High Performance Coronagraphy for Direct Imaging of Exoplanets

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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)

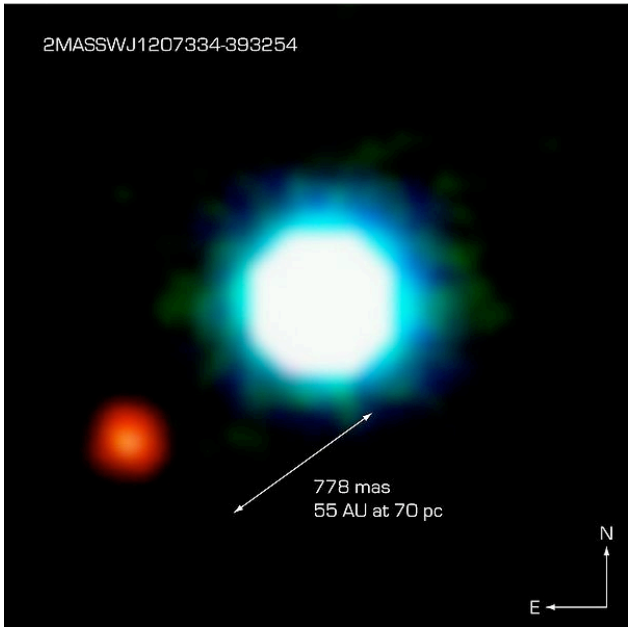
Ground-based imaging (Near-IR, with Adaptive Optics)

- **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)

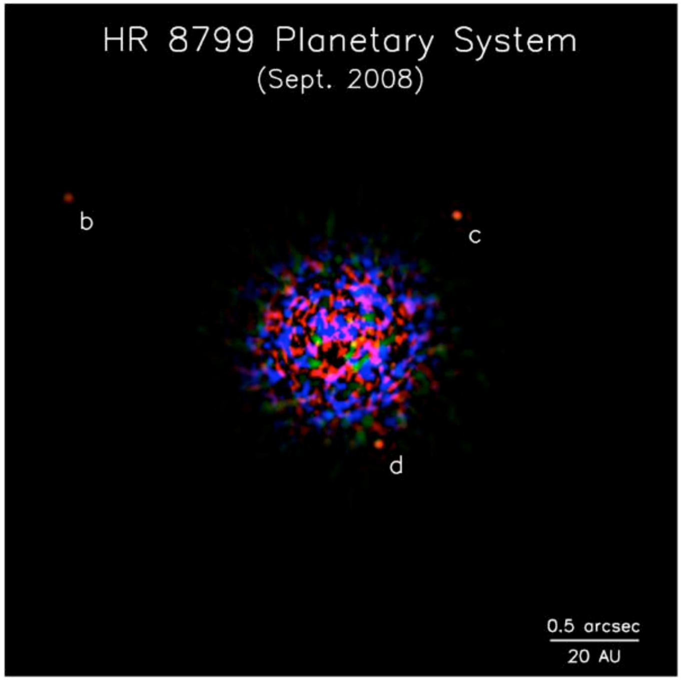
Space-based imaging (Visible, extremely high contrast)

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

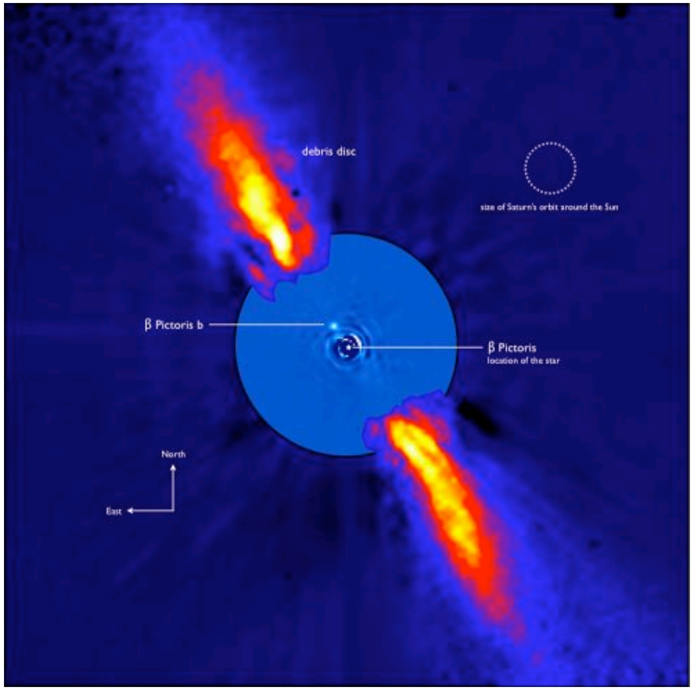
Ground-based near-IR imaging examples (without coronagraph !)



Chauvin et al. 2004

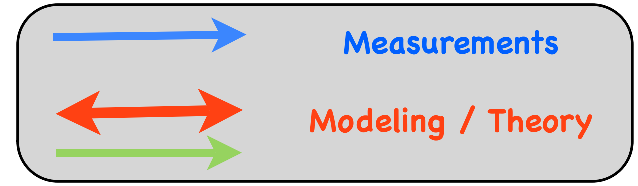


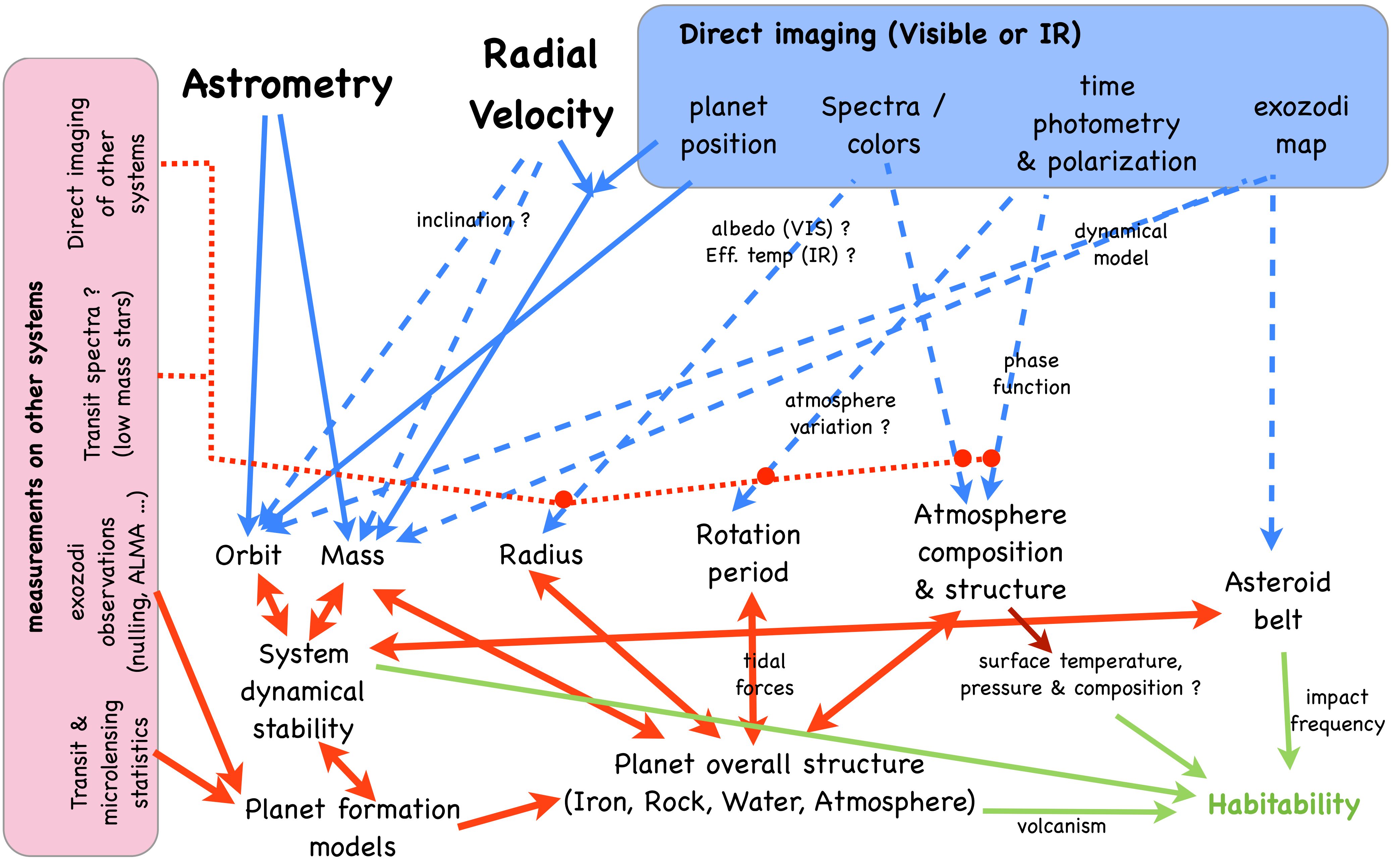
Marois et al. 2008



Lagrange et al. 2009

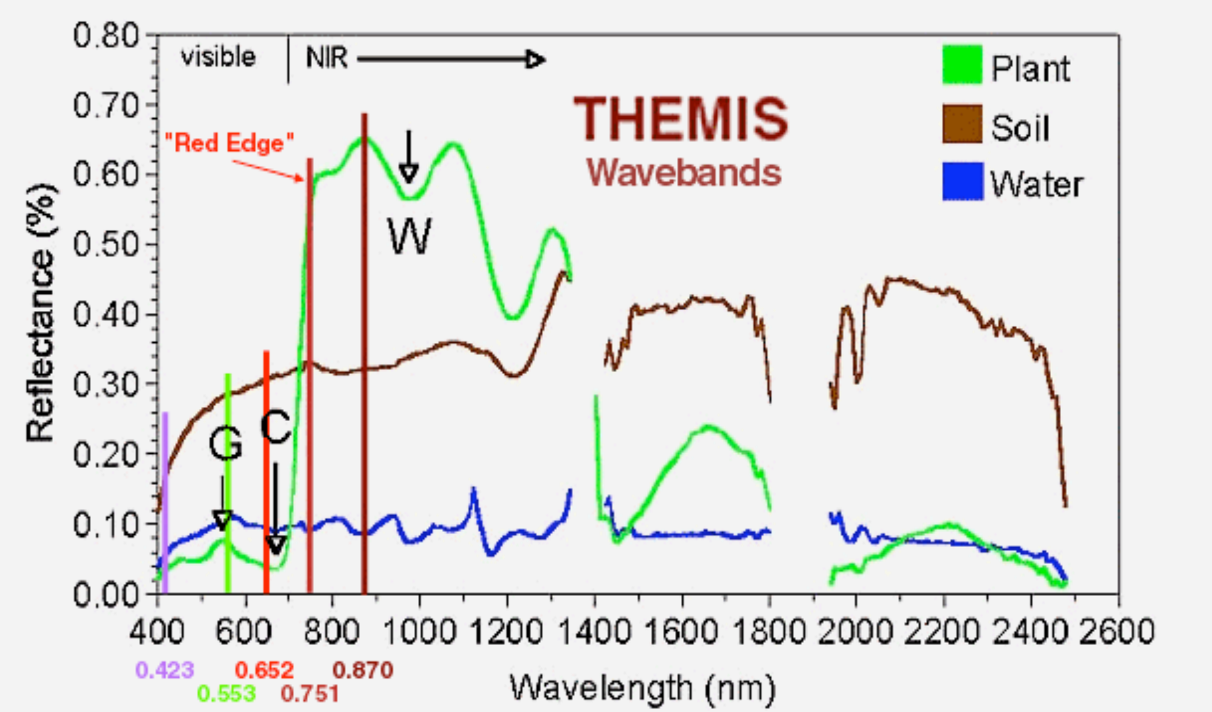
Habitable exoplanet characterization with direct imaging



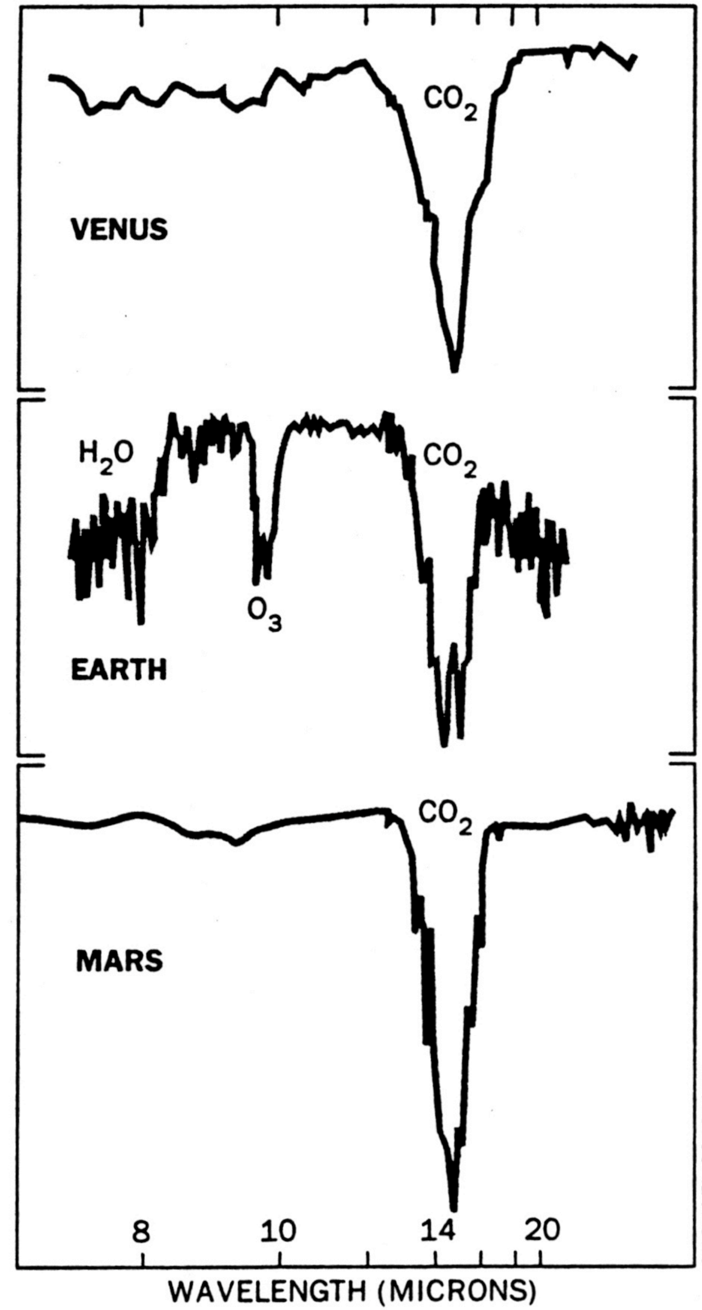


Spectroscopy

- Venus & Mars spectra look very similar, dominated by CO2
- Earth spectra has CO2 + O3 + H2O + O2 + CH4
  - Together, these gases indicate biological activity



Plant, soil, and water spectra. Letters G, C, and W refers to green peak, chlorophyll absorption, and water absorption features.



Red edge spectral feature

- Red edge in Earth spectra due to plants, and remotely detectable

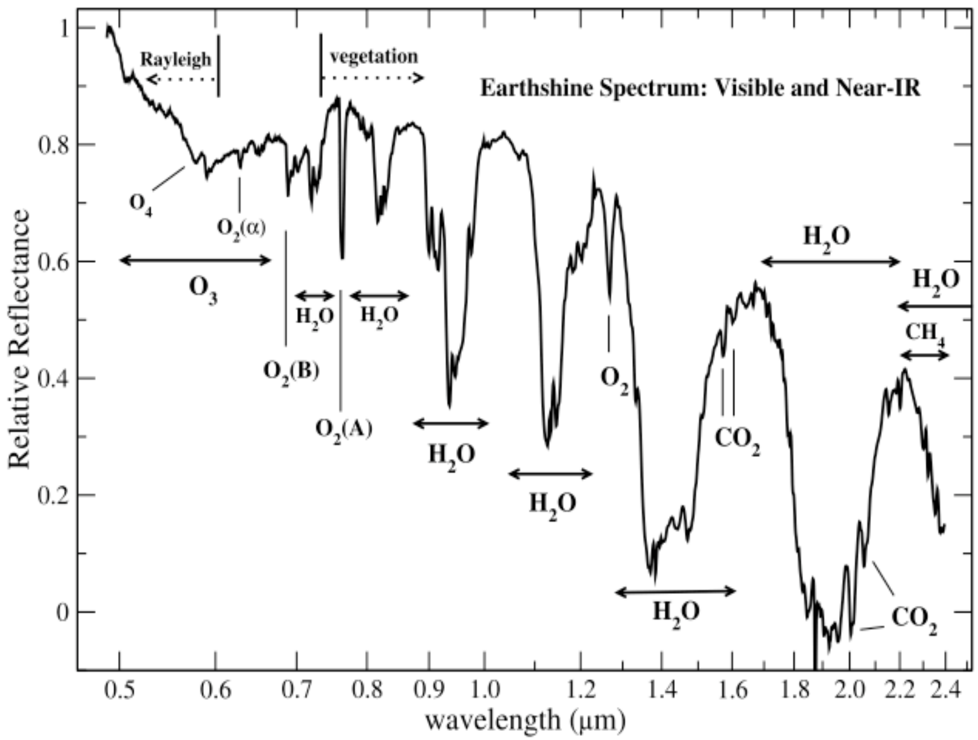


Fig. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006

Characterization (spectra) of habitable planets

Coronagraphy ideally suited for characterizing habitable planets around Sun-like stars (maybe also the best stars for habitability)

Coronagraphy / nulling (VIS)

M K G F A B

- small angular separation requires large telescope
- star/planet diameter ratio larger
- planet is faint in visible

- High contrast
- few targets, far away
-> planets are faint

Coronagraphy / nulling (IR)

M K G F A B

small angular separation requires large baseline

few targets, far away
-> planets are faint

Transit spectroscopy

M K G F A B

- transit probability < 1
- limited SNR

- insufficient SNR
- low transit probability <<1
- large period

Coronagraphy

- Coronagraph role is to block starlight and let as much planet light as possible through the system
- Most coronagraph designs are a painful tradeoff between coronagraphic rejection and throughput, inner working angle, angular resolution

- 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 well understood and 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 about 15 yrs ago

Lyot Coronagraph

The Lyot Coronagraph

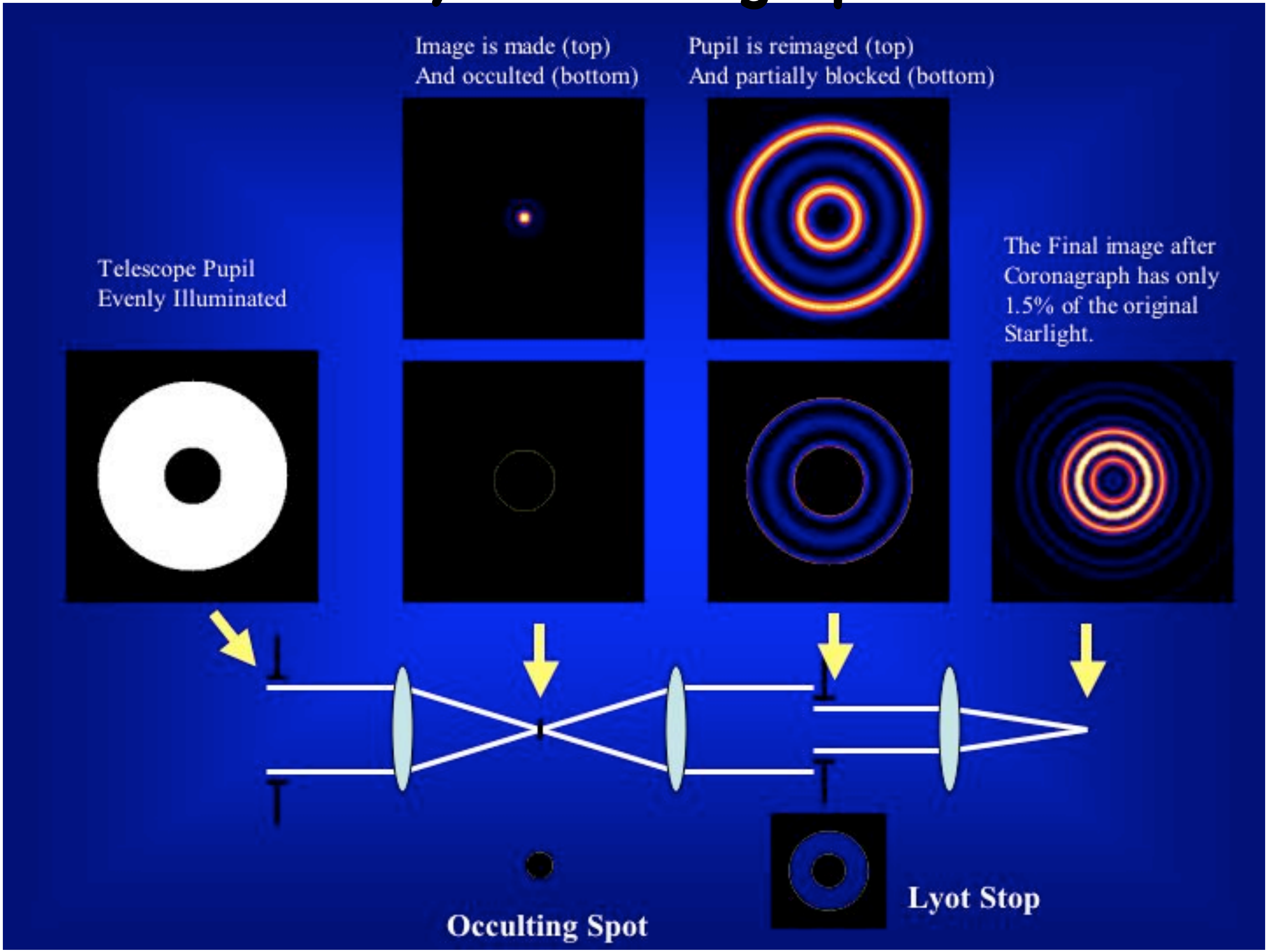
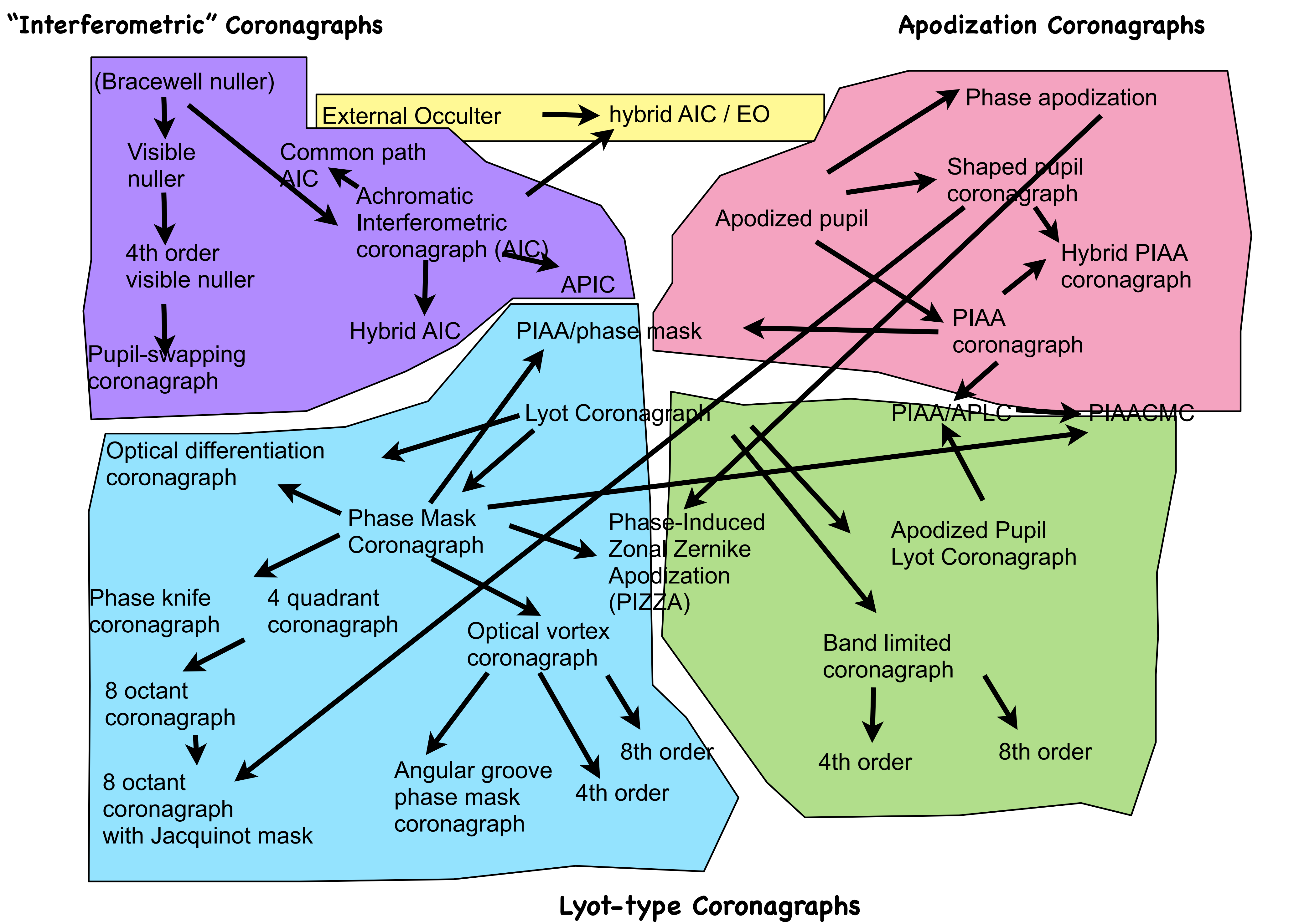


figure from Lyot project website



"Interferometric" Coronagraphs
Apodization Coronagraphs
(Bracewell nuller)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
Common path AIC
Achromatic Interferometric coronagraph (AIC)
APIC
Hybrid AIC
External Occulter
hybrid AIC / EO
Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
PIAA/APLC
PIAACMC
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
8th order
4th 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 l/D.

BUT: at high contrast, stars are not points -> performance limit is severely affected by stellar angular size

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

Coronagraph performance

New coronagraphs now approach theoretical limit.

PIAA coronagraphs appear particularly attractive

1e10 contrast

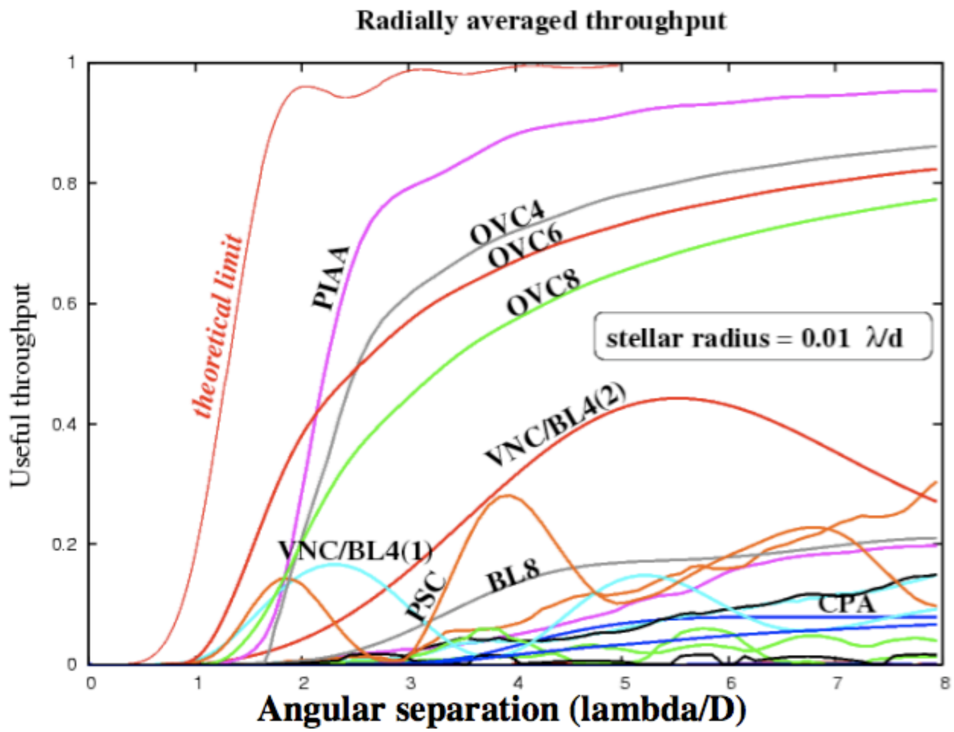


Figure 3-1: Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional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

PIAACMC (Guyon et al., in prep)

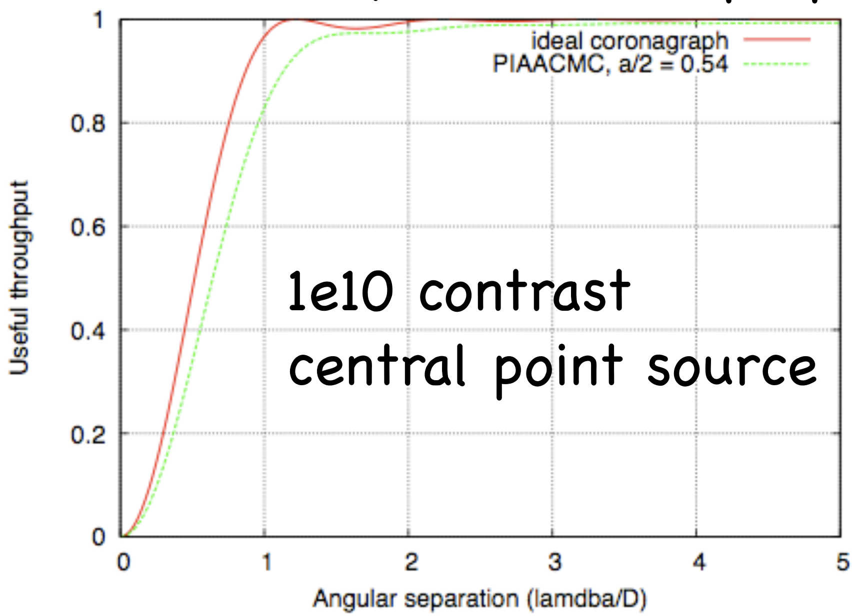


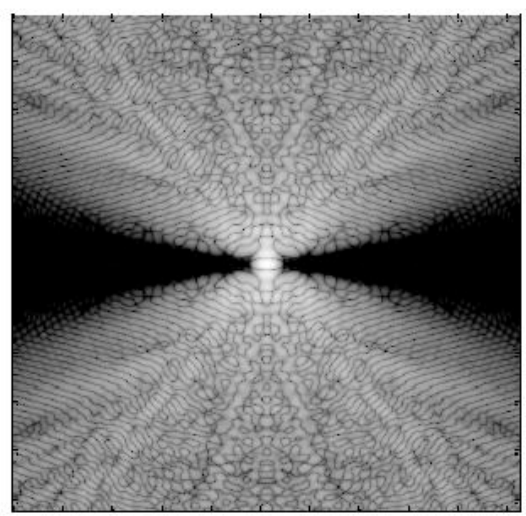
FIG. 6.— Comparison between the useful throughput of the PIAACMC with $a/2 = 0.54$ and the theoretical ideal performance limit of coronagraphy.

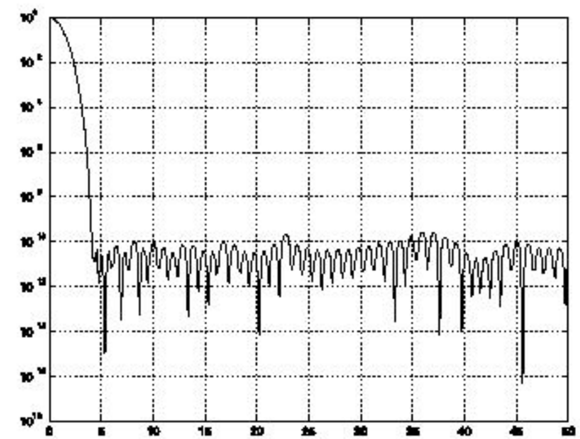
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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





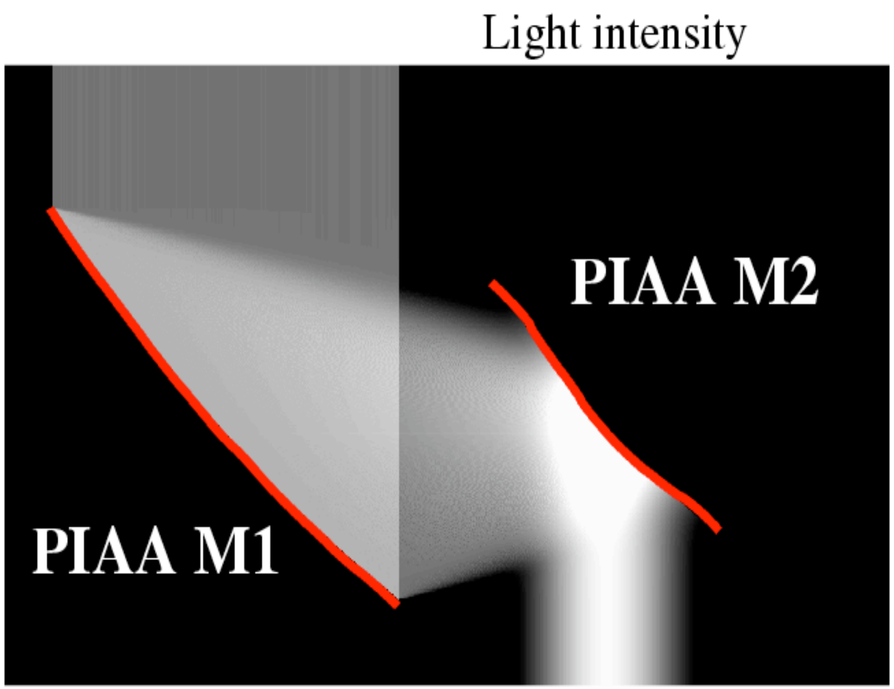
Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

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.)

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)



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

PIAA coronagraph architectures

Take any coronagraph which requires pupil apodization (left column), and replace apodizer with PIAA optics (right column).

Inverse PIAA required to recover FOV.

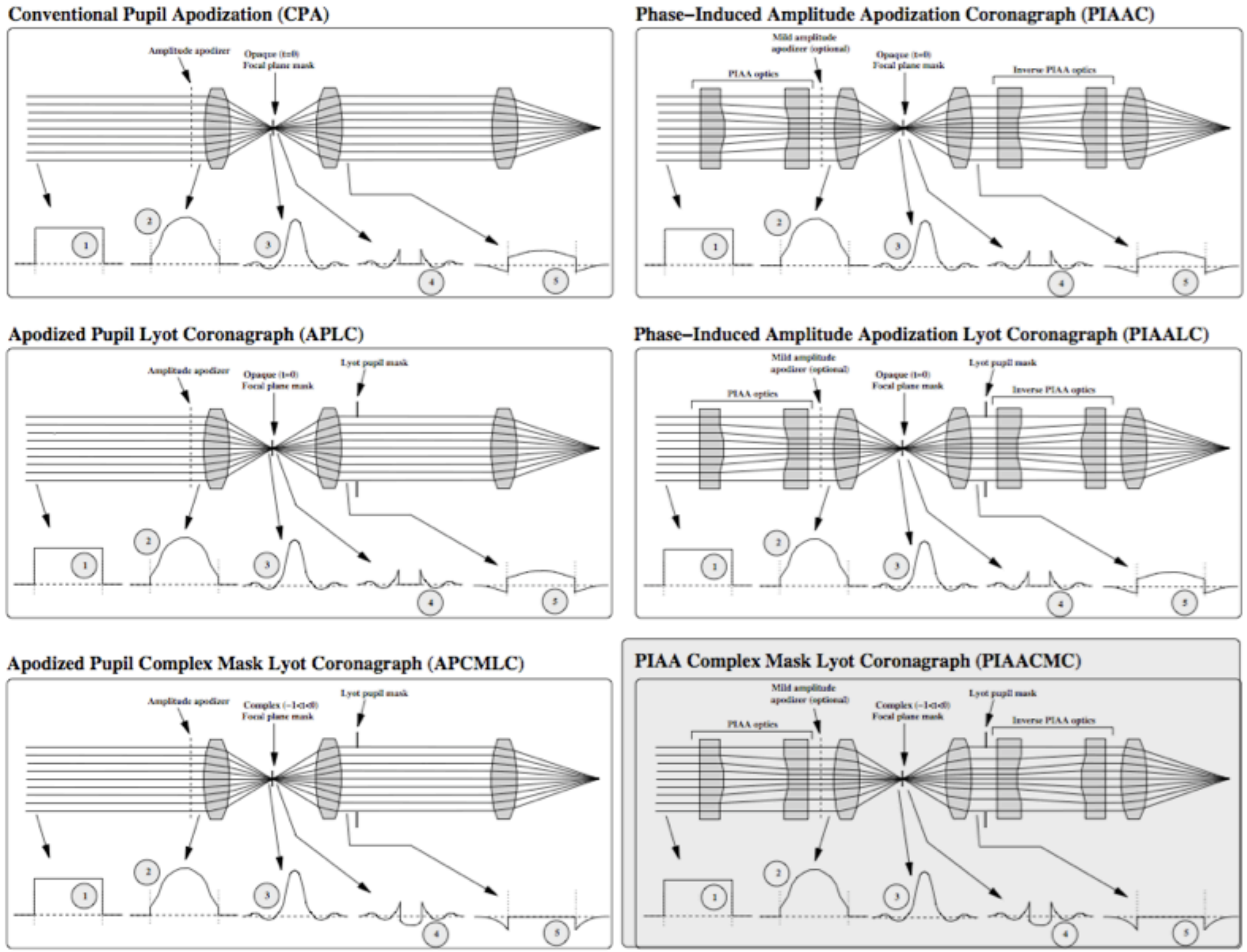
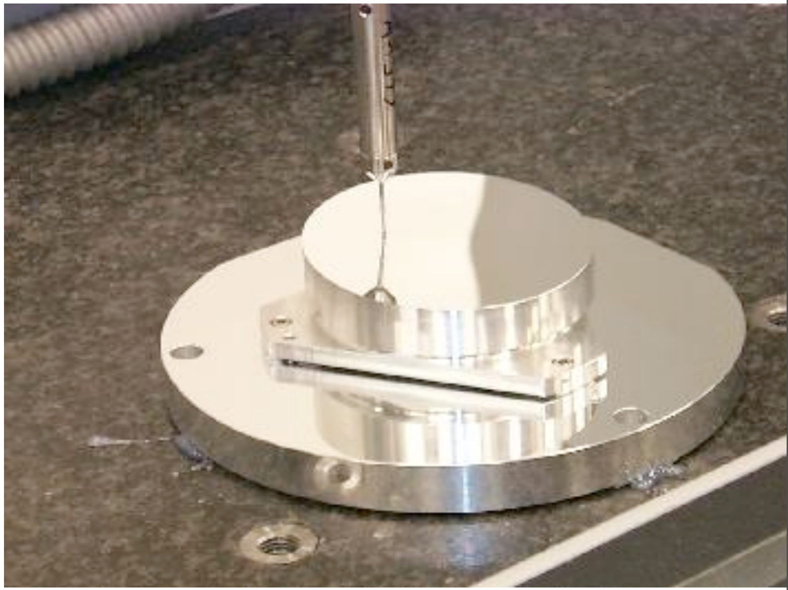


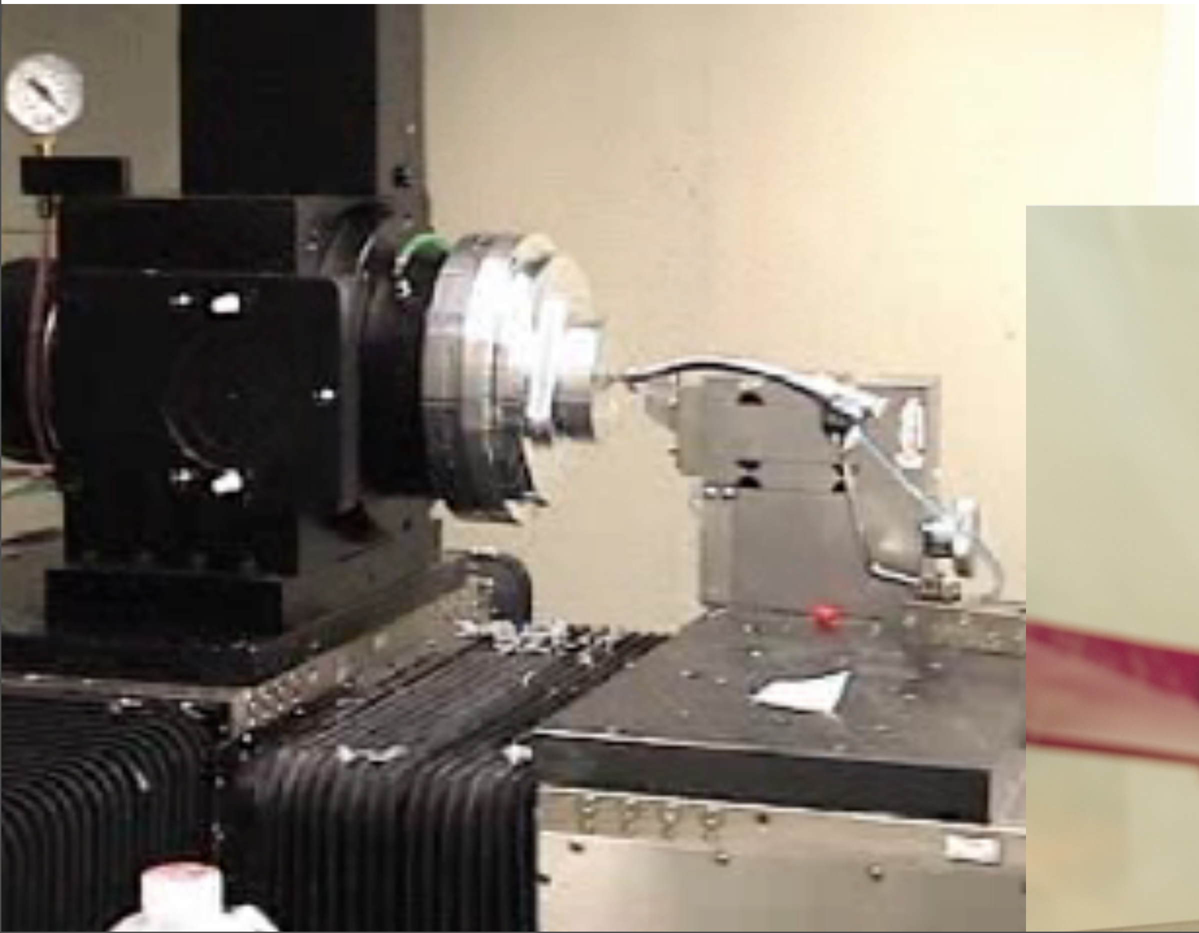
FIG. 1.— Coronagraphic architectures discussed in this paper. In conventional pupil apodization (top left), the coronagraphic effect is obtained by the combination of a pupil plane apodizer and a focal plane mask. This design is improved in the Apodized Pupil Lyot Coronagraph (APLC) by introducing a Lyot mask in the output pupil plane (center left). Further performance improvement is achieved by replacing the opaque focal plane occulting mask with a partially transmissive phase-shifting mask (bottom left). The right part of this figure shows the equivalent coronagraph designs when apodization is performed by lossless PIAA optics instead of a classical apodizer. A graphical representation of complex amplitude in a few relevant planes is shown for each coronagraph: (1) telescope entrance pupil, (2) pupil after apodization, (3) focal plane before introduction of the focal plane mask, (4) focal plane after the focal plane mask, and (5) exit pupil plane before trunctation by the Lyot mask. The PIAA Complex Mask Lyot Coronagraph (PIAACMC), shown in the bottom right of this Figure, offers the highest performance of all configurations, and its performance and design are the focus of this work.

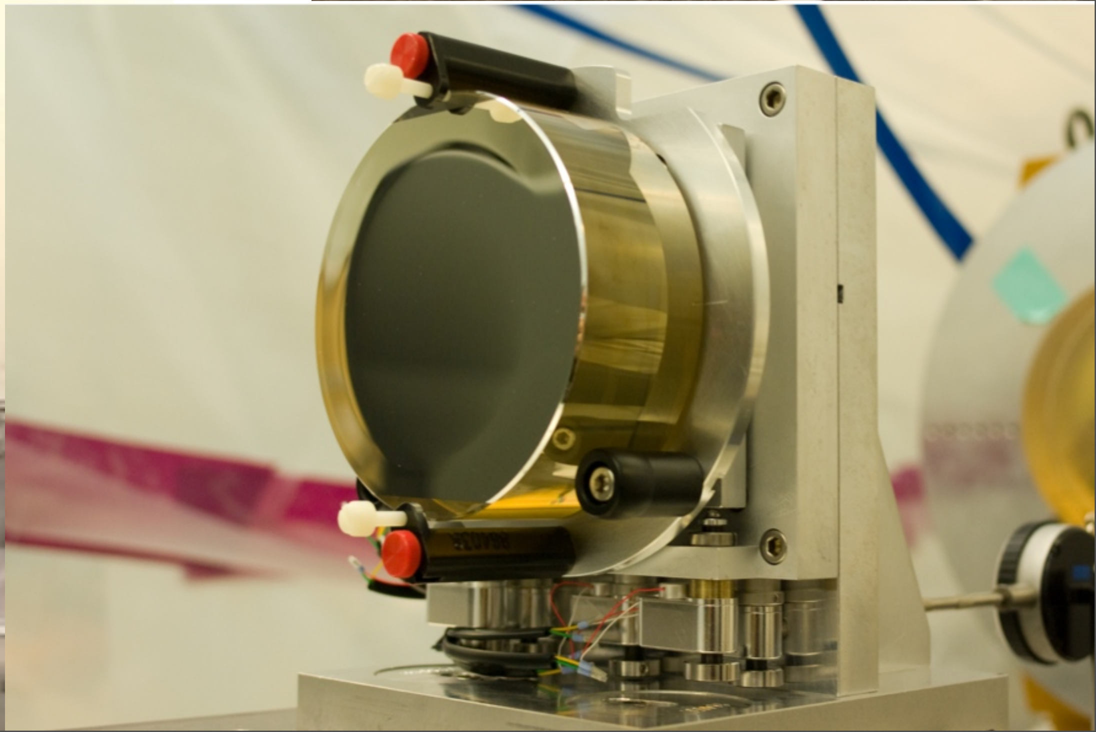
PIAA coronagraph development

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)

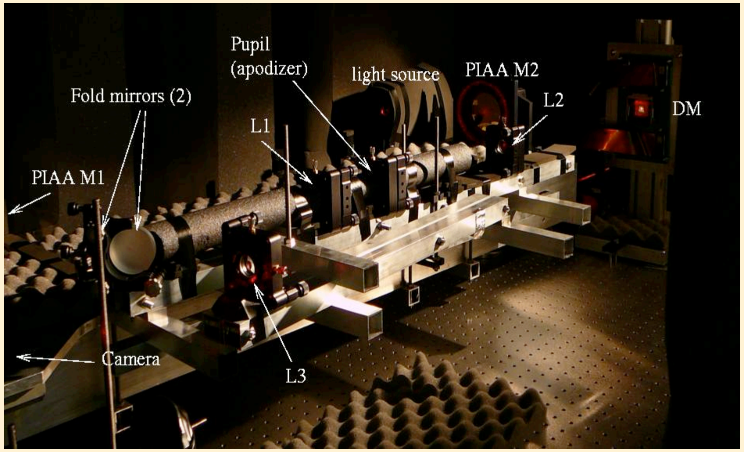




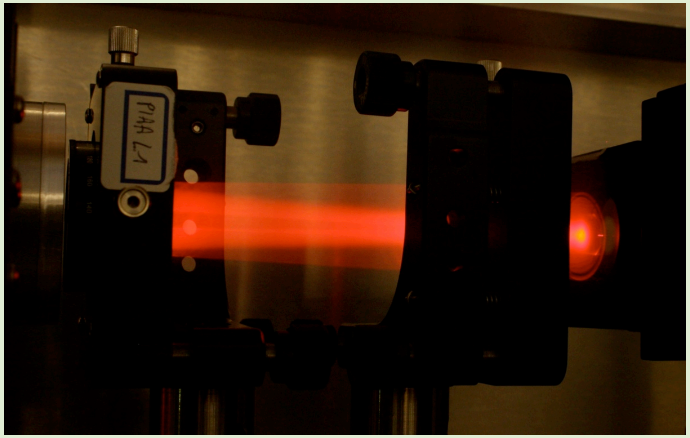


PIAA coronagraph development - labs

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

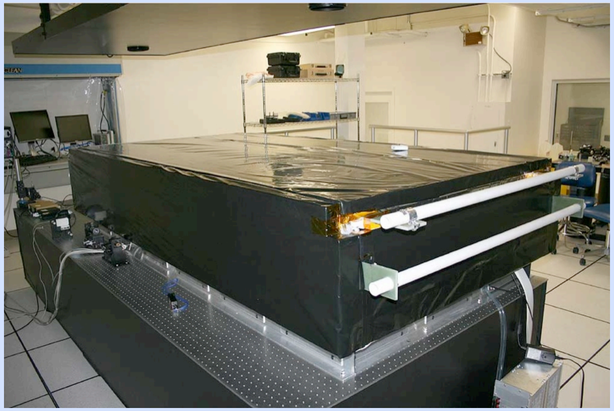


Efforts at Subaru are now focused on ground-based Subaru Coronagraphic Extreme-AO (SCExAO) system.

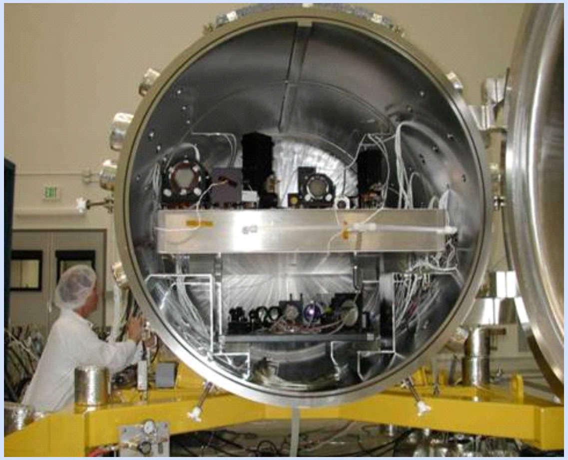


See talk by R. Belikov

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

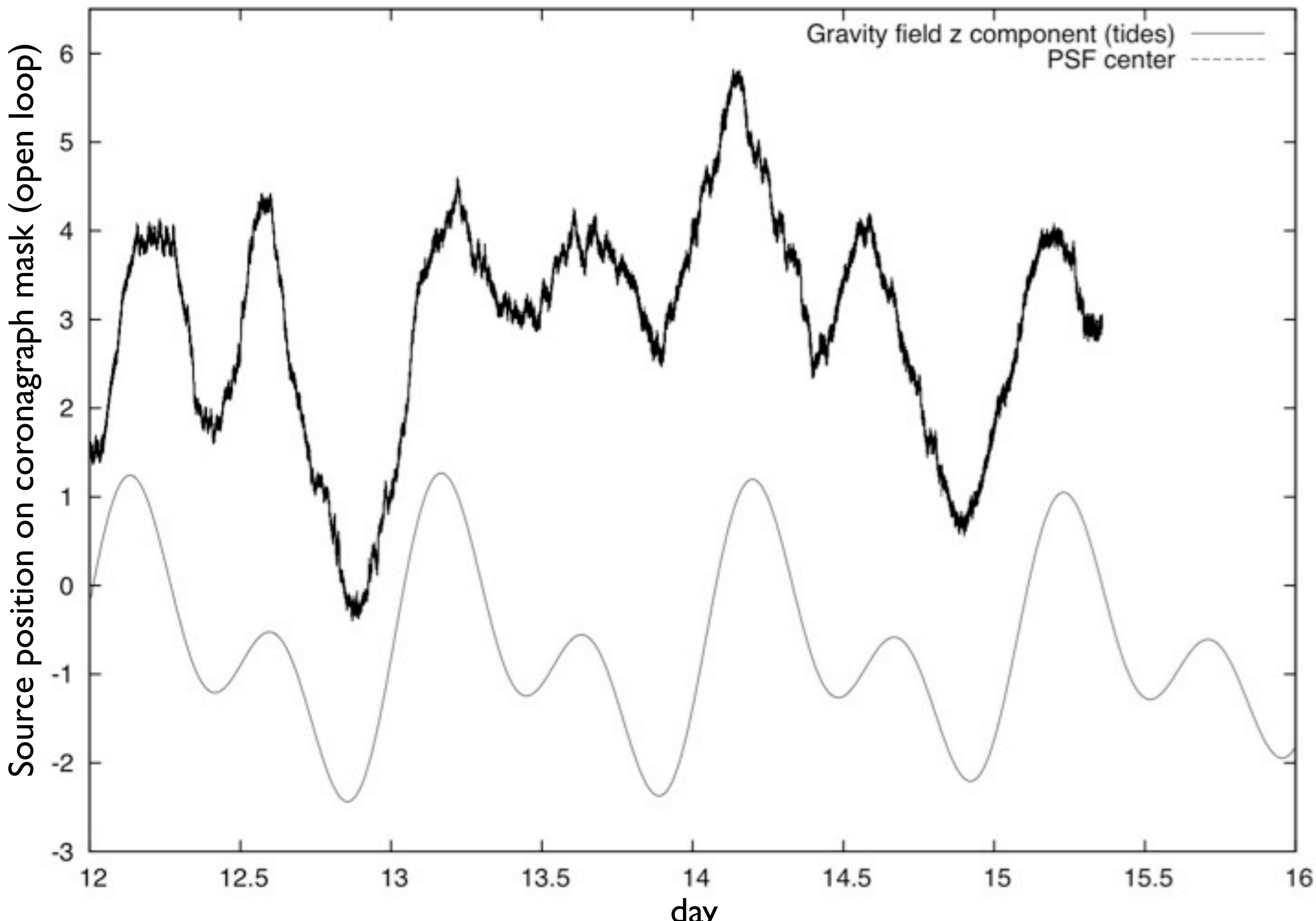


PIAA-dedicated testbed at NASA Ames testing WFC architectures with MEMs DMs.



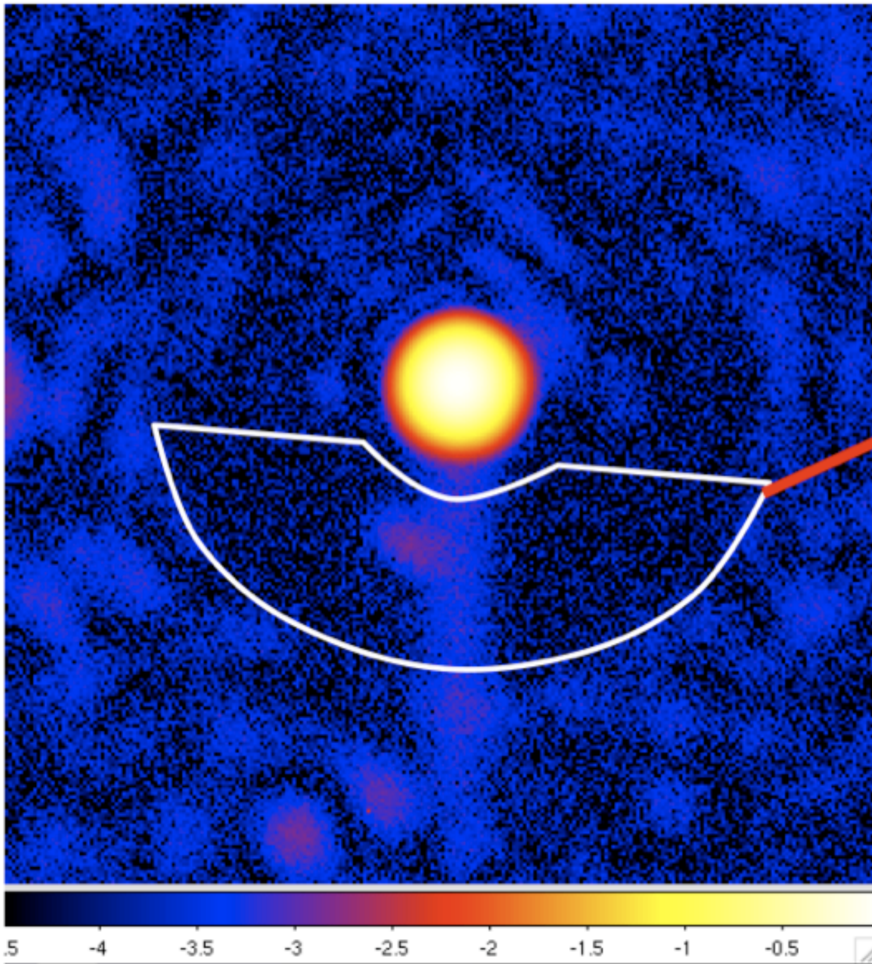
High Contrast Imaging Testbed (HCIT) at NASA JPL operates in vacuum and has been validated to 1e10 contrast. PIAA tests have started earlier this year.

Main source of instability in Subaru lab: Moon/Sun tidal forces

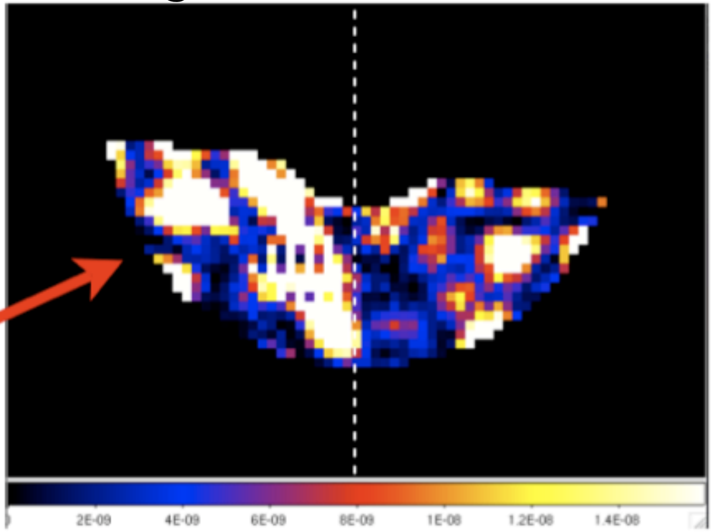


Subaru lab demonstration

Raw image



Coherent starlight (single frame)

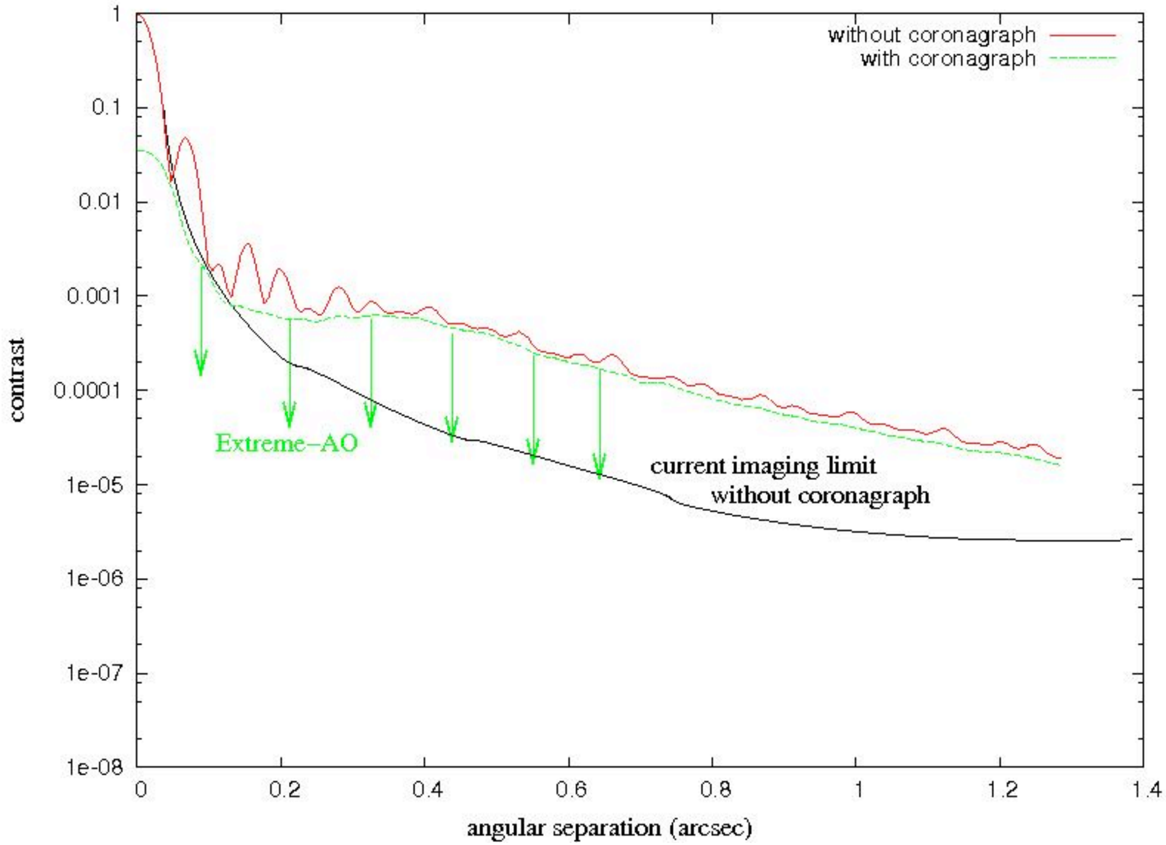


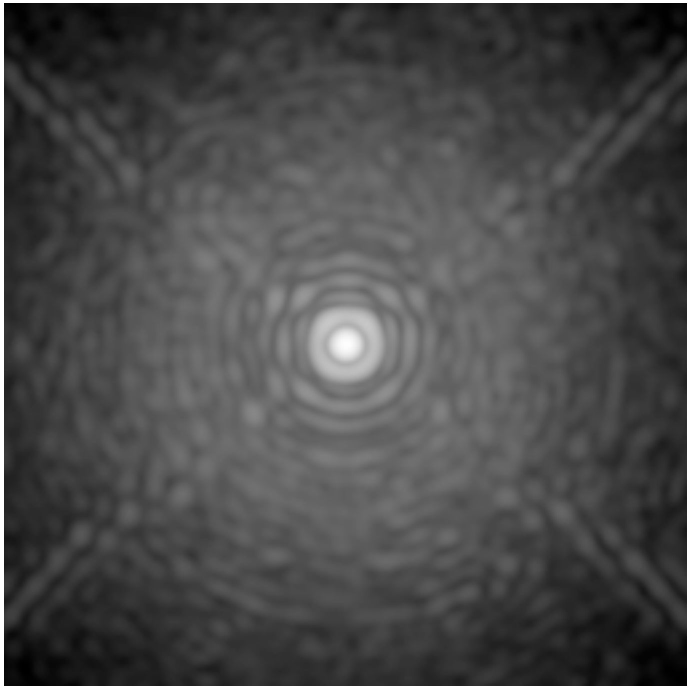
Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

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)

Wavefront control for coronagraphy

- None of the recent ground-based planet discoveries has been done with a coronagraph
- With current Telescopes+AO systems, coronagraphs offer almost no help beyond about 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) ?

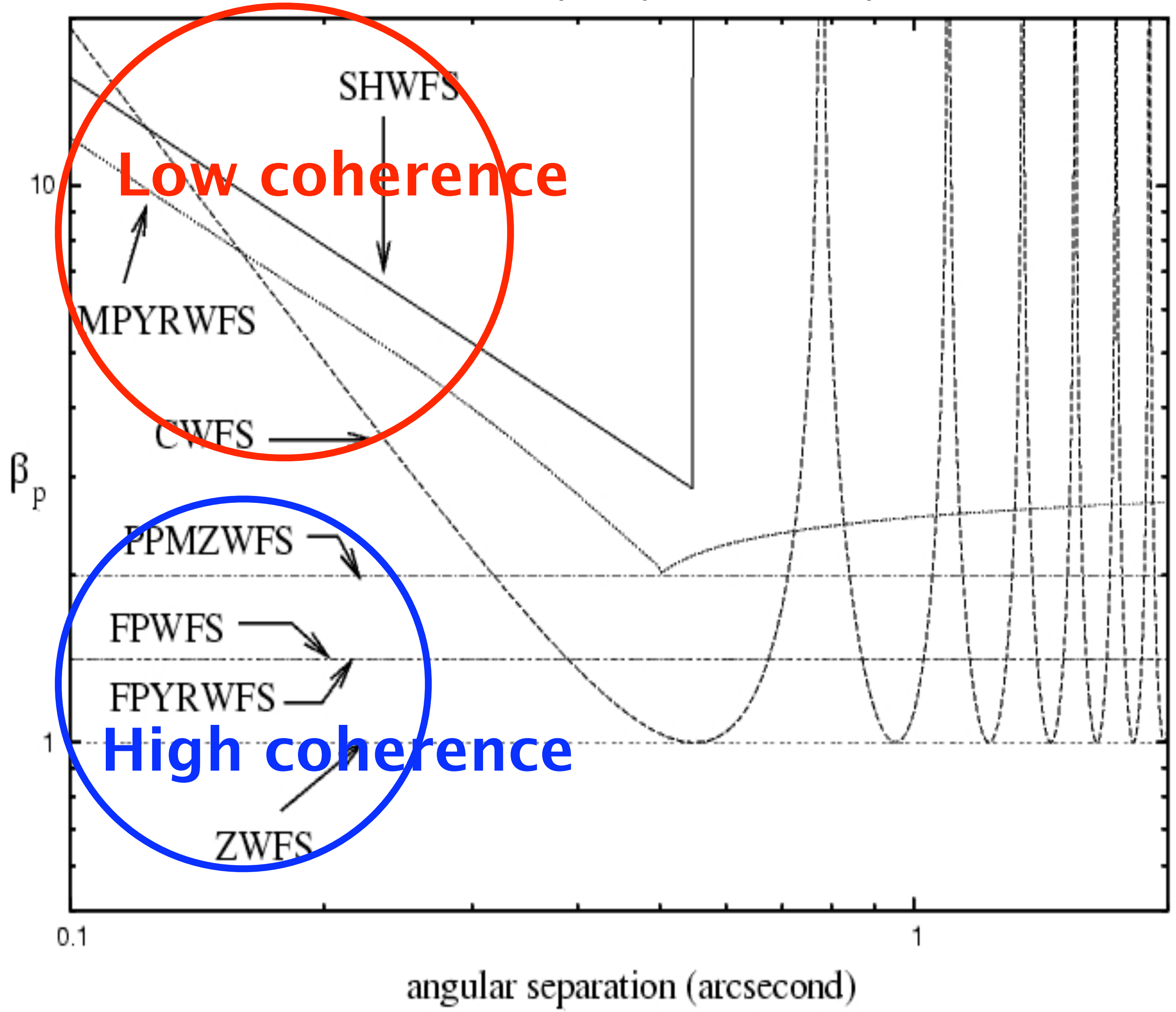
	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
SH	serious noise propagation	Very good	Yes	Low	on sky	at least 4 pixels per subaperture
Curvature	serious noise propagation	Very good	Somewhat LGS OK	Low	on sky	1 pix/subaperture 2 reads
Pyramid (modulated)	noise propagation	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)

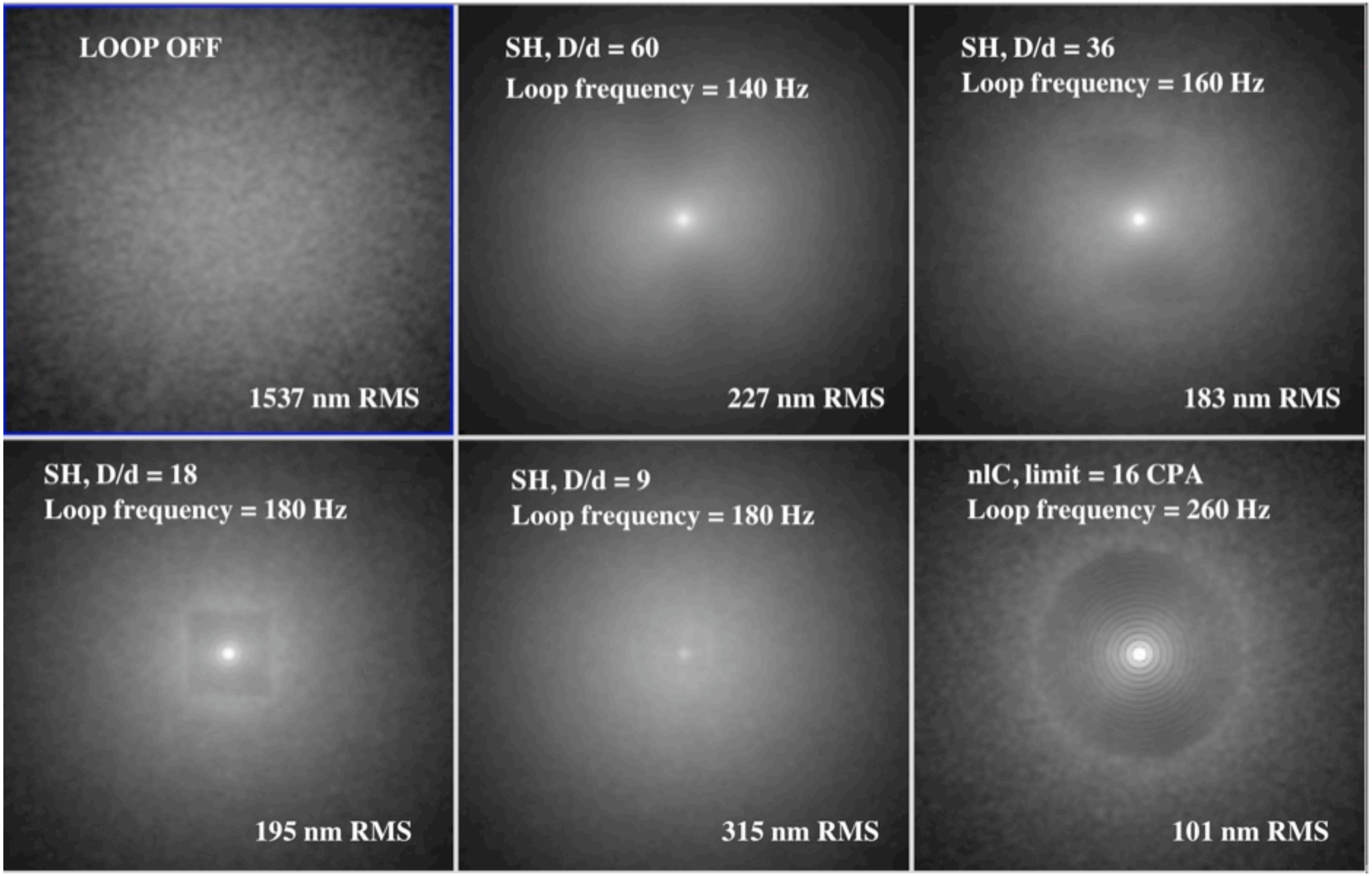


Square root of # of photons required to reach fixed sensing accuracy

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

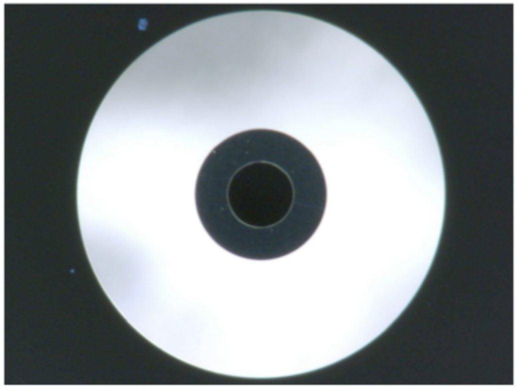


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

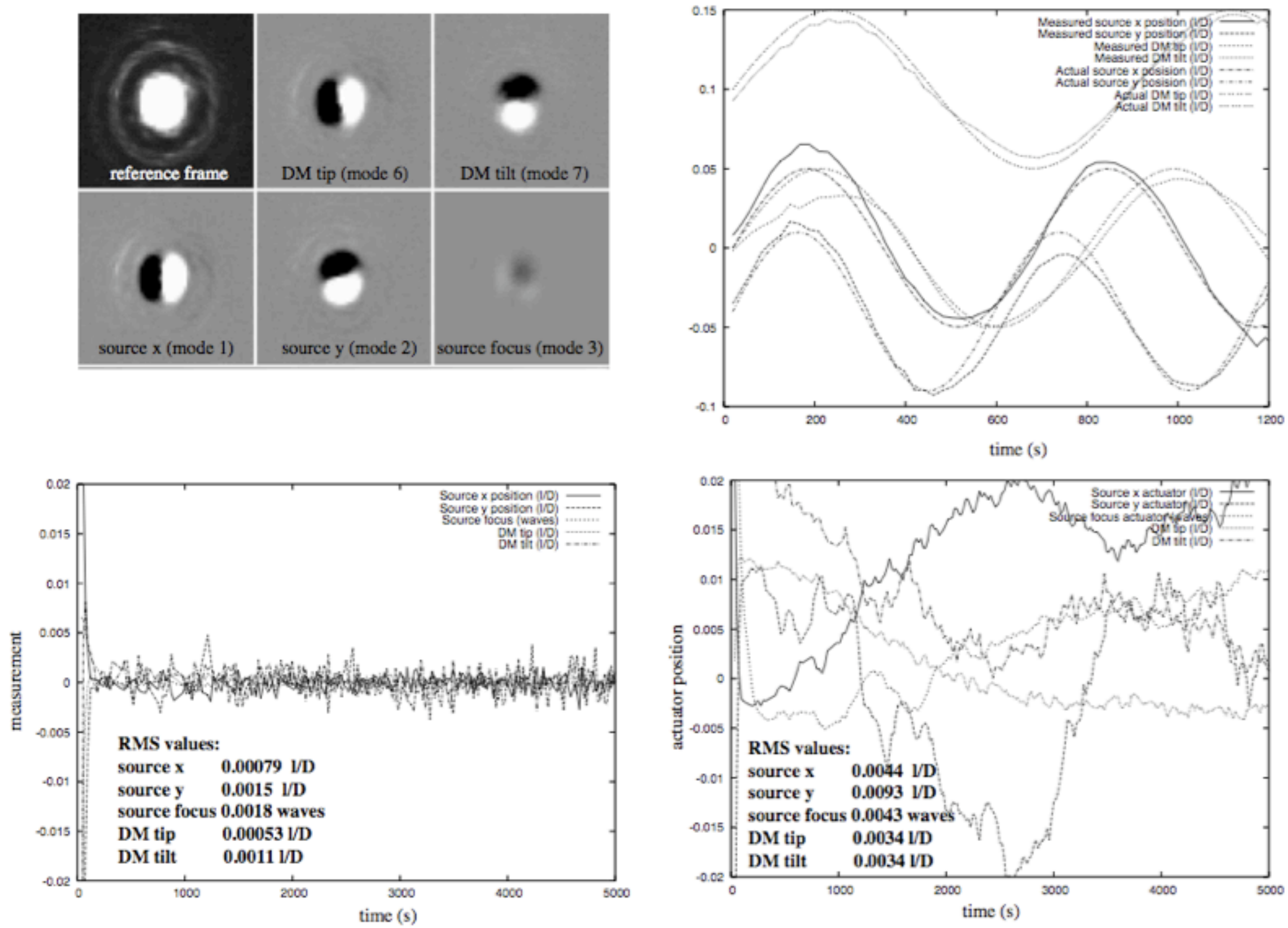


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. 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.

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.

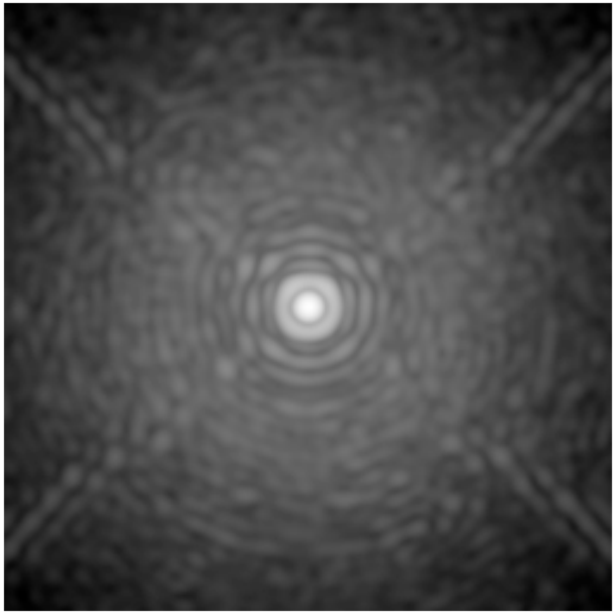
ref: Guyon, Matsuo, Angel 2009

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

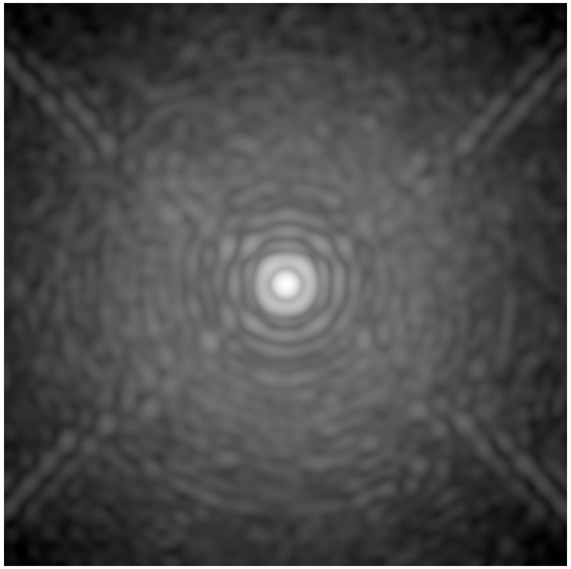
Polarization differential imaging (PDI)
Degree of polarization may be low (few %)
Only works on reflected light

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

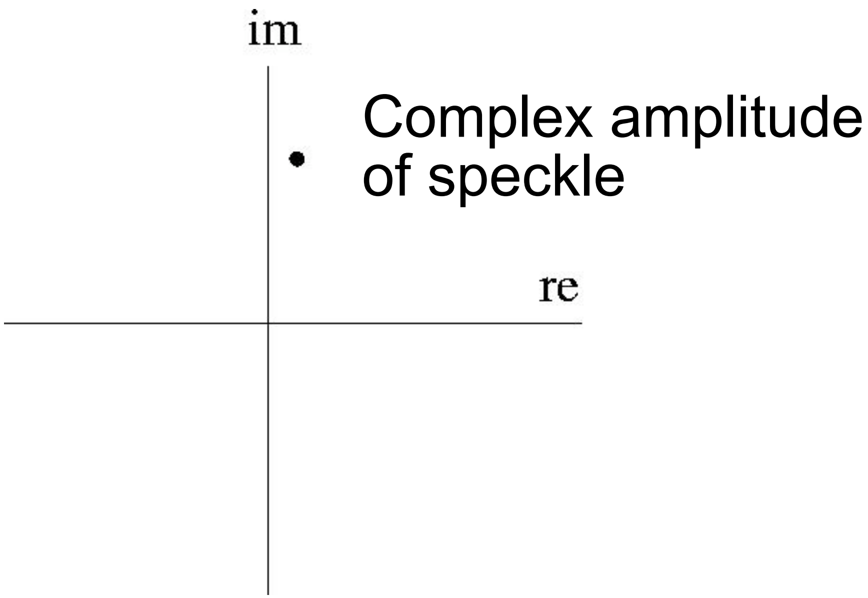
SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere (phase diversity with DM instead of simple focus)
Note: simultaneous measurement schemes also exist

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

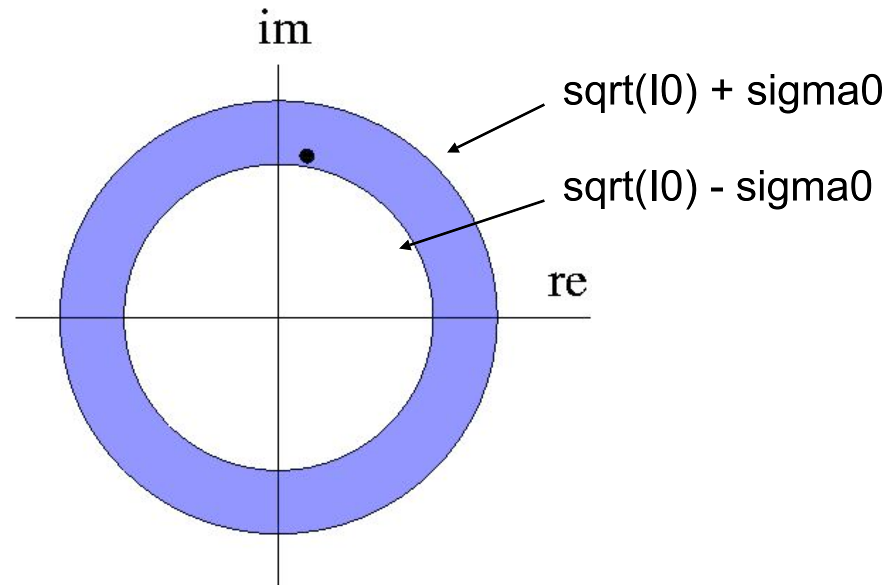
CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

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

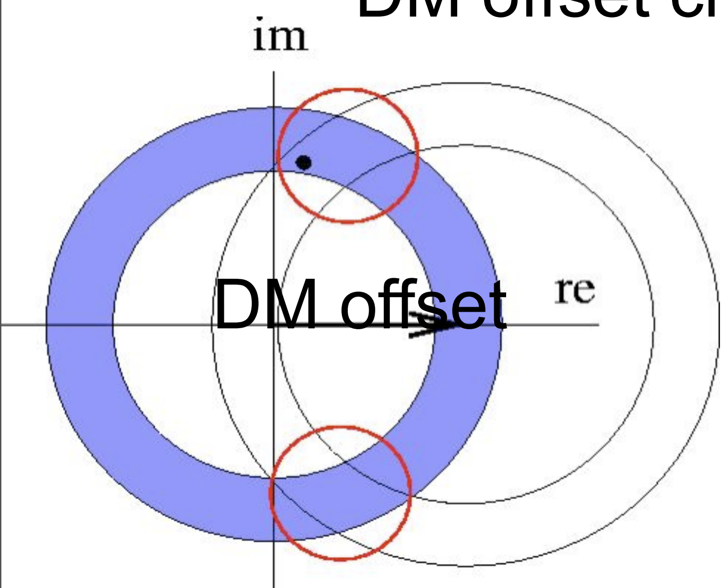
Initial problem

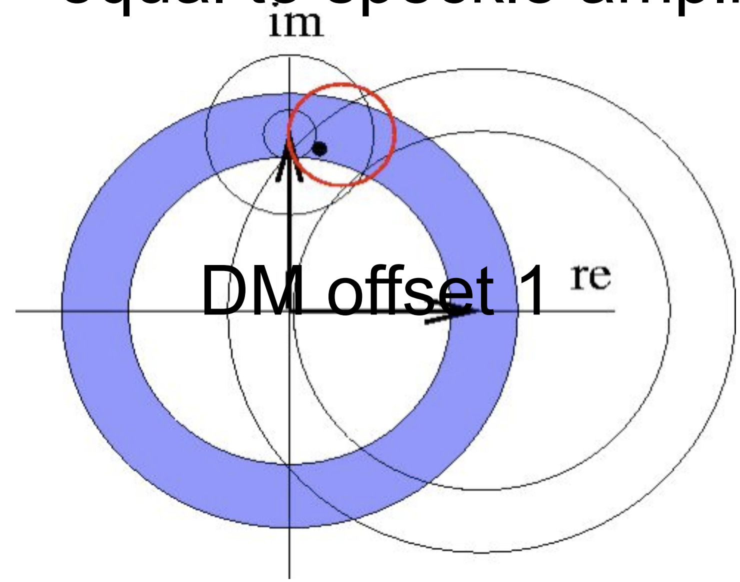


Take a frame -> measured speckle intensity = I0



DM offset chosen to be ~ equal to speckle amplitude

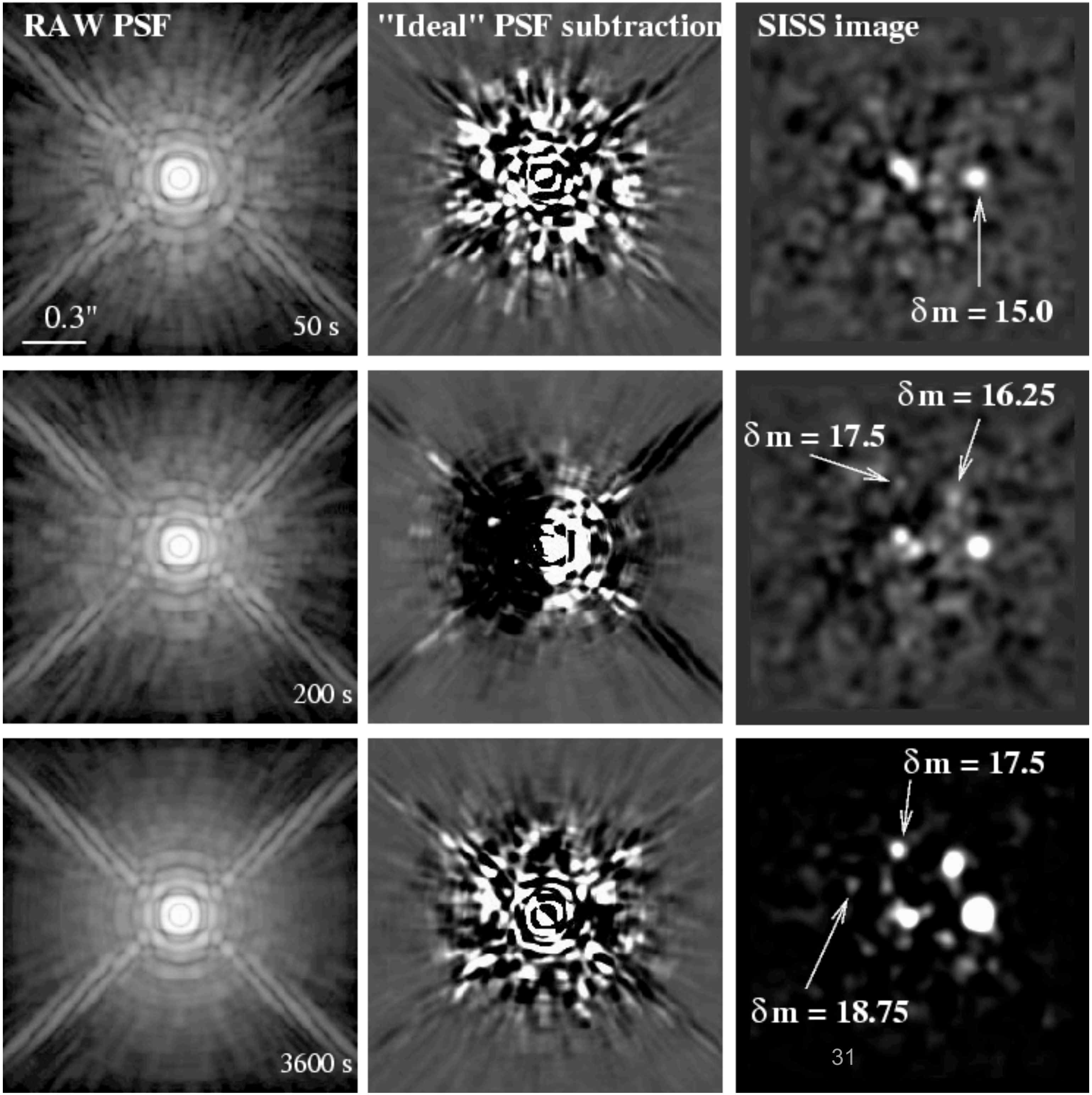




CALIBRATION

Speckle calibration with active coherent modulation recovers faint sources

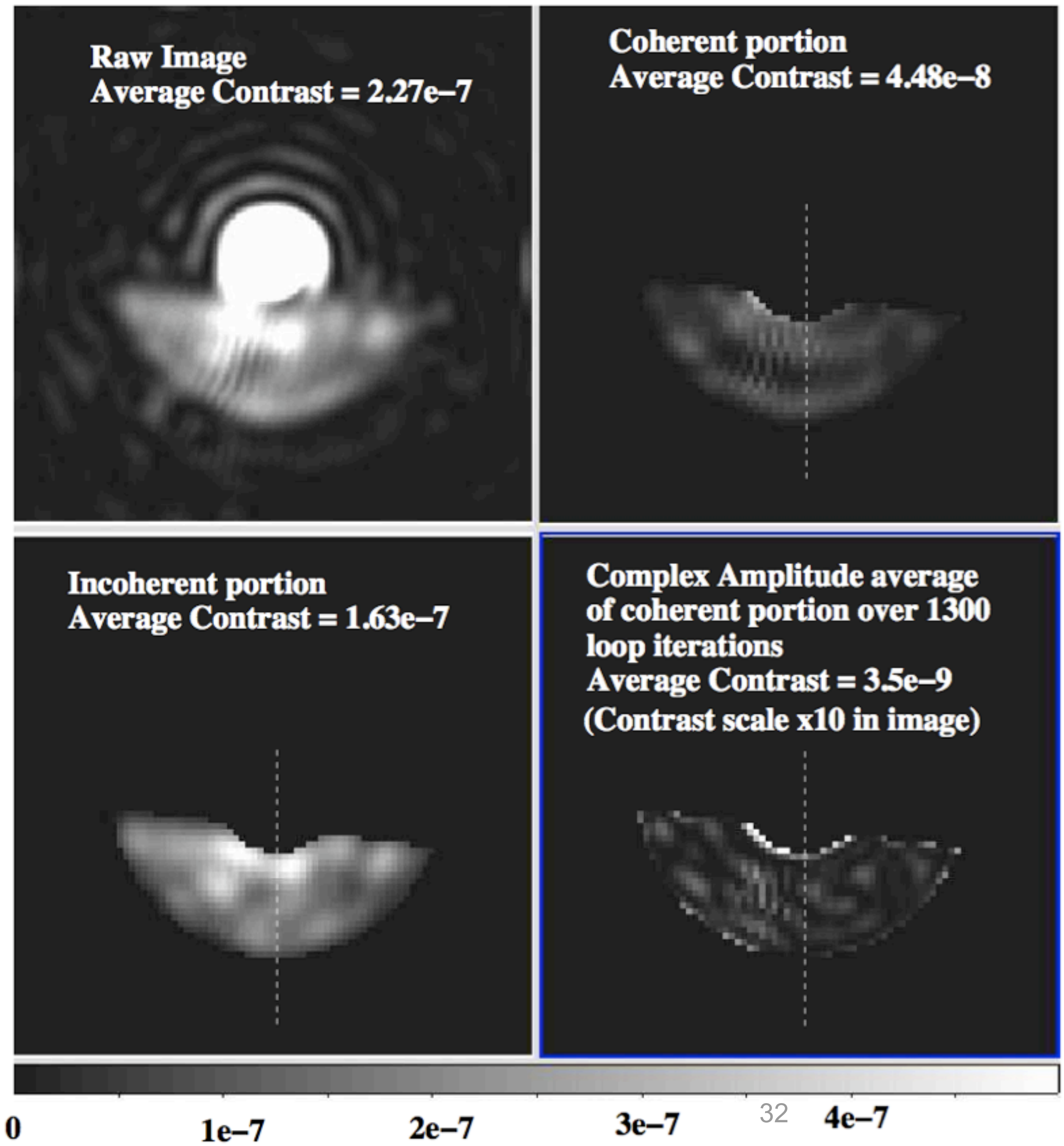
SISS (Guyon, 2004)



Coherent speckle calibration

Coherent detection works in the lab alongside FPAO

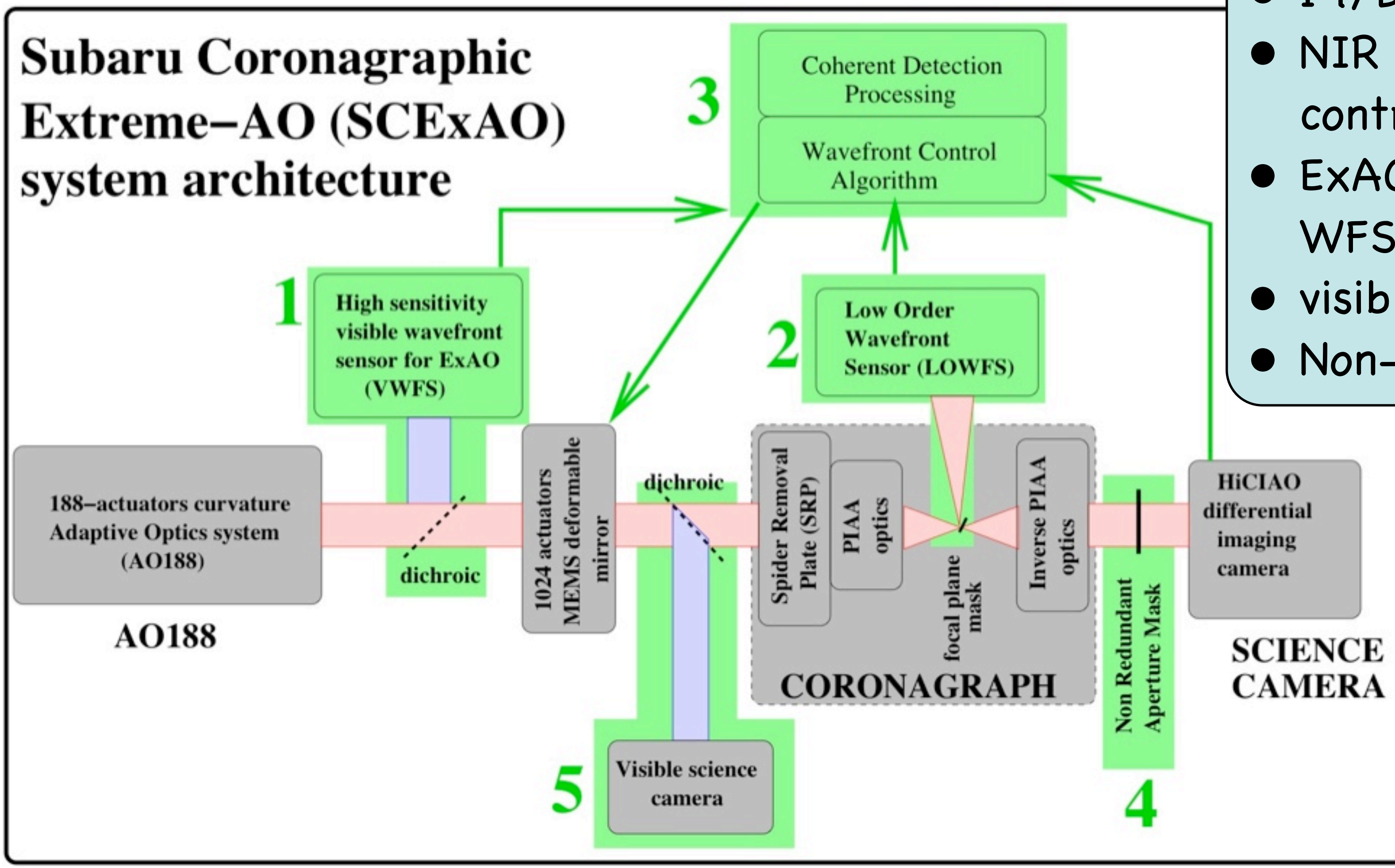
Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the fly diagnostics
- CDI post-processing



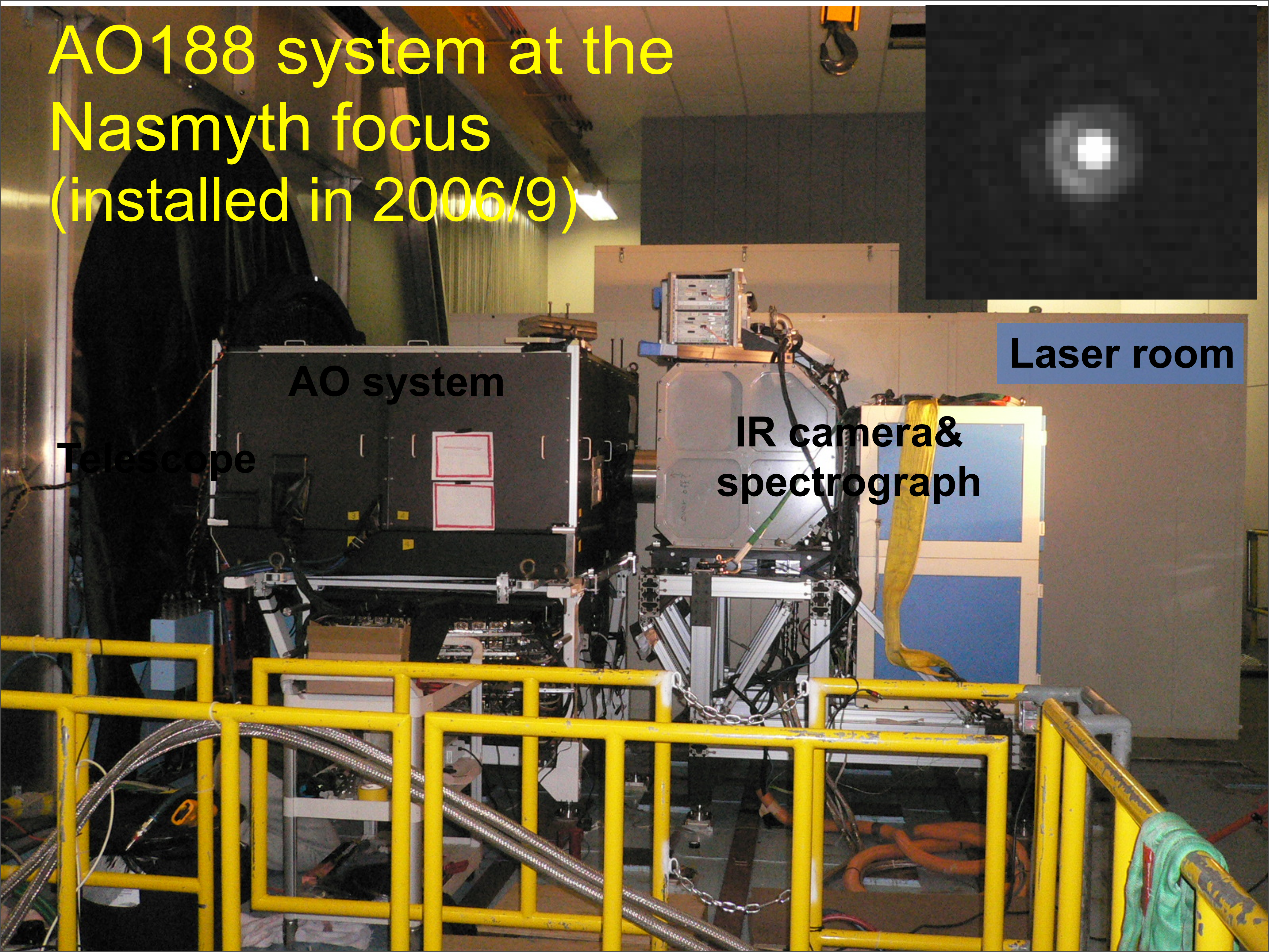
The Subaru Coronagraphic Extreme-AO (SCExAO) system

Olivier Guyon, Frantz Martinache, Vincent Garrel

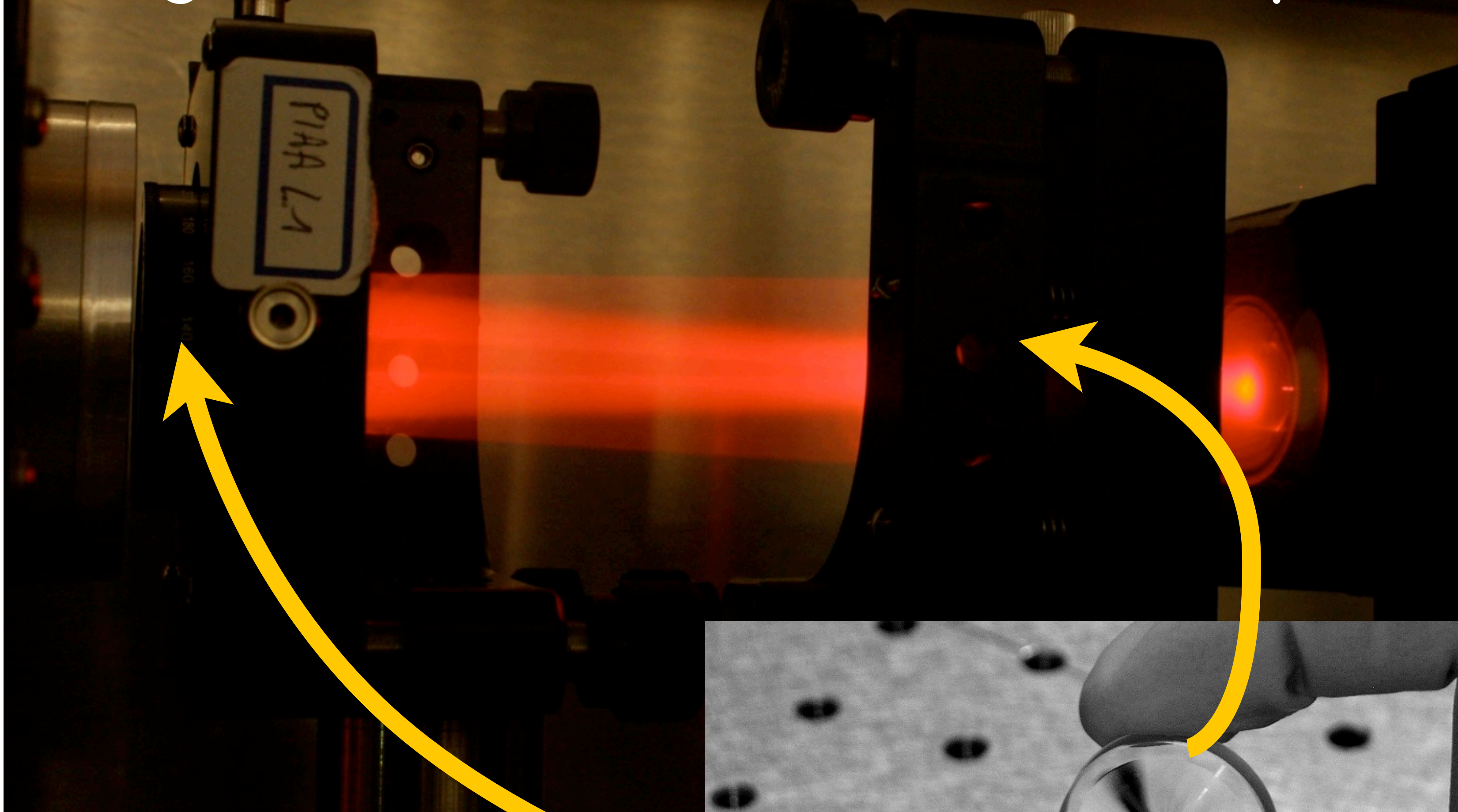
- 1 l/D PIAA coronagraph
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS
- visible channel
- Non-redundant masking

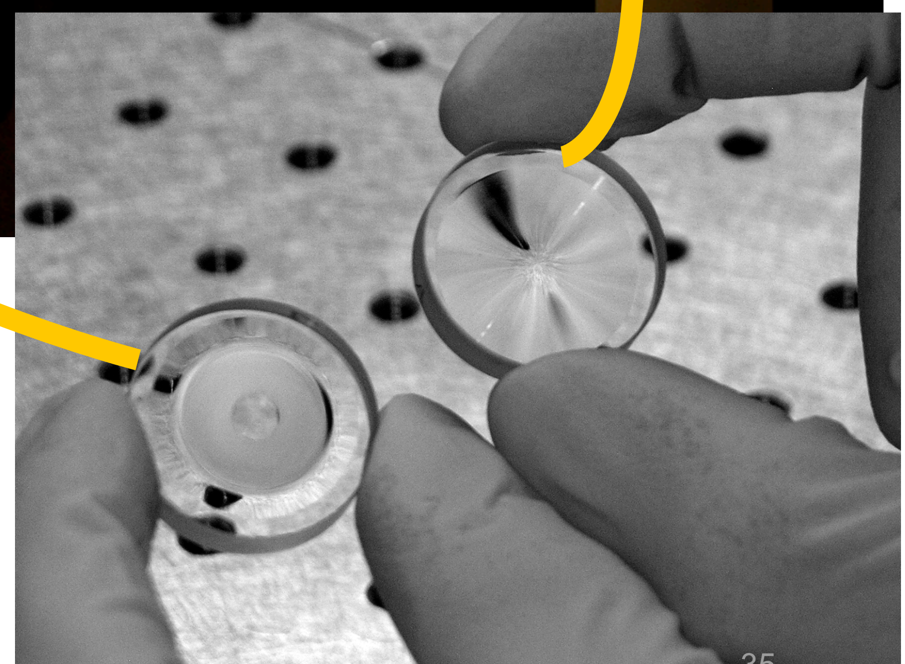


Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
First light in Feb 2010


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

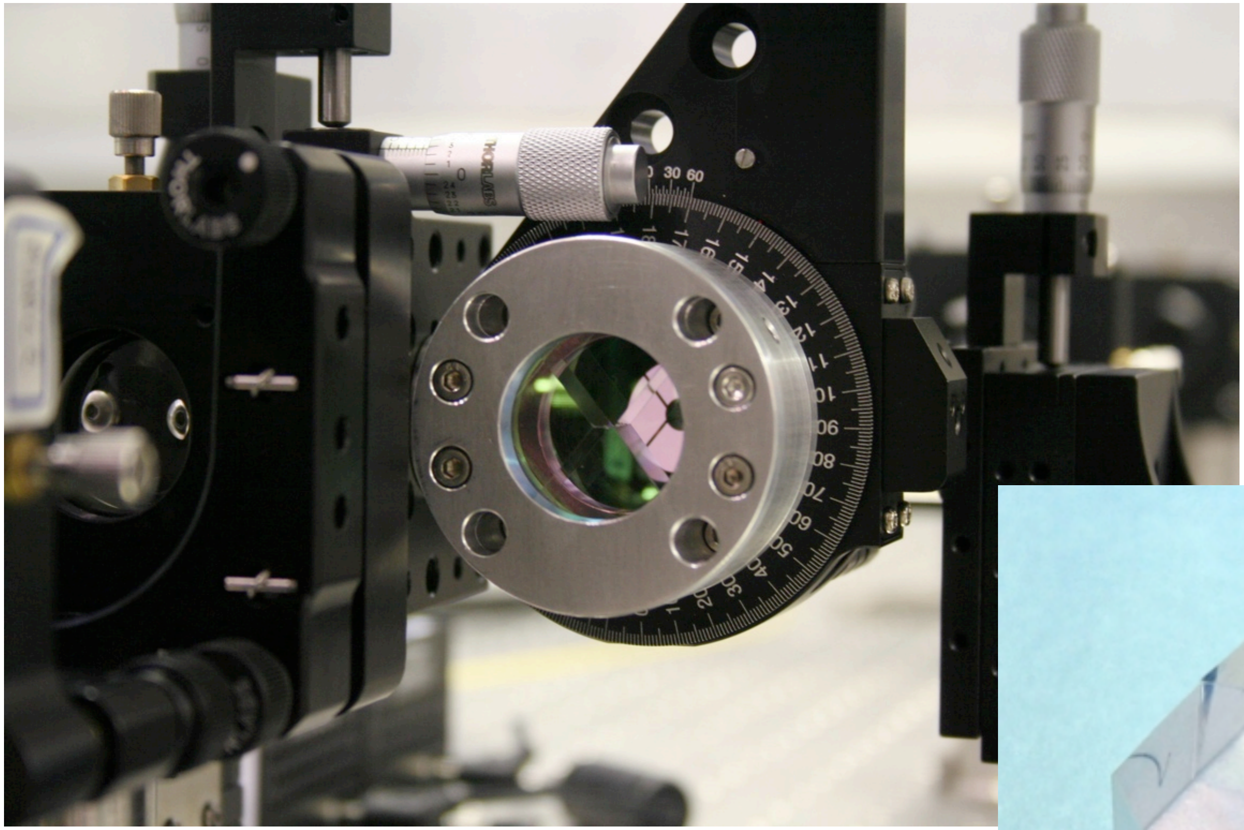
3rd generation refractive PIAA optics

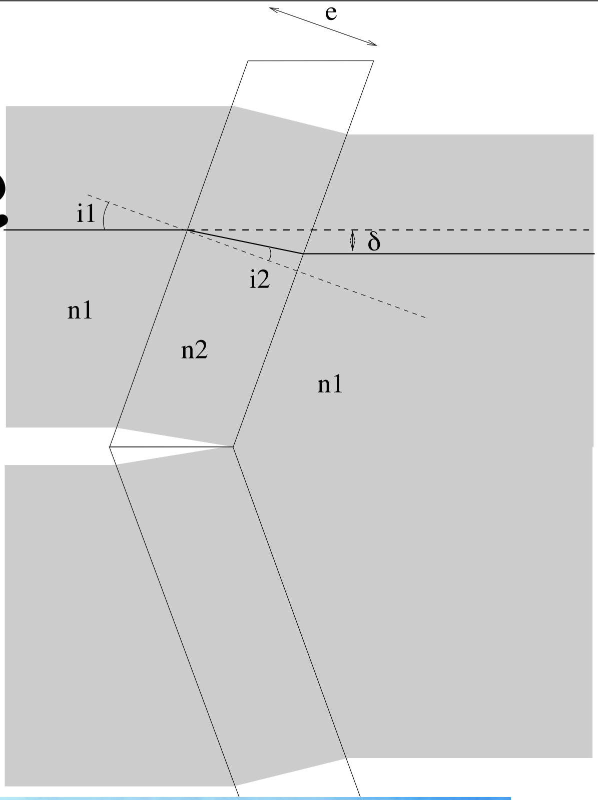


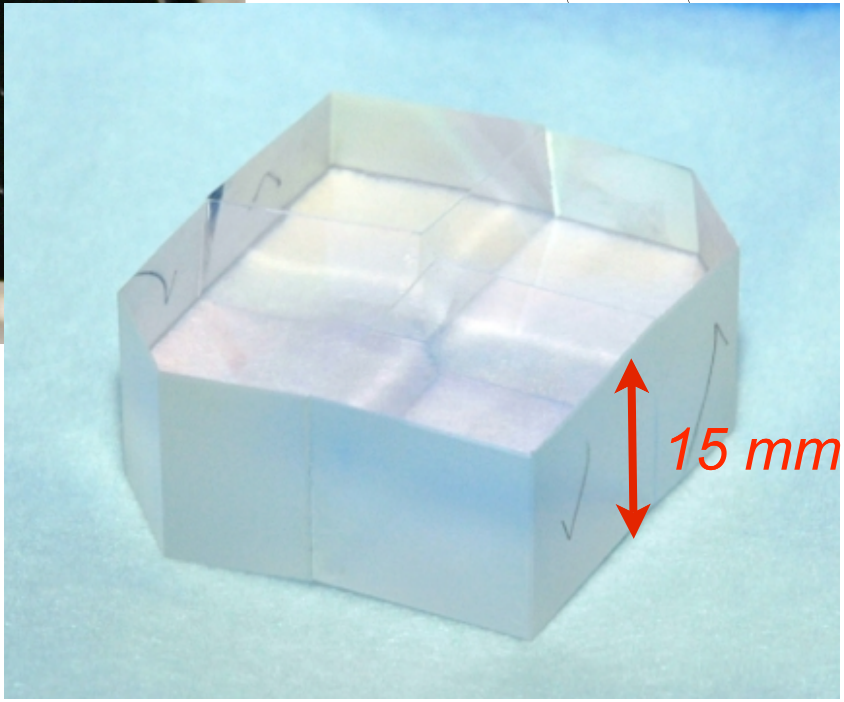


- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

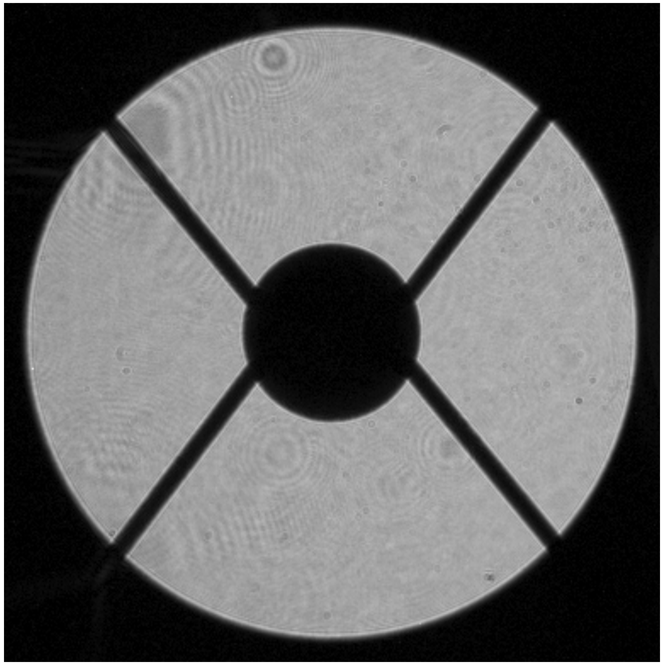
Spider Removal Plate



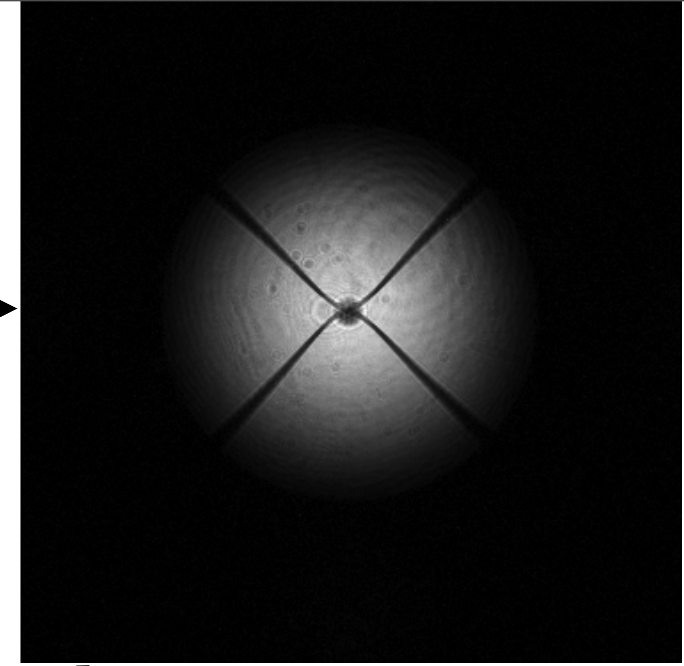




- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°

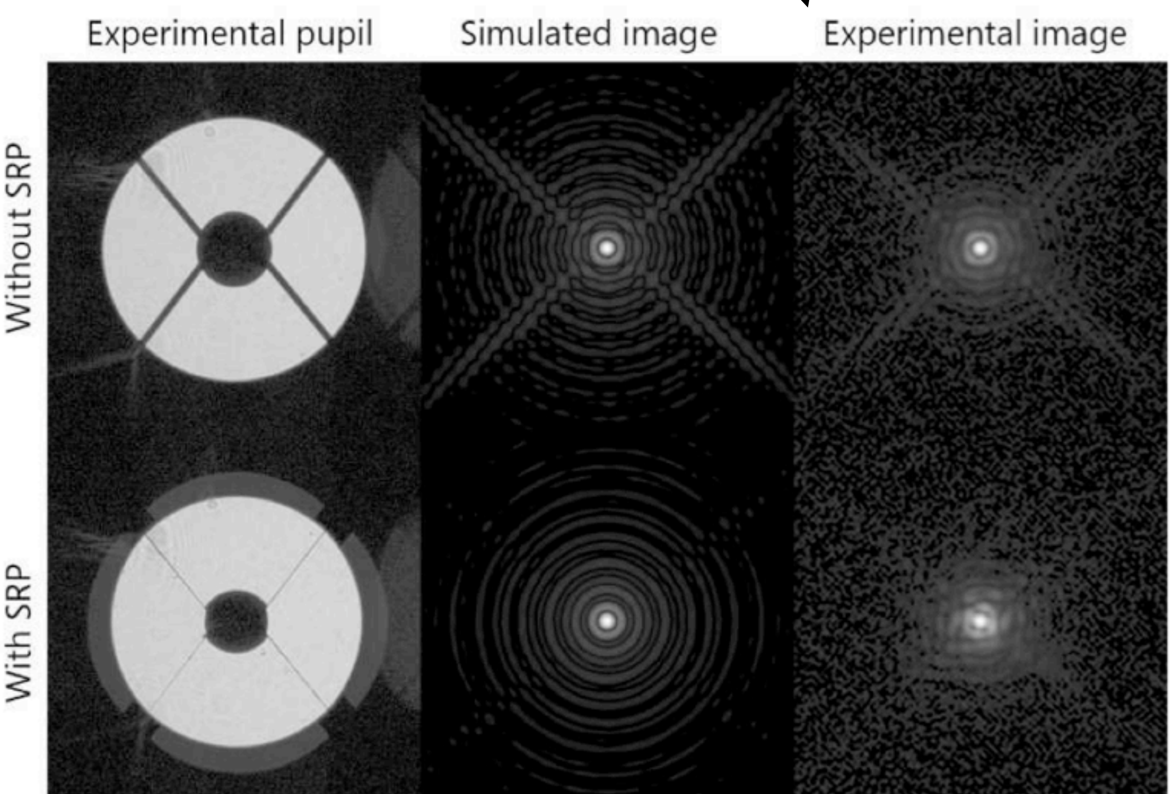


+ PIAA lenses

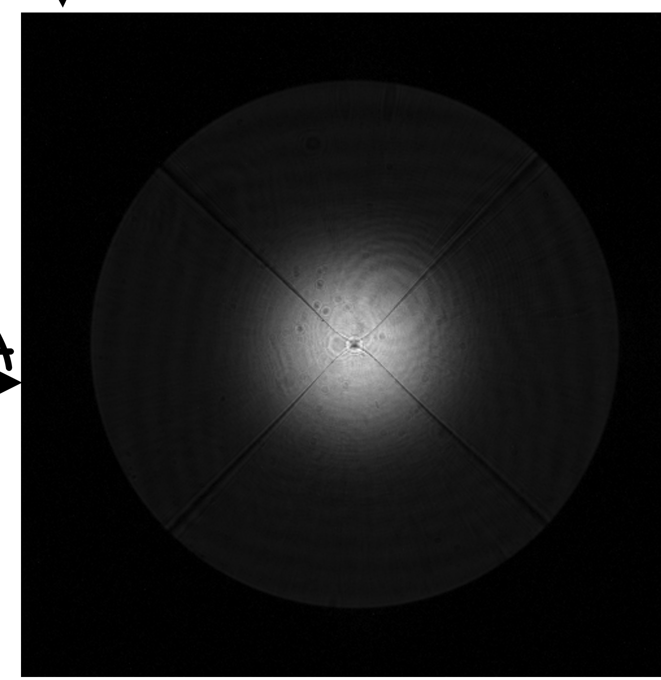


+ SRP

+ SRP



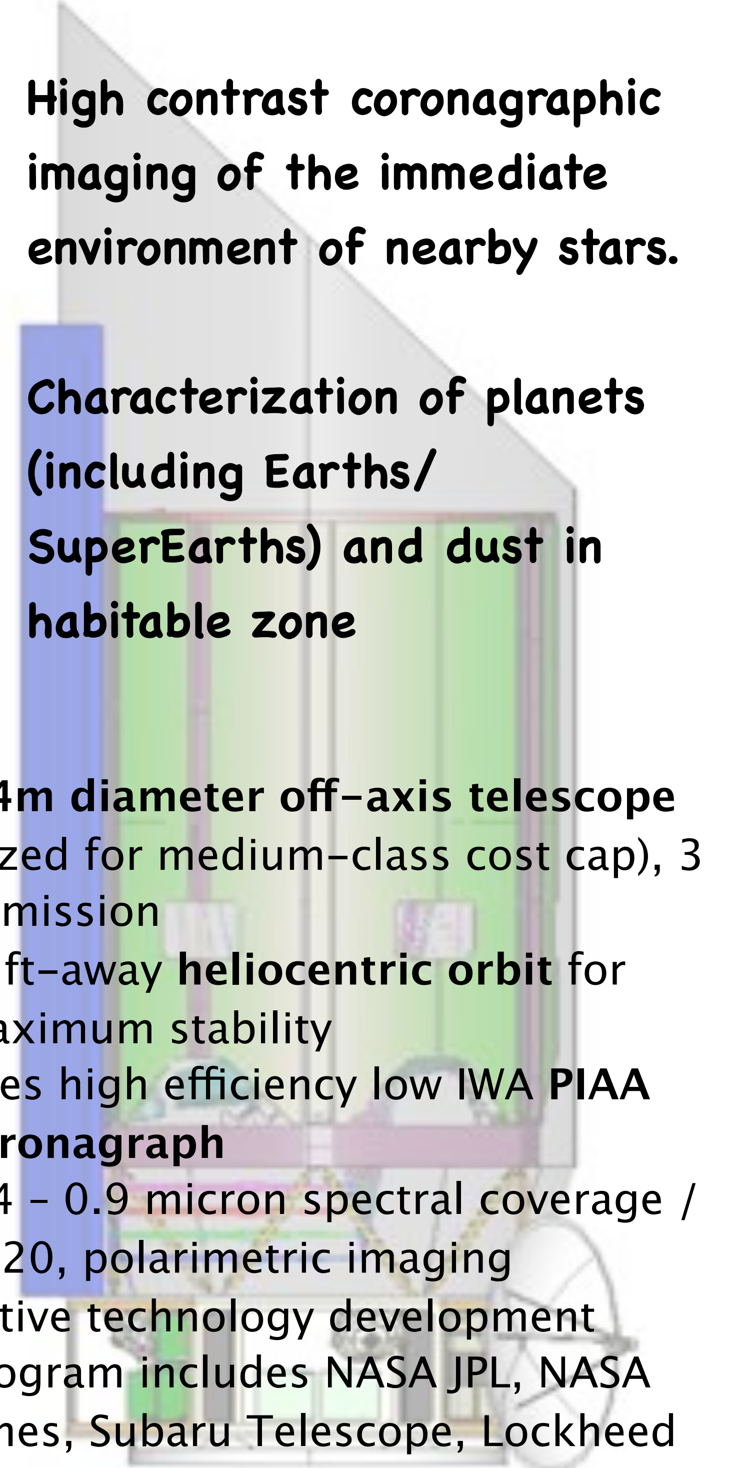
+ PIAA lenses



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



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

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

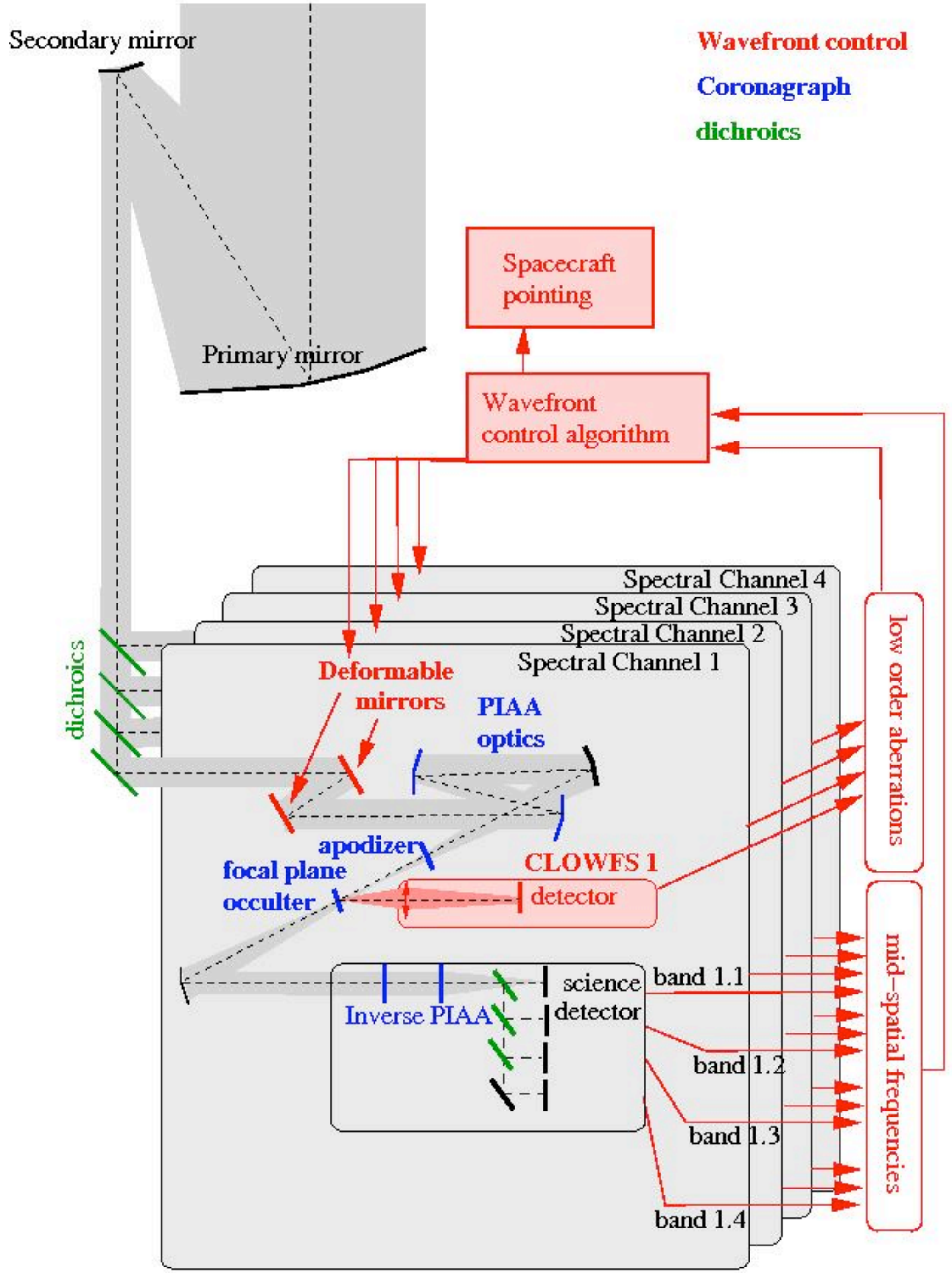
- **1.4m diameter off-axis telescope** (sized for medium-class cost cap), 3 yr mission
- drift-away **heliocentric orbit** for maximum stability
- Uses high efficiency low IWA **PIAA coronagraph**
- 0.4 - 0.9 micron spectral coverage / R~20, polarimetric imaging
- Active technology development program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

Earth/SuperEarths with a medium-class mission ?

Yes, if:

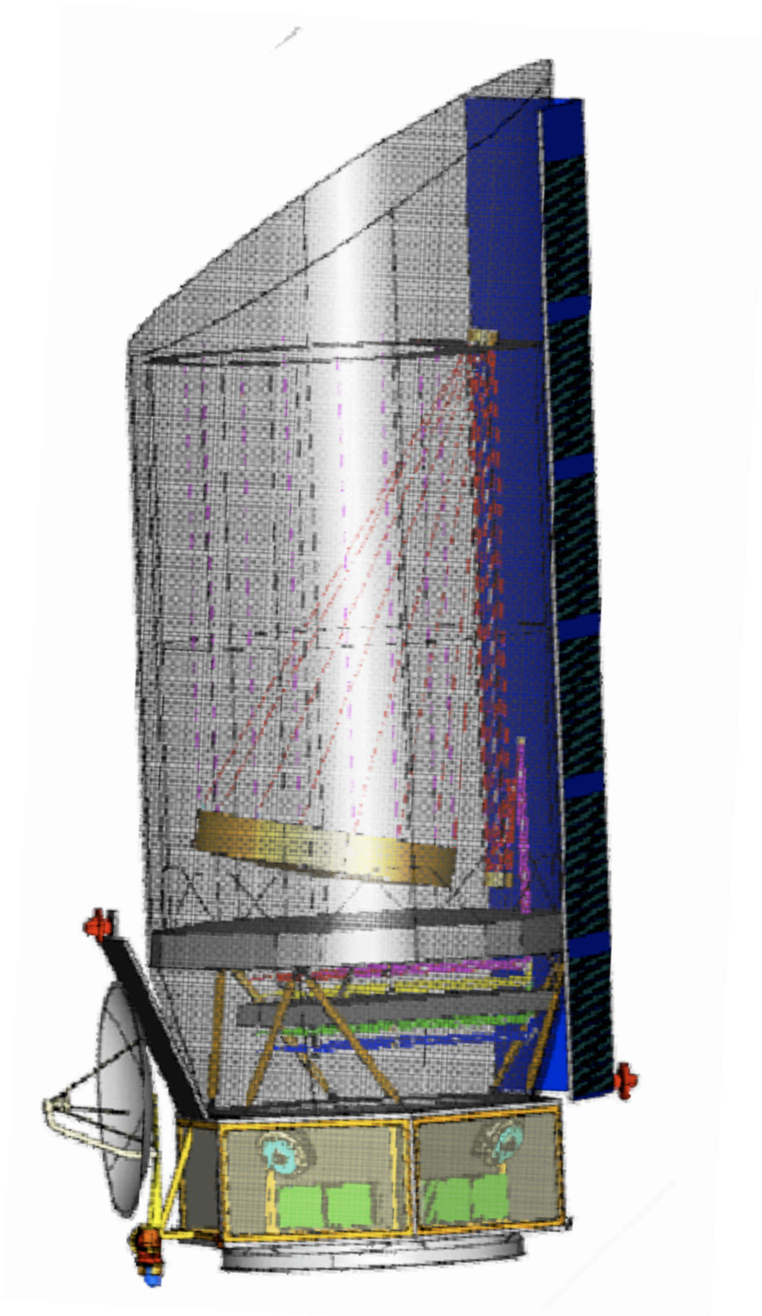
- **High throughput** instrument & good detector
  - high throughput coronagraph
  - very high efficiency (~45% of photons from the FULL aperture detected), use dichroics instead of filters
  - combined imaging & spectroscopy
  - photon counting (no readout noise allowed)
- Small **Inner Working Angle** 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

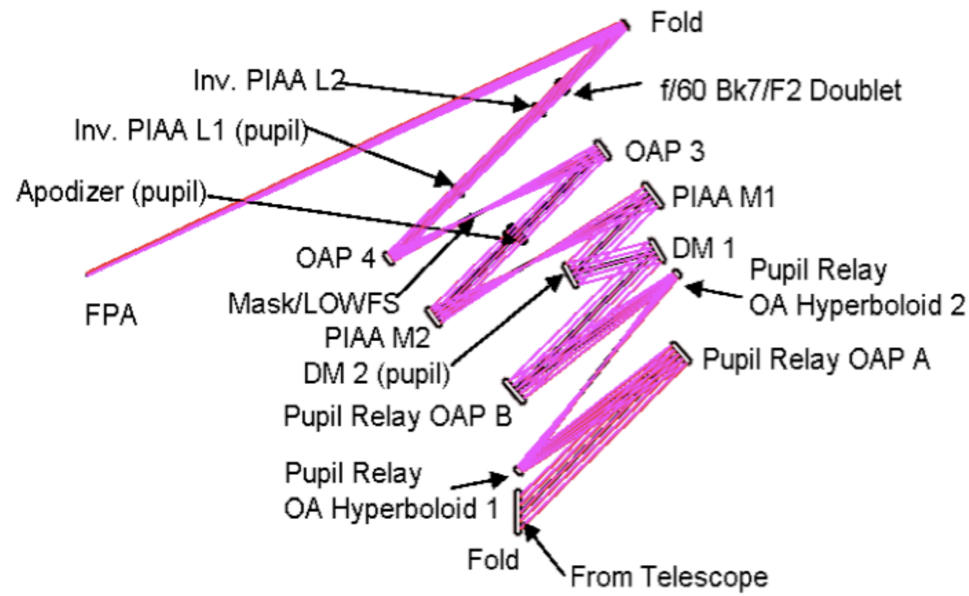
PECO approaches theoretically optimum coronagraph performance

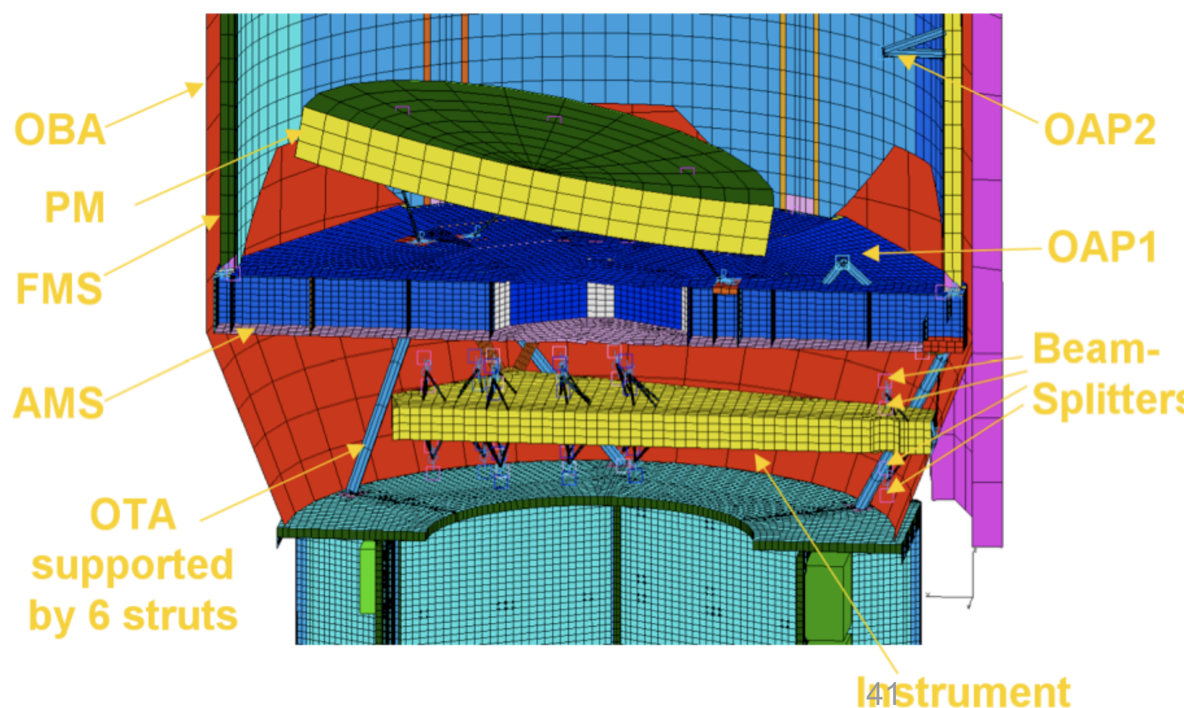


- **High performance PIAA coronagraph**
- **Simultaneous acquisition of all photons from 0.4 to 0.9 μm in 16 spectral bands x 2 polarization axis, combining detection & characterization**
  - High sensitivity for science and wavefront sensing
  - polarization splitting just before detector (helps with 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 20 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) visits for detection
  - Characterization for about 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.**

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

Known EGPs observable with PECO

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

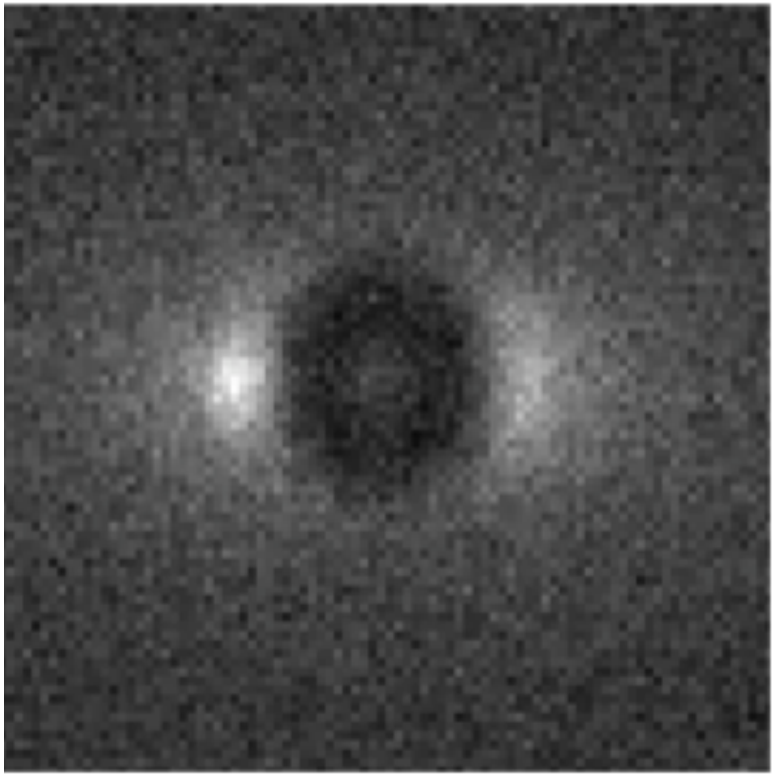
Table 4-3: Stars with Super-Earth planets in habitable zones (1 AU equiv) easily detectable with PECO

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

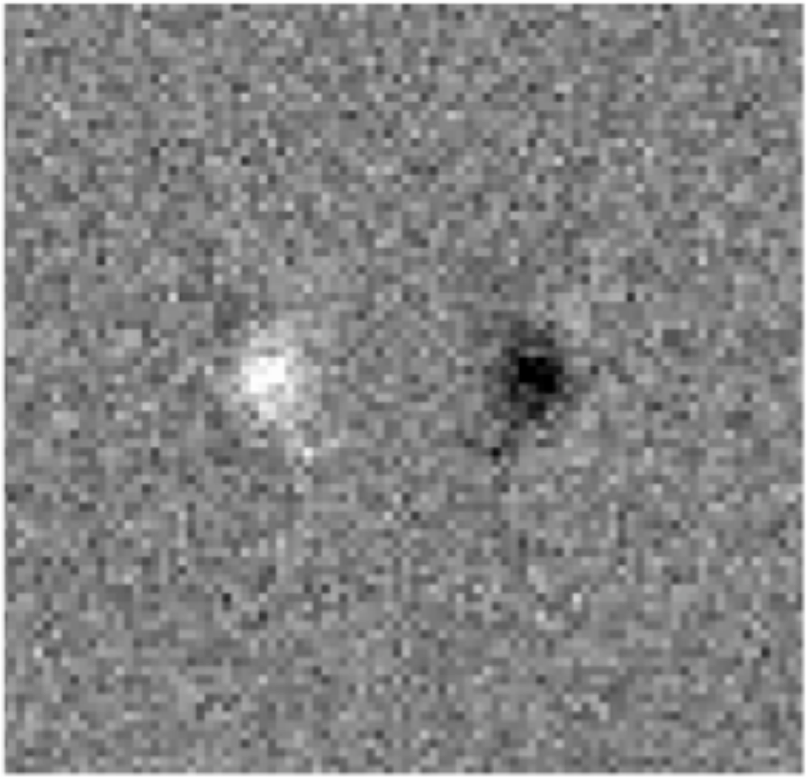
NOTE: ** indicates the presence of significant dust (~10 zodi or more) and *** indicates a close multiple star system (preventing high contrast observations) in Tables 4-2 and 4-3.

PECO can observe an Earth at distance of Tau Ceti

Initial image



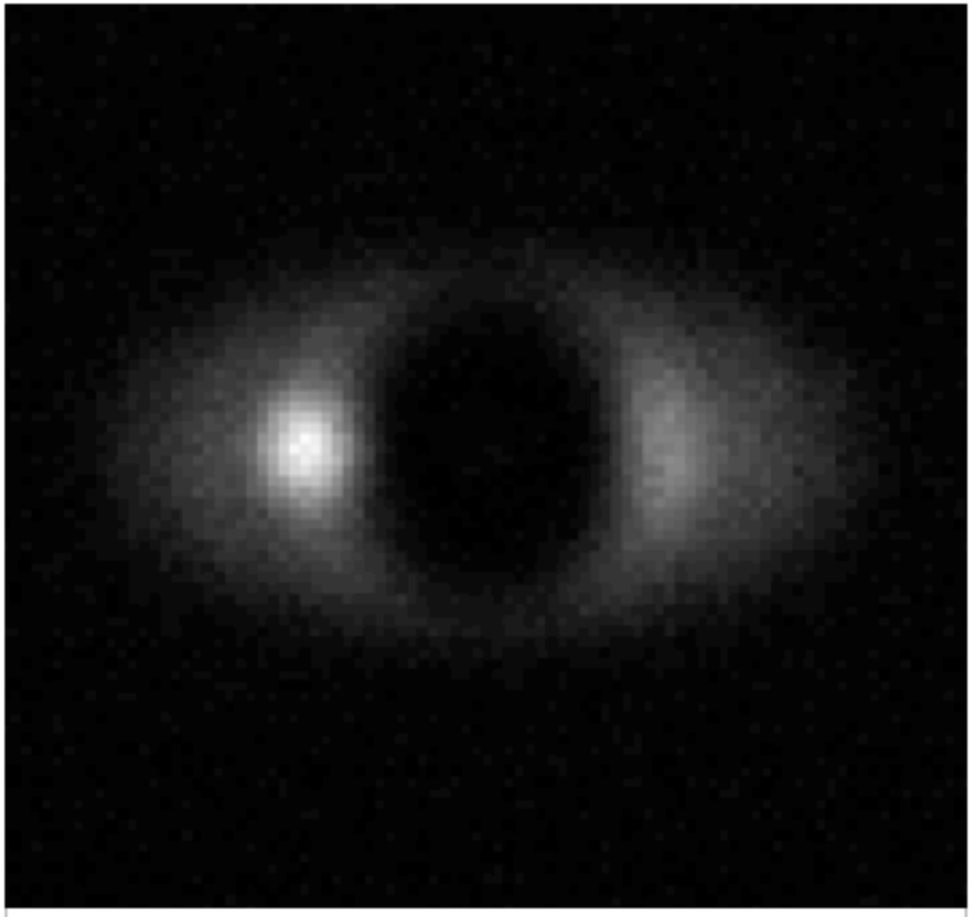
After Symmetric Dust Subtraction



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 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

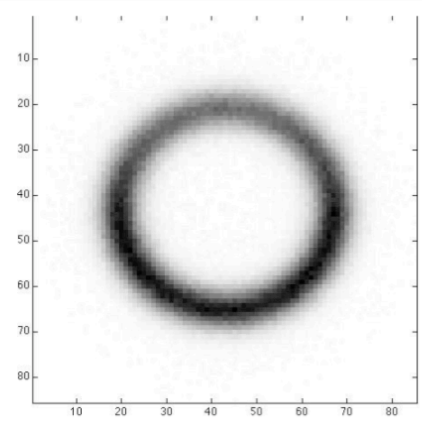


Figure 7-2: Eps Eri ring simulation. The 3 AU radius ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, inclined 22 degrees (same as its debris disk), and a total flux density of 1 zodi. Simulated for a central wavelength λ = 550 nm with a bandwidth $\delta\lambda$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

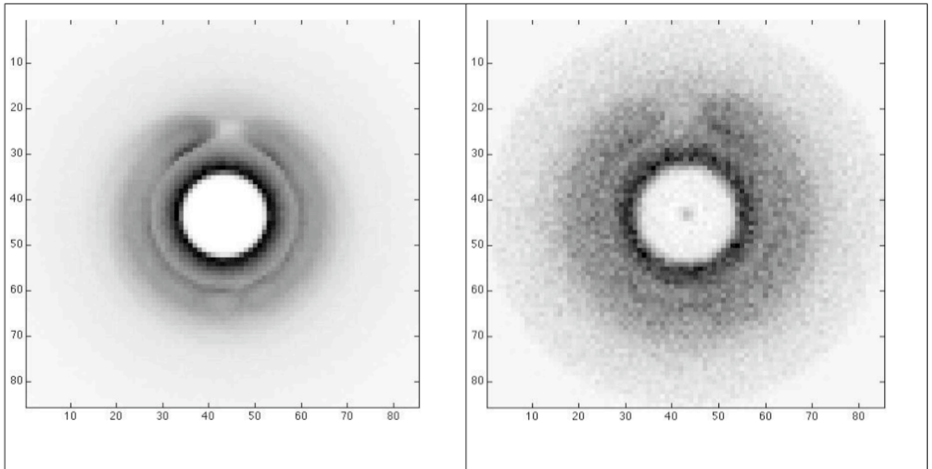
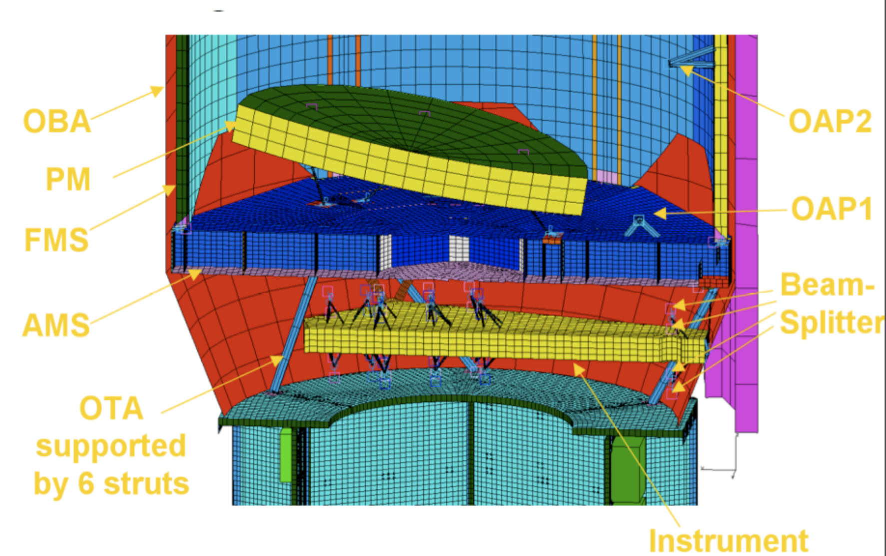
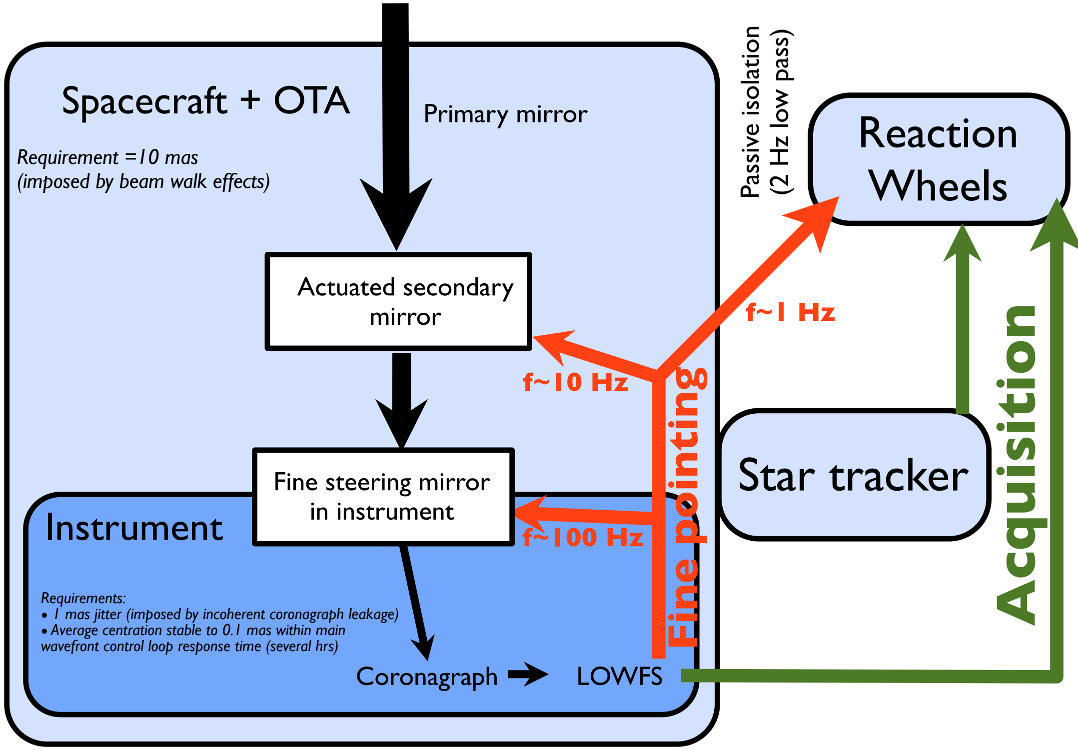


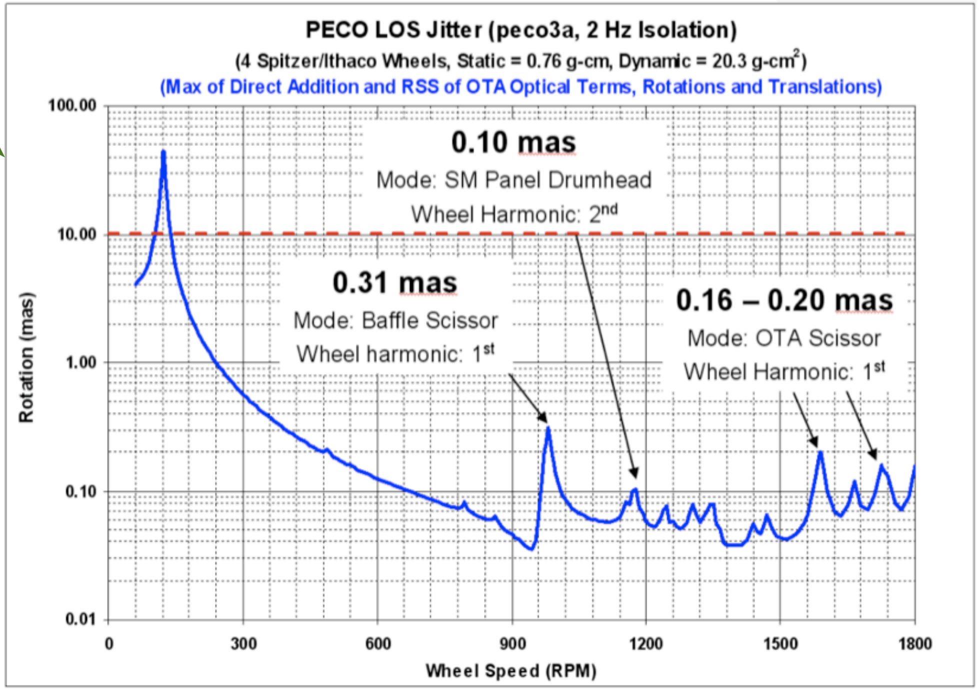
Figure 7-1: Face-on disk model provided by C. Stark (left) and simulated 1E4 s PECO 550nm image (right) of the Sun at 3.3 pc with a 1 zodi disk with the Earth (unseen) embedded at a distance of 3 AU.

PECO pointing & jitter analysis

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







PECO overview

- 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

Conclusions

- Coronagraphy is essential to assess habitability of exoplanets
- R&D in coronagraphy is very active. Theoretical limits identified and approached by new designs
- PIAA coronagraph is first full efficiency coronagraph to allow < 1 l/D IWA for ground-based system (contrast limited by WFC) and < 2 l/D at 1e10 contrast in space (limited by stellar angular size)
- Large gains to be obtained from new WFS and calibration techniques optimized for high contrast imaging

- Subaru Coronagraphic Ex-AO implements some of these new tricks
- Efficient coronagraph can allow low R spectroscopy of habitable planets with 1.4m telescope.