not "figure out which coronagraph is best", but stability and broadband wavefront control.
- Fortunately, a coronagraph is (approximately) only a module in a system, not the system itself

Conclusions

- The Ames Coronagraph Experiment lab is developing technology for EXCEDE, an Explorer mission concept designed to directly image debris disks and capable of directly imaging CS debris systems with ~ 10 zodis of dust into the habitable zones for a statistically significant sample of nearby stars

- Contrast results at small IWAs
  - 8e-7 between 1.2-2.0 λ/D, 655nm
  - 2e-8 between 2.0-3.4 λ/D, 655nm
  - 6e-6 between 1.2-2.0 λ/D, 10% band around 655nm (limited by components external to coronagraph)

- Main limiting factor is low-order instability (which may also be one of the main tall poles for all space coronagraph developers).

- Related AAS talks
  - EXCEDE tech dev: Belikov et. al. (305.02)
  - Stability: Lozi et al. (328.03D)
  - SCExAO: Jovanovic et al. (305.05)
  - New focal plane masks: Newman et al. (149.31)