Review of Coronagraphic Laboratory Results

N. Jeremy Kasdin
Princeton University

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What I'm going to try and do . . .

- Give a very brief summary/overview of activities in testing coronagraphs for space and ground
- Put the results in context and how they support a pathway to flight
- Highlight the limitations of our experiments and the hard problems everyone is tackling
- Give you a flavor for the diversity of approaches being pursued and implementation issues affecting them
- Get you thinking about the hard questions and how close (or far) we are to a space ready system

Caveats . . .

- By its nature, little detail and explanation
- Not a comparison of methods and coronagraph performance
- Not exhaustive
- Focused on measured results; extrapolations based on future tests not discussed
- Necessarily a snapshot in time

Acknowledgements*

- Olivier Guyon, Subaru Telescope, NAOJ
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- Keigo Enya, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA)
- Rus Belikov, Princeton University

*Any errors, omissions, misrepresentations, or blunders are solely my responsibility

Why Experimental Work?

Distributed effort across multiple institutions reflects measured and incremental approach

- Proof of concepts
- Learn what is difficult and where the surprises are
- Refine manufacturing and test capability
- Inspire new ideas and approaches
- Demonstrate feasibility for flight system

Goal: Demonstrate at least 10^10 contrast in a realistic lab setting with full, integrated flight like system.

Why Aren't We There Yet?

- Design Limitations
(e.g., chromaticity)

- Practical Limitations
(e.g., edge effects, polarization)

- Manufacturing Limitations
(e.g., mask precision, bandwidth, mirror accuracy)

- Algorithmic Limitations
(e.g., speckle nulling, amplitude correction)

- Experimental Limitations
(e.g., detector, thermal, vibration, vacuum)

Where Are We?

10^{0}

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-10}

Airy Function

Ideal Coronagraph (Monochromatic, All Designs)

Experimental Results of Uncorrected Coronagraph (no wavefront control)

Optical Vortex (Arizona)

PIAA (Subaru)

Lyot (HCIT), Shaped pupils (Princeton), FQPM, white

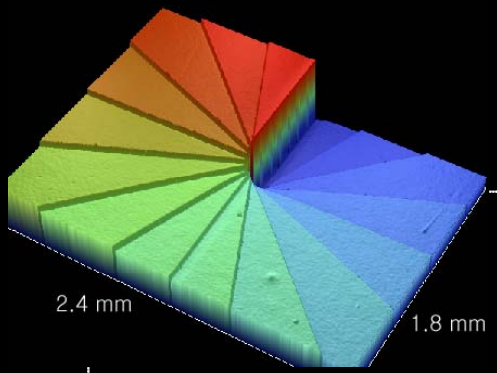
FQPM, mono (Paris)

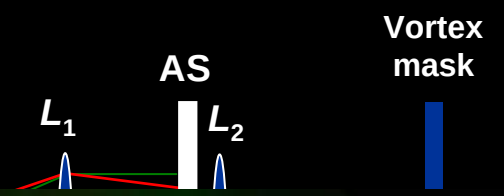
ExAO Testbed (S.C.), SPICA (NAOJ)
Occulter, white light (CU)

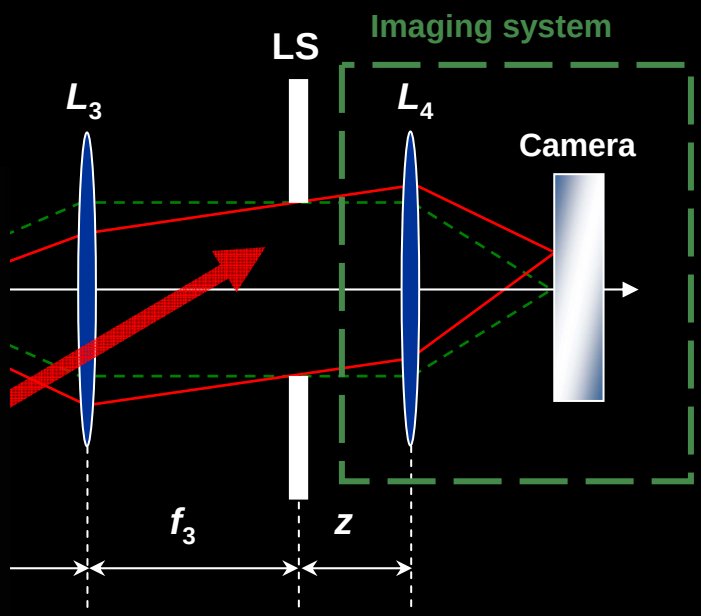
Limiting Factors:
iwa, camera range and readout noise, testbed limits, coronagraph manufacturing, *optical quality*

Optical Vortex Coronagraph

Star (green) -- Planet (red)



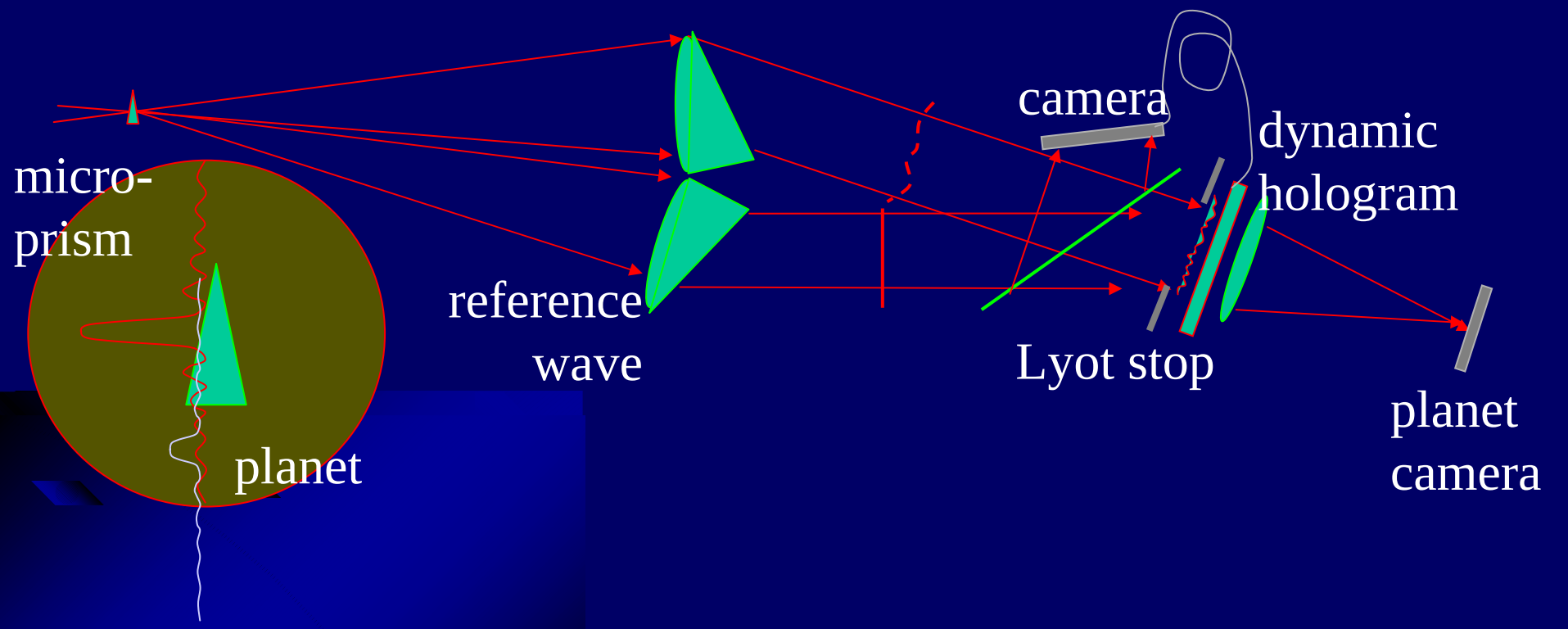




Nulling the residual starlight:

Hologram in a Lyot coronagraph

Labeyrie, 2004 in “Astronomy with High Contrast Imaging II” EAS pub. 12,.



- The focal occultor is a micro-prism…
- … separating the reference beam
- hologram subtracts starlight residue

Lab simulation

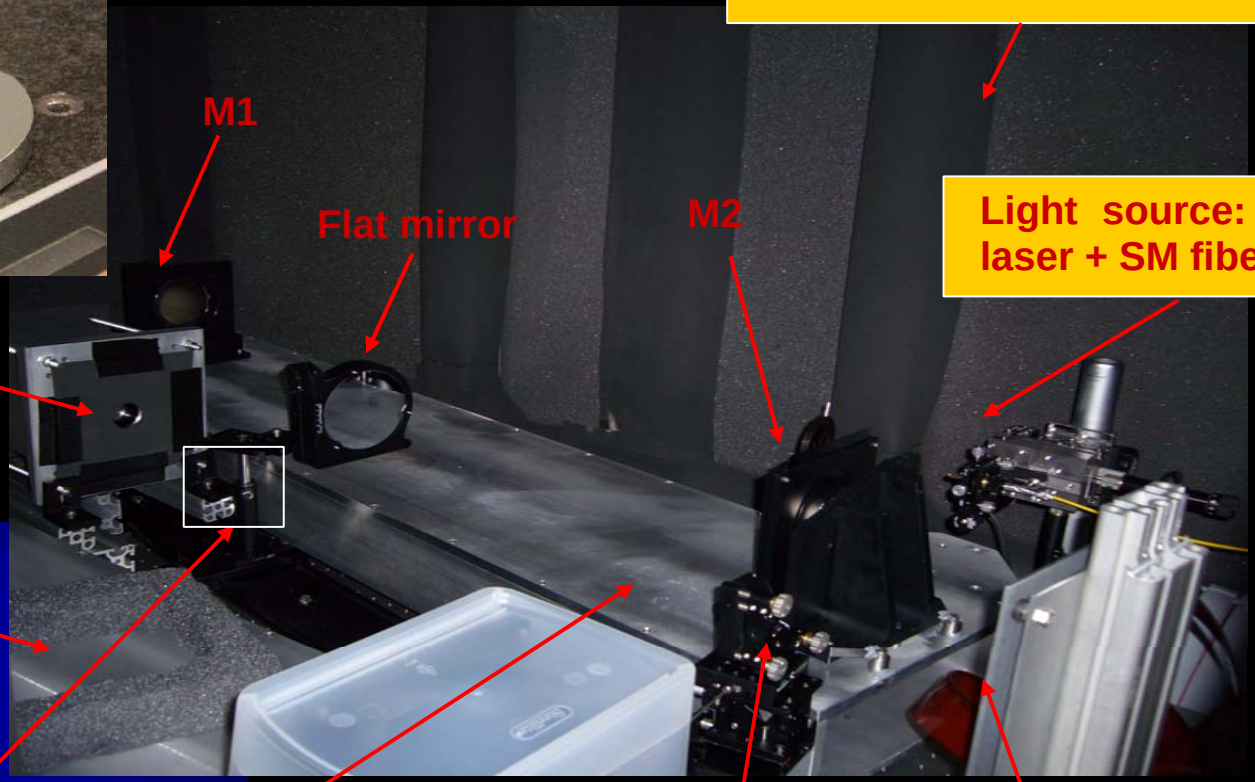
QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

- simple optics
- dynamic hologram material needed for full testing

QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

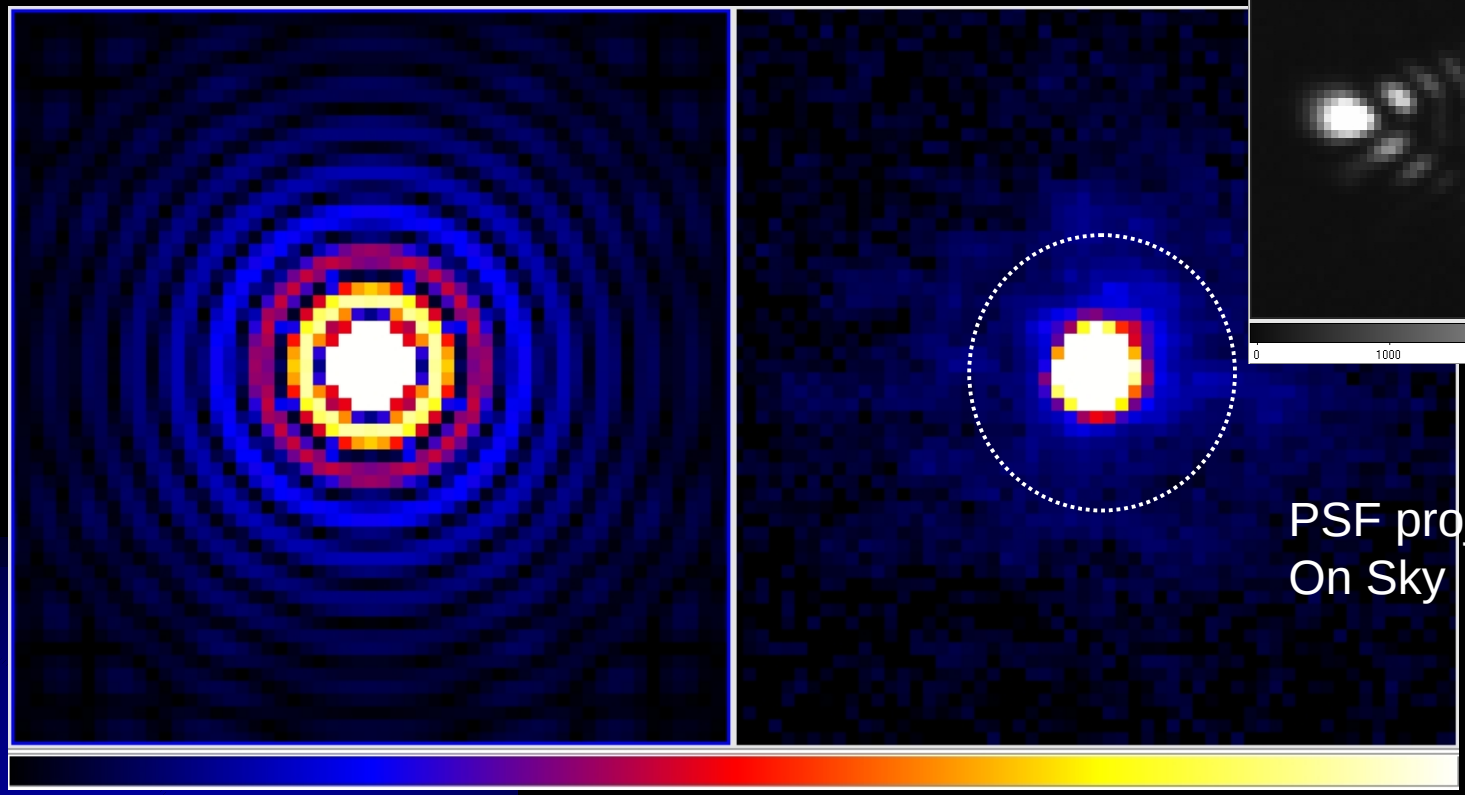
QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

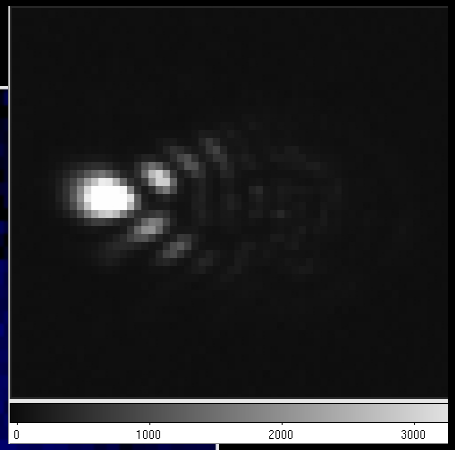
Pupil Mapping Lab *(Subaru Telescope)*



Wavefront control and a classical apodizer (binary mask) have been included in the experiment..

Uncorrected Pupil Remapped Image



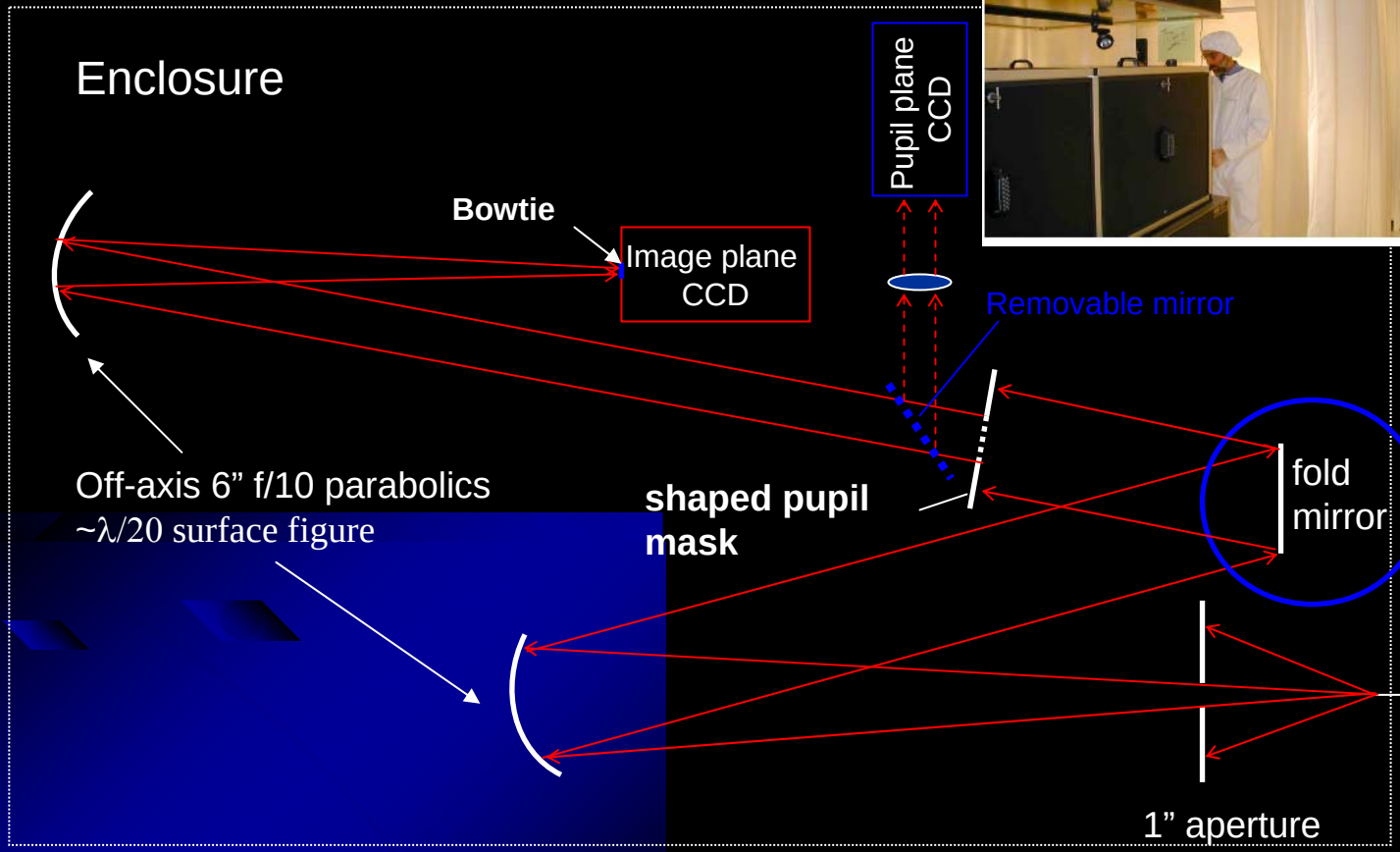


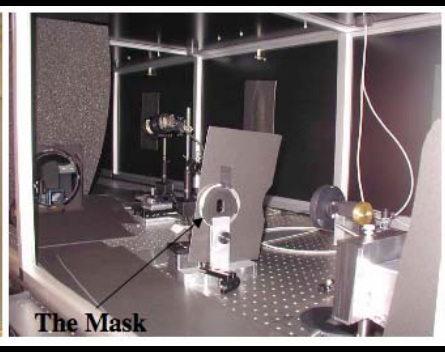
PSF projected
On Sky

Conventional image (computed)

PIAA image (obtained in the lab). White circle shows the area of the image that would be lost if we had done our apodization with a mask.

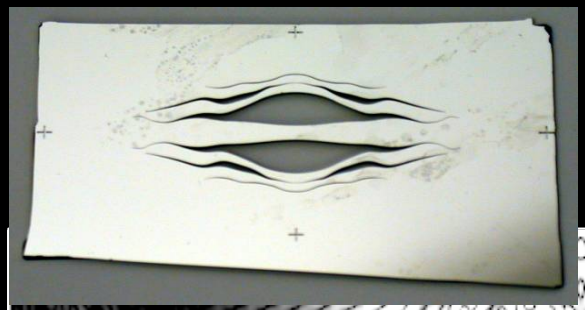
Shaped Pupil Testing (Princeton)

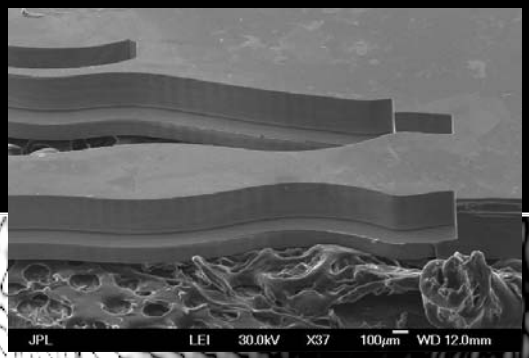




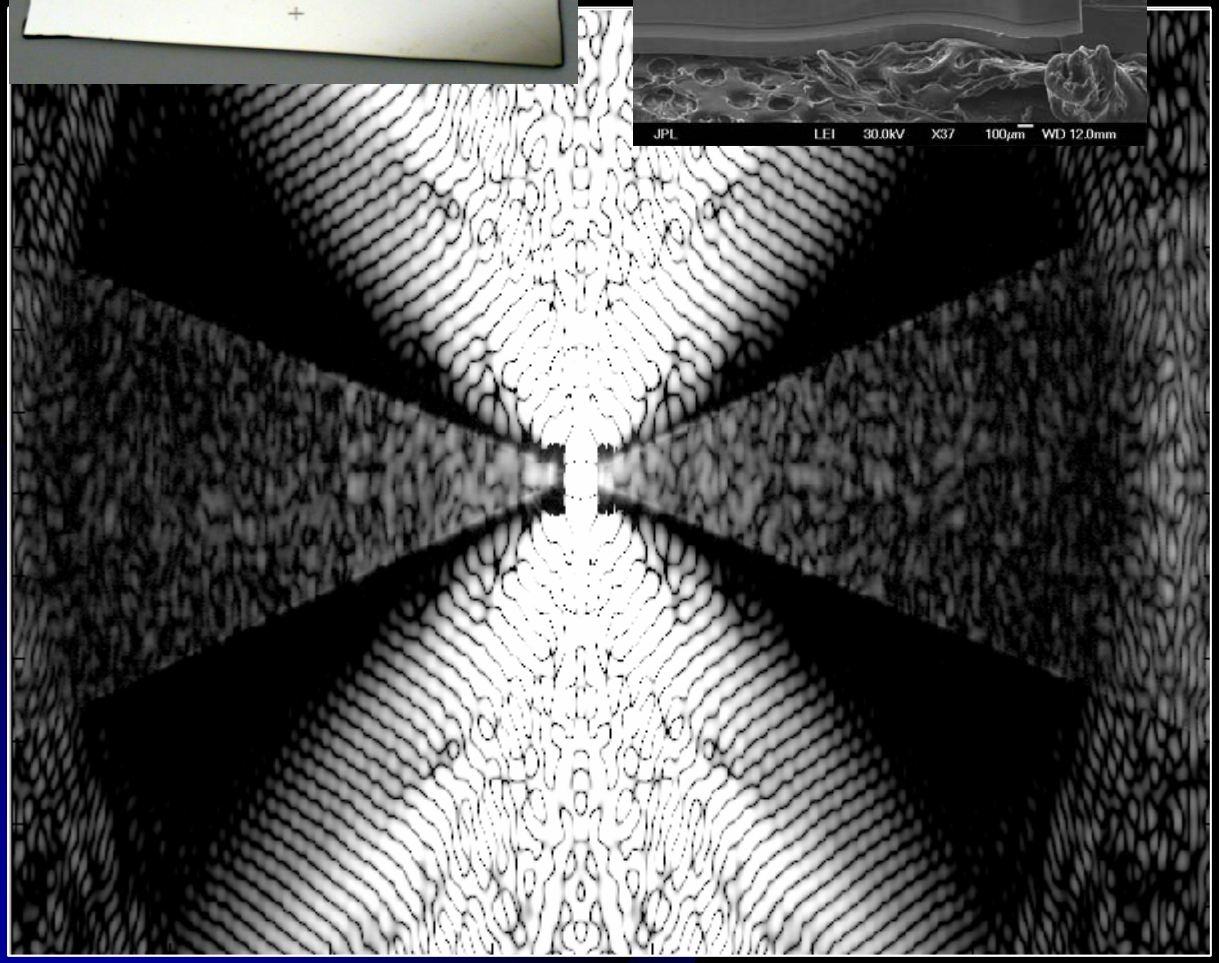
- DM is 11x11mm, so we used a 10mm shaped pupil
- Inserted a removable mirror to examine the pupil plane

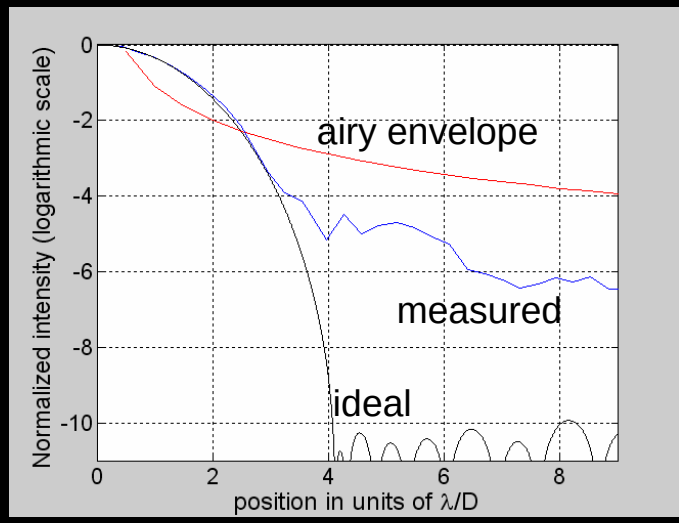
Contrast Measurement at 633nm





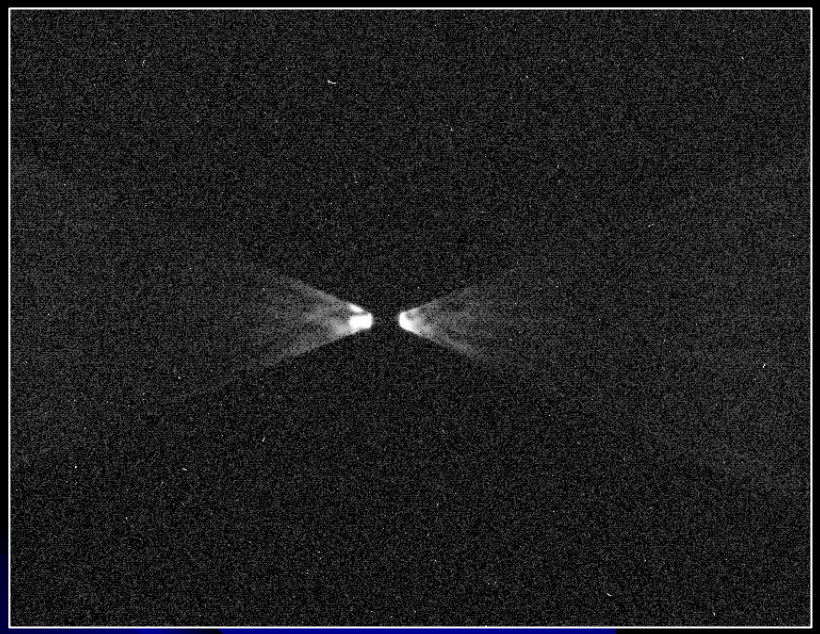
Pupils manufactured at JPL & NIST

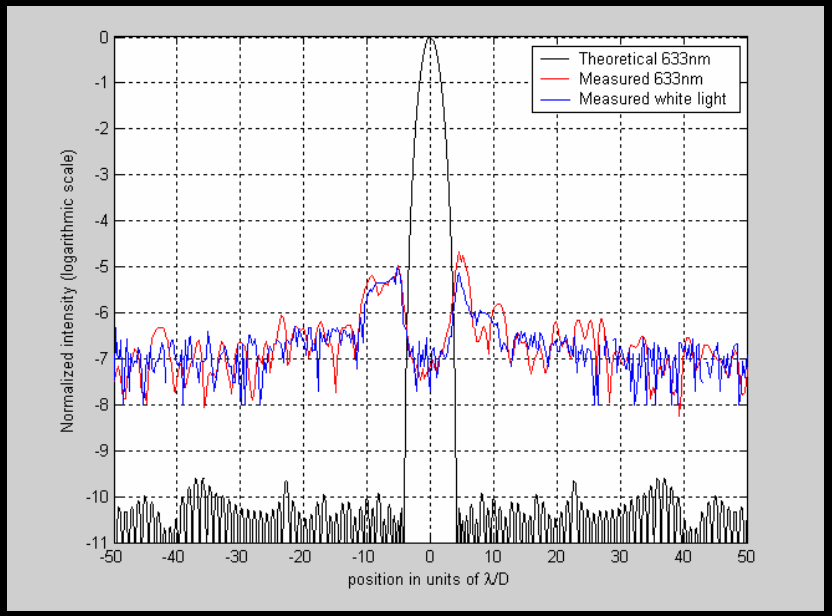




- Contrast:
  - ~10^{-5} @ 4 λ/D
  - <10^{-6} @ 7 λ/D

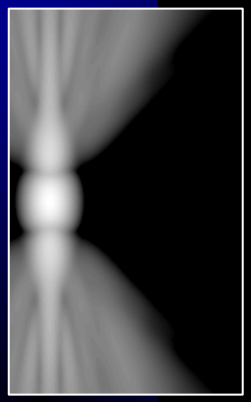
White Light Results





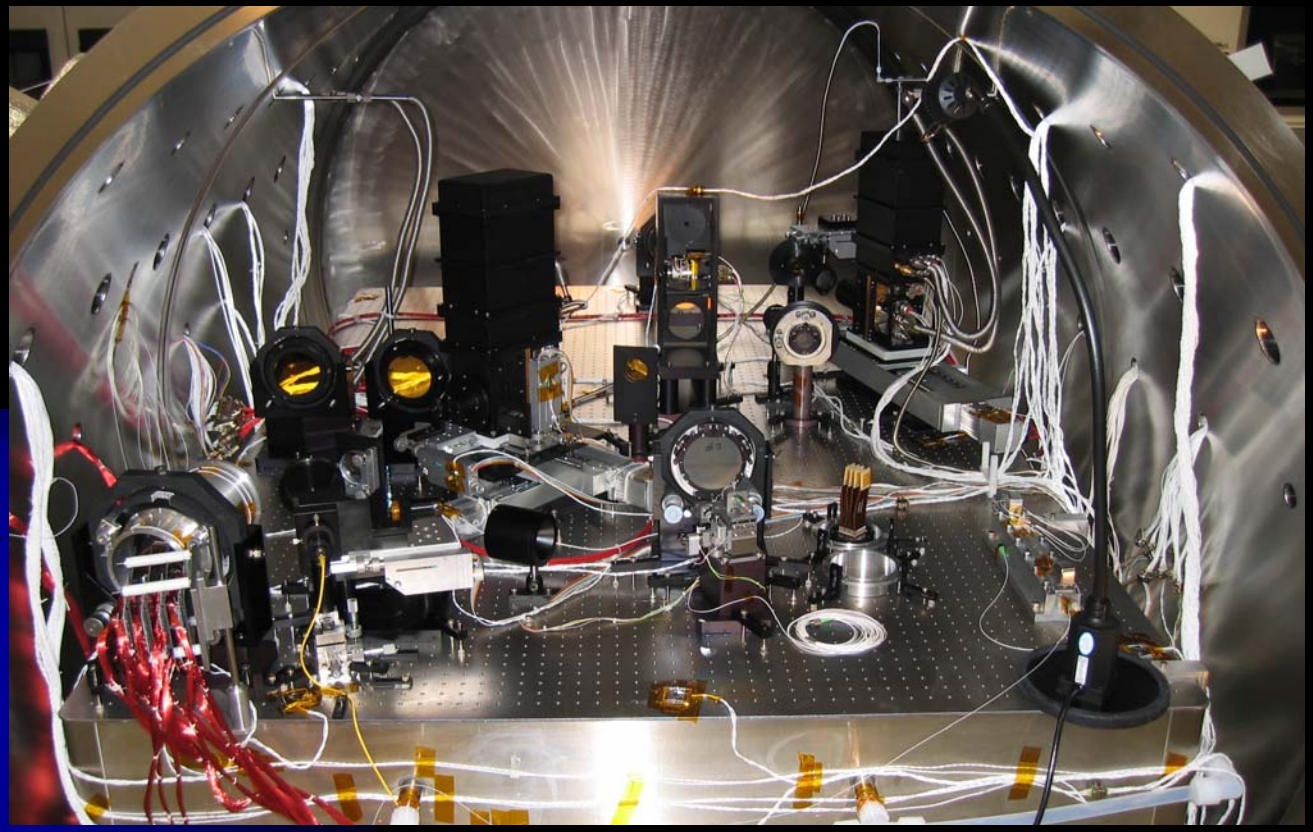
measured PSF

theoretical PSF



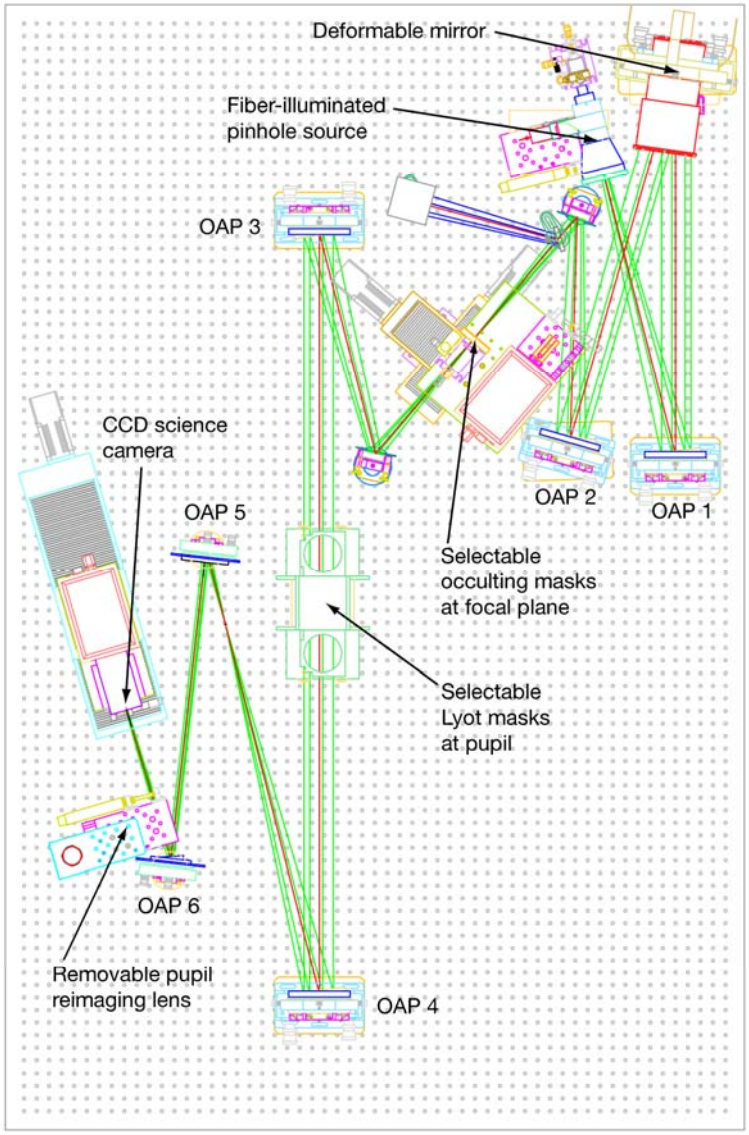
- Shaped Pupils are Broadband
- Contrast in white light is roughly the same as for monochromatic
- Speckle structure is similar to monochromatic case for low IWA

High Contrast Imaging Testbed (HCIT) provides experimental validation and guidance to models

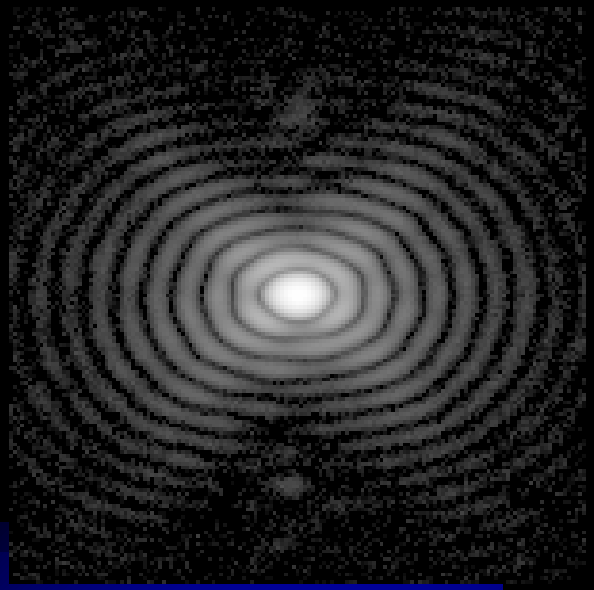


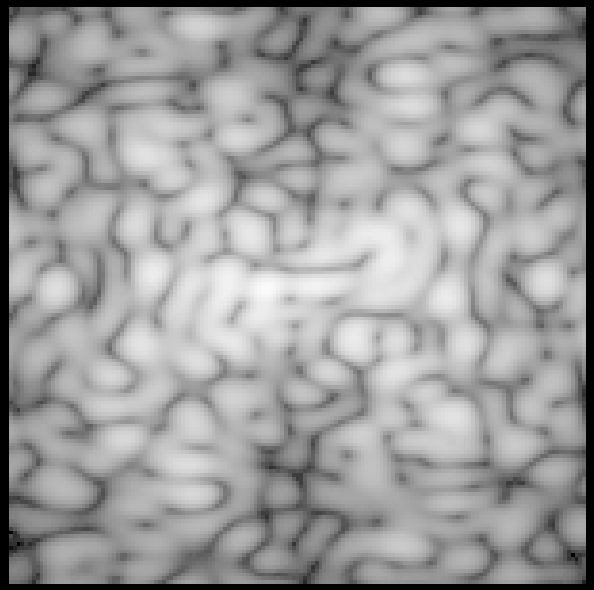
Testbed Layout

- Testbed is classical Lyot arrangement
  - 32x32 DM
    - Optics ready for 64x64 DM
  - Re-imaging back end for adequate sampling on CCD
- Monochromatic and broadband light sources
  - Broadband light generated with supercontinuum laser
  - Select bandpass using filters
    - 2%, 10%



HCIT Monochromatic Result



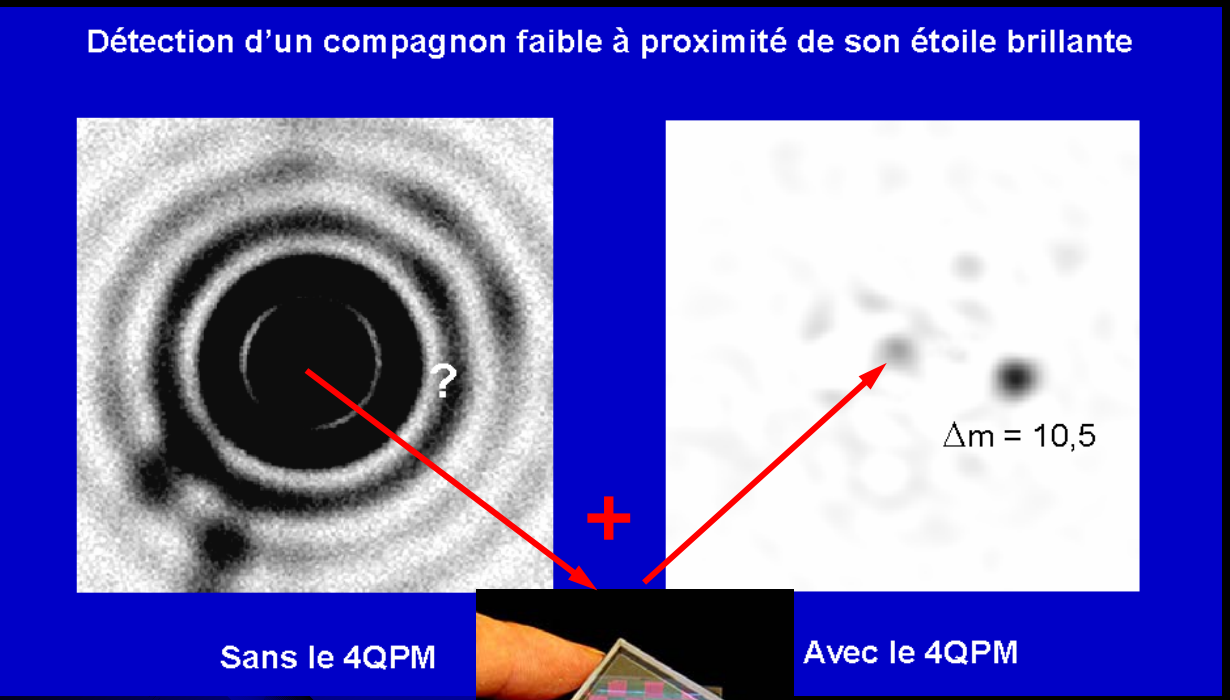


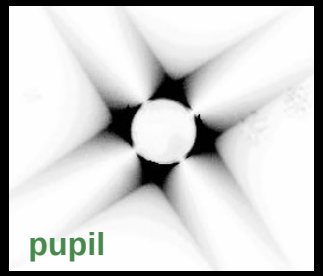
“planet” PSF: occulter moved aside, Lyot in place, narrowband diaode laserr

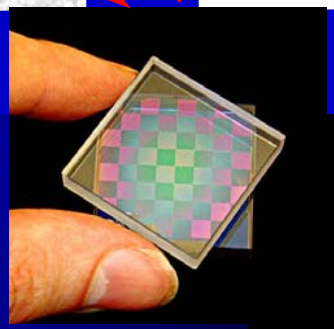
coronagraph PSF, DM “flat”, narrowband

Exquisite experimental design. Limited by optical quality!

Four Quadrant Phase Mask (LESIA)







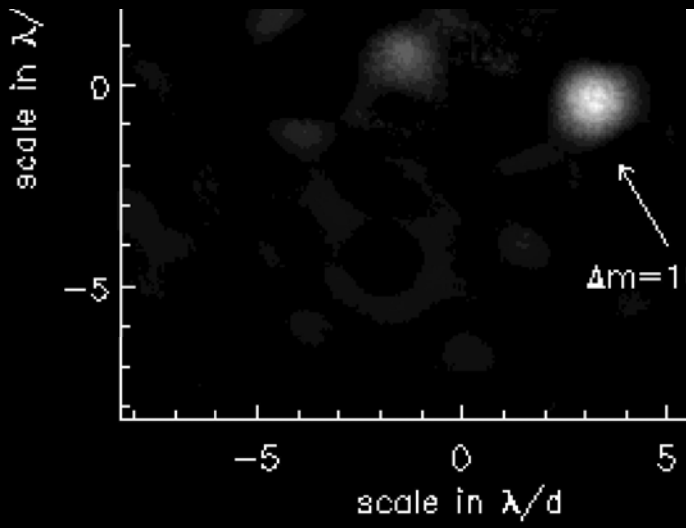
manufactured and characterized for :

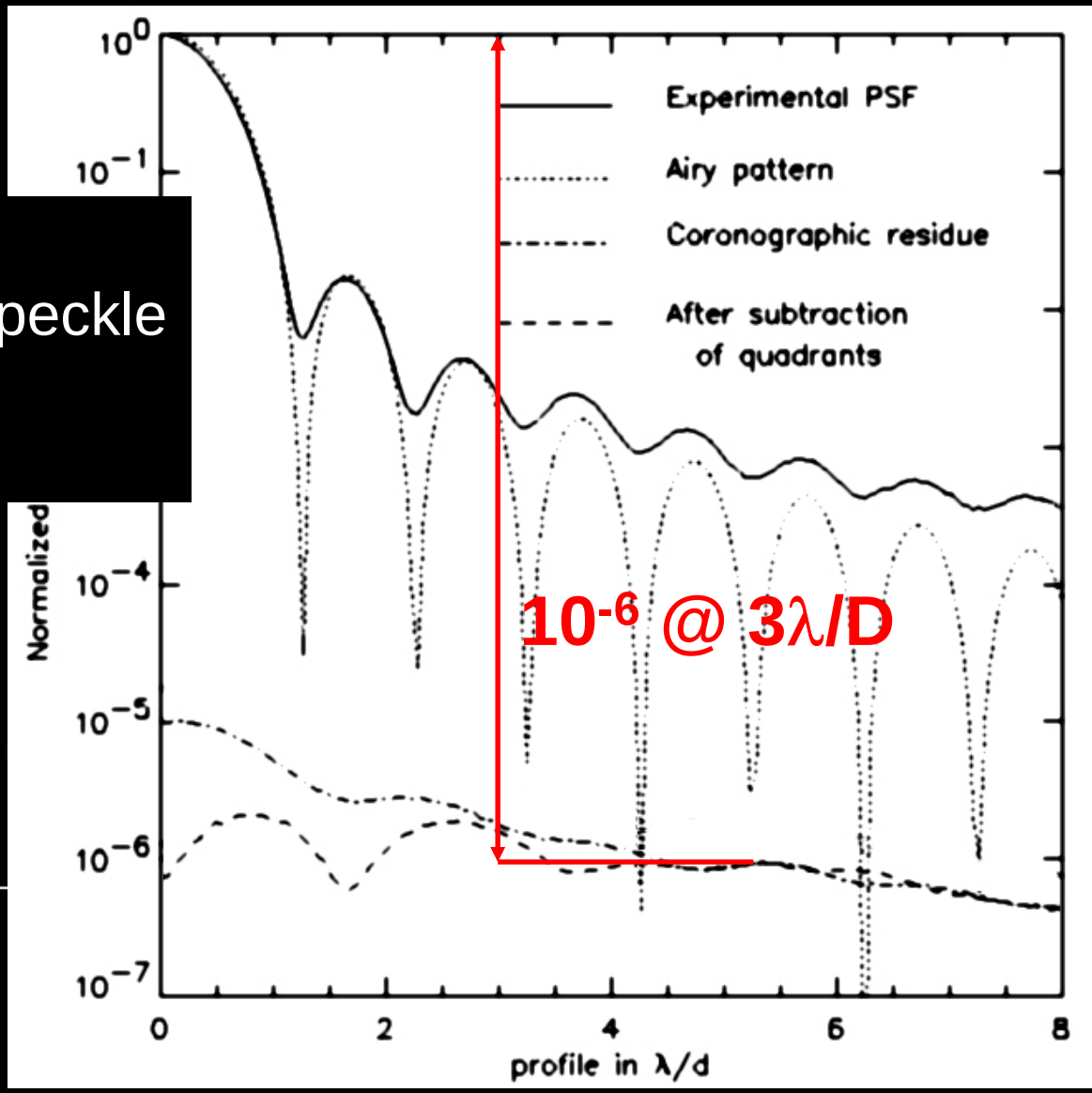
- Visible (laboratory R&D)
- Near IR (implemented on NACO/VLT)
- For mid IR (JWST/MIRI project)
- Near IR achromatic version (VLT/SPHERE project)

Rouan et al., 2000, PASP ; Riaud et al., 2001, PASP ; Riaud et al. 2003, PASP

FQPM Visible Lab Tests

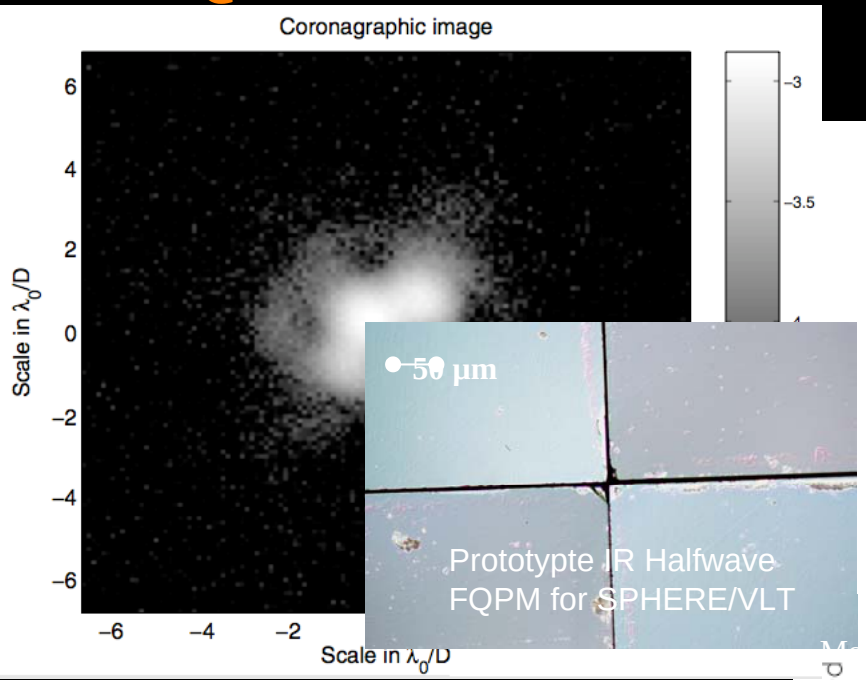
Limited by an ocean of speckle at the 10^{-6} level

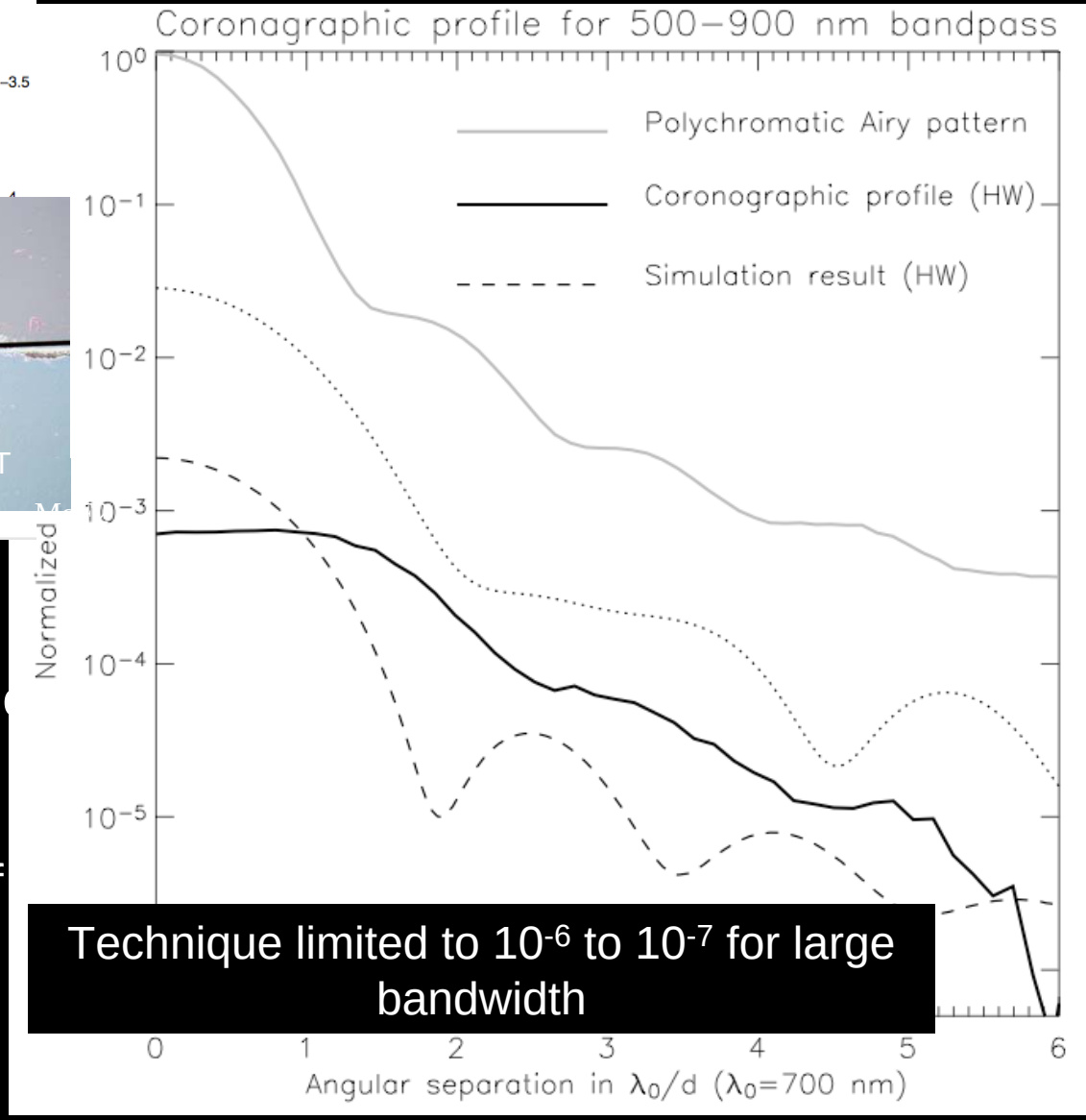




Riaud et al. 2003, PASP

FQPM - Visible Halfwave plate lab tests





Technique limited to 10^{-6} to 10^{-7} for large bandwidth

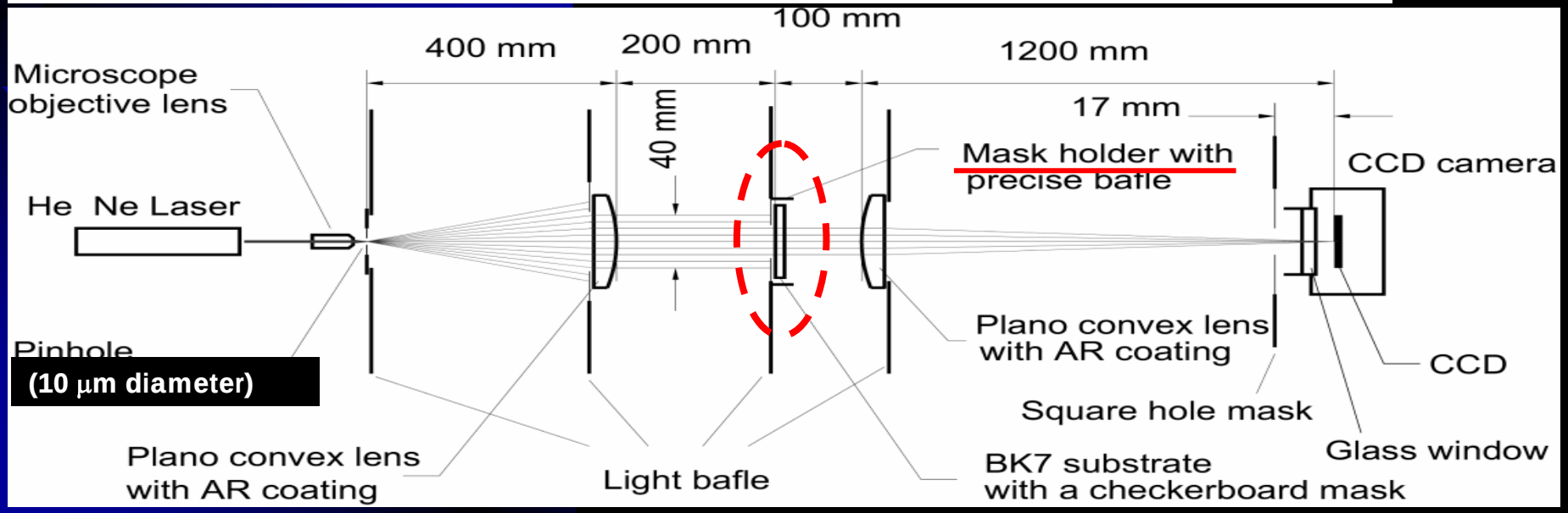
- Contrast 10^{-5} @ 4 λ/D for large bandwidth
- Expected contrast 10 to 100 times better with optimized half wave plate and R=5 to 20

Mawet et al, 2006

Shaped Pupils for SPICA (ISAS/JAXA)

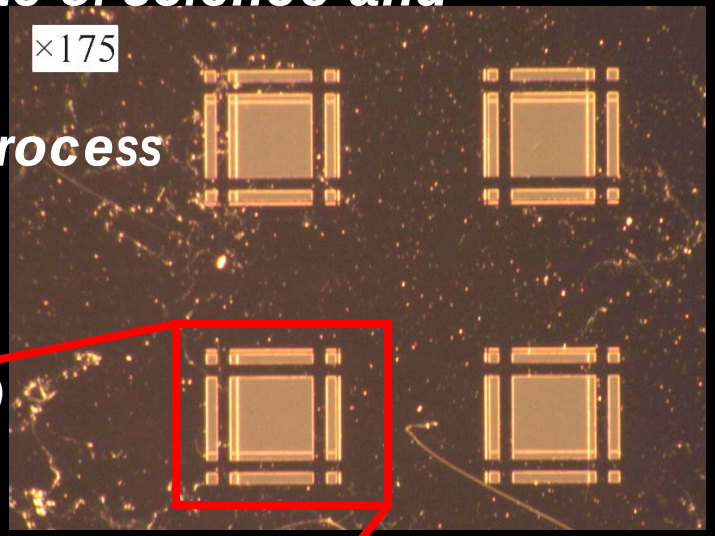
- **Conducted in ISAS**
- **Environment**
  - **Dark room**
  - **Air flow (on/off)**
  - **No temperature regulation**
- **Setup**
  - **Off-the-shelf optics** ~λ PtV, AR coating
  - **No AO system**
  - **Beam diameter: 2mm** (masks side 1.41mm) / **F# ~ 600**
  - **BITRAN cooled CCD camera** (2048×2048)

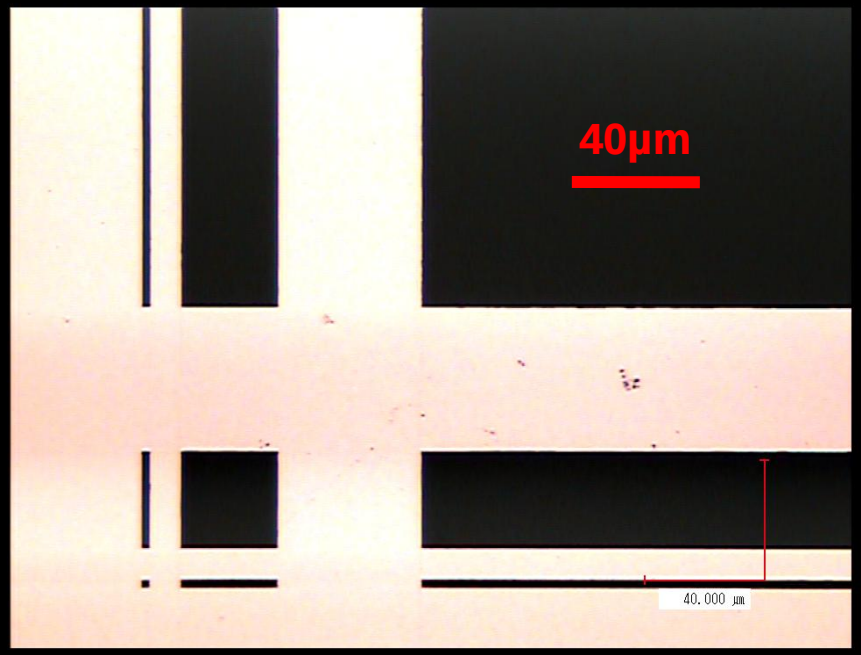
Enya, Tanaka, Abe, Nakagawa.
astro-ph/0609646

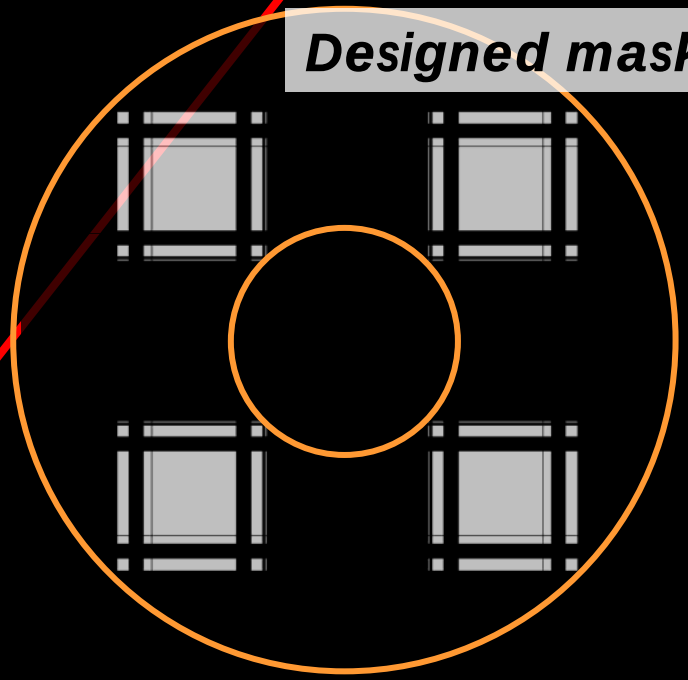


MANUFACTURING

- ***Manufactured at the Advanced Institute of Science and Technology*** *(AIST, Japan)*
- ***Electron beam patterning and lift-off process*** *(100nm aluminium)*
- ***BK7 substrates***
- ***1.41 mm side square*** *(2mm diameter pupil)*
- ***Mask1: IWA=7 / OWA=16 / Design Cont.=10^{-7}***

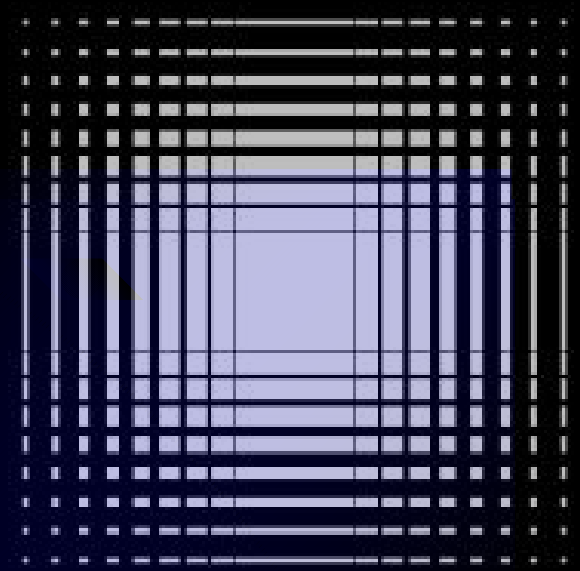






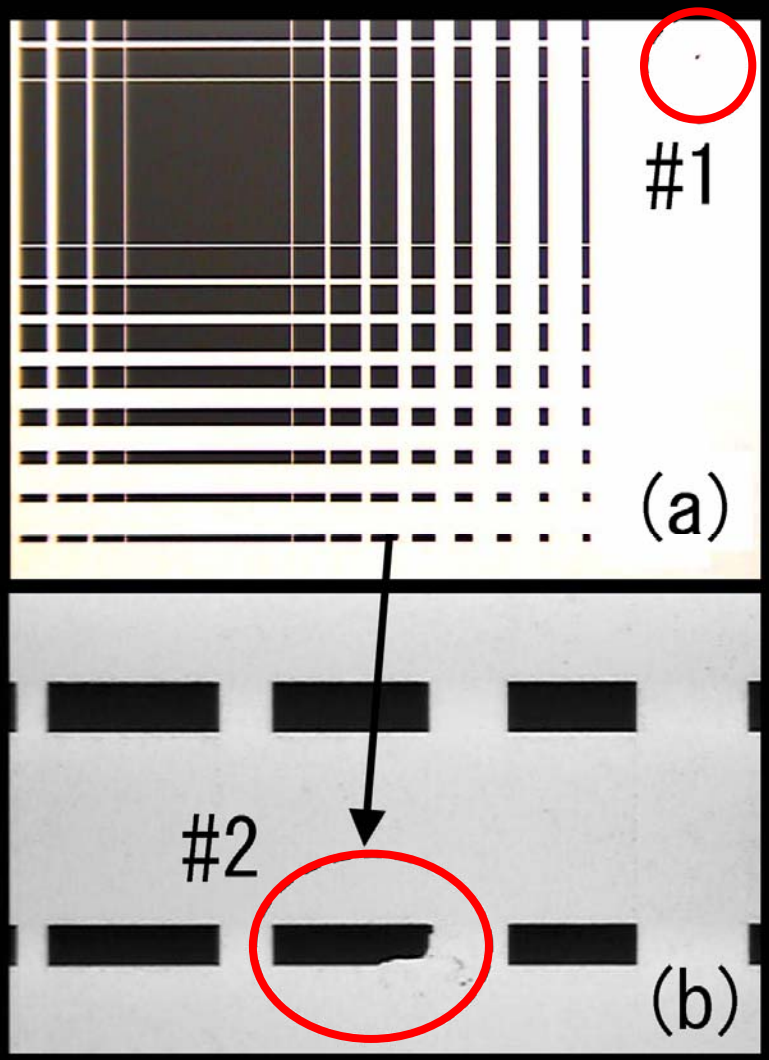
MANUFACTURING

- ***No central obstruction design***
- ***IWA=3 / OWA=30 / Design Cont.=10^{-7}***



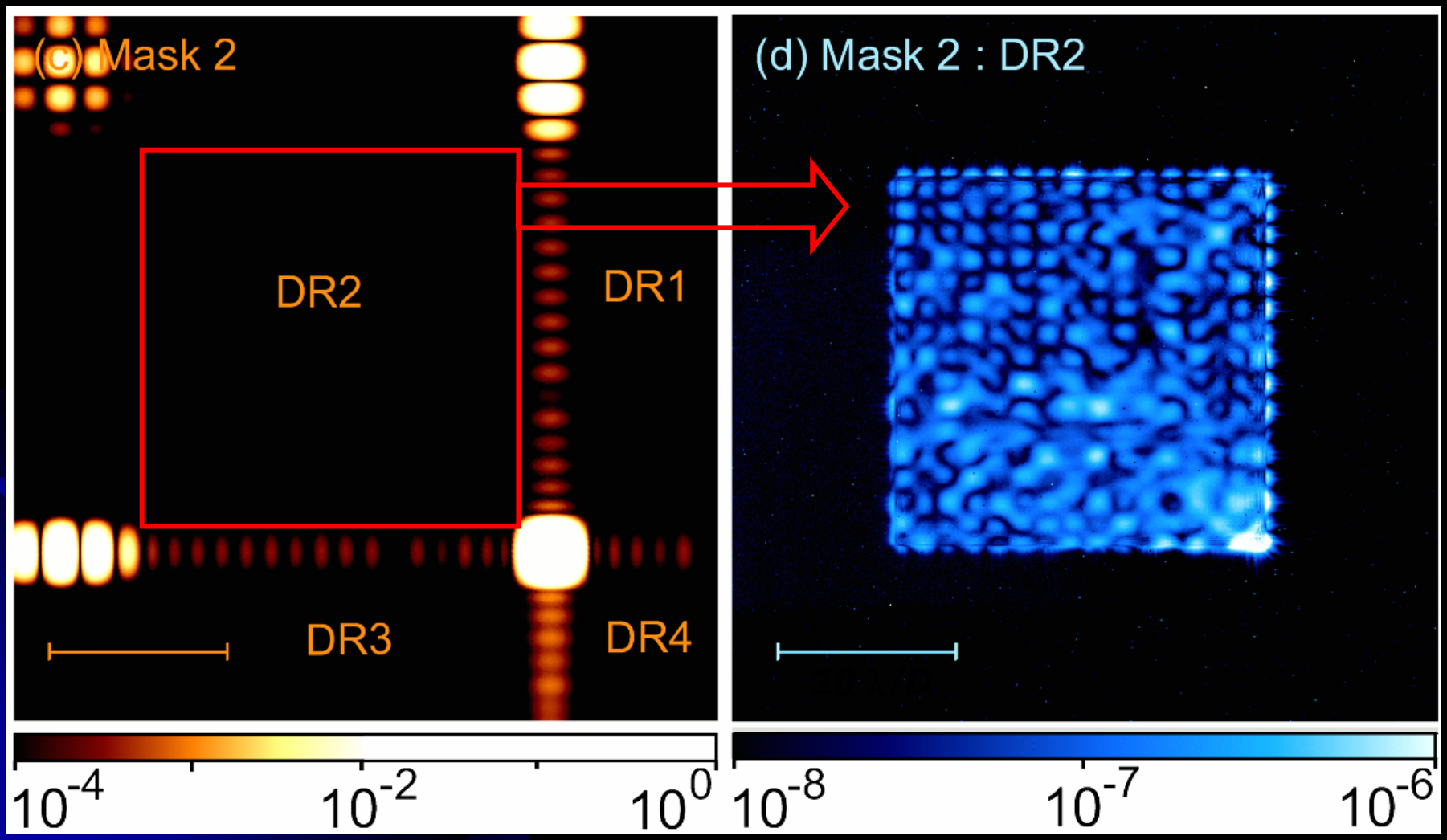
Mask defects

Mask2

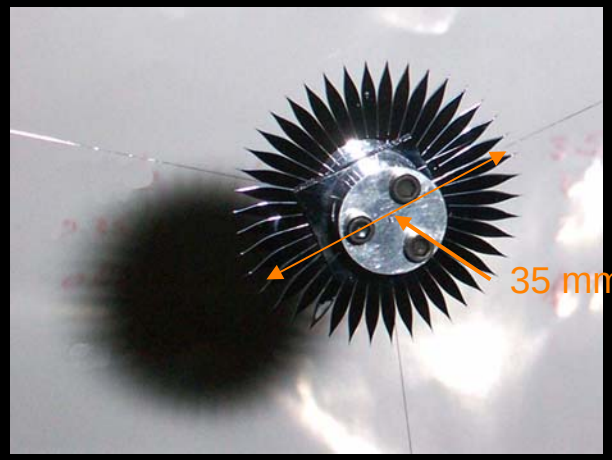


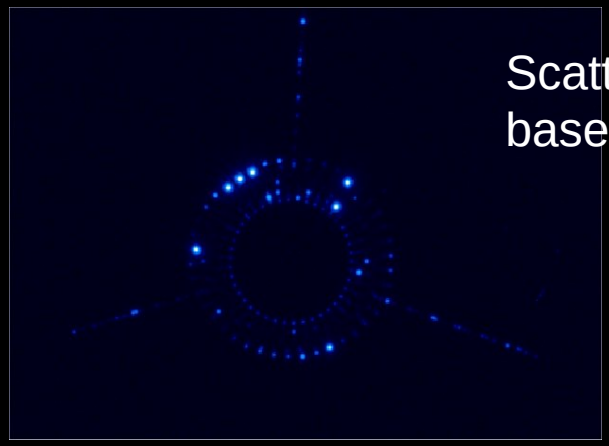
Uncorrected Performance

- **Mask2:** *IWA=**3** / OWA=**30** / Design Cont.=**10^{-7}** / Throughput=**24%***



Starshade Experiments (Colorado)

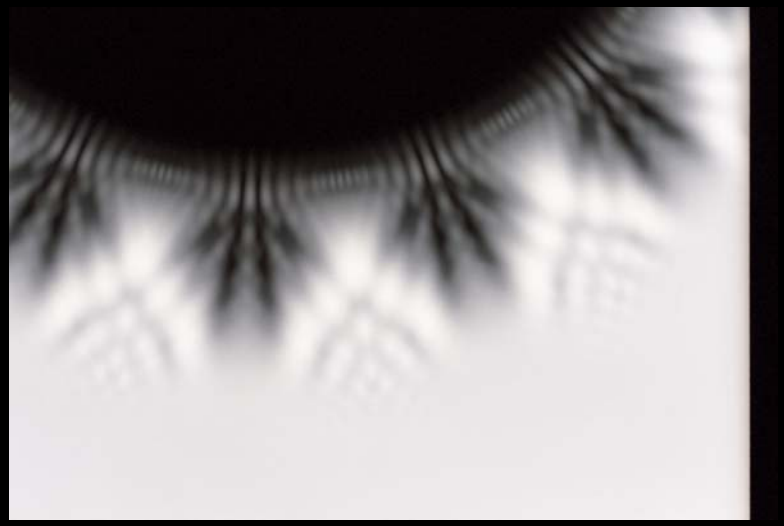




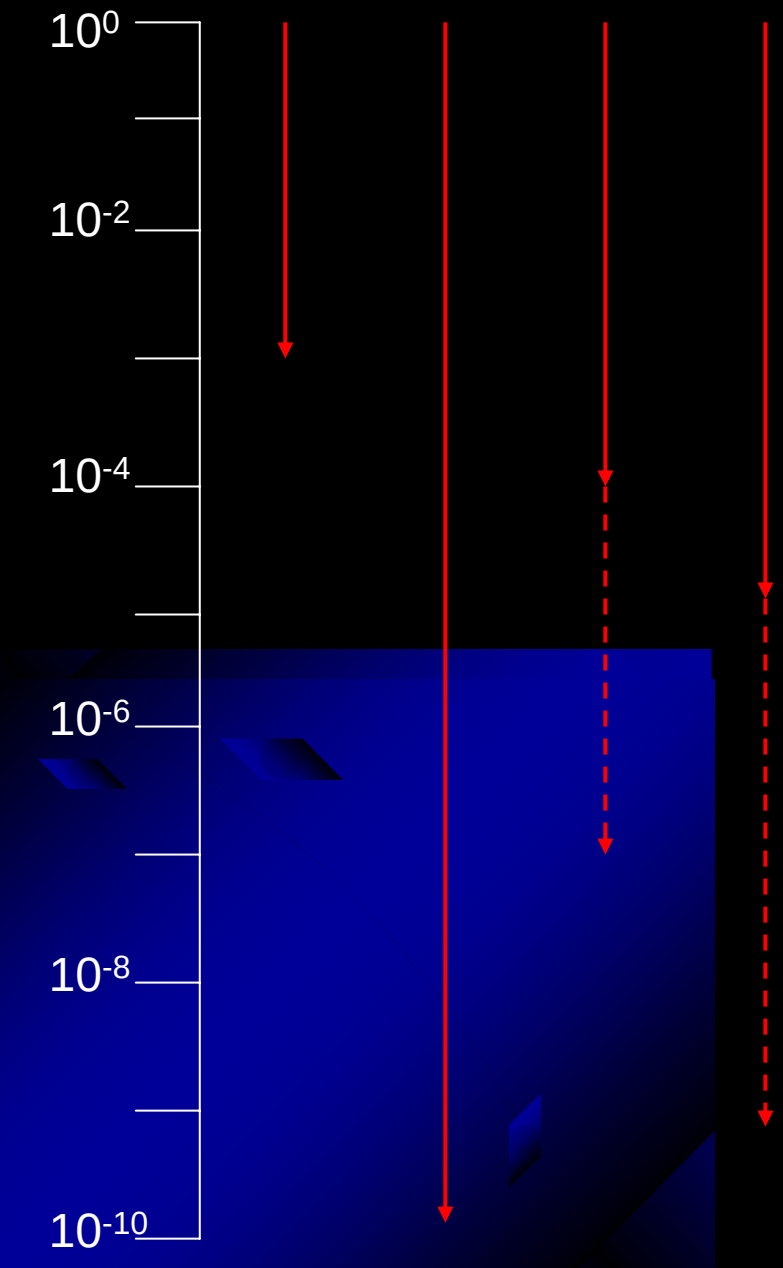
Scattered light from base and tips of petals

White light from heliostat illuminating 35 mm shade.

Average contrast in center of shadow of 5×10^{-7} broadband



Adding Wavefront Control



Experimental Results of
Corrected Coronagraph
(phase and amplitude control)

<u>Limiting Factors:</u>
Manufacturing limitations, electronics, algorithm limits, testbed limits (alignments, vacuum), DM quilting, amplitude errors

Shaped pupils (Princeton)
PIAA (Subaru), Visible Nuller, 15% band (JPL)

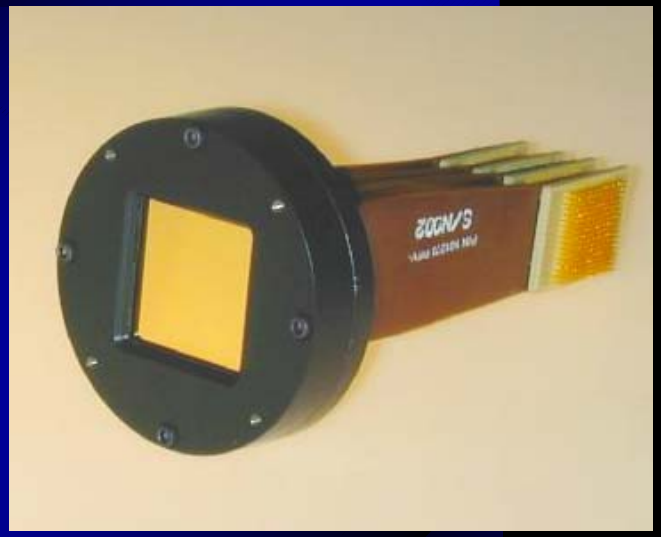
ExAO Testbed (S.C.), Visible Nuller, monochromatic (JPL)

Shaped Pupil (HCIT), Lyot, 10% bandwidth (HCIT)

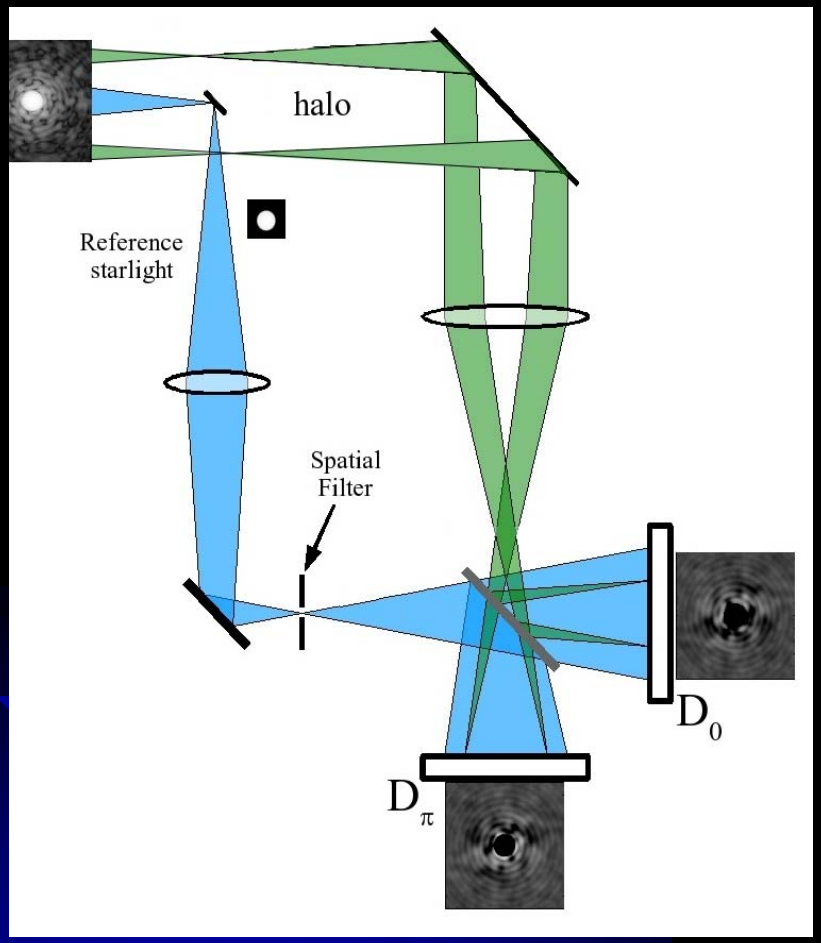
Lyot, monochromatic (HCIT)

Control Approaches / Algorithms

- Conventional AO (pupil based; non-common path errors)
- Speckle Nulling (iterative)
- Single Step (phase diversity, dark hole optimization)
- Interferometric (AHA)



Focal Plane Interferometer: FPI (Arizona)

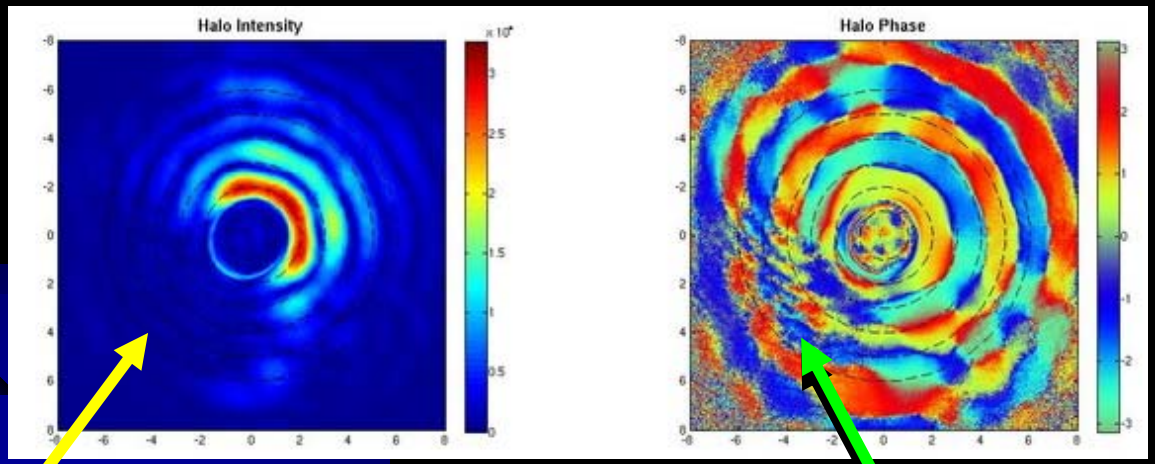


- **Uses discarded starlight**
- Core forms reference beam to probe halo.
- Halo processed as usual.
- Must capture both 0° and 180° phases for photon efficiency.
- **Gives an estimate of the halo phase from minimum number of photons.**
- **Allows measurement of halo phase in presence of bright incoherent background by using a much brighter reference beam.**

Using the FPI to drive a Pupil DM (PDM)

Using a simple speckle-steering algorithm, we used the FPI complex amplitude measurements to suppress the halo in closed loop.

Intensity Halo **Halo Phase re core**

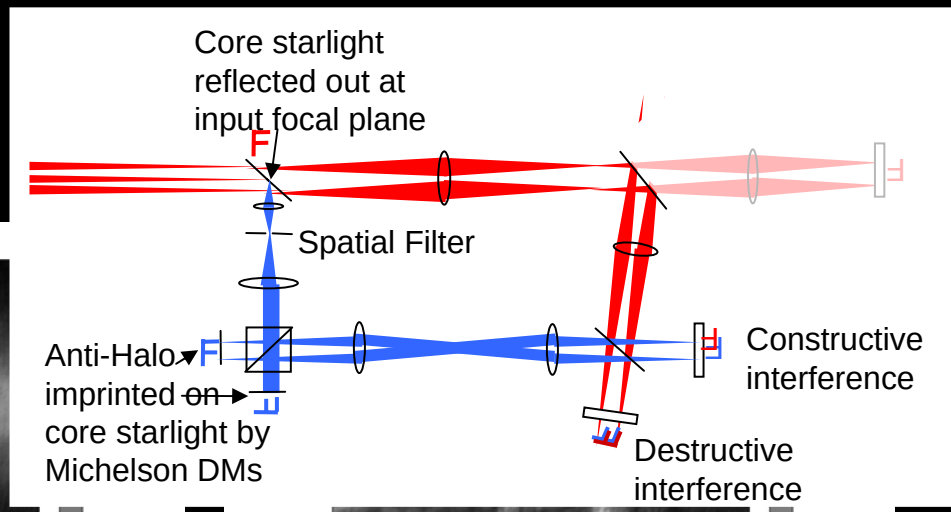


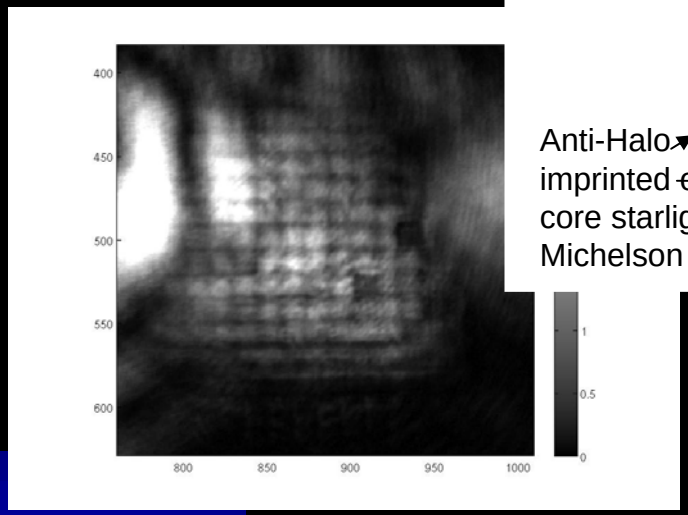
Suppressed 90° sector

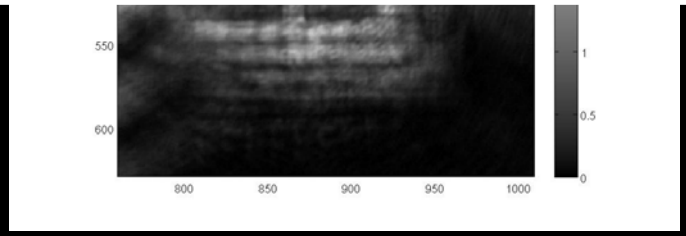
When fully suppressed, phase will become completely random. This simple system could have gone another 1-1.5 decades fainter.

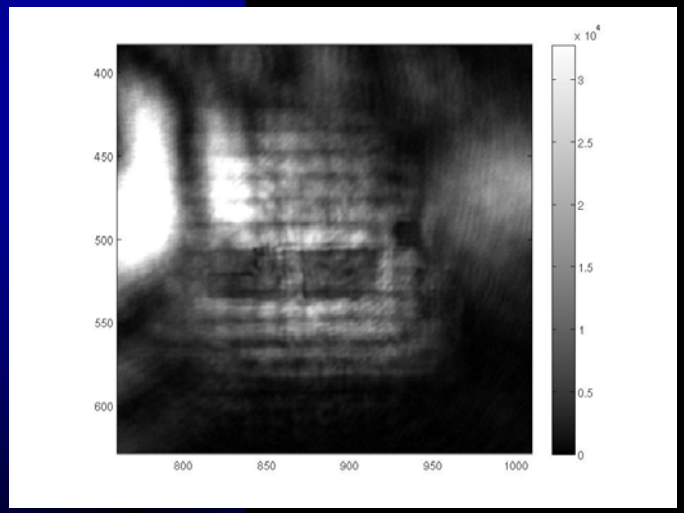
Anti-Halo Apodization for 360 degree Suppression - AHA

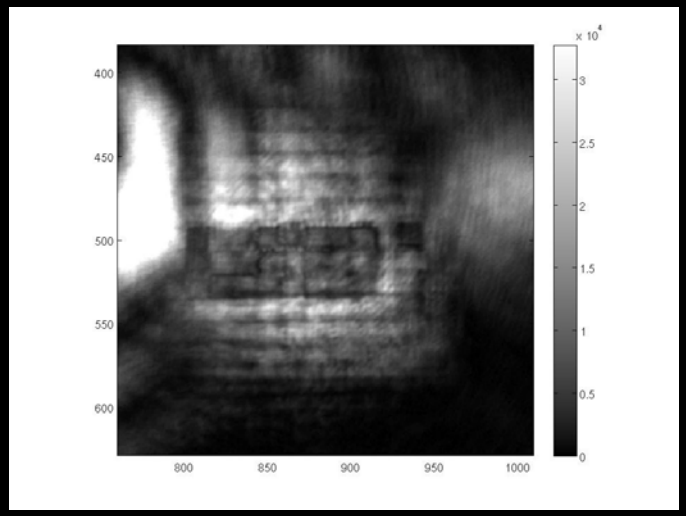
Use AHA complex spatial light modulator to directly imprint a detailed “anti-halo” which interferes destructively with the star's halo





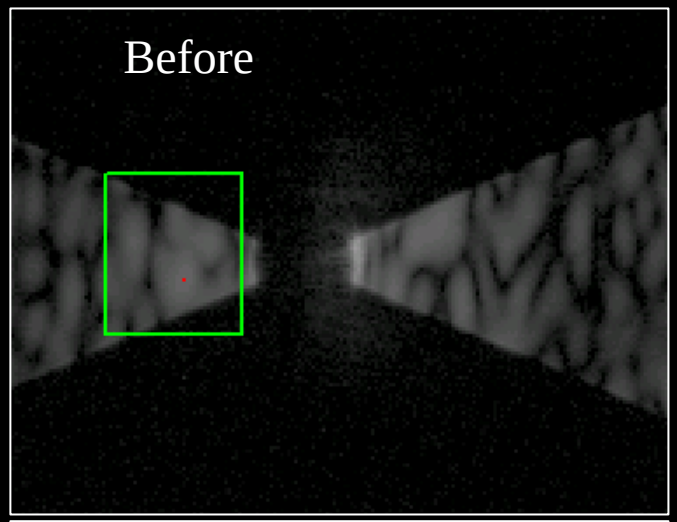


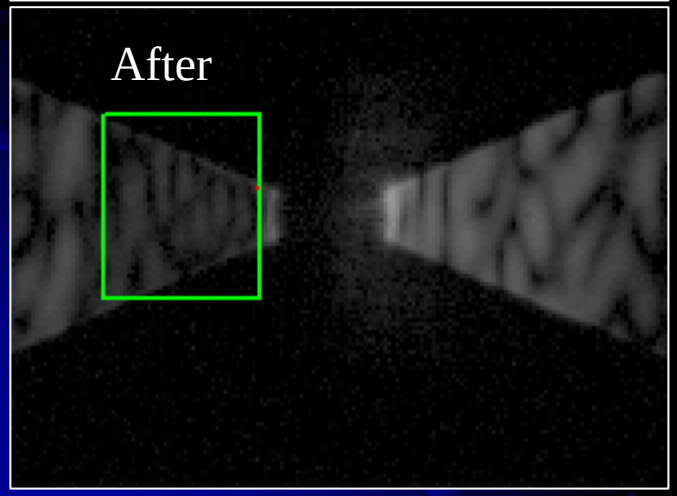


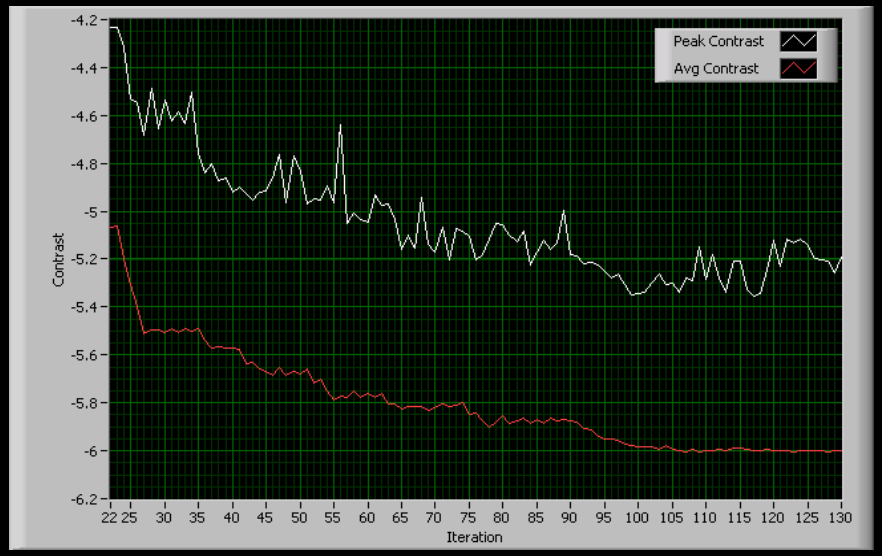


Speckle Nulling Results (Princeton)

Using single 32 x 32 MEMS DM from Boston Micromachines







- Dark hole: 4.5 to 12 l/D
- Peak contrast of 1e-5.2
- Average contrast of 1e-6
- Repeatable and stable
- Limited by mask accuracy and speckle nulling algorithm

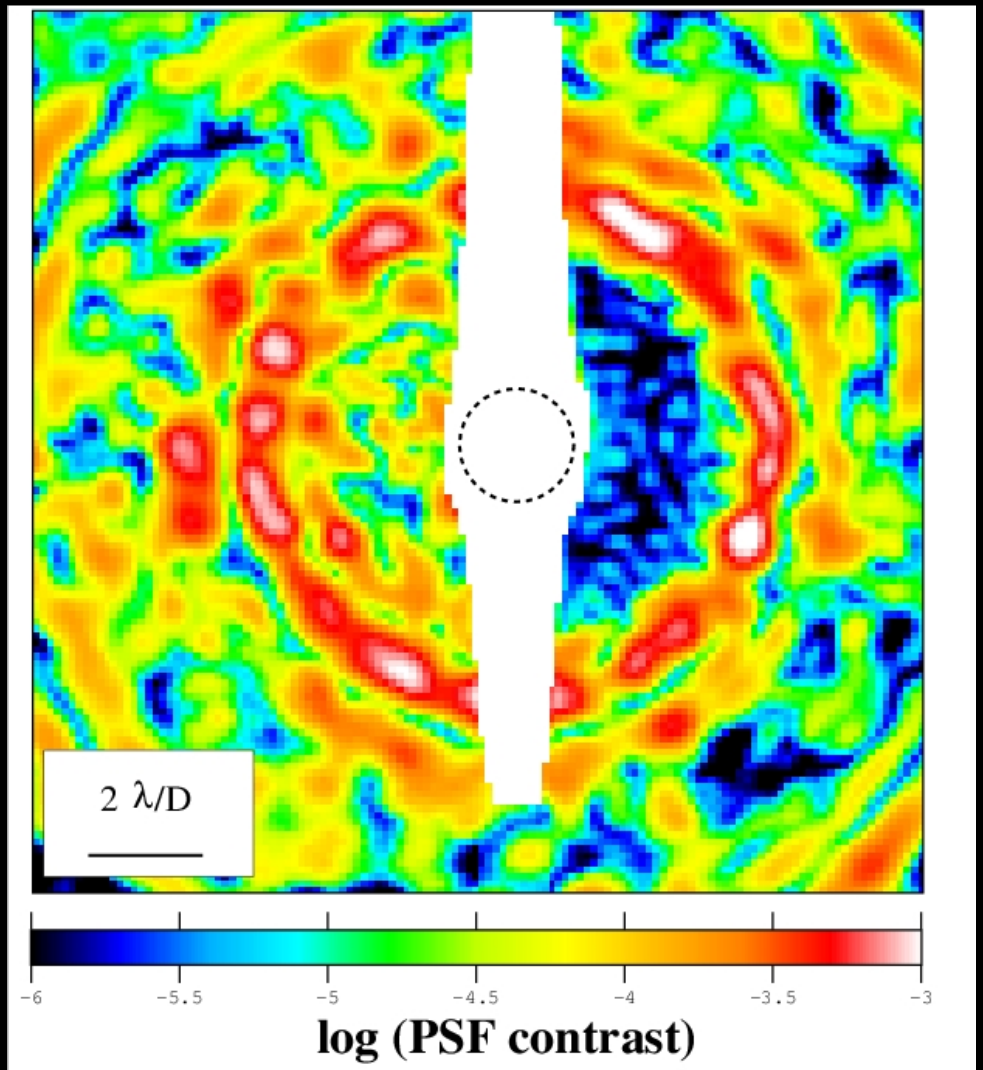
Dark Hole with Pupil Mapping (Subaru)

32x32 DM

Direct algorithm using DM induced diversity

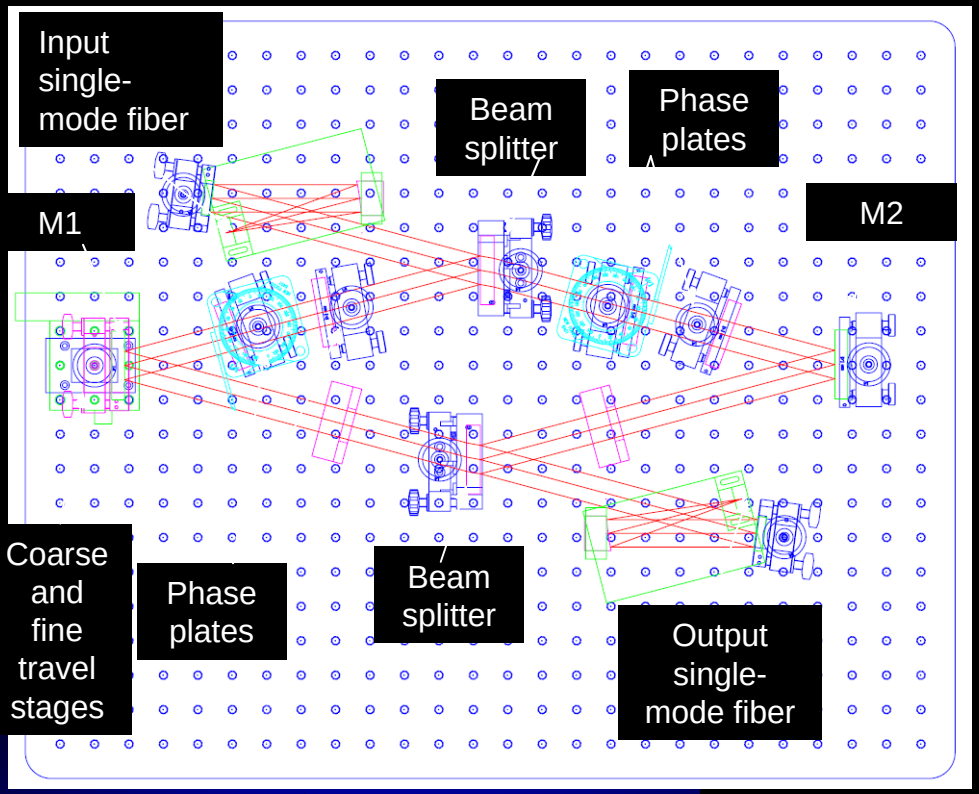
Currently limited by variable alignment between beam and binary mask (binary mask closer to focus than pupil)

No mask block starlight currently subject to camera dynamical range

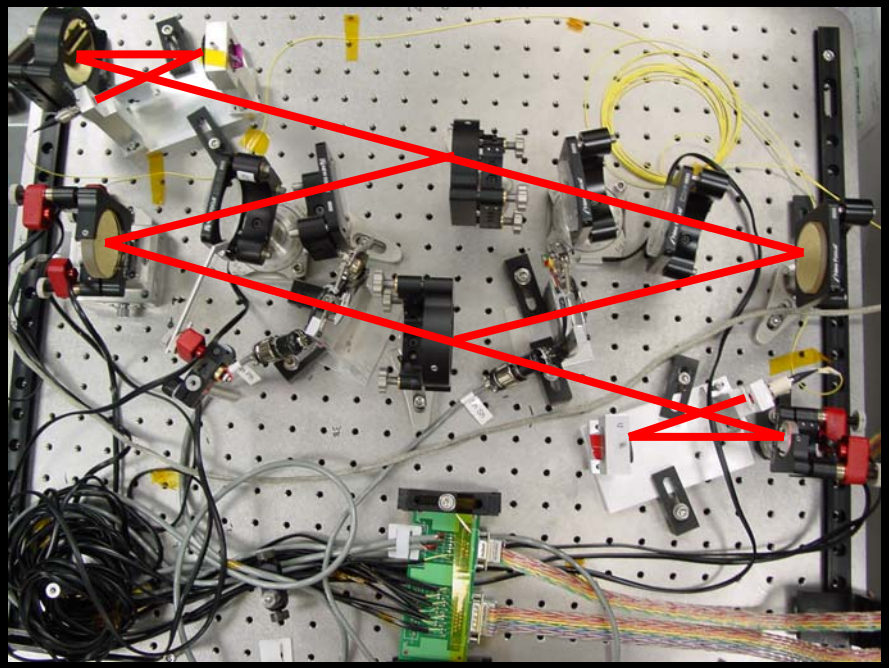


Average contrast in dark region = 2.5e−6
Vertical white feature is due to CCD saturation
Central circle is 1 lambda/D radius
Note: all distances are measured using the system chief ray

Visible Light Shearing Nuller



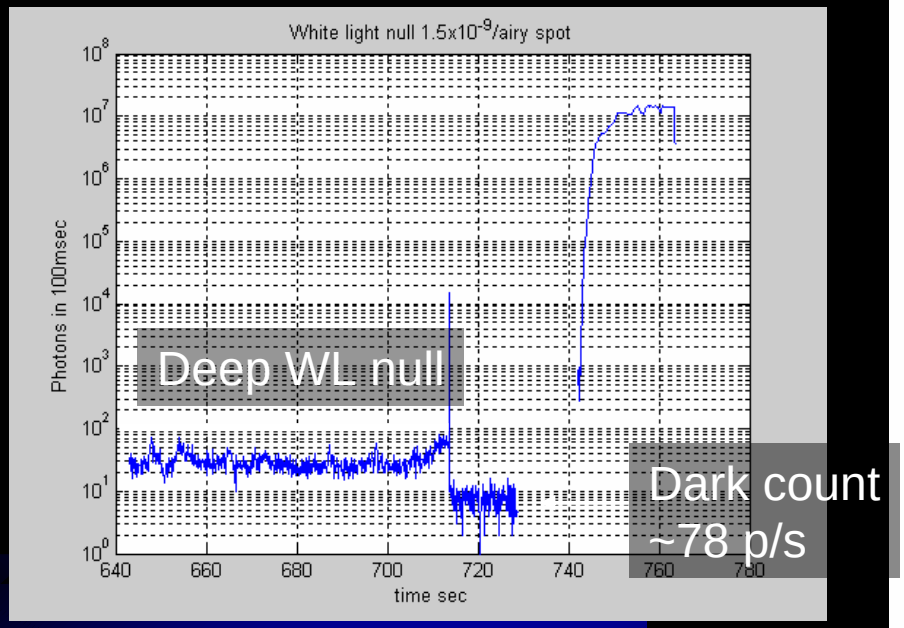
(Symmetric) Nuller Layout

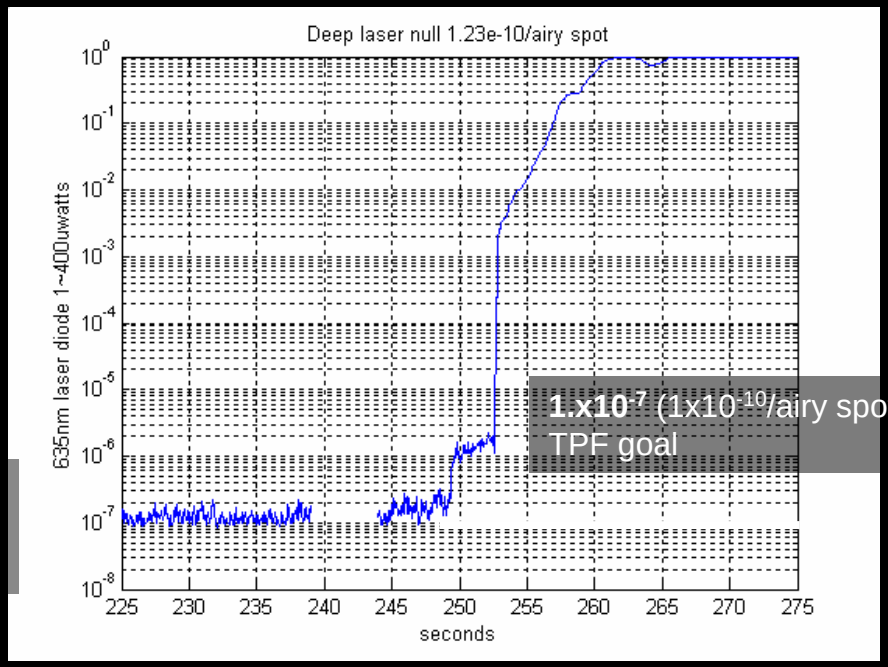


Experimental set up

- **All experiments have been run in vacuum chamber at 1 atm, with the door shut**

Monochromatic and White Light Contrast





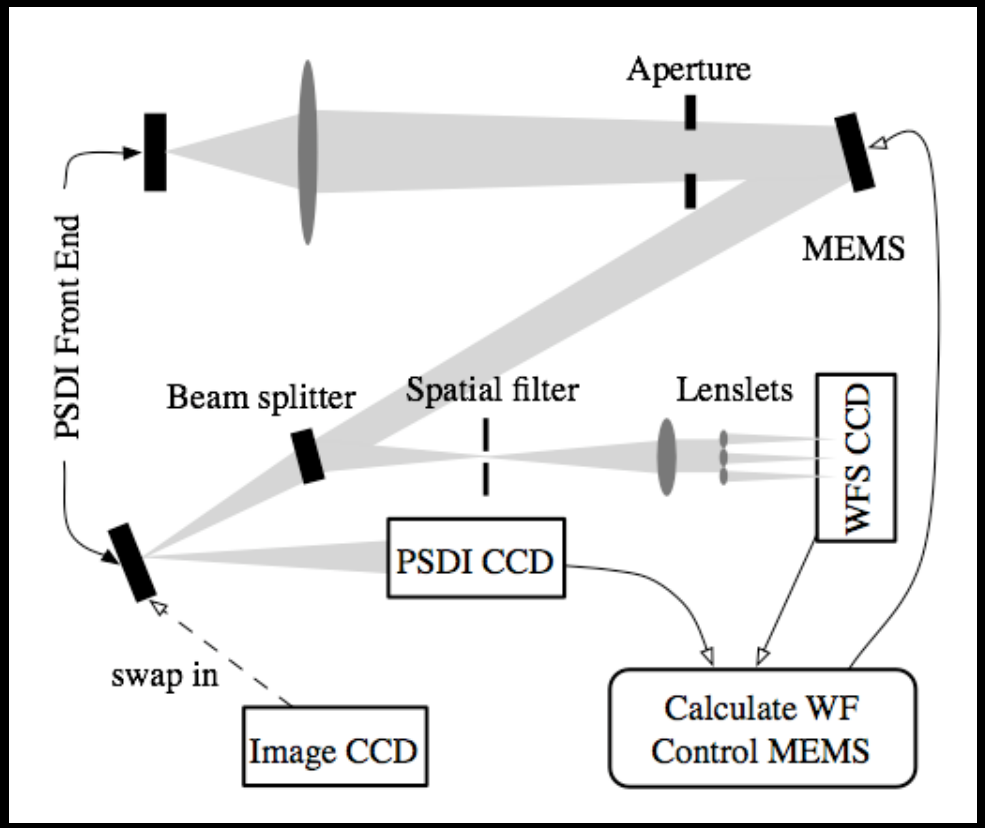
- White light data
  - null over 60 sec ~1.06×10^{-6}
  - ~15% bandwidth around 650nm.
- Better control of dispersion correction will deepen null to same limit as the laser null

- Laser data:
  - Optical path error of 90 picometer will cause 2×10^{-7}
  - rms vibration and drift over ~15 sec is ~60pm

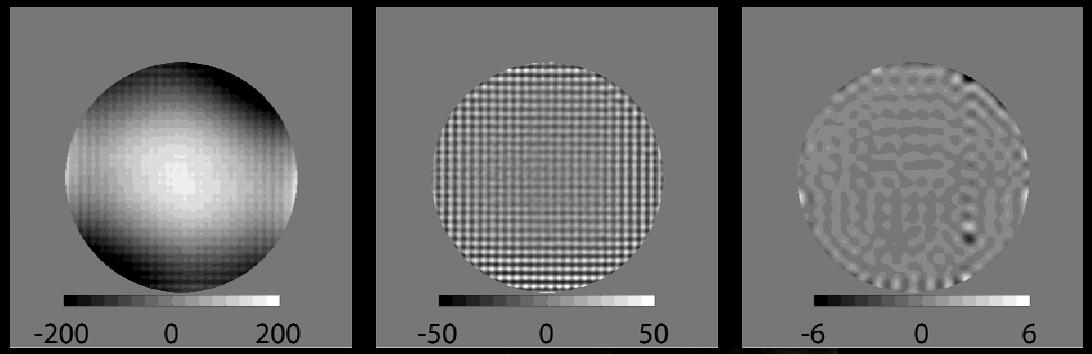
ExAO Testbed (Santa Cruz)

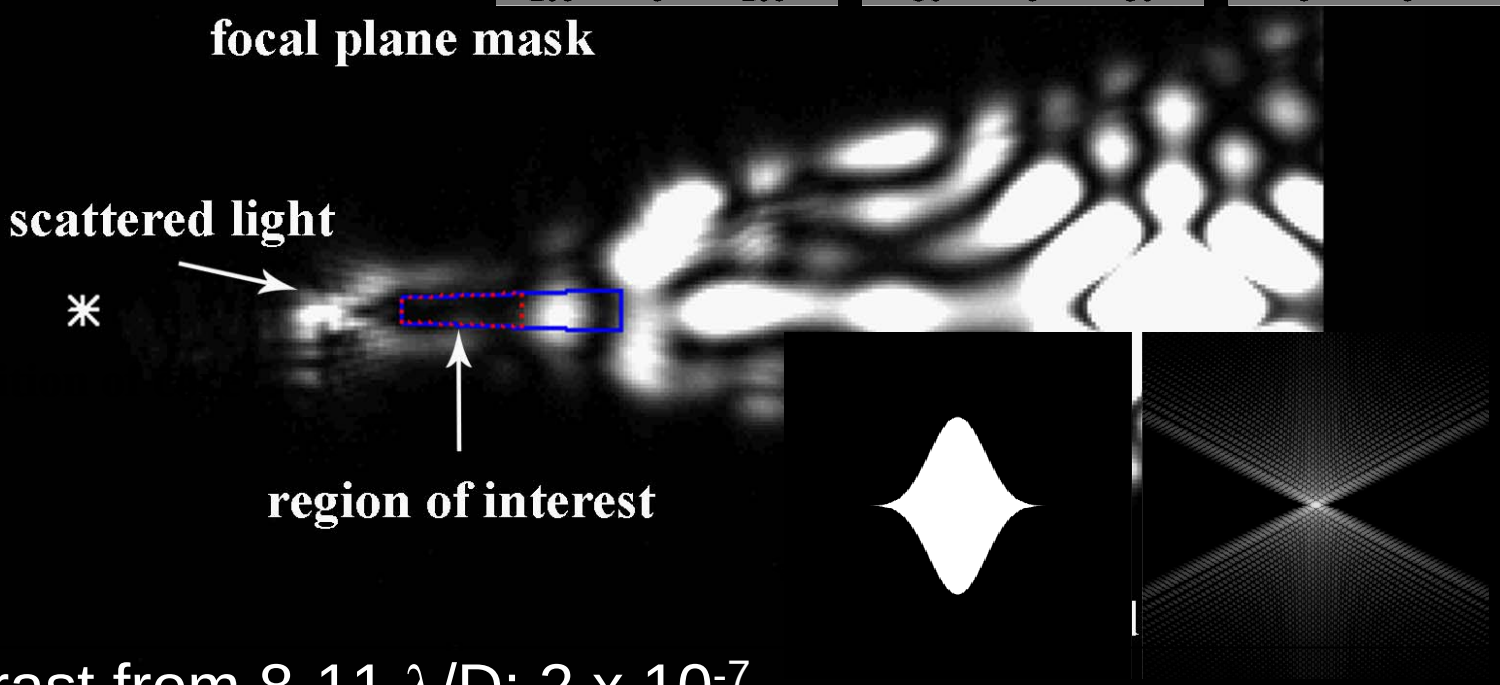
"Conventional" AO approach

- Phase Shifting Diffraction Interferometer (PSDI) for metrology
- Low wavefront-error optical design
- MEMS DM controlled in closed loop via:
  - PSDI or
  - SF Shack-Hartmann WFS
- Shaped pupils to suppress diffraction
- Science Camera in far-field for contrast measurements



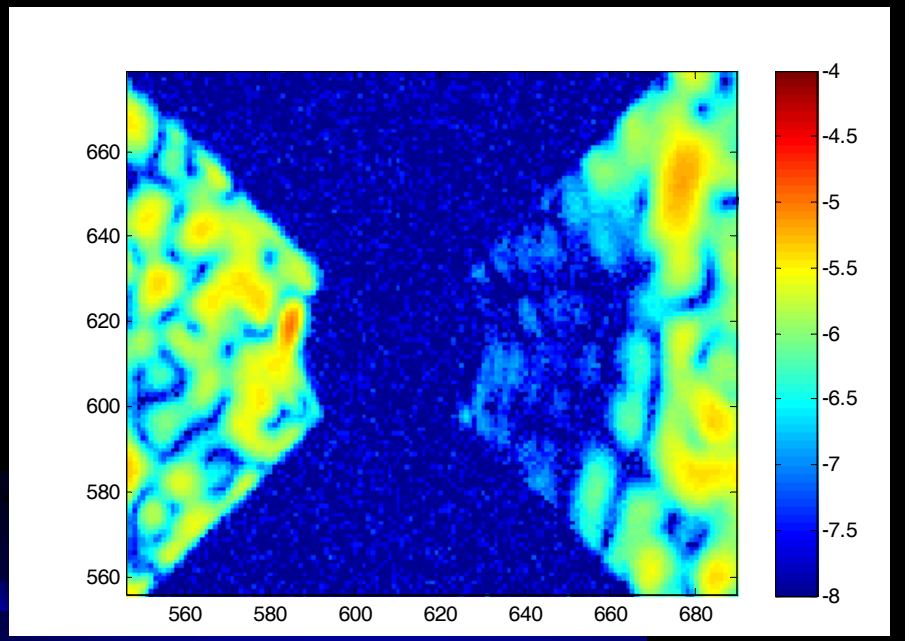
Contrast with MEMS

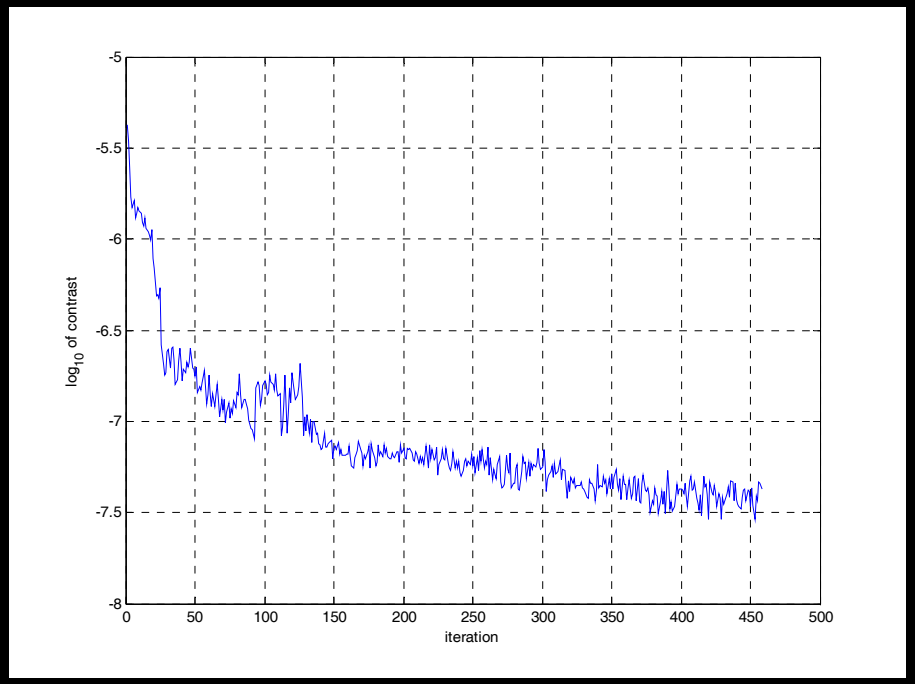




- Contrast from 8-11 λ/D: 2×10^{-7}
- Contrast from 8-13 λ/D: 6×10^{-7}
- Region of interest is limited by scattered light from the focal plane mask and controllable spatial frequencies
- Contrast is limited by phase and amplitude errors

Shaped Pupil Speckle Nulling at HCIT 785nm with Ripple 3

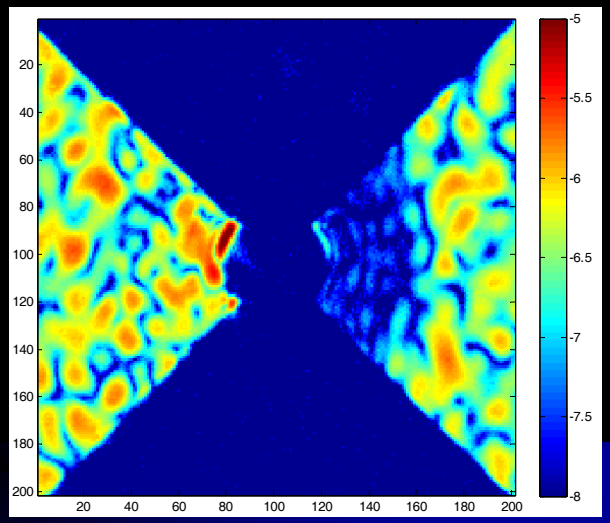




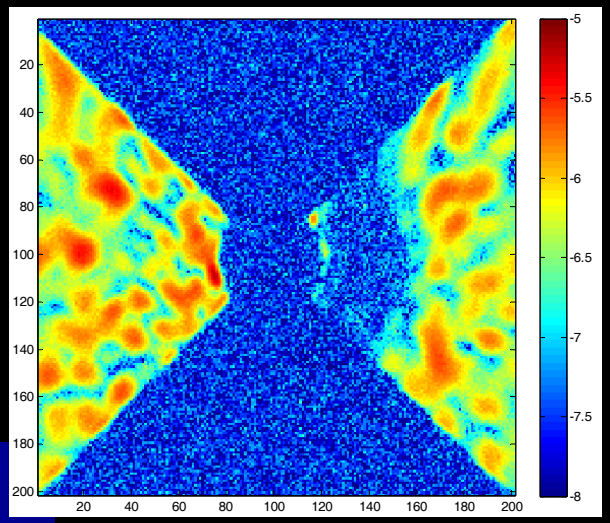
- 457 iterations over a course of 3 days
- Went down from 10^{-5} contrast to 4×10^{-8} between 4 and 9 λ/D
- Some wavefront correction on the opposite side, until we hit amplitude errors

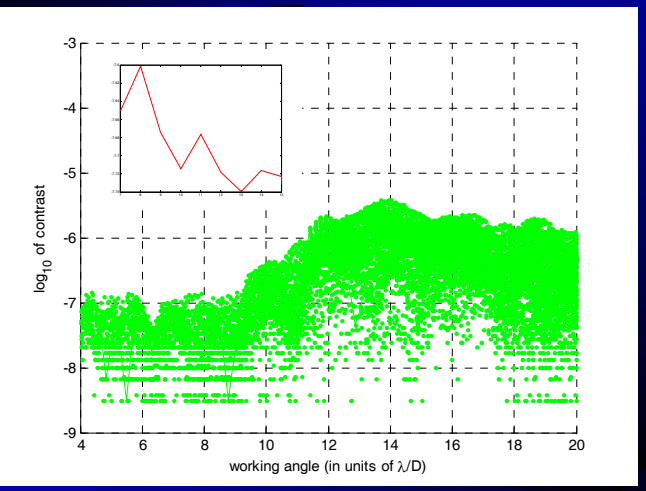
Shaped Pupils at the HCIT
Monochromatic and Broadband Performance

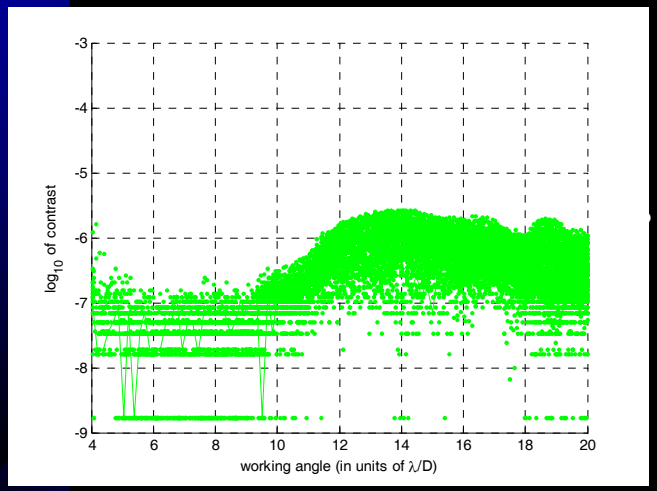
836nm



760nm-840nm



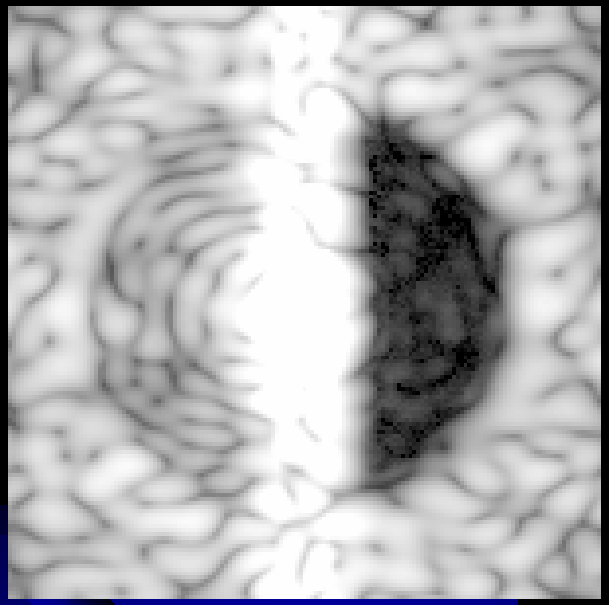


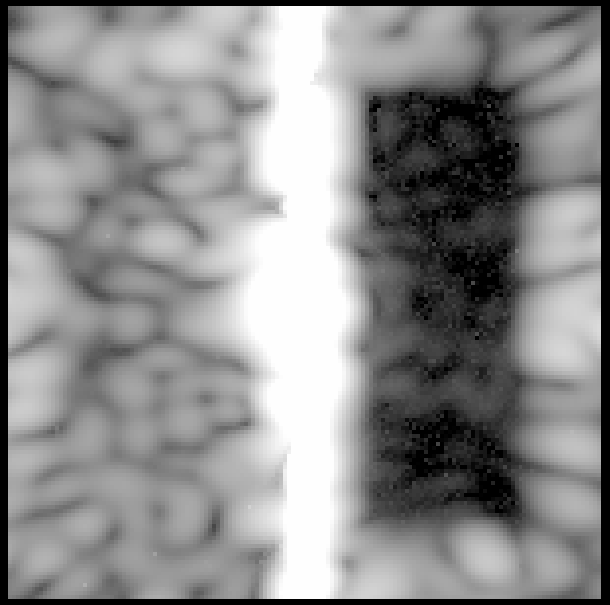


- After switching from 785 to 836nm
  - Contrast degrades very slightly
  - After a few speckle nulling iterations, contrast dips below 4×10^{-8}
  - longer wavelengths see lower aberrations

After switching to broadband light (760-840nm), contrast remained about the same

HCIT Monochromatic Result





Better than 1e-9 Contrast
4-5 Airy rings.
5e-10, 4-10 Airy rings.

10% bandwidth, Xenon lamp,
4-10 λ/D contrast = 6e-9,
Same spatial scale as
narrowband images

HCIT Contrast Test Results

- Monochromatic contrast: 6×10^{-10} (measured)
- White light contrast with HEBS occulting mask:
  - 16 nm FWHM centered at 785 nm: 1.5×10^{-9} (measured)
  - 16 nm FWHM centered at 785 nm: 7×10^{-10} (predicted, optimal Lyot)
  - 80 nm FWHM centered at 800 nm: 6×10^{-9} (measured, Xenon lamp)
- White light contrast with profiled metallic occulting mask:
  - 80 nm FWHM centered at 800 nm: 5×10^{-10} (predicted)
- Modeling guides progress towards further improvement (this year):
  - Roughly 20% agreement with models
  - Occulting mask design for mitigation of dispersion effects
  - Larger (64x64) DM for larger high-contrast dark field
  - Two DMs in series for full two-sided dark field
  - Hybrid nulling algorithms for faster convergence

Final Remarks

- Tremendous progress is being made
- Very close to a flight level proof
- 1e-6 roughly the limit of uncorrected coronagraphy
- Amplitude error limitations unknown and vary with coronagraph
- Chromatic limitations also vary with implementation and have strong amplitude dependence

Broadband contrast will ultimately depend upon ability to correct amplitude over multiwavelengths:

What does this imply about the requirements on the coronagraph?