PECO

Pupil mapping Exoplanet Coronagraphic Observer

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

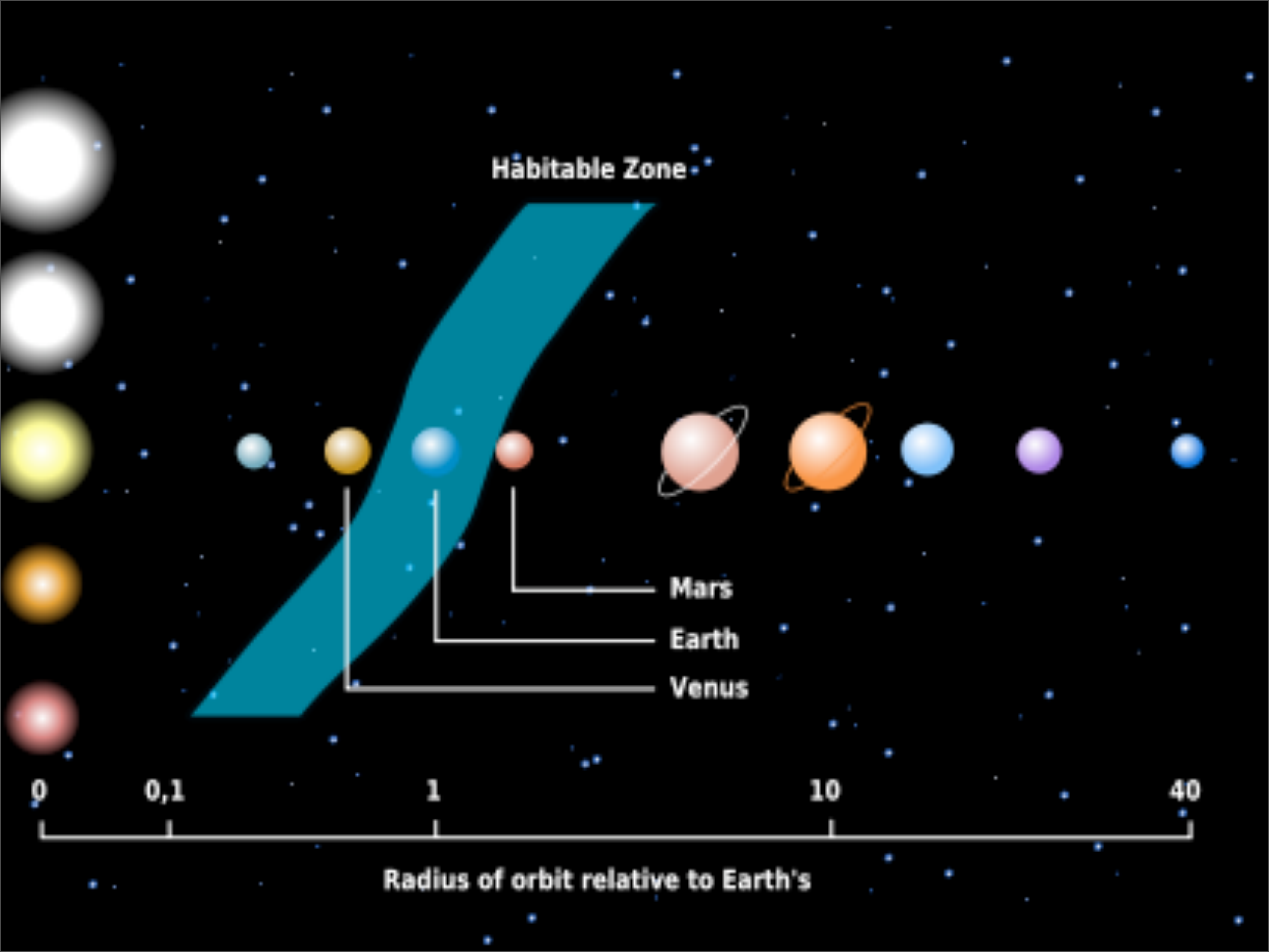
PECO Pupil mapping Exoplanet Coronagraph Observer

Olivier Guyon

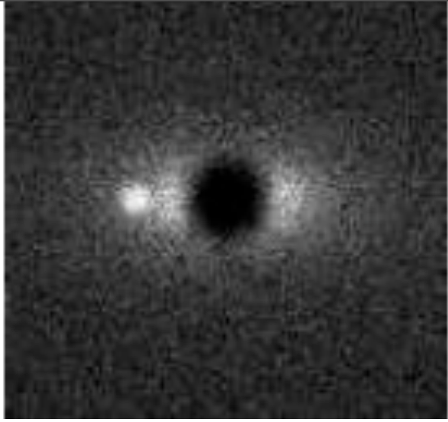
University of Arizona

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



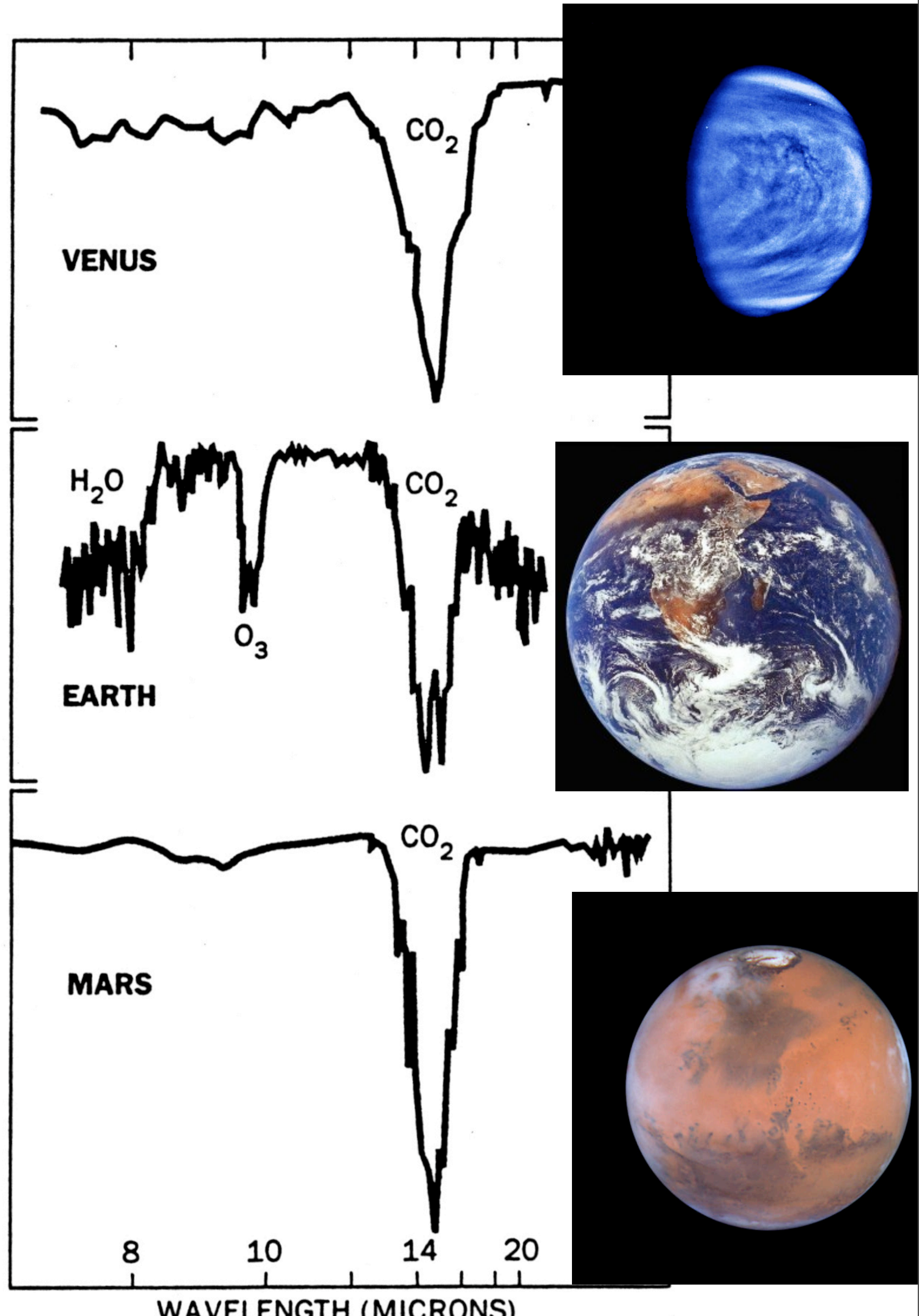
Habitable Zone
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

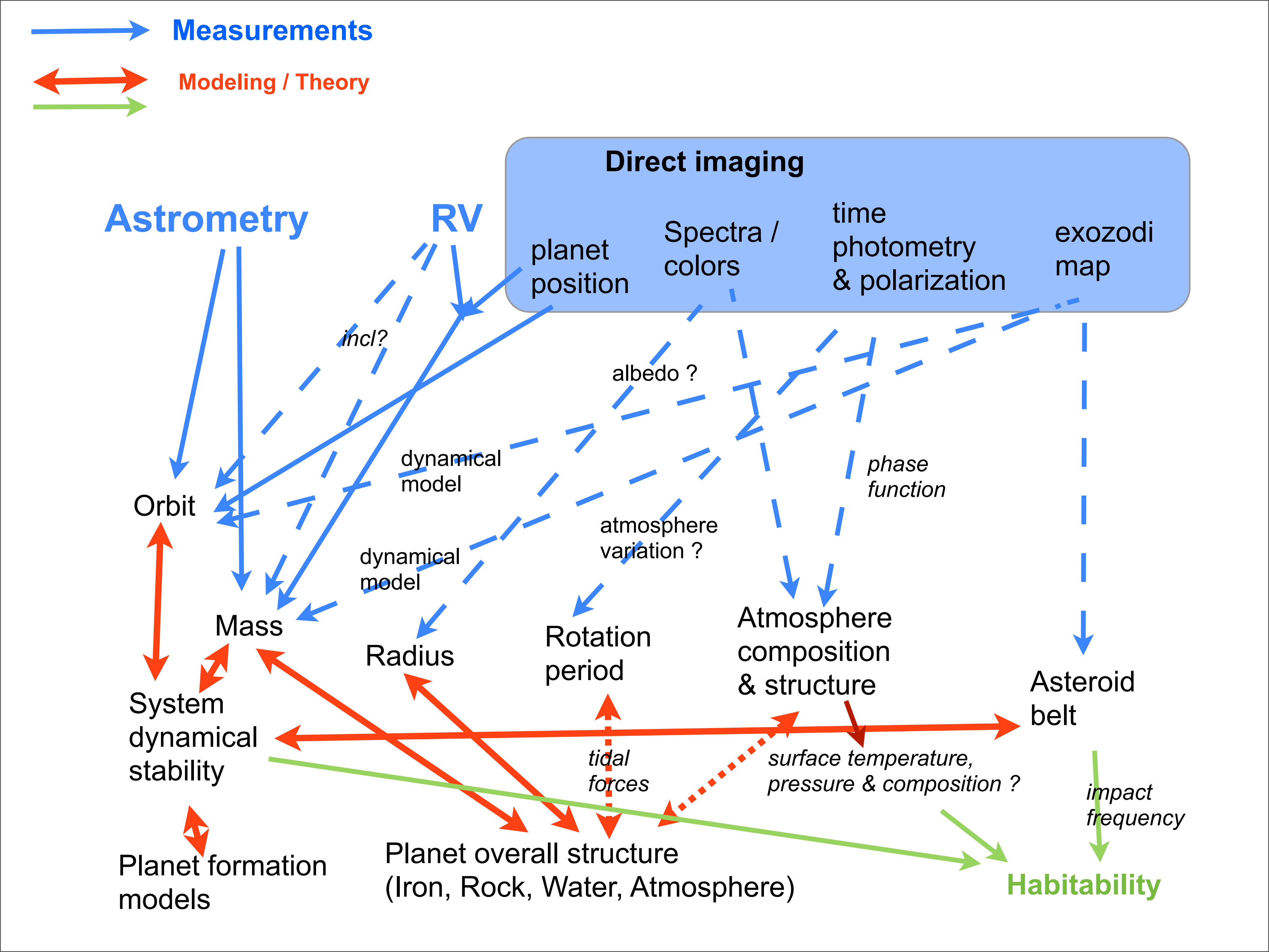


Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans ?
- Rotation period
- Weather patterns
- Planetary environment :

Planets + dust




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

Challenges

- **Contrast**
  - Visible:
    - 1e10 for Earth/Sun -> space
    - 1e9 for Jupiter/Sun -> space / ELTs ?
    - ~1e8 for close-in planets -> ground ExAO ?
  - Near-IR (~1.6 micron)
    - 1e10 for Earth/Sun
    - ~1e12 for Jupiter/Sun
    - ~1e7 for young giant planet / Sun -> Ground ExAO
  - Thermal IR (~10 micron)
    - 1e6 for Earth/Sun
    - 1e7 for Jupiter/Sun
- **Angular separation** (HZs at ~0.1”)
- **Exozodiacal light**
- **Luminosity: Earth @ 5pc ~1 ph/s/micron/m^2 in visible**

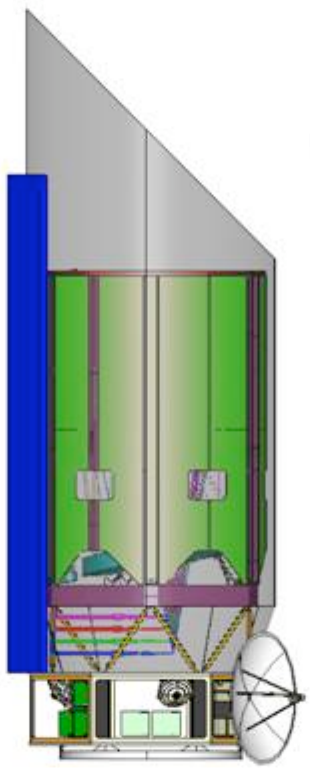
Univ. of Arizona
JPL Jet Propulsion Laboratory California Institute of Technology
LOCKHEED MARTIN
NASA Ames Research Center
ITT

PECO overview

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

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

Univ. of Arizona

Jet Propulsion Laboratory
California Institute of Technology

Ames Research Center

Earth/SuperEarths with a medium-class mission ?

Yes, if:

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

PECO driving requirements

- **High Contrast (1e10) from 400nm to 900nm (simultaneously !)**

  Key to achieve sensitivity required for science goals

  - Coronagraph / optical train design: use of dichroics feeding coronagraph channels

  - Wavefront control system needs to have sufficient degrees of freedom to correct wavefront over spectral range

- **Wavefront Stability (A)**

  Wavefront sensing & control response time at 1e10 contrast level is ~mn to ~hr. Any non calibrated WF variation on <hr timescale will seriously affect science return

  - High throughput efficient wavefront sensing to reduce response time

  - Stable telescope, temperature control, low jitter/vibrations

  - Stable drift-away heliocentric orbit, no telescope roll

- **Pointing Stability and knowledge (mas)**

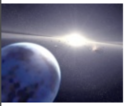
  Key to image planets/disk at small separations AND not get confused with pointing errors

  - Stable orbit / telescope design

  - Multi-stage control

  - High sensitivity sensing of pointing errors

Coronagraph choice is essential

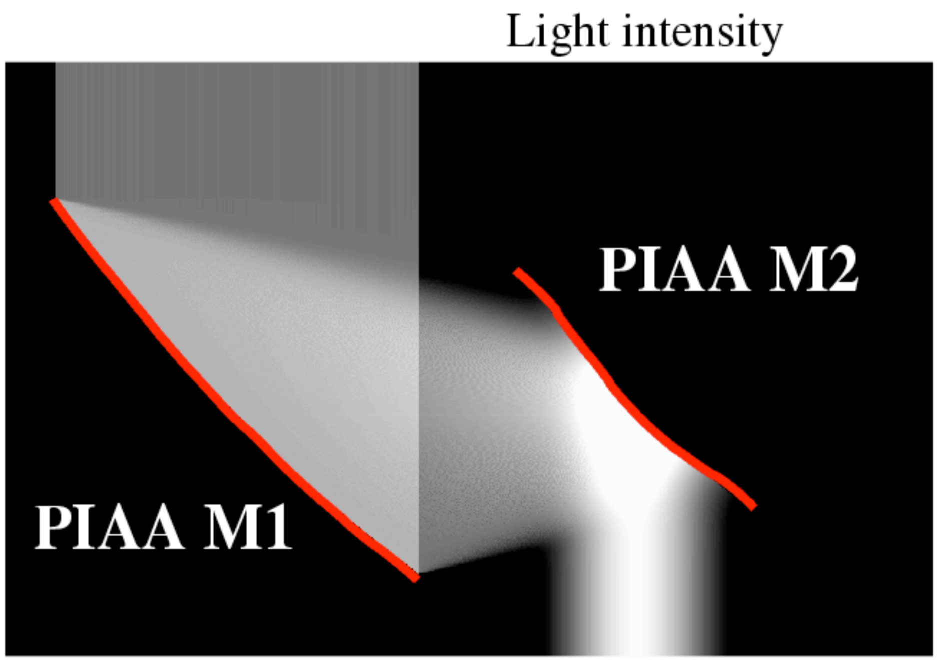


- Coronagraph role is to block starlight and let as much planet light as possible through the system
- Most coronagraph designs are a painful tradeoff between coronagraphic rejection and throughput, inner working angle, angular resolution

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)



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

PECO coronagraph performance

PECO Pupil mapping Exoplanet Coronagraph Observer

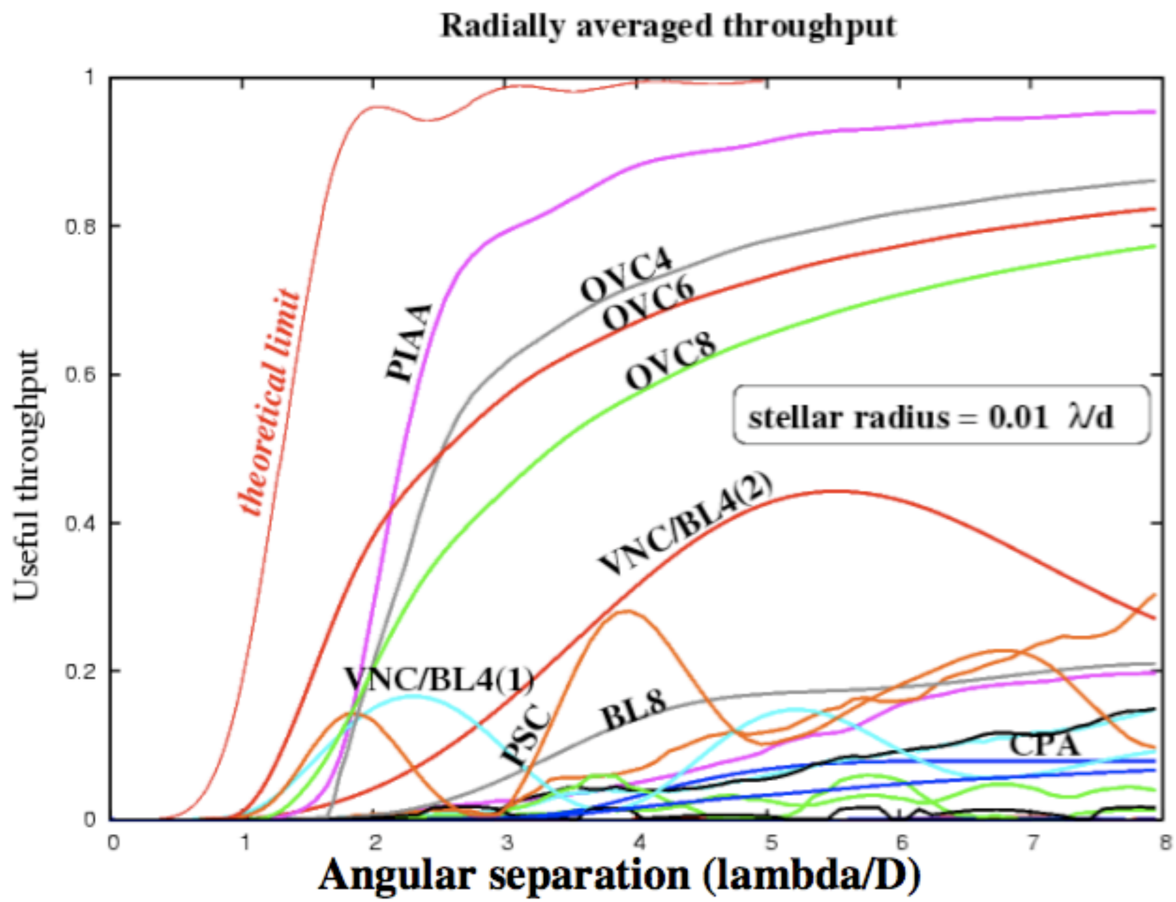
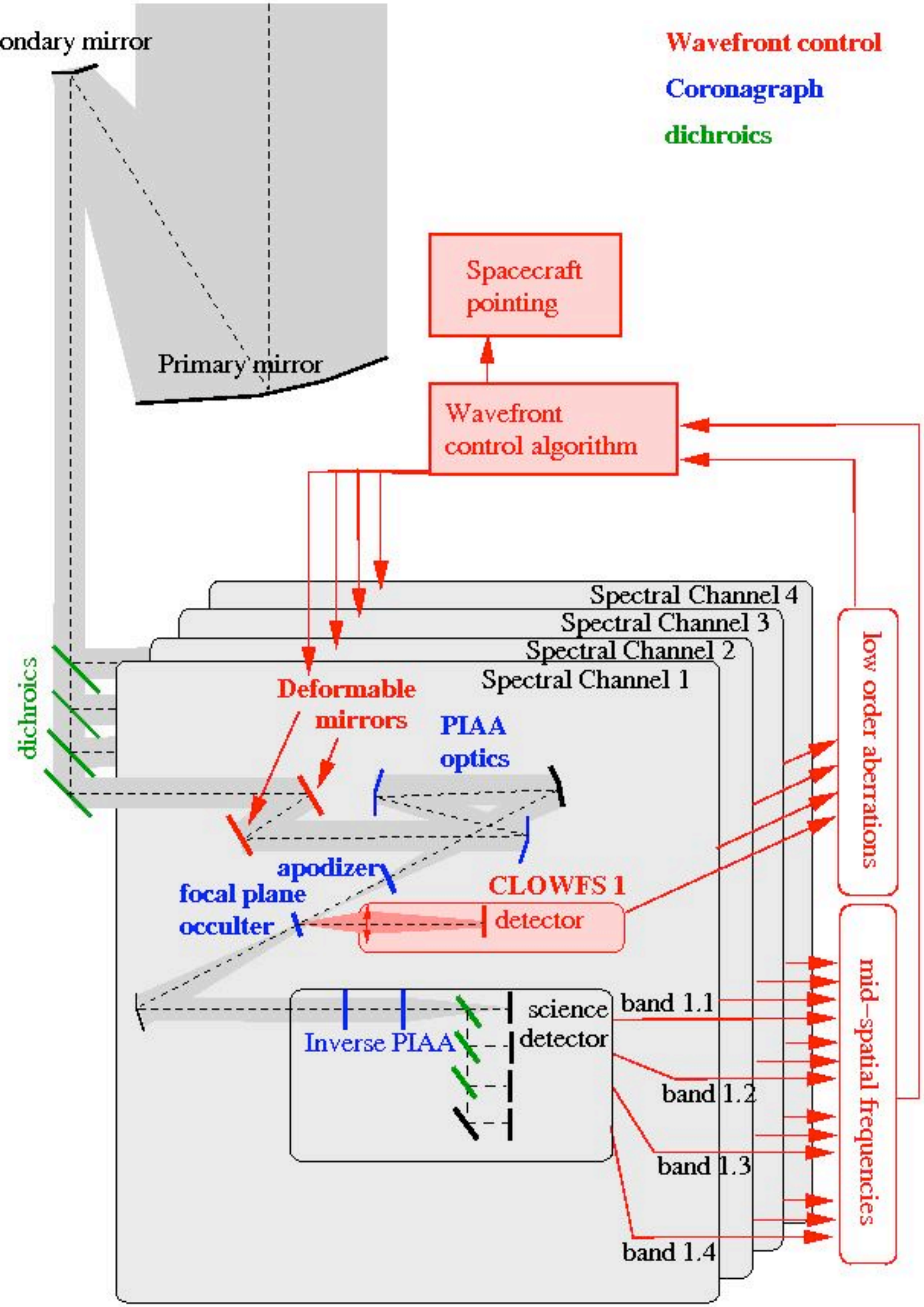


Figure 3-1: Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional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

PECO approaches theoretically optimum coronagraph performance

Univ. of Arizona

Ames Research Center

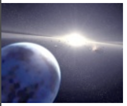


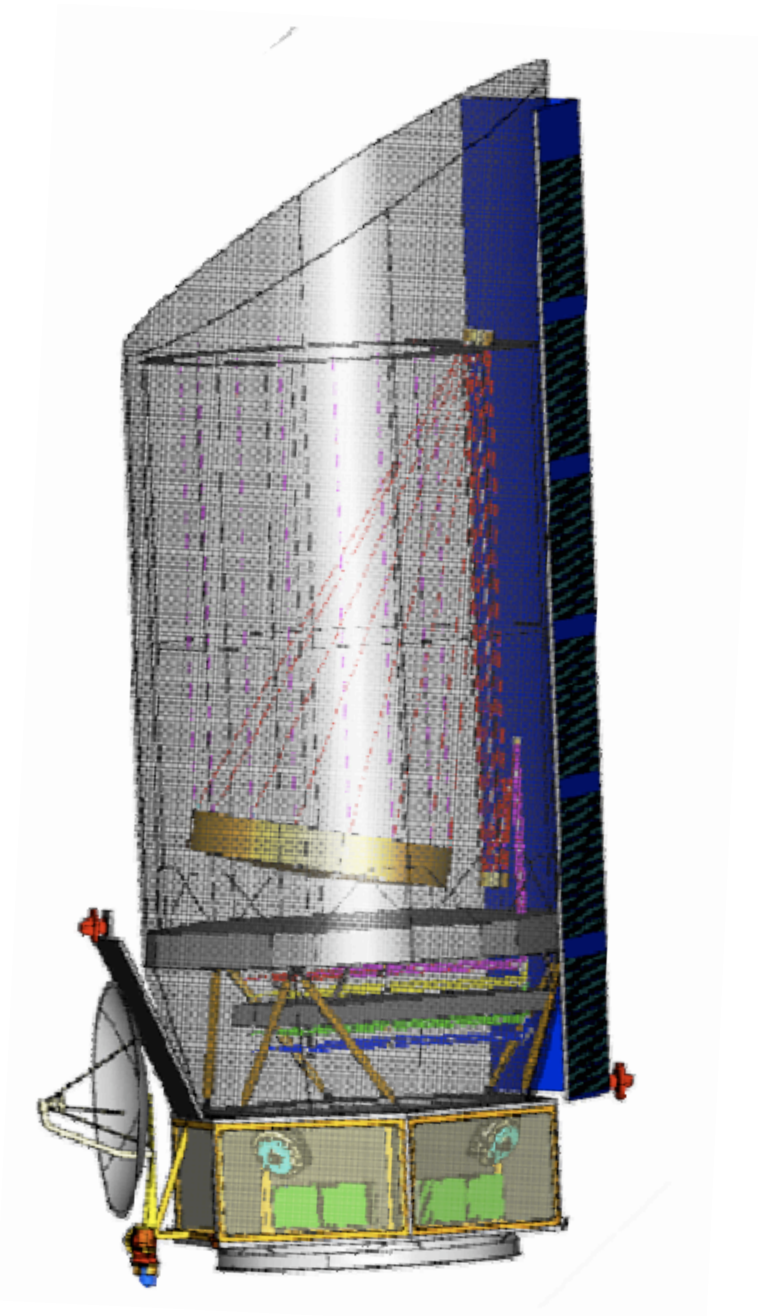
- **High performance PIAA coronagraph**
- **Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands x 2 polarization axis, combining detection & characterization**
  - High sensitivity for science and wavefront sensing
  - polarization splitting just before detector (helps with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

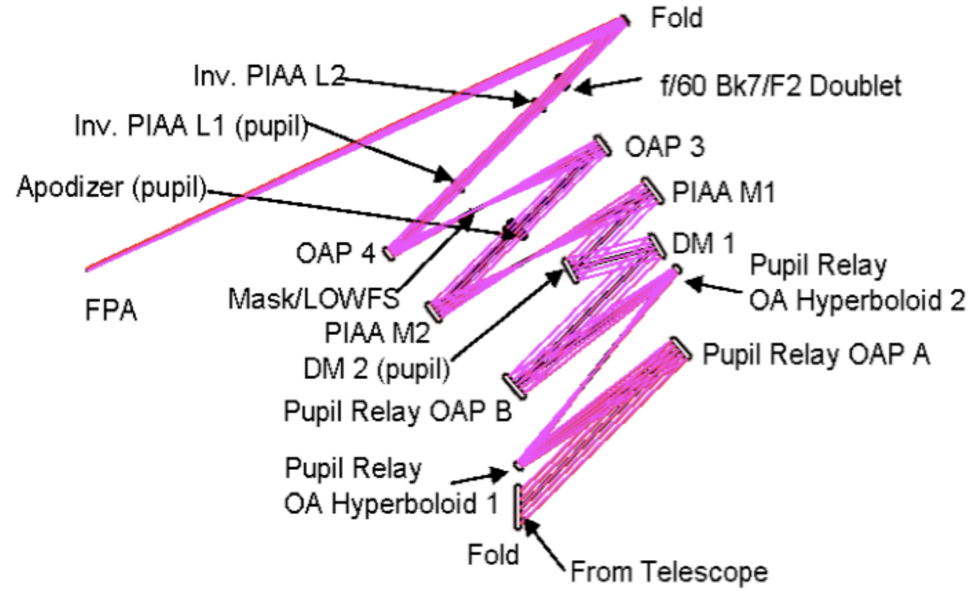
PECO Pupil mapping Exoplanet Coronagraph Observer

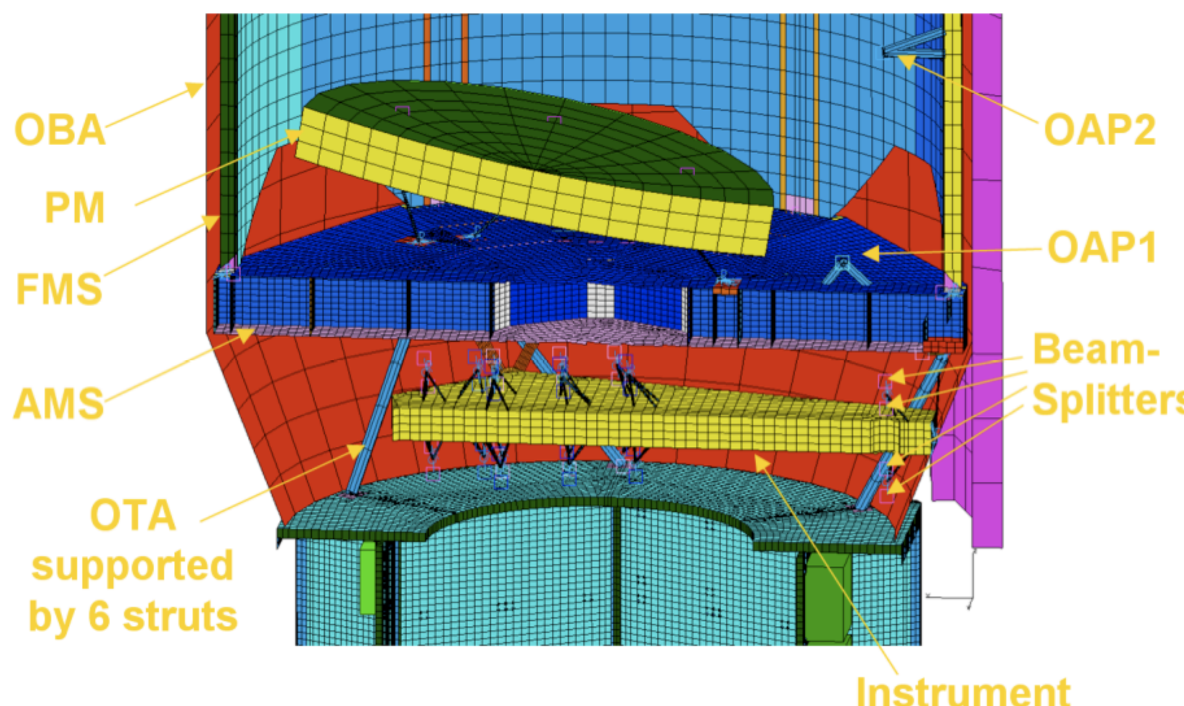
Univ. of Arizona
Jet Propulsion Laboratory
California Institute of Technology
LOCKHEED MARTIN
Ames Research Center
ITT

PECO spacecraft & instrument









PECO Pupil mapping Exoplanet Coronagraph Observer

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

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

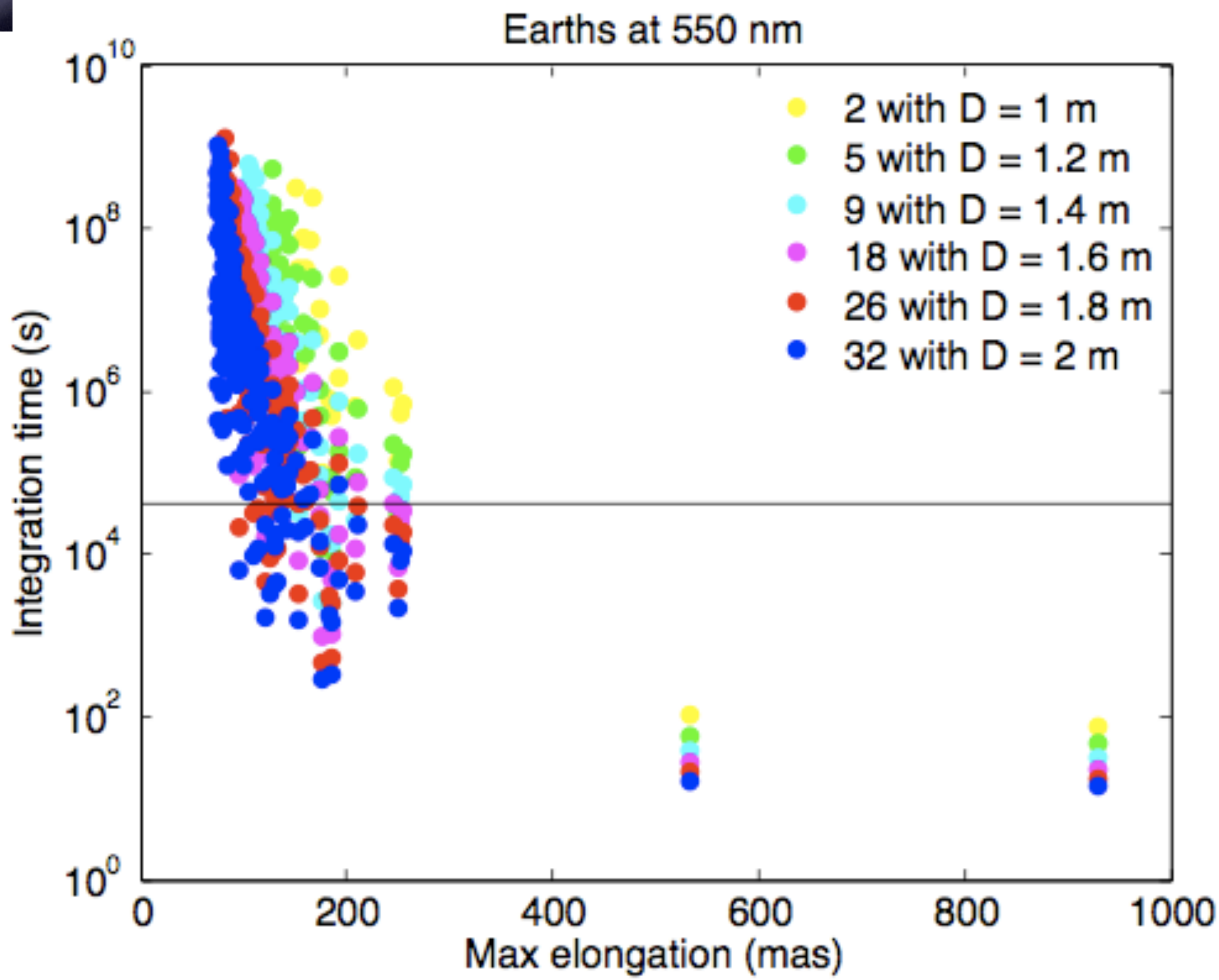
PECO imaging simulations

PECO simulated images used to predict science performance

- Assumes QE x throughput loss = 0.45, given by model of detector QE, instrument optical layout (losses in coatings)
- Assumes exozodi cloud similar to solar
- Takes into account stellar angular size
- Takes into account local zodi (level set by ecliptic latitude of target)
- Instrumental PSF computed for each point of the source (stellar disk, planet, exozodi, zodi): each image requires ~30000 coronagraphic PSFs
- Single visit detection probabilities computed assuming location of planet along its orbit is unknown

PECO science simulations performed by K. Cahoy, NASA Ames, with input from PECO science team

Number of Earths detected with PECO scales gracefully with aperture

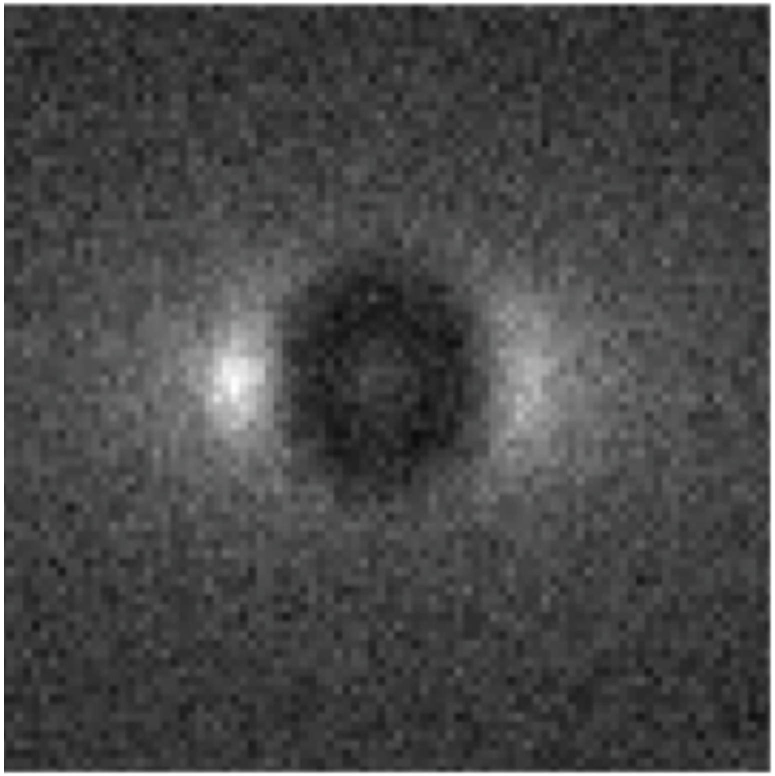


Earths still detectable at shorter wavelengths and smaller D

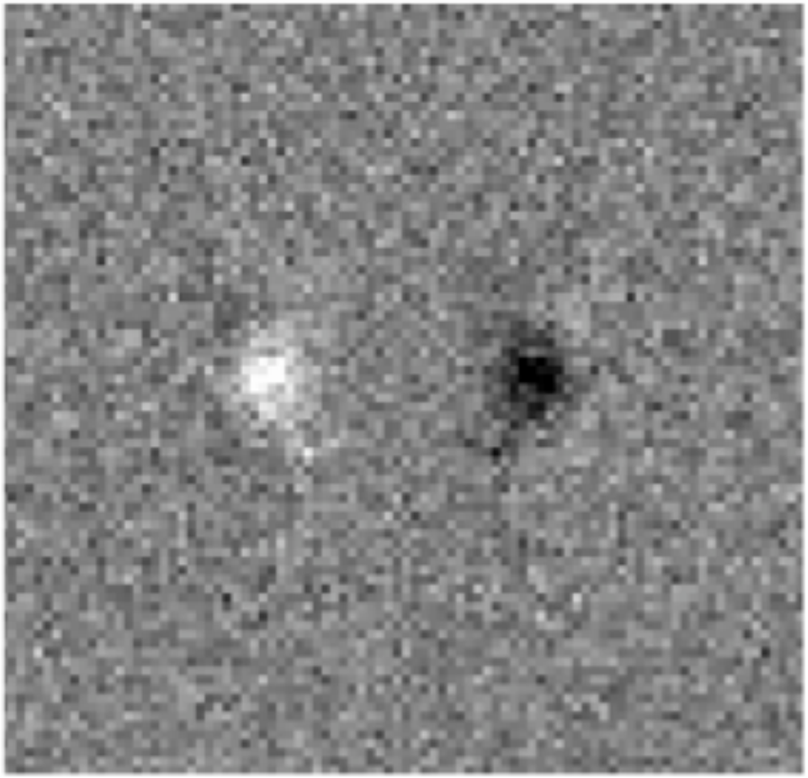
- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit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

PECO can observe an Earth at distance of Tau Ceti

Initial image



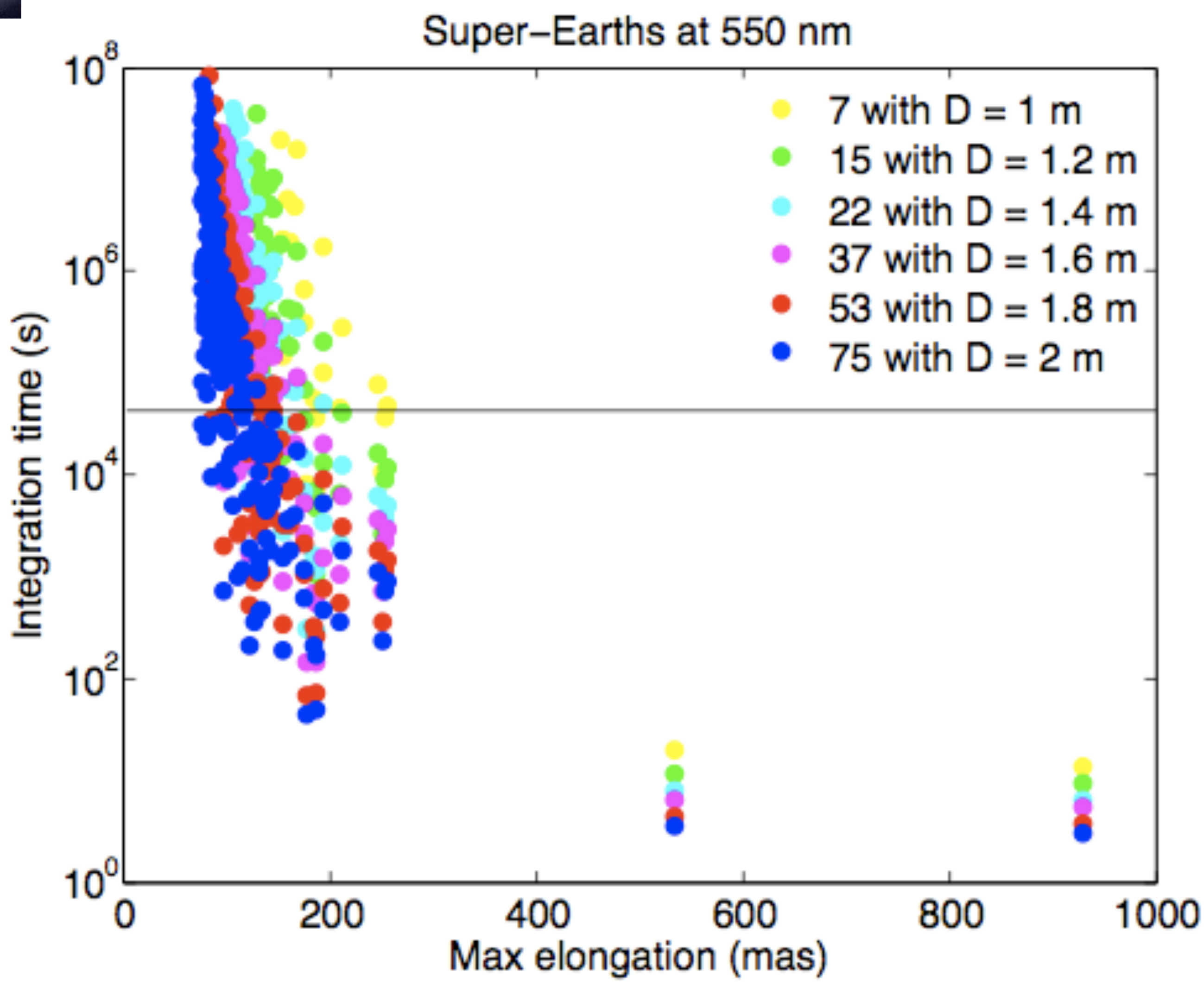
After Symmetric Dust Subtraction



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 high priority targets (detection in < 6 hr)

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

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

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

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

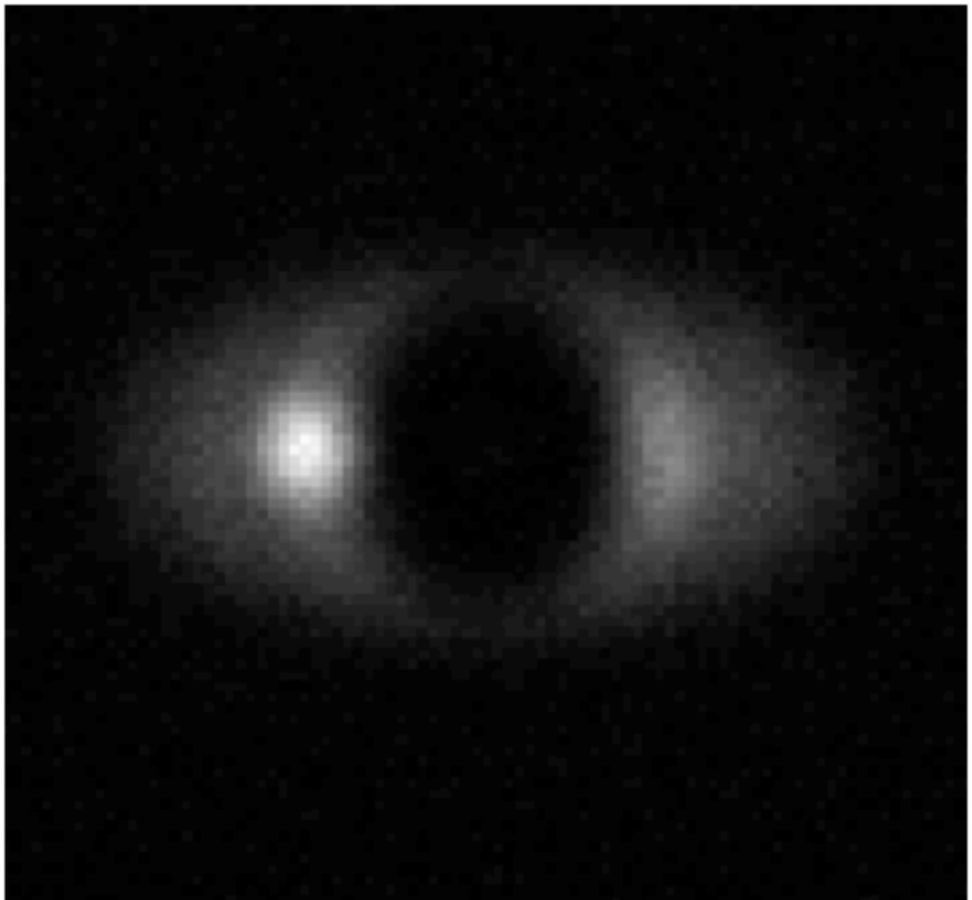
NOTE: ** indicates the presence of significant dust (~10 zodi or more) and *** indicates a close multiple star system (preventing high contrast observations) in Tables 4-2 and 4-3.

Known EGPs observable with PECO

List of known Radial Velocity EGPs observable with PECO

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

PECO easily observes EGPs



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

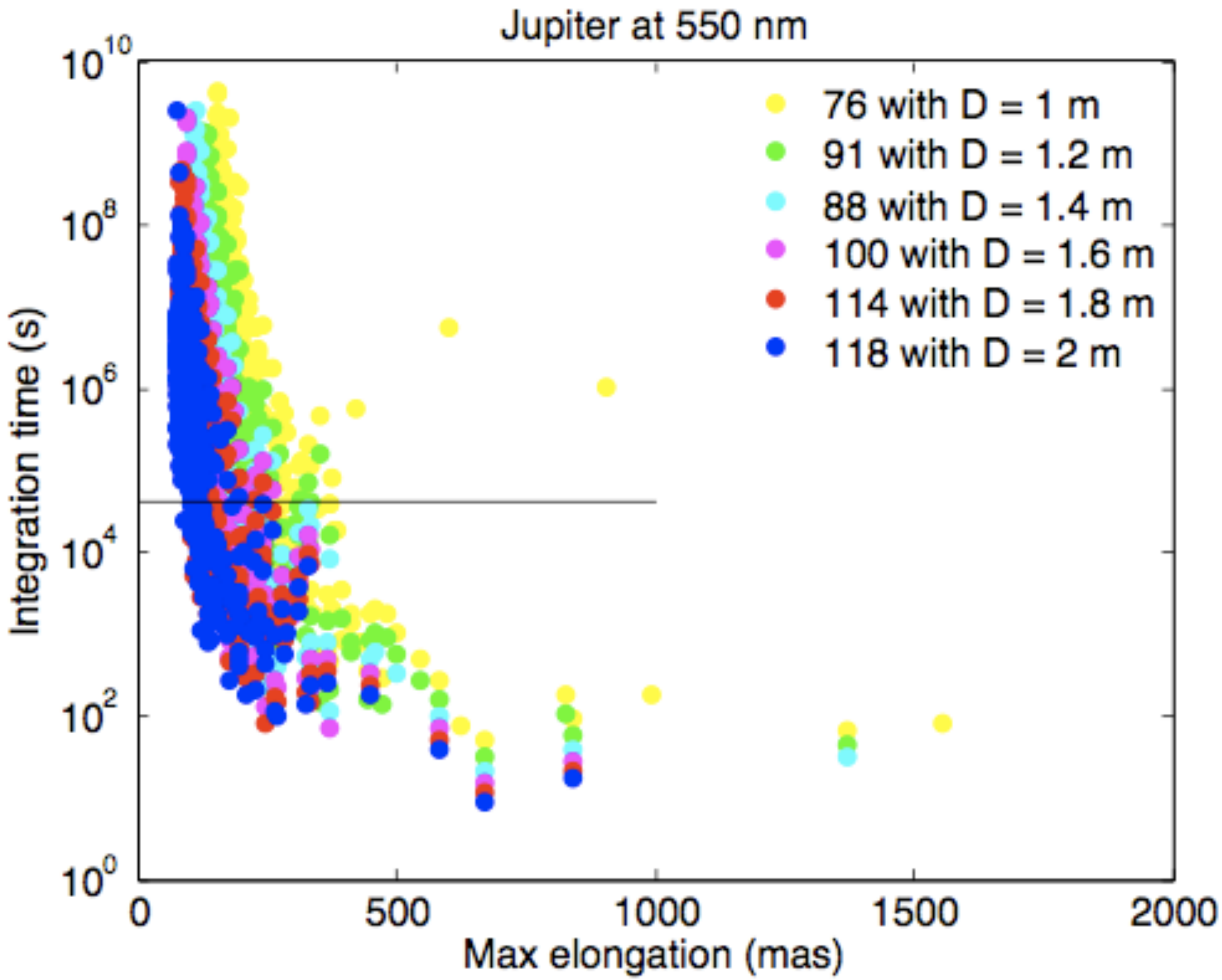
Shown is a simulation of 24 hrs of PECO data showing the Jovian planet 47 Uma b with 3 zodis of exozodi dust in a uniform density disk inclined 59 deg.

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

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

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

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.

Disk imaging with PECO

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

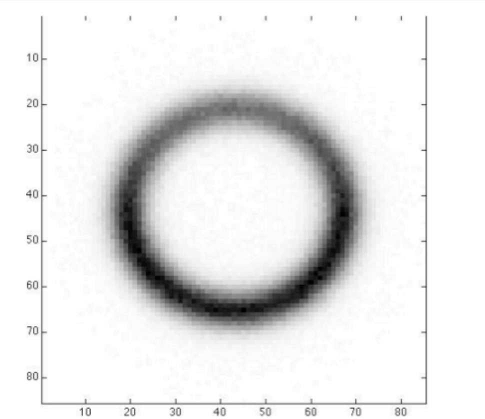


Figure 7-2: Eps Eri ring simulation. The 3 AU radius ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, inclined 22 degrees (same as its debris disk), and a total flux density of 1 zodi. Simulated for a central wavelength $\lambda = 550$ nm with a bandwidth $\delta\lambda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

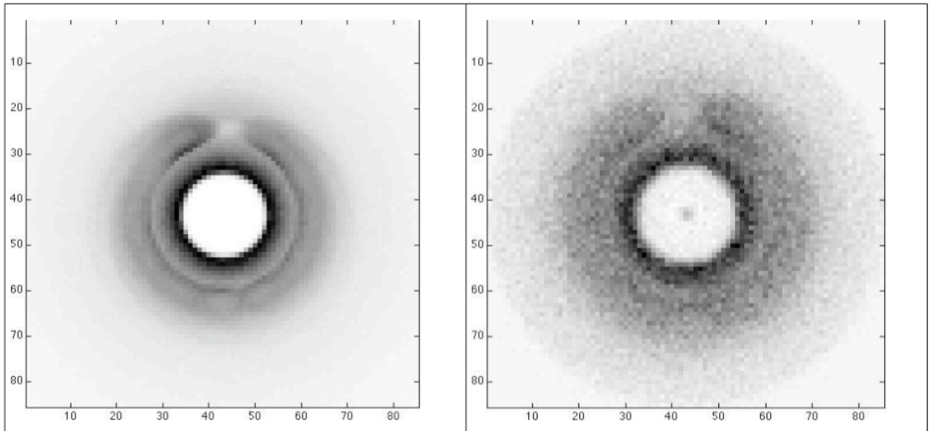
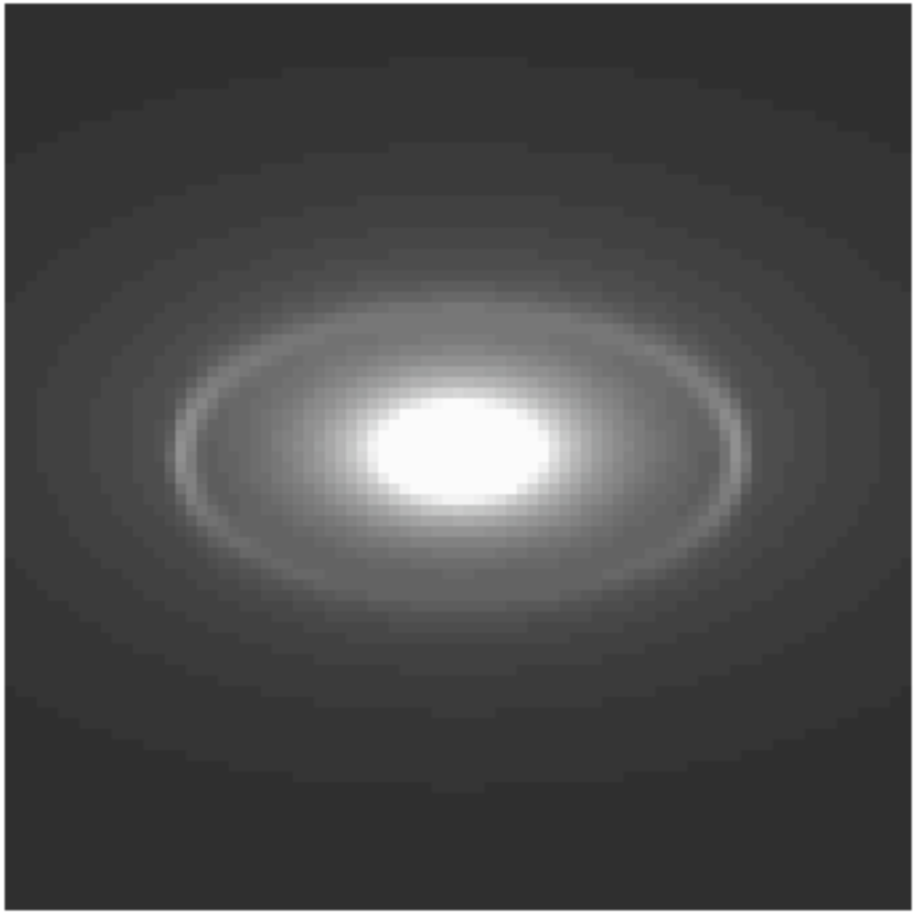


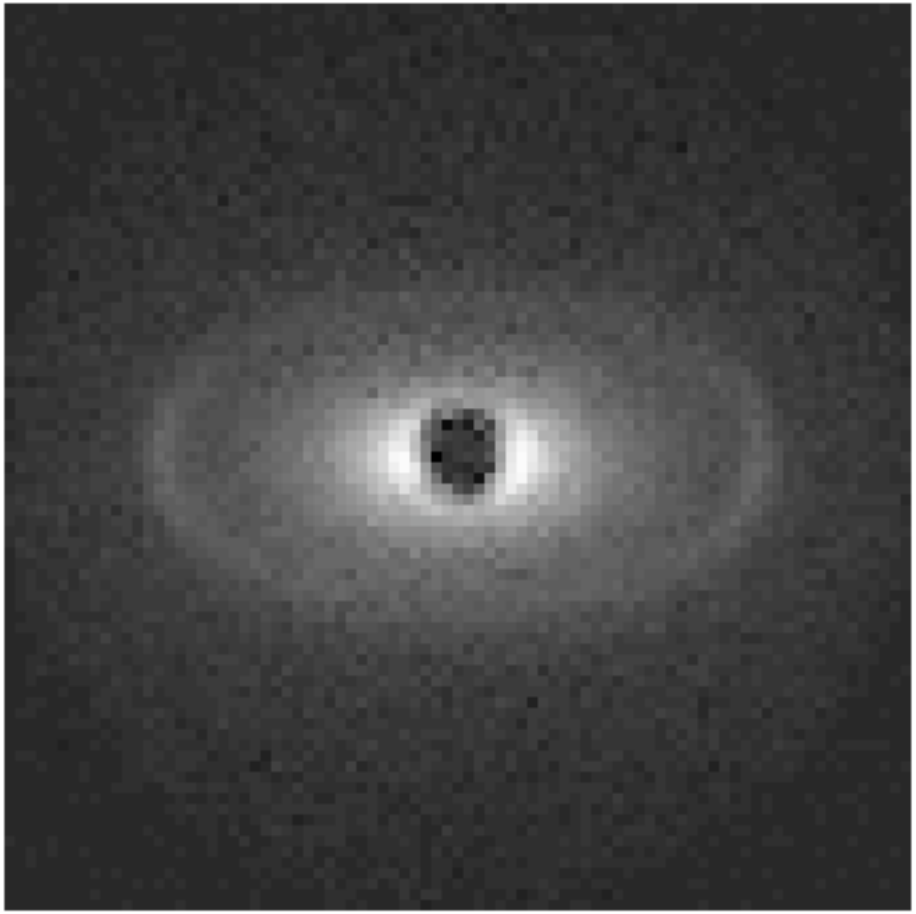
Figure 7-1: Face-on disk model provided by C. Stark (left) and simulated 1E4 s PECO 550nm image (right) of the Sun at 3.3 pc with a 1 zodi disk with the Earth (unseen) embedded at a distance of 3 AU.

PECO exozodi imaging

- Simulated PECO imaging of Alpha Cent exozodi



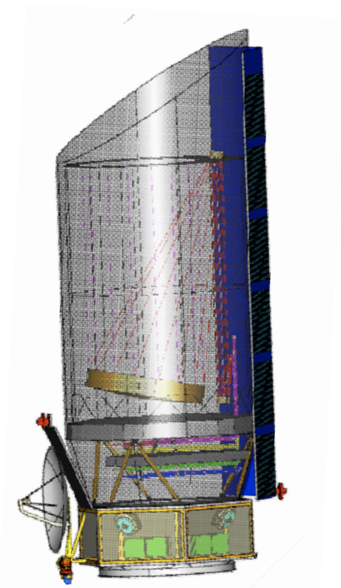
Model
1 zodi
enhancement at 1AU



PECO image
3 hr exposure
400 nm, 20% band

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

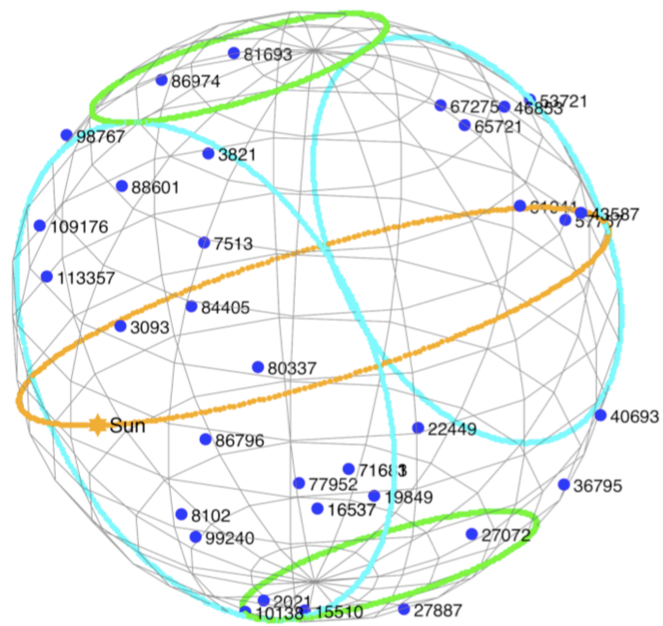


Figure 8.3.2: PECO-centric field of view for one moment in mission time. Sun/Earth avoidance and power-limited zones are outlined in blue. Continuous viewing zones are outlined in green. Grand Tour + RV targets are blue dots tagged with their HIP numbers. Please see the text in Sections 8.3.4 and 8.3.5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

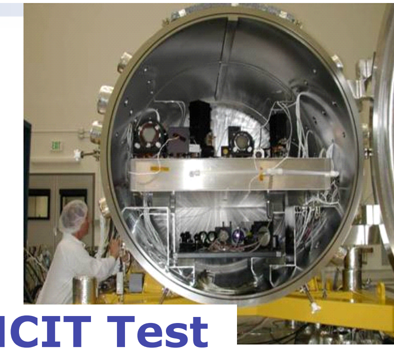
PECO top key technologies are identified and under study

- **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**

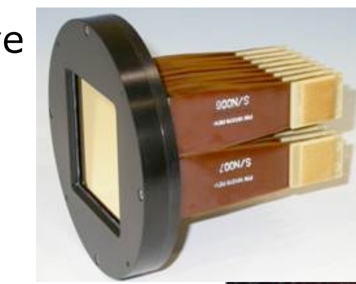
System verification combines:

- 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

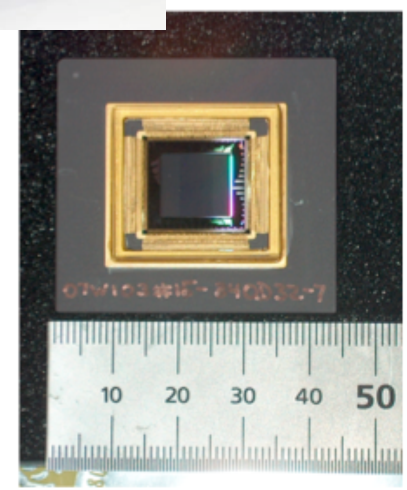
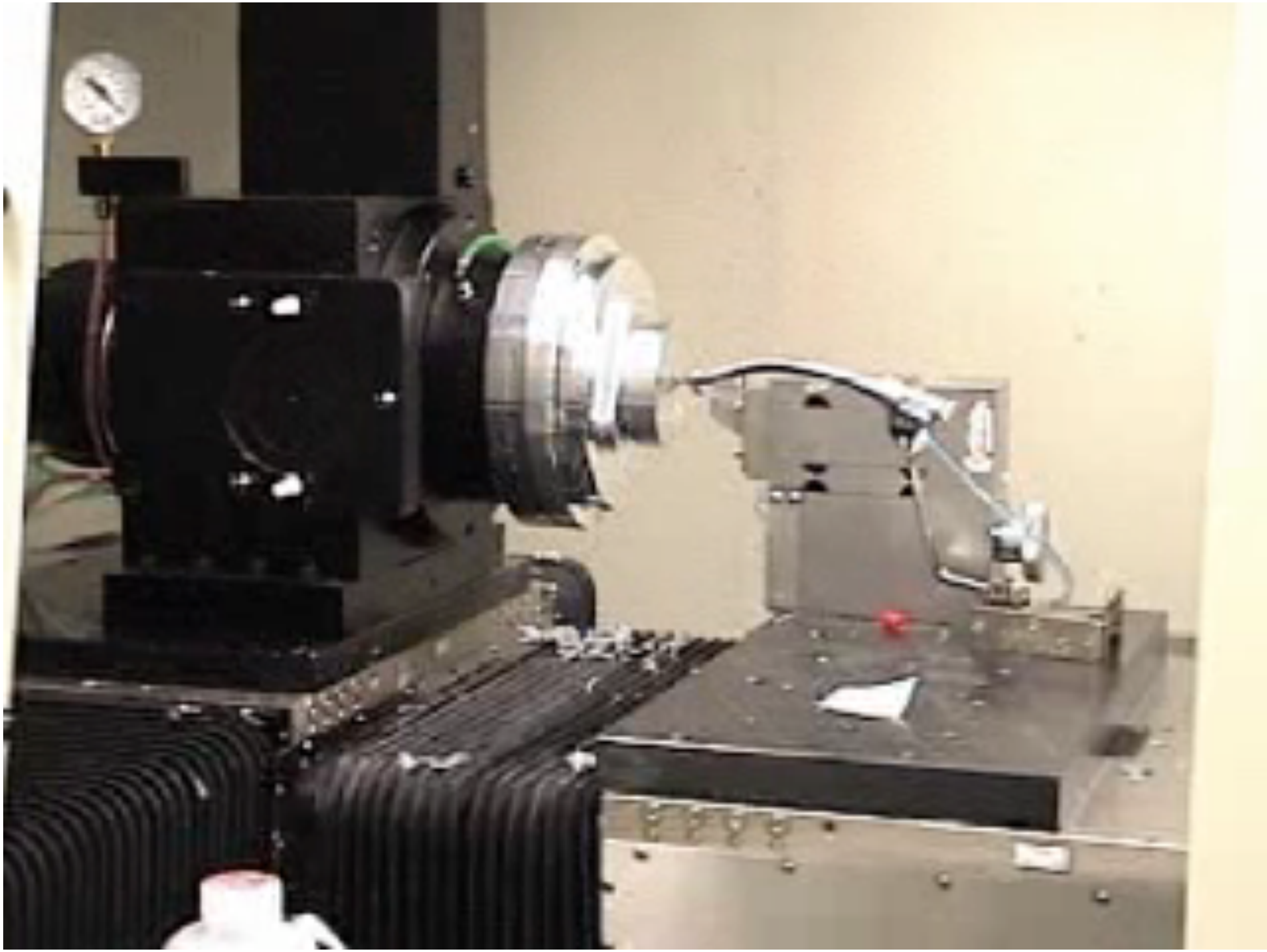
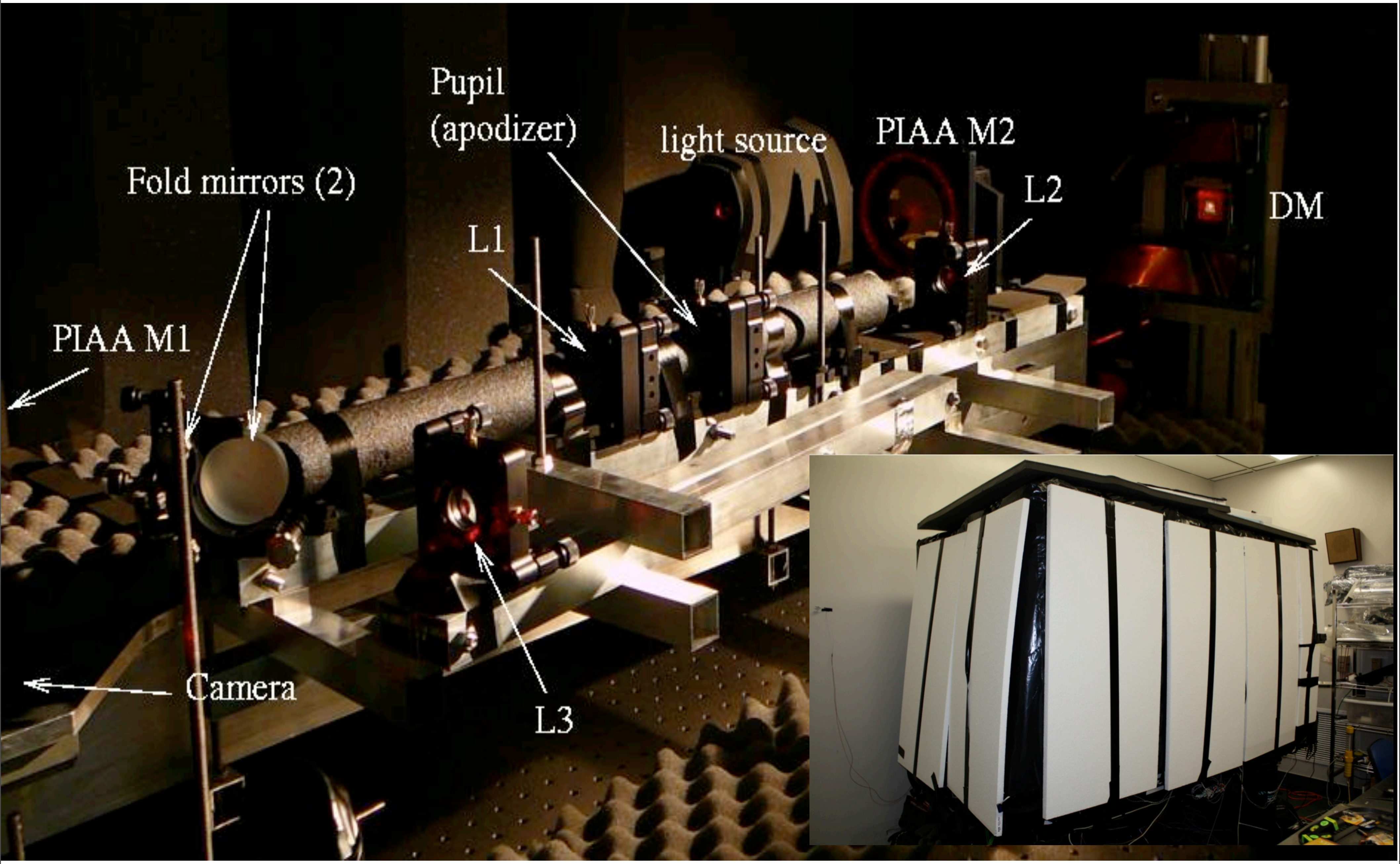


Figure 1: 1024 actuator (32x32) MEMs DM commercially available from Boston Micromachines (mm scale).

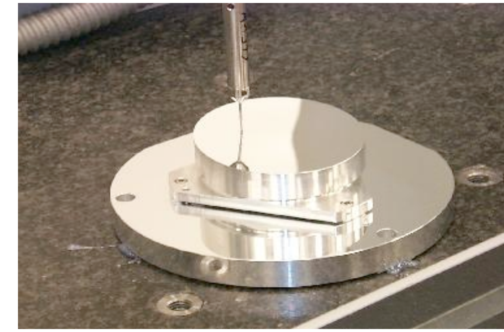
PIAA optics - Diamond turning

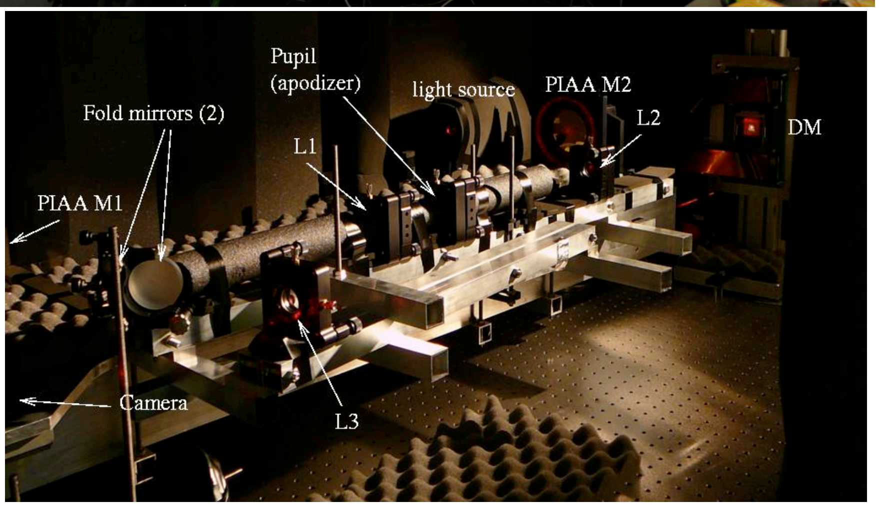



Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

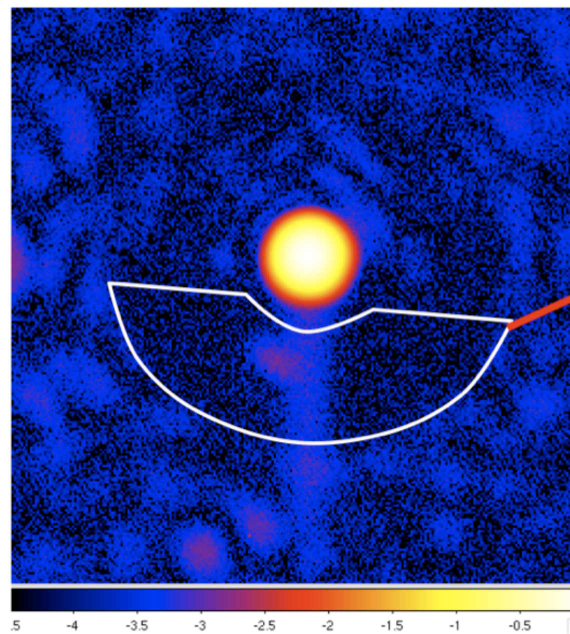
PIAA testbed at Subaru Telescope

Temperature-stabilized monochromatic testbed in air
Uses 32x32 actuator MEMs
Uses 1st generation PIAA mirrors, diamond turned Al

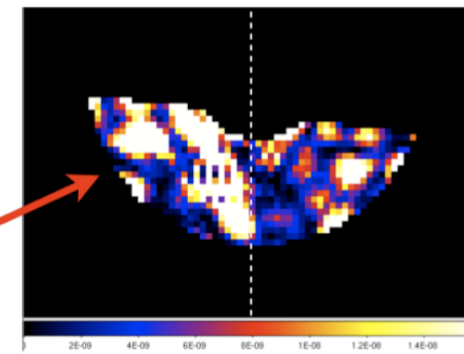




Raw image



Coherent starlight



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

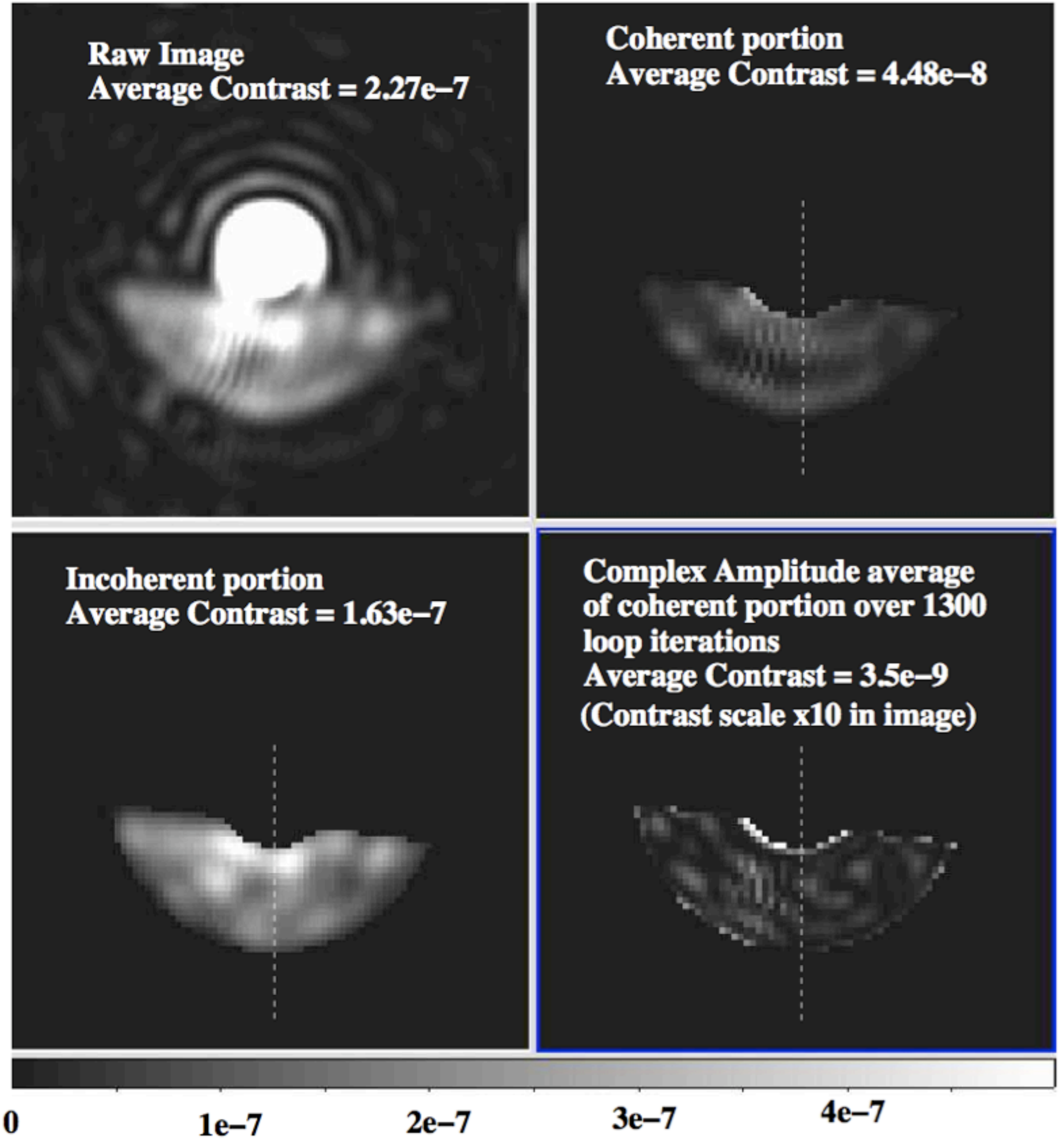
PECO Pupil mapping Exoplanet Coron

Contrast achieved in 1.65 to 4.5 l/D half field zone (1 DM only):
2e-7 incoherent halo ghost (equivalent to exozodi)
4e-8 coherent starlight speckles (turbulence, vibrations)

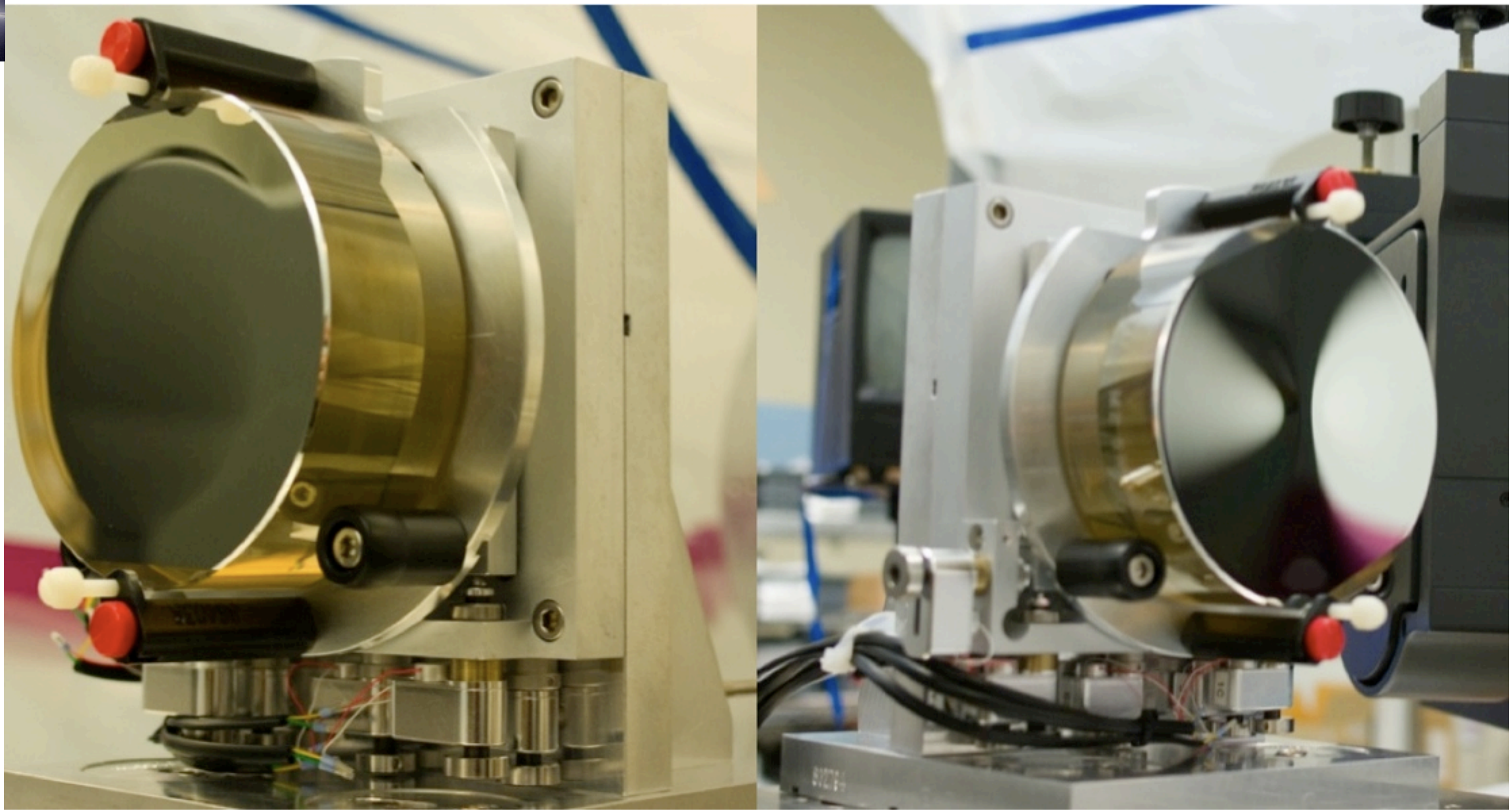
Subaru PIAA lab demo

Contrast achieved (1.65 to 4 l/D):
Raw = 2.27e-7

Ghost = 1.63e-7
turbulence = 4.5e-8
coherent bias < 3.5e-9

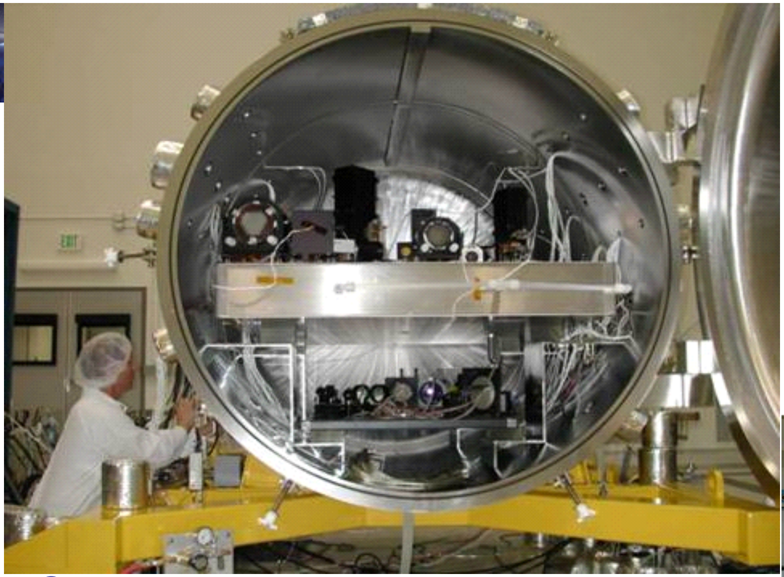


High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)



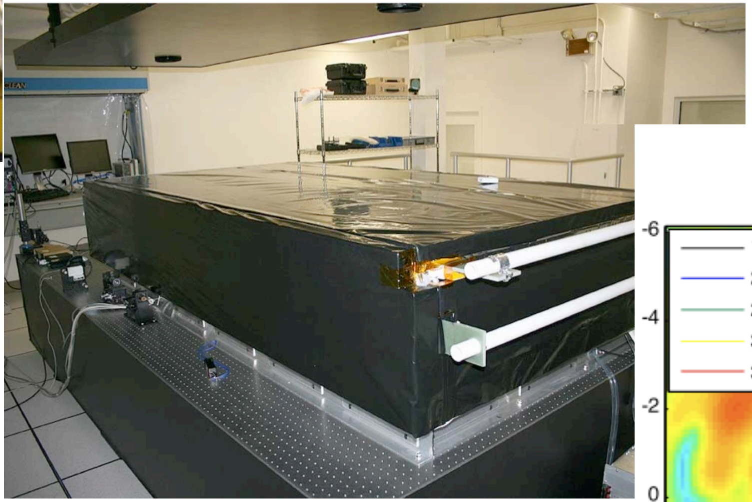
2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5 2009 (better surface accuracy, better achromatic design than PIAAgen1)

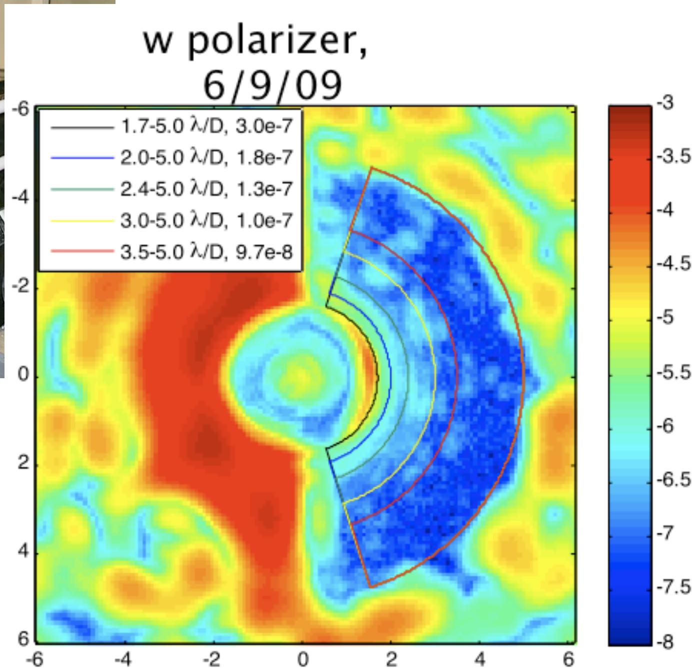
PIAA test status

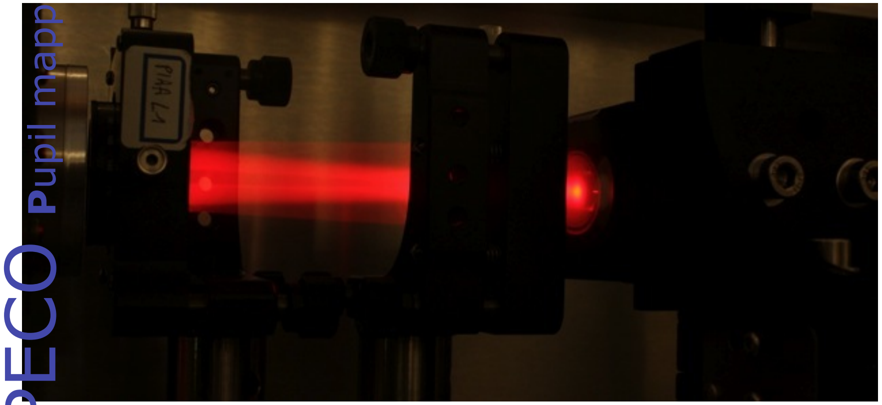


PIAA gen2 is being tested in JPL's High Contrast Imaging Testbed in vacuum and polychromatic light.

PIAA-dedicated testbed at NASA Ames testing WFC architectures & MEMs DMs (Belikov et al.).







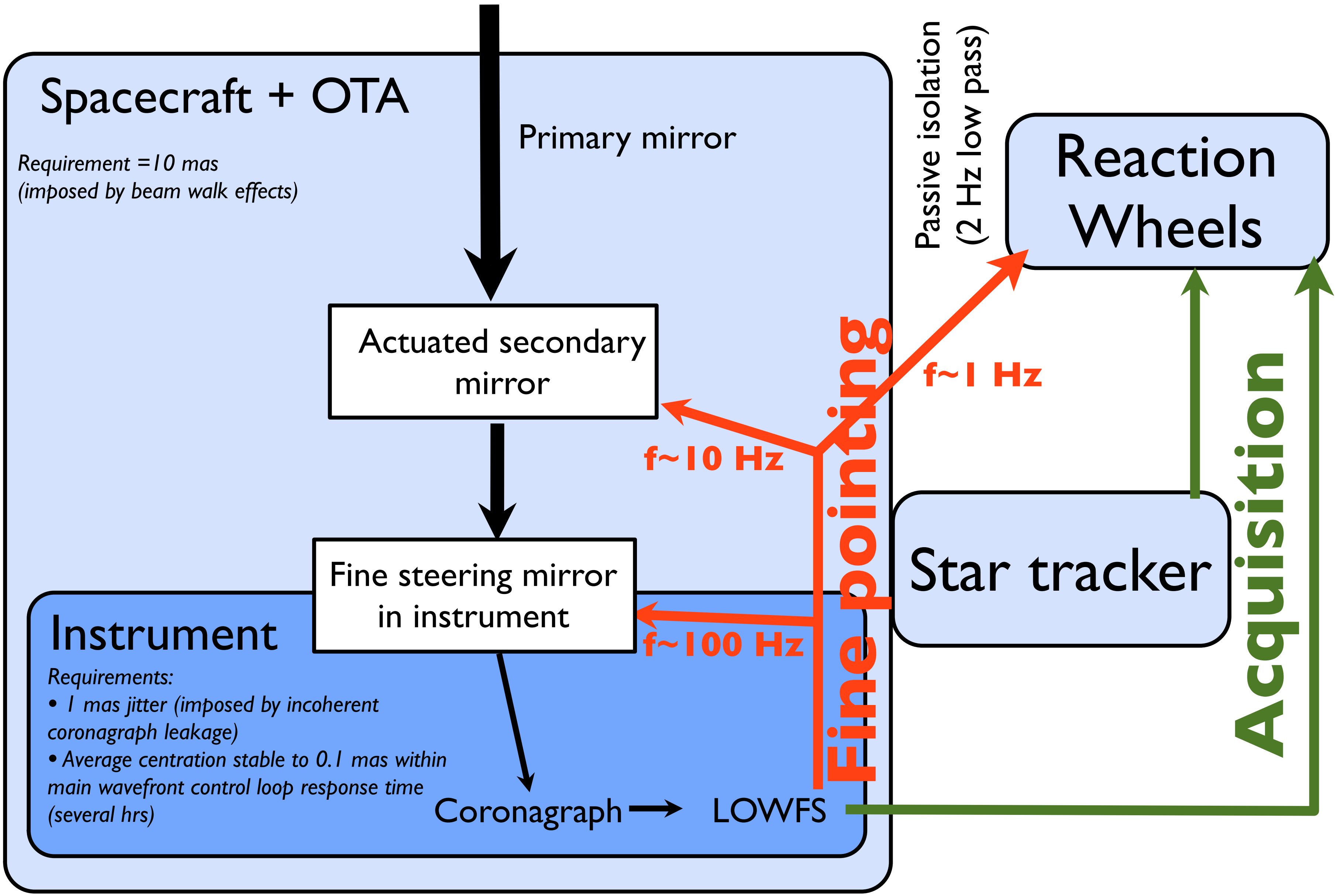
Refractive PIAA system scheduled to be on-sky in early 2010 at Subaru Telescope

PECO Pupil mapping Exoplanet Coro

PECO wavefront requirements

- **PECO optics don’t need to be very good, but they need to be STABLE**
- **Pointing stability requirements**
  - Affects performance by:
    - Coronagraph leak from tip/tilt
    - Beam walk across optics creates speckles
  - Pointing jitter <1 milliarcseconds (mas) RMS
  - zero-point pointing drift should stay (or be known to) ~0.1 mas
- **Dynamic and thermal disturbances**
  - Affect low-order aberrations & mid spatial frequencies
  - Need to be stable to ~0.1 angstrom per mode during observation
  - Primary mirror stability is dominant source of error
  - Developed detailed error budget to derive rigid body motion requirements on optics and bending of PM

PECO pointing architecture



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

Low Order Wavefront Sensor

PECO Pupil mapping Exoplanet Coronagraph Observer

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

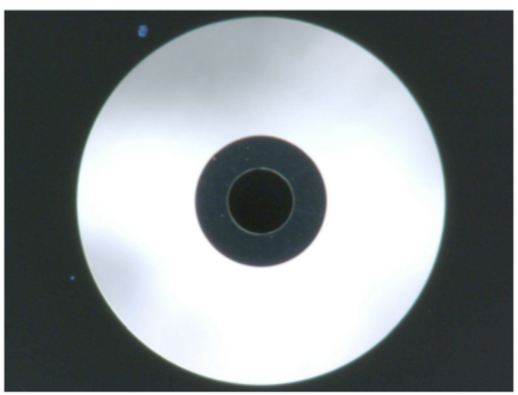


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

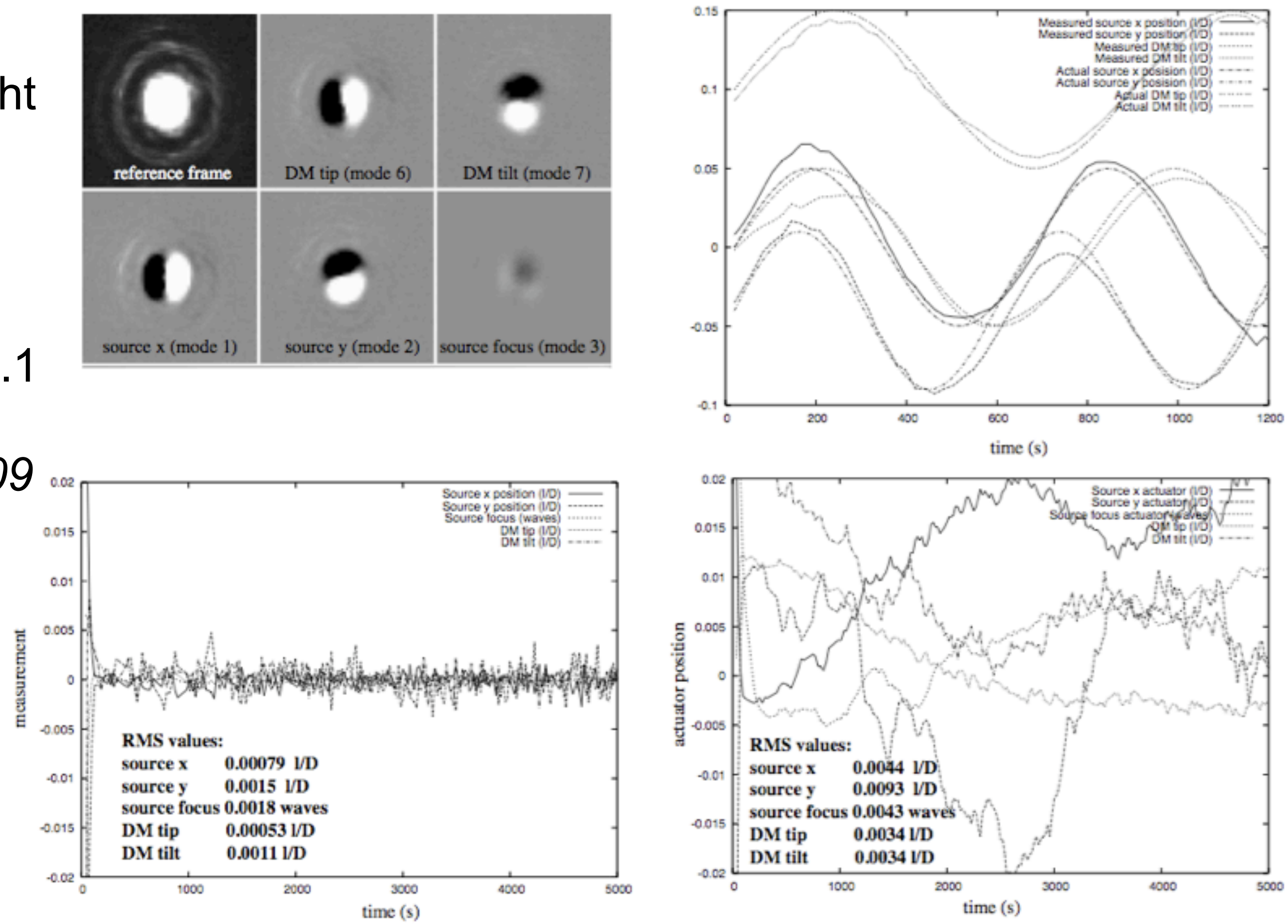


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes.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

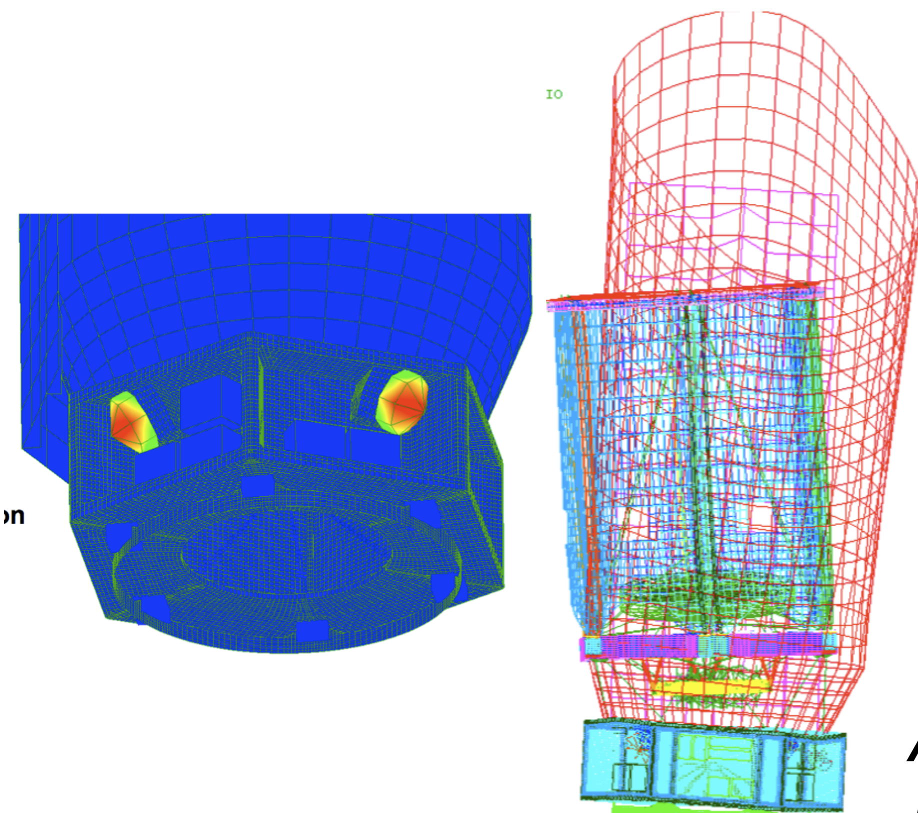
PECO stability analysis

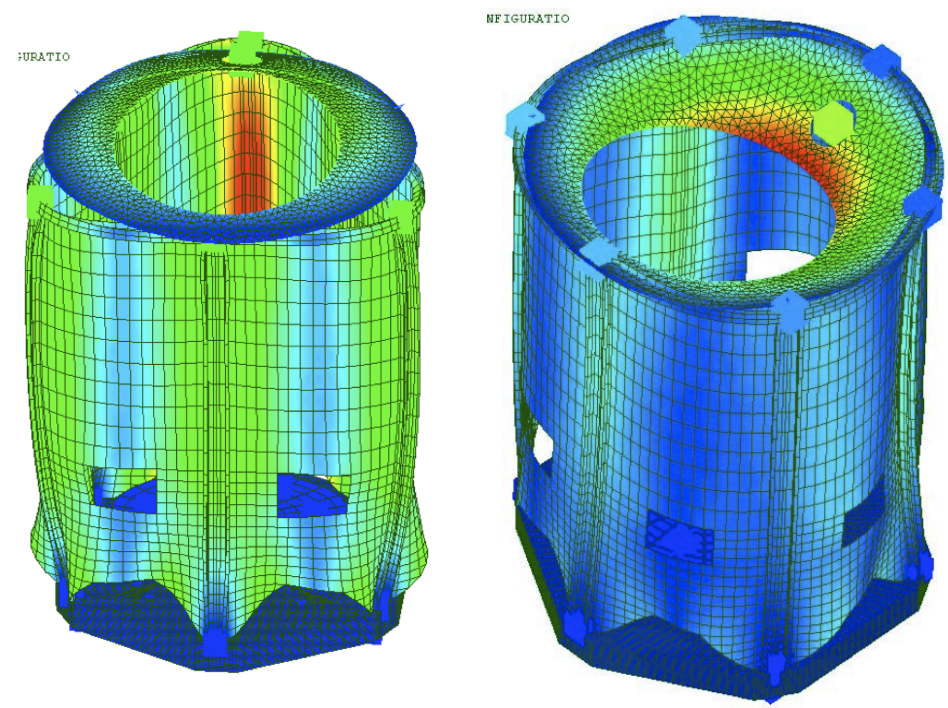
- PECO wavefront needs to be very stable
  - it takes few minutes to see an Earth-like planet
  - it takes just as long to see a speckle with the same luminosity
  - it takes a 1.5pm sine wave ripple on the wavefront to create such a speckle
- A 1.5 pm sine wave ripple on the wavefront which appears 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

PECO Pupil mapping Exoplanet Coronagraph Observer

- 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)

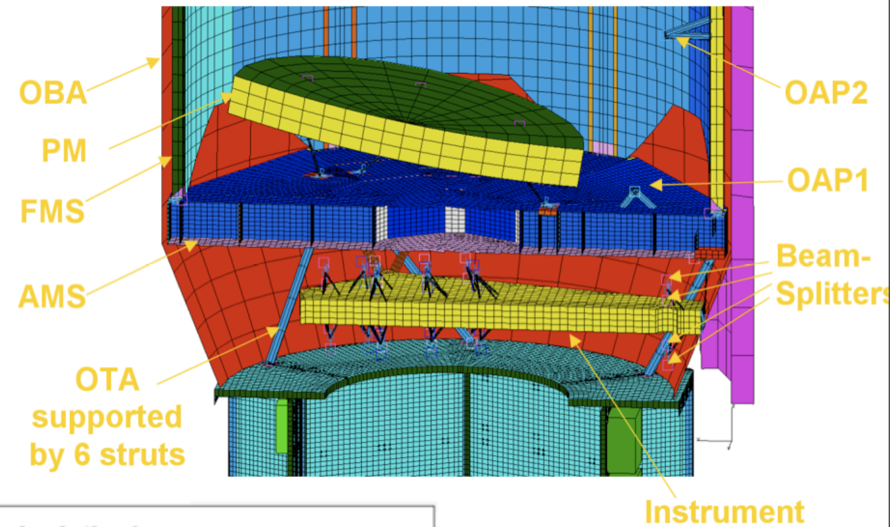


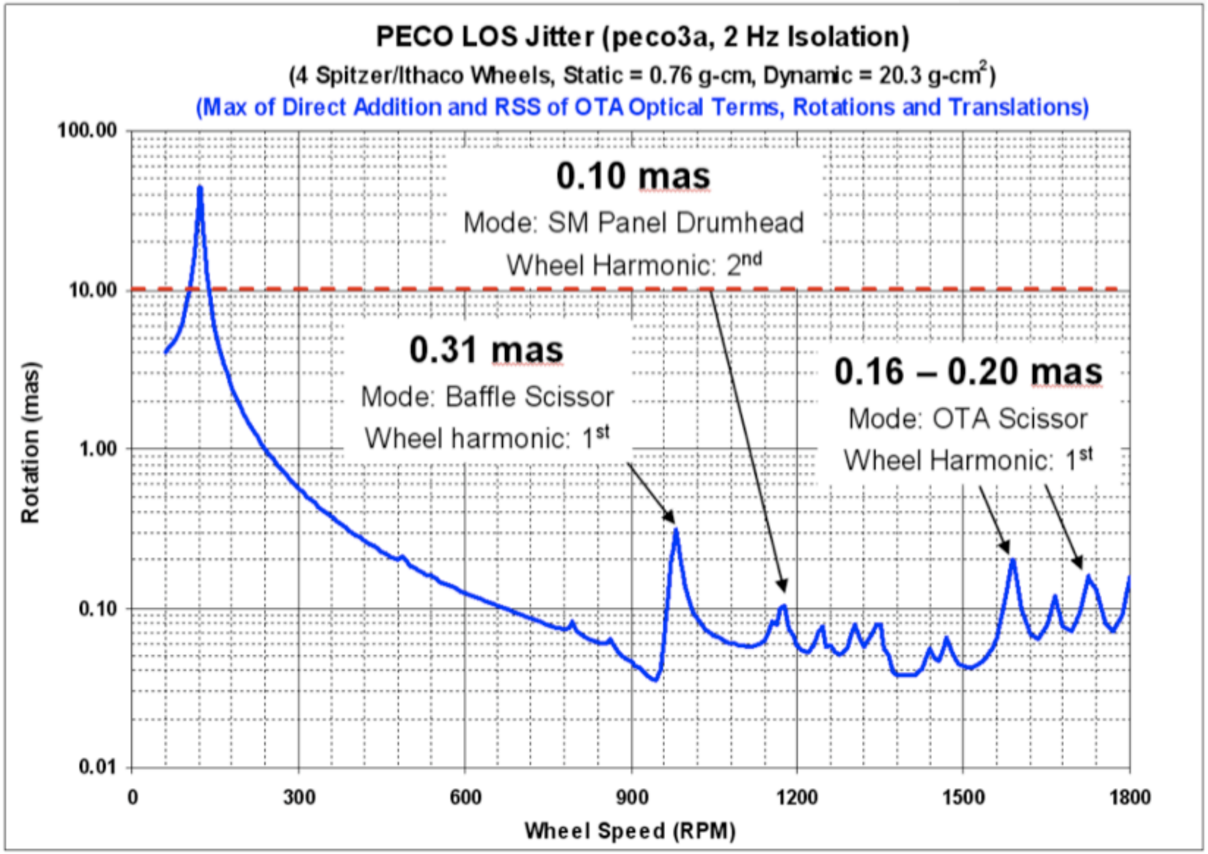


Analysis performed by Lockheed Martin

PECO jitter analysis

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





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

PECO thermal analysis

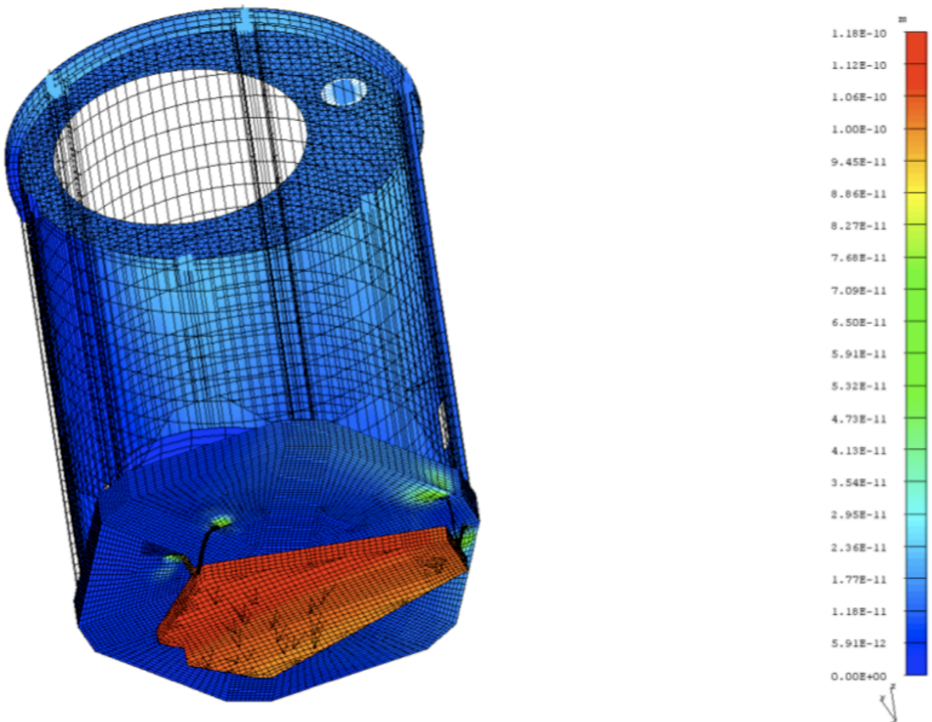
Univ. of Arizona — Jet Propulsion Laboratory, California Institute of Technology — Lockheed Martin — NASA Ames Research Center — ITT

PECO Pupil mapping Exoplanet Coronagraph Observer

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

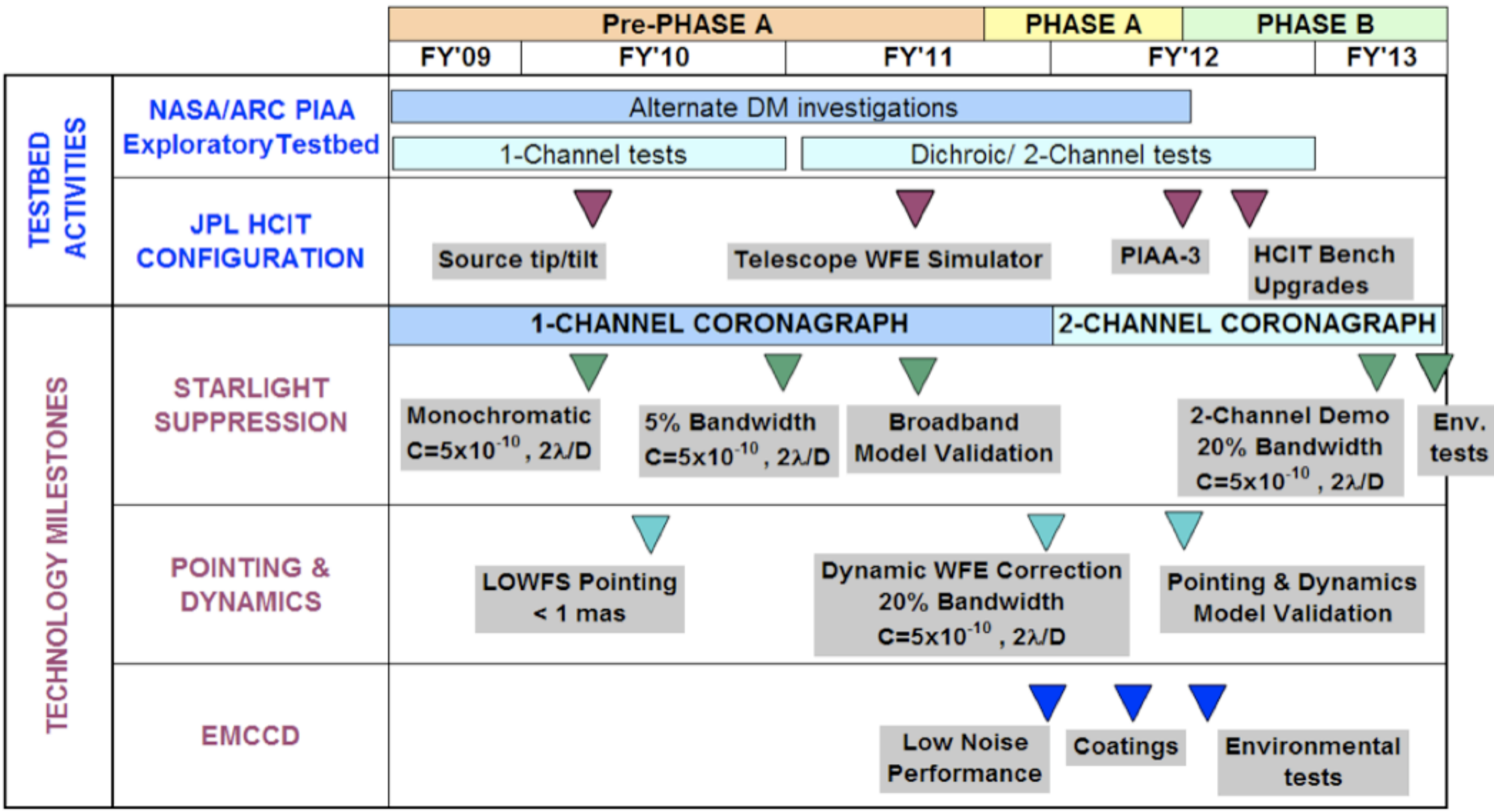
PECO technology development

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

PECO Pupil mapping Exoplanet Coronagraph Observer

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



Univ. of Arizona

Jet Propulsion Laboratory
California Institute of Technology

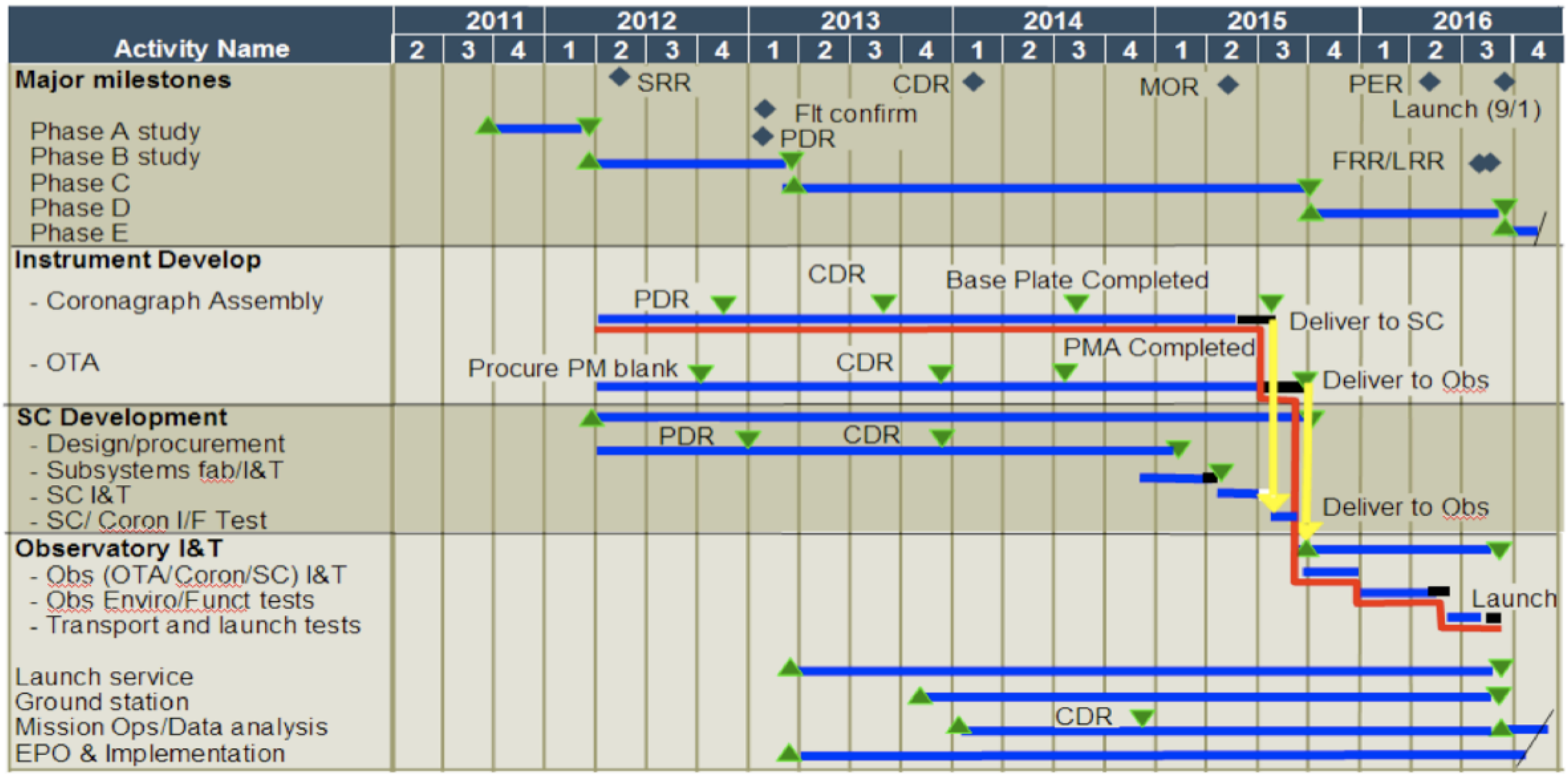
LOCKHEED MARTIN

Ames Research Center

ITT

PECO schedule

PECO can be launched in 2016



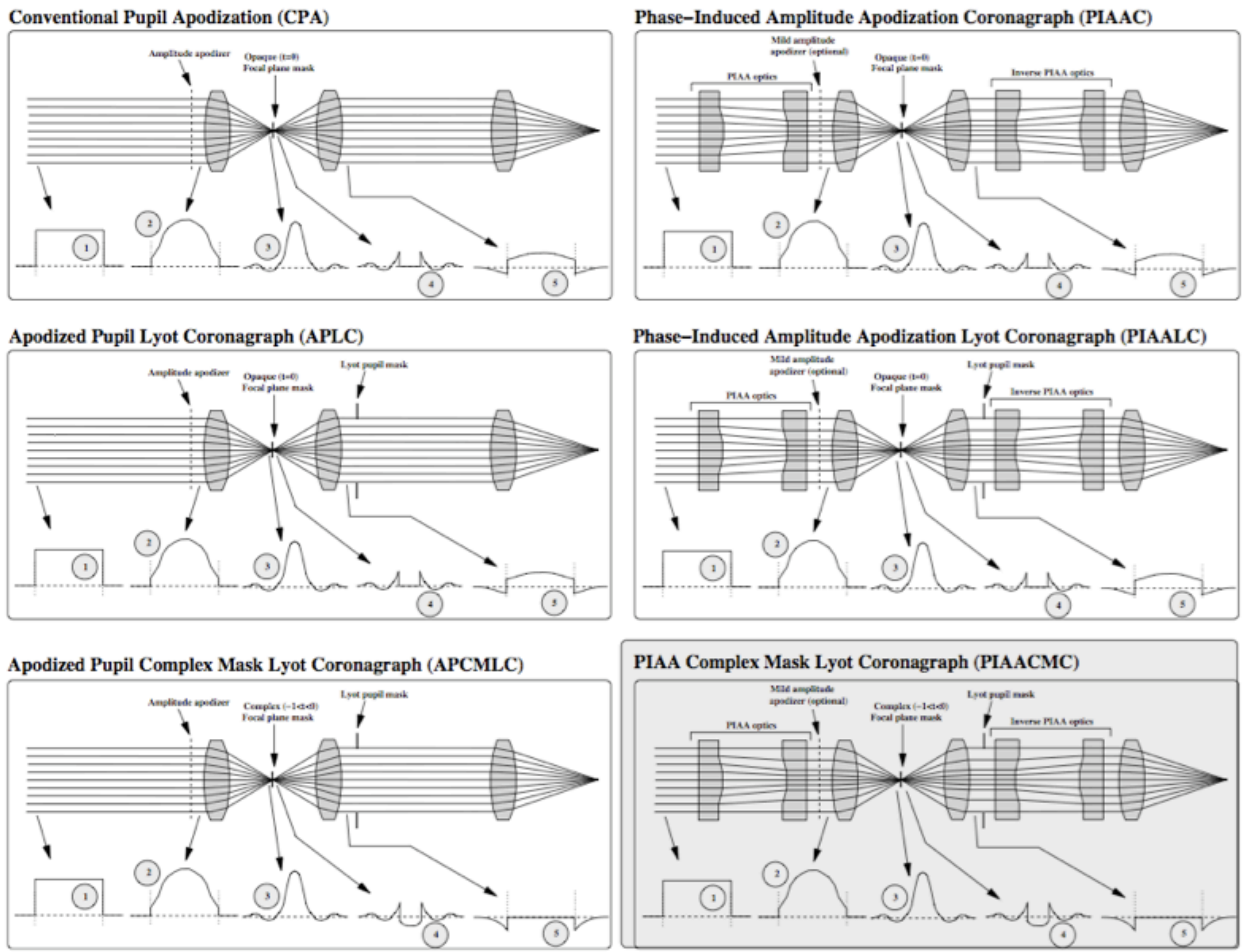
PECO **P**upil mapping **E**xoplanet **C**oronagraph **O**bserver

PECO trades

- **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

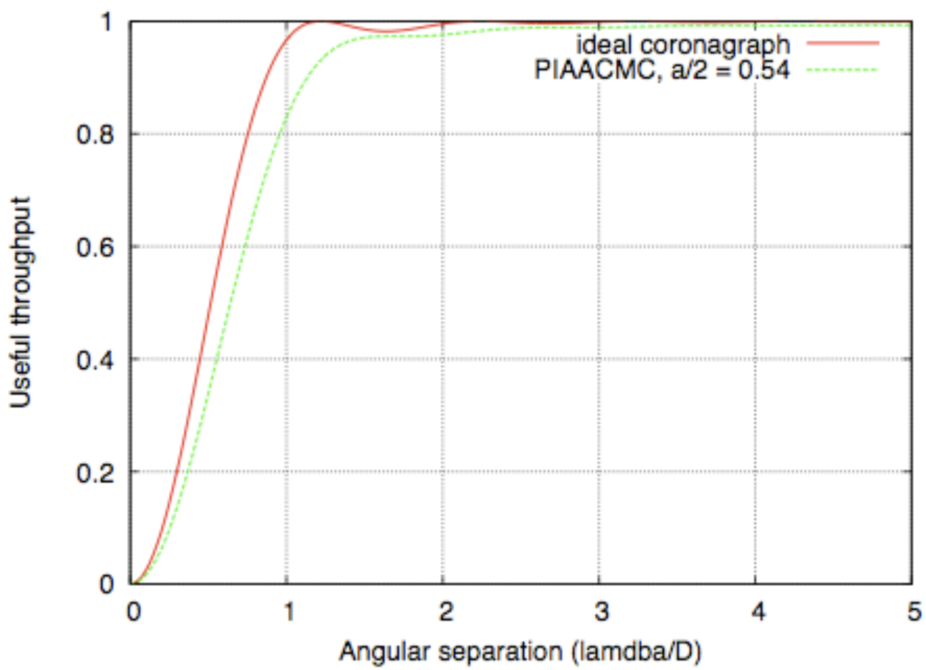
Smaller IWA PIAA

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



PIAA complex mask coron.

- 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

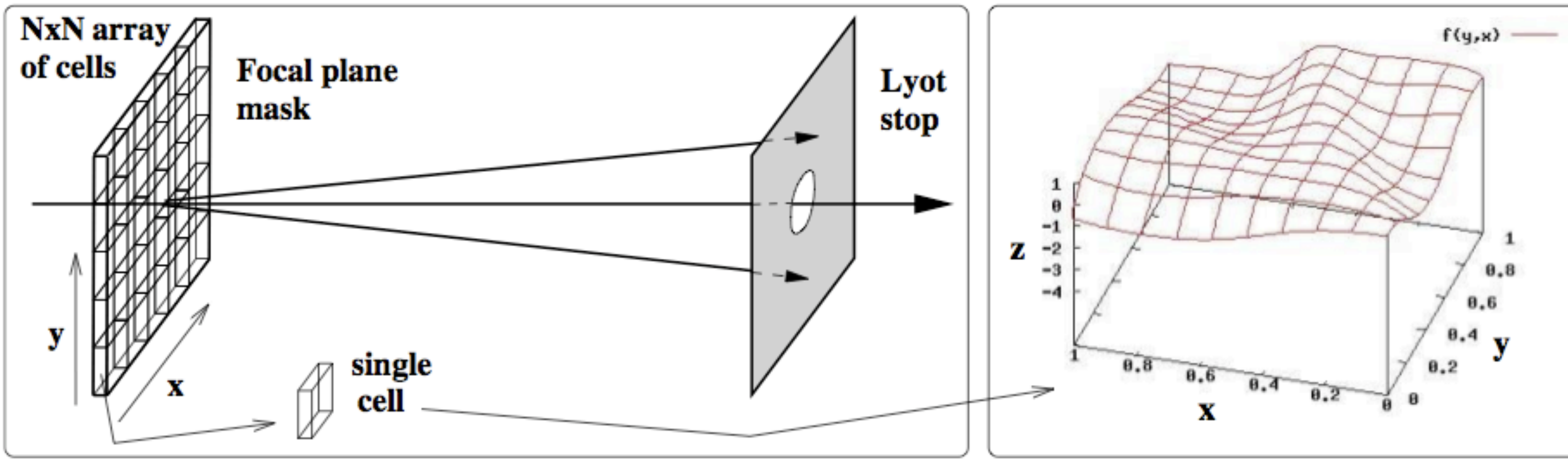
- Focal plane mask needs to be partially transmissive, and phase shifting
- Phase shift AND transmission need to be achromatic
- Mask size needs to be achromatic

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 phase 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)



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

only histogram h(t) matters
t = thickness

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

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

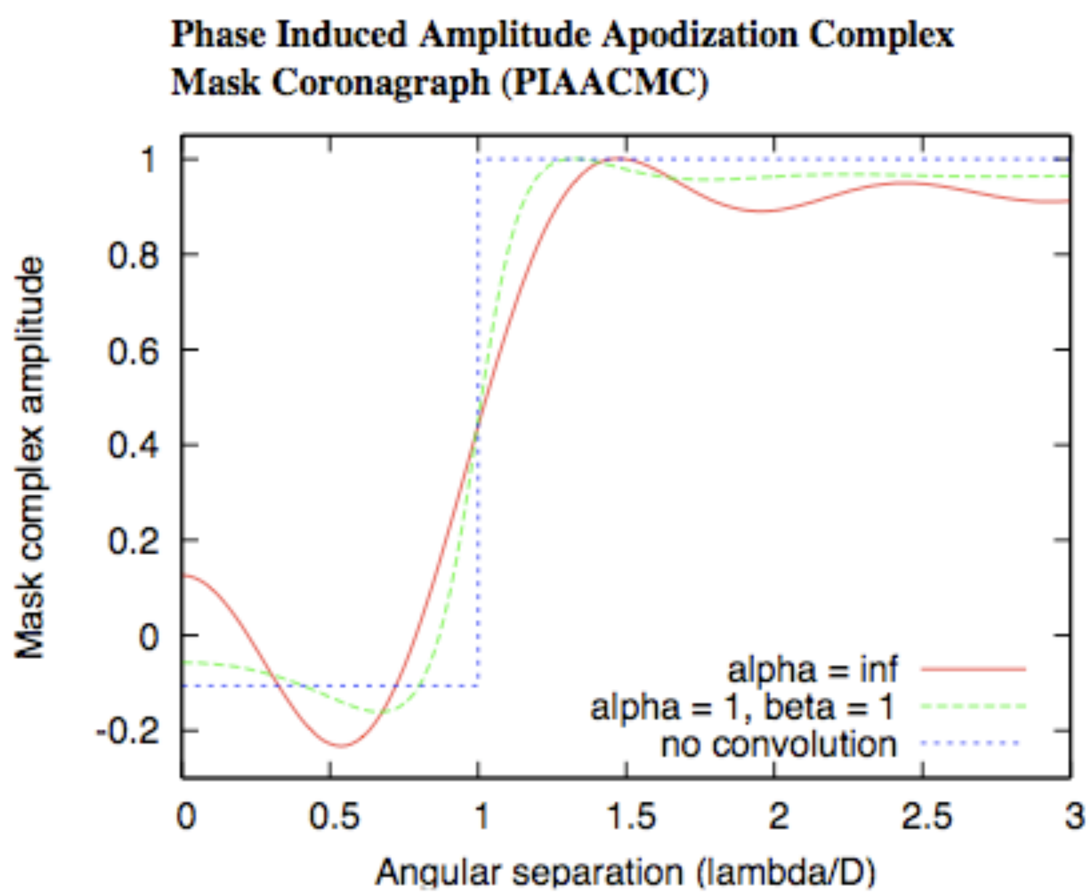
$$T(\lambda') = \int_{-\infty}^{\infty} h(t) e^{i2\pi t\lambda'}\,d\lambda'$$

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



PECO Pupil mapping Exoplanet Coronagraph Observer

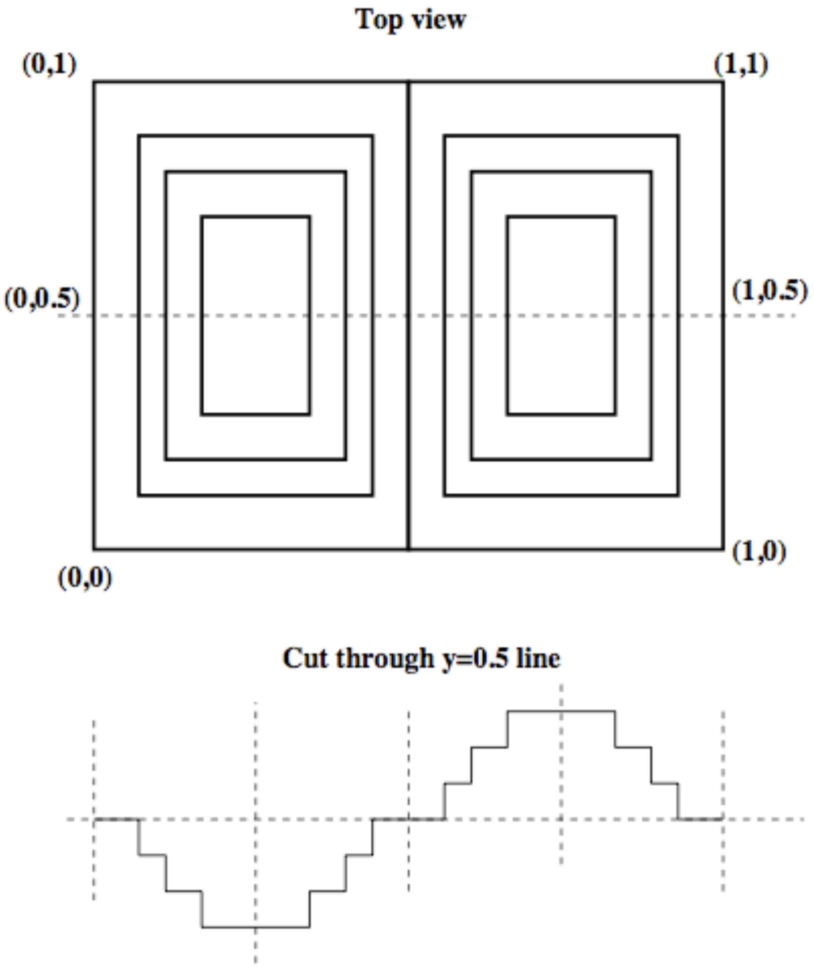
Univ. of Arizona
JPL Jet Propulsion Laboratory California Institute of Technology
LOCKHEED MARTIN
NASA Ames Research Center
ITT

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



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

PIAACMC focal mask

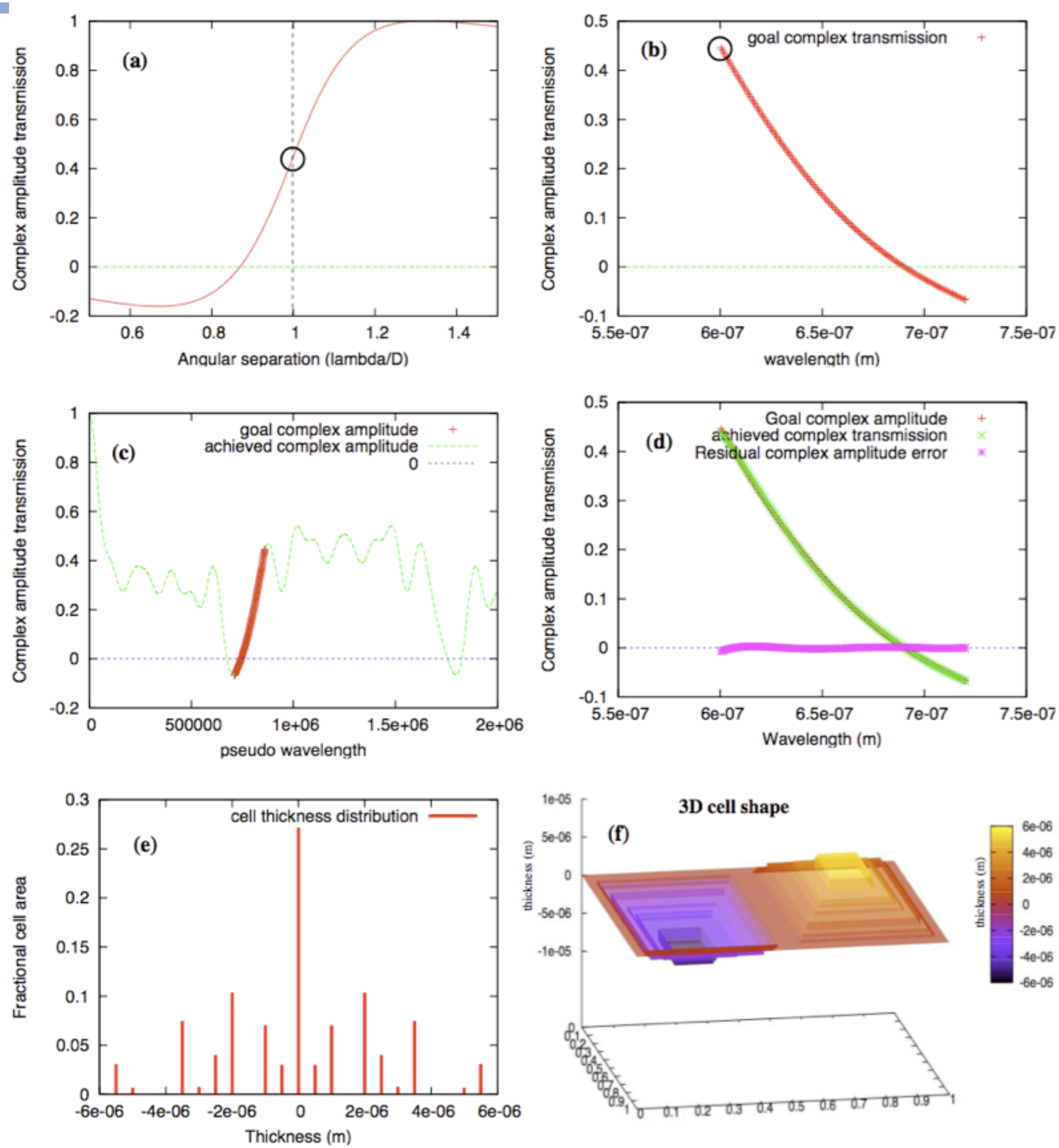
PECO Pupil mapping Exoplanet Coronagraph Observer

In this example:

Material = CaF2

Material thickness = -6 to +6 micron

Thickness is multiple of 0.5 micron



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

More information

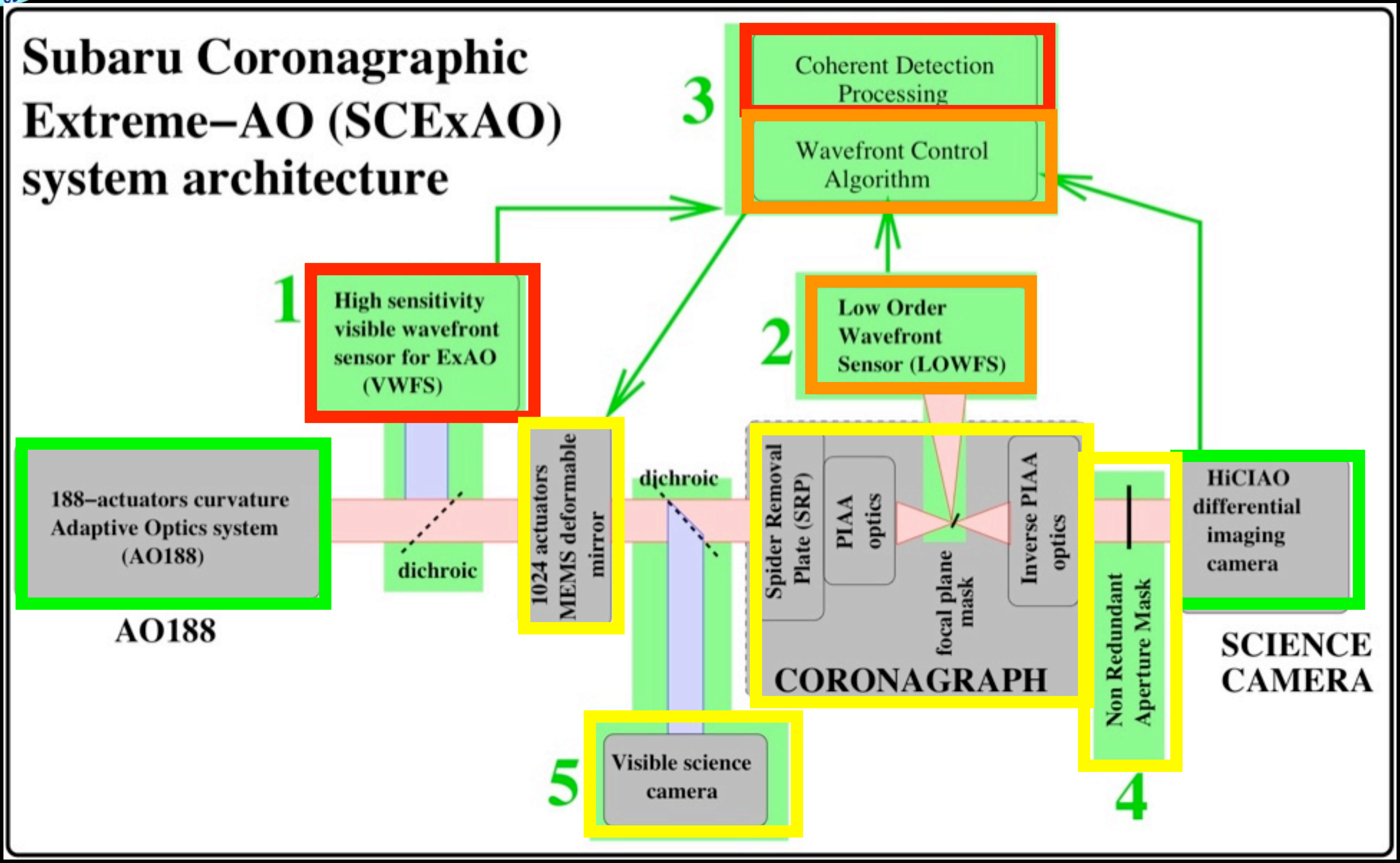
- More info on PECO website: http://caao.as.arizona.edu/PECO
  - 20-page summary of PECO activity
  - Science Requirements Document (SRD)
  - Design Reference Mission (DRM)
  - Technology development plan
  - Recent lab development updates

- Several of the key coronagraphy and WFC technologies developed for PECO will be the core of the Subaru Coronagraphic Extreme-AO system
  - PIAA & PIAACMC
  - LOWFS for fast & accurate pointing control
  - Control & calibration of focal plane speckles

Subaru Coronagraphic Extreme-AO (SCExAO)system

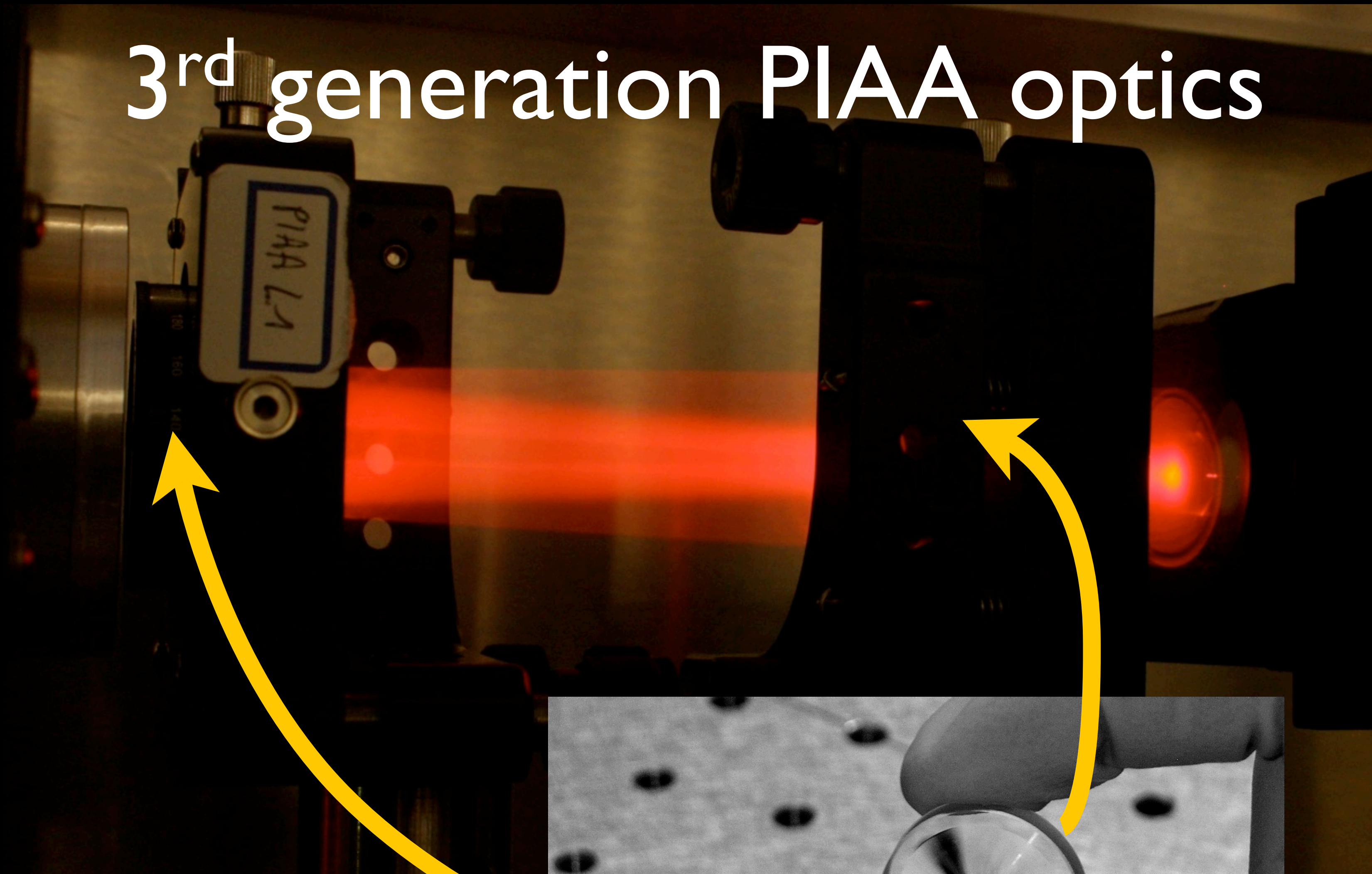
Guyon, Martinache, Lozi

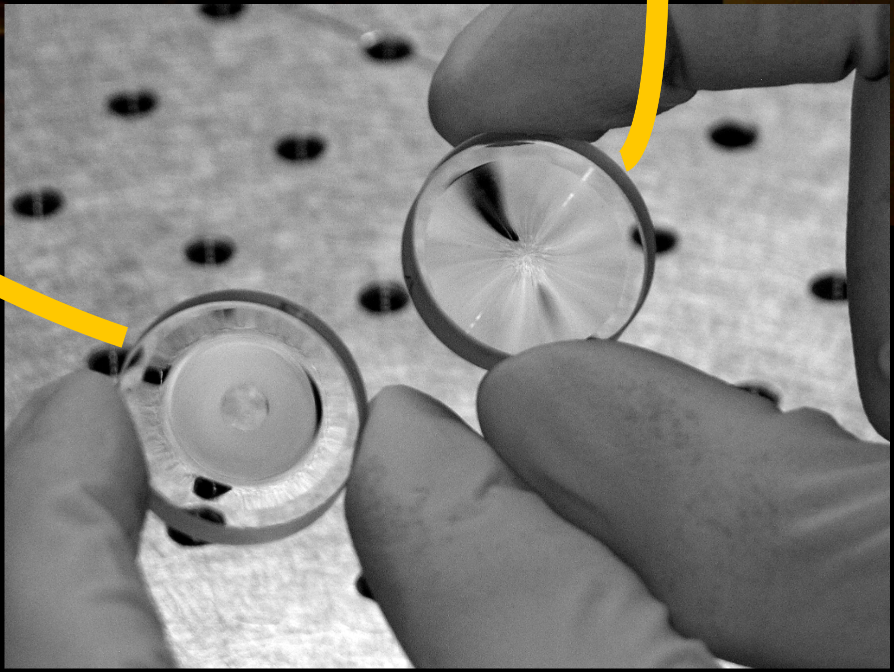
System architecture



Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera

3rd generation PIAA optics

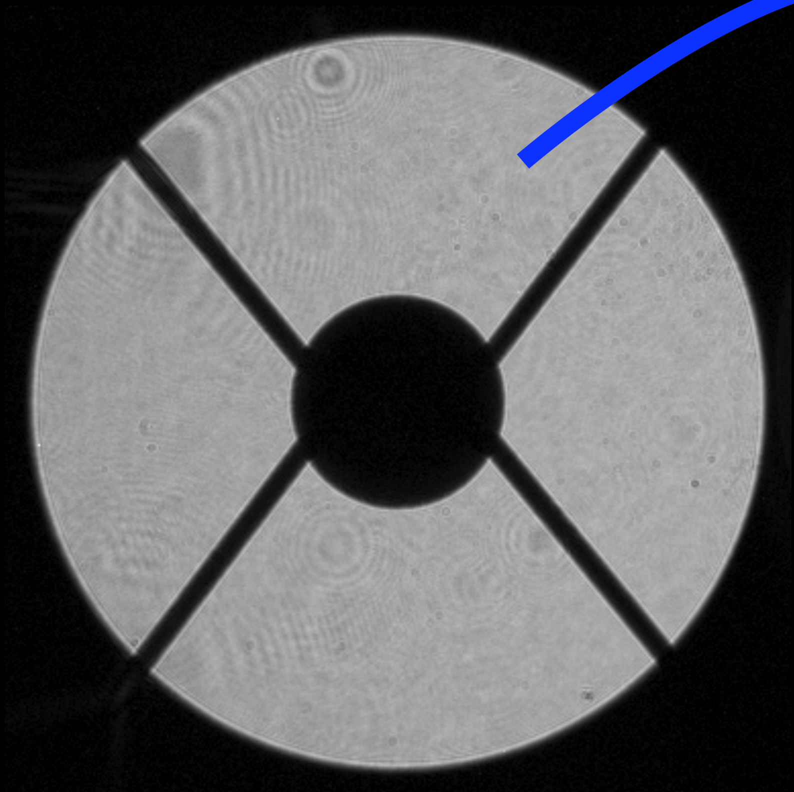


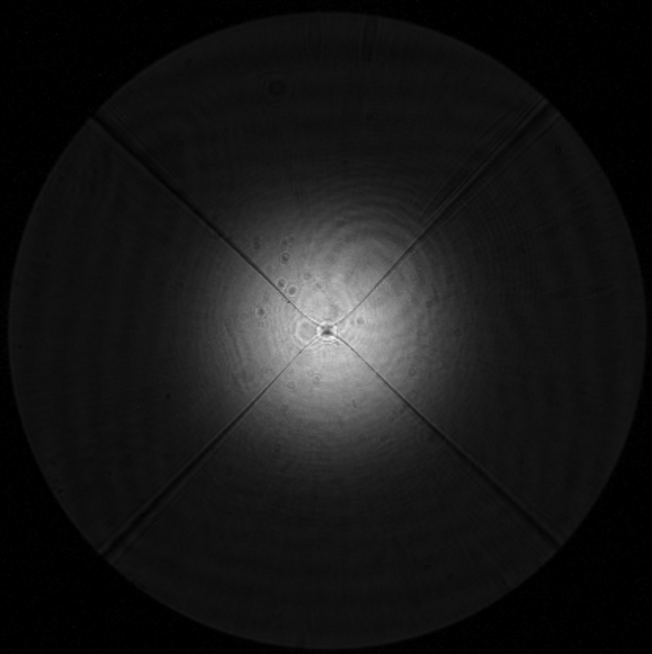


- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Optics tested, and good to go!

Subaru pupil apodization





(Lab. images)

Coherent detection works in the lab alongside FPAO

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