Phase-Induced Amplitude Apodization (PIAA) coronagraphy: recent results and future prospects

Olivier Guyon (Subaru Telescope + University of Arizona)

With contributions from:

- *Subaru Telescope SCExAO group, NAOJ*
- *NASA JPL coronagraphy group*
- *NASA Ames ACE group*
- *Tinsley, Axsys*
- *Princeton coronagraphy group*

Related papers:

8151-01, 8151-02, 8151-03, 8151-04, 8151-08, 8151-13, 8151-25

Outline

PIAA concept(s)

- PIAA imager
- PIAA coronagraph
- PIAACMC hybrid

PIAA optics design and fabrication

Recent PIAA lab results (Subaru, JPL, Ames)

Current and future technology development

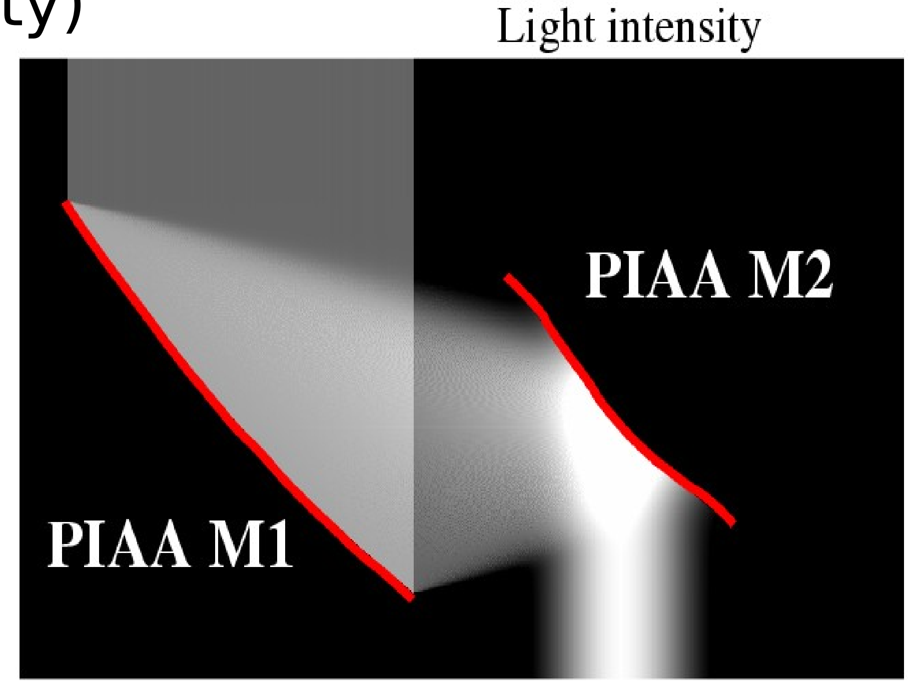
- Moderate contrast at 1 l/D (ground-based, EXCEDE)
- Higher contrast, wider spectral band (TPF, PECO)
- High contrast with PIAA in the 1 to 2 l/D range (TPF, PECO)

Ground-based PIAA activities: SCExAO

Phase-Induced Amplitude Apodization (PIAA) coronagraph

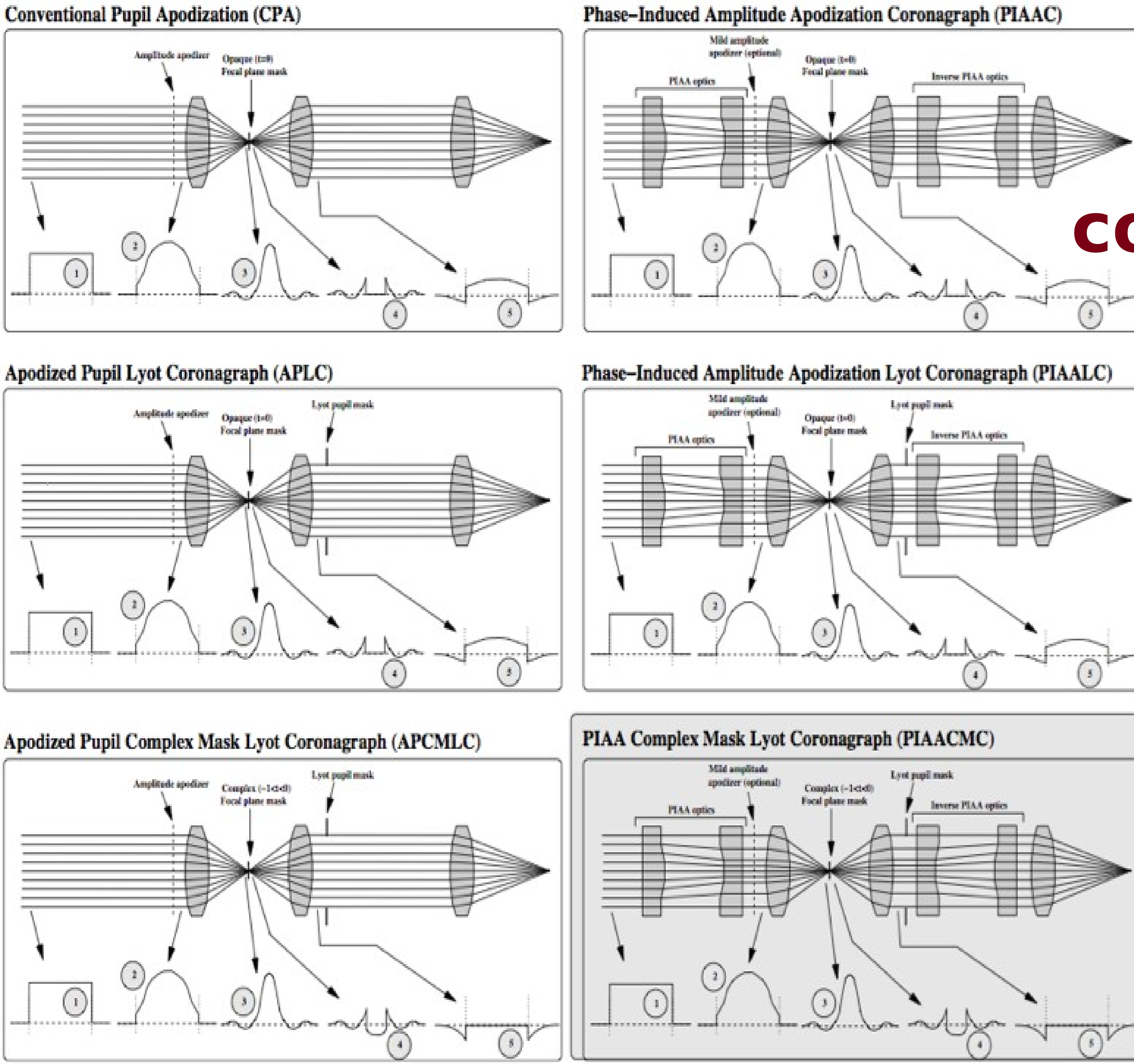
Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

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



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

PIAA concepts



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

Coronagraph performance

New coronagraphs now approach theoretical limit.

PIAA coronagraphs appear particularly attractive

1e10 contrast

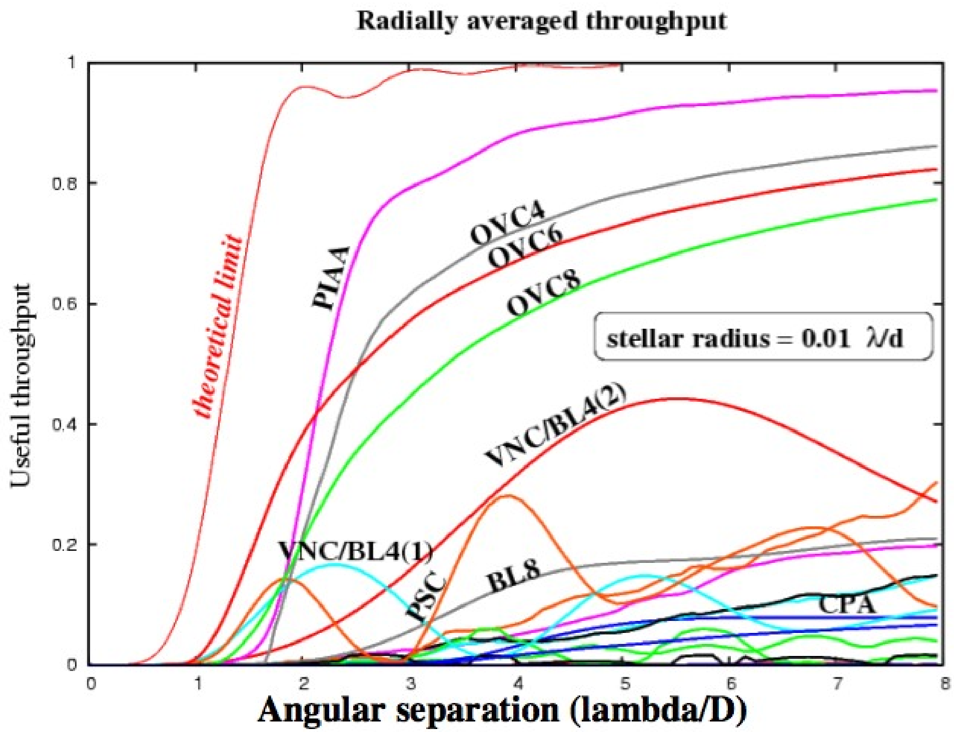
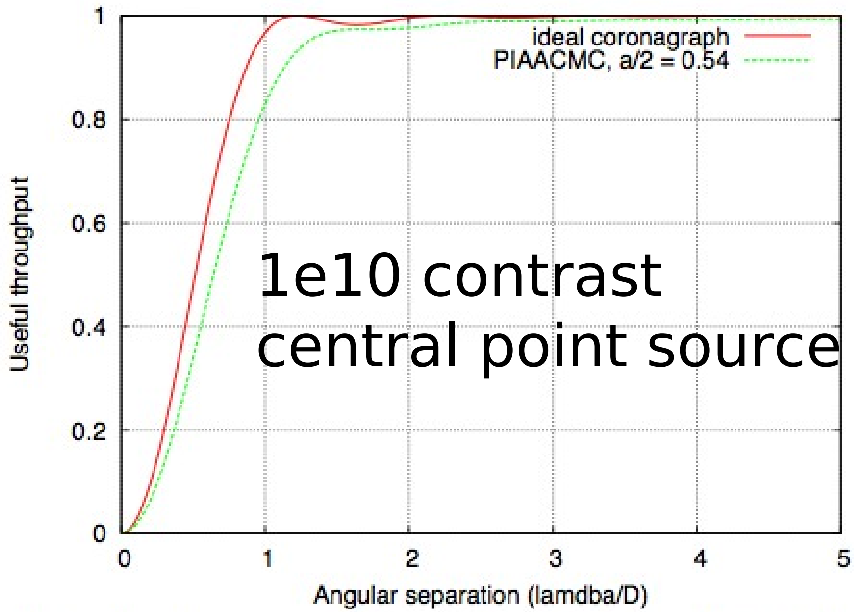


Figure 3-1: Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional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

PIAACMC (Guyon et al., 2010)

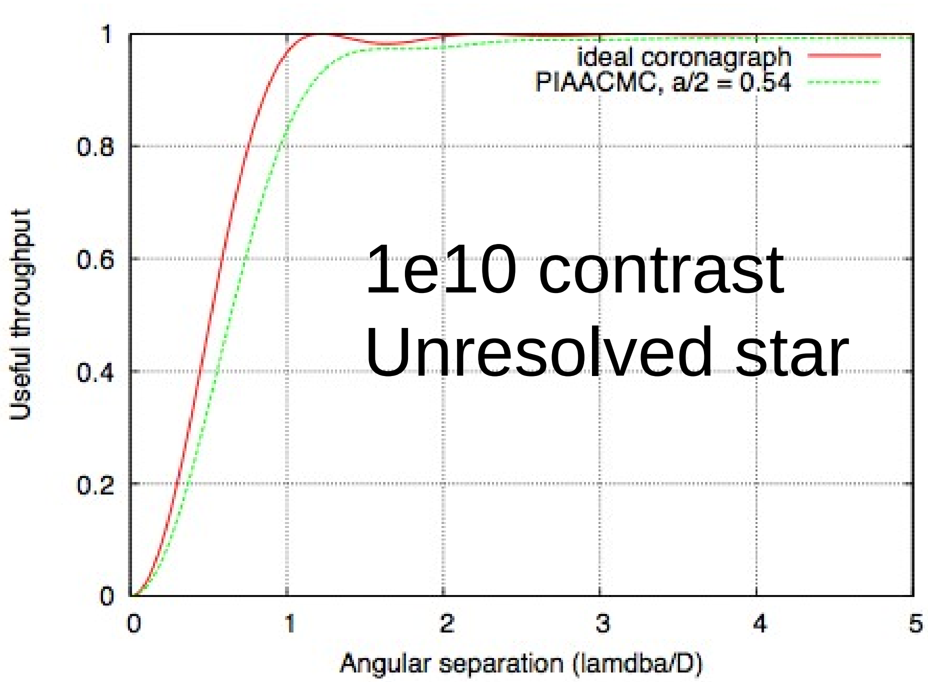


1e10 contrast
central point source

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

PIAACMC

- IWA for 1e10 contrast can be set anywhere from 0.64 λ/D to 2 λ/D, according to stellar angular size & contrast
- 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



PIAA optics design and fabrication

9 PIAA sets (18 optical elements) fabricated so far:

4 reflective PIAA sets have been made

- Diamond-turned Al set (x2), funded by NASA JPL
- Zerodur set, funded by NASA Ames (*)
- Low cost diamond turned set

5 refractive PIAA sets

- Plastic set for proof of concept (1st set made)
- CaF2 18mm beam sets (x2)
- CaF2 8mm beam sets (x2)

(*) meets 1e-9 incoherent light flight mission requirements for Earth-like planets imaging at 2 l/D in ~10% wide band

PIAA optics: system throughput, chromaticity

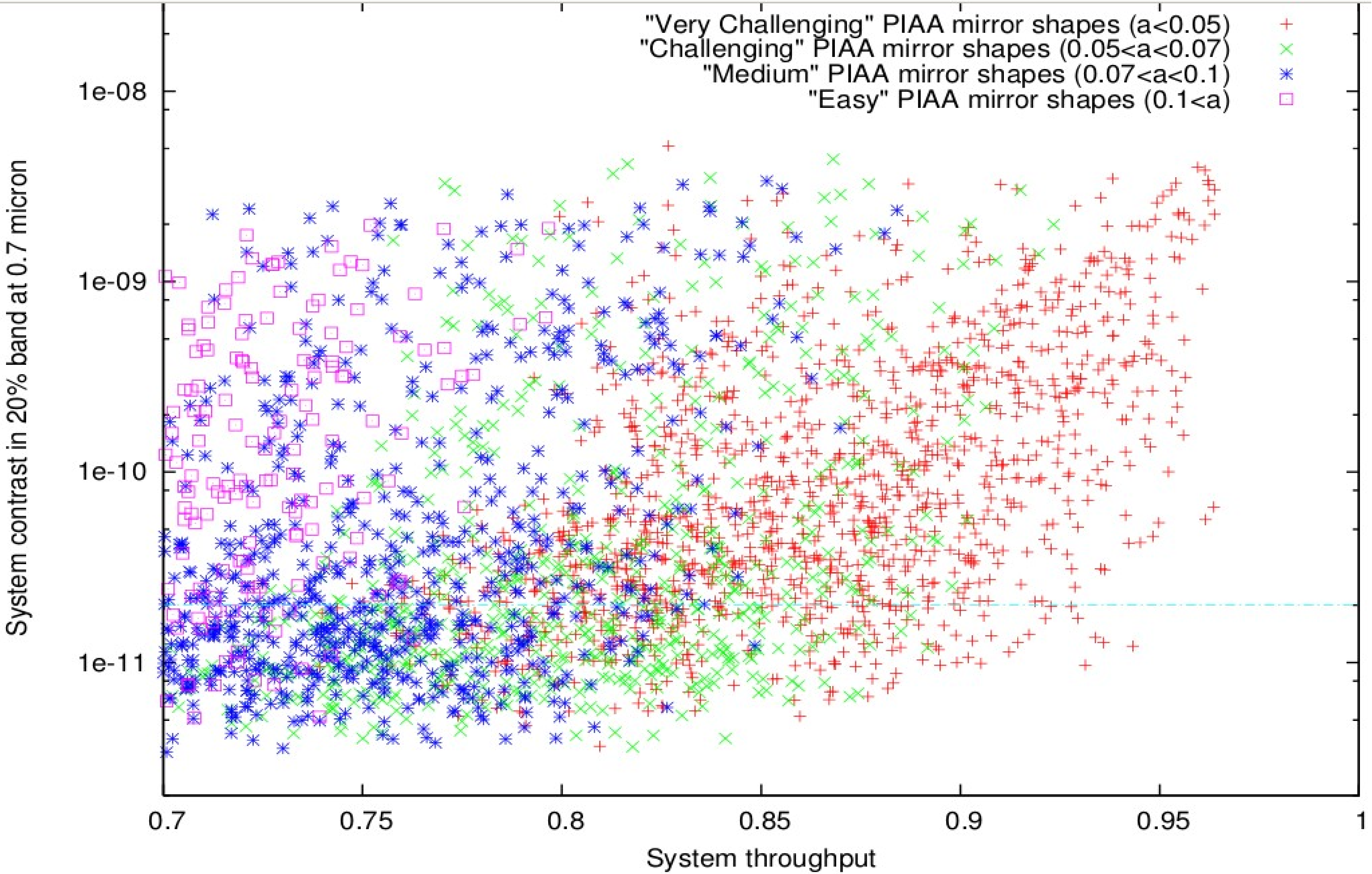
Optics are **highly aspheric**
Recent optics manufacturing progress (largely motivated by EUV lithography) allow manufacturing of high quality PIAA optics

PIAA optics **difficulty is mitigated by using conventional apodizer and design**
PIAA does most of the apodization, apodizer does the very edge (what is difficult for PIAA). Typical loss ~10% in conventional apodizer
PIAACMC: no need for apodizer, optics easier to manufacture

PIAA optics **need to be designed to support polychromatic work**

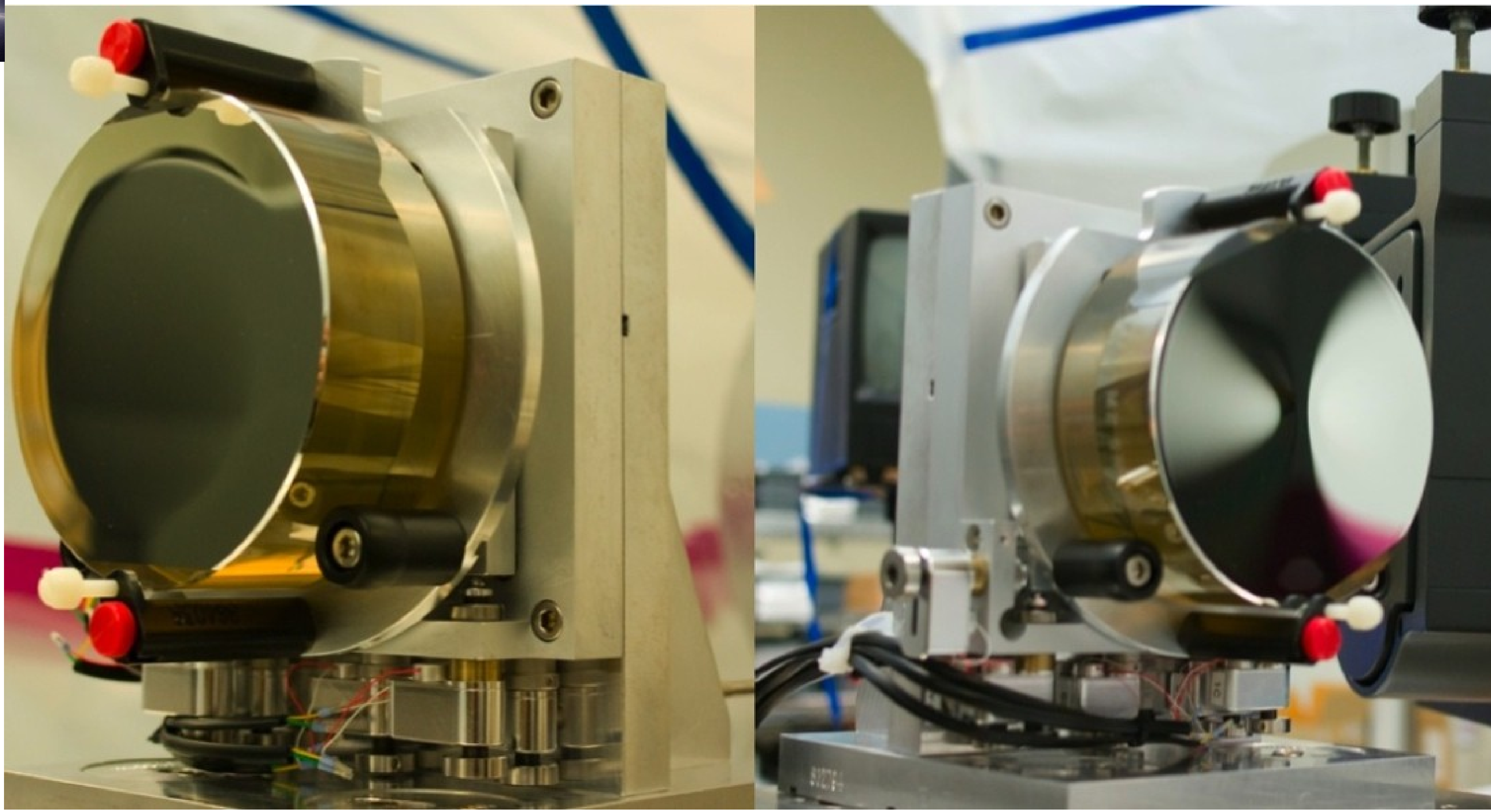
1st generation reflective optics (diamond turned Al)

PIAA optics design



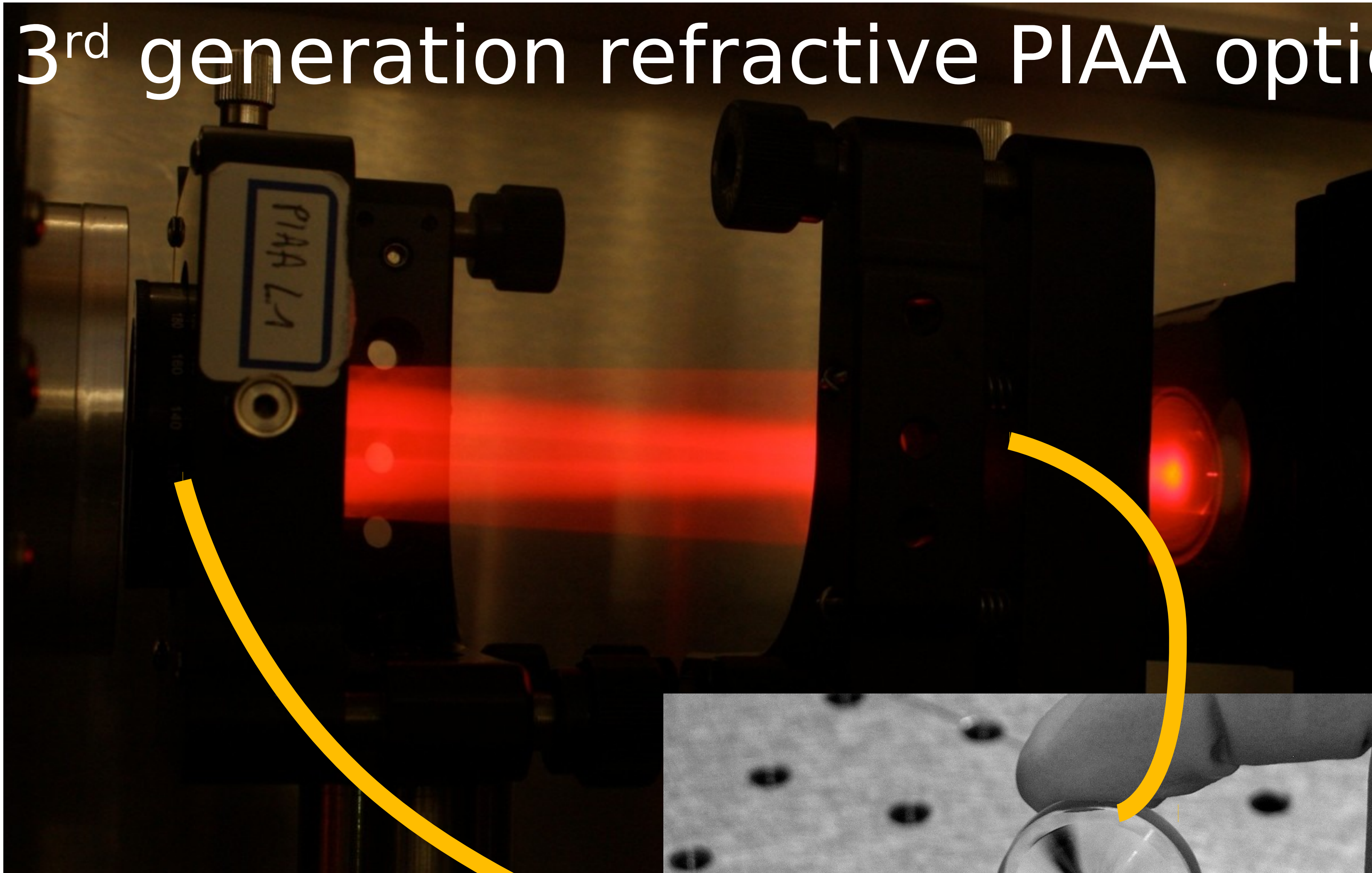
High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)

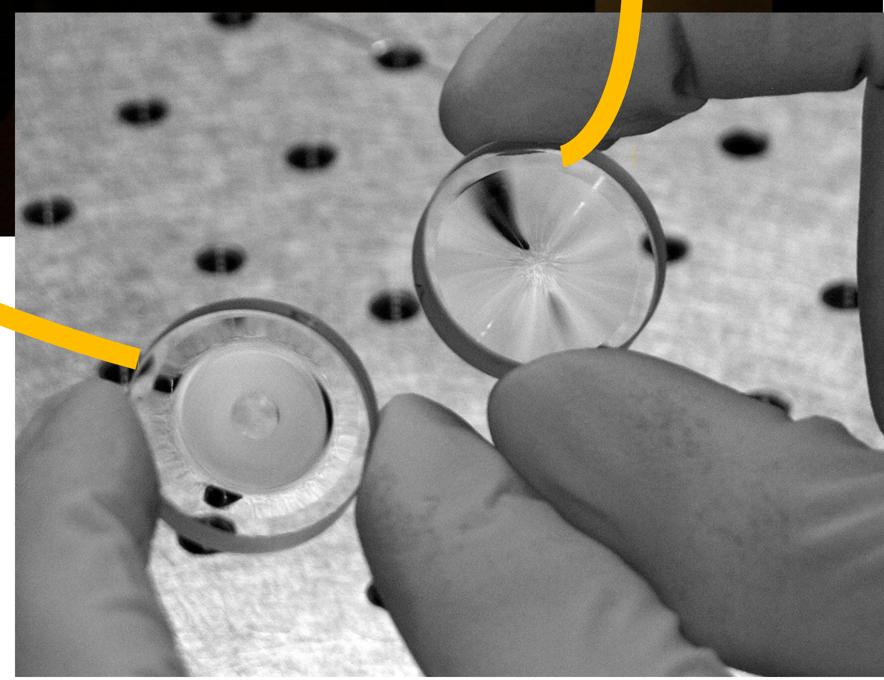
PECO Pupil mapping Exoplanet Coronagraph Observer



2nd generation PIAA optics manufacturing by Tinsley

3rd generation refractive PIAA optic





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

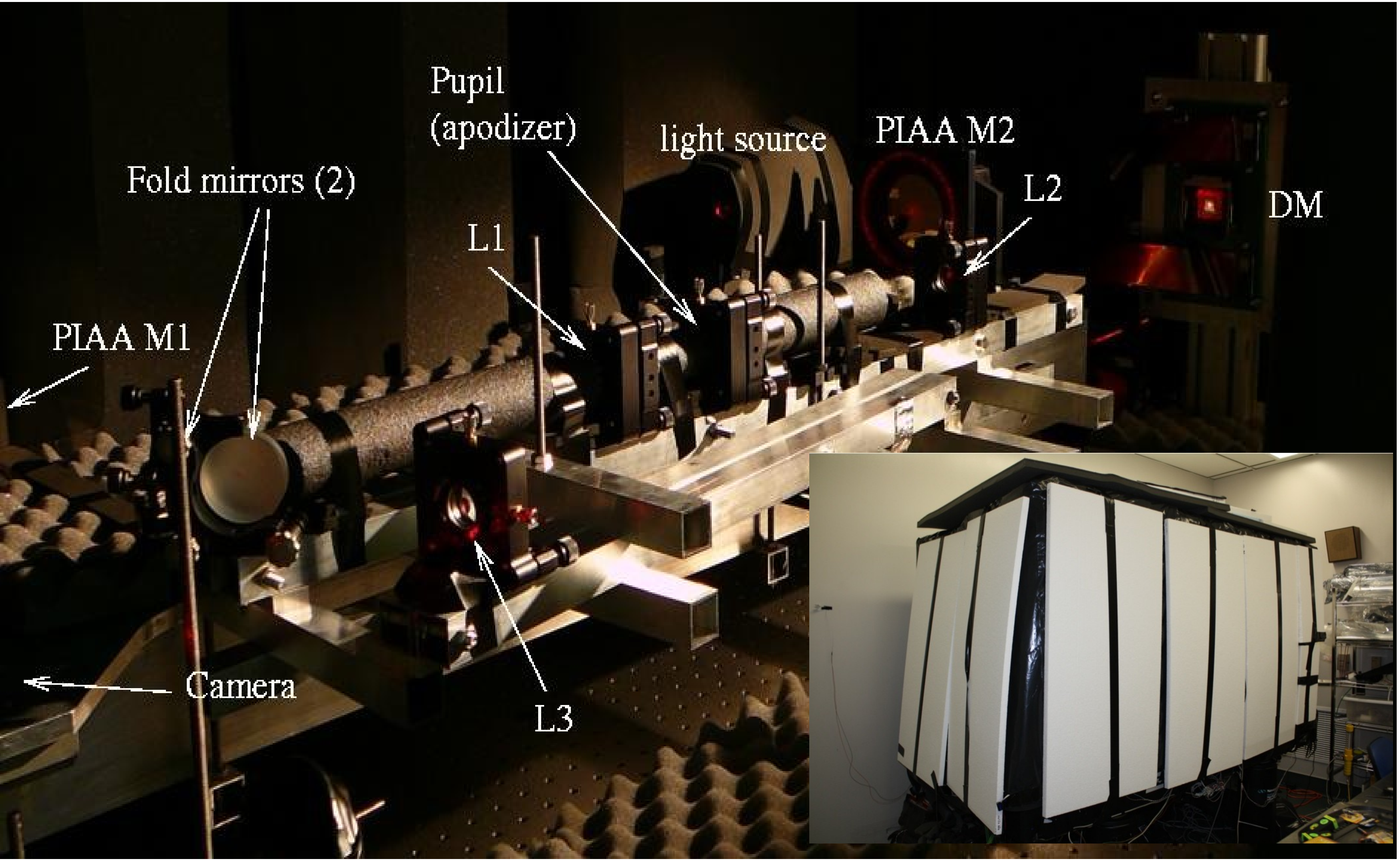
Recent lab results

TDEM milestones (our goals):

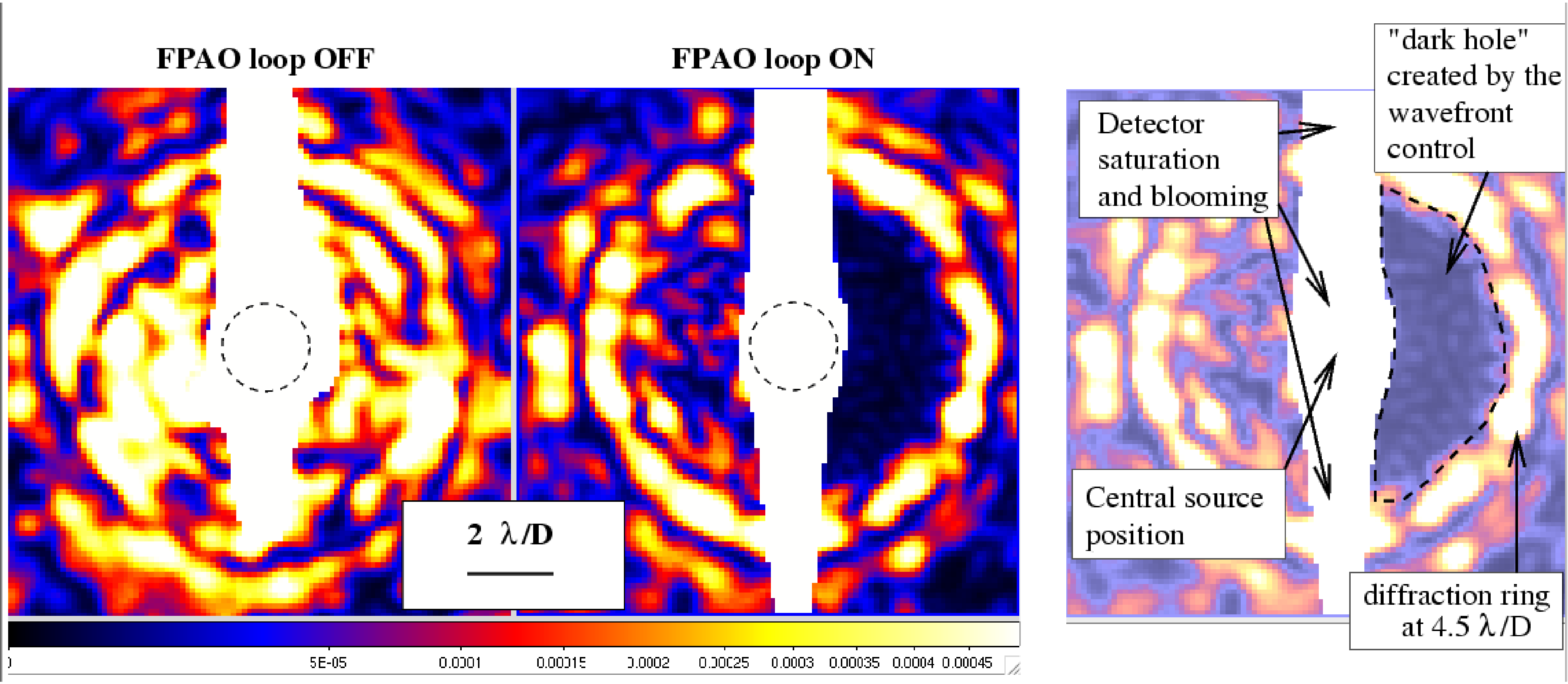
(1) 1e-9 monochromatic contrast at 2 l/D
(~1e-7 prior to TDEM start)

(2) pointing jitter control below 0.01 l/D level,
to support 1e-9 contrast

PIAA lab at Subaru Telescope



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



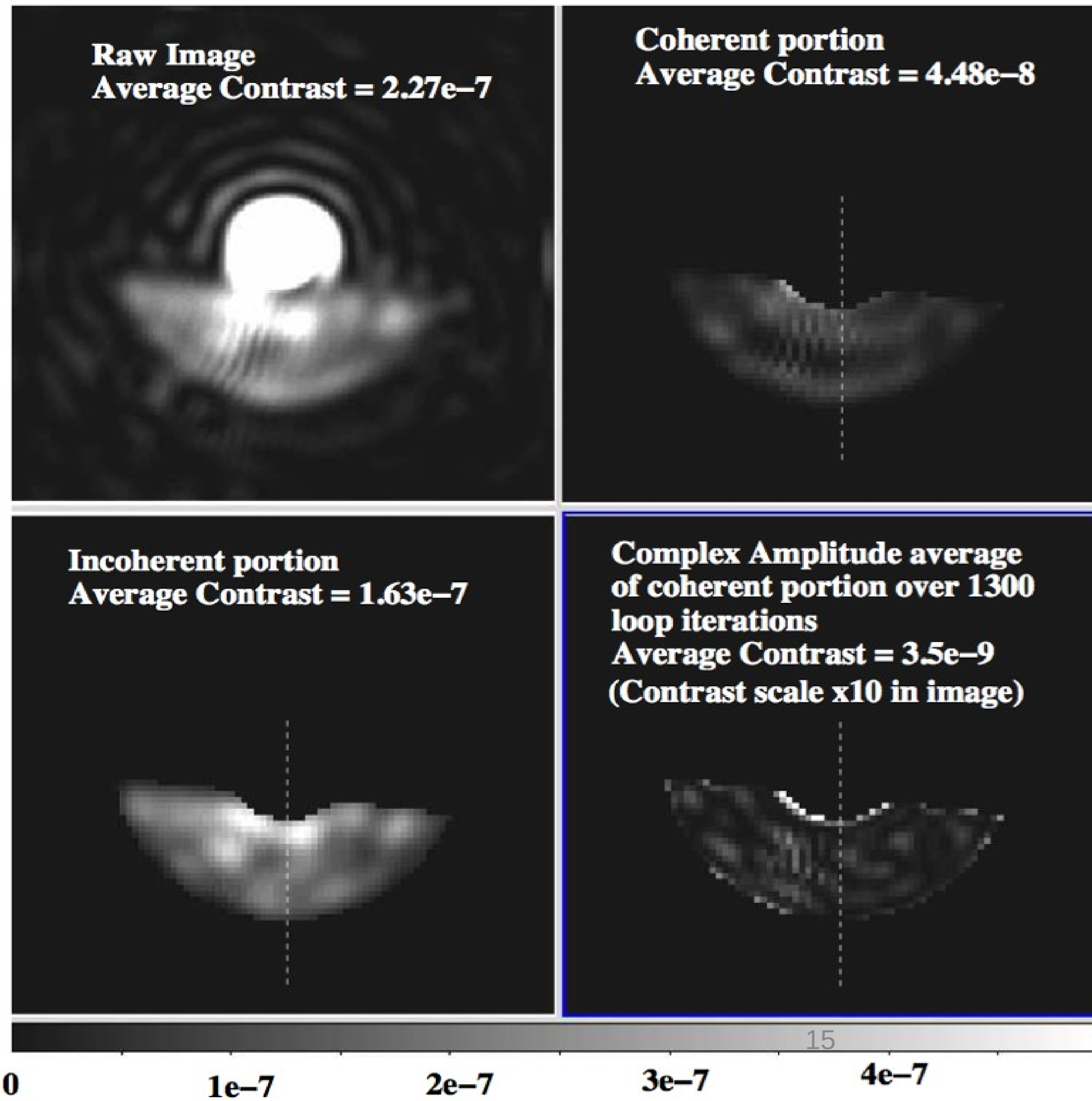
Focal plane WFS based correction and speckle calibration

2e-7 raw contrast obtained at 2 λ/D

Incoherent light at 1e-7
Coherent fast light at 5e-8
Coherent bias <3.5e-9

Test demonstrates:
- ability to separate light into coherent/incoherent fast/slow components
- ability to slow and static remove speckles well below the dynamic speckle halo

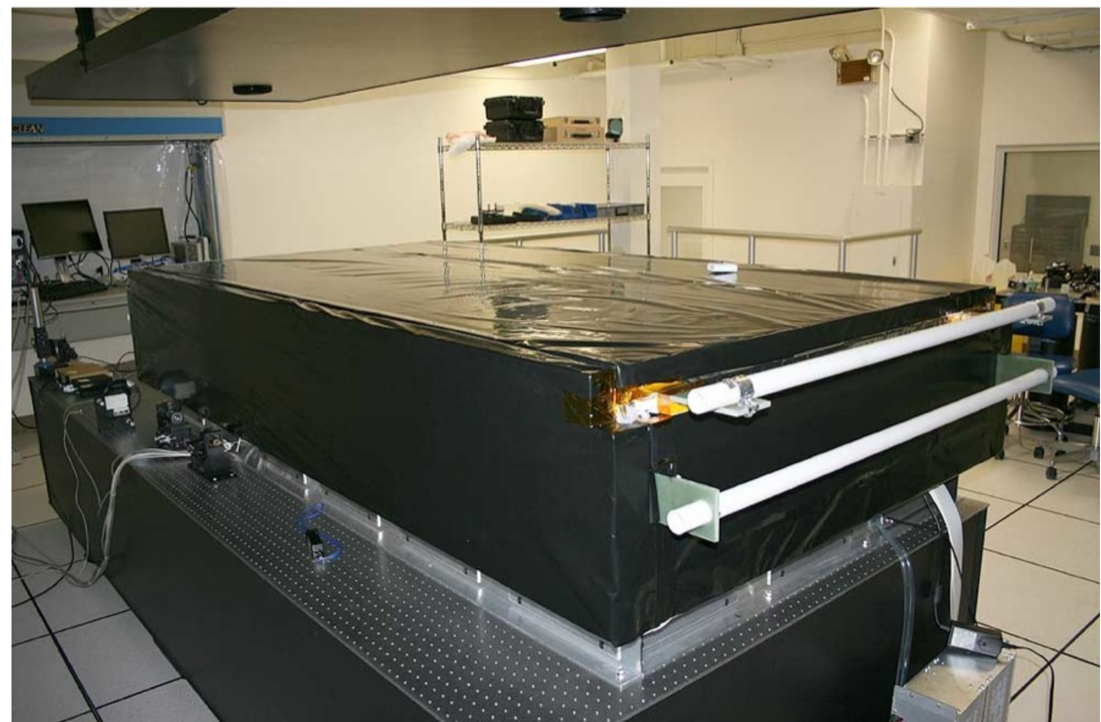
Guyon et al. 2010



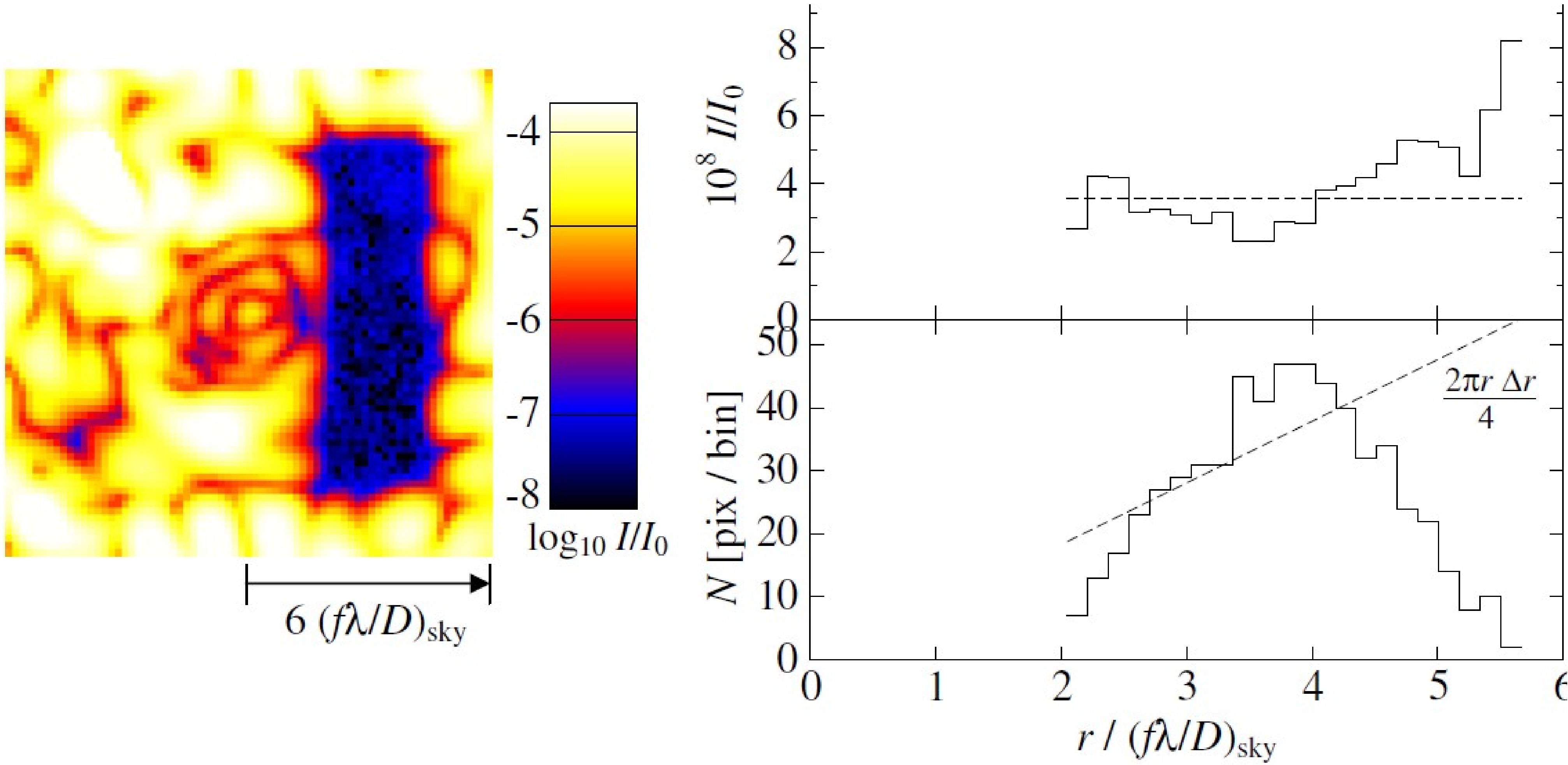
Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

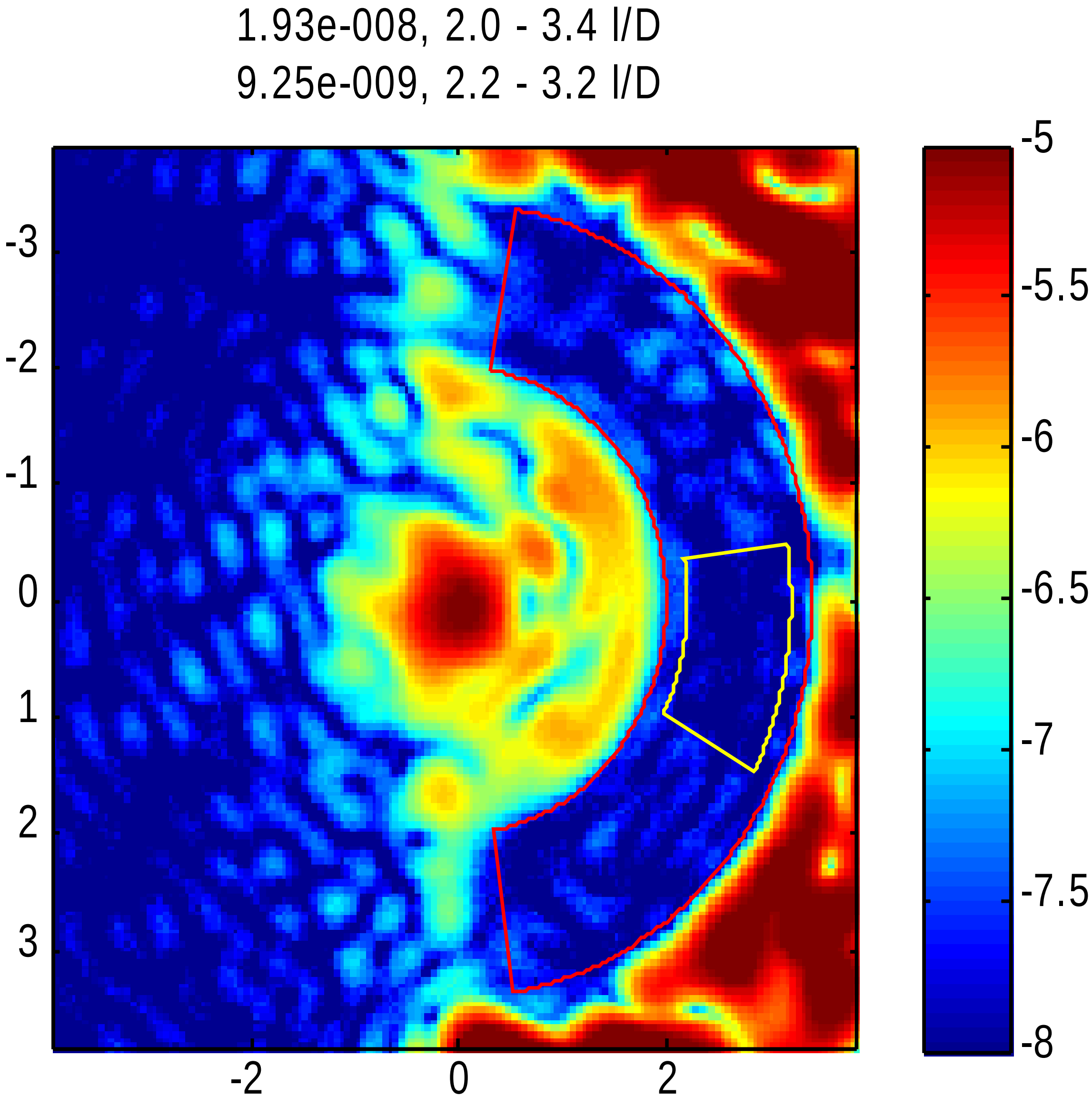
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.

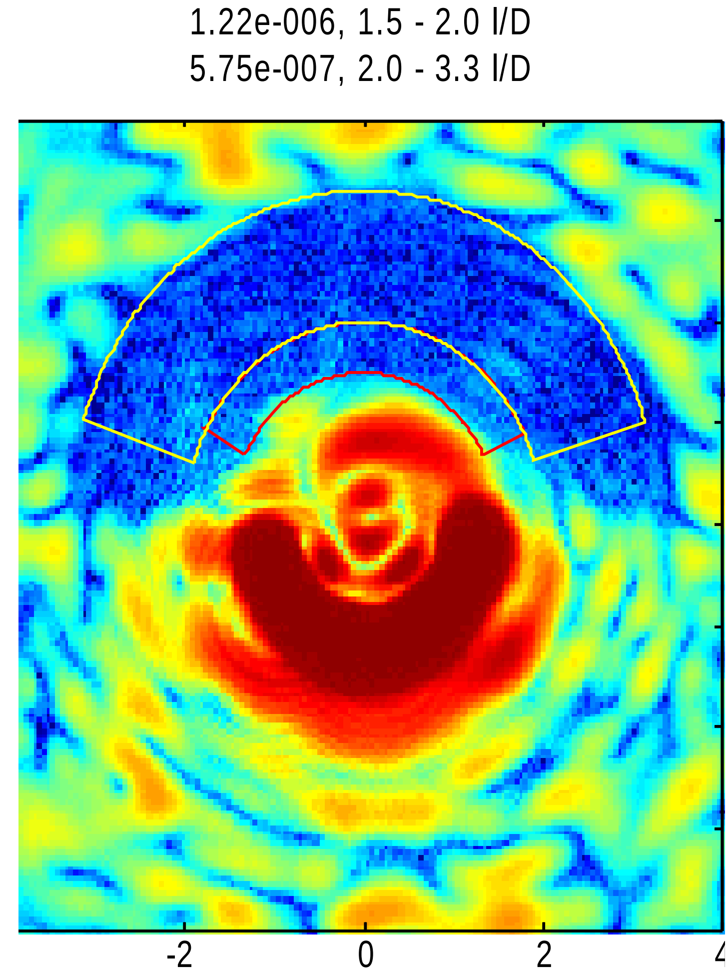


Recent lab results: JPL testbed (Kern et al.)



Recent lab results: Ames testbed (Belikov et al.)





High contrast in the 1-2 l/D range

<u>Why push IWA to < 2 l/D ?</u>

4-m telescope requires detection of planets at 2 l/D

Detection of planets with max elongation = 2 l/D with a coronagraph IWA = 2 l/D is very risky from images alone

- Observing must be done at the right time
- No information about position and flux
- Serious confusion problems with exozodi, multiple planets

# of planets goes as -3 power of IWA:

2.4x gain by going from IWA=2 to IWA=1.5

Reflected light goes as power -2 of IWA:

Same planet is 1.8x brighter at 1.5 l/D than 2 l/D

Need for spectroscopy to ~800nm:

2 l/D at 550nm = 1.375 l/D at 800nm

<u>Why is it hard ? → pointing control + focal plane mask design</u>

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.

Univ. of Arizona Jet Propulsion Laboratory California Institute of Technology LOCKHEED MARTIN 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

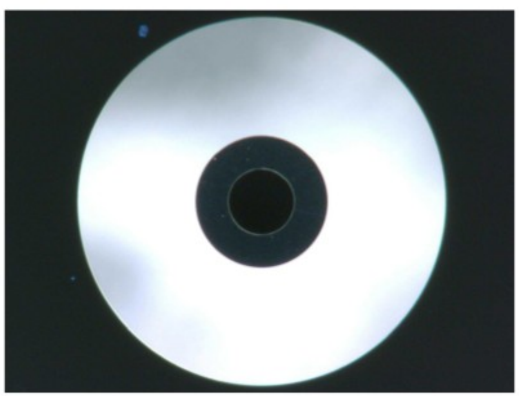


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

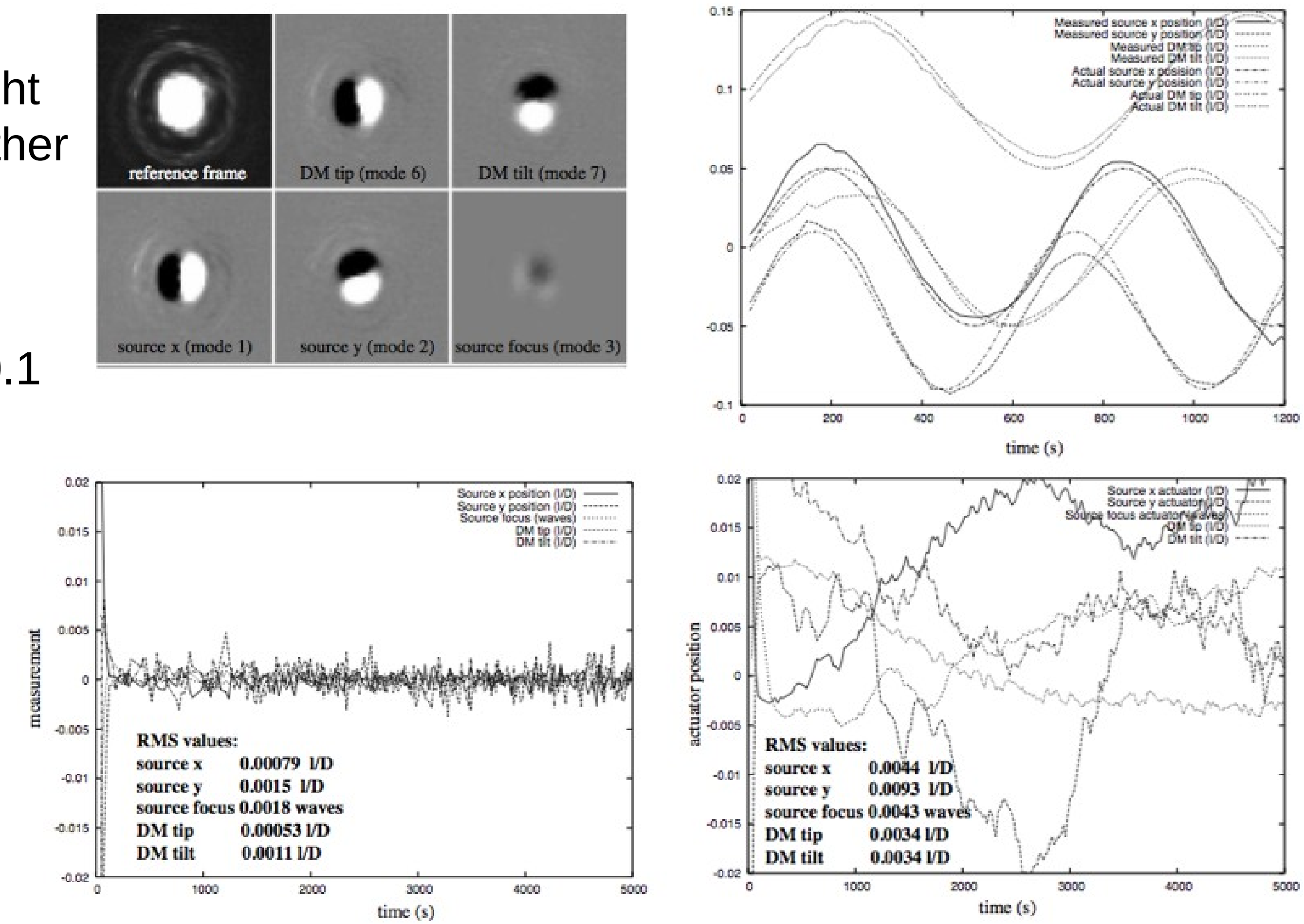
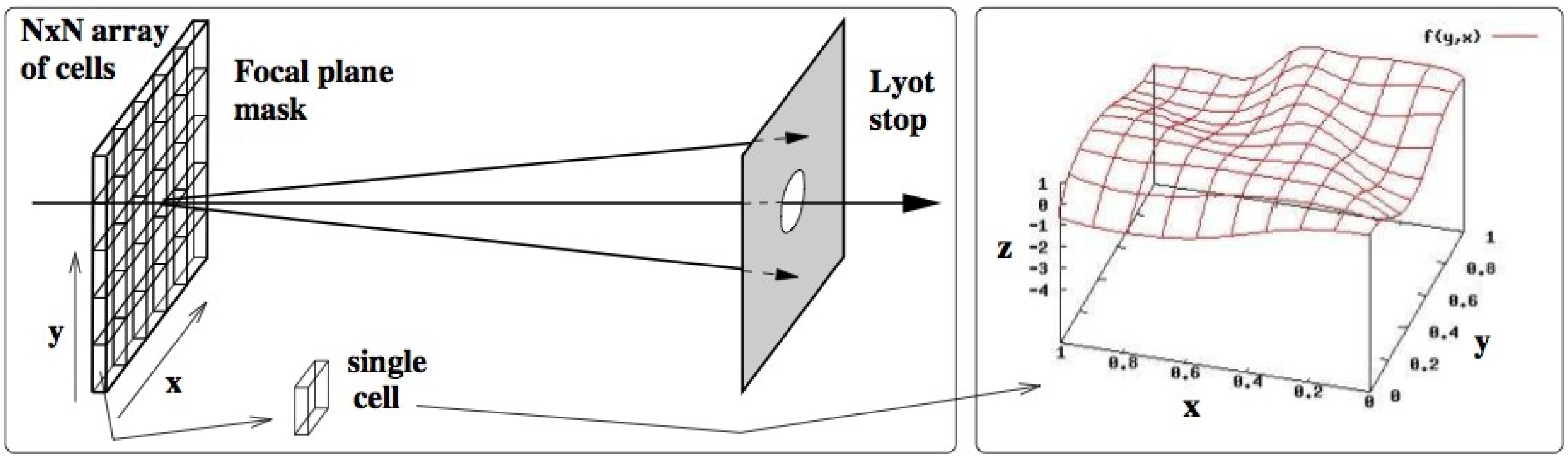


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes.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

Focal plane mask for small IWA

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



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

only histogram h(t) matters
t = thickness

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

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

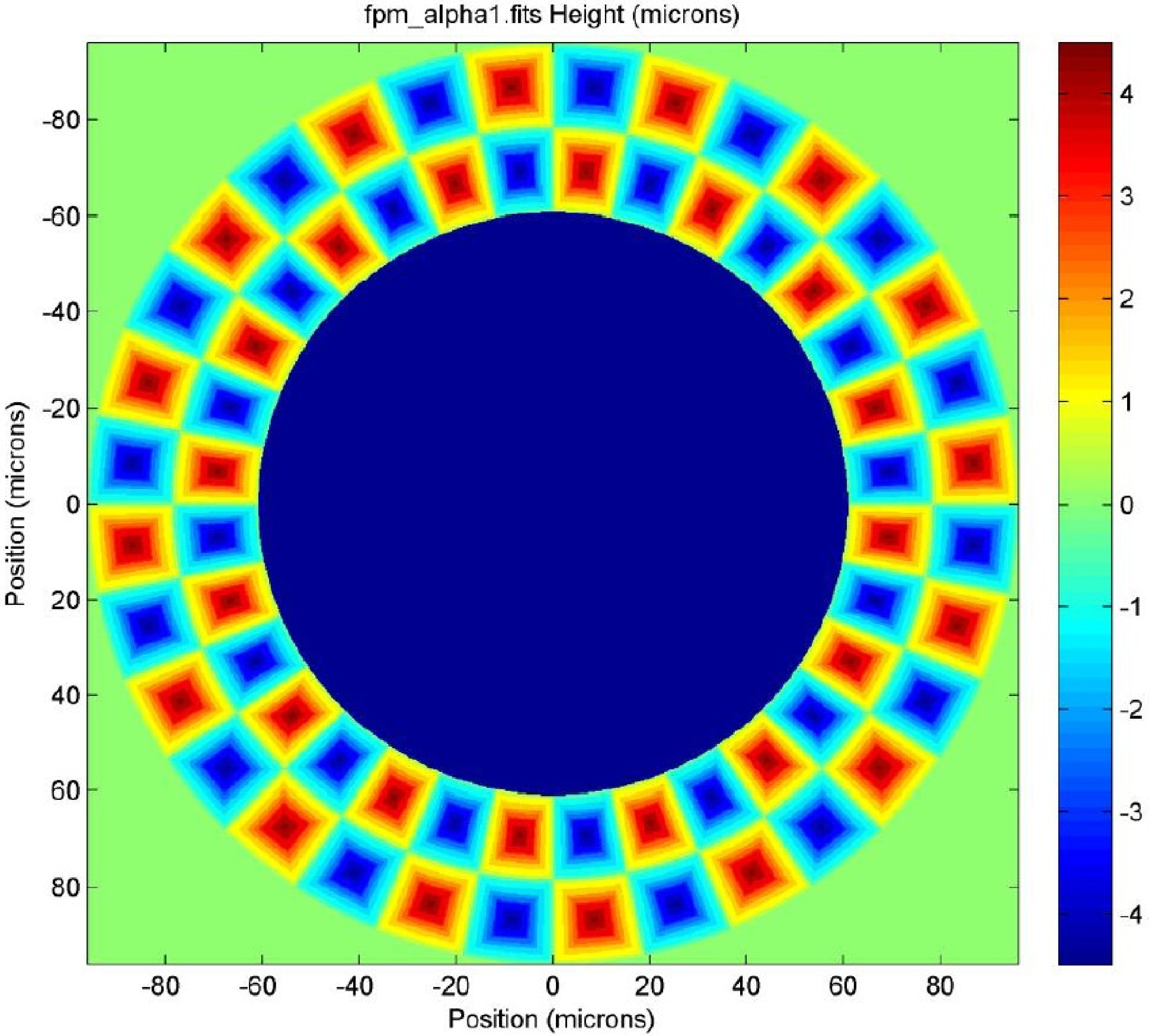
$$T(\lambda') = \int_{-\infty}^{\infty} h(t) e^{i2\pi t\lambda'}\,d\lambda'$$

Fourier Transf.

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

High contrast in the 1-2 l/D range

Belikov et al.



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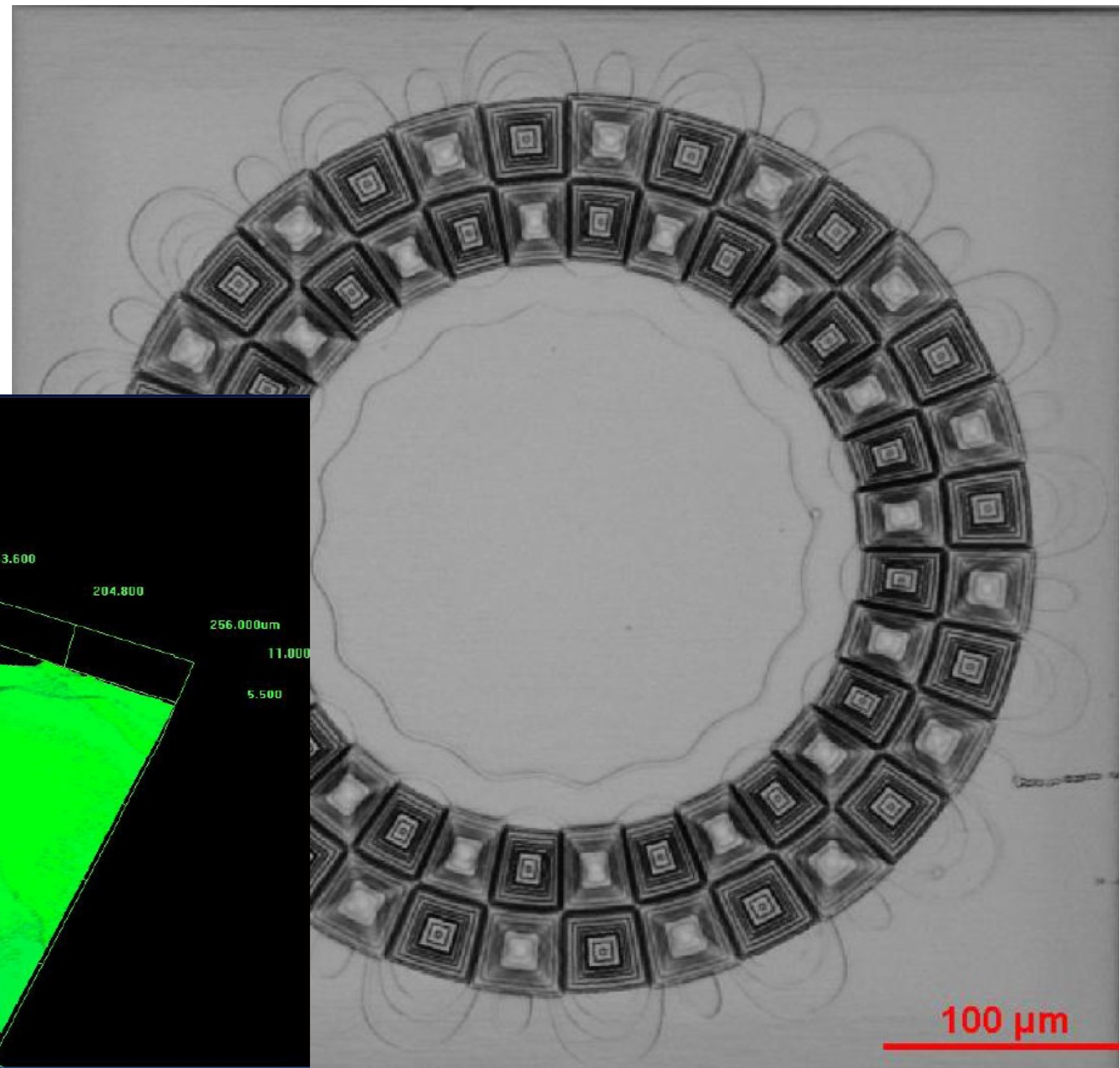
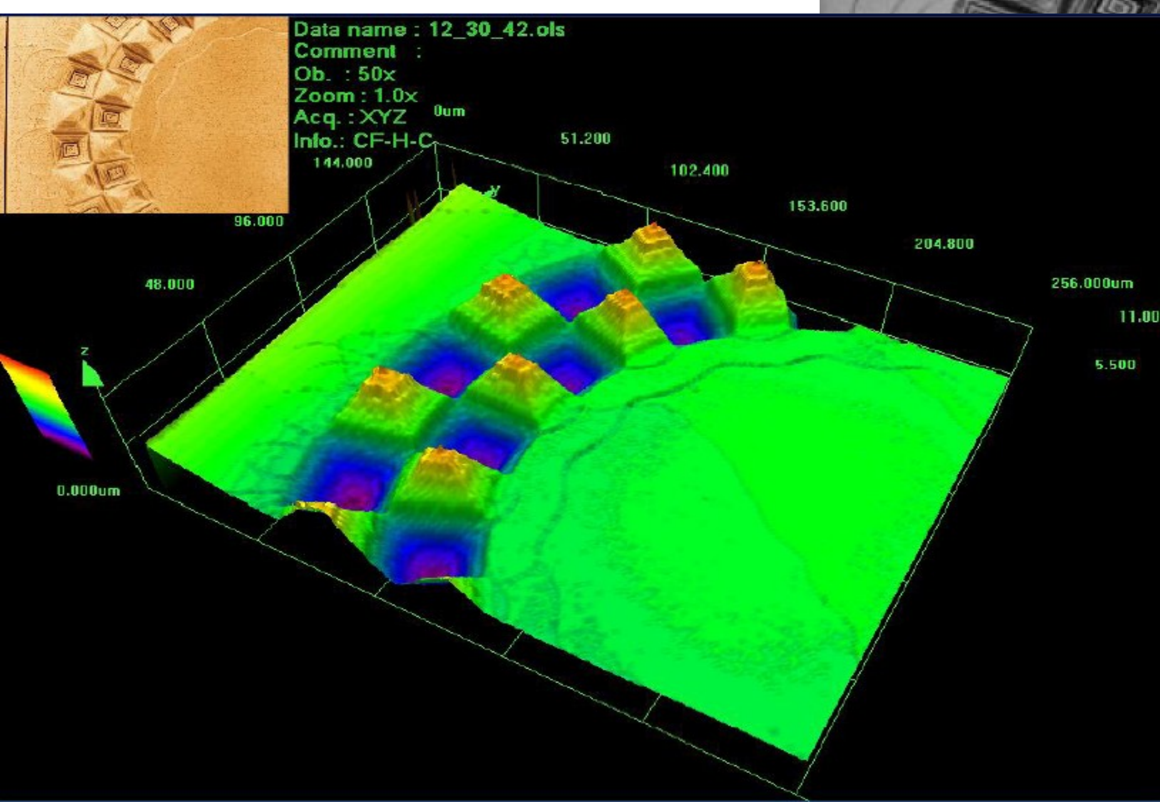
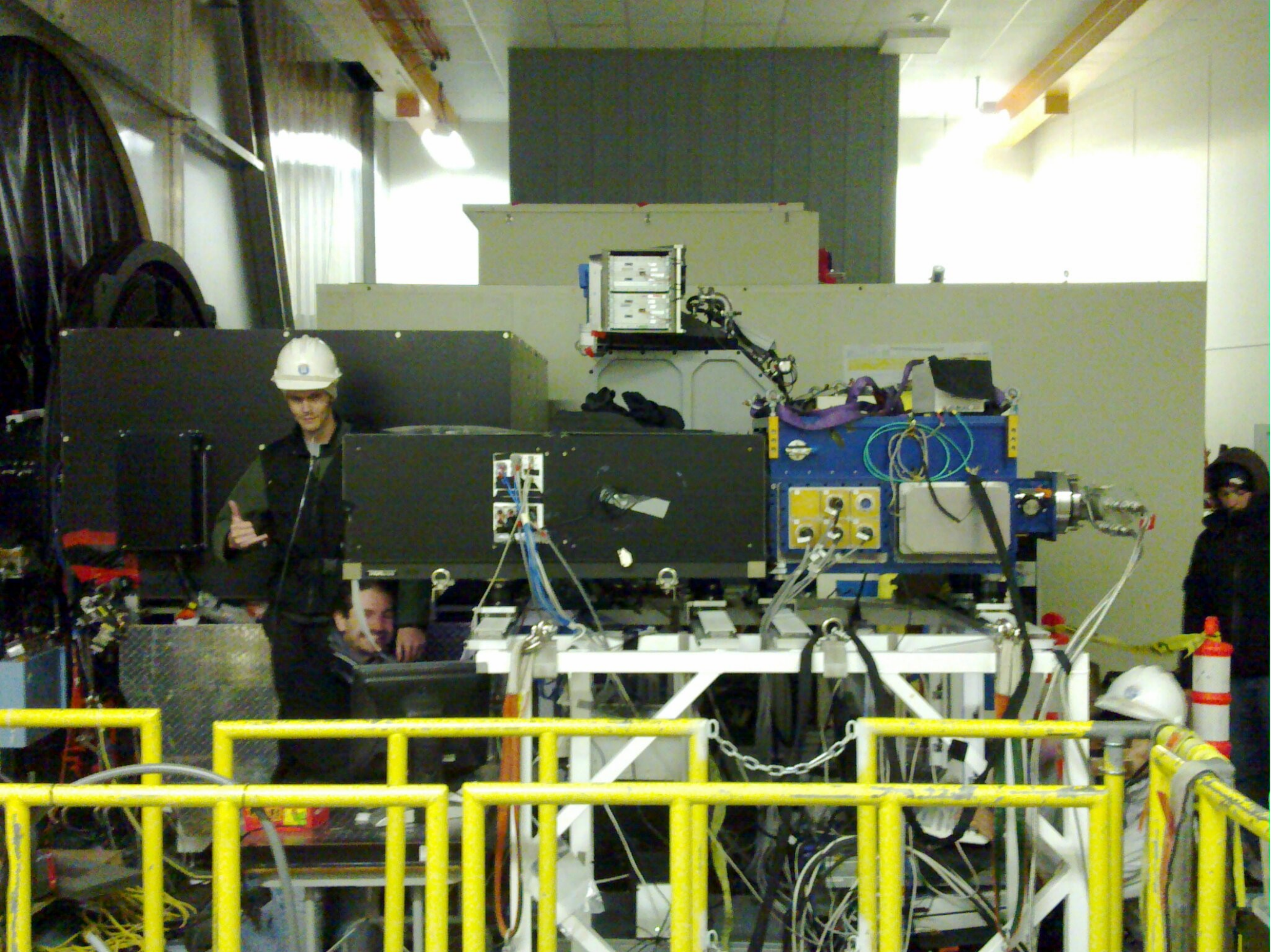




Ground-based PIAA coronagraphy:

The Subaru Coronagraphic Extreme-AO (SCExAO) system



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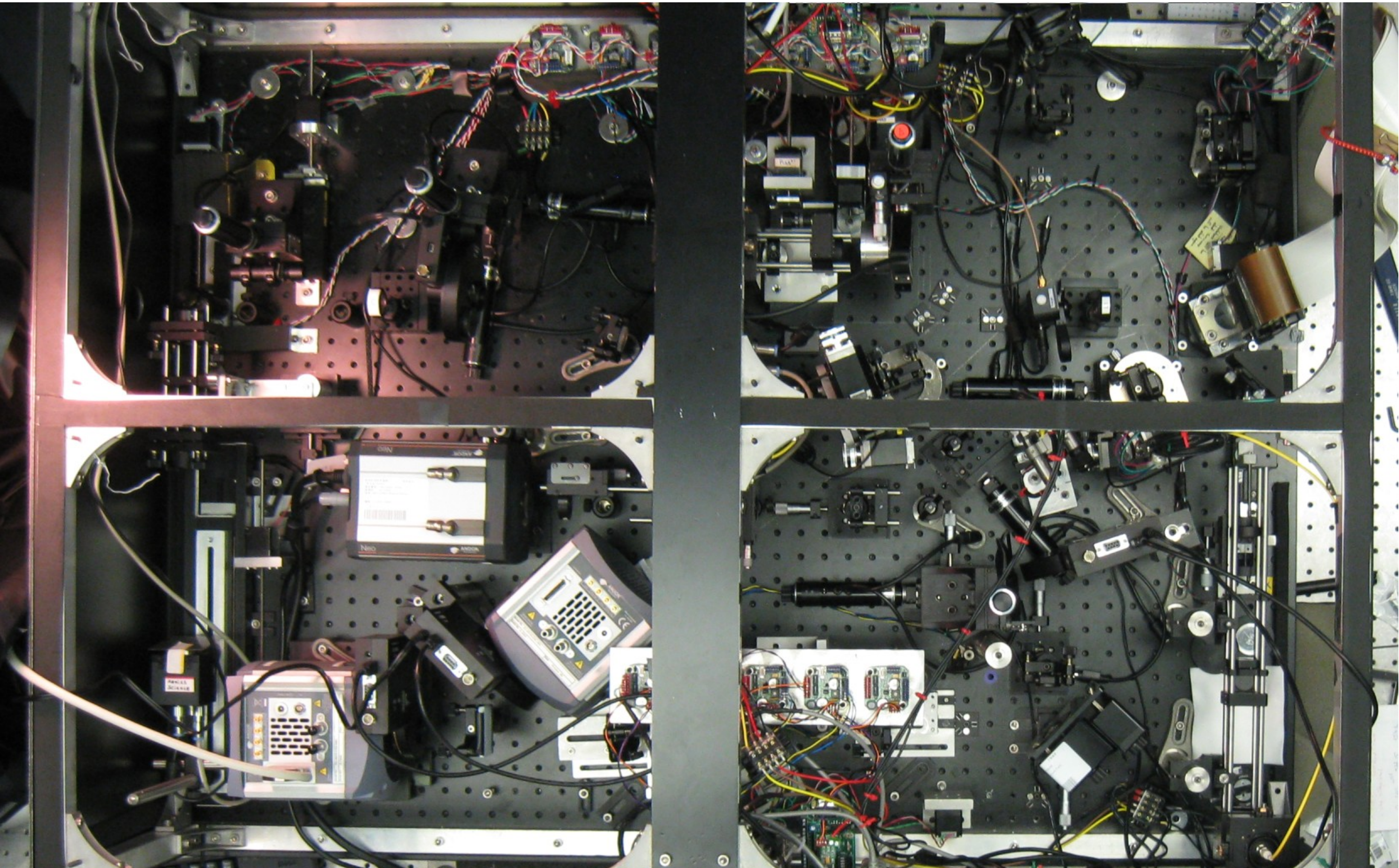

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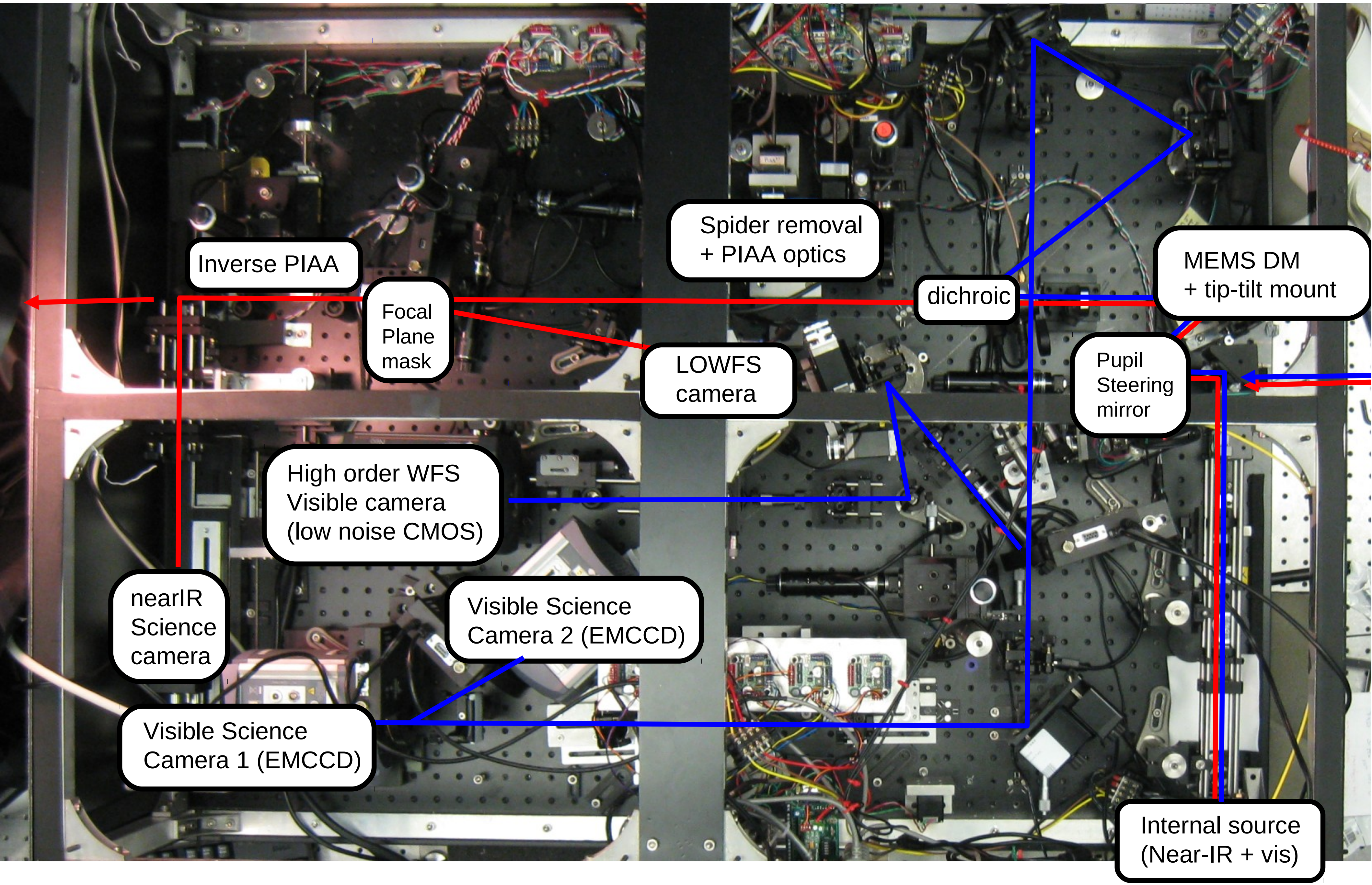

Conclusions

PIAA is a high performance coronagraph concept, theoretically able to provide high contrast between 1 and 2 l/D

Large range of design parameters → a large part of our technology development effort is to identify trades and sweet spots in design

- Bandwidth vs. PIAA size (# of spectral channels)
- IWA choice, throughput - PIAACMC vs PIAA

PIAA technology development includes 3 testbeds: Ames, JPL and Subaru

Current contrast at 2 l/D at ~2e-8, slowly but steadily improving

The most difficult part of the effort is wavefront control (probably the reason why no coronagraph currently achieves 1e-8 at ~2 l/D)

PIAA is starting on-sky observations (see talk by Martinache et al. Tomorrow)

Future directions: better contrast, closer in, with broadband light.