Pupil mapping Exoplanet Coronagraph Observer (PECO)

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PECO team

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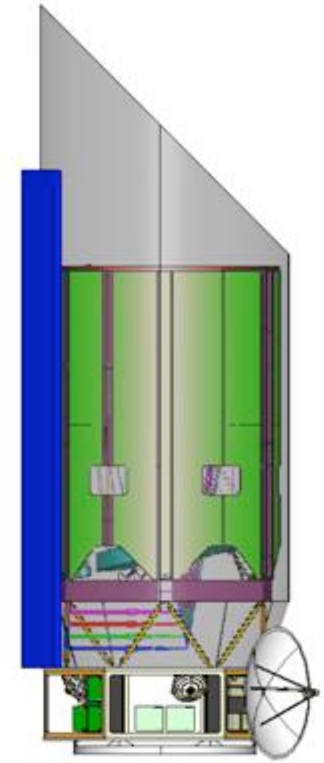
PECO overview

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

Characterization of planets and dust in habitable zone



- 1.4m diameter off-axis telescope (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
- Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin

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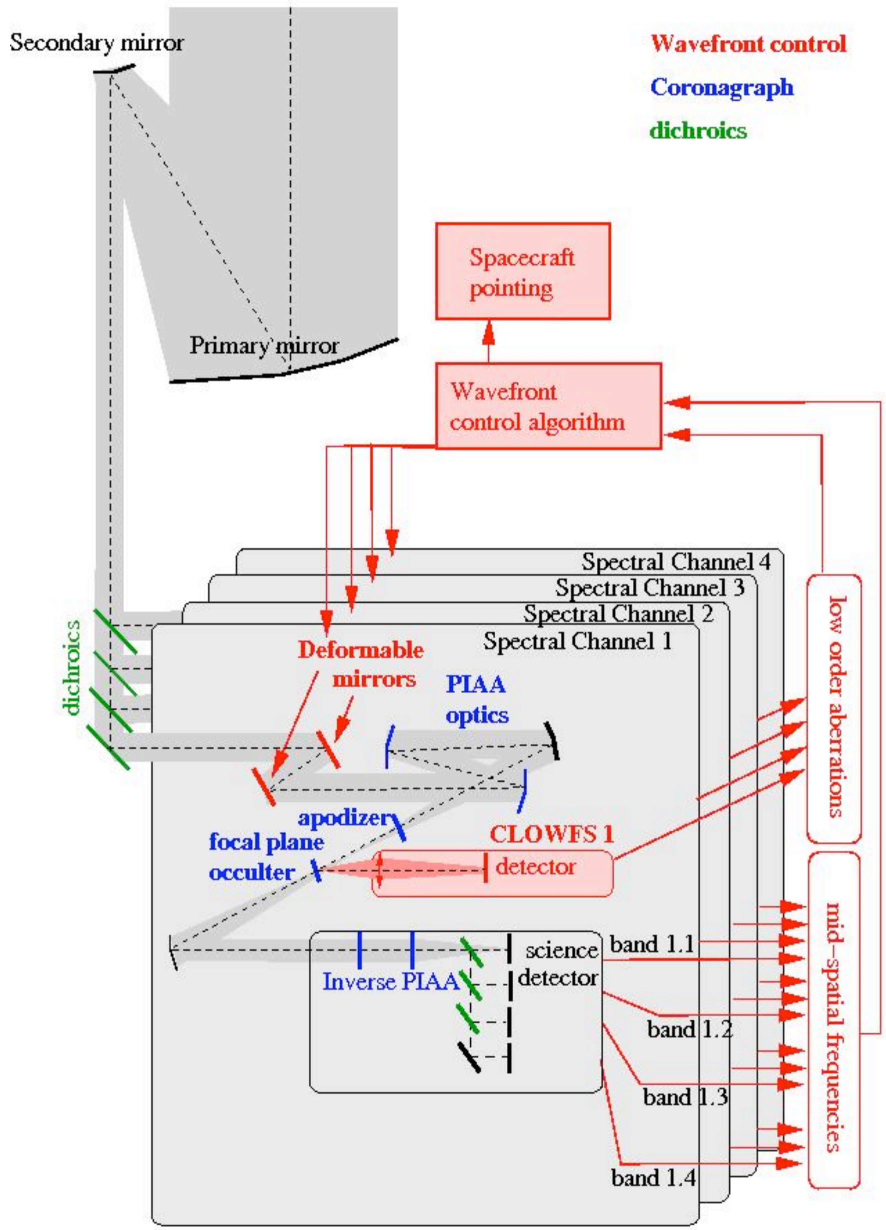
PECO approaches theoretically optimum coronagraph performance



High performance PIAA coronagraph

- IWA = 2 λ/D
- 90% coronagraph throughput
- No loss in telescope angular resolution: max sensitivity in background-limited case
- Full 360 deg field probed

Simultaneous acquisition of all photons from 0.4 to 0.9 μm in 16 spectral bands, 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

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

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

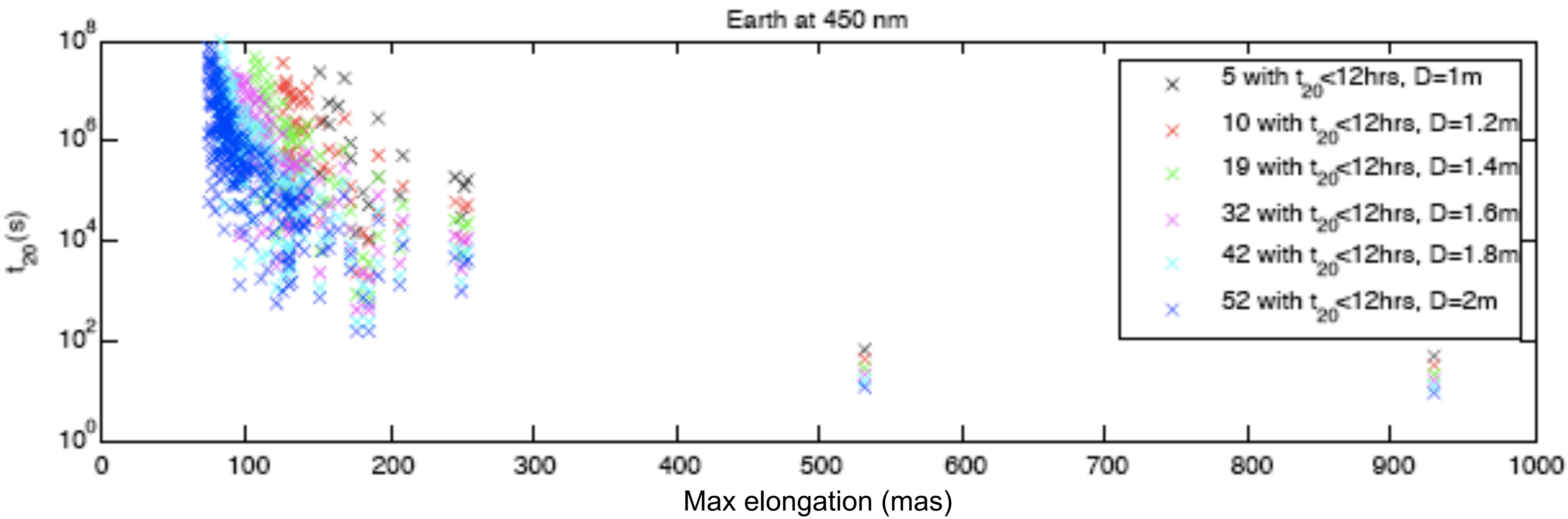
- **Conduct a "Grand Tour" of 10 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.**
  - Multiple (~10 or more) visits for detection
  - Characterization for ~5 days each to get S/N = 20-30 with ability to measure spectral features
  - exozodi distribution measurement
  - compile with other measurements (RV, Astrometry, ground imaging)
- **Study known RV planets, observing them at maximum elongation**
  - Detect at least 12 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

Telescope D(m)	# Earths, 450 nm	# Earths, 672 nm
1.0	5	2
1.2	10	5
1.4	19	8
1.6	32	14
1.8	42	20
2.0	52	30

- 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 detection in < 5 attempts of < 12 hr integration
- IWA of 2 lambda/D

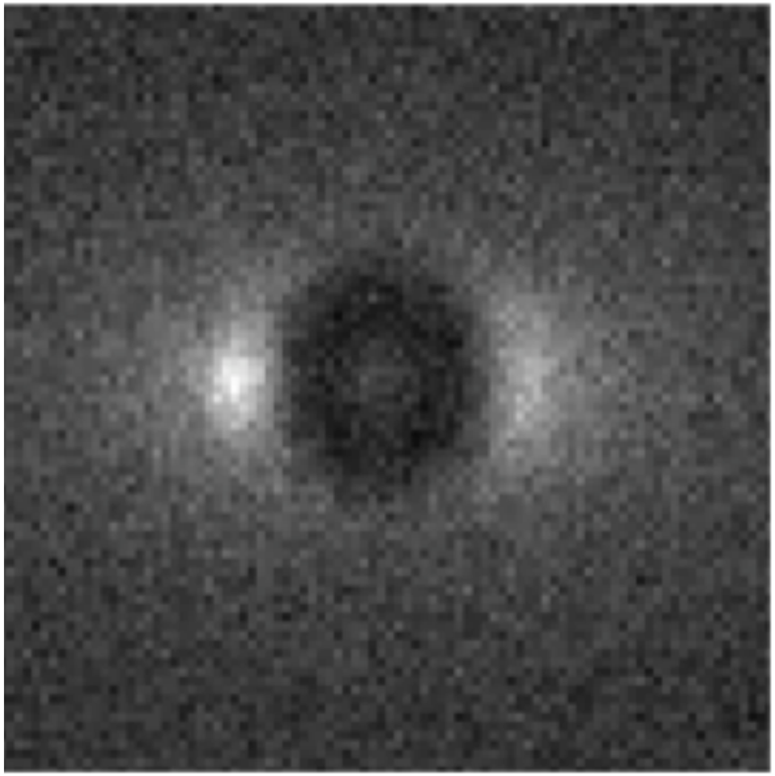
Earths still detectable at shorter wavelengths and smaller D



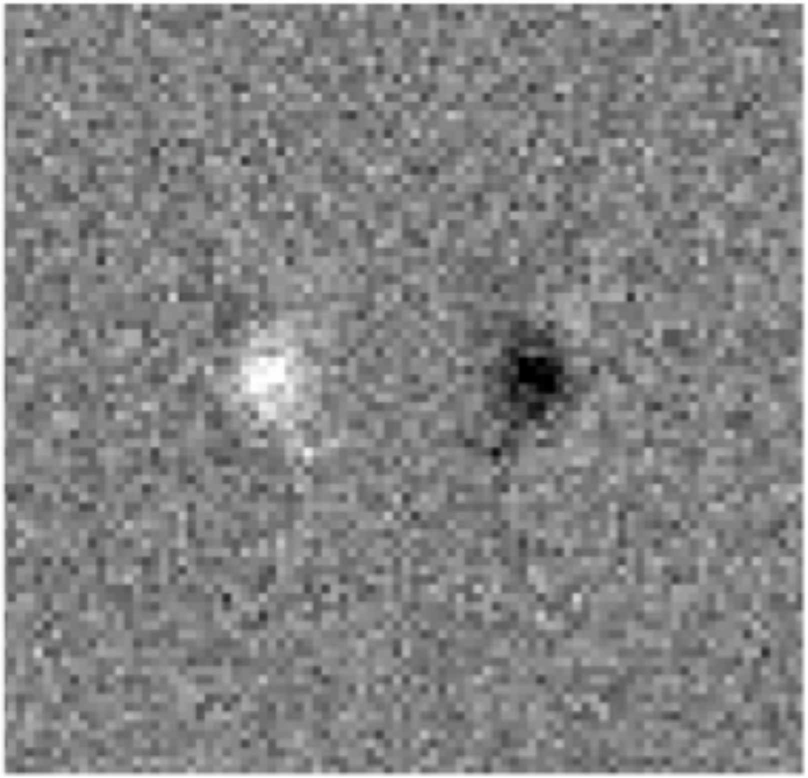
PECO **P**upil mapping **E**xoplanet **C**oronagraph **O**bserver

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.

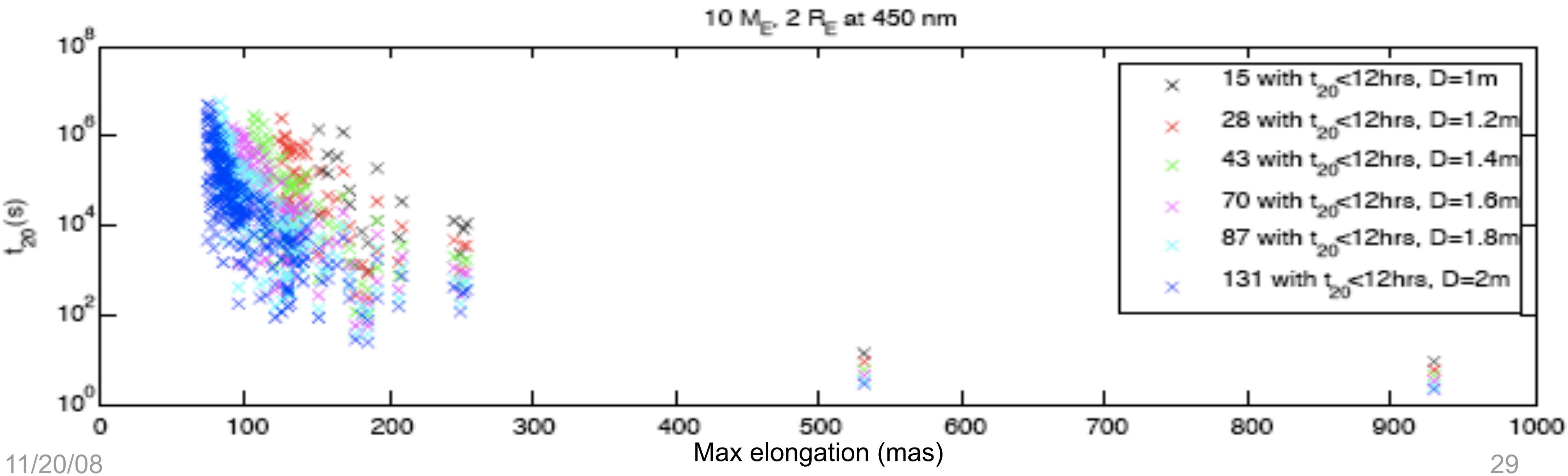
PECO can easily detect Super-Earths

Telescope D (m)	# S-Earths, 450 nm	# S-Earths, 672 nm
1.0	15	5
1.2	28	13
1.4	43	20
1.6	70	33
1.8	87	44
2.0	131	61

Can see more targets at shorter wavelengths and larger diameters

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 detection in <= 5 attempts of < 12 hr integration
- IWA of 2 lambda/D



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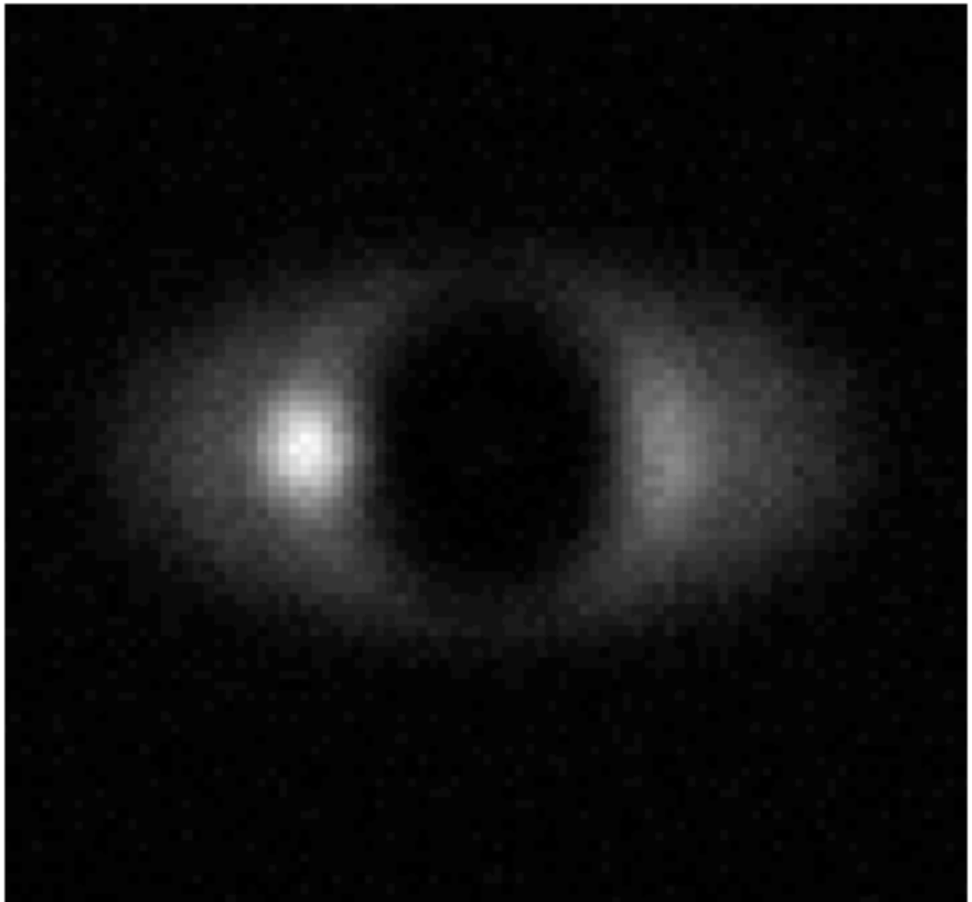
PECO easily observes Jupiters



Simulated PECO observation of 47 Uma b

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.

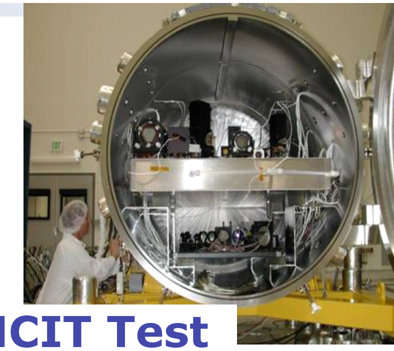
PECO telescope size

- **PECO cost driven mostly by telescope size, not by instrument**
  - 1.4 m telescope diameter chosen to fit within medium class mission ($600M to $800M)
- **PECO science as a function of telescope diameter**
  - Larger diameter allows increased number of targets and better SNR for the easiest targets
  - At 1.4m, PECO would statistically image at least one Earth is Eta_Earth>~0.1.
  - With larger telescope, spectroscopy can be extended to the red channels for more exoplanets
- **No major change in technology up to 3-4m primary mirror diameter**
  - Instrument design would be identical, with a possible increase of spectral channels to take advantage of higher SNR
  - Wavefront stability and accuracy requirements would be same as 1.4 m PECO

PECO 1.4 m PM size driven to fit within medium class mission cost, and is not limited by technical capability

PECO top 5 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
- **Thermal-Structural-Optical modeling**
  - Needed for final system verification
  - HCIT will validate optical models
  - SIM TOM testbed demonstrated thermo-structural
- **Photon-counting EMCCD Detectors**



JPL HCIT Test Facility

Xinetics 64x64 DM

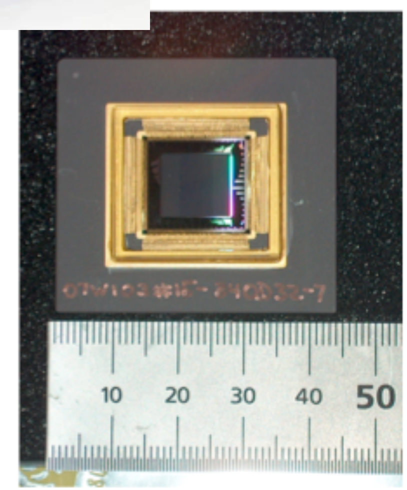
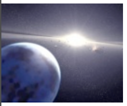


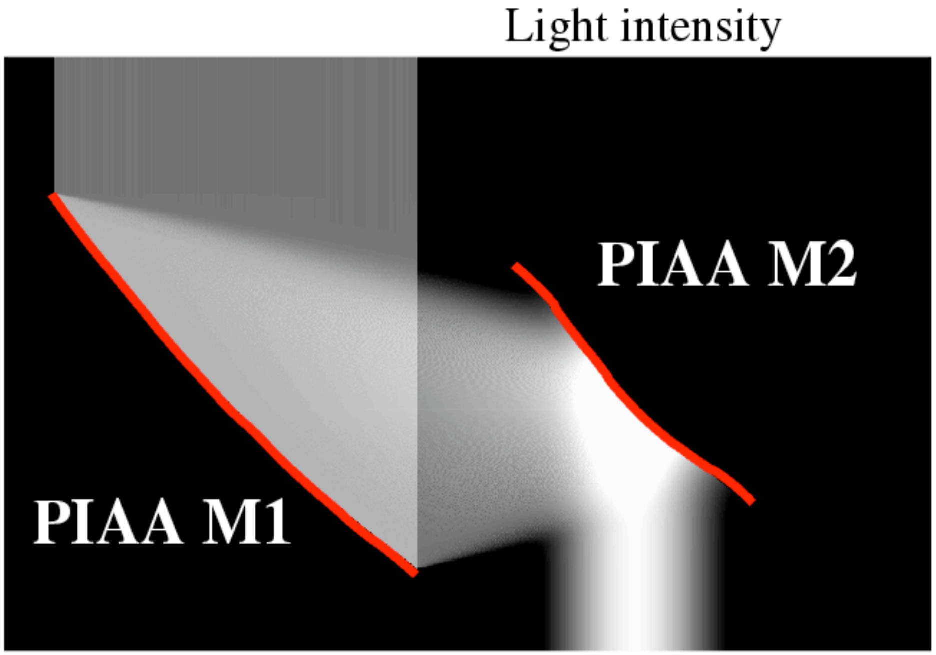
Figure 1: 1024 actuator (32x32) MEMs DM commercially available from Boston Micromachines (mm scale).

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



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

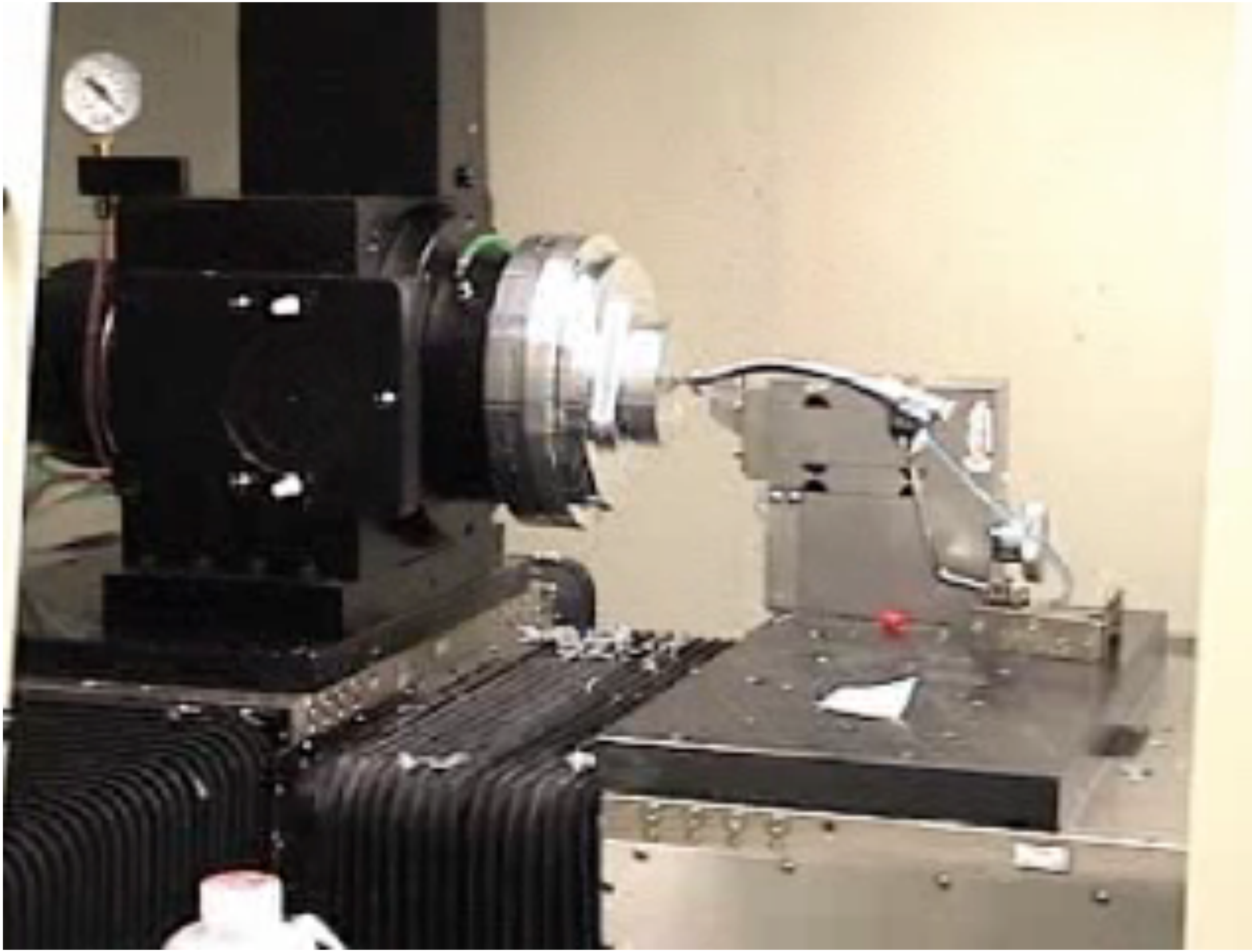
- high contrast
- Nearly 100% throughput
- IWA ~2 l/d
- 100% search area
- no loss in angular resol.
- achromatic (with mirrors)



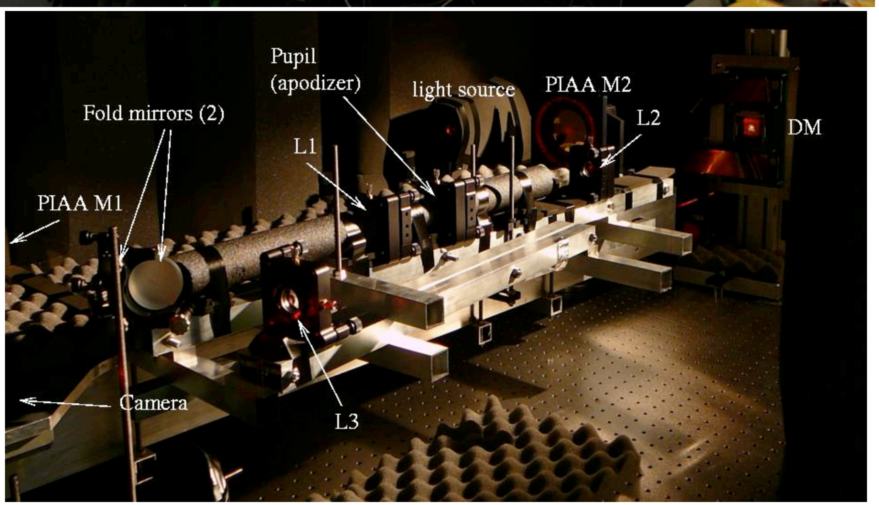
Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

More info on :
www.naoj.org/PIAA/

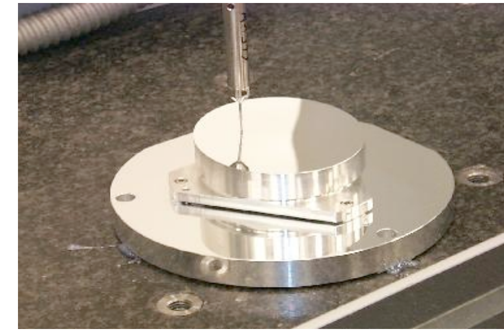
PIAA optics - Diamond turn @ Axsys, may 2005



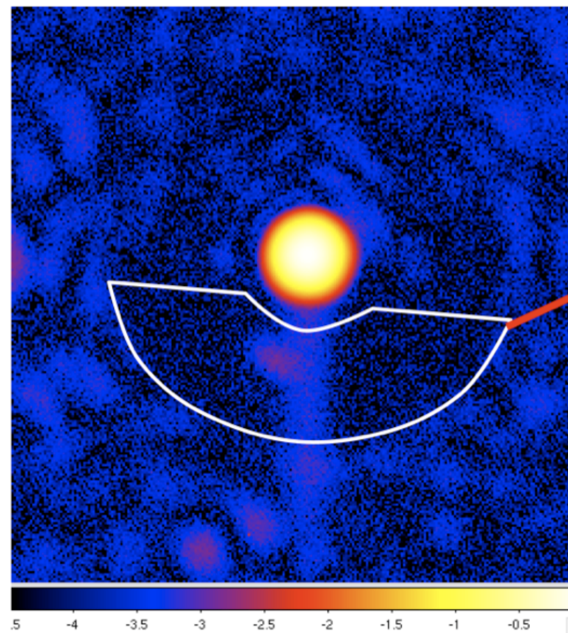
PIAA testbed at Subaru Telescope



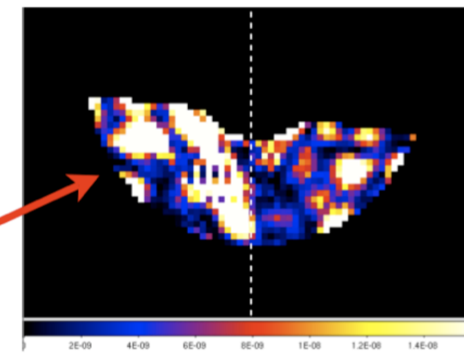
Temperature-stabilized monochromatic testbed in air
Uses 32x32 actuator MEMs
Uses 1st generation PIAA mirrors, diamond turned Al



Raw image



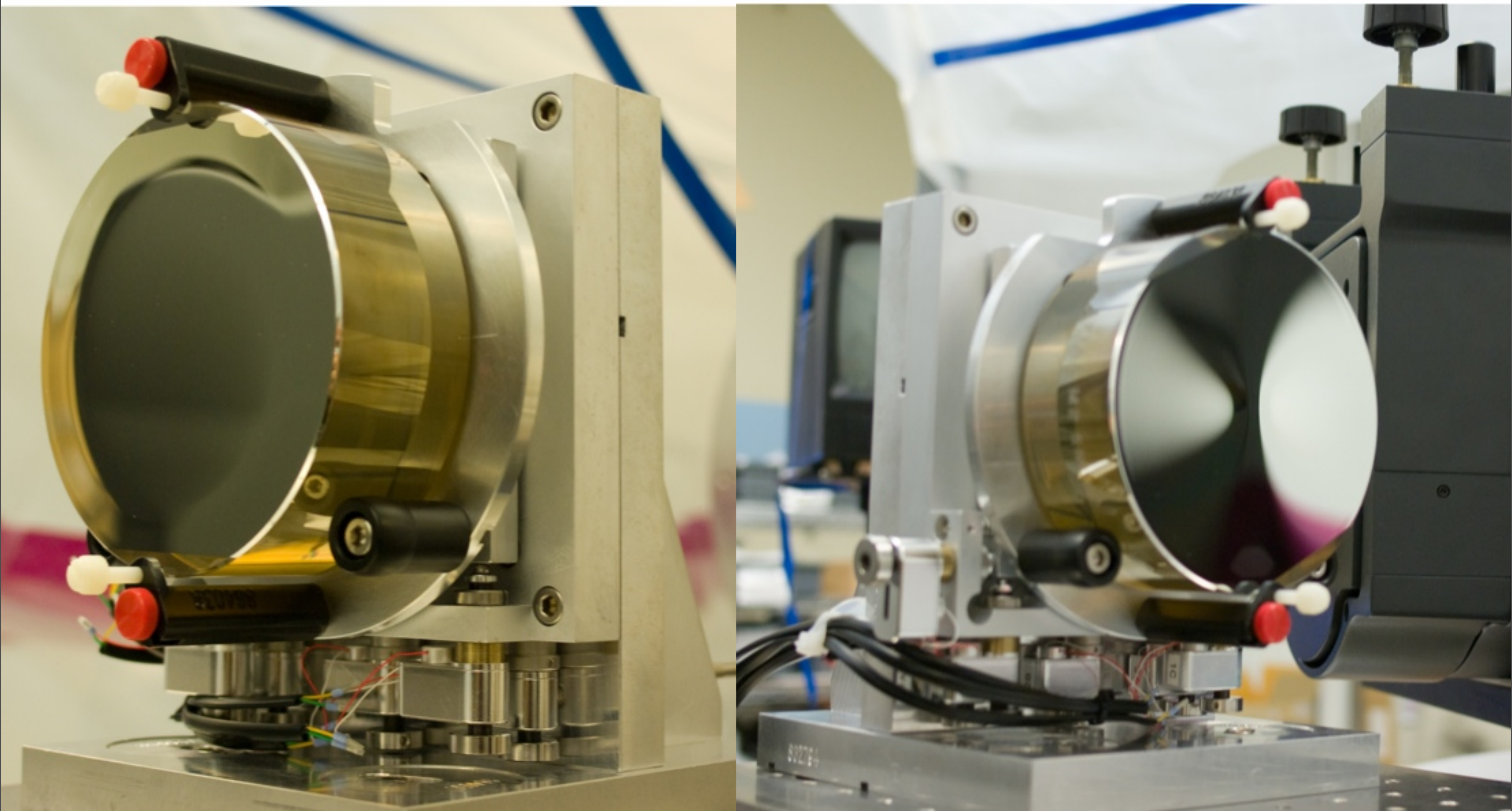
Coherent starlight



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

Contrast achieved in 2 to 5 l/D zone:
1.5e-7 incoherent halo ghost (equivalent to exozodi)
7e-9 coherent starlight speckles (turbulence, vibrations)

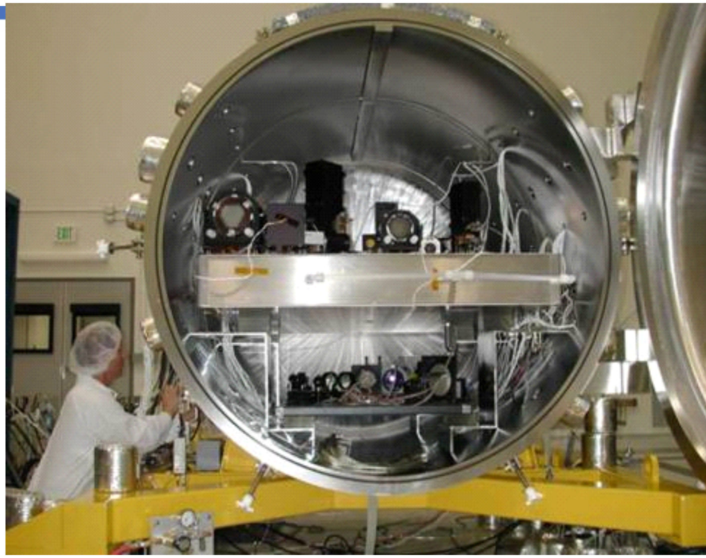
High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)



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

PECO

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



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

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

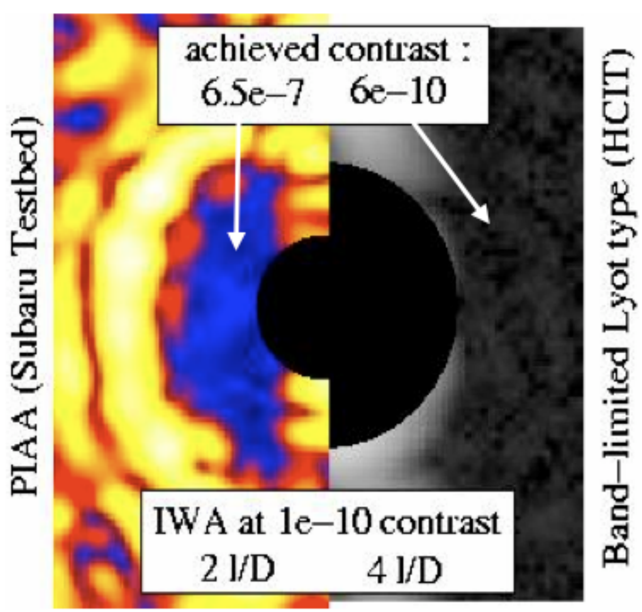
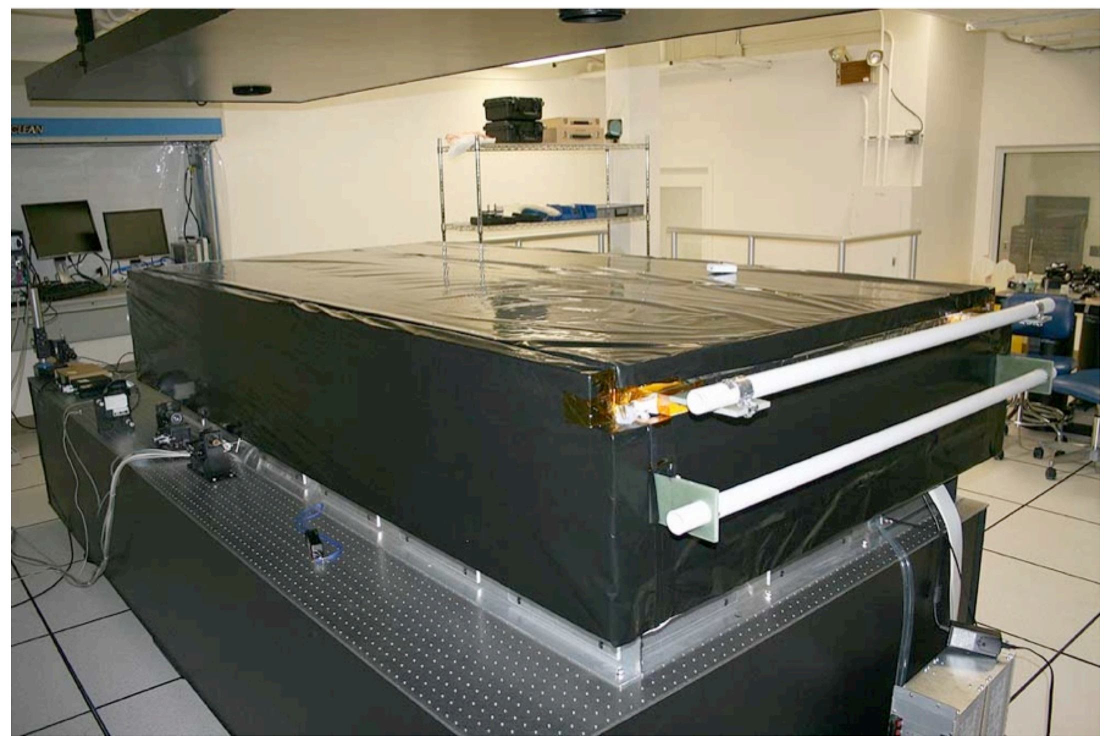


Figure 1.3-2 Comparison between the IWA of a PIAA coronagraph and a Lyot-type band limited coronagraph. Actual laboratory PSFs are shown at the same scale. The high sensitivity regions are in blue (PIAA) and black (band limited)



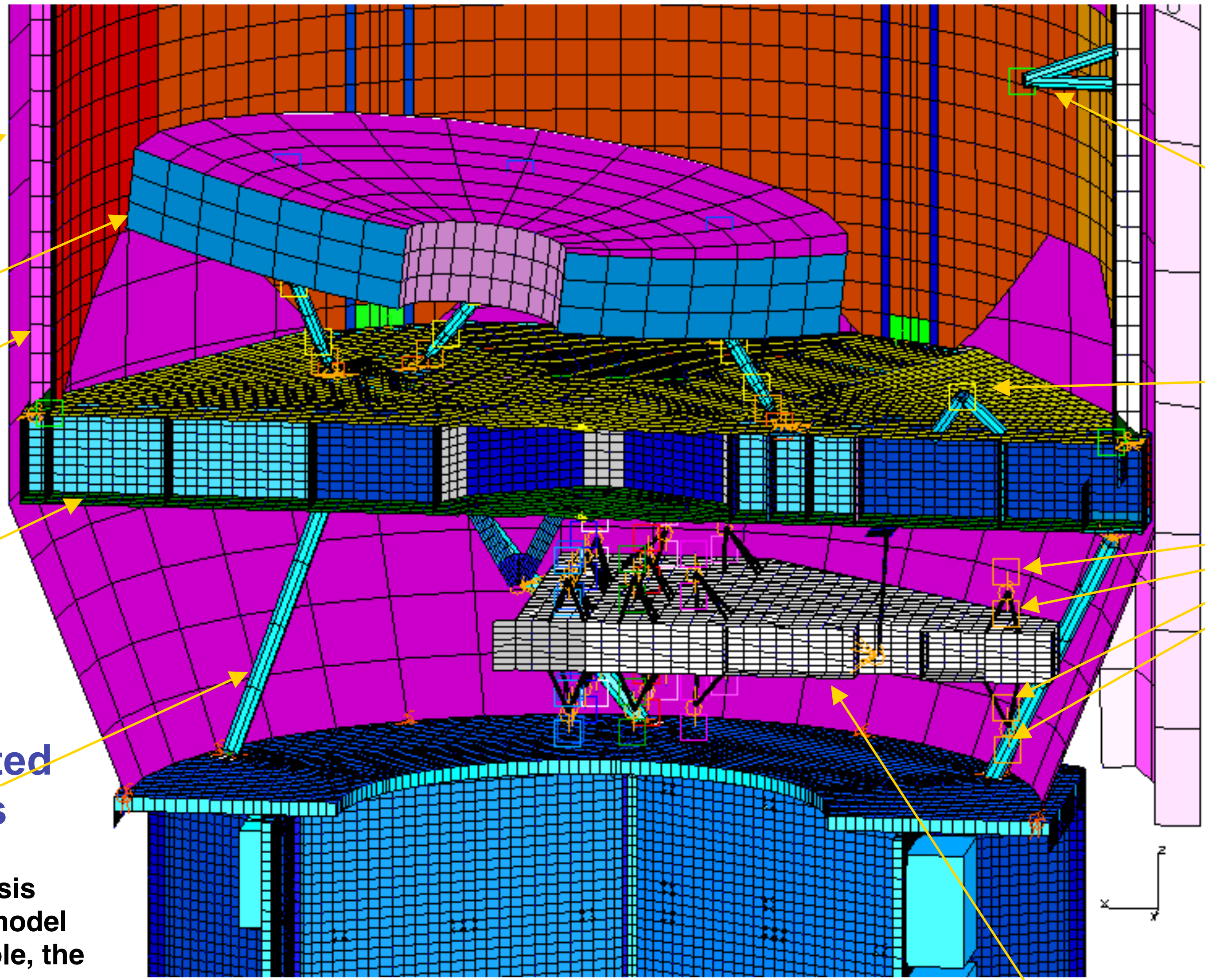
PIAA system scheduled to be on-sky in Dec 2009 at Subaru Telescope

PECO wavefront sensing requirements

- **Pointing stability**
  - Affects performance by:
    - Coronagraph leak from tip/tilt
    - Beam walk across optics
  - Pointing jitter ~1 milliarcseconds (mas) RMS
  - 5 minute RMS pointing drift should stay < ~0.5 mas
- **Dynamic and thermal disturbances**
  - Affect low-order aberrations & mid spatial frequencies
  - Need to be stable to ~0.1 angstroms 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

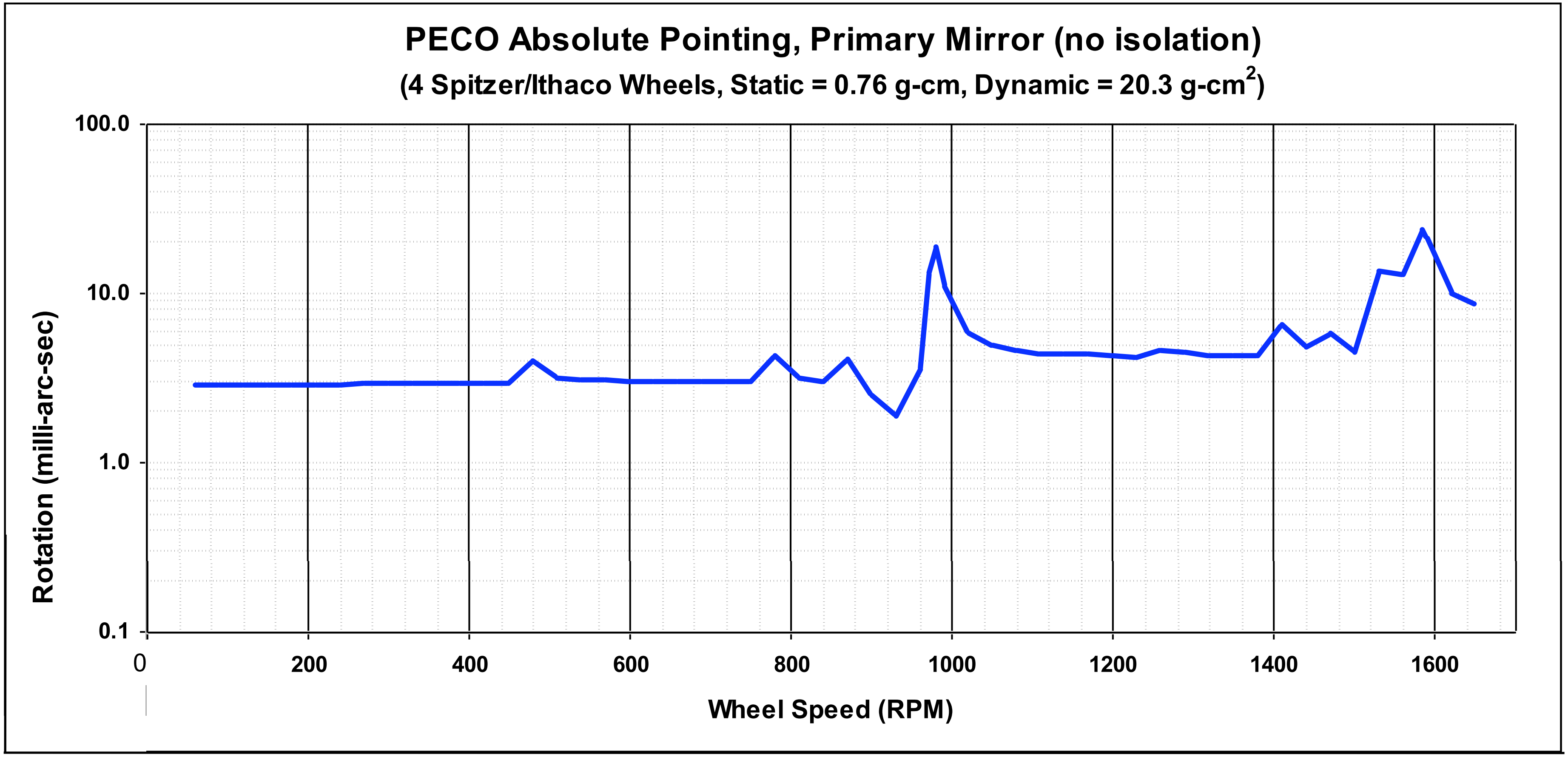
Detailed Finite Element Model for precision analyses—180 deg section (–Y half)

Detailed FEM for precision analysis (105,075 elements, 83,151 grids)



Please Note: this analysis leveraged an existing model that had a PM with a hole, the PECO PM does not have a center-hole. However, to first order, these results are still valid

Jitter analysis shows reqs can be met passively with existing technology



- Jitter requirement is ~1 mas
- Analysis performed on Ithaco wheels hard-mounted (without any isolation)
- Req should be met with passive isolation only
  - Note, can be 6 times better using fine-balanced Dynacon Microwheels
  - Future analysis will include passive isolation and verify that PECO jitter requirement is met

Low frequency pointing errors (~<100 Hz) will be accurately measured by PECO's low order wavefront sensor (LOWFS) to sub-mas level (see next slide).

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Pointing control demonstrated to 1e-3 l/D (~ 0.1 mas on PECO) at Subaru PIAA testbed

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

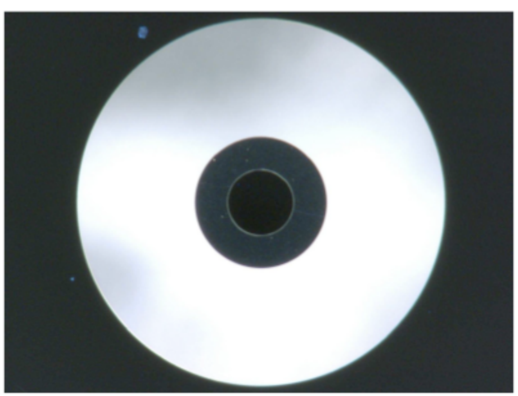


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

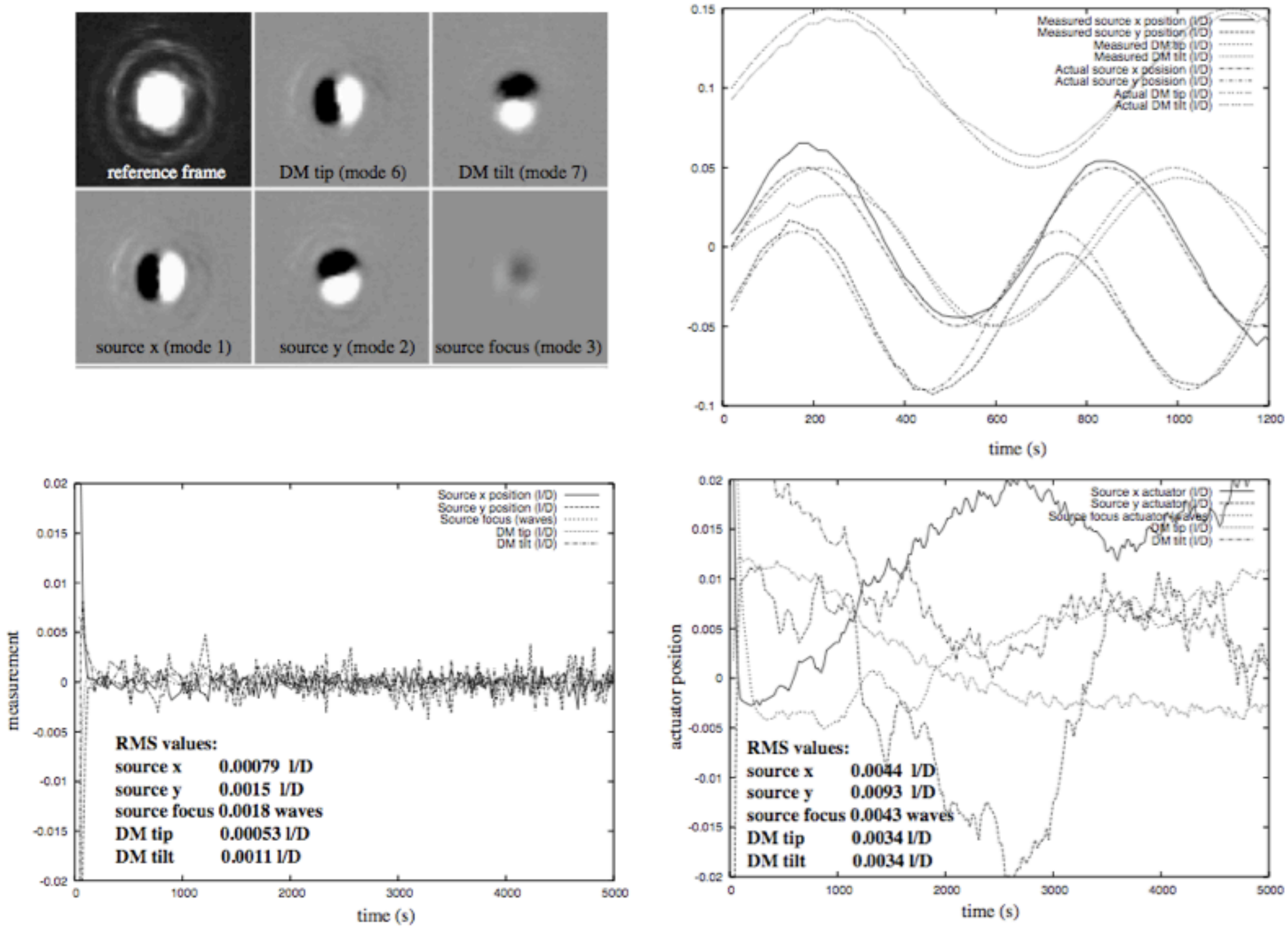


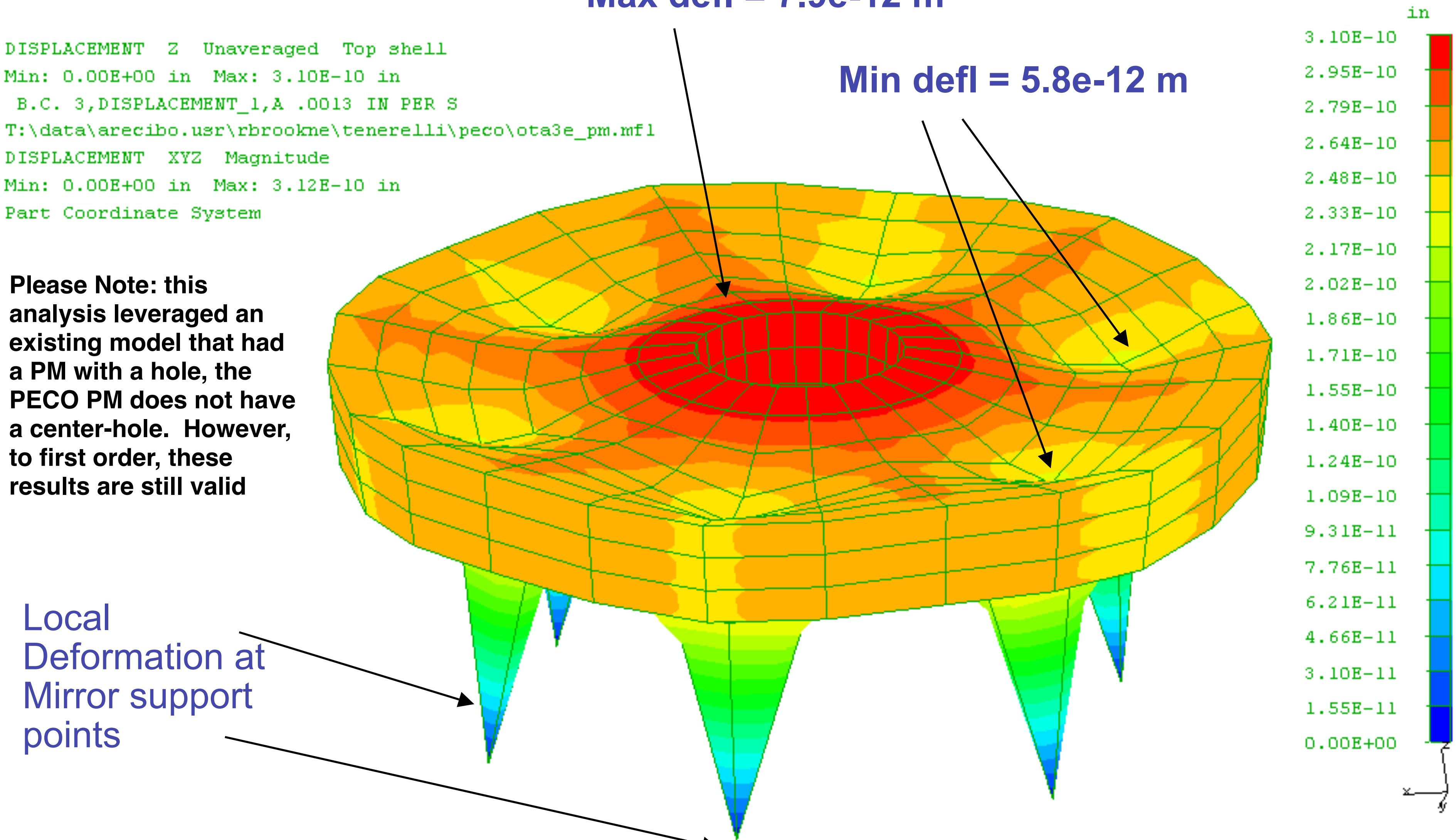
Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes.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

Primary mirror reaction wheel resp meets req's

M Distortion at 600 RPM (static analysis)
(PECO axial accel = .000033 m/s^2)

Max defl = 7.9e-12 m

Min defl = 5.8e-12 m



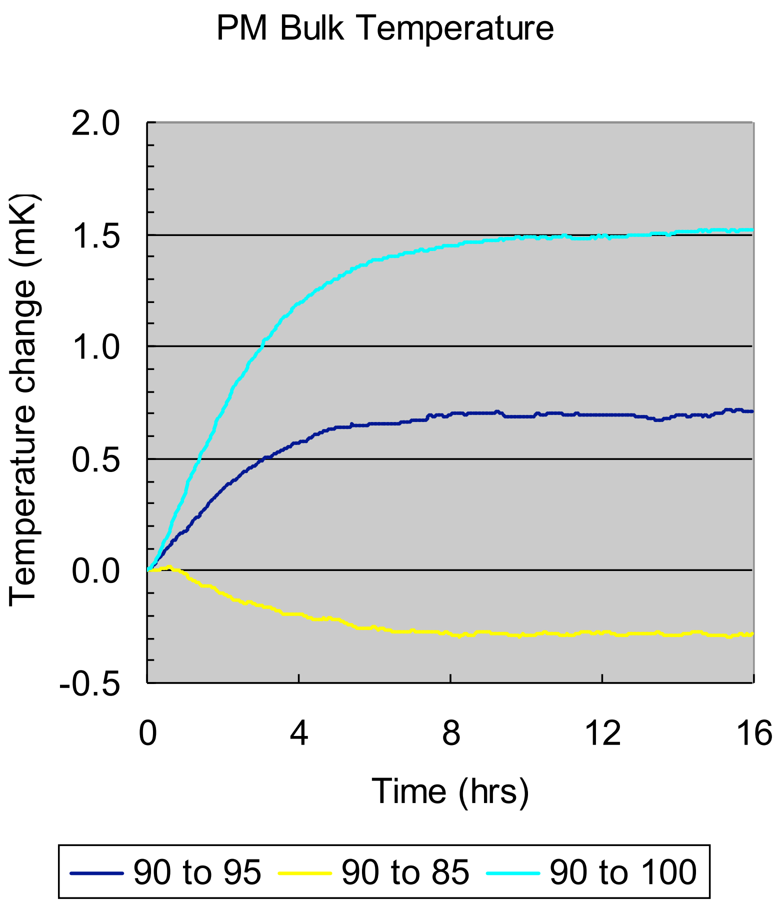
Please Note: this analysis leveraged an existing model that had a PM with a hole, the PECO PM does not have a center-hole. However, to first order, these results are still valid

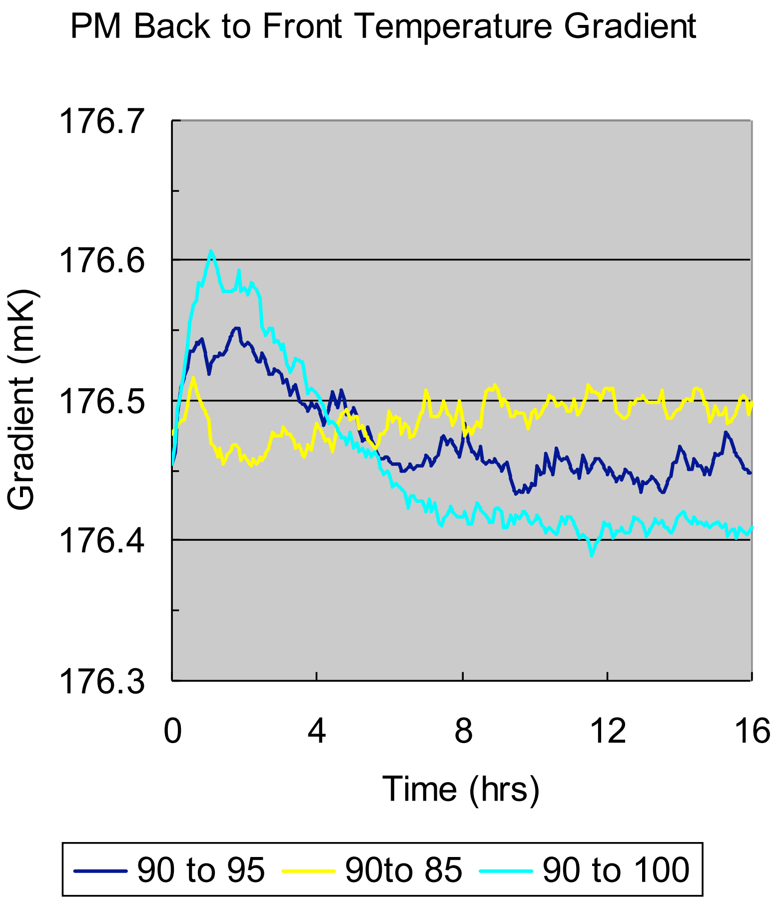
Local Deformation at Mirror support points

- Without isolation; better results possible with passive isolation
- Max surface distortion is 8 picometers

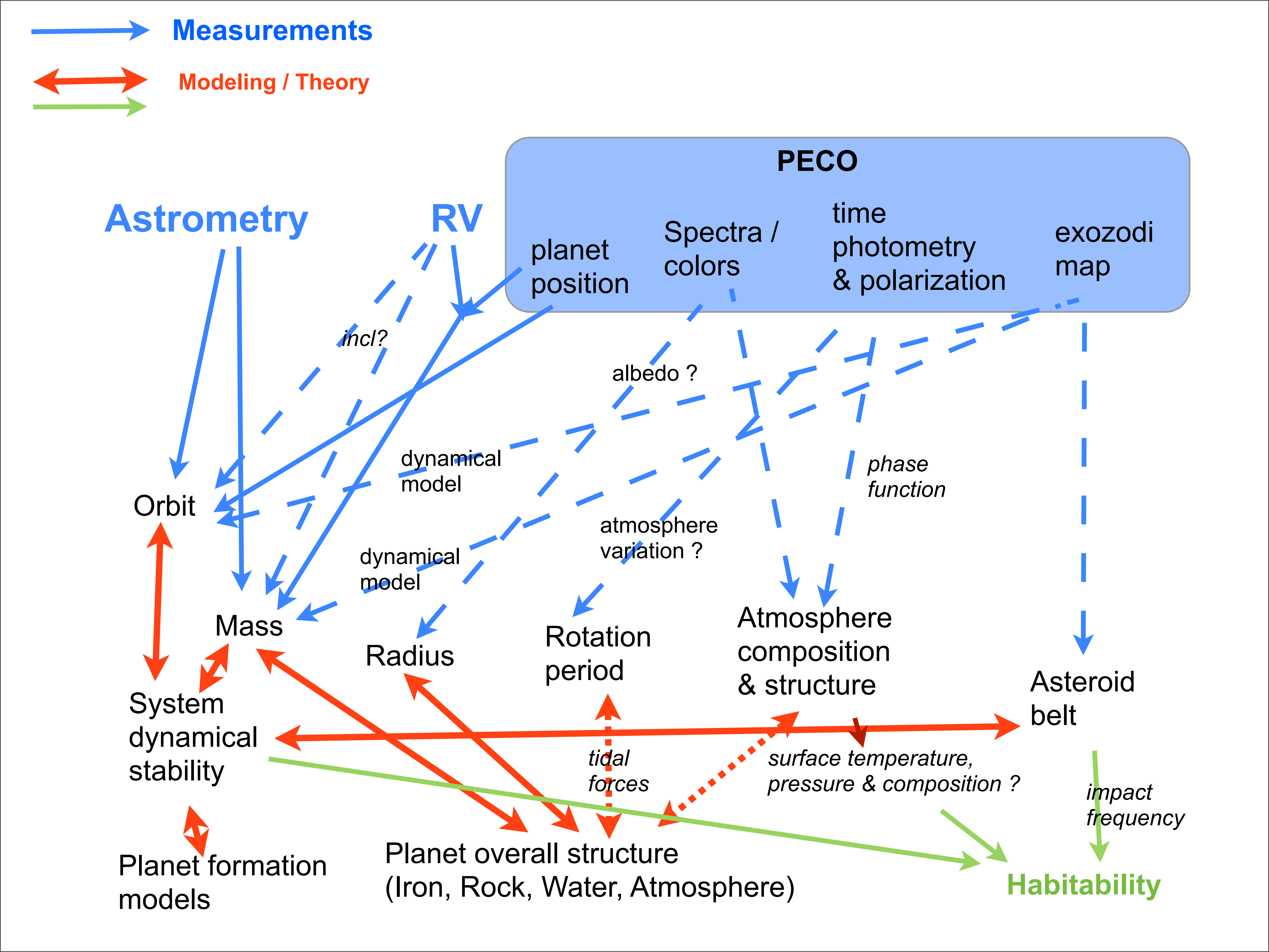
Thermal stability exceeds PECO requirement ~6—8 hours after slew

Slew analysis completed for 90 to 95, 90 to 85 and 90 to 100 degrees





Temperatures During Slews


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

Summary

- PECO can simultaneously do detection and characterization of exoplanets with no penalty in exposure time
- PECO will provide uniquely sensitive measurements of exozodi in the habitable zone, down to less than 1 zodi sensitivity
- PECO study shows **direct imaging and characterization of Earths/ Super-Earths possible with medium-scale mission** IF:
  - very high performance coronagraph (small IWA) with design which keeps ALL photons
  - observe in blue/visible
  - focus on a small number of targets ("grand tour") with many visits and long exposure time per target
- "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)**
- Earths are challenging (technical margins small, need high eta_Earth, zodi not brighter than ours), but Super-Earths easier
- Science is compelling, and would be enhanced if coupled with other measurements (RV, Astrometry)
- PECO architecture can be scaled to a flagship 3-4 m telescope without new technologies or new launch vehicles