PIAACMC

PIAA team: Guyon, Belikov, Kern et al.

Outline

1. PIAACMC

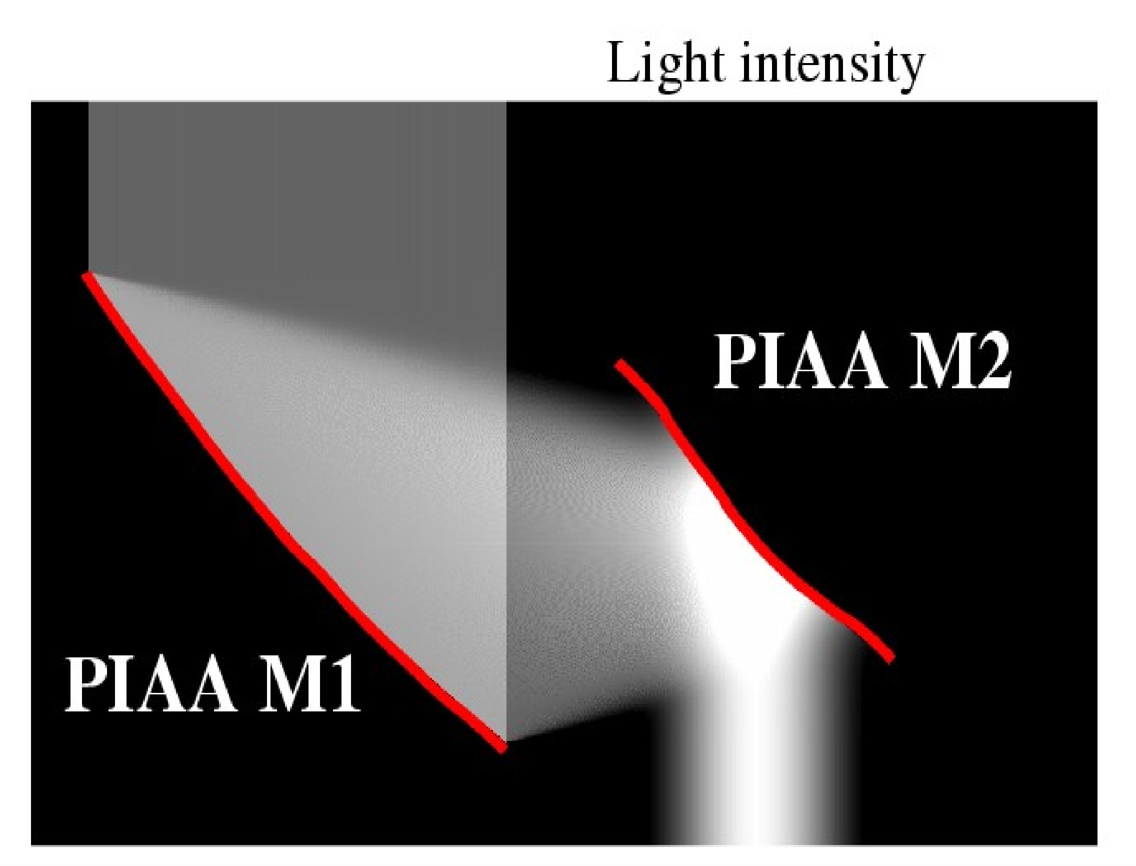
2. Scientific opportunities

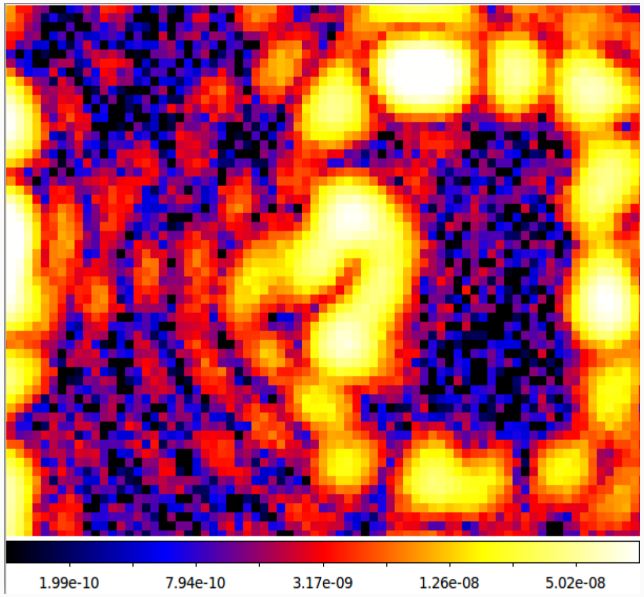
3. What could go wrong?

4. Suggestions for path forward

Short intro to PIAA

Has demonstrated high efficiency coronagraphy between 2 and 4 l/D (5e-10 contrast in monochromatic light)





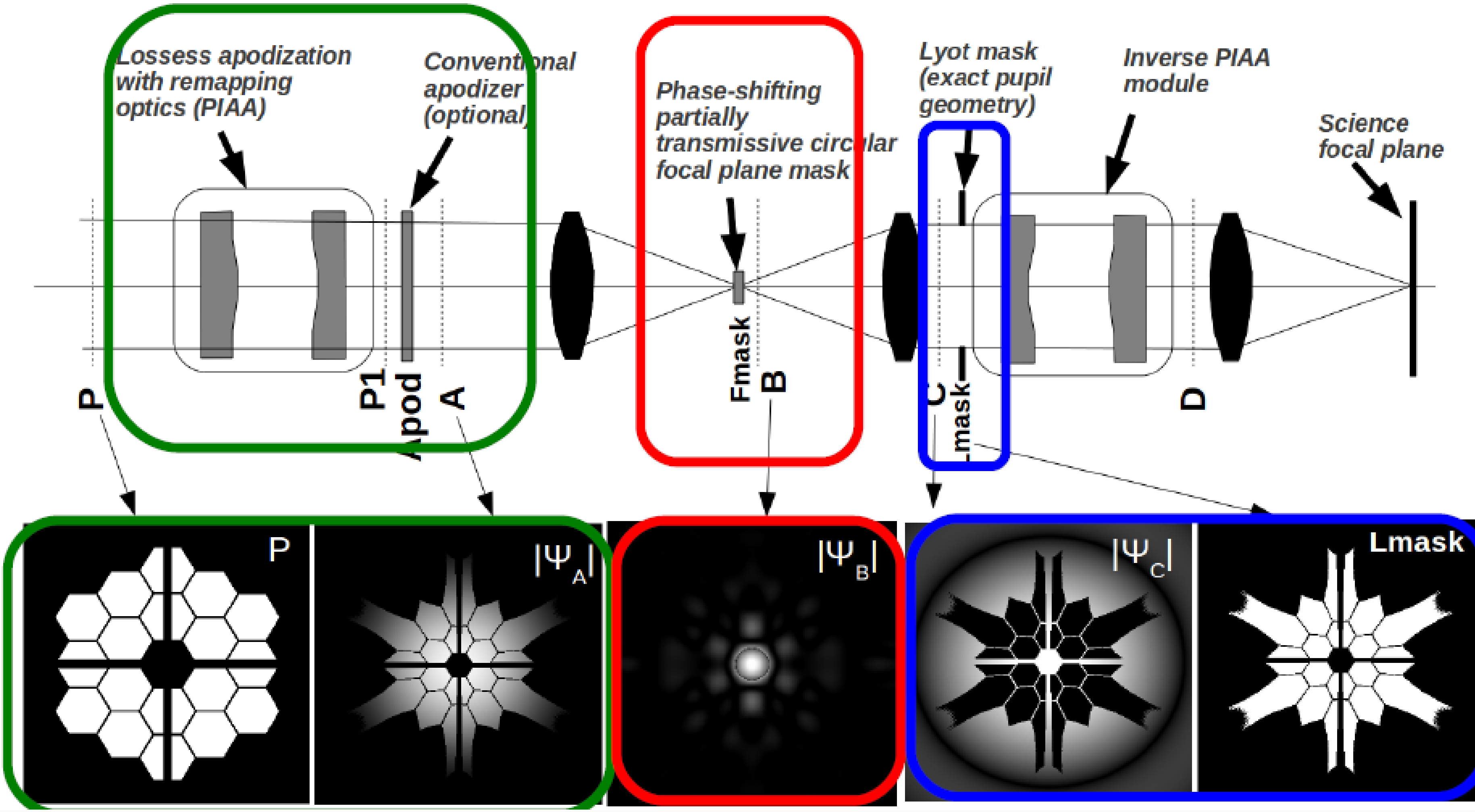
Has achieved 2.1e-8 contrast from 2 to 4 l/D in 10% band (with poor design for chromaticity)

How does PIAACMC work ?

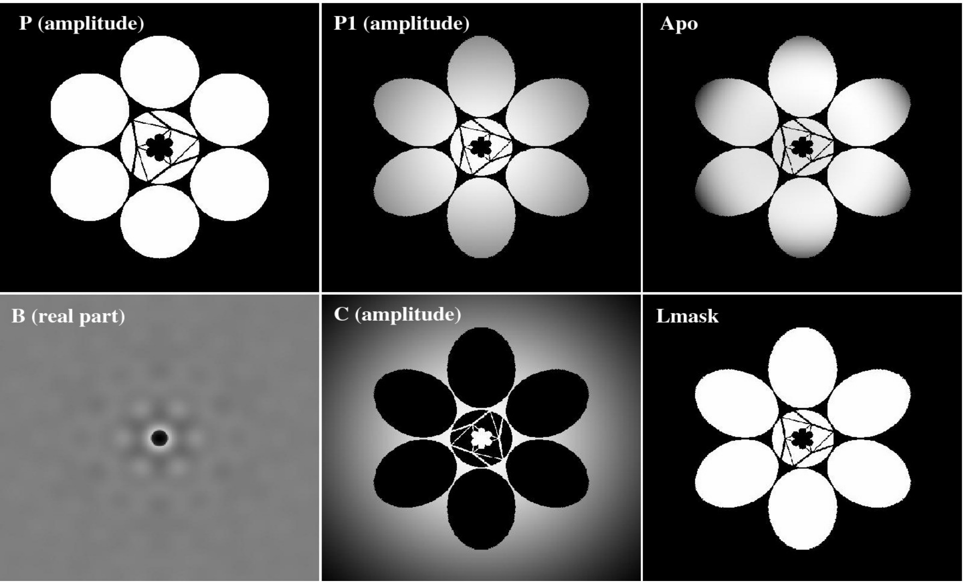
Combines 3 techniques :

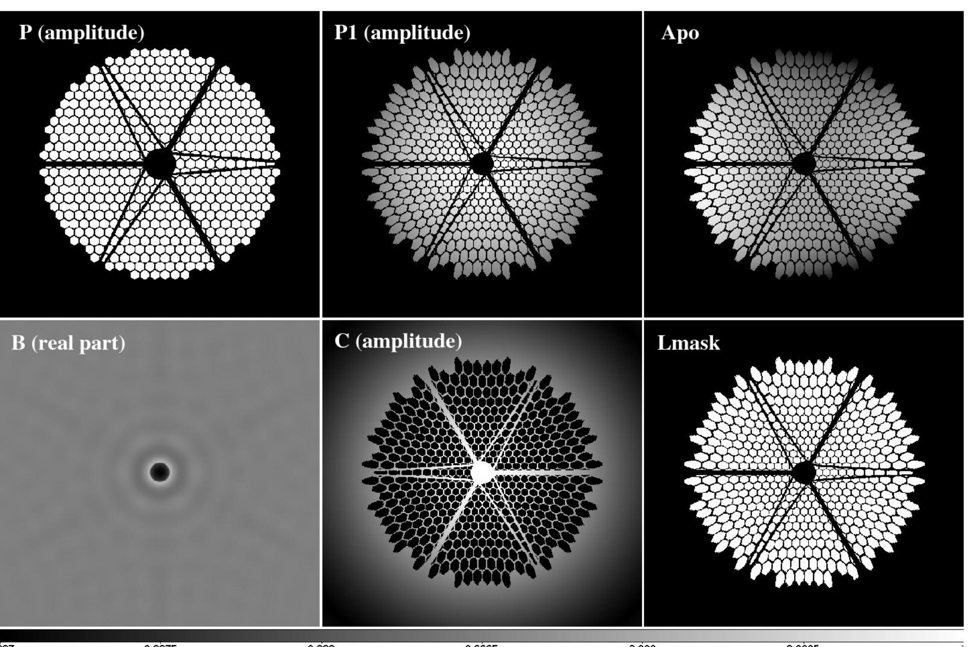
- **Lossless apodization with PIAA optics (beam shaping)**
- **Phase mask coronagraphy (focal plane mask is phase-shifting)**
- **Lyot coronagraphy (Pupil plane Lyot mask removes starlight)**

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask

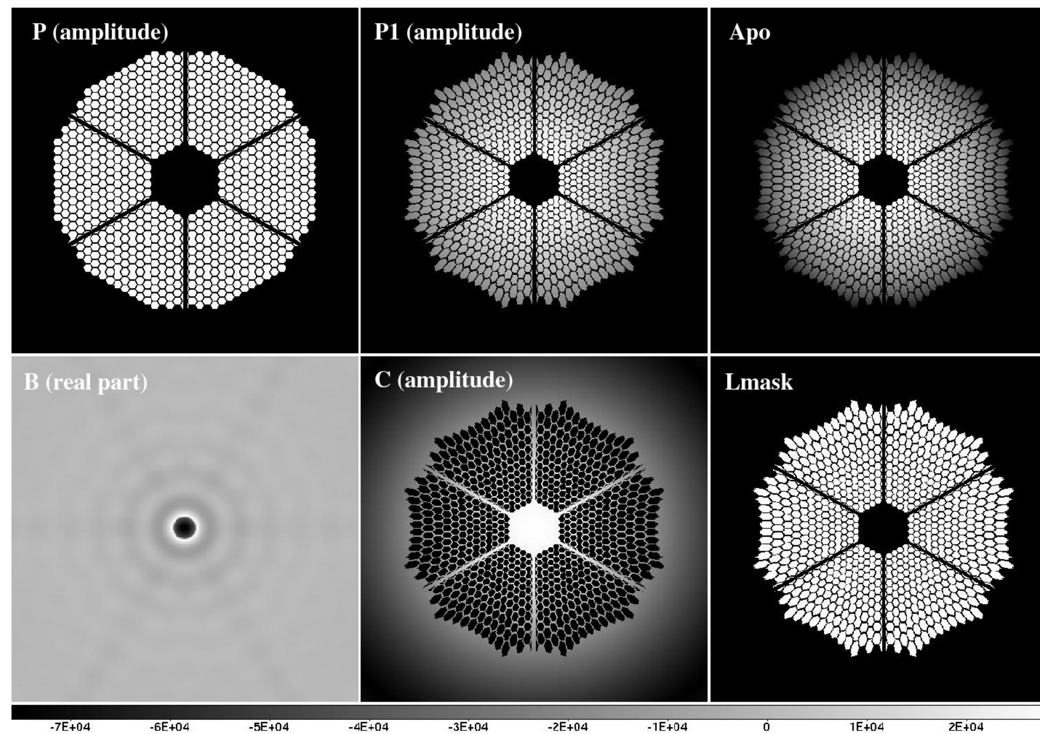


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

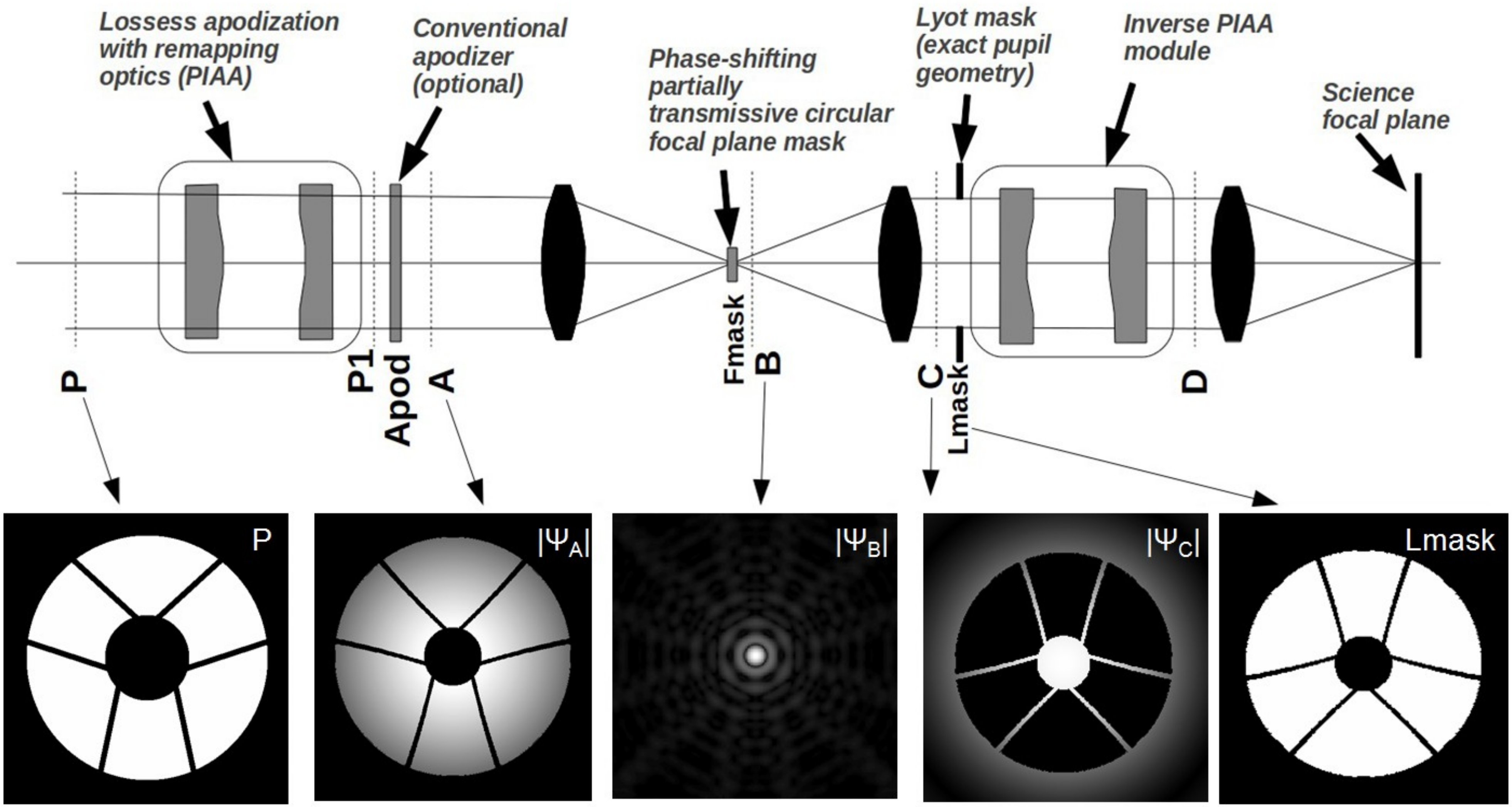




<u>Pupil shape does not matter !!!</u>



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Why PIAA → PIAACMC for AFTA ?

Higher performance → can go below 1 l/D IWA

Does not care about central obstruction, spiders (no need for DM to attempt mitigating spiders)

Milder apodization
→ PIAA optics are easier to manufacture and test
→ No need for conventional touch-up apodizer → we gain back ~10% in throughput and remove an element
→ Better achromatic behavior

But: we need a mask that has phase and amplitude...
→ encouraging results from LYOT and Vortex, + new ideas for making focal plane masks

Lots of knobs to tune design to mitigate manufacturing challenges

AFTA PIAACMC design optimization

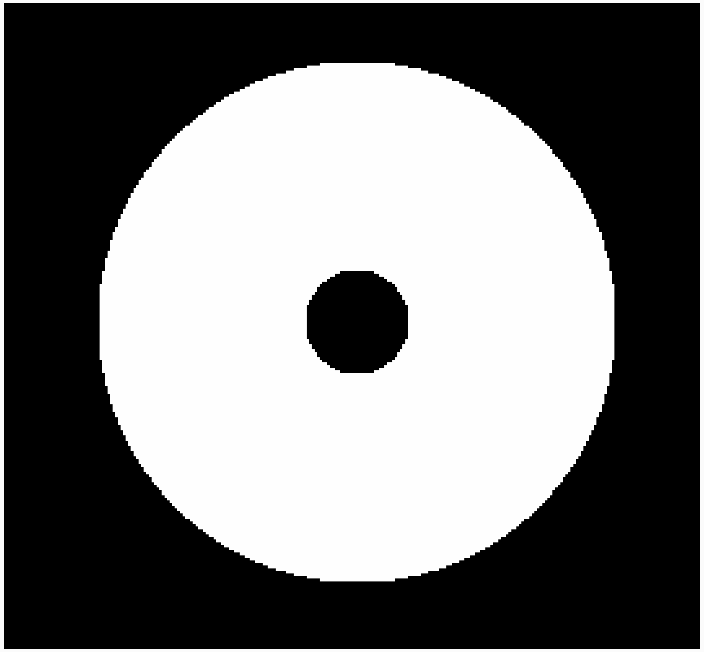
PIAACMC for AFTA:

- **Full throughput, 360 deg discovery area**
- **No limit in contrast other than WF control**

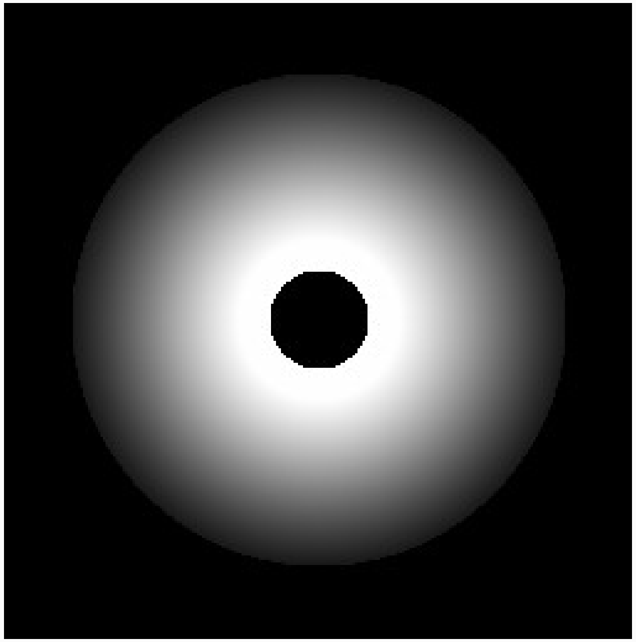
Main design constraint: IWA vs. sensitivity to stellar angular size

Two key design parameters:

- **Focal plane mask radius**
- **Output central obstruction size**



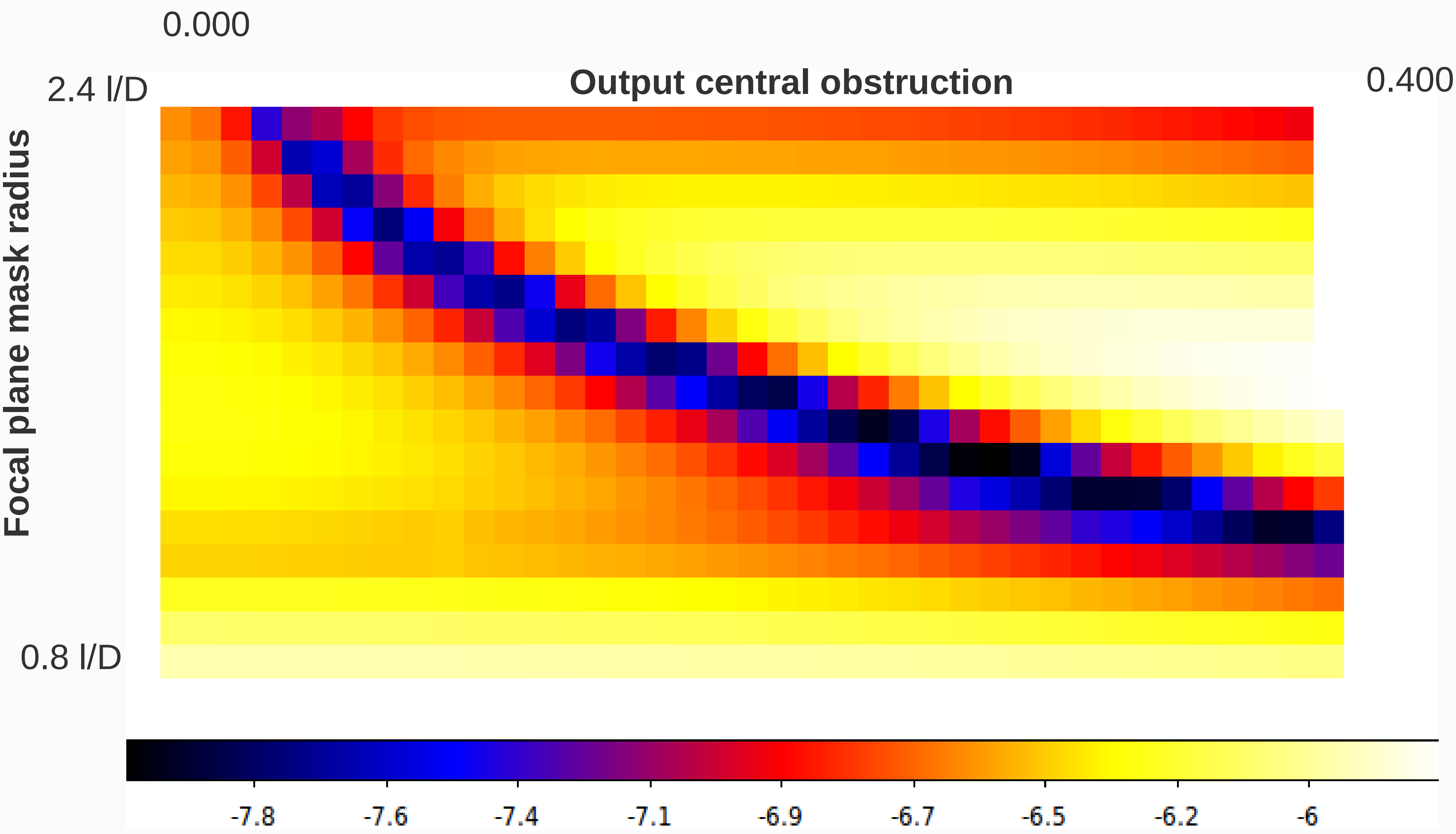
Input central obstruction



Output central obstruction

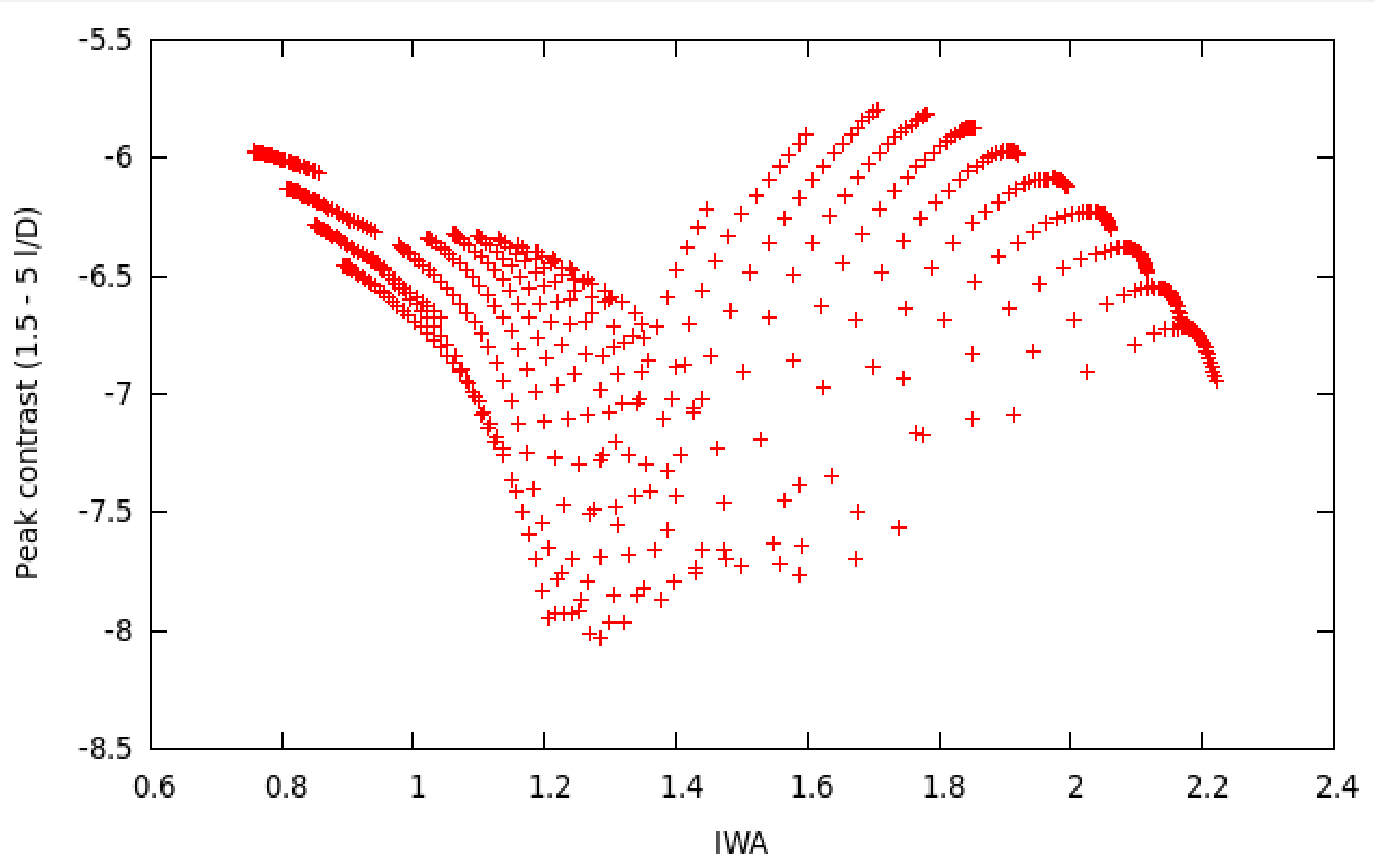
AFTA design optimization

PEAK contrast between 1.5 and 5 l/D when observing a 2% l/D disk



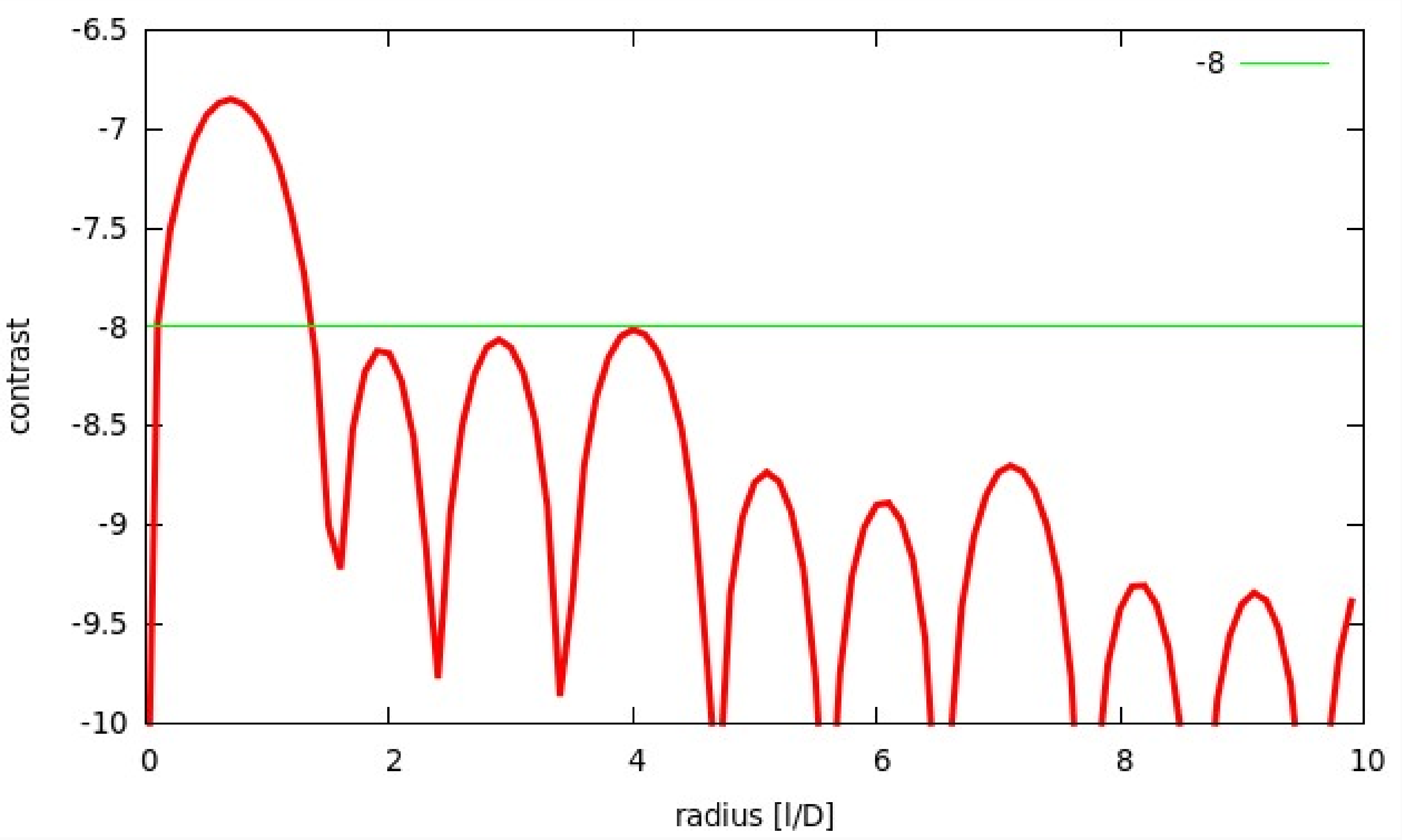
AFTA design optimization

Optimal design has IWA = 1.26 l/D, ~10% transmission mask
It is 4th order coronagraph with near-theoretically optimal performance

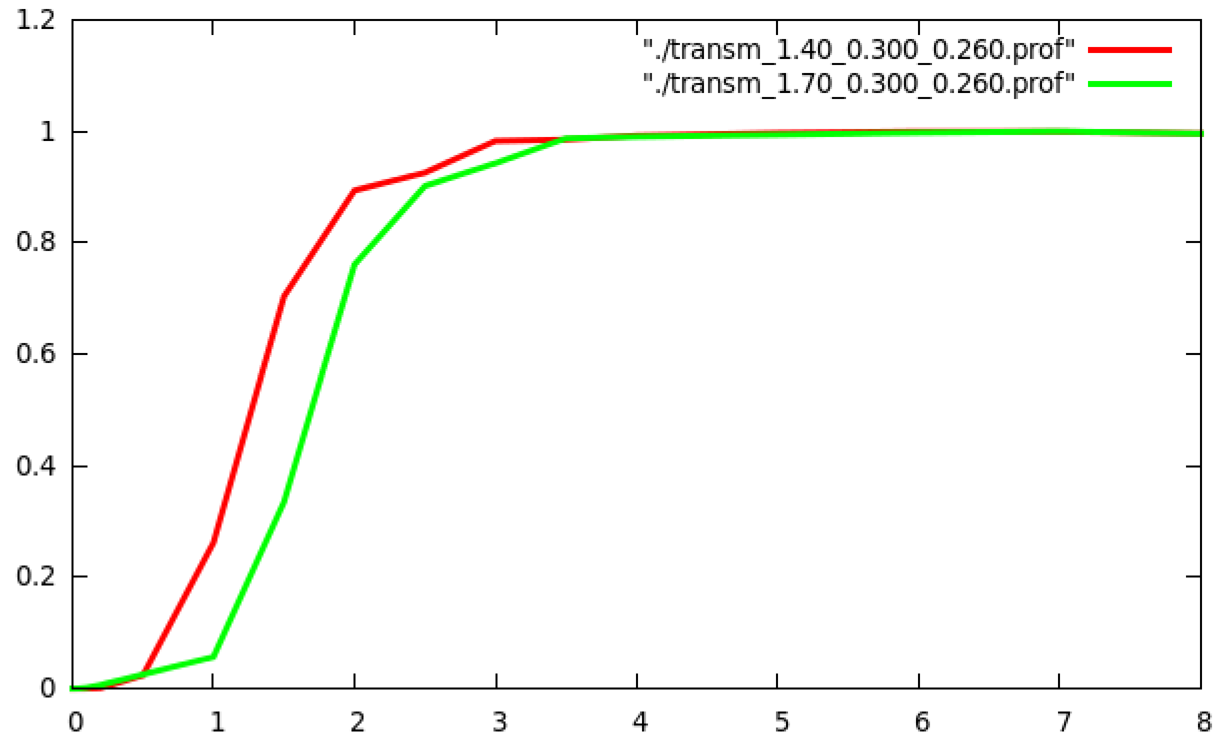


AFTA design optimization

Response to 2% l/D star

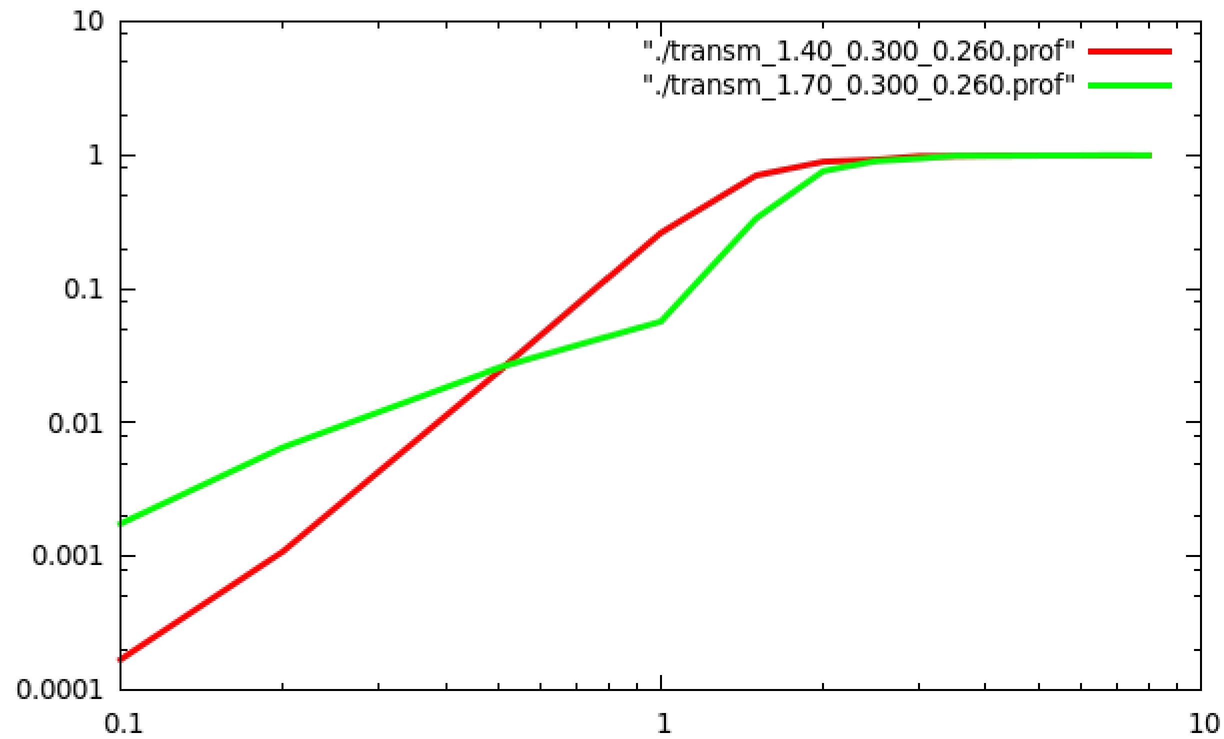


AFTA design optimization



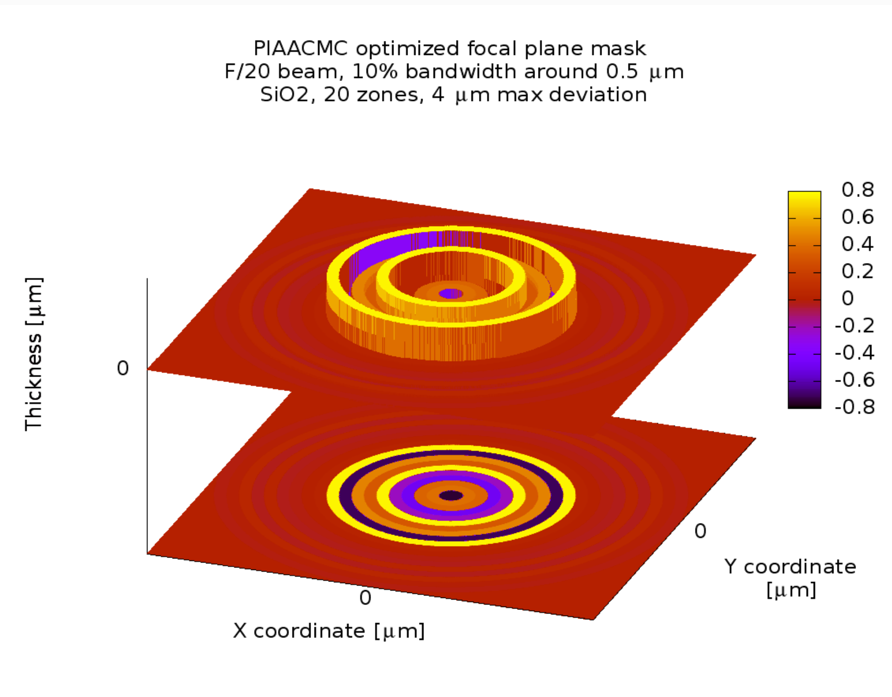
Increasing IWA → more sensitive to stellar angular size

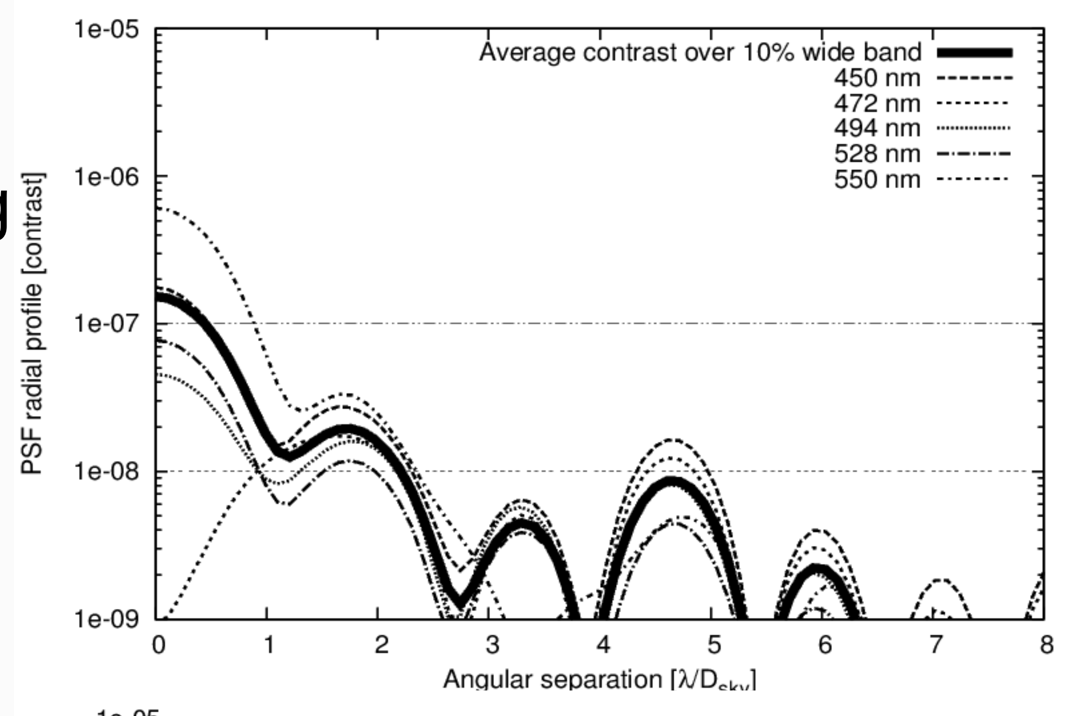
Solution is 4th order coronagraph with small IWA

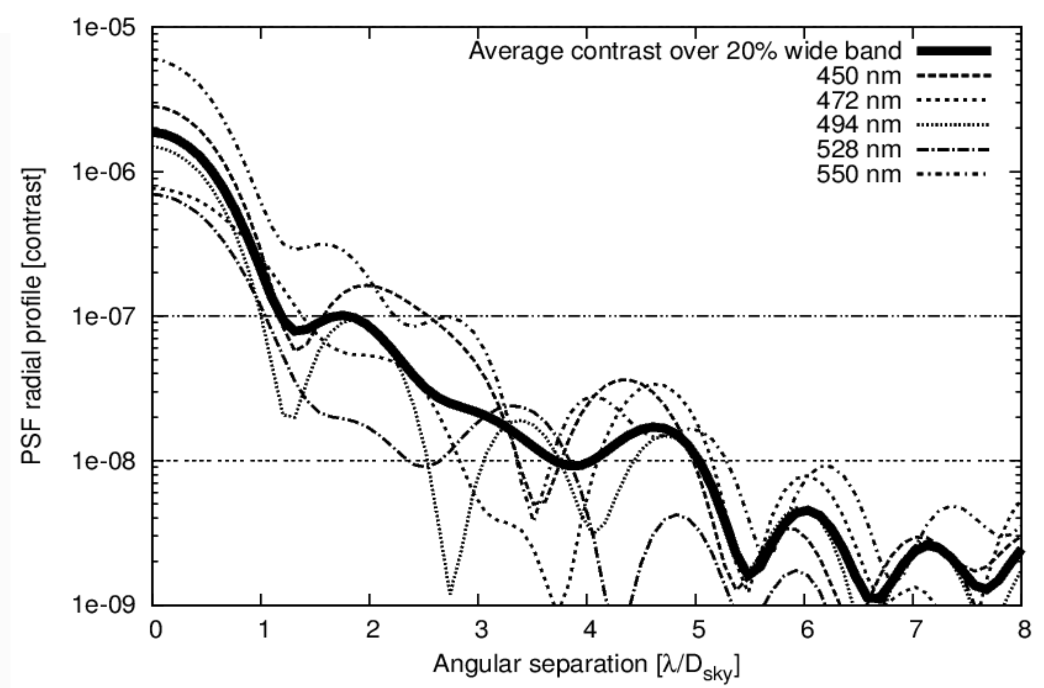


Achromatization efforts / mask design

Ongoing work... requires good understanding of manufacturing capabilities

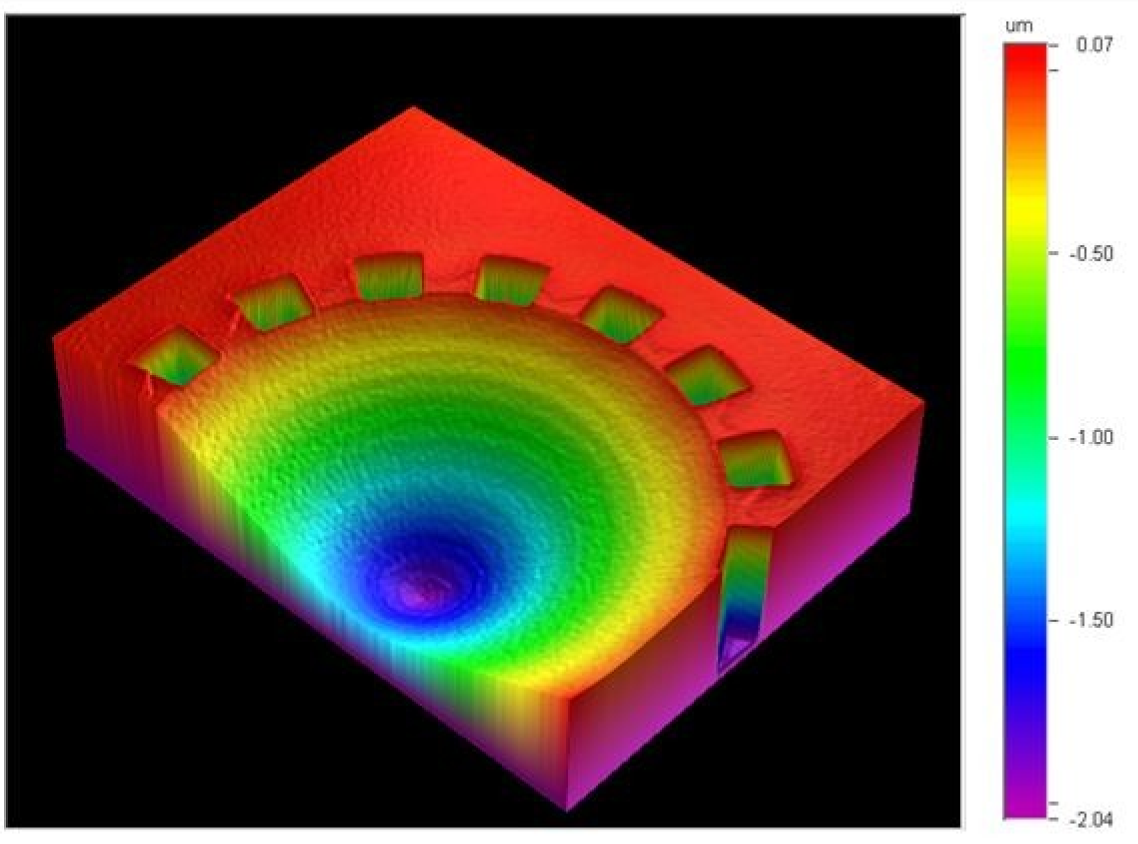


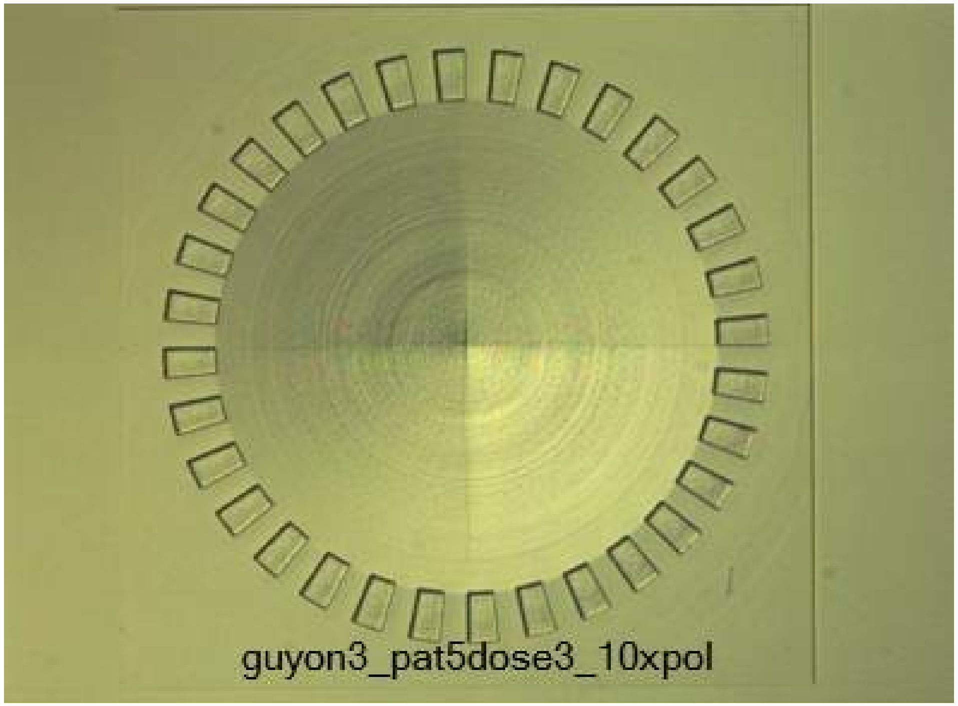




Achromatization efforts / mask design

Ongoing work... requires good understanding of manufacturing capabilities
Examples (Bala, Rus, K. Newman PhD)





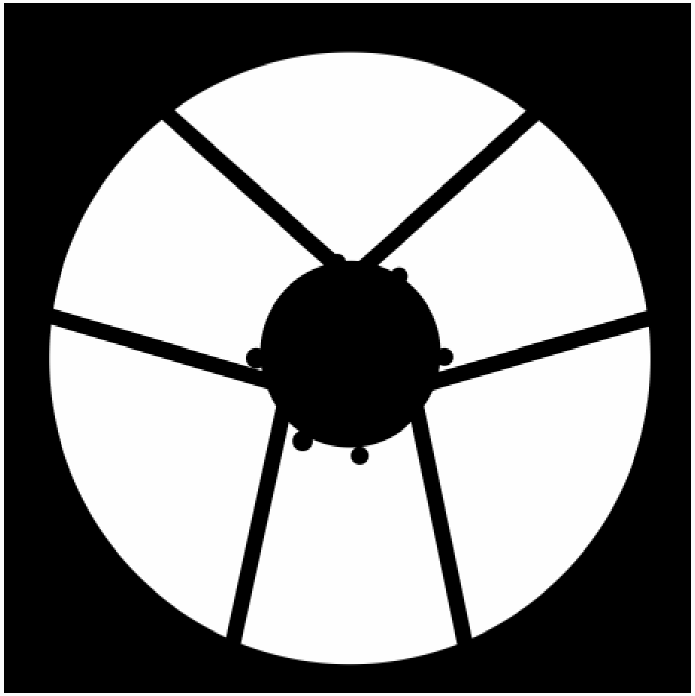
PIAACC design submitted to J. Krist

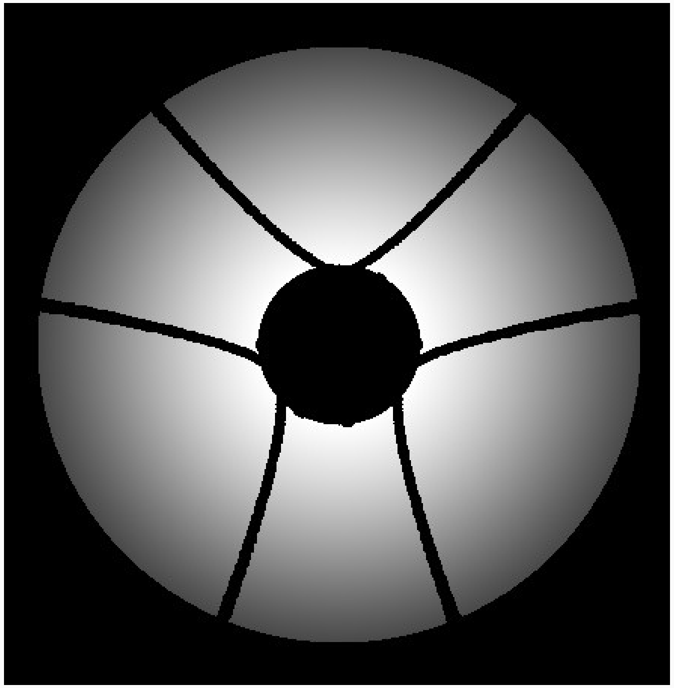
- Compatible with AFTA pupil (central obstruction, spiders, etc...)
- 1.3 l/D IWA
- ~95% throughput
- PSF sharpness factor ~ 1.0
- Monochromatic contrast, point source, no WF error: better than 1e-10 contrast
- Extended source: 1e-8 RAW contrast at 1.5l/D and beyond on 2% l/D diameter source (typical of nearby star)

Ongoing activities:

- Polychromatic mask using single material with steps → need to assume material properties, tolerances. Quantify interaction with WFC
- Removing apodizer → higher throughput (~4% gain) and removes one element
- Link WFC and coronagraph optimization

PIAACMC design submitted to J. Krist





Phase-shifting focal plane mask, 14% transmission

Scientific opportunities

What does low-IWA & high efficiency get us ?

More planets accessible: #planets accessible goes as IWA^{-3}
Difference between 1.3 and 3 l/D coronagraphs = 12x more planets in IWA-limited regime
There are as many planets between 1.3 and 1.65 l/D as between 1.65 and 10 l/D

More resilient to poorer contrast: contrast goes as IWA^{-2}
Difference between 1.3 and 3 l/D coronagraph = 5.3x brighter for same planet radius and albedo at fixed # l/D

Shorter exposure times, shorter setup time, higher sensitivity
3 l/D coronagraph with 1.5 l/D FWHM, 45% masks throughput → 5x exposure time in background-limited regime

→ **scientific return is steep function of IWA and efficiency**
1.3 l/D IWA, full sensitivity coronagraph on 2.4m is approximately equal to TPF FB1 (4 l/D, 10% throughput)

Table 1. Most favorable targets for the direct imaging of an Earth analog, ranked by decreasing SNR. The planet is assumed to be observed at maximum angular separation (given both in arcsec and λ/D) at 0.8 μm. The light contribution are given in contrast unit for the source, the background flux (zodi+exozodi) and stellar leak due to the star finite angular size. The SNR for a 10hr observation is given assuming only photon noise, with a 20% system efficiency and a 20% wide spectral band.

Target	Teff [K]	Dist [pc]	L_{bol} [L_{sun}]	max sep. ["] | [λ/D]	m_V	star Diam [mas] | [λ/D]	Contrast source| background | star	10hr SNR (R=5)
α Cen A	5809	1.34	1.52	0.92 | 13.39	0.01	8.47 | 0.1232	1.15e-10 | 3.05e-11 | 2.95e-09	43.4
α Cen B	5259	1.34	0.50	0.53 | 7.68	1.34	5.93 | 0.0862	3.48e-10 | 8.92e-11 | 1.13e-08	39.7
ϵ Eri	5104	3.21	0.34	0.18 | 2.64	3.73	2.16 | 0.0314	5.12e-10 | 7.44e-10 | 7e-09	24.0
ϵ Ind	4621	3.62	0.22	0.13 | 1.88	4.68	1.88 | 0.0274	7.91e-10 | 1.47e-09 | 1.16e-08	20.4
τ Cet	5527	3.65	0.55	0.20 | 2.95	3.49	2.06 | 0.0300	3.18e-10 | 6.67e-10 | 5.2e-09	18.2
40 Eri	5311	4.98	0.46	0.14 | 1.98	4.43	1.50 | 0.0218	3.78e-10 | 1.49e-09 | 4.21e-09	14.7
61 Cyg A	4530	3.50	0.15	0.11 | 1.63	5.20	1.69 | 0.0246	1.14e-09 | 2.13e-09 | 4.7e-08	12.8
Procyon	6546	3.51	6.93	0.75 | 10.91	0.37	5.44 | 0.0791	2.51e-11 | 5.1e-11 | 1.21e-09	11.4
82 Eri	5418	6.04	0.74	0.14 | 2.07	4.26	1.51 | 0.0219	2.35e-10 | 1.39e-09 | 3.1e-09	10.7
70 Oph	4857	5.10	0.69	0.16 | 2.36	4.21	2.14 | 0.0311	2.53e-10 | 1.14e-09 | 6.96e-09	9.6
η Cas A	6105	5.94	1.29	0.19 | 2.78	3.46	1.59 | 0.0231	1.35e-10 | 7.88e-10 | 3.32e-09	8.6
δ Pav	5582	6.11	1.22	0.18 | 2.63	3.55	1.80 | 0.0262	1.43e-10 | 7.44e-10 | 4.86e-09	8.0
σ Dra	5418	5.75	0.47	0.12 | 1.74	4.67	1.26 | 0.0184	3.69e-10 | 1.92e-09 | 1.61e-08	7.2
Altair	7524	5.12	10.60	0.64 | 9.25	0.77	3.49 | 0.0507	1.64e-11 | 9.03e-11 | 8.96e-10	6.3
ξ Boo A	4761	6.78	0.83	0.13 | 1.96	4.67	1.85 | 0.0268	2.08e-10 | 1.98e-09 | 6.4e-09	5.9
36 Oph B	5104	5.95	0.40	0.11 | 1.55	5.08	1.27 | 0.0184	4.35e-10 | 2.66e-09 | 2.63e-08	5.7
β CVn	5638	8.44	1.15	0.13 | 1.85	4.24	1.24 | 0.0180	1.51e-10 | 1.53e-09 | 5.05e-09	5.5
ζ Tuc	5926	8.59	1.44	0.14 | 2.03	4.23	1.24 | 0.0180	1.21e-10 | 1.54e-09 | 2.87e-09	5.3
β Com	5926	9.13	1.36	0.13 | 1.85	4.23	1.13 | 0.0164	1.28e-10 | 1.51e-09 | 4.17e-09	5.0
χ^1 Ori	5926	8.66	1.08	0.12 | 1.74	4.39	1.06 | 0.0154	1.61e-10 | 1.77e-09 | 6.63e-09	4.8
χ Dra	6105	8.06	2.34	0.19 | 2.76	3.55	1.58 | 0.0230	7.45e-11 | 8.47e-10 | 3.27e-09	4.6
γ Pav	6105	9.26	1.52	0.13 | 1.93	4.21	1.11 | 0.0161	1.14e-10 | 1.57e-09 | 4.02e-09	4.5
γ Lep A	6417	8.93	2.69	0.18 | 2.67	3.59	1.39 | 0.0201	6.46e-11 | 9.2e-10 | 2.7e-09	4.1
ι Per	5985	10.54	2.55	0.15 | 2.20	4.05	1.31 | 0.0191	6.83e-11 | 1.31e-09 | 2.26e-09	3.6
61 Vir	5582	8.56	0.85	0.11 | 1.57	4.74	1.07 | 0.0156	2.05e-10 | 2.25e-09 | 1.89e-08	3.4
θ Per	6045	11.13	2.70	0.15 | 2.15	4.10	1.25 | 0.0182	6.45e-11 | 1.44e-09 | 2.06e-09	3.3

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What could go wrong ?

Is low-IWA, high efficiency coronagraphy HARDER than more conservative coronagraphy ?

Manufacturing components:

PIAA mirrors: OK (much easier than current PIAA)

Focal plane mask: challenging (similar to VVC, hybrid Lyot: need to control phase, amplitude)

→ manufacturing for small IWA, high efficiency ***coronagraphs TRL/schedule/cost challenges similar***

(note: except shaped pupil, probably easier)

Wavefront control:

Common wisdom: harder for high performance coronagraphs

… not so simple...

high throughput = faster correction → better contrast

low IWA = can relax contrast requirements

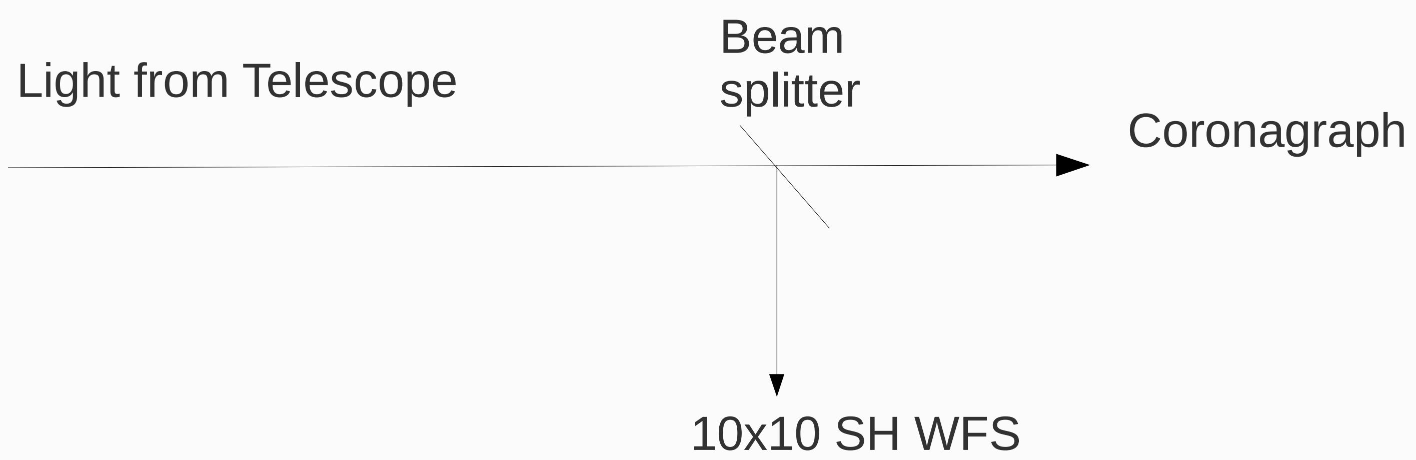
Low-order WF errors

Small-IWA tend to be more sensitive to pointing errors
Yes, but they are also more efficient at measuring pointing errors
LOWFS results at NASA JPL, Ames, and Subaru are very encouraging:
- 1e-4 l/D closed loop (HCIT)
- 1e-3 l/D closed loop with disturbances (HCIT)
- closed loop on sky, with PIAACMC, Vortex, and 4QPM (Subaru)
- post-processing removal of low order errors to 1% residual (Subaru)
- 5 modes corrected, low cross-talk (Subaru)

Requirements: ~1mas RMS jitter (~1e-2 l/D) + calibration to ~10x fainter than planet
Note: 1mas x 100x rejection factor = 0.1 arcsec
→ lets do analysis and find out...

High efficiency coronagraph with small FWHM will sense WF errors faster, therefore **RELAXING telescope stability requirements**

LOWFS options: the WRONG way to do it



PROBLEMS:

Sensitivity is poor: 100x loss in photon efficiency from using SHWFS

→ takes 100x longer to measure error to same level

Non-common path errors between coronagraph and LOWFS... what if coronagraph optics drift ?

How to **share light** between coronagraph and LOWFS

Adding a dichroic (or taking part of light) → risks of non-common path errors, loss in contrast performance

LOWFS options: the RIGHT way to do it

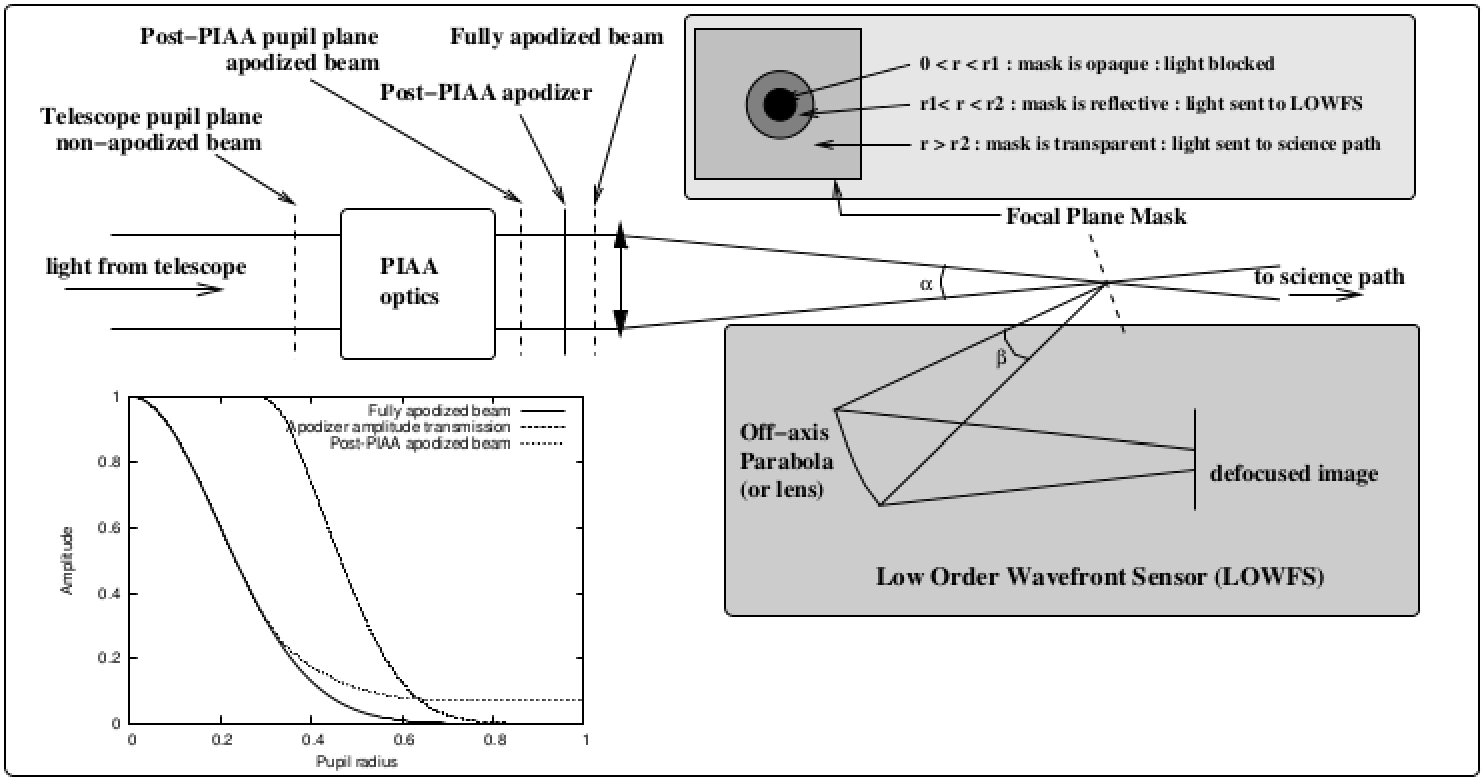


Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

See details in
Guyon et al. 2009

LOWFS sensitivity

See details in Guyon et al. 2009

Tip, focus, ast:
~1 rad RMS for 1 ph

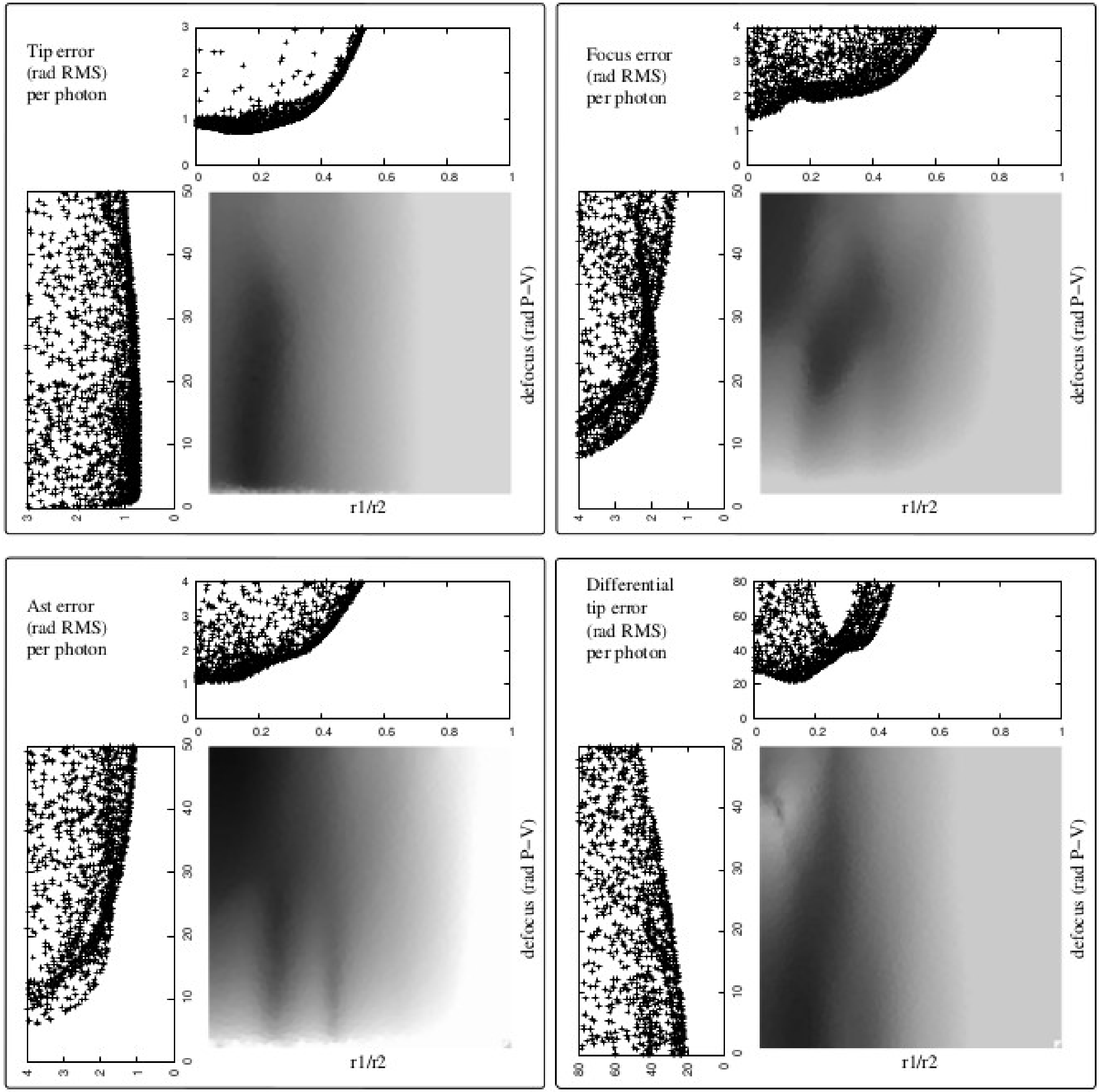


Fig. 7.— Tip (top left), focus (top right), astigmatism (bottom left) and differential tip (bottom right) sensitivity of the CLOWFS as a function of the relative size of the opaque disk in the focal plane mask (r_1/r_2) and the CLOWFS defocus distance. The sensitivity map is shown as a grey scale 2D map and the corresponding projection on the r_1/r_2 and $defocus$ axes are shown as plots above and to the left of each 2D map. Sensitivities are measured as the dispersion on a sample of 10^5 uncorrelated measurements with 10^6 photons at the telescope entrance each, and are shown here scaled to one photon (equal to the dispersion multiplied by the square root of the number of photon).

LOWFS rejection → telescope pointing tolerance

UNKNOWN Pointing drift and vibration tolerance
Star mV=5, 10% efficiency, 20% band
→ zero pt = 4e9 ph/s → 4e7 ph/s for mV=5

Tolerance: 1 mas = 1/47 l/D = 0.0334 rad RMS tip

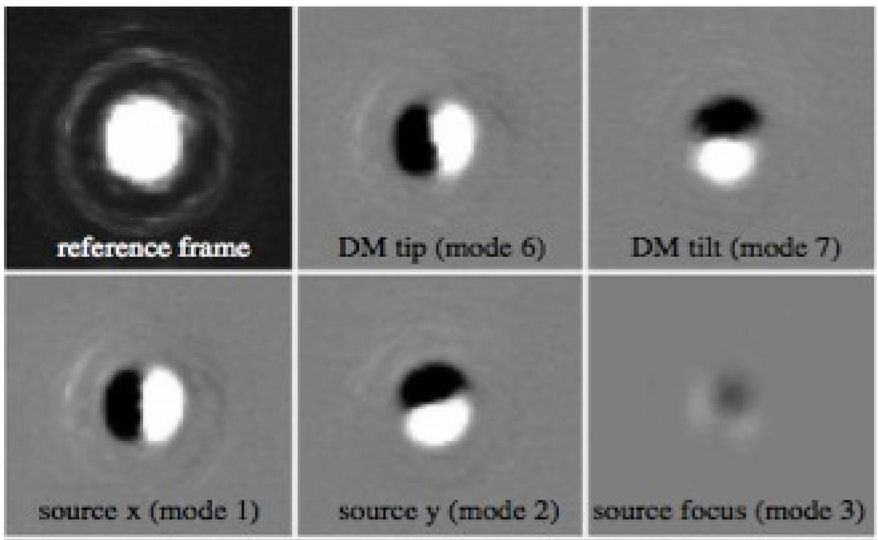
It will take 895 ph to measure this tip (44 kHz)
Assuming 10x speed loss between measurement and correction:
4 kHz (more realistic)

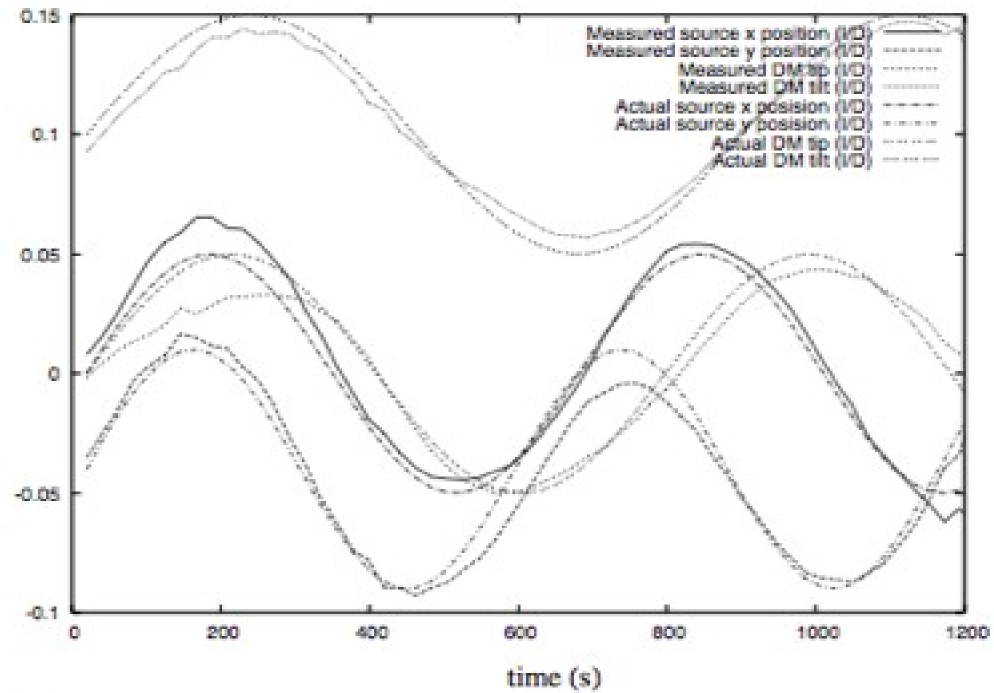
Assuming simple integrator control law (no PID), maximum unknown tip drift speed = 4” per sec

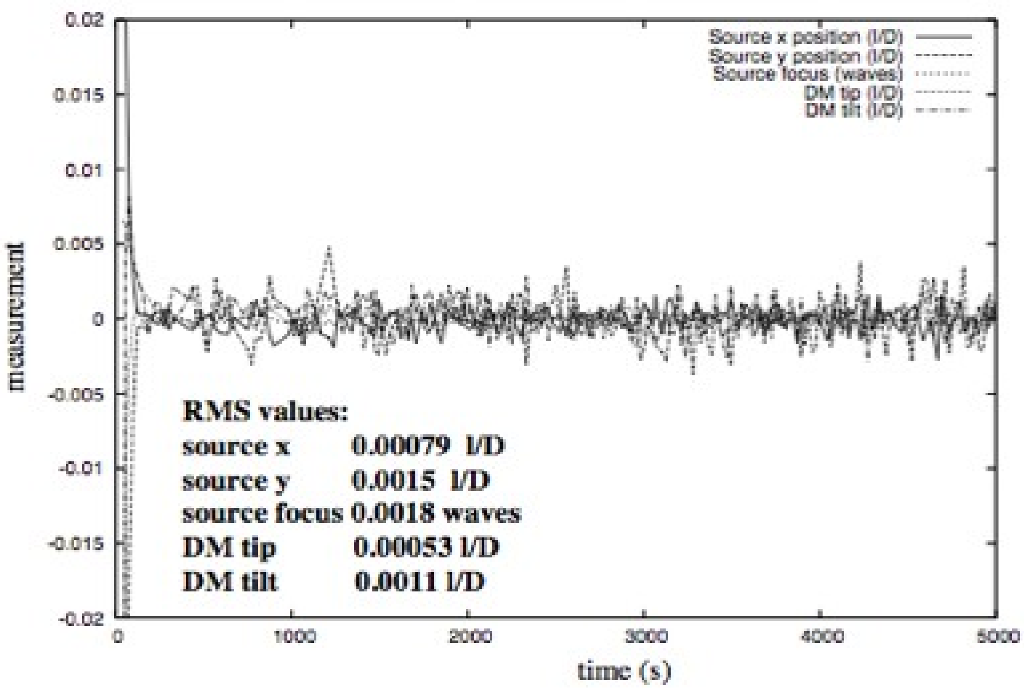
Allowable telescope vibration level:
2 Hz : 0.4” (& 400x rejection)
16 Hz: 40mas (& 40x rejection)
160 Hz : 4 mas (& 4x rejection)

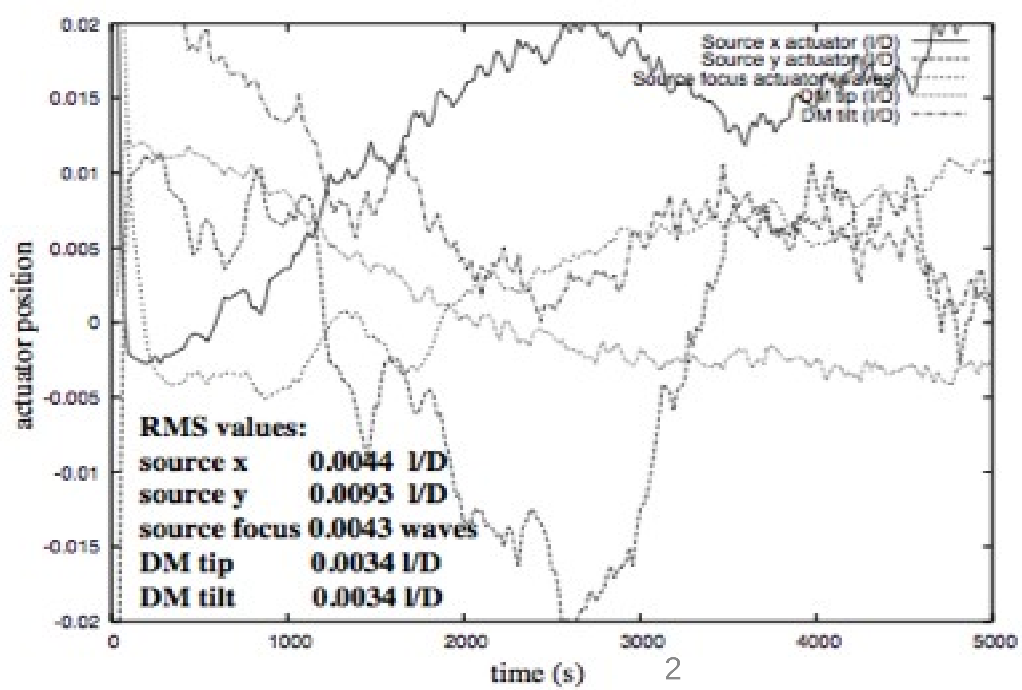
Guyon et al. 2009 (in air)

trol demonstrated to 1e-3 λ/D in visible



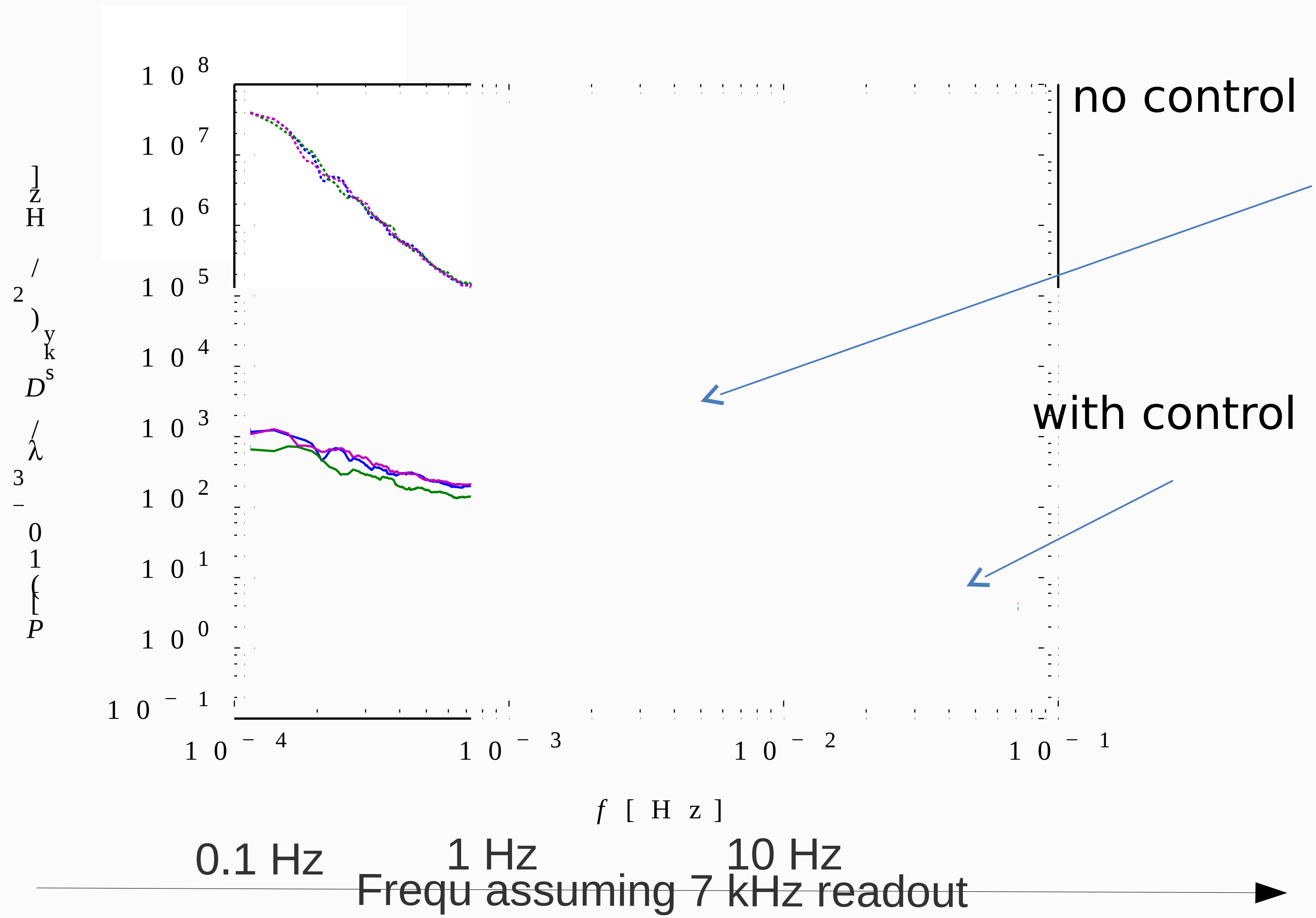






Measured LOWFS rejection (HCIT, Kern et al.)

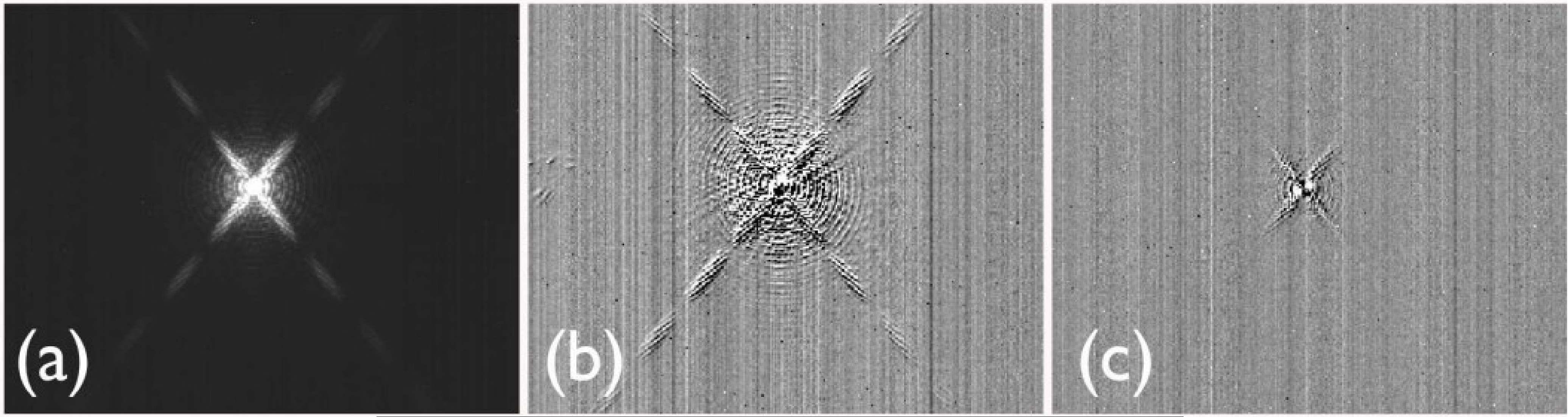
Note: One frame every 7sec (had to wait 7sec to have camera cool between exposures)

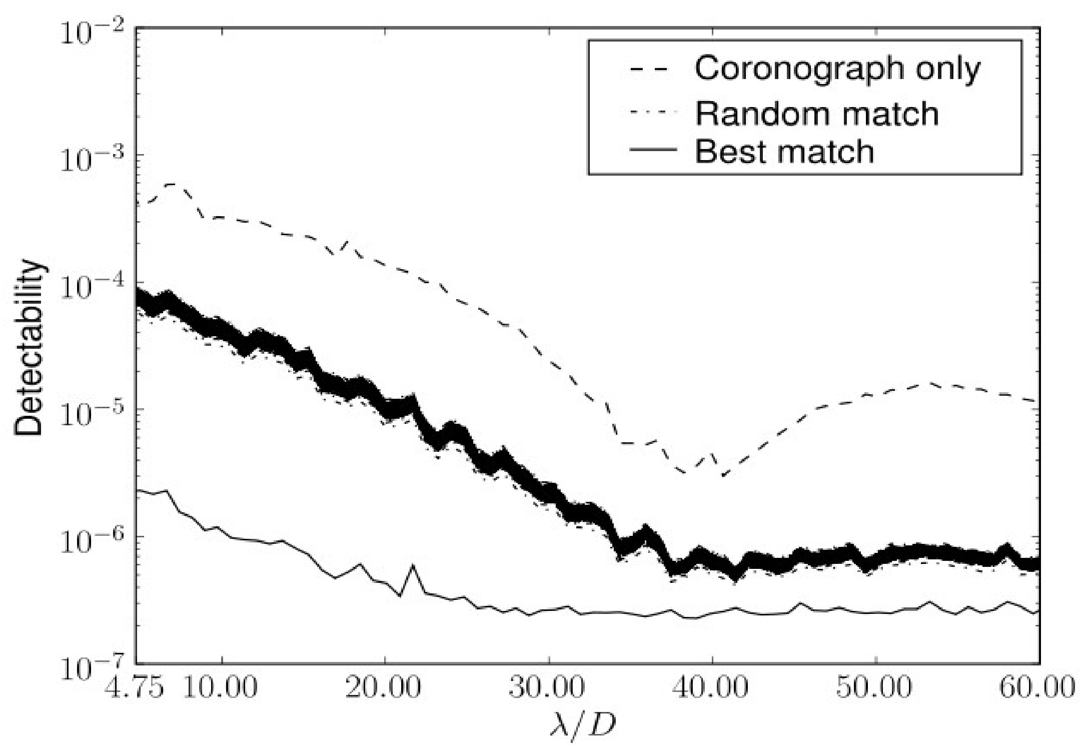


At low frequency : >4 orders of magnitude suppression measured

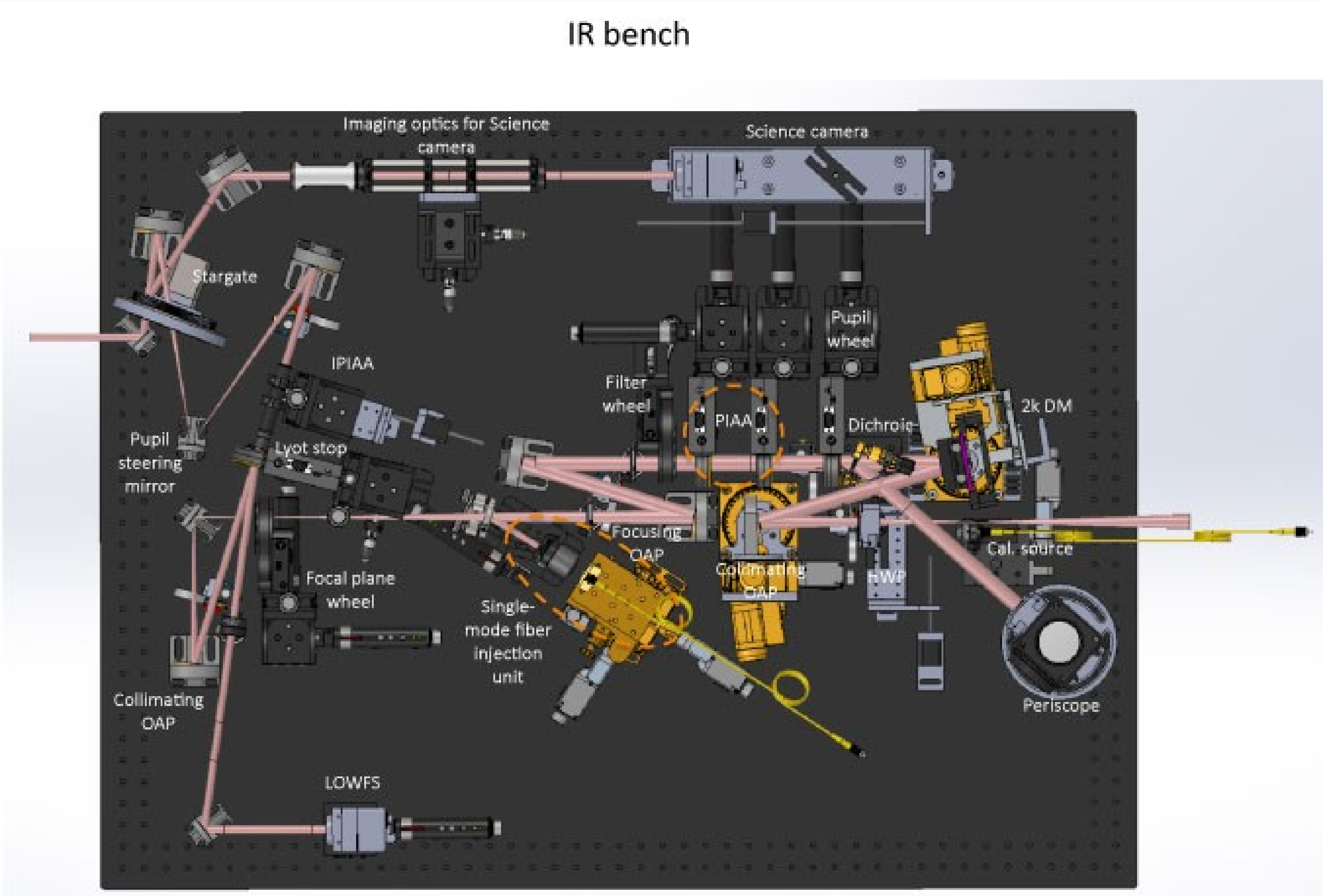
Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011)

Co-added science image
Standard PSF subtraction
MMA





The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system: LOWFS with any Lyot type coronagraph



PIAACMC: summary

IWA + high efficiency considerably increases science yield and reduces exposure times
Allows relaxing telescope requirements … should be quantified / analyzed: small IWA coronagraph system may be simpler than ~3 l/D coronagraph system when everything is considered

PIAACMC is full efficiency solution with 1.26 l/D IWA and 4^{th} order null

PIAACMC is simpler than old PIAA designs: no need for apodizer, aspheric shapes are milder and easier to add to existing optics in design → ongoing and future work to keep design simple
Experience acquired with Vortex and Lyot for focal plane mask design/manufacturing → pick optimal design

Lets play !

Suggestions for path forward

Downselect early… between Lyot-type architectures and visible nuller (because these two approaches are quite different in technology needs and instrument design)

Assuming Lyot-type architecture is selected...
DO NOT downselect within Lyot-type architectures until we know (1) how well we can control and calibrate the WF, (2) what masks can/cannot be manufactured.

DO NOT try to maintain two testbeds: build and maintain a single testbed with the A-team, including members from all point design teams

Adopt a mask that is ready now (shaped pupil ?), but keep working on other masks/components and change masks as needed

Different coronagraphs ?

Difference between Lyot-type coronagraphs (especially Vortex, Hybrid Lyot and PIAA) is very small (in technology) and has been artificially amplified by competitive TDEM process and misleading statements.

Small teams/groups have been established in a competitive environment
→ Much time has been wasted tracking testbed / system issues that have nothing to do with point design, with small team working part time on testbed.
→ expertise is distributed among teams with poor communication between teams and few opportunities to work across teams

Coronagraph design and WF control

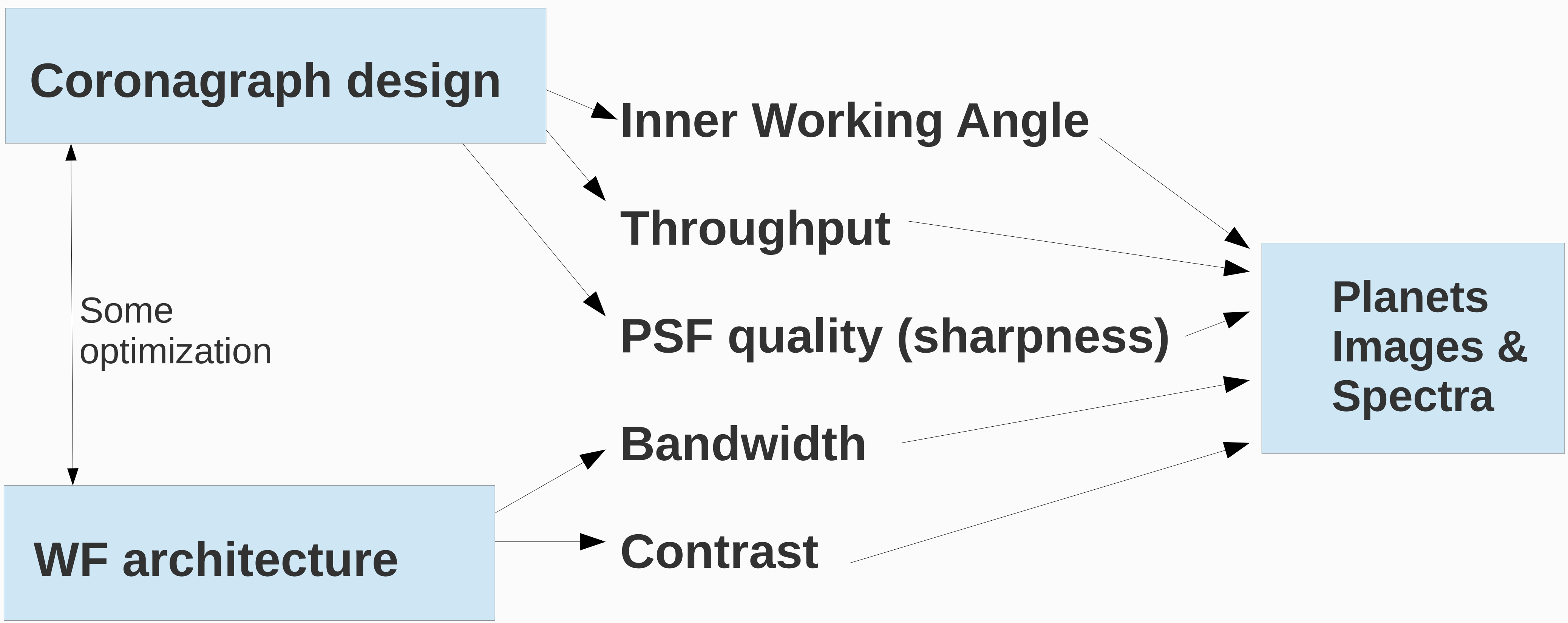
Coronagraphs OPEN up area of focal plane for the wavefront control to operate and remove speckles

Coronagraph design provides transmission between IWA and OWA, and PSF sharpness

Wavefront control removes (in broadband) starlight from this area

Some optimization of coronagraph components and WF control architecture required so that they play nicely together (make it easy for WFC to do its job)

Coronagraph design and WF control

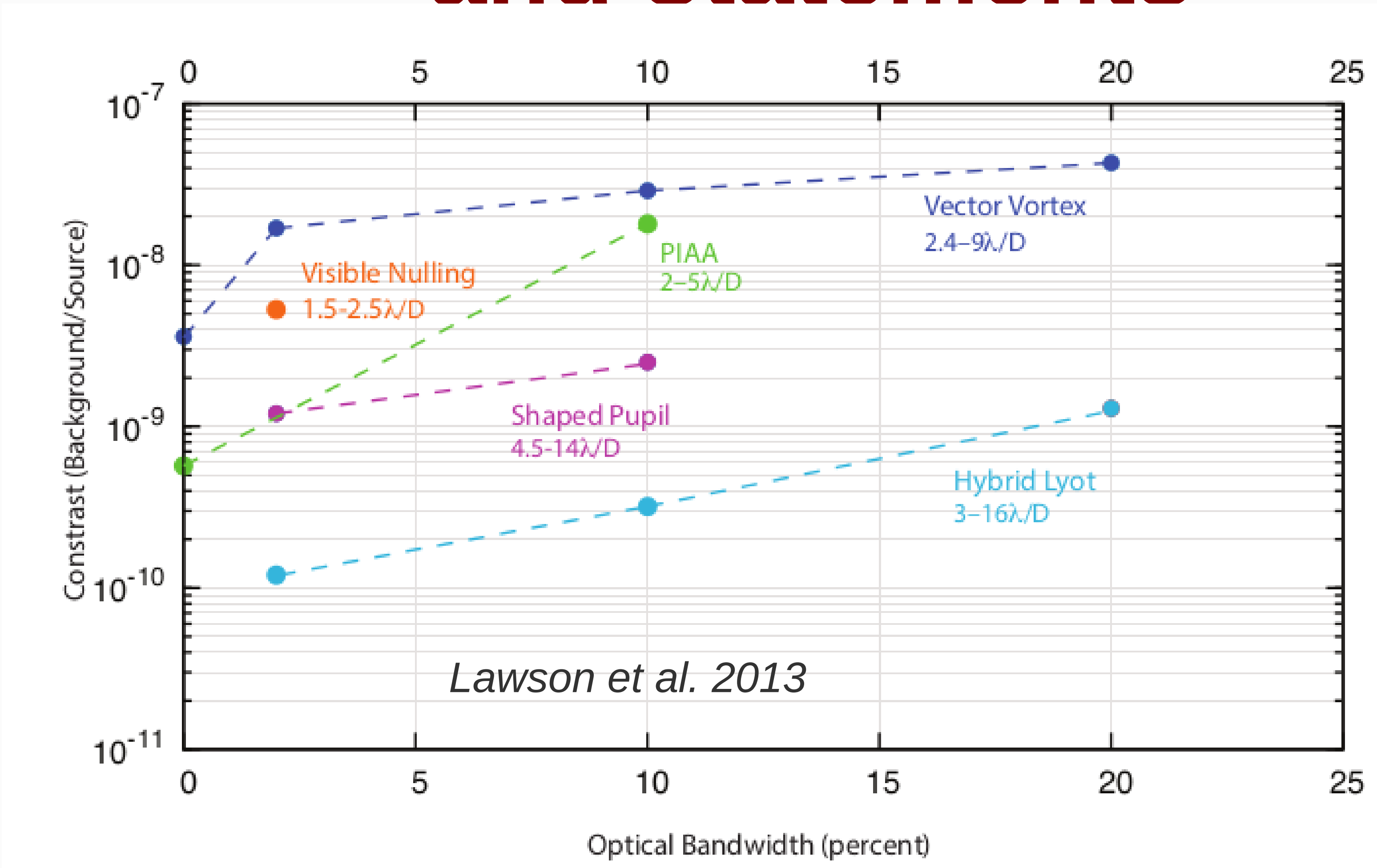


Examples of misleading material and statements

Back a couple yrs ago …
"PIAA gets to 1e-7 contrast monochromatic light, hybrid Lyot below 1e-9 contrast in 10% band"

Should be:
Wavefront control in air gets you to 1e-7 contrast, in vacuum (+lots of experience) gets you below 1e-9 contrast

Examples of misleading material and statements



This is not a comparison between coronagraph concepts...
It shows what is gained by joint polychromatic WFC+mask optimization

We should concentrate on a <u>single testbed</u>

Maintaining two testbeds is a waste of resources and WILL slow down progress (repeating past mistakes...)

If 1st testbed is really a top priority, second testbed will lag behind and will not be very useful

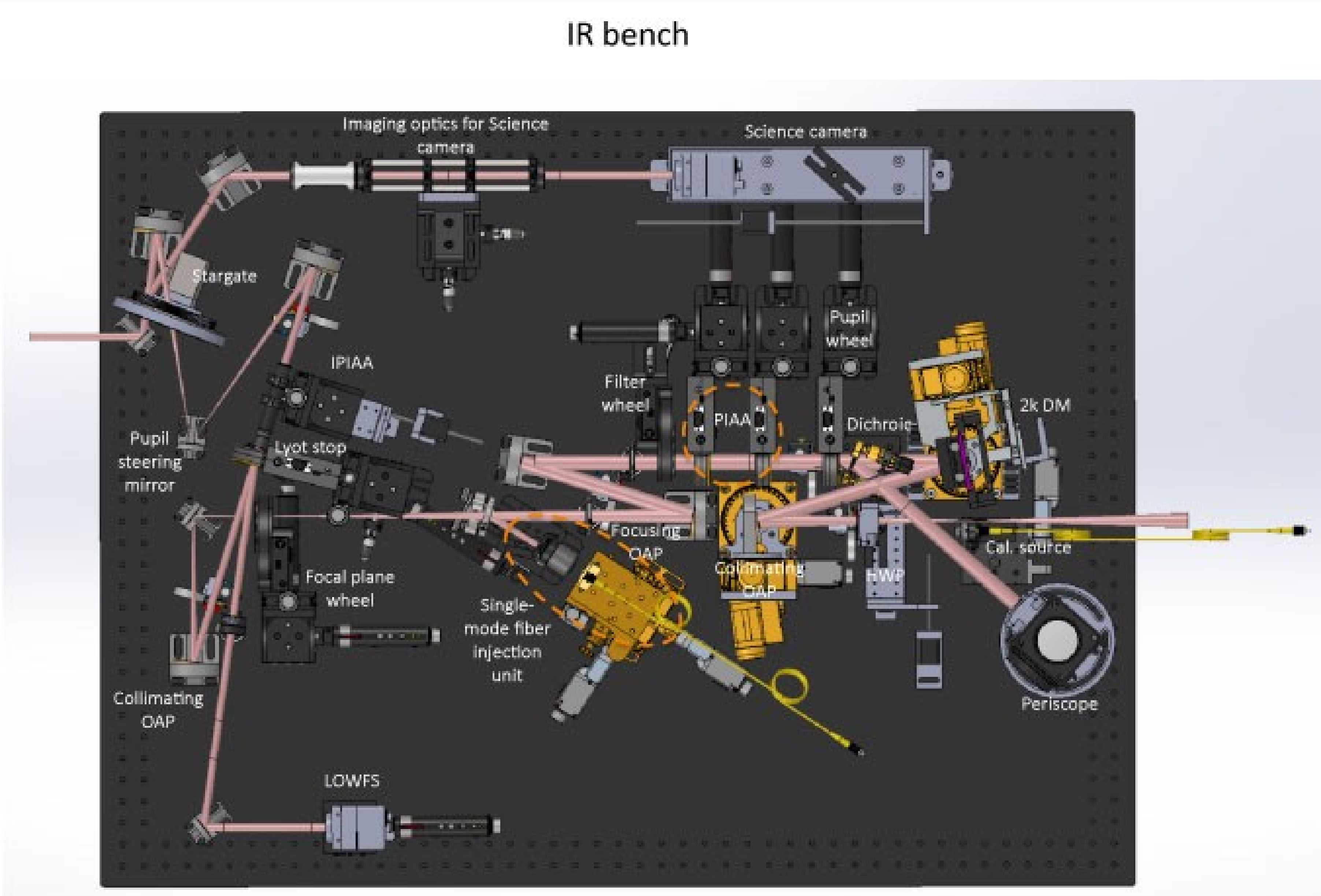
We should hit the tough problems (system level WF control) ASAP, with one mask (does not matter much which one)

Is it realistic to assemble a testbed that is generic enough to support several point designs ?

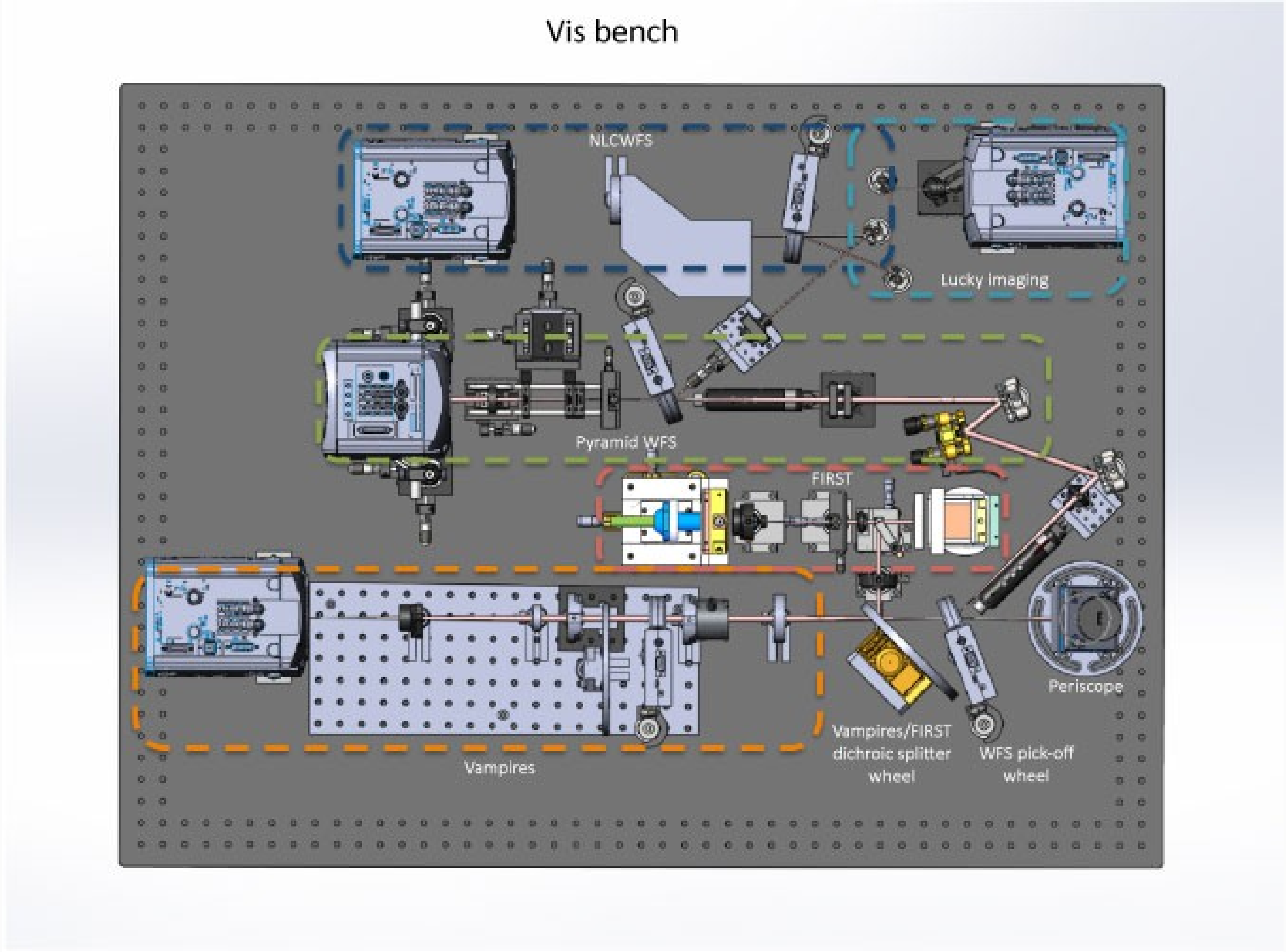
    YES (see following example)

    We NEED to think about it NOW, and can move forward with testbed design NOW

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system

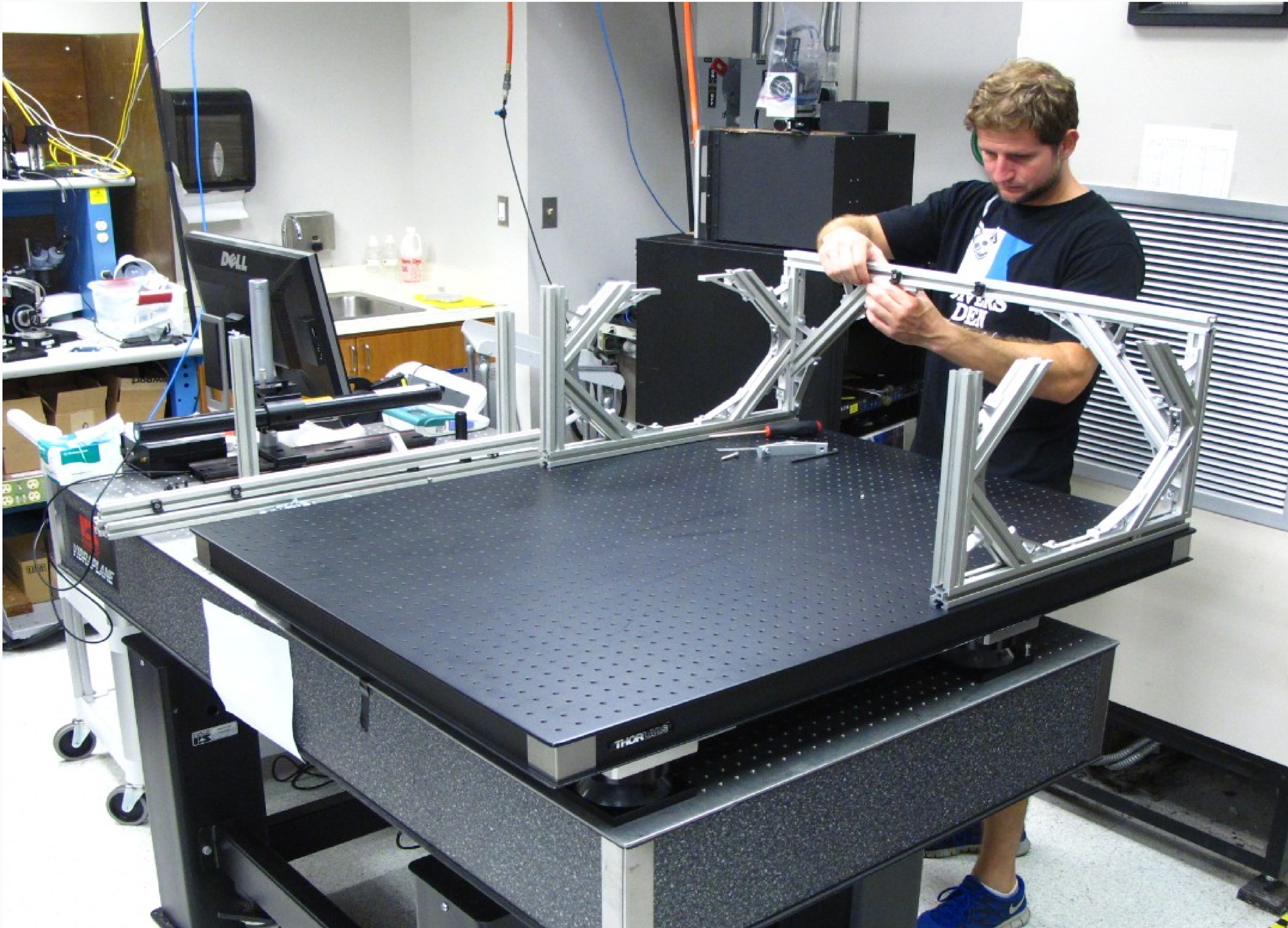


The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system

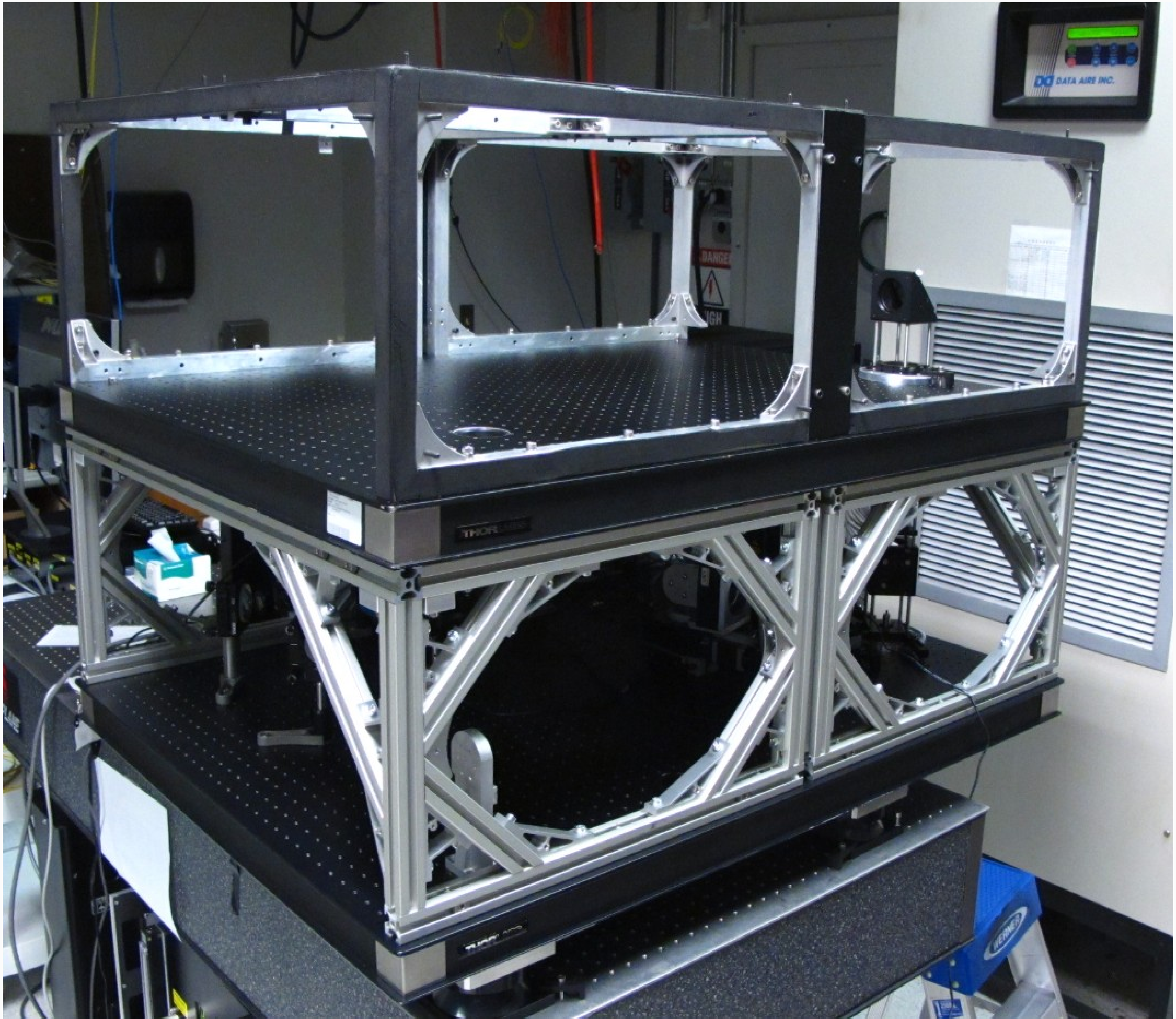


SCExAO – June 19 2013

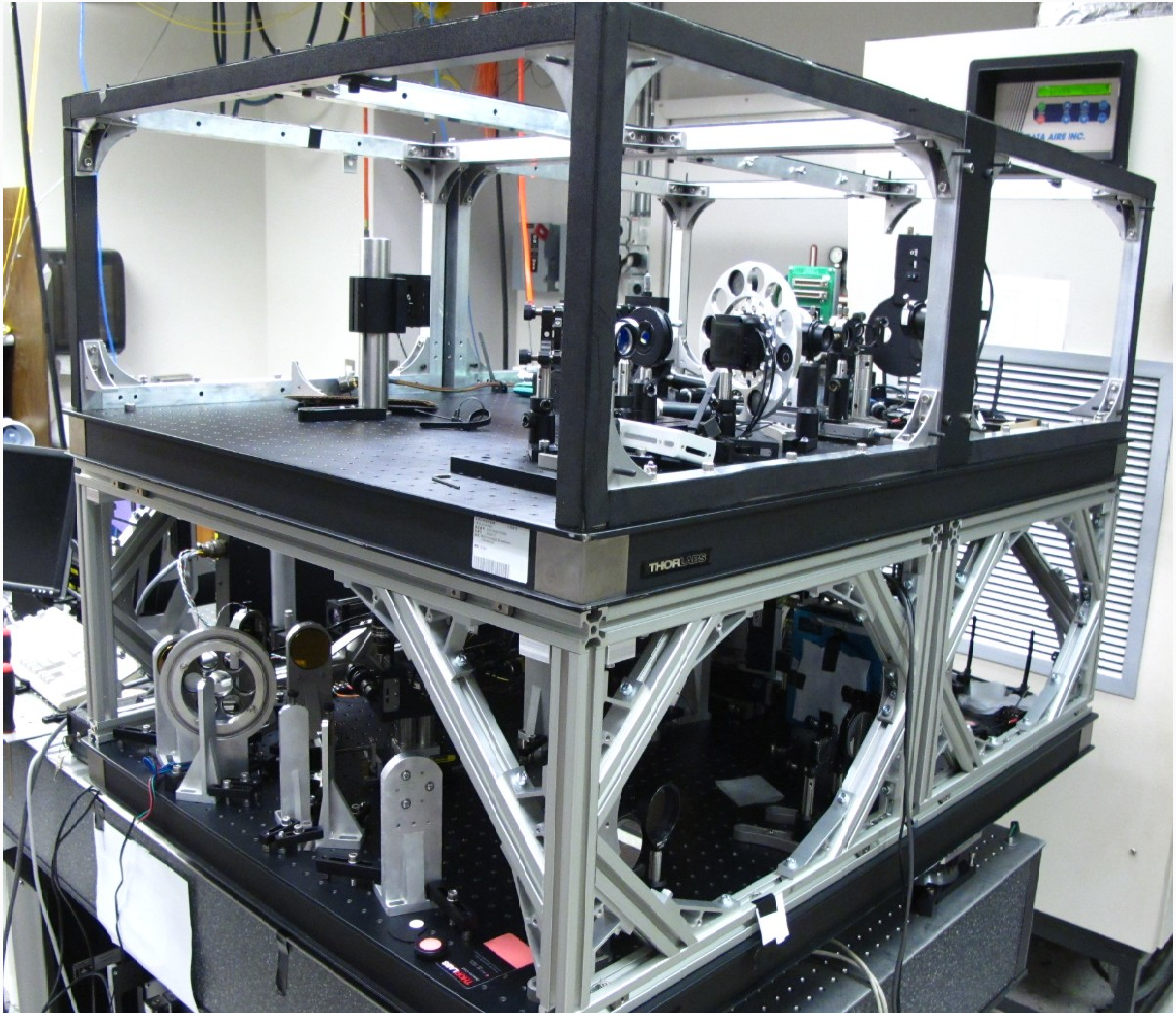
SCExAO – June 20 2013



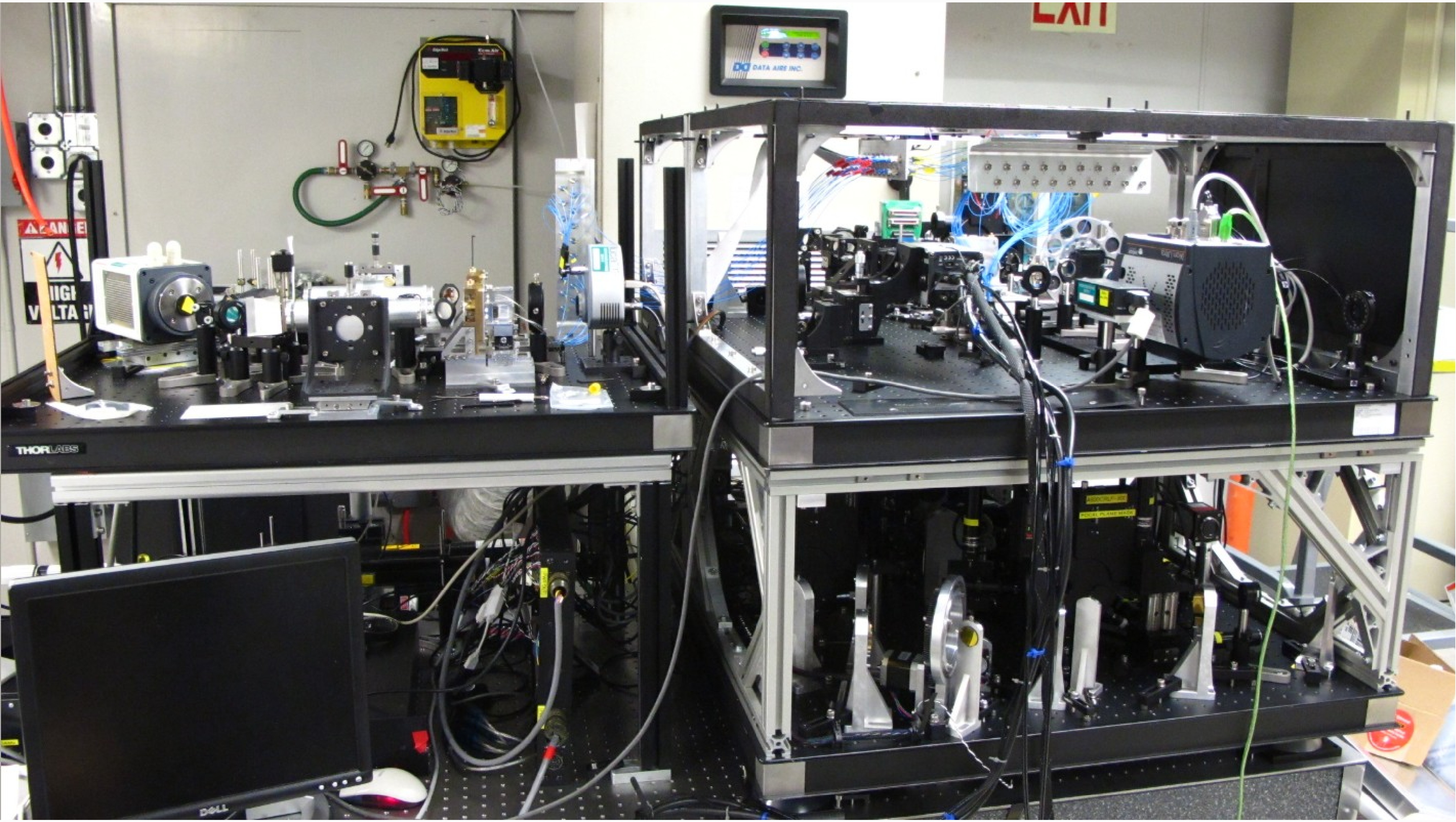
SCExAO – June 22 2013



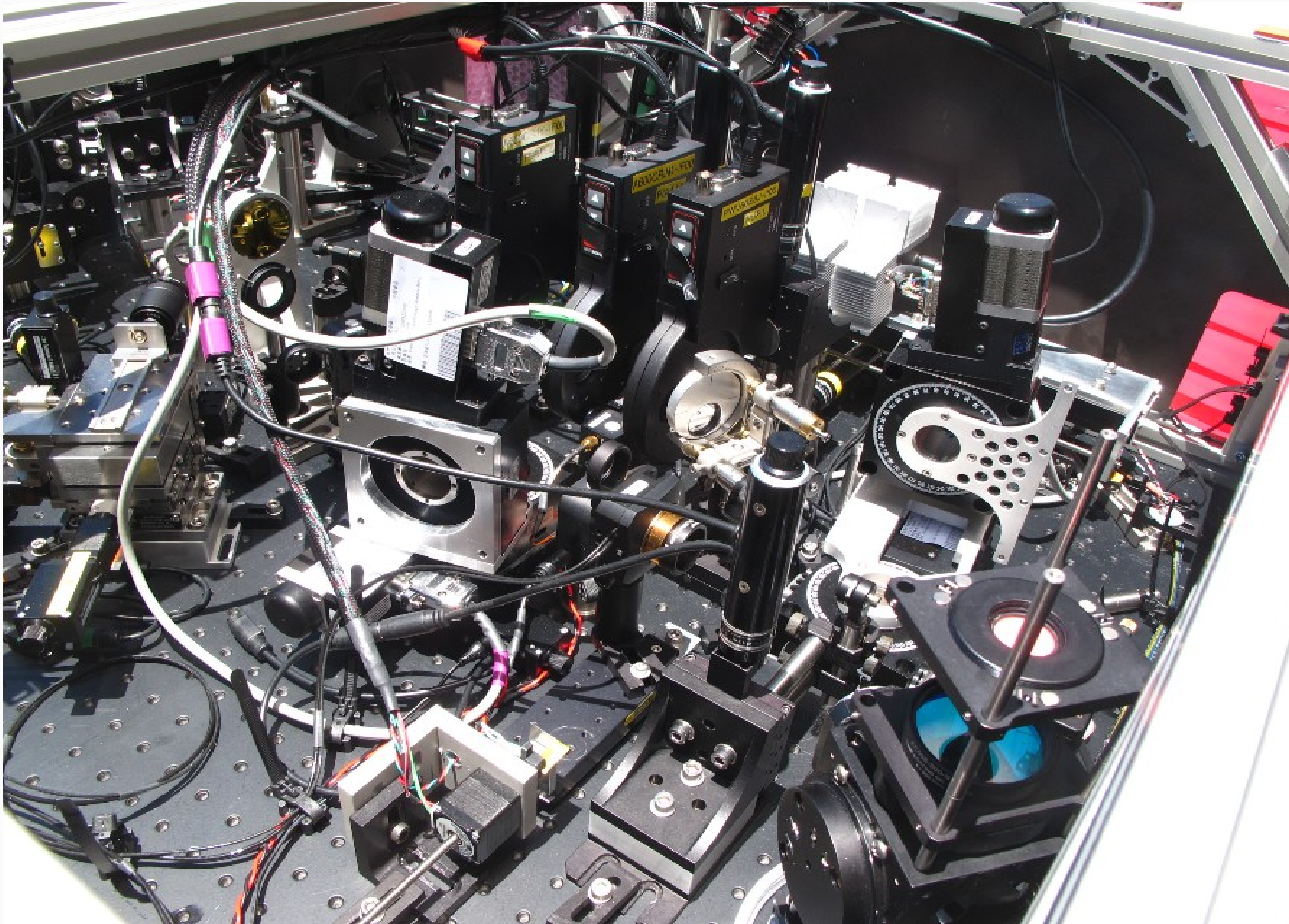
SCExAO – June 29 2013

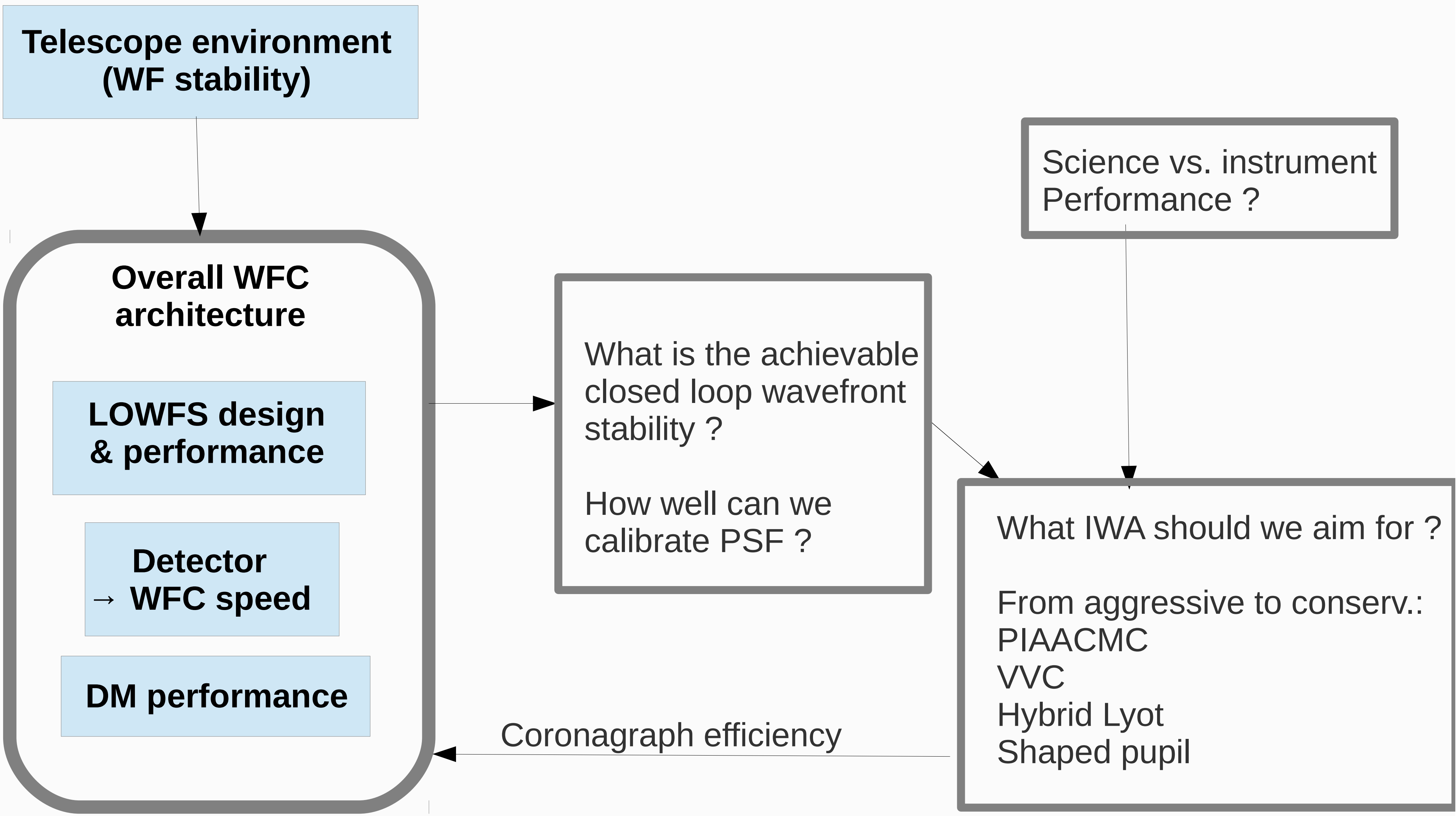


SCExAO – July 10 2013



Detail (coronagraph optics)




Telescope environment
(WF stability)
Science vs. instrument
Performance ?
Overall WFC
architecture
LOWFS design
& performance
Detector
→ WFC speed
DM performance
What is the achievable
closed loop wavefront
stability ?
How well can we
calibrate PSF ?
What IWA should we aim for ?
From aggressive to conserv.:
PIAACMC
VVC
Hybrid Lyot
Shaped pupil
Coronagraph efficiency