A bright future for direct imaging of extrasolar planets

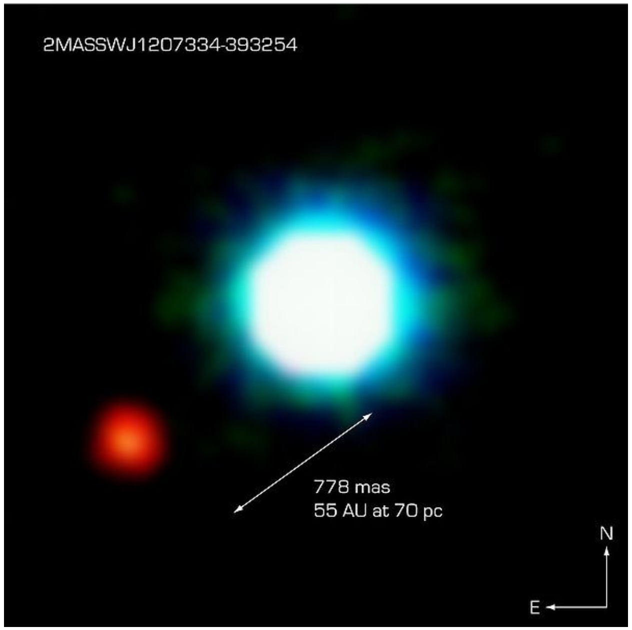
Olivier Guyon (guyon@naoj.org)
http://www.naoj.org/staff/guyon

Center for Astronomical Adaptive Optics, University of Arizona
Subaru Telescope, National Astronomical Obs. of Japan

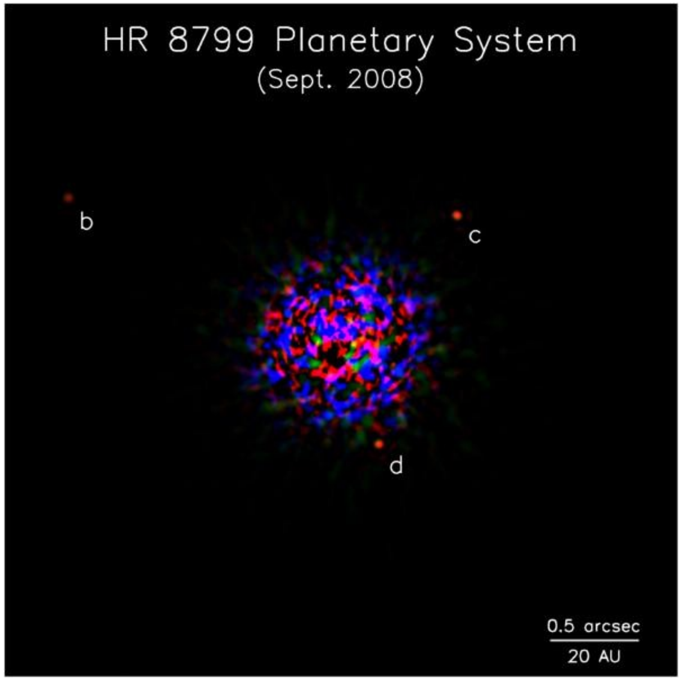
PECO team

SCExAO Team:
Frantz Martinache (Subaru)
Vincent Garrel (Subaru)
Takashi Yoshikawa (Subaru)
Kaito Yokoshi (Subaru)

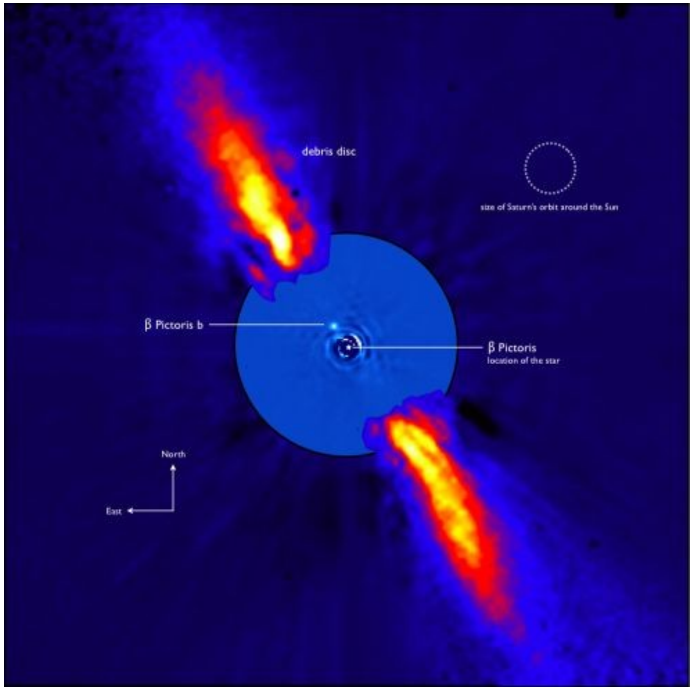
Ground-based near-IR imaging examples (without coronagraph !)



Chauvin et al. 2004

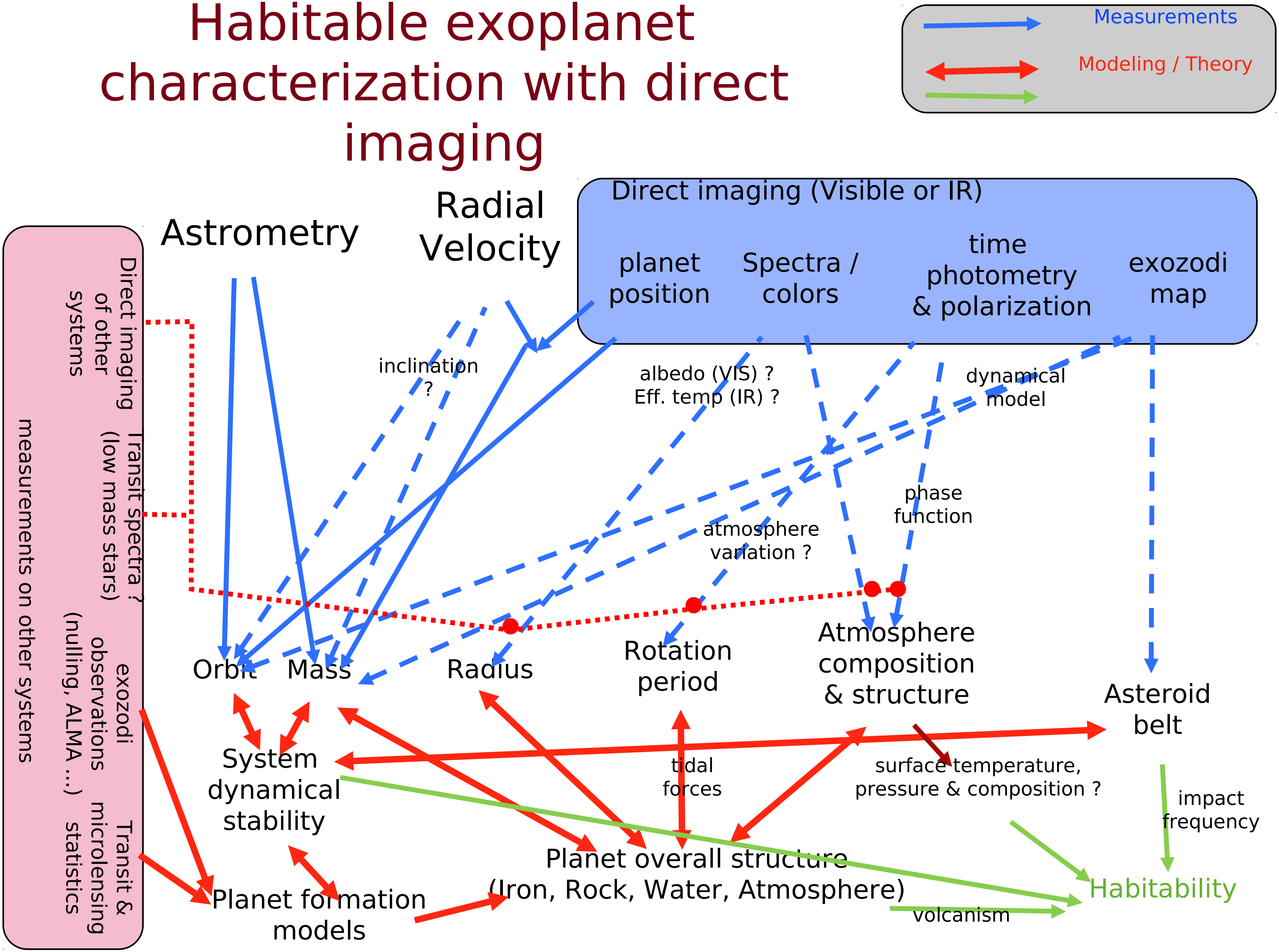


Marois et al. 2008



Lagrange et al. 2009

Habitable exoplanet characterization with direct imaging



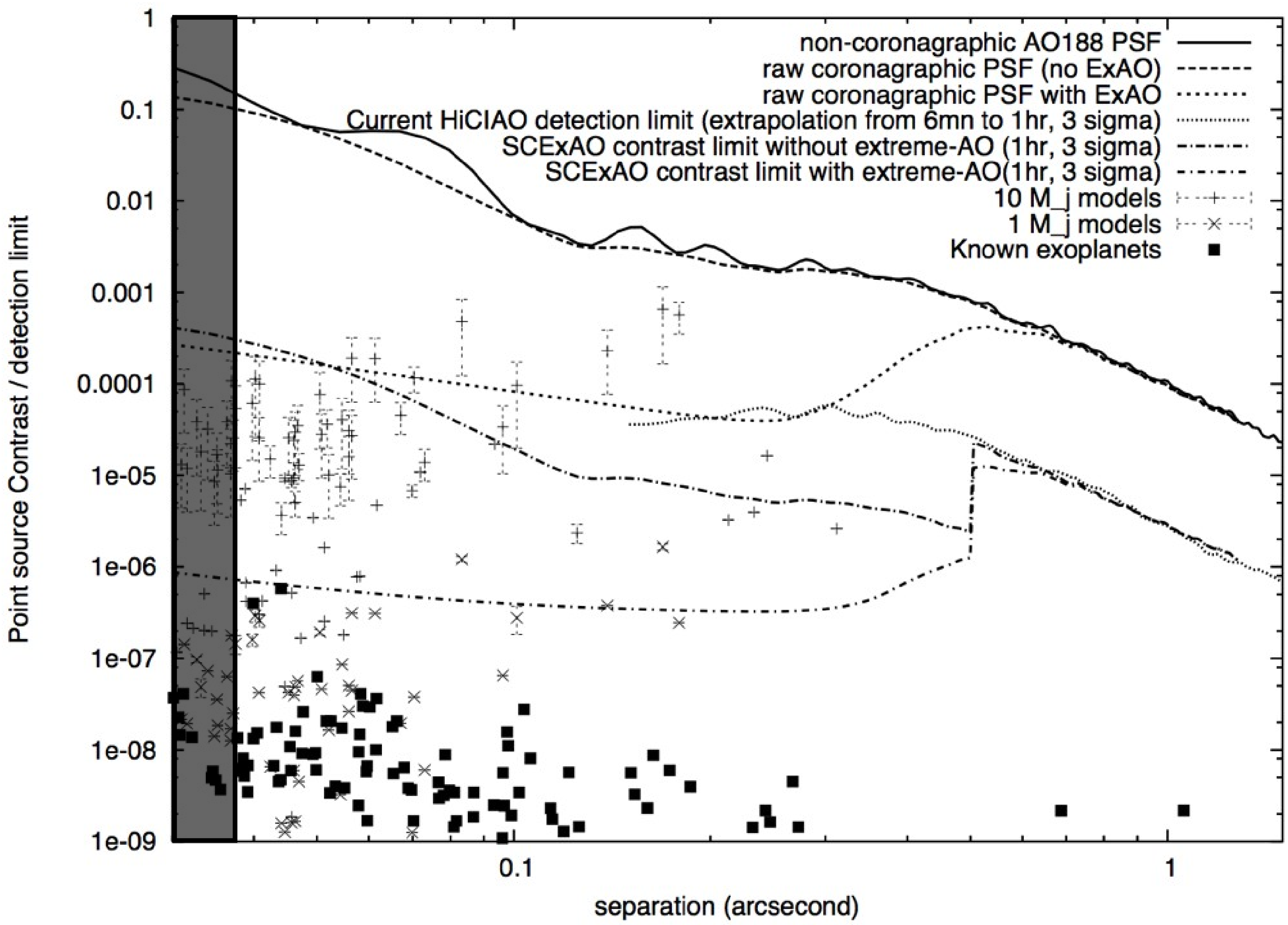
Ground-based imaging (Near-IR, with Adaptive Optics)

- DETECTION: Most sensitive to outer young massive planets (complementary to Radial Velocity, astrometry, transits) -> important for testing planetary formation models
- CHARACTERIZATION:
- Study planet formation by imaging both disks and planets
- Spectroscopy
- Small IWA + high contrast key to:
- constrain mass/age/luminosity relationship (cooling rate) with overlap with RV
- capture reflected light: large sample of “old” planet, many known from RV
- increase sample size (currently <10, probably most of them are “exceptions” to the rule)

Space-based imaging (Visible, extremely high contrast)

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

Example: SCExAO Expected performance

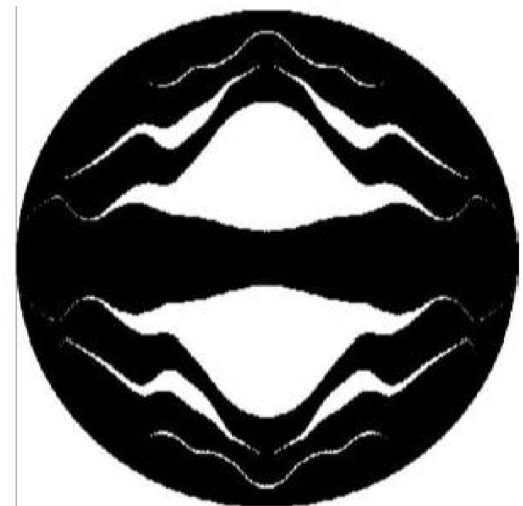


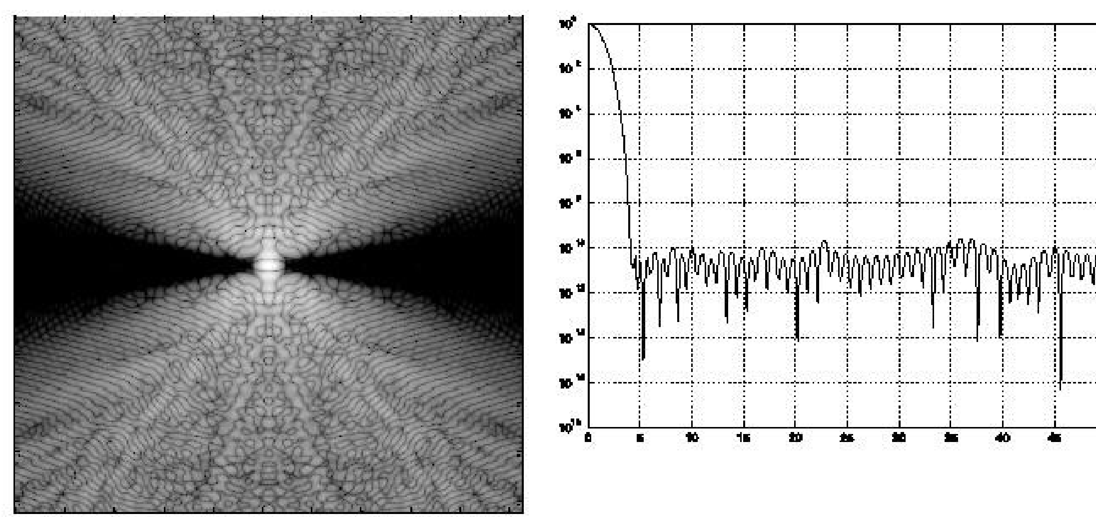
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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





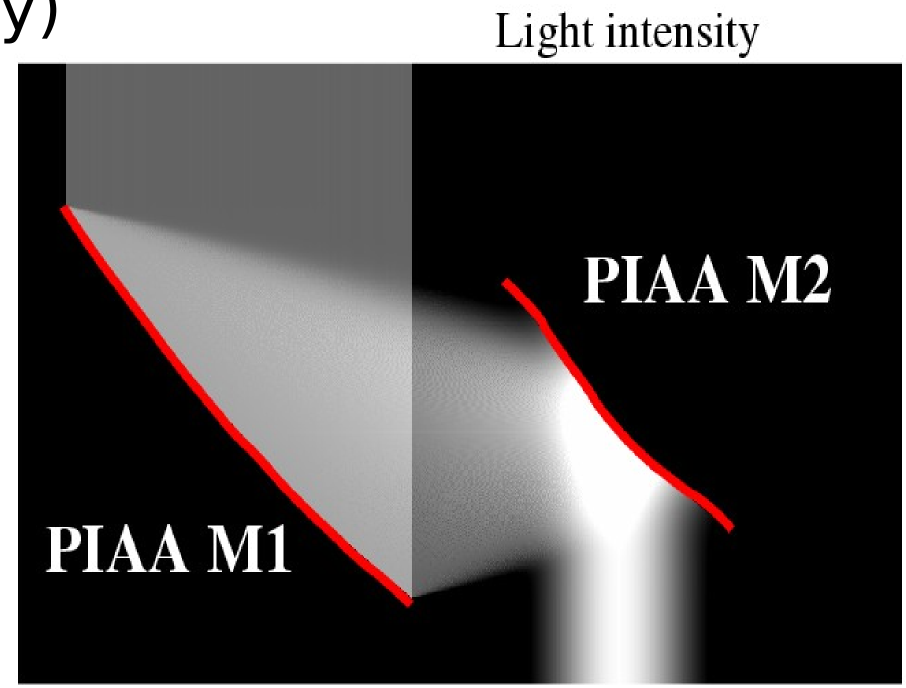
cquinot & Roisin-Dossier 1964
asdin et al. 2003, ApJ, 582, 1147
anderbei et al. 2003, ApJ, 590, 593
anderbei et al. 2003, ApJ, 599, 686
anderbei et al. 2004, ApJ, 615, 555

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.)

Phase-Induced Amplitude Apodization (PIAA) coronagraph

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

- high contrast (limited by WF quality)
- 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)



yon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

Coronagraph performance

New coronagraphs now approach theoretical limit.

PIAA coronagraphs appear particularly attractive

1e10 contrast

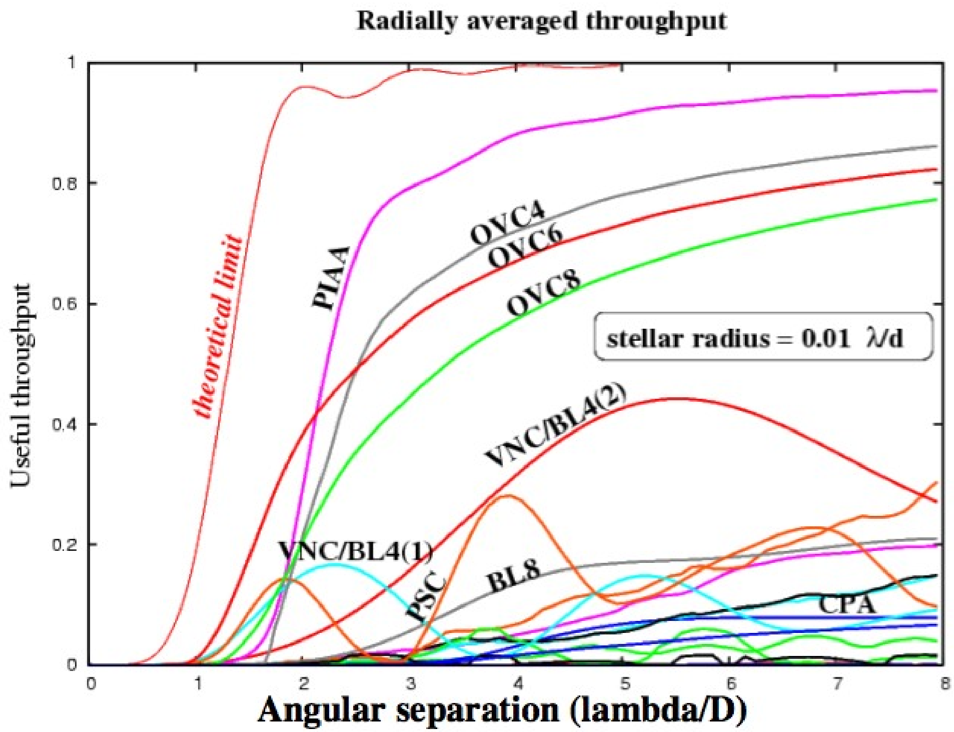


Figure 3-1: Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional Pupil Apodization.

PIAACMC (Guyon et al., submitted)

1e10 contrast
central point source

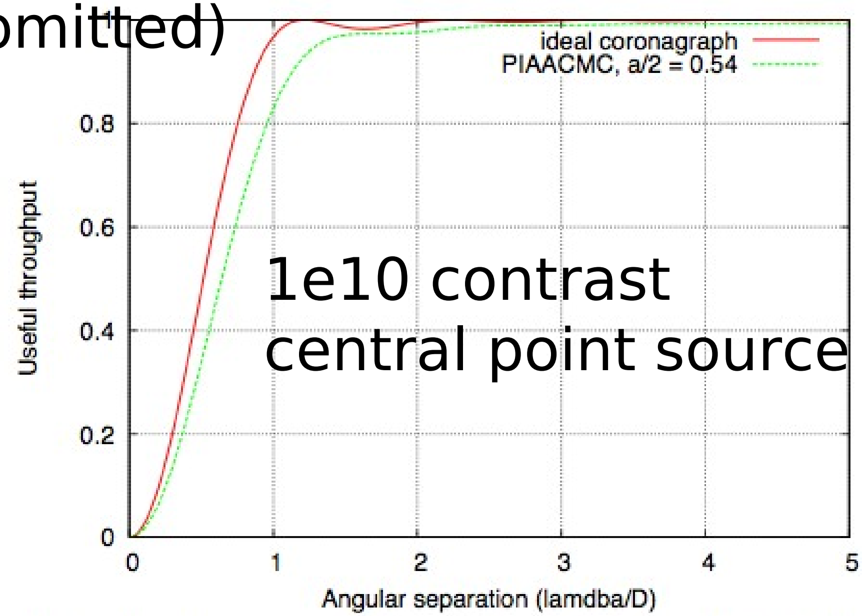
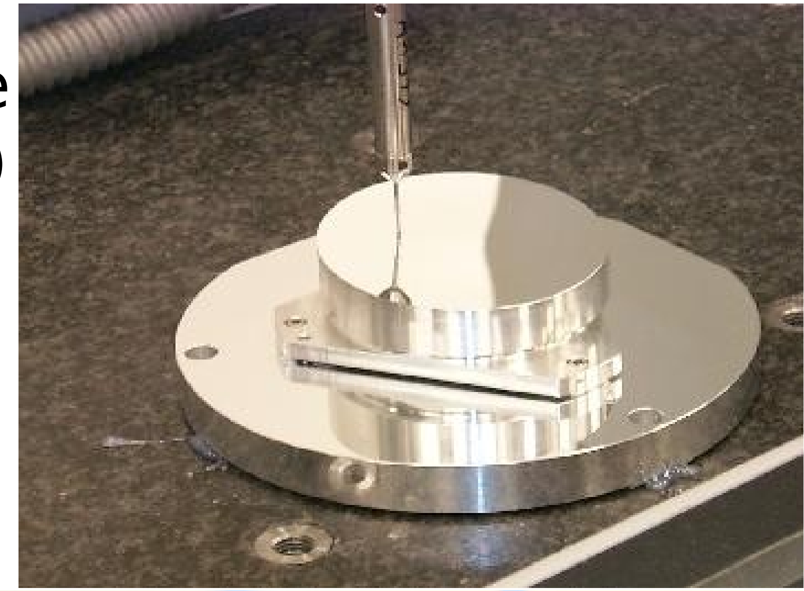


FIG. 6.— Comparison between the useful throughput of the PIAACMC with $a/2 = 0.54$ and the theoretical ideal performance limit of coronagraphy.

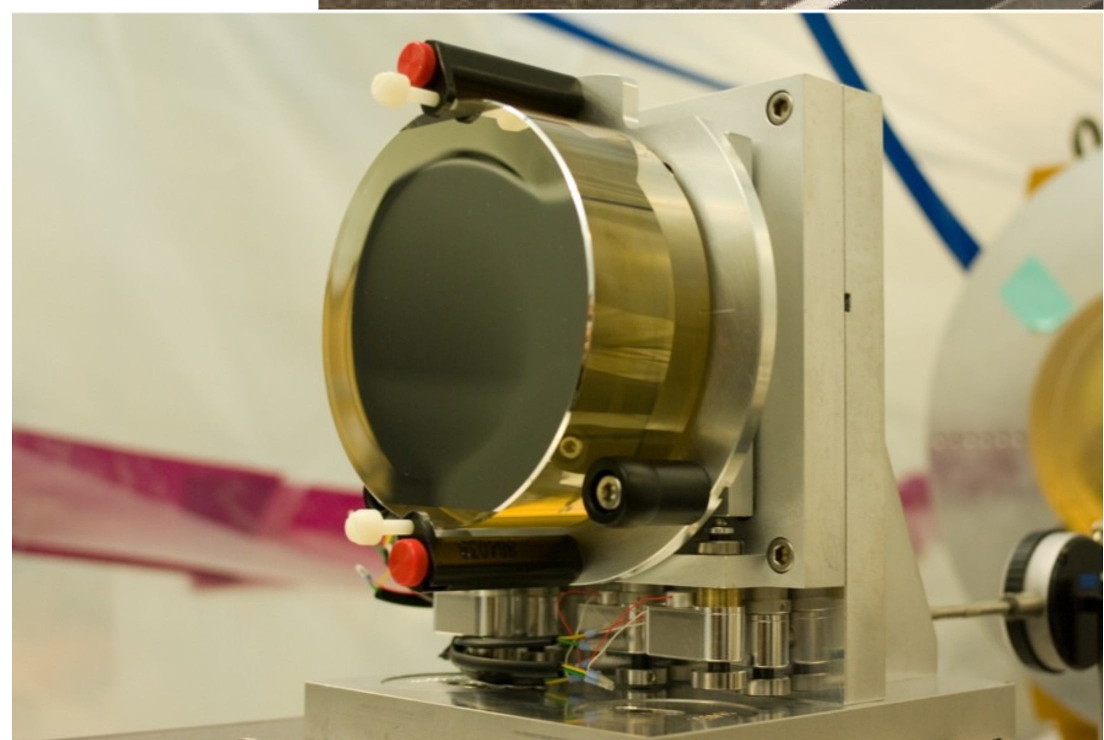
PIAA coronagraph development

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

- PIAA optics design & fabrication for Space
- 1st generation optics (diamond turned Al)
- 2nd generation optics (Zerodur)

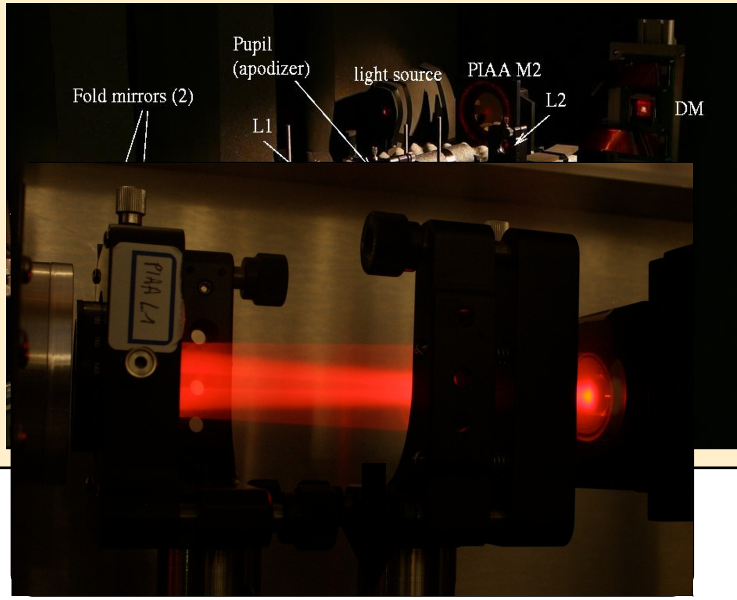


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

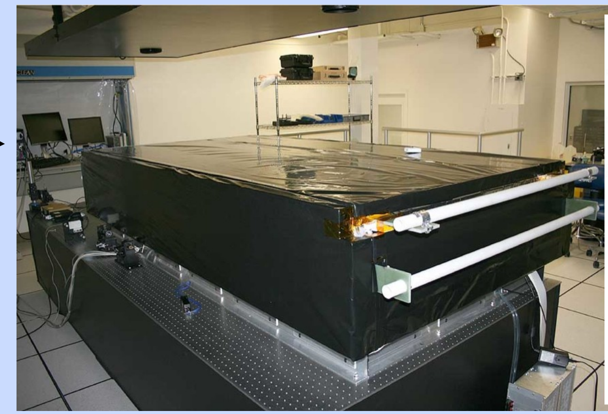


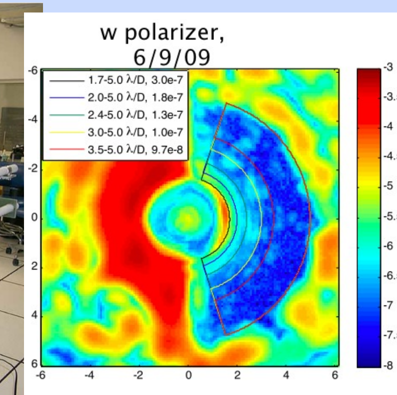
PIAA coronagraph development - labs

Subaru PIAA testbed was used for the first demonstration of PIAA coronagraphy.



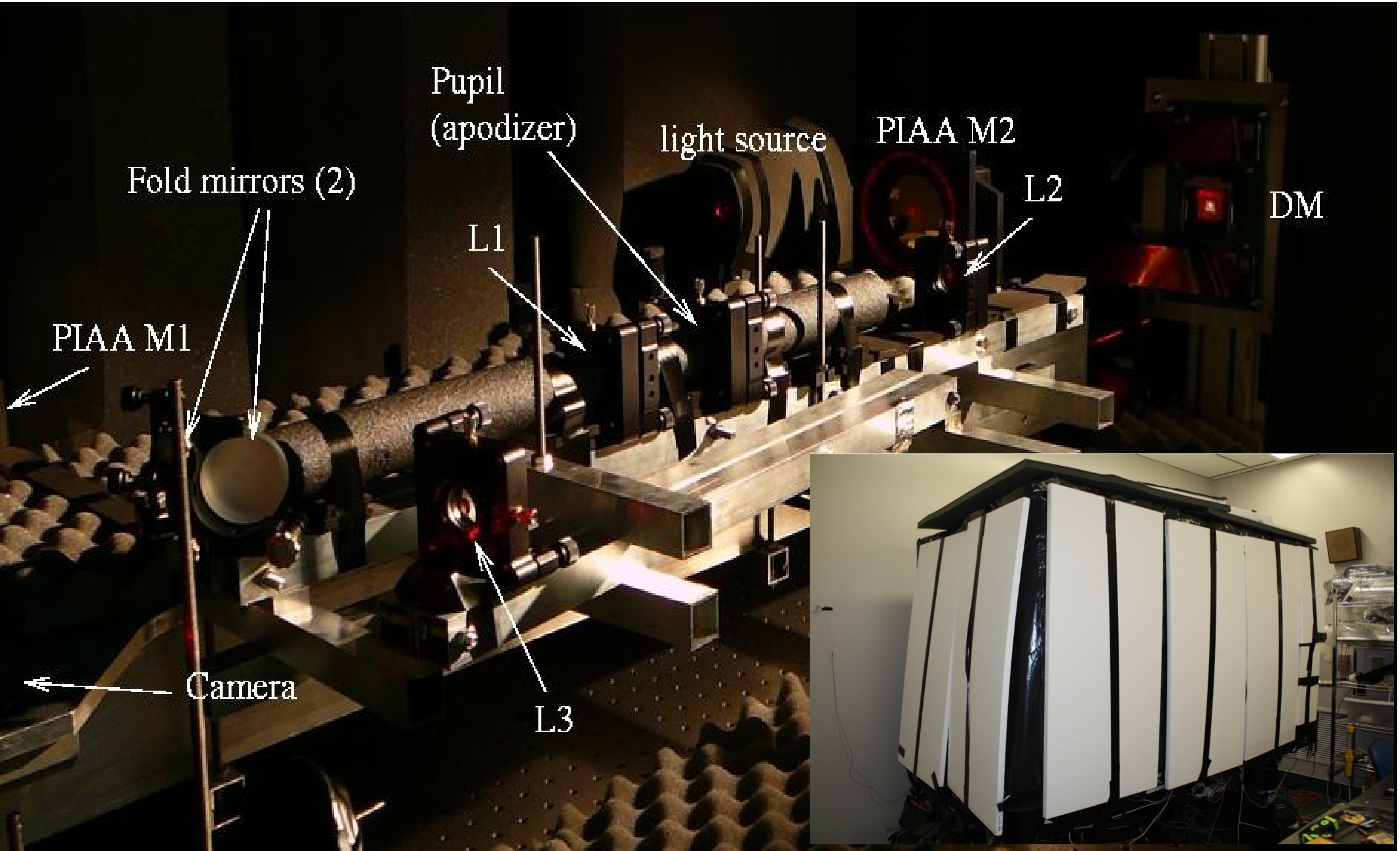
High contrast (space) lab efforts now at NASA JPL & NASA Ames.





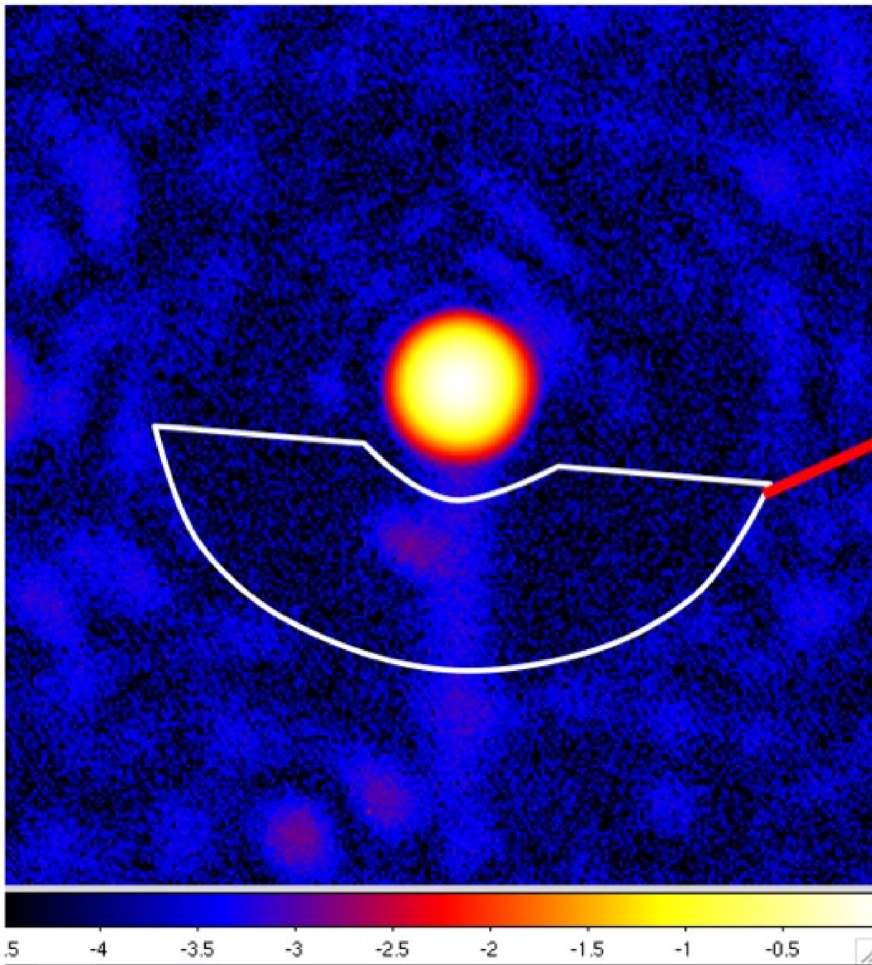
PIAA-dedicated testbed at NASA Ames testing WFC architectures with MEMs DMs.

High Contrast Imaging Testbed (HCIT) at NASA JPL operates in vacuum and has been validated to 1e10 contrast. PIAA tests have started earlier this year.

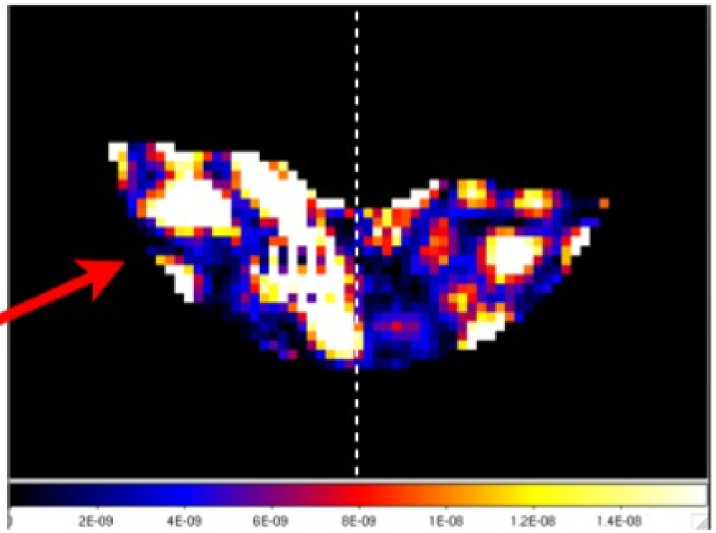

Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

Subaru lab demonstration

Raw image



Coherent starlight (single frame)



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

Contrast achieved in 1.65 to 4.5 l/D zone:
1.6e-7 incoherent halo ghost (equivalent to exozodi)
3.5e-9 coherent bias (measured over 1300 frames)

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

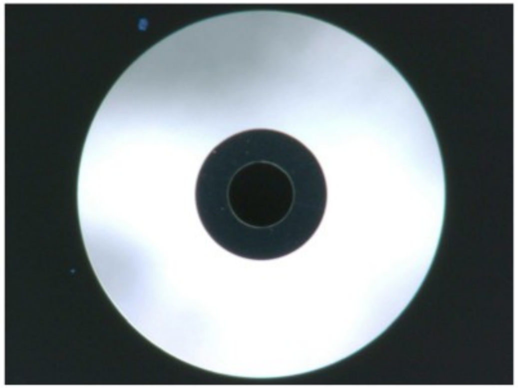
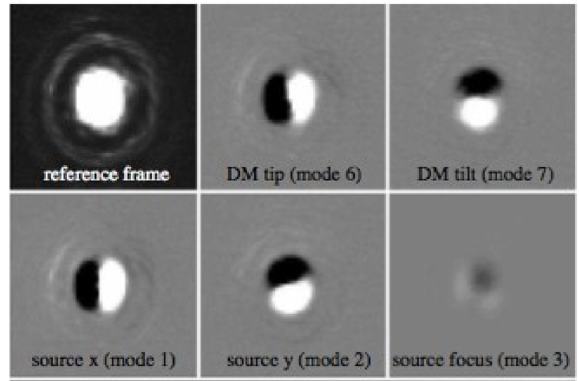
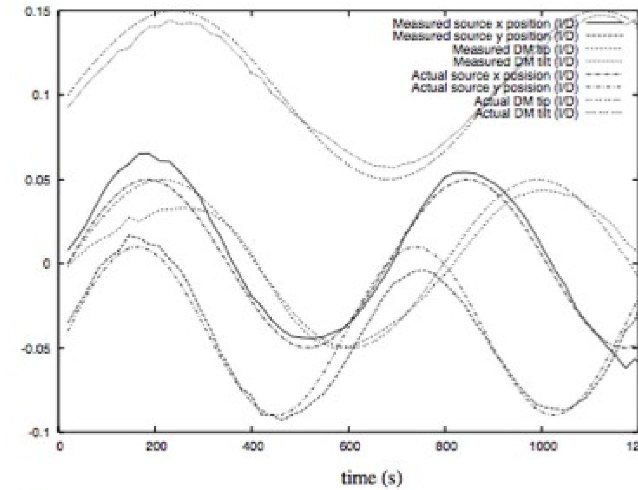
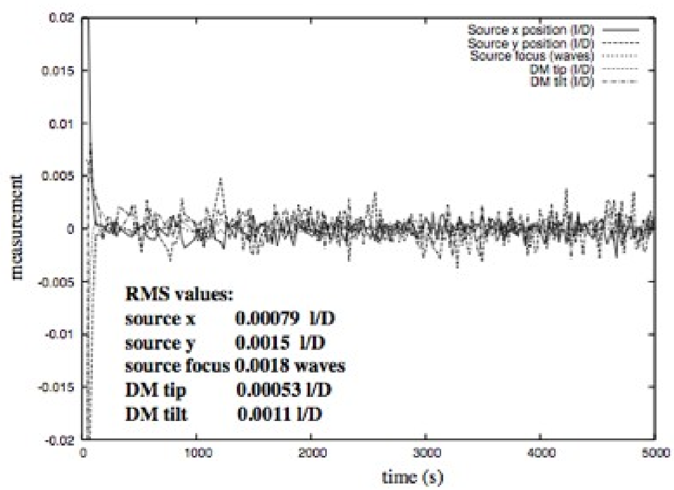


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

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.
New “lookup table” algorithm removes residual low order coronagraphic leaks.
ref:
Guyon, Matsuo, Angel 2009
Vogt et al. 2010 (in prep)







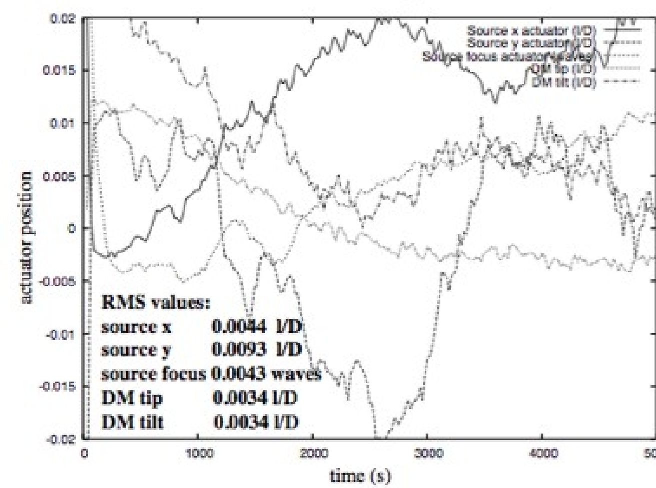
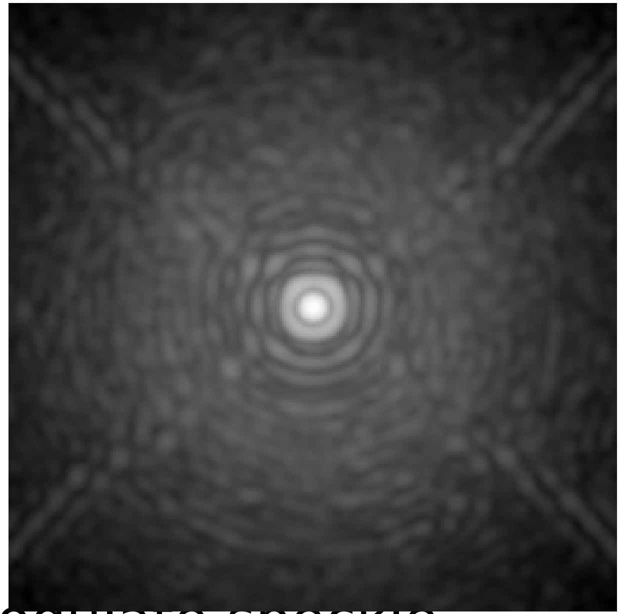


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. 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} λ/D for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

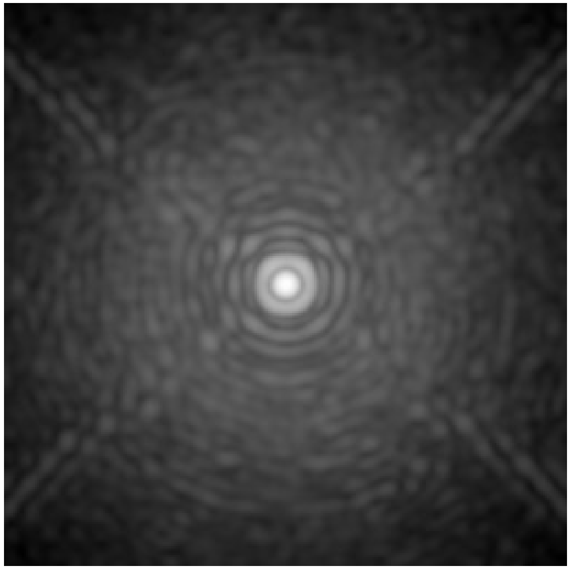
Calibration: Is is a Speckle, is it a planet ?

pectra differential imaging (SDI)
ptimized for methane-bearing giant planets
Vill only detect planets with a given spectral feature
olarization differential imaging (PDI)
egree of polarization may be low (few %)
nly works on reflected light
ngular differential imaging (ADI)
erforms well if static speckles are strong
oes not work well at small angular separations



oherent differential imaging (CDI)
se DM to introduce a know variation in the WF to modulate speckle
ntensity
an reach photon noise limit if system is very well calibrated and CDI is
erformed quickly (or simultaneously)

Focal plane wavefront sensing and calibration



Use Deformable Mirror (DM) to add speckles

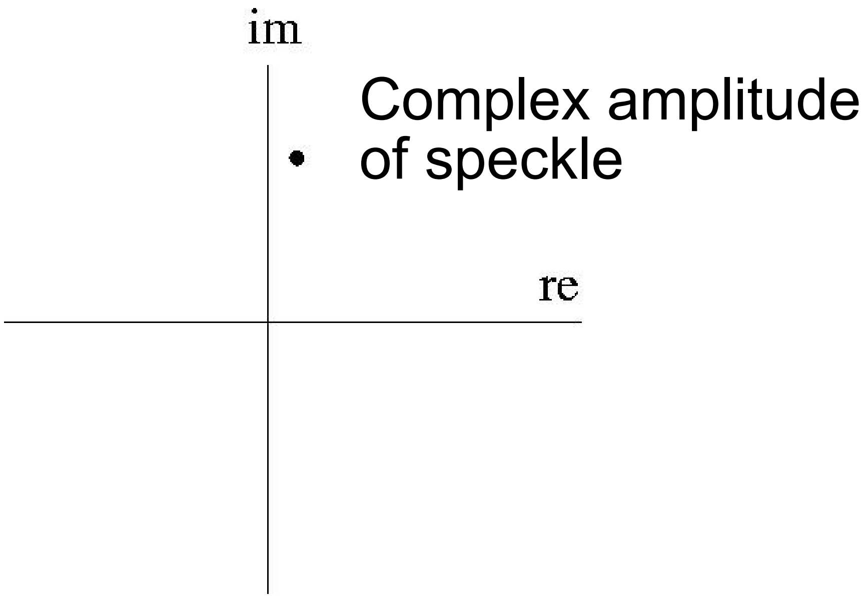
SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere (phase diversity with DM instead of simple focus)
Note: simultaneous measurement schemes also exist

CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

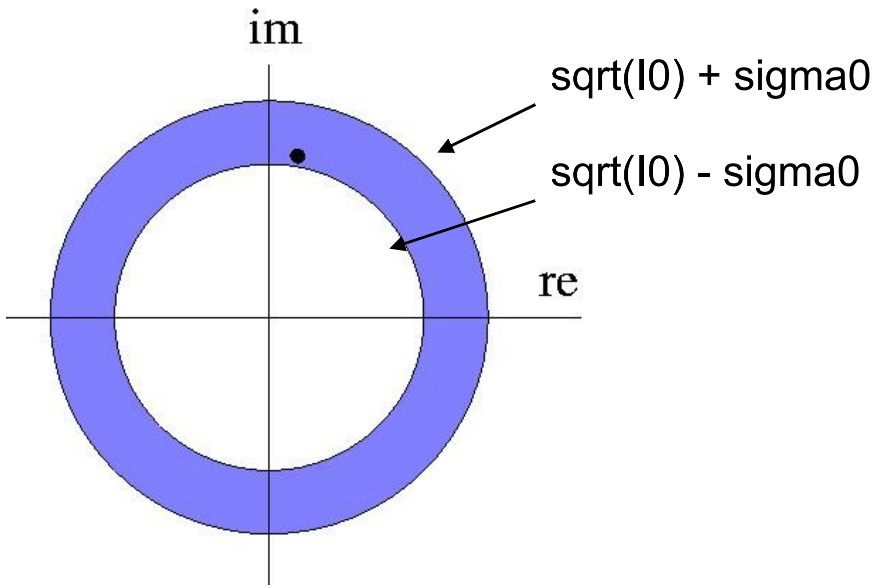
CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

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

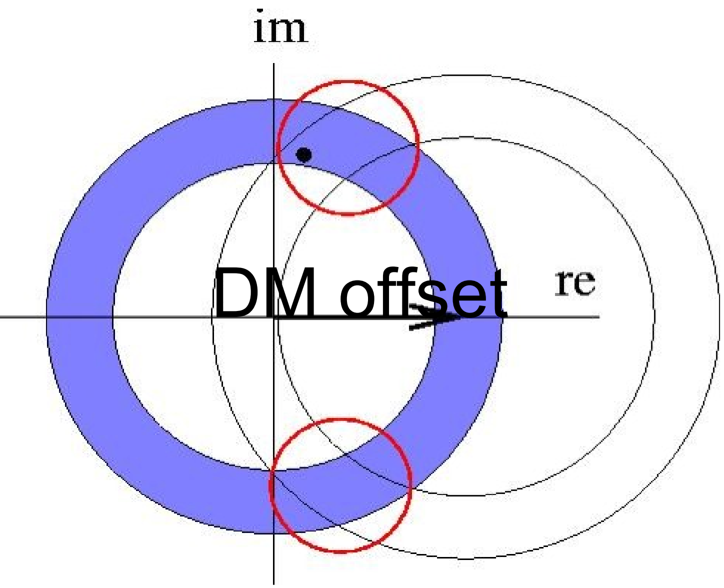
Initial problem

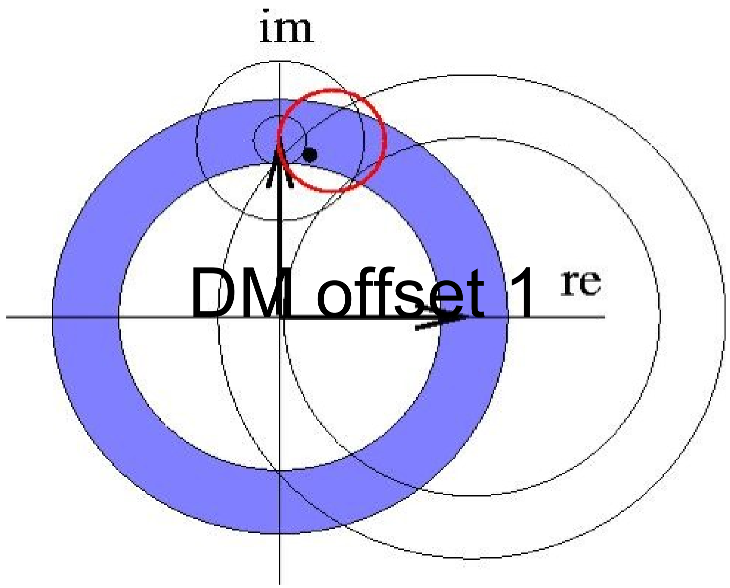


Take a frame -> measured speckle intensity = I0



DM offset chosen to be ~ equal to speckle amplitude

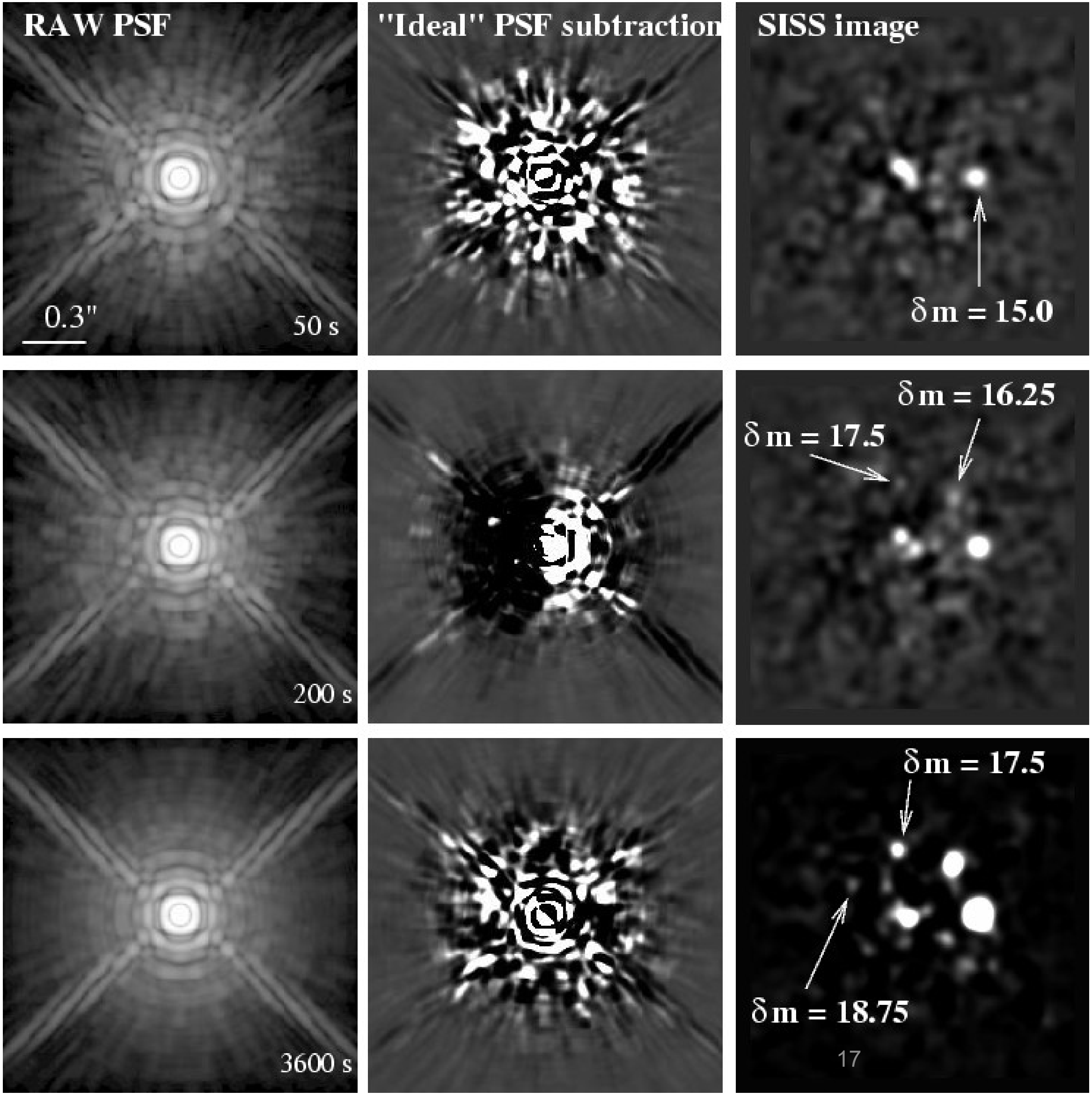




CALIBRATION

Speckle calibration with active coherent modulation recovers faint sources

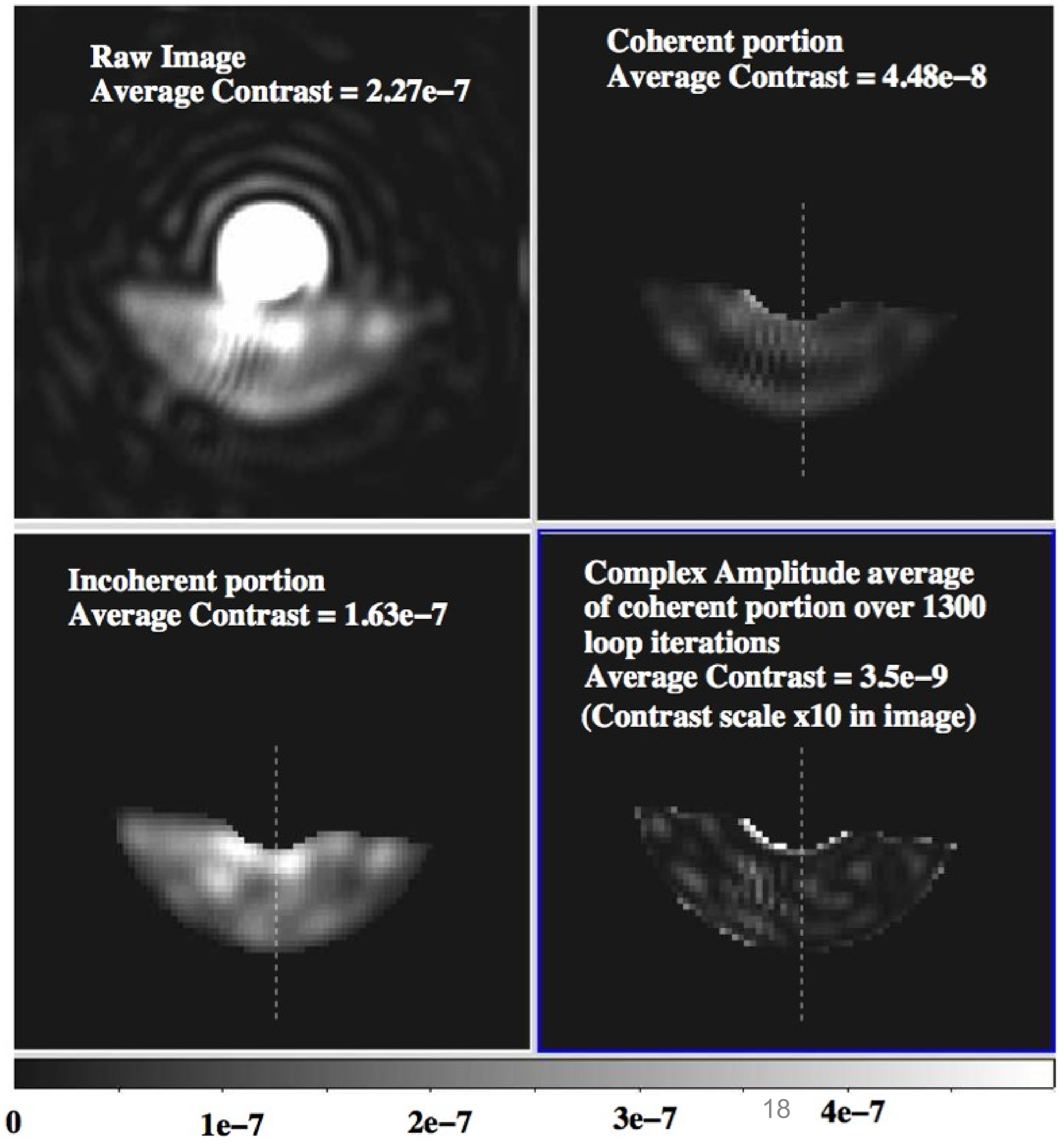
SISS (Guyon, 2004)



Coherent speckle calibration

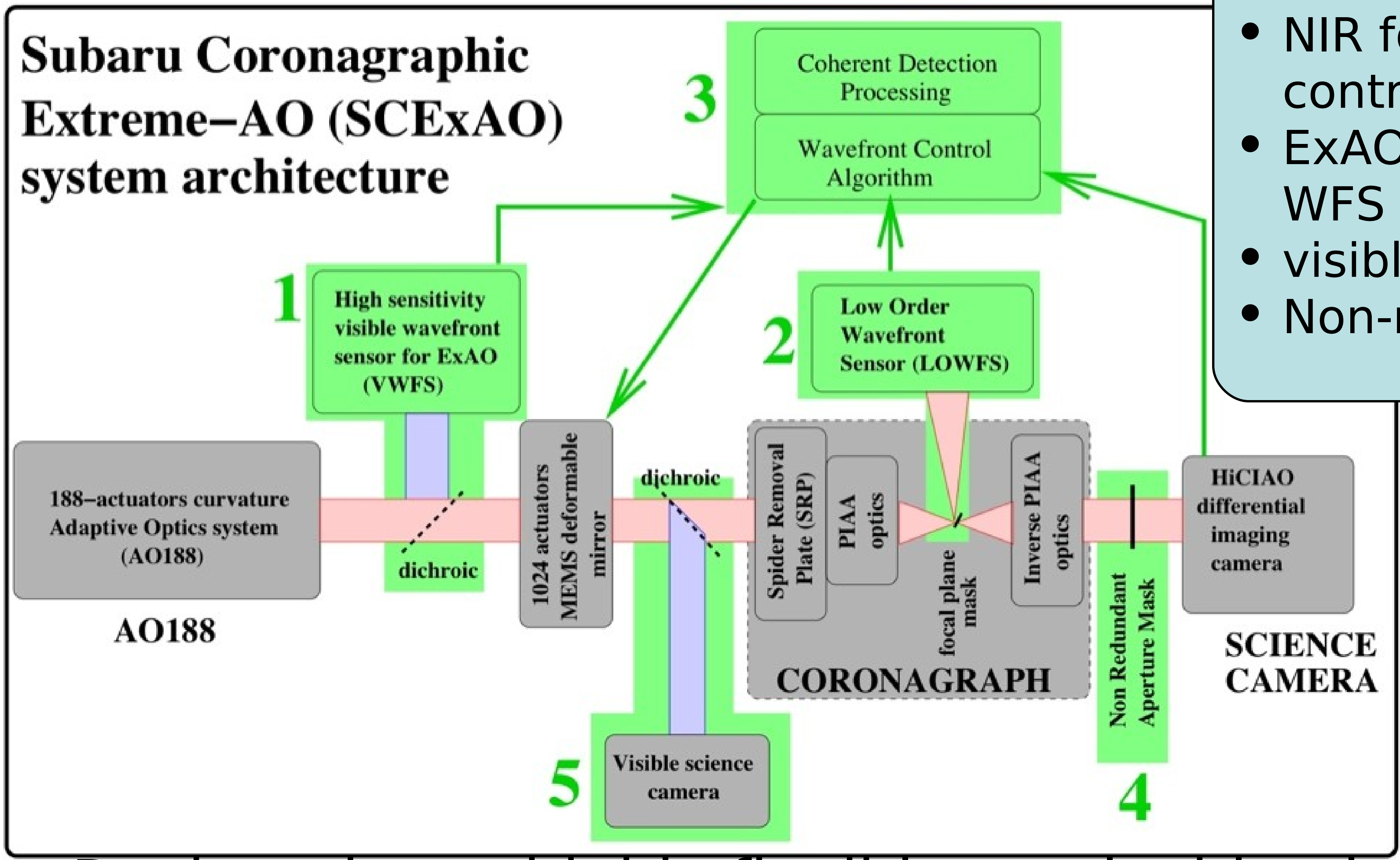
Coherent detection works in the lab alongside FPAO

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



The Subaru Coronagraphic Extreme-AO (SCExAO) system

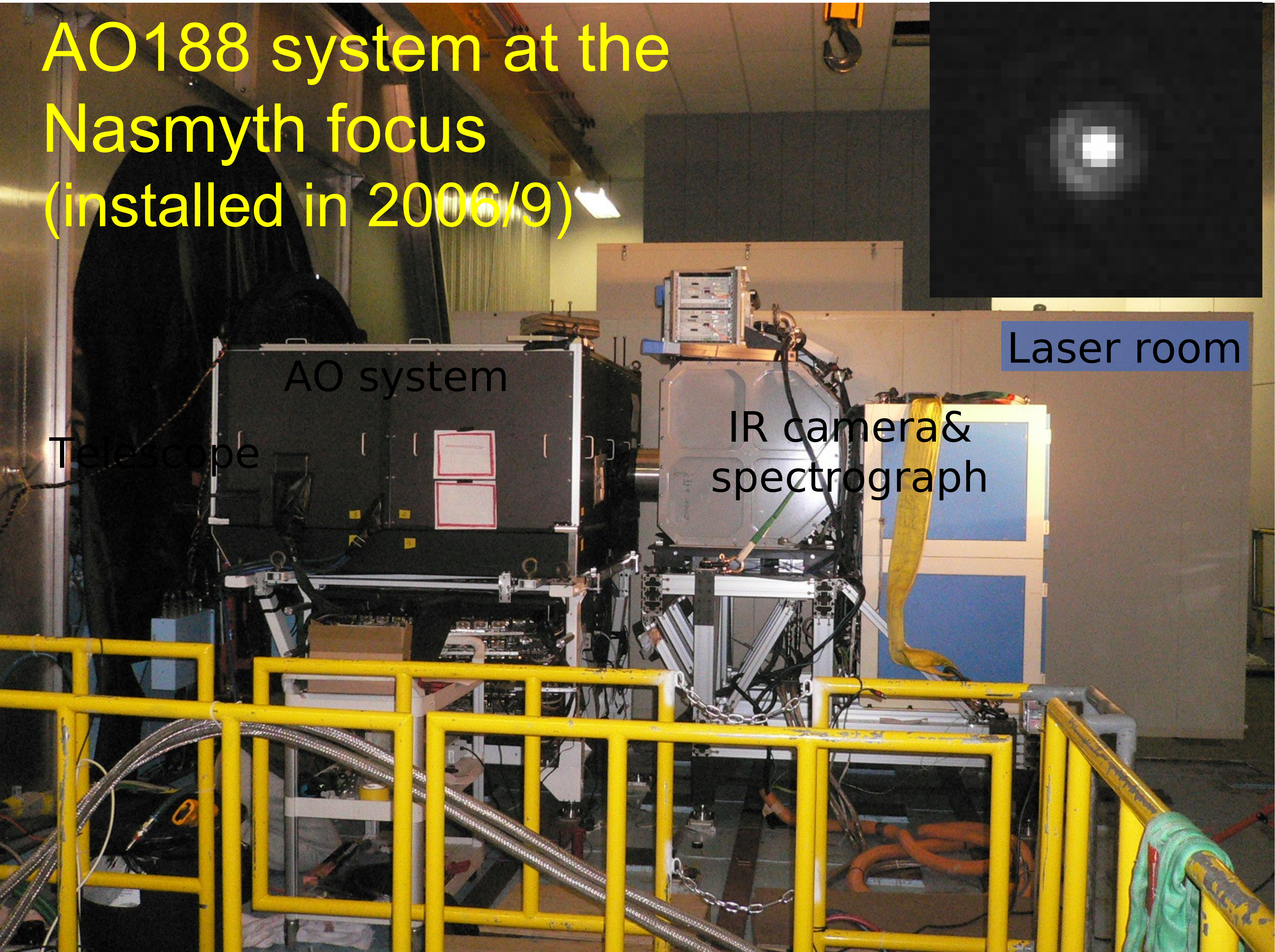
http://www.naoj.org/Projects/SCEXAO/



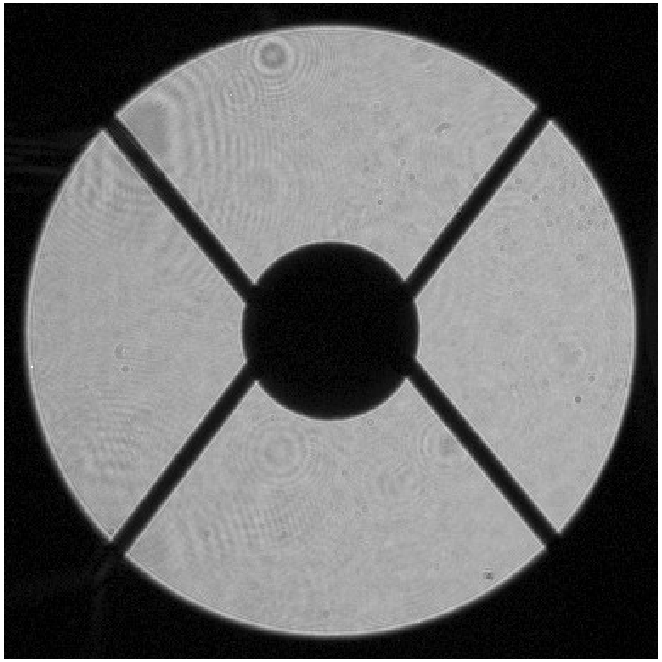
- 1 l/D PIAA coronagraph
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS
- visible channel
- Non-redundant masking

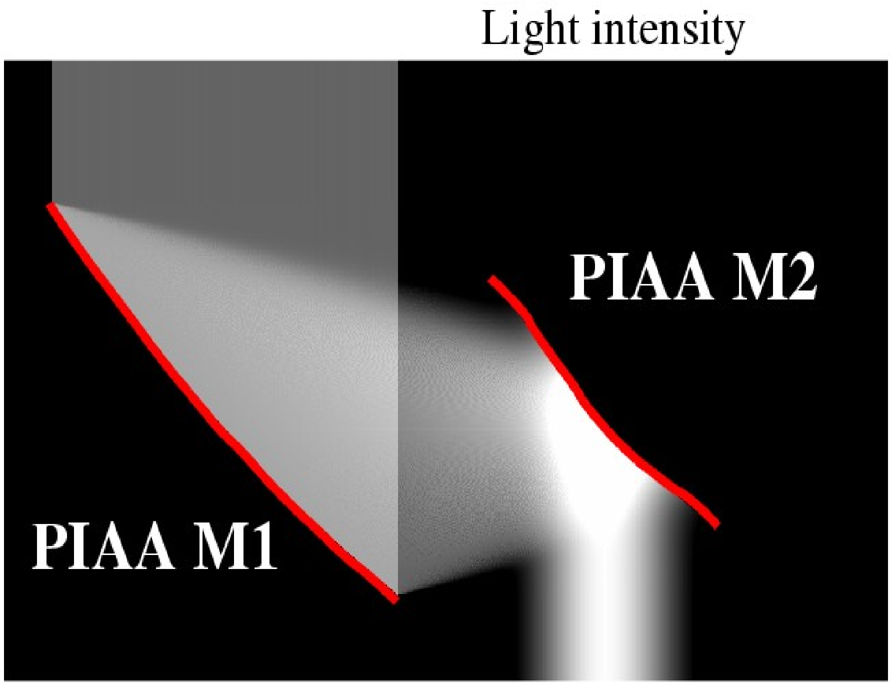
Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
First light in mid 2010

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

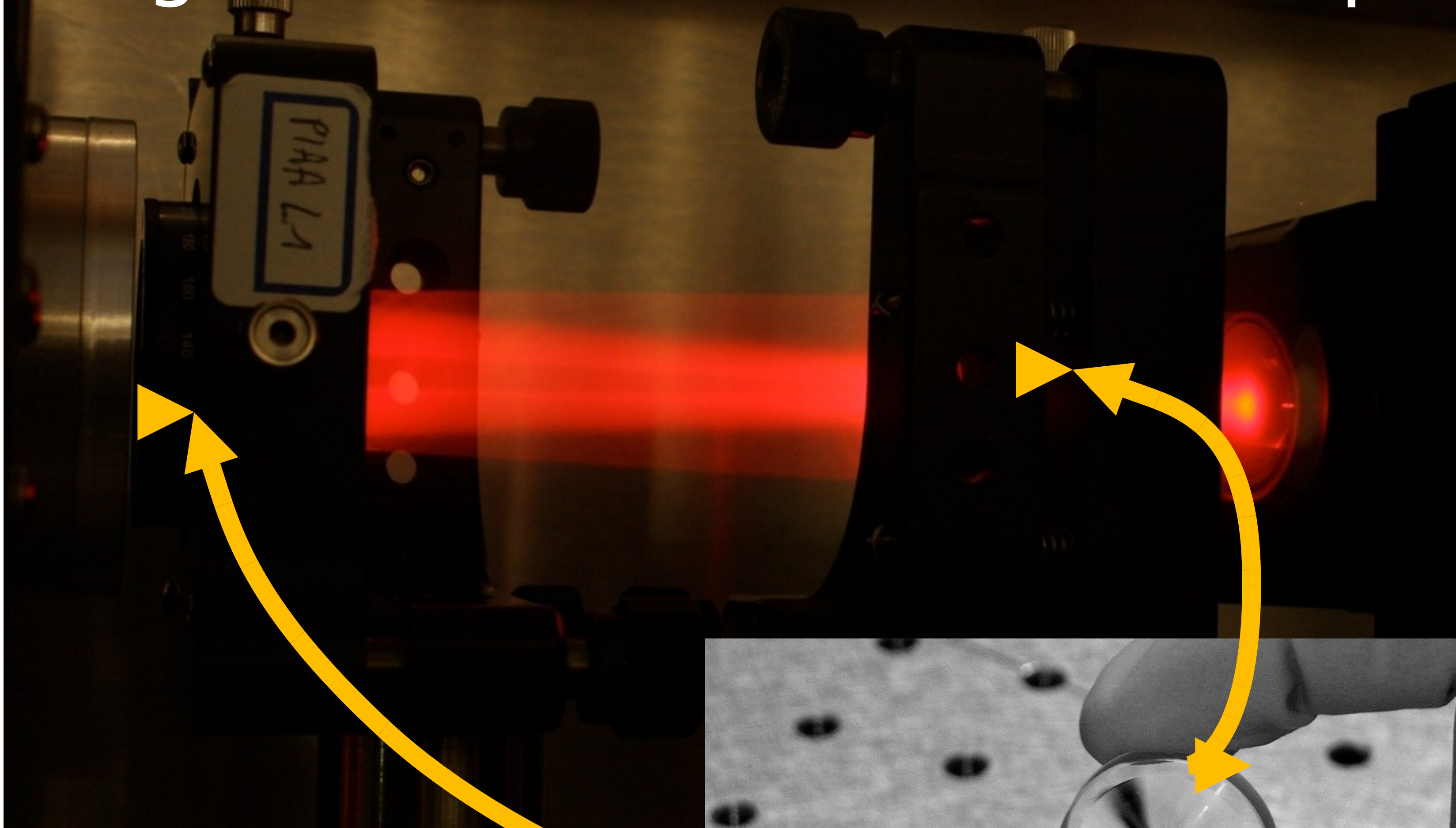


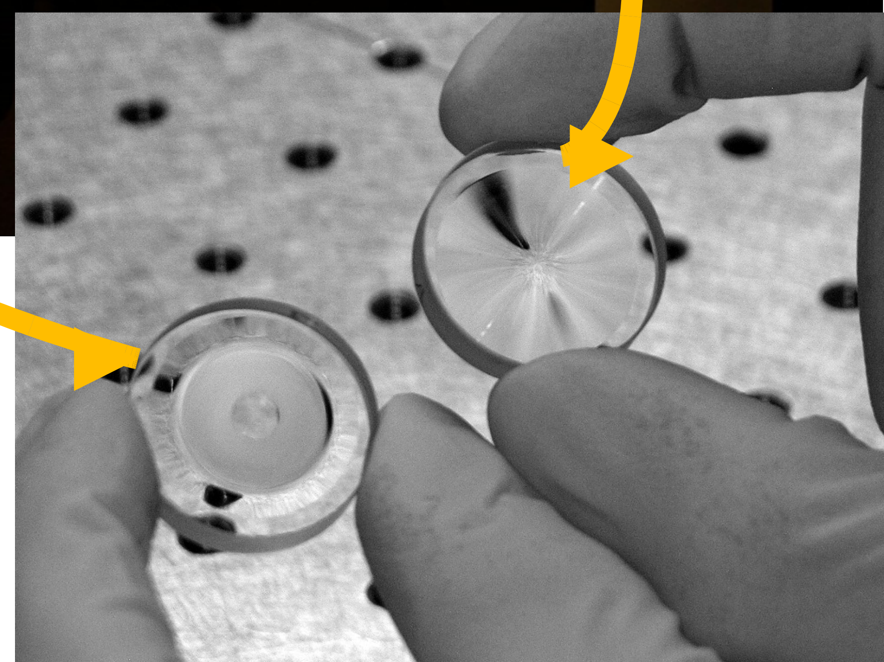
Pupil shape: challenge for coronagraphy





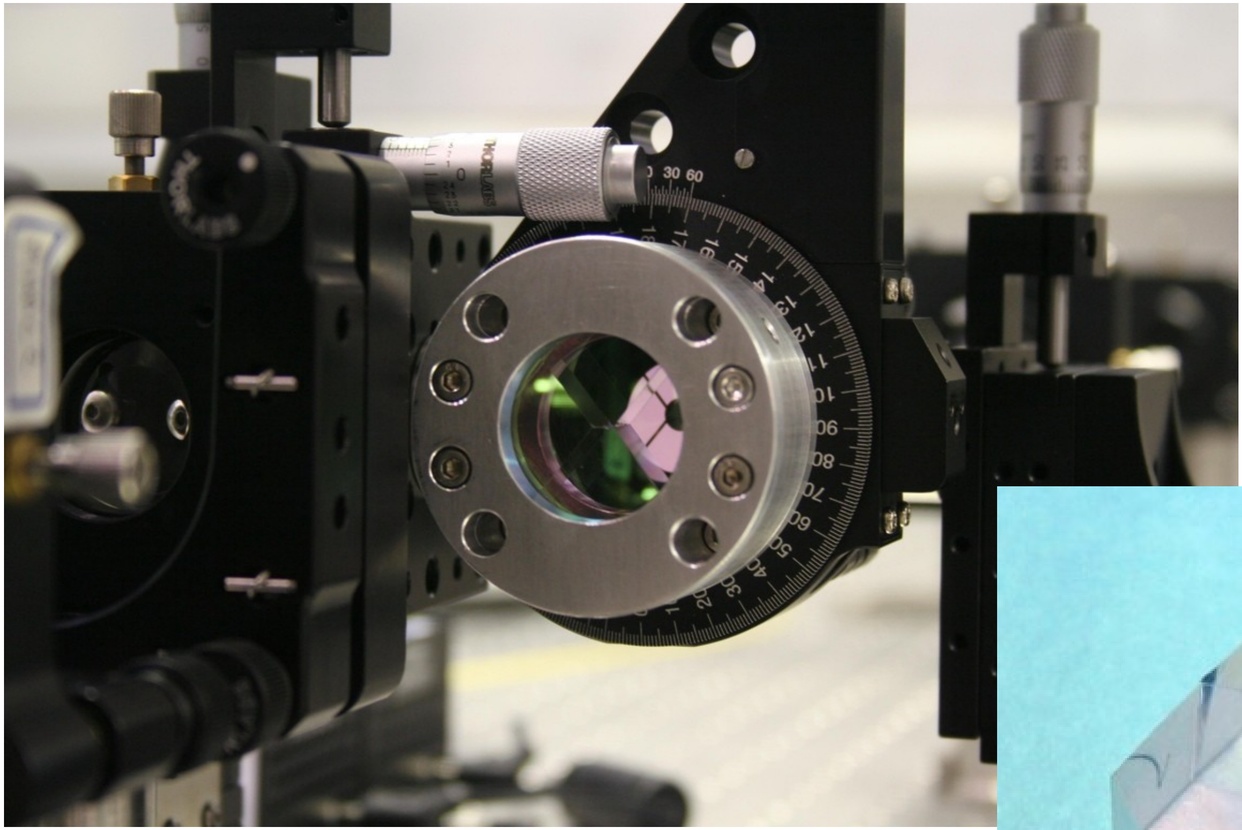
3rd generation refractive PIAA optic

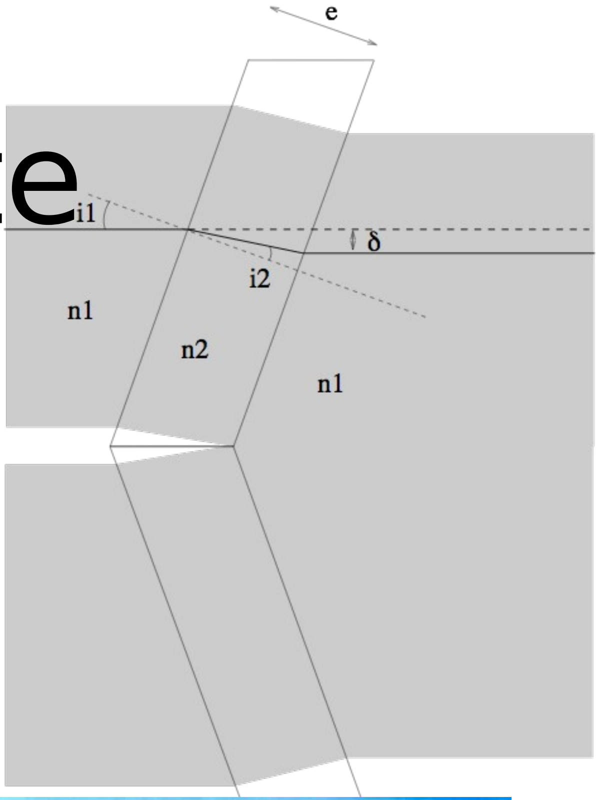




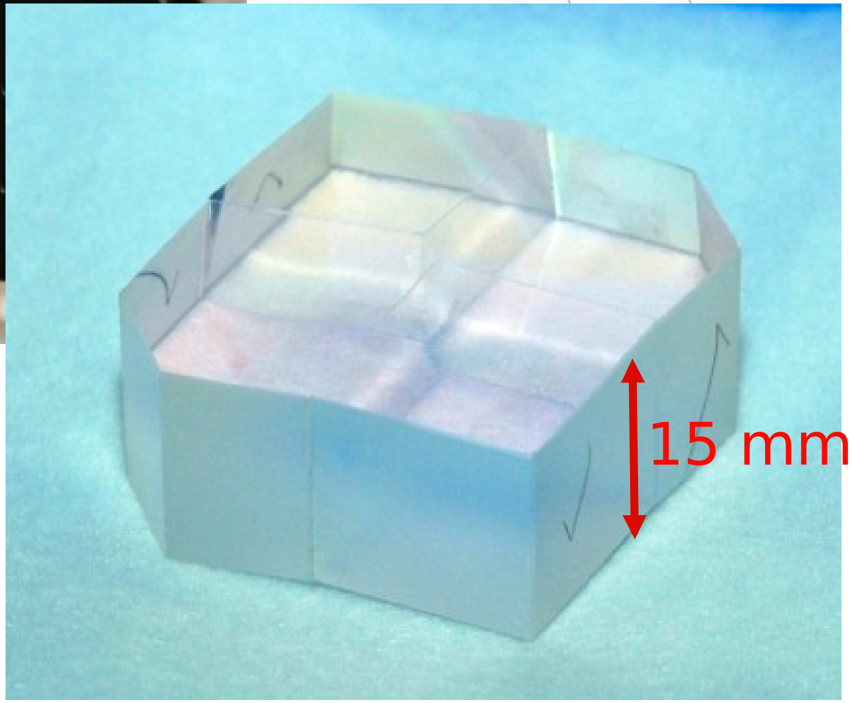
- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

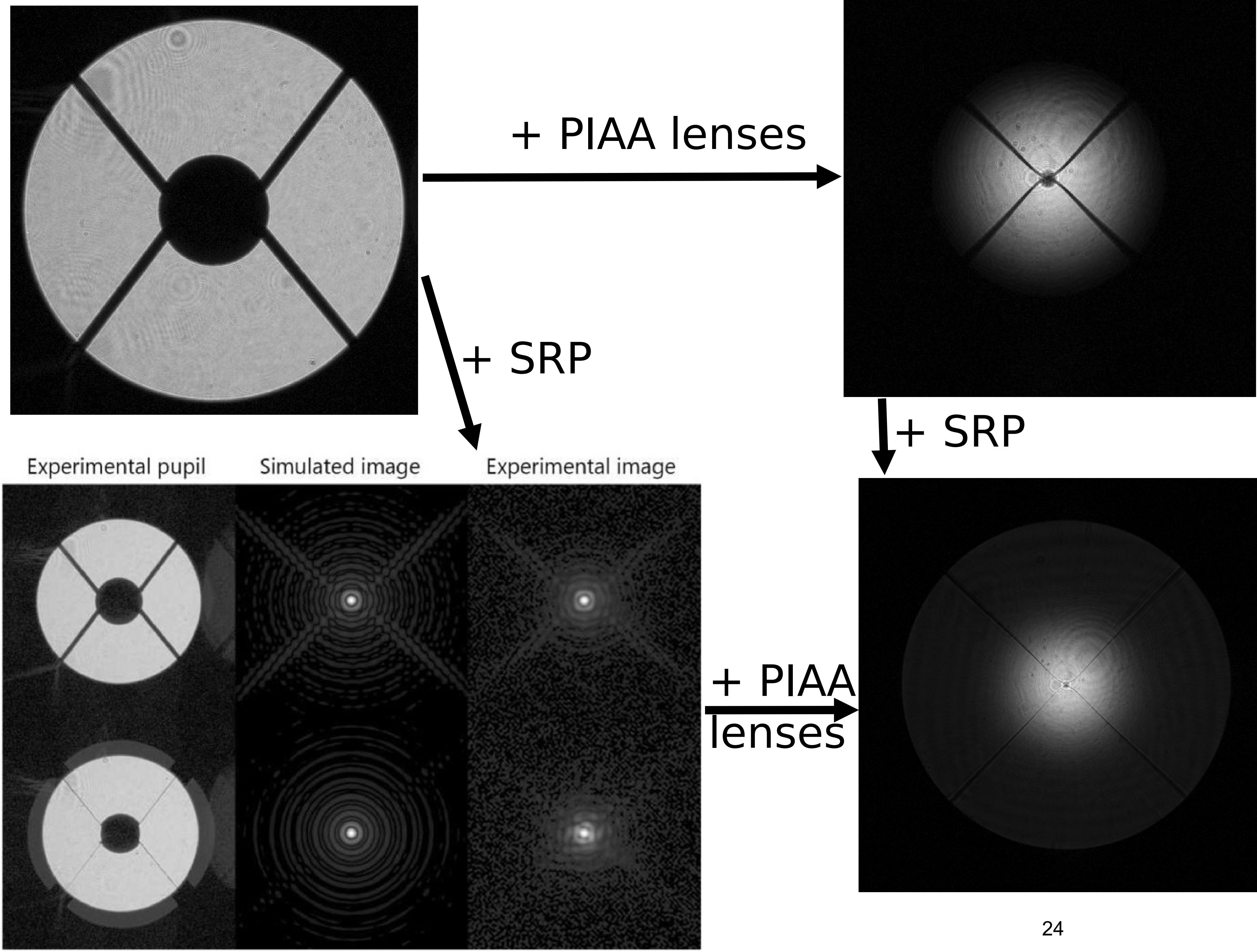
Spider Removal Plate





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




+ PIAA lenses
+ SRP
+ SRP
Experimental pupil
Simulated image
Experimental image
Without SRP
With SRP
+ PIAA lenses

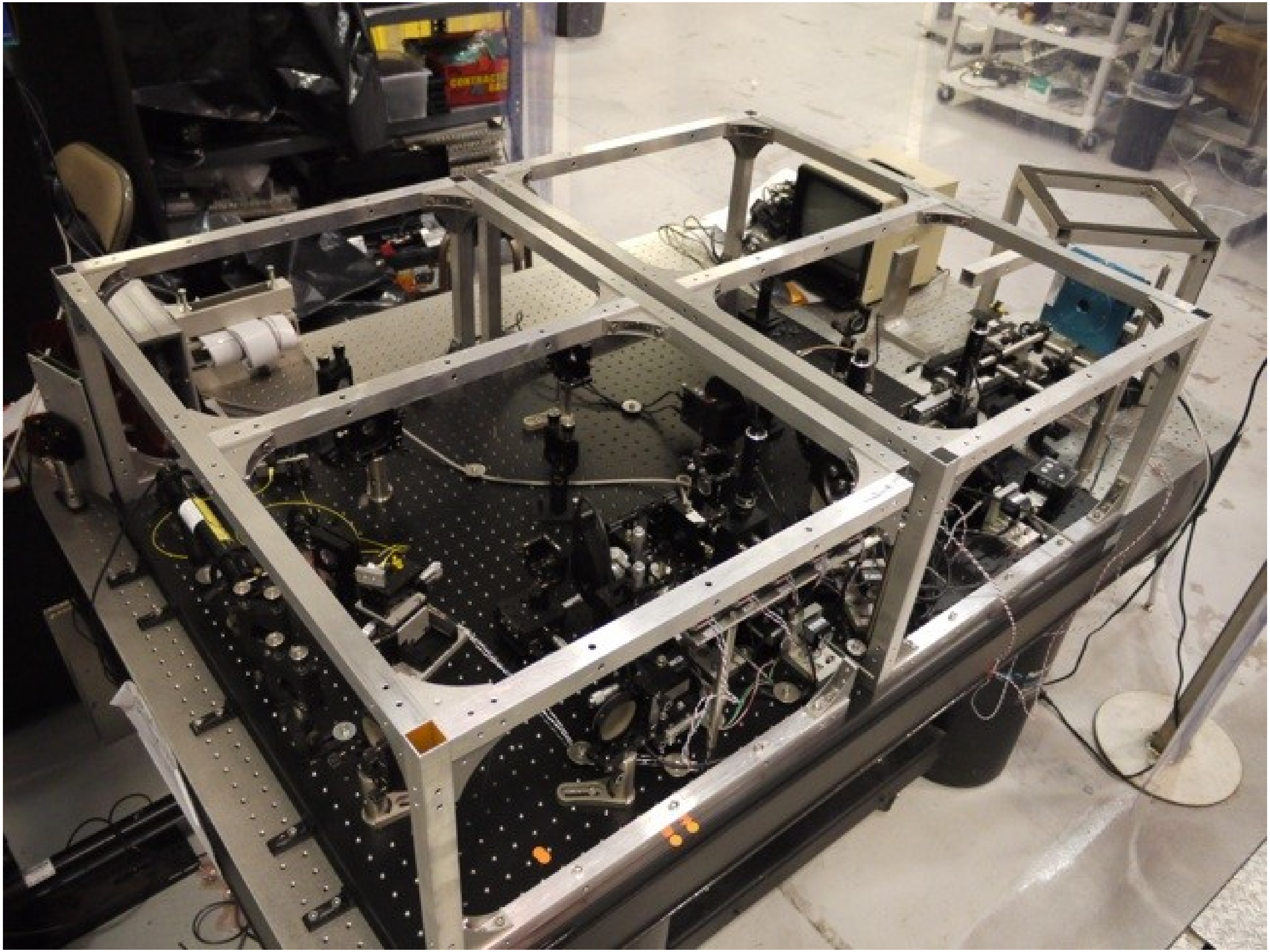
Project Overview

- Highly flexible system, incremental upgrade
- Uses HiCIAO differential camera, optimized for H band
- New frame can hold [SCExAO + HiCIAO] or HiCIAO only
- First light in mid 2010

- Phase 1 (2010):
  - PIAA
  - Vis imaging
  - Aperture Masking
  - Focal plane AO
  - LOWFS

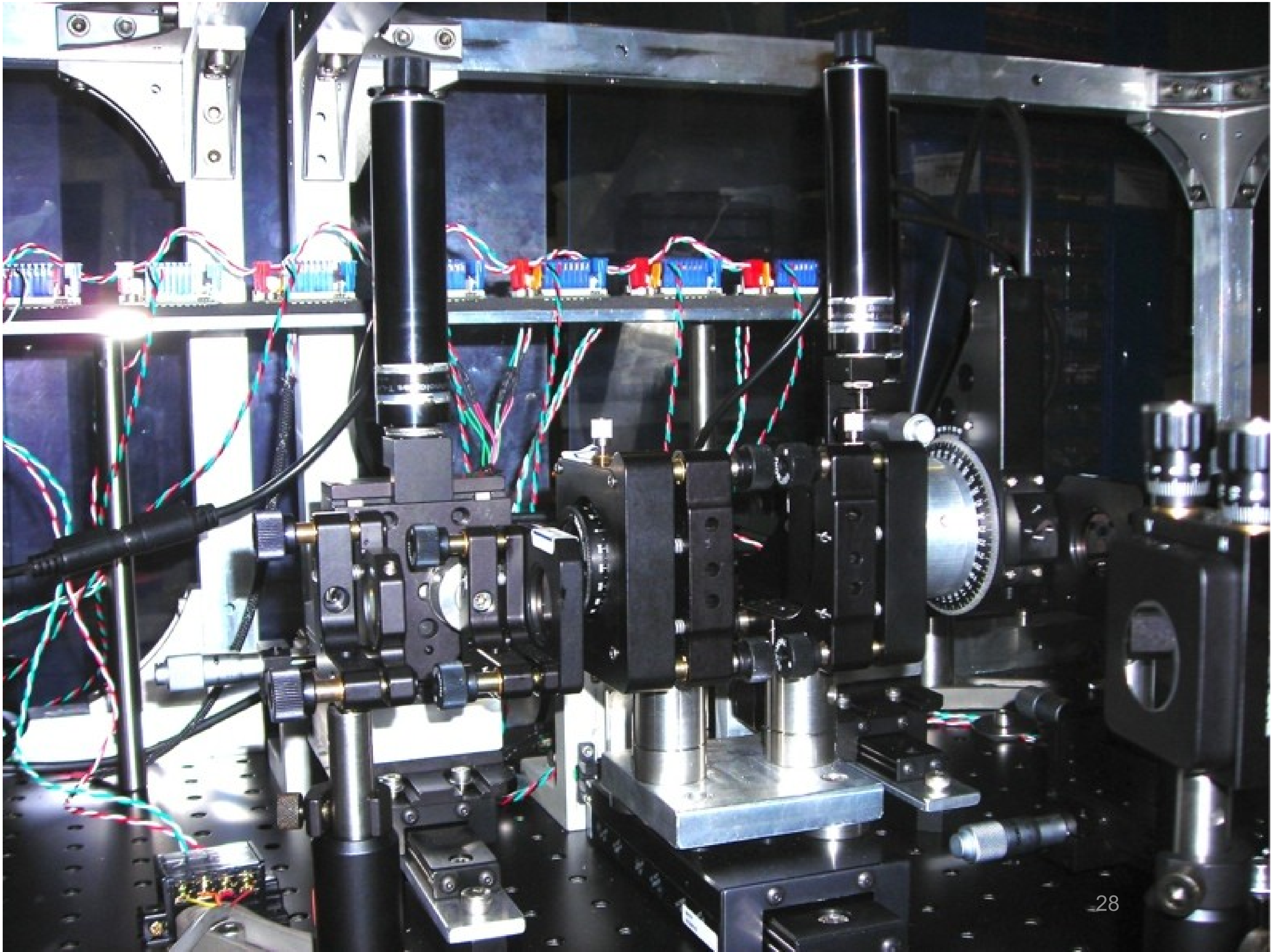
- Phase 2:
  - High speed ExAO WFS (under dev.)
  - Spectroscopy/IfU (funding has been requested for IfU)

SCExAO bench

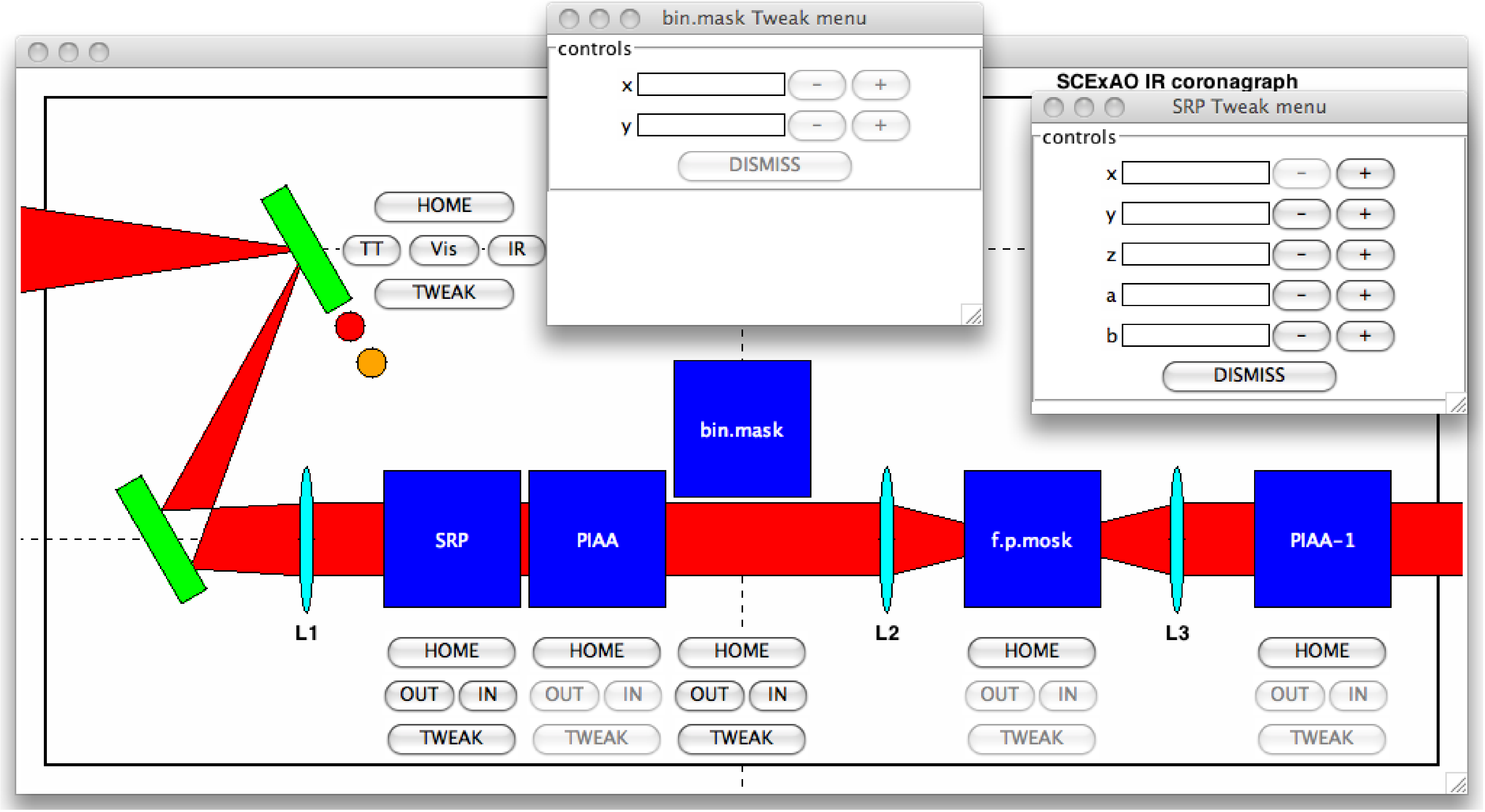


Bench (no frame)

Beam shaping hardware



Coronagraph configuration: software control



Visible imaging channel
(work with PhD student Garrel)
(work with PhD student Garrel)
(work with PhD student Garrel)

- 500 Hz frame rate (1” x 1”) to 1 kHz (0.6” x 0.6”)
- EMCCD: no readout noise, 90% QE
- 0.6 to 0.85 um. Using ADC/dichroic configuration of Kyoto-3D visible AO IfU

- End-to-end data simulation and processing pipeline used to estimate performance / algorithms
- Initial data processing: Fourier-based statistical filter
- higher performance options under study

New R&D

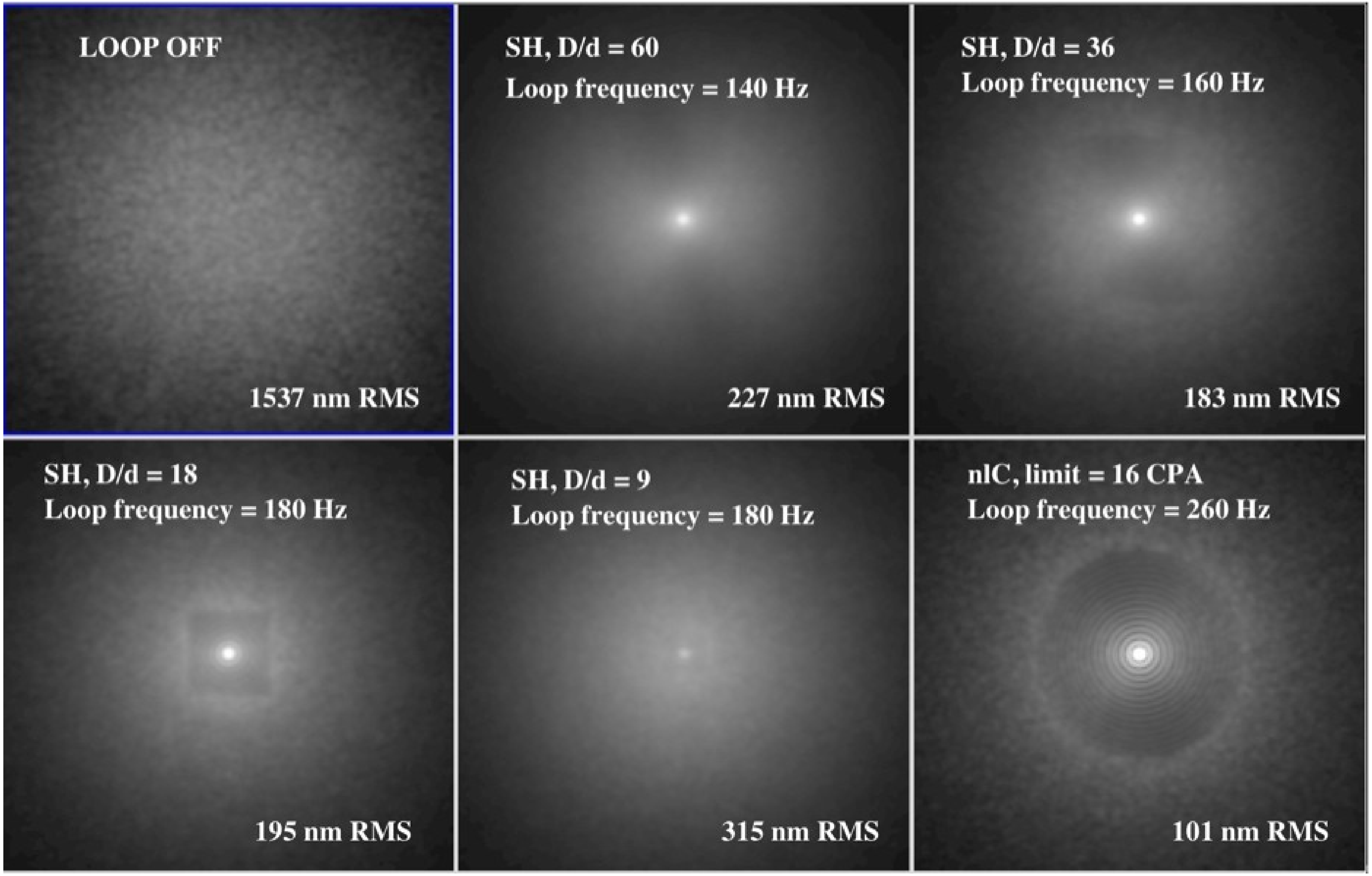
- Coherence-based detection and wavefront control
  - better algorithms
  - self-tuning AO loop (learns as it goes)
  - better understanding of limits (tip-tilt very important, understanding and calibration of non coherent light critical)

- Quantitative dark speckle analysis for AO images

- High efficiency WFS
  - collaboration with HIA to develop WFS for SCExAO
  - non-ExAO version under study for 6.5m MMT, would be deployed in // with SH WFS

- PIAACMC for higher performance coronagraphy

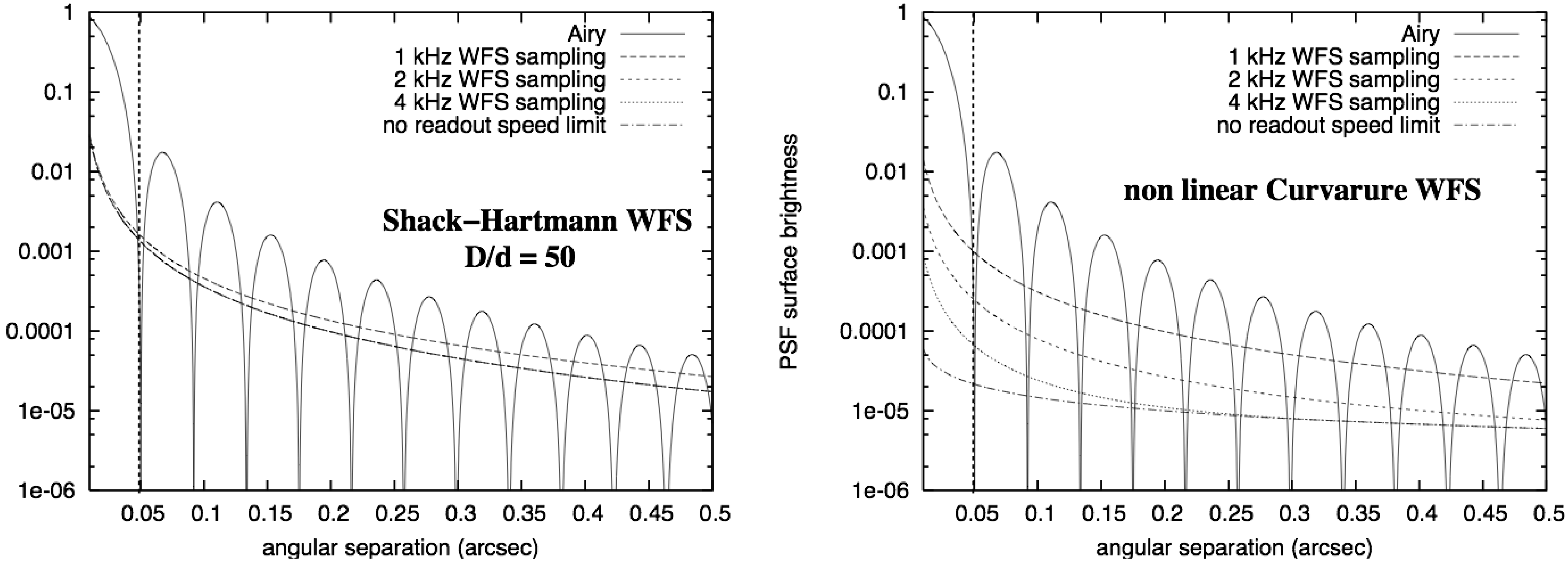
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)



m ~ 13

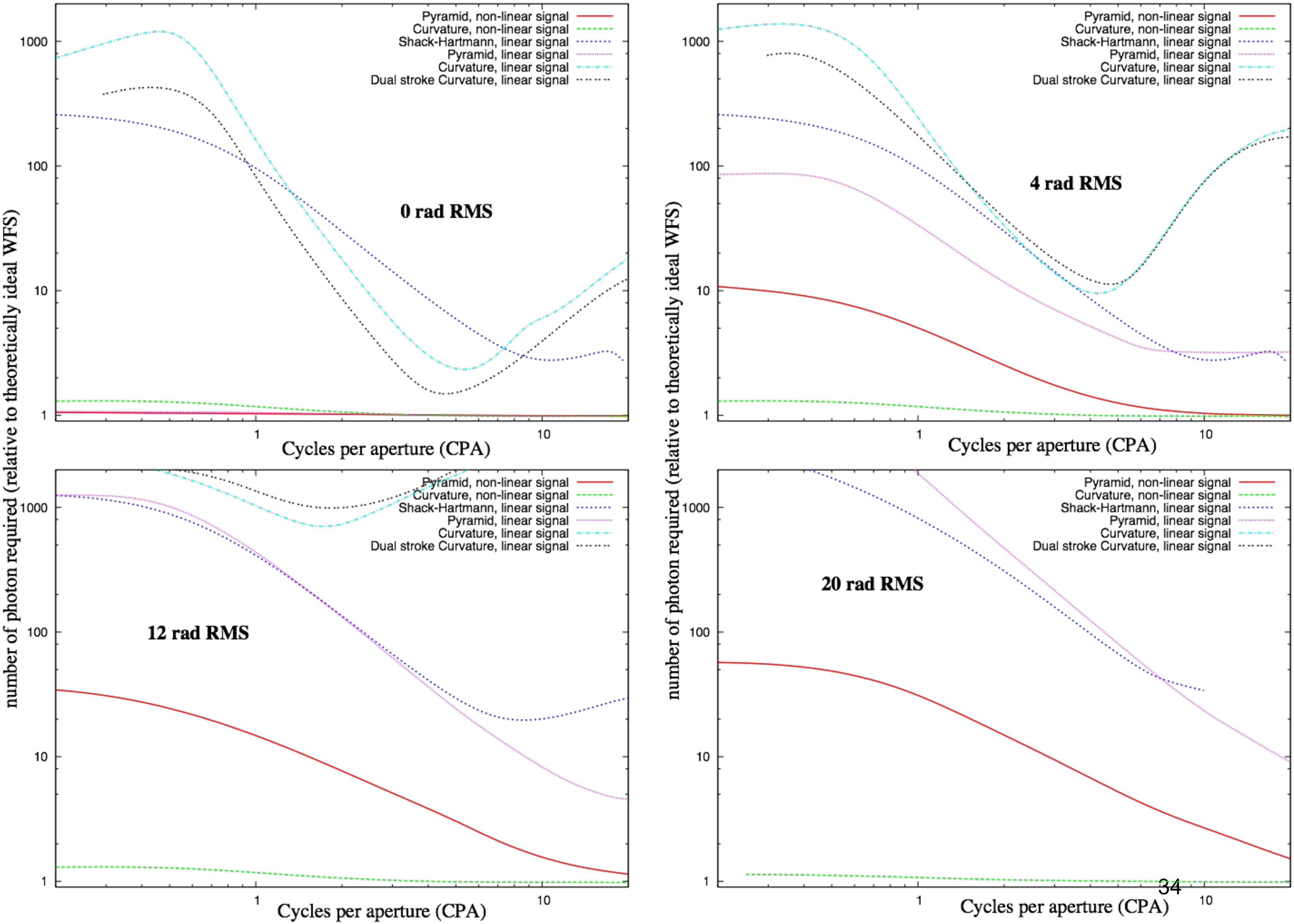
WFS	Loop frequ	RMS	SR @ 0.85 mu	SR @ 1.6 mu
nlCurv	260 Hz	101 nm	57%	85%
SH - D/9	180 Hz	315 nm	~4%	22%
SH - D/18	180 Hz	195 nm	~13%	56%
SH - D/36	160 Hz	183 nm	~16%	60%
SH - D/60	140 Hz	227 nm	~6%	45%

Performance gain for ExAO



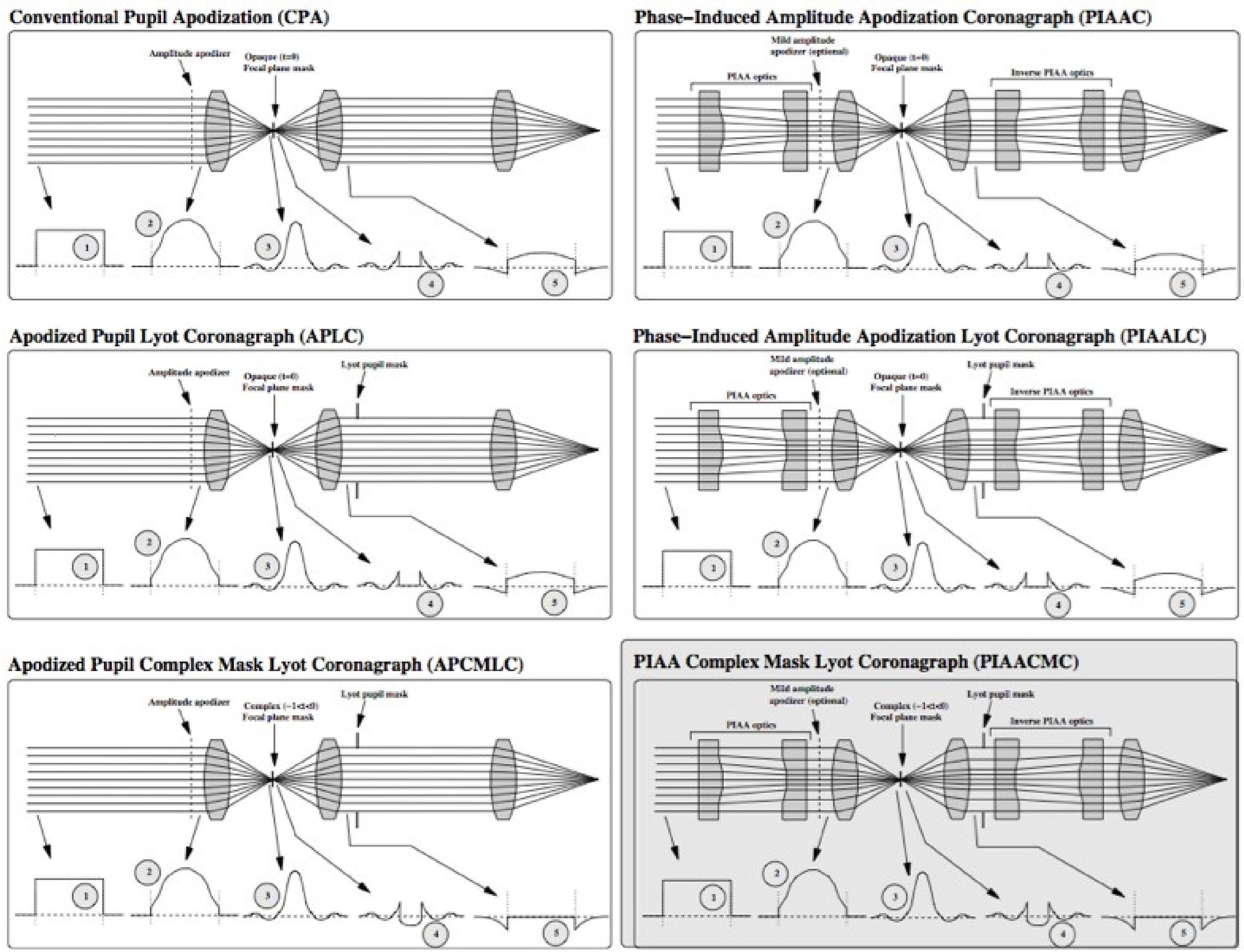
Large gain at small angular separation:
ideal for ExAO

Sensitivity compared with other schemes



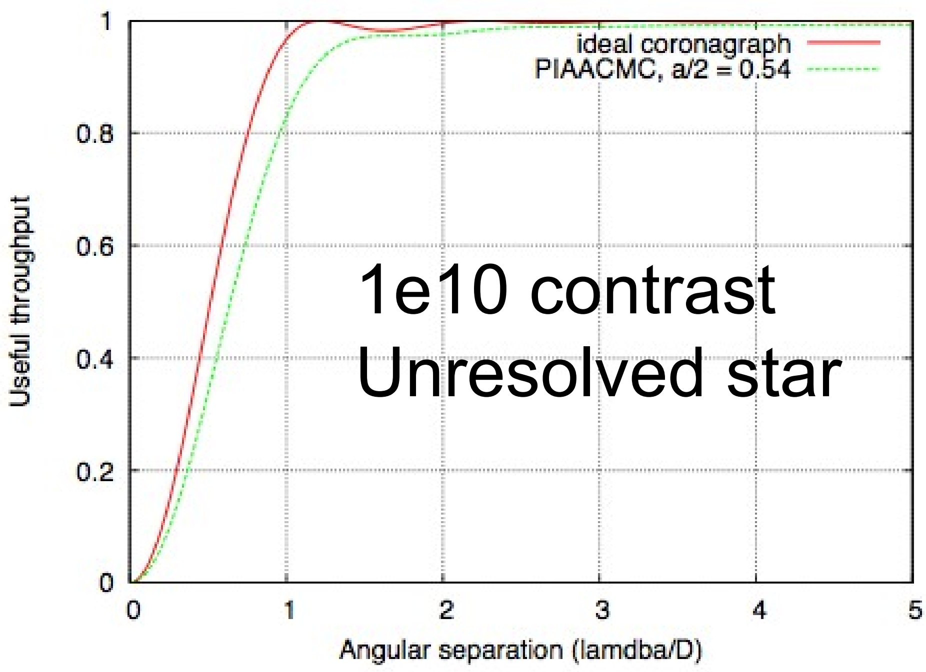
Smaller IWA coronagraphs with PIAA

- Rely on BOTH focal plane mask and Lyot mask for starlight rejection, with phase-shifting mask



PIAA complex mask coronagraph

- IWA can be set anywhere from 0.64 l/D to 2 l/D, according to stellar angular size
- Approaches ideal coronagraph performance limit set by fundamental physics
- milder apodization -> PIAA optics easier to make
- Focal plane mask is hard to make for polychromatic light



PIAACMC focal plane mask

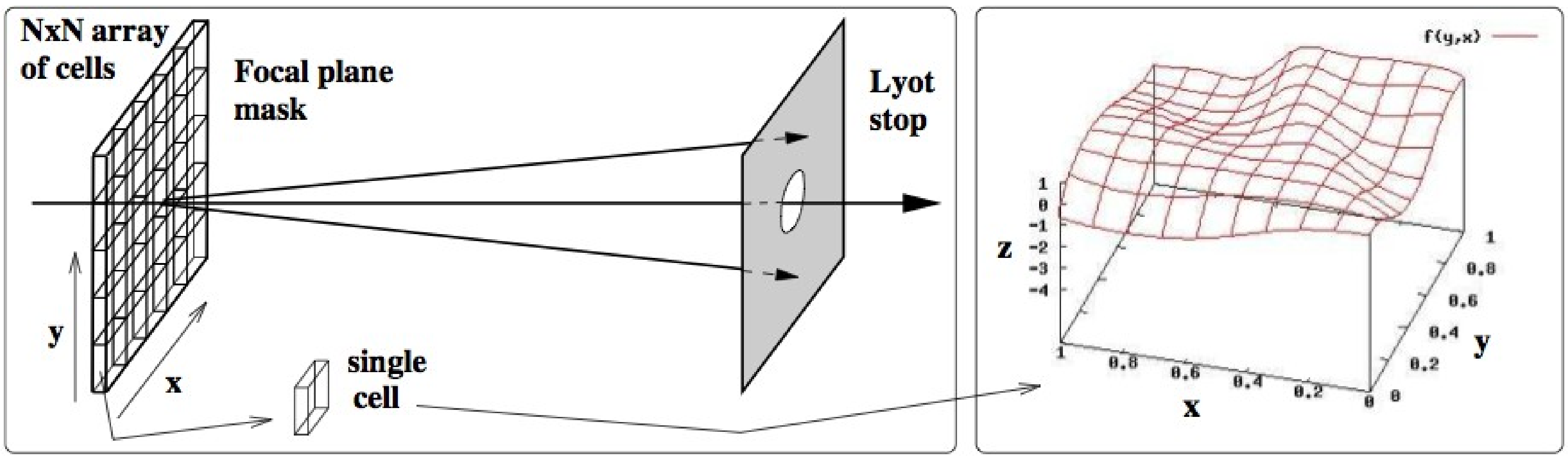
- Focal plane mask needs to be partially transmissive, and phase shifting
- Phase shift AND transmission need to be achromatic
- Mask size needs to be achromatic

PIAACMC DESIGN EXAMPLES

Mask radius $a/2$	Eigenvalue Λ_0	Mask transm t^2	Light fraction on foc. mask	Prolate throughput	Prolate edge value $\phi_a(1.0)$	Inner Working Angle 50% throughput (λ/D)
0.54	0.50830	93.6%	47.7%	71.6%	48%	0.64
0.70	0.69437	19.4%	67.0%	59.3%	30%	0.73
1.00	0.90428	1.12%	89.3%	40.8%	9.7%	0.90
1.50	0.99199	$6.5\ 10^{-5}$	99.1%	24.7%	0.86%	1.09
2.00	0.99948	$2.7\ 10^{-7}$	99.95%	17.7%	$6\ 10^{-4}$	1.23
3.00	0.999998	$3.2\ 10^{-12}$	99.9998%	11.4%	$2.5\ 10^{-6}$	1.47
4.00	0.999999995	$2.4\ 10^{-17}$	99.999988%	8.4%	$9.3\ 10^{-9}$	1.67

Polychromatic focal plane mask

- Think of focal plane mask as diffraction grating. Some light misses the Lyot opening, some goes through
- Mask made of a single material, with known n(lambda)



$$T(\lambda) = \int e^{i\frac{2\pi(n(\lambda)-1)f(x,y)}{\lambda}}\,dx\,dy$$

only histogram h(t) matters
t = thickness

$$T(\lambda) = \int_{-\infty}^{\infty} h(t)\, e^{i\frac{2\pi(n(\lambda)-1)t}{\lambda}}\,dt$$

$\lambda' = (n(\lambda) - 1)/\lambda$

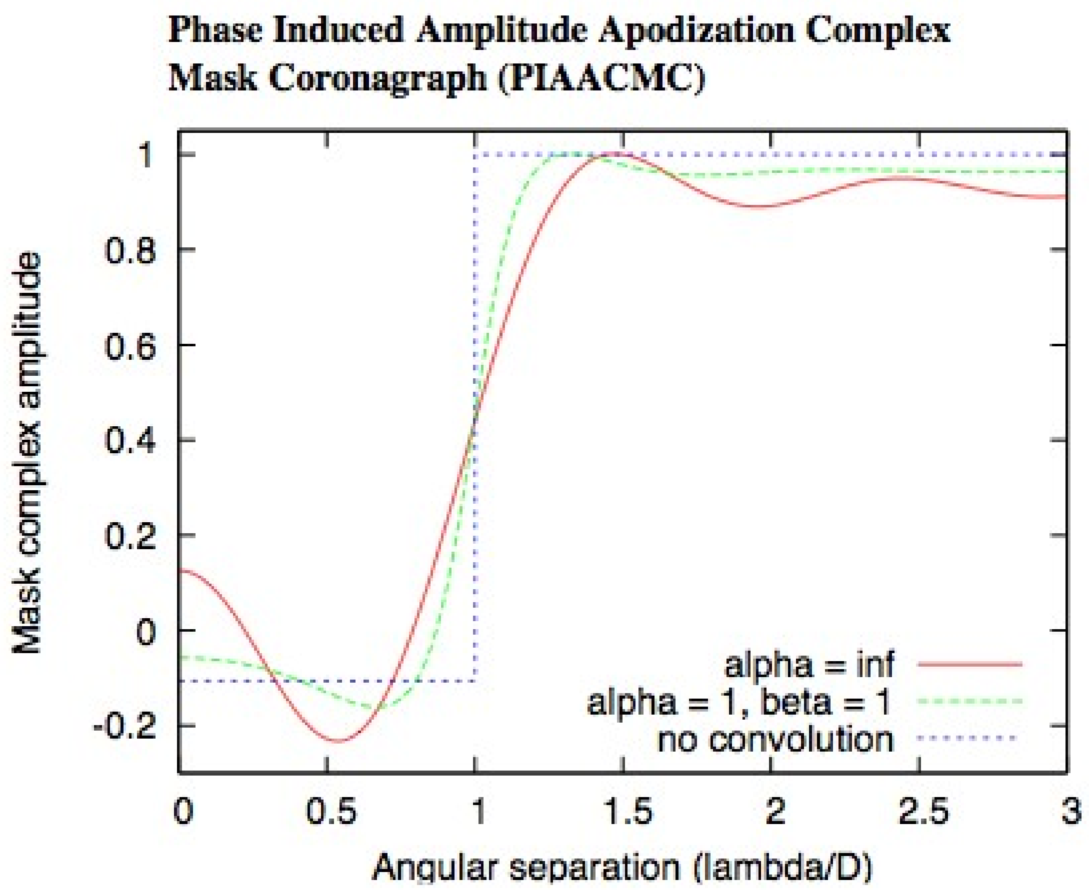
$$T(\lambda') = \int_{-\infty}^{\infty} h(t) e^{i2\pi t\lambda'}\,d\lambda'$$

Fourier Transf.

$$h(t) = -\int_{-\infty}^{\infty} T(\lambda') e^{-i2\pi t\lambda'}\,d\lambda'$$

PIAACMC focal plane mask

- Focal plane mask is first convolved by Airy to smooth edges

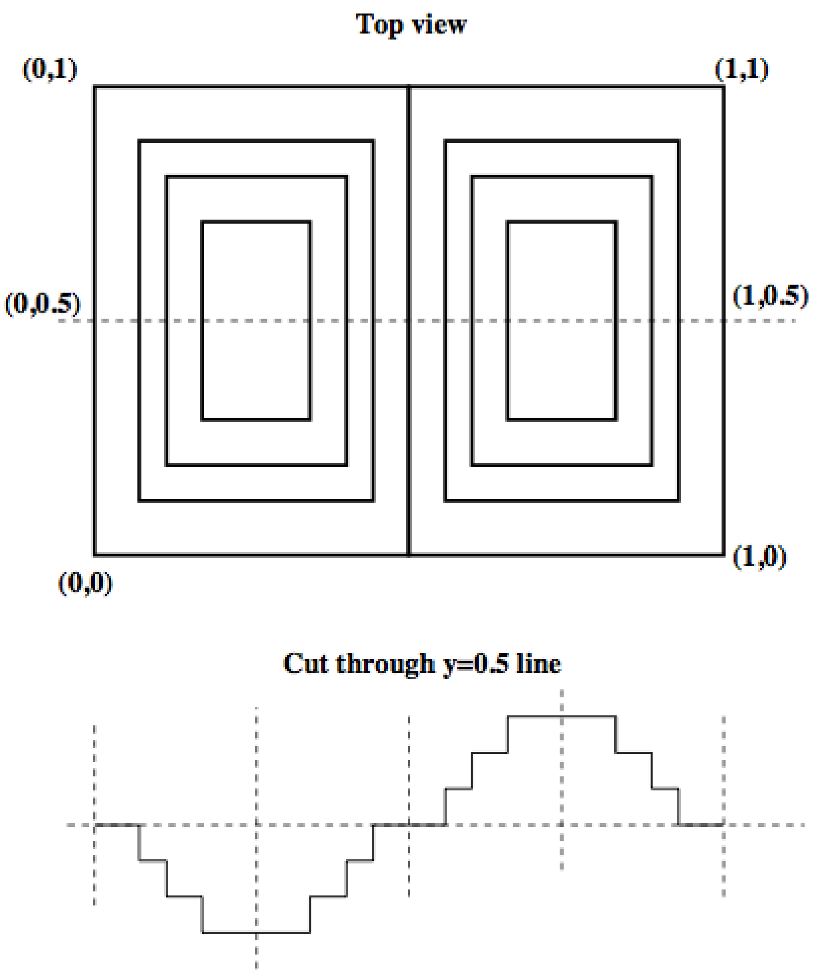


PIAACMC focal plane mask

Cell design is chosen for easy manufacturing by lithography / thin film deposition techniques: finite number of material thickness available

Nested steps design allows for lateral registration errors

No need to take into account slope reflection



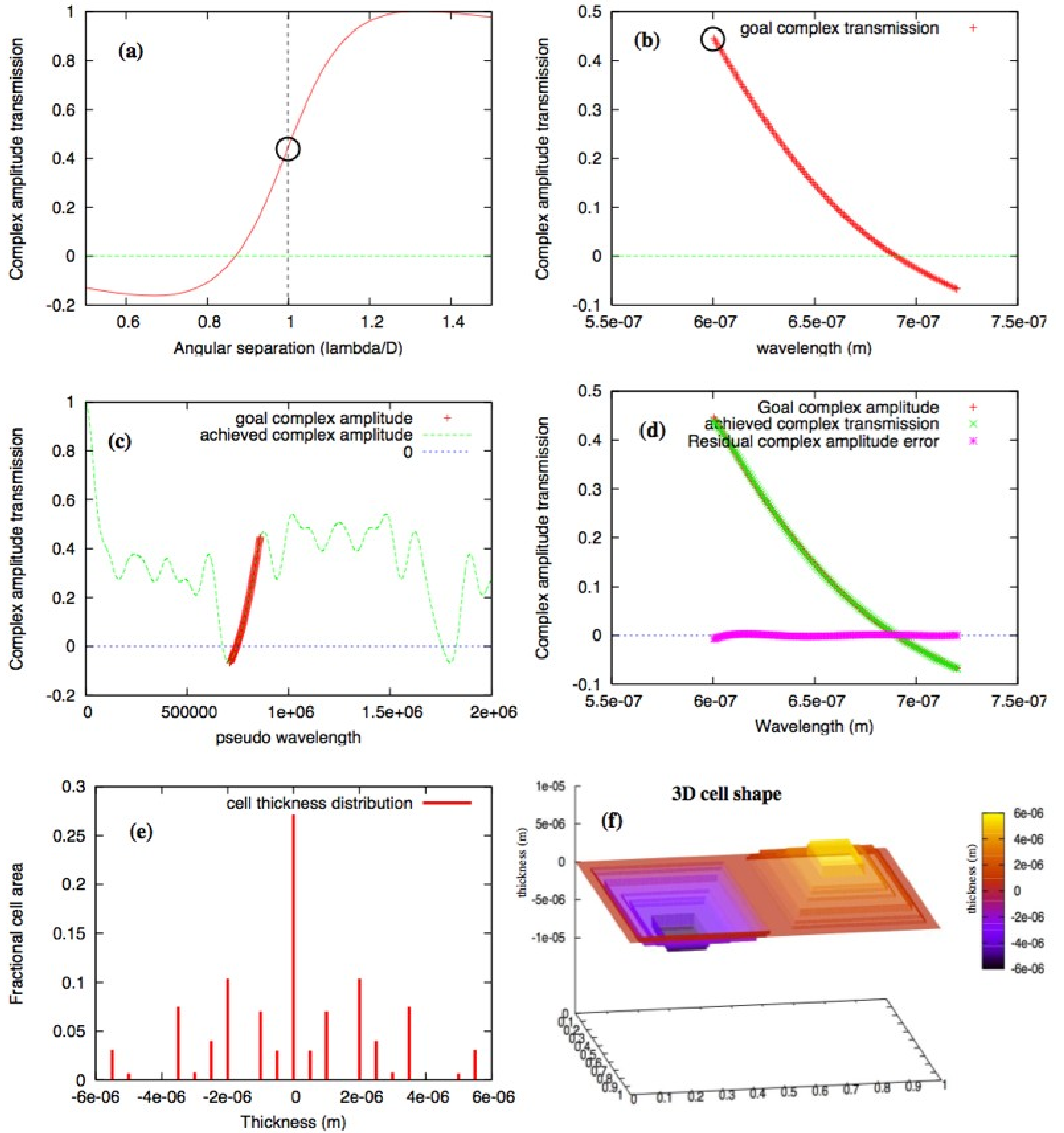
PIAACMC focal plane mask

In this example:

Material = CaF2

Material thickness = -6 to +6 micron

Thickness is multiple of 0.5 micron



PECO

Pupil mapping Exoplanet Coronagraphic Observer

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

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

http://caao.as.ariz

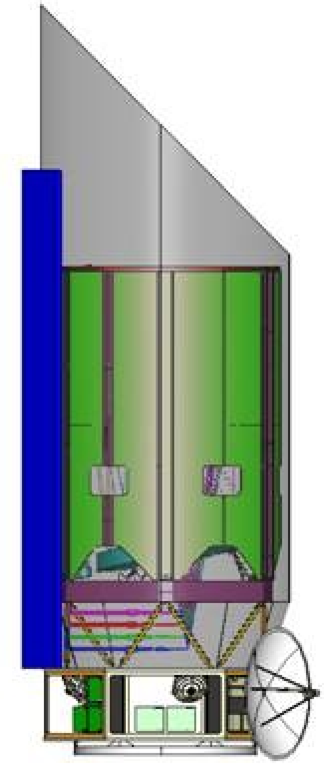
Olivier Guyon
University of Arizona
Subaru Telescope

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

Univ. of Arizona
Jet Propulsion Laboratory
California Institute of Technology
Lockheed Martin
Ames Research Center
ITT

PECO overview

PECO Pupil mapping Exoplanet Coronagraph Observer



NASA-funded Advanced Strategic Mission Concept Study, medium class mission (~$800M cost cap)

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 ?

Telescope diameter is expensive (more so than instrument)
Size, mass, launch, stability

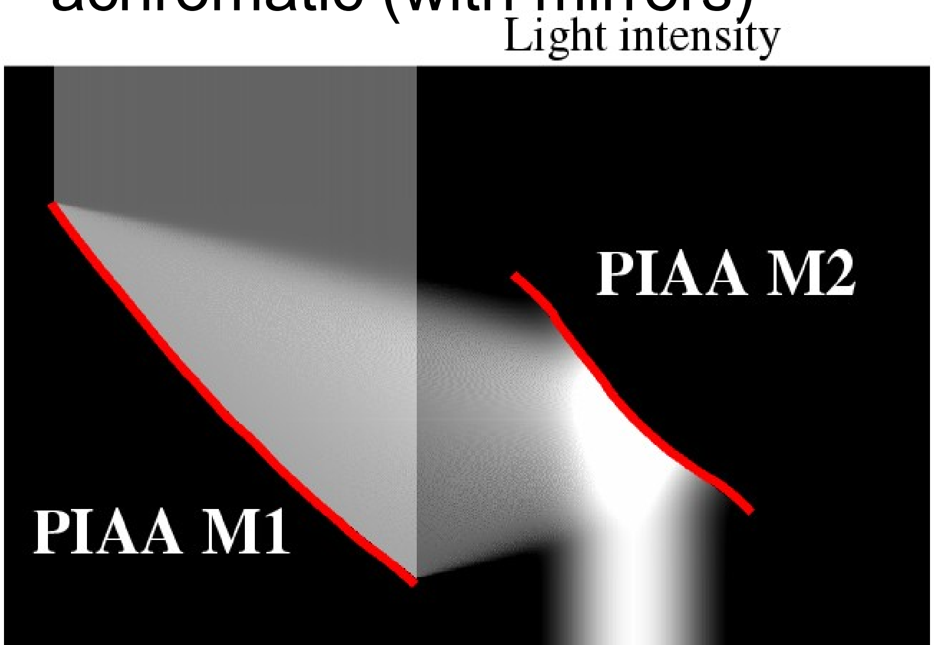
1.4m can see Earths/SuperEarths, if:

- 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 uses highly efficient PIAA coronagraph (equ. x2.5 gain in tel. diam.)

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)



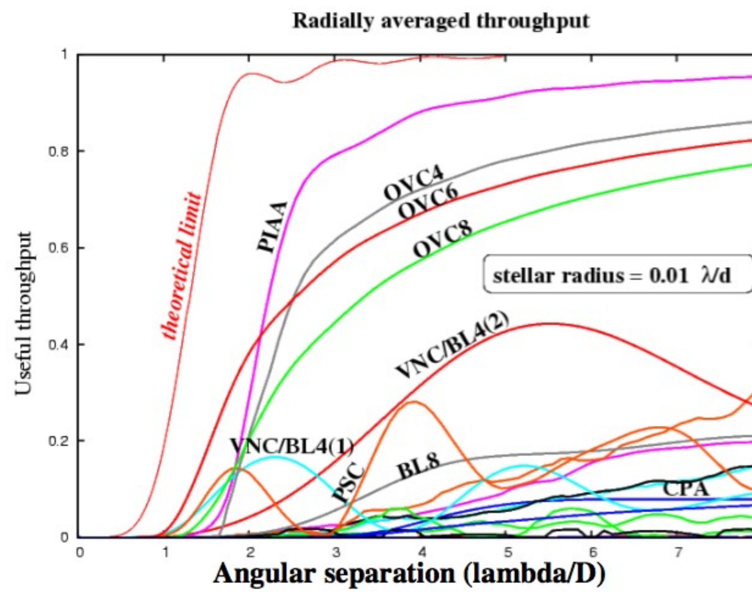
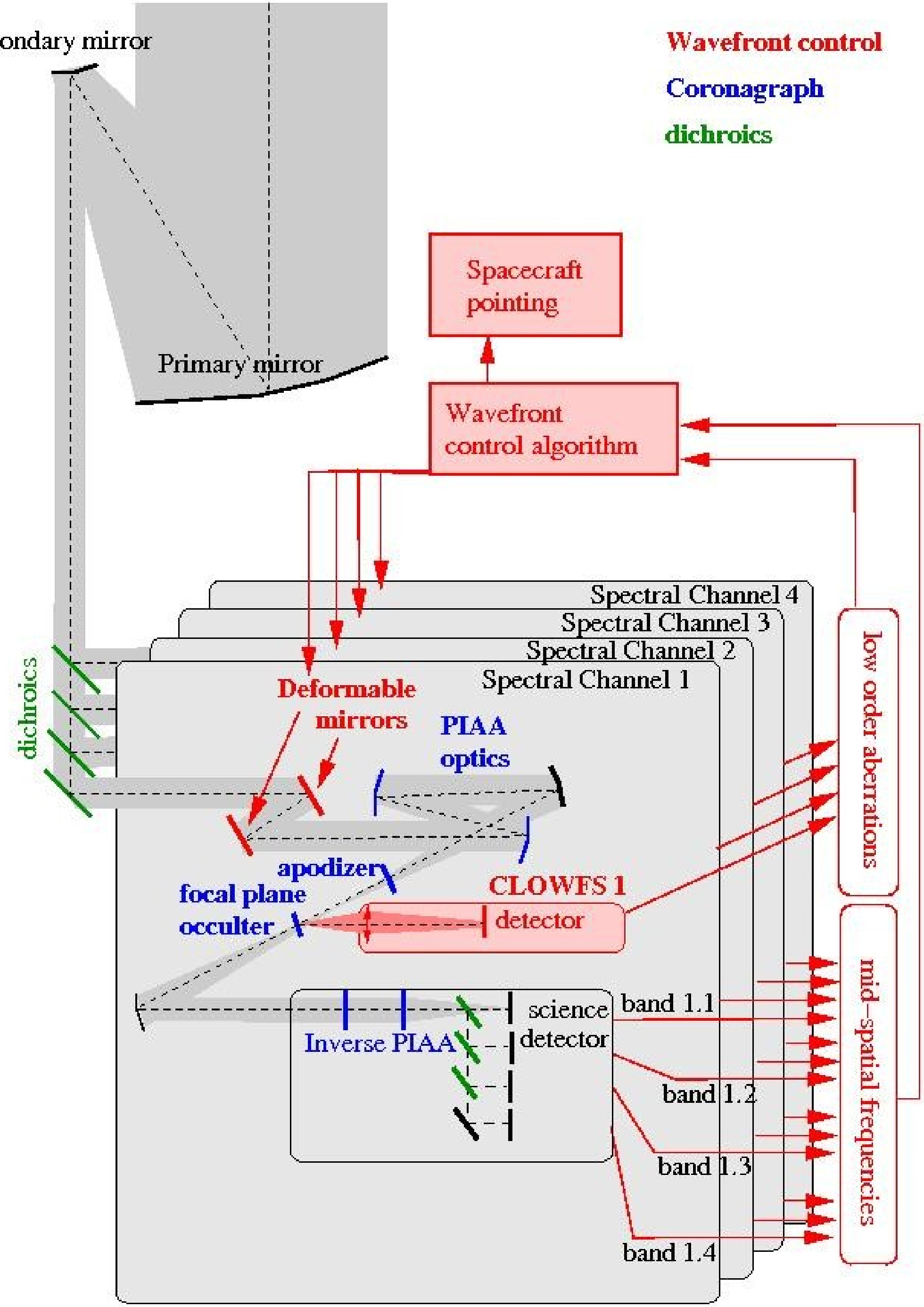


Figure 3-1: Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional Pupil Apodization.

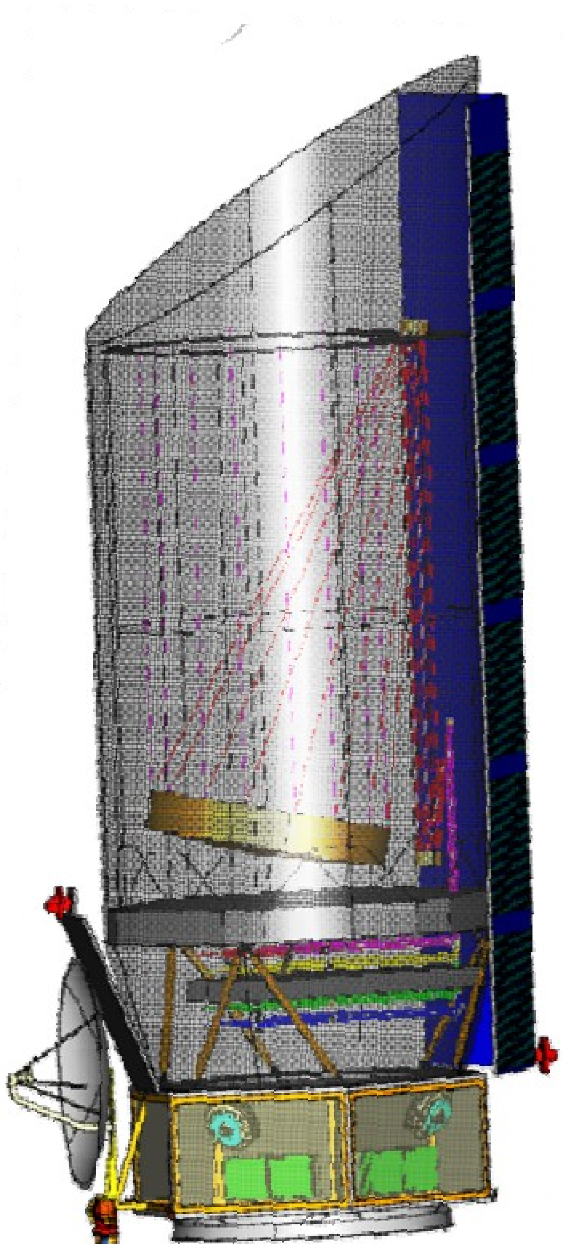
Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

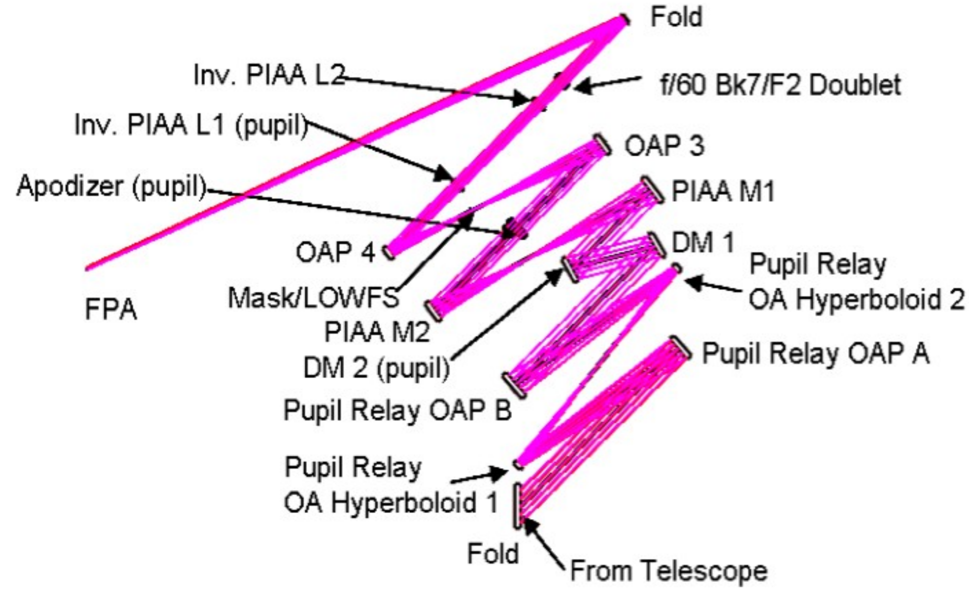
PECO approaches theoretically optimum coronagraph performance

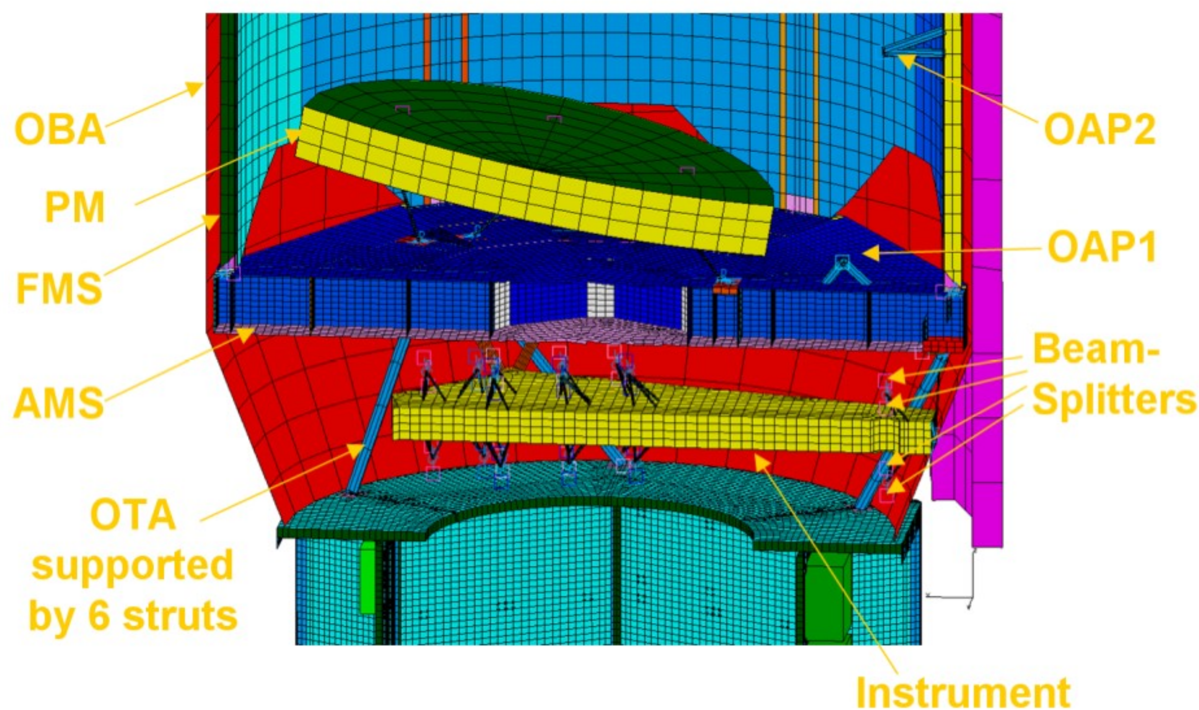


- High performance PIAA coronagraph
- Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands x 2 polarization axis, combining detection & characterization
  - High sensitivity for science and wavefront sensing
  - polarization splitting just before detector (helps with exozodi & 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



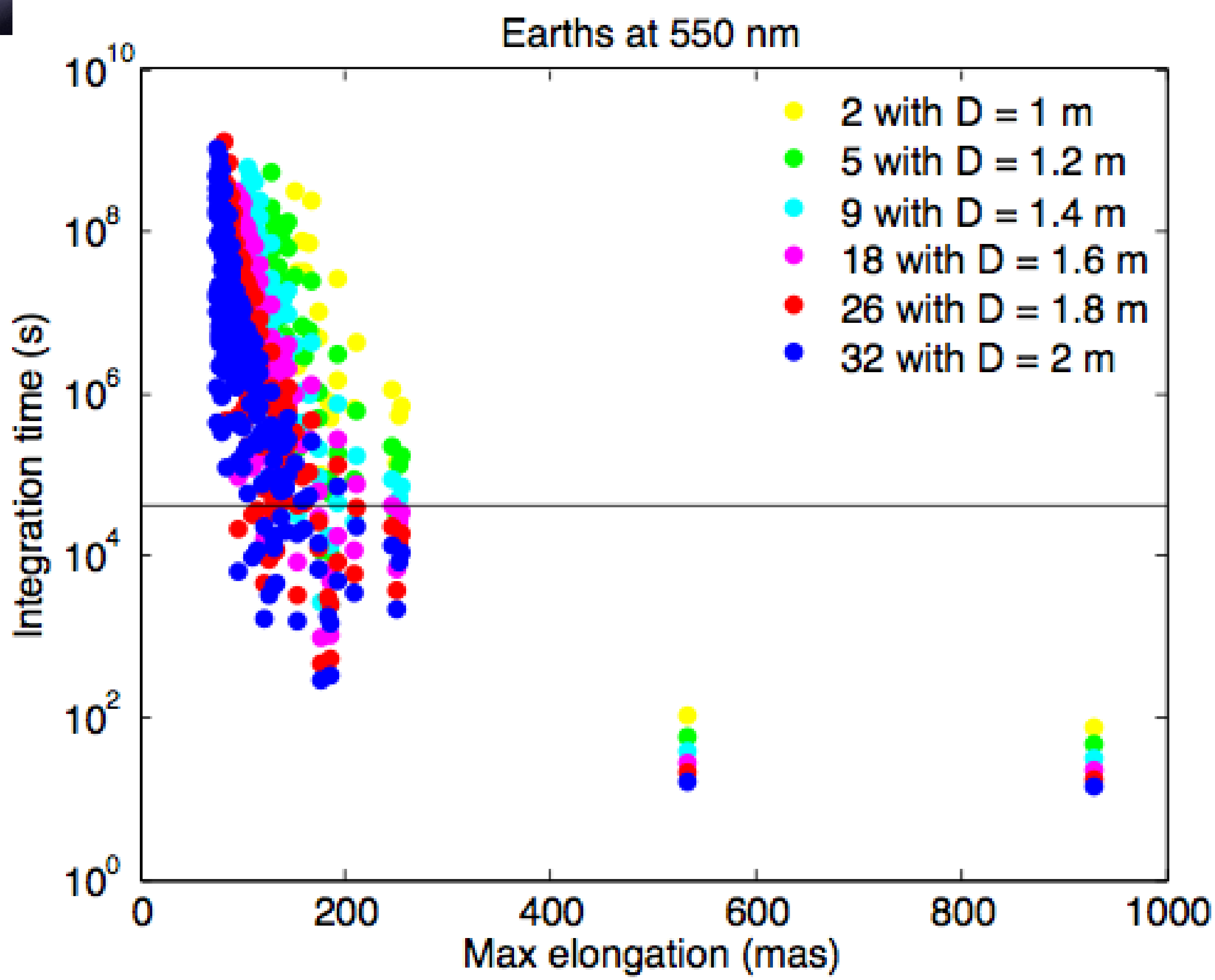




PECO Design Reference Mission
A Grand Tour of 10 nearby sun-like stars

- 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.

Number of Earths detected with PECO scales gracefully with aperture

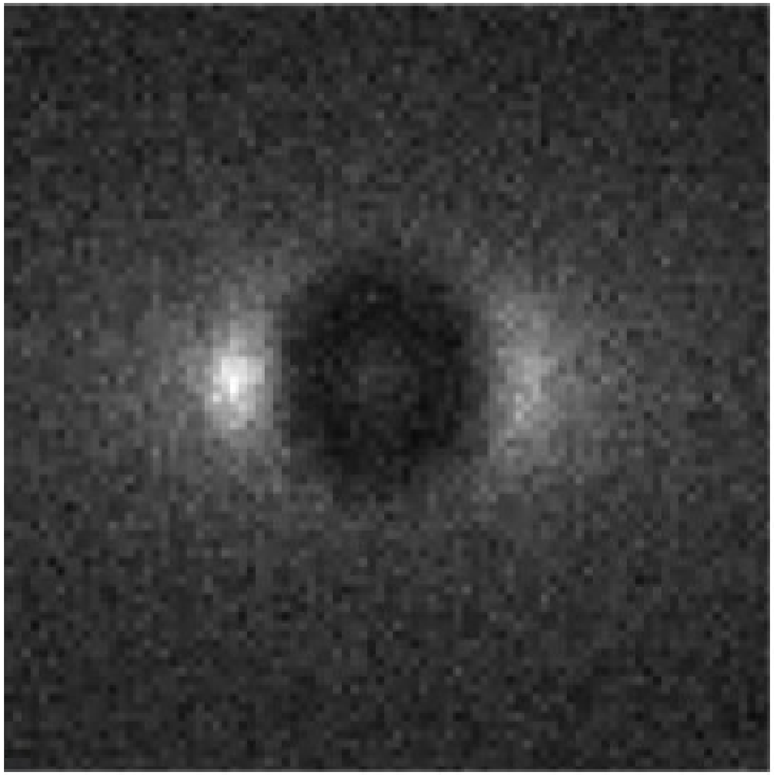


Earths still detectable at shorter wavelengths and smaller D

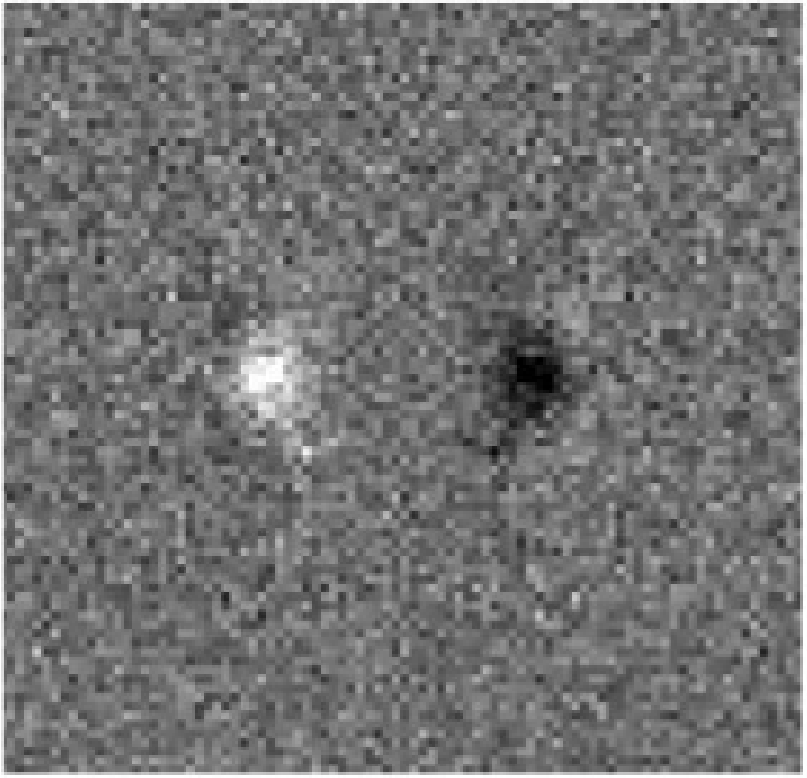
- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- IWA of 2 lambda/D

PECO can observe an Earth at distance of Tau Ceti

Initial image



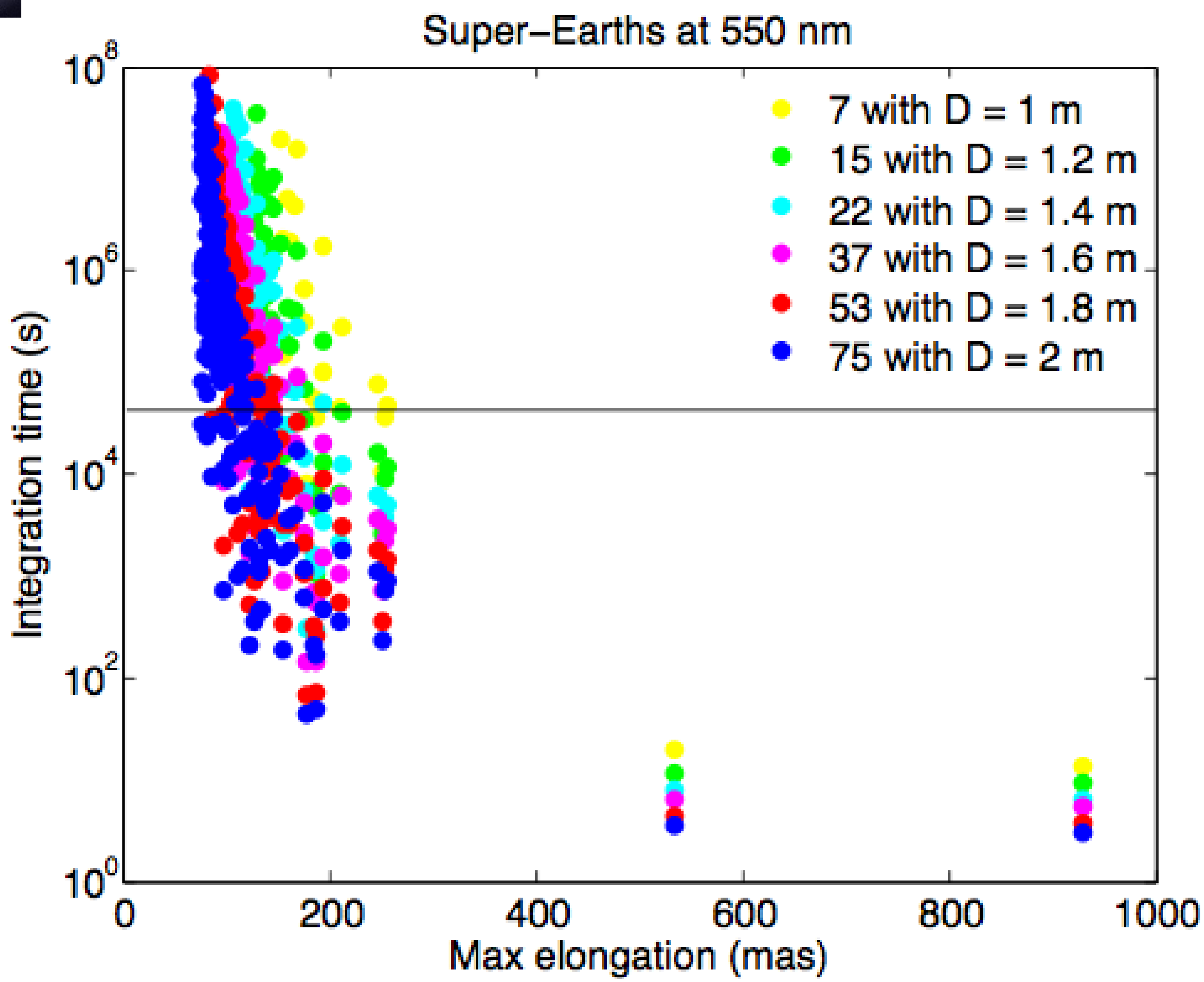
After Symmetric Dust Subtraction



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 can easily detect Super-Earths

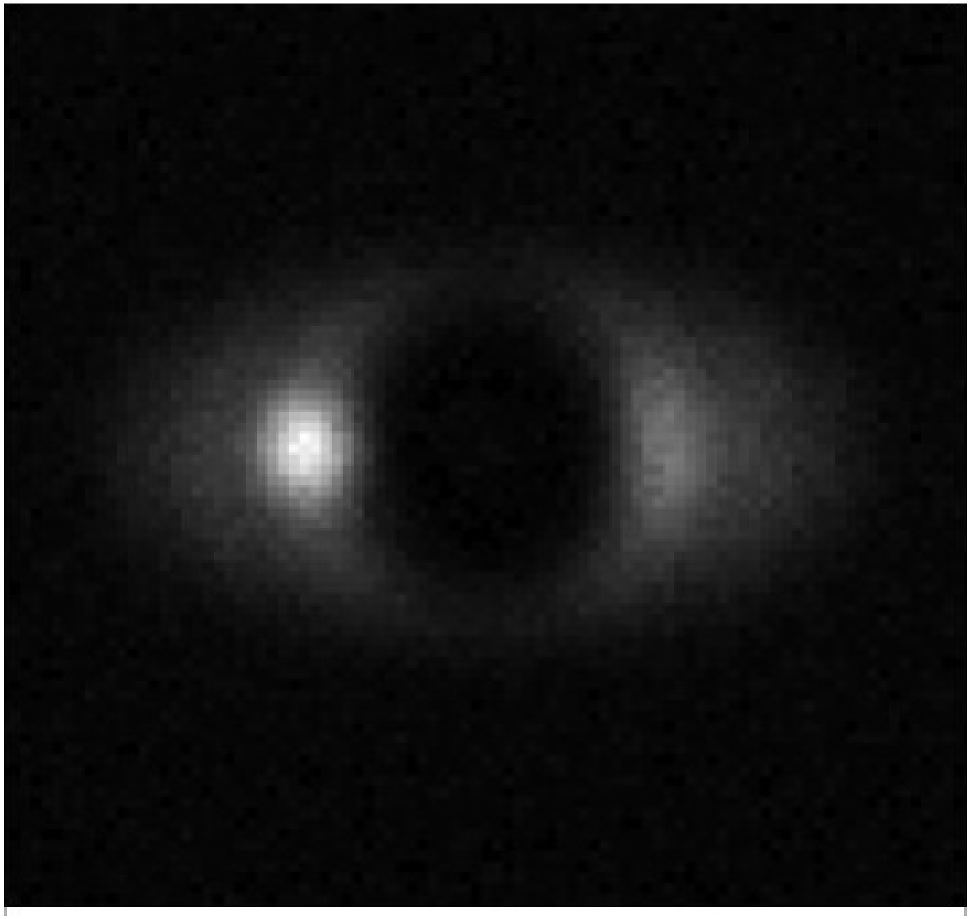


Trade study shows number of Super-Earths detected for different telescope diameters

- PECO simulation of 2 x Earth-radius planet with 10 x Earth-mass and Earth-like albedo in habitable zone of candidate star
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- IWA of 2 lambda/D

Can see more targets at shorter wavelengths and larger diameters

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.

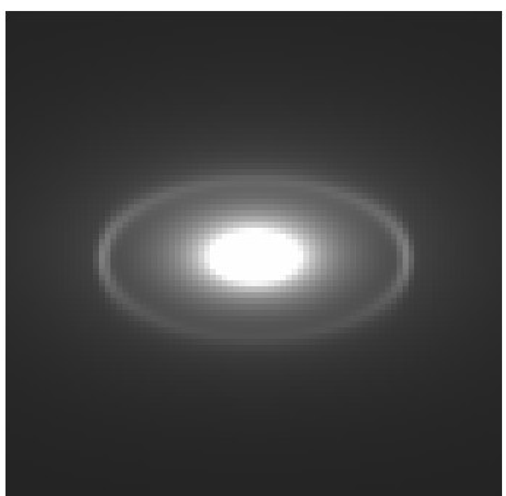
PECO could detect a Jupiter analog around 250 stars.

PECO exozodi imaging

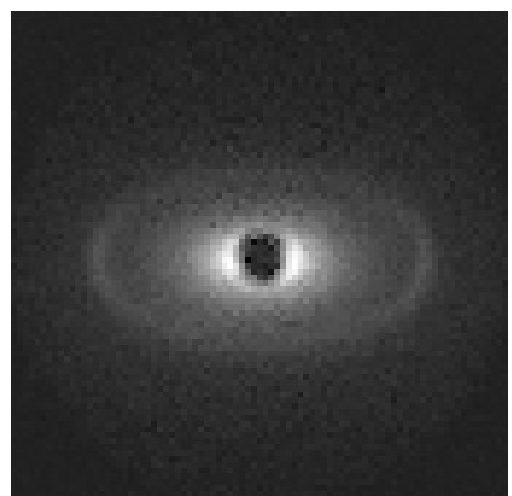
PECO Pupil mapping Exoplanet Coronagraph Observer

- 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

- Simulated PECO imaging of Alpha Cent exozodi



Model
1 zodi
enhancement at 1AU



PECO image
3 hr exposure
400 nm, 20% band

PECO 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
- PECO team actively maturing technology, and exploring further improvements to coronagraph/WFC design

Astrometry, Coronagraphy

Astrometry:

Planet orbit
Planet mass
Limited characterization (no spectra or brightness measurement)
Technology is ready (SIM)
If done first, can identify targets for a coronagraph mission (where and when to observe)

Coronagraphy:

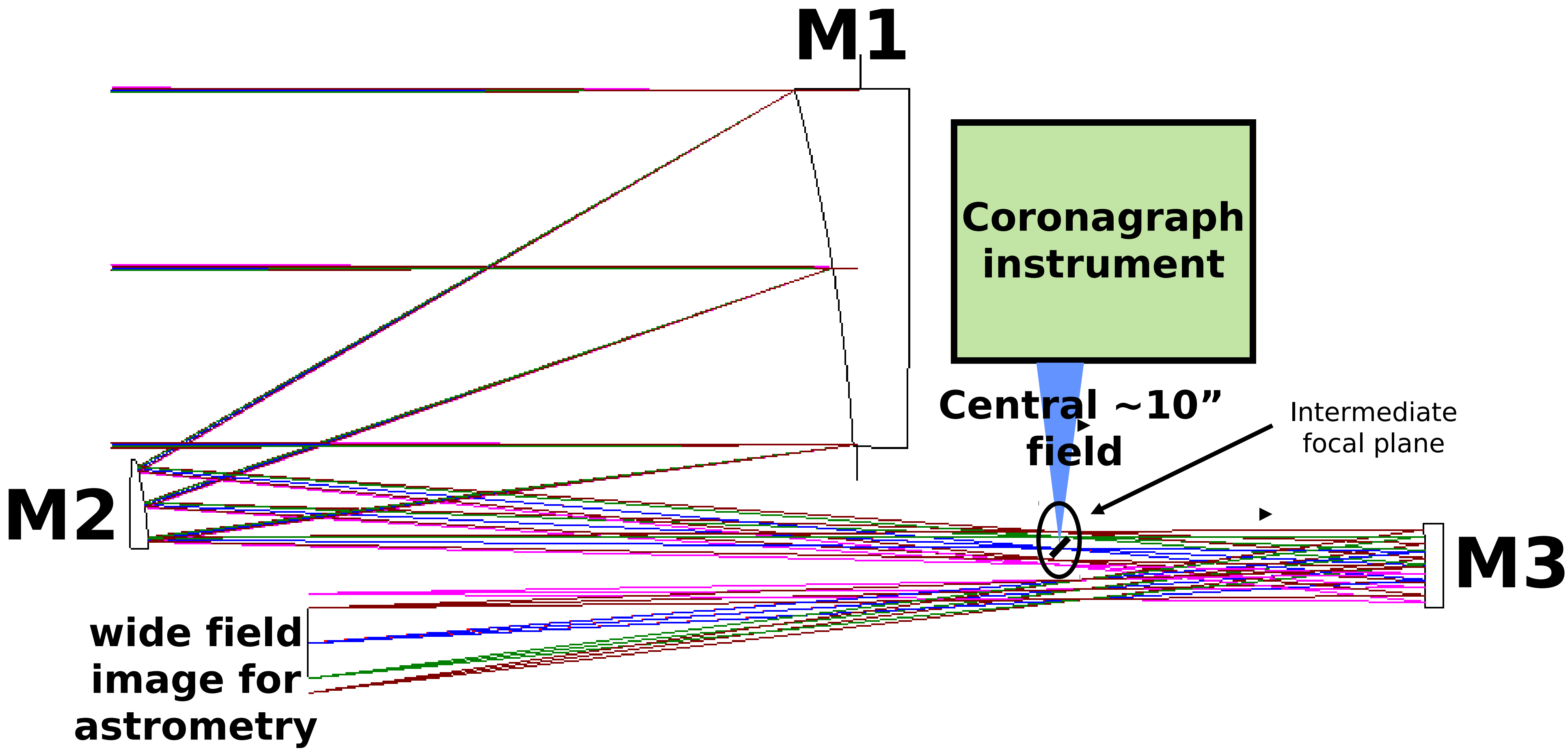
Planet orbit
No direct mass measurement
Spectra, brightness phase function, (polarization?)
Planetary system environment (dust, multiple planets)
Rapidly developing technology, but still ~2yr from being ready (TRL 6)

Exoplanet characterization requires both coronagraphy and astrometry.

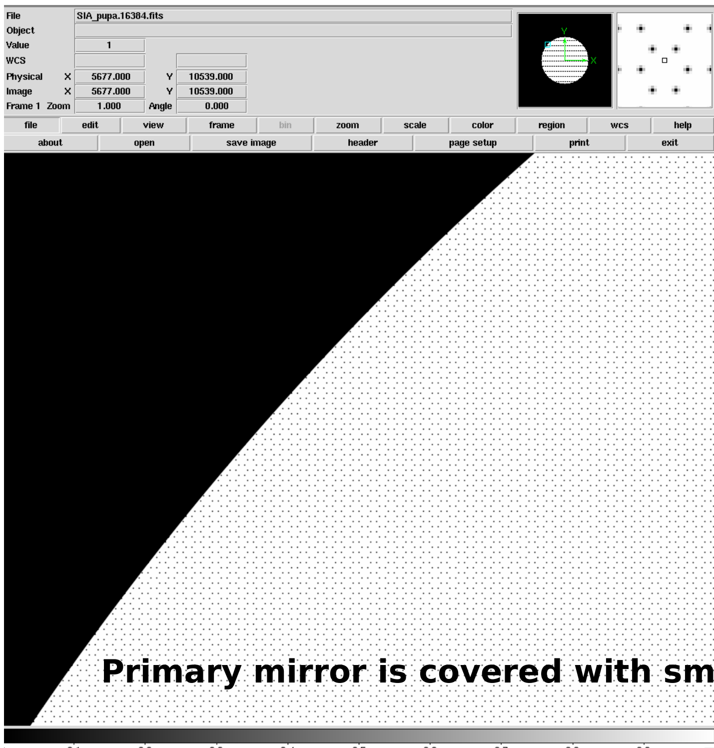
If possible, coronagraphy and astrometry should be done simultaneously (or close in time) to avoid propagation of orbital phase error with time.

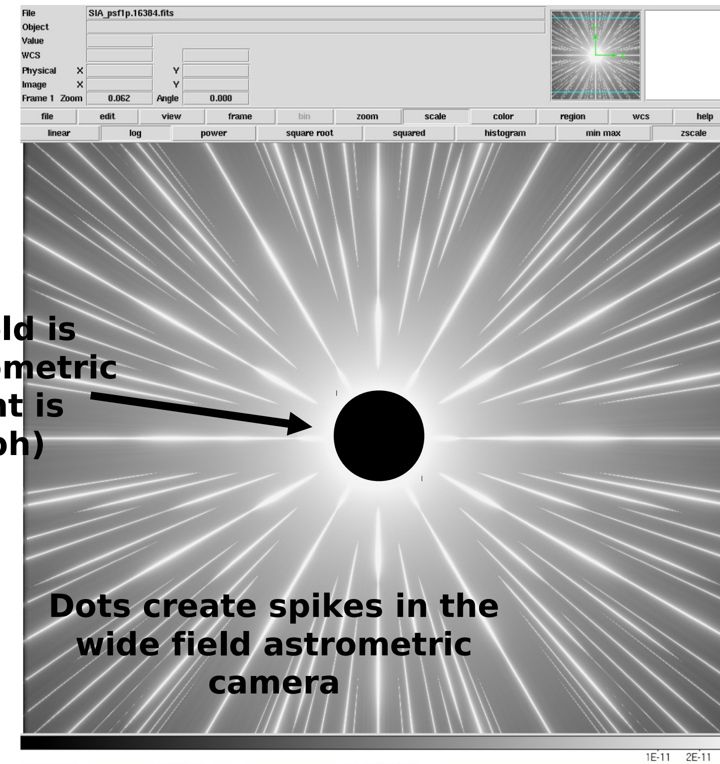
Optical Layout for simultaneous coronagraphy and astrometry

The telescope is a conventional TMA, providing a high quality diffraction-limited PSF over a 0.5 x 0.5 deg field with no refractive corrector. The design shown here was made for a 1.4m telescope (PECO).
Light is simultaneously collected by the coronagraph instrument (direct imaging and spectroscopy of exoplanet) and the wide field astrometric camera (detection and mass measurement of exoplanets)



Dots on primary mirror create a series of diffraction spikes used to calibrate astrometric distortions



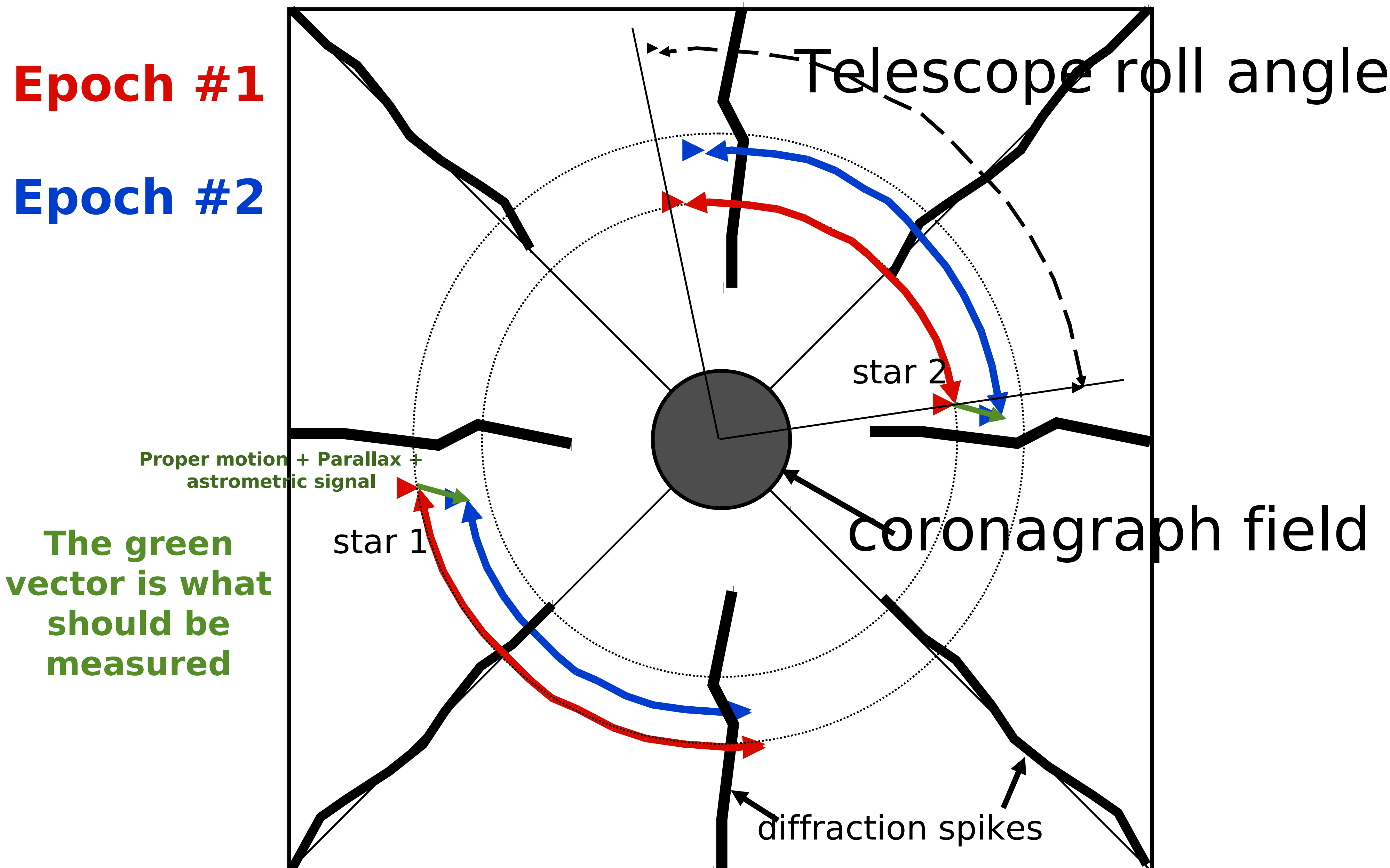


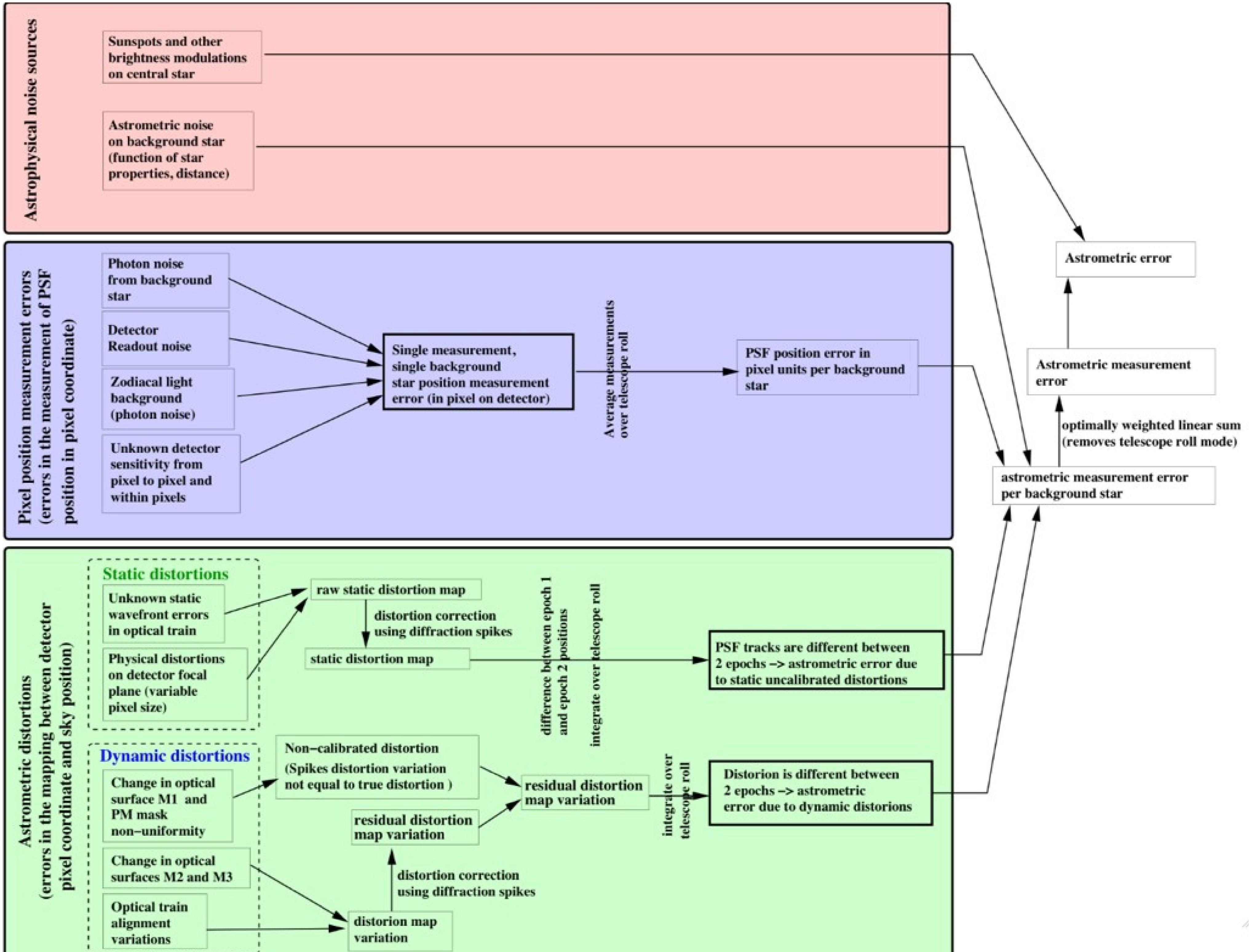
All astrometric distortions (due to change in optics shapes of M2, M3, and deformations of the focal plane array) **are common to the spikes and the background stars**. By referencing the background star positions to the spikes, the astrometric measurement is immune to astrometric distortions.

Instead of requiring ~pm level stability on the optics over yrs, the stability requirement on M2, M3 is now at the nm-level over approximately a day on the optics surfaces, which is within expected stability of a coronagraphic space telescope. (Note: the concept does not require stability of the primary mirror).

Observation scheme

A slow telescope roll is used to average out small scale distortions, which are due to non-uniformity in the pixel size, (spectral) response, and geometry




Astrophysical noise sources
Sunspots and other brightness modulations on central star
Astrometric noise on background star (function of star properties, distance)
Astrometric error
Pixel position measurement errors (errors in the measurement of PSF position in pixel coordinate)
Photon noise from background star
Detector Readout noise
Zodiacal light background (photon noise)
Unknown detector sensitivity from pixel to pixel and within pixels
Single measurement, single background star position measurement error (in pixel on detector)
Average measurements over telescope roll
PSF position error in pixel units per background star
Astrometric measurement error
optimally weighted linear sum (removes telescope roll mode)
astrometric measurement error per background star
Astrometric distortions (errors in the mapping between detector pixel coordinate and sky position)
Static distortions
Unknown static wavefront errors in optical train
Physical distortions on detector focal plane (variable pixel size)
raw static distortion map
distortion correction using diffraction spikes
static distortion map
difference between epoch 1 and epoch 2 positions
integrate over telescope roll
PSF tracks are different between 2 epochs -> astrometric error due to static uncalibrated distortions
Dynamic distortions
Change in optical surface M1 and PM mask non-uniformity
Change in optical surfaces M2 and M3
Optical train alignment variations
Non-calibrated distortion
(Spikes distortion variation not equal to true distortion)
residual distortion map variation
residual distortion map variation
integrate over telescope roll
Distorion is different between 2 epochs -> astrometric error due to dynamic distorions
distortion correction using diffraction spikes
distorion map variation

Science requirements, expected performance

Coronagraph observes high priority targets frequently. For PECO (1.4-m diameter telescope), there are 20 high priority targets (= targets around which a super-Earth could be imaged).
Assuming 2-day single pointing, 5 yr total mission, and 70% of observing time devoted to high priority targets, each high priority targets is observed 32 times (2 day per observation).

Performance is a function of FOV. Preliminary analysis shows that the error is between 0.9 uas and 4 uas for a 0.03 sq deg FOV in a 1 day observation, depending on the level of telescope stability and detector characteristics.
<u>An ambitious camera could cover the full 0.5x0.5 deg FOV (0.25 sq deg) with 1.7 Gpix (GAIA = 1 Gpix), and would reach 0.22 uas to 1 uas per measurement for galactic pole pointing.</u>

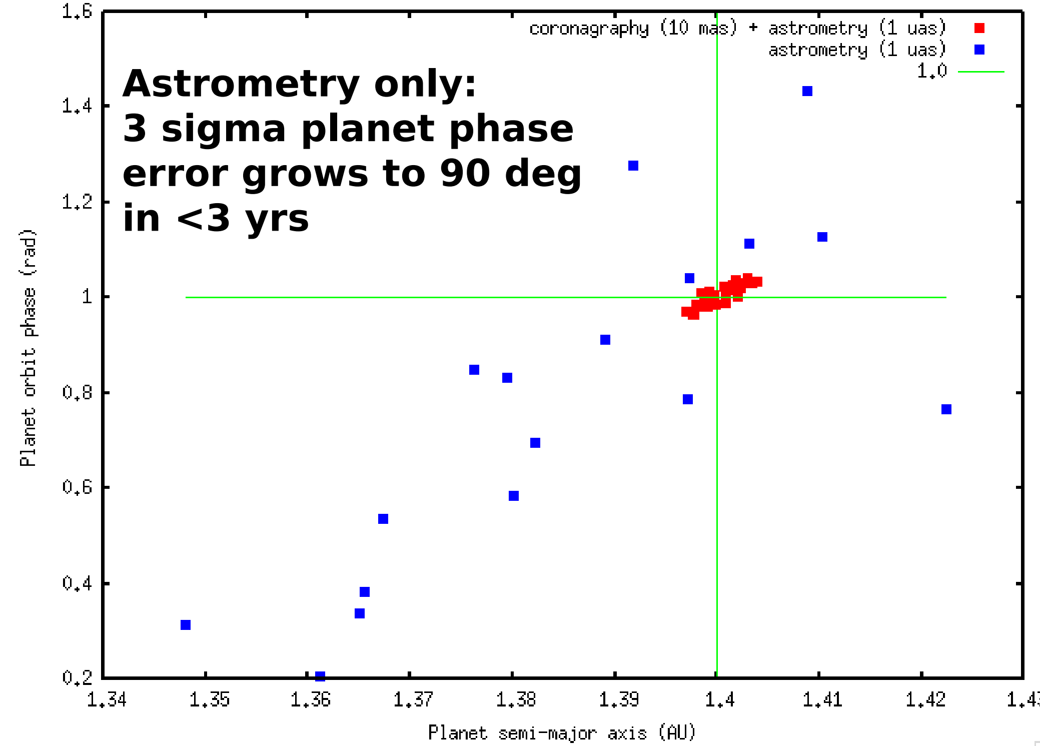
With this level of performance, measurement of planet mass is possible for Earth-mass planets for all 20 high priority targets. For detection, the astrometric camera will likely be more sensitive than the coronagraph in the habitable zone.
Note: 1 Earth at 10pc = 0.3 uas amplitude signal (from -0.3 uas to +0.3 uas, 1 yr period).

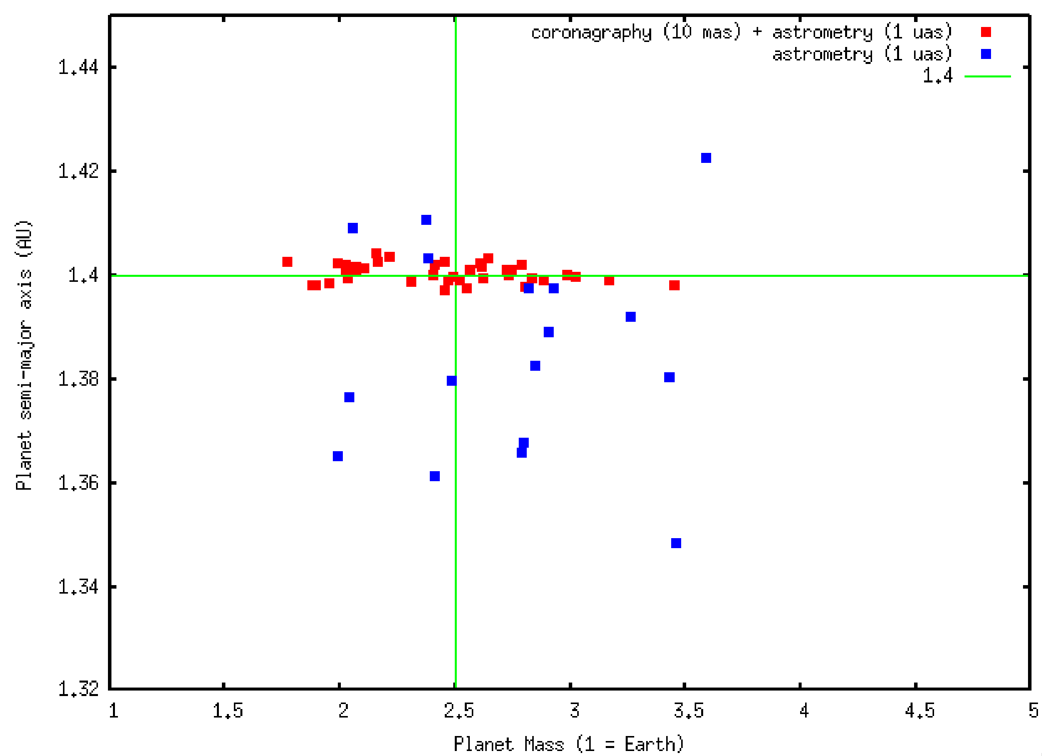
Solving for planet orbit and mass **using the combined astrometry + coronagraphy** measurement is scientifically very powerful:
- mitigates the 1 yr period problem with astrometry
- reduces confusion with multiple planets. Outer massive planets (curve in the astrometric measurement) will be seen by the coronagraph. Astrometry will separate planets from exozodi clumps.
- reduced error in the orbit parameter will enhance coronagraph science (example:

Combined coronagraph + astrometry solution

32 observations over 5 yr
2.5 Earth mass planet around sun at 6pc, inclined orbit (some coronagraph images do not show planet).
Coronagraph IWA = 130mas

Circular orbit assumed, star mass assumed to be known
8 free parameters:
- star distance (1)
- proper motion (2)
- planet mass (1)
- planet orbit inclination (2)
- planet orbit phase (1)
- semi-major axis (1)





Outstanding issues, future work

More detailed analysis is required to develop error budget
- model of time-variable deformations in the telescope under development
- data processing needs to be developed further
- science performance of combined astrometric + coronagraphic data reduction needs to be quantified

How to make dots on the primary mirror ?
This needs to be explored.
Lithographic processes exist to do this on smaller optical elements (up to ~30cm).
CMM machines with 0.1 um absolute accuracy over 1.4-m are commercially available, and could be suitable if modified. Need to ensure that process to put dots does not impact coronagraph performance.

Small scale lab demonstration under planning at U of Arizona
Will benefit from strong expertise in optics (Mirror lab, College of Optical Sciences).

Non-exoplanet science should be explored
Deep diffraction-limited imaging over a wide field is likely to be of high scientific value. Need to evaluate interest in the non-exoplanet community and explore if wide field camera could be enhanced for non-astrometric use (filters ?).
Issue: non-exoplanet science will require large data transfer (more than just the ~1000 stars used for astrometry) which will increase mission cost.

More information

- More info on PECO website: http://caao.as.arizona.edu/PECO
  - 20-page summary of PECO activity
  - Science Requirements Document (SRD)
  - Design Reference Mission (DRM)
  - Technology development plan
  - Recent lab development updates

- Several of the key coronagraphy and WFC technologies developed for PECO will be the core of the Subaru Coronagraphic Extreme-AO system: http://www.naoj.org/Projects/SCEXAO/
  - PIAA & PIAACMC
  - LOWFS for fast & accurate pointing control
  - Control & calibration of focal plane speckles

- Astrometry with a coronagraphic space telescope:

http://www.naoj.org/staff/guyon/04research.web/astrometry.web/astrometry.html

PECO top key technologies are identified and under study

- PIAA Coronagraph System Path to TRL6
  - PIAA mirror fabrication
  - Performance demonstrations in JPL HCIT
  - Brassboard component qualification
    - Note that existing PIAA coronagraph bench is the same scale as flight components
- Broadband Wavefront Control
  - Baseline Xinetics DM near TRL 6
  - MEMs DM technology in progress as potential cheaper alternative (NASA Ames Funding)
  - Algorithms tested in HCIT
- Pointing Control Demonstration
  - LOWFS provides fine guidance, to be tested in HCIT
  - Models predict 0.5 mas possible with existing technology (1 mas demonstrated with PIAA in the lab in air)
- Photon-counting EMCCD Detectors

System verification combines:

- Subsystem testing & observatory testing

- Thermal-Structural-Optical modeling
  - Needed for final system verification
  - HCIT will validate optical models
  - SIM TOM testbed demonstrated thermo-structural

JPL HCIT Test Facility

Xinetics 64x64 DM

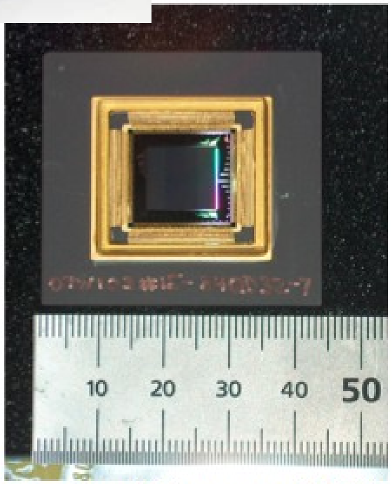


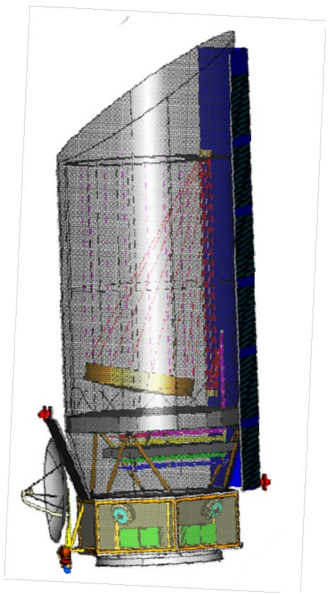
Figure 1: 1024 actuator (32x32) MEMs DM commercially available from Boston Micromachines (mm scale).

PECO trades, further studies

- Telescope diameter, currently 1.4m (cost constrained)
- Drift-away vs L2 ?
- Active tip/tilt secondary for pointing control ?
- Need for active isolation between payload & spacecraft vs passive isolation of reaction wheels only ?
- Number of coronagraph channels & spectral coverage
  - Currently 4 spectral channels in PECO design, 400nm to 900nm
  - More channels relaxes optical quality requirements at the expense of more complex instrument
- Lower IWA PIAA coronagraph designs
  - PIAA can be pushed theoretically to < l/D IWA at 1e10 contrast with Lyot stop and phase mask for point source
  - Sensitivity to pointing error, stellar leaks due to stellar diameter and chromaticity increase
  - Need to balance gains and losses taking into account all these effects
  - strong potential to reduce IWA in the red PECO channels
- MEMs as alternative to larger Xinetics Deformable mirrors
  - Would allow smaller & cheaper instrument
  - Lab testing / validation (NASA Ames / JPL)
  - Number of actuators (32x32 to 64x64) defines PECO OWA
- Astrometric measurement to sub micro-arcsecond for mass determination

PECO Design Reference Mission

Mission Phase	Initial Detection and Characterization				Follow-up High SNR Characterization				Total
	Number of Systems	Integration (hours each)	Overhead (hours each)	Visits (each)	Number of Systems	Integration (hours each)	Overhead (hours each)	Visits	(hours)
Commissioning	-	-	-	-	-	-	-	-	1,440
Grand Tour Earths + Super-Earths	20	16	8	10	5	400	200	2	10,800
Follow-up of Radial Velocity	15	16	8	3	15	200	100	2	10,080
Giant Planets + Disks Snapshot	120	16	8	1	-	-	-	-	2,880
							Total (hours)		25,200
							3-yr mission (hours)		26,280
							Margin (hours)		1,080



Sun avoidance angle = 60 deg
anti-Sun avoidance angle = 45 deg

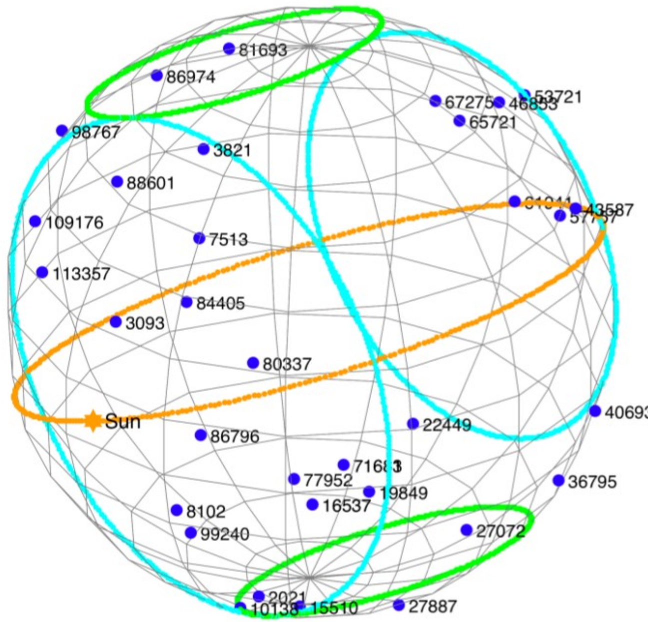
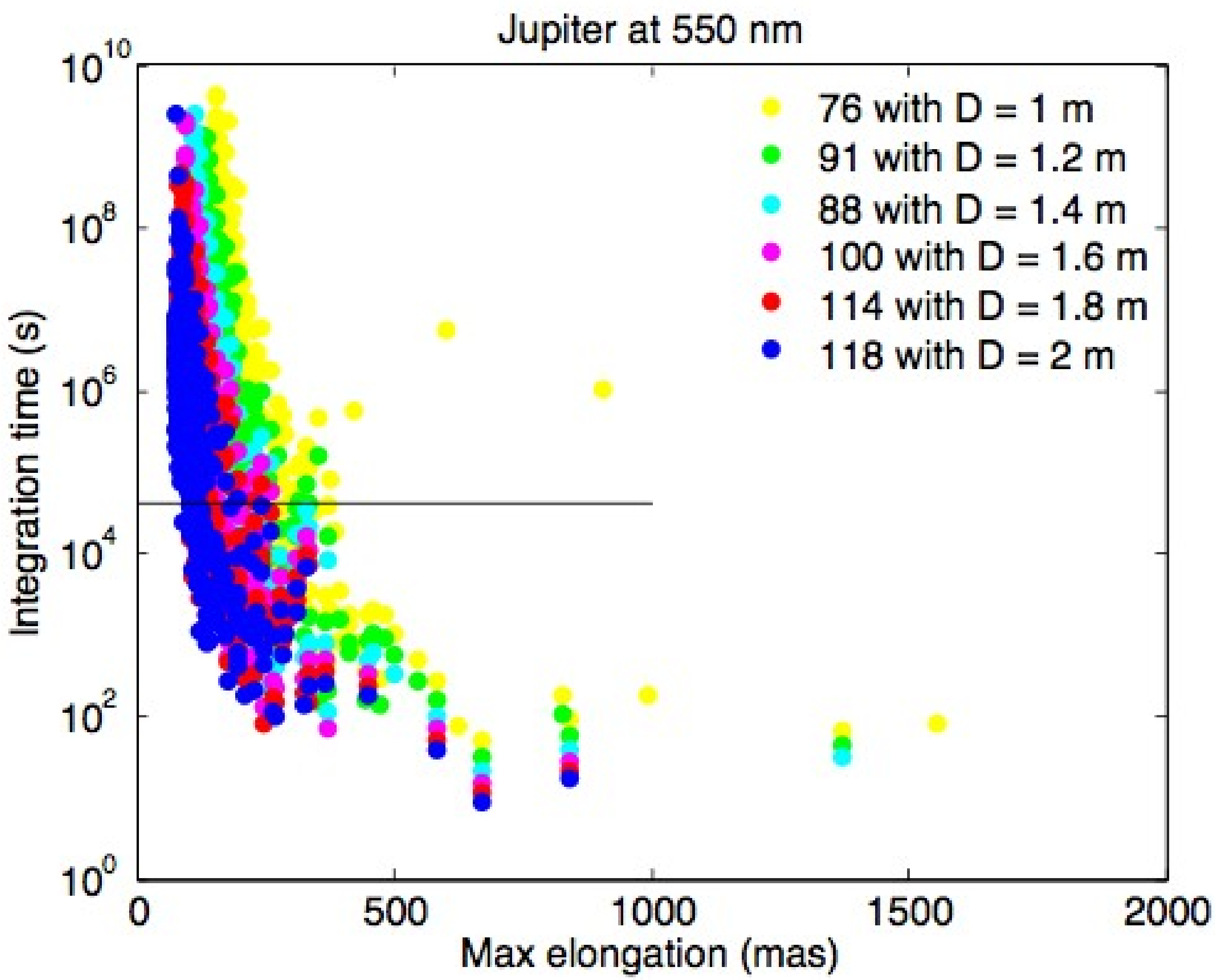


Figure 8.3.2: PECO-centric field of view for one moment in mission time. Sun/Earth avoidance and power-limited zones are outlined in blue. Continuous viewing zones are outlined in green. Grand Tour + RV targets are blue dots tagged with their HIP numbers. Please see the text in Sections 8.3.4 and 8.3.5 for detail.

PECO can easily detect Jupiters



Can see more targets at shorter wavelengths and larger diameters

Trade study shows number of Jupiters detected for different telescope diameters

- PECO simulation Jupiter-like planets at 5 AU
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- hard IWA of 2 lambda/D - sources within 2 lambda/D are excluded. Including partially extinguished planets brings count from 88 to ~250 for 1.4m PECO.

Univ. of Arizona
Jet Propulsion Laboratory
California Institute of Technology
LOCKHEED MARTIN
Ames Research Center
ITT

(detection in < 6 hr)
(detection in < 6 hr)
(detection in < 6 hr)

PECO Pupil mapping Exoplanet Coronagraph Observer

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

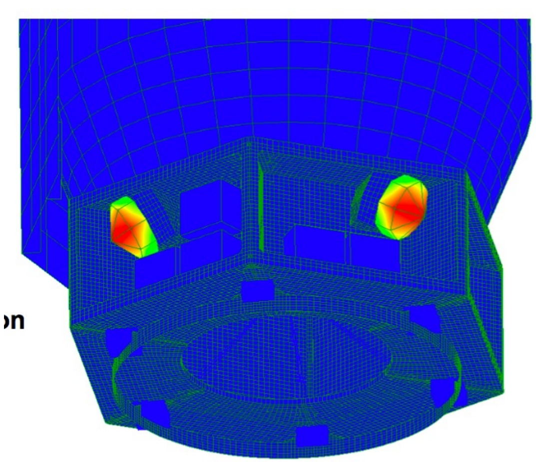
Planet Name	Mp (Mjup)	Period (d)	a (AU)	sep``	550nm/D	Dist (pc)	St. Sp T	M*	St. Mag. V.	Pl mag V	Contrast
Epsilon Eridani b	1.55	2502	3.39	1.06	13.07	3.2	K2 V	0.8	3.73	25.7	1.6E-09
55 Cnc d	3.84	5218	5.77	0.43	5.31	13.4	G8 V	1.0	5.95	29.1	5.5E-10
HD 160691 c	3.1	2986	4.17	0.27	3.36	15.3	G3 IV-V	1.1	5.15	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

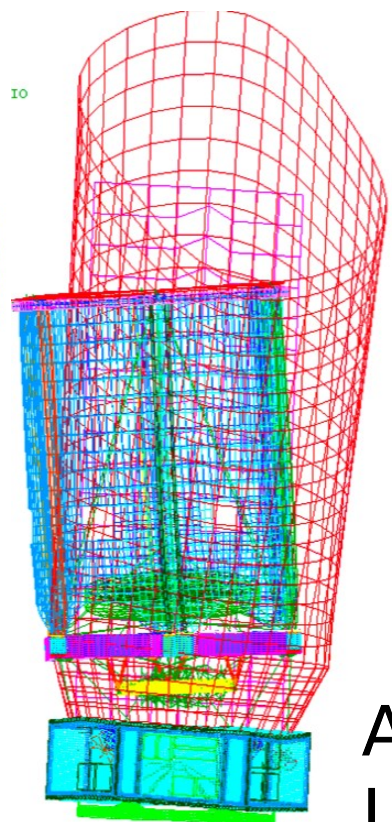
PECO stability analysis

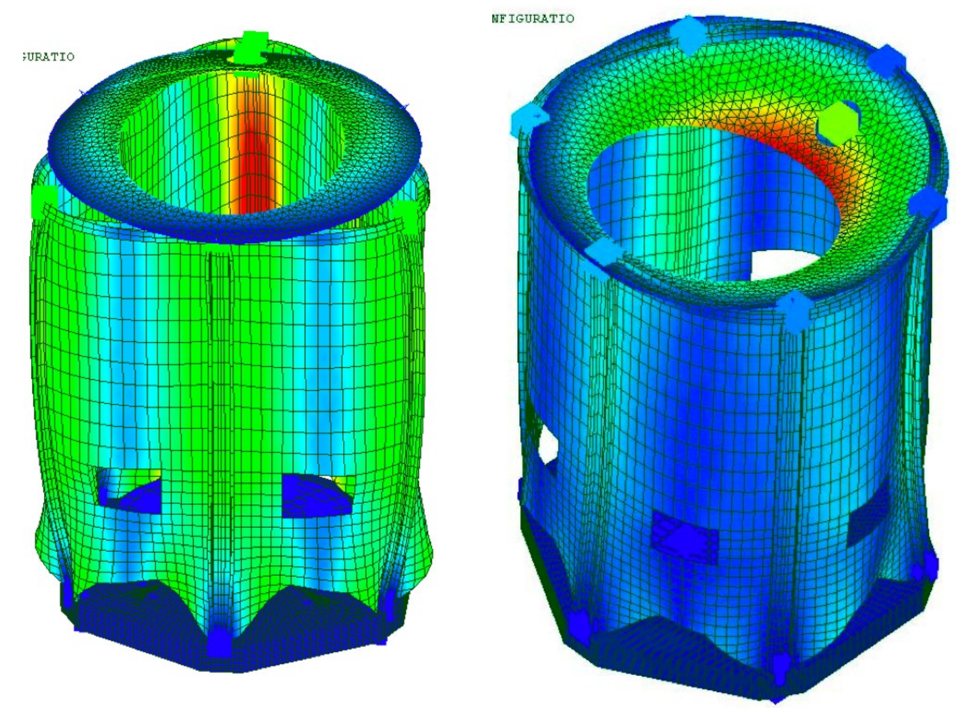
- PECO wavefront needs to be very stable
  - it takes few minutes to see an Earth-like planet
  - it takes just as long to see a speckle with the same luminosity
  - it takes a 1.5pm sine wave ripple on the wavefront to create such a speckle
- A 1.5 pm sine wave ripple on the wavefront which appears in a few minutes is sufficient to confuse the detection of Earths
- Detailed analysis with design iterations have to be done to verify that PECO is sufficiently stable to detect Earths

PECO vibration analysis

- Identify vibration modes & frequencies
- Compute mode amplitude as a function of reaction wheel speed
- Use optical model to convert results in wavefront aberrations (tip/tilt, focus & other modes)







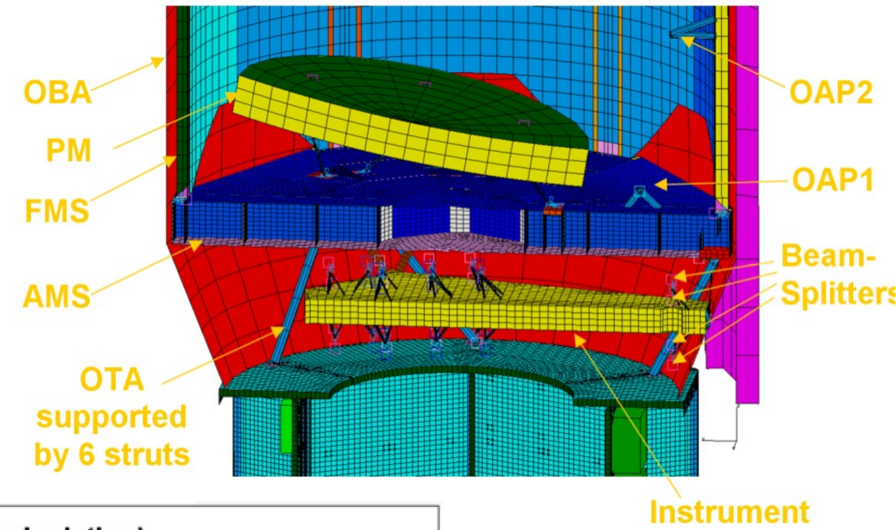
Analysis performed by Lockheed Martin

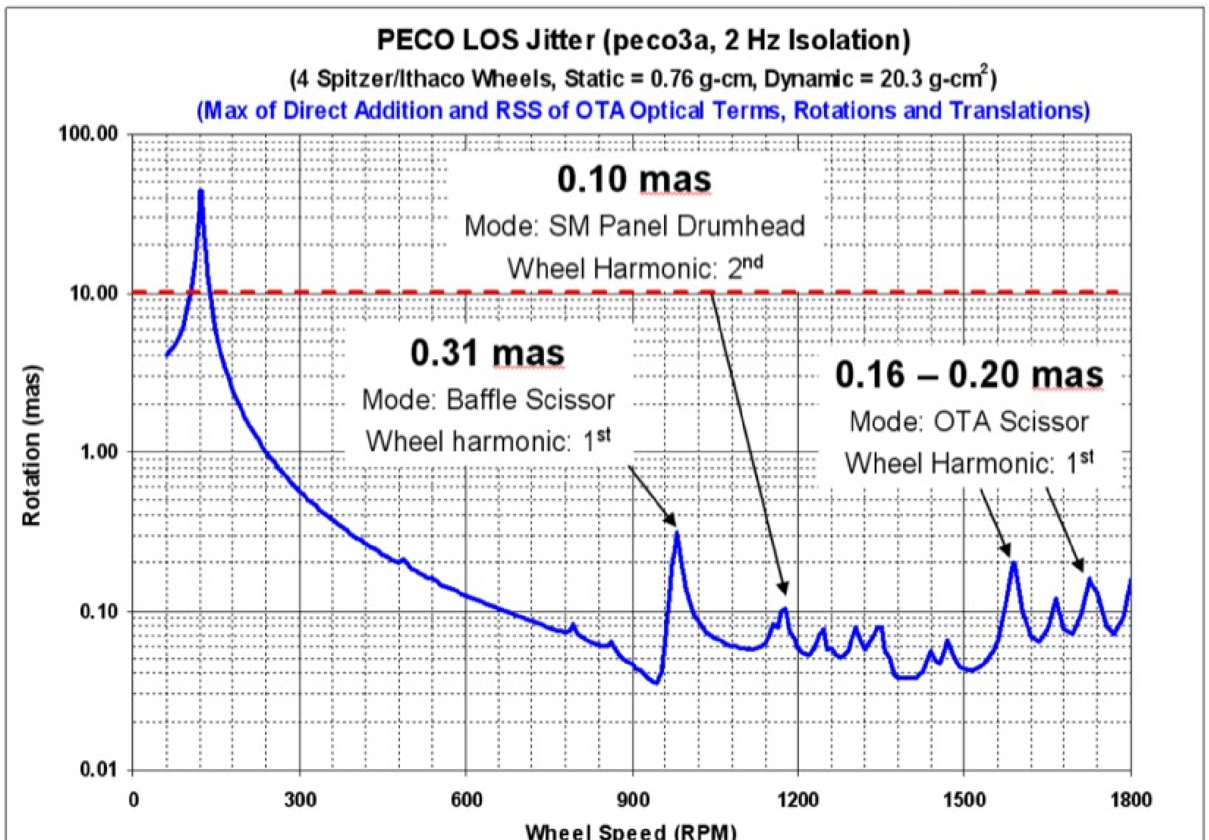
PECO jitter analysis

Univ. of Arizona

PECO Pupil mapping Exoplanet Coronagraph Observer

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



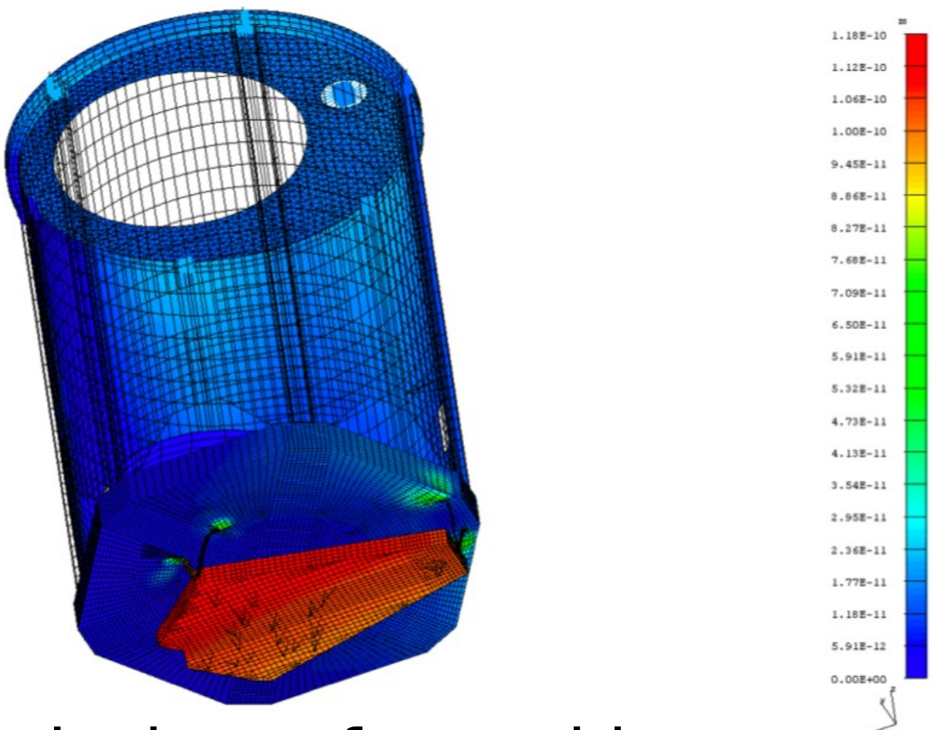


PECO thermal analysis

Thermal disturbance introduced when PECO sun angle is changed (pointing to new target)

How long after repointing does PECO become sufficiently stable ?

- Compute displacements & rotations of PECO optics for a given thermal disturbance
- Estimate thermal disturbances evolution after PECO repointing
- Analysis ongoing. Preliminary results show PECO meets stability requirements after ~2hr



Analysis performed by Lockheed Martin. NASA JPL analysis effort also initiated.

PECO cost estimate

- PECO costed by JPL Team-X
- Independent Price-H model in good agreement with Team-X estimates

At this pre-phase A phase of the mission, cost estimate should be considered indicative rather than predictive

Item	Cost $M 2009
Management, Systems Engr., Mission Assurance	40
Payload System	213[1]
-- OTA + OTB	130
-- Coronagraph	80
-- Other	3
Flight System	150
Mission Ops Preparation/ Ground Data System	40
Launch vehicle	140[2]
Assembly, Test, Launch Operations	15
Science	22
Education and Public Outreach	5
Mission Design	5
Reserves	140
Total Project Cost	**770**

Notes
1. Payload system includes instruments.
2. Atlas V 401

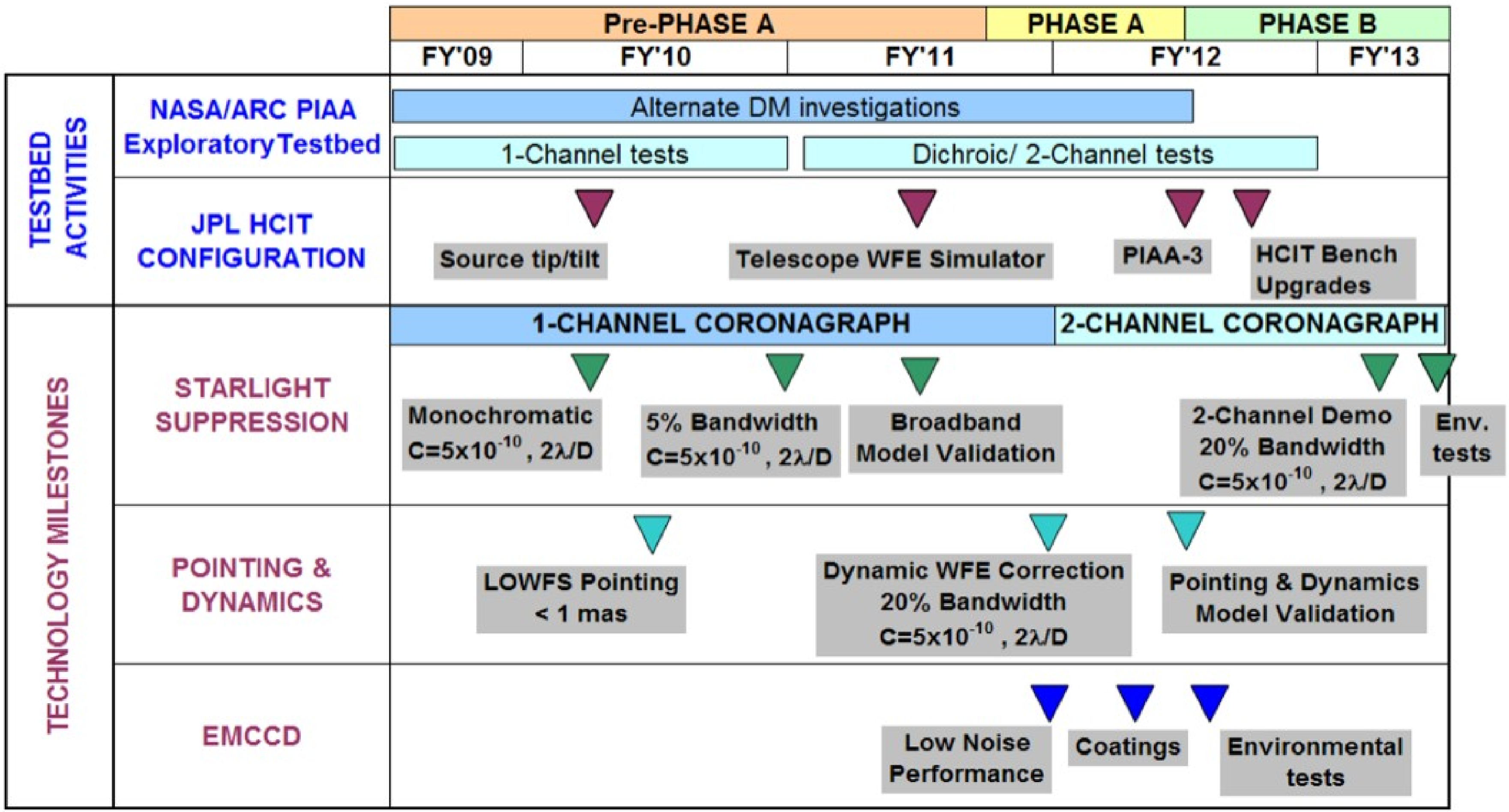
Total cost = $810M (with reserves)
$770M
+ $40M (technology development)

A 2-m version of PECO would increase cost to $1B to $1.5B range

PECO technology development

4-year plan for technology development to TRL6, costed at $40M

Technology	$M
Starlight Suppression	17
Pointing & Dynamics	8
EMCDD	3
NASA/ARC Support Demos	6
Testbed Upgrades & Procurements	6
Total	40



PECO schedule

Univ. of Arizona | Jet Propulsion Laboratory, California Institute of Technology | Lockheed Martin | NASA Ames Research Center | ITT

PECO Pupil mapping Exoplanet Coronagraph Observer

PECO can be launched in 2016