Pupil mapping Exoplanet Coronagraph Observer (PECO)

Olivier Guyon
(guyon@naoj.org)

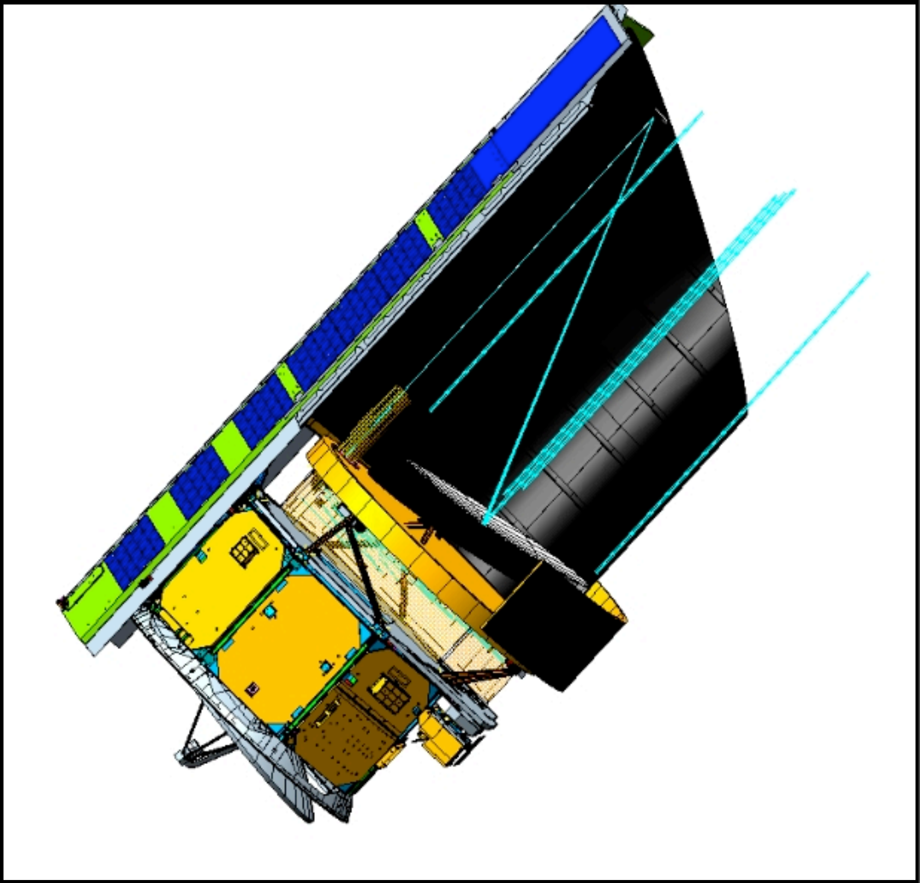
University of Arizona
Subaru Telescope

PECO team

U of Arizona
NASA JPL
NASA Ames
Lockheed
ITT

Principal Investigator: Olivier Guyon – University of Arizona	
Mission Study Manager: Marie Levine – NASA Jet Propulsion Laboratory	
Science Studies (Lead: Co-I T. Greene – NASA Ames Research Center)	
J. Kasting (Penn State) Co-I	Terrestrial planets: spectral characterization
M. Marley (ARC) - Co-I	Giant planets: spectral characterization, modeling
M. Meyer (UofA) - Co-I	Planetary systems formation, evolution
W. Traub (JPL) - Co-I	Science plan and participate in the HCIT test demonstrations.
D. Backman (SOFIA) – Collaboratr	Exozodiacal dust
G. Schneider (UofA) - Collaborator	Exozodiacal dust
M. Tamura (NAOJ) – Collaborator	Planetary systems formation
N. Woolf (UofA) – Collaborator	Characterization of planetary atmospheres, habitability
Architecture Studies (Lead: Co-I S. Shaklan – NASA Jet Propulsion Laboratory)	
A. Give'on (JPL) - Co-I	WFS&C algorithms for Architecture studies and HCIT test demo
R. Vanderbei (Princeton) - Co-I	Coronagraph architecture and analysis
R. Belikov (Princeton) – Collabor..	Coronagraph architecture and analysis
J. Kasdin (Princeton) - Collaborator	Architecture
E. Serabyn (JPL) - Collaborator	Wavefront sensing and speckle nulling
Mission Technology (Lead: Co-I M. Levine –NASA JPL / Co-Lead Co-I T. Greene –NASA ARC)	
R. Angel (UofA) - Co-I	Technology development, Wavefront sensing, primary mirror
D. Gavel (UCSC) - Collaborator	Characterization of MEMS type DMs for PECO
M. Shao (JPL) - Collaborator	MEMS DMs characterization, wavefront sensing & control
J. Trauger (JPL) - Collaborator	Xinetics DMs expertise, wavefront sensing & control
Mission Implementation (Lead: Co-I D. Tenerelli – Lockheed Martin)	
R. Woodruff (LM) - Co-I	PECO instrument design, implementation, cost and technology
C. Lloyd (ITT) – Co-I	PECO telescope design, implementation, cost and technology
J. Wynn (ITT) - Collaborator	PECO telescope design, implementation, cost and technology.

PECO overview

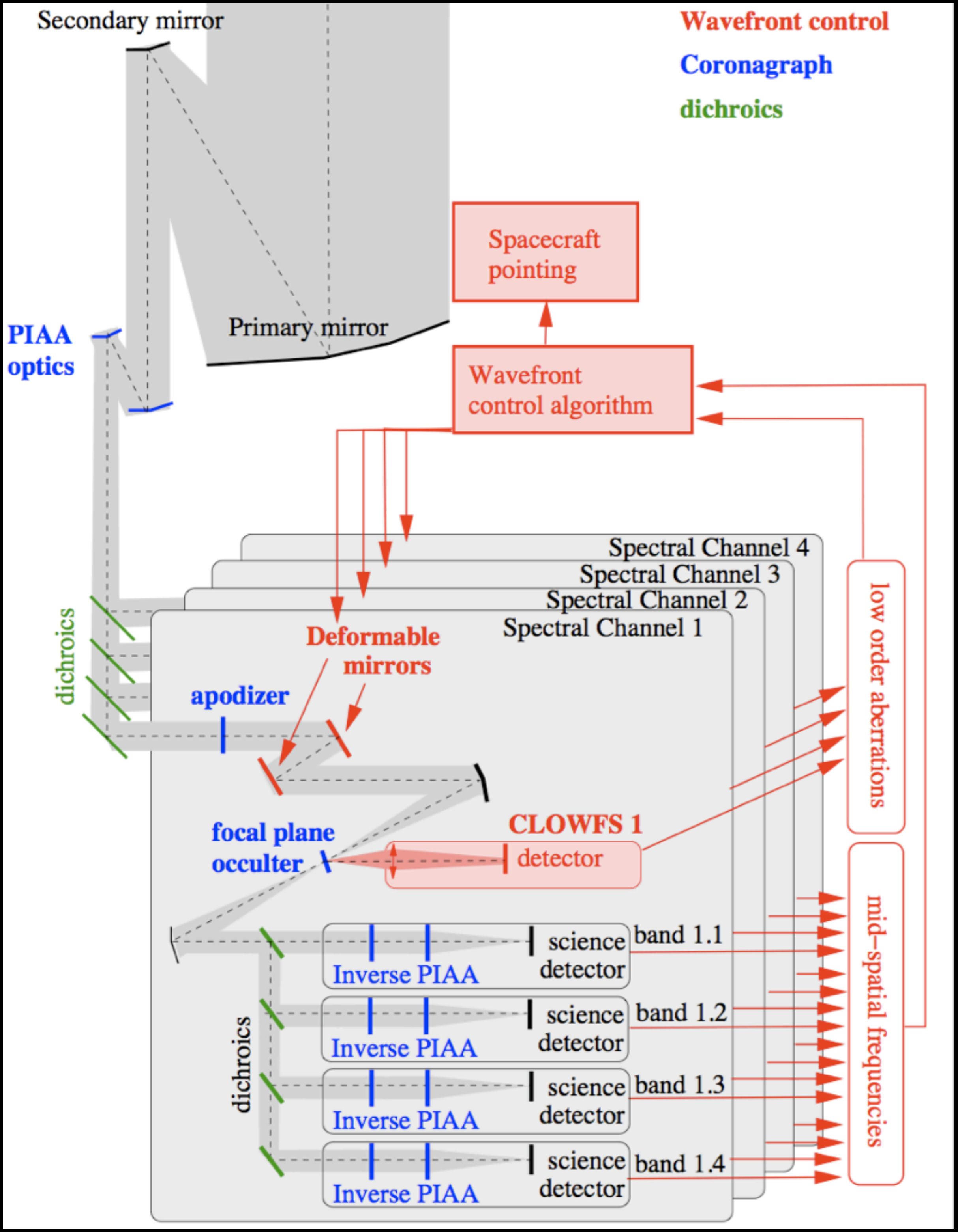


High contrast coronagraphic imaging of the immediate environment of nearby stars

Characterization of planets and dust in habitable zone

1.4m diameter off-axis telescope
0.4 - 1.0 micron spectral coverage / R~20

PECO is one of the "probe-class" (<$1B) NASA-funded Advanced Mission Concept Studies.



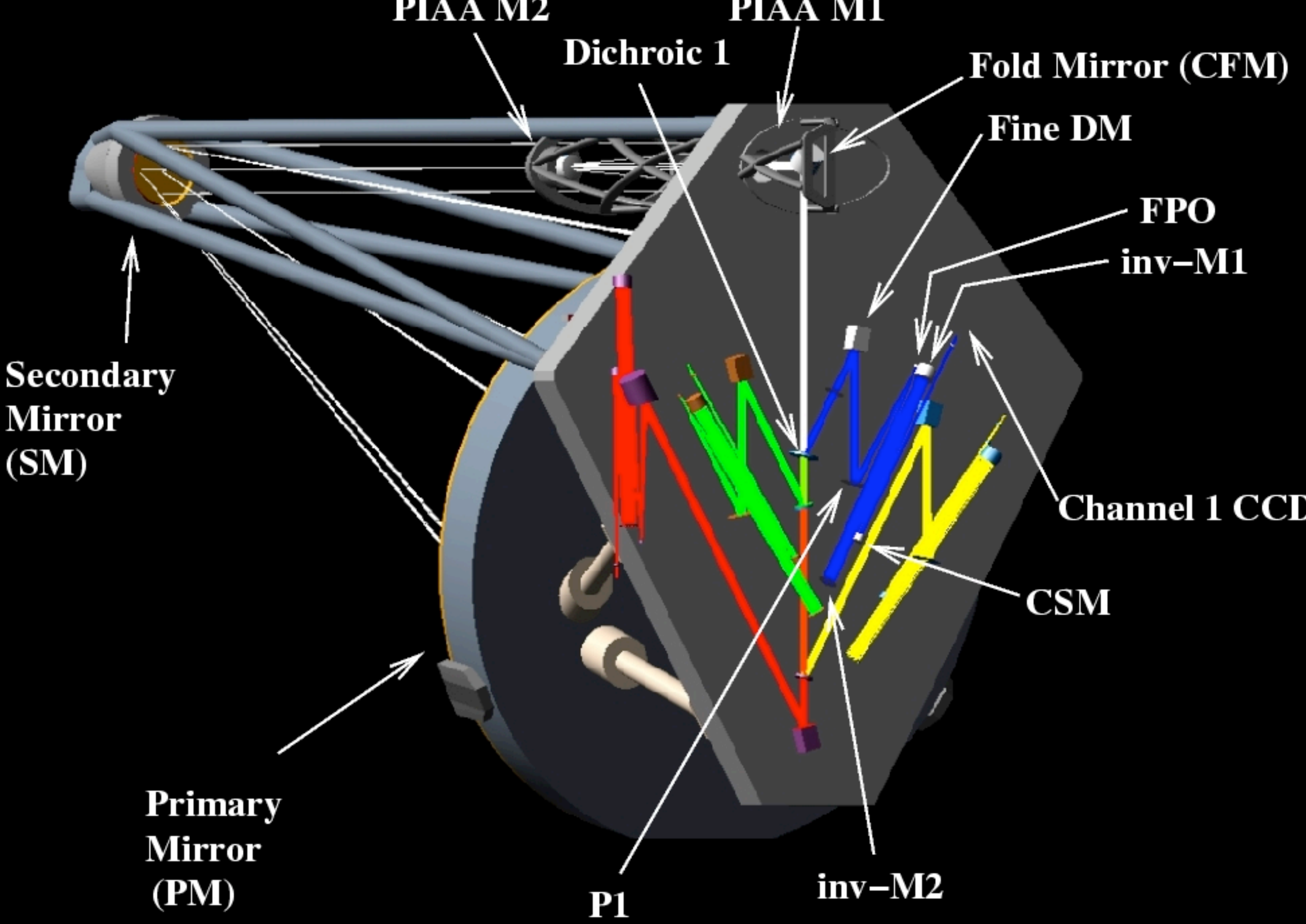
Optimal use of photons from 0.4 to 1.0 micron, for WFC and science

- Common detector for WFS and science
- Dichroics
- EMCCDs
- PIAA coronagraph
- CLOWFS

Dichroics for science (R~15) and wavefront control / coronagraphy

Full angular resolution

Optical Telescope Assembly (TOPS)



Exoplanet science with a 1.4 m telescope ? Don’t we need an 8m ? (TPF-C)

Coronagraph technology is making very good progress

- since “TPF-C”, we know how to reduce telescope diameter by almost 3x with the same science capabilities.

- Lab testbeds are making huge progress

We can (somewhat) relax number of targets since Eta (Earth+SuperEarth) probably > 0.1 (RV/transits/ microlensing)

- This also means we can also spend more time per target (weeks, months...)

- RV and/or astrometry will help constrain mass of planets and increase efficiency of observations. Will also help tell difference between planets and exozodi clumps

Biggest risk is Exozodi. How many systems have < 2 to 5 zodi within ~10pc ? How clumpy is it ?

Characterization on very limited # of targets in red. Low resolution spectroscopy (R~15 to 20).

Coronagraph

Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

\+ Simple, robust, achromatic

\- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

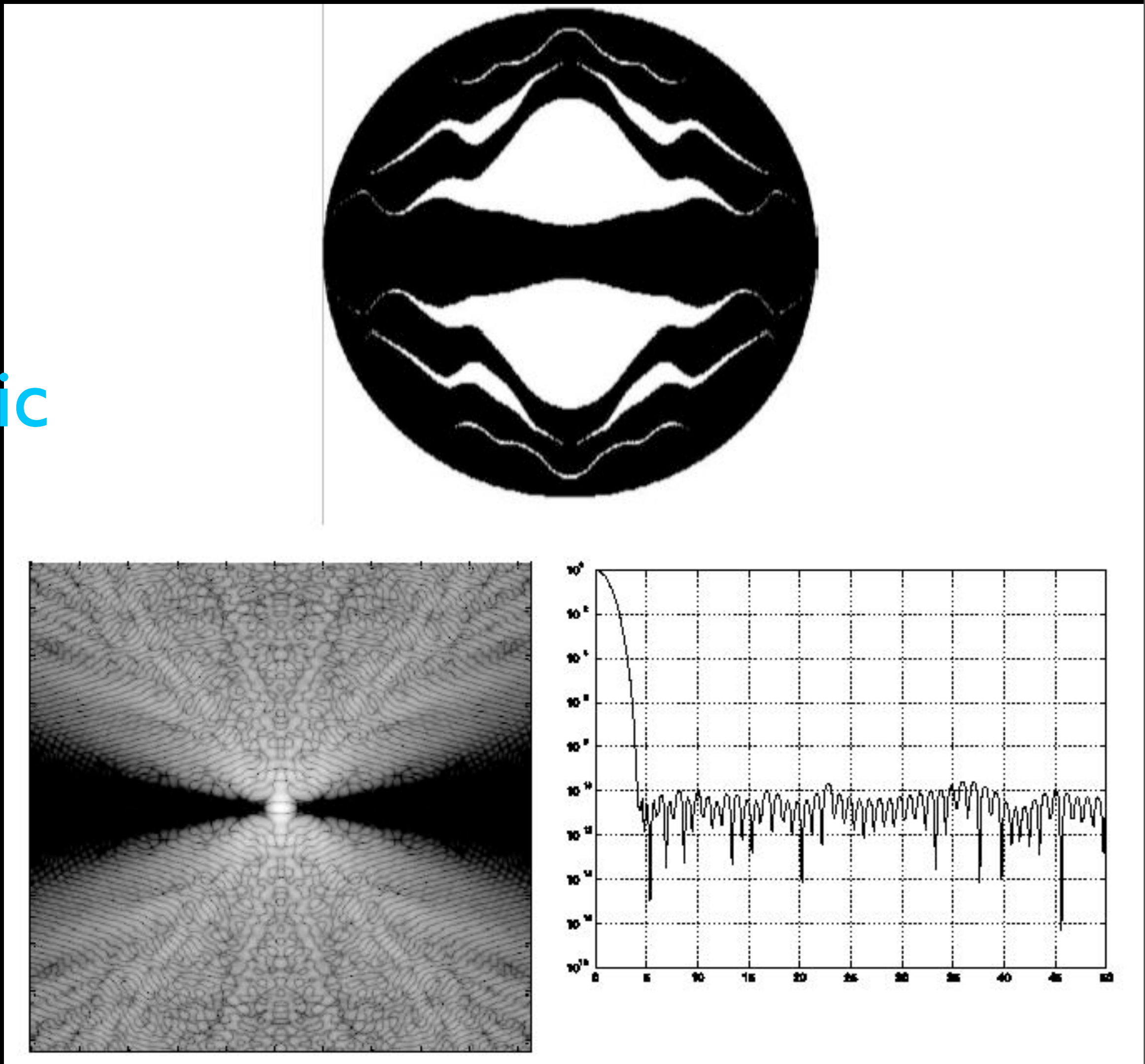
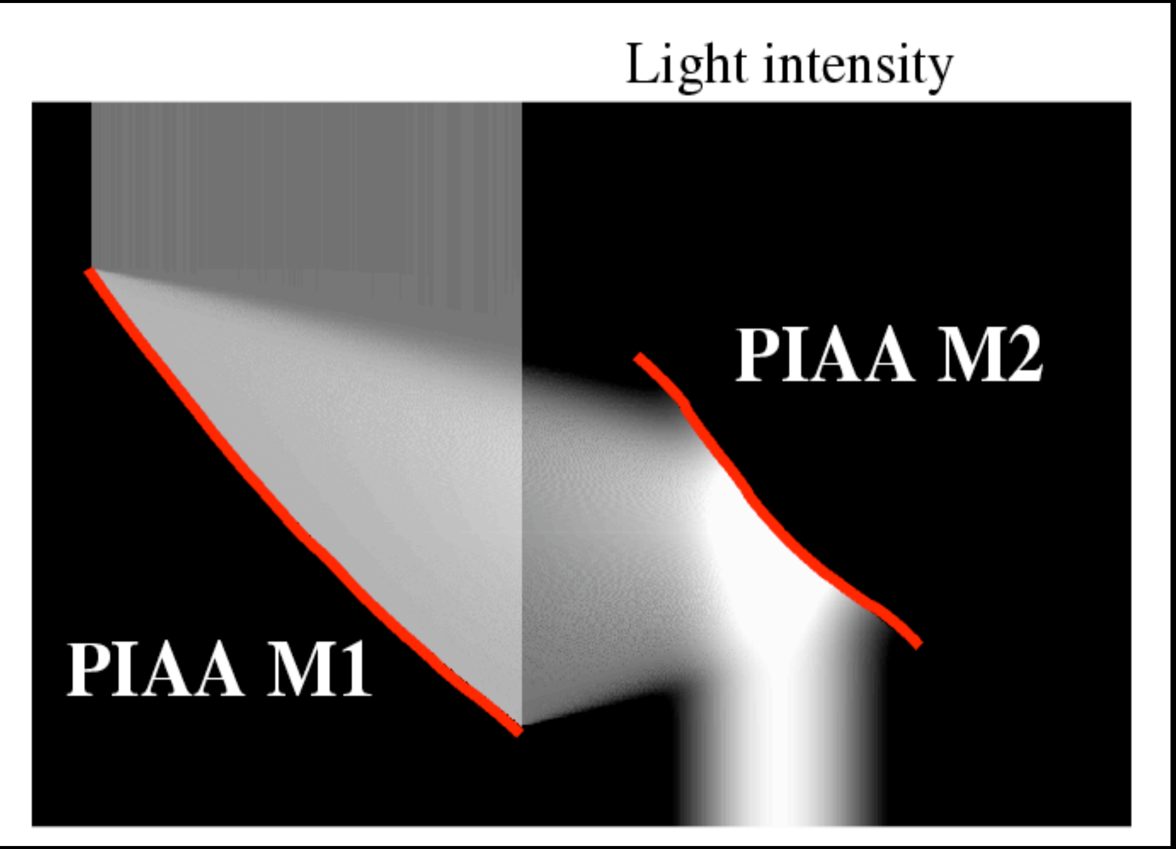


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

PIAA coronagraph

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight is single diffraction peak (no Airy rings).



- high contrast
- Nearly 100% throughput
- IWA ~1.5 l/d
- 100% search area
- no loss in angular resol.
- achromatic (with mirrors)

More info on :

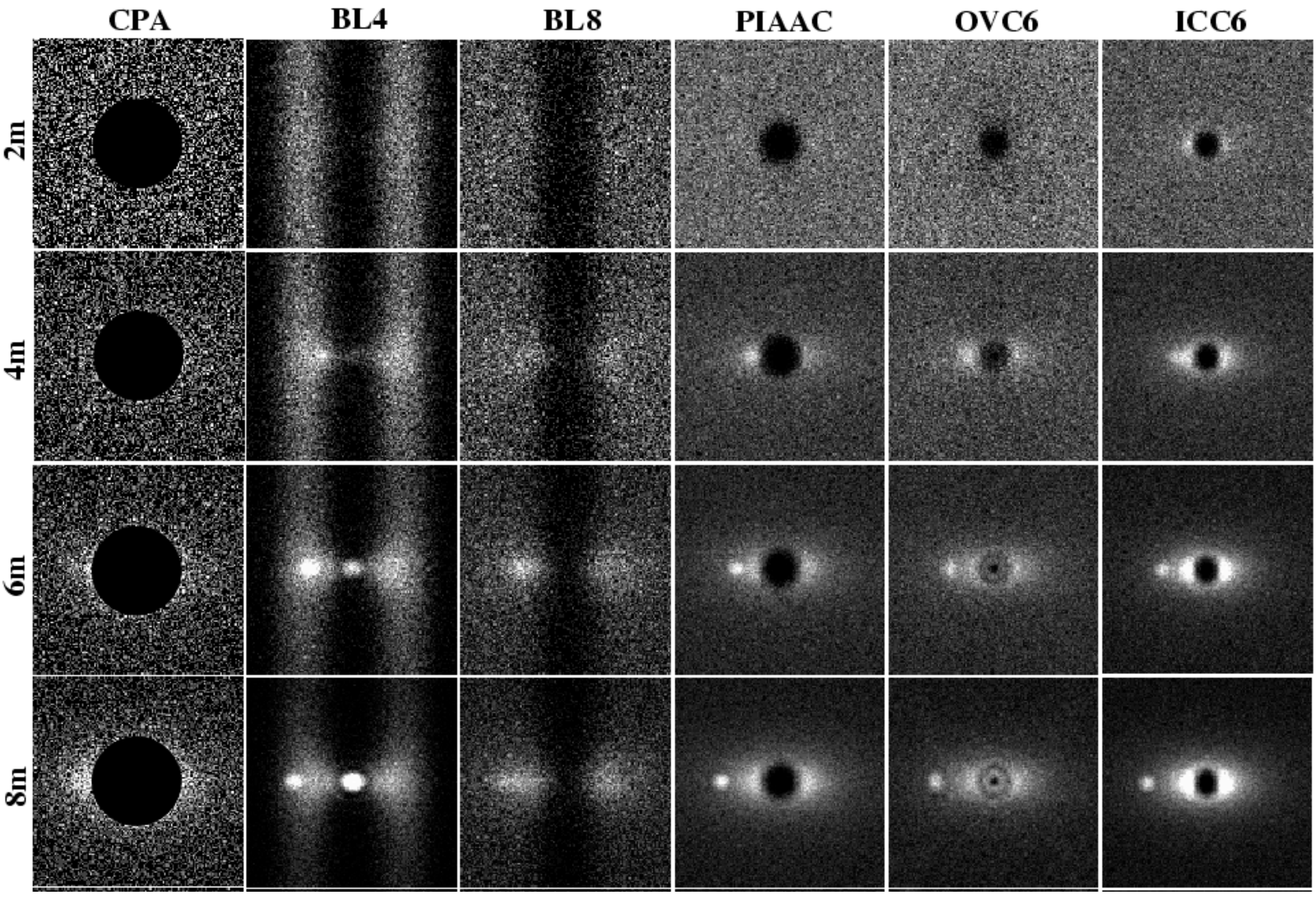
www.naoj.org/PIAA/

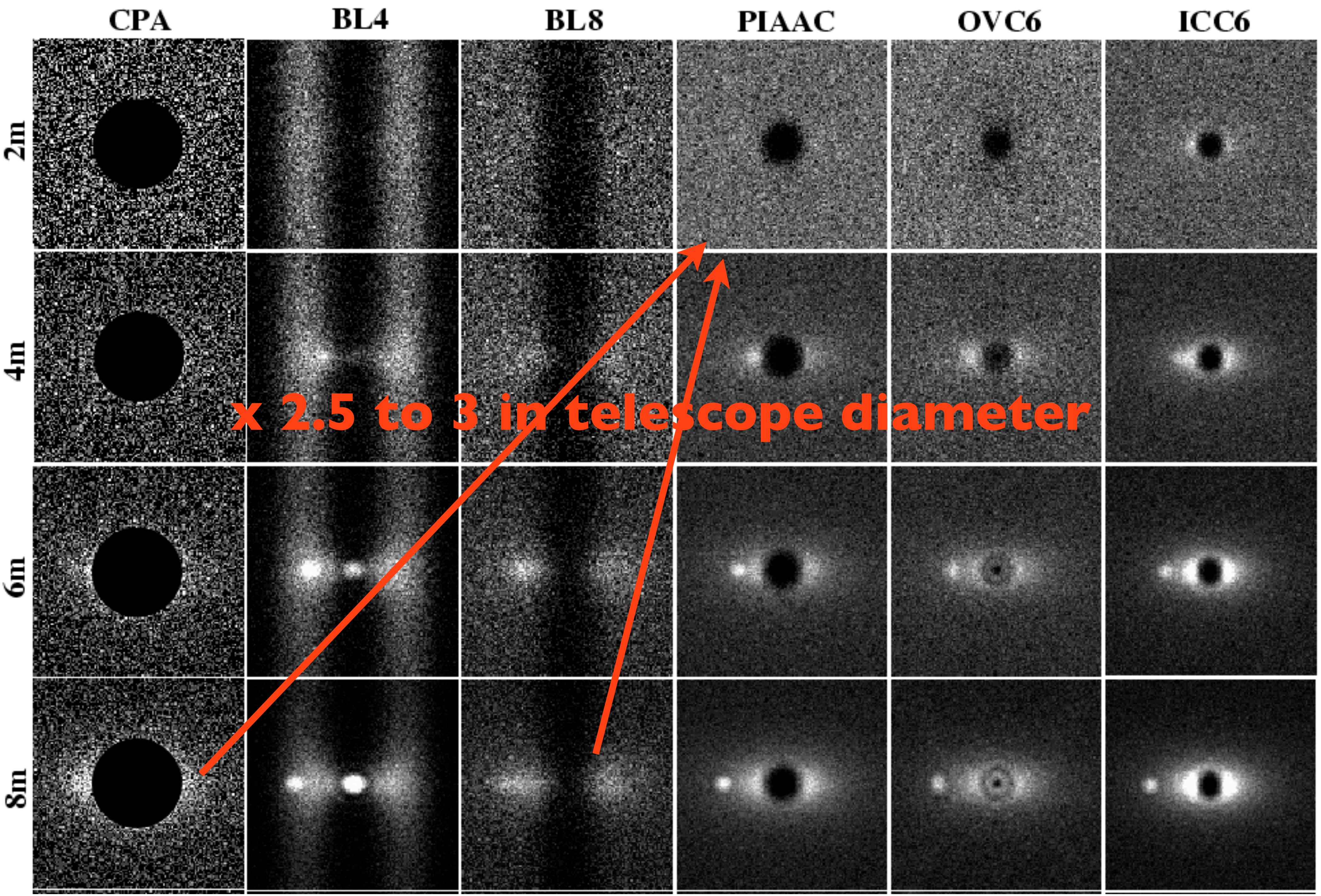
Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

Example:
HIP 56997 (G8 star at 9.54pc)
0.55 micron, 0.1 micron band
Planet at maximum elongation (80 mas)
Earth albedo = 0.3 (C=6e9)
4h exposure, 0.25 throughput, perfect detector

Exozodi : 1 zodi
System observed at time when zodi is minimal

Each image is 20x20 lambda/d


CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m


CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m
x 2.5 to 3 in telescope diameter

PECO Science

Telescope size and coronagraph type	Earth @ 1 HZ albedo 0.3	SuperEarth @ 1 HZ albedo 0.3	SuperEarth @ 1.8 HZ albedo 0.3	Jupiter @1AU albedo 0.6	Jupiter @5AU albedo 0.6
1.0 m PIAA	5	13	23	21	437
1.4 m PIAA (PECO)	**20**	**38**	**56**	**52**	**1179**
1.8 m PIAA	41	79	127	103	2545
1.4 m Shaped Pupil	2	2	4	15	131

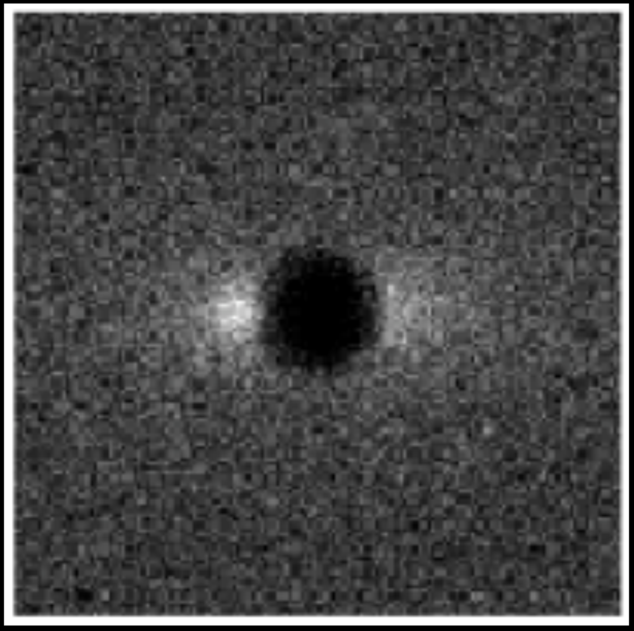
Table 1.2-1 Number of FGK main sequence stars around which different planet types can be detected (SNR=5 at R=5 at 0.55 micron) with an ideal (perfect wavefront) 1.4m PIAA telescope adn other telescope diameter/coronagraph combinations. Details of this simulation can be found in Guyon et al. 2006. This table assumes a 1 zodi cloud around each star and a 50% throughput loss due to coatings and detector. The numbers given are for 20% detection probability for a single 1 day exposure with no prior information on the planet location, corresponding to 90% probability of at least one detection in 10 uncorrelated visits. Super Earths are assumed here to have 2x Earth radius. The HZ unit denotes the distance at which an Earth-like planet would have the same temperature as the Earth.

Science is steep function of telescope diameter

PECO design could be applied to larger telescope size

A “difficult” PECO target

PECO one day image in 0.4-0.5 micron band of an Earth/Sun system analog at 4.5 pc



Illustrates:

- very high SNR detection of exozodi
- risk of confusion with exozodi
- risk of confusion with other planets

“Earths” are at limit of PECO

super-Earths are significantly easier

- High contrast needs to be maintained at 1e-10

PECO's goal is to image and characterize nearby exoplanetary systems (Planets + dust) down to Earth/"SuperEarth" mass

- deep survey:
50 targets (~2/3 of observing time)
- large survey:
+150 targets (~1/3 of observing time)

Spectral characterization at R~20

-> Planets orbits, colors and map of exozodi cloud
-> understand planetary systems architecture & habitability

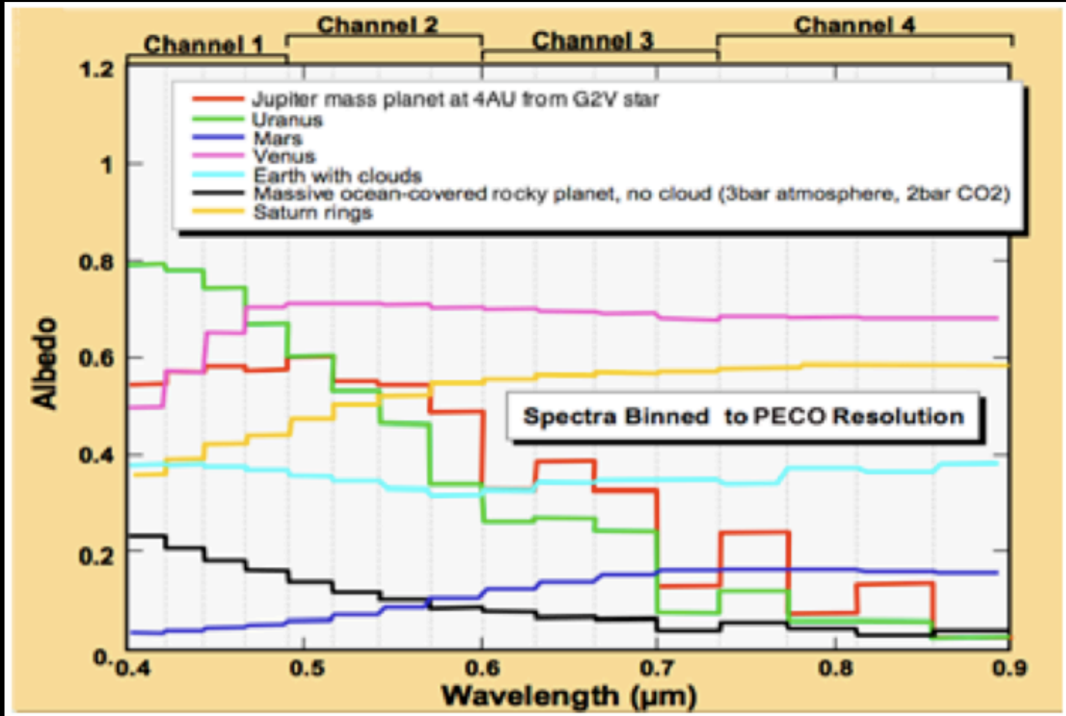
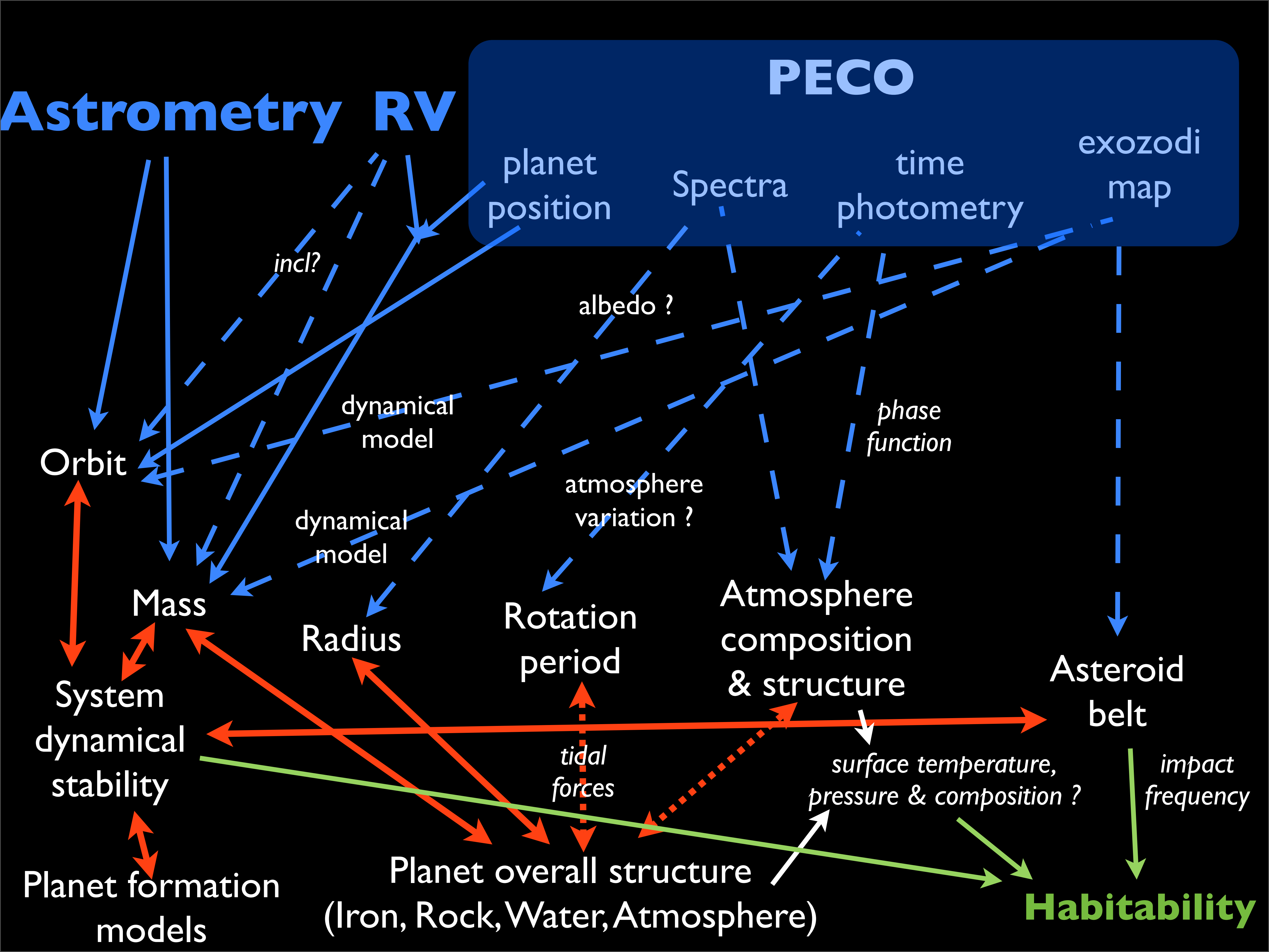


Figure 1.2-1 PECO Spectral Bands. Earth's atmosphere has a relatively constant albedo across the PECO bands, with a slight absorption near 600 nm due to ozone. EGPs like Jupiter will have relatively flat spectra, with deep methane absorption in the red adjacent to bright continua arising from clouds. Cooler, lower gravity, and/or methane-rich ice giants like Uranus & Neptune are bluer and much darker in the red.



PECO
Astrometry
RV
planet position
Spectra
time photometry
exozodi map
incl?
albedo ?
dynamical model
phase function
atmosphere variation ?
dynamical model
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure & composition ?
impact frequency
Planet formation models
Planet overall structure (Iron, Rock, Water, Atmosphere)
Habitability

PECO Technology

Technical challenges

Coronagraph -> can you build it ? does it really work ?

Wavefront control with coronagraph

Pointing stability/calibration

Telescope wavefront stability

vibration isolation & good thermal design

drift-away orbit

Detectors

~zero readout noise visible CCD are now available

PIAA Coronagraph Technology Development

Testbed @ Subaru Telescope
Ground-based coronagraphic ExAO project
2nd generation PIAA design & manufacturing
Space projects studies: TOPS -> PECO, EXCEDE, TPF-C, SPICA

Main funding sources

Ground-based

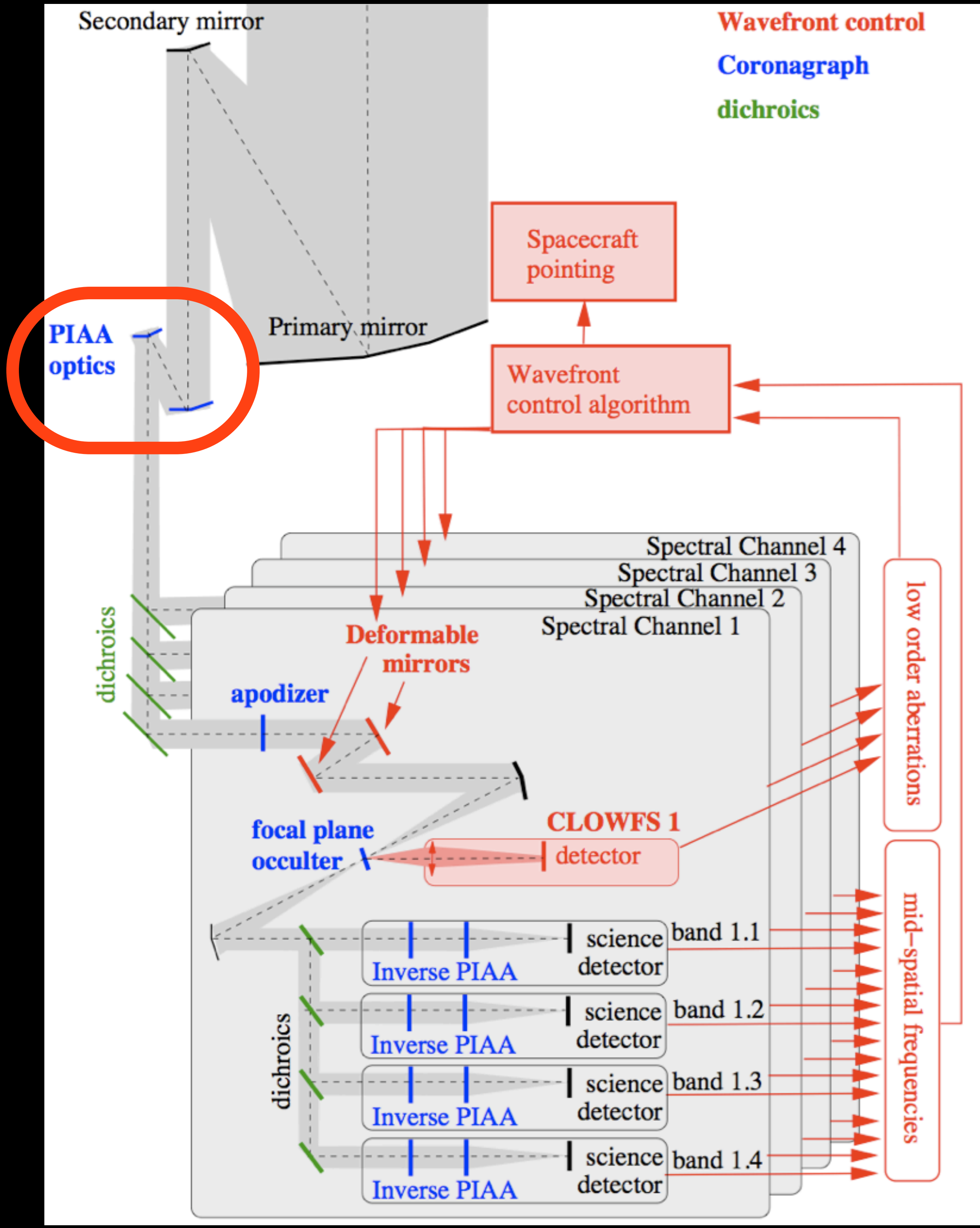
Space

NASA JPL
Navigator program

Subaru Telescope/NAOJ

MEXT (Japan)

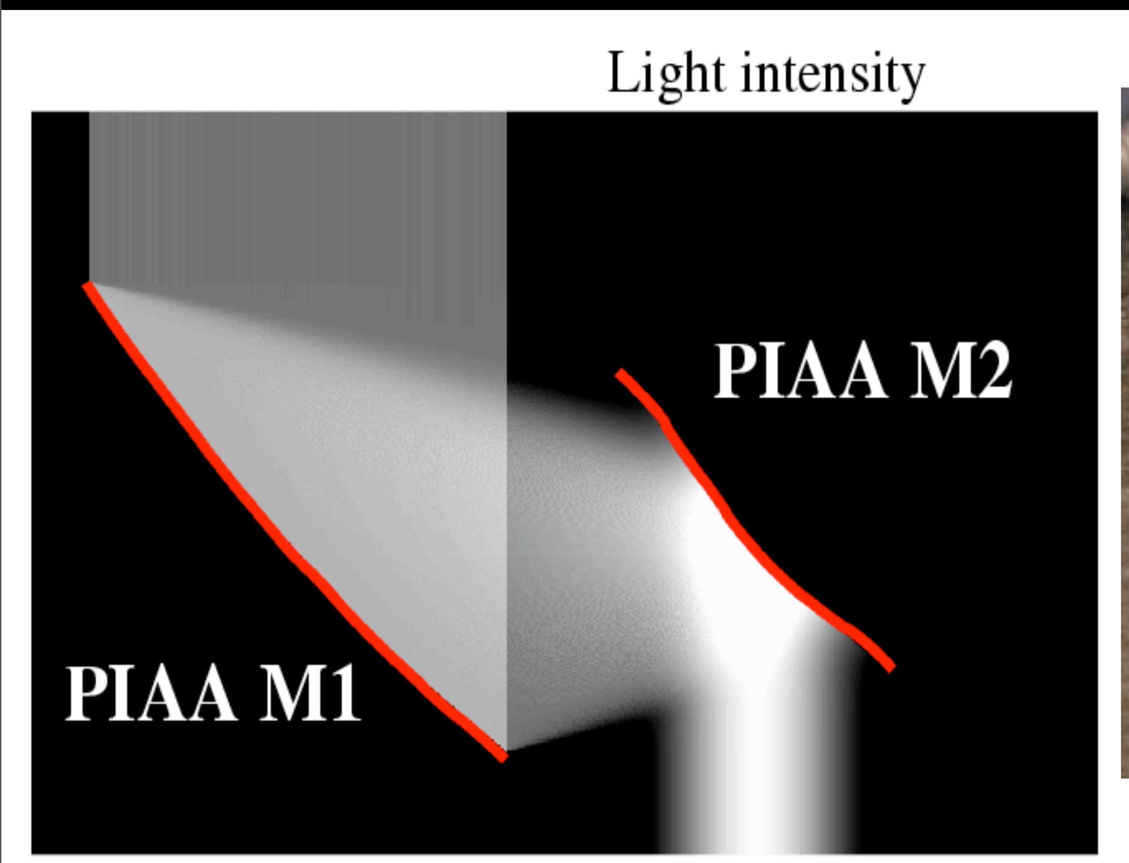
NASA Ames
TOPS partnership

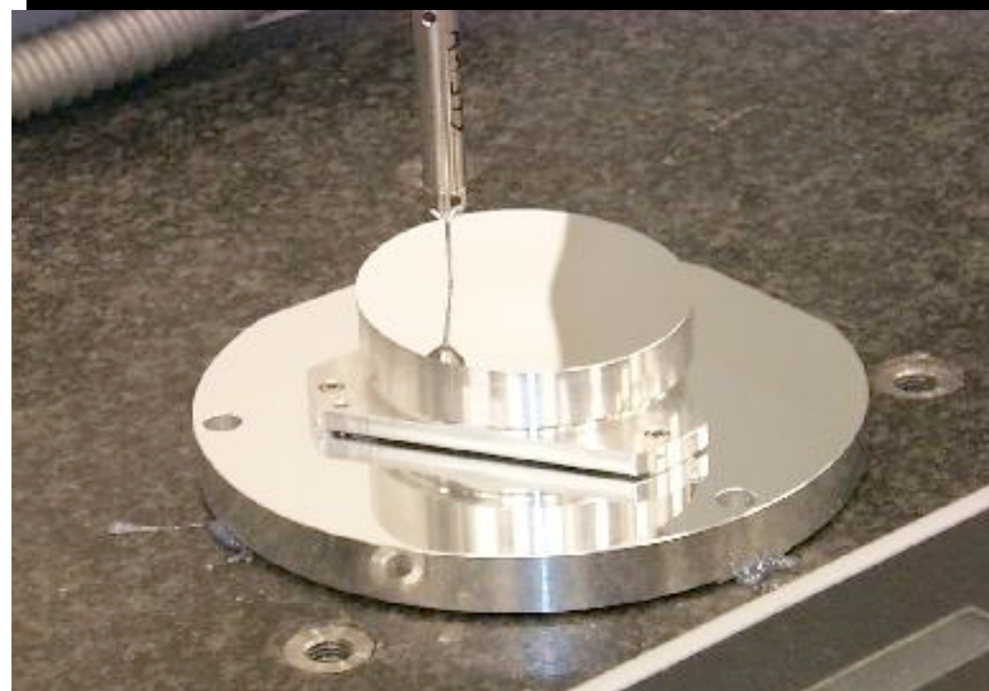


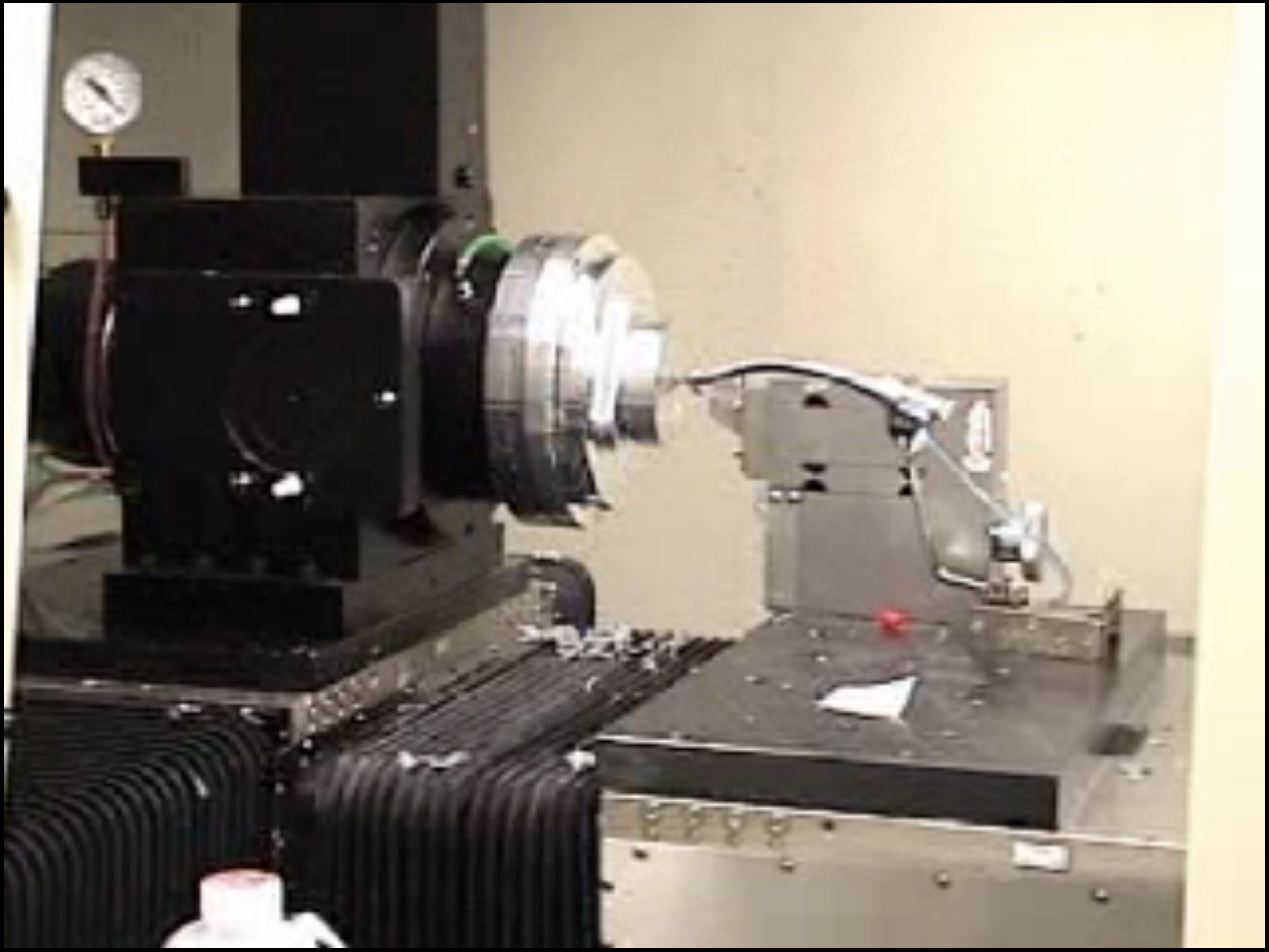
Secondary mirror
Wavefront control
Coronagraph
dichroics
Spacecraft pointing
PIAA optics
Primary mirror
Wavefront control algorithm
Spectral Channel 4
Spectral Channel 3
Spectral Channel 2
Spectral Channel 1
dichroics
Deformable mirrors
apodizer
low order aberrations
focal plane occulter
CLOWFS 1
detector
mid−spatial frequencies
science detector
band 1.1
Inverse PIAA
science detector
band 1.2
Inverse PIAA
science detector
band 1.3
Inverse PIAA
science detector
band 1.4
Inverse PIAA
dichroics

9.5 PIAA optics sets made so far:

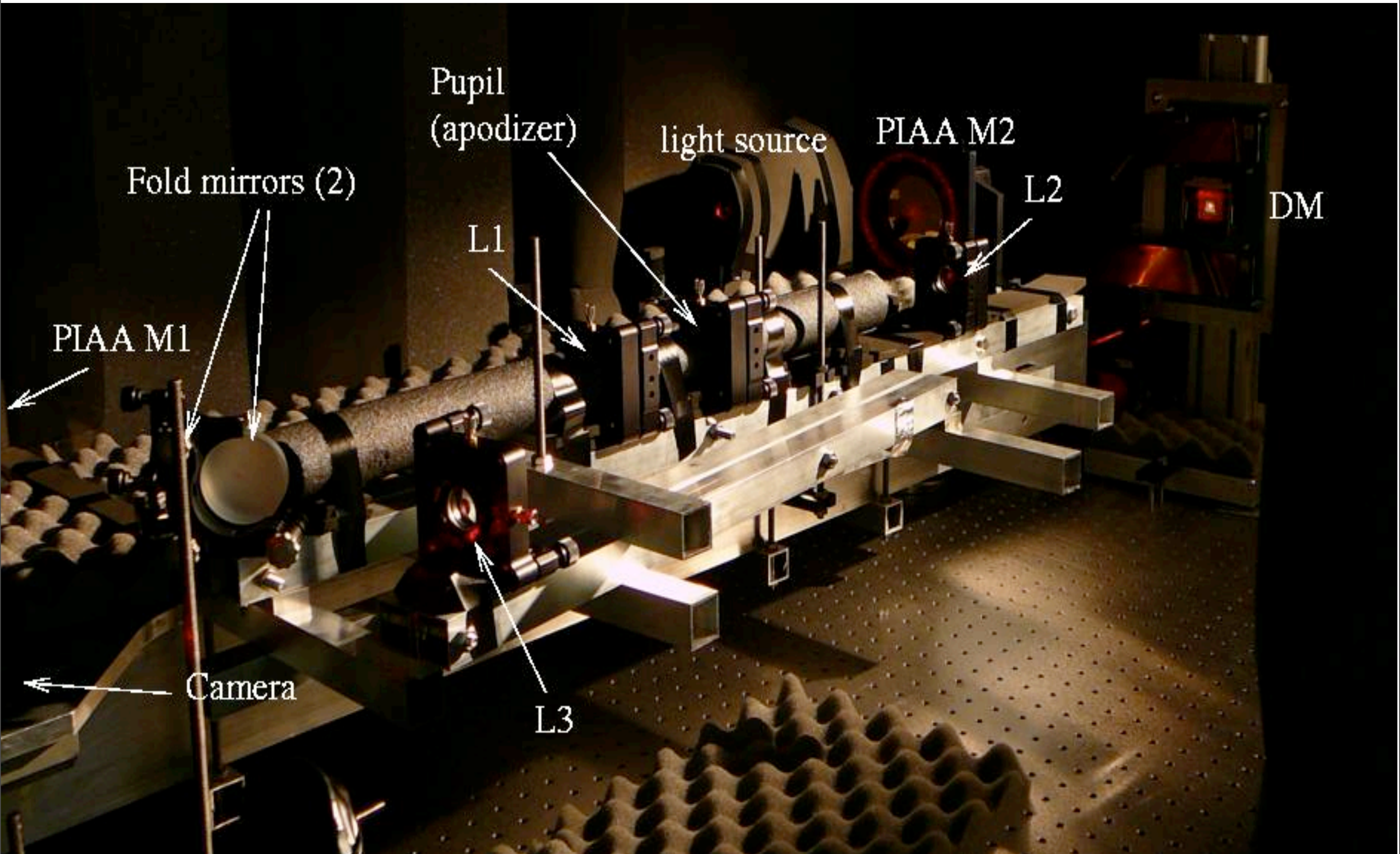
1 refractive PIAA system, diamond turned plastic [NAOJ]
2 reflective PIAA systems, Nickel-plated diamond turned Al (1 design x2) [Axsys]
6 refractive PIAA systems, diamond turned CaF2 (3 designs x2) [Axsys]
+ 1 reflective PIAA system, Zerodur, currently in manufacturing [Tinsley]

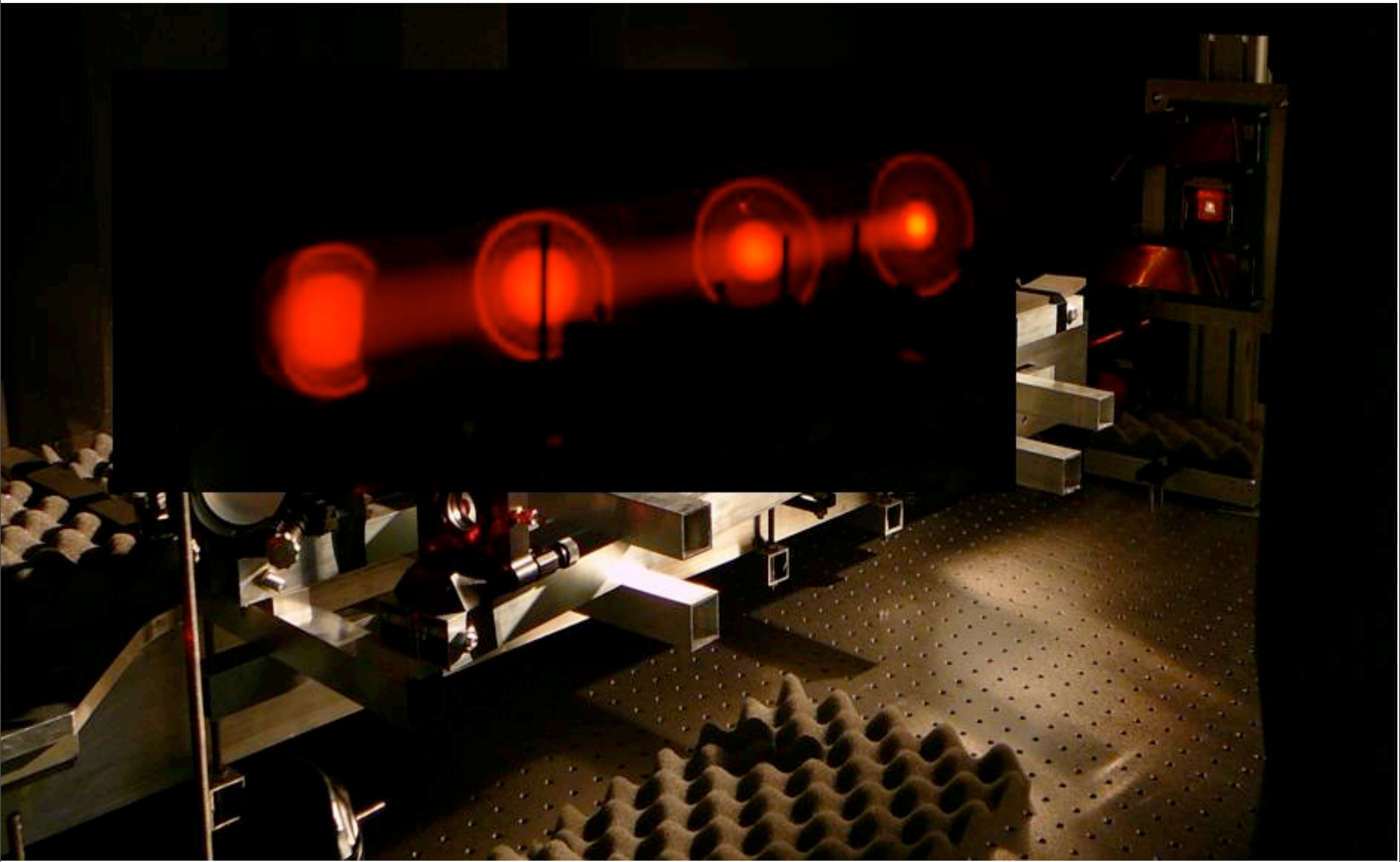


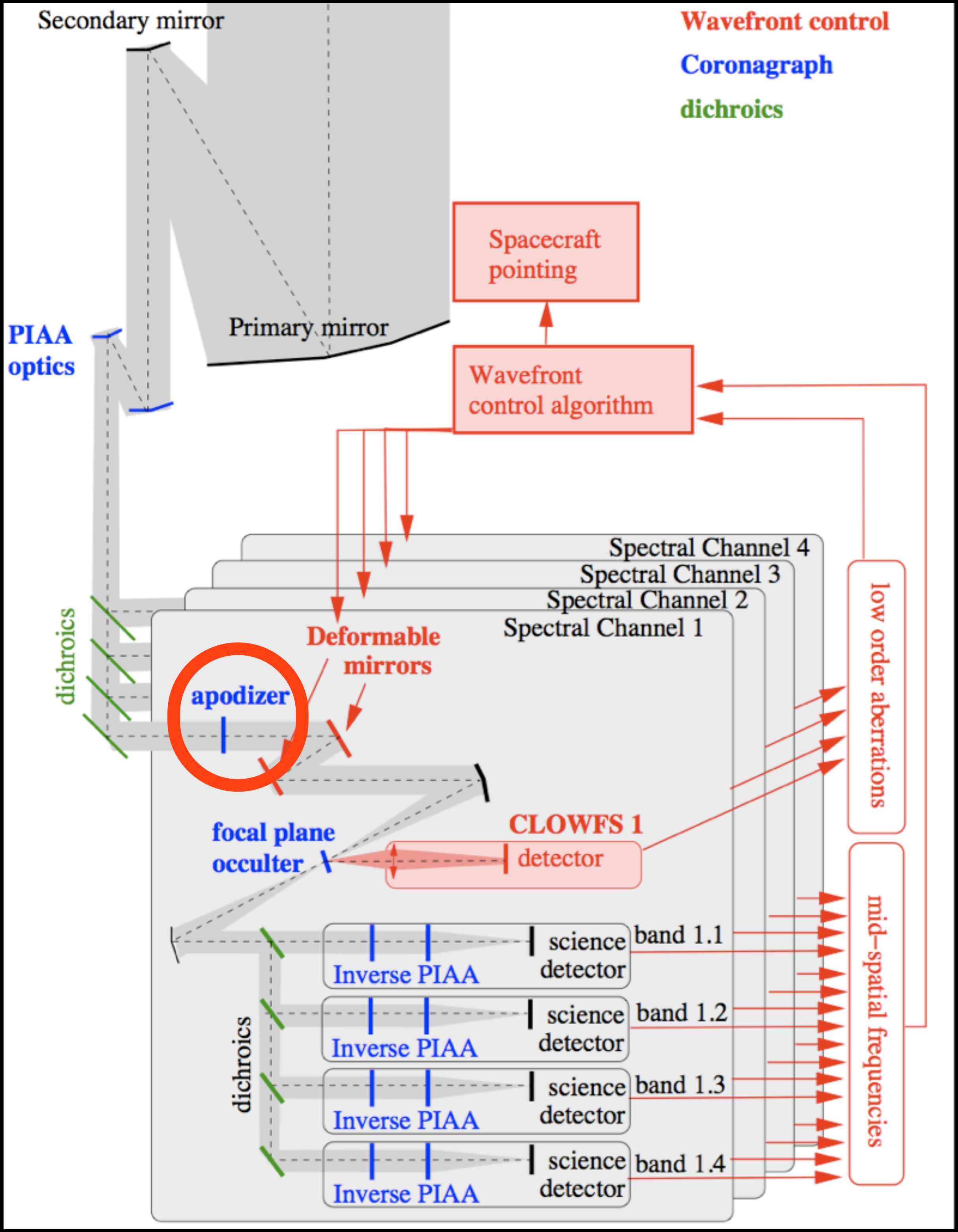




Subaru lab experiment
co-funded by Subaru/NAOJ & JPL







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detector
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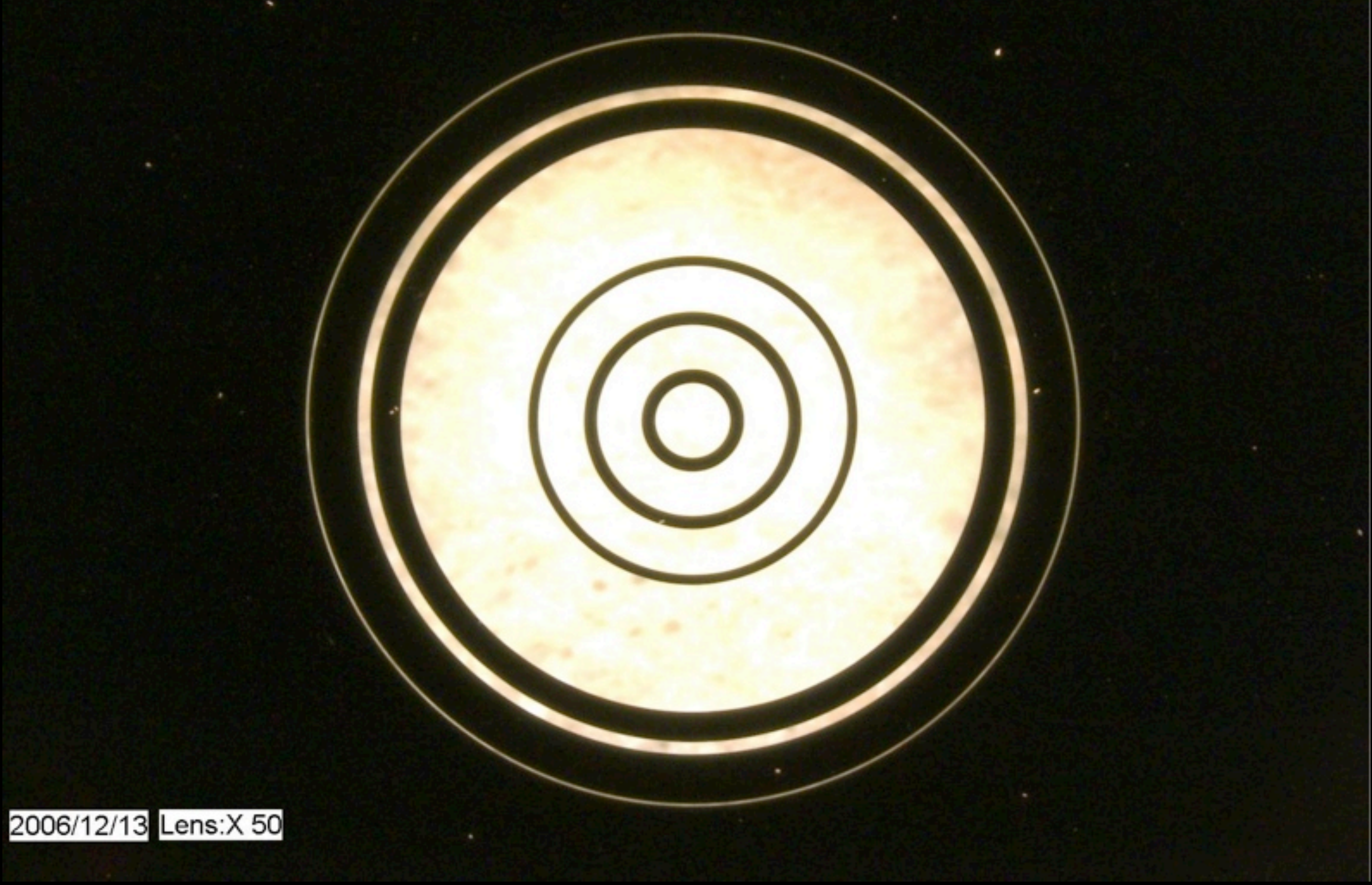
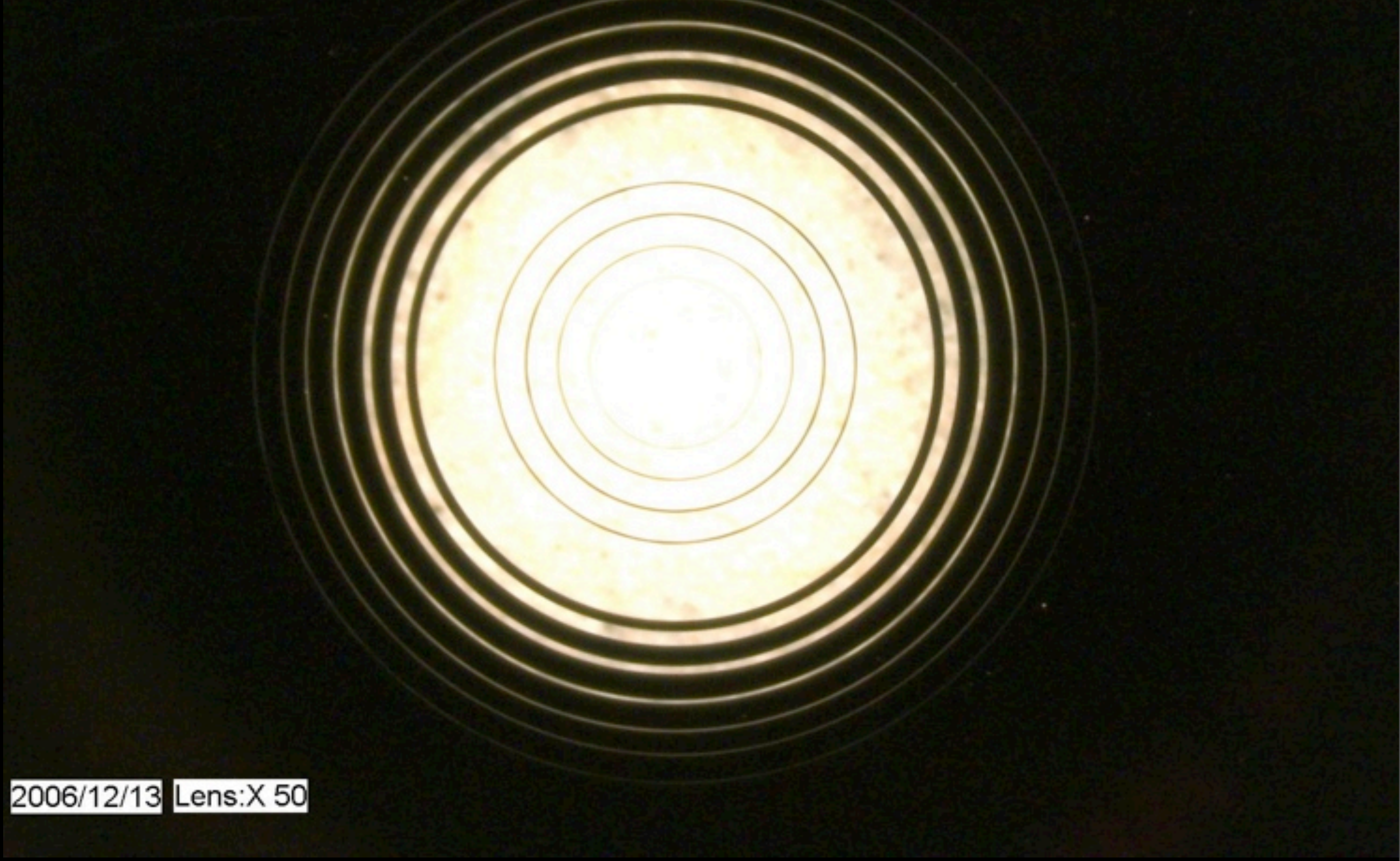
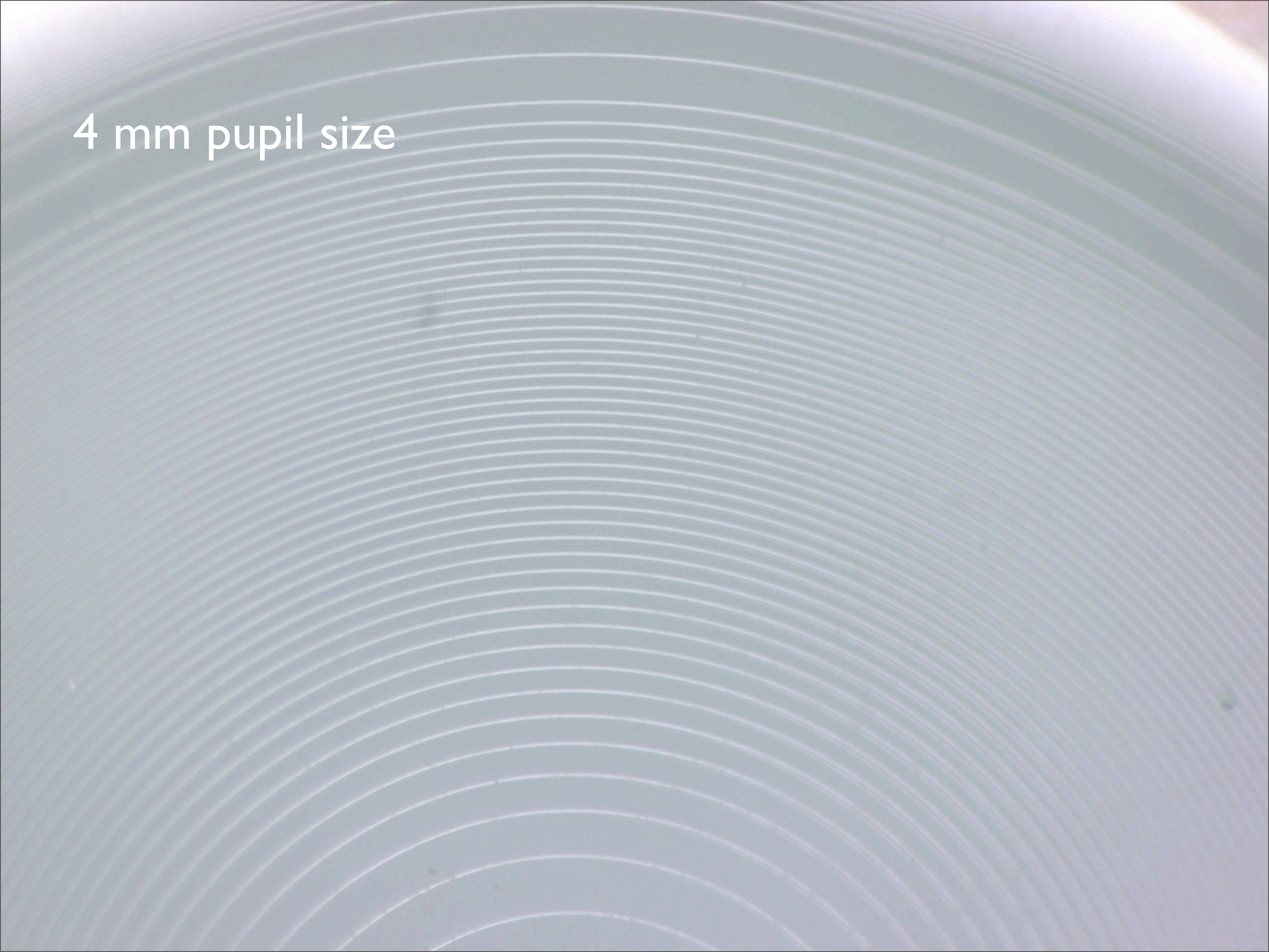
science detector
band 1.1
band 1.2
band 1.3
band 1.4
dichroics
mid–spatial frequencies

4 mm pupil size

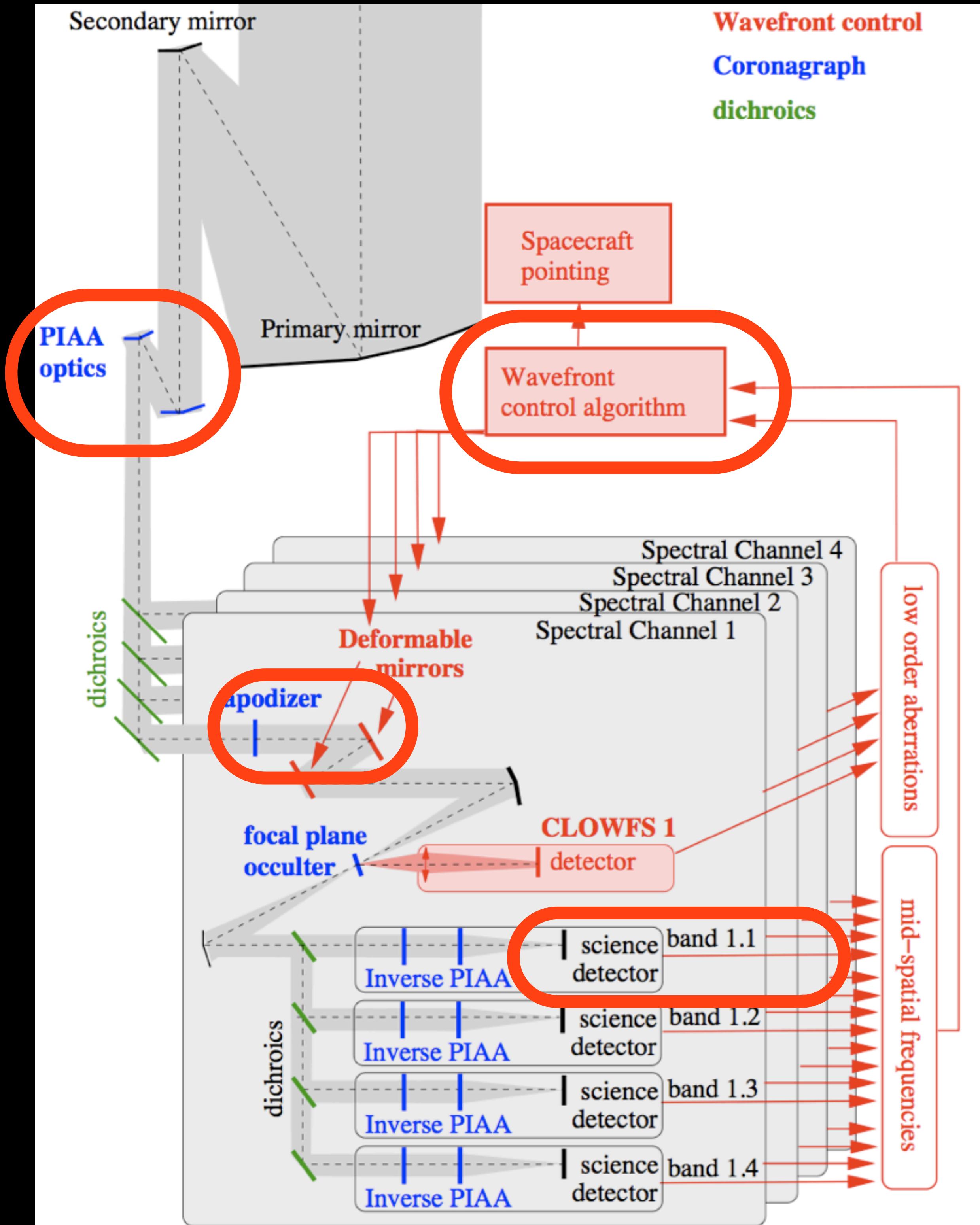


4 mm pupil size




4 mm pupil size

4 mm pupil size



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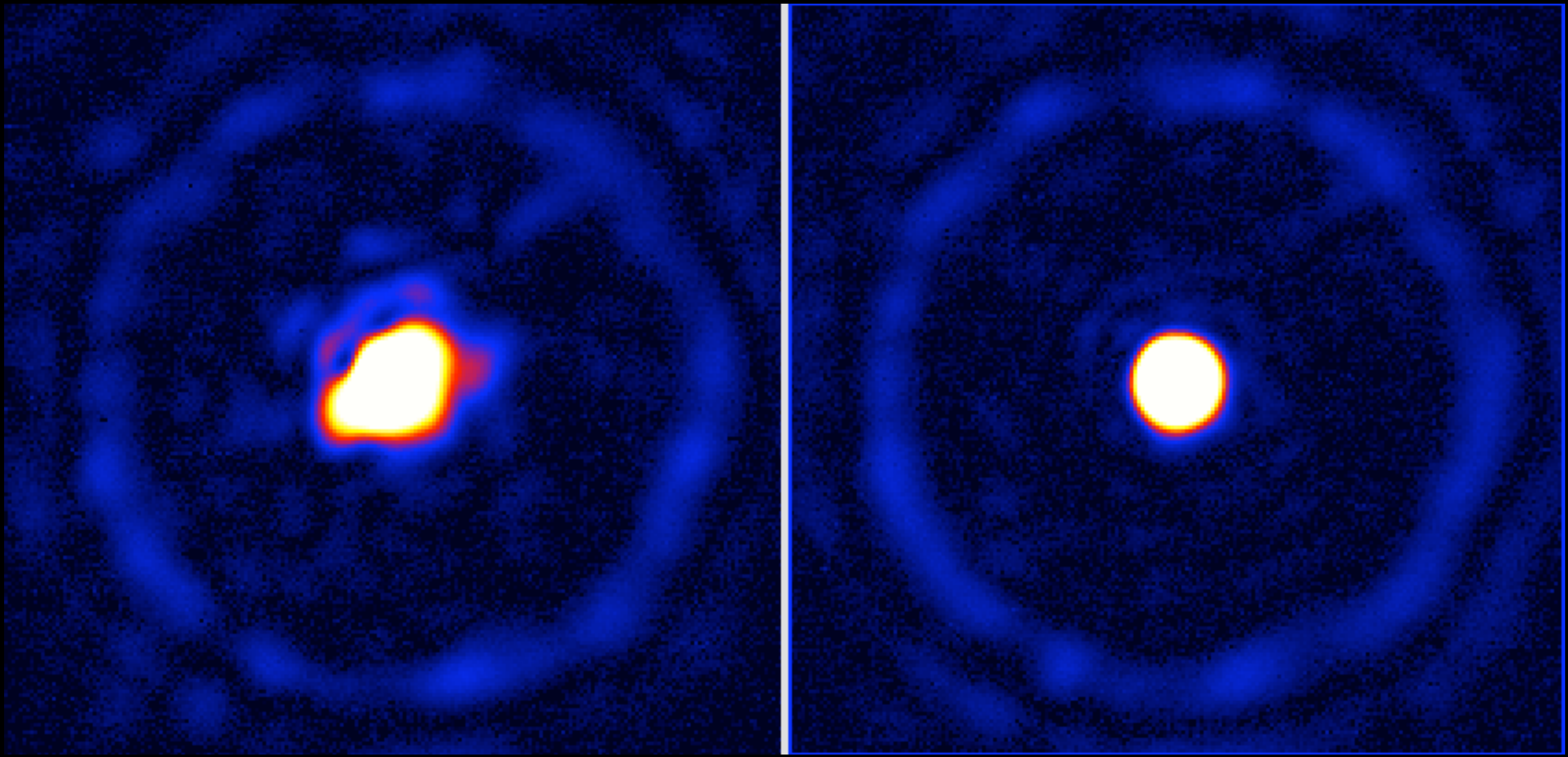
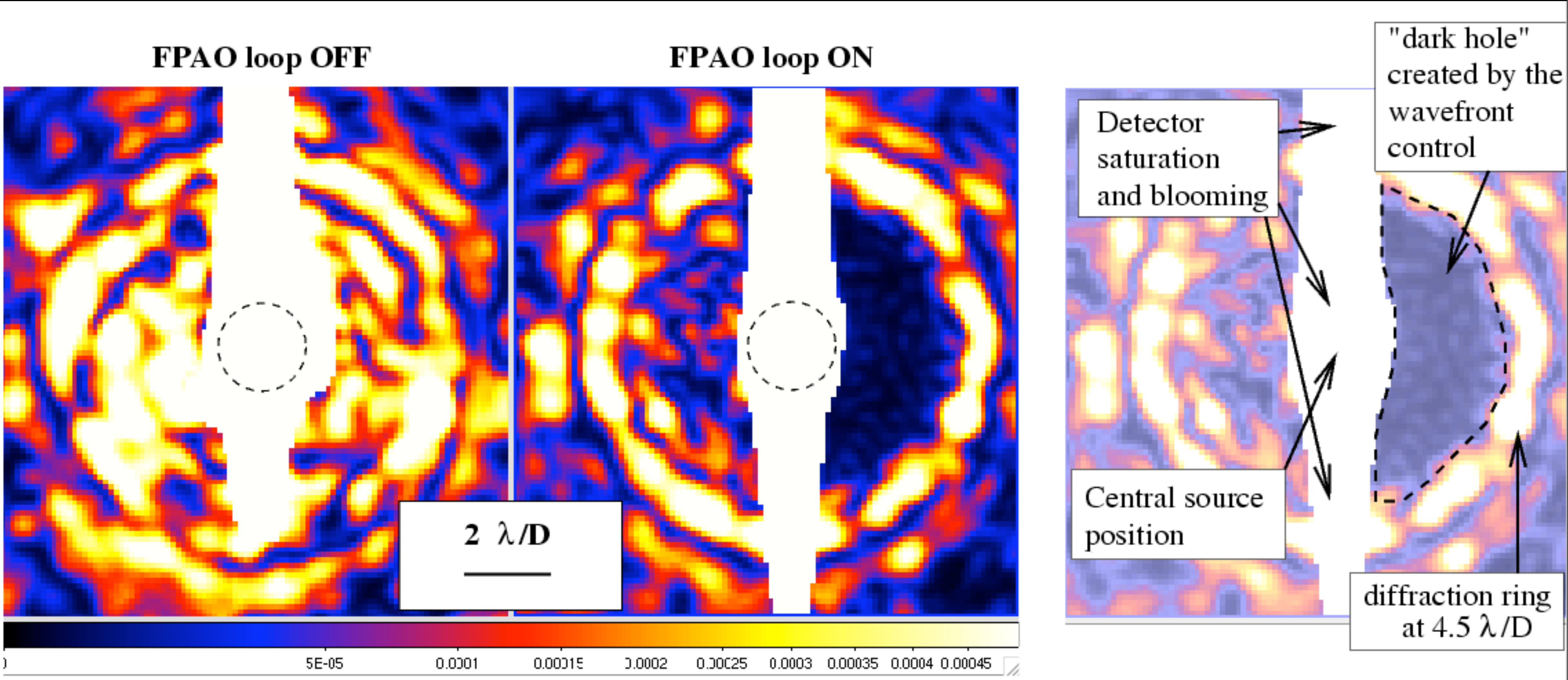
dichroics
mid−spatial frequencies

Lab results with PIAA coronagraph + FPAO



Step 1: phase diversity -> DM correction

Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM



See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)

Next important step is to test PIAA coronagraph in High Contrast Imaging Testbed @ NASA JPL

New refractive PIAA optics which are being polished for this 1e-10 polychromatic contrast test (Funding: NASA Ames)

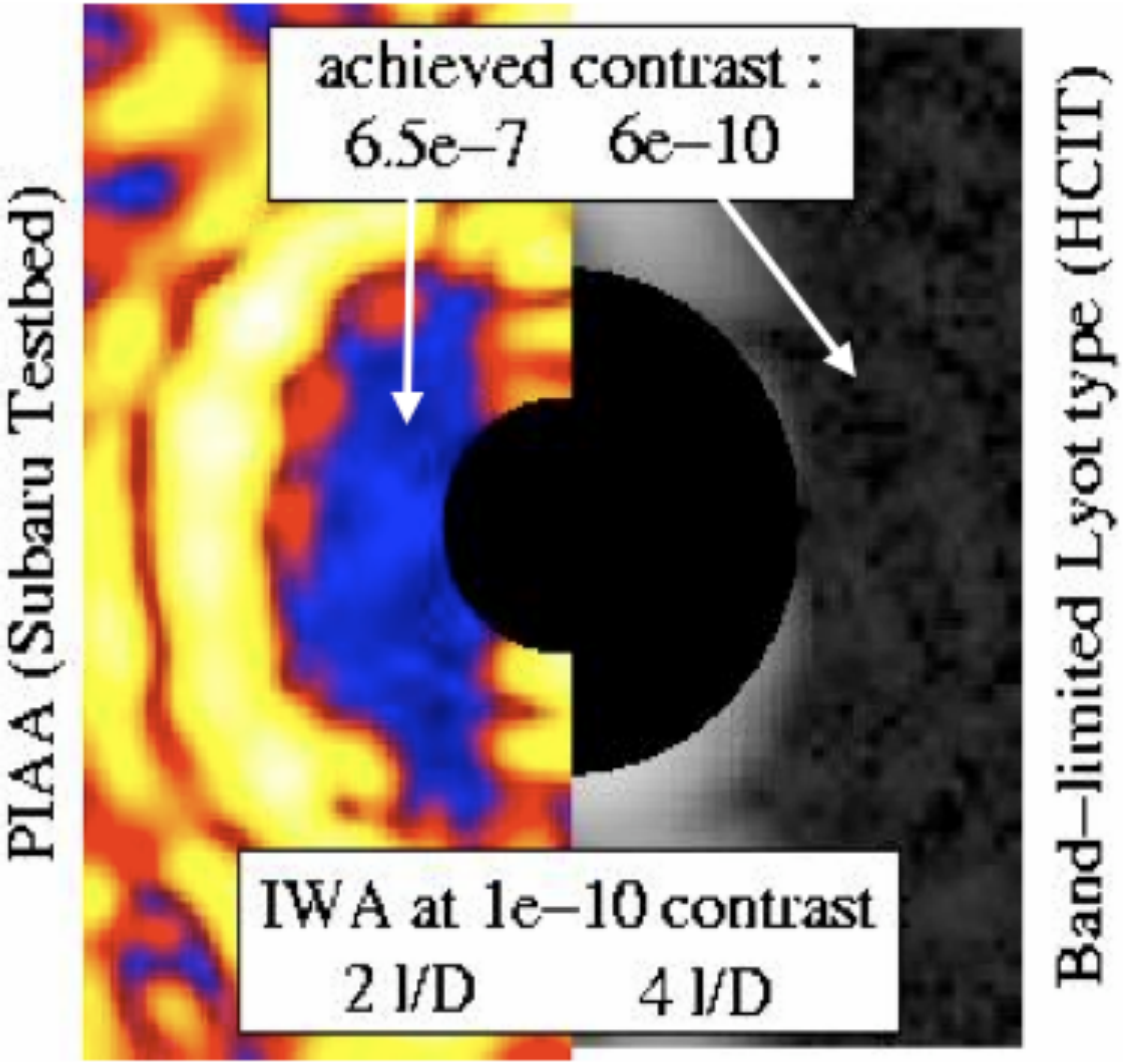
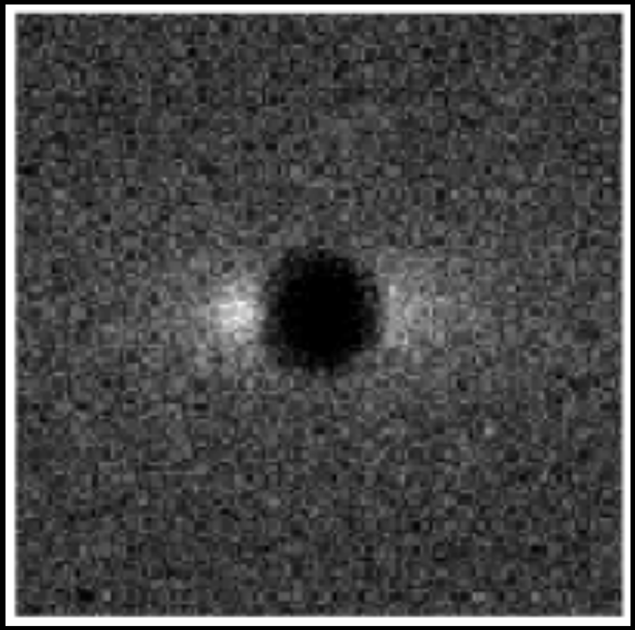
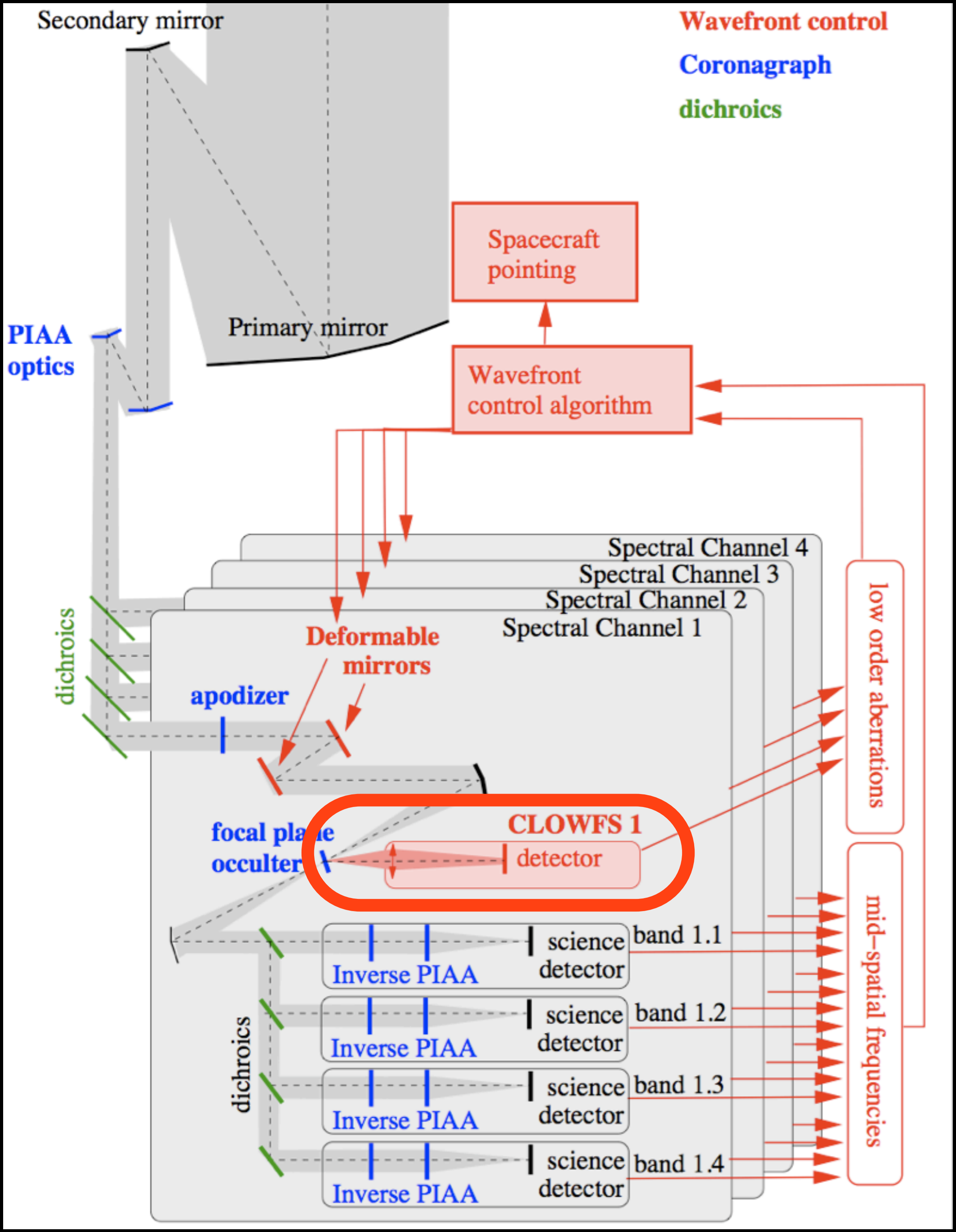


Figure 1.3-2 Comparison between the IWA of a PIAA coronagraph and a Lyot-type band limited coronagraph. Actual laboratory PSFs are shown at the same scale. The high sensitivity regions are in blue (PIAA) and black (band limited).

0.4 mas pointing accuracy

0.13 mas pointing knowledge





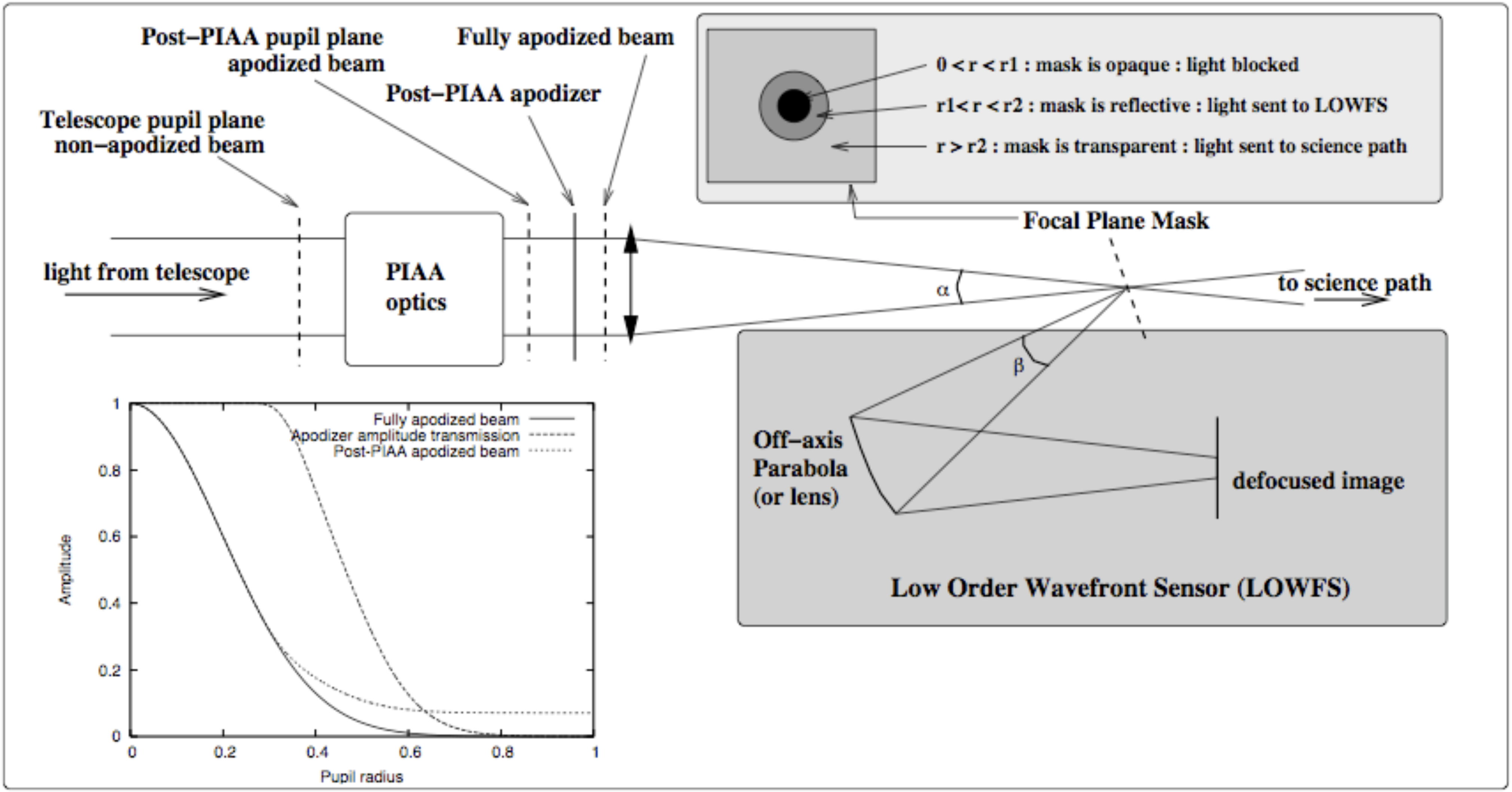


Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

Guyon, Matsuo, Angel, 2008 - to be submitted
Can also be applied to phase mask type coronagraphs (Matsuo & Guyon, in preparation)

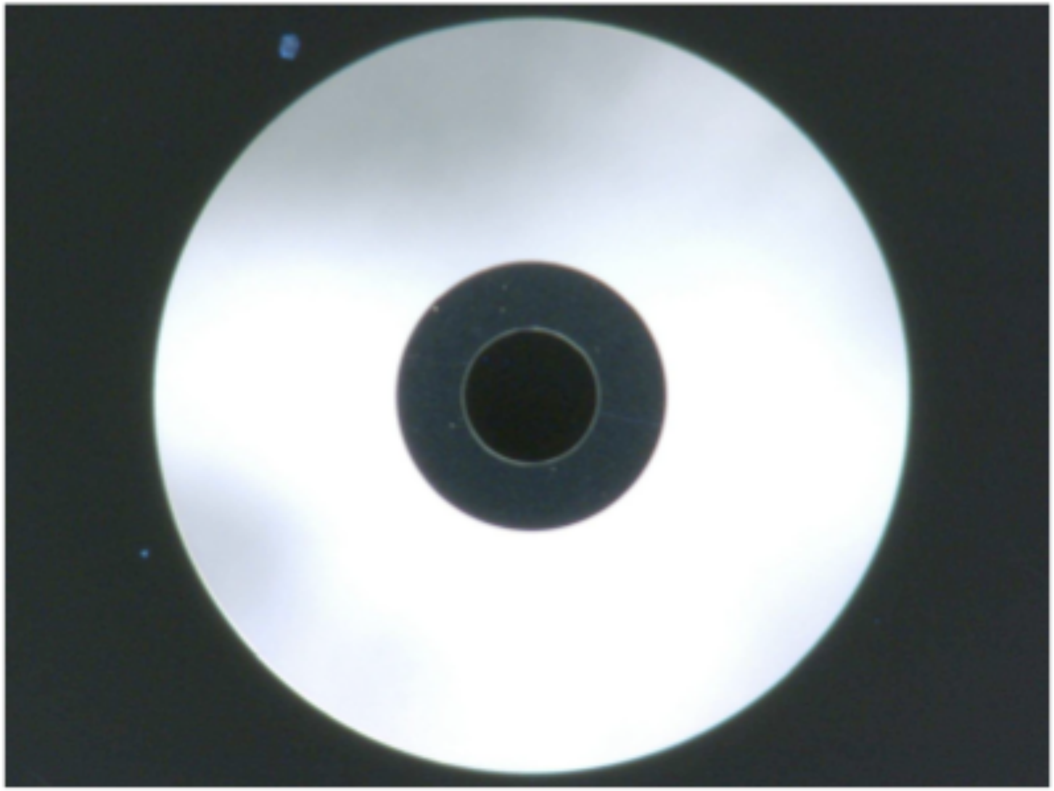
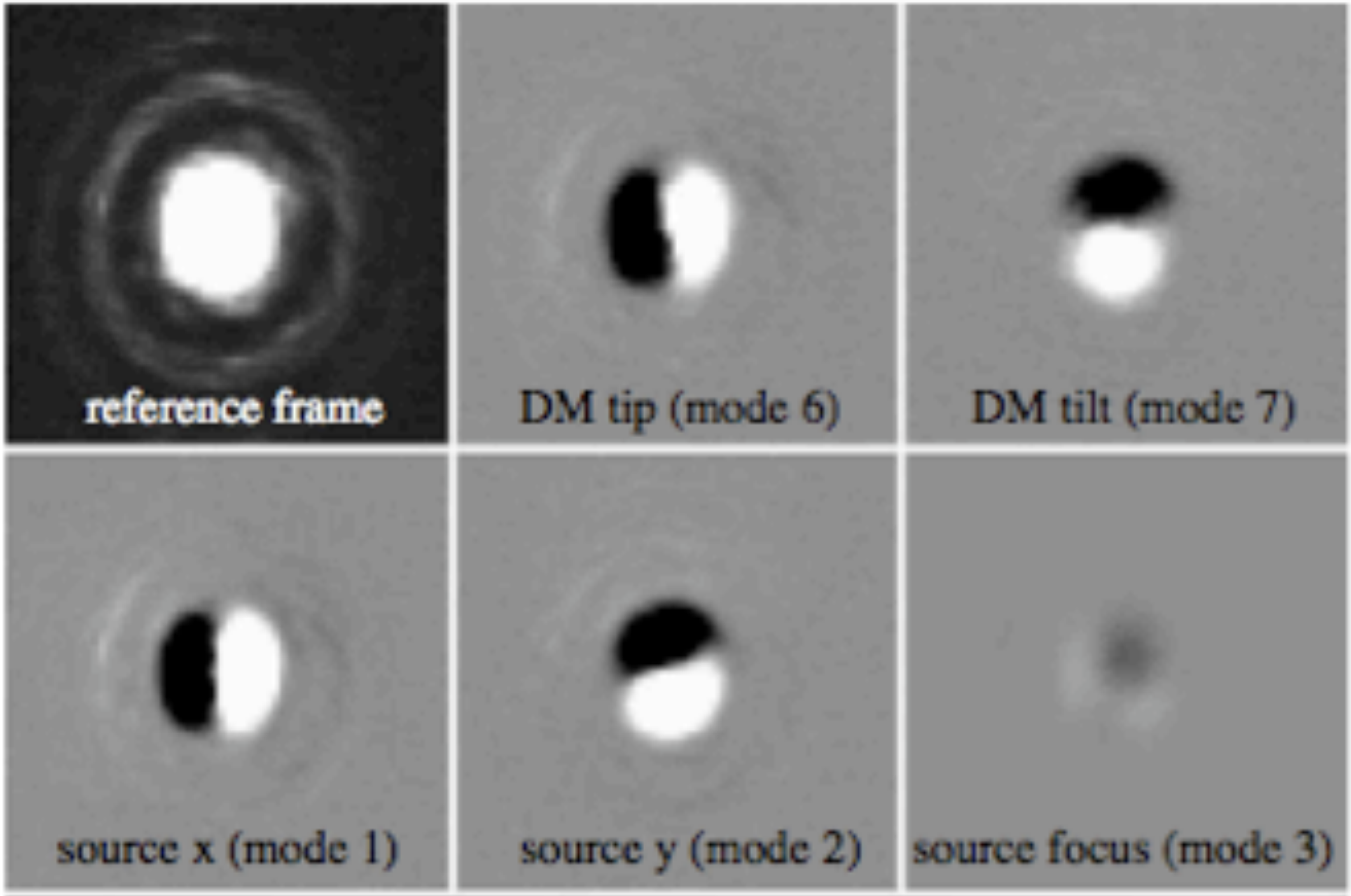
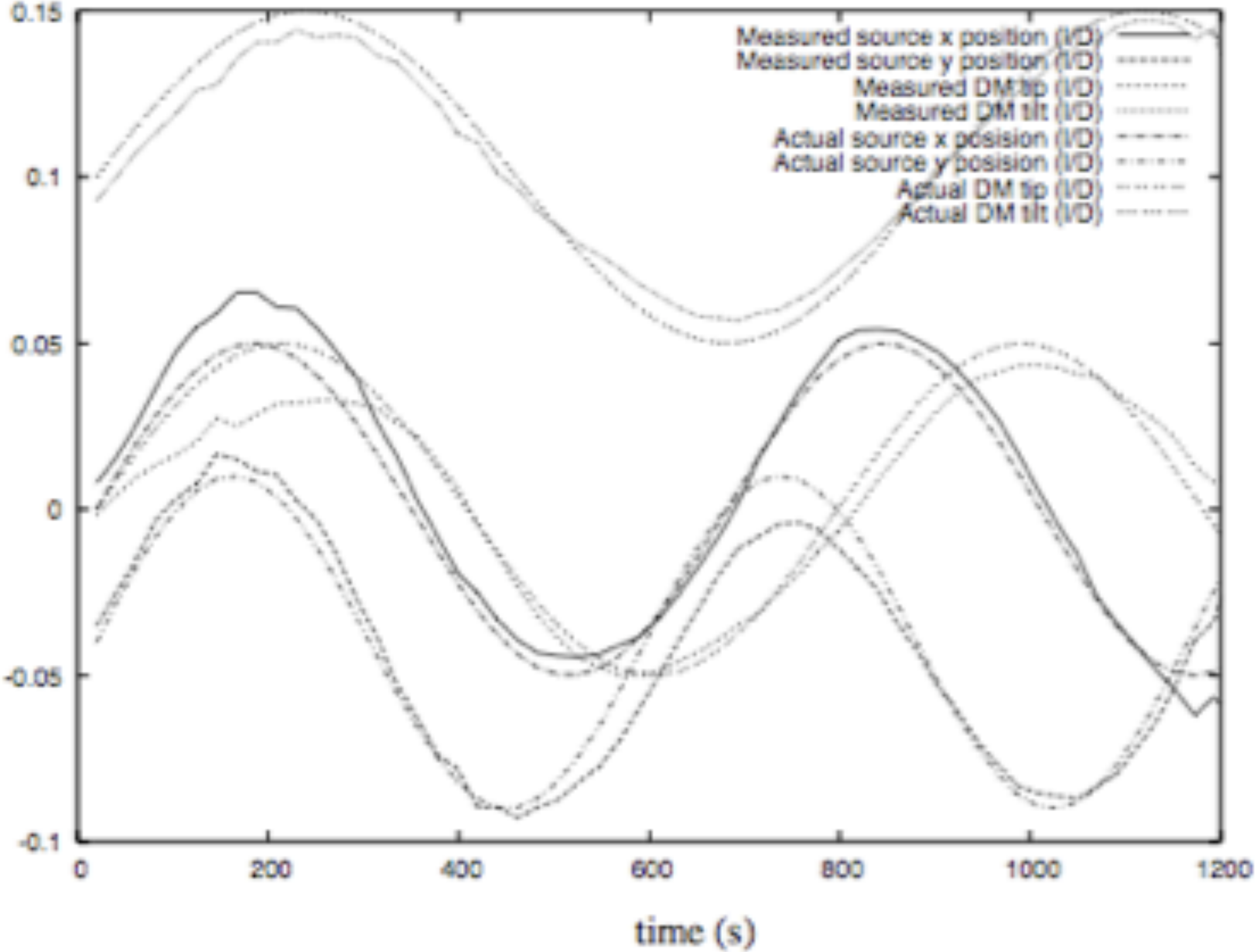


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from 200 micron to 550 micron radius.

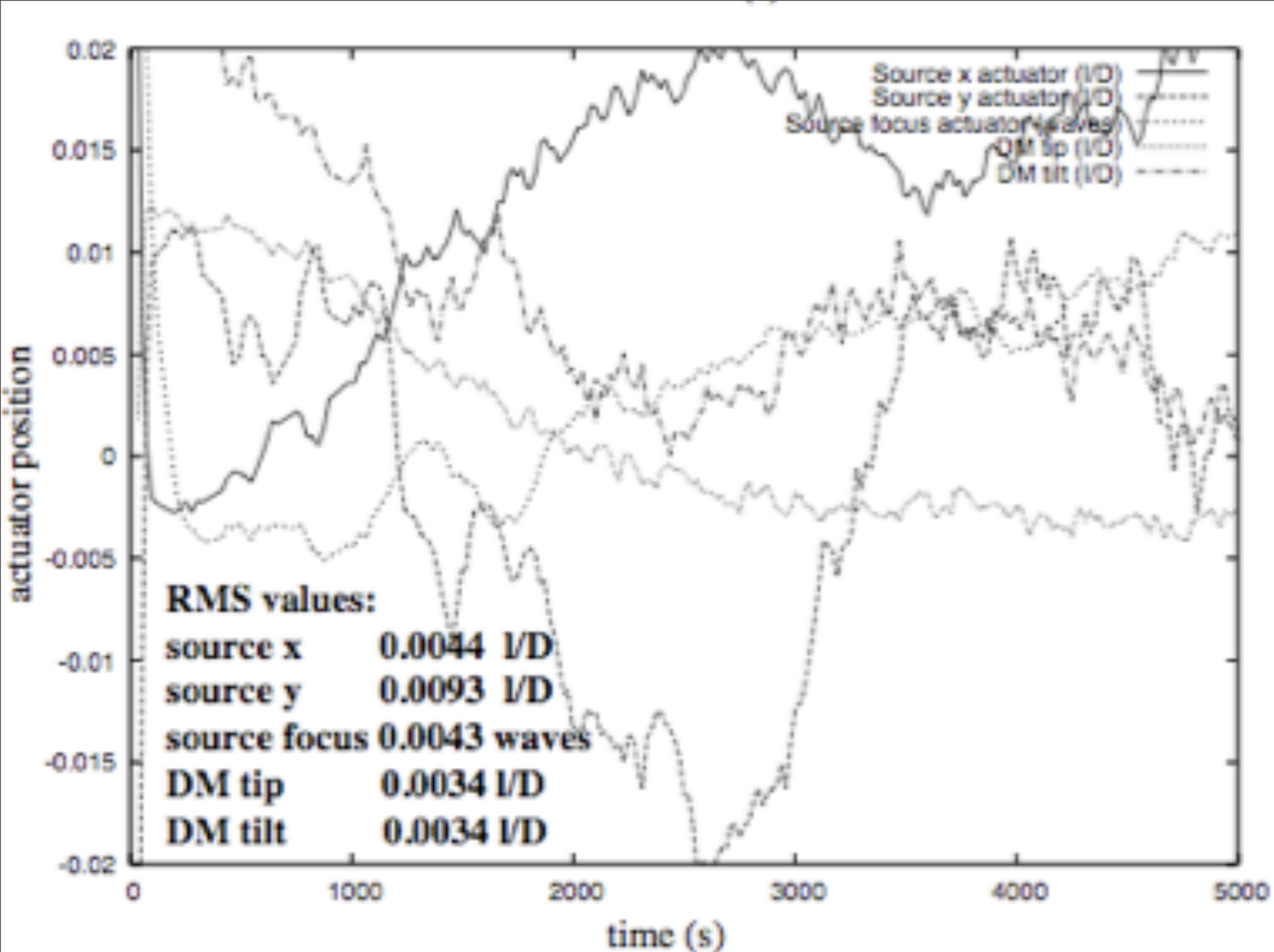
Why a central dark spot?

(1) Signal amplification
(2) Accurate reference

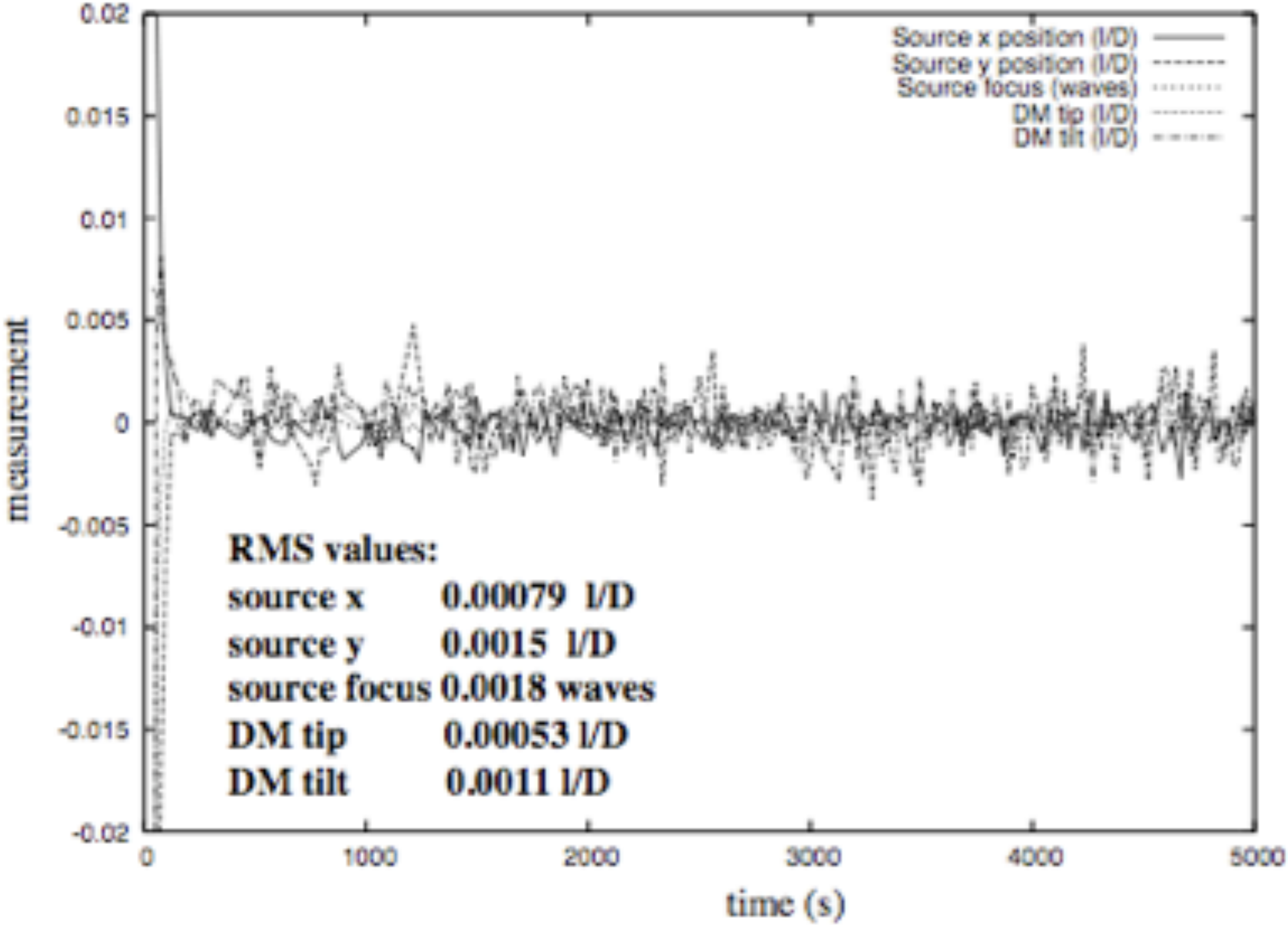

reference frame
DM tip (mode 6)
DM tilt (mode 7)
source x (mode 1)
source y (mode 2)
source focus (mode 3)



Measured source x position (l/D)
Measured source y position (l/D)
Measured DM tip (l/D)
Measured DM tilt (l/D)
Actual source x posision (l/D)
Actual source y posision (l/D)
Actual DM tip (l/D)
Actual DM tilt (l/D)
0.15
0.1
0.05
0
-0.05
-0.1
0
200
400
600
800
1000
1200
time (s)



Source x actuator (l/D)
Source y actuator (l/D)
Source focus actuator (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.0044 l/D
source y 0.0093 l/D
source focus 0.0043 waves
DM tip 0.0034 l/D
DM tilt 0.0034 l/D
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
actuator position
0
1000
2000
3000
4000
5000
time (s)



Source x position (l/D)
Source y position (l/D)
Source focus (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.00079 l/D
source y 0.0015 l/D
source focus 0.0018 waves
DM tip 0.00053 l/D
DM tilt 0.0011 l/D
measurement
time (s)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
1000
2000
3000
4000
5000

TABLE 1

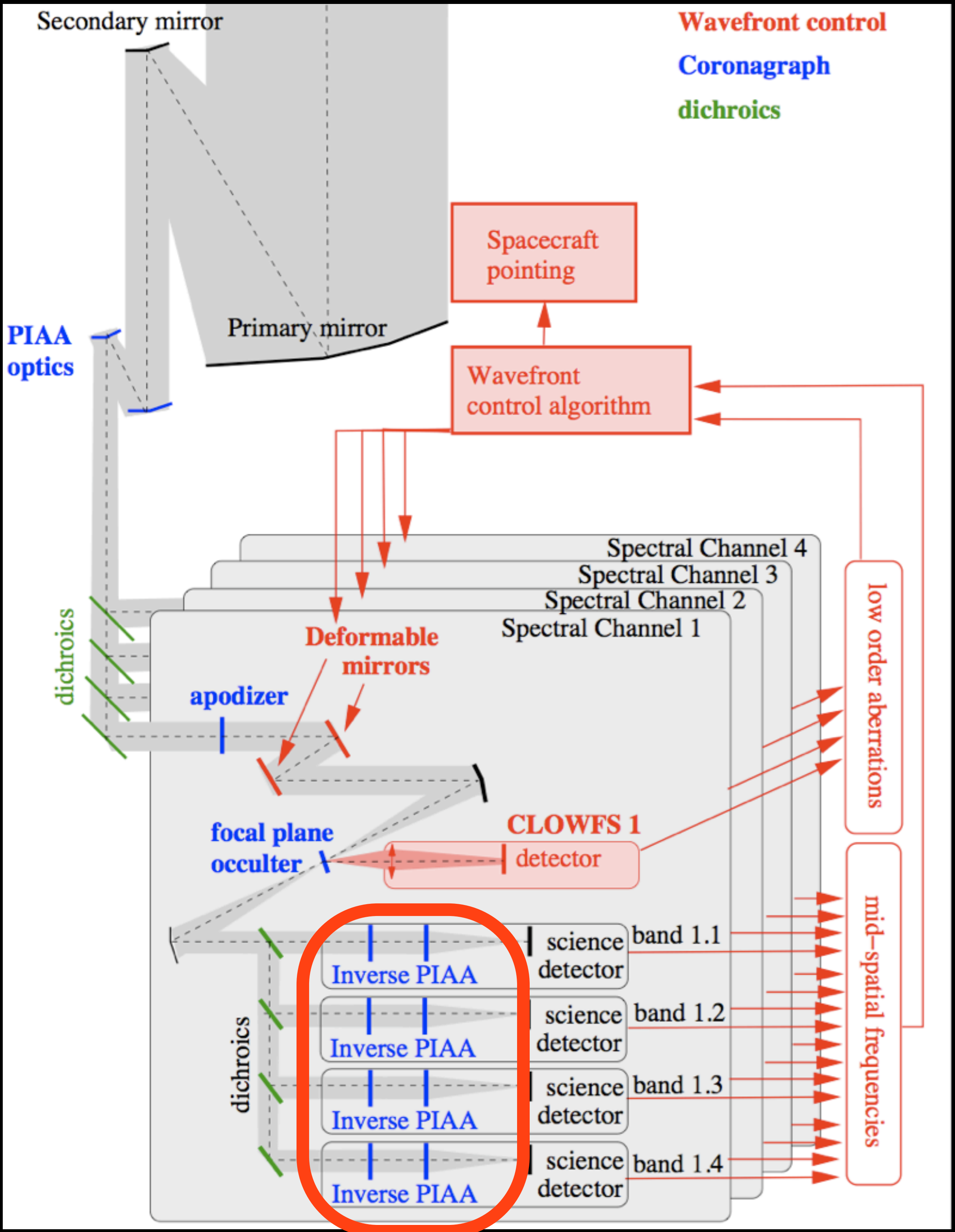
POINTING STABILITY REQUIREMENTS FOR A PIAA CORONAGRAPH WITH AND WITHOUT CLOWFS [a]

	Without CLOWFS	With CLOWFS
Required pointing calibration accuracy	0.0016 λ/D (0.13 mas)	
Maximum RMS pointing excursion	0.005 λ/D (0.4 mas)	
Required sampling time[b]	5 s[c]	38 μs
Maximum allowed uncalibrated pointing drift rate	0.026 mas/s	3.4 arcsec/s

[a]For a $m_V = 6$ star observed with a 1.4-m telescope in a 0.2μm wide band centered at 0.55 μm with a 50% system throughput.

[b]Sampling time required to measure the pointing error with a 1-σ error equal to the "Required pointing calibration accuracy".

[c]Assumes that 50% of the observing time is dedicated to measurement of low order aberrations. Also assumes that the signal is well above readout noise and zodi/exozodi background.



Wavefront control
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dichroics
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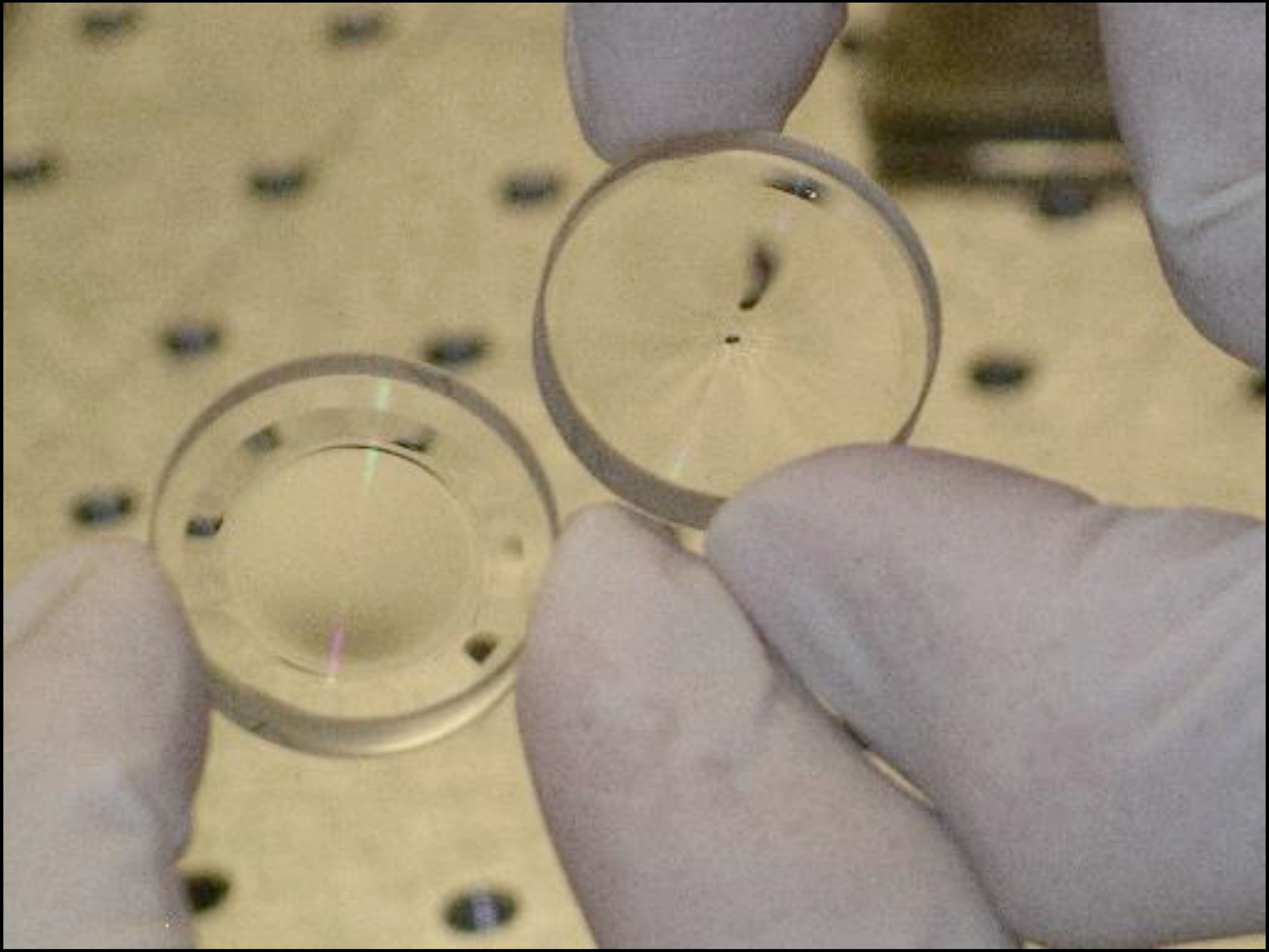
science detector
band 1.3
Inverse PIAA
science detector
band 1.4
mid–spatial frequencies

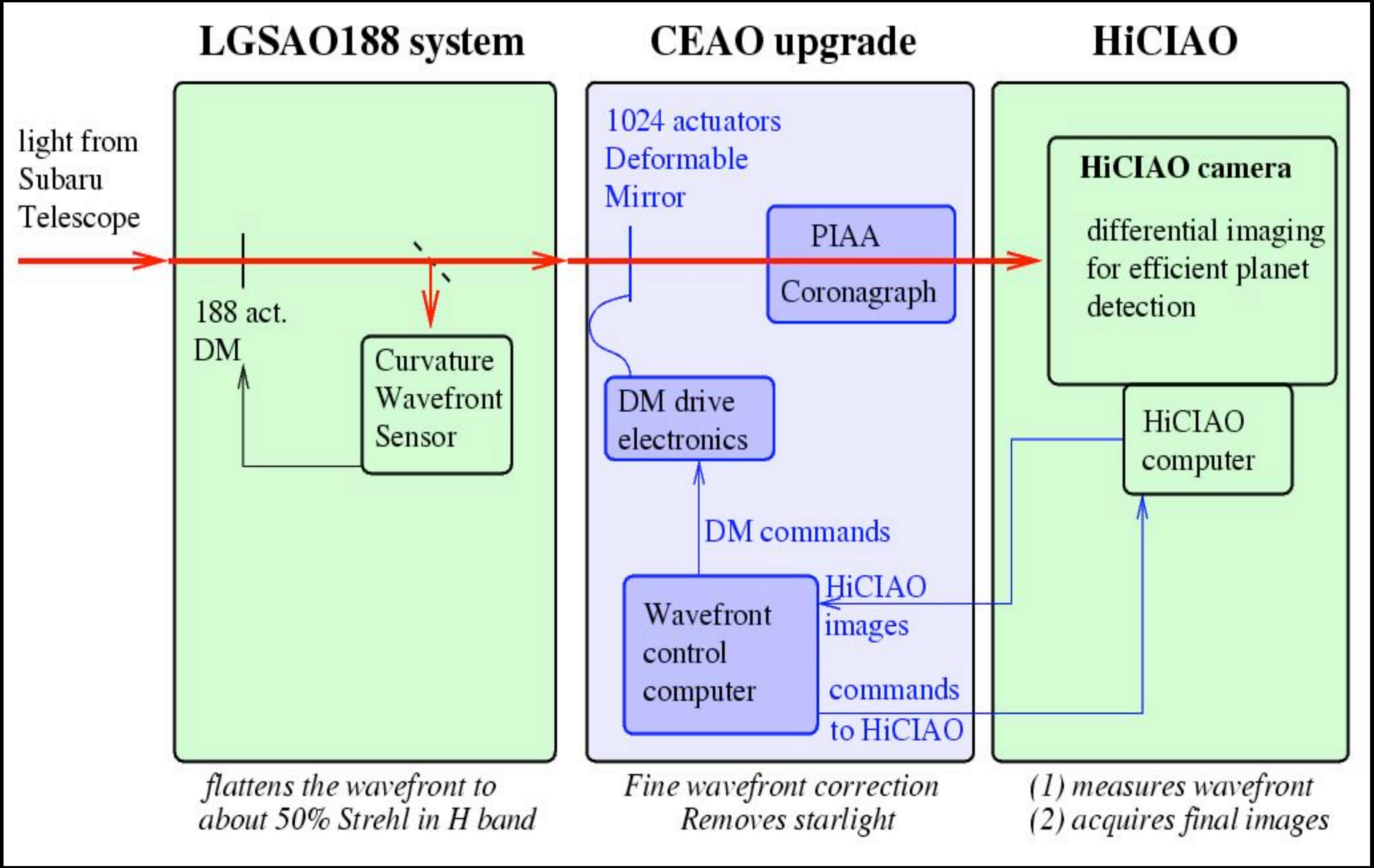
PIAA refractive optics (CaF2)

6 CaF2 refractive PIAA systems have been made so far (3 different designs)

One design also removes central obstruction for Subaru



Subaru Telescope
Coronagraphic ExAO system architecture



We are hiring a postdoc for Subaru Coronagraphic ExtremeAO system and PIAA technology development: www.naoj.org

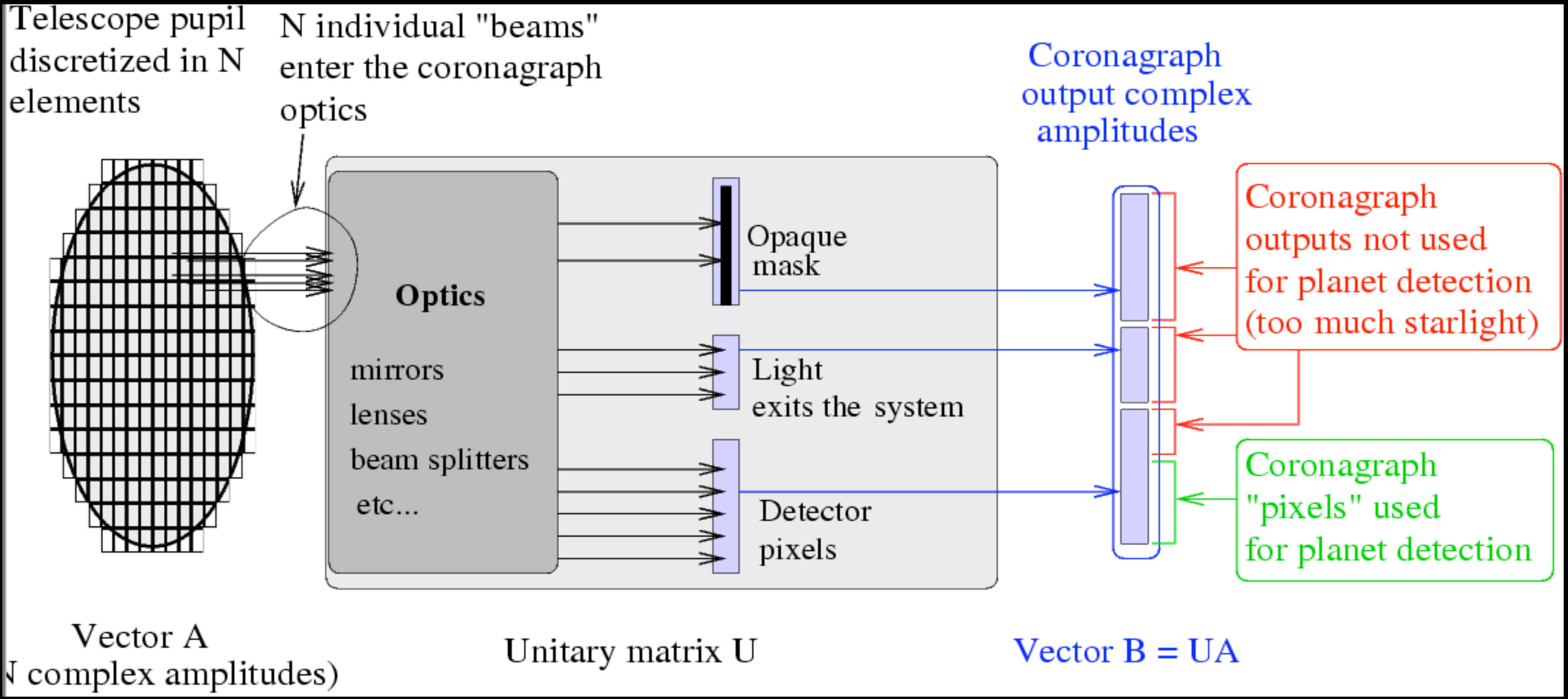
More info on coronagraph on:

www.naoj.org/PIAA

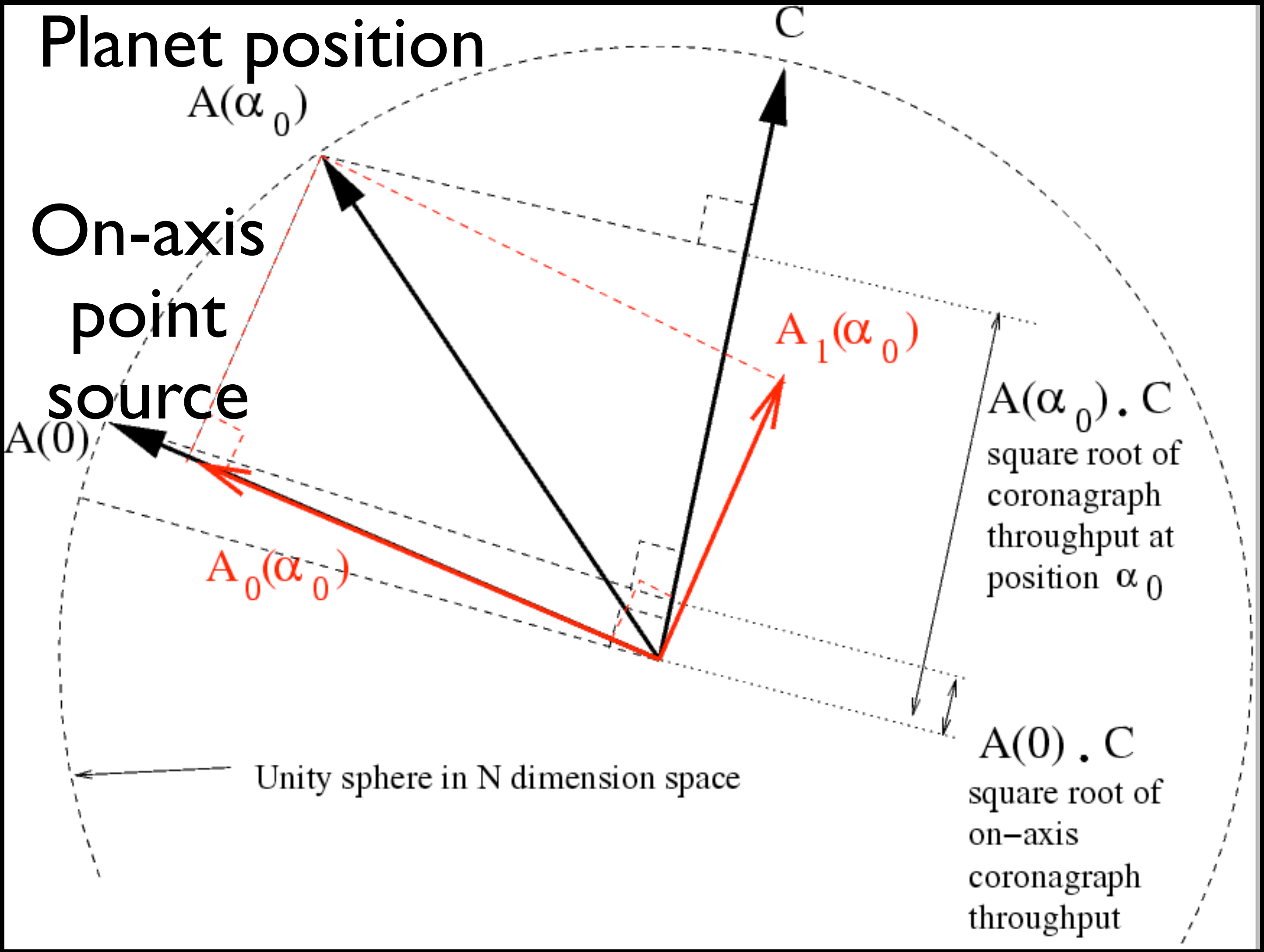
guyon@naoj.org

Coronagraph model

Linear system in complex amplitude
Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: **all are linear**

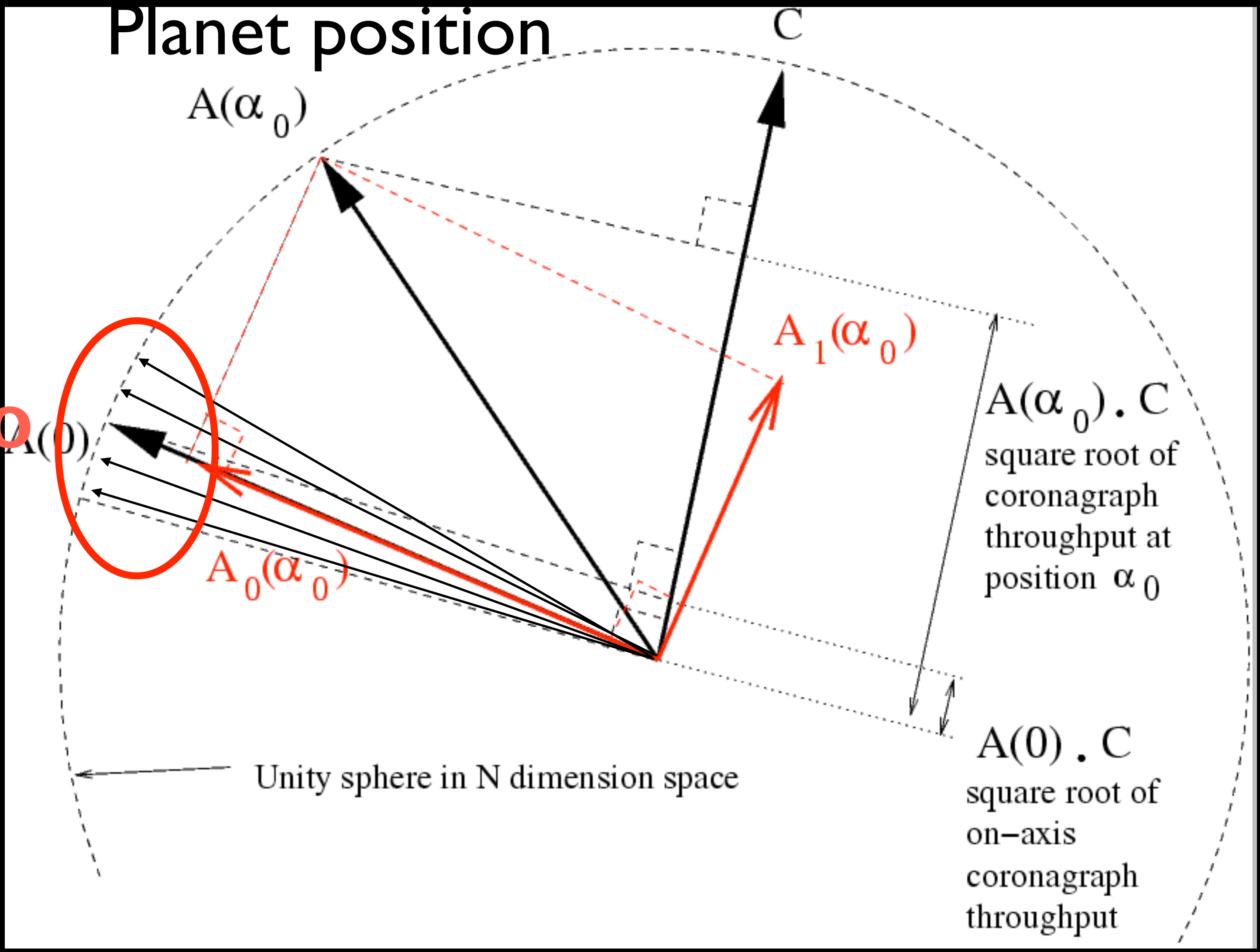


Graphical representation of the coronagraph throughput

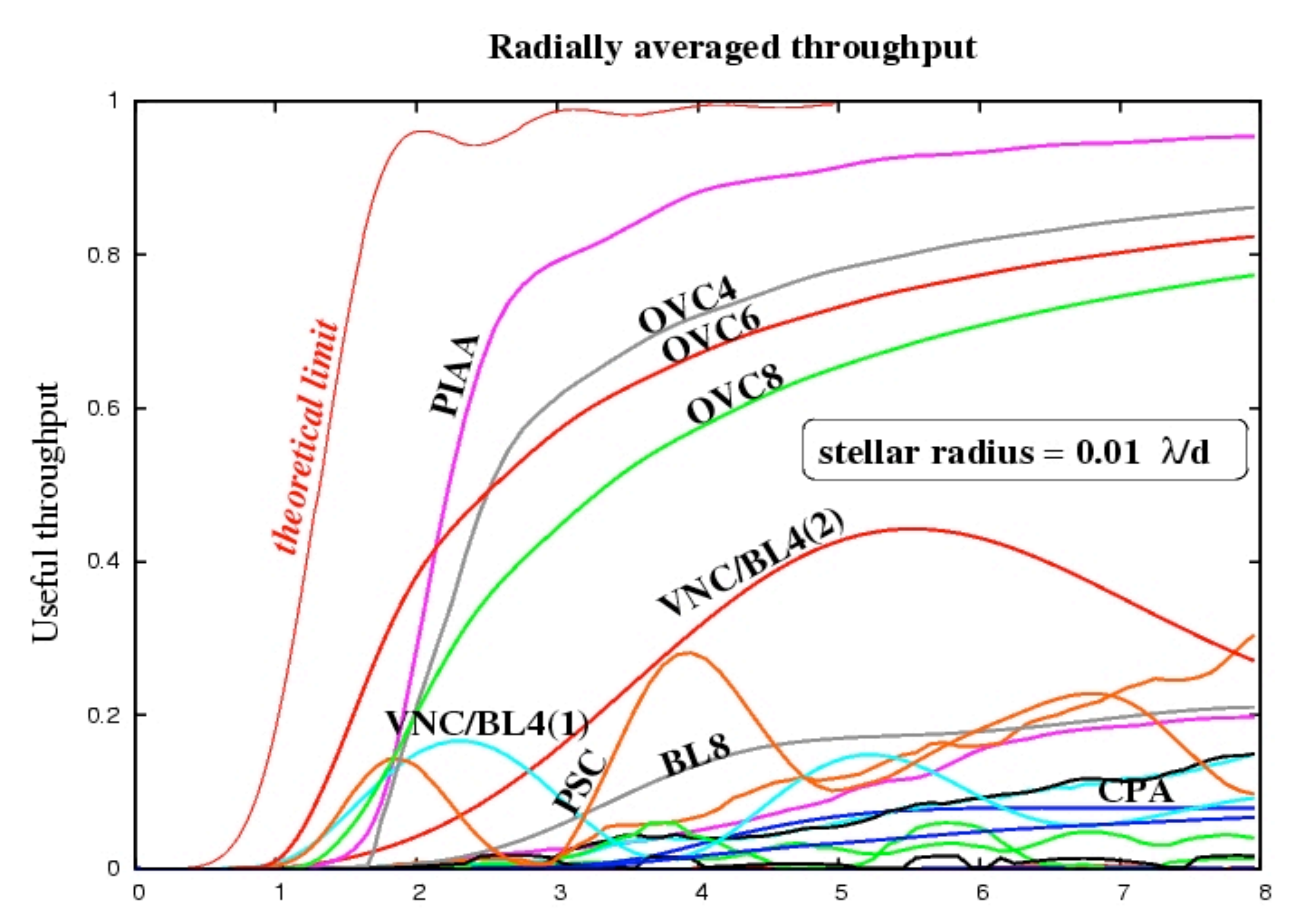


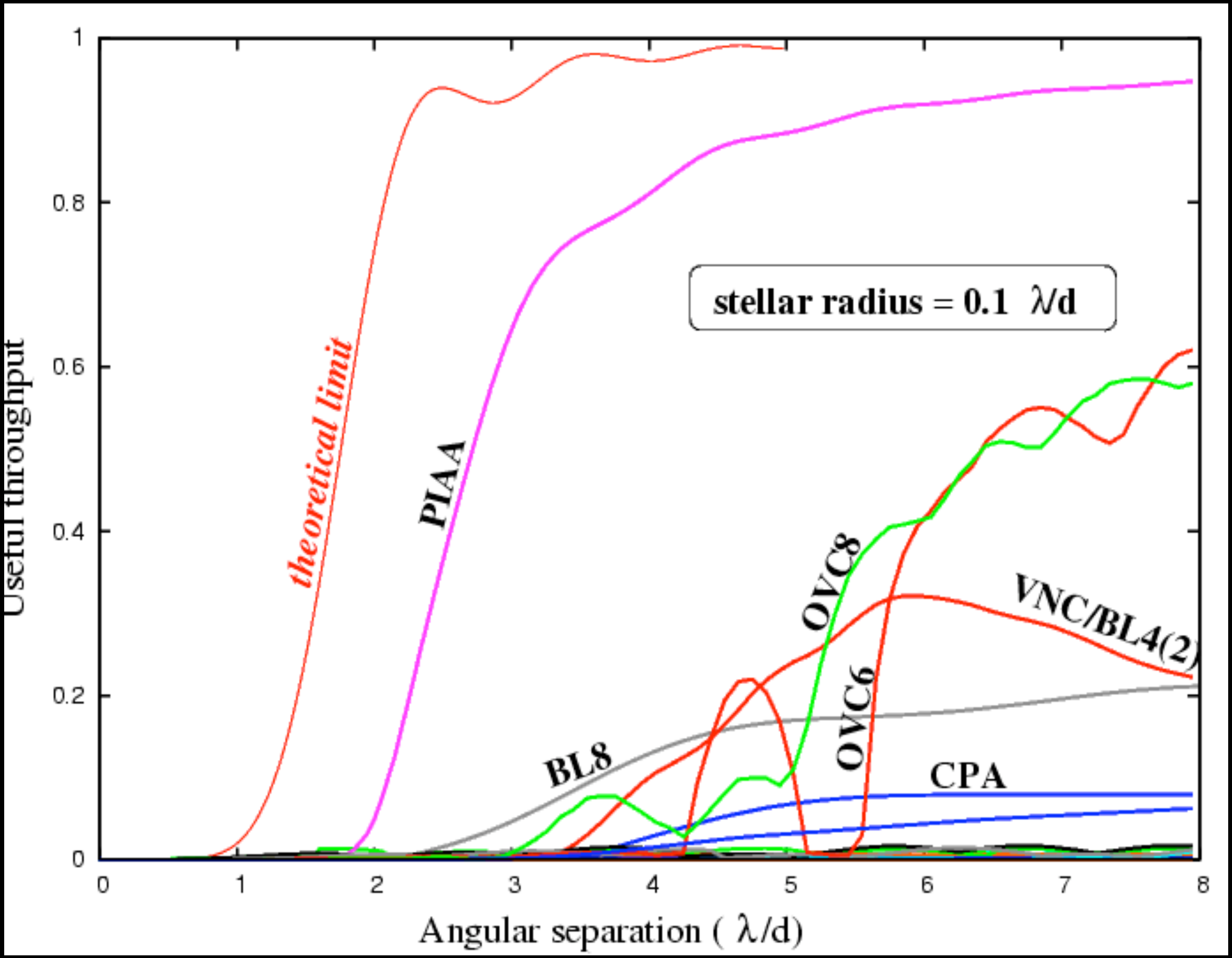
Graphical representation of the coronagraph throughput

Central star is made
of a group of vectors,
ALL of which need to
be cancelled to some
degree.

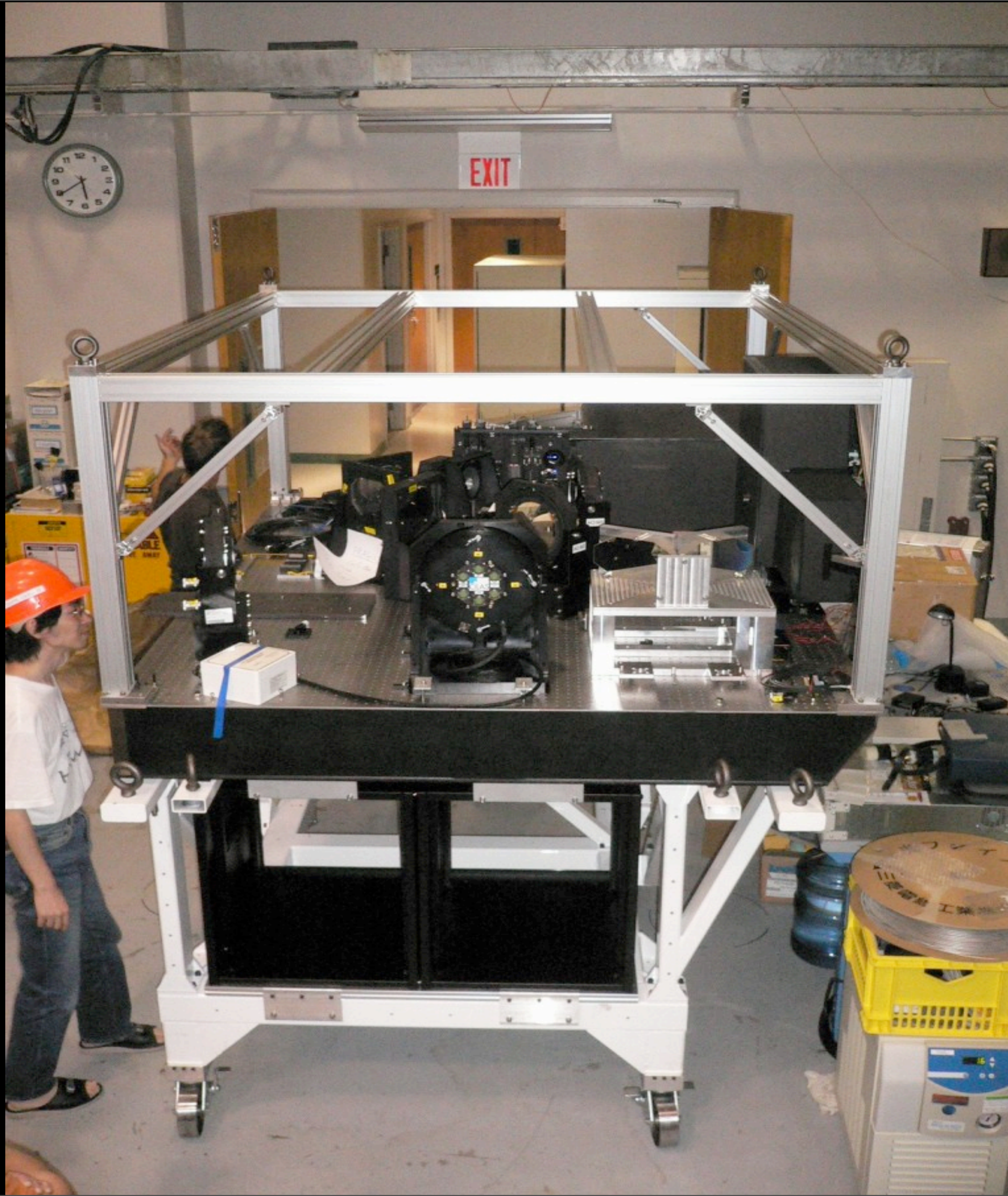


Problem: stars are not points !
Sun diameter ~1% of 1 AU
If 1AU=2 l/d, Stellar radius ~ 0.01 l/d
Wavefront control cannot solve it

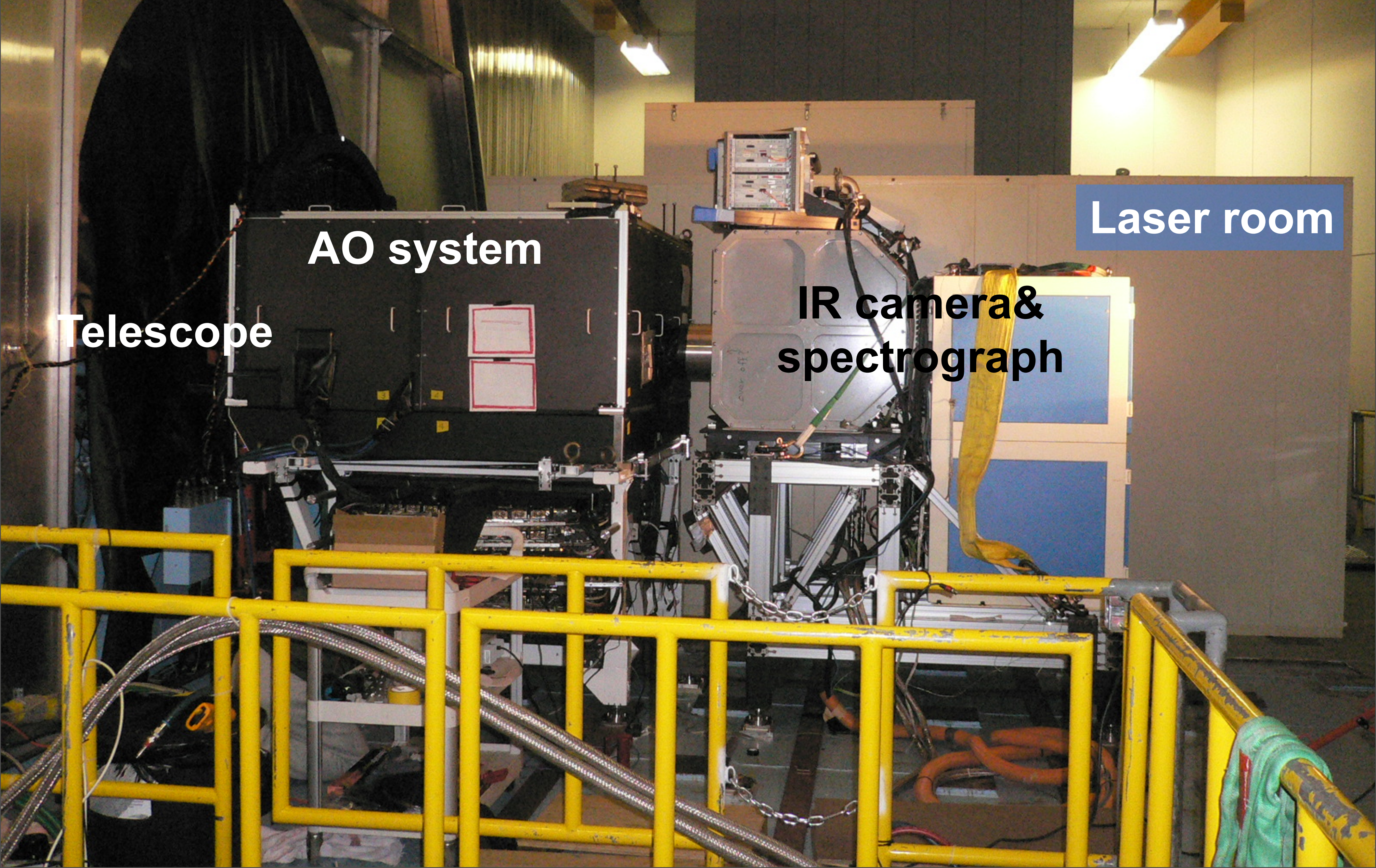




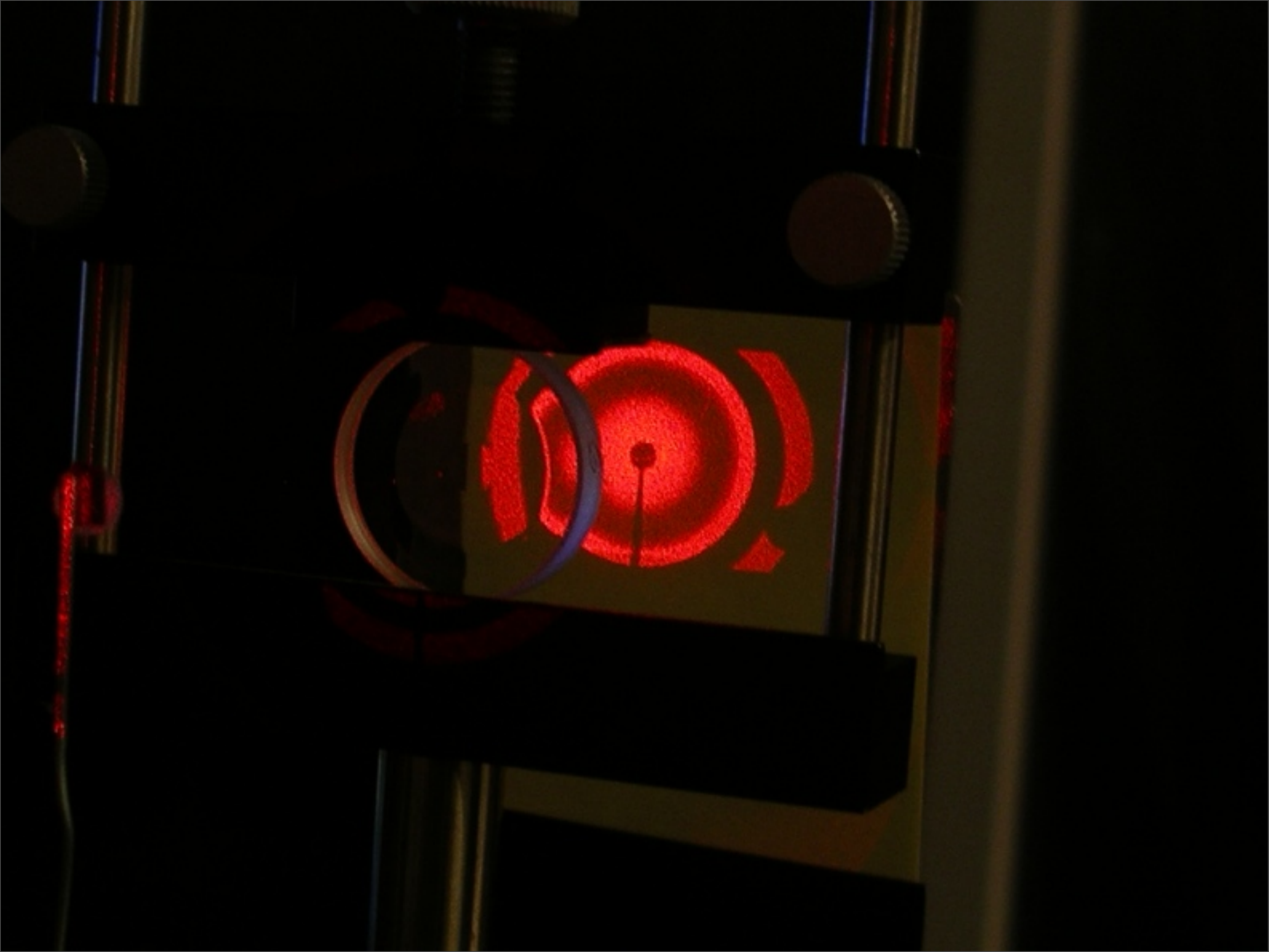
stellar radius = 0.1 λ/d
theoretical limit
PIAA
OVC8
OVC6
VNC/BL4(2)
BL8
CPA
Useful throughput
Angular separation (λ/d)
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7
8

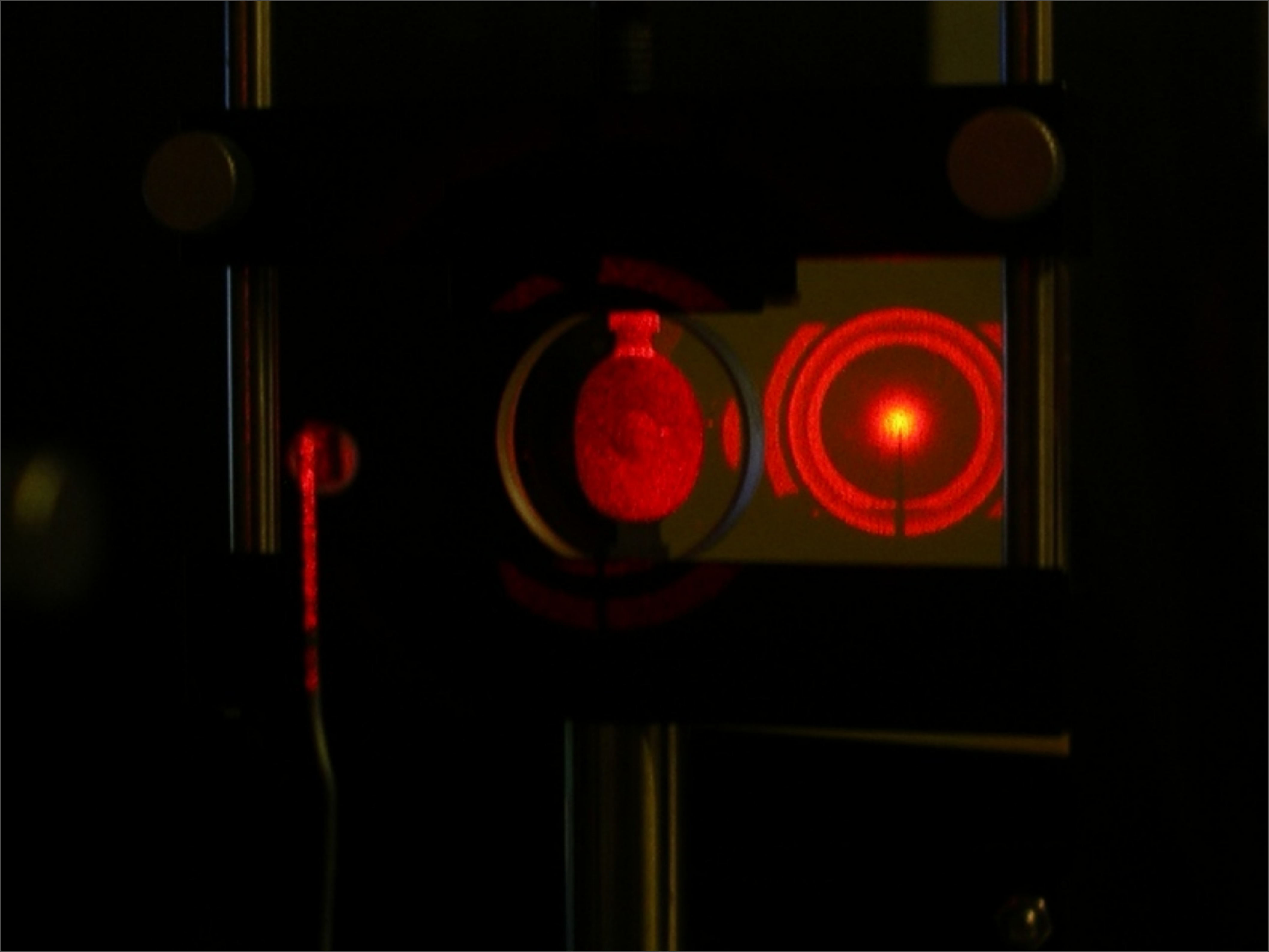

EXIT

AO188 system at the Nasmyth focus (installed in 2006/9)

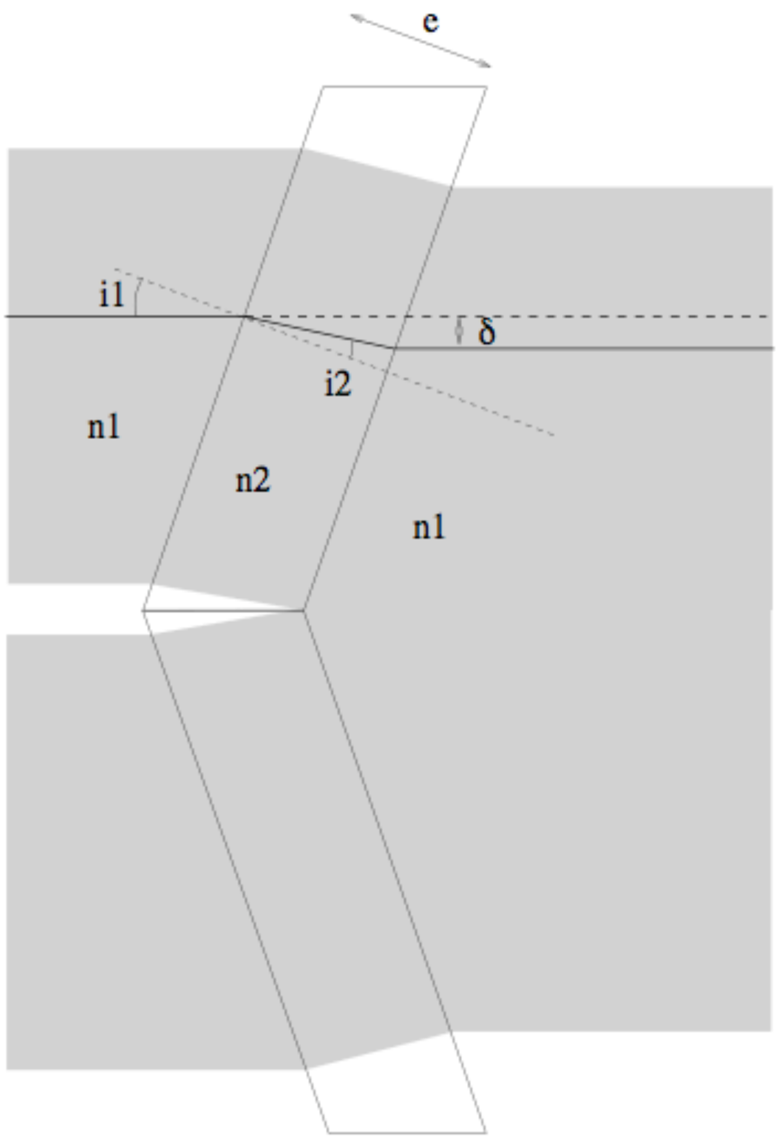


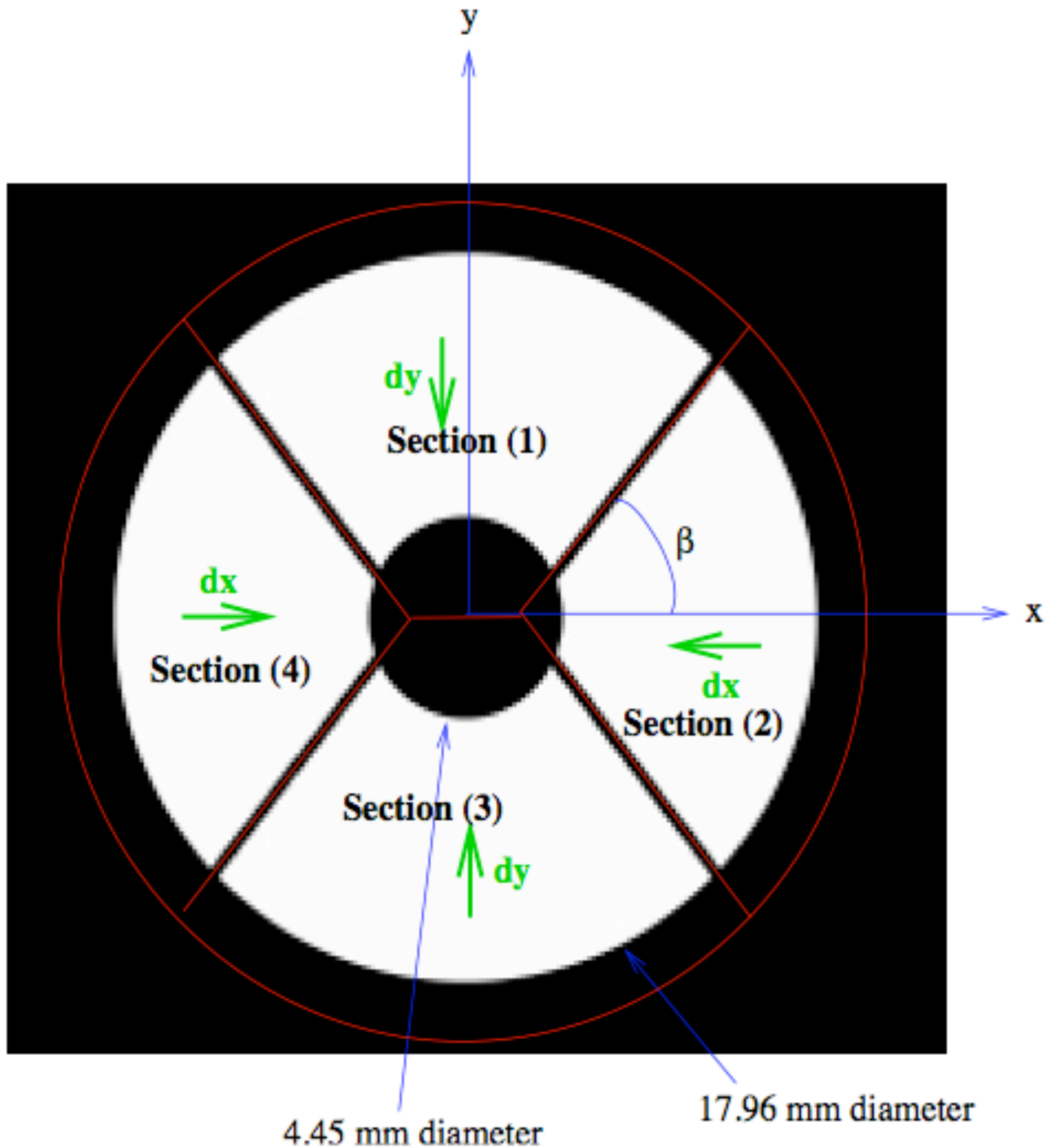
HiCIAO first light (2007)





Spider Removal Plate





Spider Removal Plate (SRP)