New technologies for direct imaging of exoplanets
from ground and space

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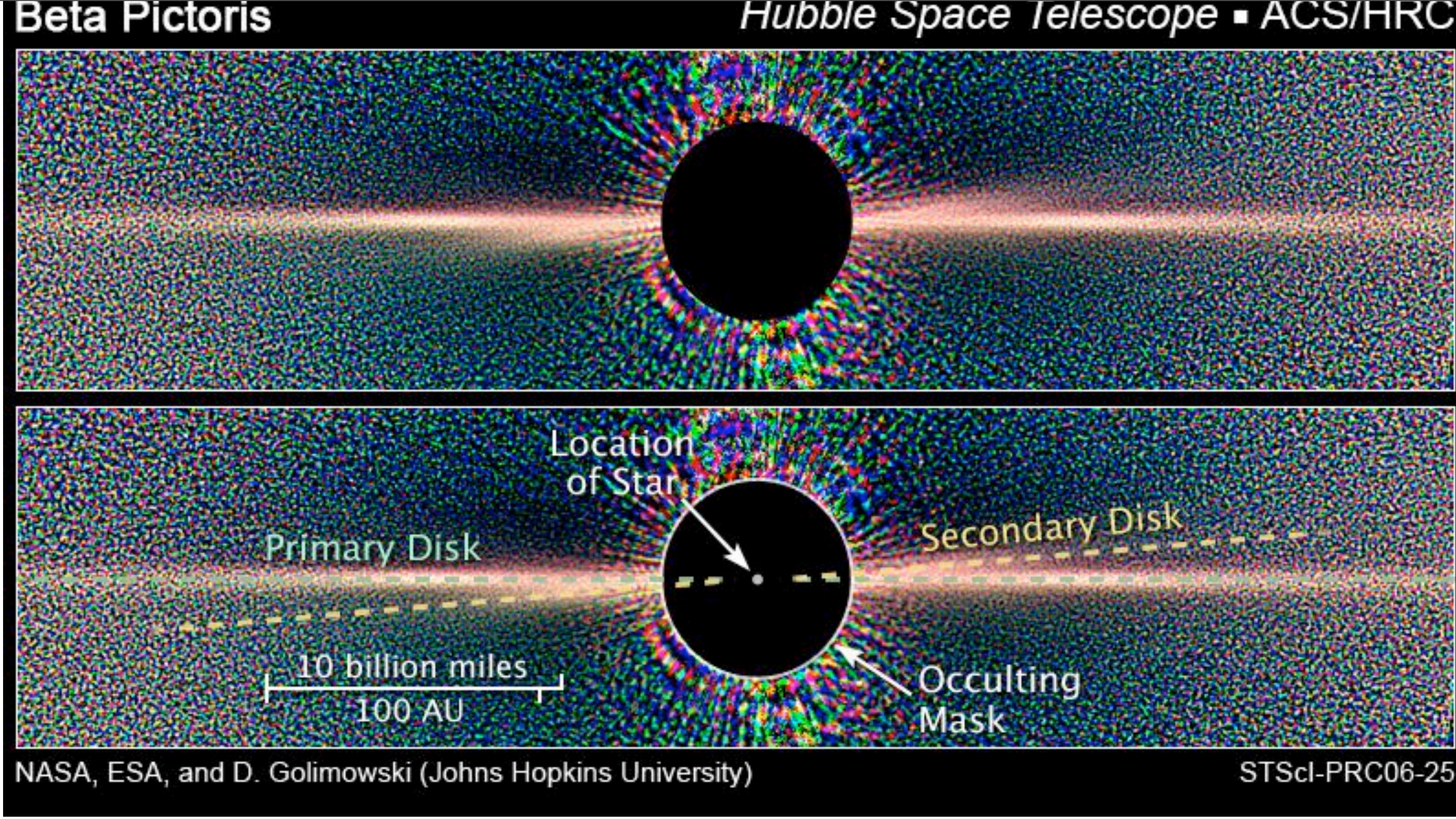
Outline

- Coronagraphy
- Wavefront control
- Differential detection / calibration
- Subaru Coronagraphic Extreme-AO (SCExAO) system
- Can we image Earths with ELT ?
- Imaging Earths from space with a small telescope: PECO

Exoplanet imaging: current and near future capabilities

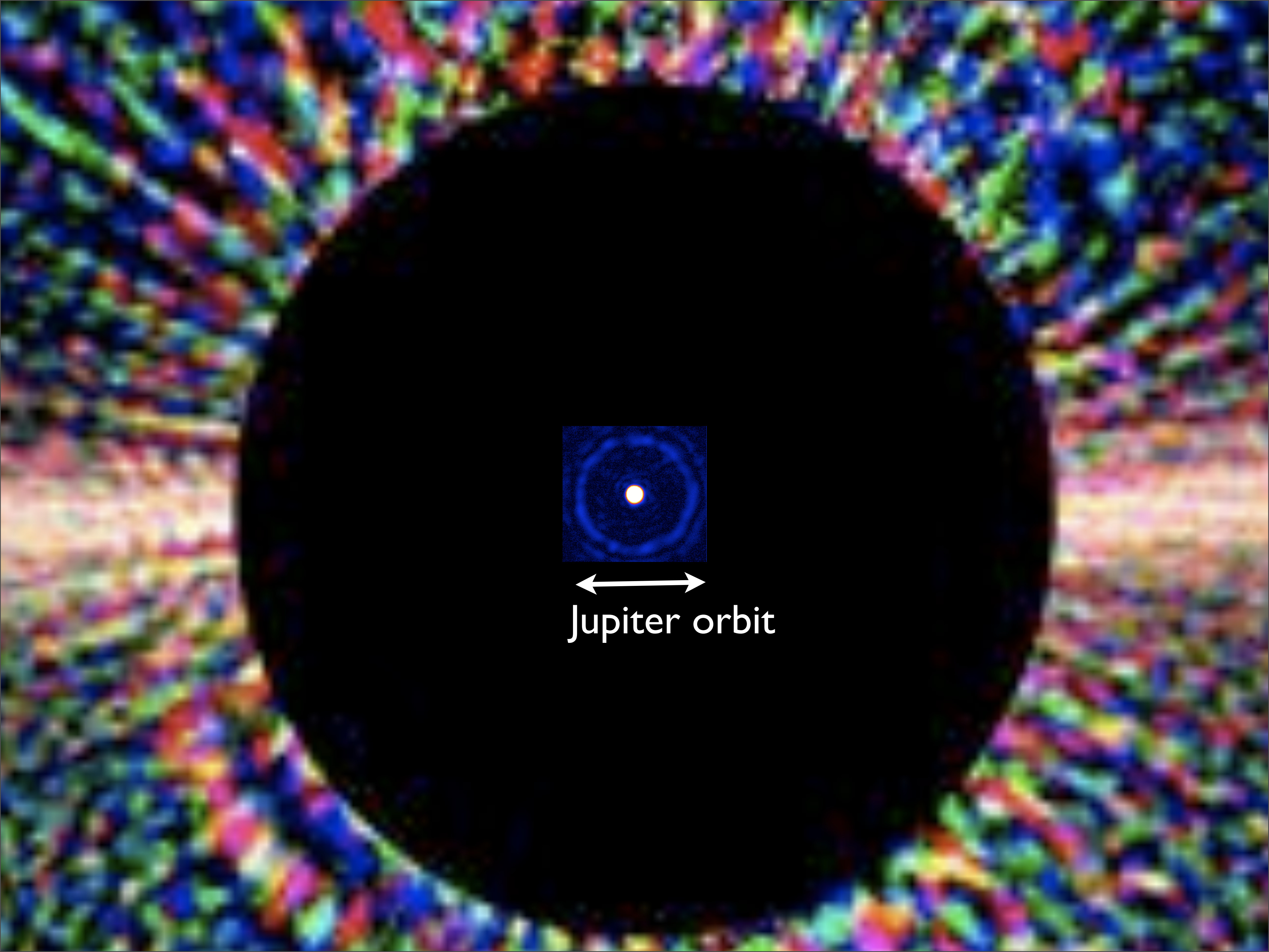
- We can currently image planets down to ~10 MJ at > 10 AU in very young stars
- We still cannot image the inner part (habitable zone) of planetary systems
  - Reflected light out of reach
  - Habitable zones only probed with indirect techniques with very limited characterization capability

Planetary systems formation & architecture in habitable zone ?
How frequent are Earth to Super-Earth planets ?
Planet characterization: mass, radius, atmosphere, life ?



Beta Pic is at 20 pc
ACS mask is 30 AU radius

1 l/D on Subaru in H = 40 mas = 0.7 AU
In Taurus, ~ 5 AU


Jupiter orbit

Coronagraphy

Old (current) coronagraph designs are a painful compromise between inner working angle, throughput, angular resolution and contrast

New coronagraph techniques allow 1e6 contrast at 1 l/D (ground) or 1e10 contrast at 2 l/D (space) with no "side effect"

Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

+ Simple, robust, achromatic
 - low efficiency for high contrast

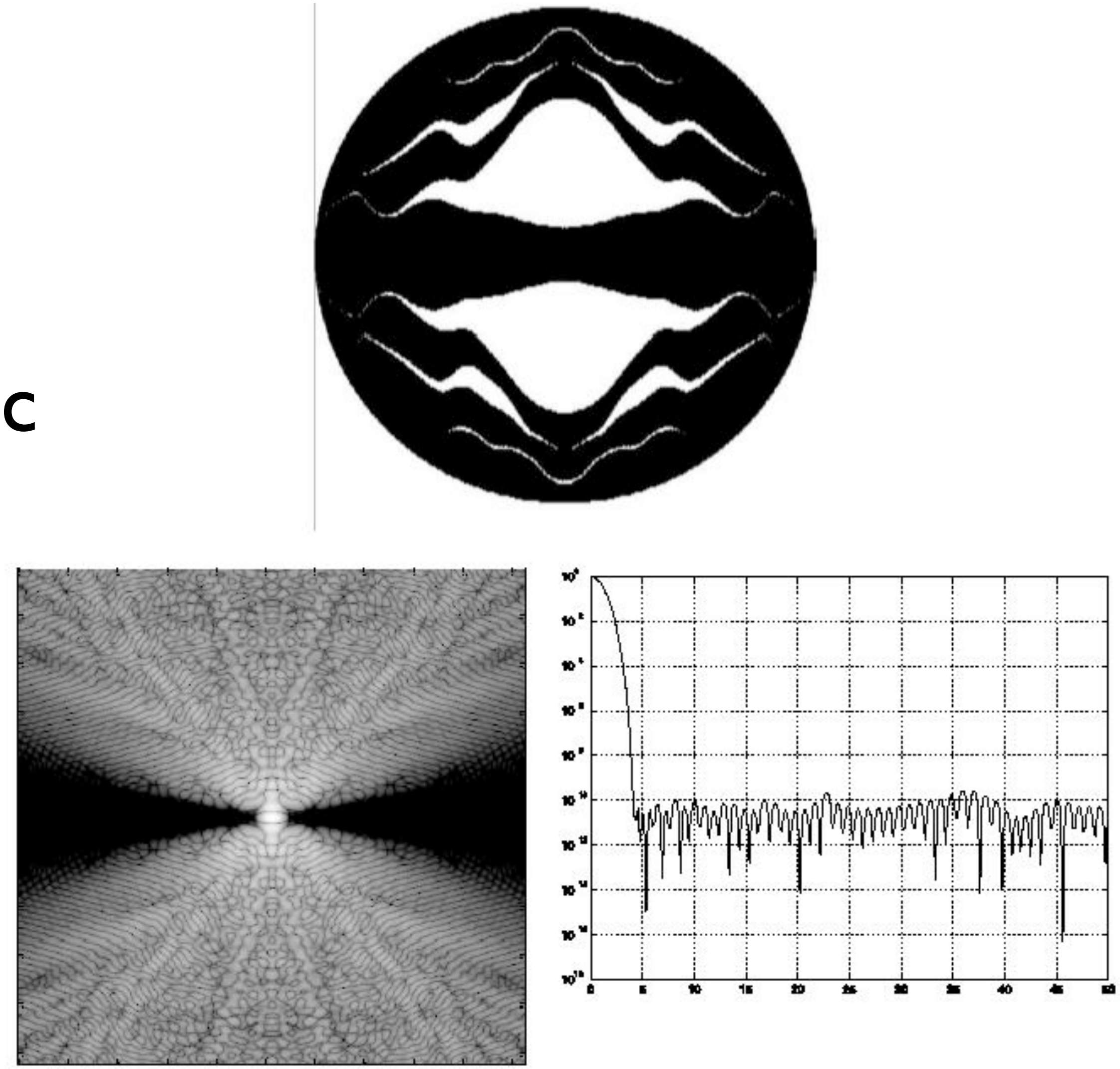


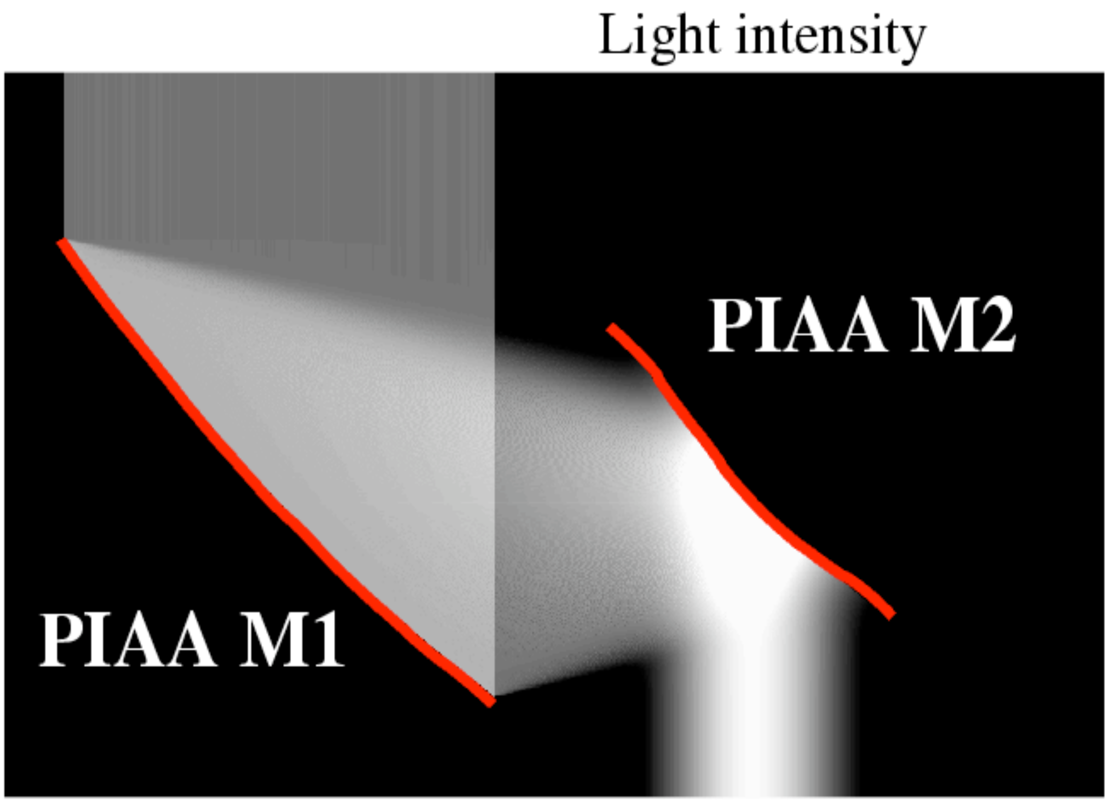
Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

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

Phase Induced Amplitude Apodization 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 l/d for 1e6 contrast
- 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

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

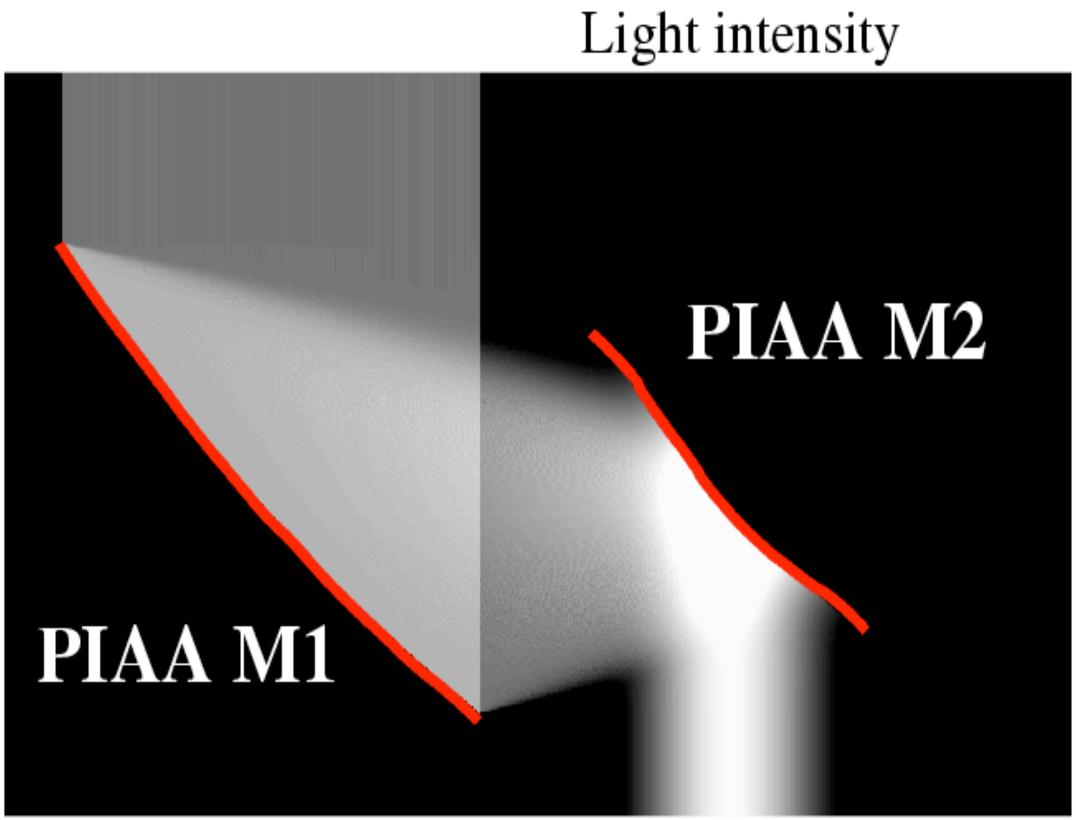
8.5 PIAA optics sets made so far:

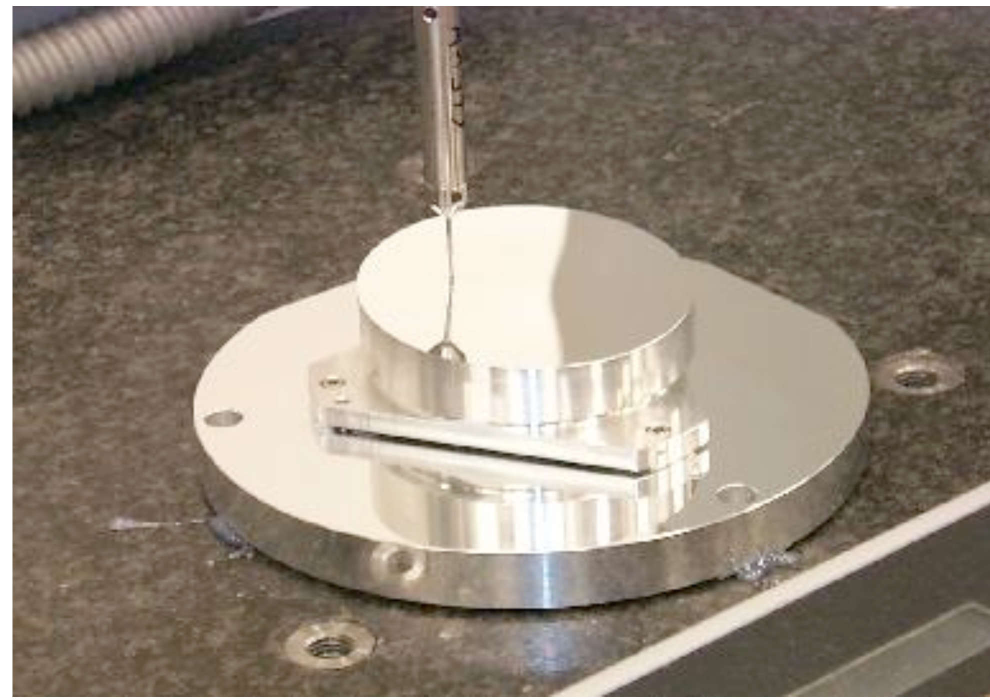
1 refractive PIAA system, diamond turned plastic [NAOJ]

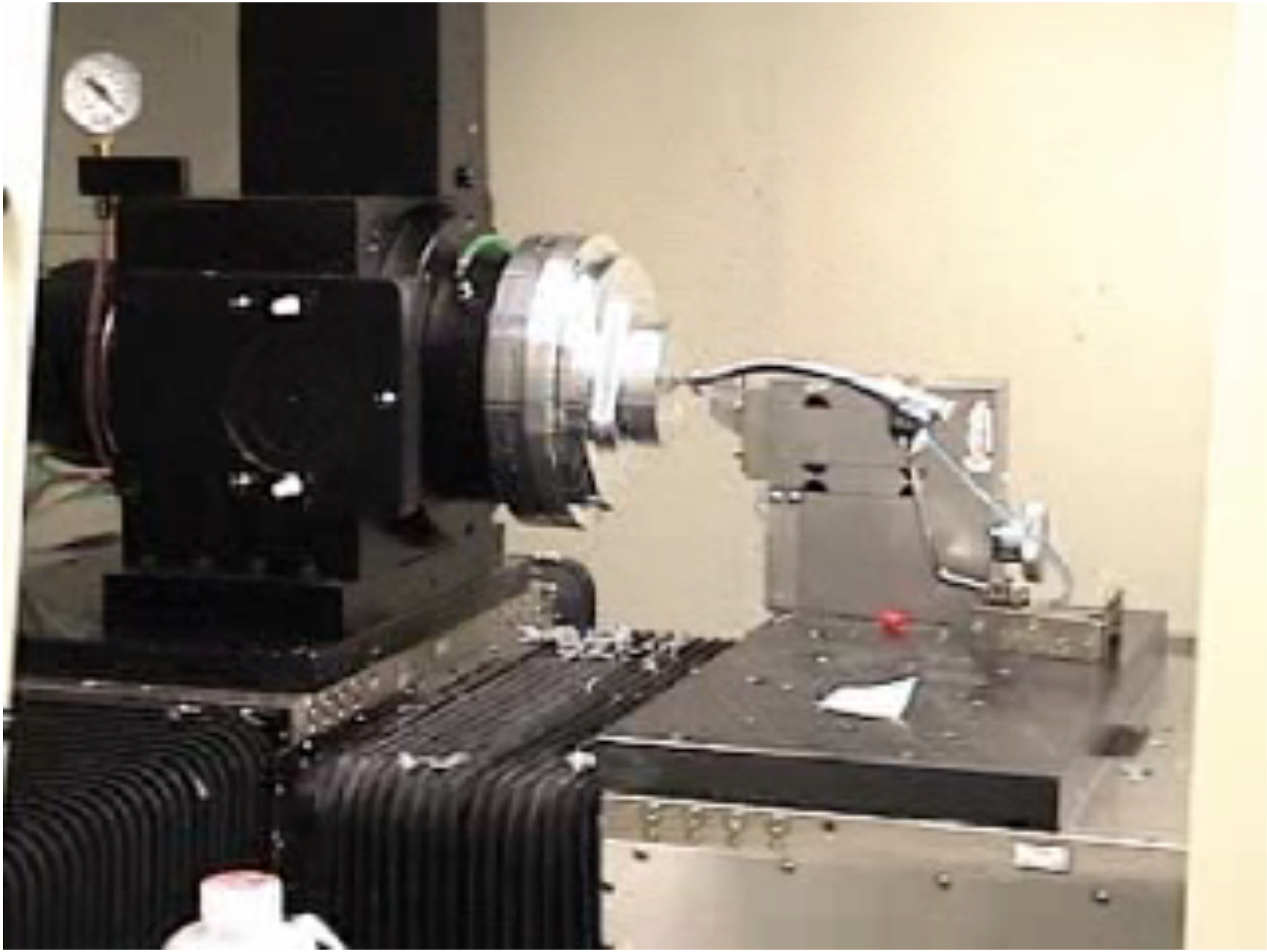
2 reflective PIAA systems, Nickel-plated diamond turned Al (1 design x2) [Axsys]

6 refractive PIAA systems, diamond turned CaF2 (3 designs x2) [Axsys]

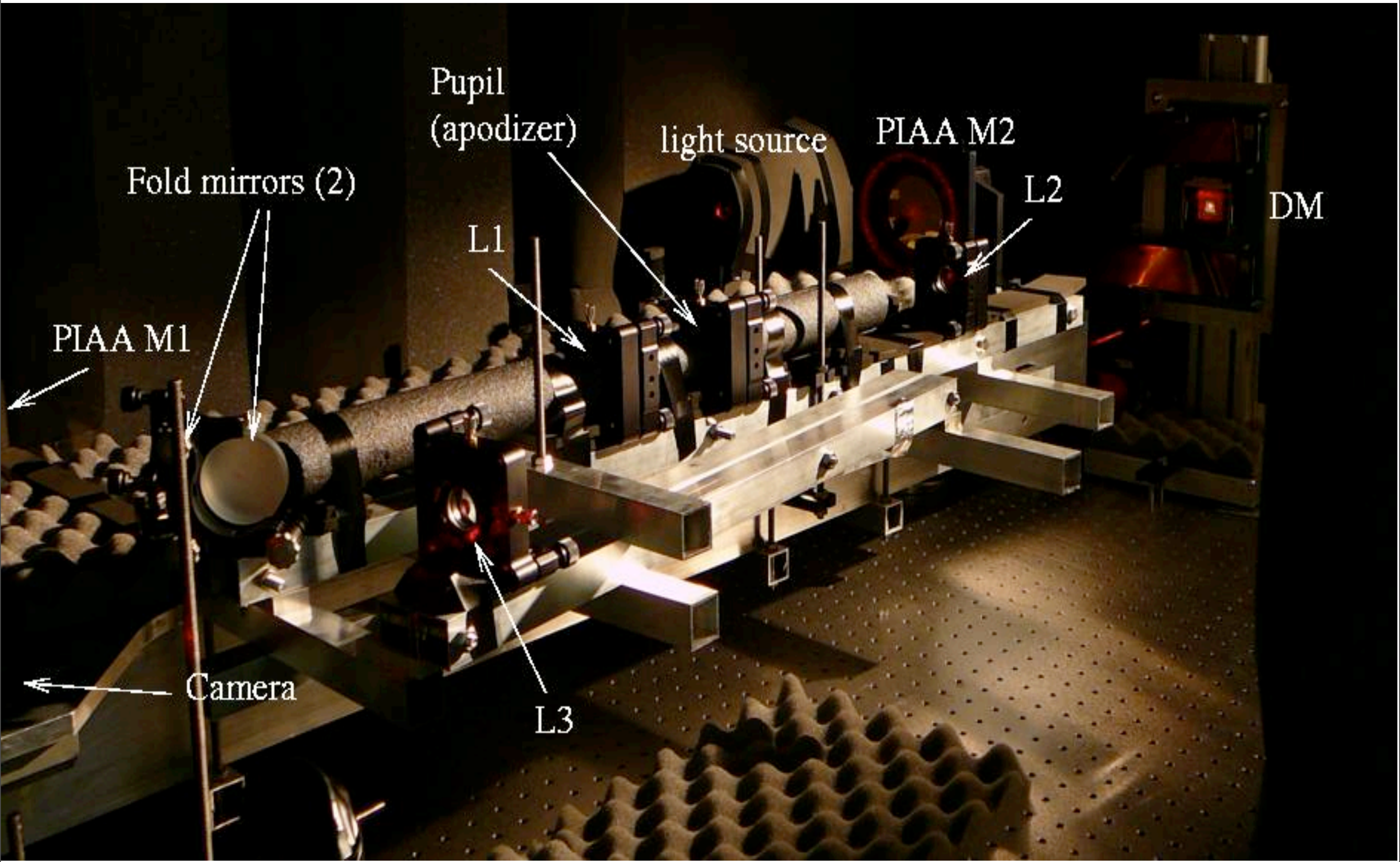
+ 1 reflective PIAA system, Zerodur, currently in manufacturing [Tinsley]

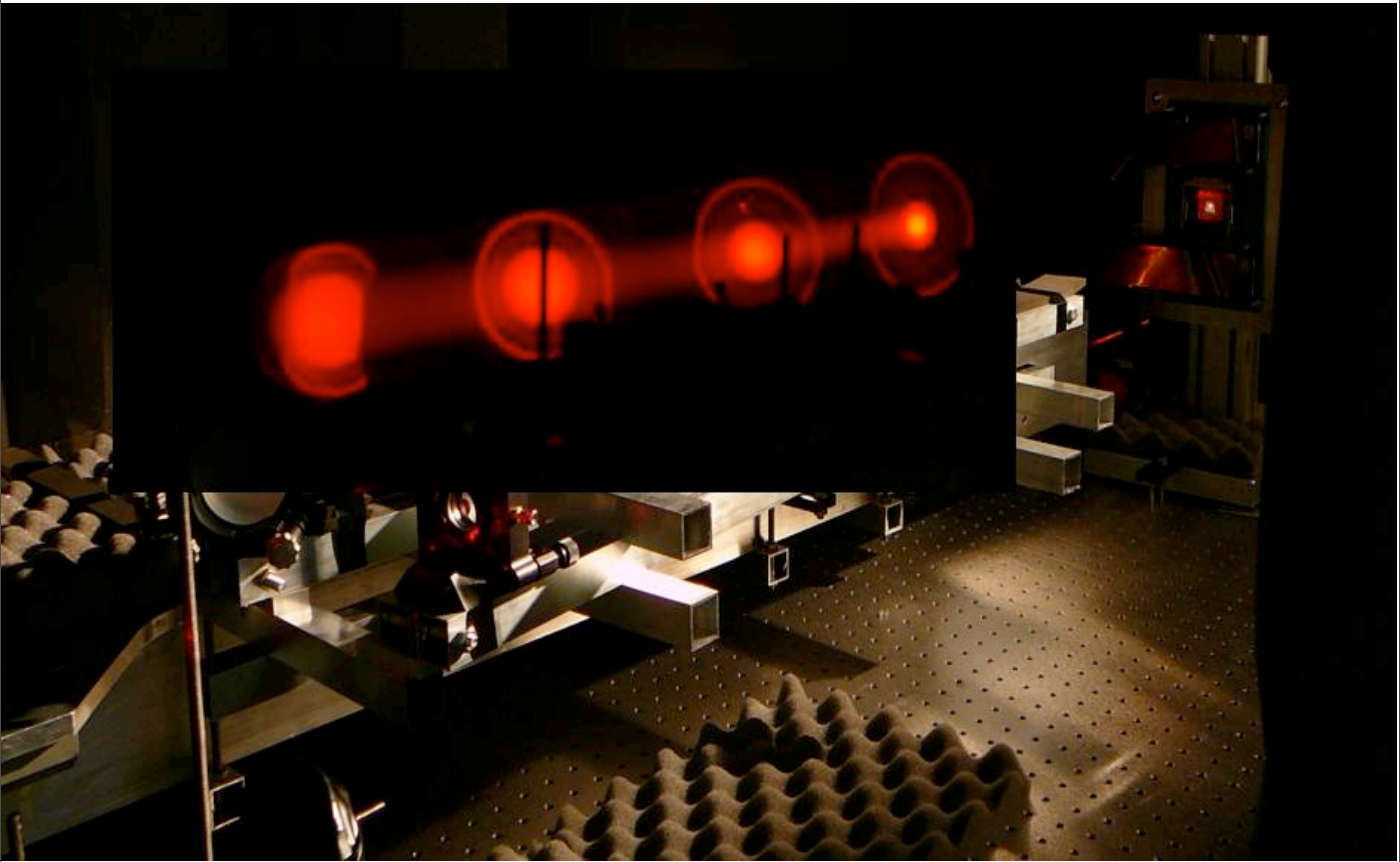




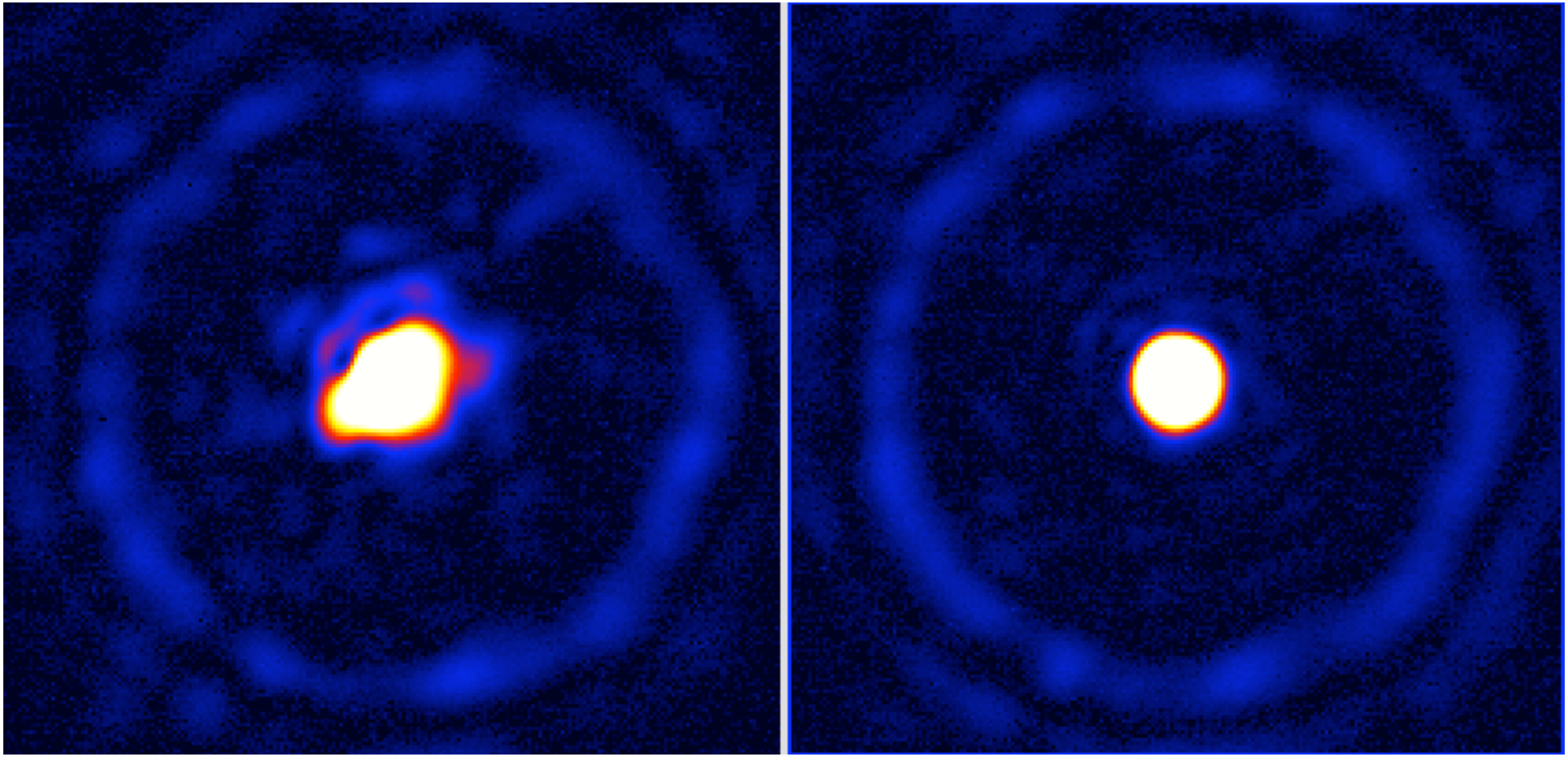


Subaru lab experiment
co-funded by Subaru/NAOJ & JPL



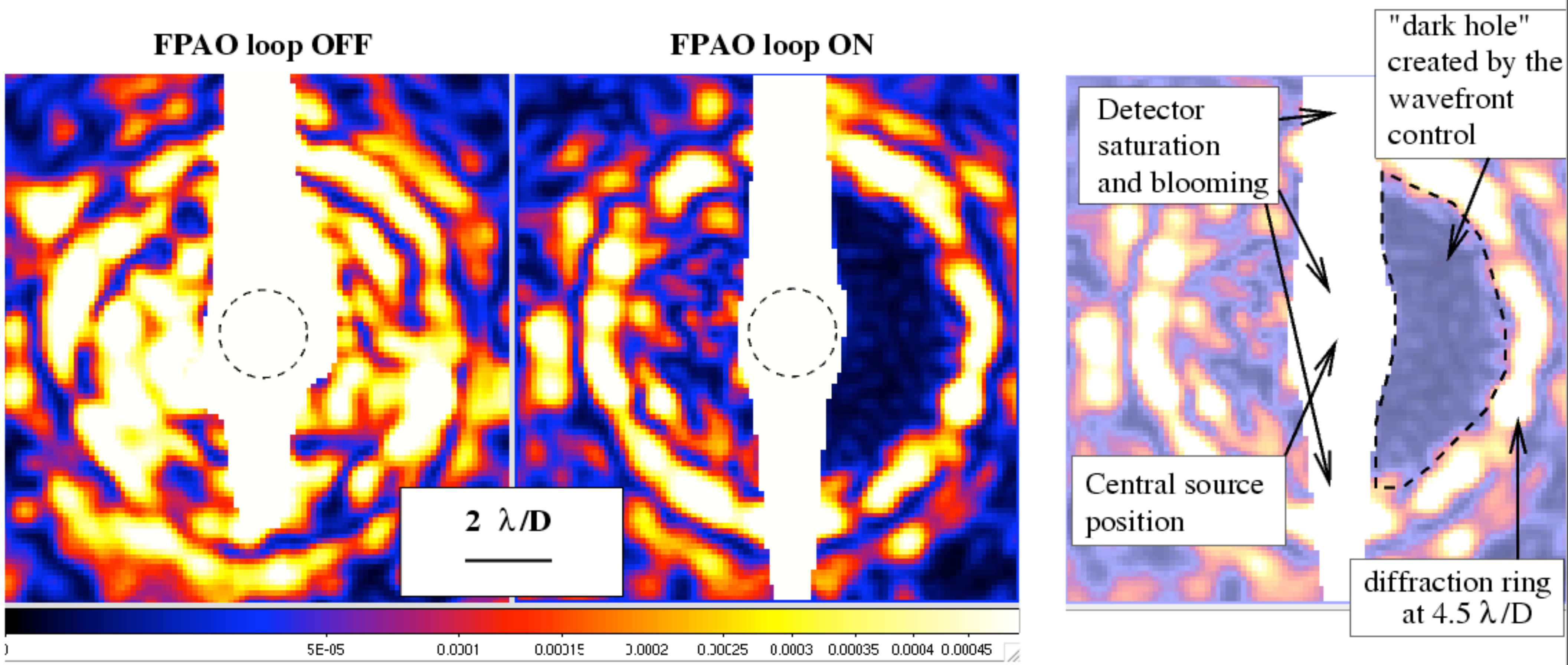


Lab results with PIAA coronagraph + FPAO



Step 1: phase diversity -> DM correction

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



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)

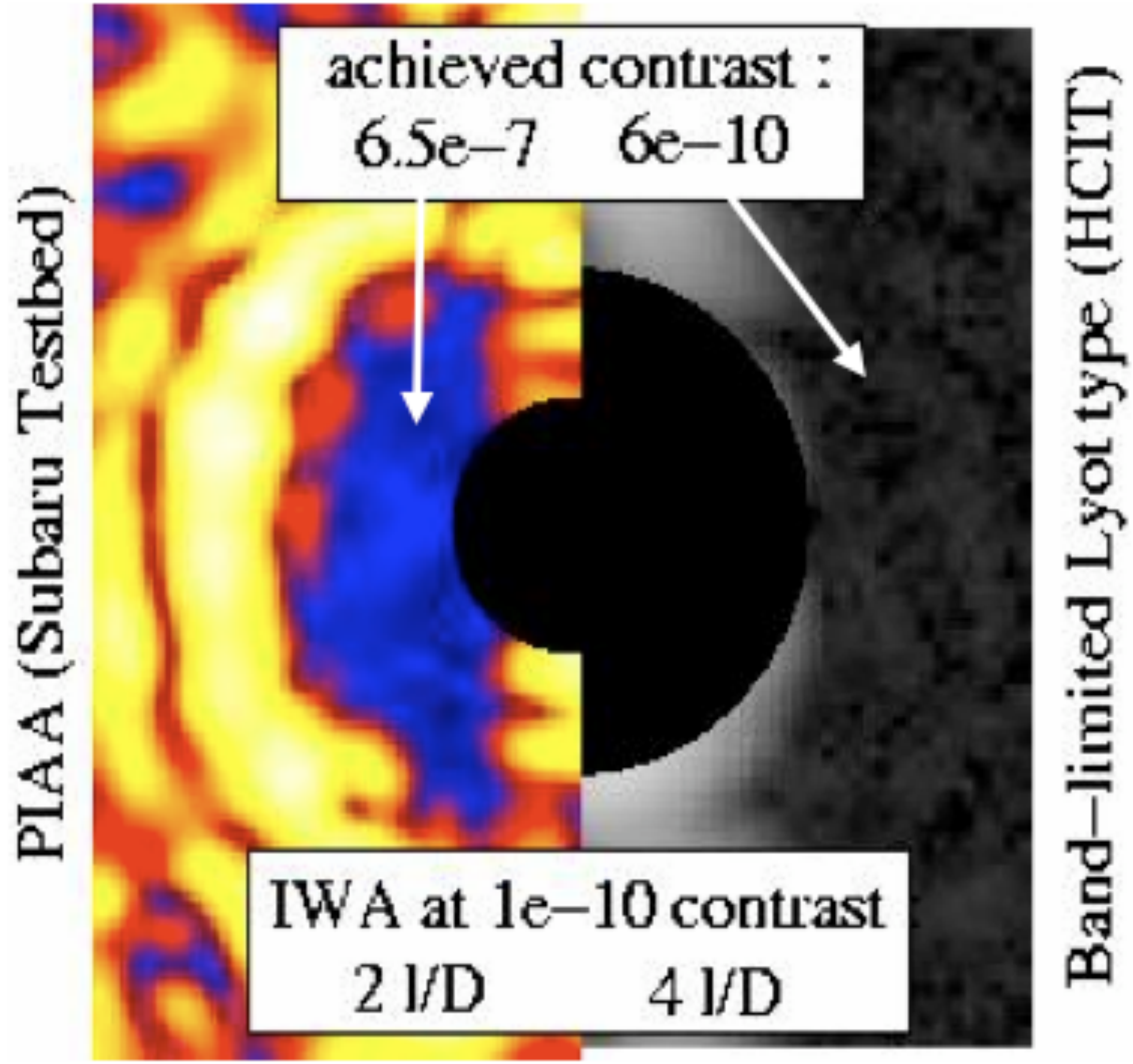
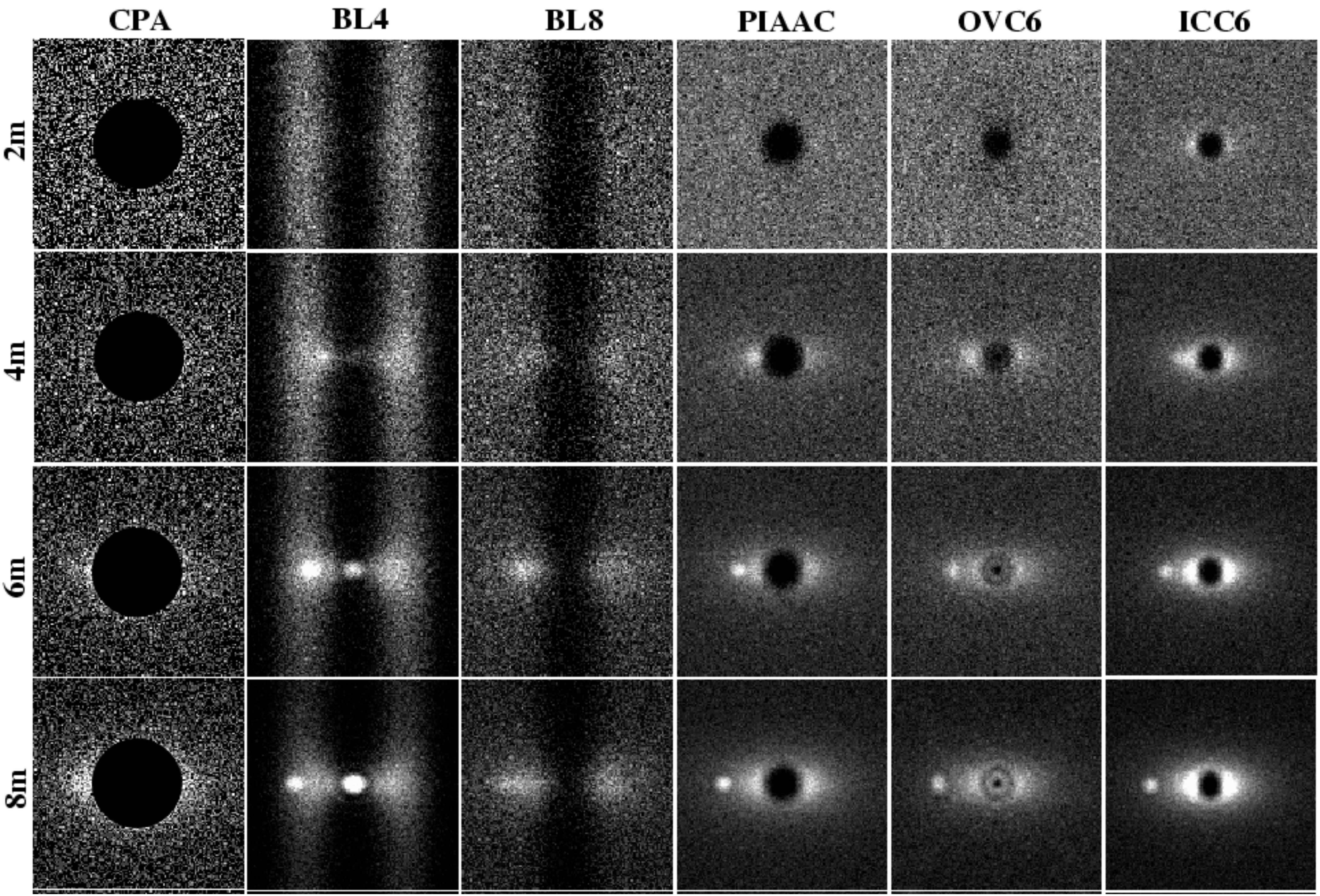


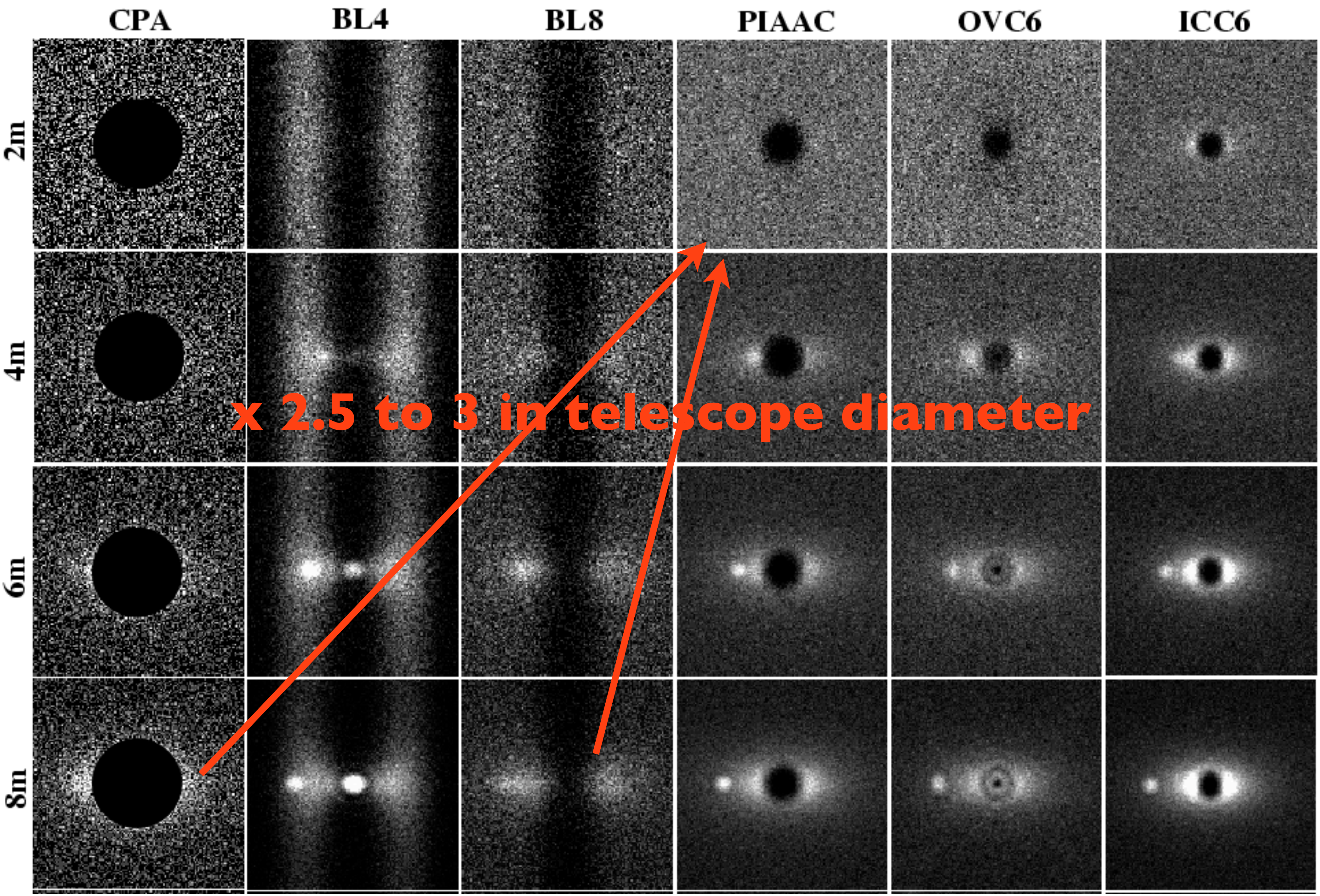
Figure 1.3-2 Comparison between the IWA of a PIAA coronagraph and a Lyot-type band limited coronagraph. Actual laboratory PSFs are shown at the same scale. The high sensitivity regions are in blue (PIAA) and black (band limited).

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

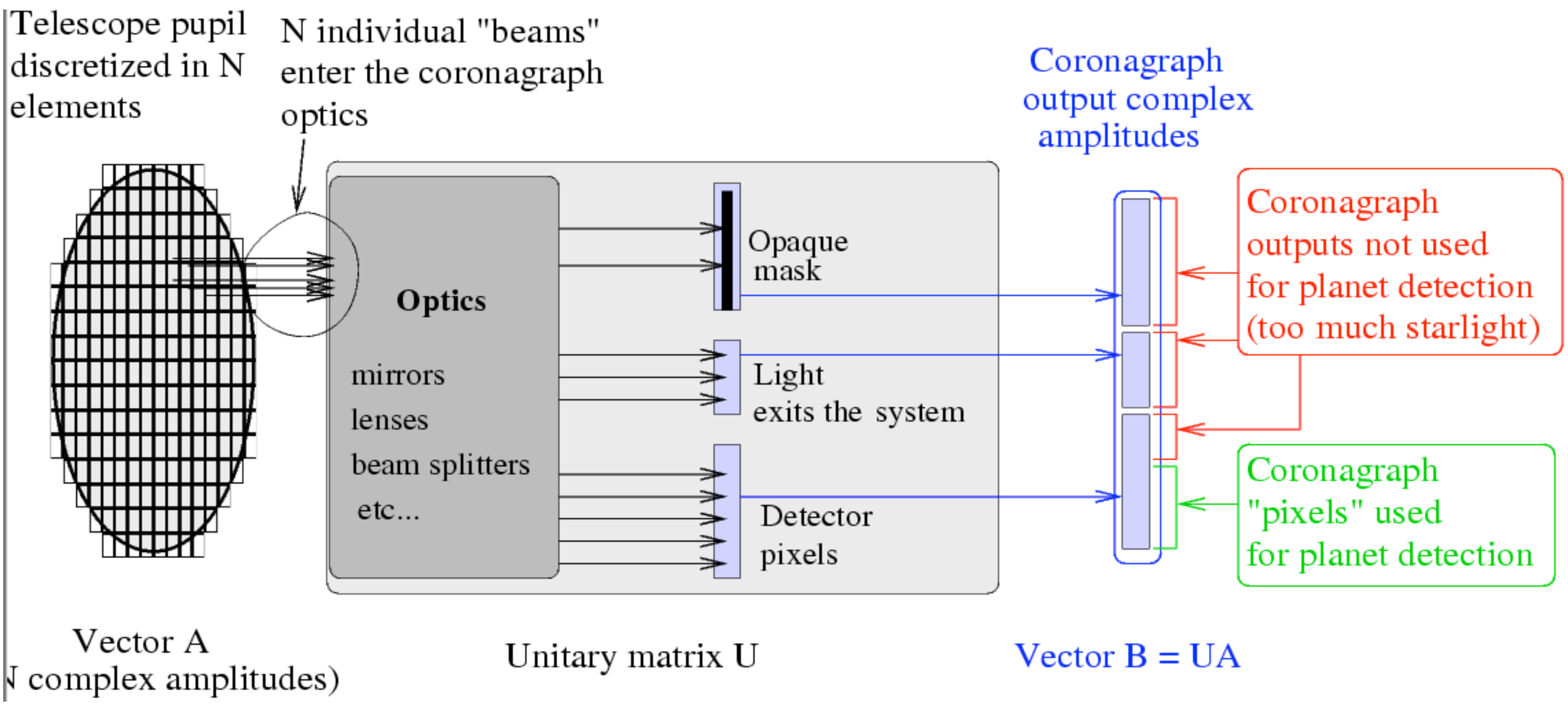

CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m

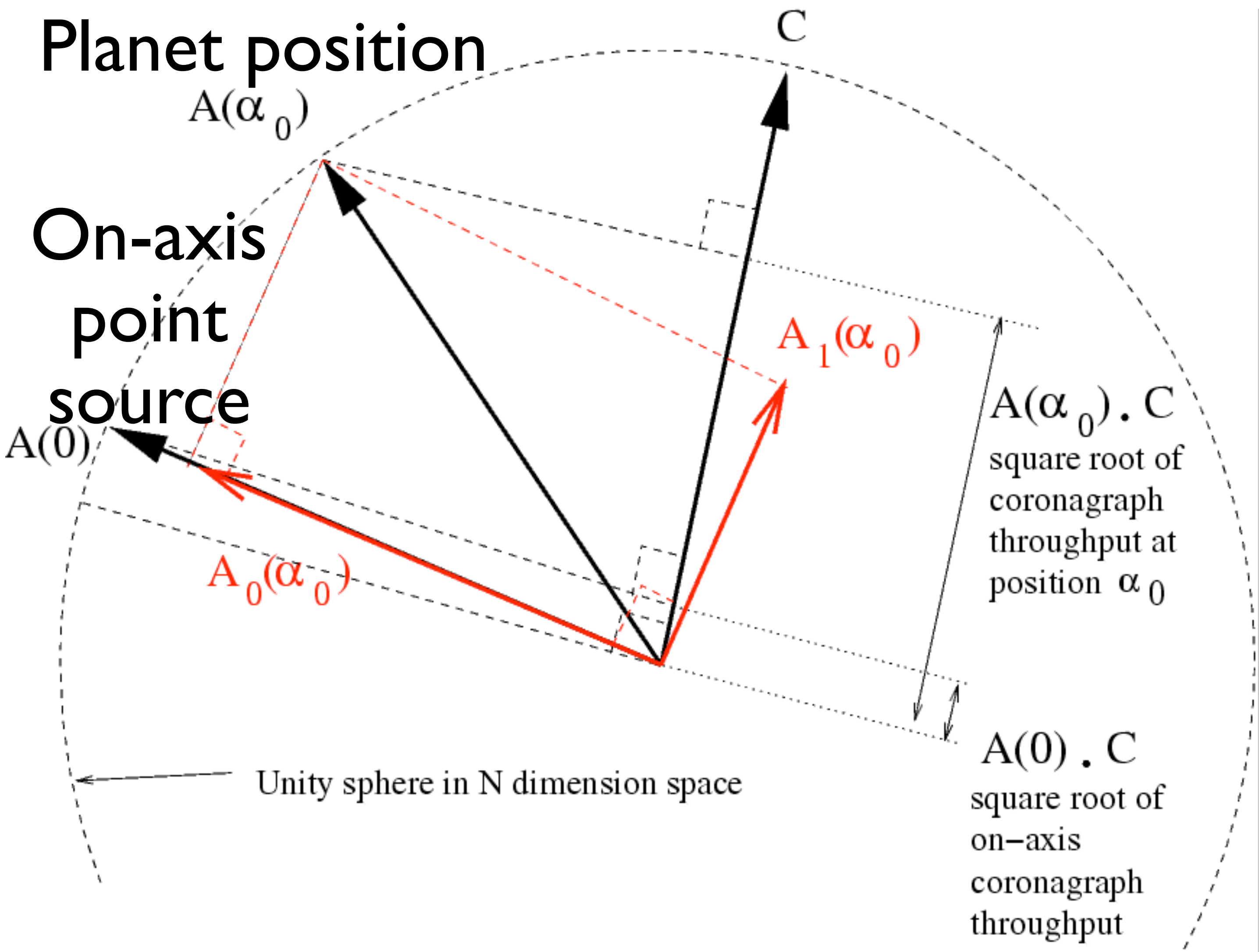


CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m
x 2.5 to 3 in telescope diameter

Linear system in complex amplitude

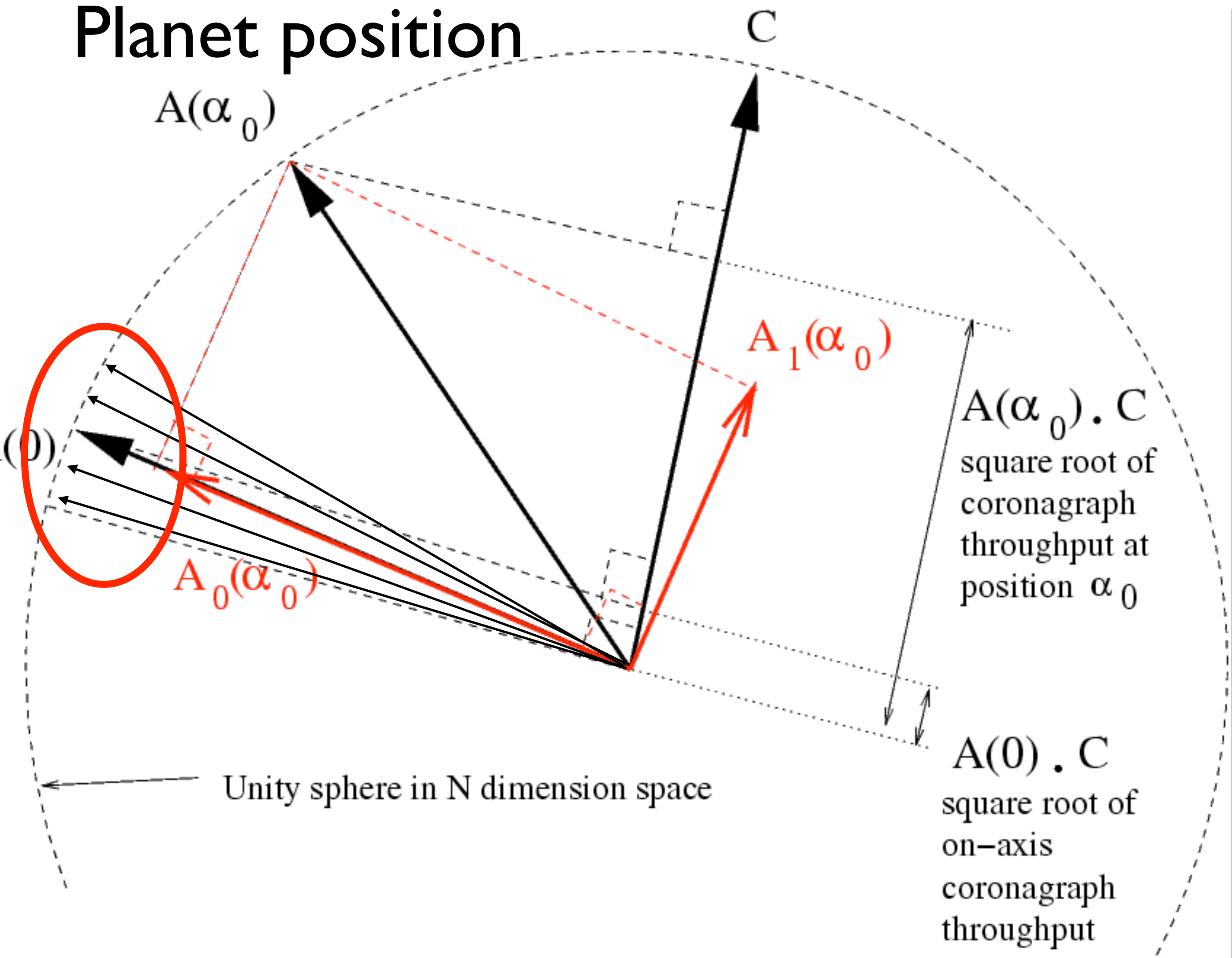
Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: **all are linear**



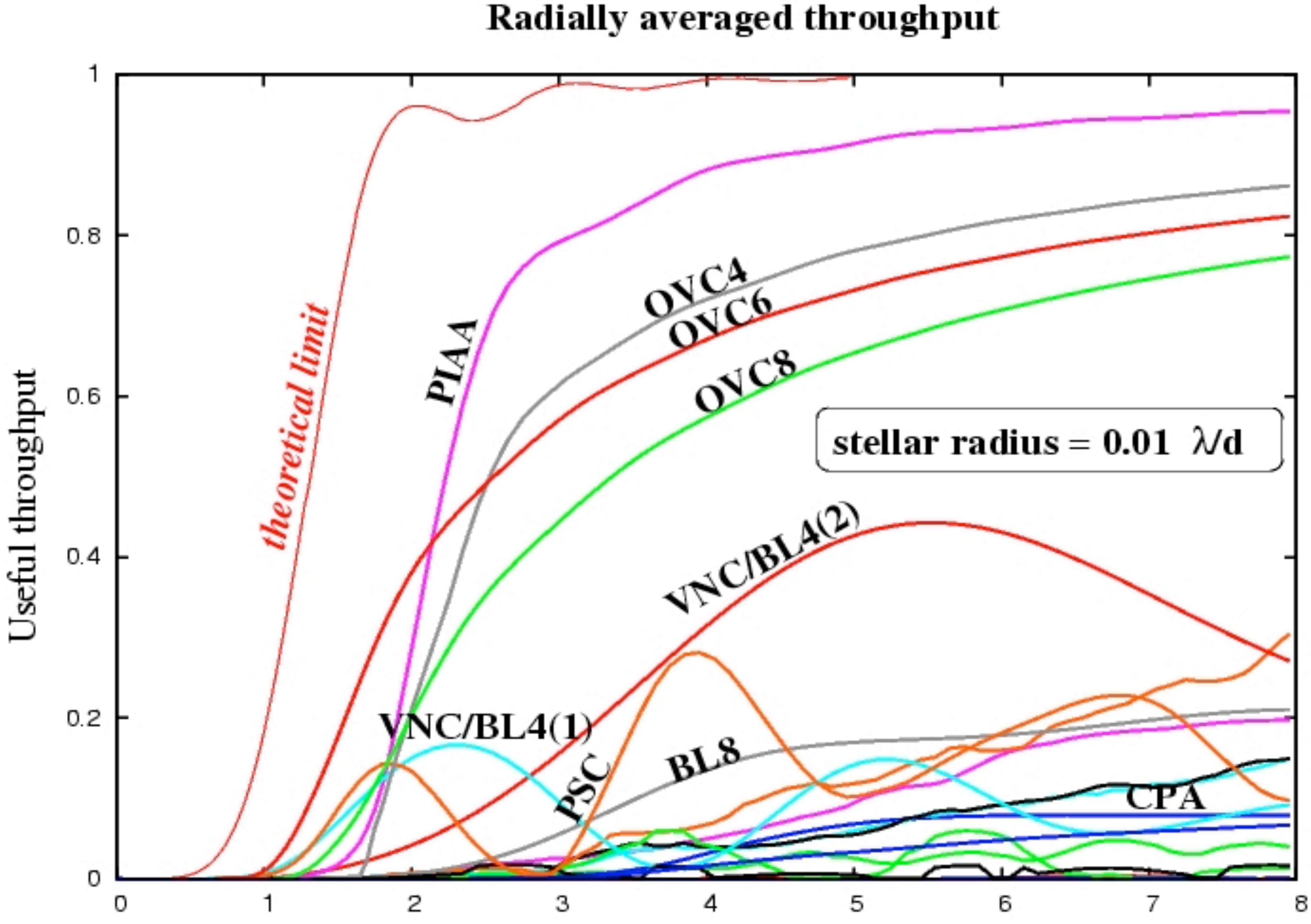


Planet position
On-axis point source
C
A(α 0)
A 1(α 0)
A(α 0) . C
square root of coronagraph throughput at position α 0
A(0)
A 0(α 0)
Unity sphere in N dimension space
A(0) . C
square root of on–axis coronagraph throughput

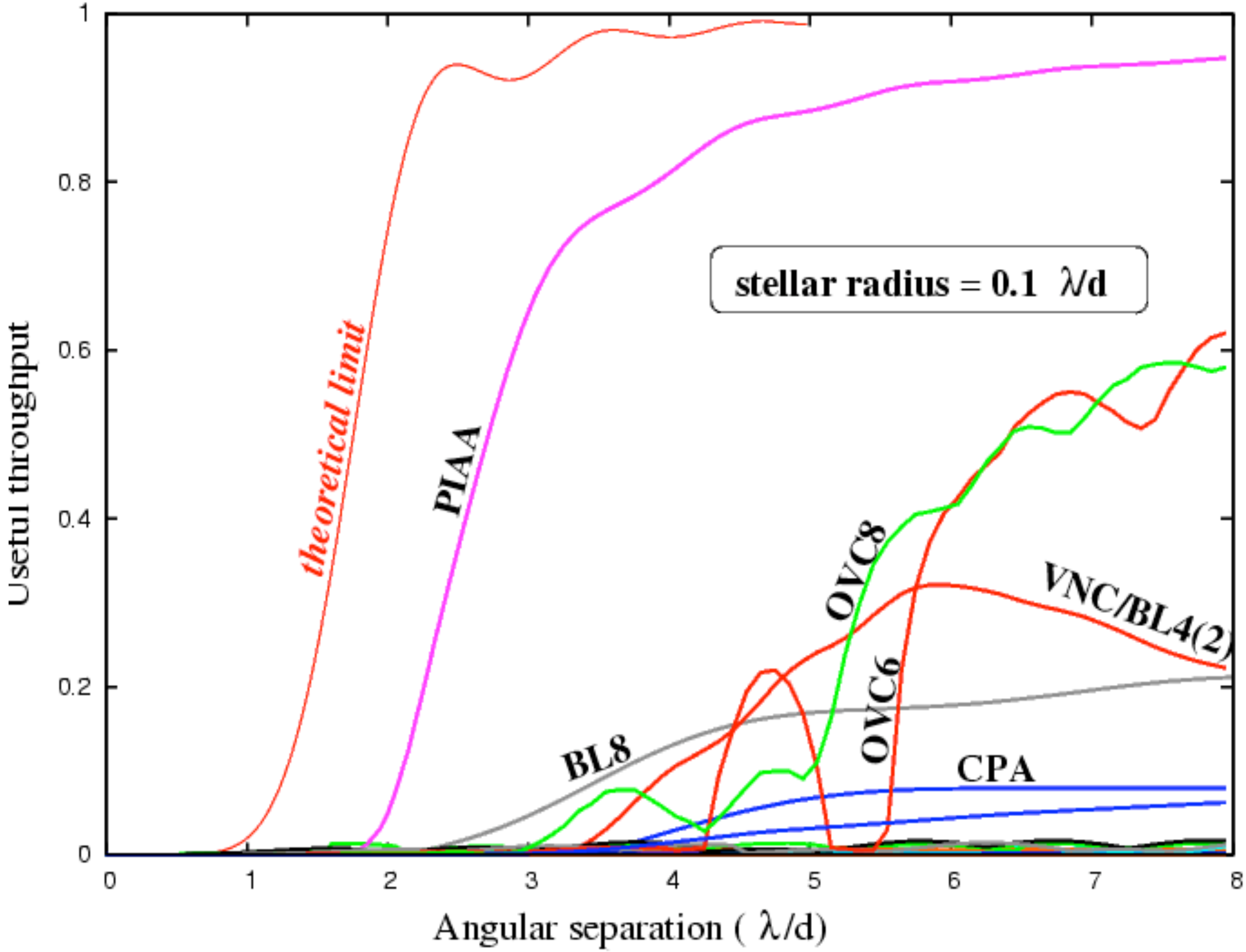
Central star is made
of a group of vectors,
ALL of which need to
be cancelled to some degree.



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



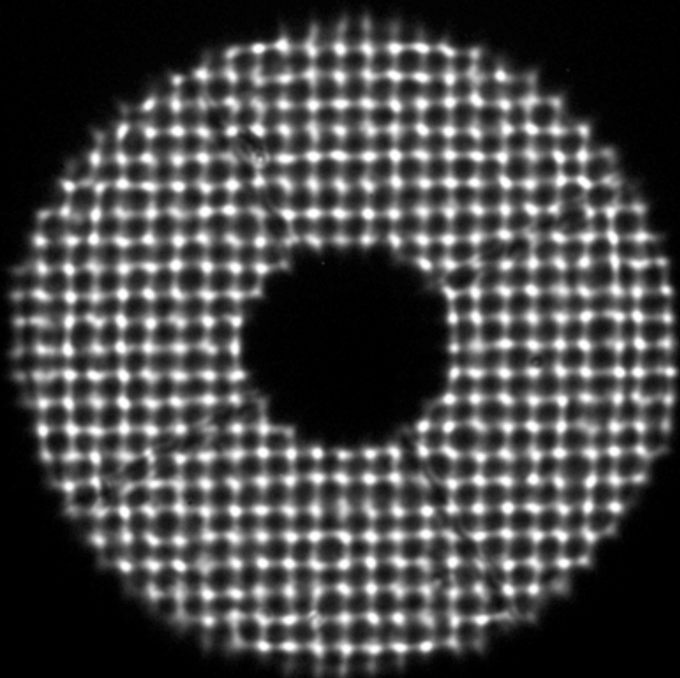
Useful throughput – average, 0.1 l/d



Wavefront control

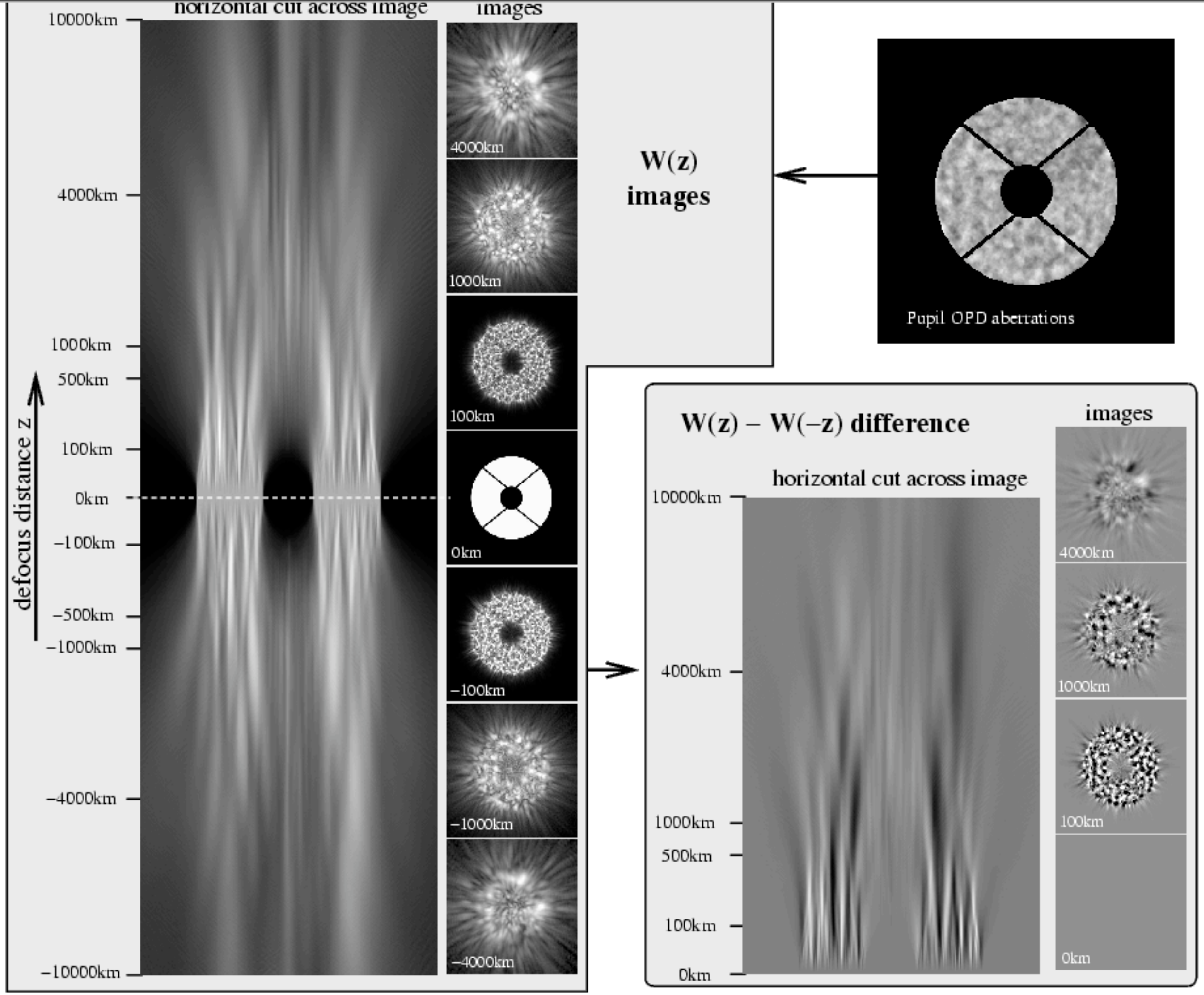
Current WFS schemes are seeing-limited
Ex-AO should use diffraction-limited WFS

SH WFS is also suffering from noise propagation



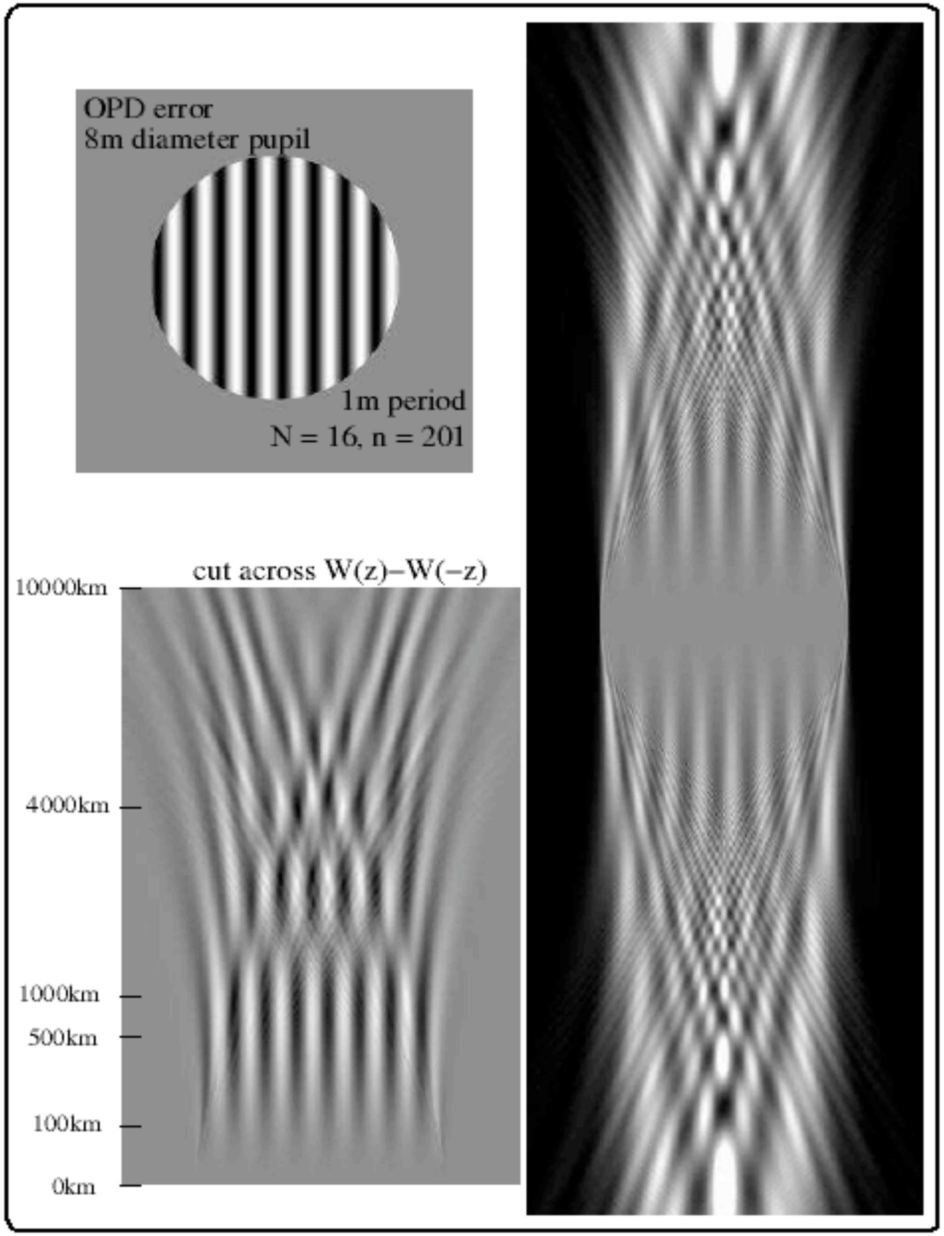
Spot sizes is lambda/r0 at best (lambda/d if d<r0) >> lambda/D

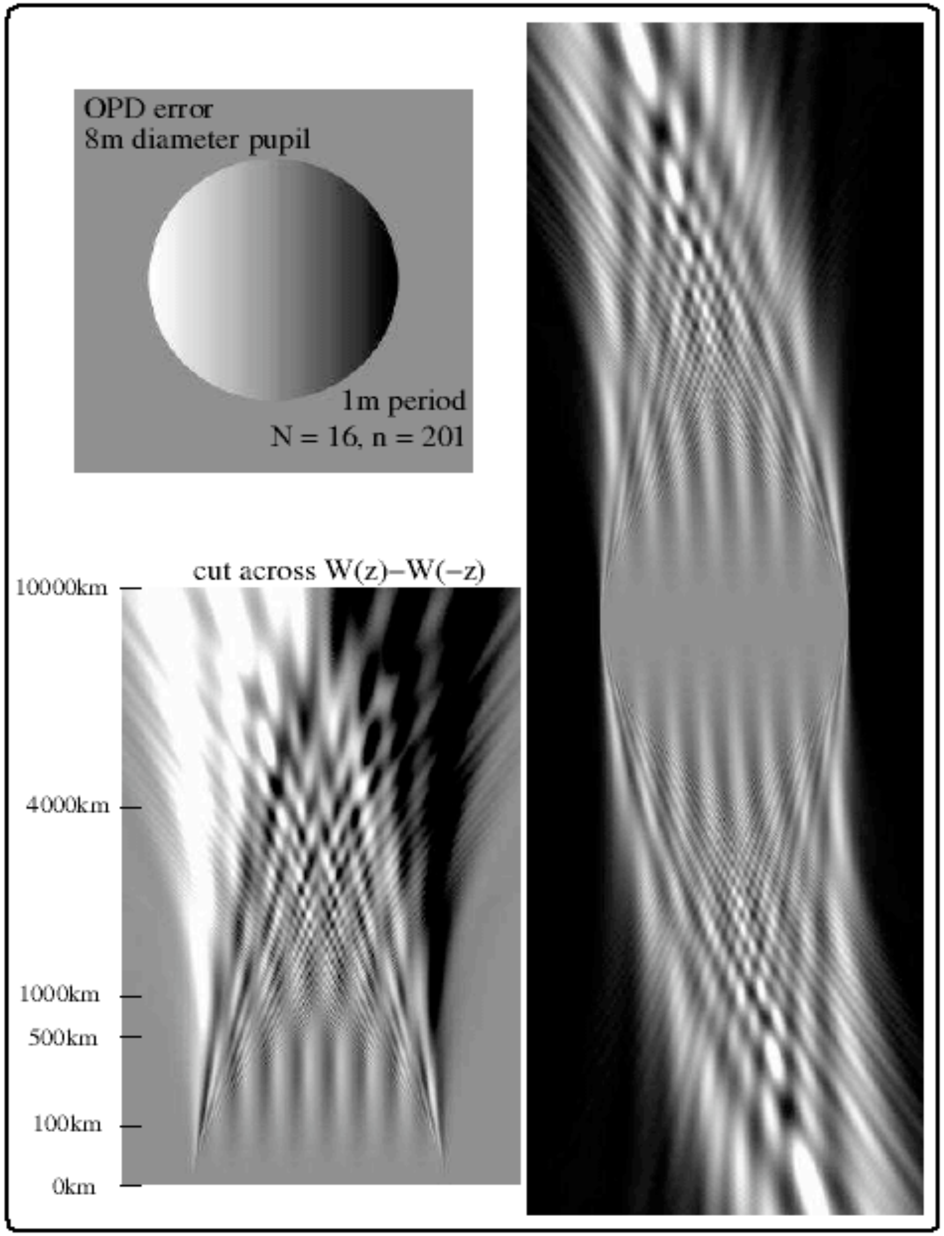
Low order modes suffer from very poor SNR



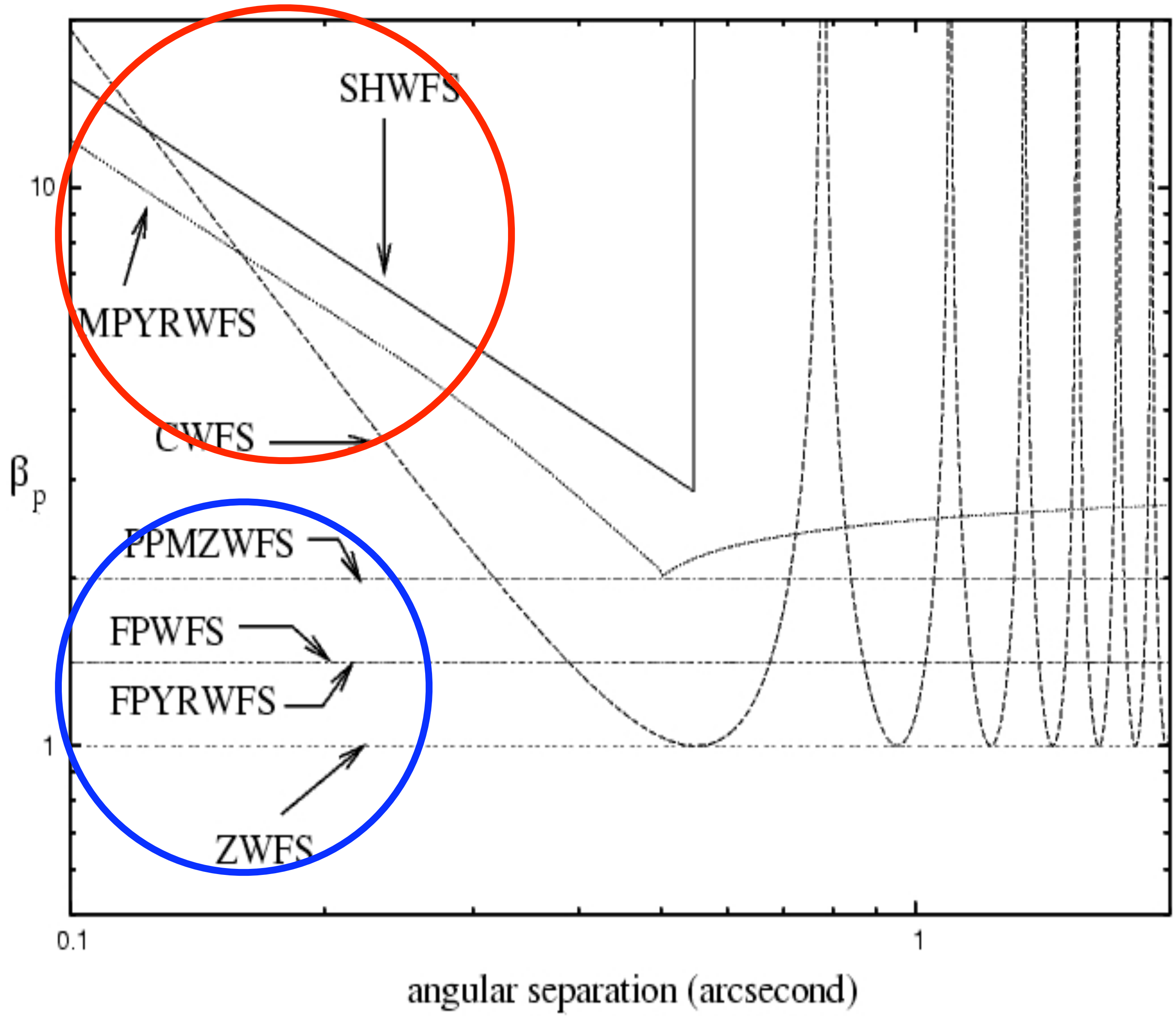
horizontal cut across image
images
10000km
4000km
1000km
500km
100km
0km
−100km
−500km
−1000km
−4000km
−10000km
defocus distance z
4000km
1000km
100km
0km
−100km
−1000km
−4000km
W(z)
images
Pupil OPD aberrations
W(z) − W(−z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km
0km
4000km
1000km
100km
0km

Problem #2: Low order aberrations "scramble" high spatial frequencies
-> defocus distance must be kept small





Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)



Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5" from central star.

Why do SH, Curvature (& modulated pyramid) have bad sensitivity for low order aberrations ?

Good measurement of low order aberrations requires interferometric combination of distant parts of the pupil
FPWFS does it, but:

- SH chops pupil in little pieces -> no hope !
- Curvature has to keep extrapupil distance small (see previous slides) -> same problem

Things get worse as # of actuators go up.
-> **This makes a big difference for ELTs**

Tip-tilt example (also true for other modes):
With low coherence WFS, sigma2 ~ 1/D^2 (more photons)
Ideally, one should be able to achieve:
sigma2 ~ 1/D^4 (more photons + smaller l/D)

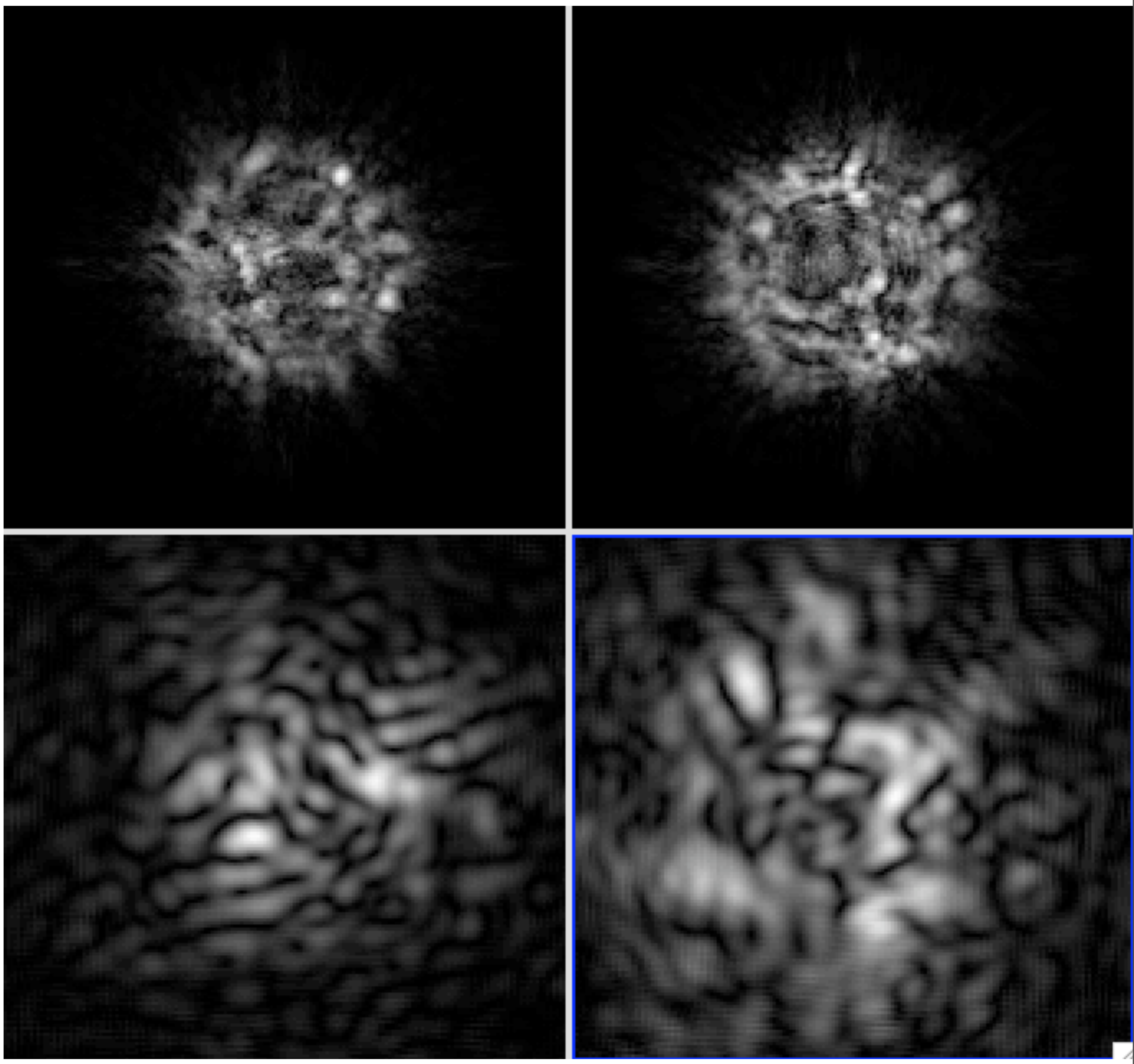
SH: Noise propagation limitation is introduced at the optical level (chopping the pupil in small pieces)

Curvature: Noise propagation comes from processing of WFS frames, which imposes linearity

-> possible to mitigate / solve ?

Defocused pupil images are full of lambda/D speckles

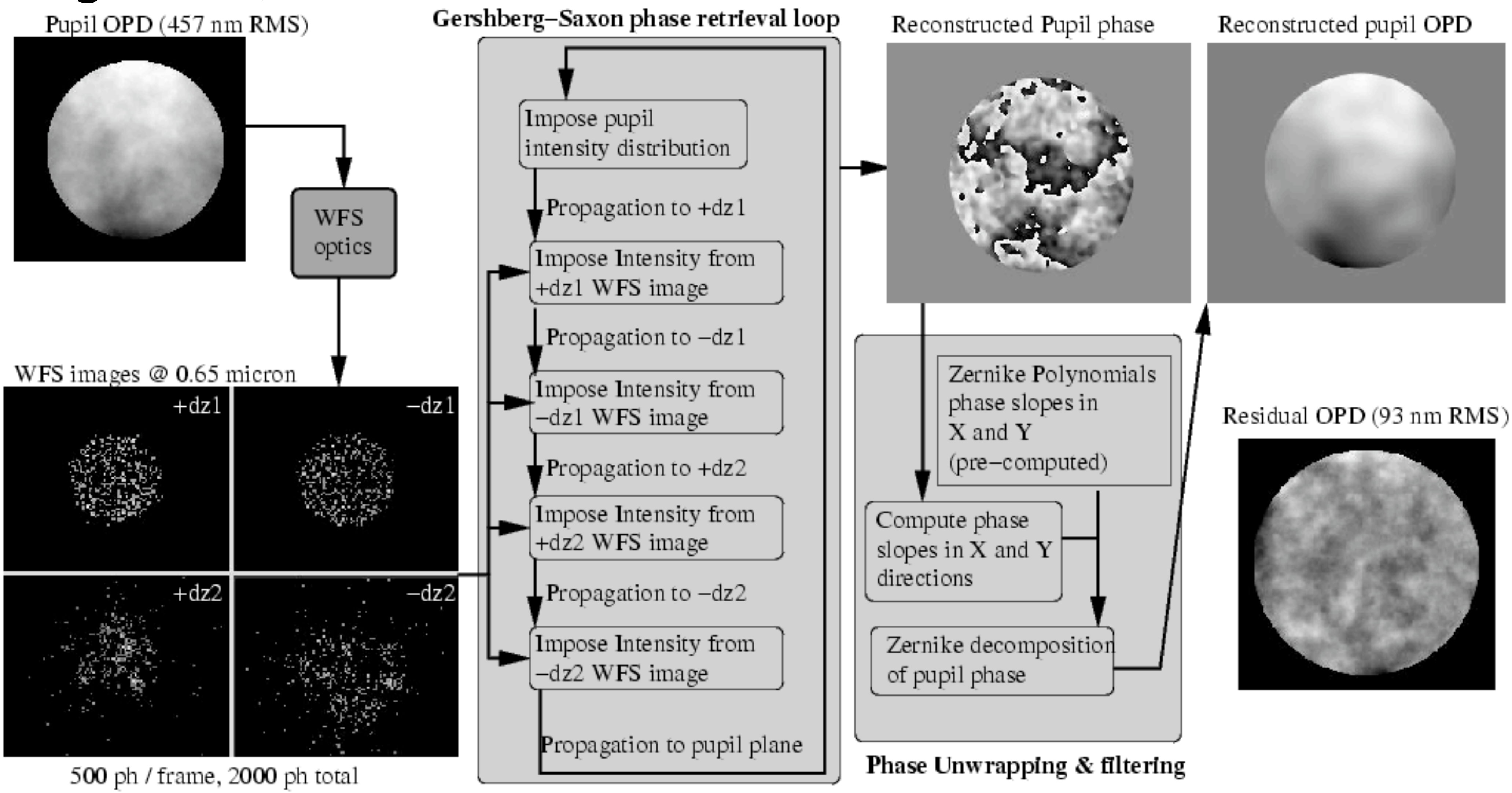
+/- 1000km



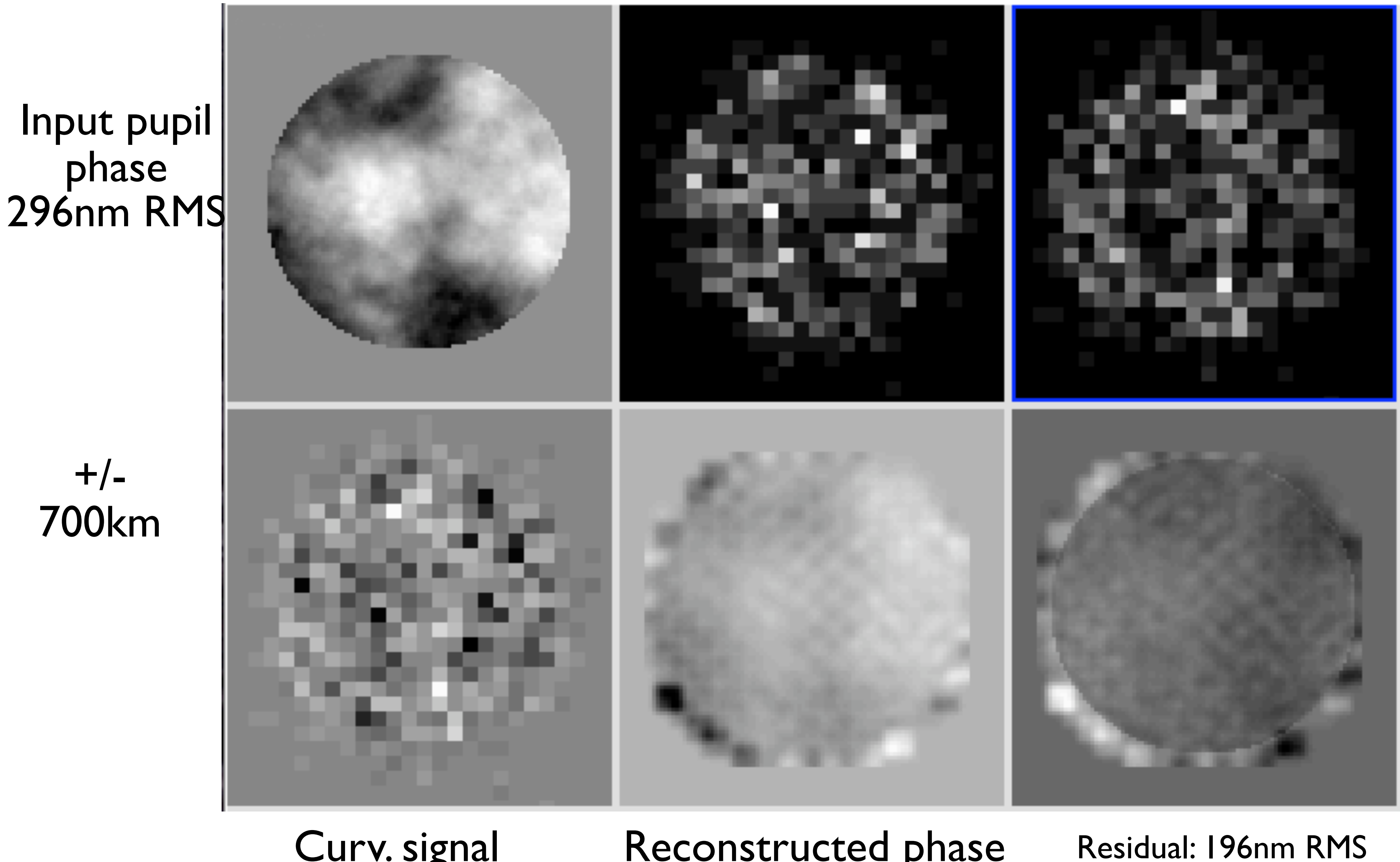
+/- 8000km

Standard phase diversity algorithm, working around pupil plane. There are probably better/faster algorithms (see for example: van Dam & Lane 2002, JOSA vol. 19)

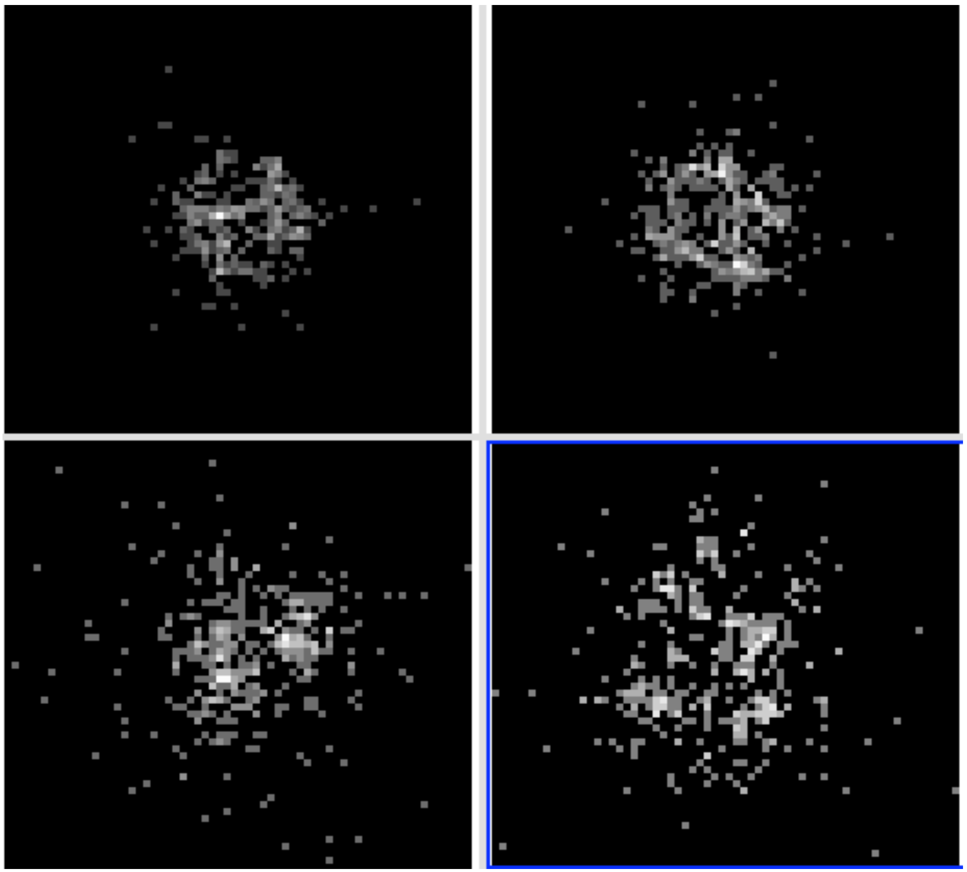
kHz operation appears to be possible with current chips for few 100s actuators system (100 32x32pix FFT = 0.2ms on single CPU)



Linear single stroke WFS, 2000 ph total 8m telescope, 0.65 mu, 373 ill. subapert.



Non linear dual stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.

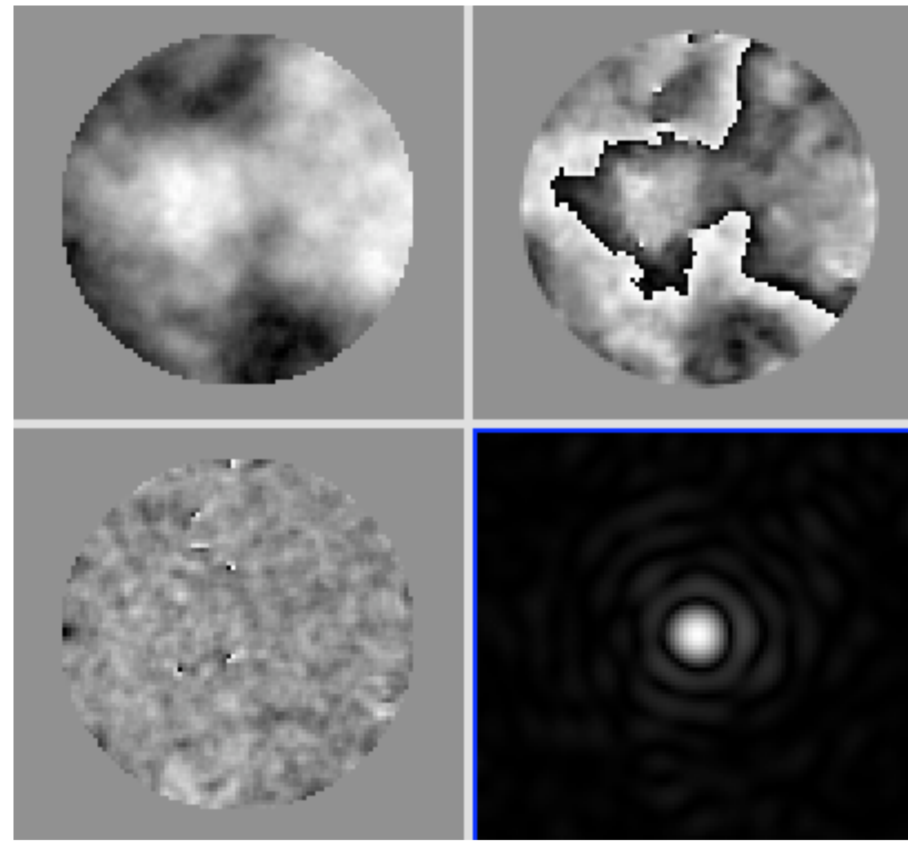


Defocused pupil images

500 ph / frame
Top : +/- 2000km
Bottom: +/- 8000km

Input pupil phase 296nm RMS

Reconstructed phase



Residual: 55nm RMS

SR = 0.763 at 0.65 micron

Magn 16 source -> 2000 ph/ms on 8m telescope

Why is is so good ??? -> uses HSF to infer LSF

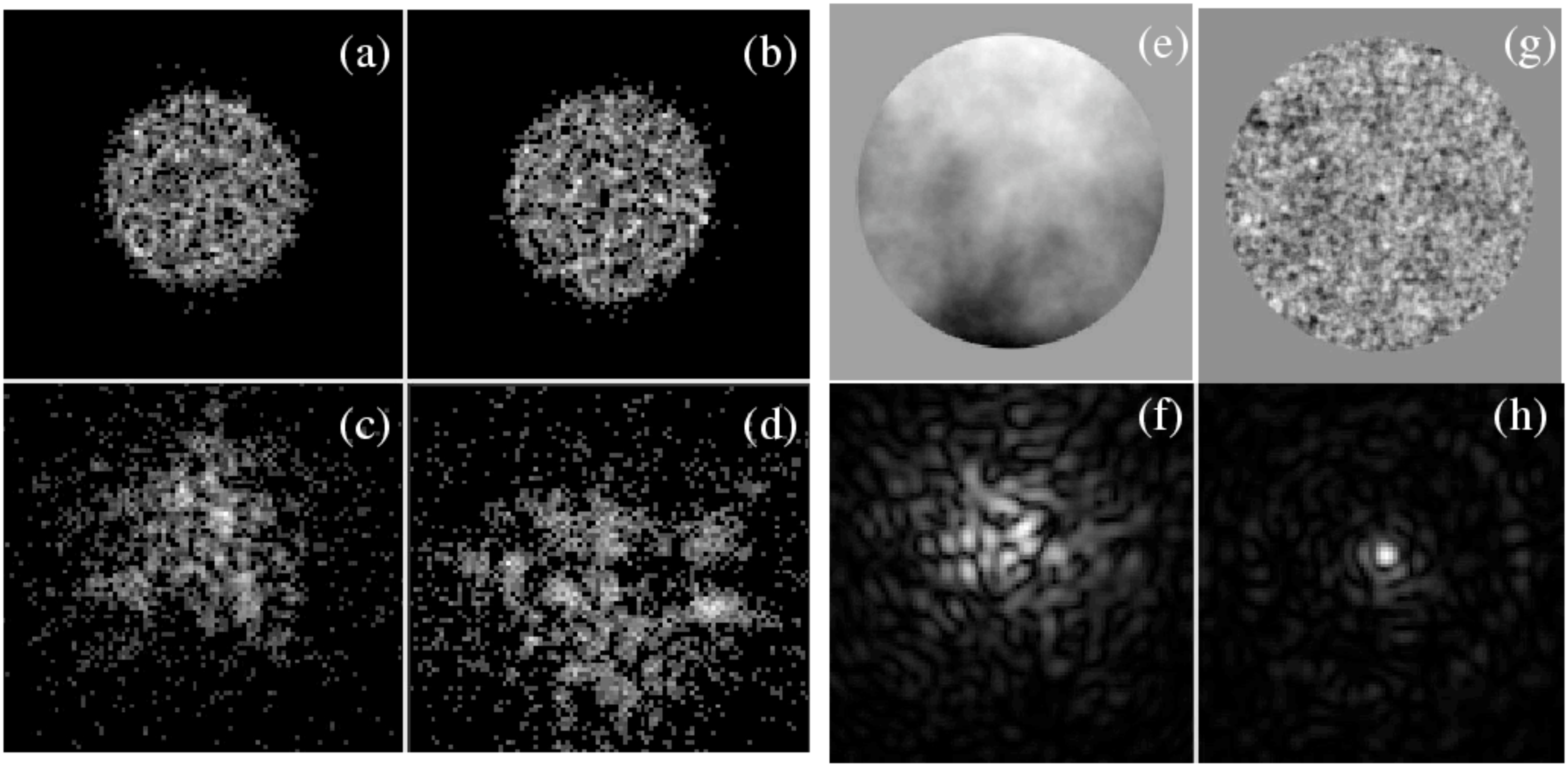
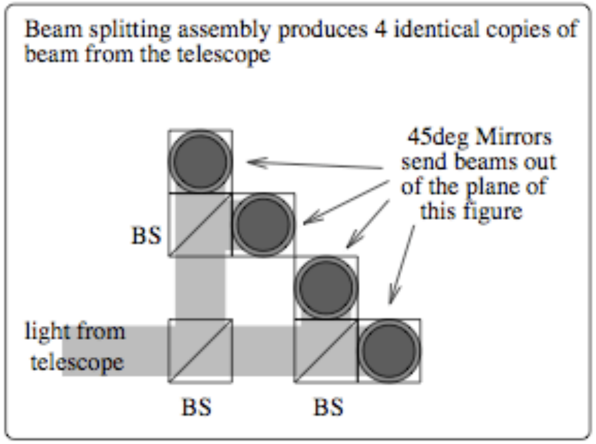
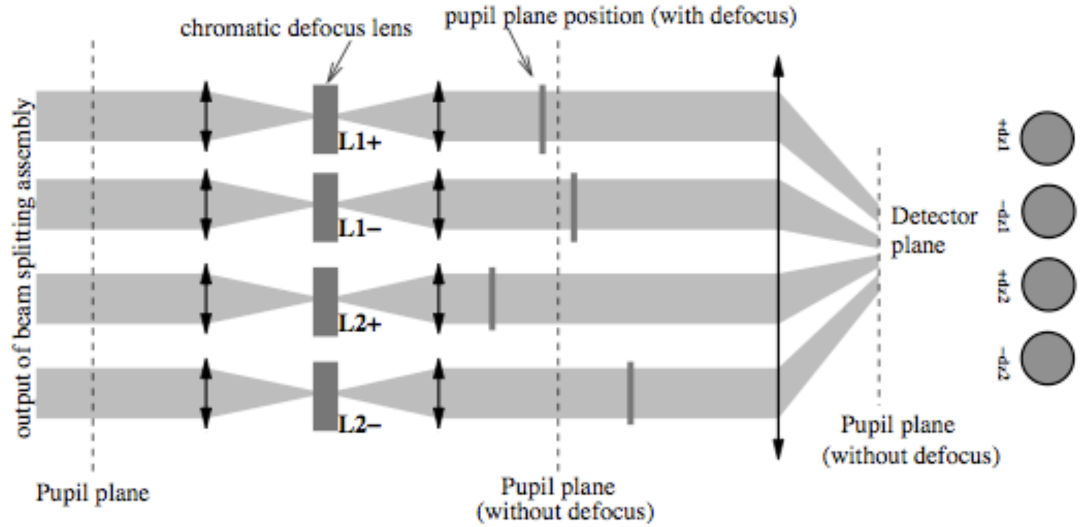
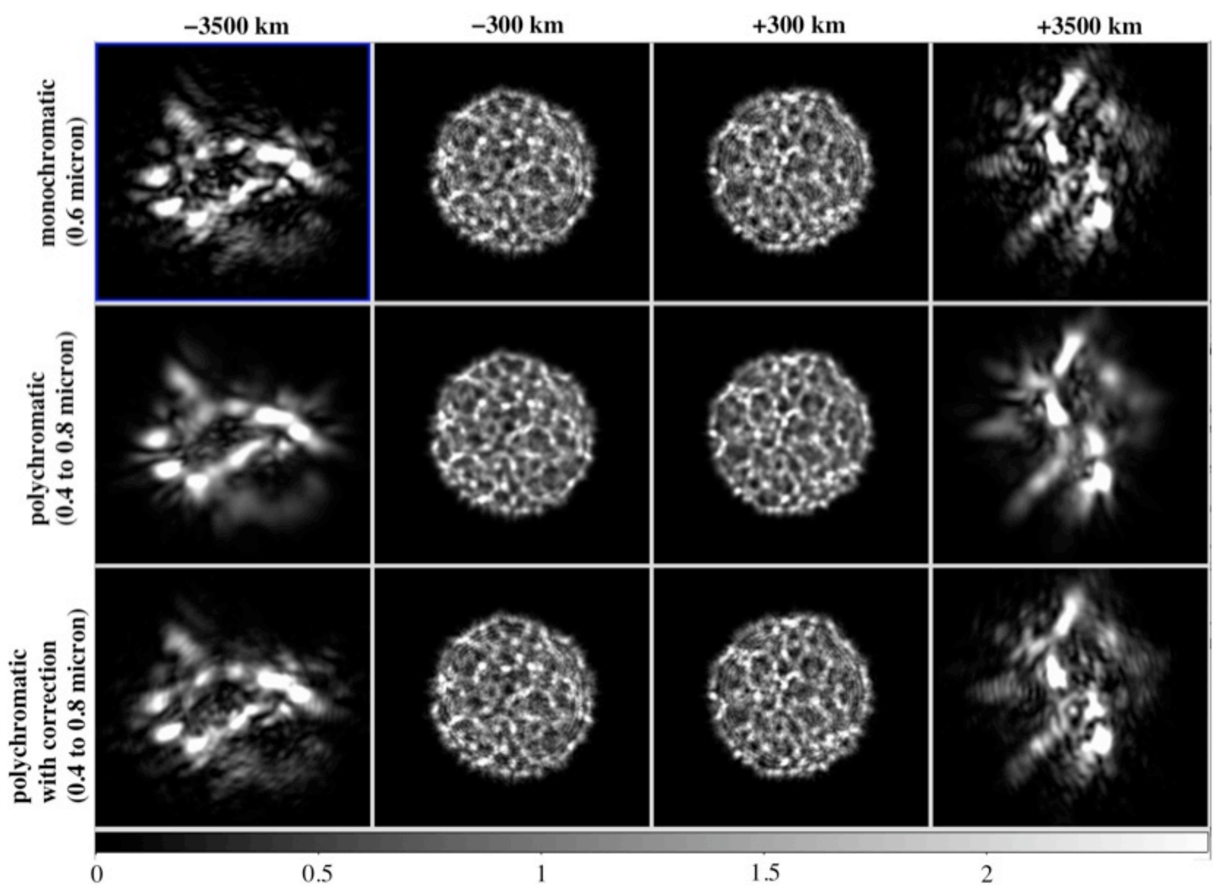
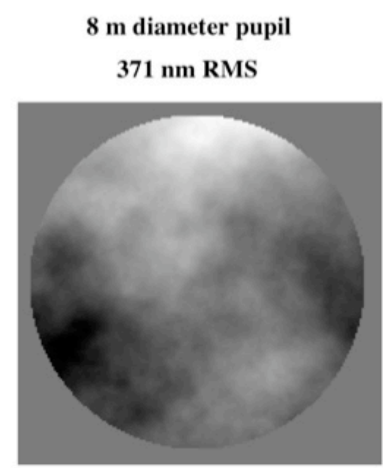


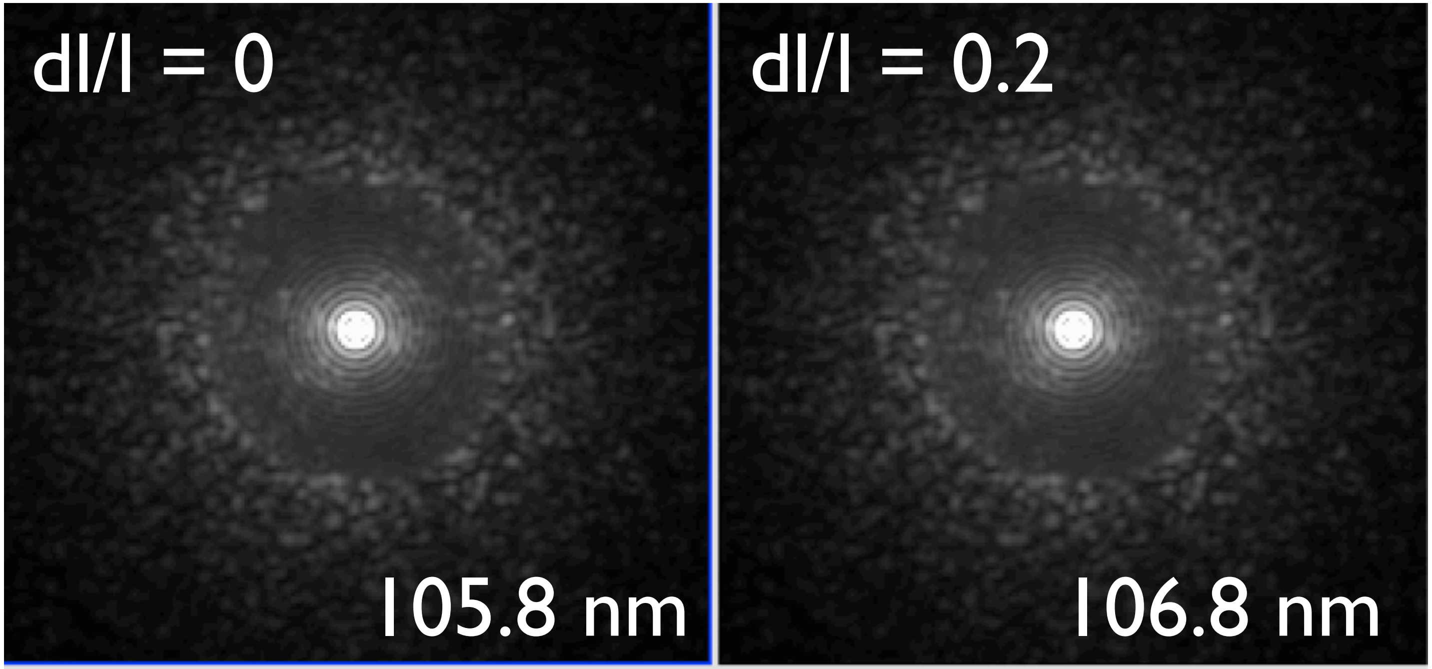
Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.

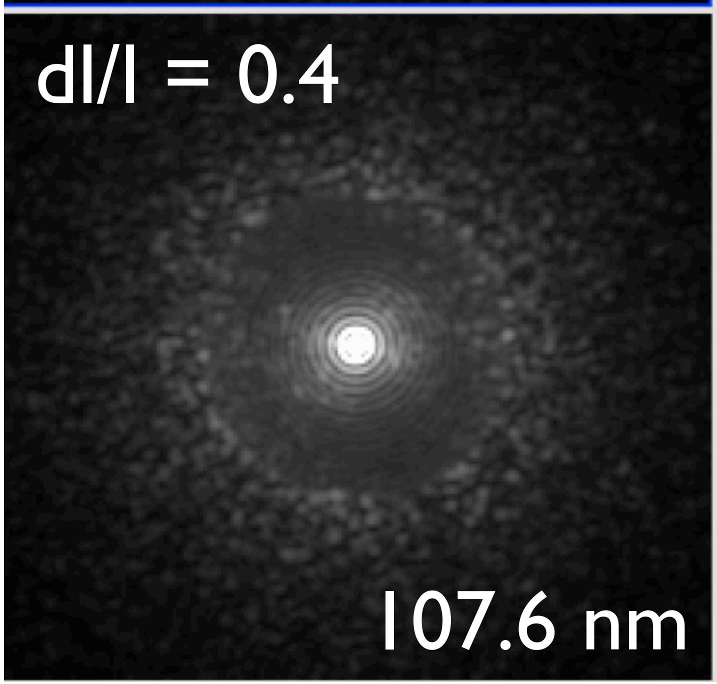

Beam splitting assembly produces 4 identical copies of beam from the telescope
45deg Mirrors send beams out of the plane of this figure
BS
light from telescope
BS
BS


chromatic defocus lens
pupil plane position (with defocus)
output of beam splitting assembly
L1+
L1−
L2+
L2−
Detector plane
+dz1
-dz1
+dz2
-dz2
Pupil plane
Pupil plane (without defocus)
Pupil plane (without defocus)


−3500 km
−300 km
+300 km
+3500 km
monochromatic (0.6 micron)
polychromatic (0.4 to 0.8 micron)
polychromatic with correction (0.4 to 0.8 micron)
0
0.5
1
1.5
2

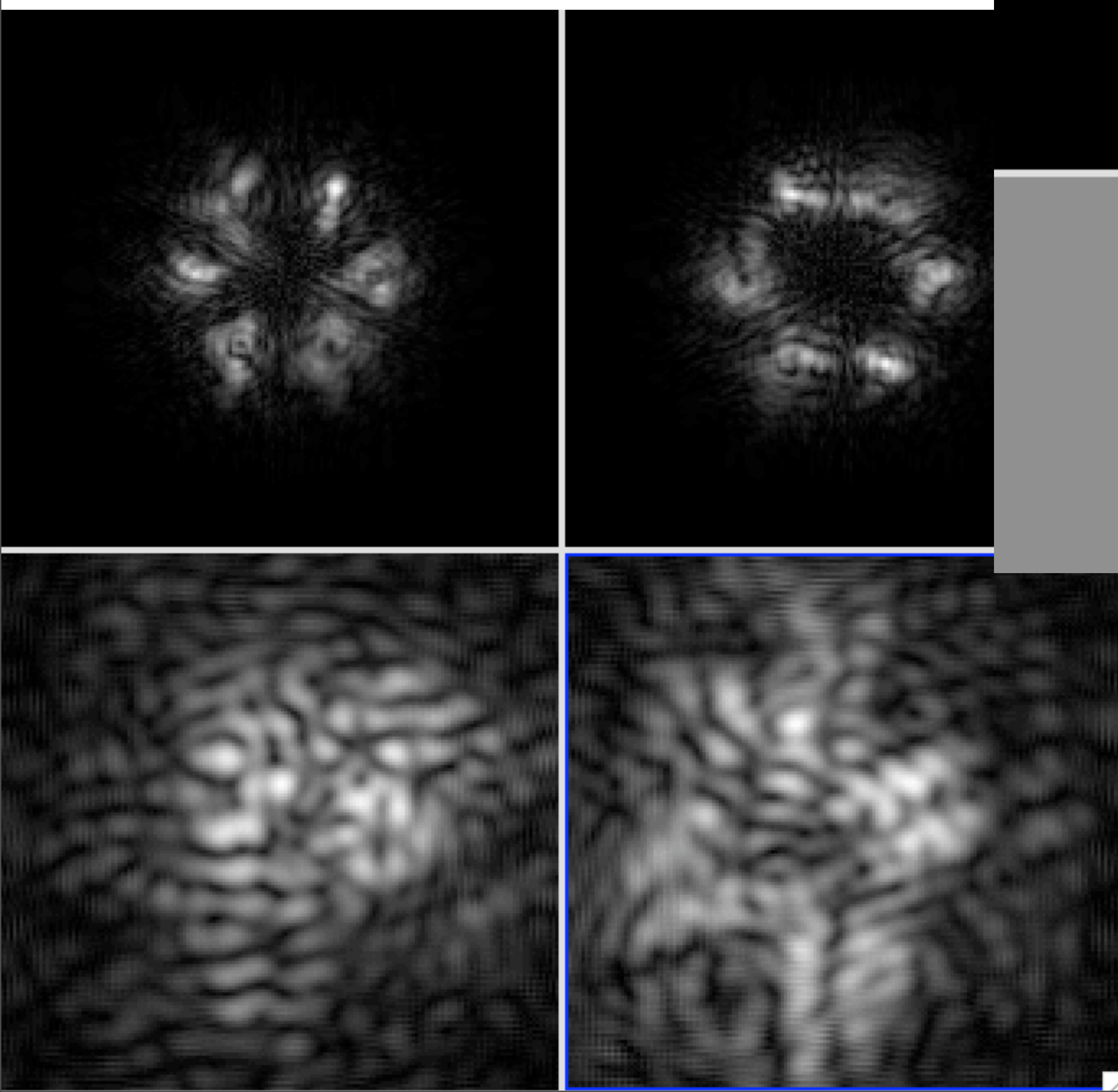

8 m diameter pupil
371 nm RMS

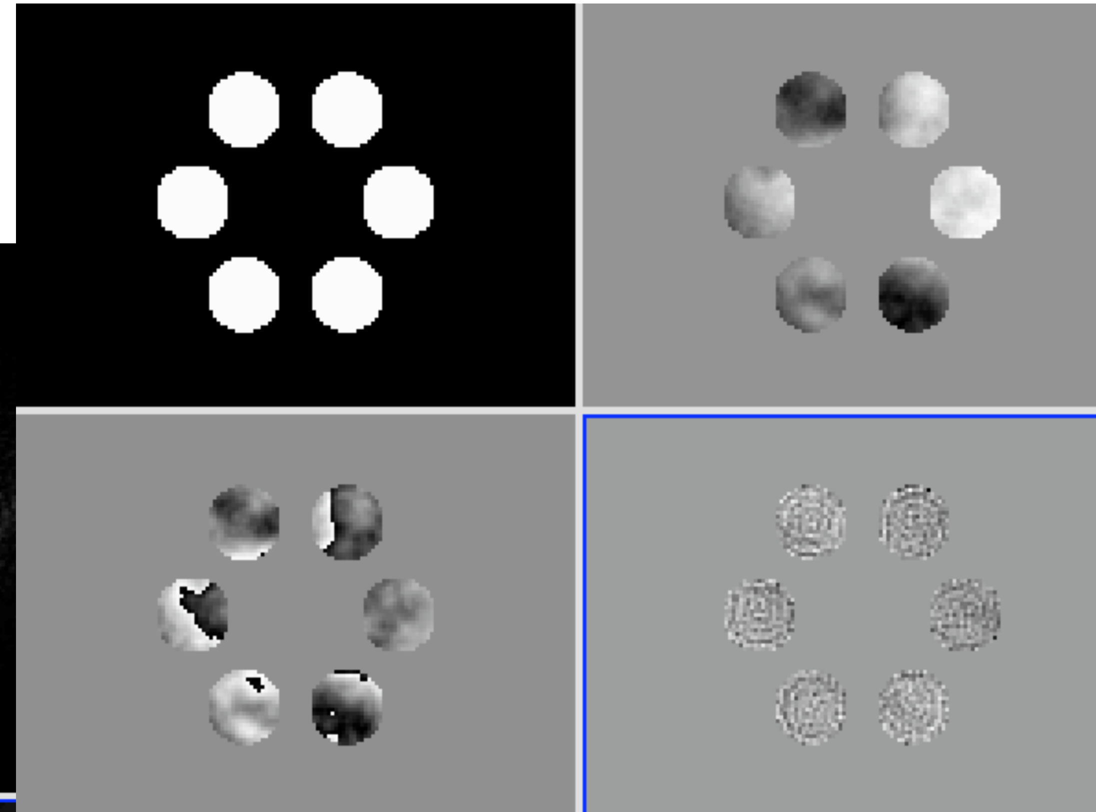




Polychromatic nlCWFS with monochromatic wavefront reconstruction algorithm

Very good for Sparse pupil or thick spiders

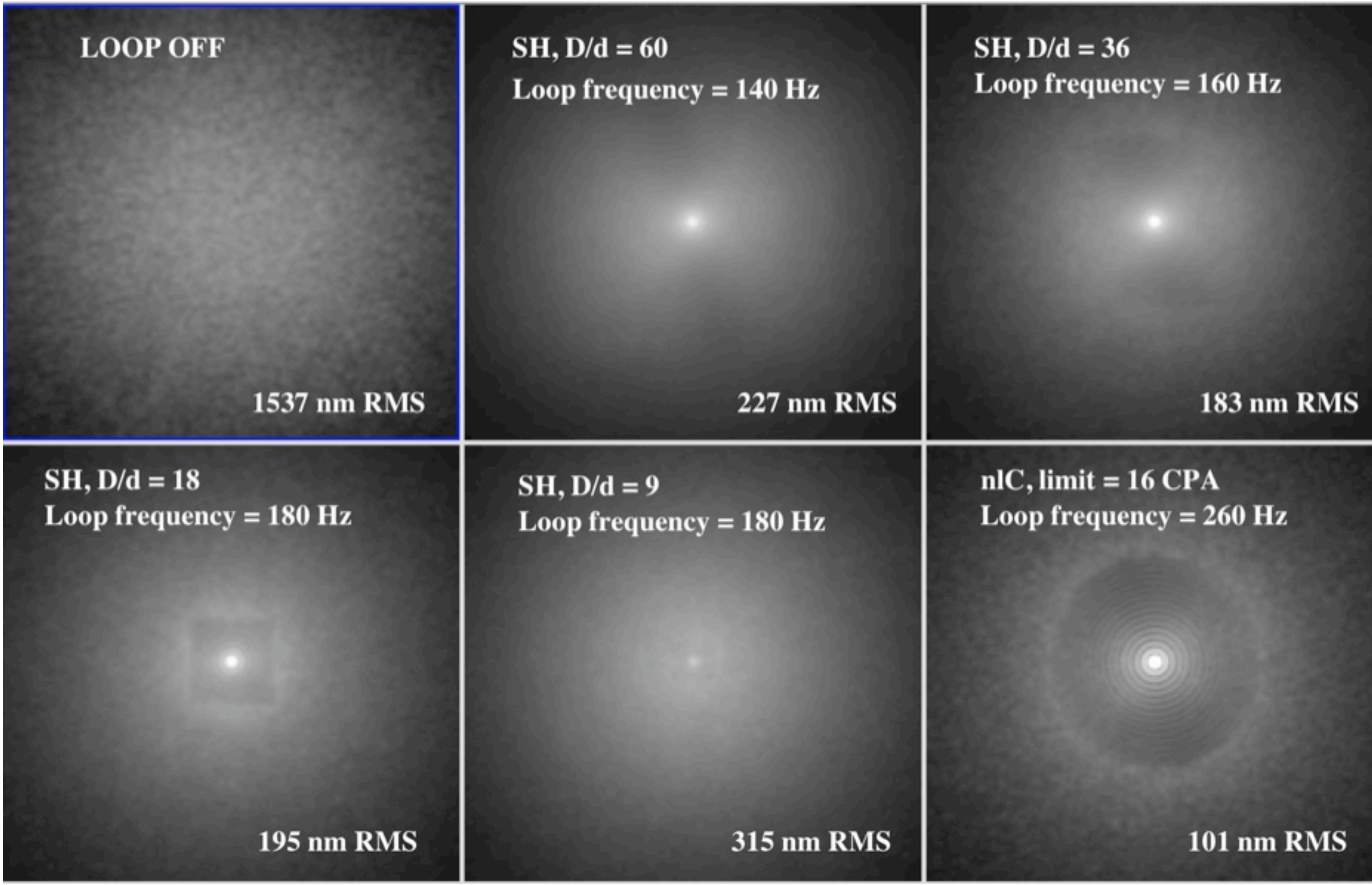




13nm RMS

2e8 ph

m ~ 13



WFS	Loop frequ	RMS	SR @ 0.85 mu	SR @ 1.6 mu
nlCurv	260 Hz	101 nm	57%	85%
SH - D/9	180 Hz	315 nm	~4%	22%
SH - D/18	180 Hz	195 nm	~13%	56%
SH - D/36	160 Hz	183 nm	~16%	60%
SH - D/60	140 Hz	227 nm	~6%	45%

Example of how choosing longer sensing wavelength helps by increasing wavefront coherence (even though phase signal gets smaller !!!)

Closed loop simulations

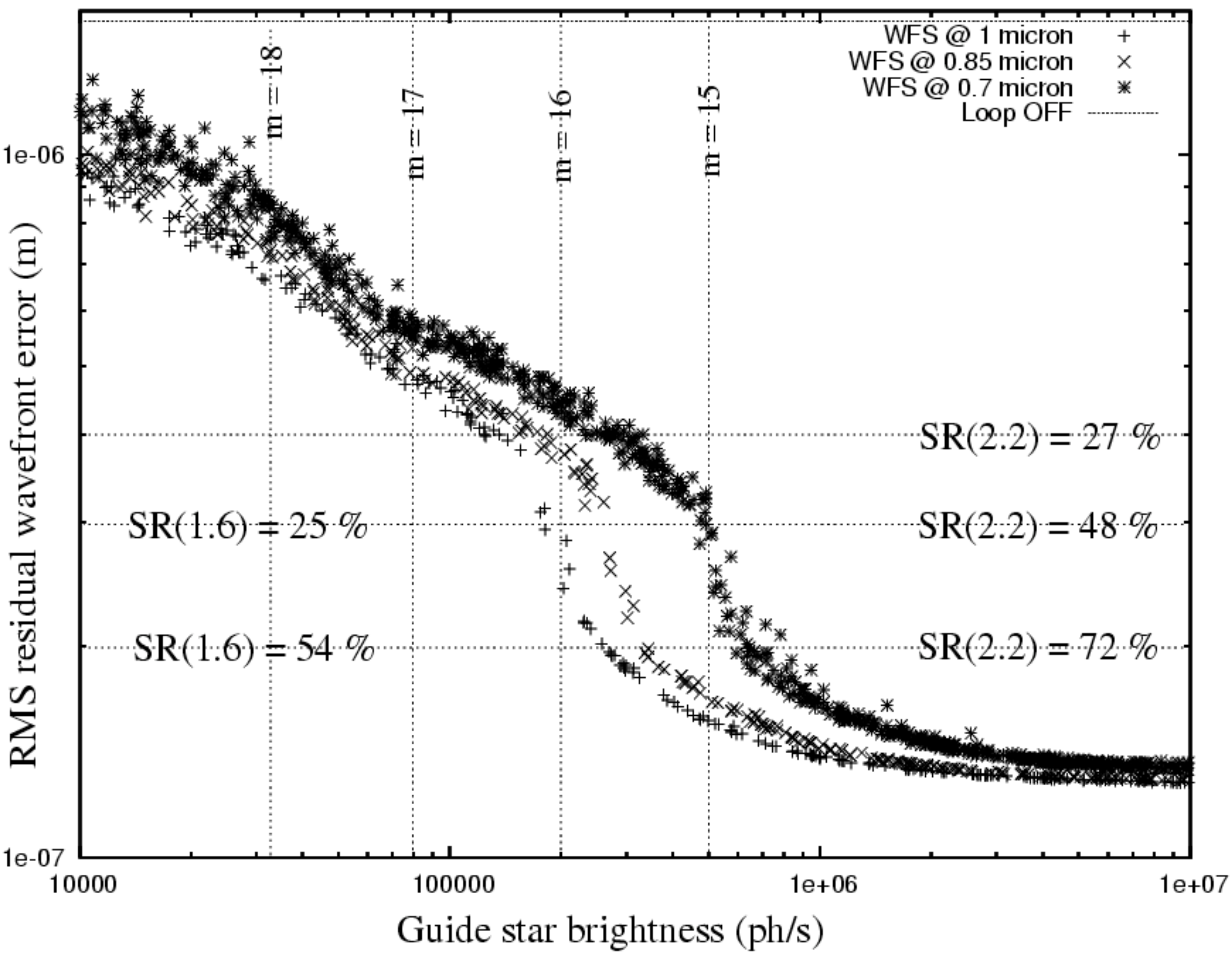


Fig. 11.— Simulated performance of a non-linear Dual stroke Curvature as a function of sensing wavelength (0.7, 0.85 and 1.0 μm) and guide star brightness. The stellar magnitudes given in this figure assume a 20% efficiency in a 0.5μm wide band. See text for details.

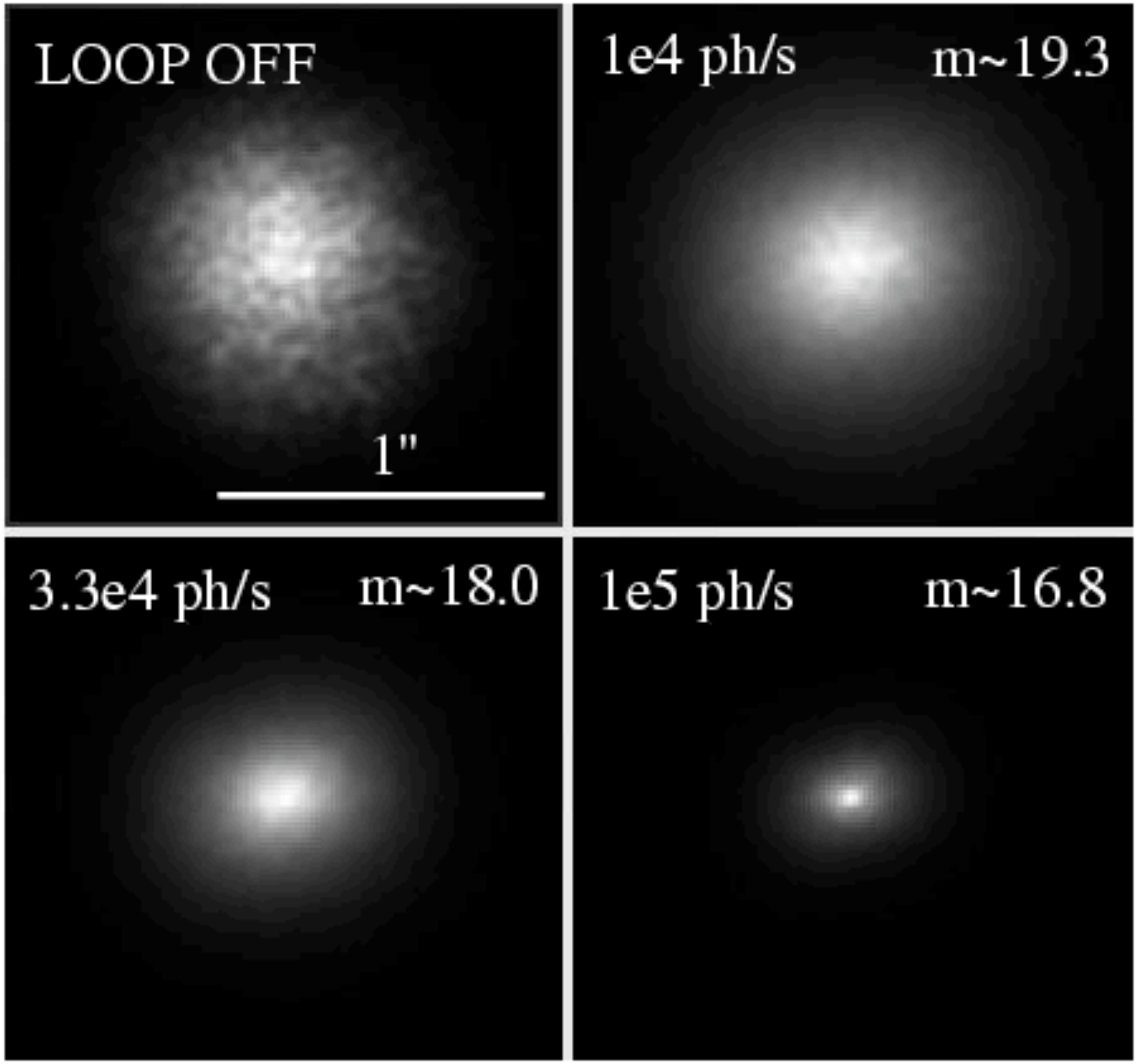
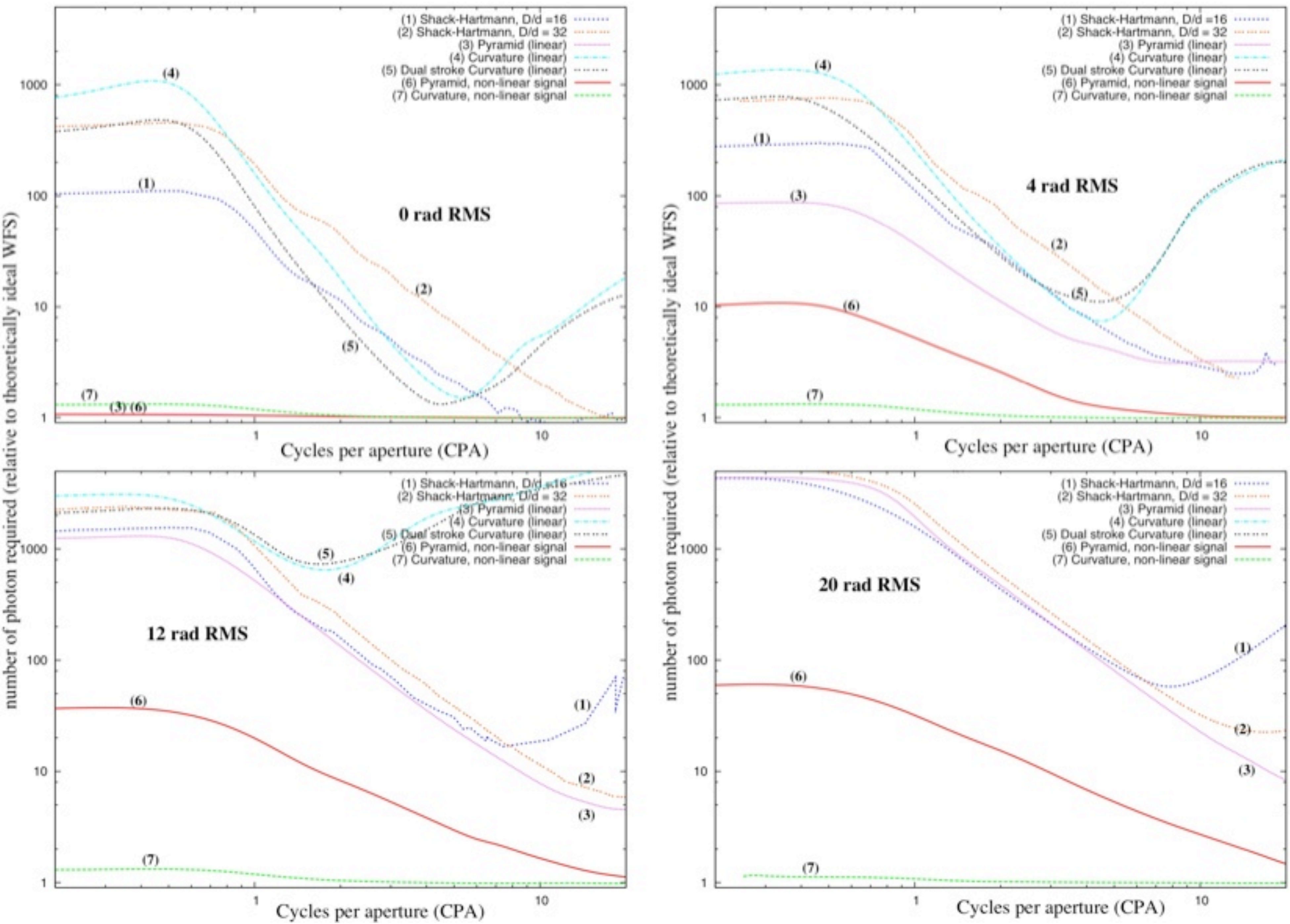


Fig. 12.— Simulated long exposure 1.6 μm PSFs obtained with a non-linear Dual stroke Curvature-based AO system. The sensing wavelength was 0.85 μm for this simulation.



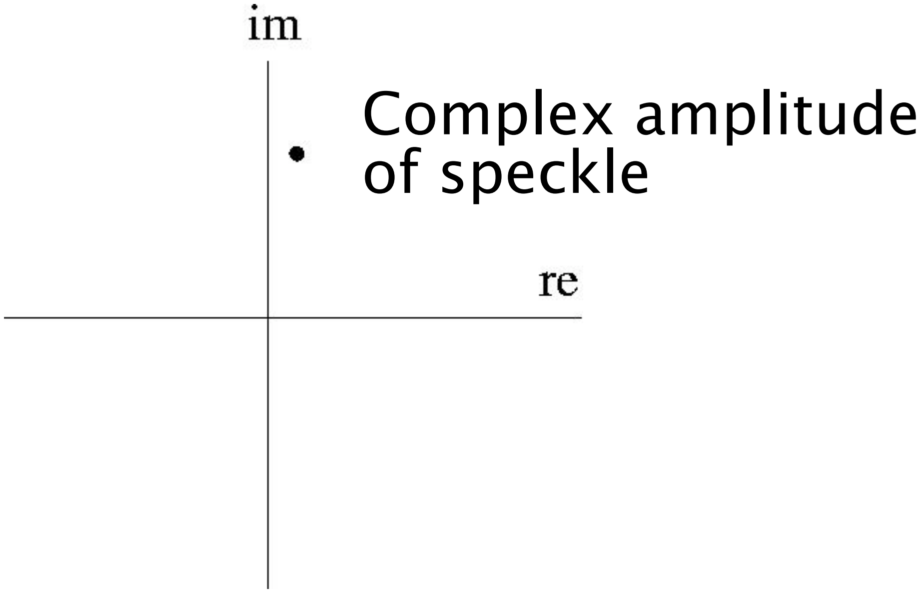
(1) Shack-Hartmann, D/d =16
(2) Shack-Hartmann, D/d = 32
(3) Pyramid (linear)
(4) Curvature (linear)
(5) Dual stroke Curvature (linear)
(6) Pyramid, non-linear signal
(7) Curvature, non-linear signal
0 rad RMS
4 rad RMS
12 rad RMS
20 rad RMS
number of photon required (relative to theoretically ideal WFS)
Cycles per aperture (CPA)
1000
100
10
1

Speckles vs. planet

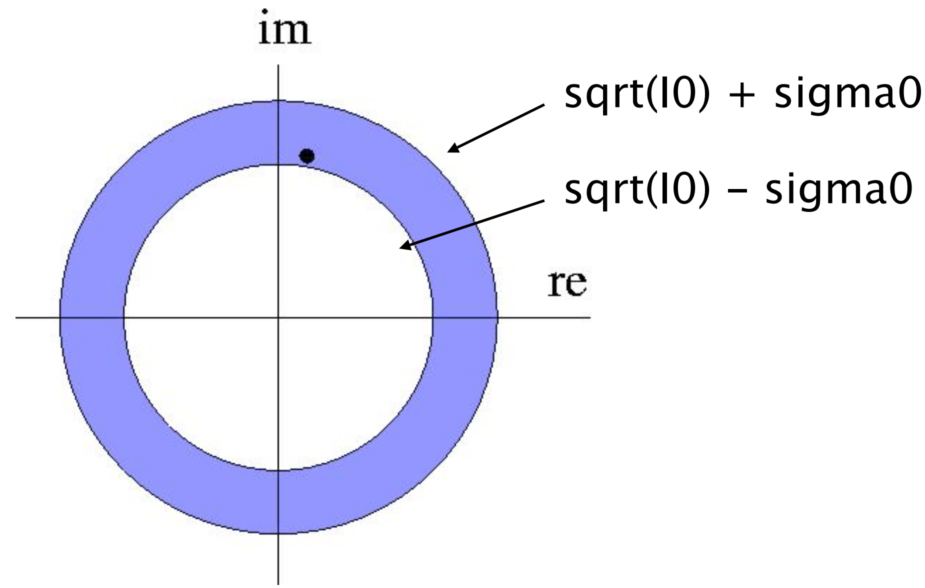
Spectra differential imaging (SDI)
Optimized for methane-bearing giant planets
Will only detect planets with a given spectral feature
Polarization differential imaging (PDI)
Degree of polarization may be low (few %)
Only works on reflected light
Angular differential imaging (ADI)
Performs well if static speckles are strong
Does not work well at small angular separations

Coherent differential imaging (CDI)
Use DM to introduce a know variation in the WF to modulate speckle intensity
Can reach photon noise limit if system is very well calibrated and CDI is performed quickly (or simultaneously)

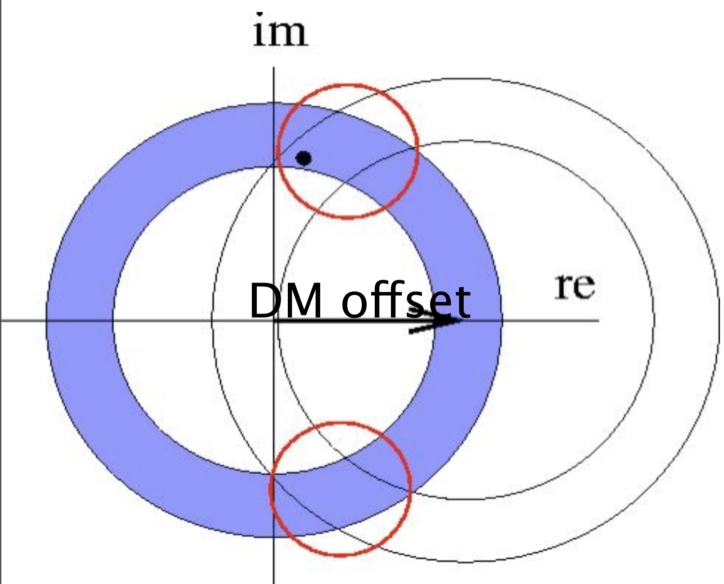
Initial problem

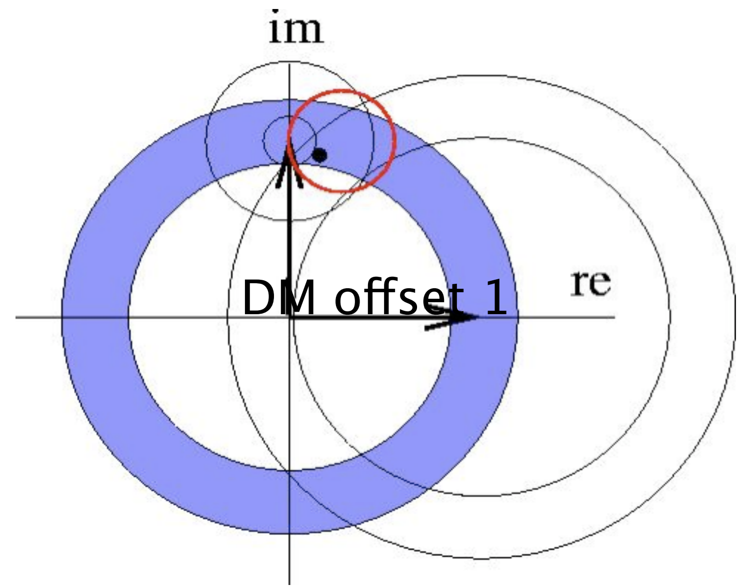


Take a frame -> measured speckle intensity = I0

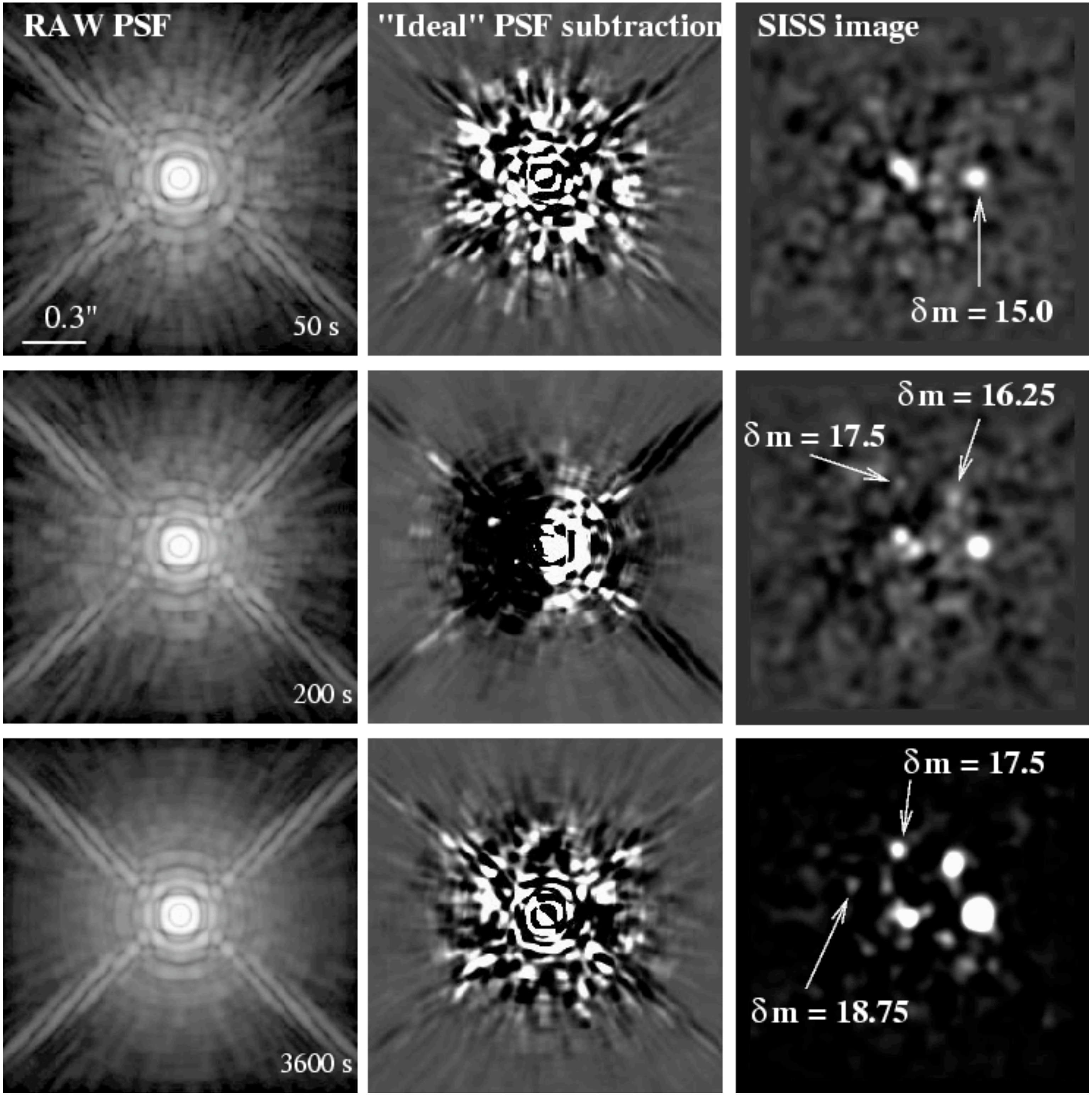


DM offset chosen to be ~ equal to speckle amplitude



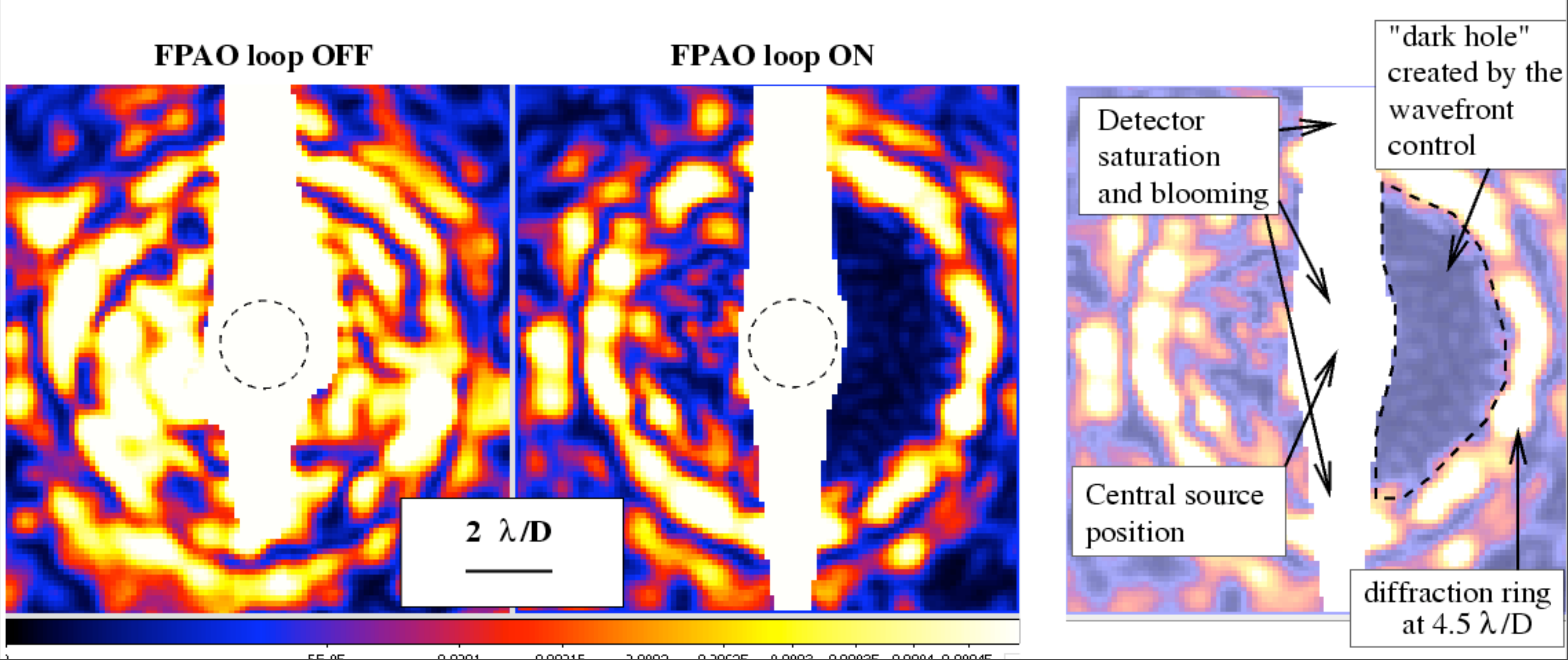


Speckle calibration with active coherent modulation



Focal plane wavefront sensing and CDI use the same modulation: if something is a speckle, we can kill it with the DM !

With FPAO, separation between coronagraph and wavefront control becomes blurry



Subaru Coronagraphic Extreme-AO (SCExAO) system

Motivations

Performance improvement through:

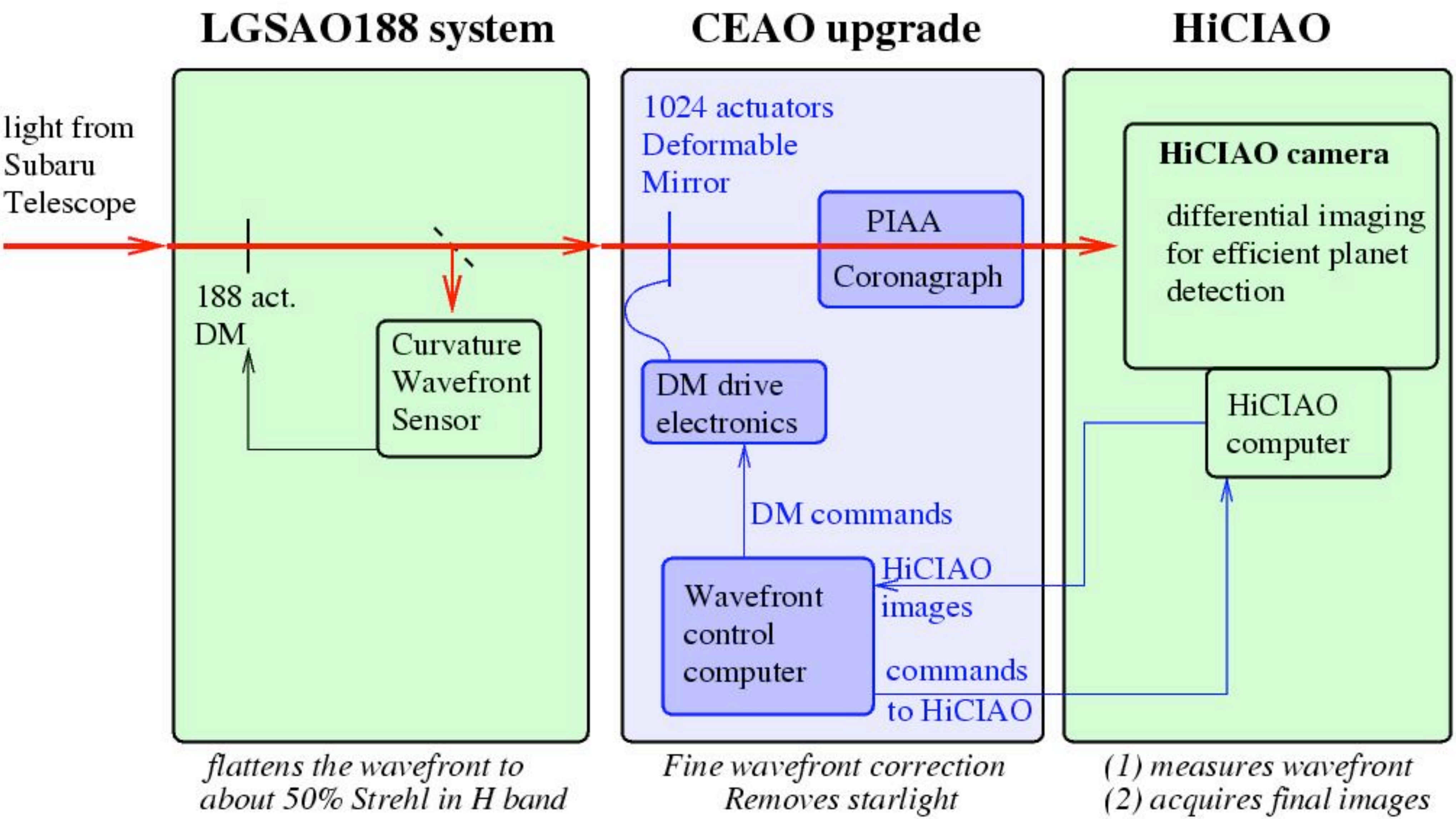
- Smaller IWA (allows 5 AU at Taurus) - essential to understand planetary systems formation/evolution
- Higher "raw" contrast (fainter disks & planets)
- Coherent speckle calibration (can allow x10 to x100 gain in final contrast)

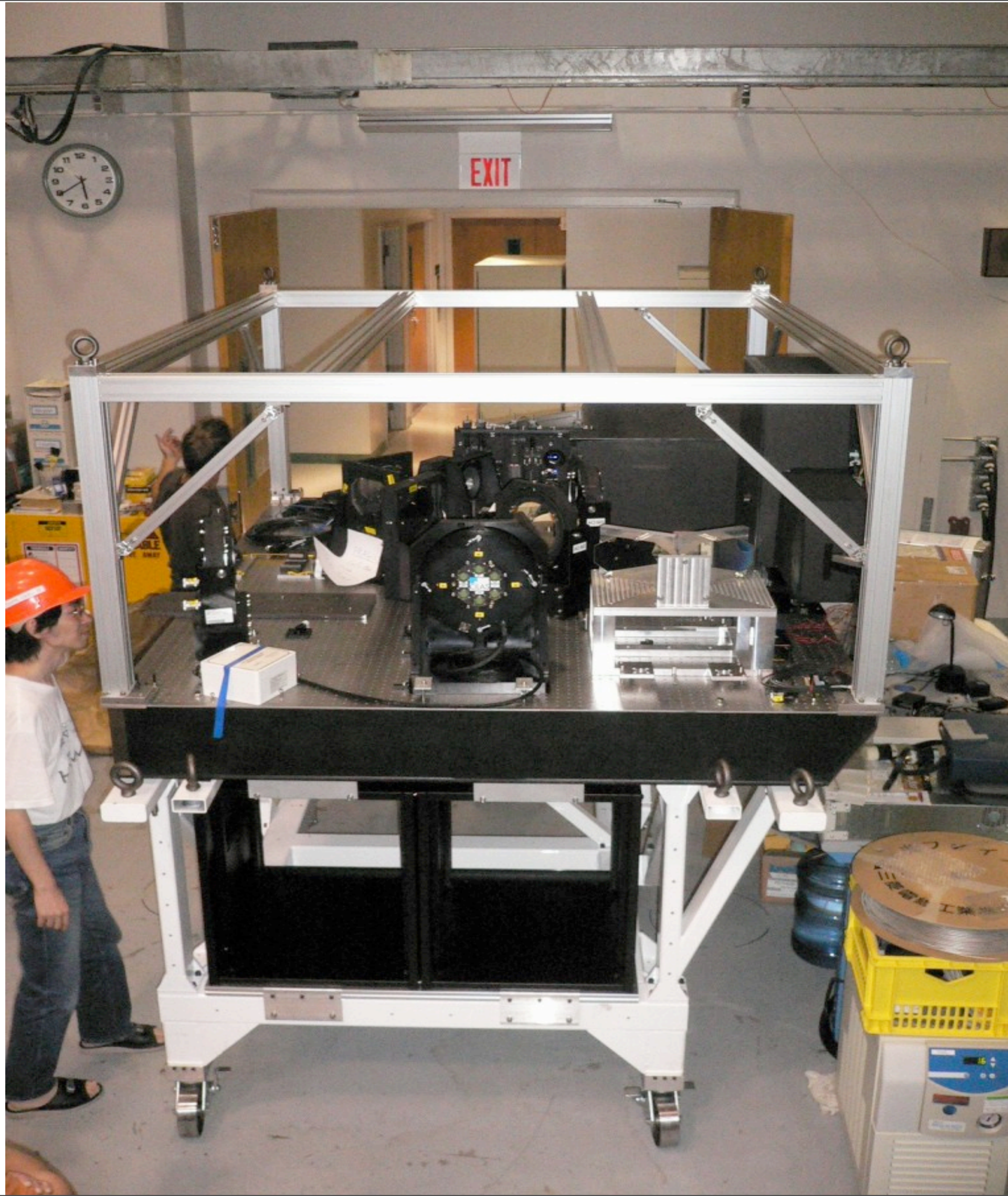
Aimed at keeping HiCIAO scientifically competitive in next ~5+ years (GPI & SPHERE come online in ~2 to 3 years).

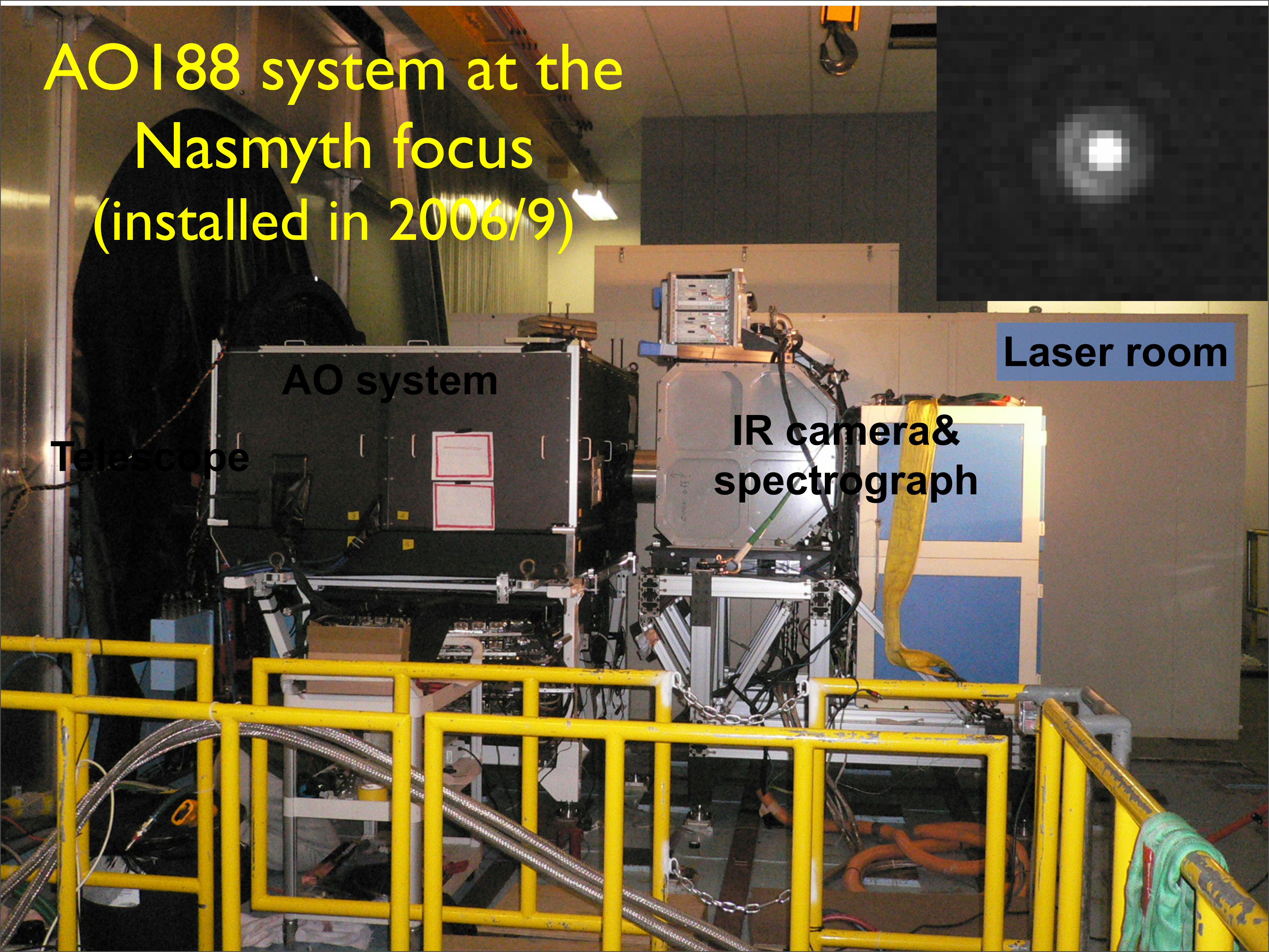
Fully takes advantage of flexibility offered by AO188+HiCIAO (unique advantage over system like GPI). Rapidly incorporates key technological advances for maximum science return.

HiCIAO can compete with ~$20M+ Ex-AO systems at a fraction of the cost.

Overall system architecture




EXIT


AO188 system at the
Nasmyth focus
(installed in 2006/9)
AO system
Telescope
IR camera&
spectrograph
Laser room

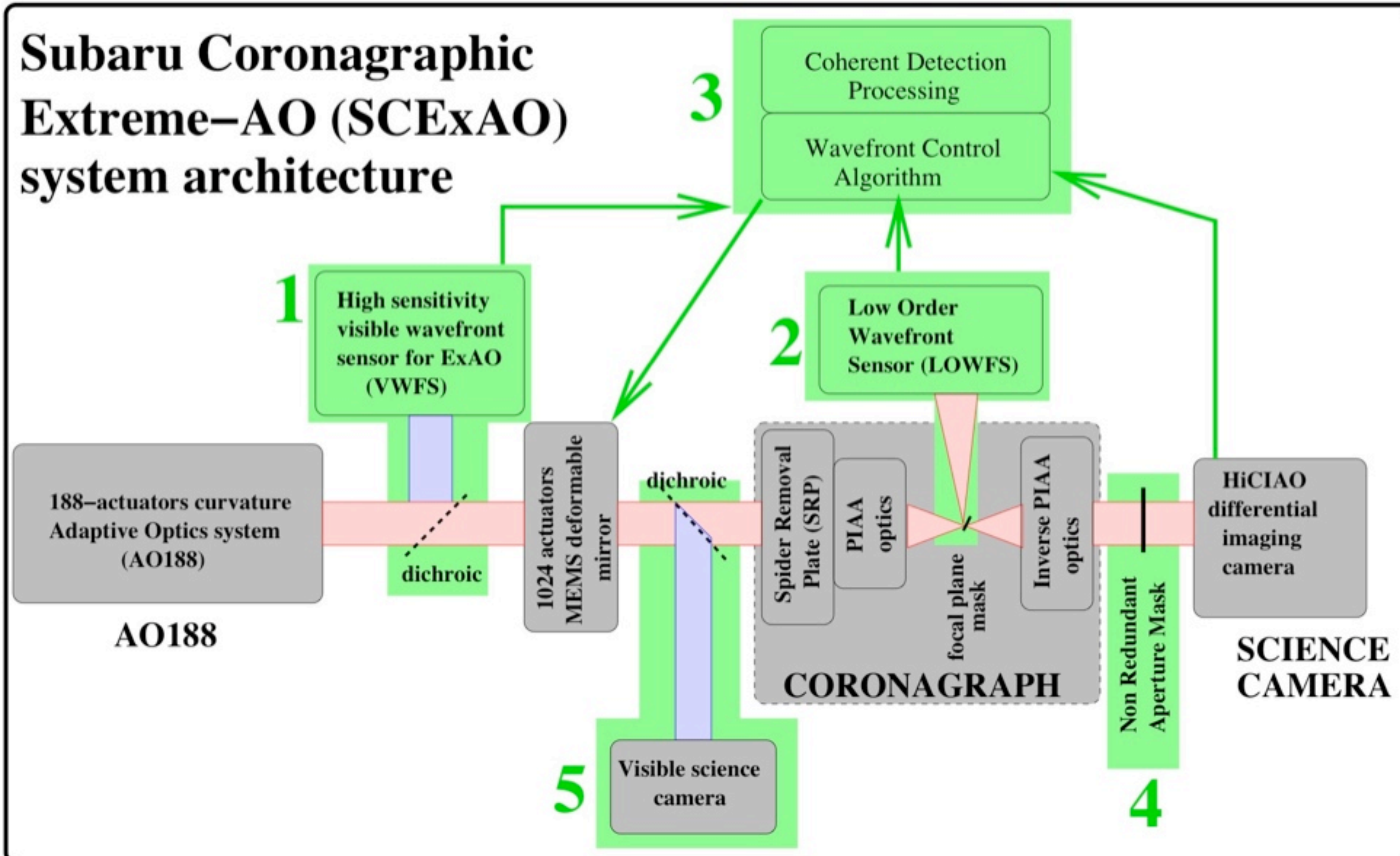
HiCIAO first light (2007)

CEAO system design drivers:

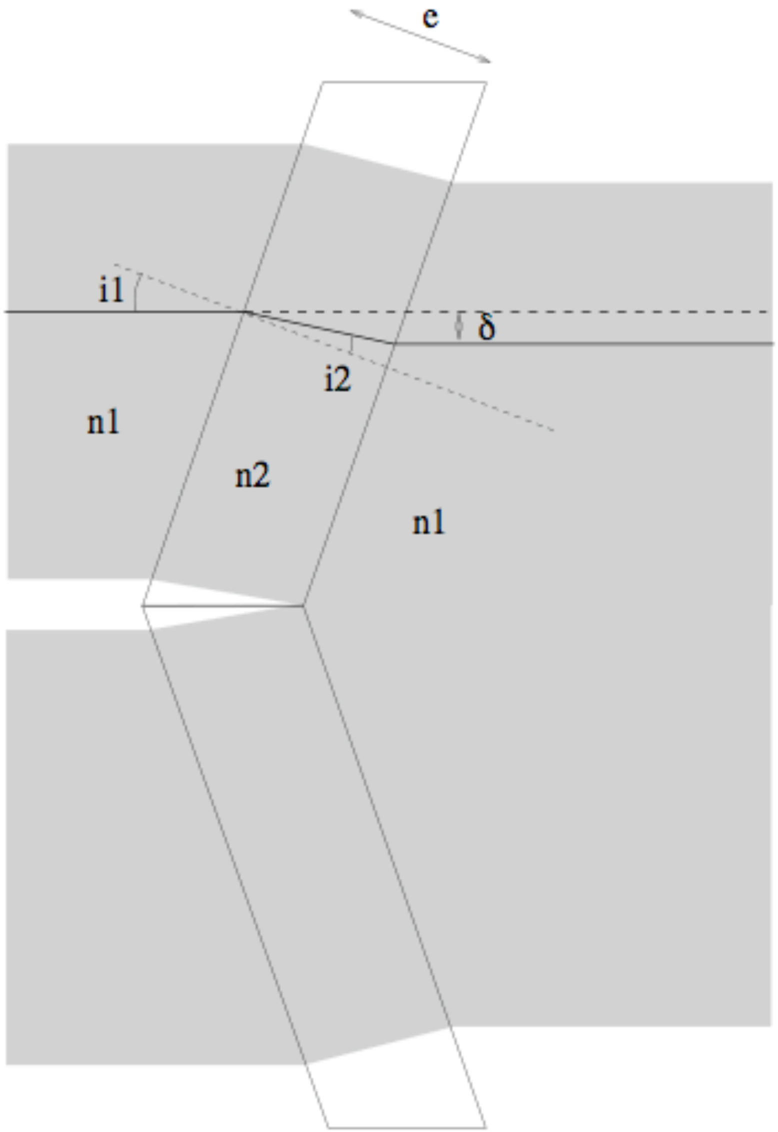
- CEAO system will preserve previous HiCIAO modes (but add 2 reflections)
- All elements (SRP, PIAA, DM) must be remotely controlled and can be removed at any time within a few sec.
- Space will be made available for one additional HiCIAO-size instrument (Princeton IFU ?)
- CEAO will reuse lower part of HiCIAO frame - no change in footprint
- Switch between HiCIAO to HiCIAO + CEAO system must be quick and safe to comfortably fit between SEEDS observing runs (including time for testing)

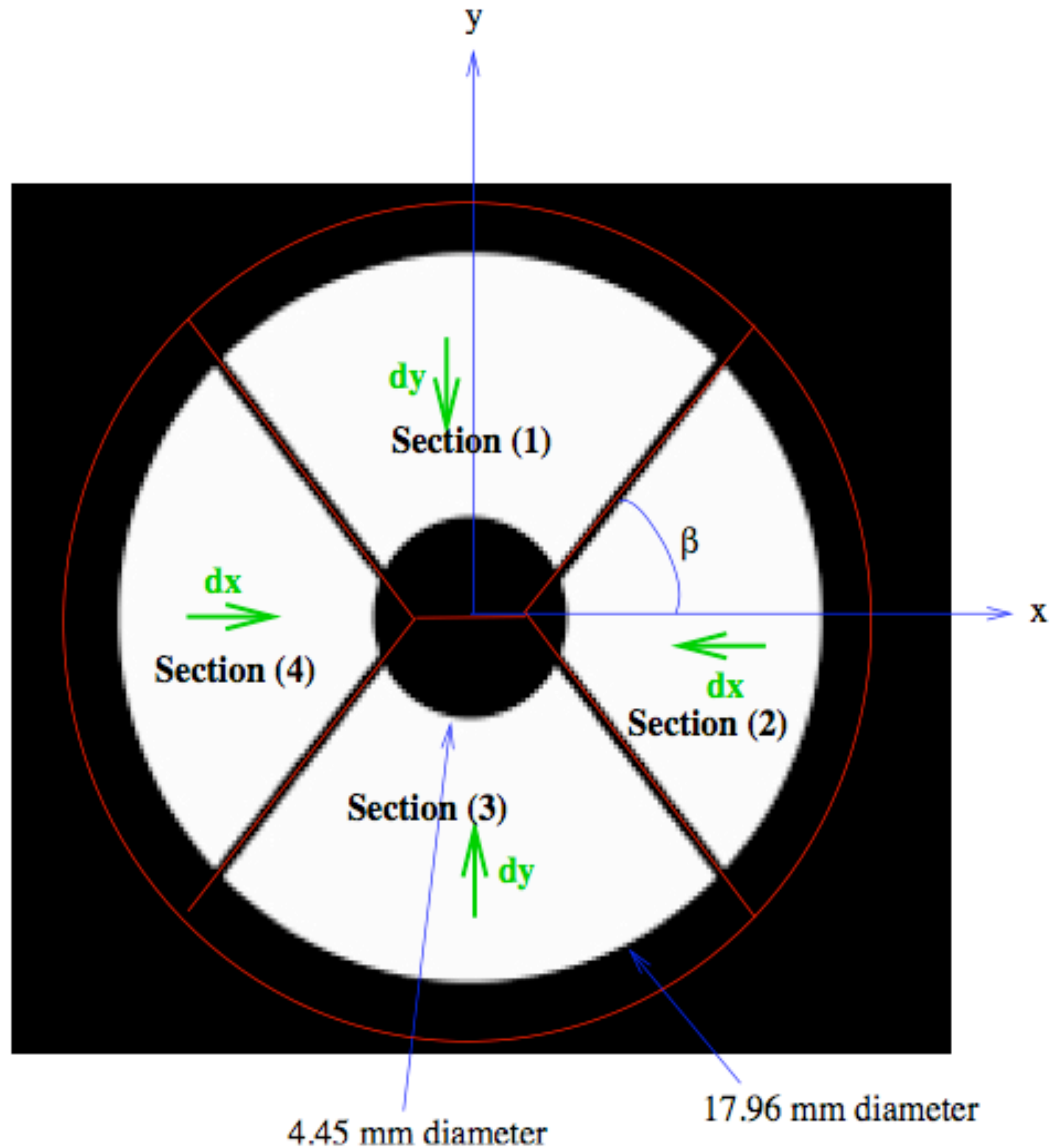
Project schedule

- 2003-2007: Lab prototype to demonstrate key technologies (PIAA, focal plane WFC with MEMS) - **COMPLETED**
- 2006-2007: Design & procurement of key custom-made optics (PIAA, apodizer, SRP) - **COMPLETED**
- 2008: Assembly & test of full optical train -> Final system design and assembly - **ONGOING**
- mid 2009: System complete & ready to be interfaced with HiCIAO and AO188 (initial configuration = PIAA + MEMS with slow control)
- From mid 2009: Faster control of MEMS + dedicated WFS for Extreme-AO, upgrade to 4000 actuators MEMS - **ONGOING R&D**

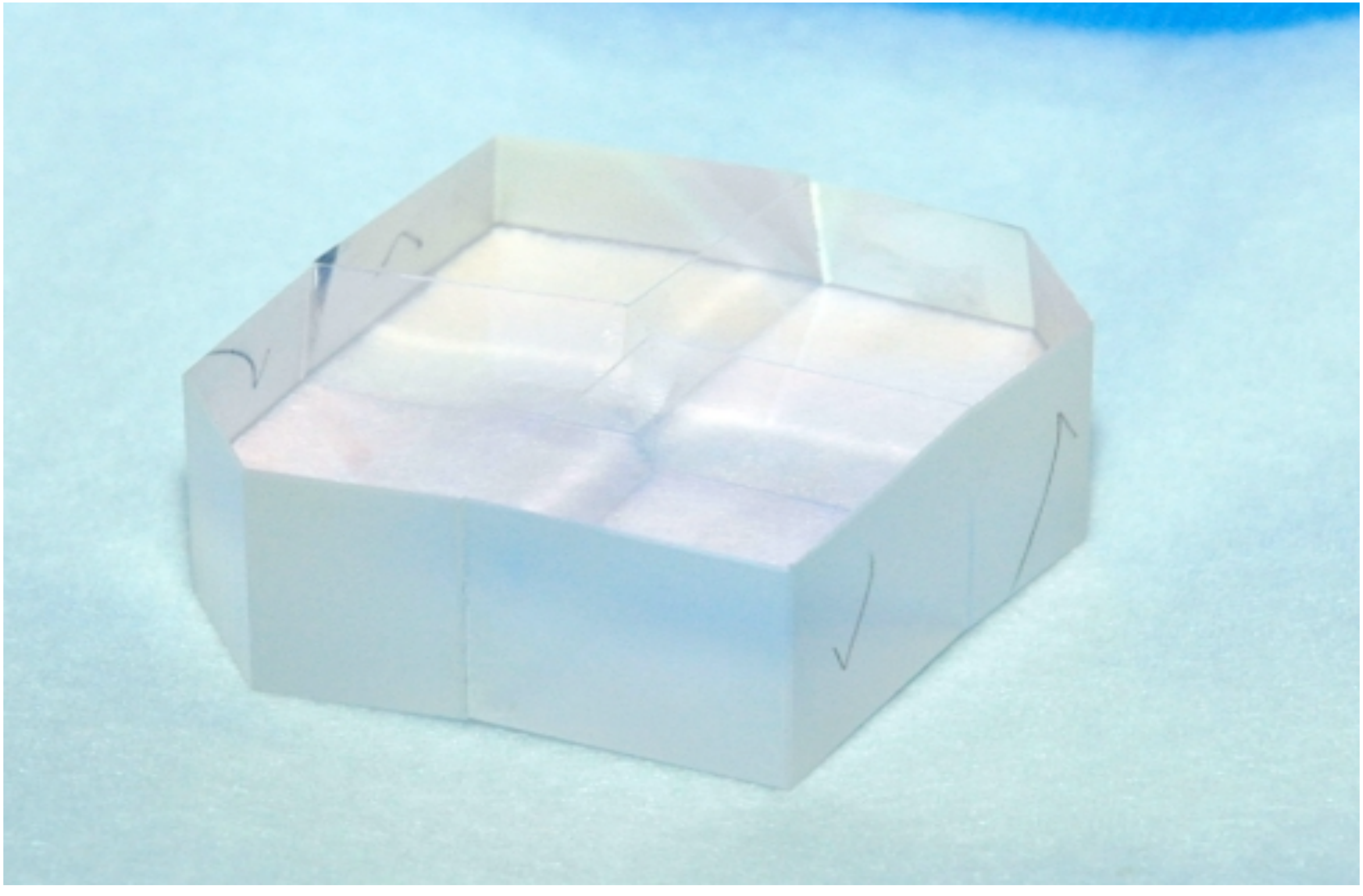

Subaru Coronagraphic Extreme−AO (SCExAO) system architecture
3
Coherent Detection Processing
Wavefront Control Algorithm
1
High sensitivity visible wavefront sensor for ExAO (VWFS)
2
Low Order Wavefront Sensor (LOWFS)
188−actuators curvature Adaptive Optics system (AO188)
dichroic
1024 actuators MEMS deformable mirror
dichroic
Spider Removal Plate (SRP)
PIAA optics
focal plane mask
Inverse PIAA optics
CORONAGRAPH
Non Redundant Aperture Mask
HiCIAO differential imaging camera
AO188
SCIENCE CAMERA
5
Visible science camera
4

Spider Removal Plate



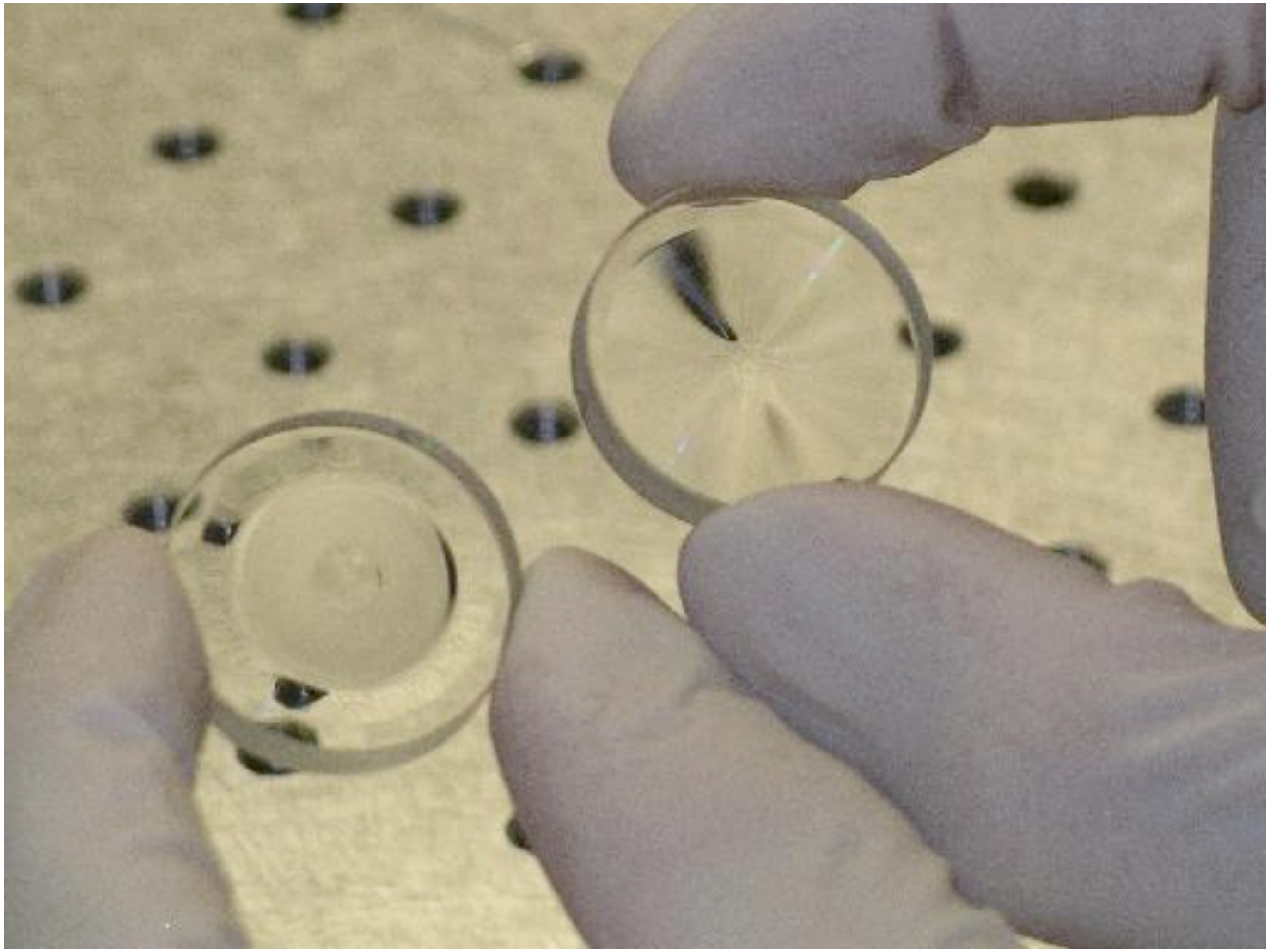


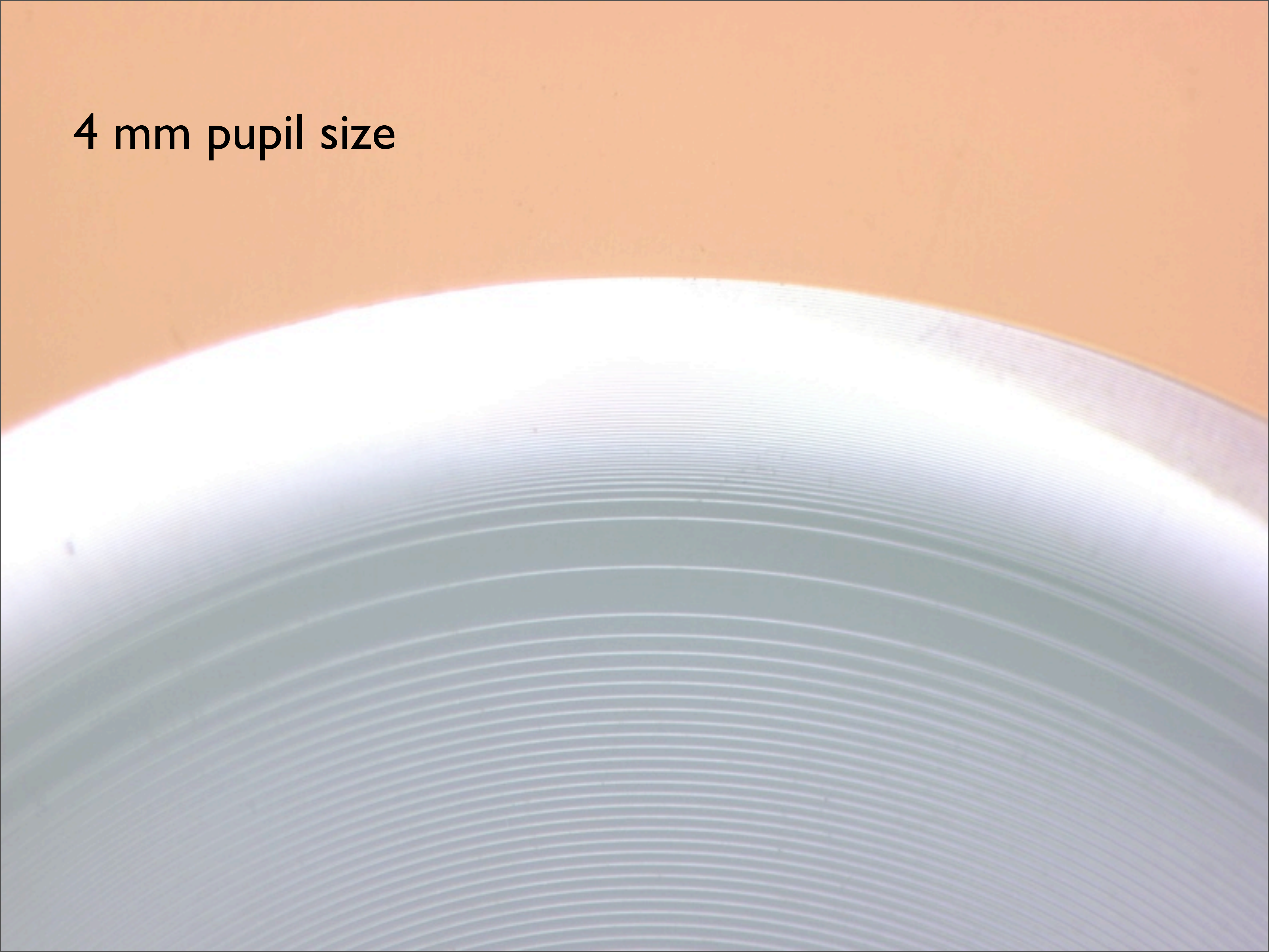
Spider Removal Plate (SRP)



PIAA refractive optics (CaF2)

removes central obstruction for Subaru




4 mm pupil size

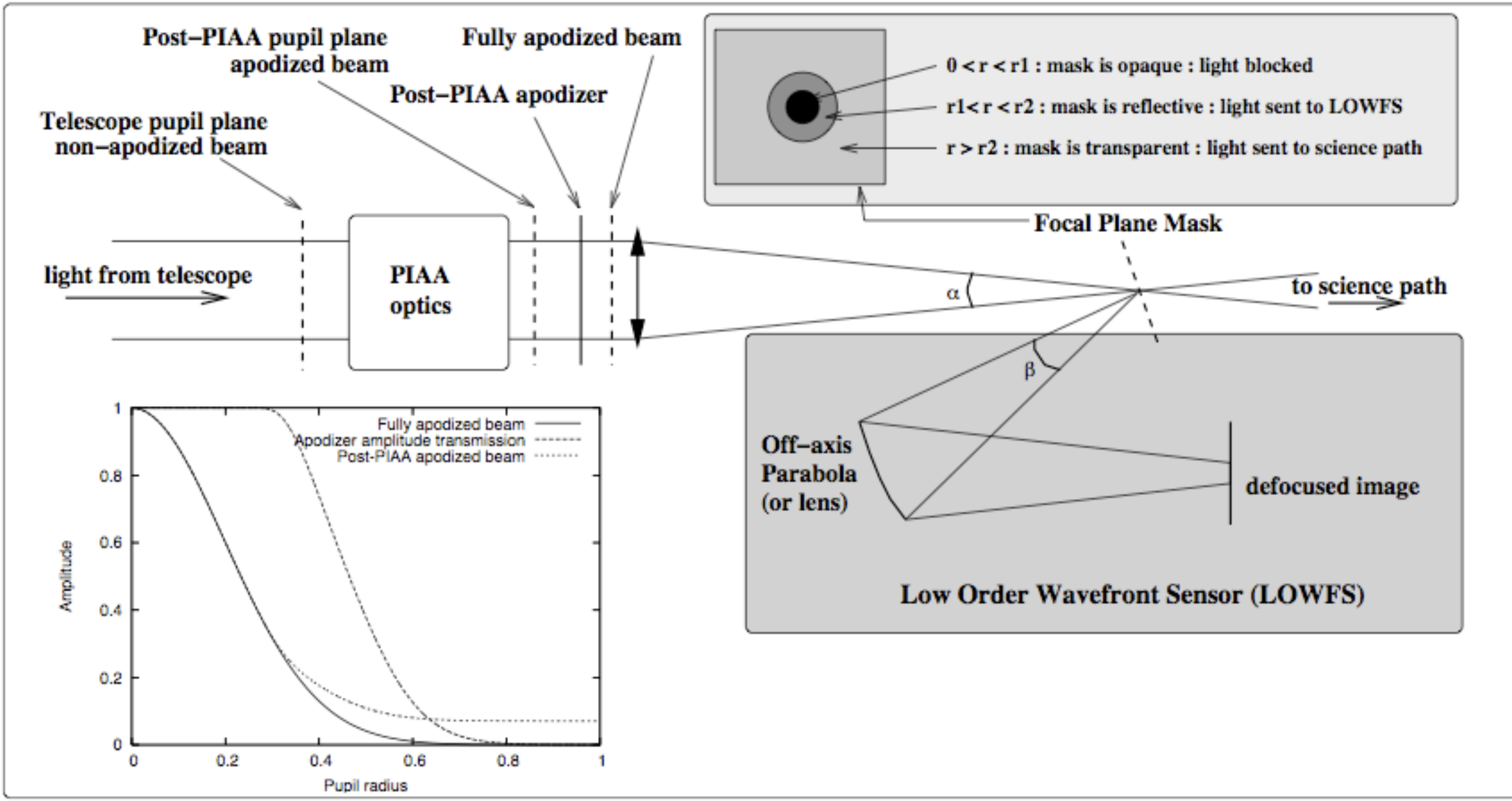


Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

Guyon, Matsuo, Angel, 2008 - in press

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

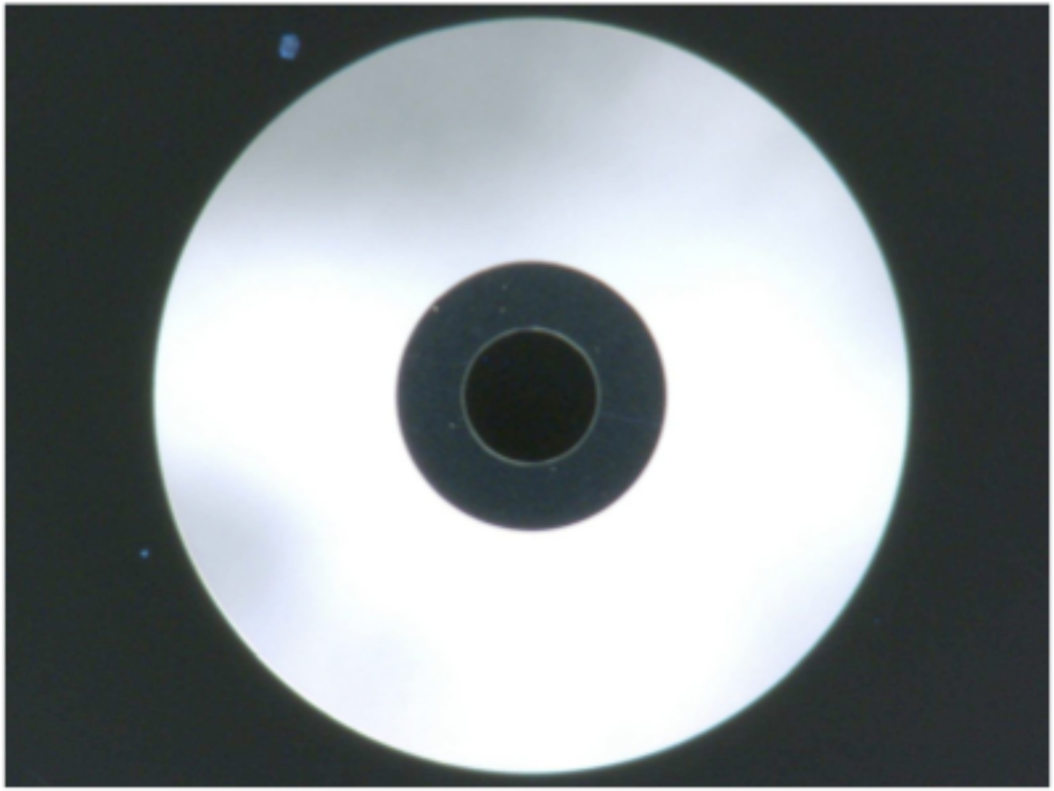
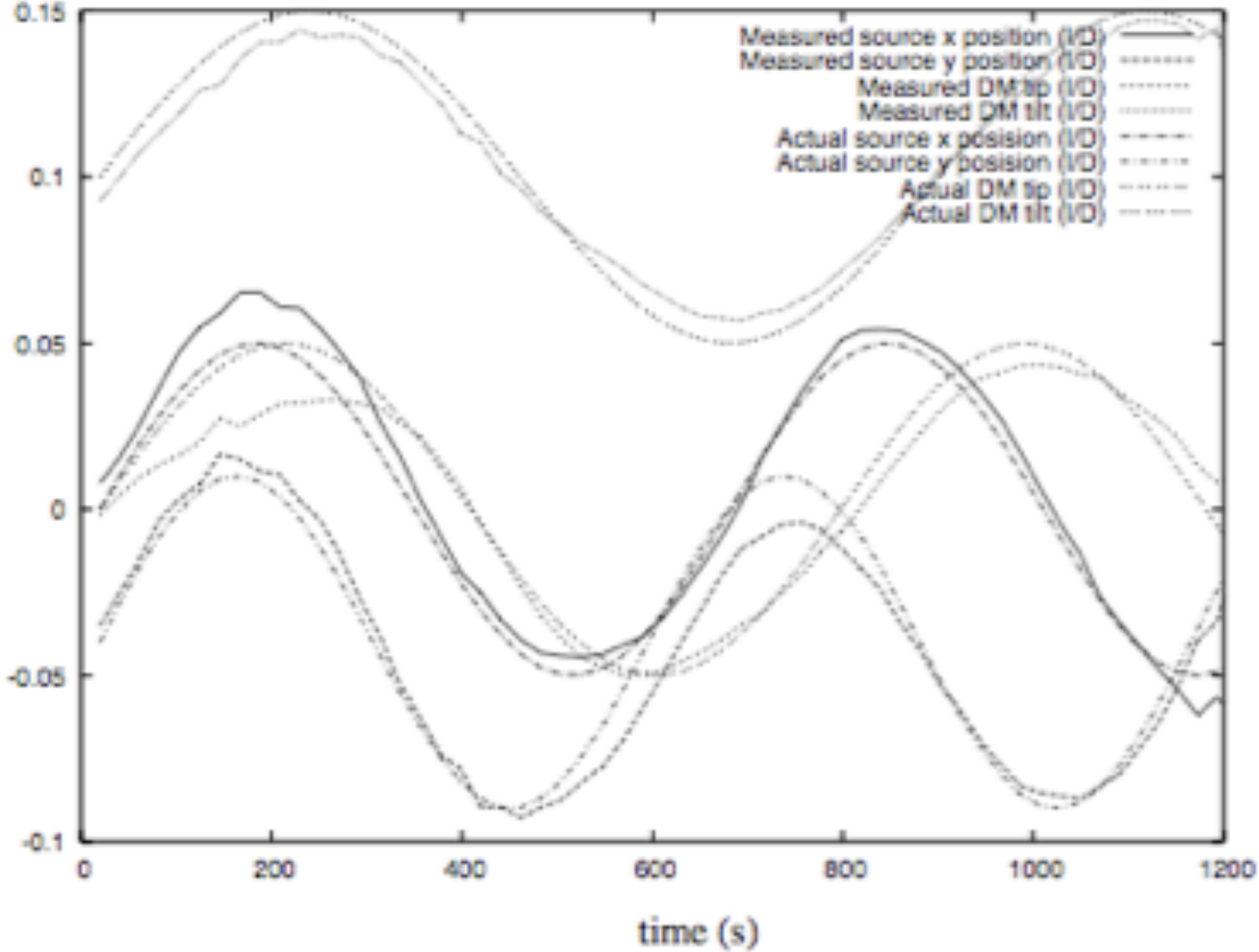


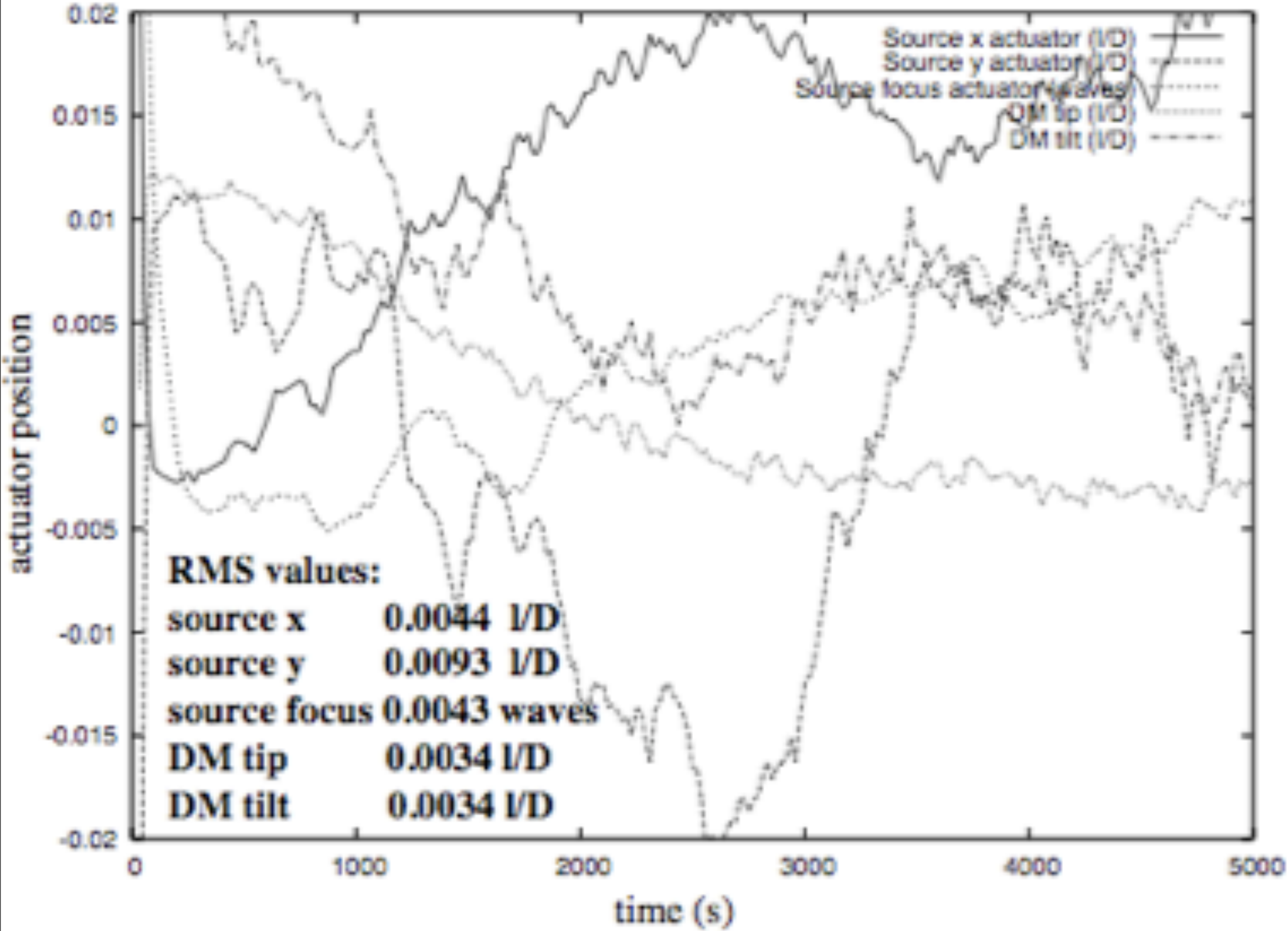
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

Why a central dark spot?

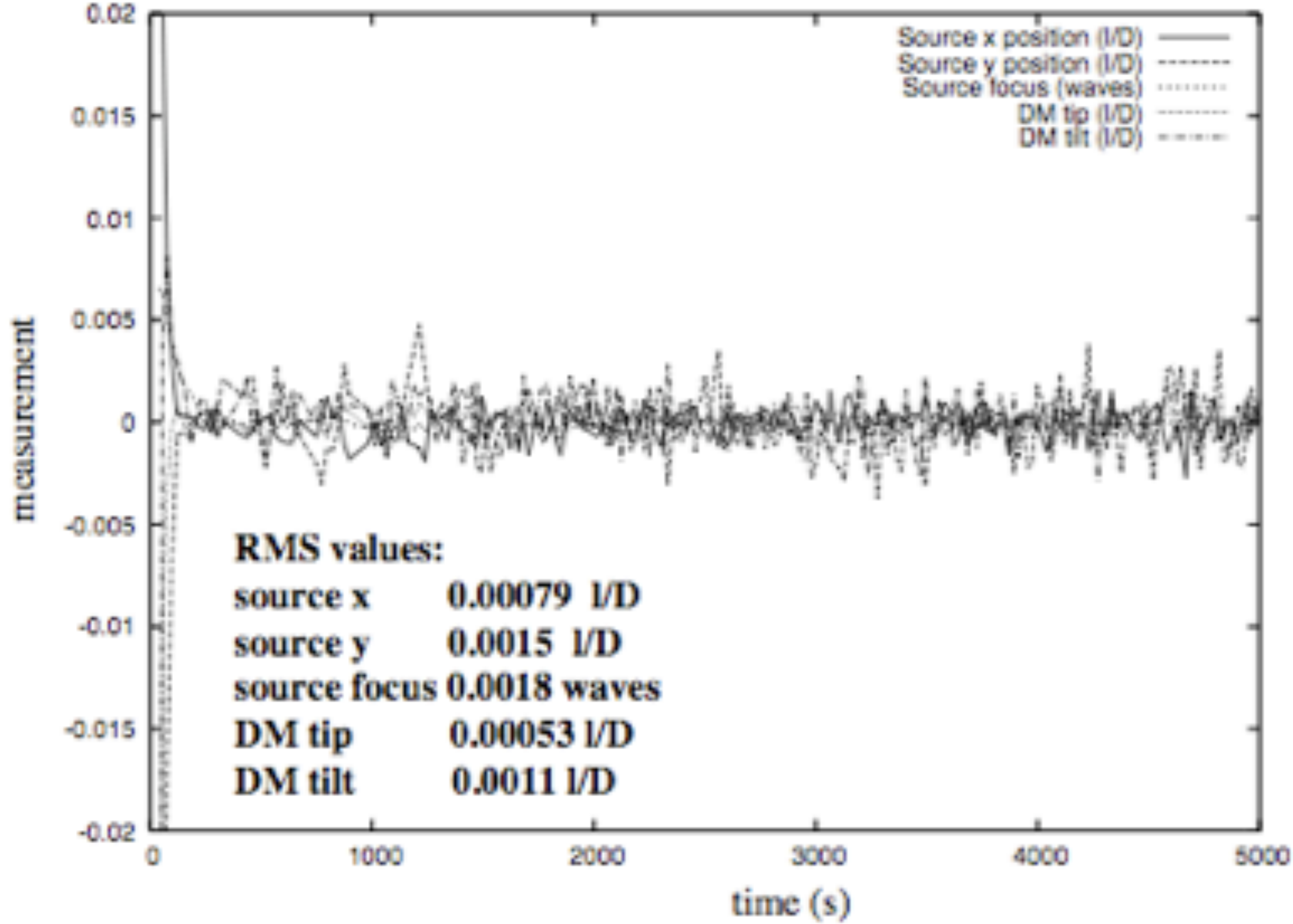
(1) Signal amplification
(2) Accurate reference



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)

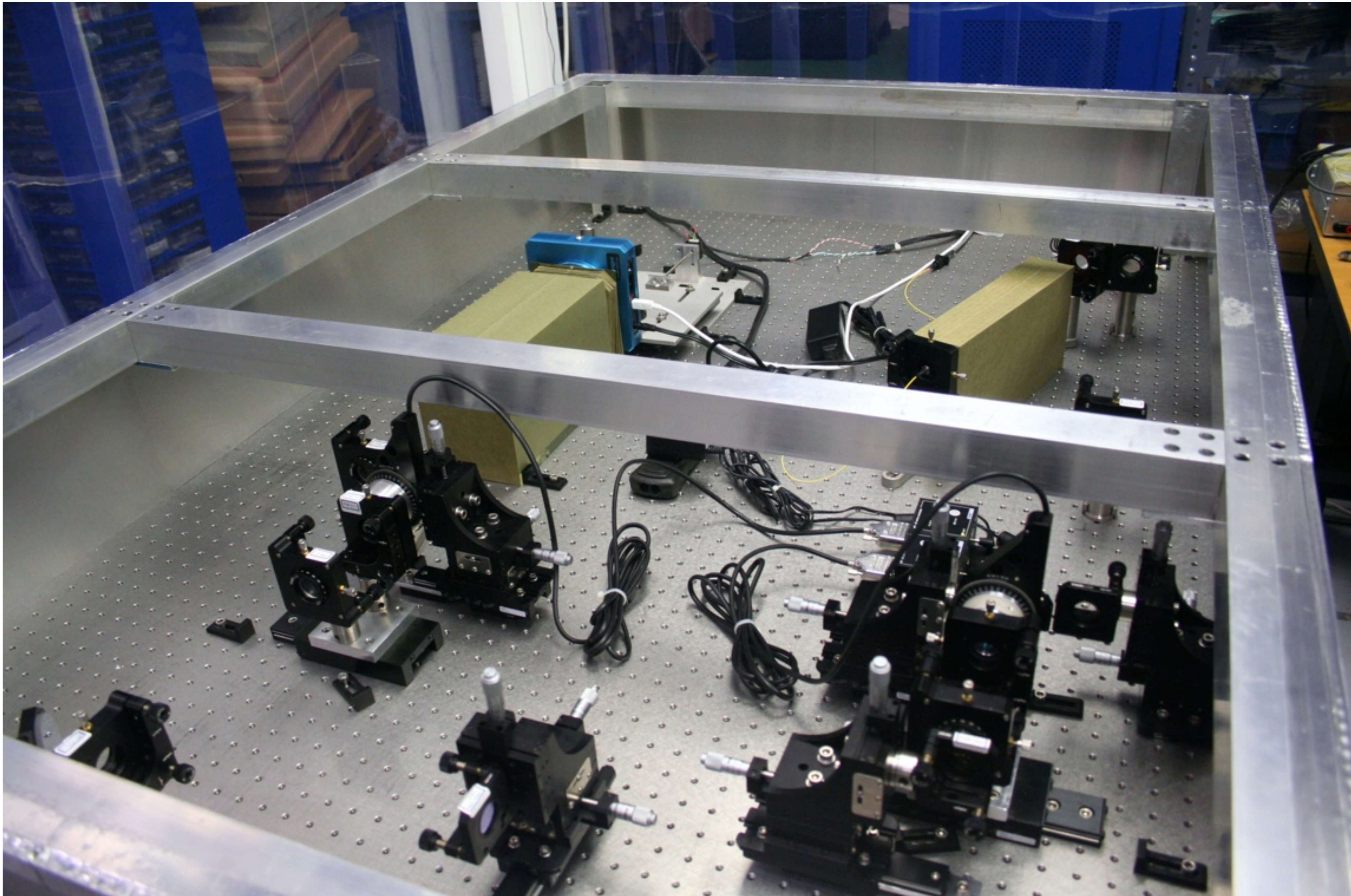


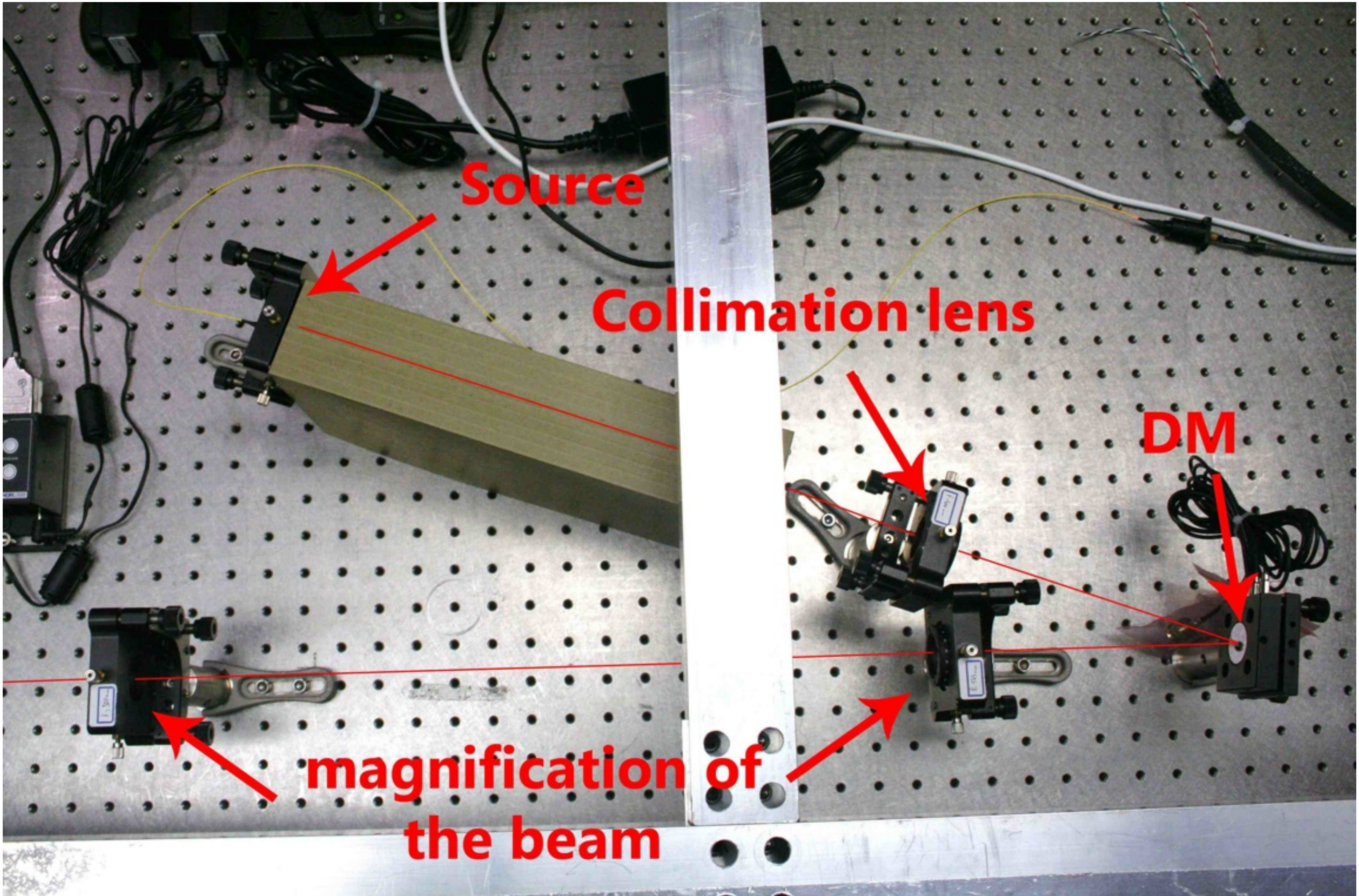
Source x actuator (l/D)
Source y actuator (l/D)
Source focus actuator (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.0044 l/D
source y 0.0093 l/D
source focus 0.0043 waves
DM tip 0.0034 l/D
DM tilt 0.0034 l/D
actuator position
time (s)

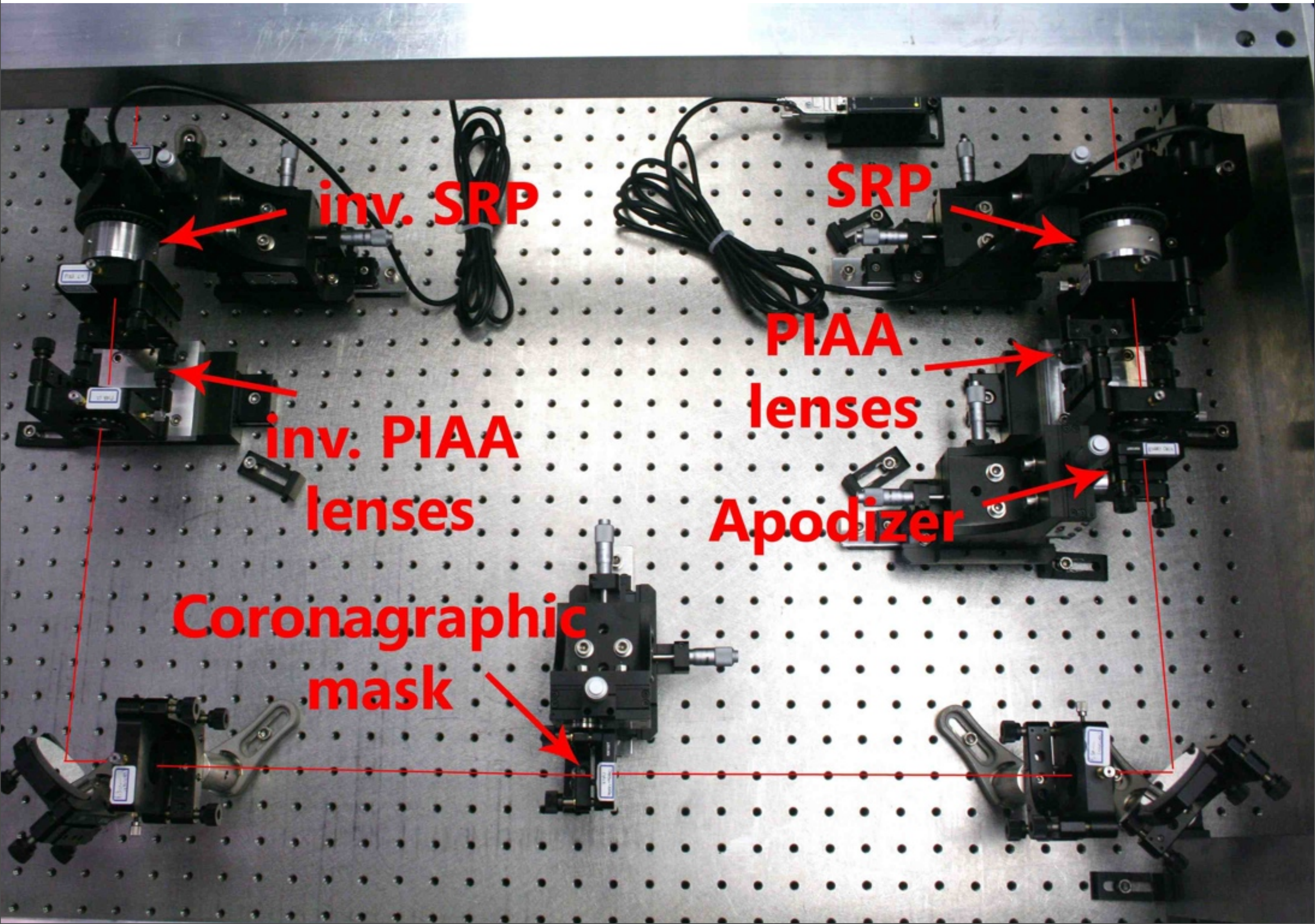


0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
measurement
0
1000
2000
3000
4000
5000
time (s)
Source x position (l/D)
Source y position (l/D)
Source focus (waves)
DM tip (l/D)
DM tilt (l/D)
RMS values:
source x 0.00079 l/D
source y 0.0015 l/D
source focus 0.0018 waves
DM tip 0.00053 l/D
DM tilt 0.0011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

CEAO lab at Subaru

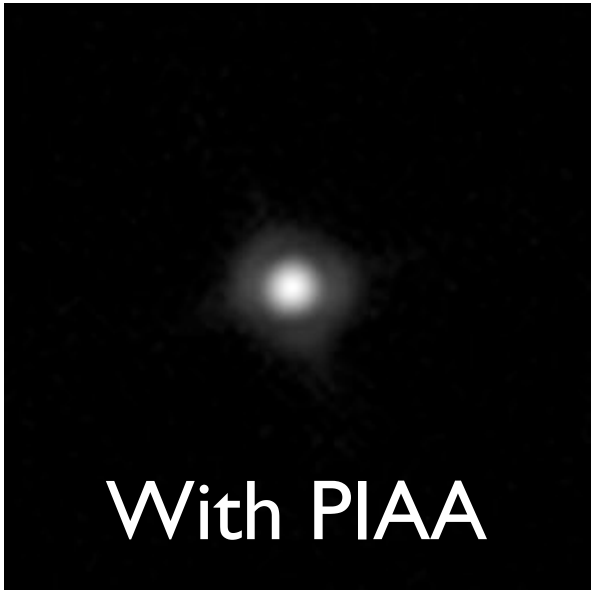


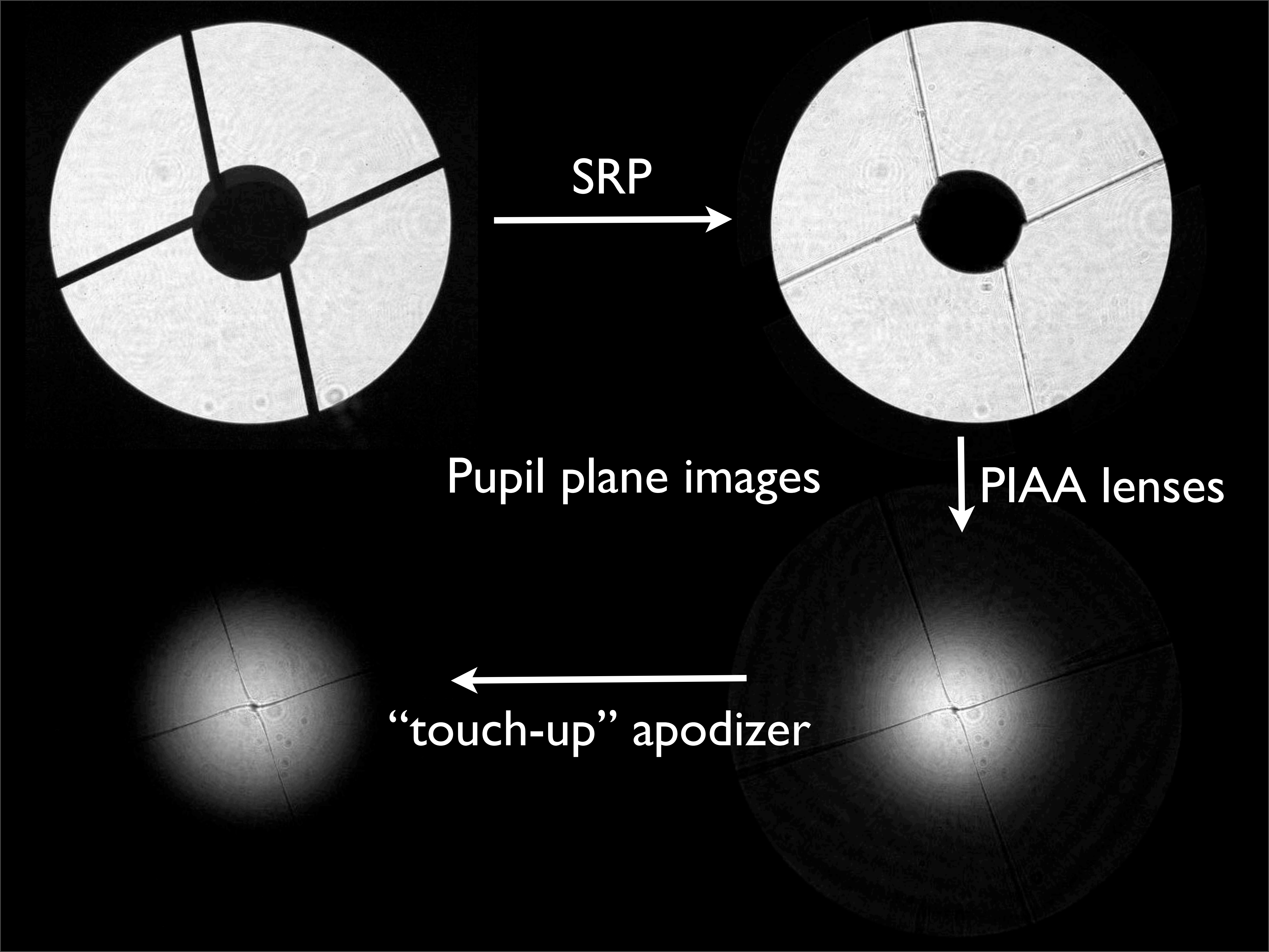

Source
Collimation lens
DM
magnification of
the beam


inv. SRP
SRP
PIAA lenses
inv. PIAA lenses
Apodizer
Coronagraphic mask

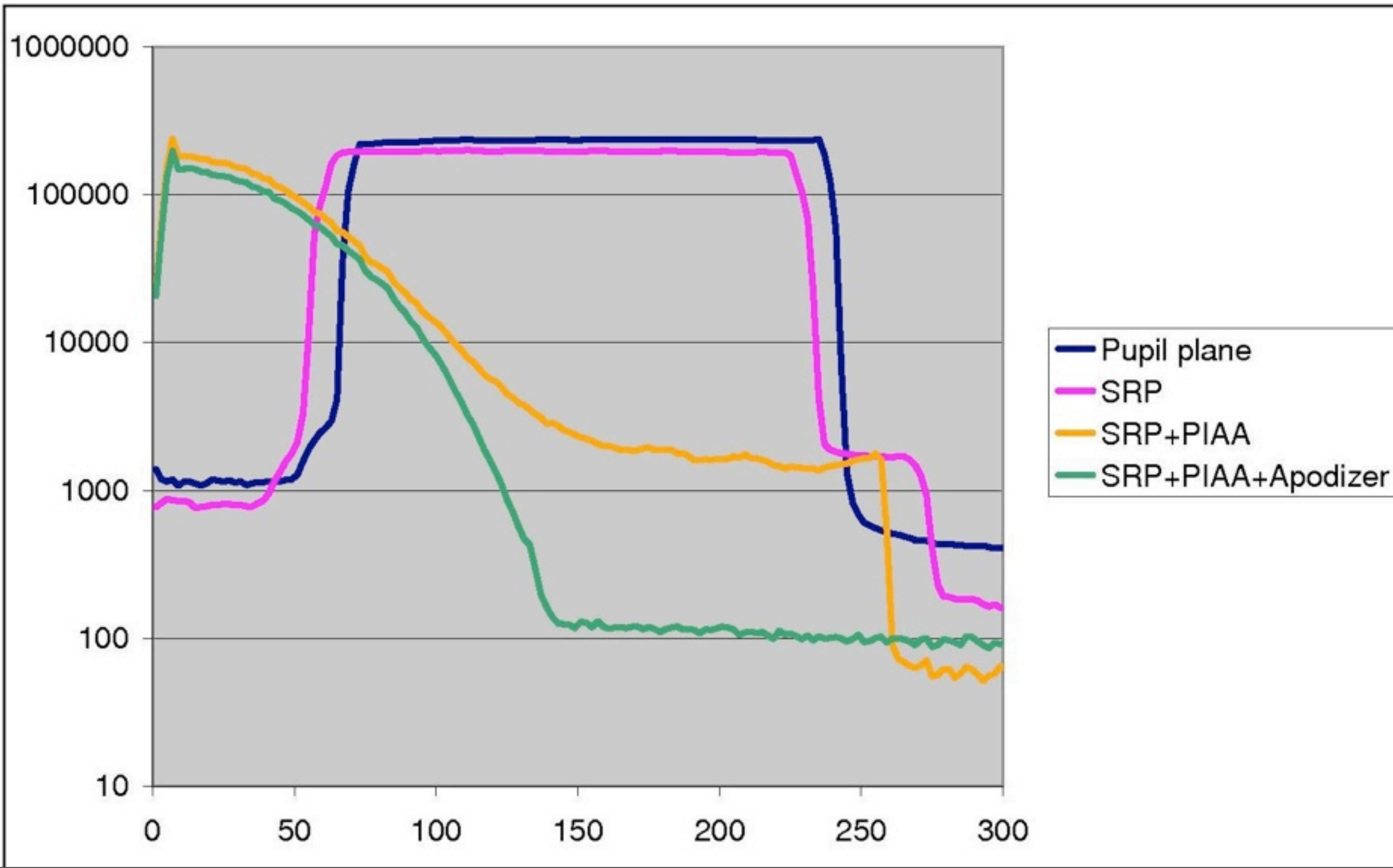
System already delivers diffraction-limited images in the visible without wavefront control.

Near-IR wavefront quality expected to be excellent (PIAA optics were designed for near-IR, not visible). A very small fraction of the MEMS DM stroke will be used for high contrast imaging (benefit: MEMS DM does not need to be in pupil plane).

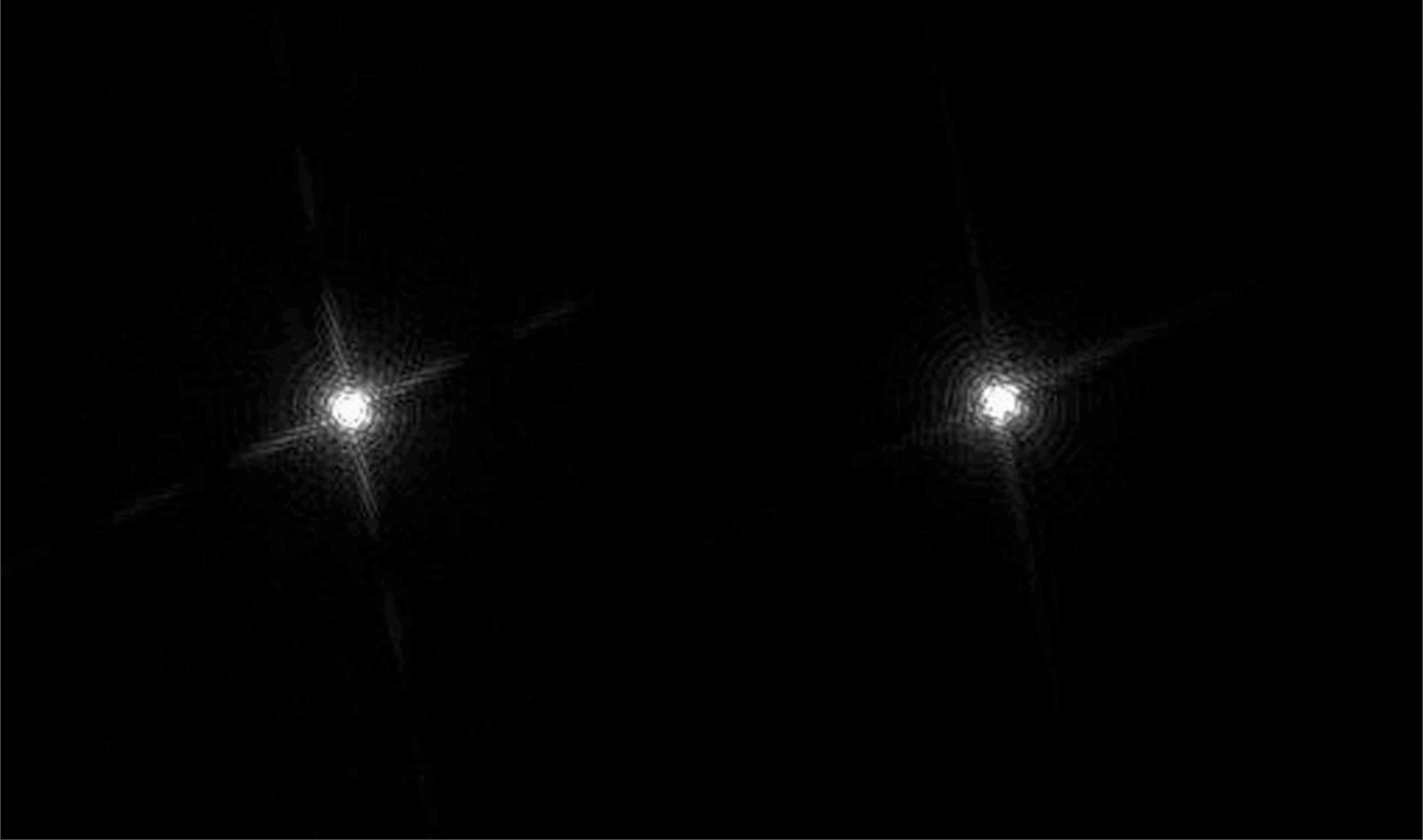



SRP
Pupil plane images
PIAA lenses
“touch-up” apodizer

Full apodization obtained with SRP + PIAA lenses + apodizer

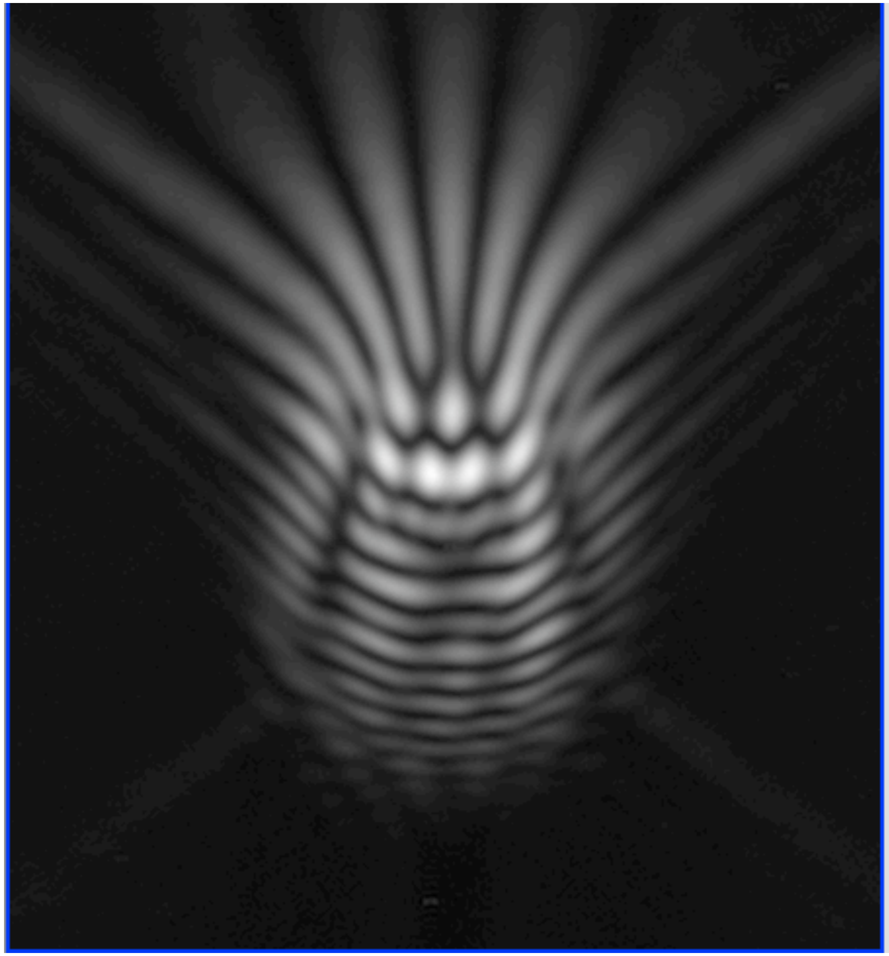


SRP removes spiders in PSF

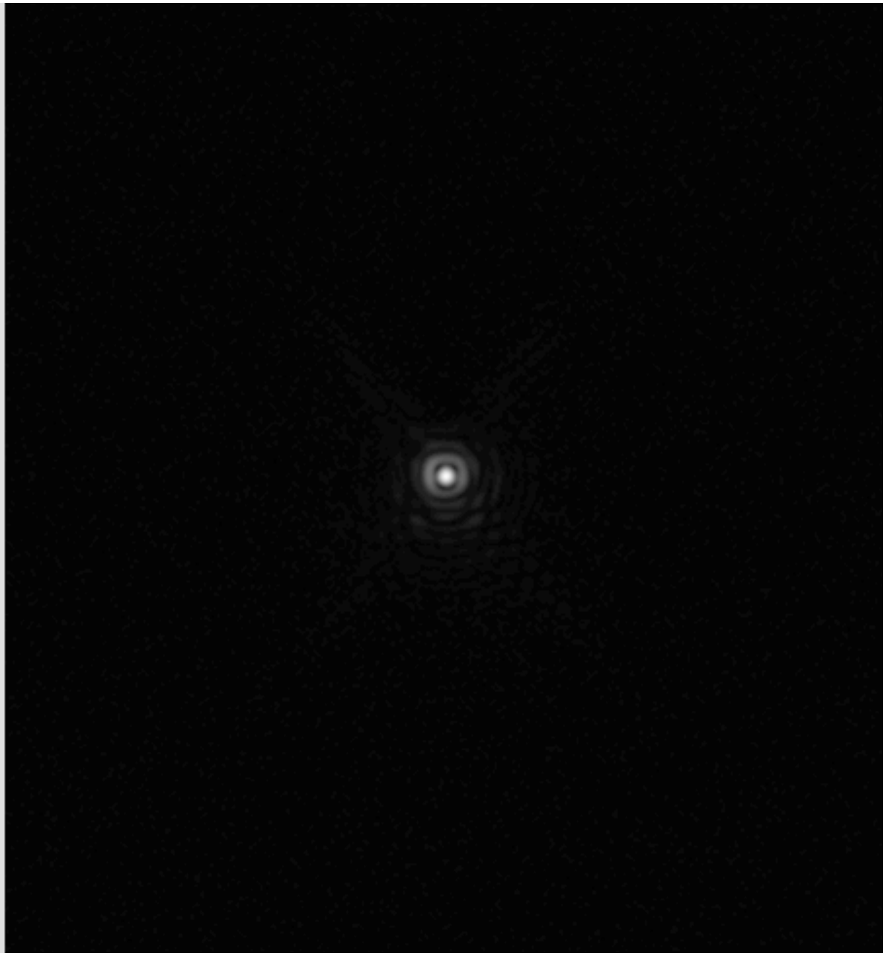


Source 20 l/D off-axis

No inverse PIAA



Inverse PIAA



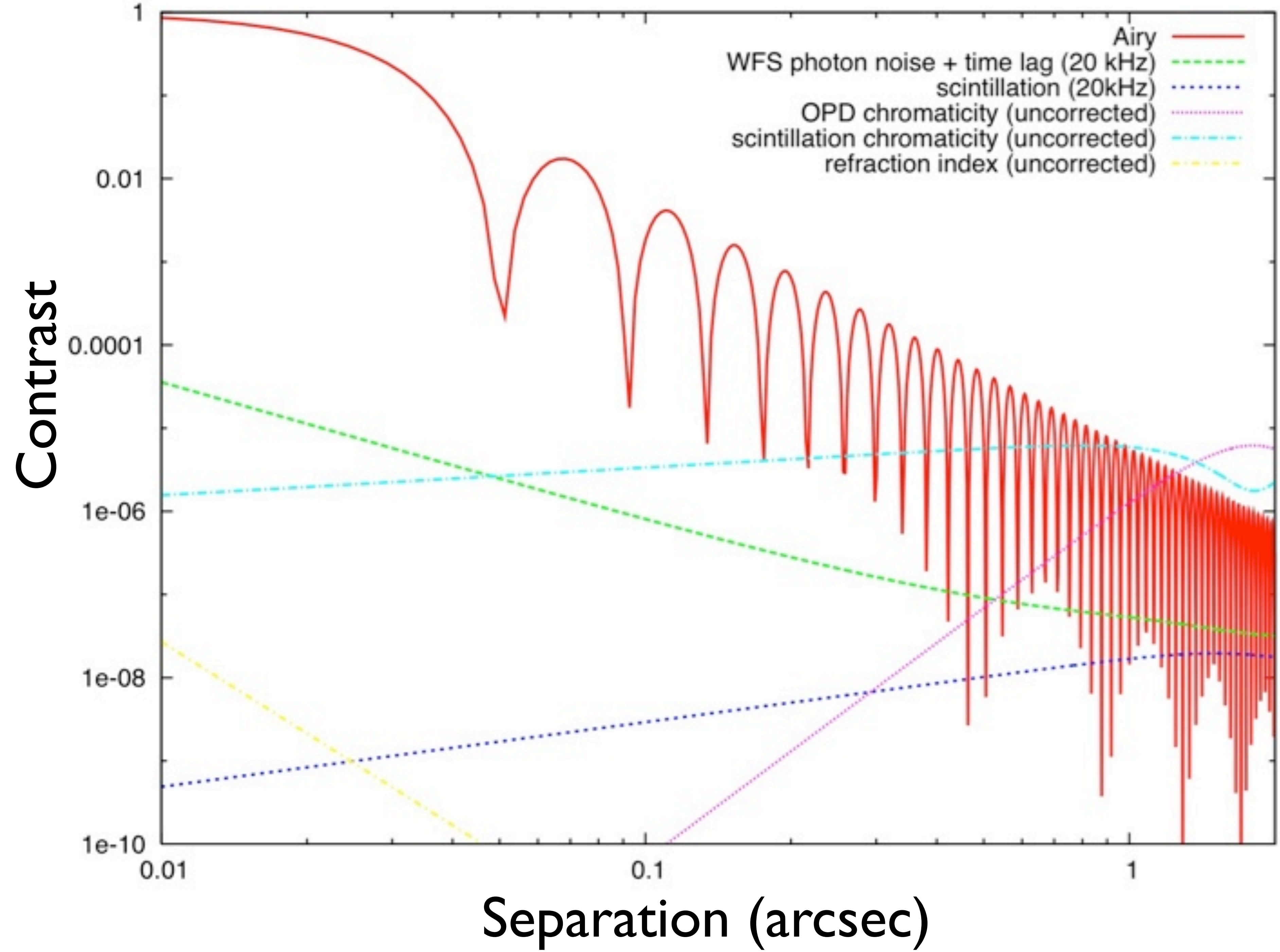
- AO188 / HiCIAO / Nasmyth platform provides ideal environment to quickly implement new techniques on telescope (Can be tested independently of telescope light).
- High flexibility is key to success in this area and maximize science per $. Continuous dev., watching for new technologies to stay ahead.
- Overlap between and co-location of coronagraphy/ExtremeAO, AO188 & HiCIAO teams highly advantageous
- Subaru CEAO system should be more capable & more flexible than GPI/Sphere
- These techniques also pave the way for highly efficient exoplanet science with ELTs.

Can we image Earths with ground-based telescopes ?

Reflected light:

- Earth/Sun contrast ~ 1e-9
- SuperEarth ~ 4e-9
- Jupiter @ 1 AU: 2.5e-8

8-m telescope

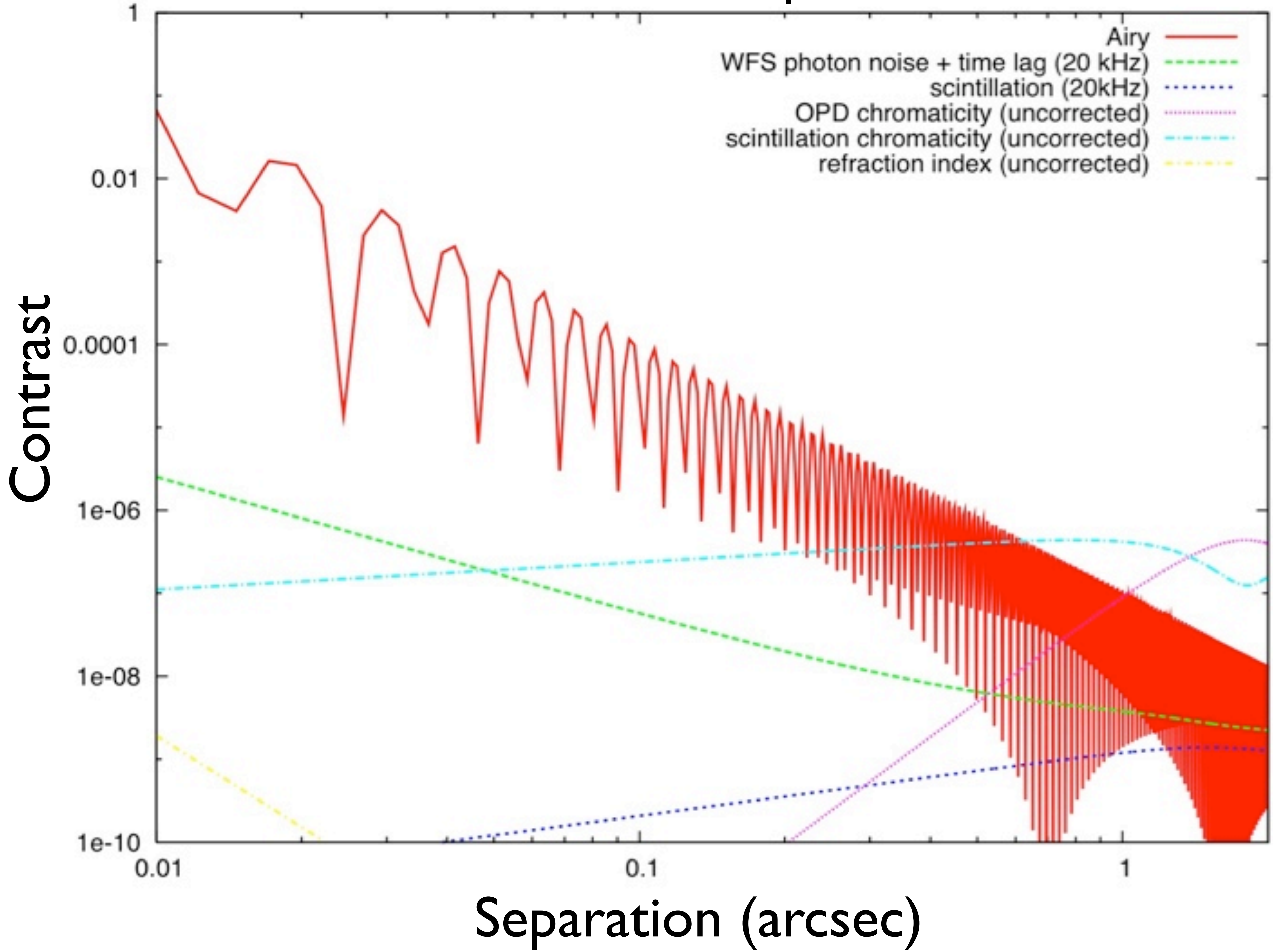


8m telescope, very good ExAO + slow near-IR correction

mV = 5, mH = 5
Contrast in H ~ 1e-5 ~ 1e4 ph/s/speckle (H band background ~1/2 of this)
with ~10 Hz residual speckle timescale
Photon noise from Halo = 1e-7 x 1/sqrt(t(s))
Speckle noise from Halo = 3e-6 x 1/sqrt(t(s))

in 1hr, 3-sigma detection limit =
1.5e-7 (no differential detection)
1e-8 (differential detection, 1/4 photons)

30-m telescope



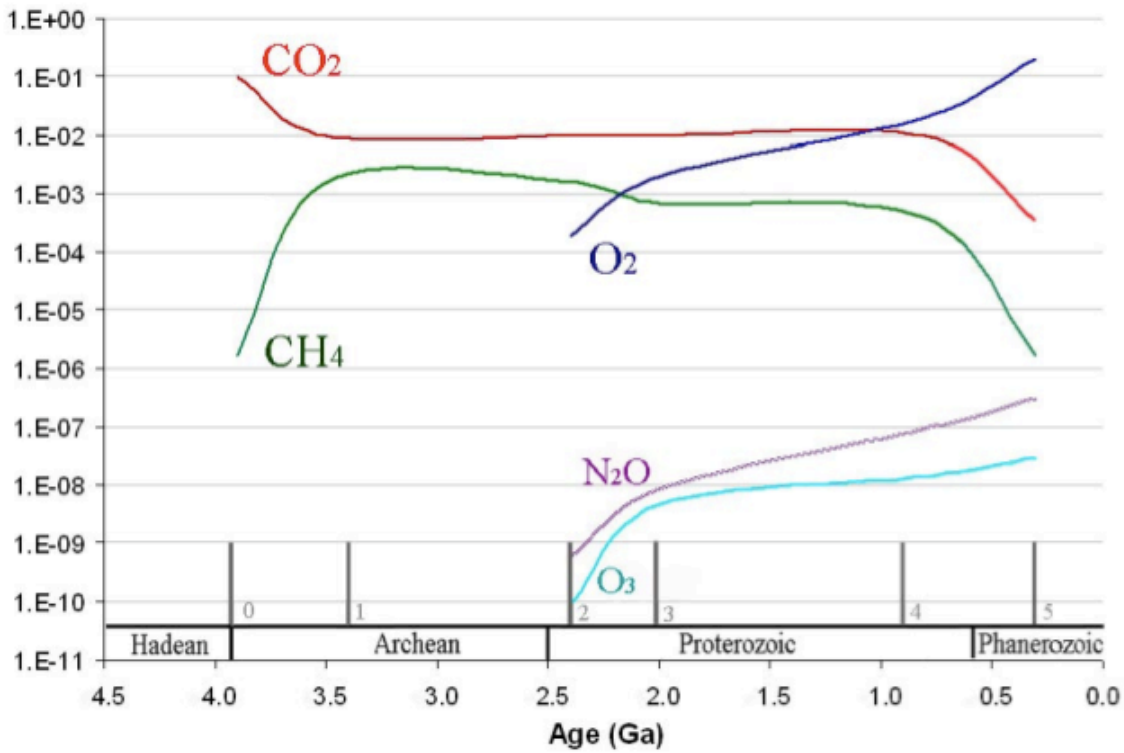
30m telescope, very good ExAO + slow near-IR correction

14x more photons in planet and star, contrast 14x better
still ~1e4 ph/s/speckle (7e-7 contrast)
Photon noise from Halo = 7e-9 x 1/sqrt(t(s))
Speckle noise from Halo = 2e-7 x 1/sqrt(t(s))

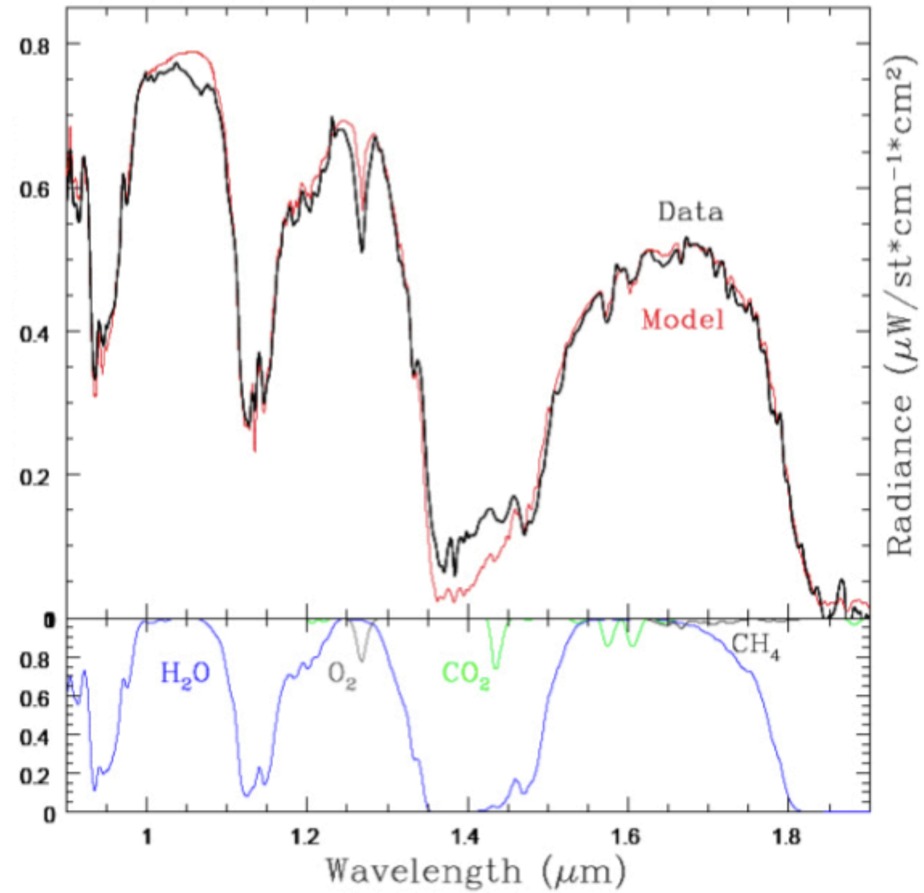
in 1hr, 3-sigma detection limit =
1.1e-8 (no differential detection)
7e-10 (differential detection, assuming 1/4 photons)

Near-IR Earth spectra

- Water is easiest to detect
- CO2, CH4, O2



Kasting 2004



Turnbull et al 2006

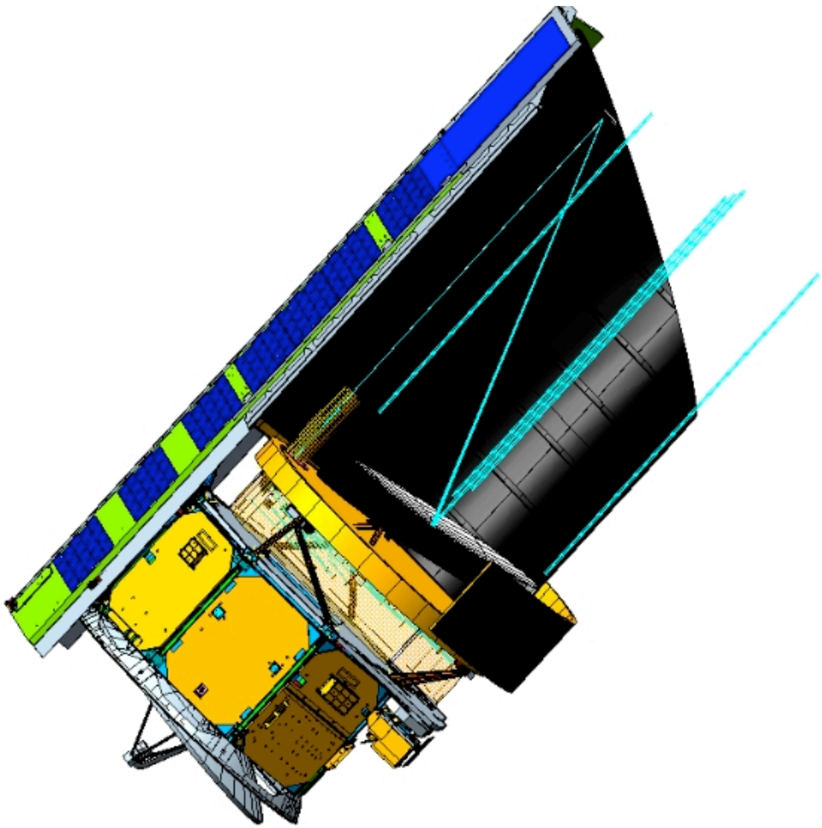
Pupil remapping Exoplanet Coronagraphic Observer (PECO)

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

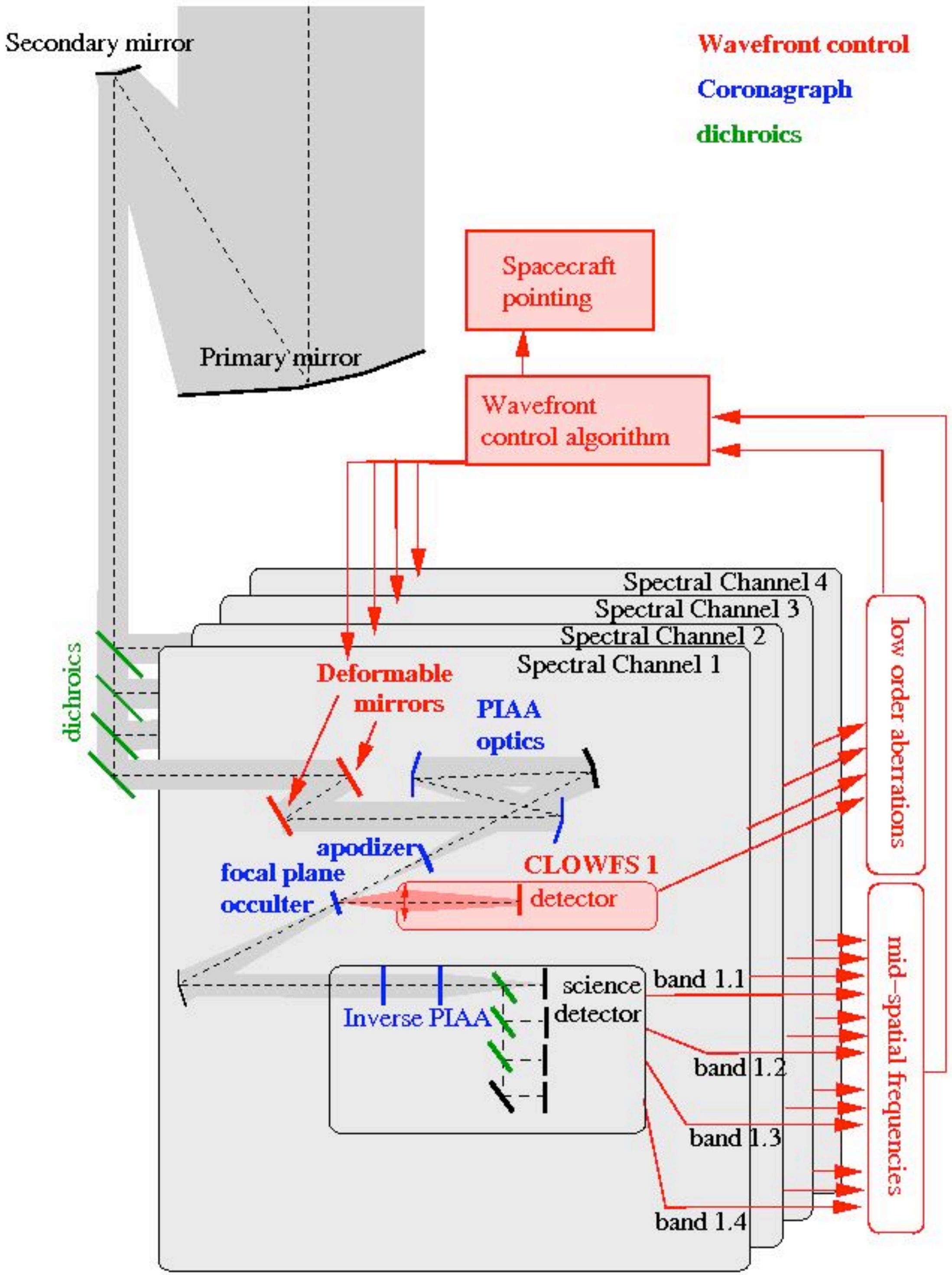


High contrast coronagraphic imaging of the immediate environment of nearby stars

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" ($600M - $800M) NASA-funded Advanced Mission Concept Studies.



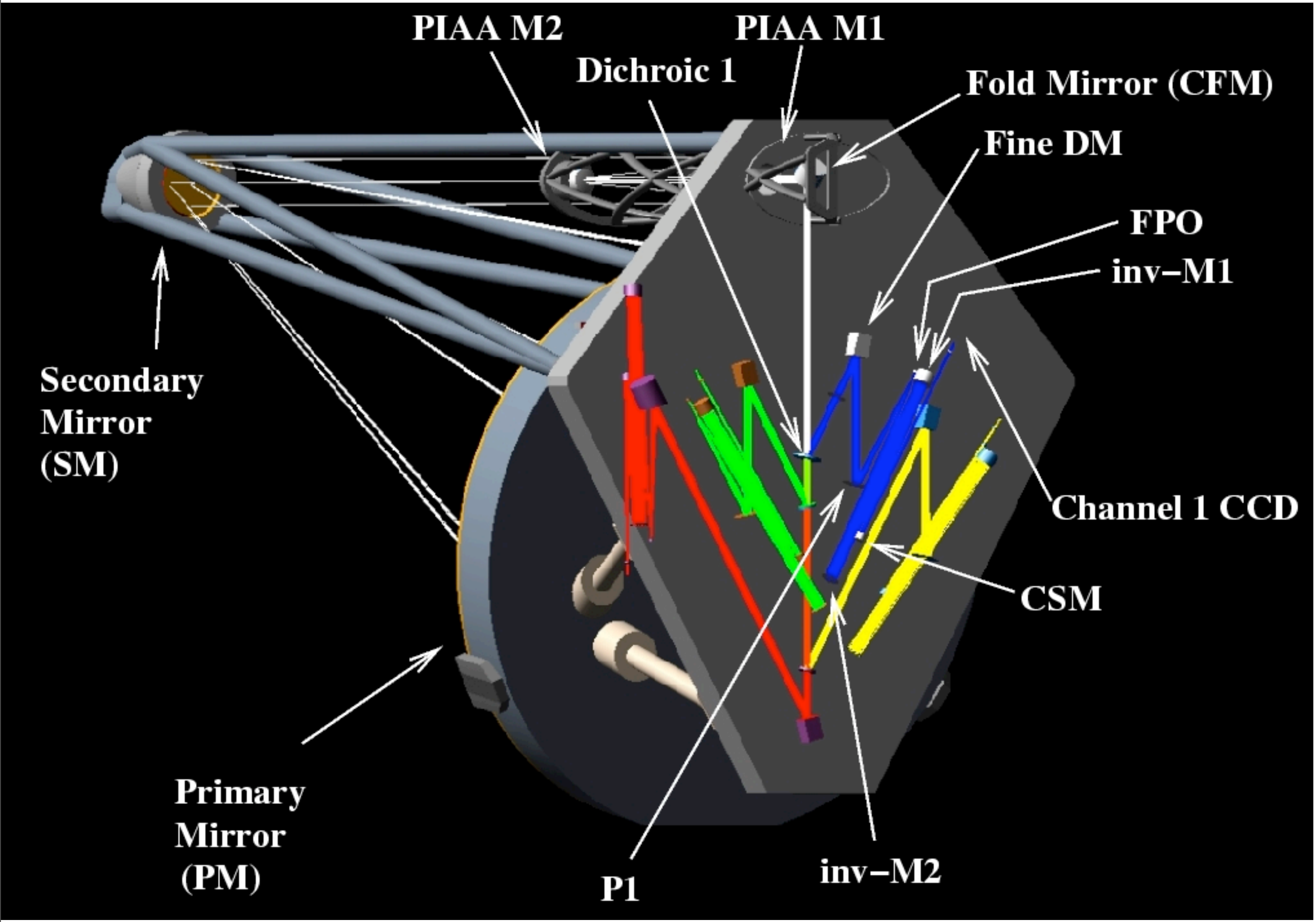
Optimal use of photons from 0.4 to 1.0 micron, for WFC and science

- 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).

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

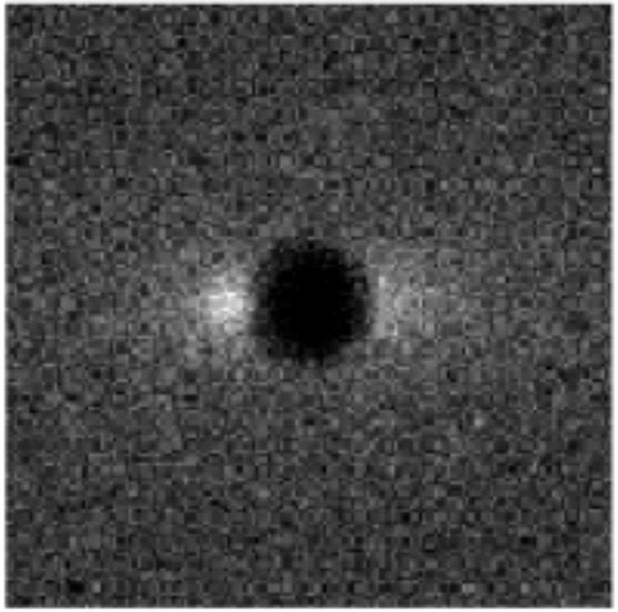
Table 1.2-1 Number of FGK main sequence stars around which different planet types can be detected (SNR=5 at R=5 at 0.55 micron) with an ideal (perfect wavefront) 1.4m PIAA telescope adn other telescope diameter/coronagraph combinations. Details of this simulation can be found in Guyon et al. 2006. This 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

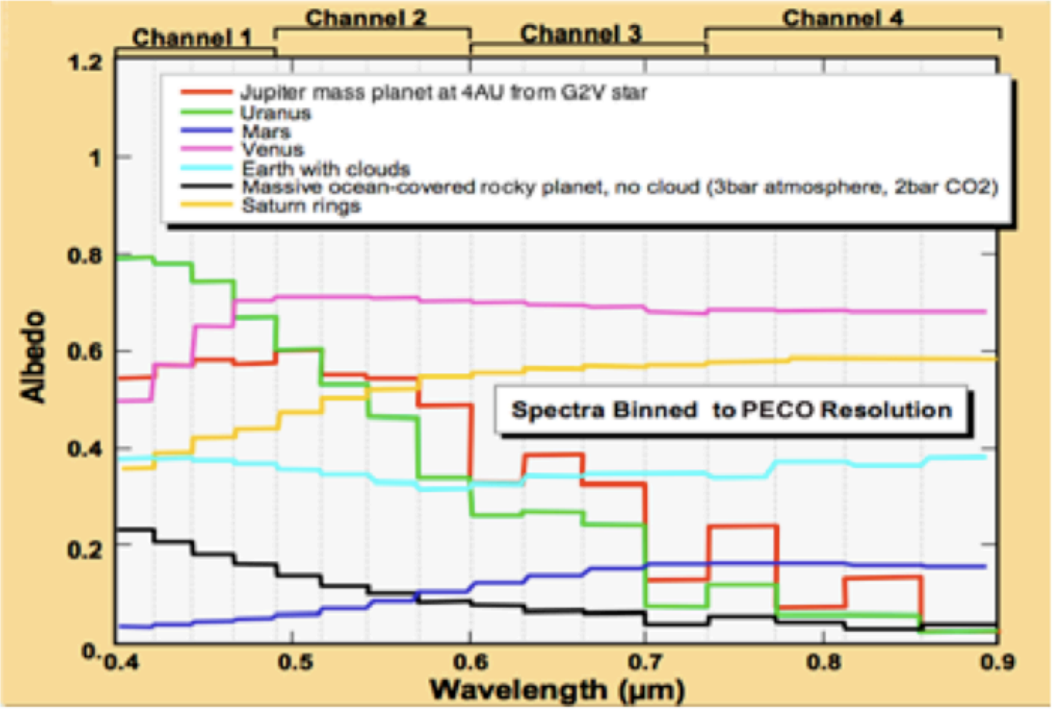
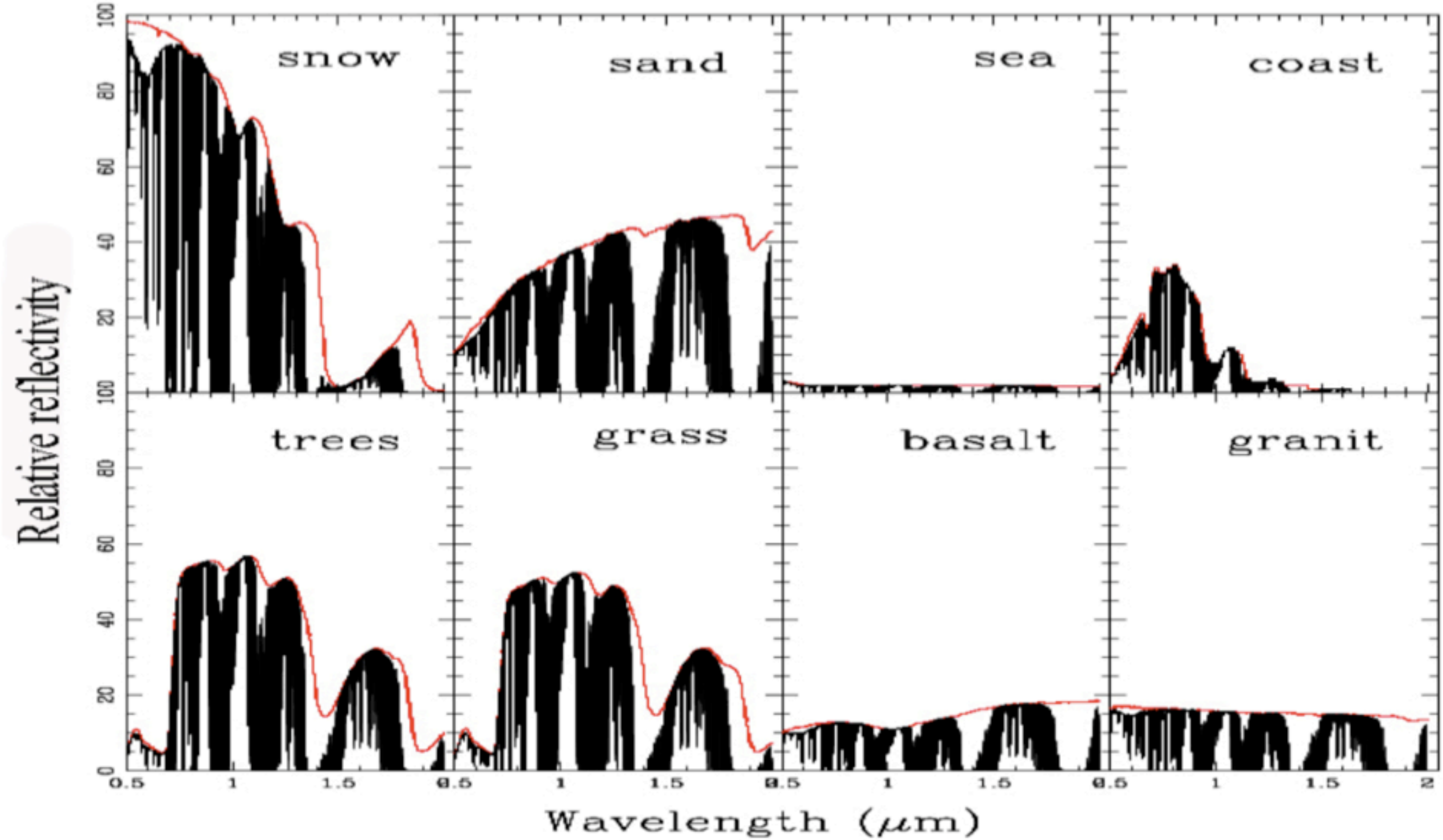
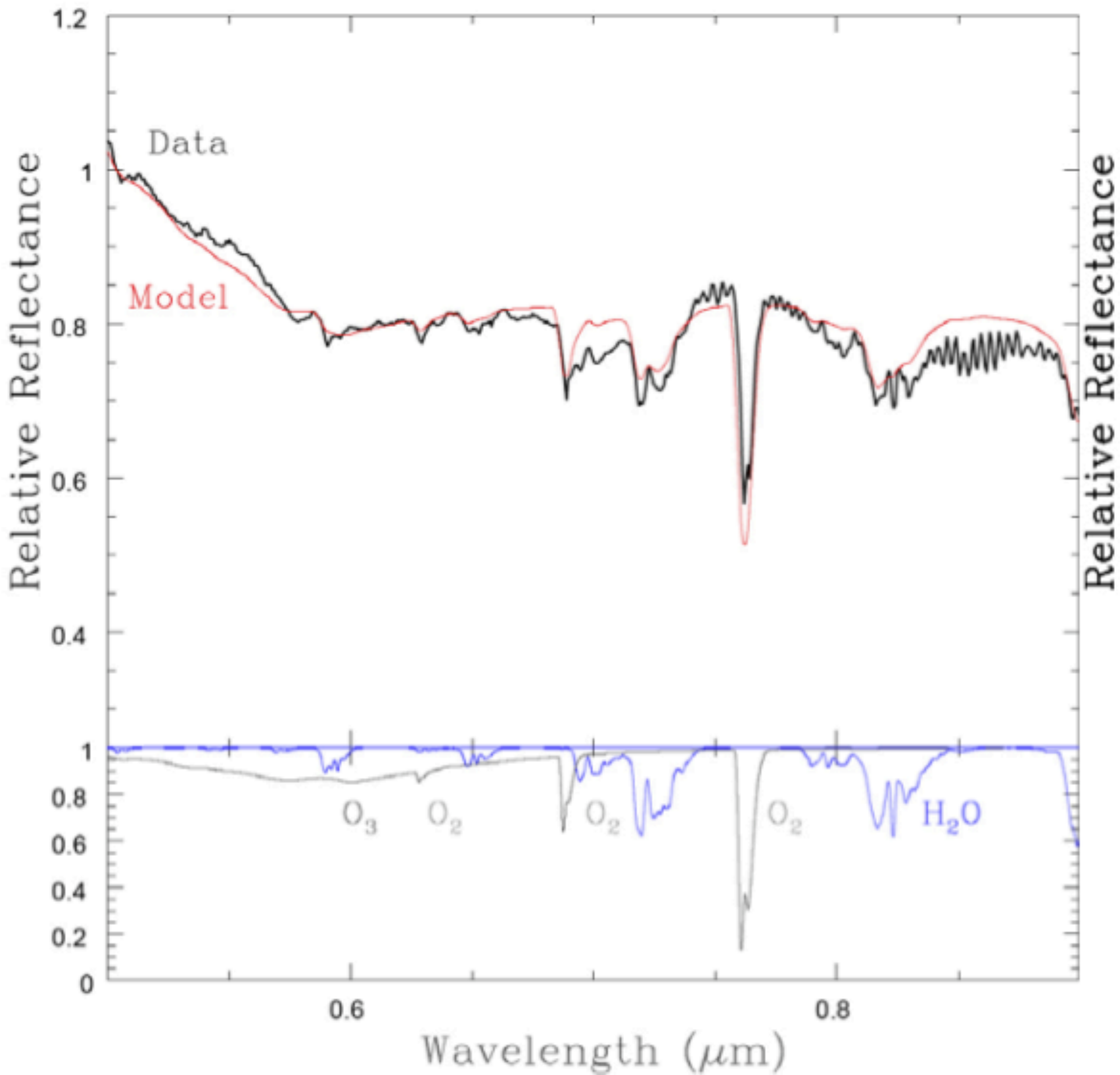


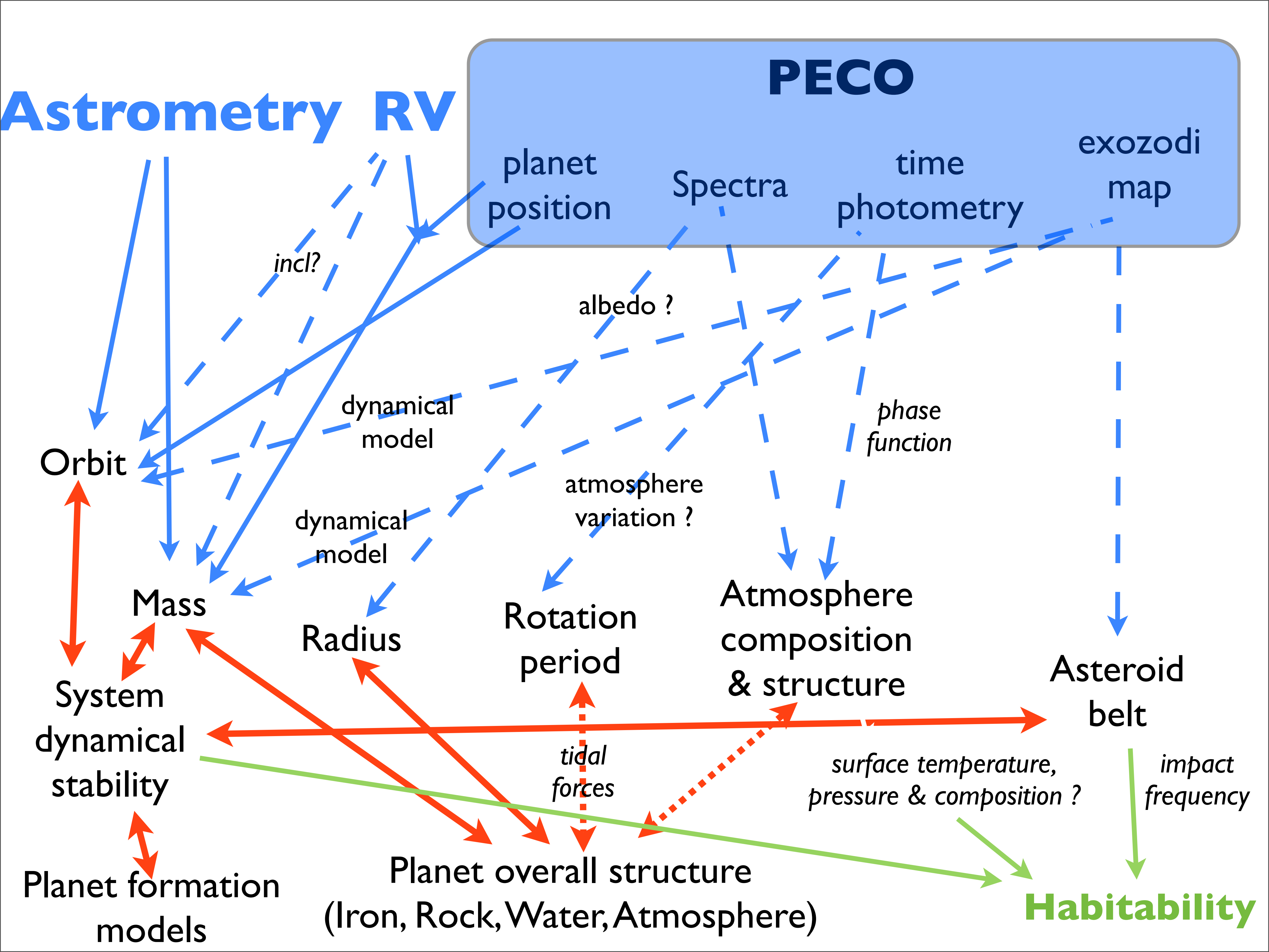
Figure 1.2-1 PECO Spectral Bands. Earth's atmosphere has a relatively constant albedo across the PECO bands, with a slight absorption near 600 nm due to ozone. EGPs like Jupiter will have relatively flat spectra, with deep methane absorption in the red adjacent to bright continua arising from clouds.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



Kalteneger et al. 2006



Woolf et al. 2002


Astrometry
RV
PECO
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