# A bright future for direct imaging of extrasolar planets & disks

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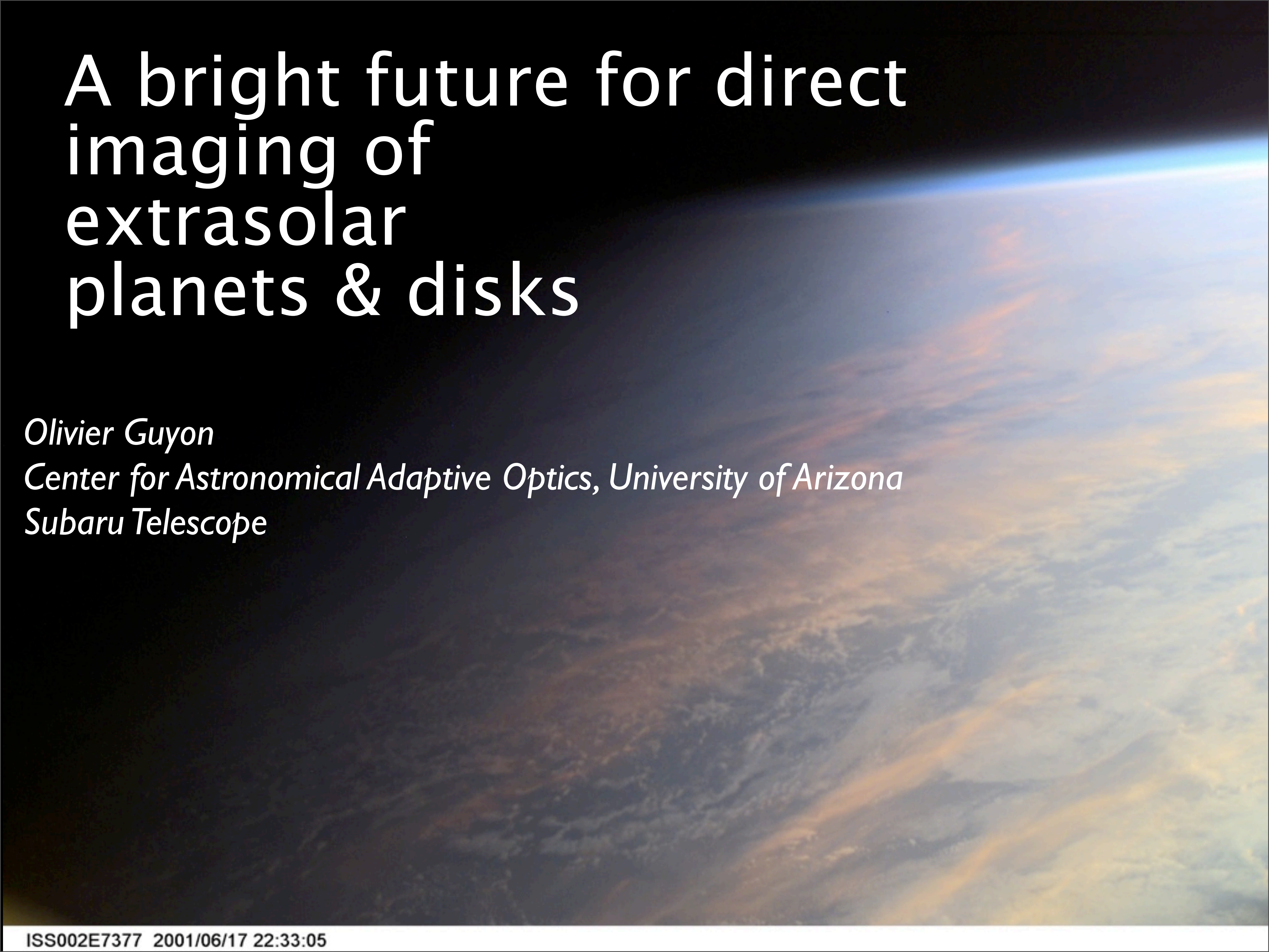
*Center for Astronomical Adaptive Optics, University of Arizona*
*Subaru Telescope*



# Outline

- Scientific motivation

- Tools for high contrast imaging
  - **Coronagraphy** - optical system to remove starlight
  - **Wavefront control** - keep the image sharp and achieve high contrast
  - **PSF / speckles Calibration**

- Subaru Coronagraphic Extreme-AO (SCExAO)
- Pupil mapping Exoplanet Coronagraphic Observer (PECO)

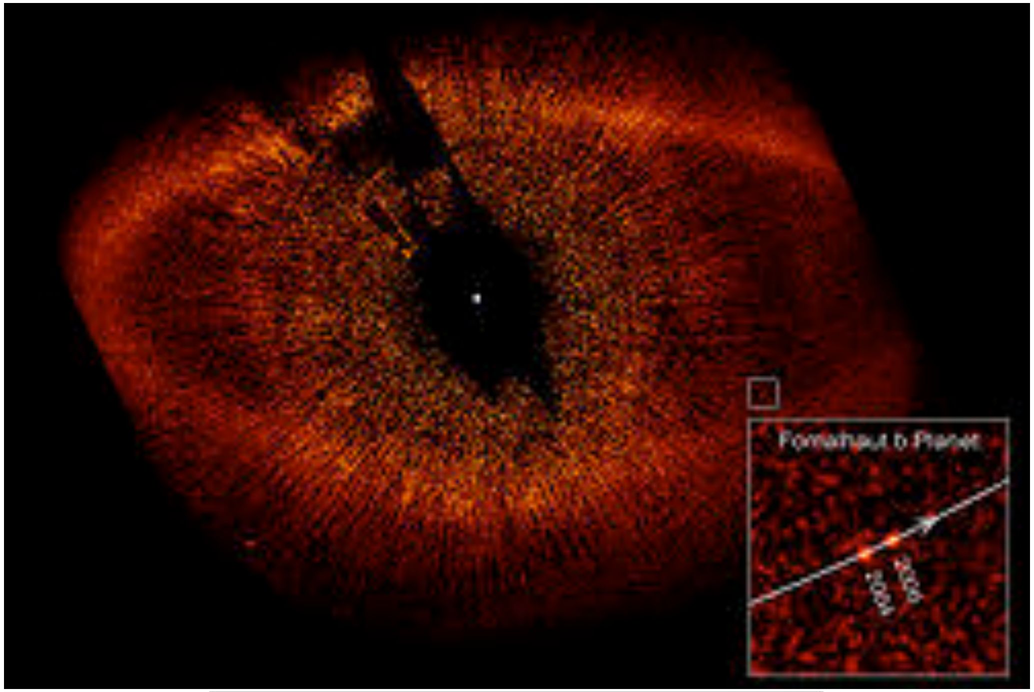
## Ground-based imaging (Near-IR, with Adaptive Optics)

- Most sensitive to outer young planets: very complementary to Radial Velocity, astrometry, transits -> important for testing planetary formation models (core accretion, gravitational collapse of disk instabilities ?)
- Study planet formation by imaging disks and planets
- Current limitation: mass/age/luminosity relationship (cooling rate) poorly known
- NEED to get closer in to the star / higher contrasts for overlap with radial velocity planets -> constrain mass/age/luminosity models
- NEED to get closer in/higher contrasts to capture REFLECTED light -> “old” planets can then be detected around nearby stars (known targets from radial velocity)
- NEED to increase sample size (currently ~5, possibly most of them are “exceptions” to the rule) with spectral characterization

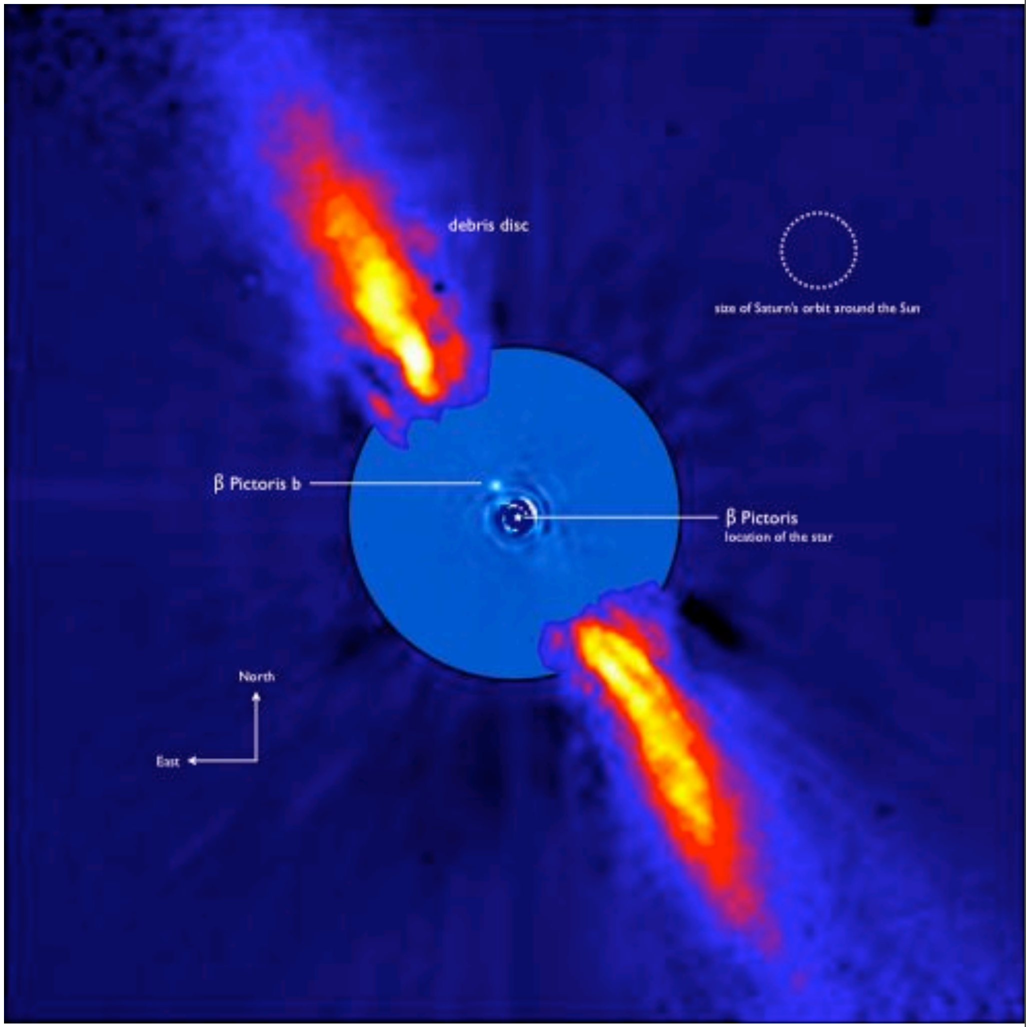
## Space-based imaging (Visible, extremely high contrast)

- Characterization (spectroscopy) of Earth-mass planets in habitable zone
- Simultaneous imaging of exozodi cloud, massive and rocky planets

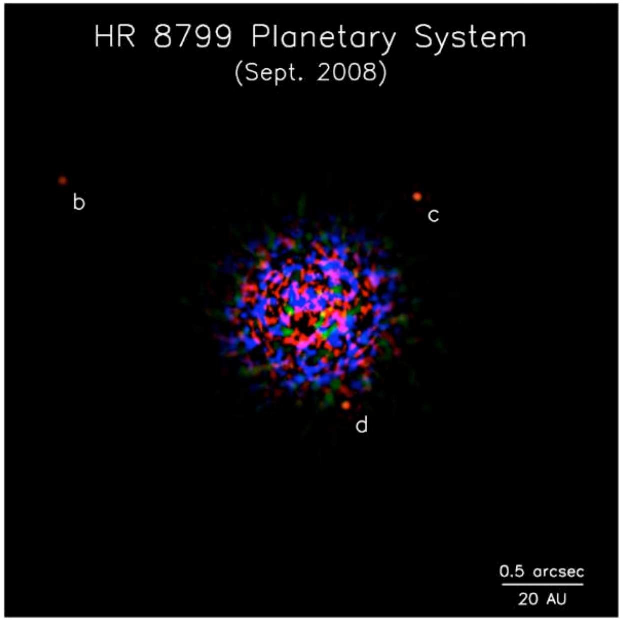
- understanding planetary systems formation & evolution
- Planetary atmospheres, physical properties



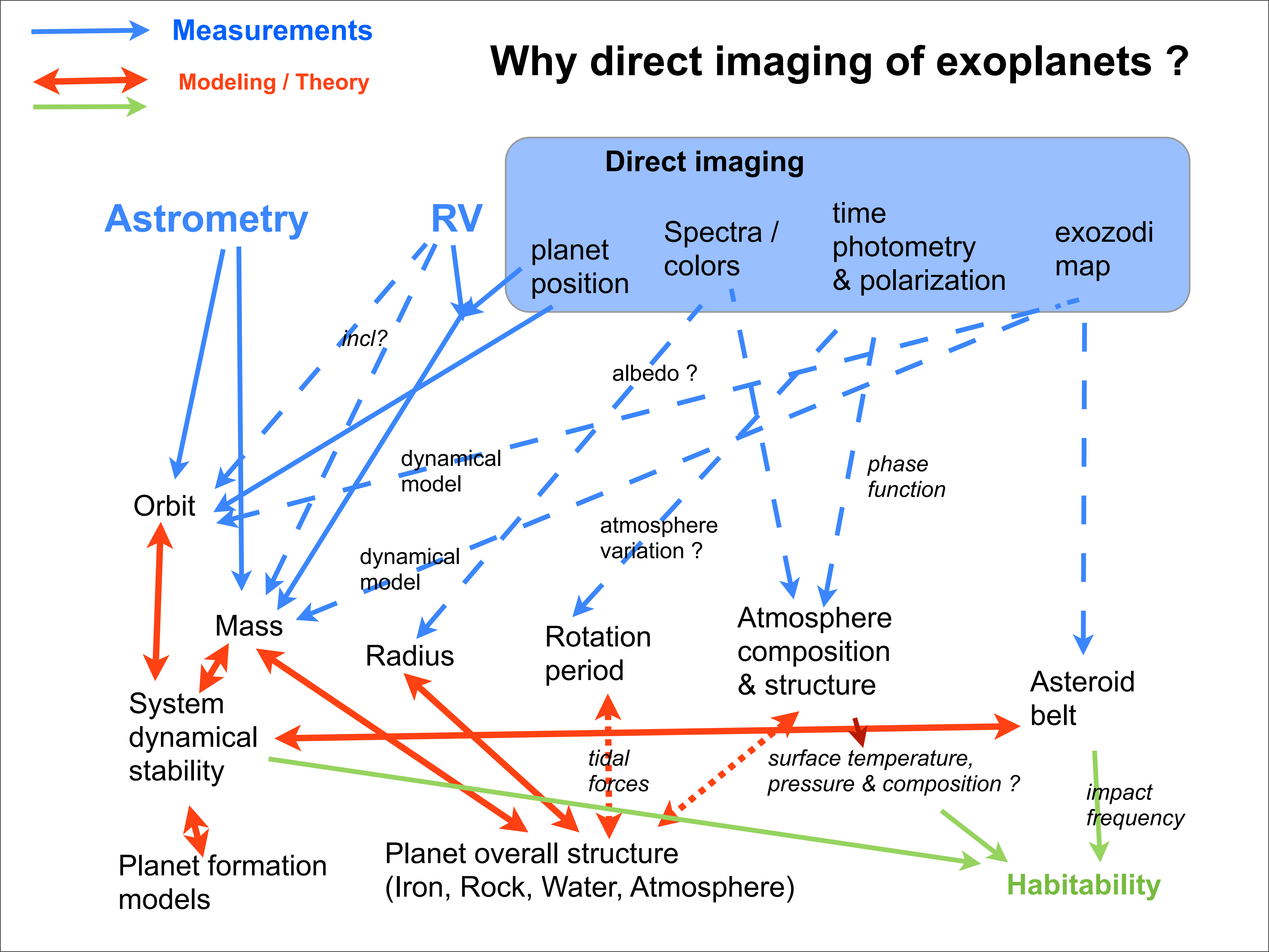

*Kalas et al. 2008*




*Lagrange et al. 2009*




*Marois et al. 2008*



Measurements
Modeling / Theory
Why direct imaging of exoplanets ?
Direct imaging
Astrometry
RV
planet position
Spectra / colors
time photometry & polarization
exozodi map
incl?
albedo ?
dynamical model
dynamical model
atmosphere variation ?
phase function
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

# Coronagraphy

- R&D in coronagraph has been extremely active in the last 10-15 yrs
- Many good coronagraph designs now exist
- The theoretical limit imposed by fundamental physics is now approached by a few concepts
- Coronagraph performance achieved in labs is already much beyond the requirements of ground-based systems, and at or close to requirements for space mission

Coronagraphy: 1930 to ~15 yrs ago

Lyot Coronagraph

# The Lyot Coronagraph

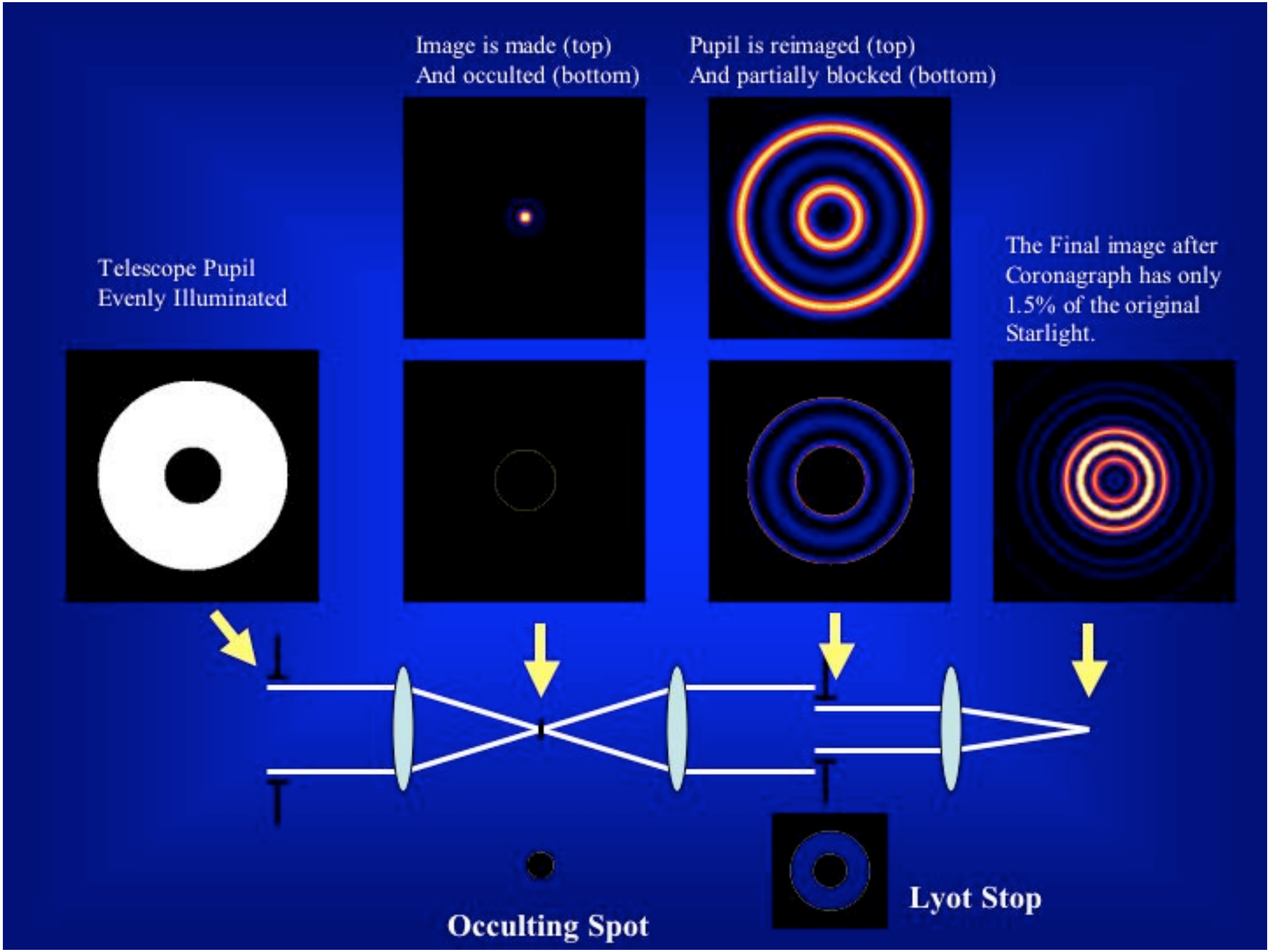
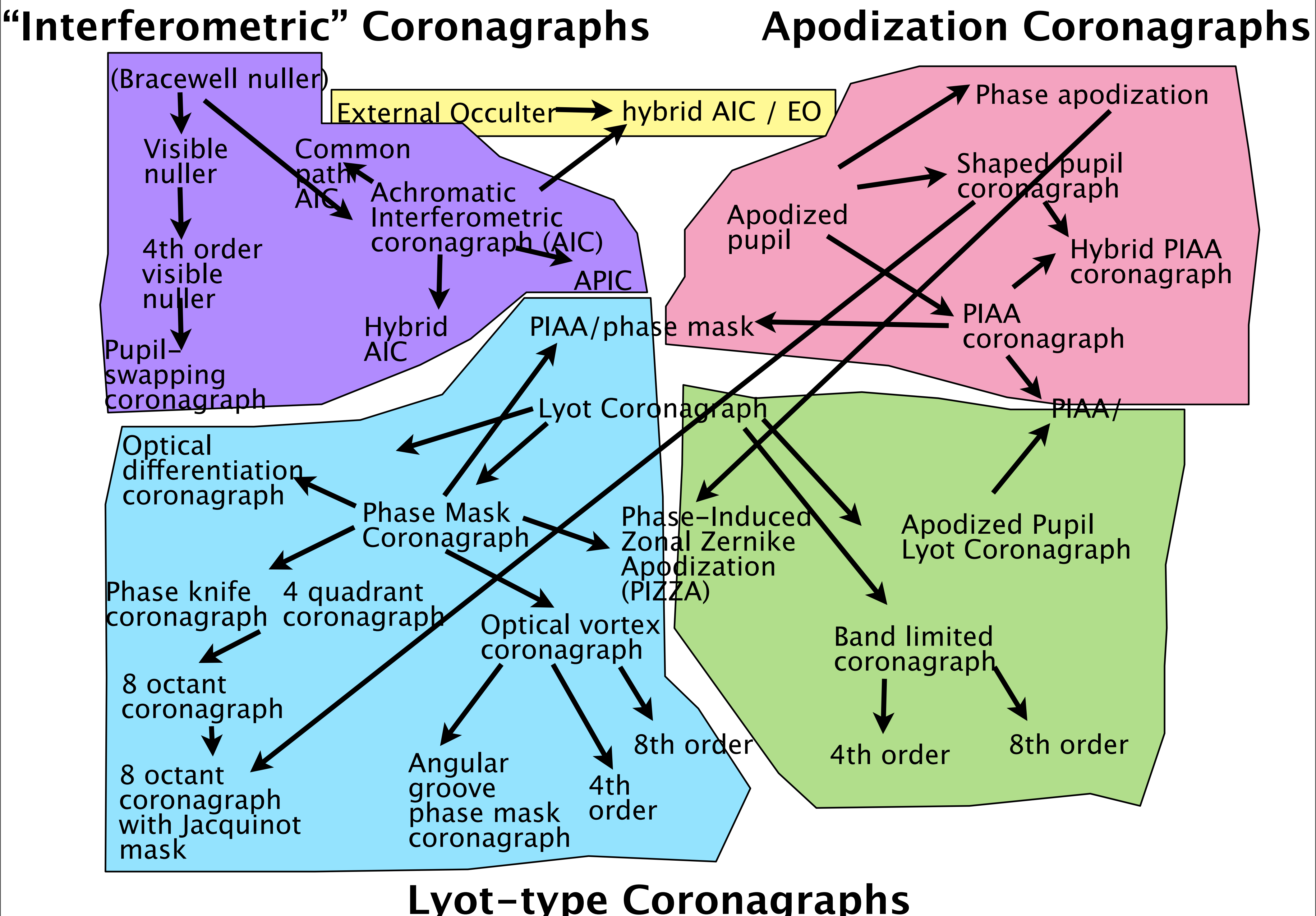



*figure from Lyot project website*



"Interferometric" Coronagraphs
Apodization Coronagraphs
(Bracewell nuller)
External Occulter
hybrid AIC / EO
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
4th order visible nuller
APIC
Hybrid AIC
Pupil-swapping coronagraph
Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
PIAA/
Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
4th order
8th order
4th order
8th order
Lyot-type Coronagraphs

## What is the theoretical performance limit of coronagraphy ?

Coronagraph is a linear filter (in complex amplitude) which removes starlight.
If :
planet = 0.2 x starlight wavefront + **0.8 x something else**
then:
coronagraph throughput for planet < 0.8

**Theoretical limit would offer high contrast with little loss in throughput and inner working angle close to 1 lambda/D.**

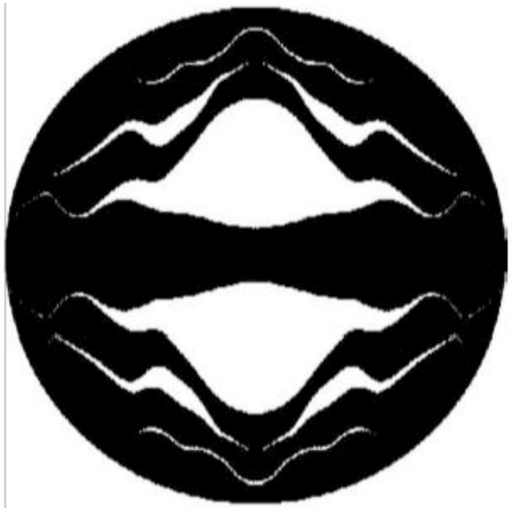
(Guyon, Pluzhnik, Kuchner, Collins & Ridgway 2006, ApJS 167, 81)

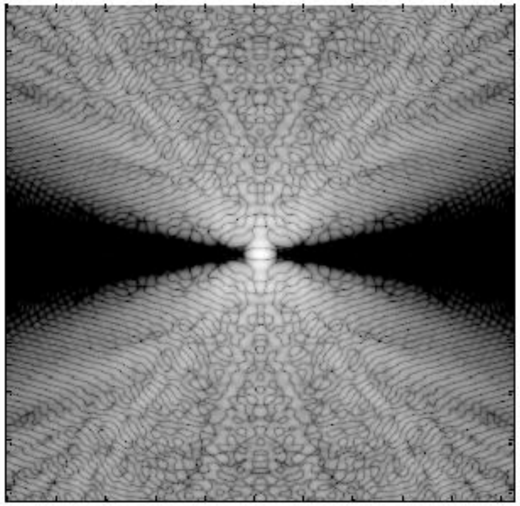
# Conventional Pupil Apodization (CPA)

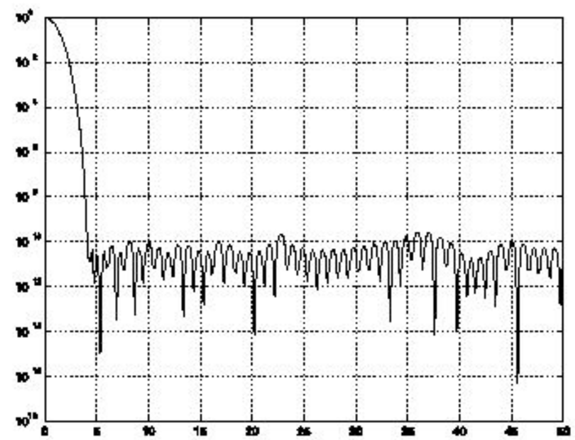
Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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







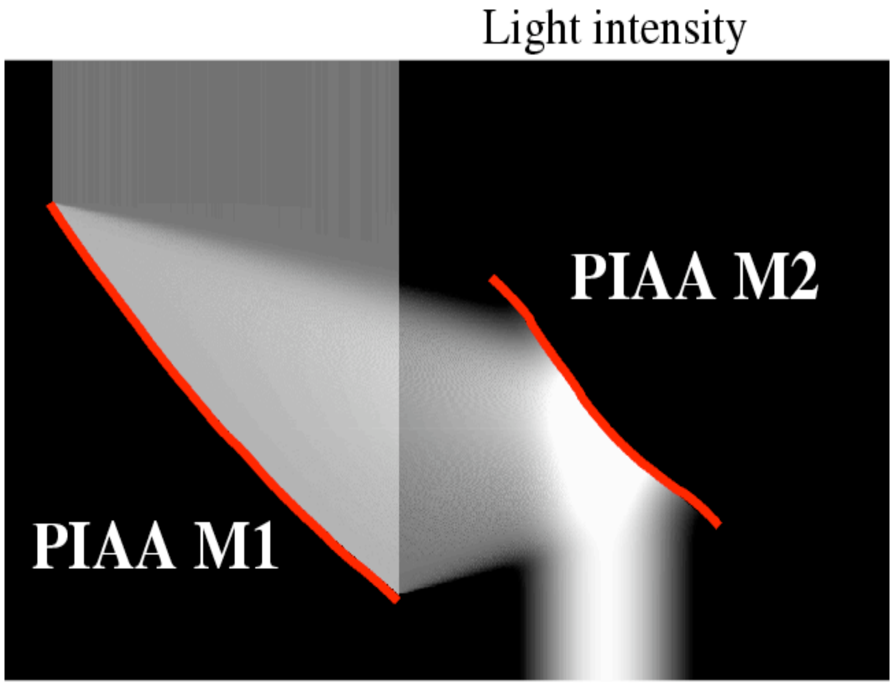

Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

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 development at Subaru
co-funded by Subaru/NAOJ, NASA JPL & NASA Ames

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

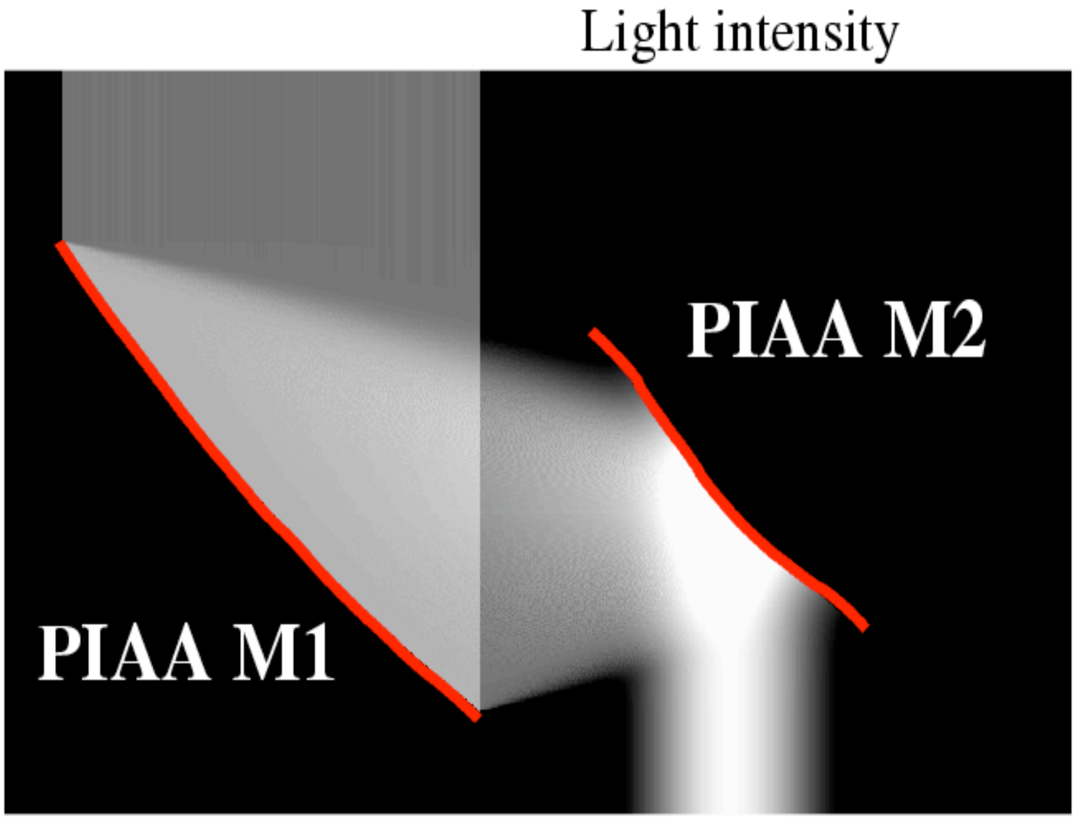
- high contrast
- Nearly 100% throughput
- IWA 0.64 l/D to 2 l/D
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

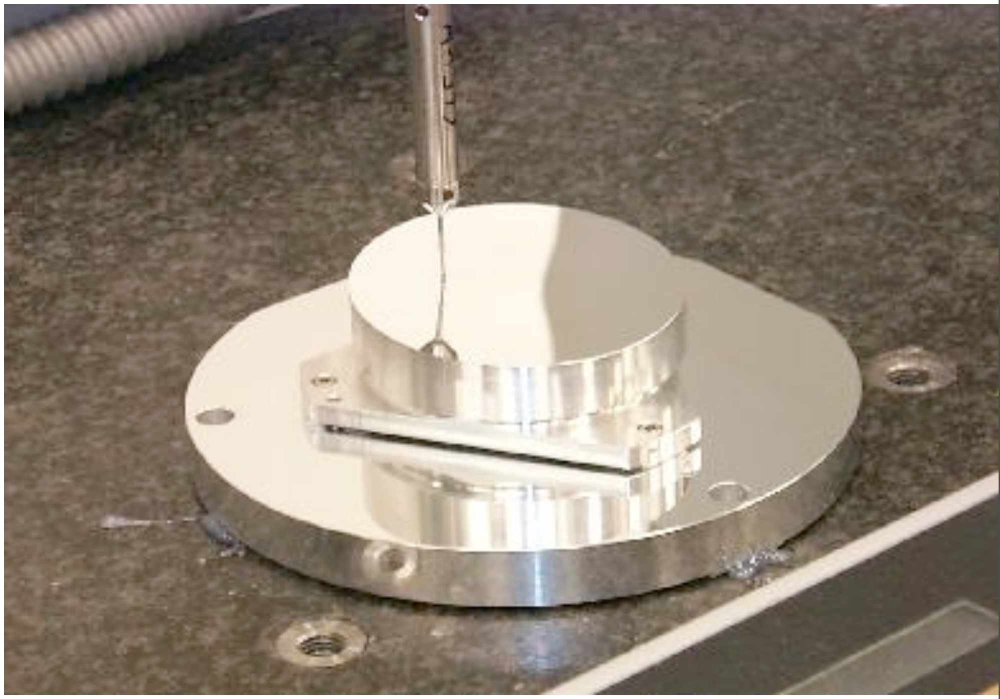



**For Subaru, Lyot Coronagraph with PIAA- apodized input pupil.  IWA ~ 1 lambda/d**

# Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

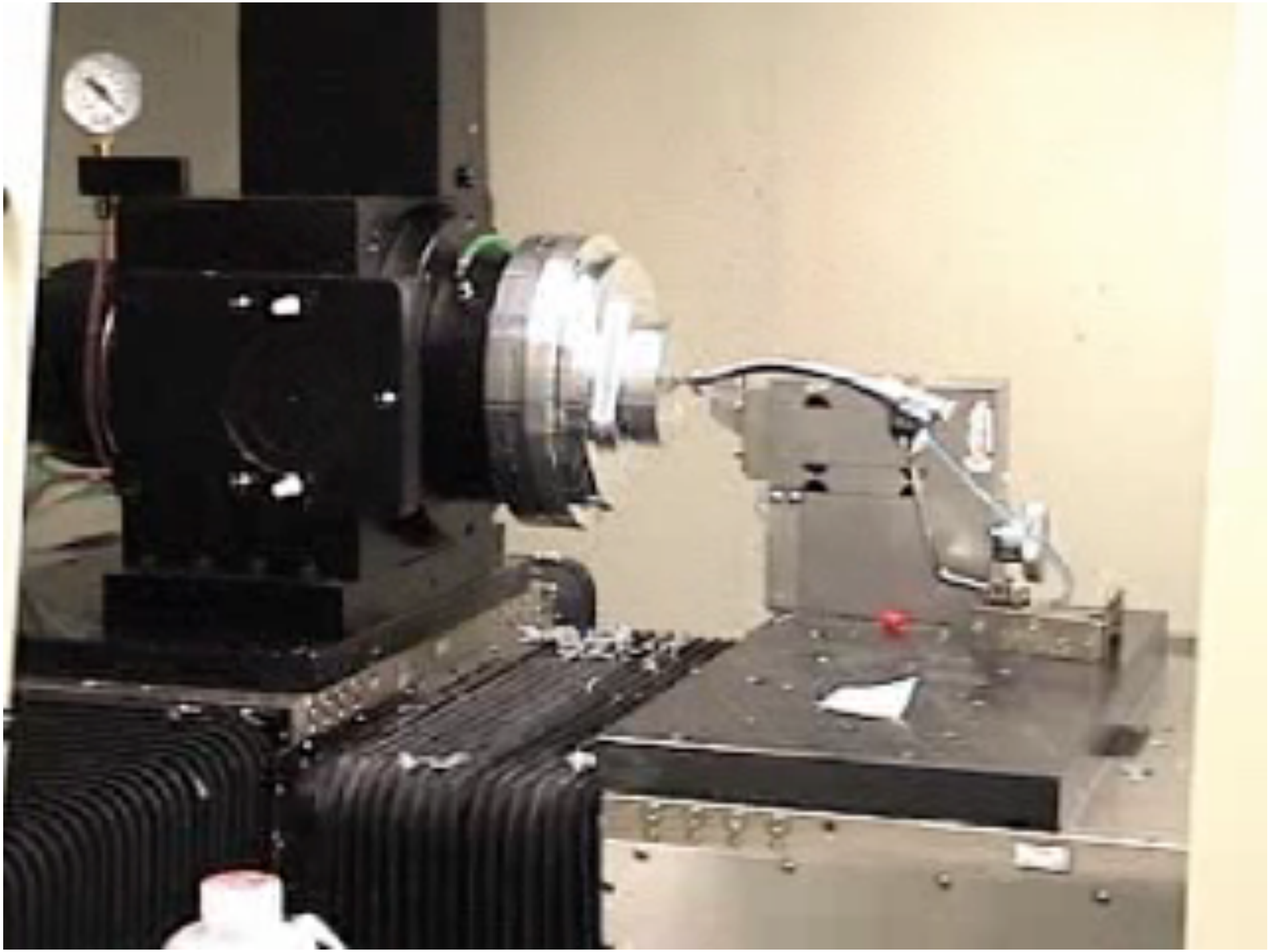
Lossless apodization by aspheric optics.

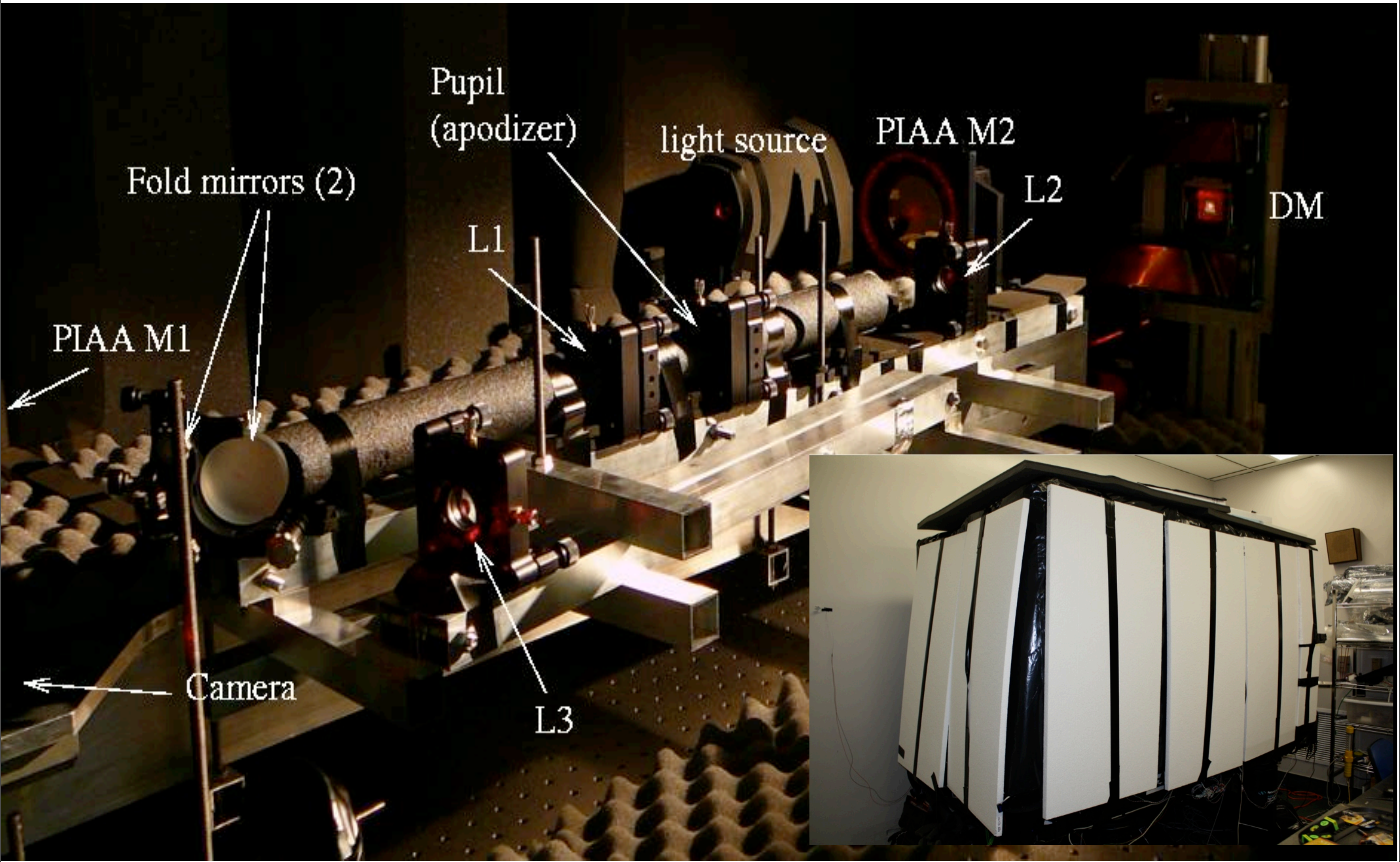


Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

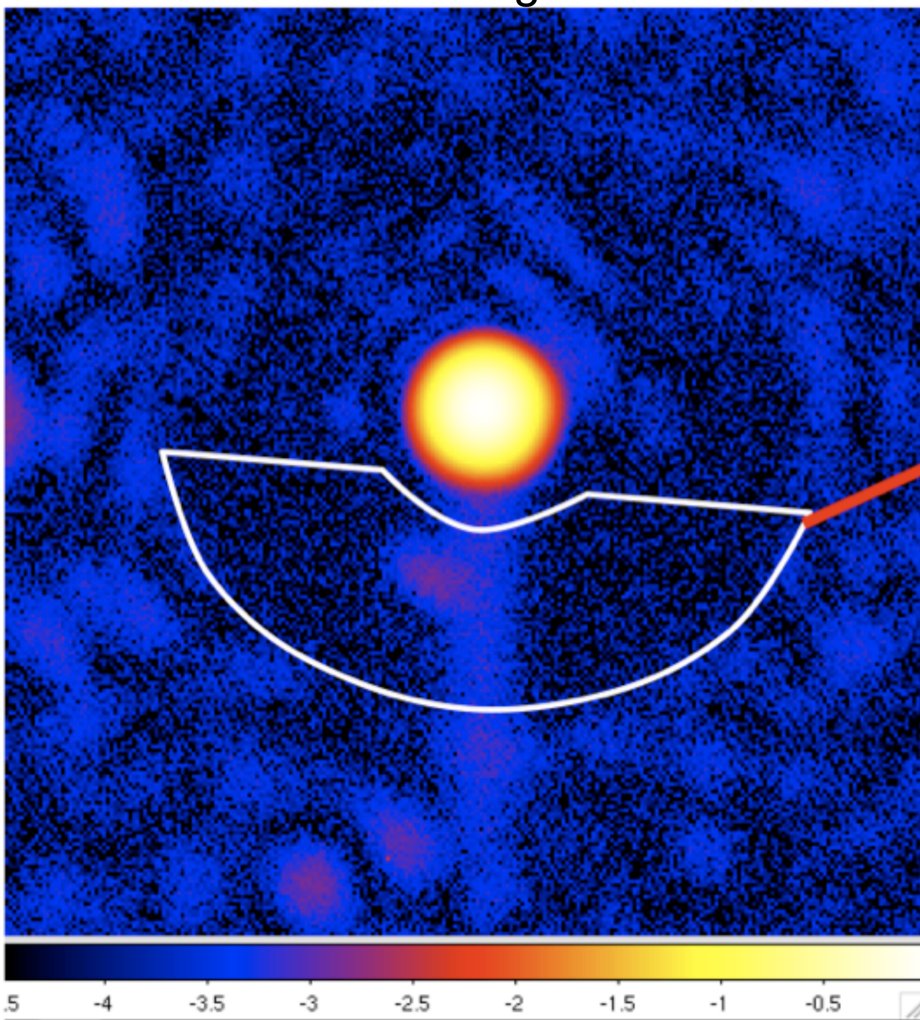
# PIAA optics – Diamond turning



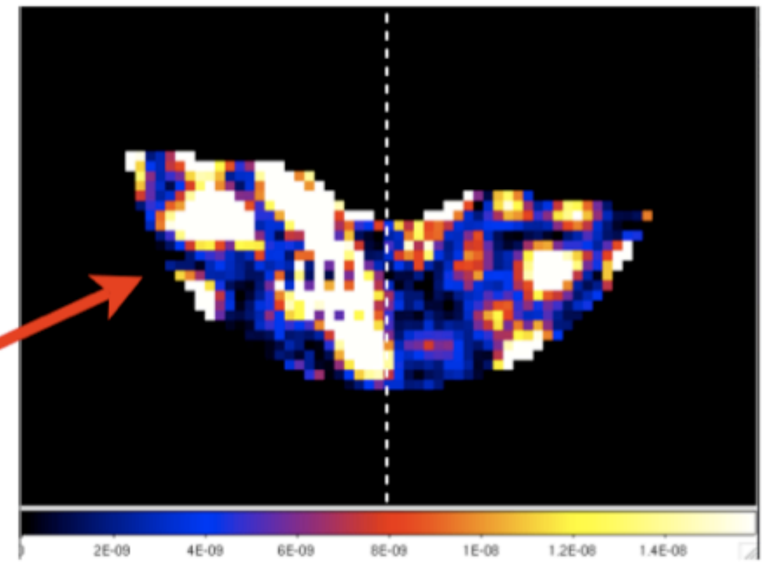

Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

# Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image




Coherent starlight



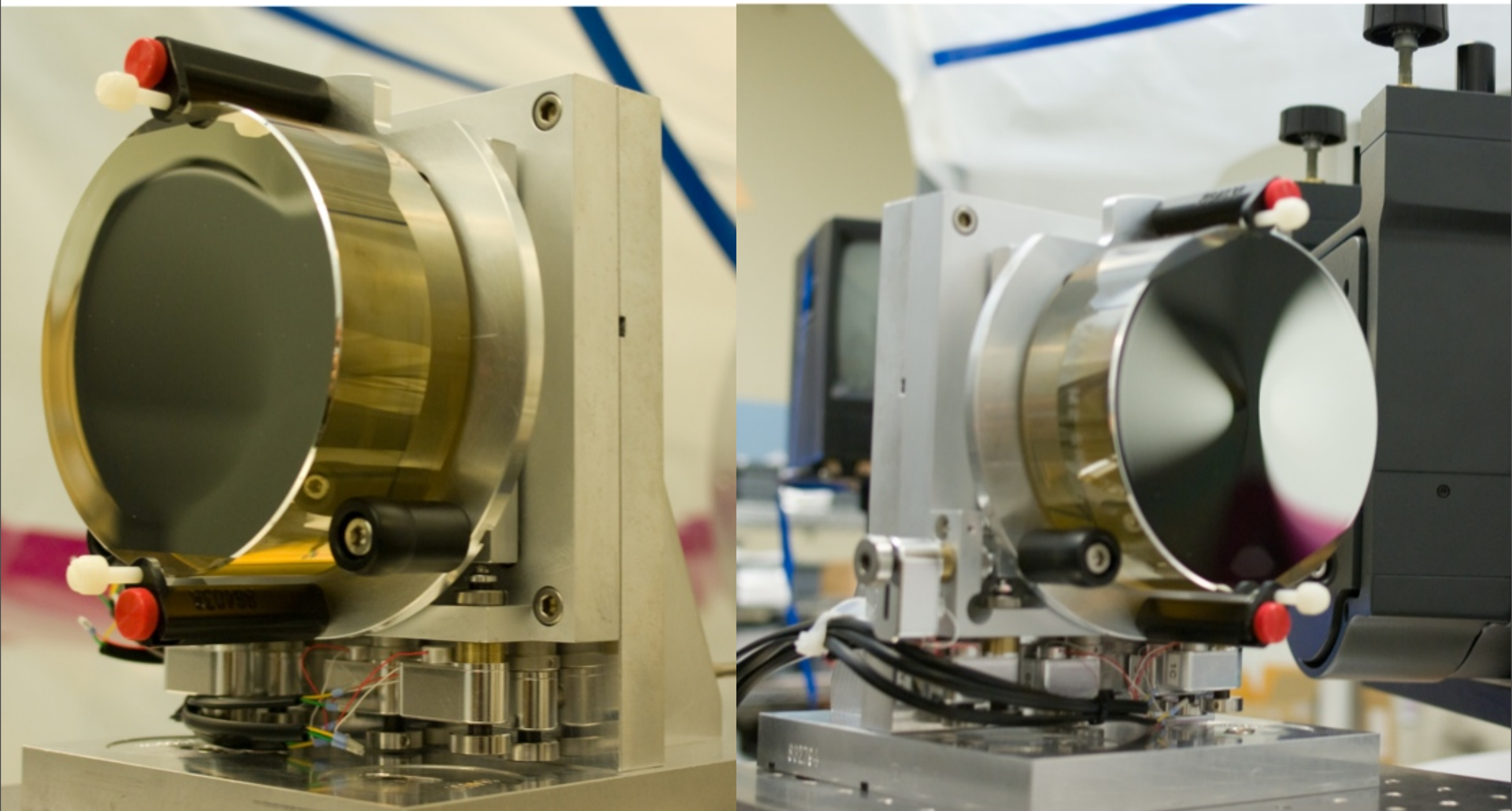

Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

Contrast achieved in 1.6 to 4.5 l/D zone:

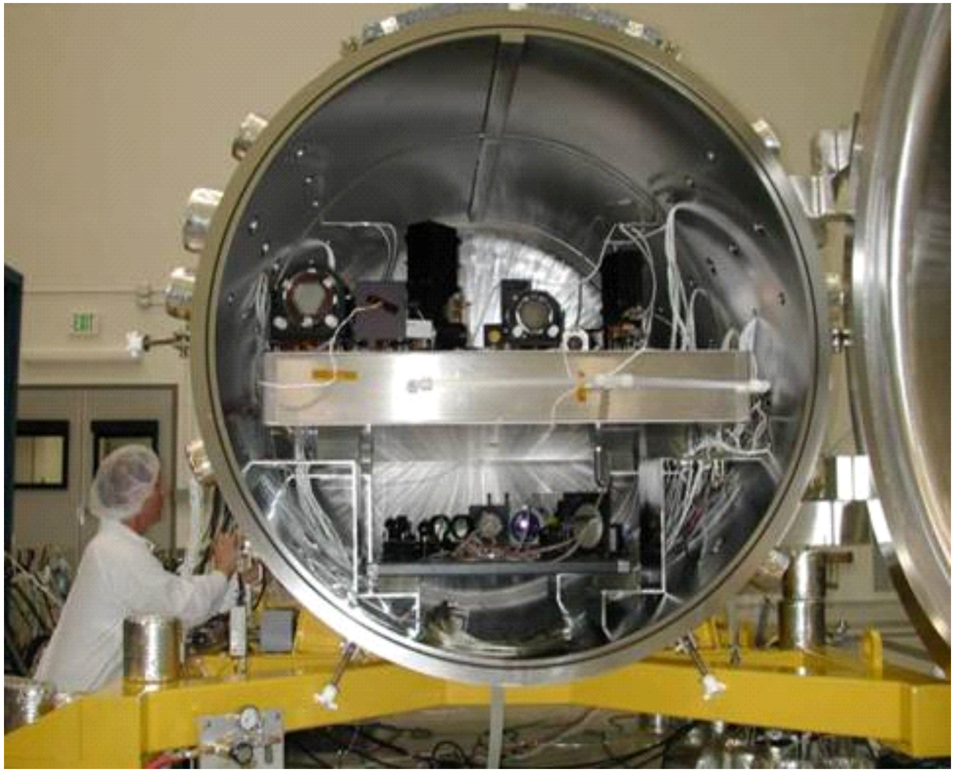
1.5e-7 incoherent halo ghost (equivalent to exozodi)

7e-9 coherent starlight speckles (turbulence, vibrations)

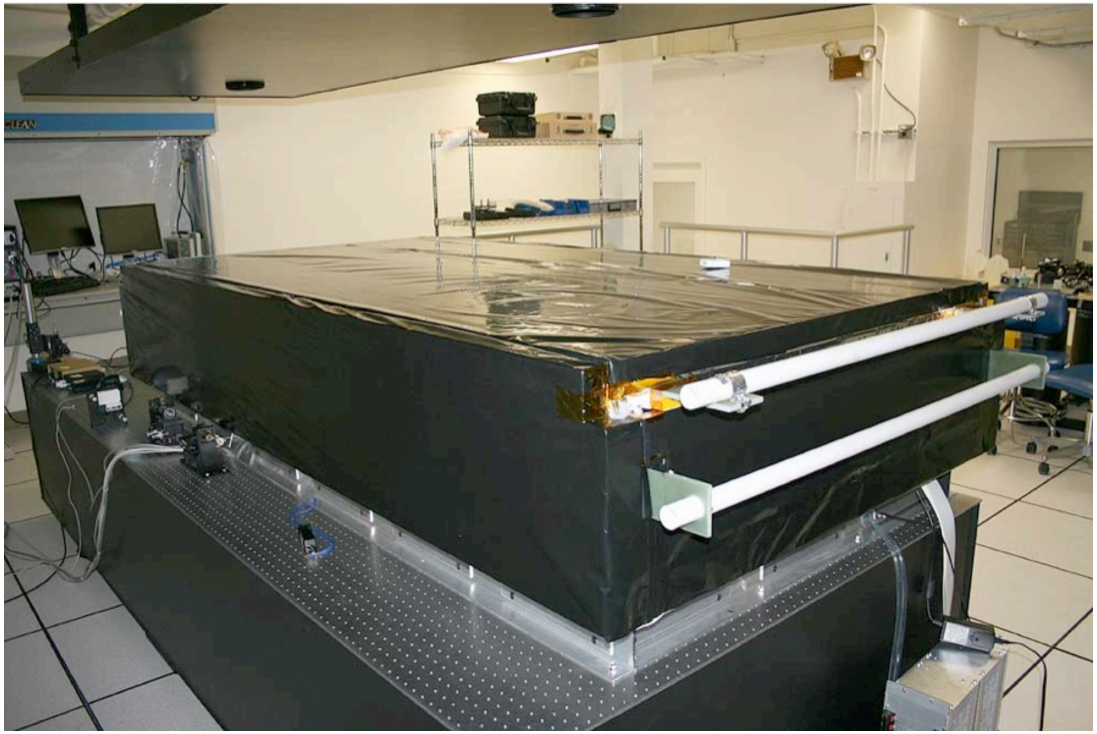
# High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)



2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)



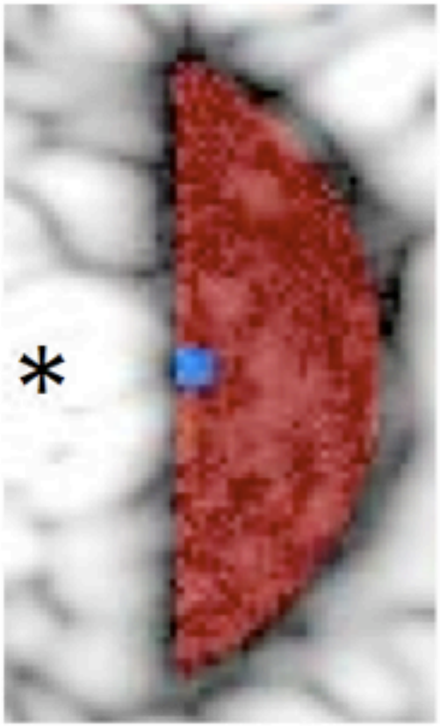
PIAA-dedicated testbed at NASA Ames testing WFC architectures & MEMs DMs.

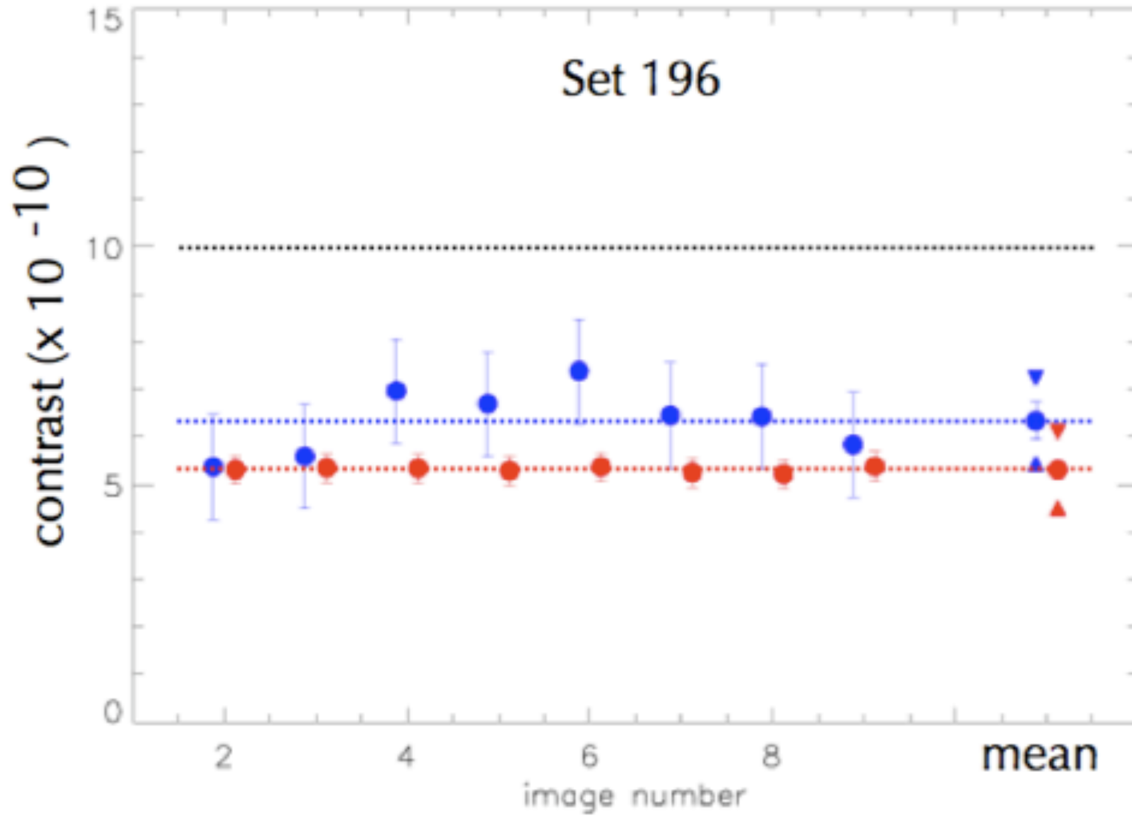


Coronagraph labs in:
- NASA JPL (vacuum)
- NASA Ames
- Princeton Univ.
- Subaru Telescope
- Japan/ISAS (vacuum)

# Vacuum tests at NASA JPL have reached close to 1e-10 contrast at 4 l/D with band-limited masks

*"Classical" speckle nulling with the HCIT*

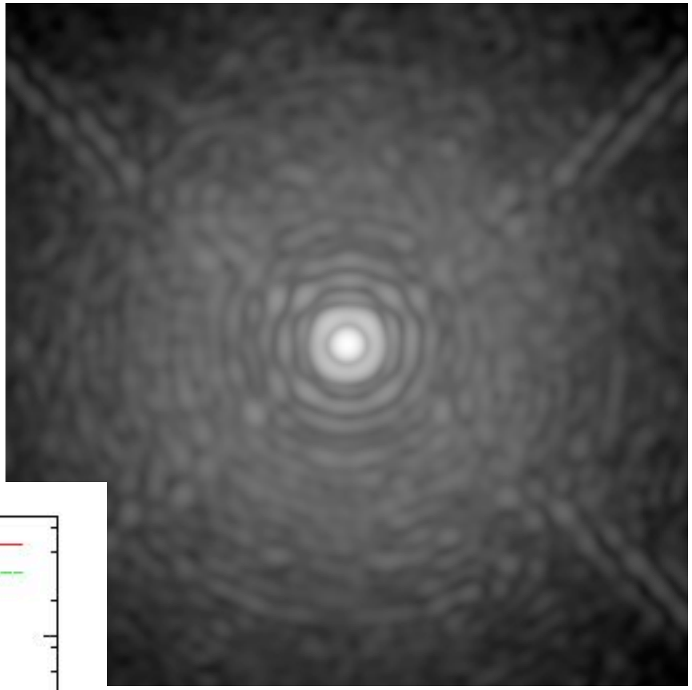


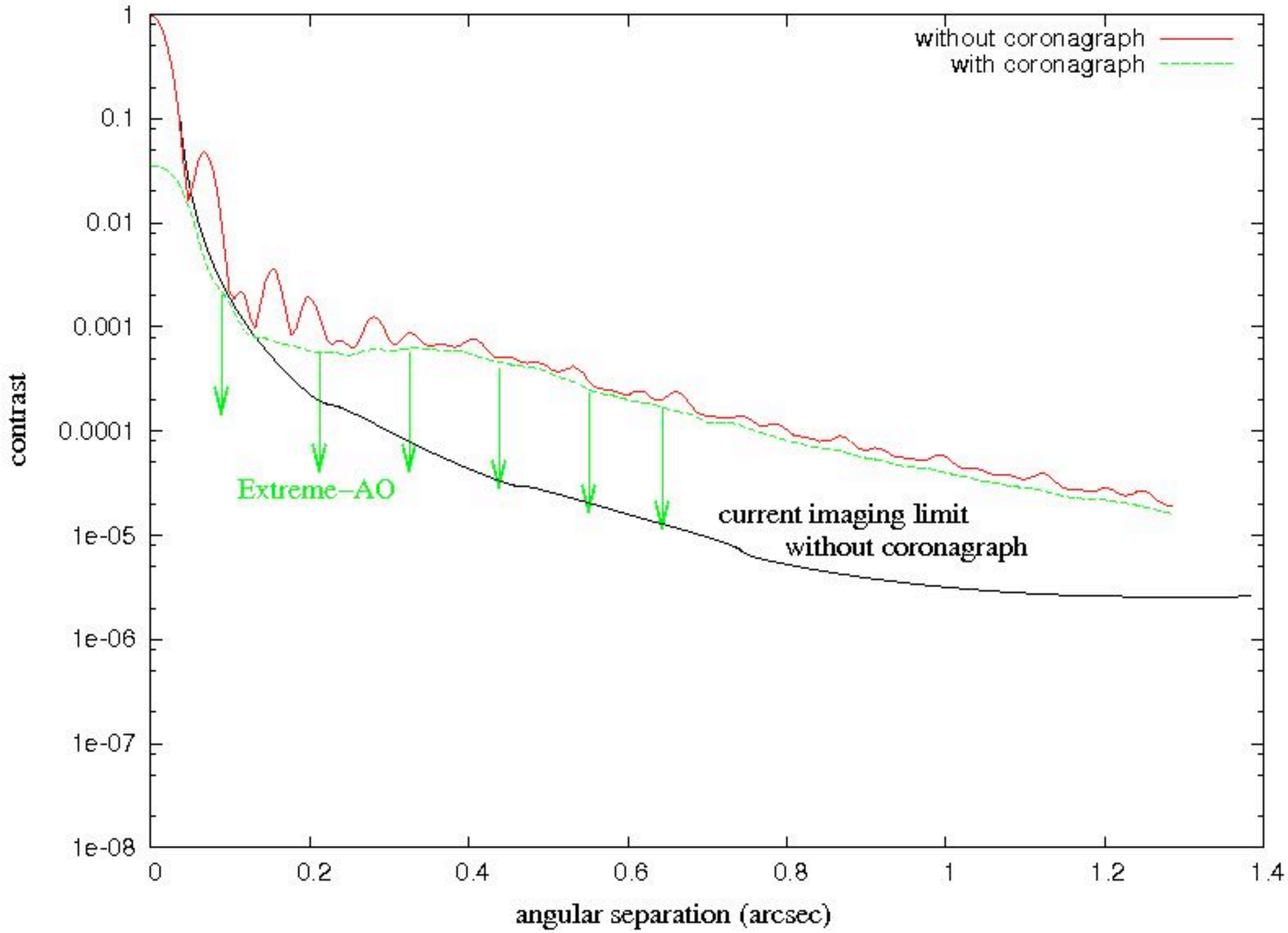




Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. 1-σ error bars indicate the measurement noise estimated from pairwise data.

# Wavefront control for coronagraphy

- None of the recent ground-based planet discoveries has been done with coronagraph
- With current Telescopes+AO systems, coronagraphs offer almost no help beyond ~0.3” in H band
- PSF calibration with coronagraphs is more complicated






**ExAO systems currently under construction improve contrast with AO + coronagraphy**

# Wavefront Sensor Options...

**Linear, large dynamical range, poor sensitivity:**
Shack-Hartmann (SH)
Curvature (Curv)
Modulated Pyramid (MPyr)

**Linear, small dynamical range, high sensitivity:**
Fixed Pyramid (FPyr)
Zernike phase constrast mask (ZPM)
Pupil plane Mach-Zehnder interferometer (PPMZ)

**Non-linear, moderate to large dynamical range, high sensitivity:**
Focal Plane (FP)
Non-linear Curvature (nlCurv)
Non-linear Pyramid (nlPyr) ?

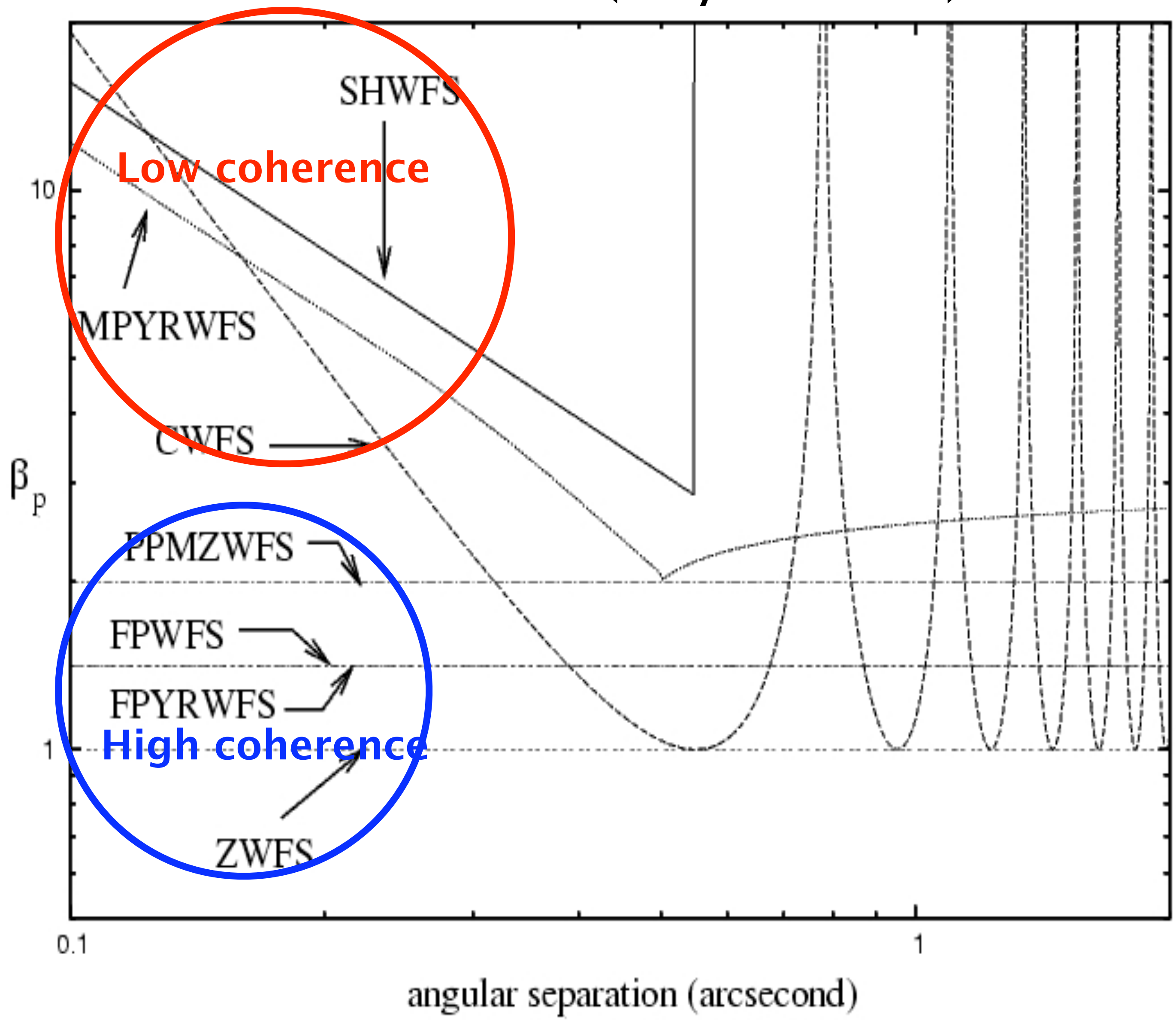
| | sensitivity | range | Extended target ? (LGS) | chromaticity | maturity | detector use |
|---|---|---|---|---|---|---|
| **SH** | serious noise propagation | Very good | Yes | Low | on sky | at least 4 pixels per subaperture |
| **Curvature** | serious noise propagation | Very good | Somewhat LGS OK | Low | on sky | 1 pix/subaperture 2 reads |
| **Pyramid (modulated)** | noise propagation | very good | Somewhat LGS OK | Low | on sky | 4 pix/subaperture |
| **Pyramid (fixed)** | Excellent | limited to < 1 rad in closed loop | No | Low | closed loop lab AO w turbulence | 4 pix/subaperture |
| Zernike phase contrast | Excellent | limited to < 1 rad in closed loop | No | mask manufacturing | ? | 1 pix/subaperture |
| Mach-Zehnder | Excellent | limited to < 1 rad in closed loop | No | low if near zero OPD | ? | 2 pix/subaperture |
| **Focal plane** | Excellent | Good, can have > 1 rad error, but needs coherence | No | serious | closed loop lab AO no turbulence | 4 pix/speckle |
| **Non-linear curvature** | Excellent | Good, can have > 1 rad error, but needs coherence | No | Low | in lab with no turbulence | 4 pix/subaperture |

**Good range/linearity but poor sensitivity**

**Good sensitivity over a small range**

**Non-linear reconstruction algorithm allows good sensitivity and larger range**

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

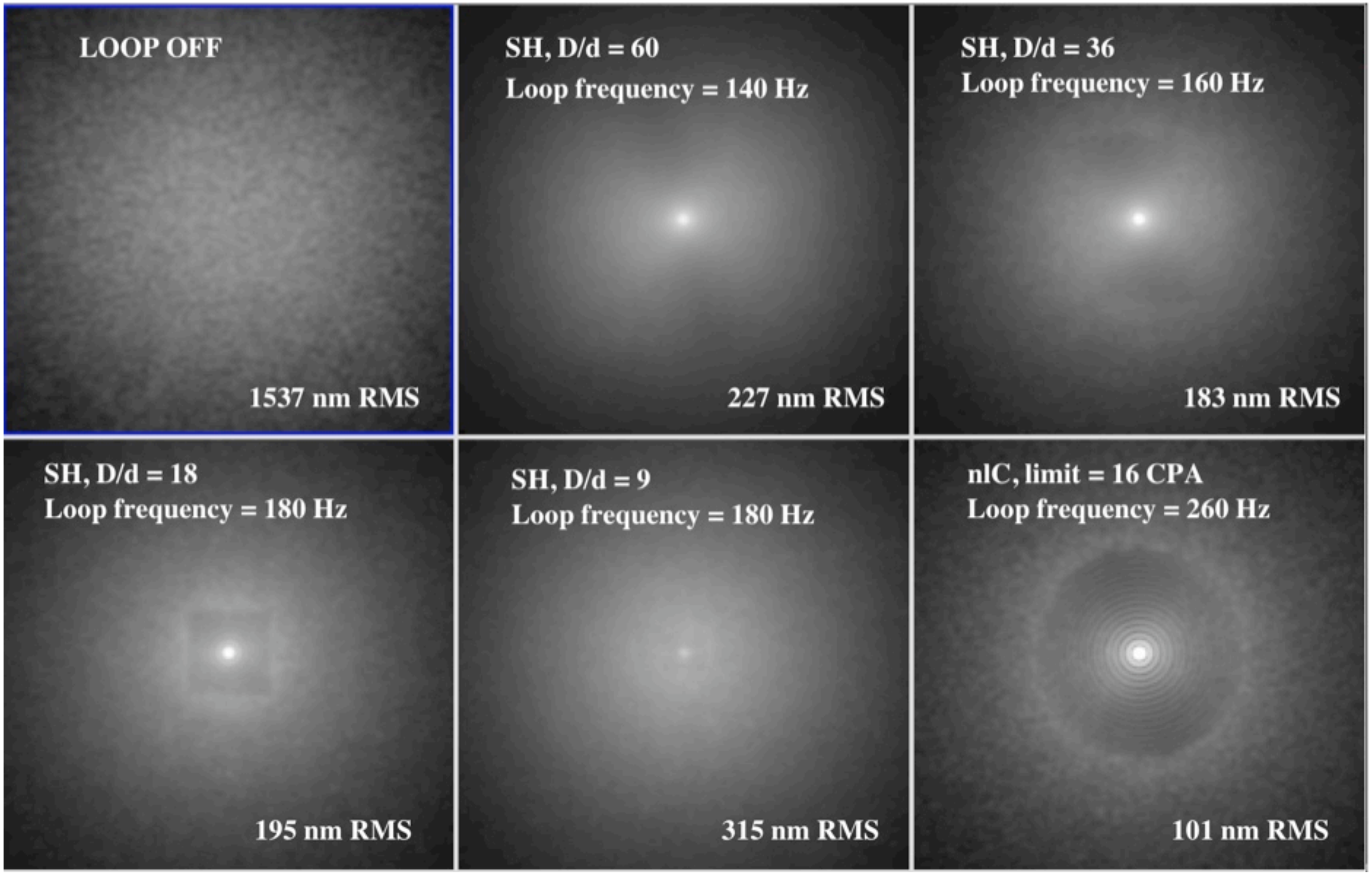



Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for 0.5” separation.

Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

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% |

# Pointing control demonstrated to 1e-3 l/D at Subaru PIAA testbed

LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes.
Subaru Testbed has demonstrated closed loop pointing control to 1e-3 l/D ~ 0.1 mas on 1.4m PECO.
ref: Guyon, Matsuo, Angel 2009

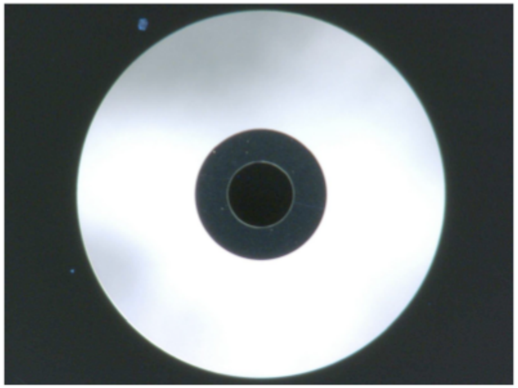


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

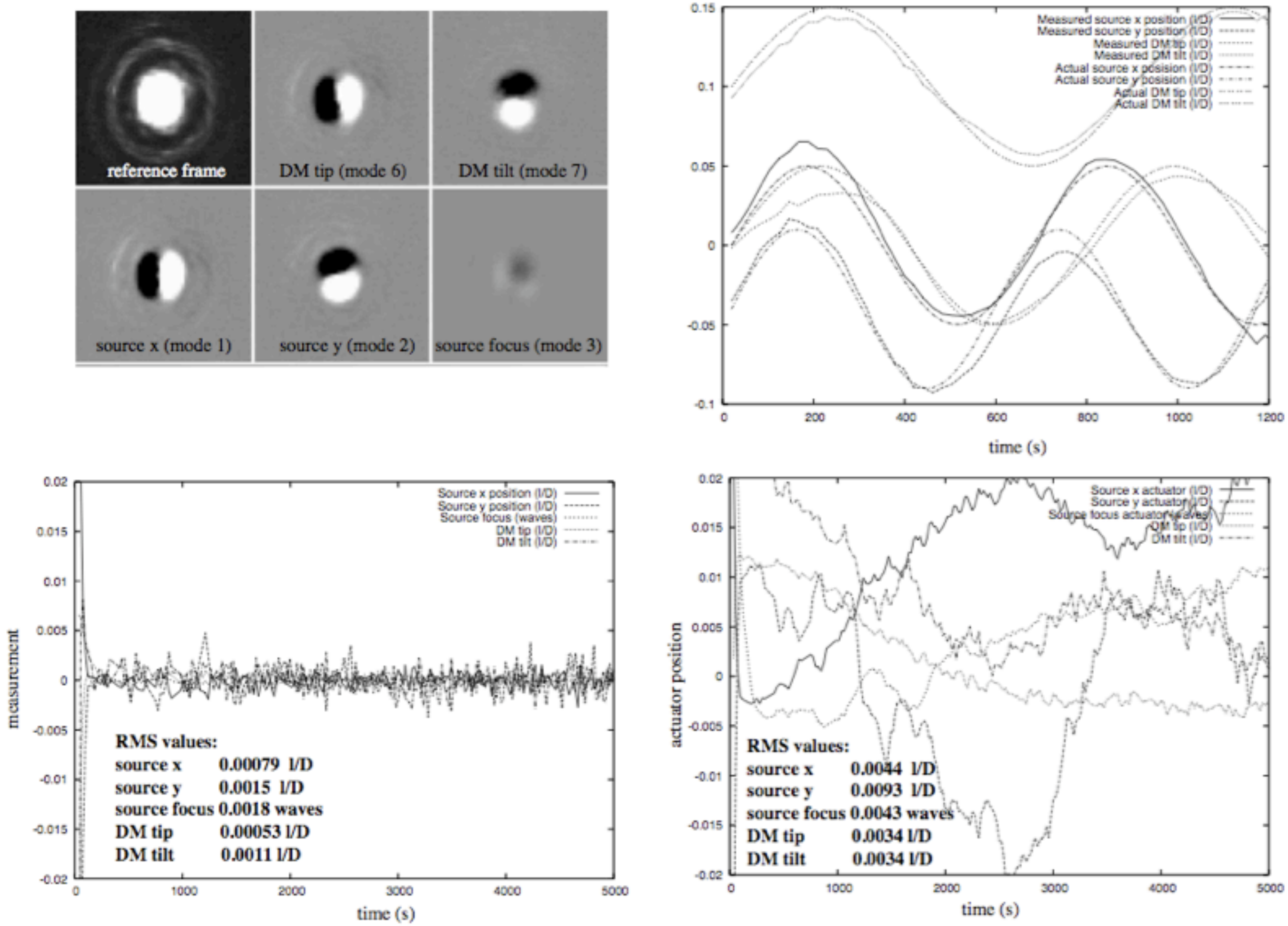
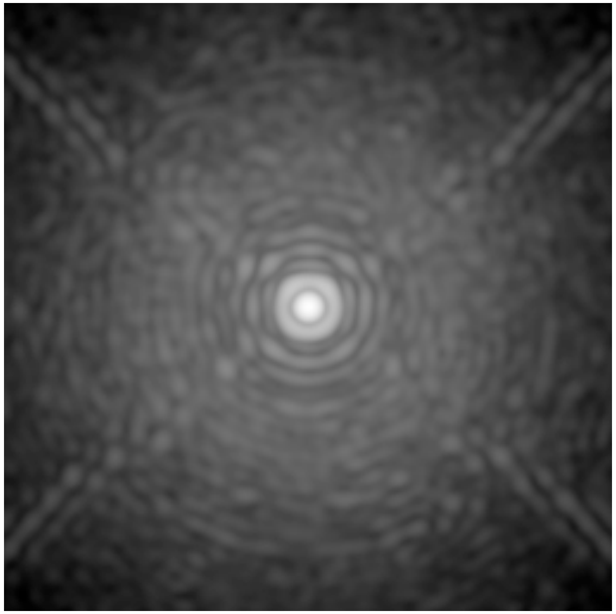



Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about $10^{-3}$ $\lambda/D$ for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

# Focal plane Wavefront Sensing & calibration

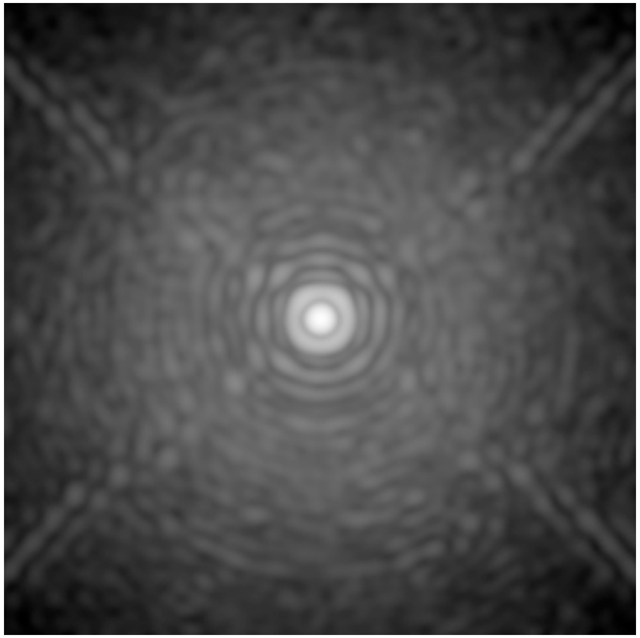
# Is is a Speckle, is it a planet ?



**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)

# Focal plane wavefront sensing and calibration



Use Deformable Mirror (DM) to add speckles

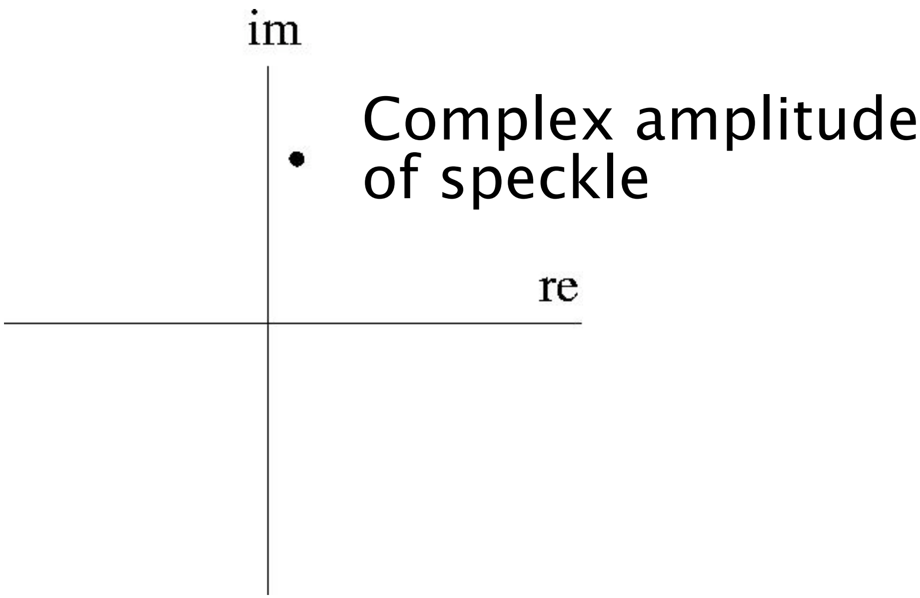
<u>CORRECTION</u>: Put "anti speckles" on top of "speckles" to have destructive interference between the two

<u>SENSING</u>: Put "test speckles" to measure speckles in the image, watch how they interfere

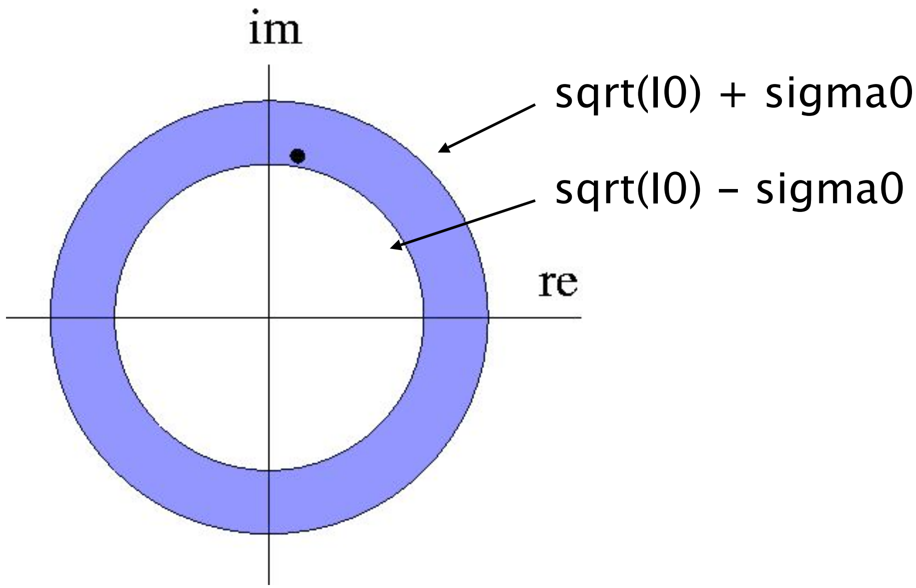
<u>CALIBRATION</u>: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed"

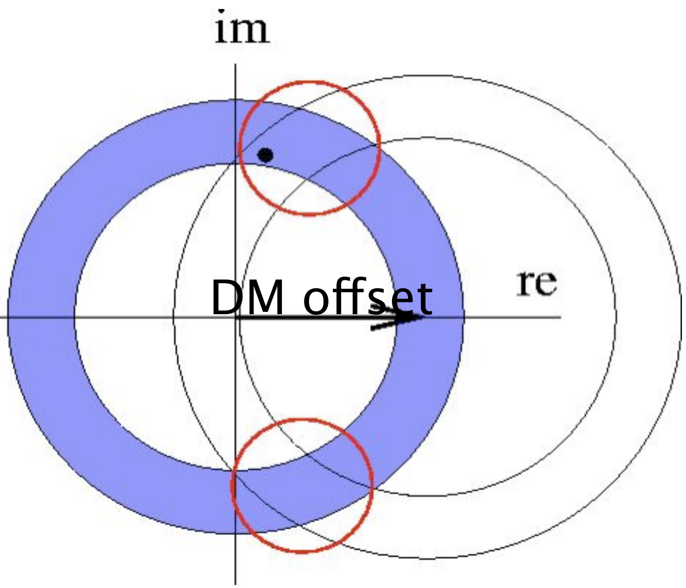
## Initial problem

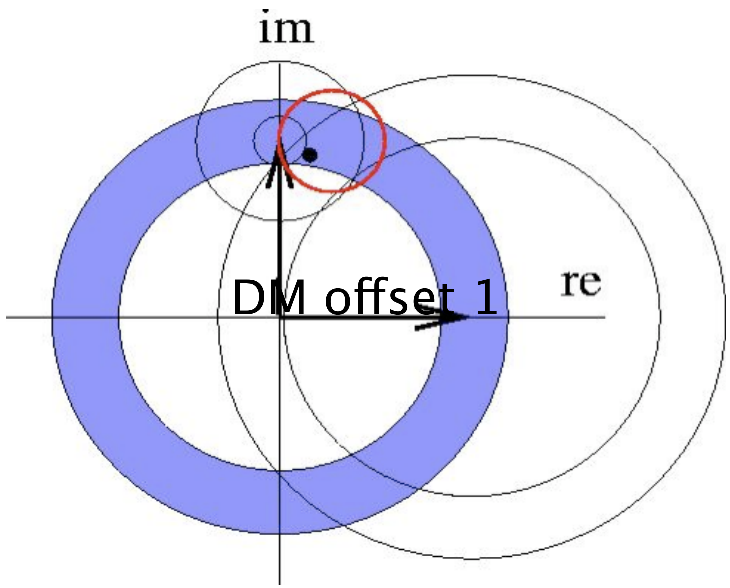



## Take a frame -> measured speckle intensity = I0

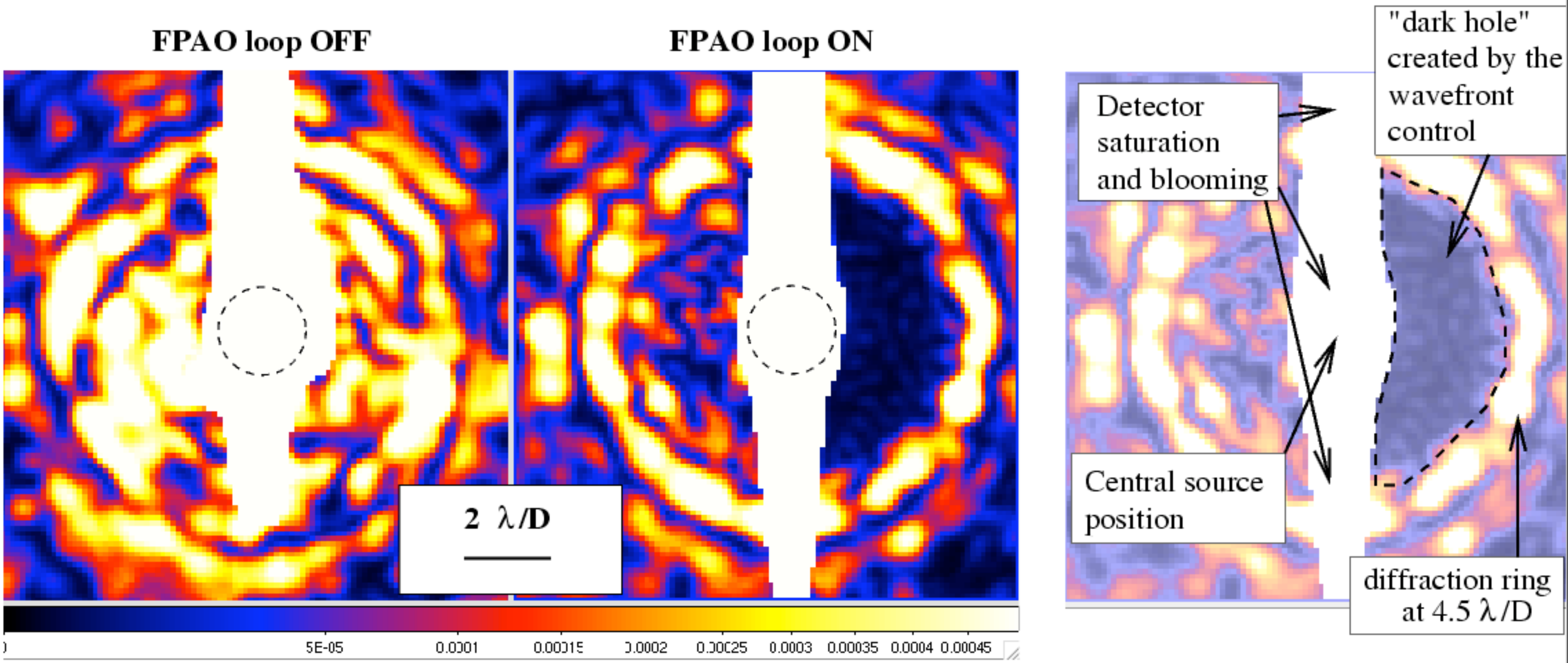



DM offset chosen to be ~ equal to speckle amplitude



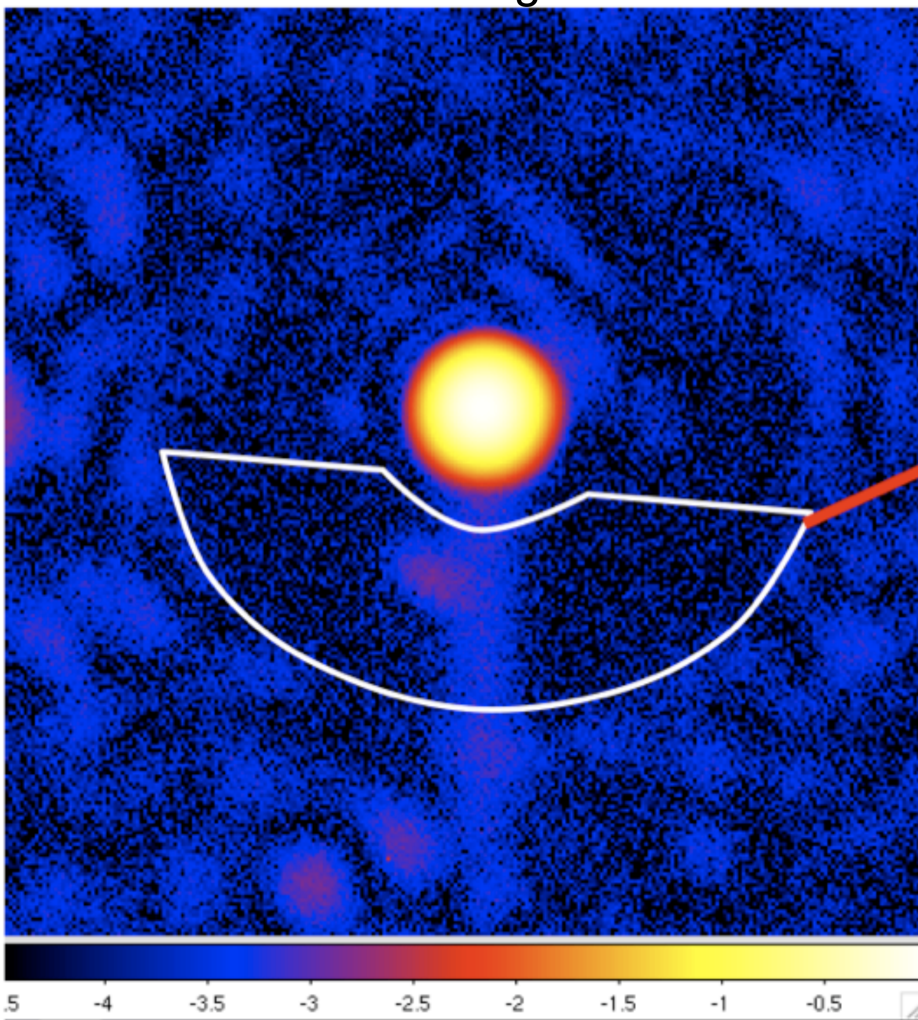



# Subaru Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

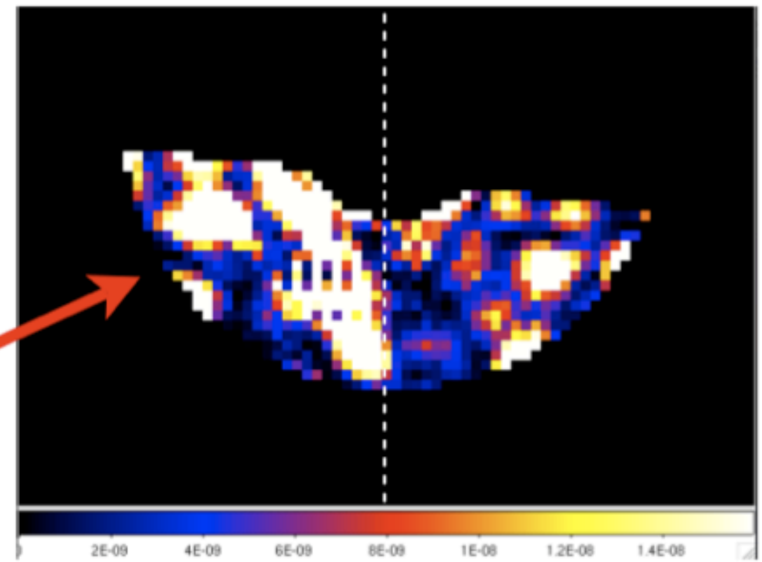


# Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image




Coherent starlight



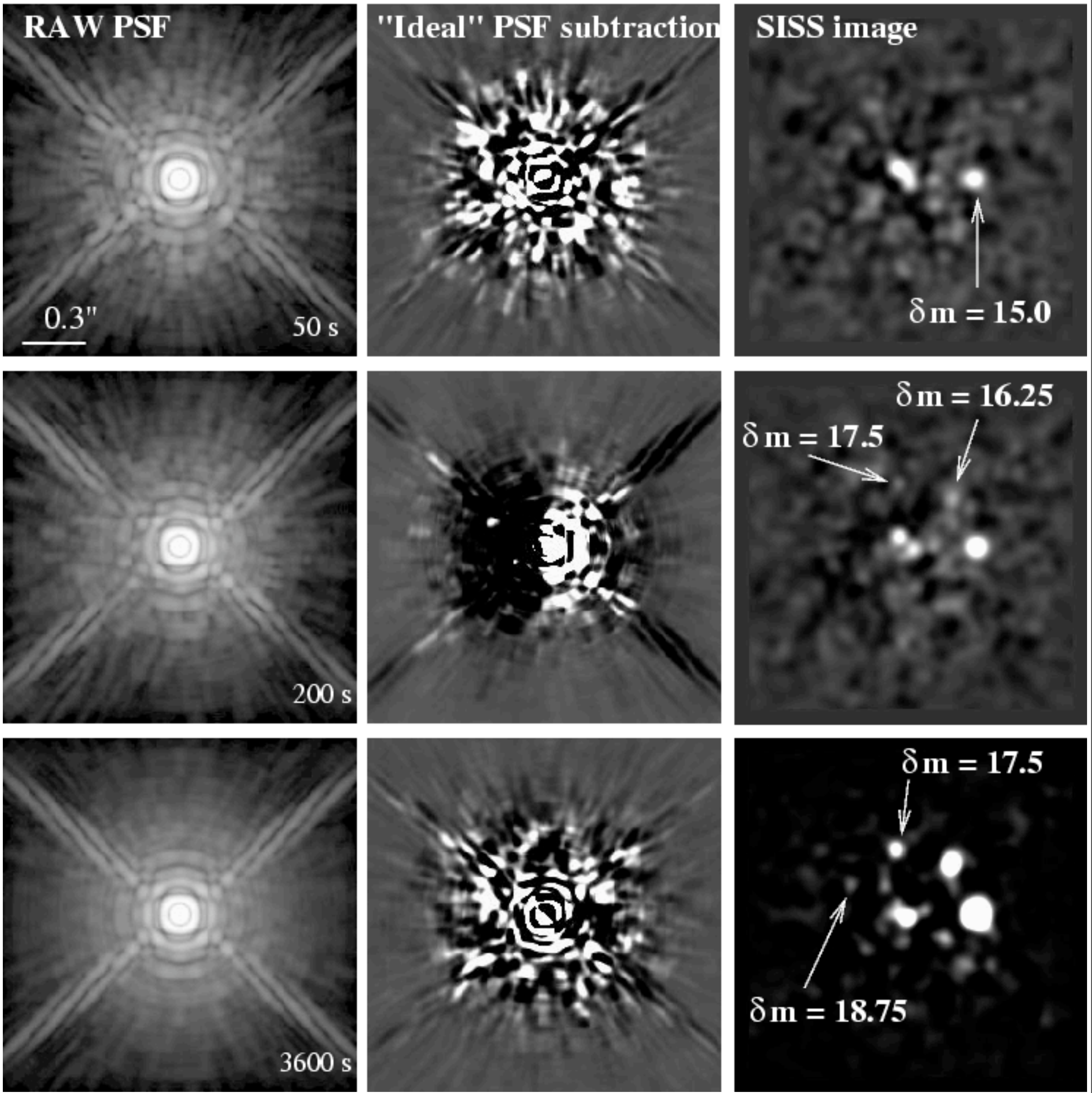

Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

Contrast achieved in 1.6 to 4.5 l/D zone:

1.5e-7 incoherent halo ghost (equivalent to exozodi)

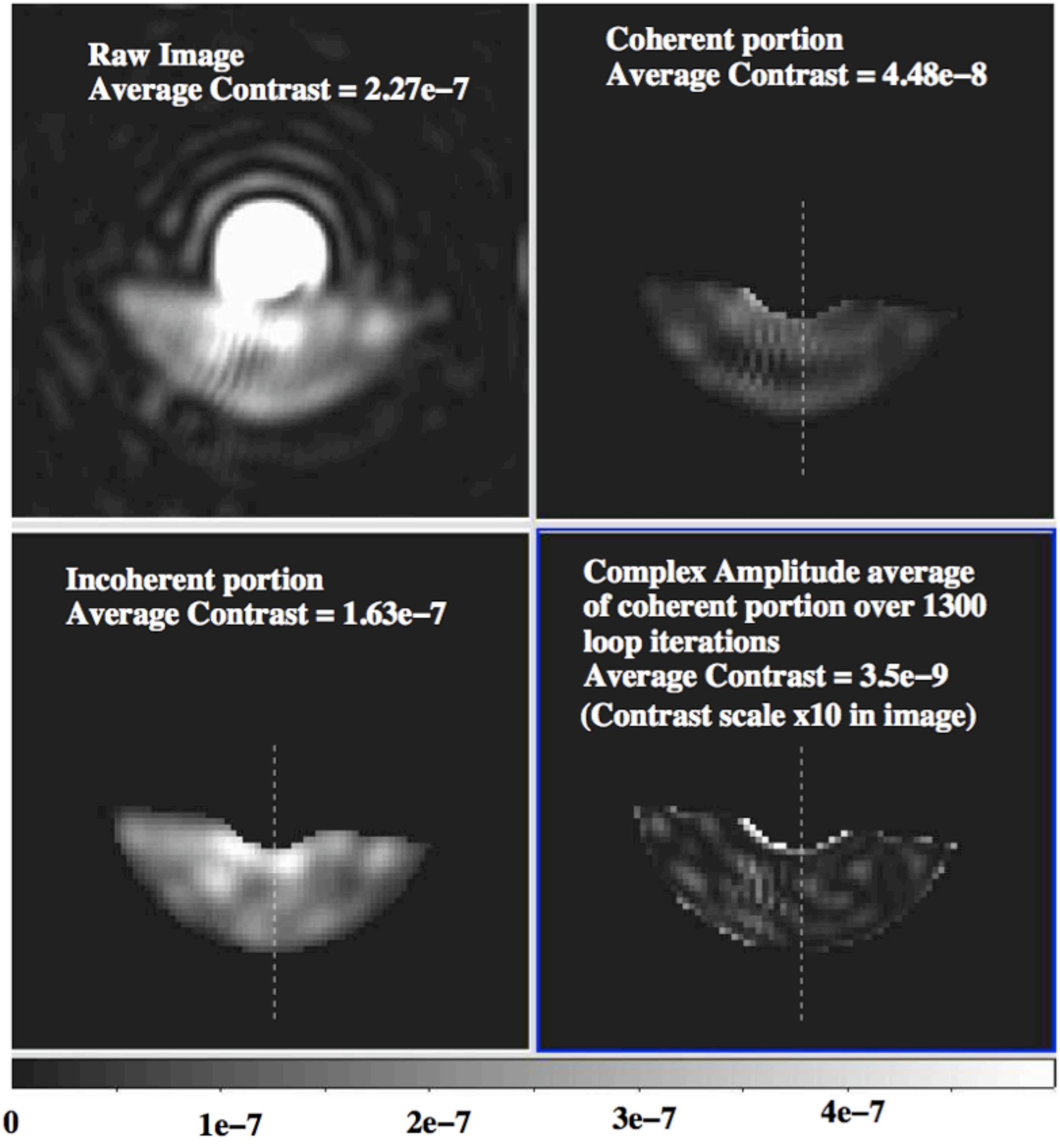
7e-9 coherent starlight speckles (turbulence, vibrations)

Speckle calibration with active coherent modulation



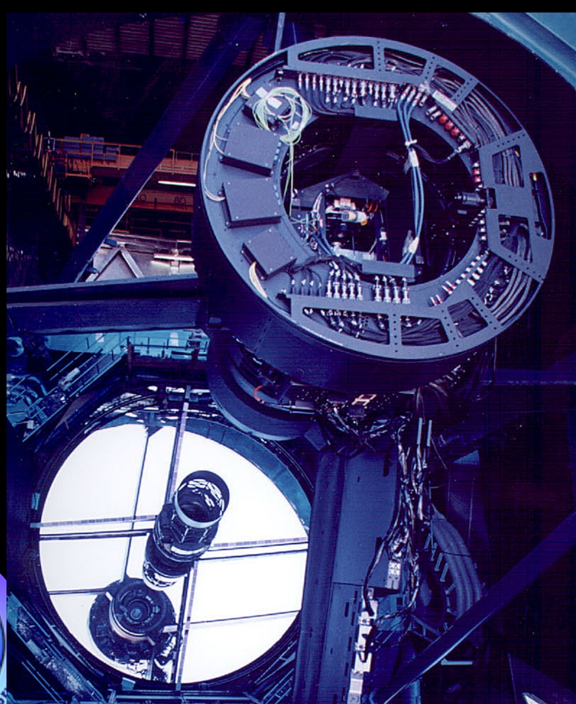
Coherent detection works in the lab alongside FPAO

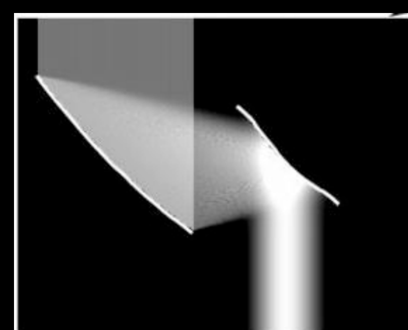
Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the fly diagnostics
- CDI post-processing

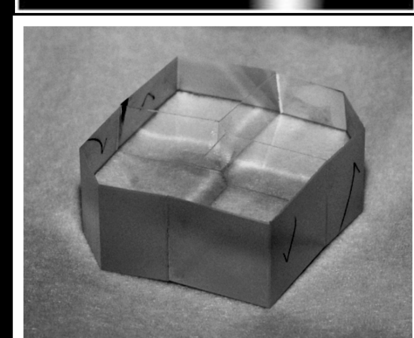


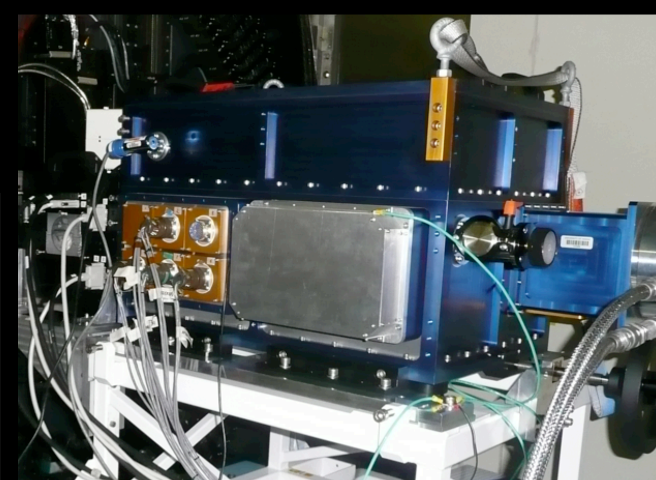
# The Subaru Coronagraphic Extreme AO Project (SCExAO)

Olivier Guyon, Frantz Martinache,
Julien Lozi, Vincent Garrel

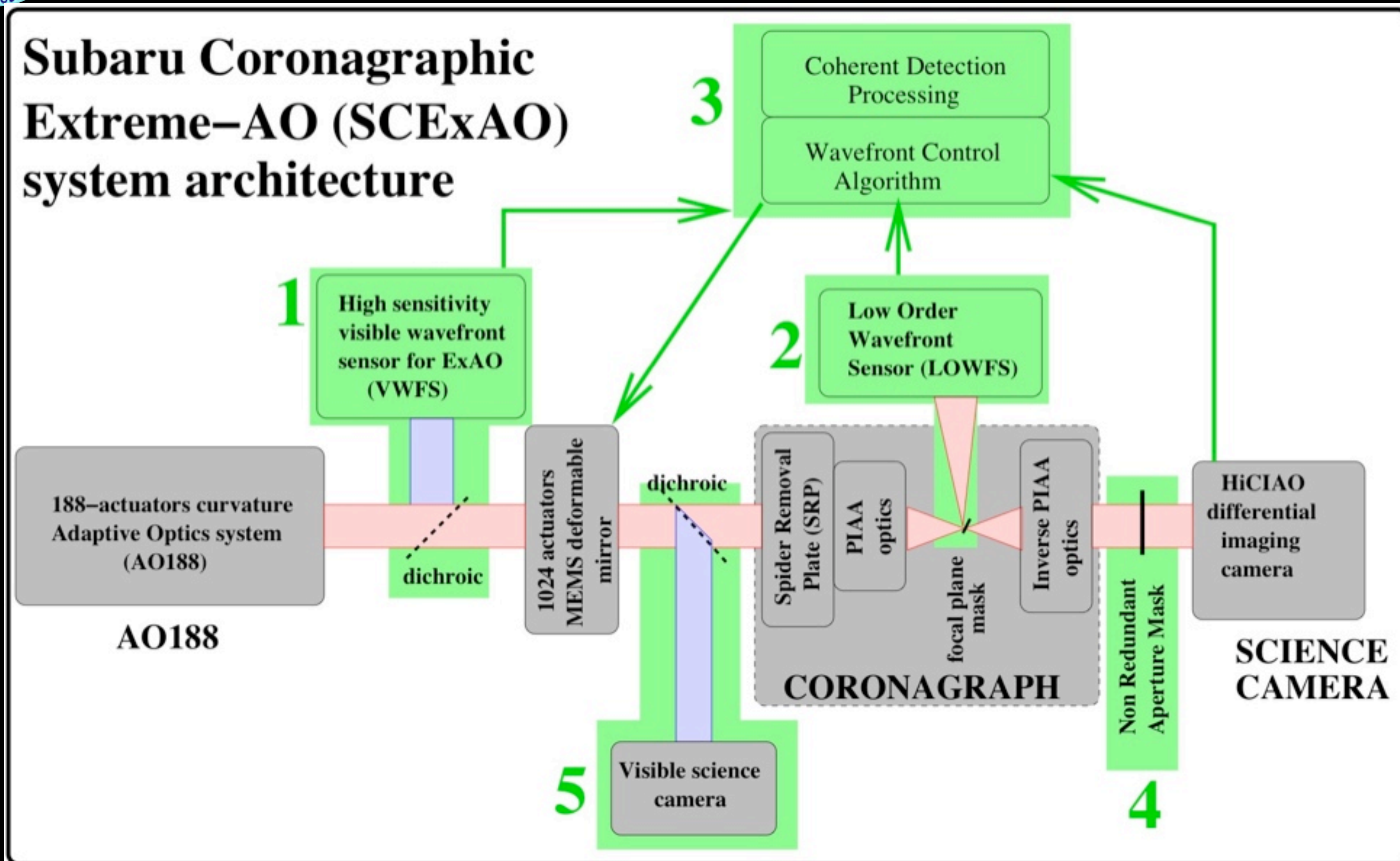




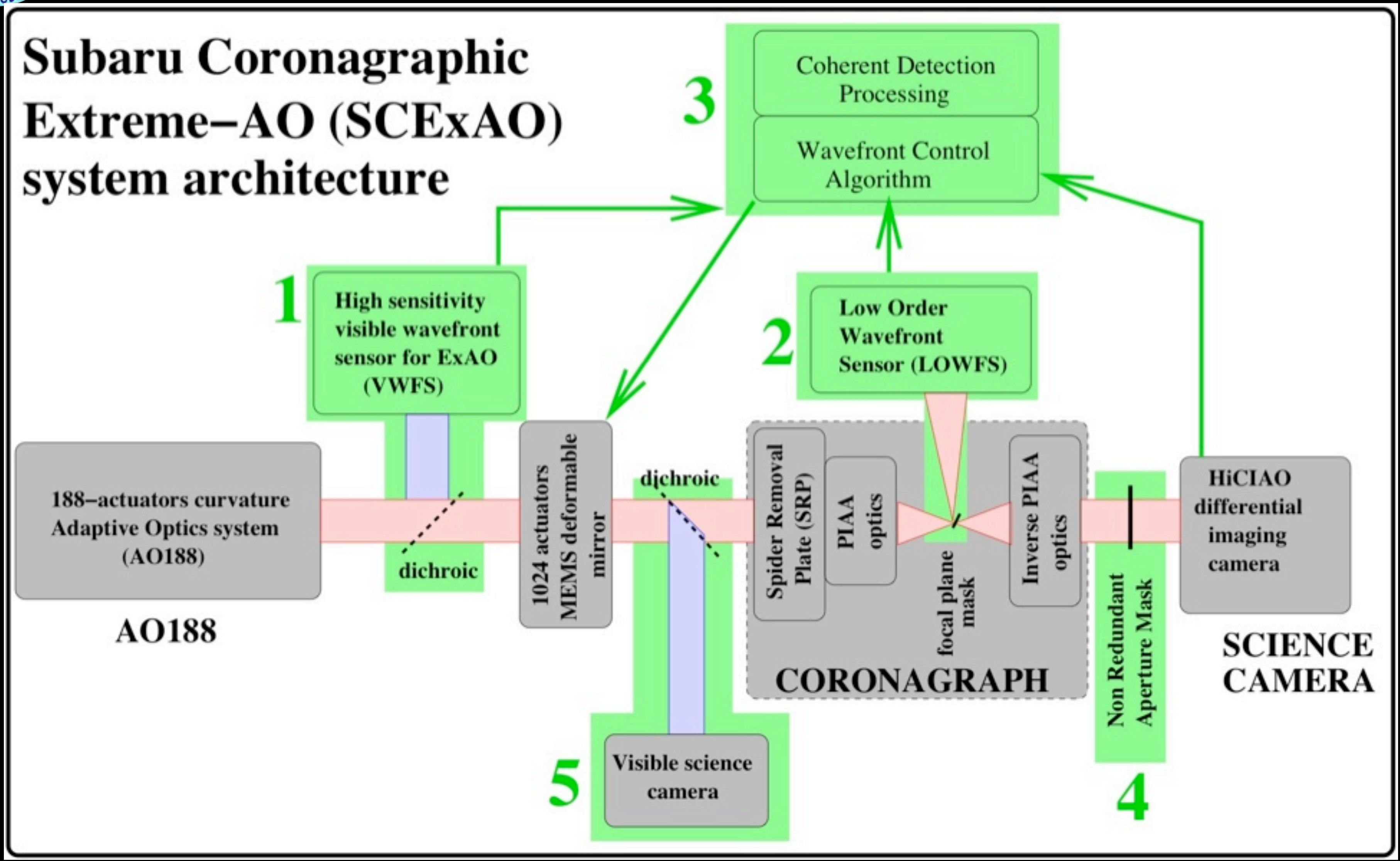




# System architecture



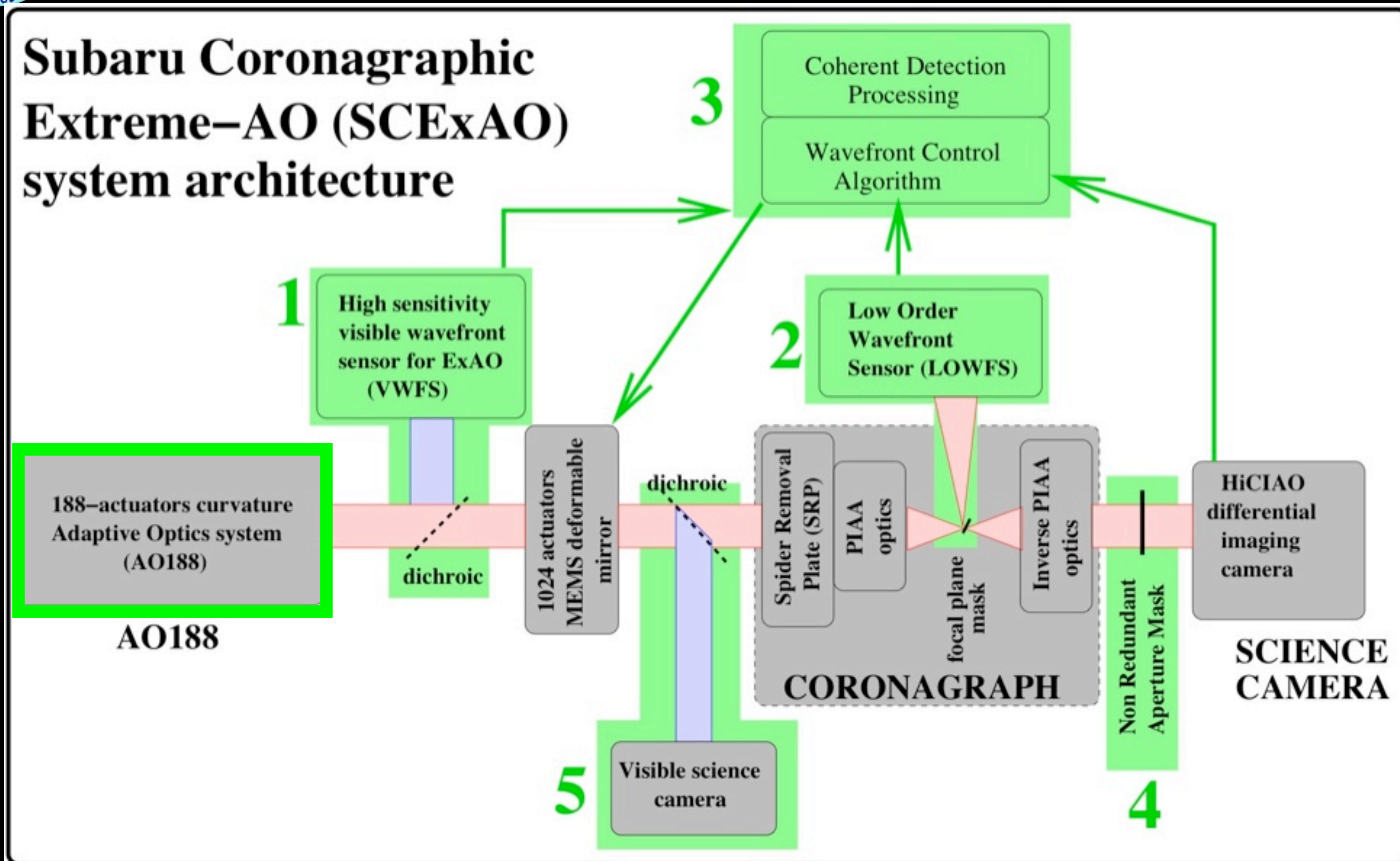
# System architecture




Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

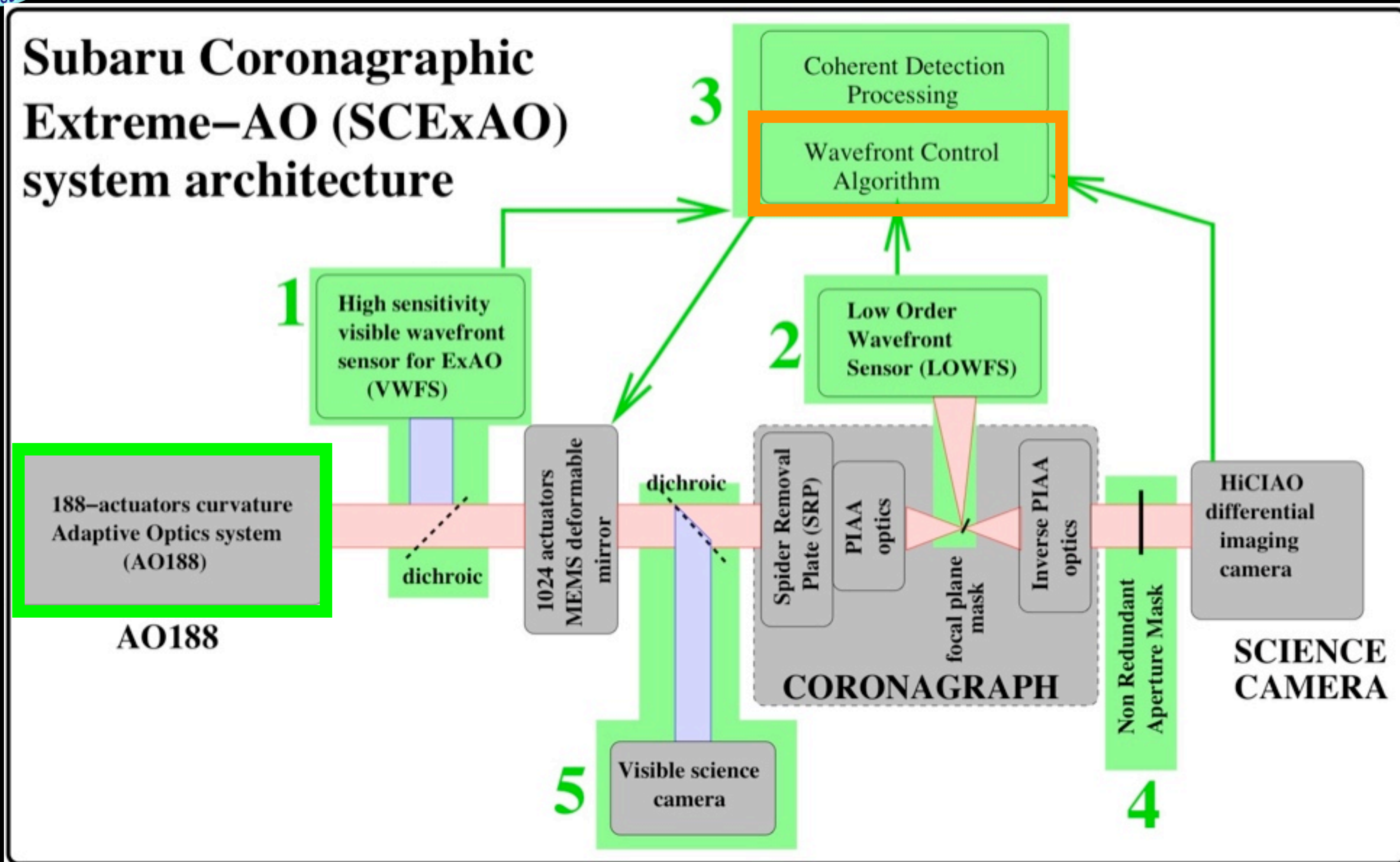
# System architecture




Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

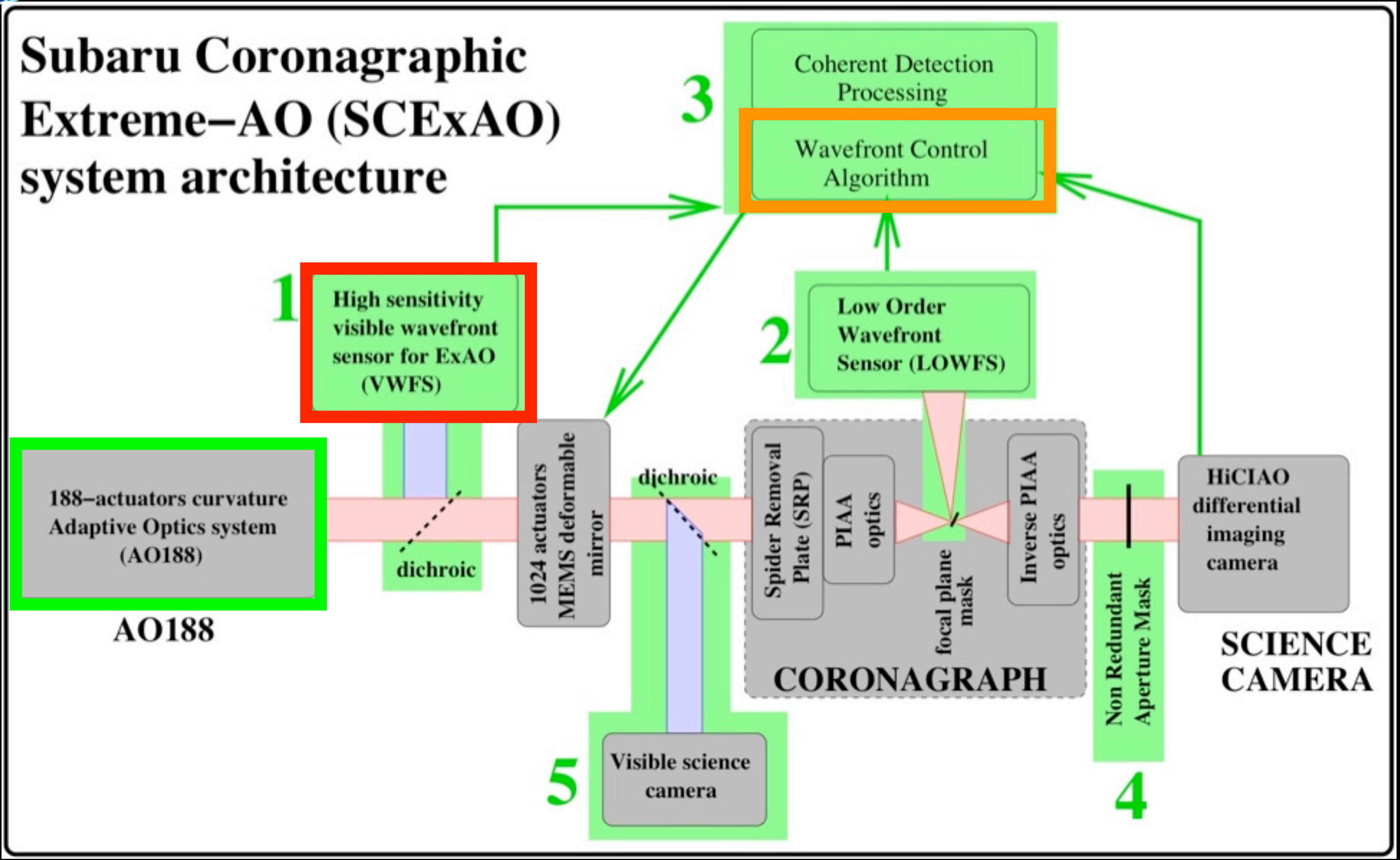
# System architecture




Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

# System architecture

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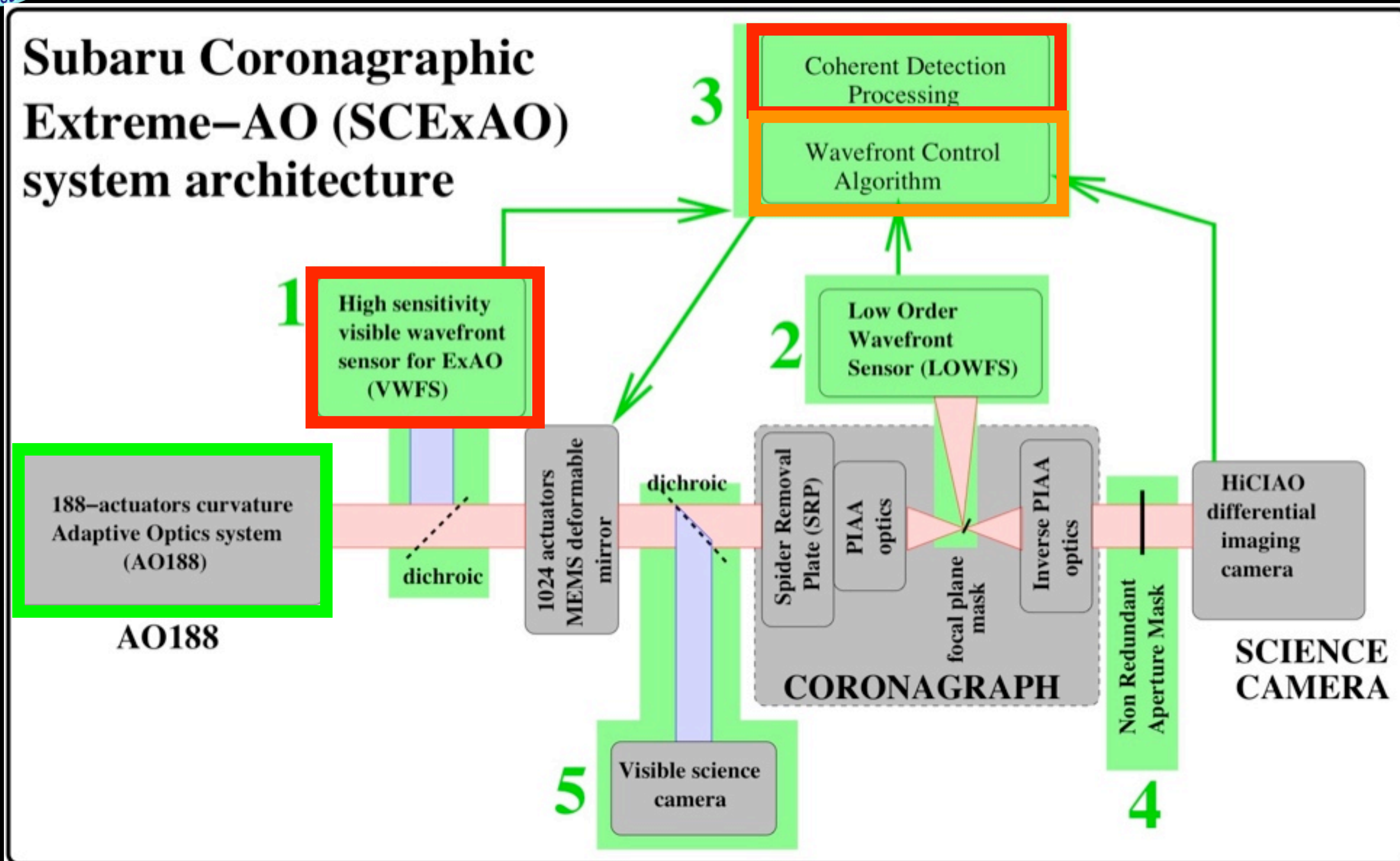
# System architecture

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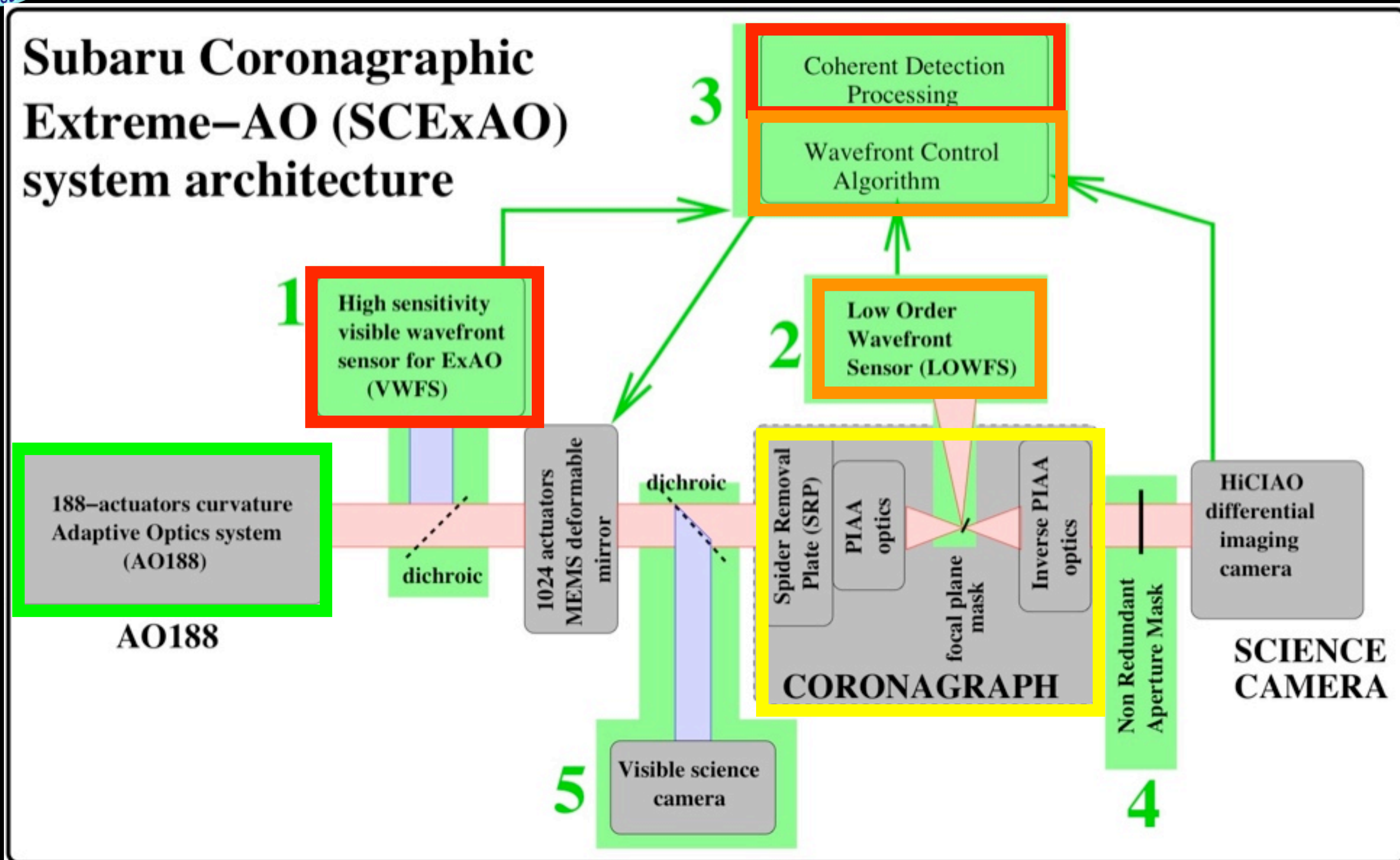
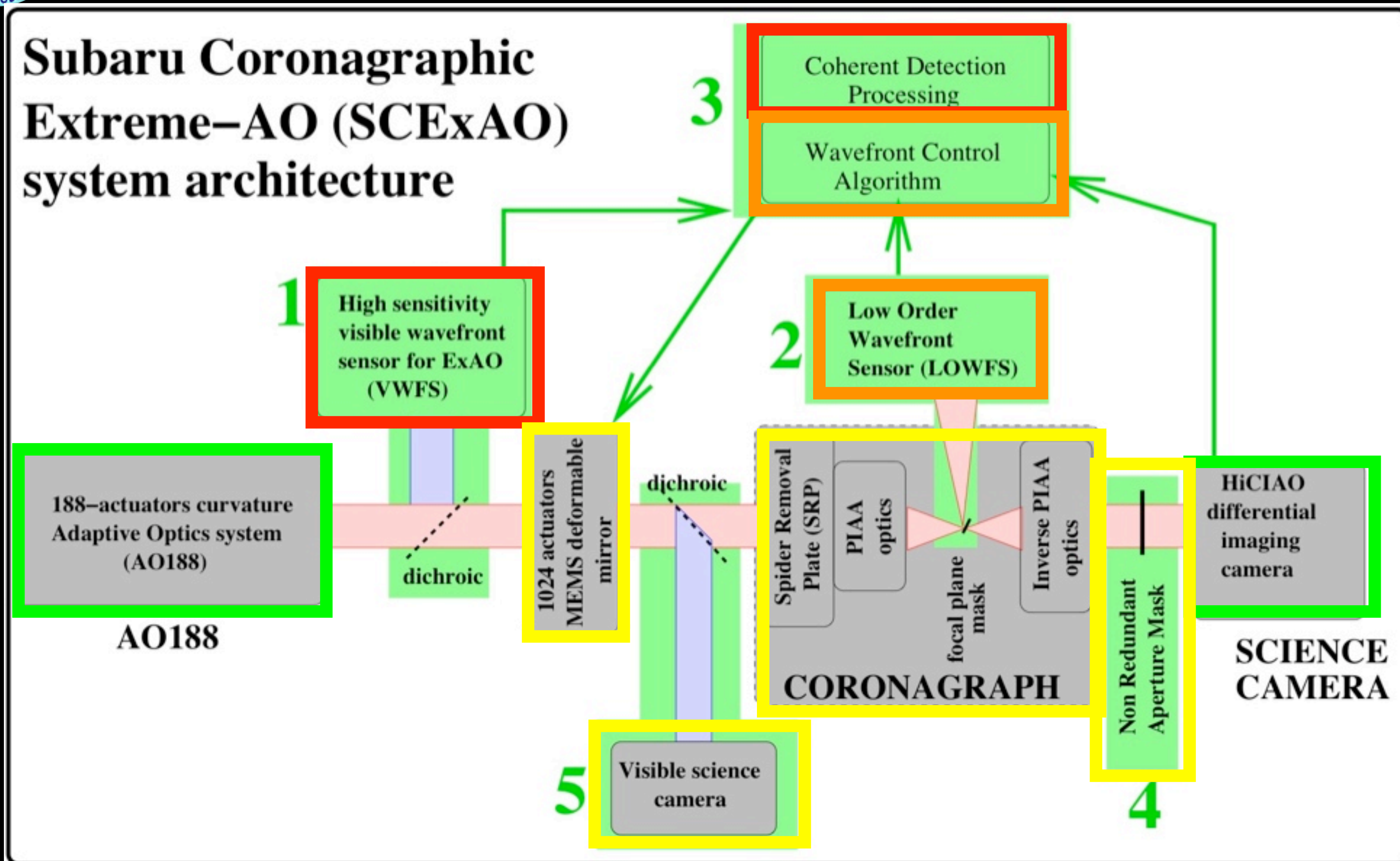
# System architecture




Designed as a highly flexible, evolvable platform

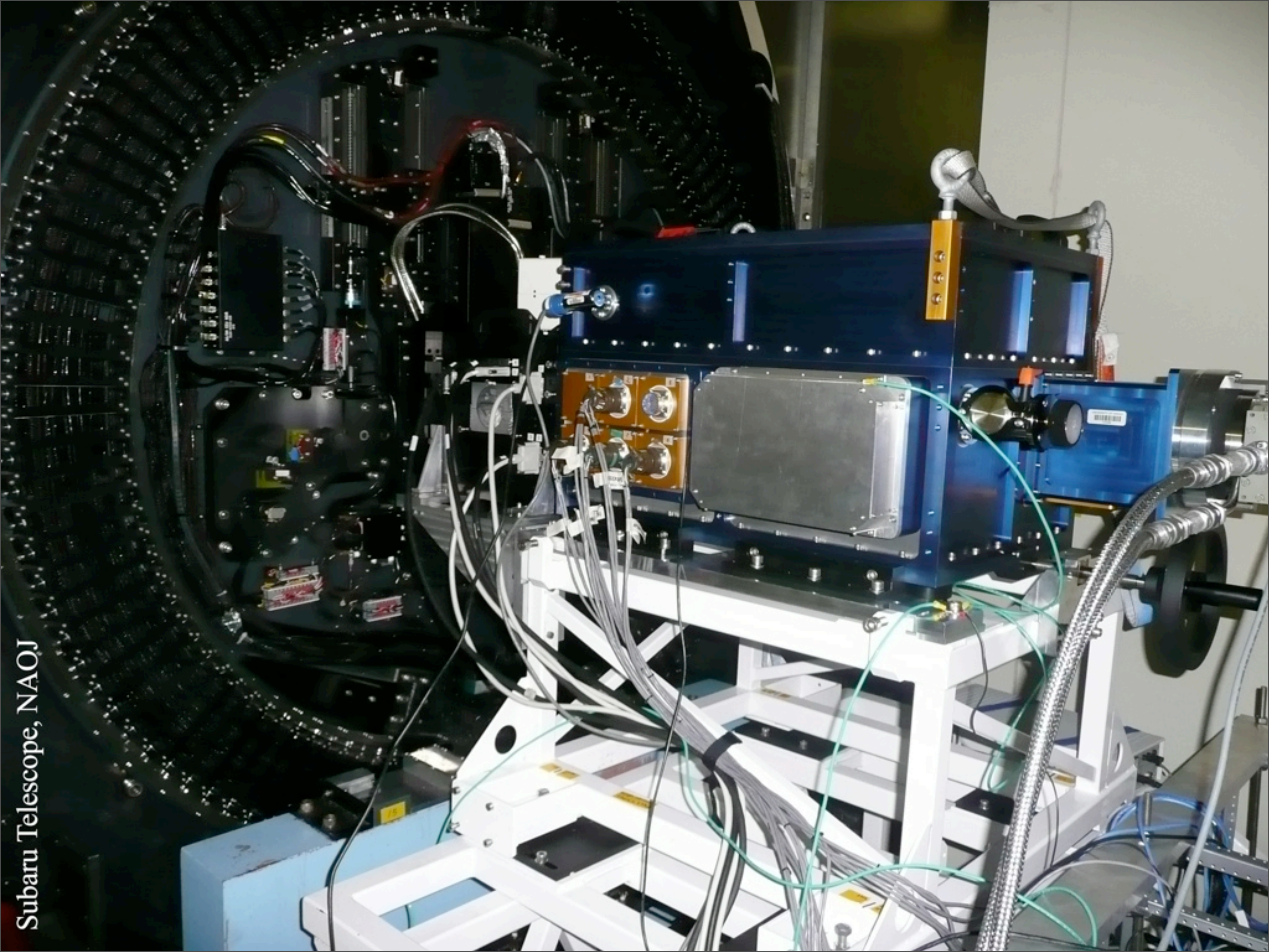
Efficient use of AO188 system & HiCIAO camera

# System architecture

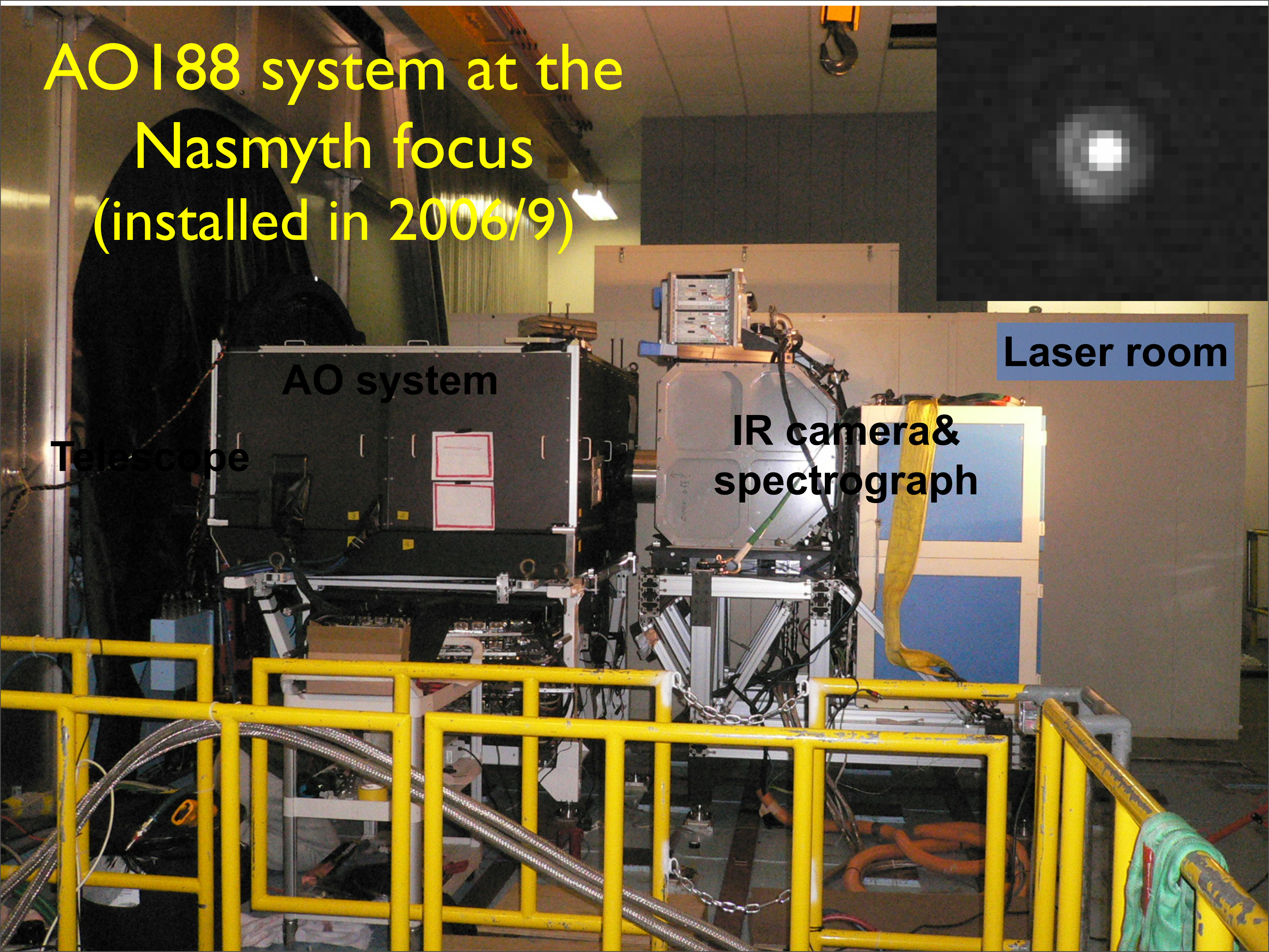



Designed as a highly flexible, evolvable platform

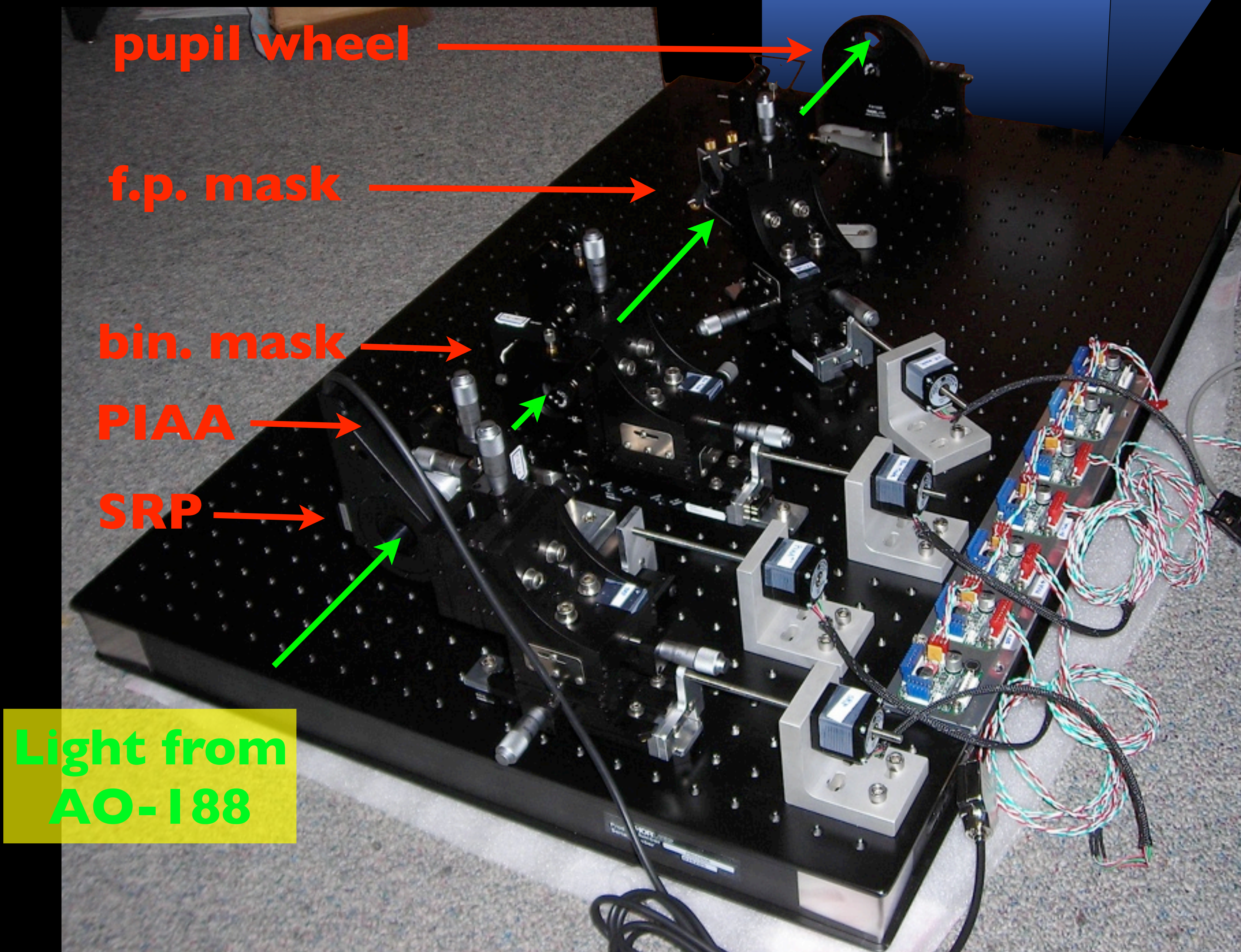
Efficient use of AO188 system & HiCIAO camera


Subaru Telescope, NAOJ

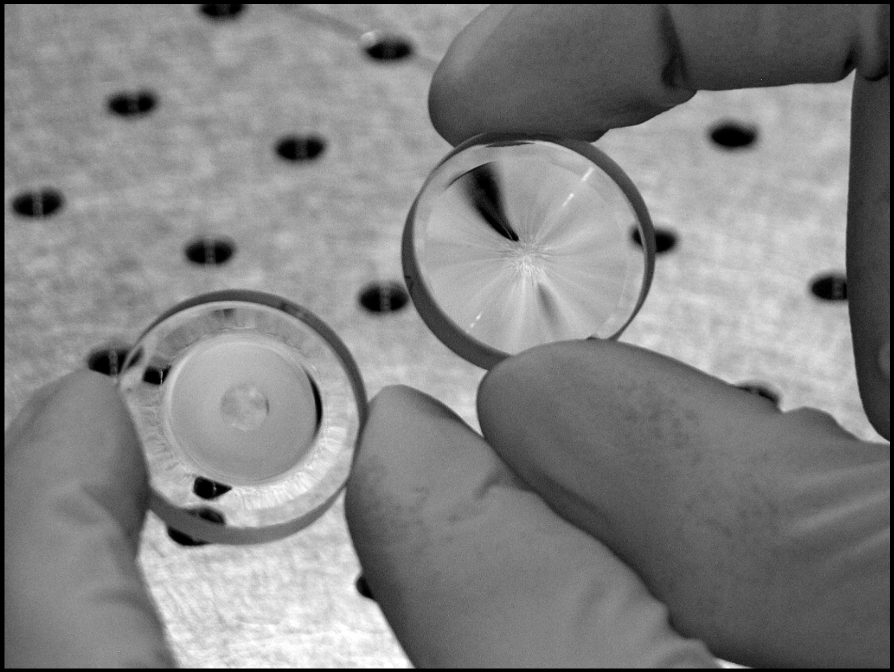
# AO188 system at the Nasmyth focus (installed in 2006/9)



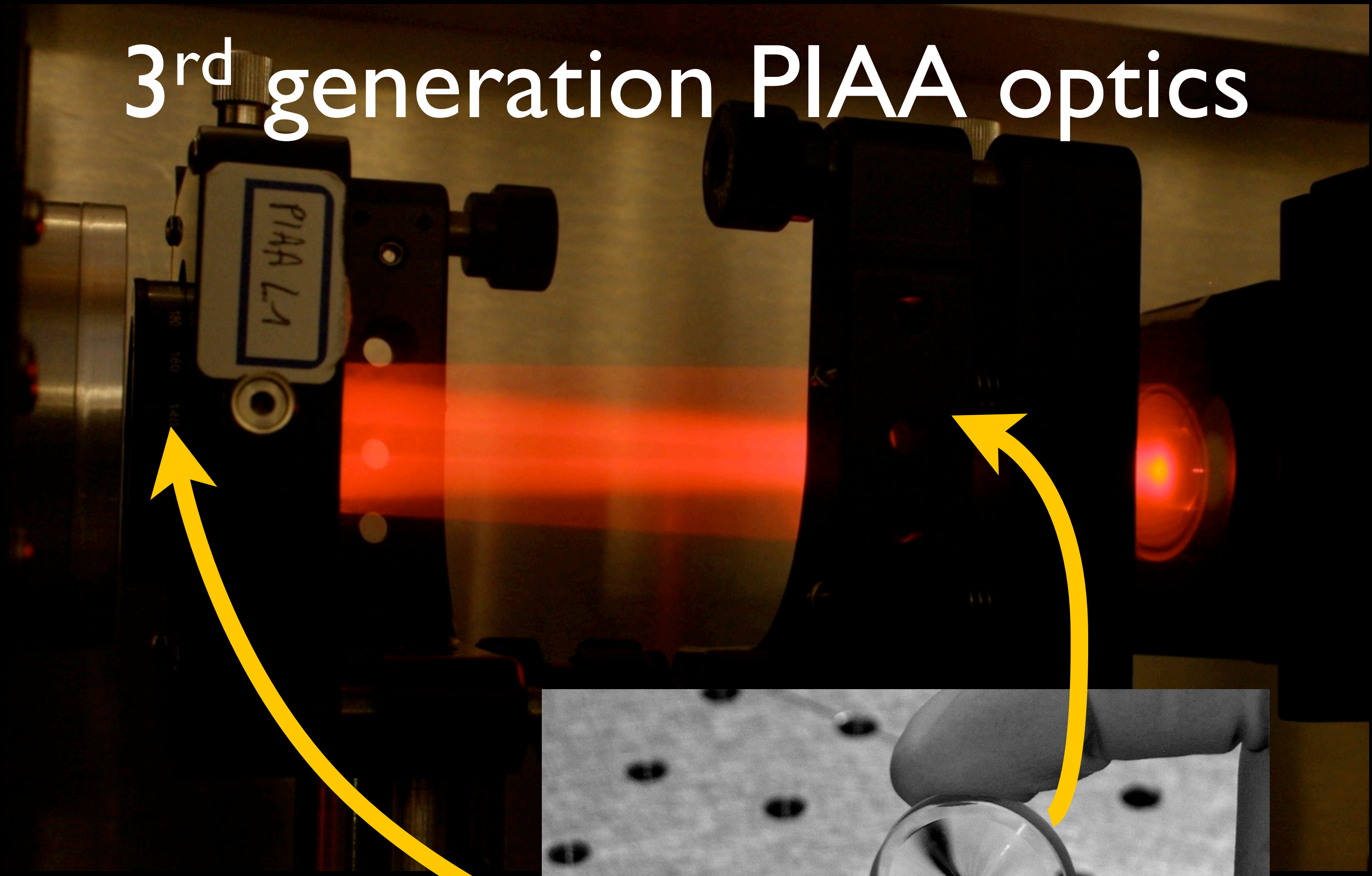
# Integration

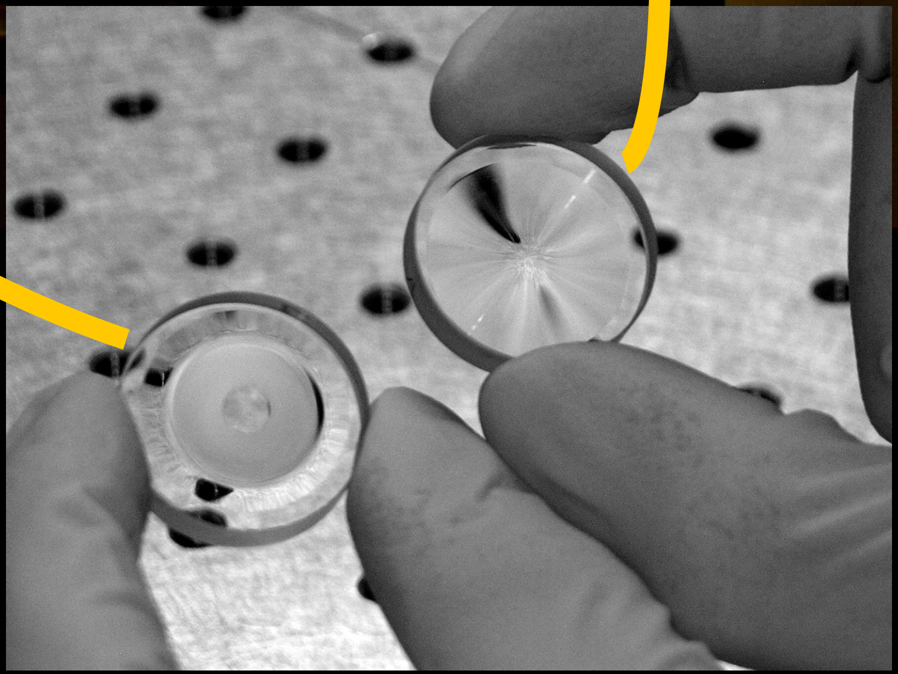


# 3rd generation PIAA optics



# 3rd generation PIAA optics

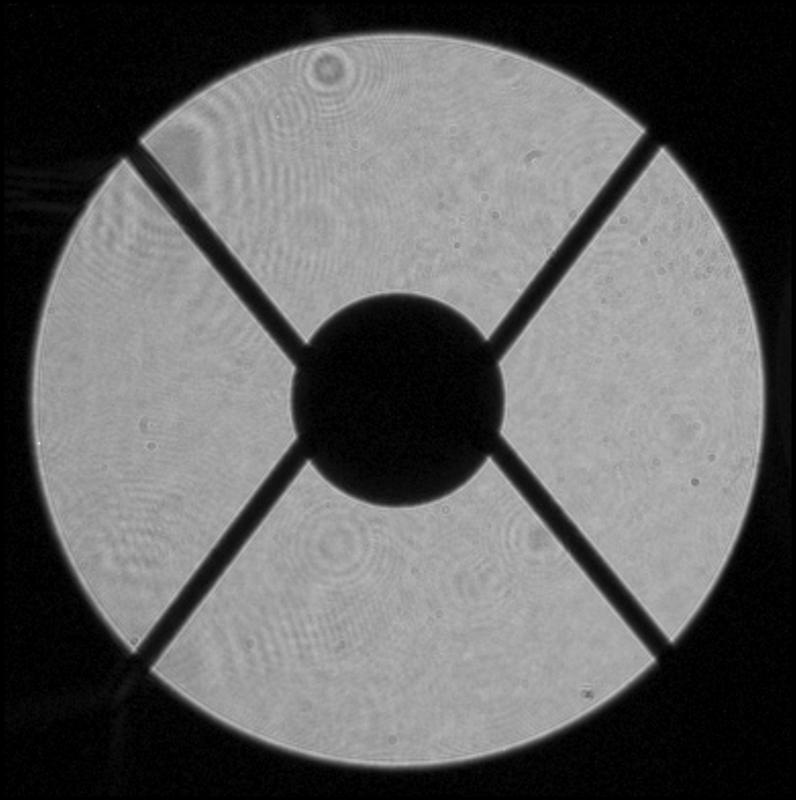


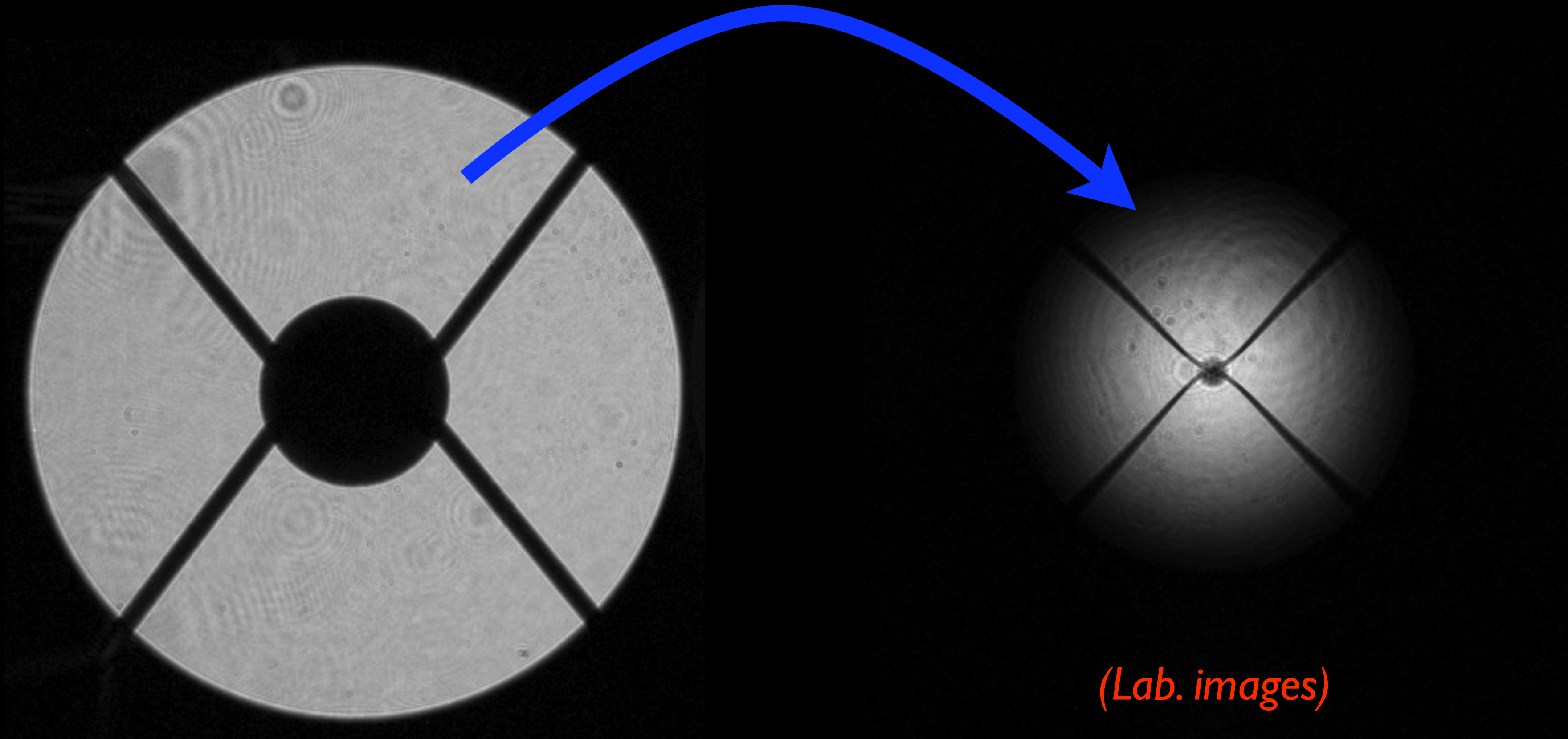
- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Optics tested, and good to go!

# Apodized beam



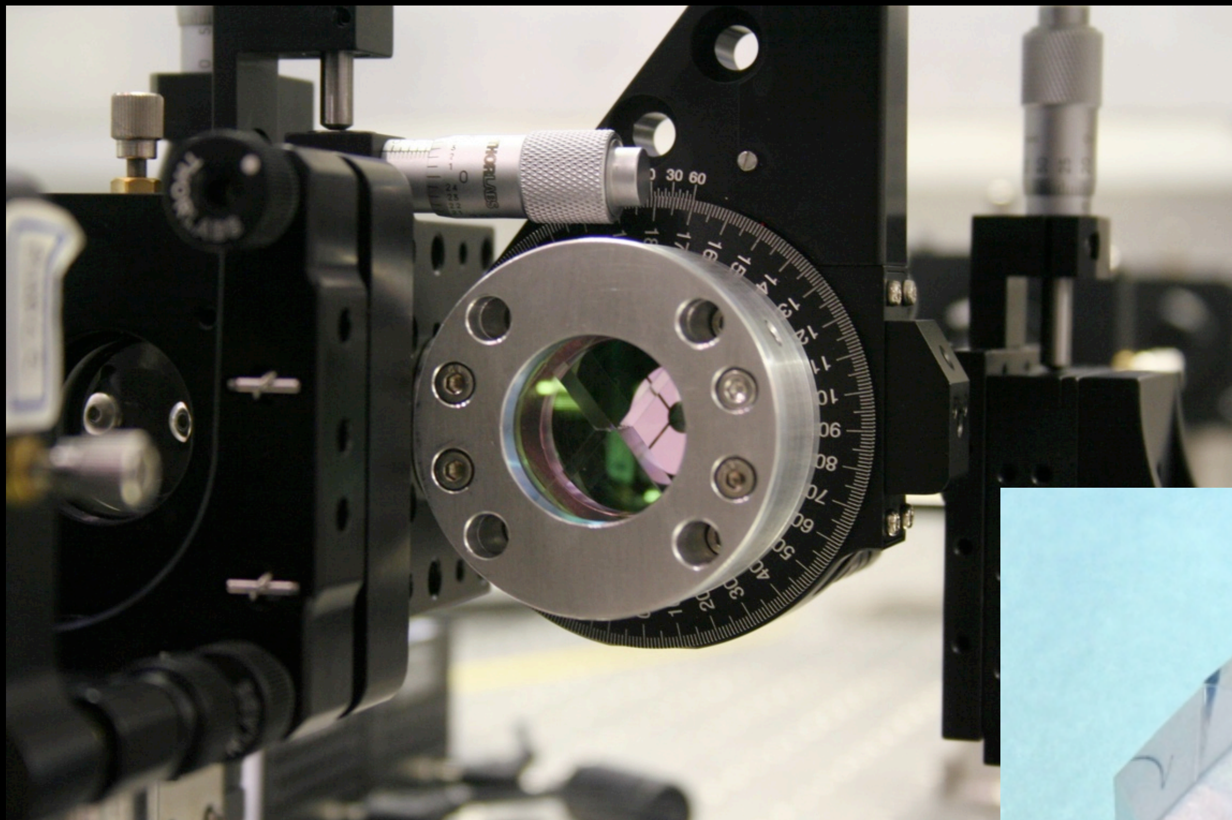
# Apodized beam

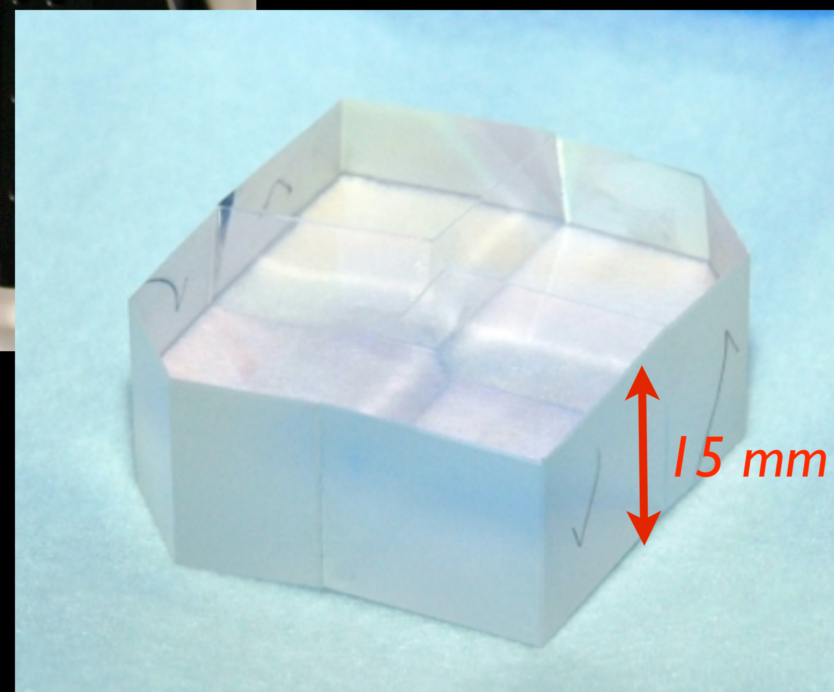


*(Lab. images)*

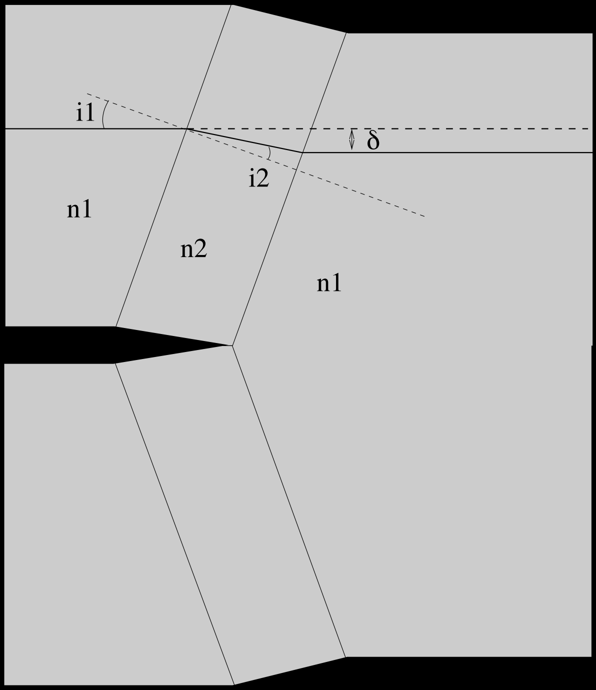
The PIAA does its job but spider vanes remain...

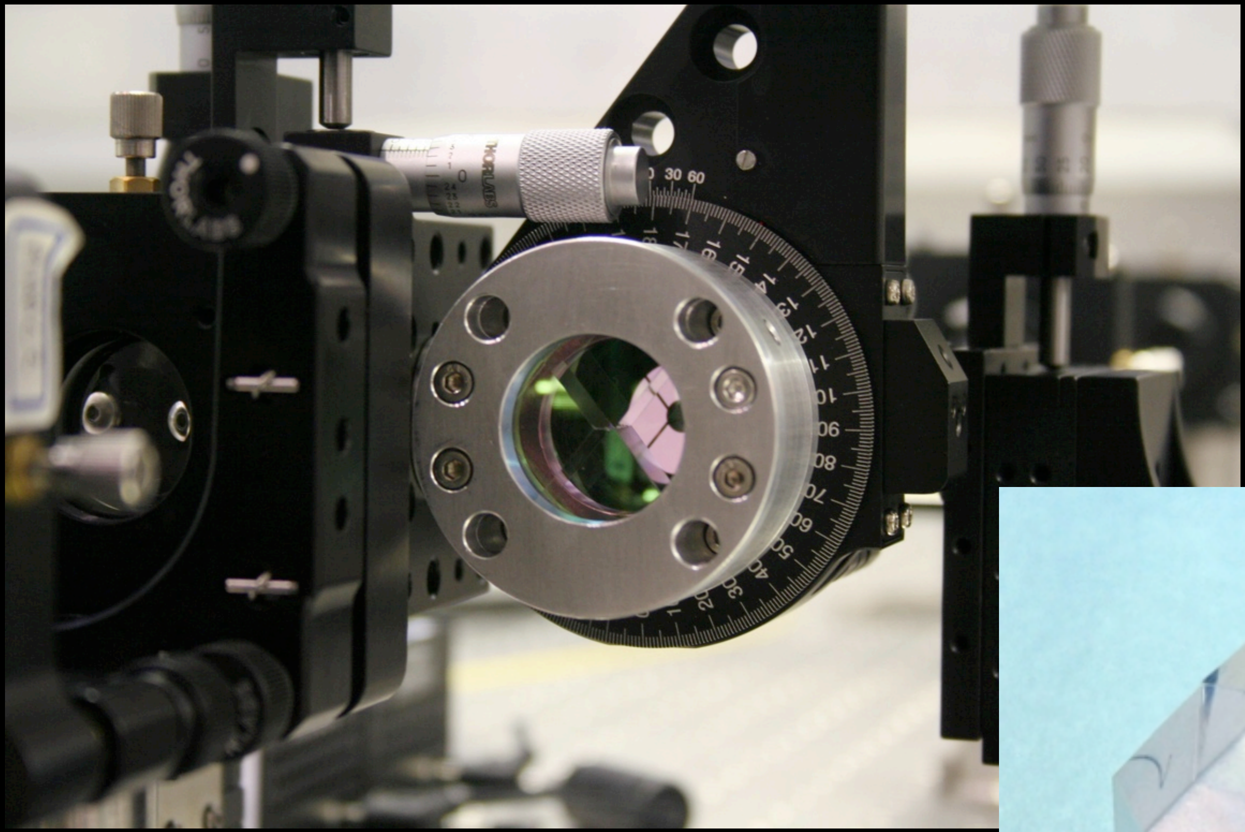
# Spider Removal Plate

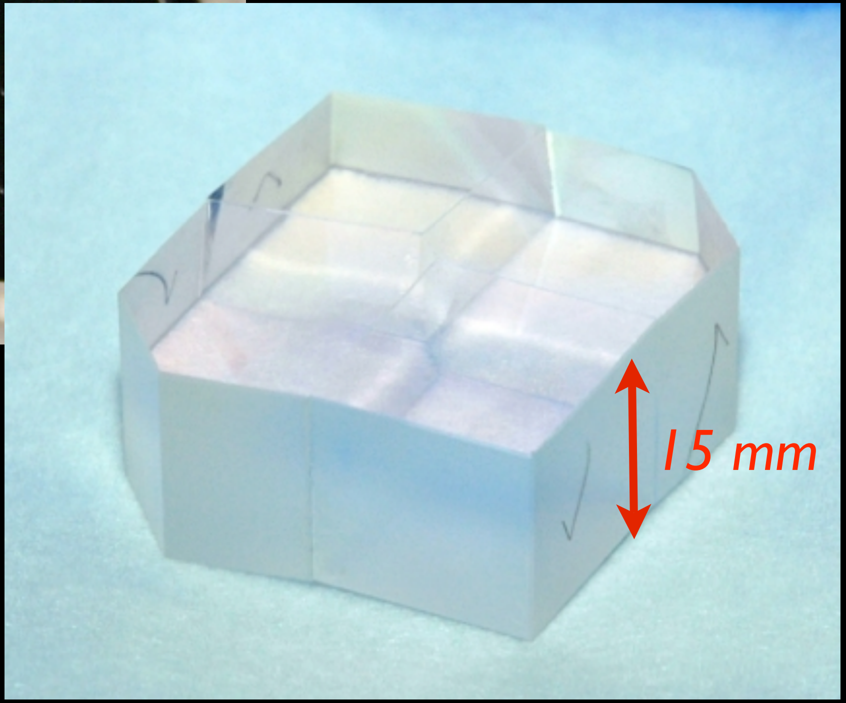




# Spider Removal Plate






- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°

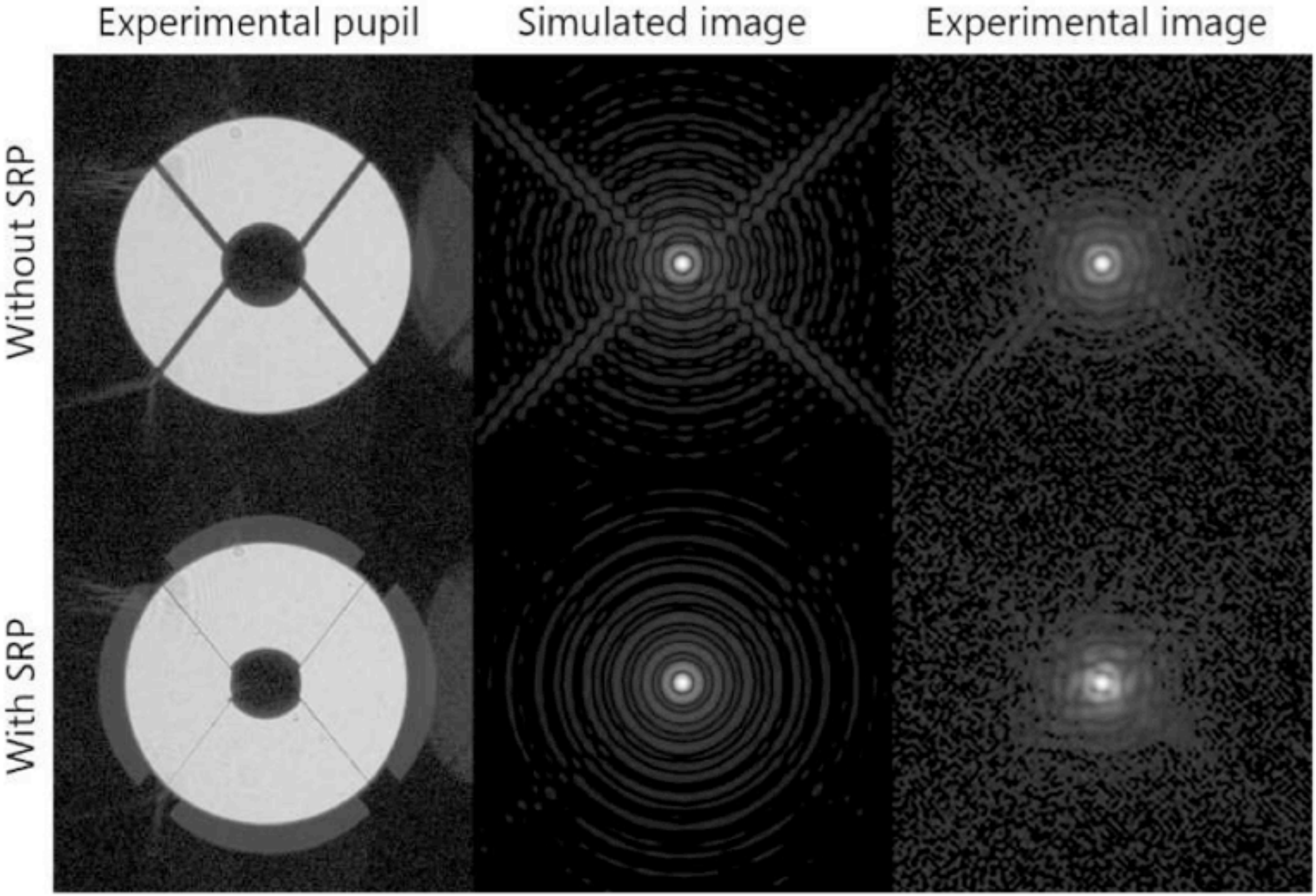
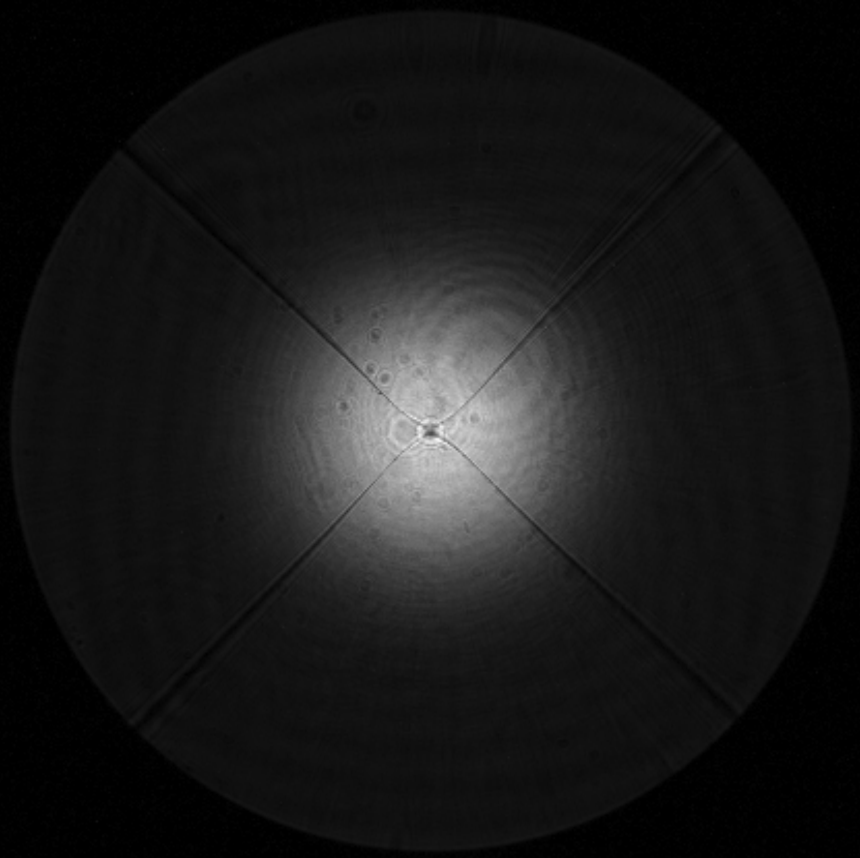



Fig. 8.— Effect of the SRP on the pupil. The three top panels show (from left to right): an image taken with the camera in a location conjugated with the pupil plane, showing the mask simulating the Subaru telescope pupil, as well as the corresponding simulated and experimental images. The three bottom panels show the same images when the SRP is inserted into the beam (cf. Sec. 3.3 for details).

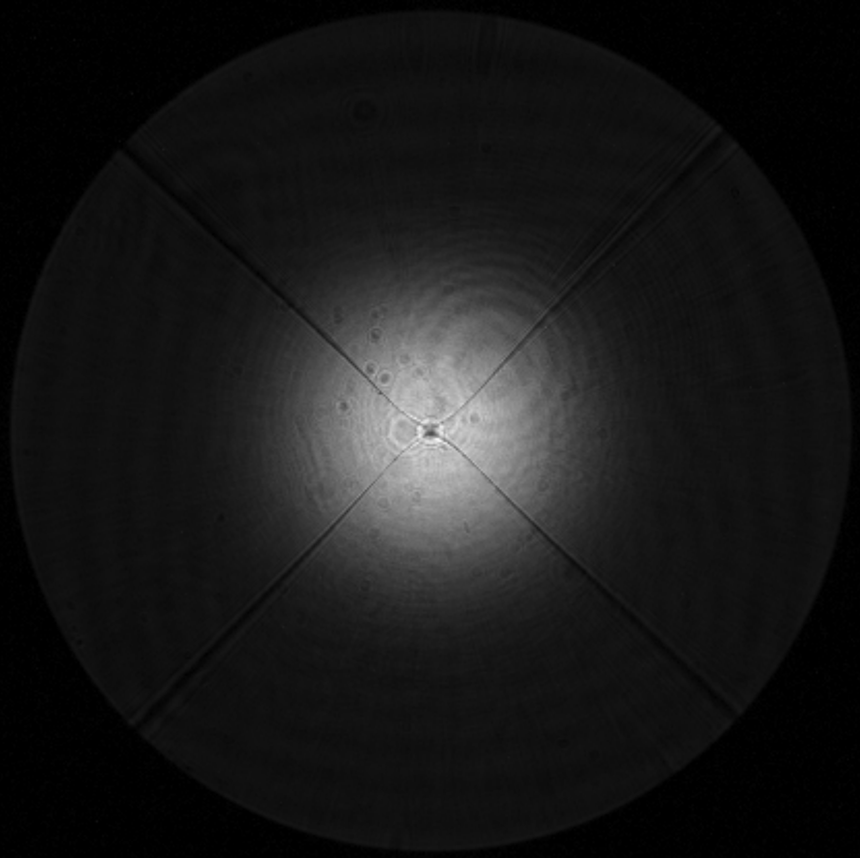
# Putting things together: SRP+PIAA

# Putting things together: SRP+PIAA



*(Lab. image)*

# Putting things together: SRP+PIAA



(Lab. image)

✓ Spider vanes gone

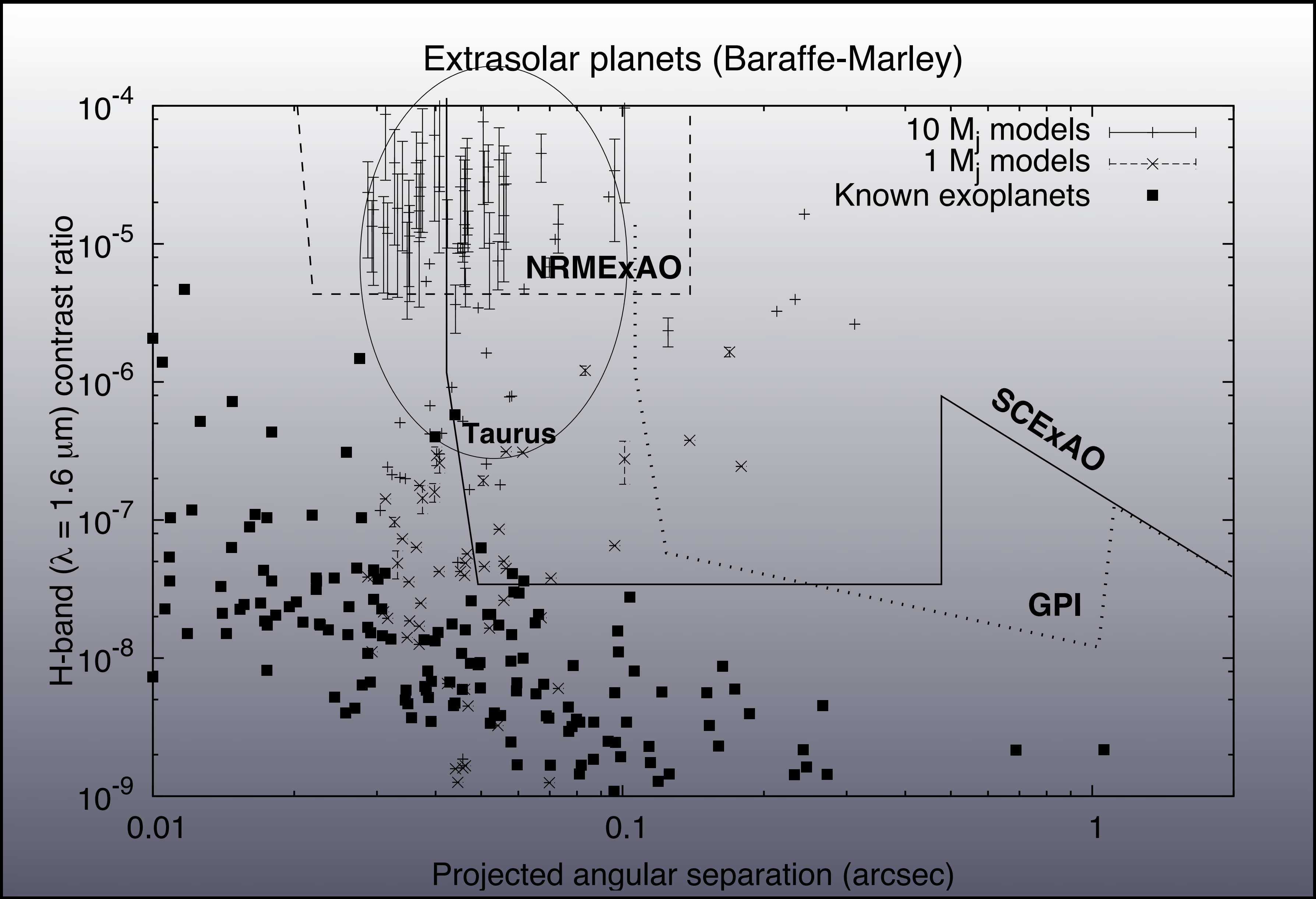
✓ Cent. obscur. gone

✓ Pupil apodized

-> coronagraphy with no losses with with inner working angle = 1 lambda/D

# Expected performance?

# Expected performance?



Univ. of Arizona

Jet Propulsion Laboratory
California Institute of Technology

LOCKHEED MARTIN

Ames Research Center

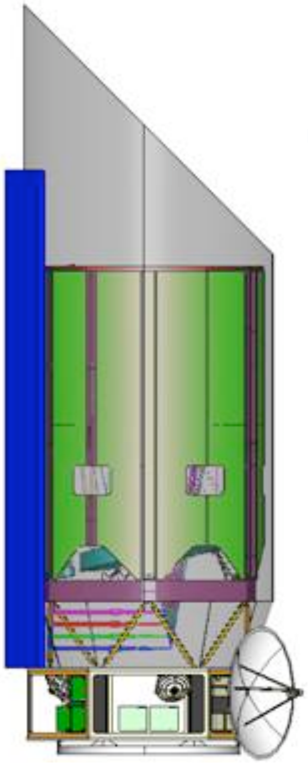
ITT

# Pupil mapping Exoplanet Coronagraphic Observer (PECO)

## http://caao.as.arizona.edu/PECO/

| | |
|---|---|
| **Principal Investigator: Olivier Guyon – University of Arizona (808) 934 5901 guyon@naoj.org** | |
| **Mission Study Manager: Marie Levine – NASA Jet Propulsion Laboratory -California Institute of Technology** | |
| **Science Studies (Lead: NASA Ames Research Center)** | |
| **K. Cahoy (NASA ARC) – Co-I** | Design Reference Mission |
| **J. Kasting (Penn State) Co-I** | Terrestrial planets: spectral characterization |
| **M. Marley (NASA ARC) – Co-I** | Giant planets: spectral characterization, modeling |
| **M. Meyer (U of A) – Co-I** | Planetary systems formation, evolution |
| **W. Traub (JPL-Caltech) – Co-I** | Science plan |
| **S. Ridgway (NOAO) – Co-I** | Science advisor |
| D. Backman (SOFIA) – Collaborator | Exozodiacal dust |
| G. Schneider (U of A) – Collaborator | Exozodiacal dust |
| M. Tamura (NAOJ) – Collaborator | Planetary systems formation |
| N. Woolf (U of A) - Collaborator | Characterization of planetary atmospheres, habitability |
| **Architecture Studies (Lead: Co-I S. Shaklan – NASA Jet Propulsion Laboratory - Caltech)** | |
| **A. Give'on (JPL-Caltech) – Co-I** | WFS&C algorithms for Architecture studies and HCIT test demo |
| **E. Jordan (JPL-Caltech) – Co-I** | Systems Engineering |
| **R. Vanderbei (Princeton) – Co-I** | Coronagraph architecture and analysis |
| R. Belikov (NASA ARC) – Collaborator | Coronagraph architecture and analysis |
| J. Kasdin (Princeton) – Collaborator | Architecture |
| E. Serabyn (JPL-Caltech) – Collaborator | Wavefront sensing and speckle nulling |
| **Mission Technology (Lead: Co-I Marie Levine – NASA JPL w/ contributions from NASA ARC)** | |
| **R. Angel (U of A) – Co-I** | Technology development, wavefront sensing, primary mirror |
| D. Gavel (UCSC) – Collaborator | Characterization of MEMS type DMs for PECO |
| M. Shao (JPL-Caltech) – Collaborator | MEMS DMs characterization, wavefront sensing & control |
| J. Trauger (JPL-Caltech) – 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 |
| **R. Egerman (ITT) – Co-I** | PECO telescope design, implementation, cost and technology |

# PECO overview



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

**Characterization of planets (including Earths/ SuperEarths) and dust in habitable zone**

- 1.4m diameter off-axis telescope (sized for medium-class cost cap), 3 yr mission
- drift-away heliocentric orbit for maximum stability
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 - 0.9 micron spectral coverage / R~20, polarimetric imaging
- Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin

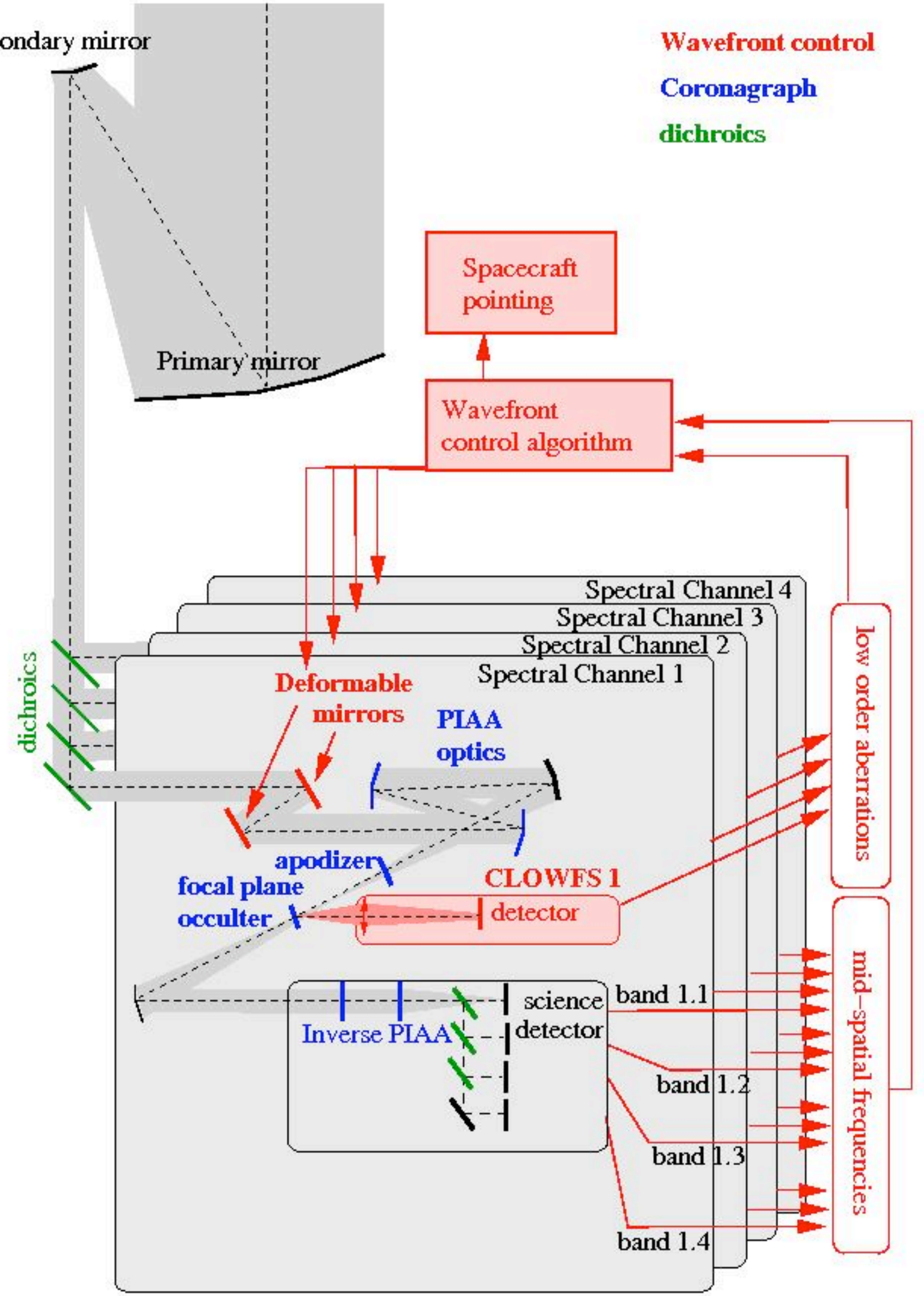
# Earth/SuperEarths with a medium-class mission ?

**Yes, if:**

- **High throughput** instrument & good detector
  - high throughput coronagraph
  - very high efficiency (~45% of photons from the FULL aperture detected), use dichroics instead of filters
  - combined imaging & spectroscopy
  - photon counting (no readout noise allowed)
- Small **Inner Working Angle** AND full telescope **angular resolution**
  - good coronagraph
  - use blue light for discovery & orbit determination
- Large amount of **observation time** on few targets
  - small sample of the easiest ~20 targets
  - long exposure times & many revisits
- Risks: high exozodi & low Earth frequency
  - broader science case:
    - exoplanetary system architecture
    - extrasolar giant planets characterization
    - exozodi disks imaging - **exozodi level measurement**

# PECO approaches theoretically optimum coronagraph performance

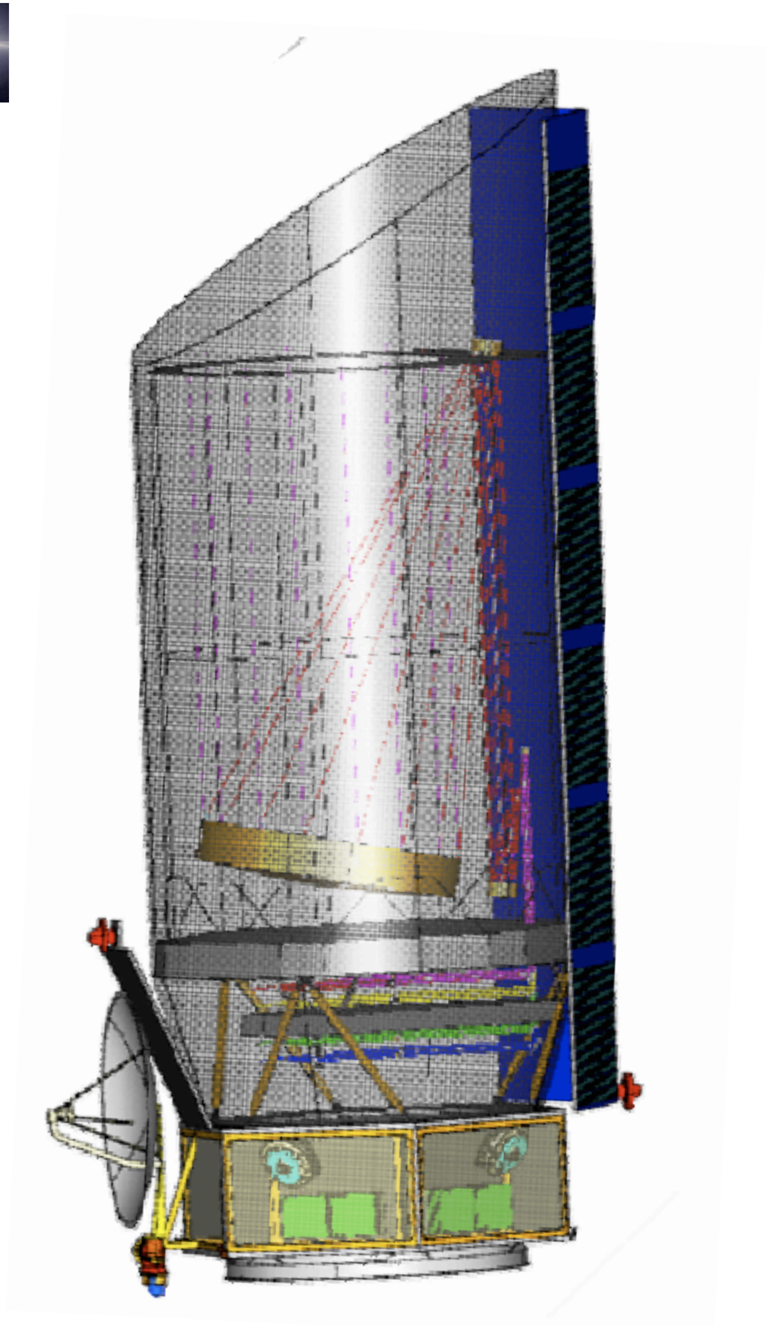


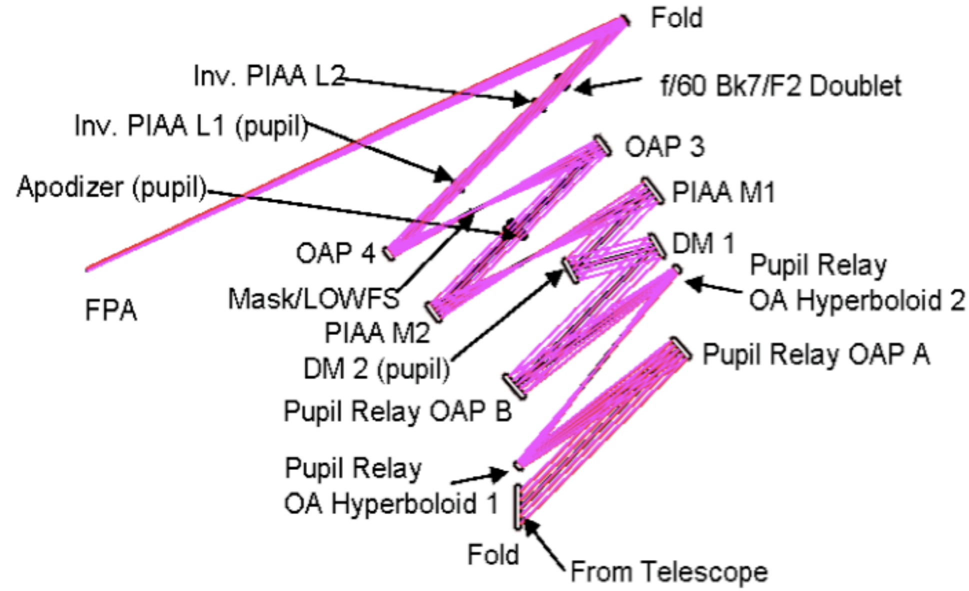


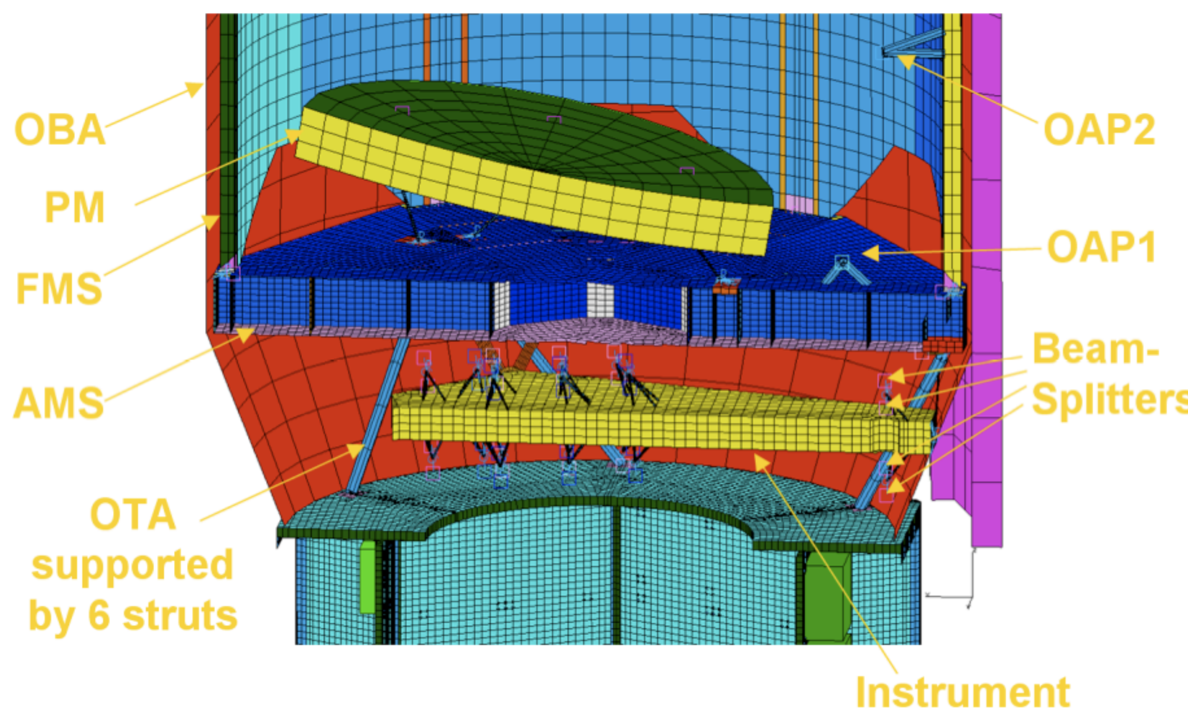

- **High performance PIAA coronagraph**
- **Simultaneous acquisition of all photons from 0.4 to 0.9 μm in 16 spectral bands x 2 polarization axis, combining detection & characterization**
  - High sensitivity for science and wavefront sensing
  - polarization splitting just before detector (helps with exozodi & characterization)
- **Wavefront control and coronagraph perform in 4 parallel channels**
  - Allows scaling of IWA with lambda
  - Allows high contrast to be maintained across full wavelength coverage

# PECO spacecraft & instrument

PECO Pupil mapping Exoplanet Coronagraph Observer





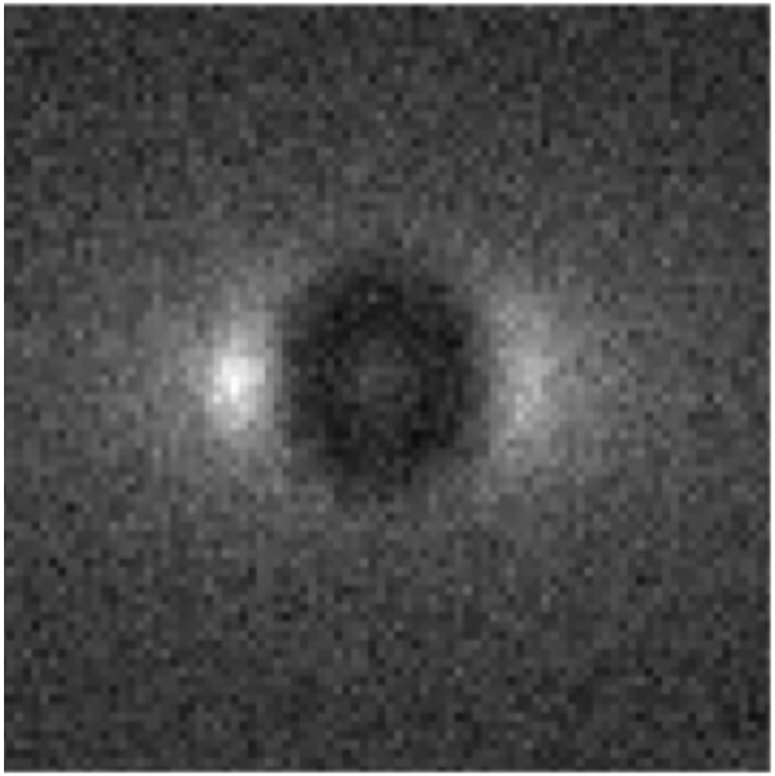
# PECO Design Reference Mission
# A Grand Tour of 10 nearby sun-like stars

- **Conduct a "Grand Tour" of ~20 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.**
  - Multiple (~10 or more) visits for detection
  - Characterization for ~5 days each to get S/N = 20-30 with ability to measure spectral features
  - exozodi distribution measurement
  - compile with other measurements (RV, Astrometry, ground imaging)
- **Study known RV planets, observing them at maximum elongation**
  - Detect at least 13 RV planets with single visits at maximum elongation
  - Characterize at least 5 RV planets for ~2-5 days each to get S/N > 30 with ability to measure spectral features
- **Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.**

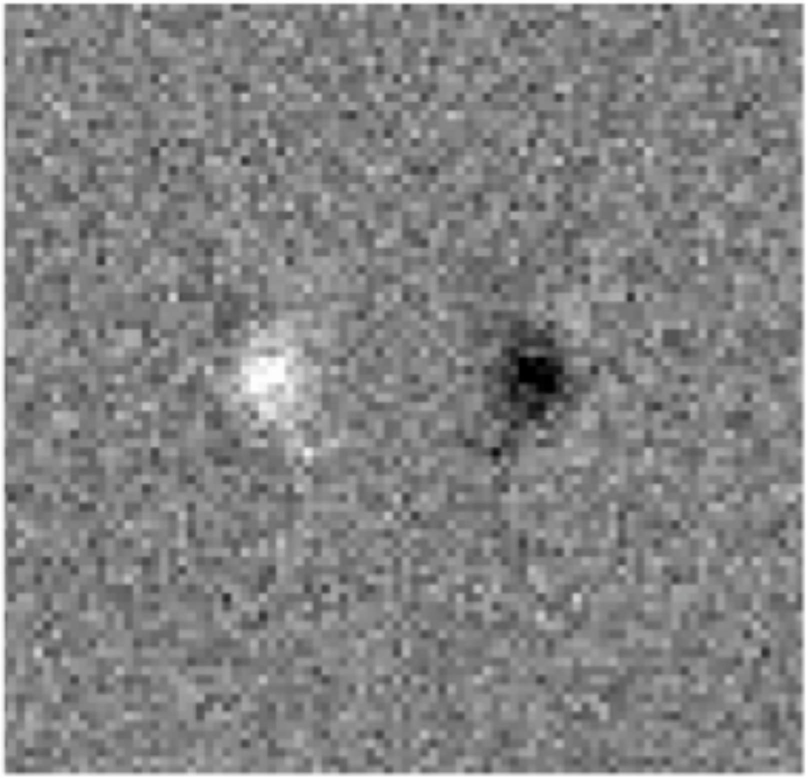
# PECO can observe an Earth at distance of Tau Ceti



## Initial image



## After Symmetric Dust Subtraction



**Left:** a simulation of 24 hr of PECO data showing an Earth-like planet (a=0.2) around Tau Ceti with 1 zodi of exododi dust in a uniform density disk inclined 59 degrees. This is a simulation of λ= 550 nm light in a 100 nm bandpass PECO (1.4-m aperture). Photon noise and 16 electrons total detector noise for an electron multiplying CCD have been added.

**Right:** the PECO image after subtracting the right half from the left half, effectively removing the exozodiacal dust and other circularly symmetric extended emission or scattered light. The Earth-like planet is obvious as the white region on the left, and the dark region on the right is its mirror image artifact.

# PECO high priority targets (detection in < 6 hr)

Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO.

| HIP# | dist (pc) | max el(λ/D) | *rad (λ/D) | SNR(1s,tp) | t20% (s,tp) | Comment |
|---|---|---|---|---|---|---|
| 71683 | 1.3 | 11.5 | 0.06 | 0.84 | 35 | Alf Cen A G2 V, V=0 |
| 71681 | 1.3 | 6.6 | 0.04 | 0.75 | 44 | Alf Cen B K2 IV, V=1.3 |
| 8102 | 3.6 | 2.3 | 0.01 | 0.1 | 2750 | Tau Cet G8.5 V, V=3.5 ** |
| 16537 | 3.2 | 2.2 | 0.01 | 0.09 | 2968 | Eps Eri K2 V, V=3.7 ** |
| 3821 | 6.0 | 2.3 | 0.01 | 0.04 | 14329 | Eta Cas G0 V V=3.5 *** |
| 2021 | 7.5 | 3.1 | 0.01 | 0.04 | 14878 | Bet Hyi G0 V, V=2.8 |
| 99240 | 6.1 | 2.2 | 0.01 | 0.04 | 19636 | Del Pav G8 IV, V=3.6 |

Table 4-3: Stars with Super-Earth planets in habitable zones (1 AU equiv) easily detectable with PECO

| HIP# | dist (pc) | max el(λ/D) | *rad (λ/D) | SNR(1s,tp) | t20% (s,tp) | Comment |
|---|---|---|---|---|---|---|
| 71683 | 1.35 | 11.48 | 0.06 | 1.88 | 7 | Alf Cen A G2 V, V=0 |
| 71681 | 1.35 | 6.57 | 0.04 | 1.7 | 9 | Alf Cen B K2 IV, V=1.3 |
| 8102 | 3.65 | 2.3 | 0.01 | 0.28 | 328 | Tau Cet G8.5 V, V=3.5 ** |
| 16537 | 3.22 | 2.19 | 0.01 | 0.27 | 338 | Eps Eri K2 V, V=3.7 ** |
| 2021 | 7.47 | 3.08 | 0.01 | 0.14 | 1248 | Bet Hyi G0 V, V=2.8 |
| 3821 | 5.95 | 2.29 | 0.01 | 0.14 | 1286 | Eta Cas G0 V V=3.5 *** |
| 99240 | 6.11 | 2.25 | 0.01 | 0.12 | 1743 | Del Pav G8 IV, V=3.6 |
| 22449 | 8.03 | 2.57 | 0.01 | 0.1 | 2310 | Pi3 Ori, F6 V, V=3.2 |
| 88601 | 5.09 | 1.88 | 0.01 | 0.09 | 3114 | V* 70 Oph, K0 V, V=4.0 *** |
| 86974 | 8.4 | 2.39 | 0.01 | 0.08 | 3820 | Mu Her, G5 IV, V=3.4 |
| 81693 | 10.8 | 3.11 | 0.01 | 0.08 | 4240 | Zet Her, G0 IV, V=2.9 *** |
| 61941 | 11.83 | 3.15 | 0.01 | 0.07 | 5545 | Gam Vir, F0 V, V=3.6 *** |
| 77952 | 12.31 | 3.03 | 0.01 | 0.06 | 6880 | Bet TrA, F1 V, V=2.9 |
| 108870 | 3.63 | 1.5 | 0.01 | 0.06 | 7719 | Eps Ind, K4 V, V=4.7 *** |
| 27072 | 8.97 | 2.14 | 0.01 | 0.04 | 7786 | Gam Lep, F6.5 V, V=3.6 |
| 19849 | 5.04 | 1.54 | 0.01 | 0.04 | 13513 | V* DY Eri , K0.5 V, V=4.4 |
| 46853 | 13.49 | 2.59 | 0.01 | 0.04 | 13904 | 25 Uma, F6 IV, V=3.2 *** |
| 57757 | 10.9 | 2.14 | 0.01 | 0.04 | 15868 | Bet Vir, F9 V, V=3.6 |
| 84405 | 5.99 | 1.63 | 0.01 | 0.04 | 16495 | 36 Oph, K2 V, V=4.3 *** |
| 15510 | 6.06 | 1.61 | 0.01 | 0.04 | 16777 | 82 Eri, G8 V, V=4.3 |

NOTE: ** indicates the presence of significant dust (~10 zodi or more) and *** indicates a close multiple star system (preventing high contrast observations) in Tables 4-2 and 4-3.

# Known EGPs observable with PECO

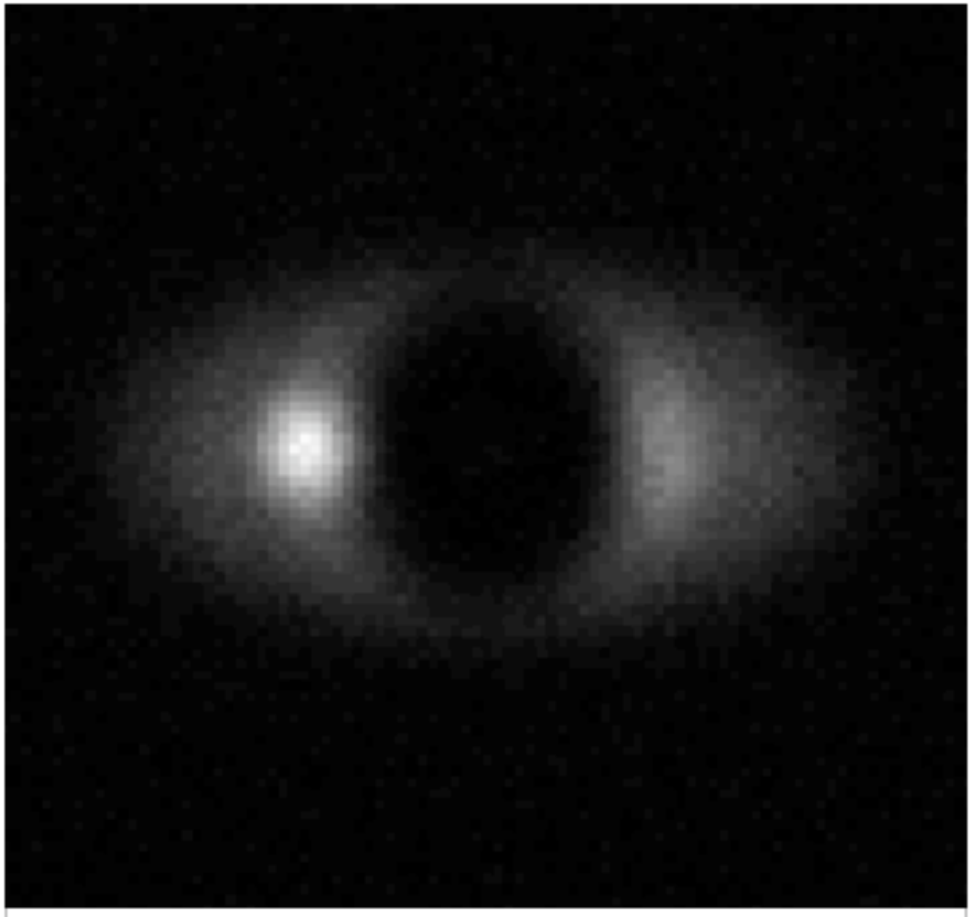


## List of known Radial Velocity EGPs observable with PECO

| Planet Name | Mp (Mjup) | Period (d) | a (AU) | sep`` | 550nm/D | Dist (pc) | St. Sp T | M* | St. Mag. V. | Pl mag V | Contrast |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Epsilon Eridani b | 1.55 | 2502 | 3.39 | 1.06 | 13.07 | 3.2 | K2 V | 0.8 | 3.73 | 25.7 | 1.6E-09 |
| 55 Cnc d | 3.84 | 5218 | 5.77 | 0.43 | 5.31 | 13.4 | G8 V | 1.0 | 5.95 | 29.1 | 5.5E-10 |
| HD 160691 c | 3.1 | 2986 | 4.17 | 0.27 | 3.36 | 15.3 | G3 IV-V | 1.1 | 5.15 | 27.6 | 1.1E-09 |
| Gj 849 b | 0.82 | 1890 | 2.35 | 0.27 | 3.3 | 8.8 | M3.5 | 0.4 | 10.42 | 31.6 | 3.3E-09 |
| HD 190360 b | 1.5 | 2891 | 3.92 | 0.25 | 3.04 | 15.9 | G6 IV | 1.0 | 5.71 | 28.0 | 1.2E-09 |
| 47 Uma c | 0.46 | 2190 | 3.39 | 0.24 | 2.99 | 14.0 | G0V | 1.0 | 5.1 | 27.1 | 1.6E-09 |
| HD 154345 b | 0.95 | 3340 | 4.19 | 0.23 | 2.86 | 18.1 | G8V | 0.9 | 6.74 | 29.2 | 1.0E-09 |
| Ups And d | 3.95 | 1275 | 2.51 | 0.19 | 2.3 | 13.5 | F8 V | 1.3 | 4.09 | 25.4 | 2.9E-09 |
| Gamma Cephei b | 1.6 | 903 | 2.04 | 0.17 | 2.14 | 11.8 | K2 V | 1.4 | 3.22 | 24.1 | 4.4E-09 |
| HD 62509 b | 2.9 | 590 | 1.69 | 0.16 | 2.02 | 10.3 | K0IIIb | 1.9 | 1.15 | 21.6 | 6.4E-09 |
| HD 39091 b | 10.35 | 2064 | 3.29 | 0.16 | 1.97 | 20.6 | G1 IV | 1.1 | 5.67 | 27.6 | 1.7E-09 |
| 14 Her b | 4.64 | 1773 | 2.77 | 0.15 | 1.89 | 18.1 | K0 V | 0.9 | 6.67 | 28.2 | 2.4E-09 |
| 47 Uma b | 2.6 | 1083 | 2.11 | 0.15 | 1.86 | 14.0 | G0V | 1.0 | 5.1 | 26.1 | 4.1E-09 |

# PECO easily observes EGPs





Simulated PECO observation of 47 Uma b (raw image, no zodi or exozodi light subtraction necessary for detection)

Shown is a simulation of 24 hrs of PECO data showing the Jovian planet 47 Uma b with 3 zodis of exozodi dust in a uniform density disk inclined 59 deg.

This is a simulation of 550 nm light in a 100 nm bandpass with predicted PIAA performance in the PECO observatory (1.4-m aperture).

Photon noise and 16 electrons total detector noise (for an electron-multiplying CCD) have been added.

This and other RV planets are very easy detections for PECO even in the presence of significant exozodiacal dust, demonstrating that PECO will likely obtain high S/N data on numerous radial velocity EGPs.

# Disk imaging with PECO

- High sensitivity (<zodi) for large number of targets
- full angular resolution (1 l/D): disk structures can be resolved by PECO
- wide spectral coverage, from 400nm to 900nm & polarimetric imaging: dust properties

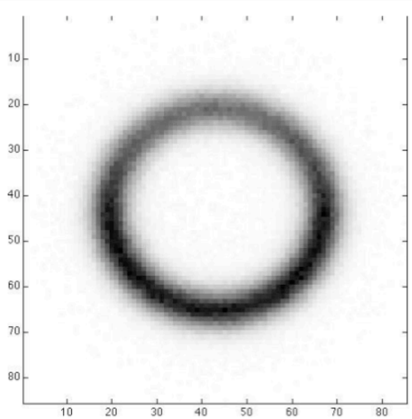



*Figure 7-2:* Eps Eri ring simulation. The 3 AU radius ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, inclined 22 degrees (same as its debris disk), and a total flux density of 1 zodi. Simulated for a central wavelength $\lambda$ = 550 nm with a bandwidth $\delta\lambda$ = 110 nm and an exposure time of 1E4 seconds.

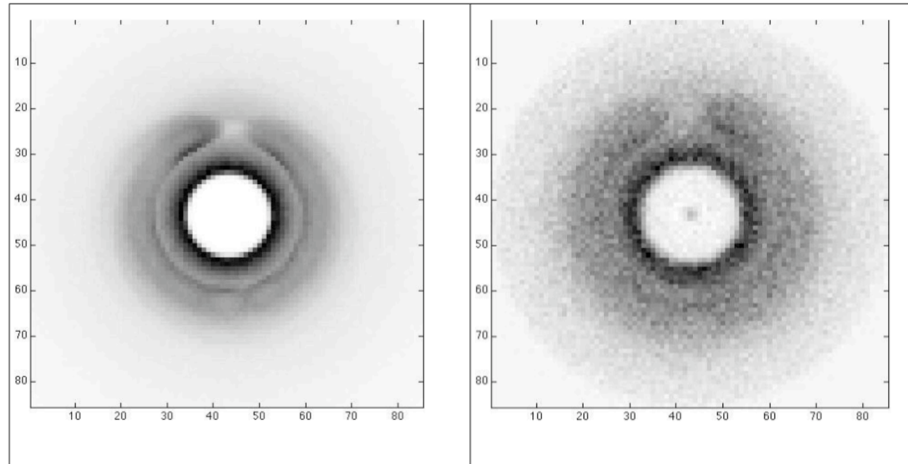
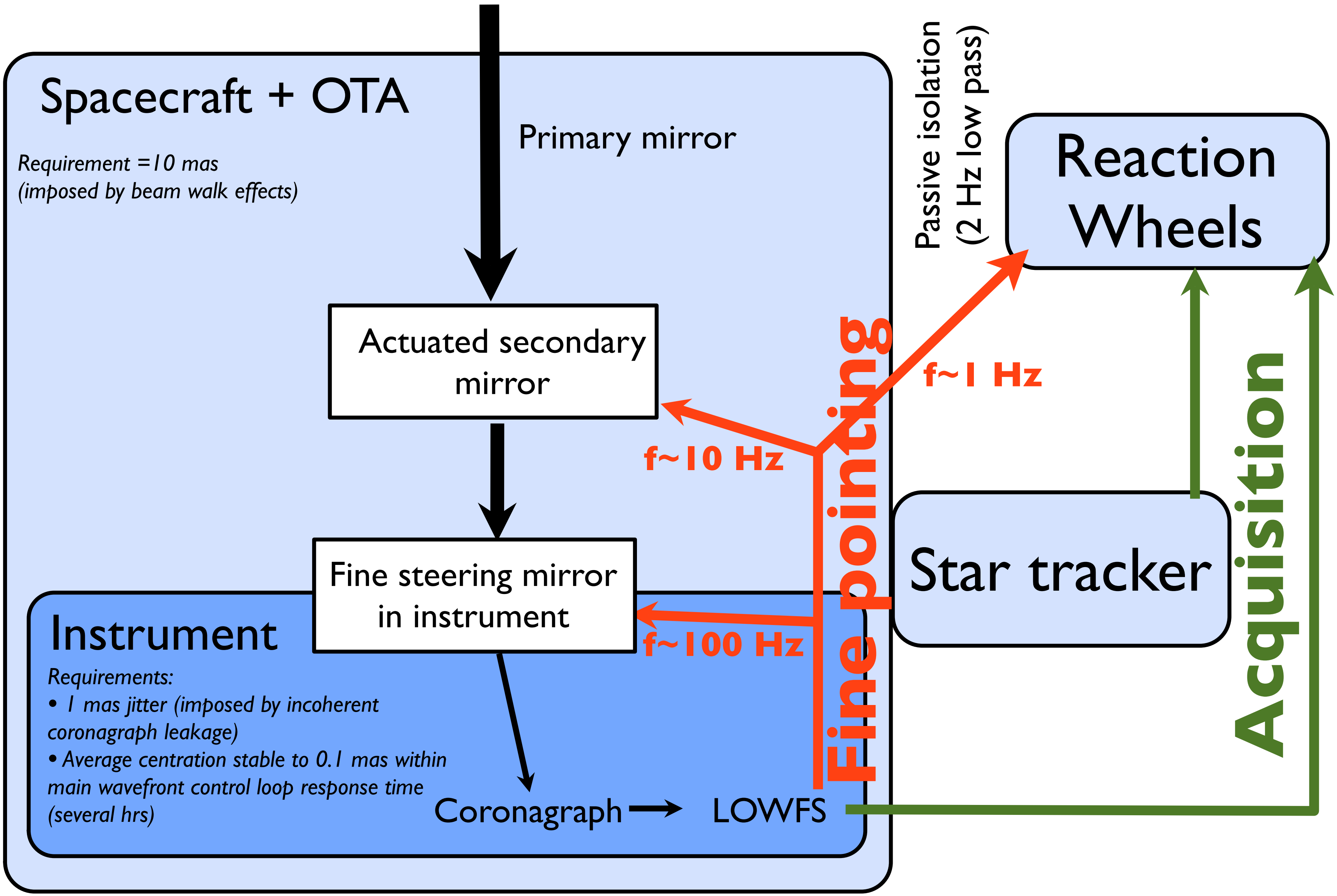



*Figure 7-1:* Face-on disk model provided by C. Stark (left) and simulated 1E4 s PECO 550nm image (right) of the Sun at 3.3 pc with a 1 zodi disk with the Earth (unseen) embedded at a distance of 3 AU.

PECO **P**upil mapping **E**xoplanet **C**oronagraph **O**bserver

# PECO pointing architecture



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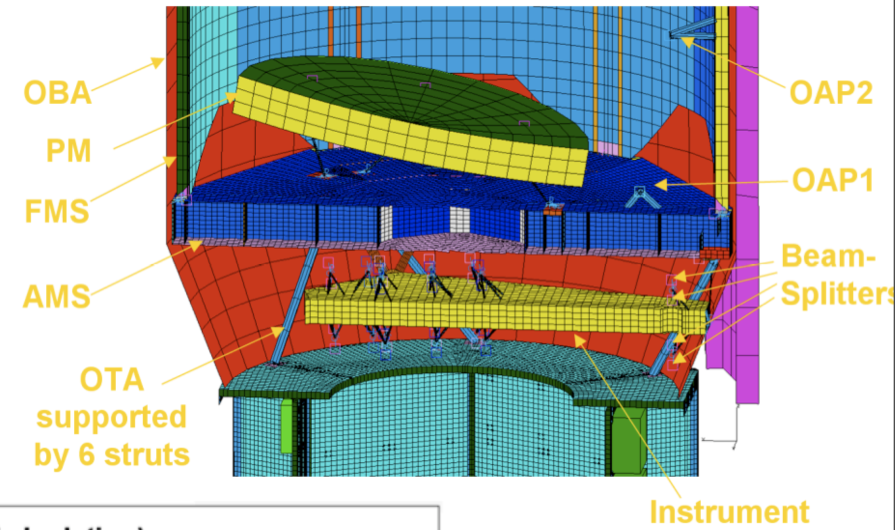
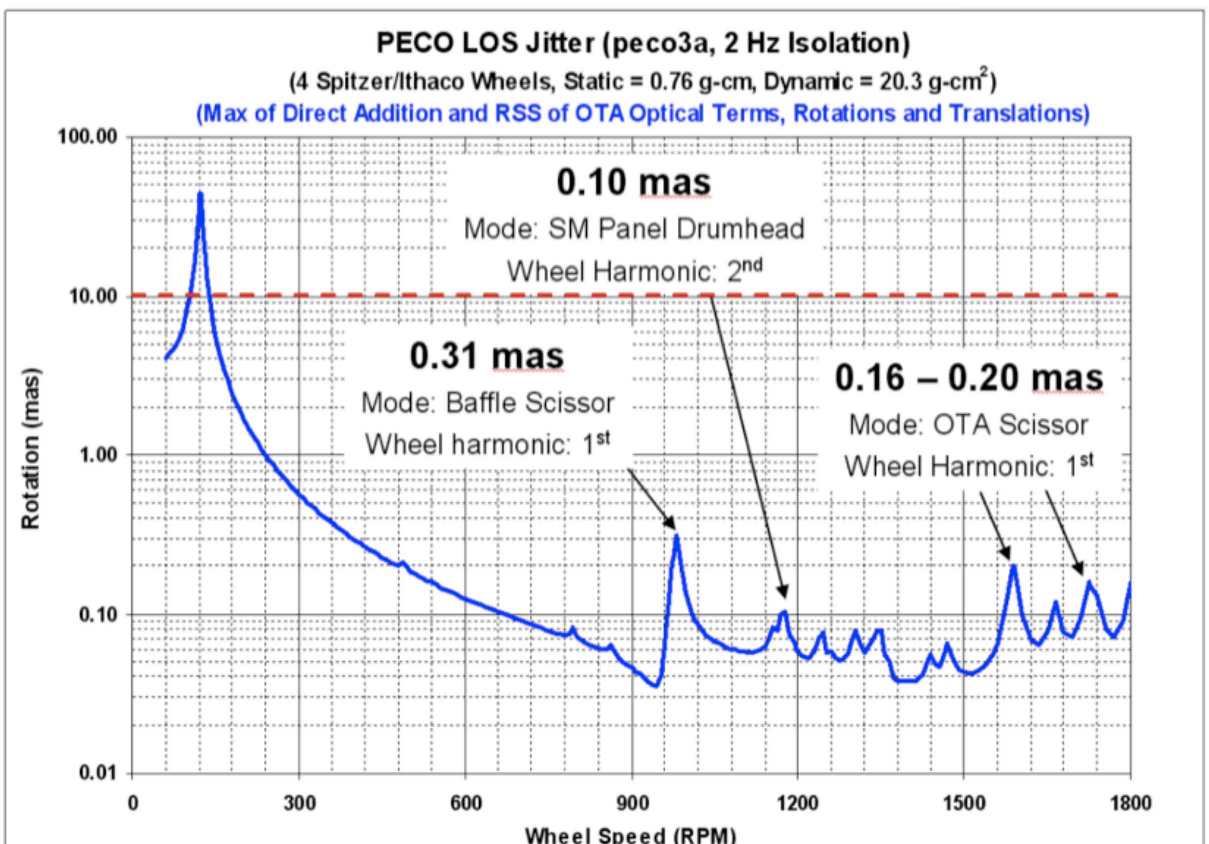
ITT

# PECO jitter analysis

- PECO model shows jitter requirement can be met with no new technology
- Reaction wheels passively isolated




PECO Pupil mapping Exoplanet Coronagraph Observer

# Summary

- PECO study shows **direct imaging and characterization of Earths/ Super-Earths possible with medium-scale mission** and:
  - maps exozodi down to <1 zodi sensitivity
  - census of planets and orbits  in each exosystem
  - extrasolar giant planets characterization

- "Conventional" telescope with off-axis mirror can be used (stability OK, wavefront quality OK). All the "magic" is in the instrument -> **raising TRL for instrument is key (coronagraph, wavefront control)**
  - technology development at ~$40M, 4yr

- PECO could launch in 2016. Total mission cost ~$810M including technology development

- PECO architecture can be scaled to a flagship 3-4 m telescope without new technologies or new launch vehicles