# Towards Imaging Other Earths:
## Coronagraph development at Princeton and NASA

- Background
- Shaped pupils at Princeton (2005-2007)
- PIAA at NASA Ames (2008-)

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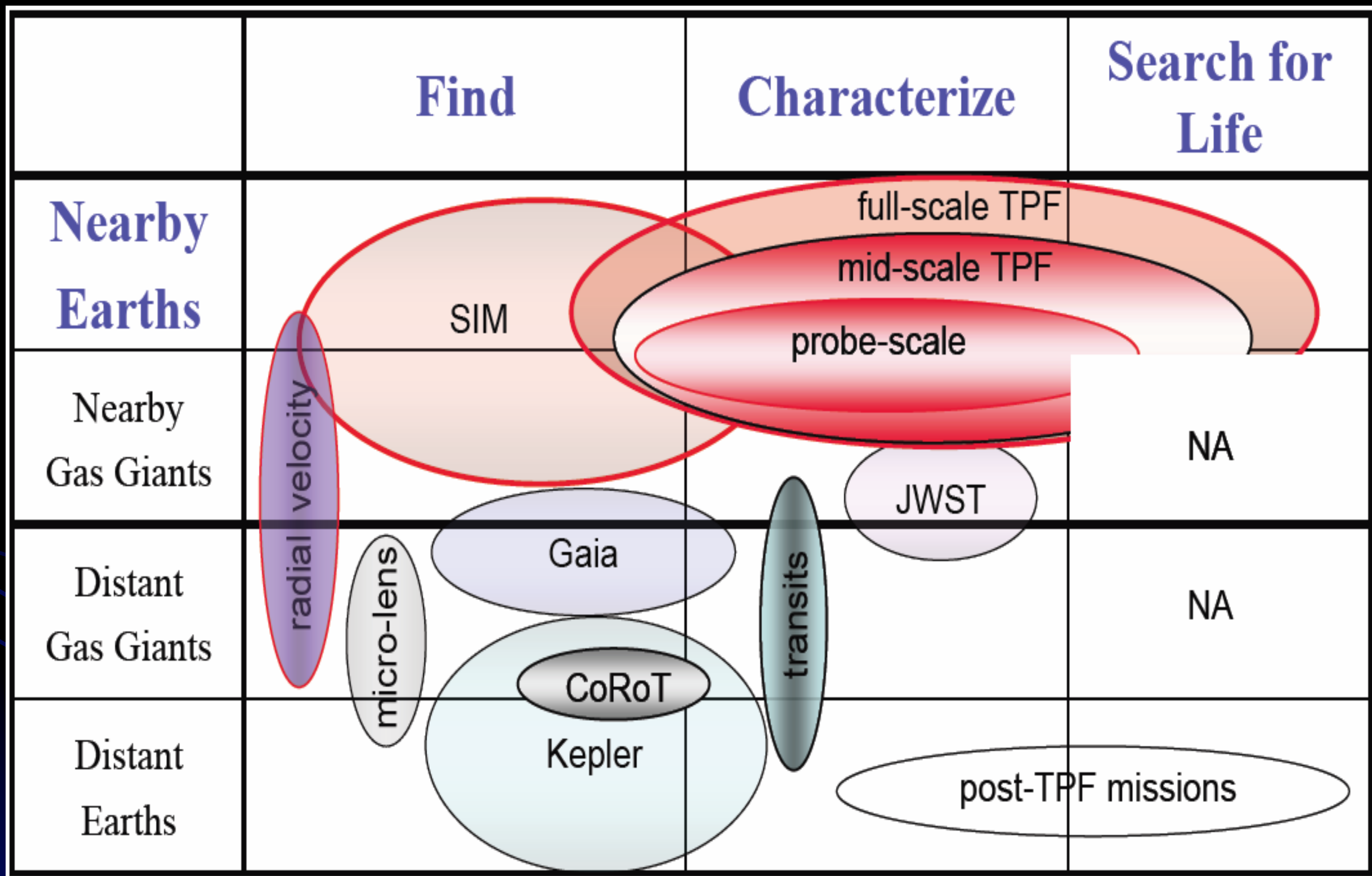
NASA Ames Research Center
2009 Sagan/Michelson Fellows Symposium
11/12/2009


Is there another Earth out there?

# Exoplanet Discovery Space




Courtesy of W. Traub

# Main Challenge

- Build a coronagraph to the following specifications

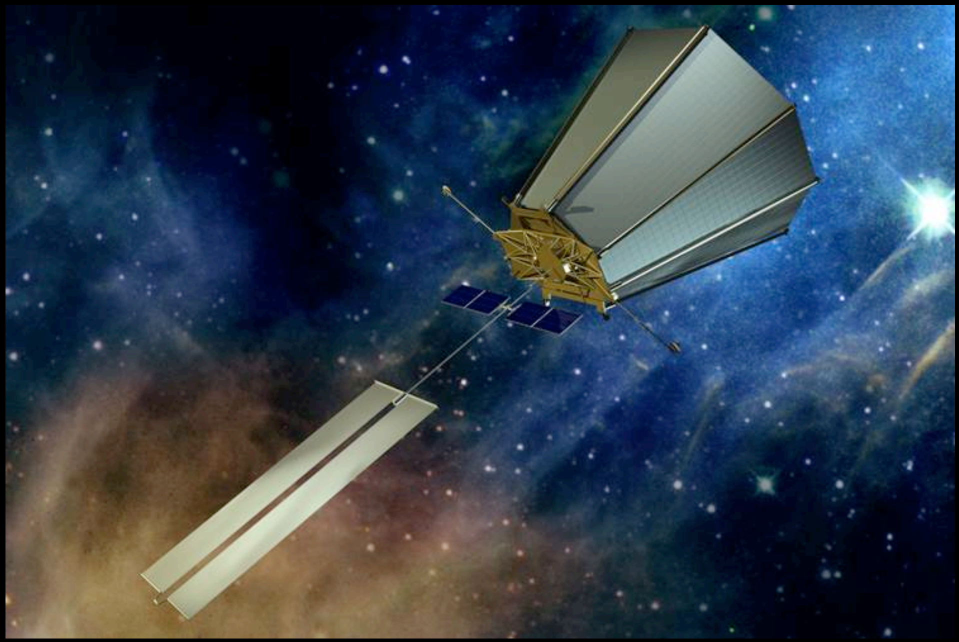
  - $10^{10}$ Contrast
  - Inner working angle of
    - 4 λ/D (~ 4-8m full scale TPF)
    - 2 λ/D (~ 1.5-m probe-scale)

  - Oh yeah, be able to achieve these specs
    - in space
    - with very few photons
    - in broadband!

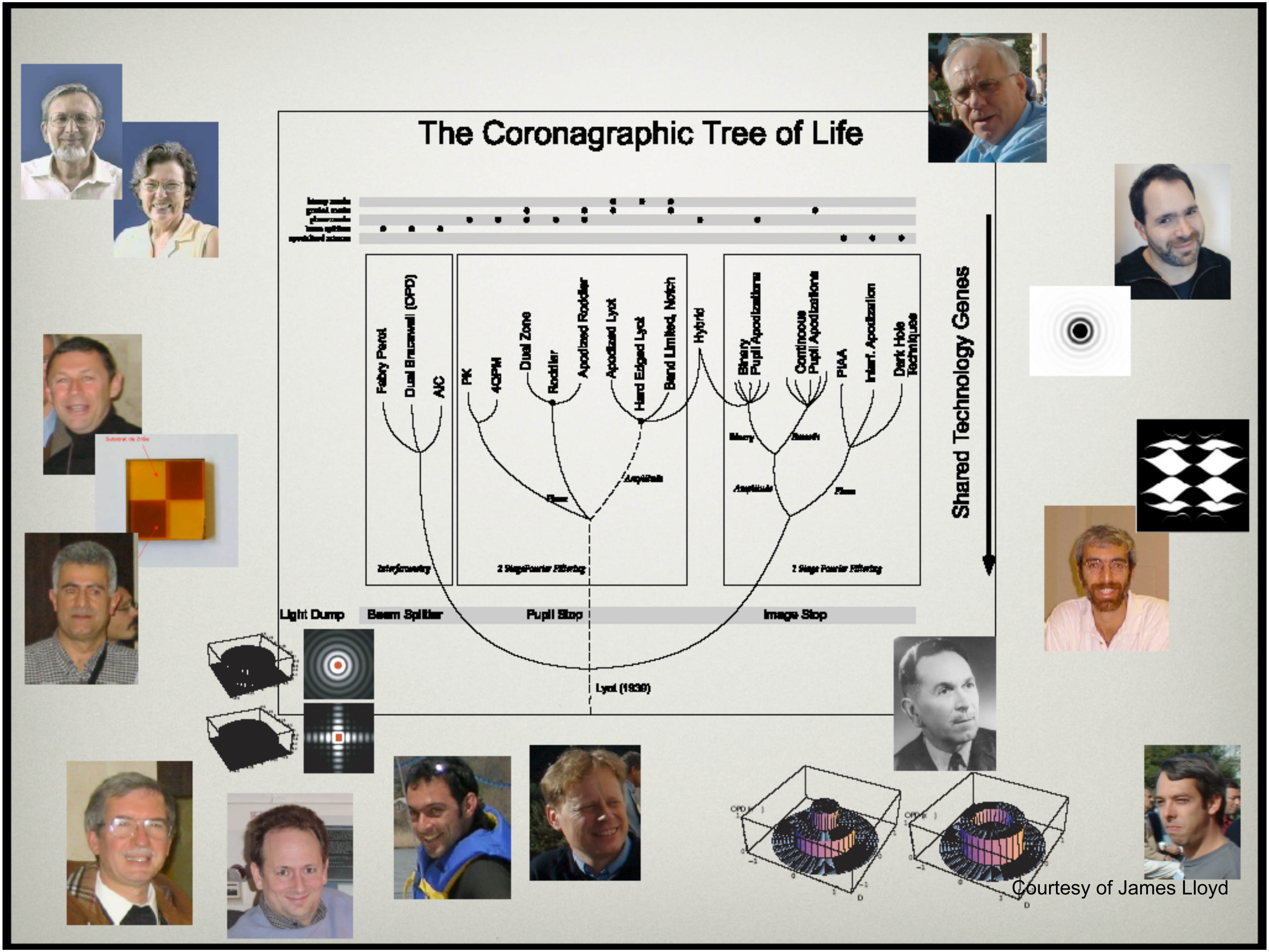

TPF AT PRINCETON

# TPF-C: Original Flagship Mission

TPF-C

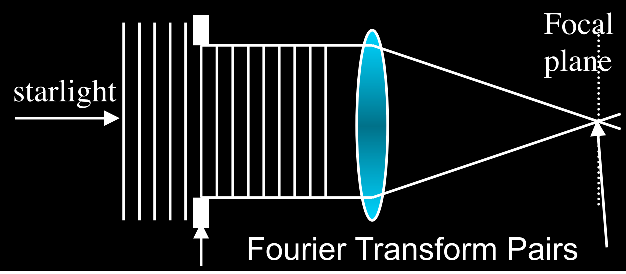


- TPF-C
  - Detection
    - 35 core nearby stars (150 extended mission)
    - Distance from star: 0.7-1.5 a.u.
    - Surface area: 0.5 of Earth and greater
  - Characterization
    - Orbit, distance
    - Photometry: size, rotation
    - Spectroscopy: atmosphere, water
    - Life
  - General Astrophysics
- 8 x 3.5 m off-axis telescope w/ coronagraph
- $ 4B

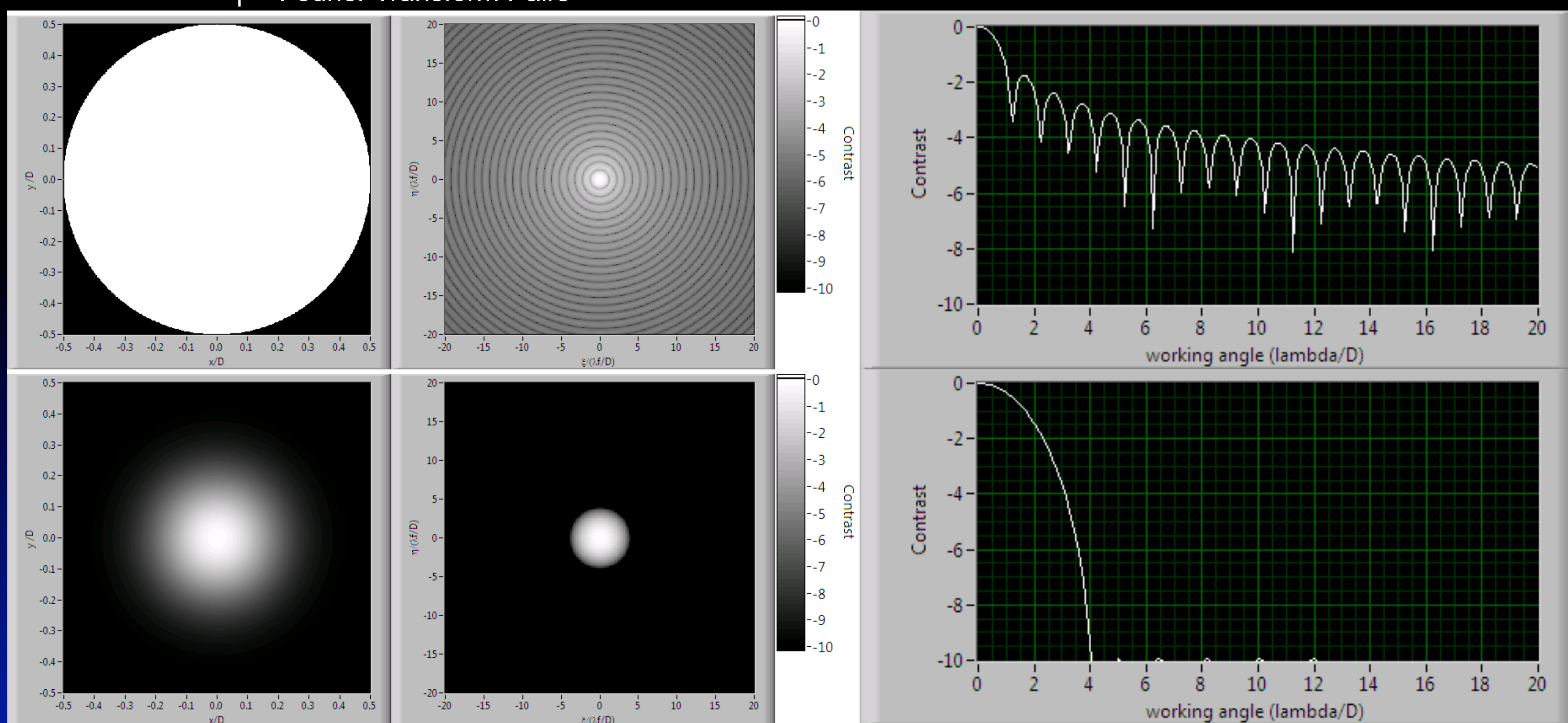


Courtesy of James Lloyd

# Pupil Apodization Overview



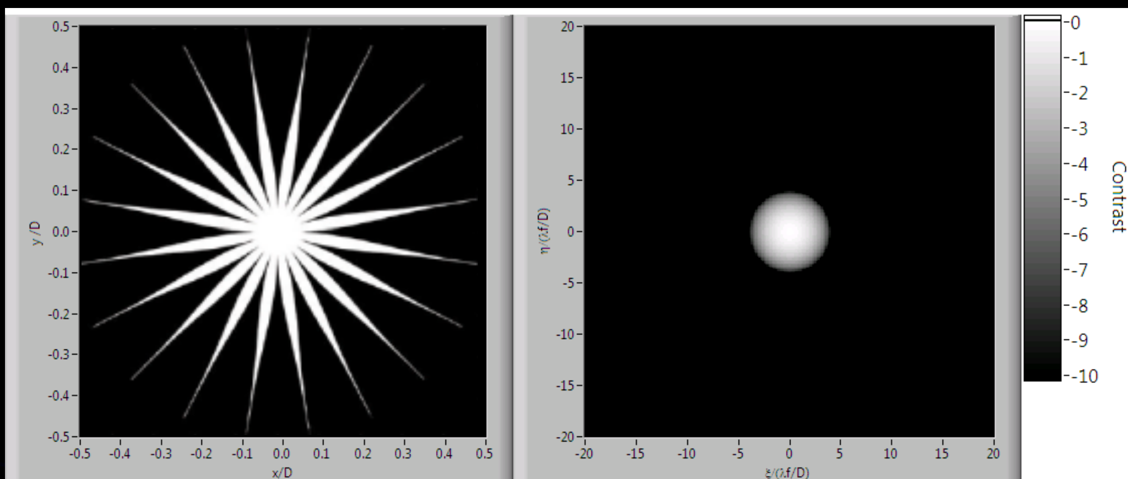

- E.g. Splepian 1963 (1D analytical solution – the prolate spheroidal
- 2D solutions can also be found through optimization (Vanderbei 2003)
- However
  - Grey apodizations are difficult to make
  - Loss of throughput
  - Loss of resolution



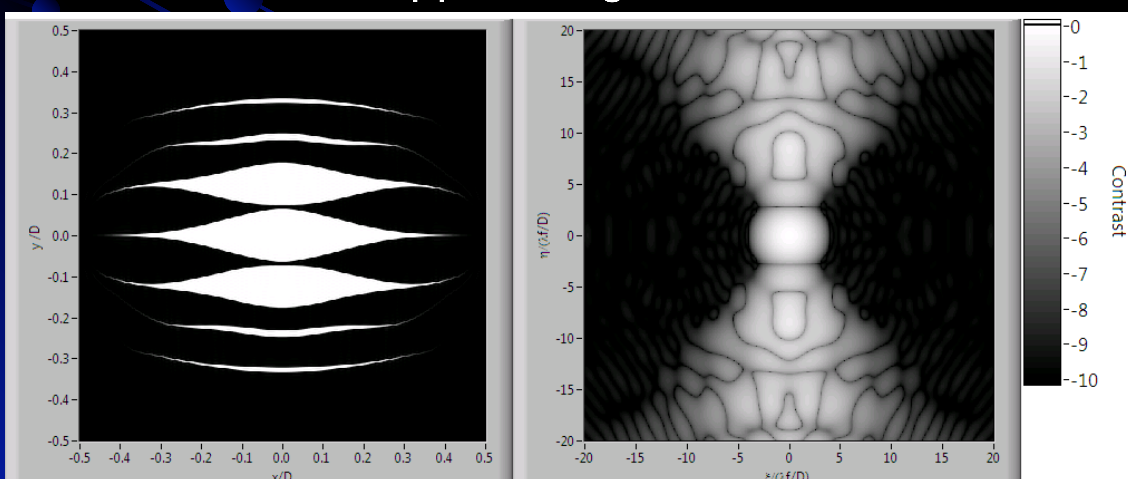
# Solution #1: Shaped pupils

## (Spergel, Kasdin, Vanderbei 2003-2005)

Starshape design

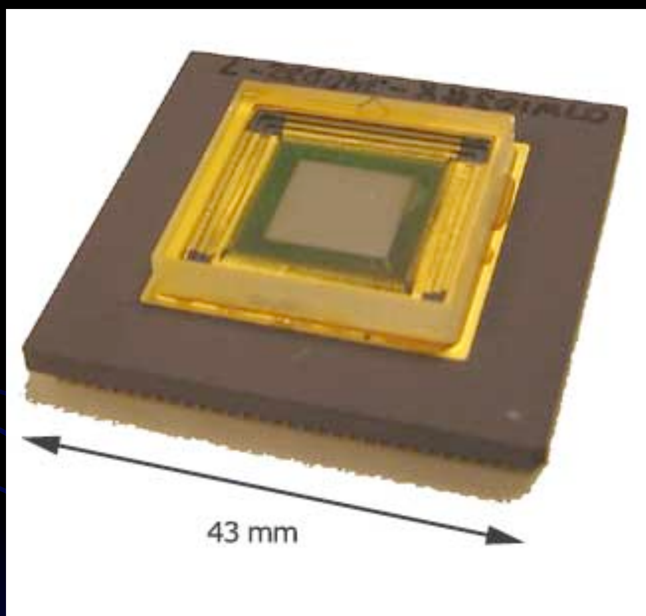



Ripple design

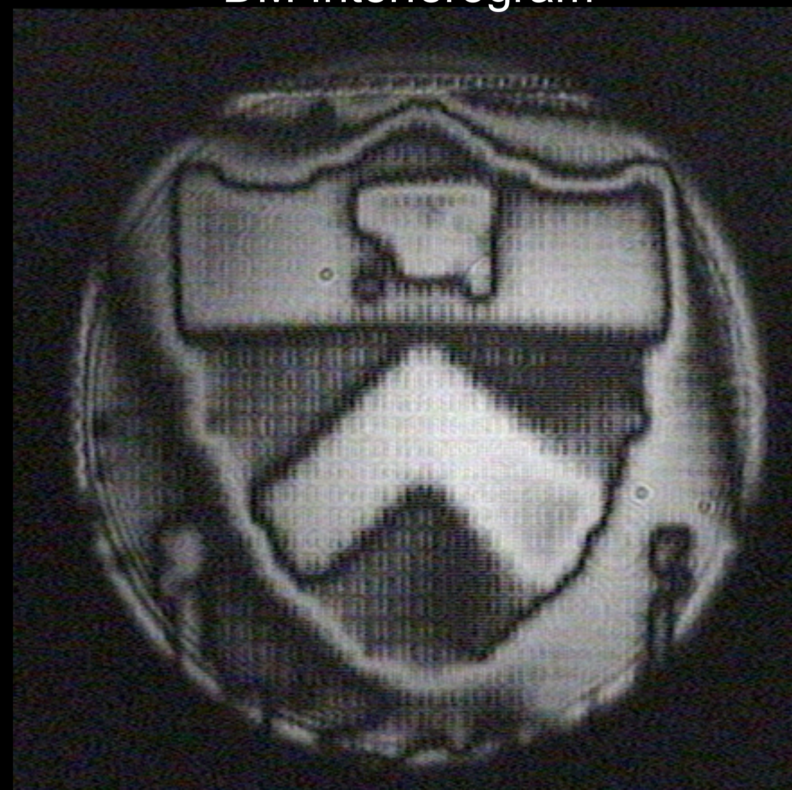



- Free-standing masks are probably better than masks on glass
- The "ripple"-type masks are easiest to make
- For ripple-type mask, the dark zone is only a wedge, but throughput is greater.

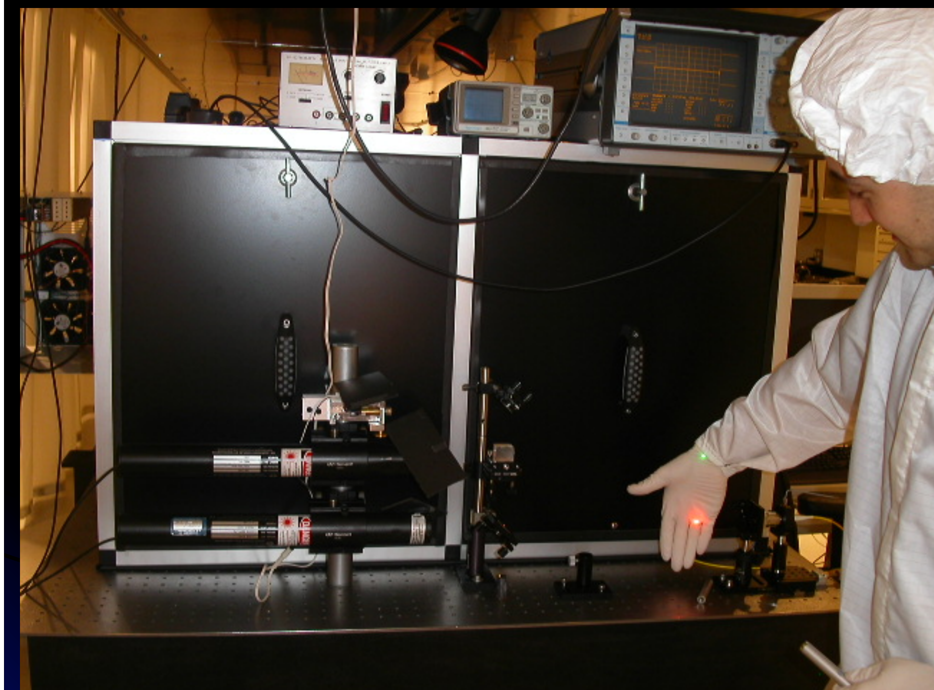
# Deformable Mirror (Boston Micromachines)

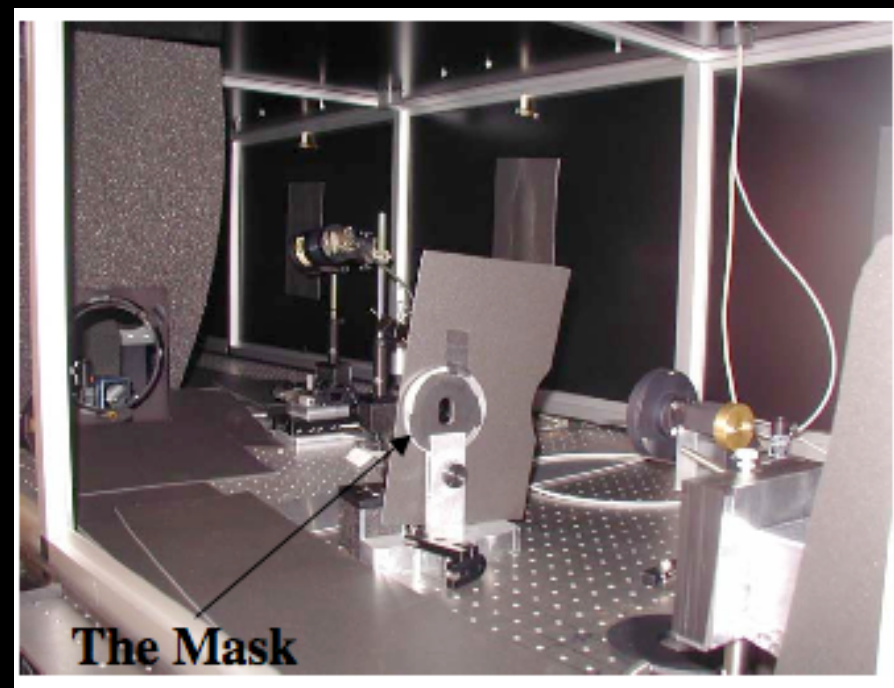



DM Interferogram



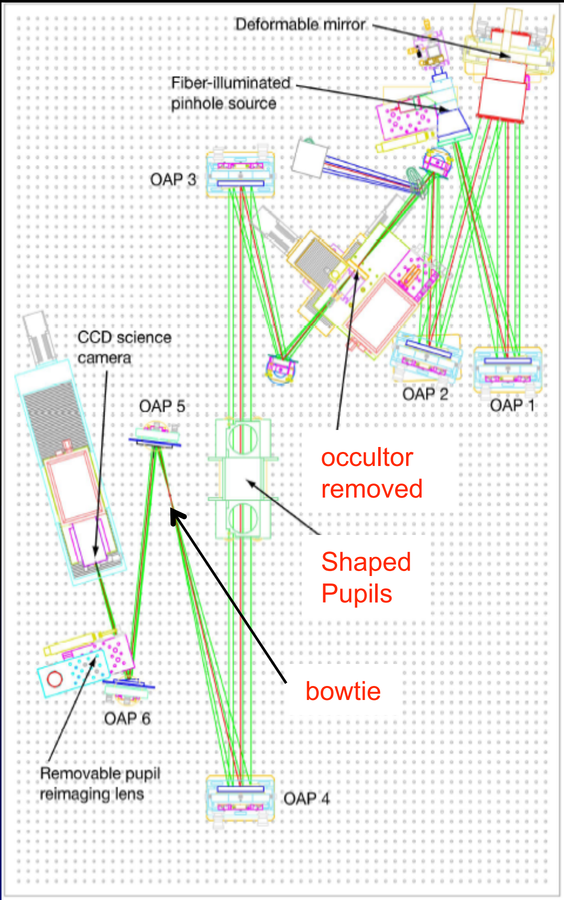
# The Princeton Laboratory

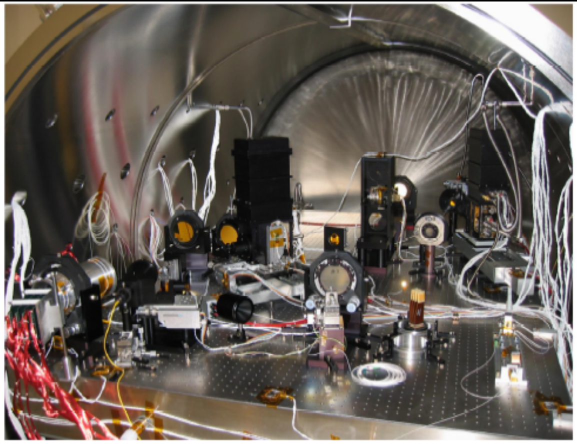





- Clean room
- 1.2 x 5 m vibration-isolated optical bench
- Enclosure to eliminate thermal convection, air turbulence, particulate contamination, and stray light

# JPL's vacuum High Contrast Imaging Testbed



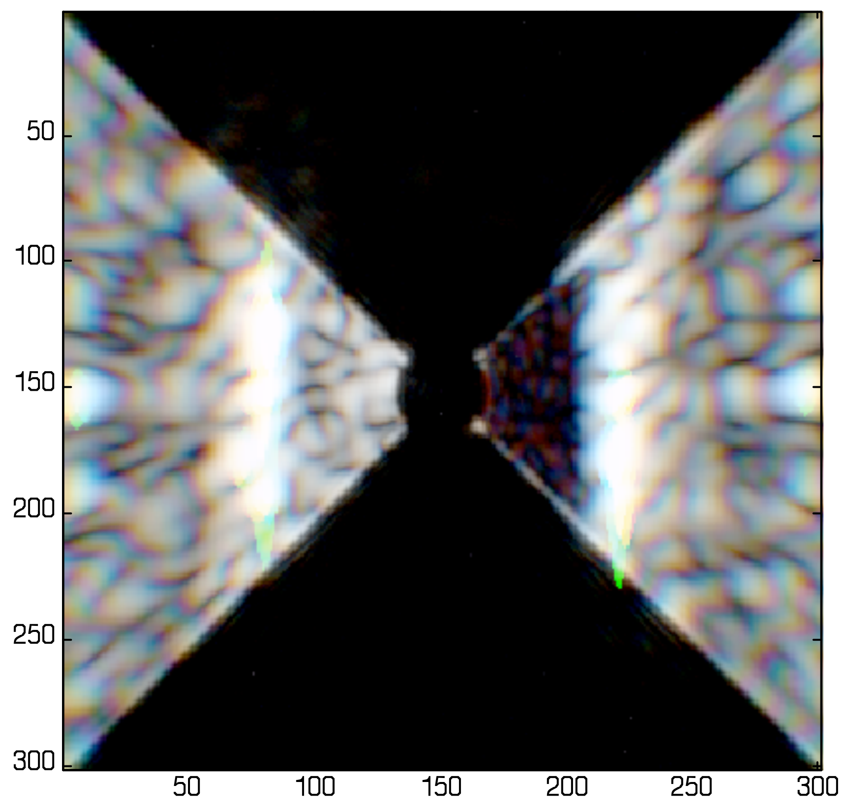



- State-of-the-art facility for testing high-contrast imaging concepts and wavefront correction schemes
- Vacuum chamber
  - 6' diameter
  - 10 mTorr or better
  - 5'x7' vibration isolated optical table
- Xinetics DM
  - 32x32 actuators, 1mm pitch
- 30mm beam
  - 785nm, 836nm, or 760-840 broadband
- Fully automated and remote-controlled



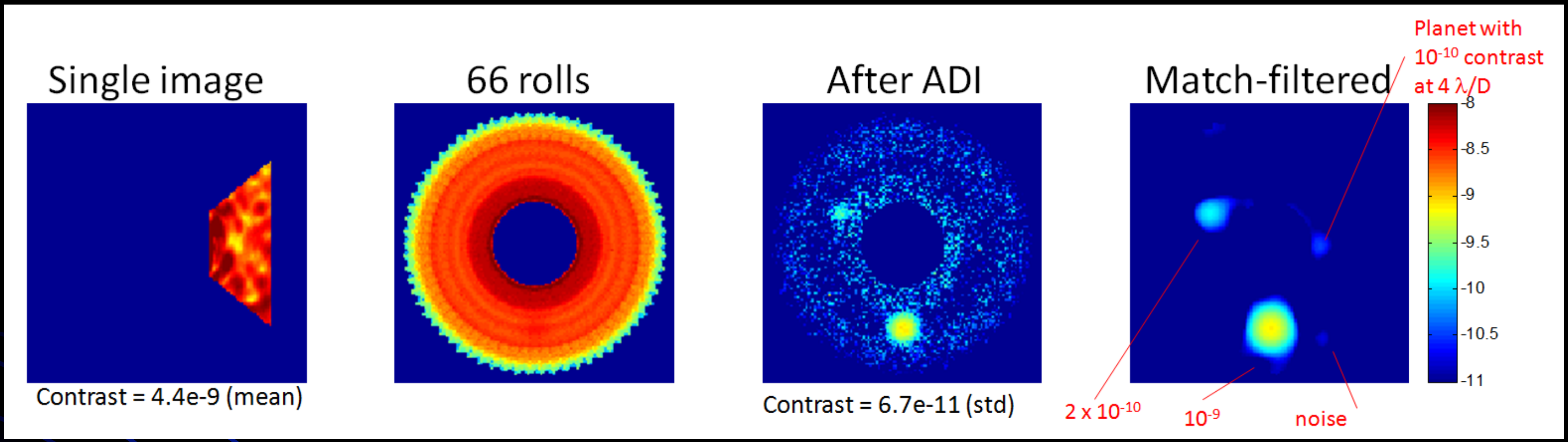
Courtesy of J. T. Trauger

# One of the deepest contrast demonstrations (HCIT + Princeton, Shaped Pupil Coronagraph)



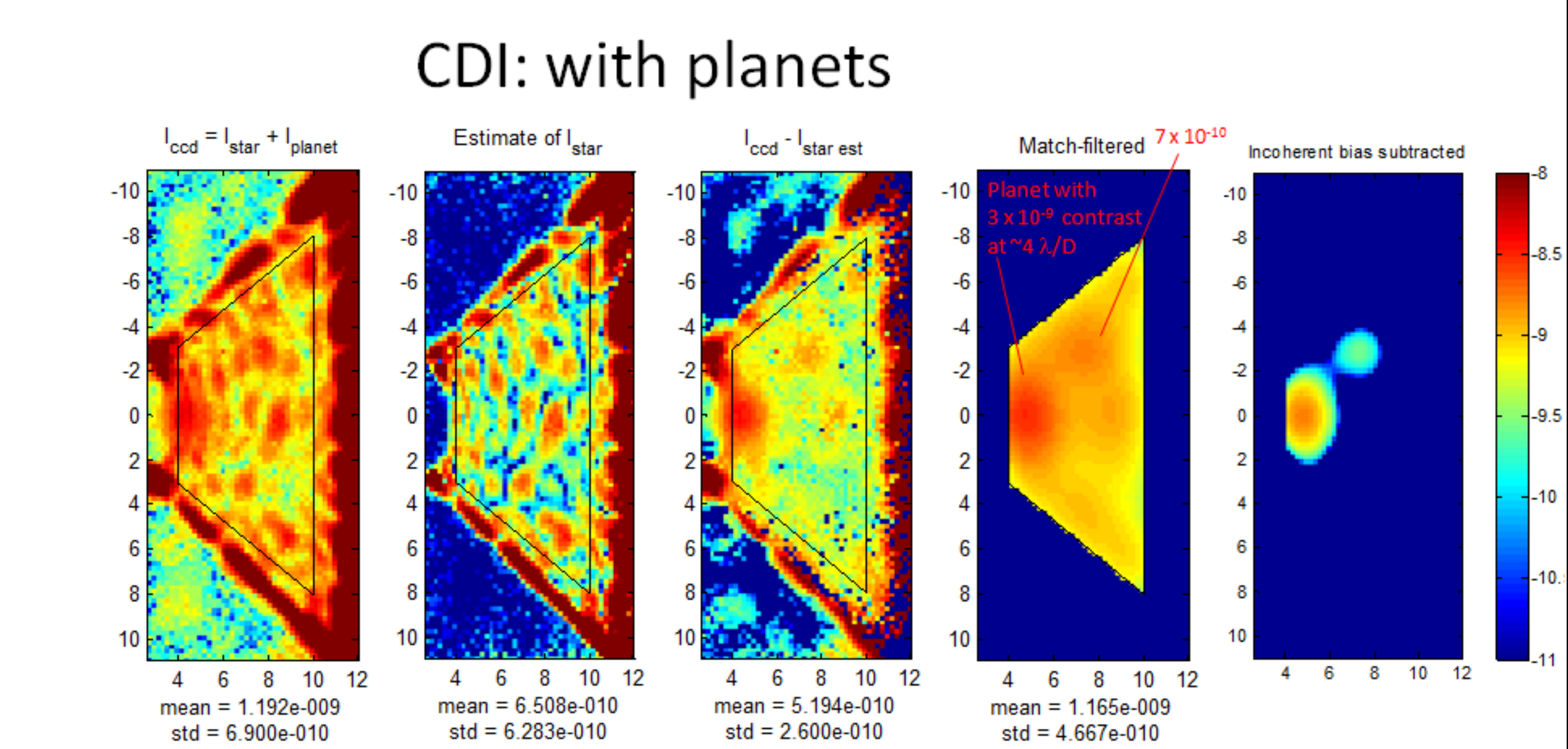

| | |
|---|---|
| Contrast: | $2.4 \times 10^{-9}$ |
| Bandwidth: | 10% @ 800nm |
| IWA: | $4\ \lambda/D$ |

# Post-processing: roll deconvolution at HCIT




- Belikov et. al., 2008

# Post-processing: coherent differential imaging (CDI)

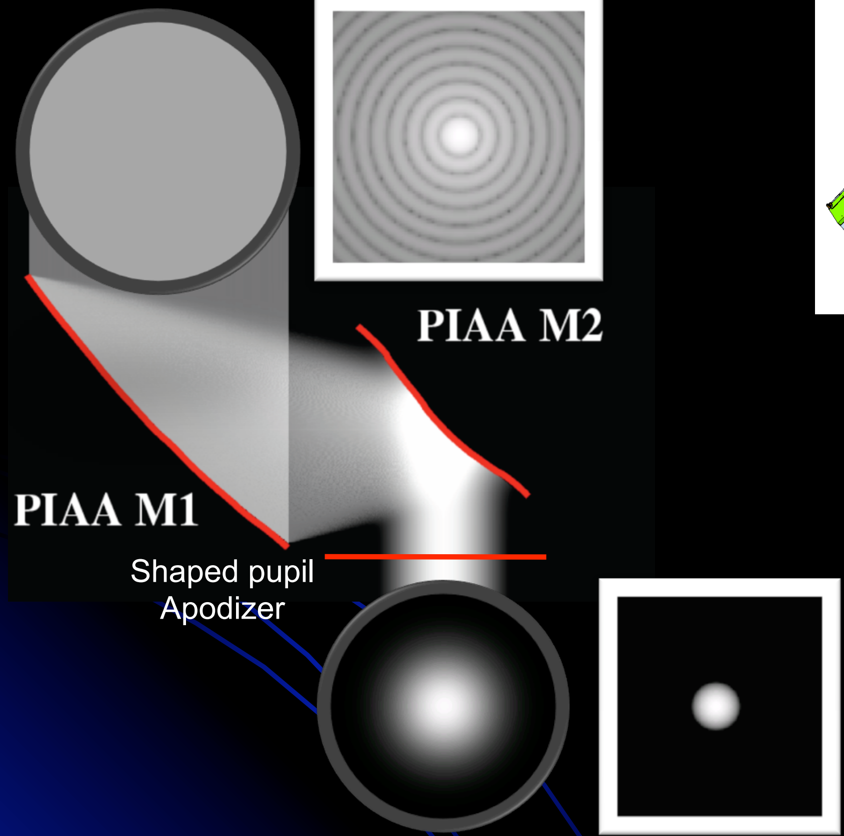


# Princeton project acknowledgements

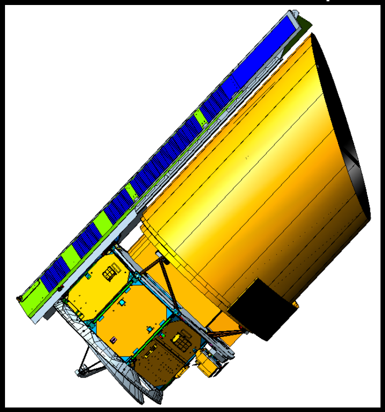
- 1. Shaped Pupil design
  - Original concept and classical designs
    - Vanderbei, Kasdin, Spergel, et. al.
  - Theoretical analysis
    - Ceperley, Lieber, Neureuther, Vanderbei, Belikov, et. al.
  - Final manufacturable designs
    - Belikov, Shaklan, Cady, et. al.
- 2. Shaped Pupil Manufacturing
    - Balasubramanian, White, Echternach, Dickie, Belikov, Beal, et. al.
- 3. Testbed design and setup
    - Trauger, Kern, Shi, Kuhnert, Niessner, Belikov, et. al.
- 4. Wavefront Correction Algorithms
  - Speckle nulling
    - Trauger, Burrows, et. al.
  - Others
    - Give'on, Belikov, Borde, Traub, Pueyo, et. al.
- 5. Designing experiments; post-processing and data analysis.
    - Belikov, Kasdin, Give'on, et. al.


NASA Ames

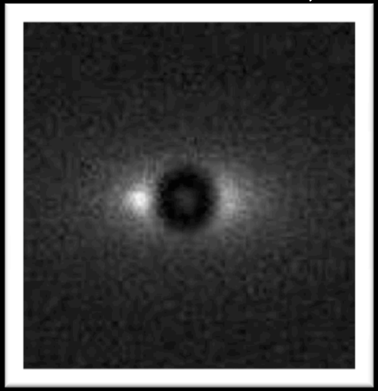
# PIAA (phase-induced amplitude apodization) overview and motivation




PECO mission concept



Simulated Earth image around Tau Ceti,



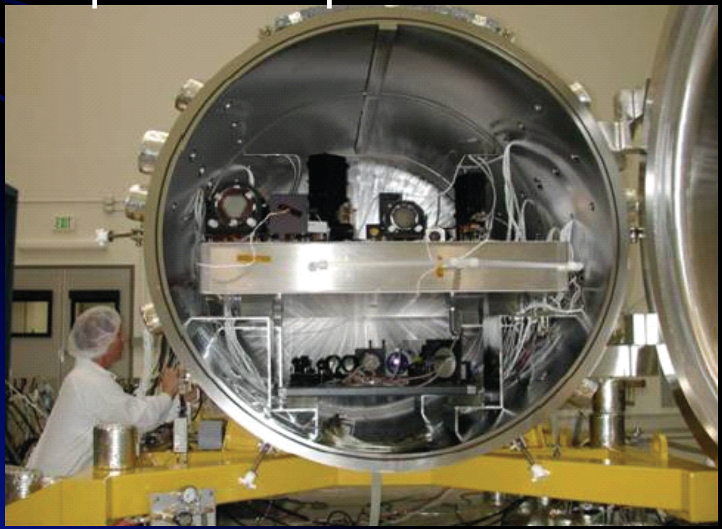
- PIAA invented by Olivier Guyon with significant contributions by Bob Vanderbei, Wesley Traub
- High-throughput (almost 100%)
- Aggressive IWA (2 λ/D)
- Potentially enables Earth-like planet imaging with a 1.4m telescope (PECO)
- Can also be used on a balloon (planetscope) or TPF Flagship
- Track record of successful hardware development and testing

Ruslan Belikov, NASA Ames Coronagraph Laboratory

# ARC testbed description and role in PIAA technology development

Ames Coronagraph Lab

In a partnership with JPL's HCIT



- New (March 08), flexible, rapidly reconfigurable facility in air
- Successor to Olivier Guyon's 1st PIAA testbed at Subaru
- Dedicated to testing PIAA and related technologies

- Partnering with JPL's HCIT, with complementary roles identified
  - ARC
    - initial validation of lower TRL technologies and concepts
      - MEMS DMs
      - WFC architecture trades
      - dichroics
    - PIAAgen2 mirror manufacture
  - JPL/HCIT
    - higher TRL and vacuum validation
    - testing a variety of coronagraphs

# Partnerships and roles

***NASA Ames Research Center***

| | |
|---|---|
| Tom Greene | ARC testbed director |
| Mark McKelvey | ARC testbed manager |
| Rus Belikov | technical lead |
| Eugene Pluzhnik | experiments |
| Michael Connelley | experiments |
| Fred Witteborn | thermal enclosure |
| Dana Lynch | optical design |

***UofA/Subaru***

***(PIAA design and consulting)***

Olivier Guyon

***UCSC***

***(DM characterization)***

Donald Gavel
Daren Dillon
Renate Kupke
Andrew Norton

***NASA Jet Propulsion Lab***

John Trauger
Andy Kuhnert
Brian Kern
Marie Levine
Wesley Traub
Stuart Shaklan
Amir Give'on
Laurent Pueyo

***Tinsley Laboratories***

***(PIAA mirror manufacture)***

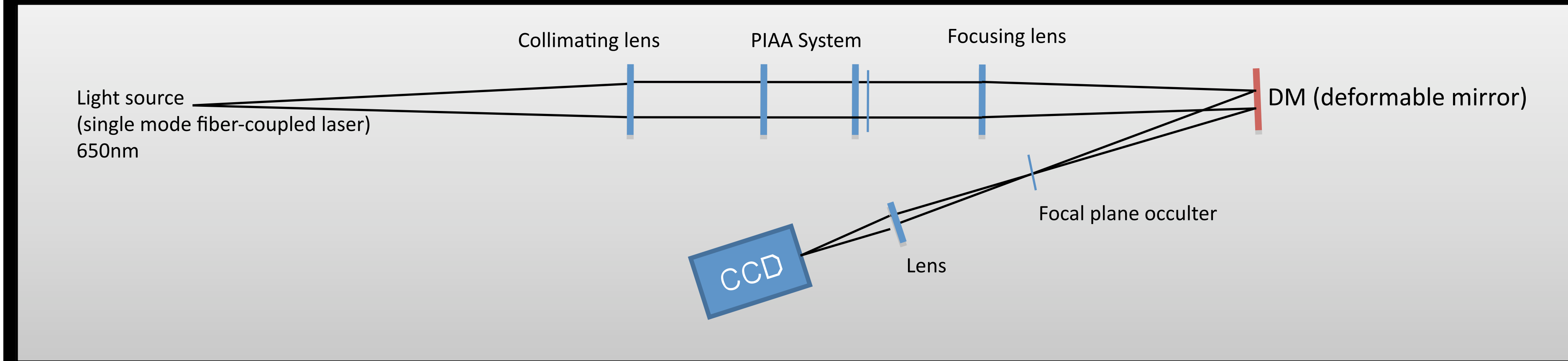
Daniel Jay
Asfaw Bekele
Lee Dettmann
Bridget Peters
Titus Roff
Clay Sylvester

***Lockheed Martin***

***(Optical design)***

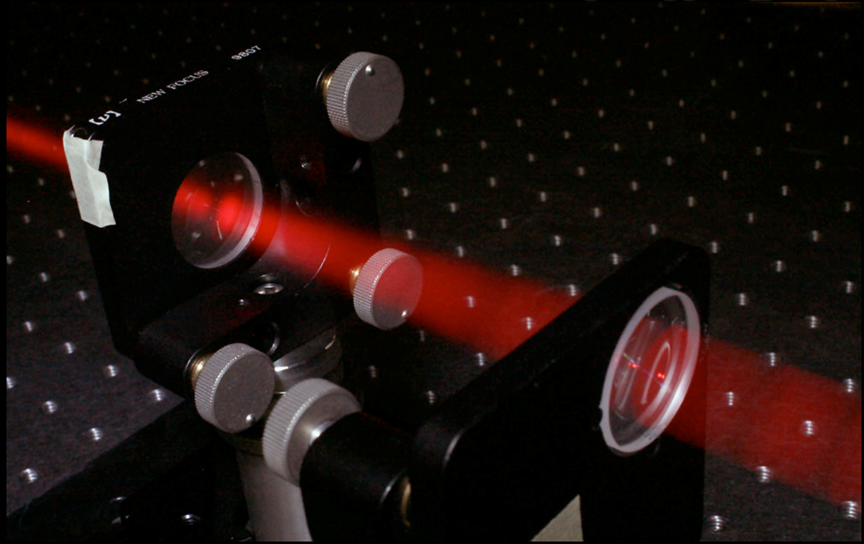
Rick Kendrick
Rob Sigler
Alice Palmer

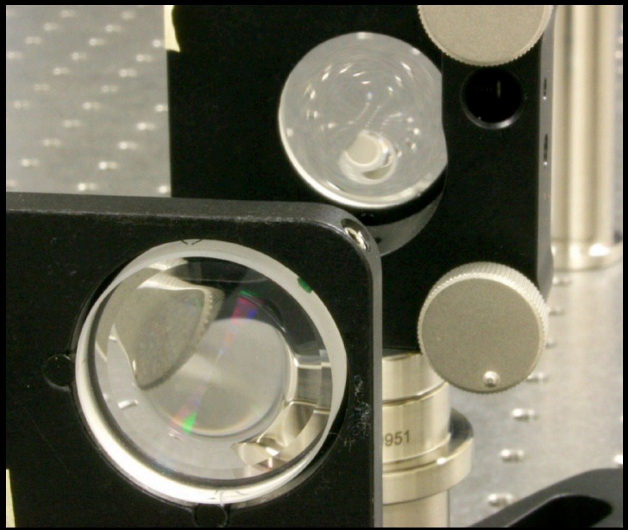
# First stage of experiments



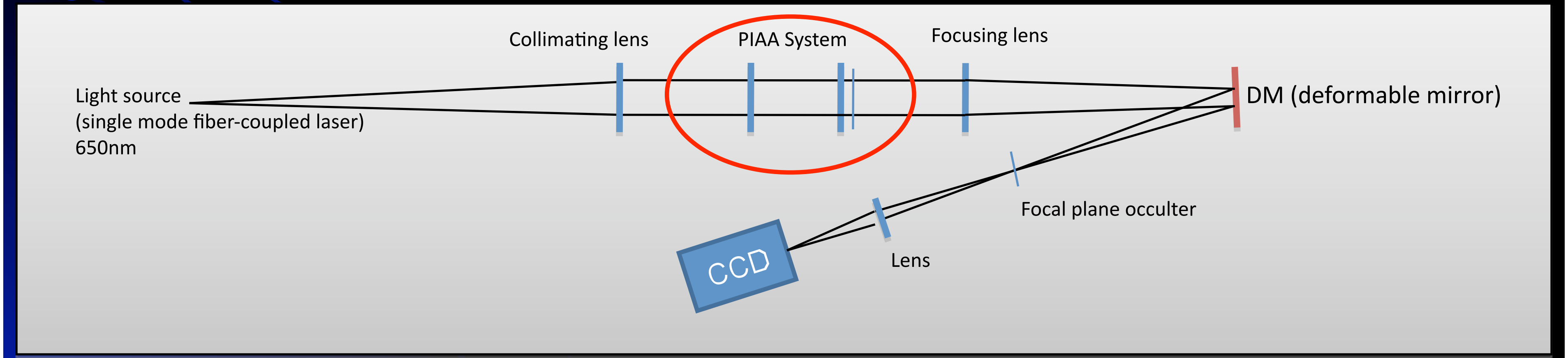

- Initial goal: create a testbed capable of supporting high contrast levels (1e-9)
- Approach: keep things as simple as possible
  - Use lenses
  - Use monochromatic light
  - Switch to mirrors and broadband light once testbed stability and wavefront control are developed to better than ~1e-8 contrast
  - (Or maybe lenses can be made sufficiently achromatic and with a good enough AR coating?)

# PIAA system

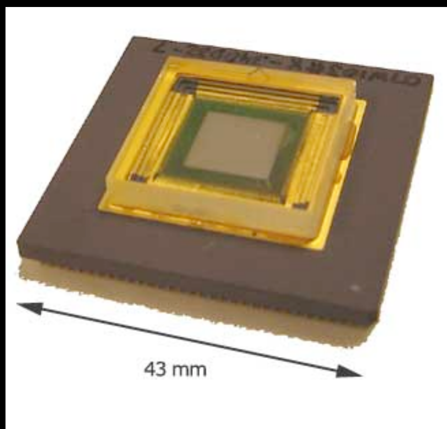


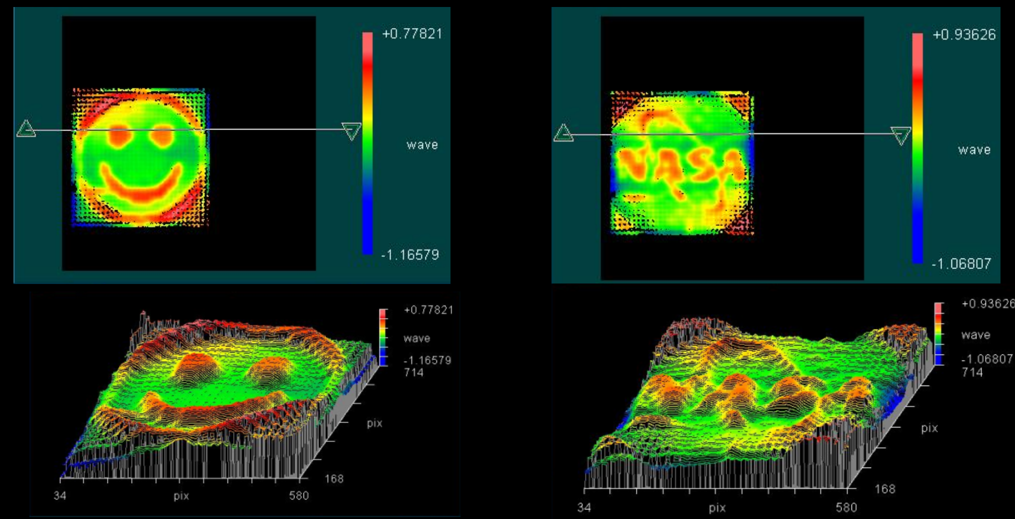


- Made by Axsys, diamond-turned $CF_2$, 16mm active diameter
- Post-apodizer (concentric-ring shaped pupil) made by JPL's Microdevices laboratory, aluminum on glass

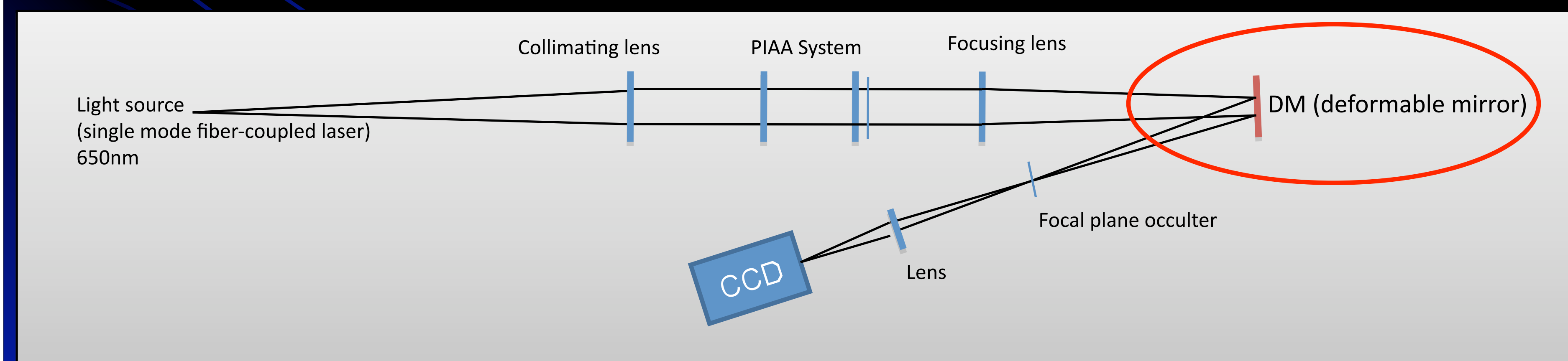


# MEMS Deformable Mirror

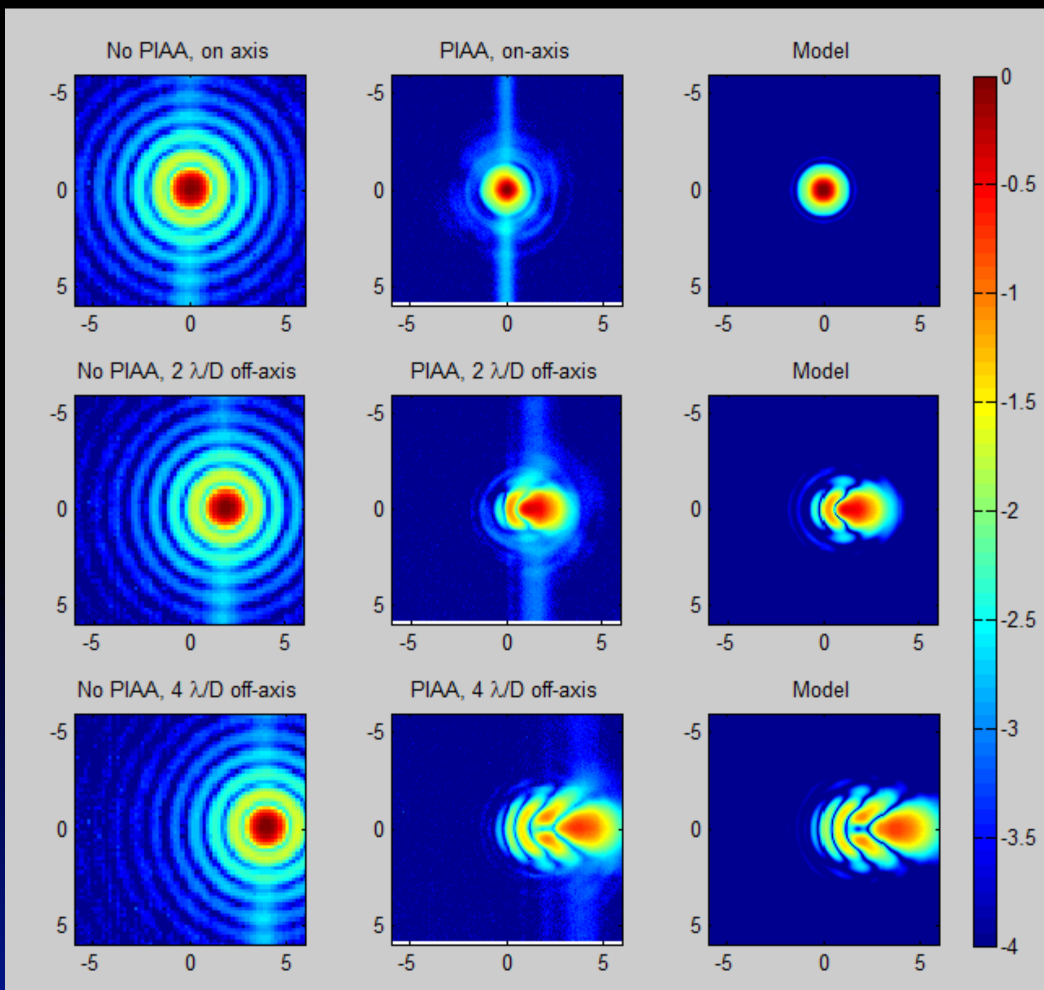


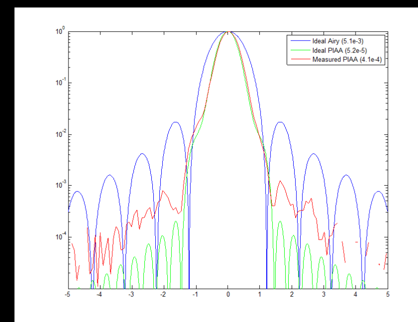




- Made by Boston Micromachines, 32x32 actuators, 10mm active area
- Strong motivation for small MEMS DMs: for small telescopes, small DM size may be necessary to keep instrument size reasonable

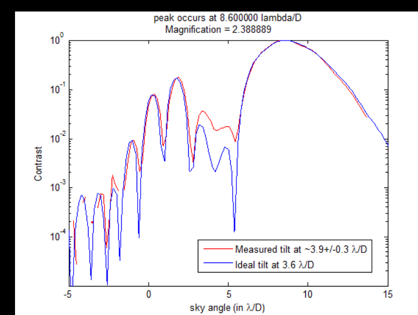


# Initial validation of hardware, models, and IWA

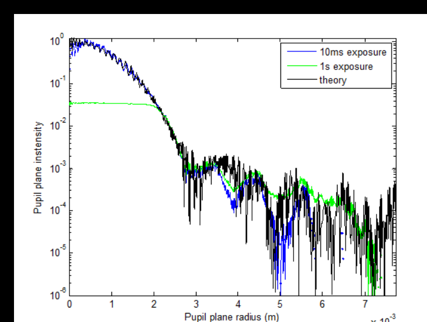


on-axis slices

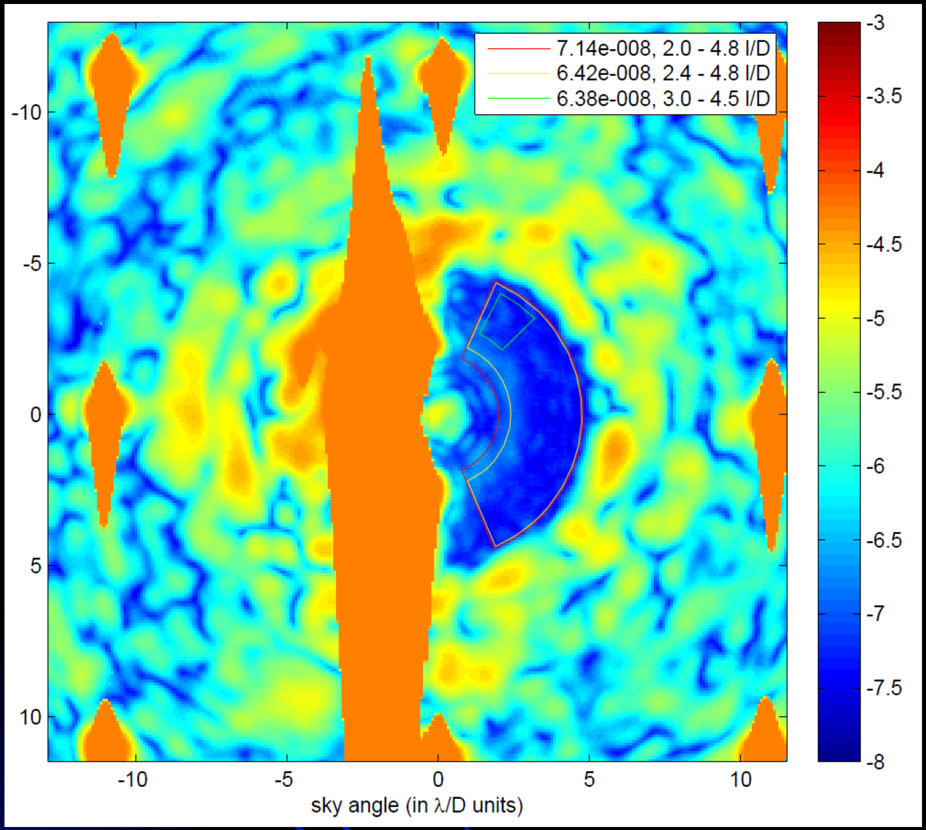



off-axis slices




DM-plane slices

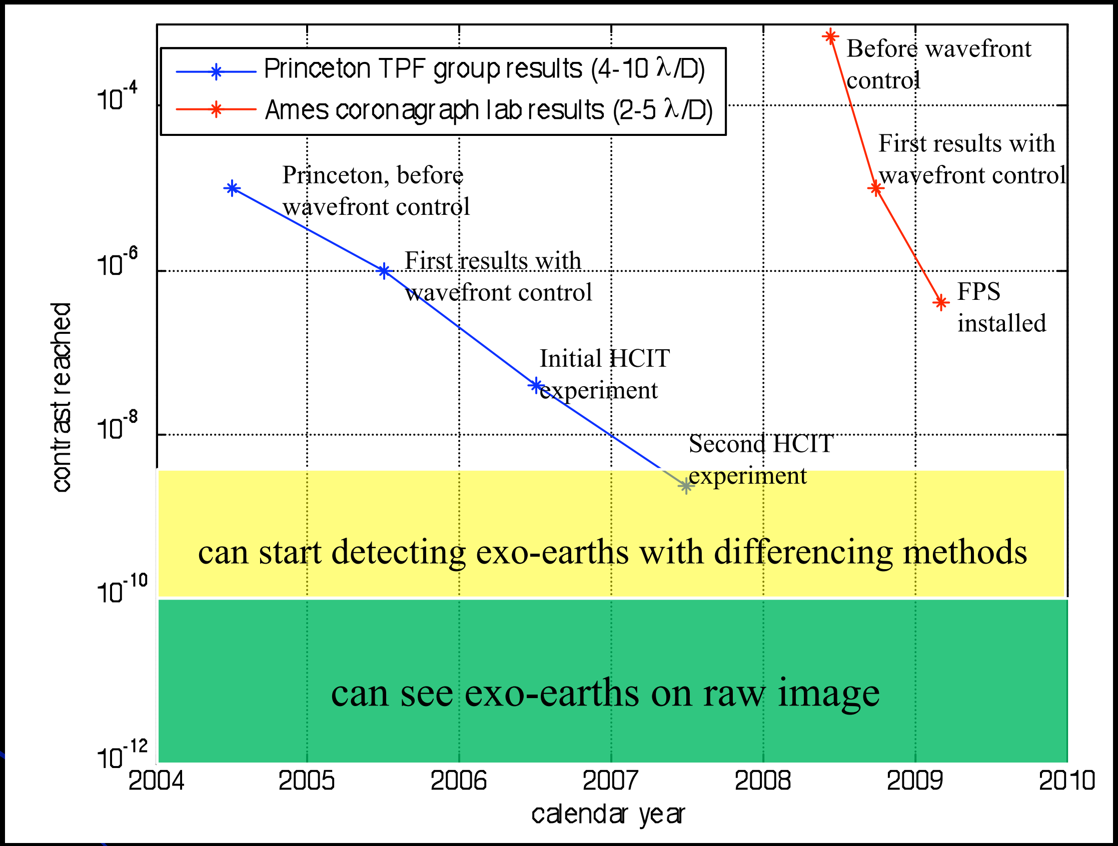
# Contrast results




7e-8 from 2.0 to 4.8 λ/D

- Wavefront control algorithms (both based on image-plane sensing through DM diversity):
  - Variant of classical speckle nulling (Trauger and Burrows)
    - Based on targeting and removing individual speckles
    - Many speckles at a time
    - For each speckle, scan not only the phase, but also the amplitude of corresponding ripples on DM
    - Slow (100s of iterations, hours), but does not require detailed system model
  - "Classical" Electric Field Conjugation (Give'on et. al.)
    - Estimates and corrects the entire dark zone on each iteration
    - Fast (minutes), but requires a precise system model

# Contrast Moore's law?




- Shaped pupil coronagraph generated contrast progress of about 20 per year
- Better funding (and prior experience) are the reasons for faster progress at Ames

# Conclusions

- PECO mission can potentially image exo-Earths this decade
- Technology development on the PIAA coronagraph is proceeding at a new lab at NASA Ames and JPL's HCIT.
- State of the art coronagraph performance at 2 $\lambda$/D : 7e-8

Earth, as seen by Voyager 1 at a distance of 4 billion miles.

# Backup slides

# Limiting factors

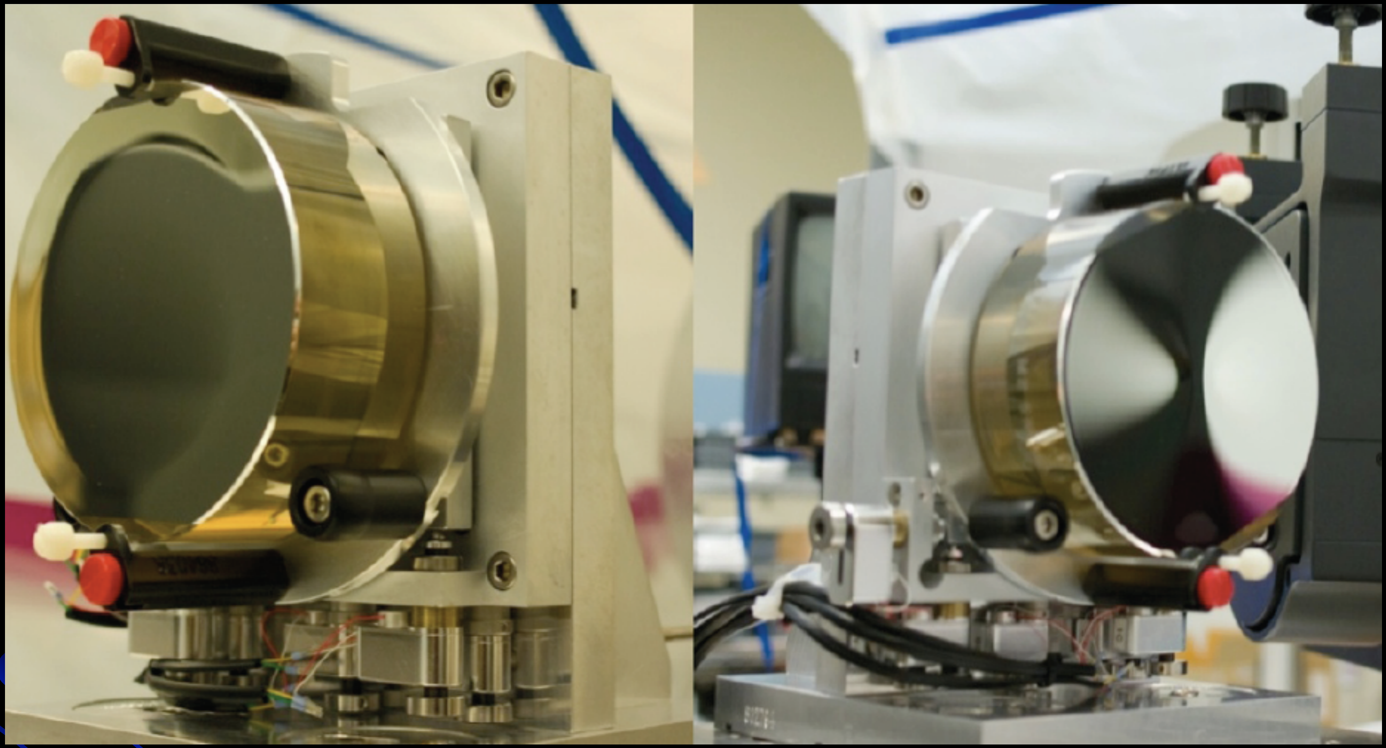
- Major limiting factors in the past:
  - **CCD artifacts (scattering off microlenses, CCD circuitry and shutter)**
    - Eliminated by introducing a focal plane stop
  - **Ghosts from transmissive elements**
    - Eliminated by a long-coherence-length laser
  - Alignment, baffling, system model, air currents

- Current known limiting factors
  - Polarization effects
    - Starting to control with polarizers

- Expected future limiting factors
  - Stability (1e-8)
  - DM voltage level quantization (1e-9 to 1e-8)

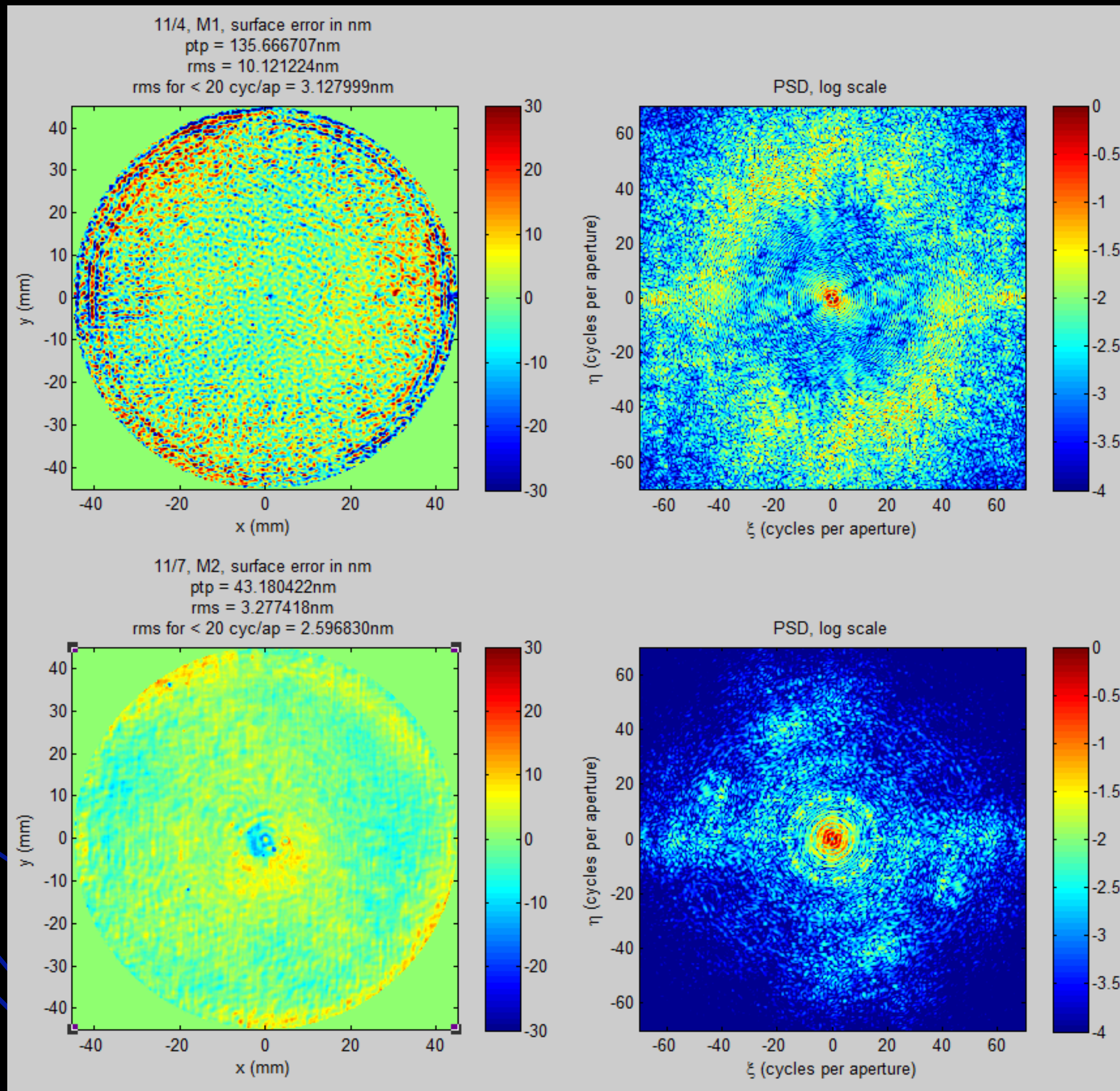
- **Solving limiting factors seems to proceed at a predictable rate (2x improvement in contrast every 6 weeks), as long as funding persists**

# New PIAA mirrors manufactured



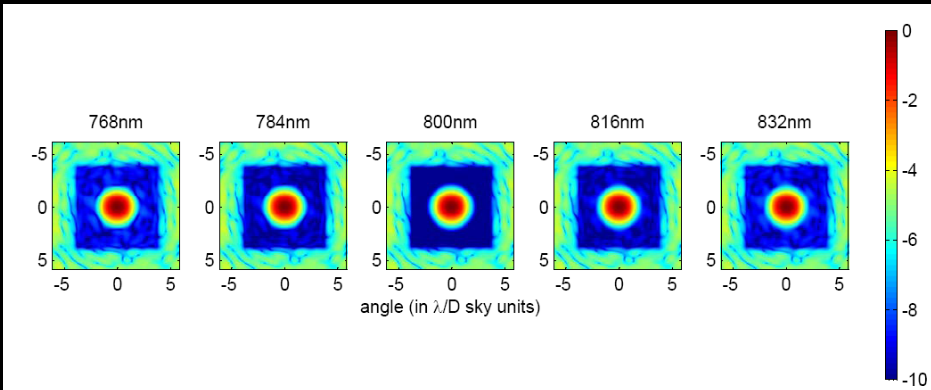
- Made by Tinsley
- Gen2: Better achromatic design, better surface accuracy than gen1 mirrors
- Currently being tested at HCIT

# Wavefront quality




- Surface figure spec was only for spatial frequencies < 20 cycles per aperture
- That left mid-spatial frequency errors high
- We now know though simulations that these errors can hurt us

# Modeling of gen2 mirrors




- Fast but approximate model confirmed by higher fidelity ones (Amir Give'on and Laurent Pueyo)
- Predicts that current Tinsley mirrors will get to no better than 1e-9
- Limited by chromaticity of frequency folding of mid-spatial frequency errors
- Different WFC architectures don't help much
- Mirrors can be smoothed by a factor of 2, bringing theoretically possible contrast to 1e-10
- Modeling of PIAA is mature, but accuracy of fast approximate models not well quantified