Pupil mapping Exoplanet Coronagraph Observer (PECO)

Olivier Guyon, on behalf of PECO team

University of Arizona
Subaru Telescope

PECO team

U of Arizona
NASA JPL
NASA Ames
Lockheed
ITT

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Mission Study Manager: Marie Levine – NASA Jet Propulsion Laboratory	
Science Studies (Lead: Co-I T. Greene – NASA Ames Research Center)	
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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.
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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)	
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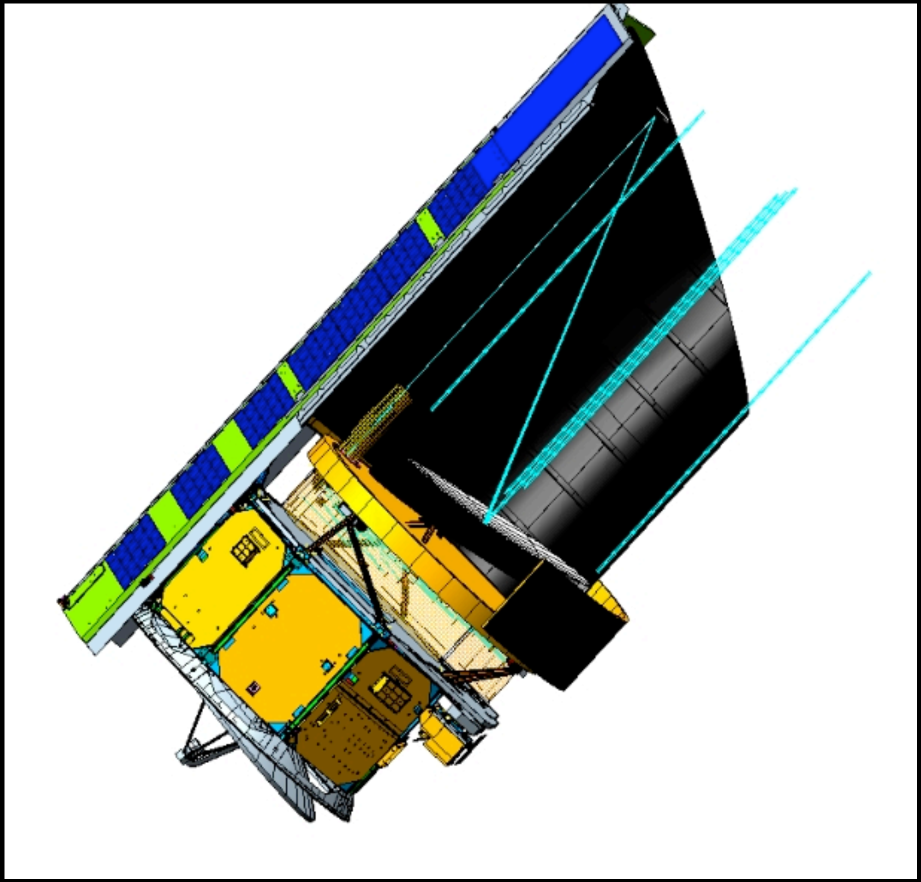
R. Belikov (Princeton) – Collabor..	Coronagraph architecture and analysis
J. Kasdin (Princeton) - Collaborator	Architecture
E. Serabyn (JPL) - Collaborator	Wavefront sensing and speckle nulling
Mission Technology (Lead: Co-I M. Levine –NASA JPL / Co-Lead Co-I T. Greene –NASA ARC)	
R. Angel (UofA) - Co-I	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

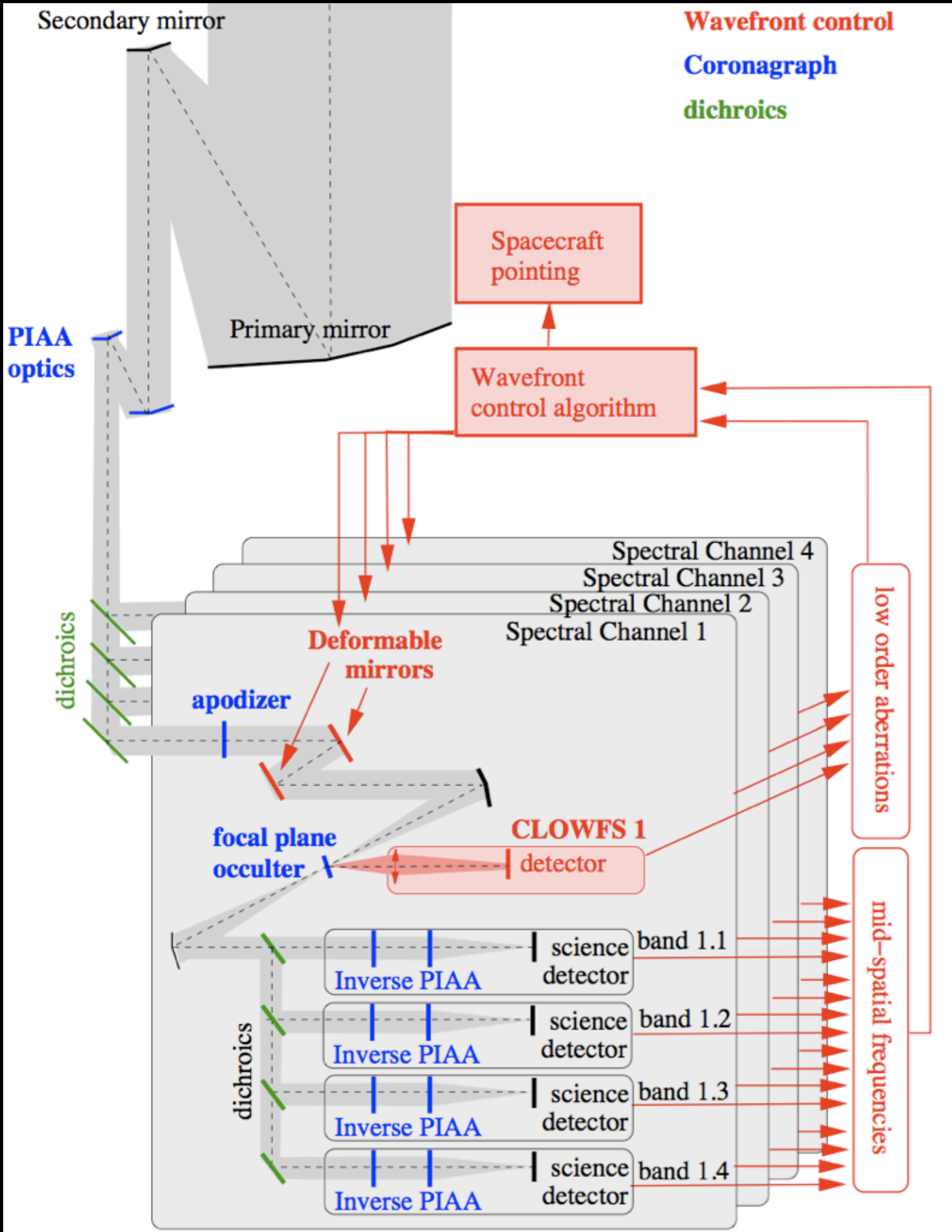


High contrast coronagraphic imaging of the immediate environment of nearby stars.

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.

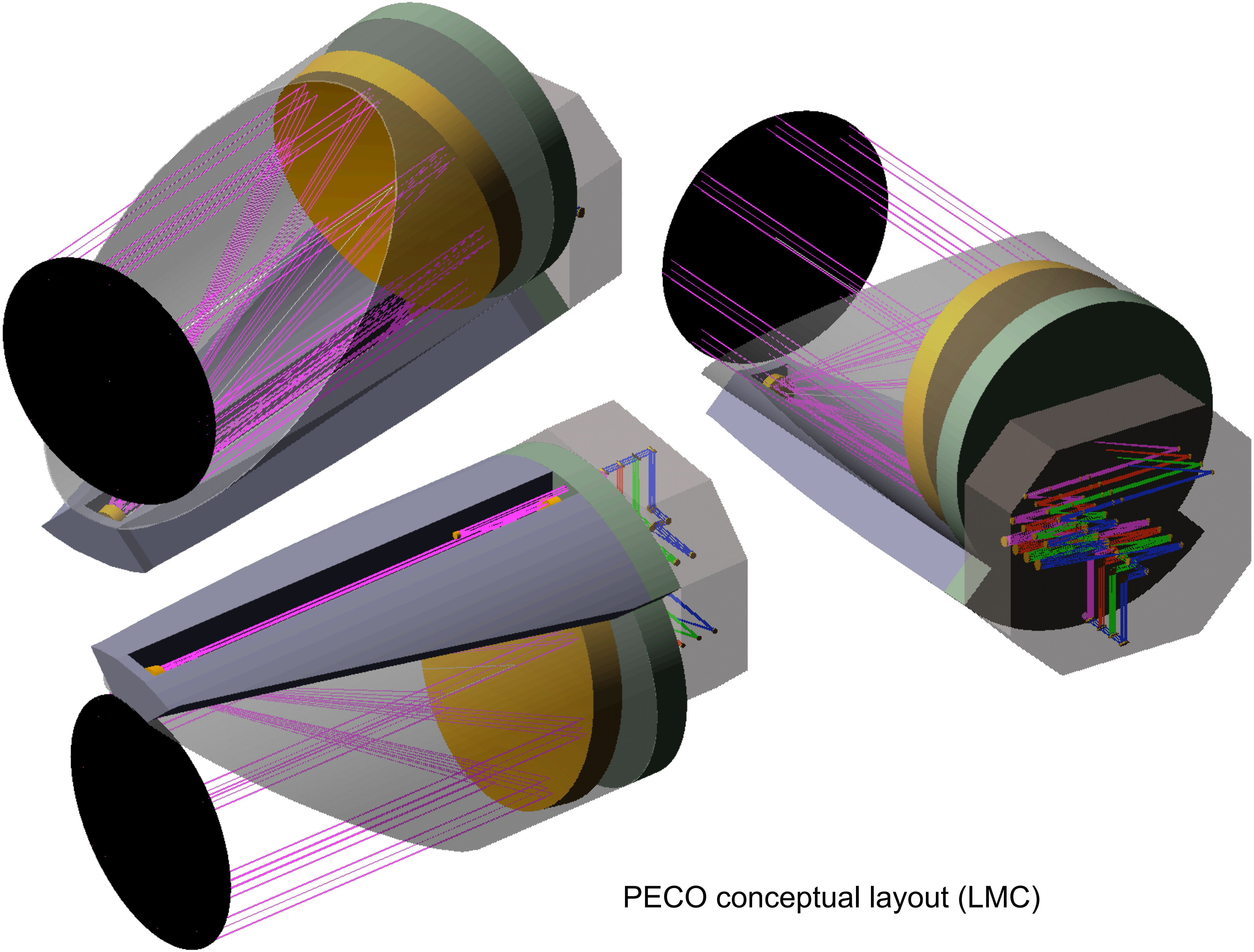


Optimal use of photons from 0.4 to 1.0 micron, for both wavefront control and science

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

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

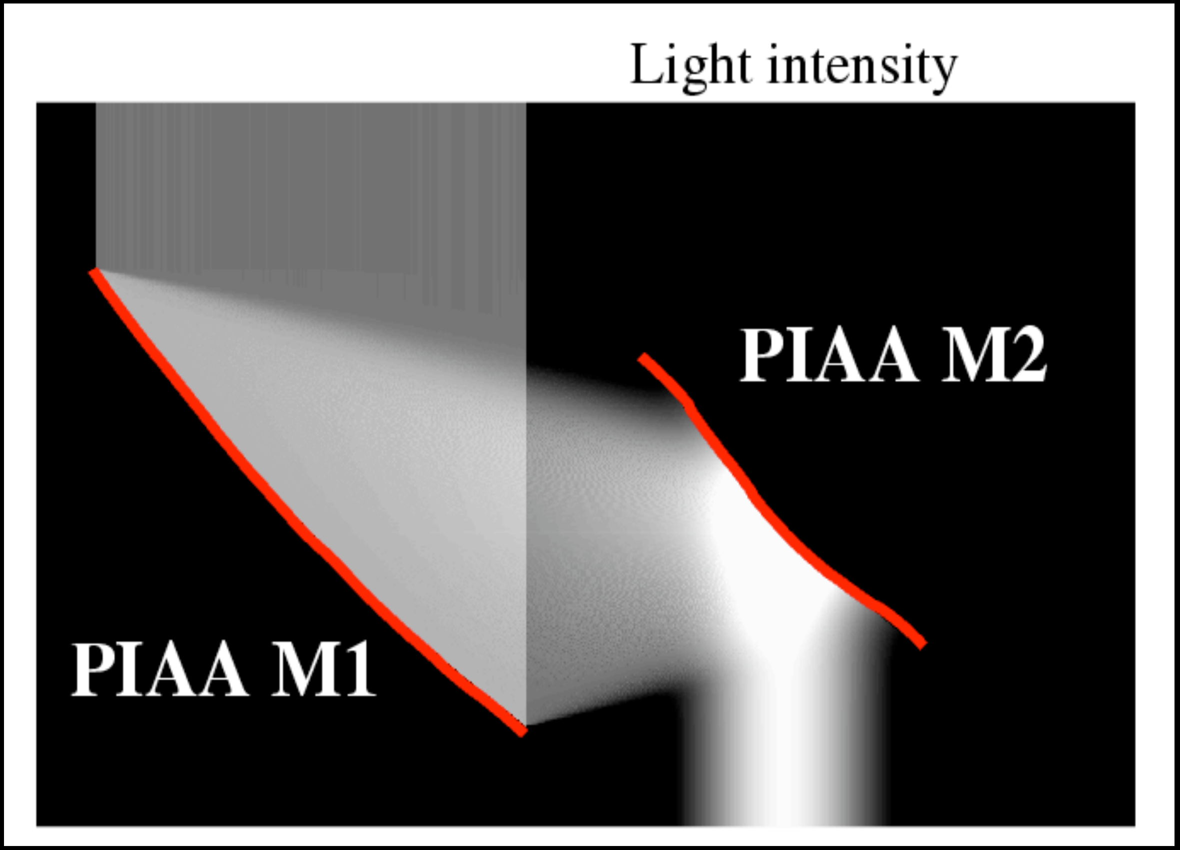
Full angular resolution



PECO conceptual layout (LMC)

Use of highly efficient PIAA coronagraph equivalent to x2 gain in telescope diameter

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

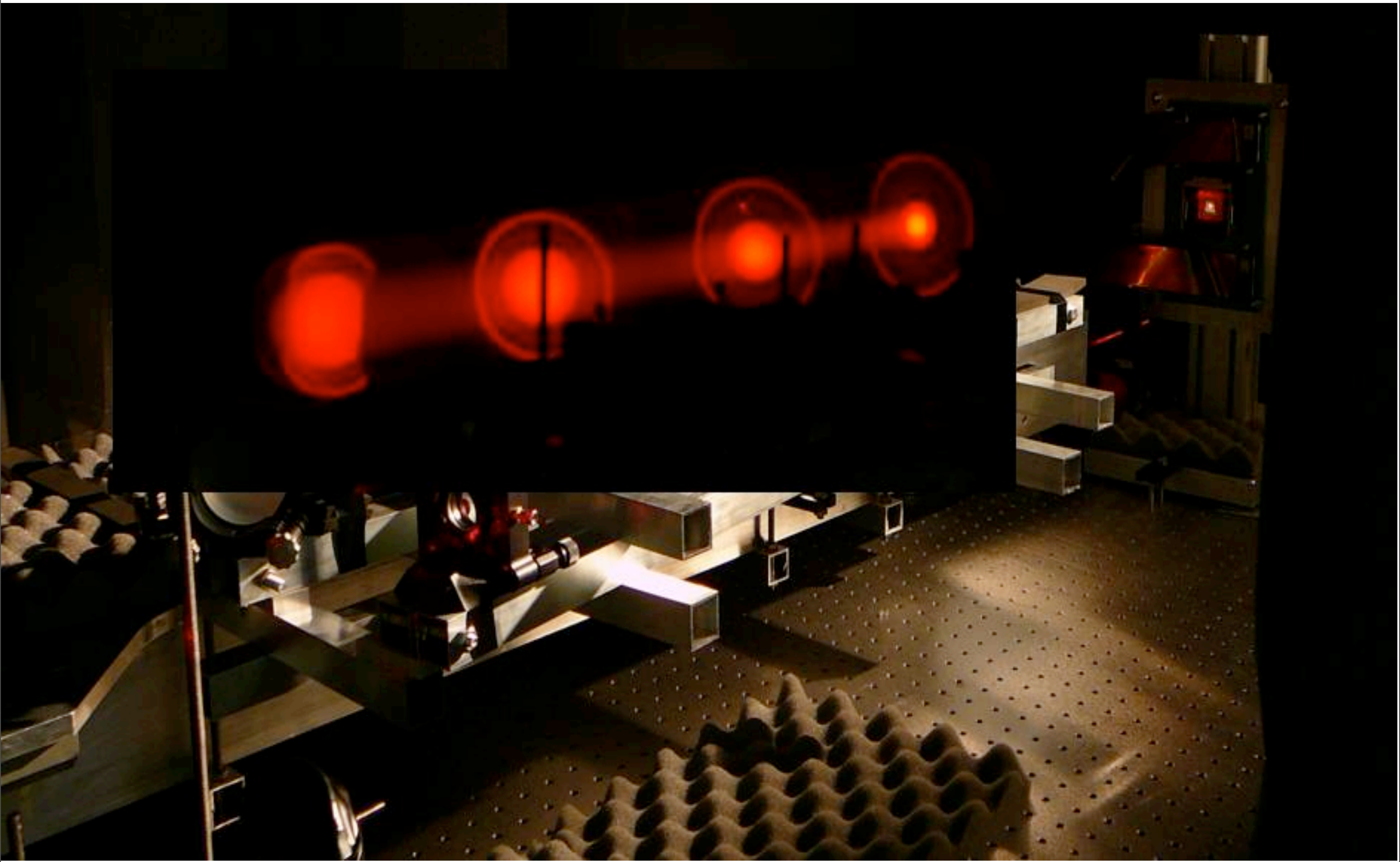


- high contrast
- Nearly 100% throughput
- IWA ~2 l/d
- 100% search area
- no loss in angular resol.
- achromatic (with mirrors)

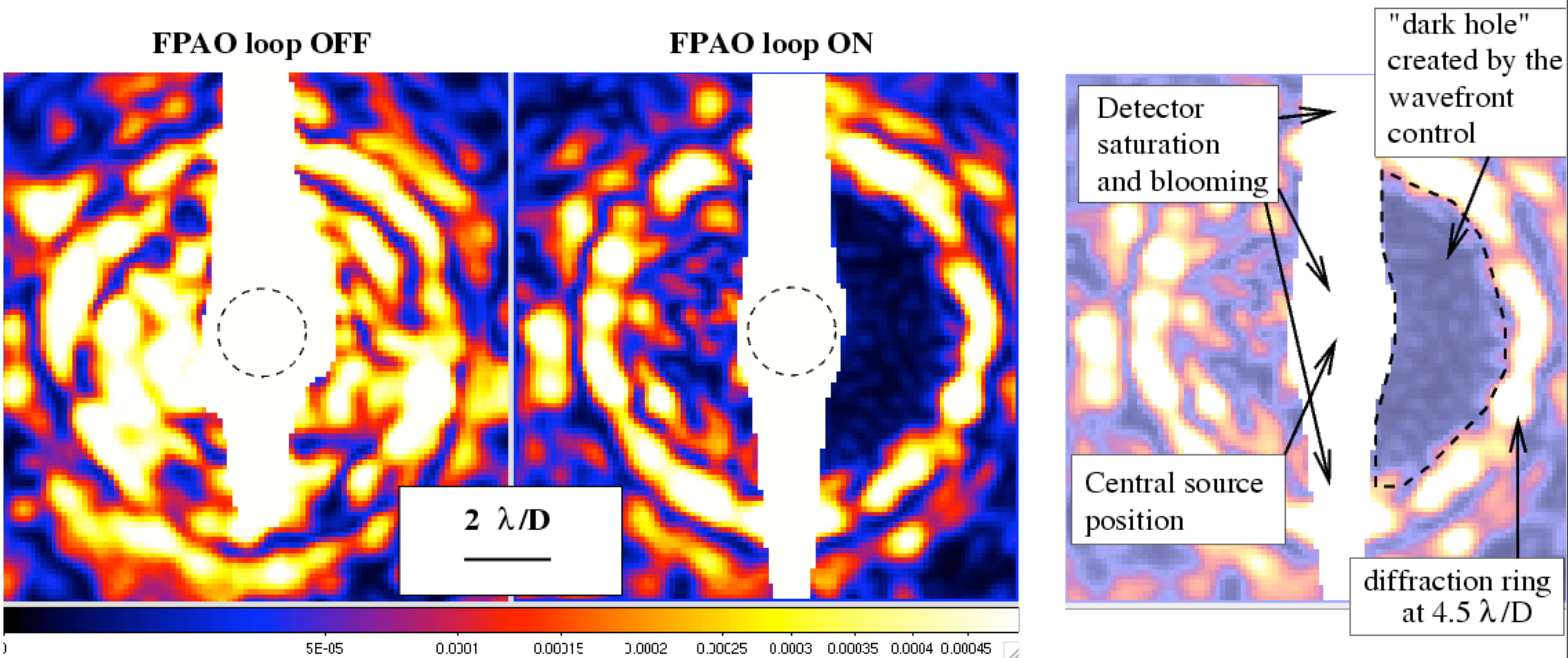
More info on :

www.naoj.org/PIAA/

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



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)

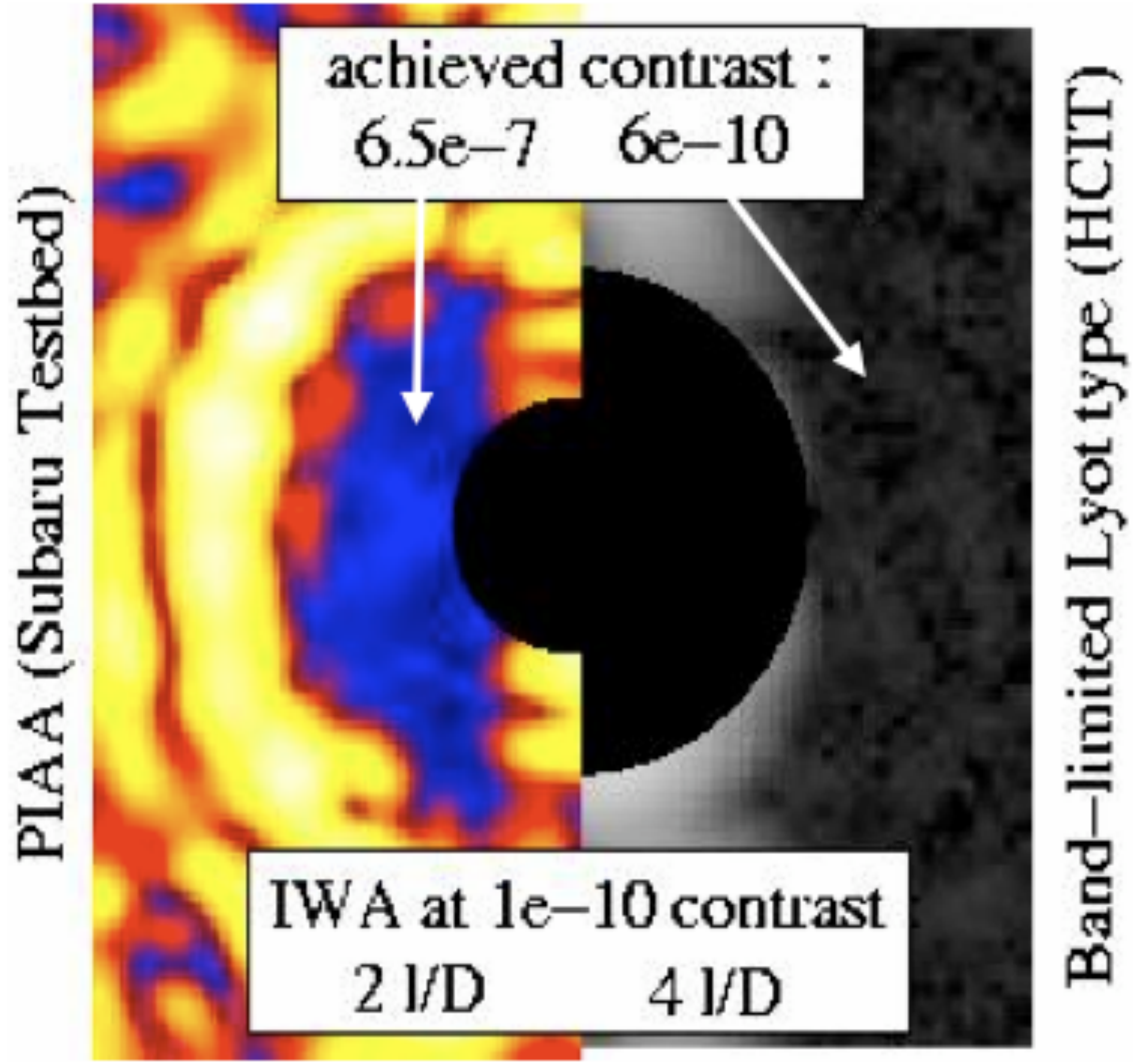


Figure 1.3-2 Comparison between the IWA of a PIAA coronagraph and a Lyot-type band limited coronagraph. Actual laboratory PSFs are shown at the same scale. The high sensitivity regions are in blue (PIAA) and black (band limited).

PIAA Coronagraph allows imaging of Earths/SuperEarths with probe-scale mission

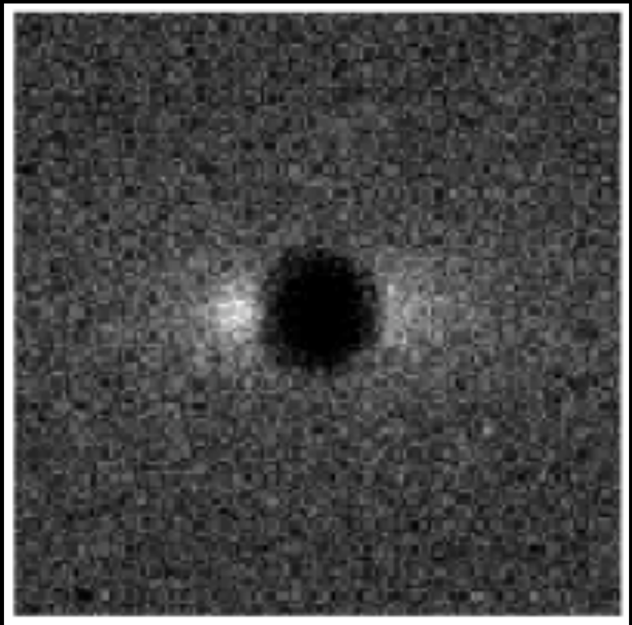
Telescope size and coronagraph type	Earth @ 1 HZ albedo 0.3	SuperEarth @ 1 HZ albedo 0.3	SuperEarth @ 1.8 HZ albedo 0.3	Jupiter @1AU albedo 0.6	Jupiter @5AU albedo 0.6
1.0 m PIAA	5	13	23	21	437
1.4 m PIAA (PECO)	**20**	**38**	**56**	**52**	**1179**
1.8 m PIAA	41	79	127	103	2545
1.4 m Shaped Pupil	2	2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

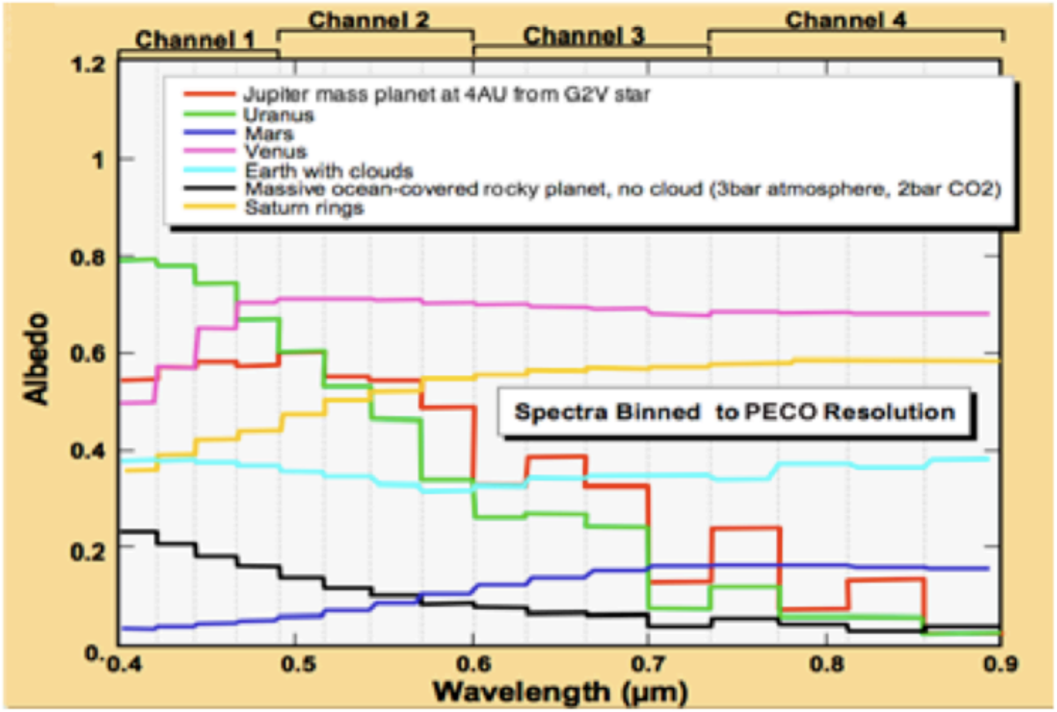


Figure 1.2-1 PECO Spectral Bands. Earth's atmosphere has a relatively constant albedo across the PECO bands, with a slight absorption near 600 nm due to ozone. EGPs like Jupiter will have relatively flat spectra, with deep methane absorption in the red adjacent to bright continua arising from clouds.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

What can we learn about exoplanets with PECO and other missions ?

Radial Velocity, Astrometry

Orbit
Mass

PECO

Brightness
Spectra
Variability
Exozodiacal dust

Constraints on planet size, internal structure
Atmosphere composition, temperature
Planetary system dynamics, history & evolution

Technical challenges

Coronagraph -> Manufacturing, Wavefront control

Pointing stability/calibration

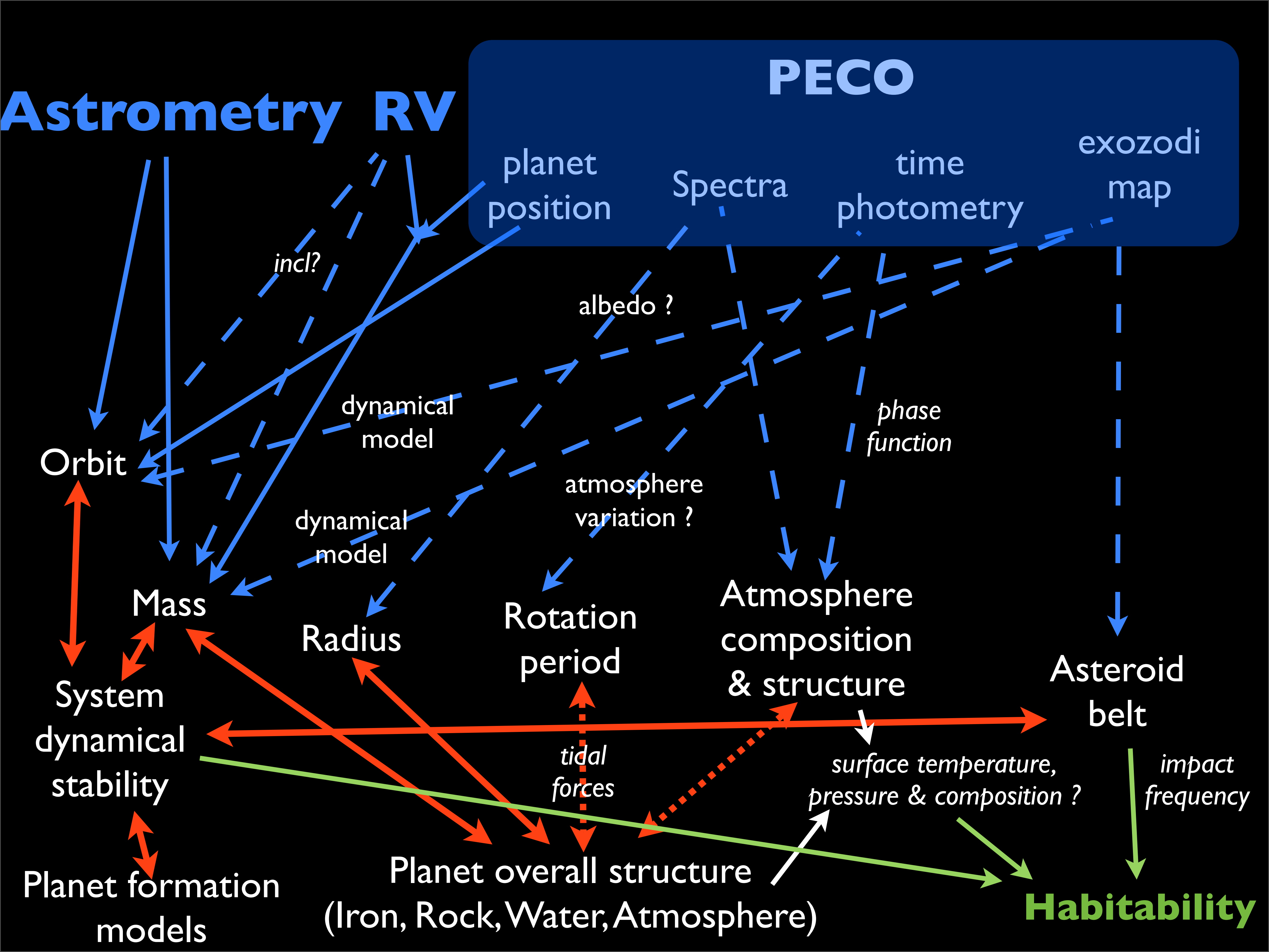
Telescope wavefront stability

vibration isolation & good thermal design

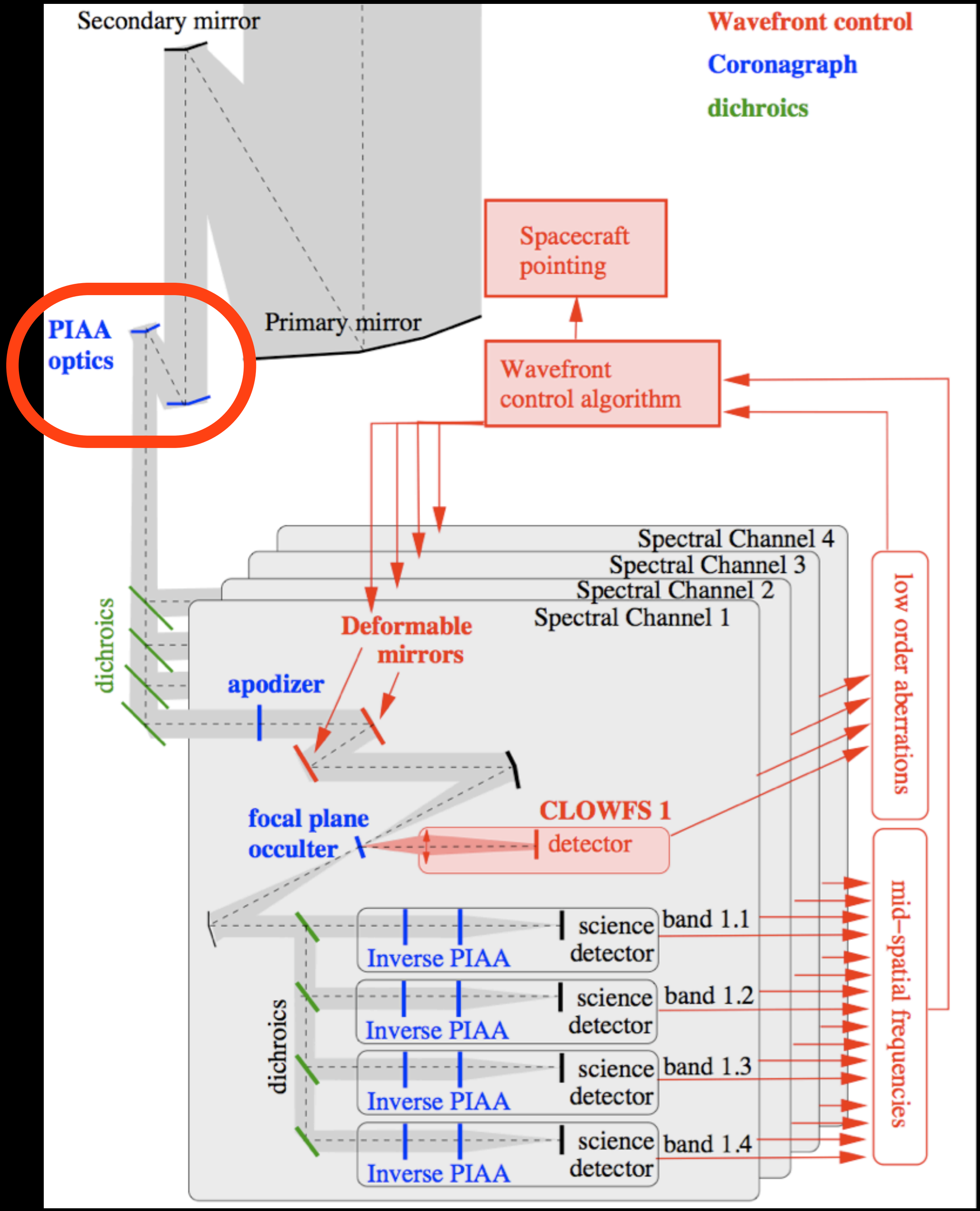
drift-away orbit

Detectors

~zero readout noise visible CCD are now available



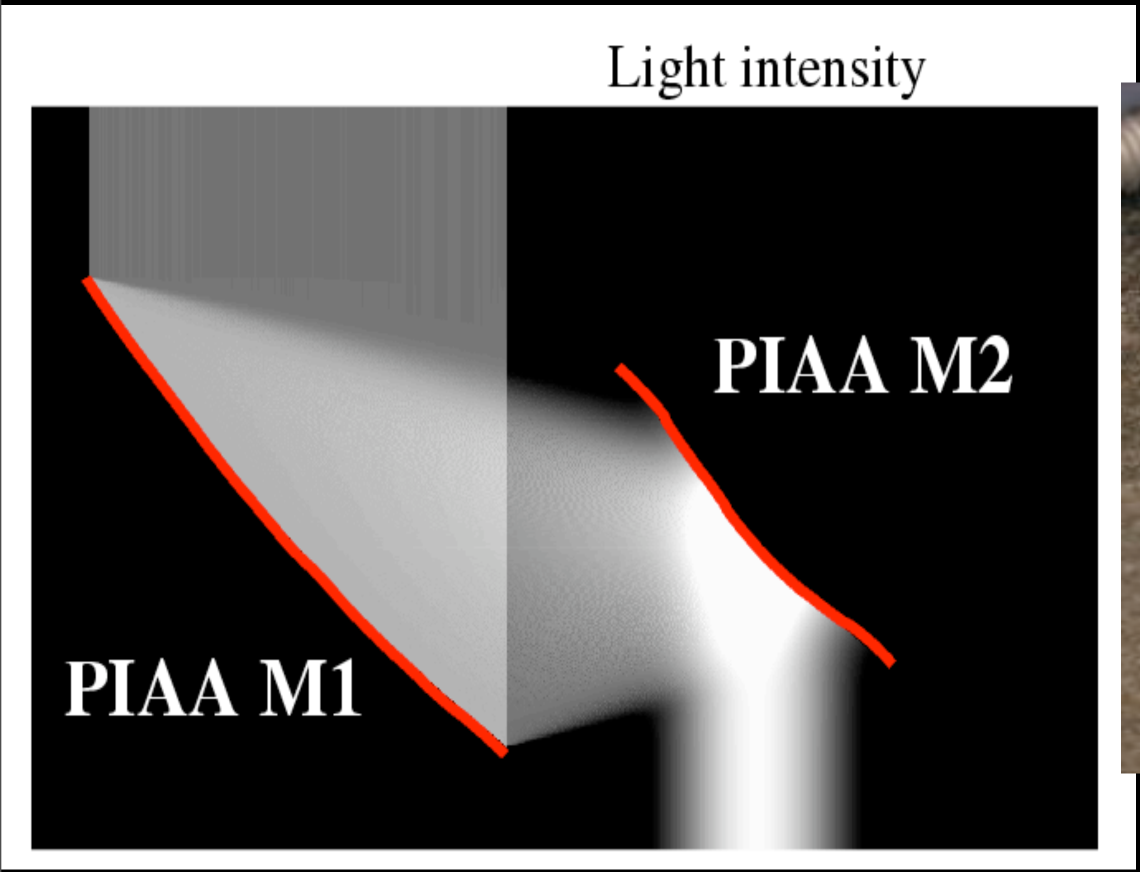
PECO
Astrometry
RV
planet position
Spectra
time photometry
exozodi map
incl?
albedo ?
dynamical model
phase function
atmosphere variation ?
dynamical model
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure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

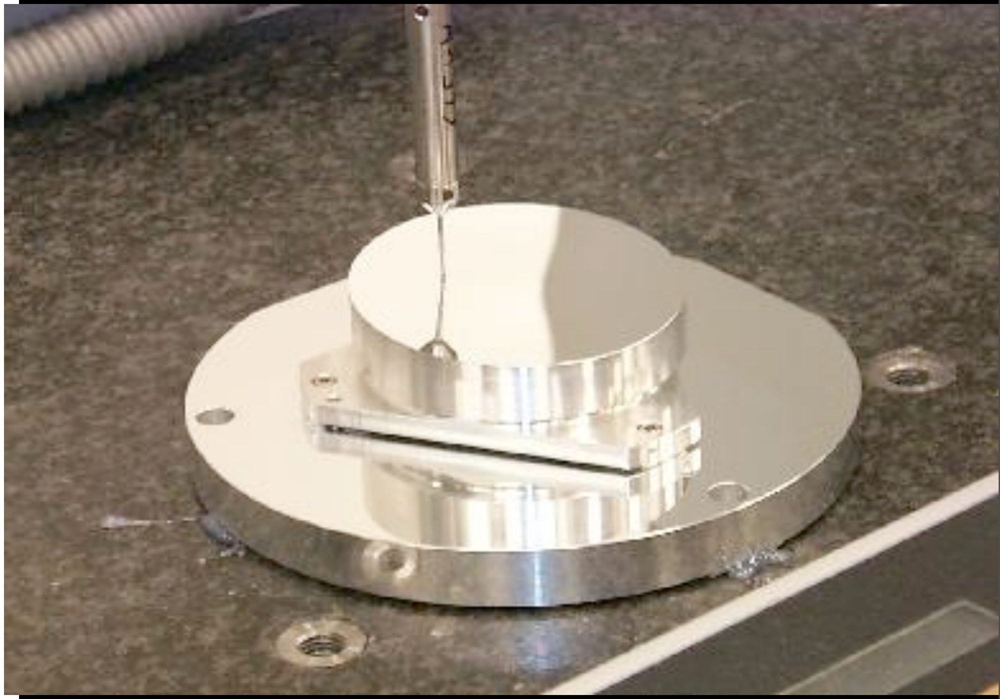


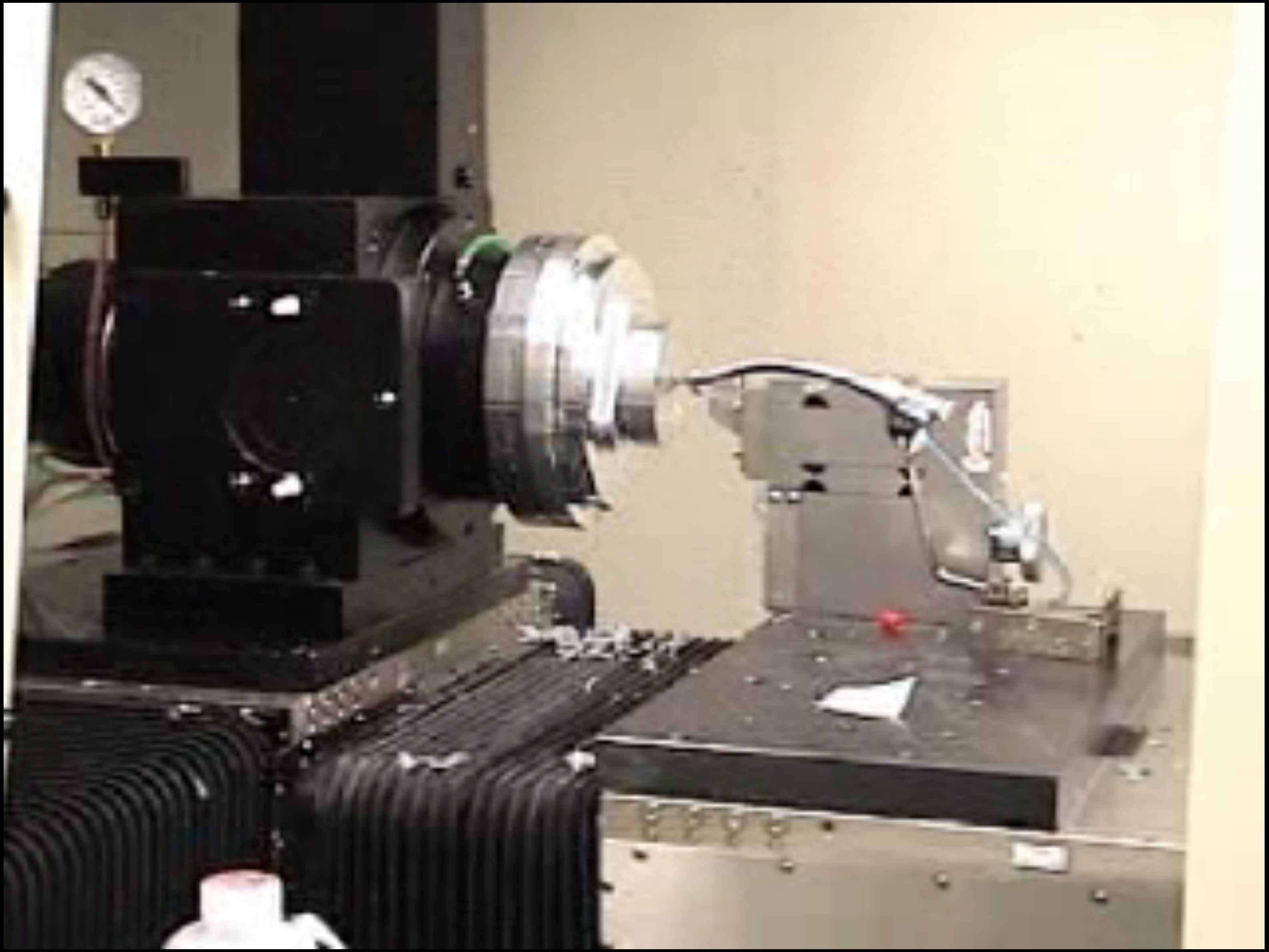
Secondary mirror
Wavefront control
Coronagraph
dichroics
Spacecraft pointing
PIAA optics
Primary mirror
Wavefront control algorithm
Spectral Channel 4
Spectral Channel 3
Spectral Channel 2
Spectral Channel 1
Deformable mirrors
dichroics
apodizer
low order aberrations
focal plane occulter
CLOWFS 1
detector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

9.5 PIAA optics sets made so far:

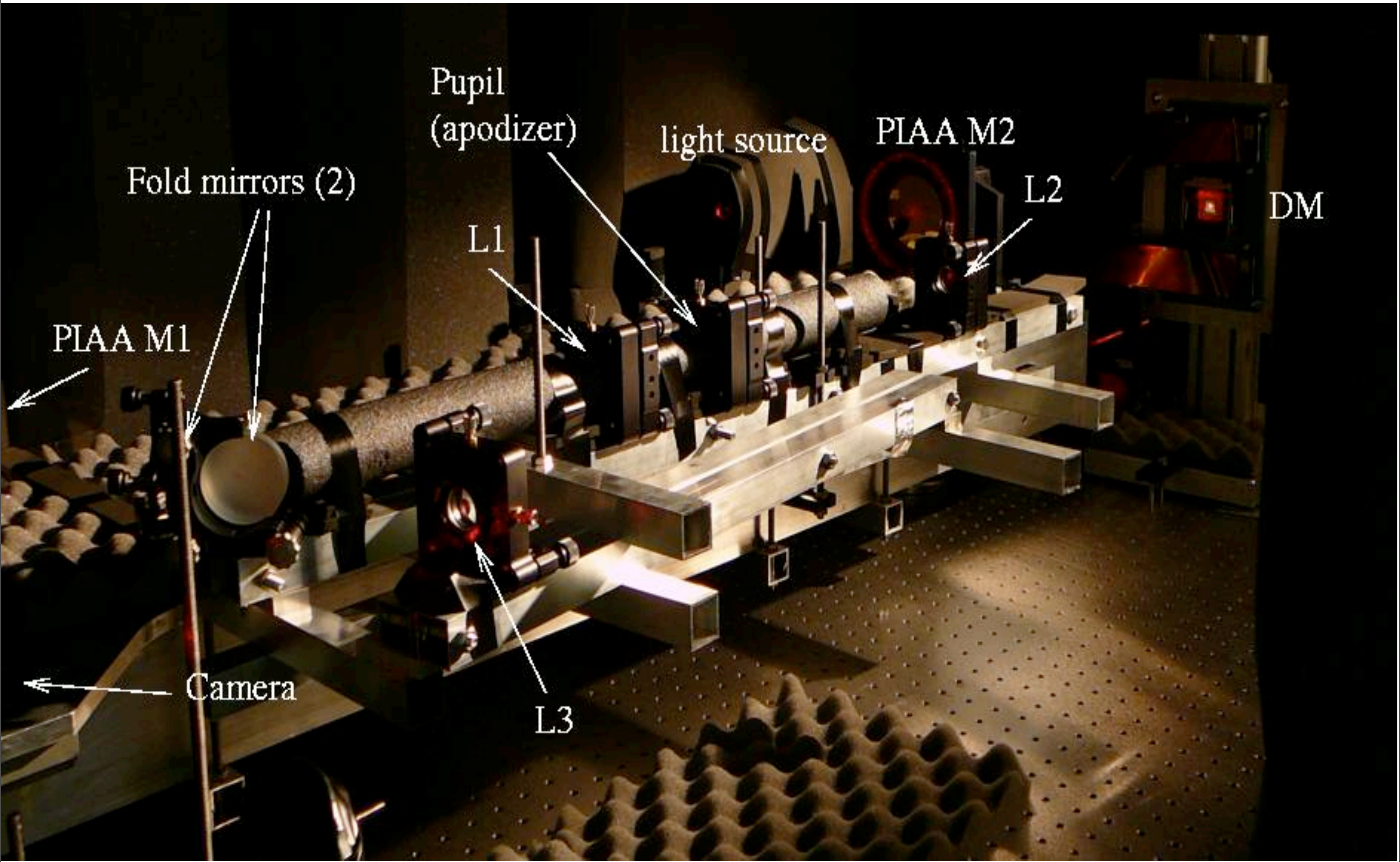
1 refractive PIAA system, diamond turned plastic [NAOJ]
2 reflective PIAA systems, Nickel-plated diamond turned Al (1 design x2) [Axsys]
6 refractive PIAA systems, diamond turned CaF2 (3 designs x2) [Axsys]
+ 1 reflective PIAA system, Zerodur, currently in manufacturing [Tinsley]

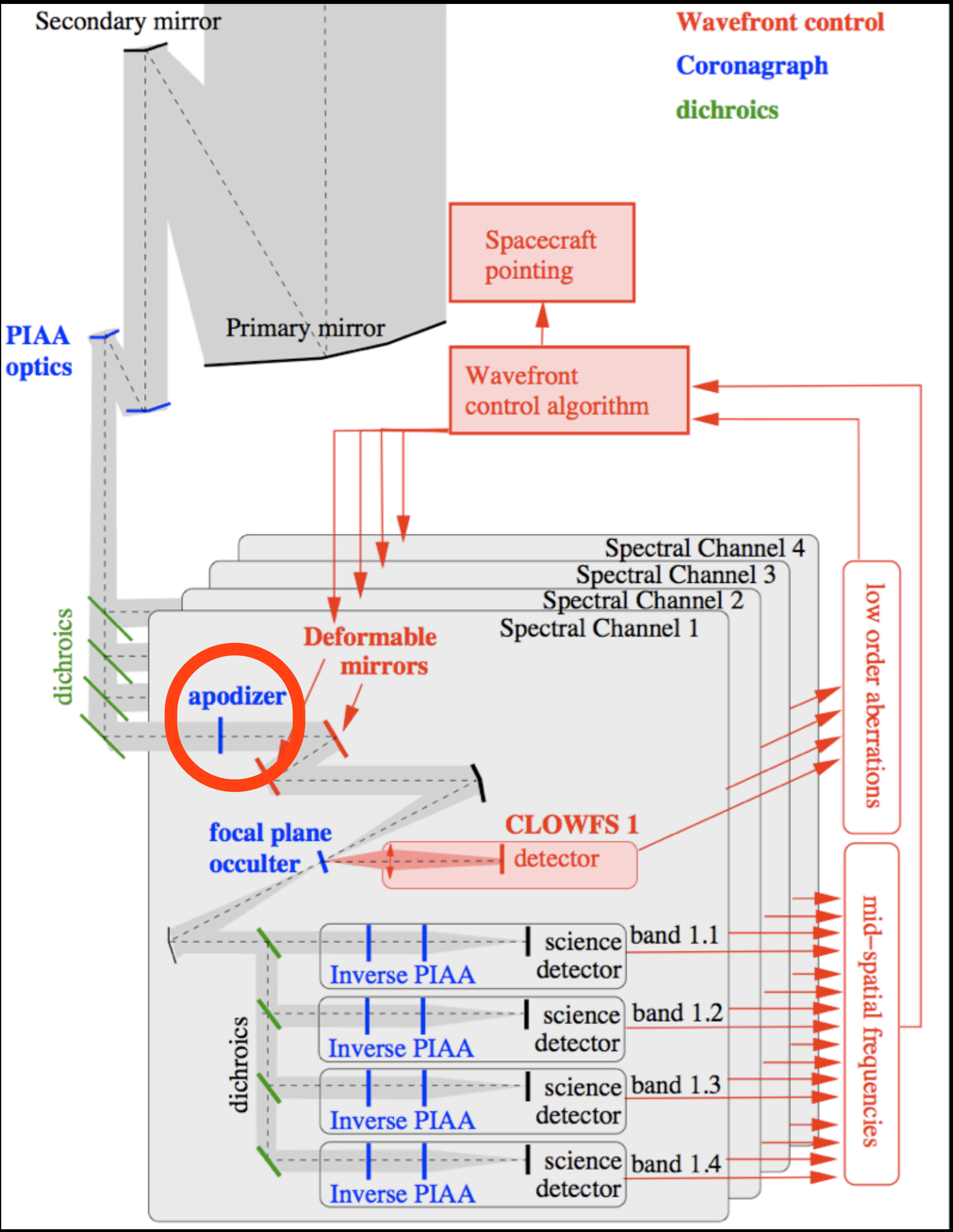






Subaru lab experiment
co-funded by Subaru/NAOJ & JPL





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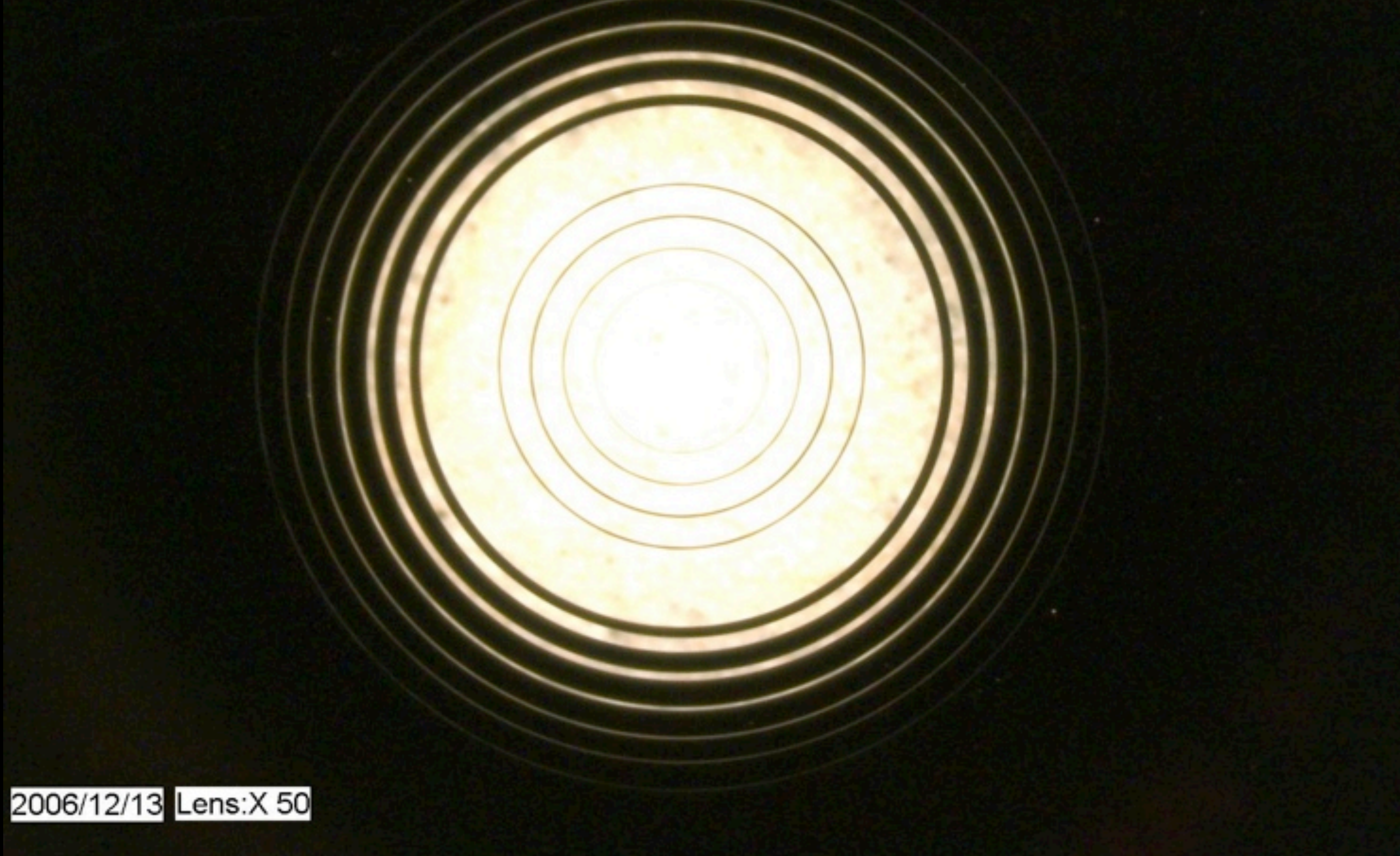
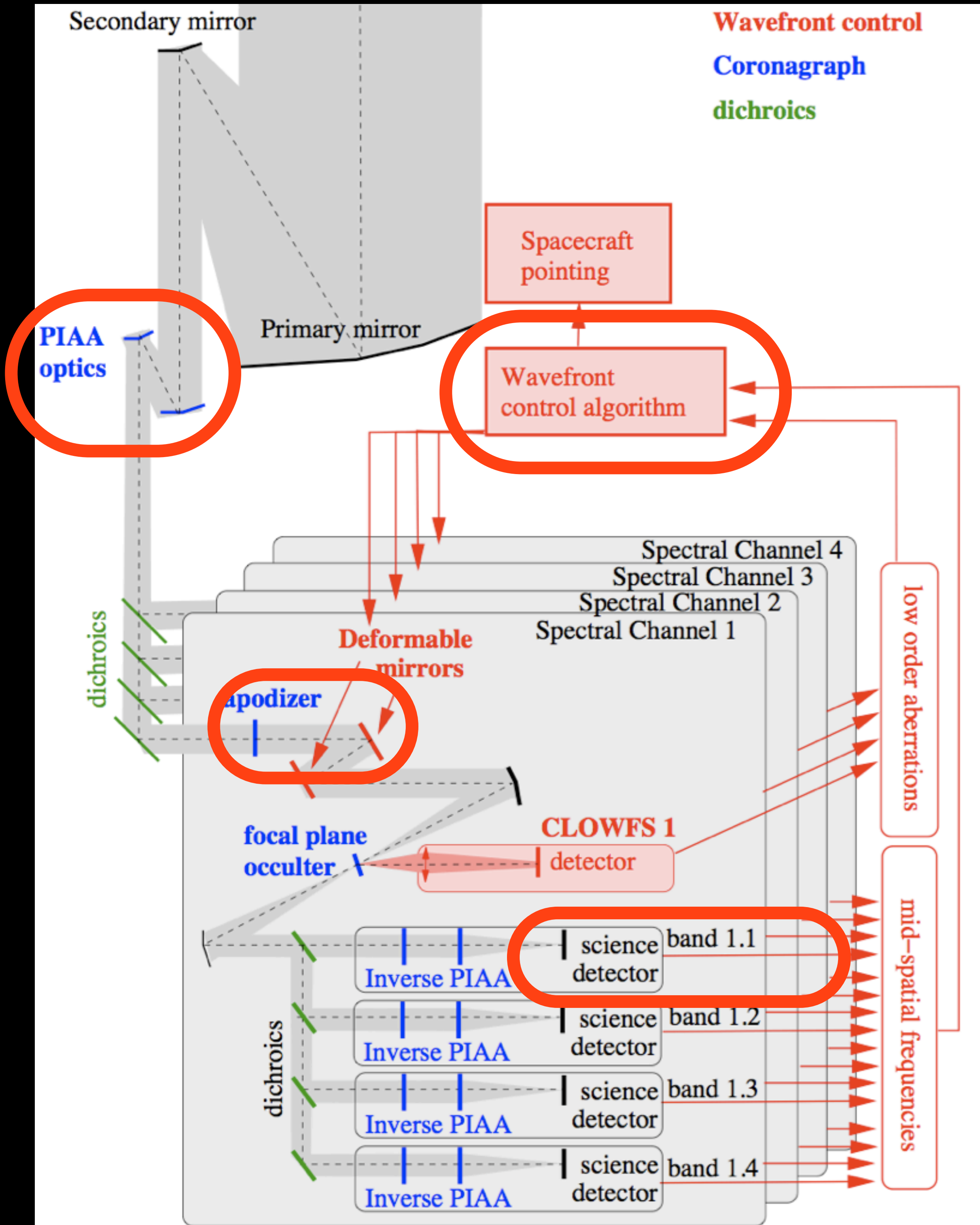
band 1.3
Inverse PIAA
science detector
band 1.4
Inverse PIAA
mid–spatial frequencies

4 mm pupil size





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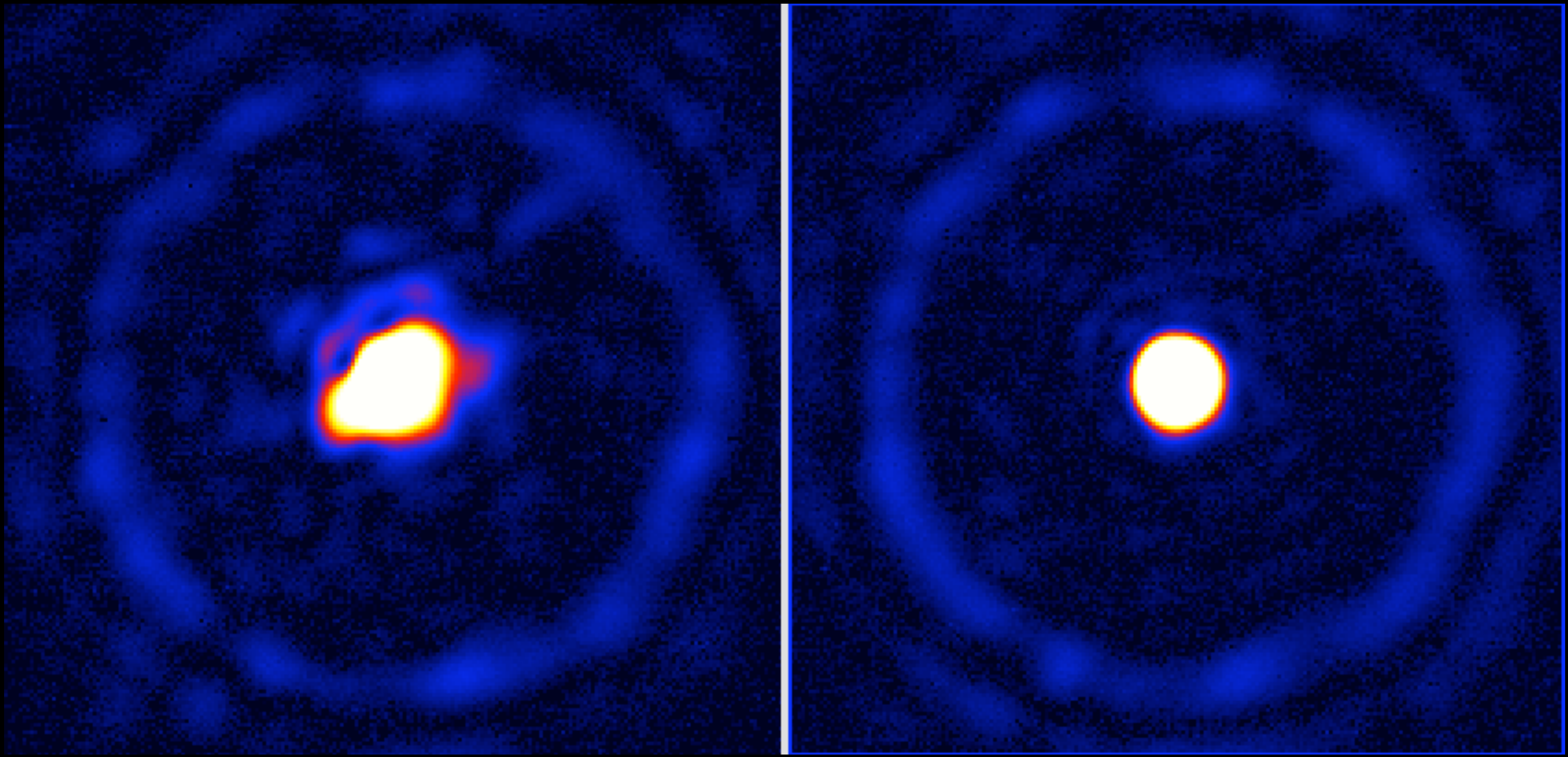
science detector
band 1.4
Inverse PIAA
dichroics
mid-spatial frequencies

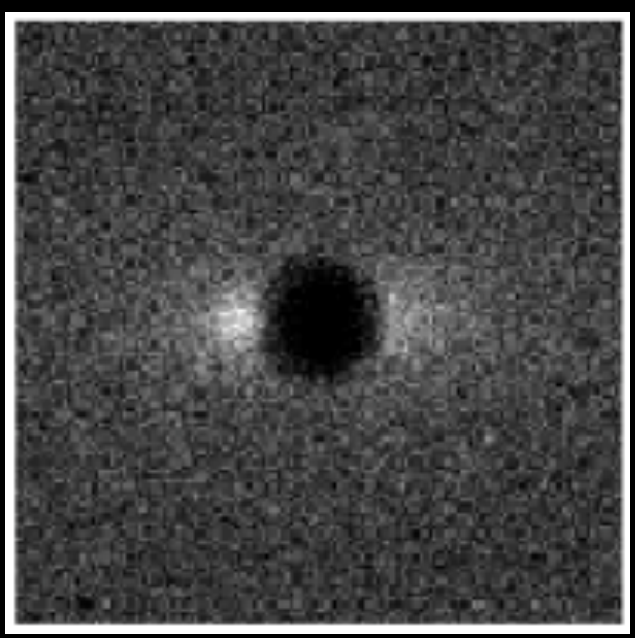
Lab results with PIAA coronagraph + FPAO

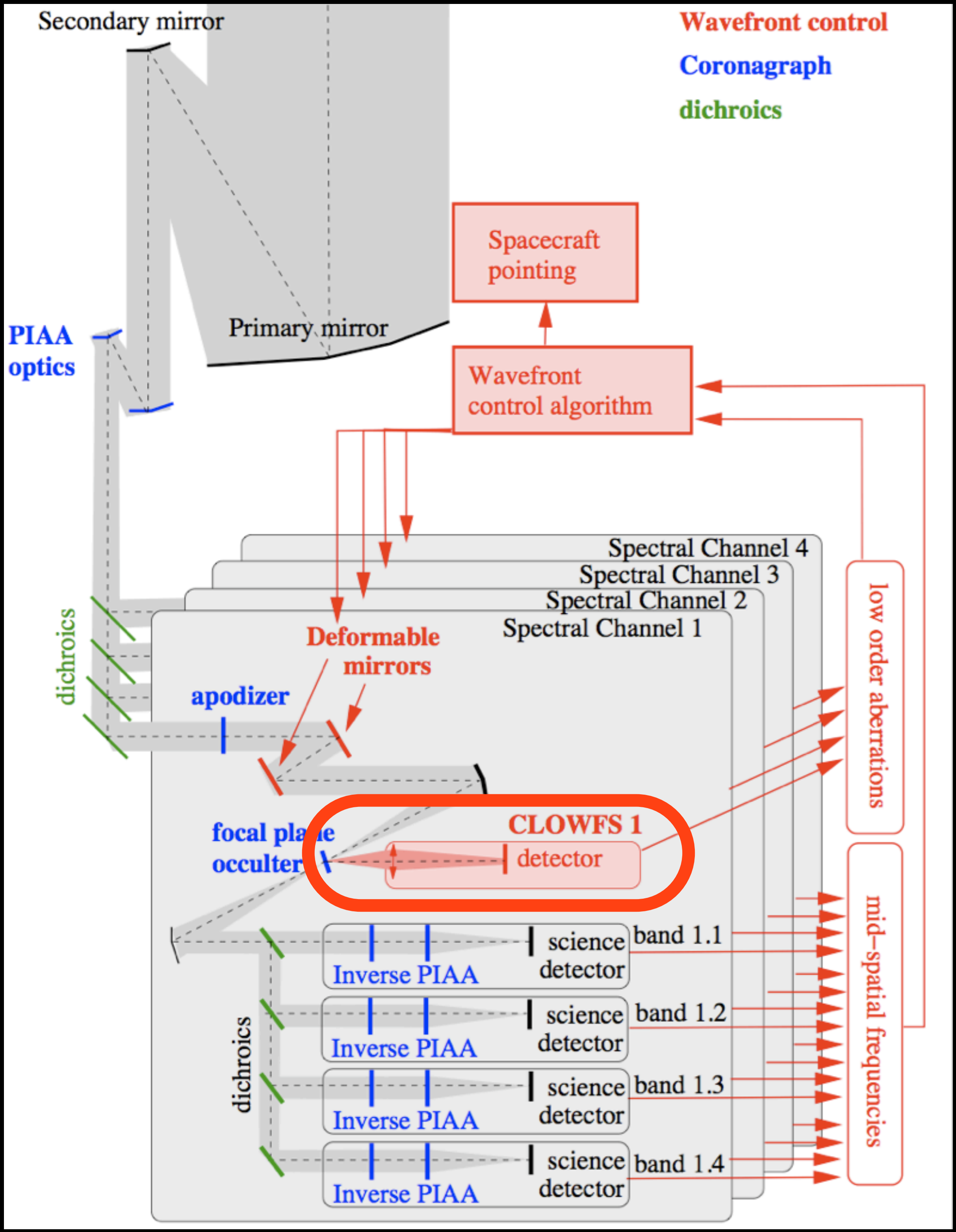


Step 1: phase diversity -> DM correction

0.4 mas pointing accuracy

0.13 mas pointing knowledge





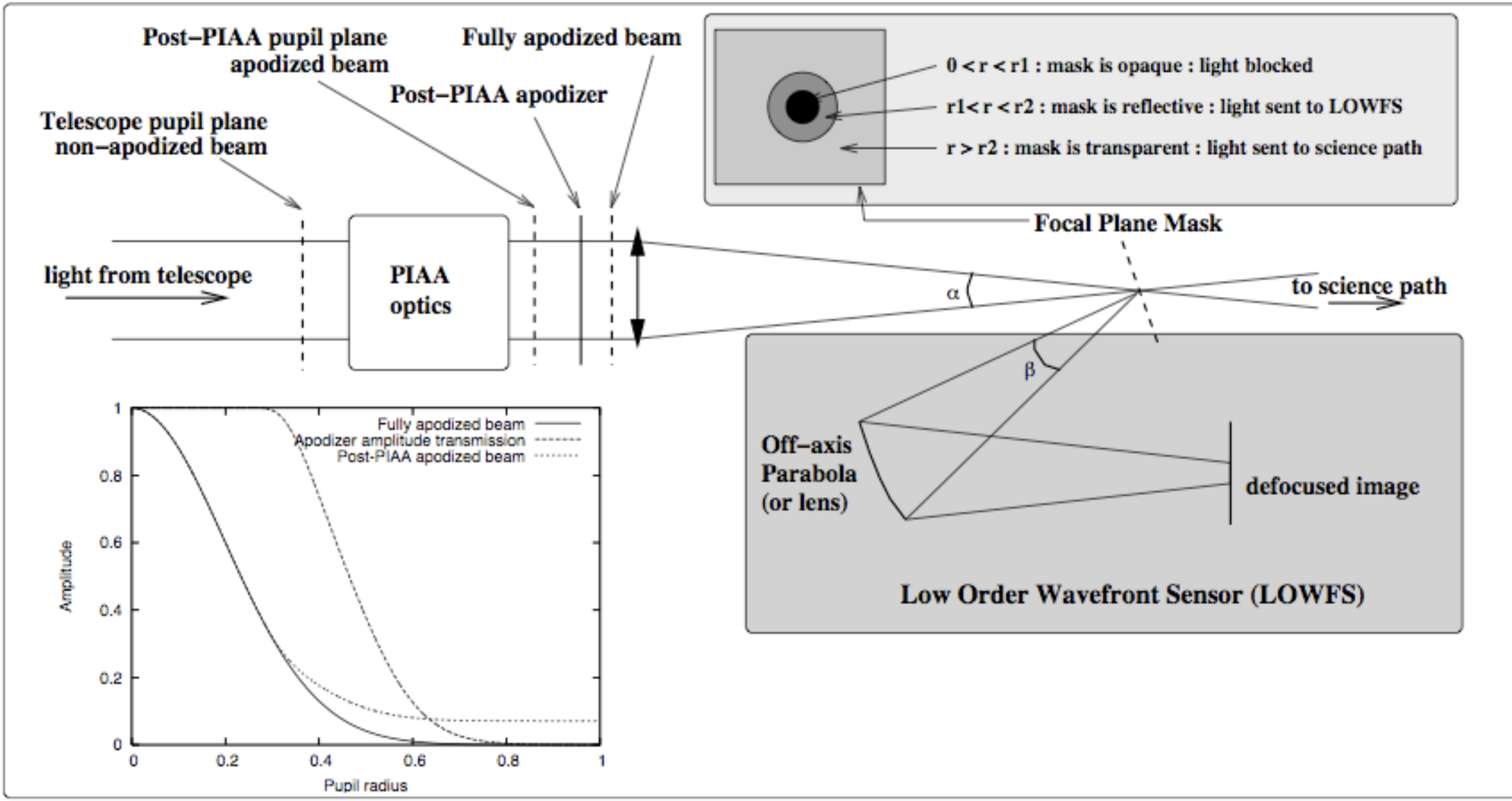


Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

Guyon, Matsuo, Angel, 2008 - to be submitted

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

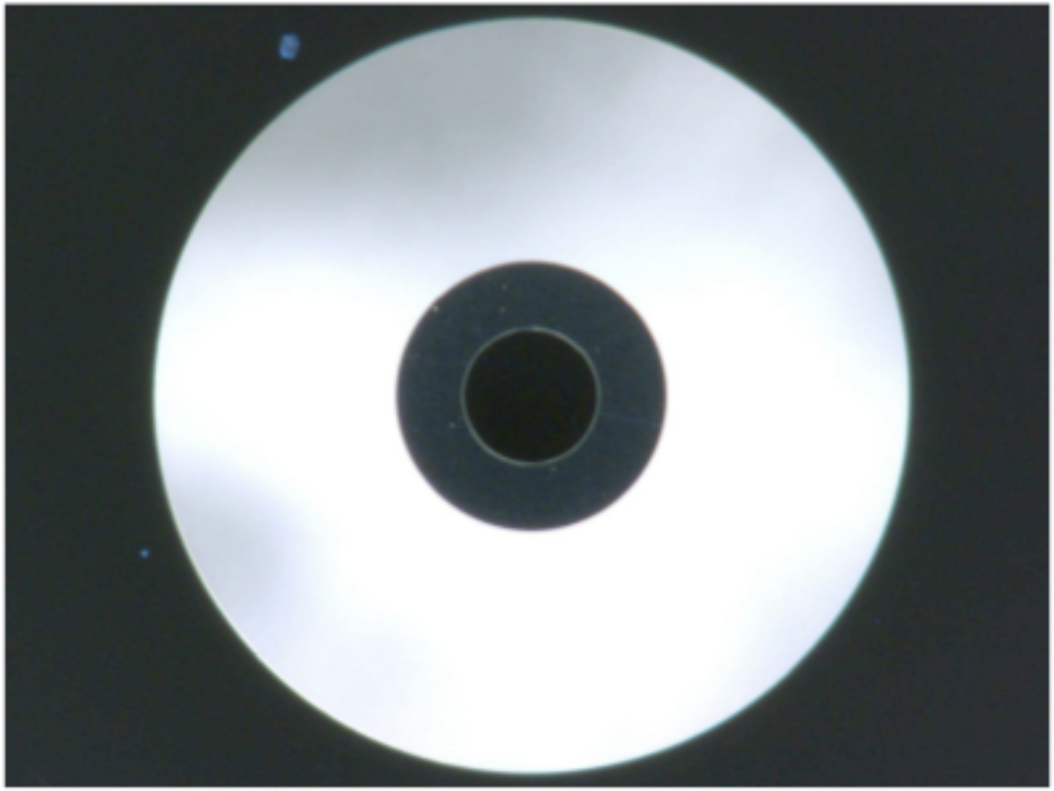
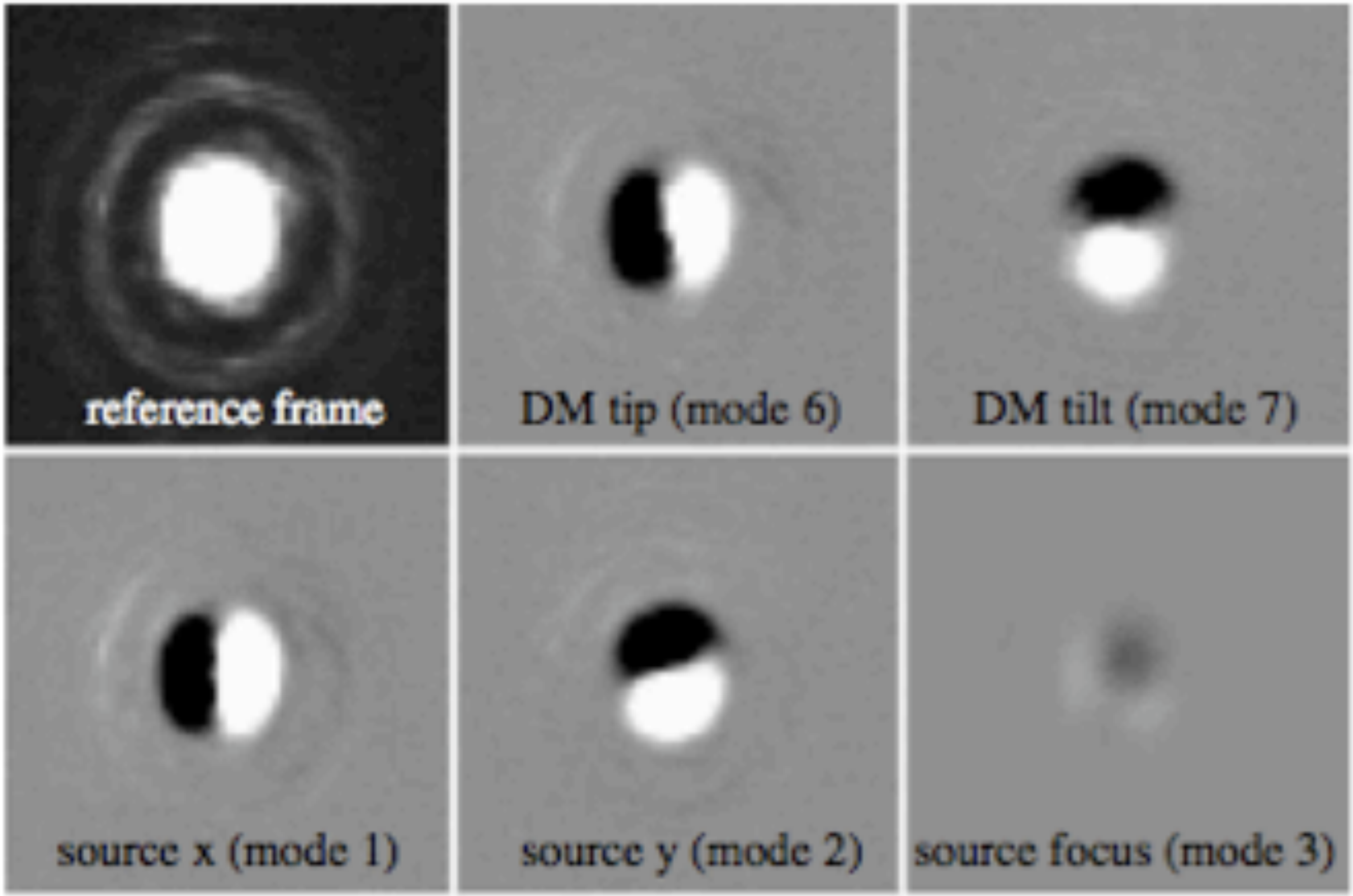
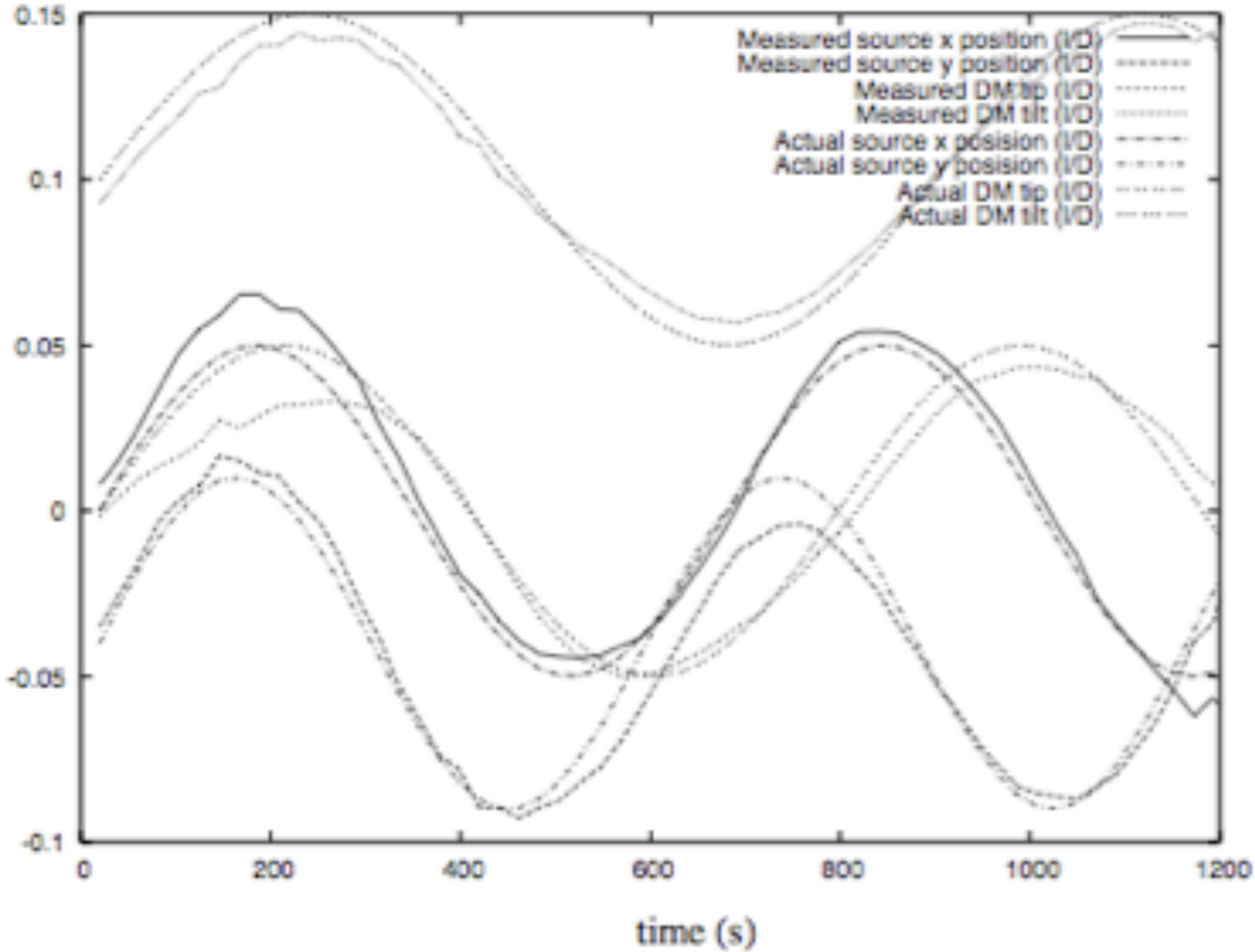


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

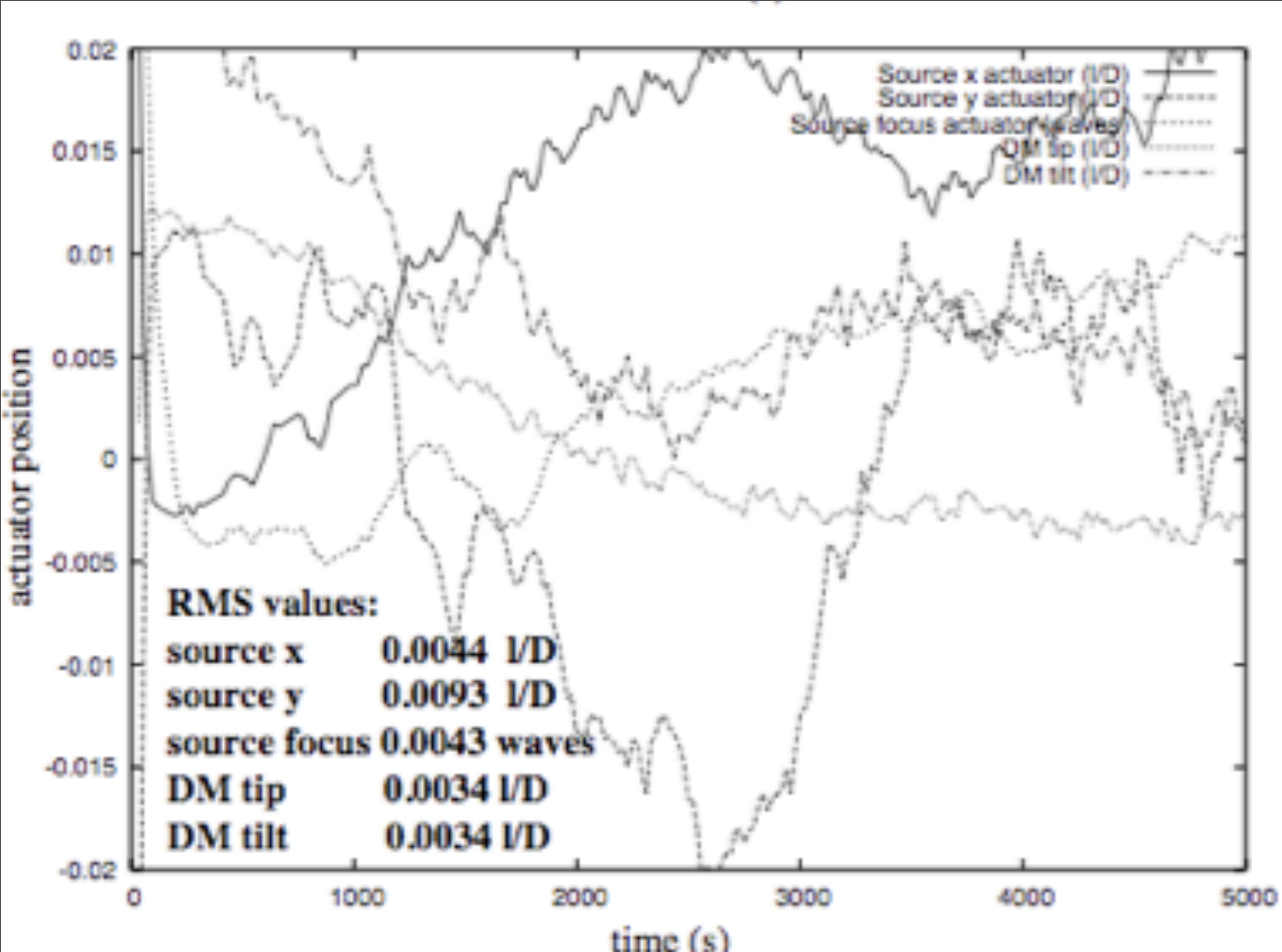
Why a central dark spot?

(1) Signal amplification
(2) Accurate reference

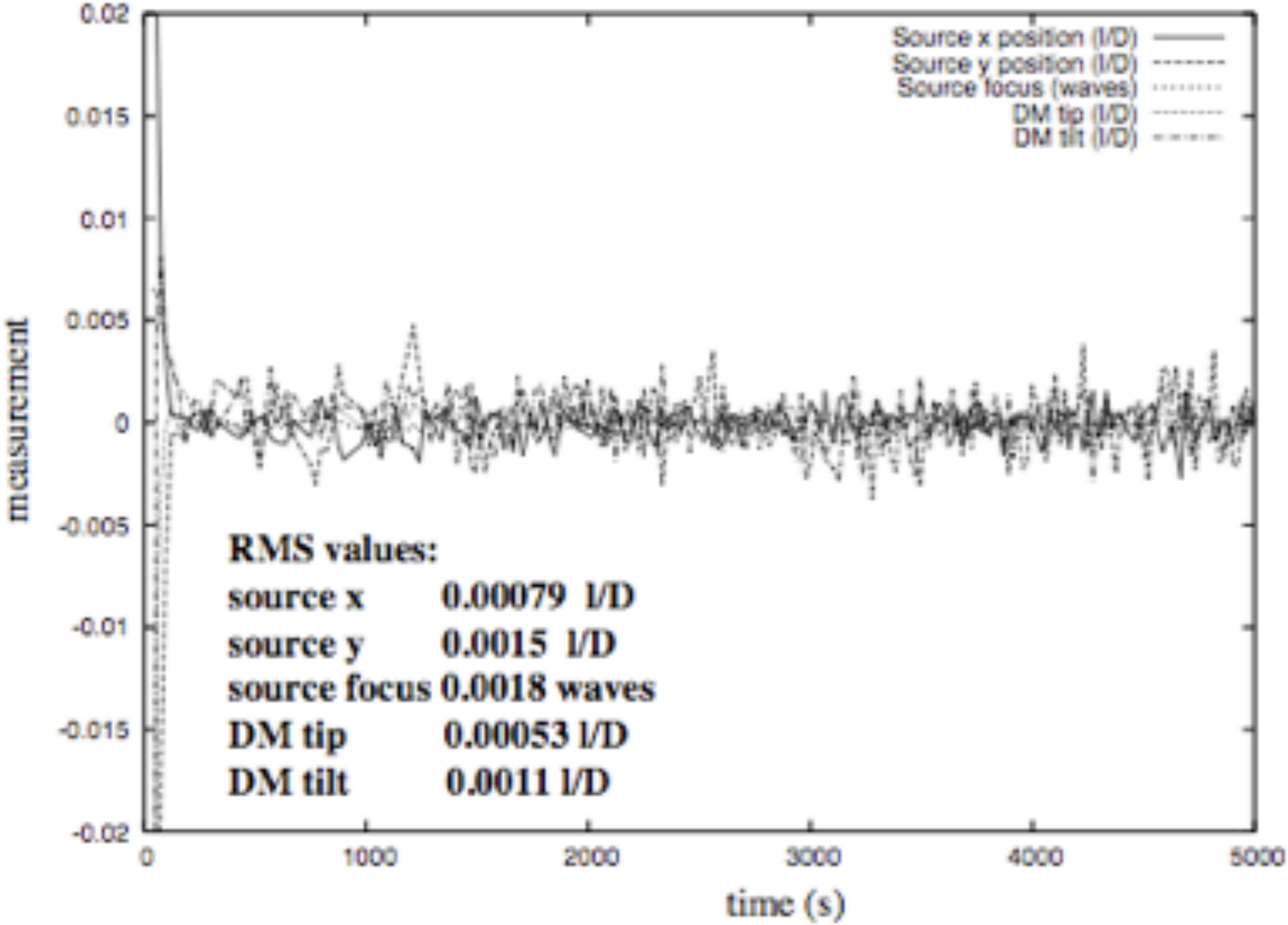

reference frame
DM tip (mode 6)
DM tilt (mode 7)
source x (mode 1)
source y (mode 2)
source focus (mode 3)



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
actuator position
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



0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
measurement
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

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.