# Direct Imaging of Nearby Exoplanets with a Small Size Telescope: Telescope to Observe Planetary Systems (TOPS)

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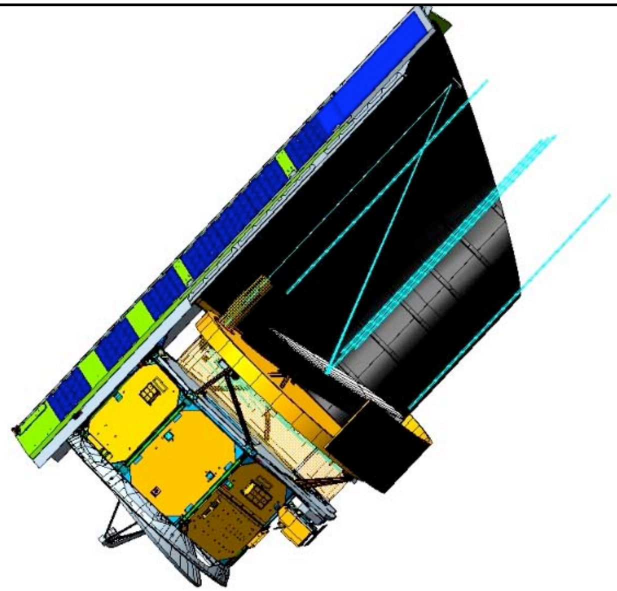
## TOPS overview

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

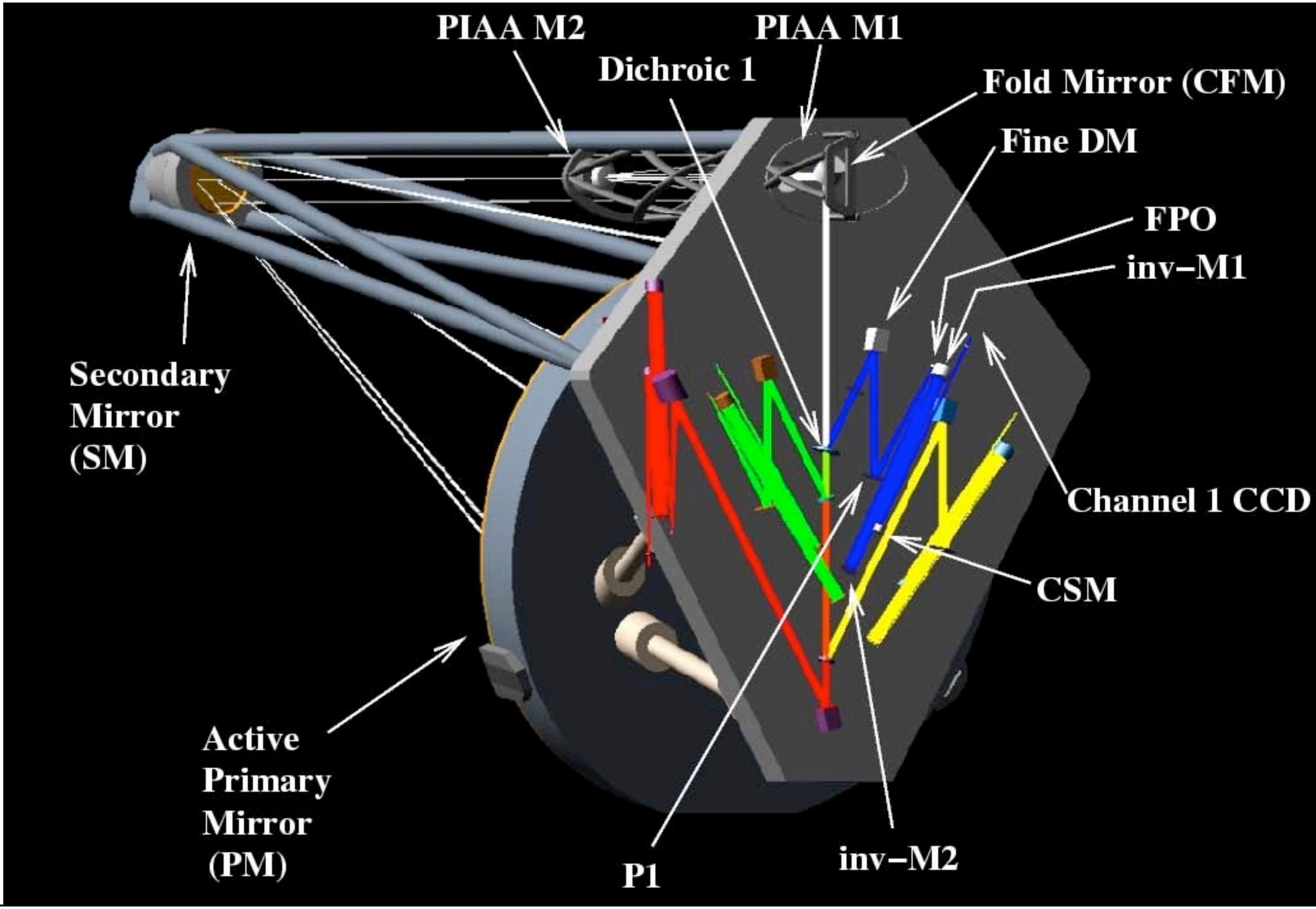


Originally proposed as a DISCOVERY-class mission:

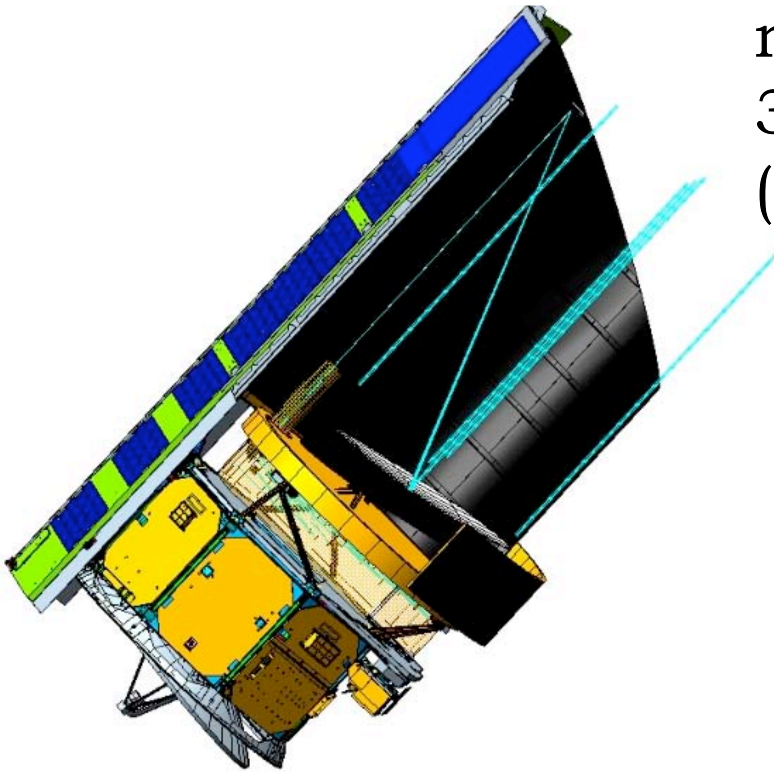
- 1.2m diameter off-axis telescope -> **If sized at ~2m, can detect & characterize Exo-Earths**
- 0.4 – 0.9 micron spectral coverage / R~20
- High contrast coronagraphic imaging of a narrow field of view with **efficient PIAA coronagraph**
- Active primary mirror -> thermal actuation
- Efficient wavefront control scheme
- Extremely stable Optical Telescope Assembly (OTA)

**Ongoing technology development**

# TOPS Optical Telescope Assembly



## Providing a stable environment for high contrast imaging



**Earth-trailing orbit** (Spitzer-like)
receding at ~0.11 AU per year
3-year mission baseline
(5-year would be possible)

**Disturbance-free payload**
OTA "floats" within the spacecraft with no mechanical contact.
Electromagnets control OTA position & pointing within spacecraft

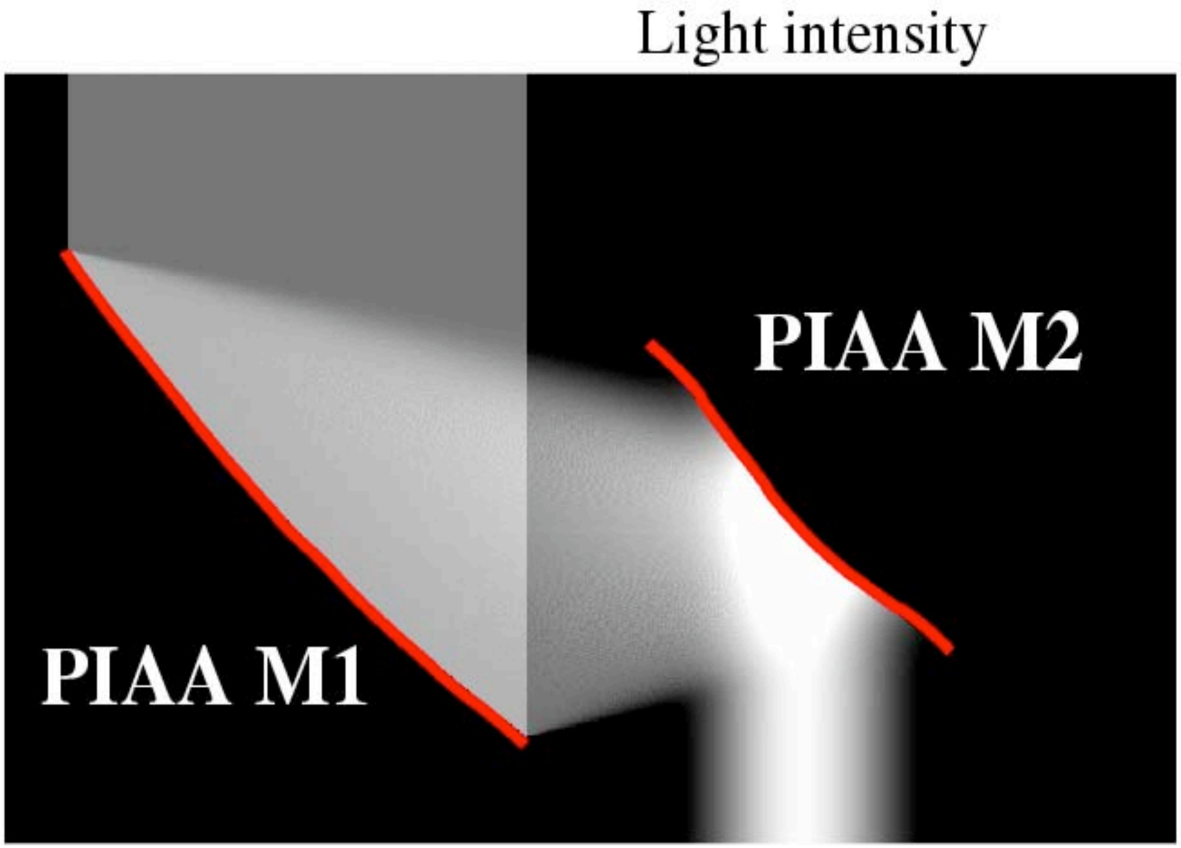
**Coronagraph Choice & Performance**

**Why a PIAA coronagraph ?**

What science can we do with choices of coronagraph architectures / telescope size ?

**Ongoing technology development**

How to get there ?




Nearly 100% throughput
100% search area
small (<2 lambda/d) Inner Working Angle

# Many Coronagraph Choices...

Coronagraphs able to achieve $10^{10}$ PSF contrast within 5 $\lambda/d$

| Coronagraph | abrev. | reference | Design(s) adopted |
|---|---|---|---|
| **"Interferometric" Coronagraphs** | | | |
| Achromatic Interferometric Coronagraph | AIC | Baudoz et al. (2000) | |
| Common-Path Achromatic Interferometer-Coronagraph | CPAIC | Tavrov et al. (2005) | (=AIC) |
| Visible Nulling Coronagraph, X-Y shear ($4^{th}$ order null)[a] | VNC | Mennesson et al. (2003) | Shear distance = ±0.3 pupil radius |
| Pupil Swapping Coronagraph | PSC | Guyon & Shao (2006) | Shear distance = 0.4 pupil diameter |
| **Pupil apodization** | | | |
| Conventional Pupil Apodization and Shaped-Pupil[b] | CPA | Kasdin et al. (2003) | Prolate[c]($r = 4.2\lambda/d$, 8% throughput) |
| Achromatic Pupil Phase Apodization | PPA | Yang & Kostinski (2004) | $\phi = \phi_2(x) + \phi_2(y)$; $a = 2$; $\epsilon = 0.01$ |
| Phase Induced Amplitude Apodization Coronagraph | PIAAC | Guyon (2003) | Prolate apodization |
| Phase Induced Zonal Zernike Apodization | PIZZA | Martinache (2004) | Not simulated |
| **Improvement on the Lyot concept with amplitude masks** | | | |
| Apodized Pupil Lyot Coronagraph | APLC | Soummer et al. (2003) | $r = 1.8\lambda/d$ |
| Apodized Pupil Lyot Coronagraph, $N$ steps | $\mathrm{APLC}_N$ | Aime & Soummer (2004) | $(N, r) = (2, 1.4); (3, 1.2); (4, 1.0)$ |
| Band limited, $4^{th}$ order[a] | BL4 | Kuchner & Traub (2002) | $\sin^4$ intensity mask, $\epsilon = 0.21$ |
| Band limited, $8^{th}$ order | BL8 | Kuchner et al. (2005) | $m = 1, l = 3, \epsilon = 0.6$ |
| **Improvement on the Lyot concept with phase masks** | | | |
| Phase Mask | PM | Roddier & Roddier (1997) | with mild prolate pupil apod. |
| 4 quadrant | 4QPM | Rouan et al. (2000) | |
| Achromatic Phase Knife Coronagraph | APKC | Abe et al. (2001) | (=4QPM) |
| Optical Vortex Coronagraph, topological charge $m$ | $\mathrm{OVC}_m$ | Palacios (2005) | $m = 2, 4, 6, 8$ |
| Angular Groove Phase Mask Coronagraph | AGPMC | Mawet et al. (2005) | (=OVC) |
| Optical Differentiation | ODC | Oti et al. (2005) | mask: $x \times \exp^{-(x/10)^2}$[d] |

[a]The Visible Nulling Coronagraph (VNC) and Band limited $4^{th}$ order (BL4) coronagraphs belong to the same class of pupil-shearing $4^{th}$ order coronagraphs, and are simply 2 ways of achieving the same result. They can be designed to have exactly the same performance. In this Table, the VNC is chosen with a small IWA and 2 orthogonal shear directions, while the BL4 is designed with a larger IWA and 2 shears in the same direction. To reflect this similarity, they are referred to as VNC/BL4(1) for the small IWA option (listed as VNC in this Table) and VNC/BL4(2) for the large IWA option (listed as BL4 in this Table).

[b]The CPA design adopted here is a continuous apodization (rather than binary apodization/shaped pupil) which maximizes the radially averaged performance at $\approx 4\lambda/d$. More optimal designs exist in other conditions: CPA with high contrast at specific position angles for observations at $\approx 3\lambda/d$ or high throughput CPA for observations at $> 4\lambda/d$.

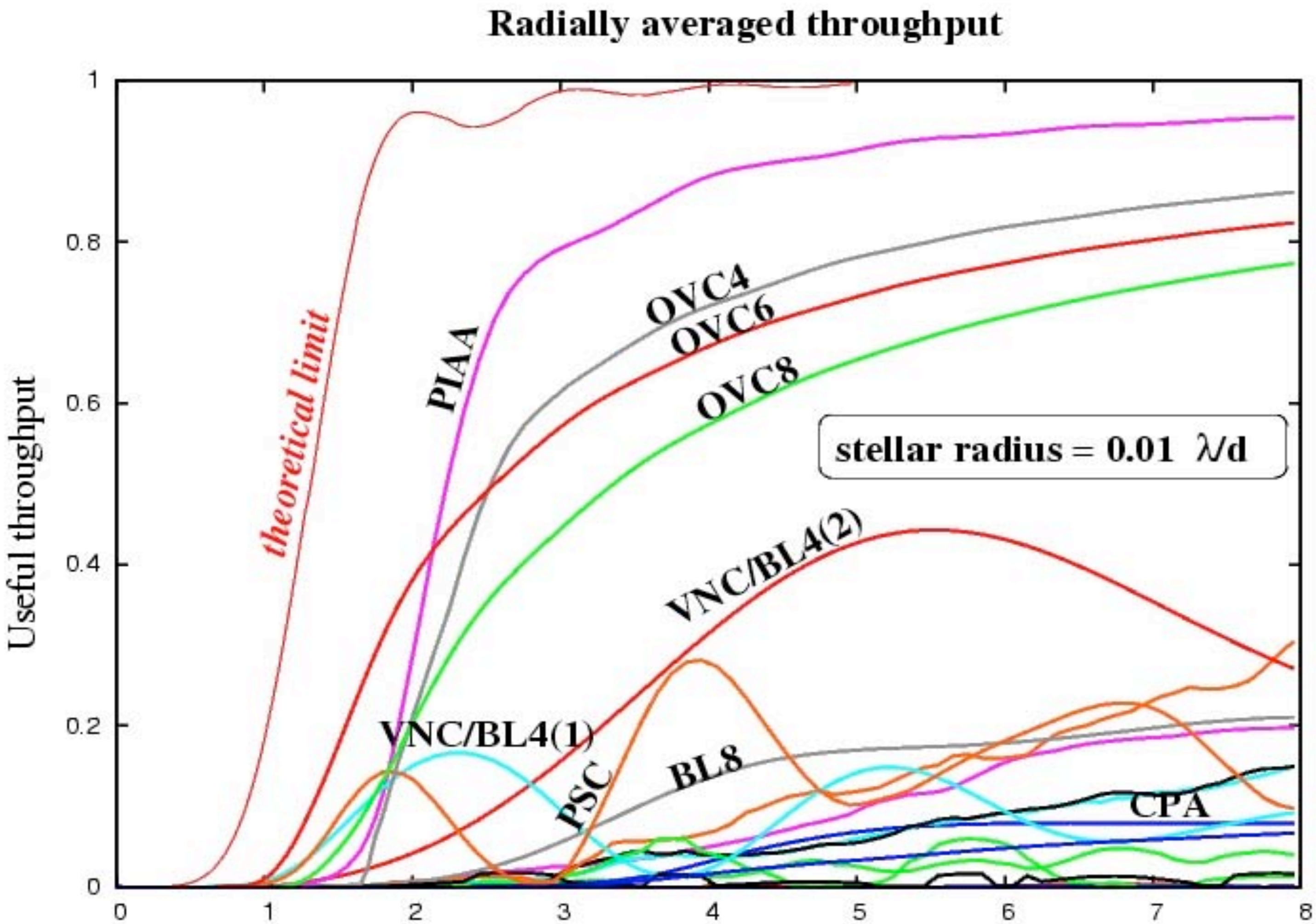
[c]CPA, APLC, $\mathrm{APLC}_N$: $r$ is the radius, in $\lambda/d$, of the mask within which the circular prolate function is invariant to a Hankel transform. This parameter is half of the mask diameter $a$ defined in Soummer et al. (2003).

[d]ODC: x is in $\lambda/d$. Maximum mask transmission at $7\lambda/d$. Lyot pupil mask radius = 0.85 times pupil radius.

Problem: stars are not points !
Sun diameter ~1% of 1 AU
If 1AU=2 l/d, Stellar radius ~ 0.01 l/d
Wavefront control cannot solve it

Fundamental physics tells us limits of coronagraphy

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



# Coronagraph Choice

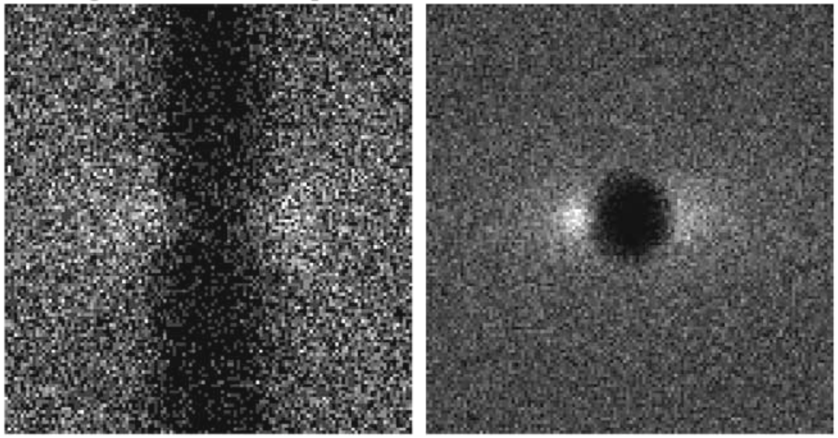
Best coronagraphs are less technologically mature.

There are **huge performance differences** between coronagraphs.

For example, Conventional Pupil Apodization (CPA) has 1/10$^{th}$ the throughput of PIAA.
Amount of starlight detected by PIAA @ 1.5 l/d = CPA @ 4.2 l/d.

<u>Other benefits of high-perf. Coronagraphs:</u>

- better angular resolution
  -> **less exozodi/zodi mixed** with planet
  -> less confusion, **smaller # of revisits** needed
  -> faster active AO correction leads to **better wavefront quality**




Direct imaging of a large terrestrial planet (2x Earth diameter) at 2 AU around a Sun−like star at 6 pc.

**1.2 m telescope with TPF baseline coronagraph sees dust but not planet found by TOPS**

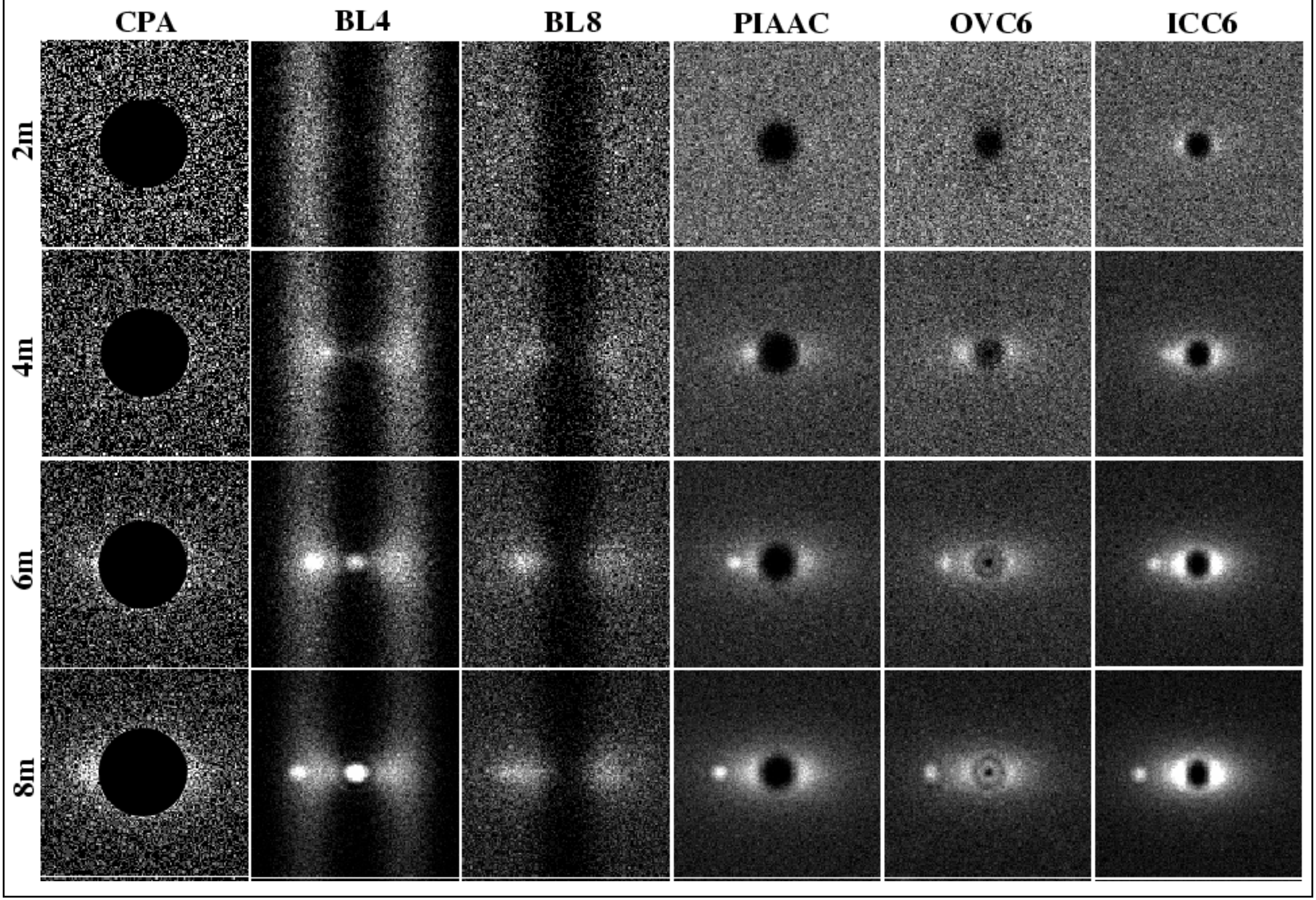
**PIAA's advanced technology is equivalent to <u>2x to 3x increase</u> in telescope diameter (2m PIAA ~ 4m BL8 ~ 5m CPA) – allows great science with TOPS affordable aperture**

**Example:**

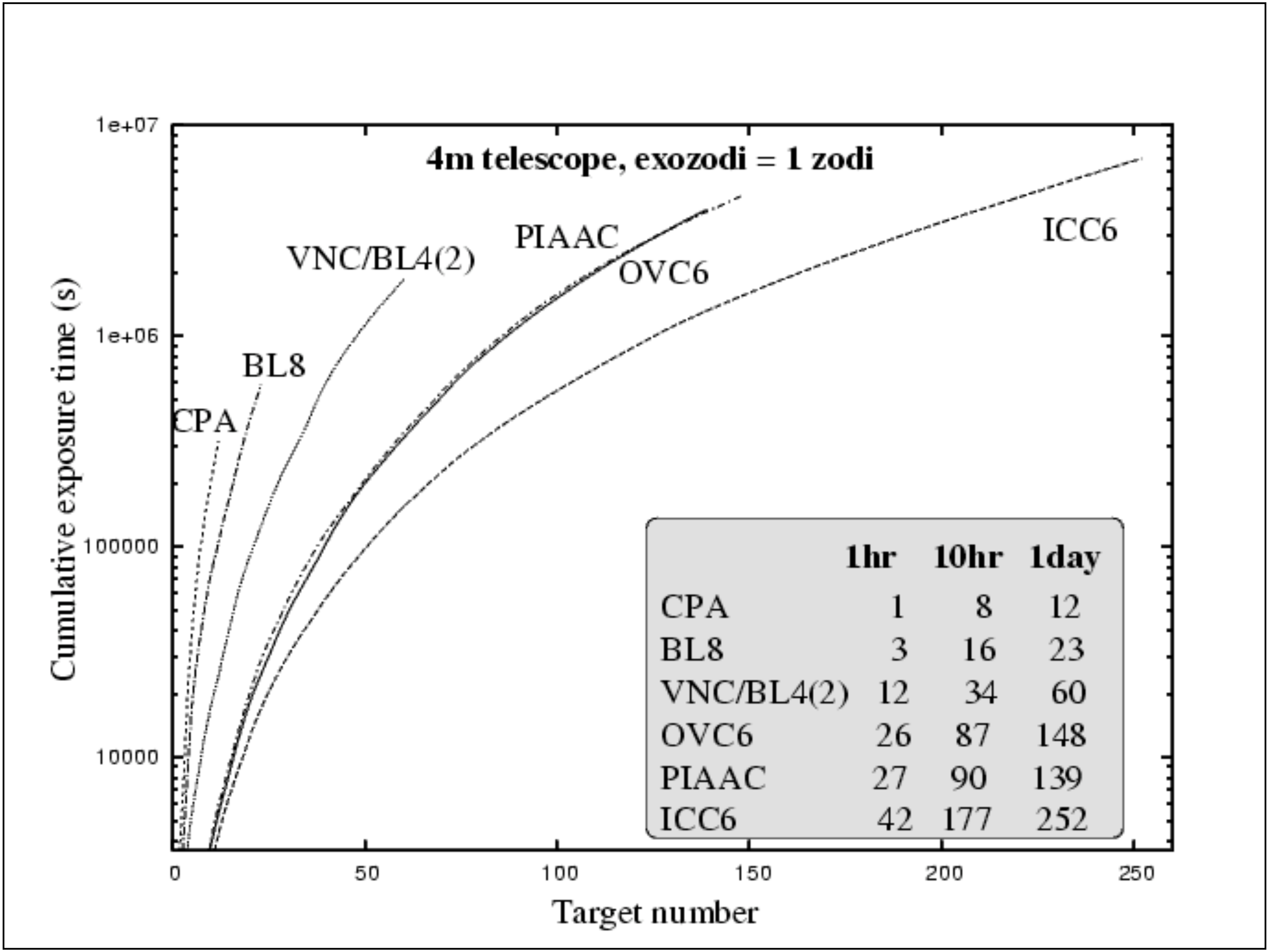
HIP 56997 (G8 star at 9.54pc)
0.55 micron, 0.1 micron band
Planet at maximum elongation (80 mas)
Earth albedo = 0.3 (C=6e9)
4h exposure, 0.25 throughput, perfect detector

Exozodi : 1 zodi
System observed at time when zodi is minimal

Each image is 20x20 lambda/d



CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m



4m telescope, exozodi = 1 zodi
Cumulative exposure time (s)
Target number
1e+07
1e+06
100000
10000
0
50
100
150
200
250
CPA
BL8
VNC/BL4(2)
PIAAC
OVC6
ICC6
1hr 10hr 1day
CPA 1 8 12
BL8 3 16 23
VNC/BL4(2) 12 34 60
OVC6 26 87 148
PIAAC 27 90 139
ICC6 42 177 252

# Effective exposure times in 0.5-0.6 micron band

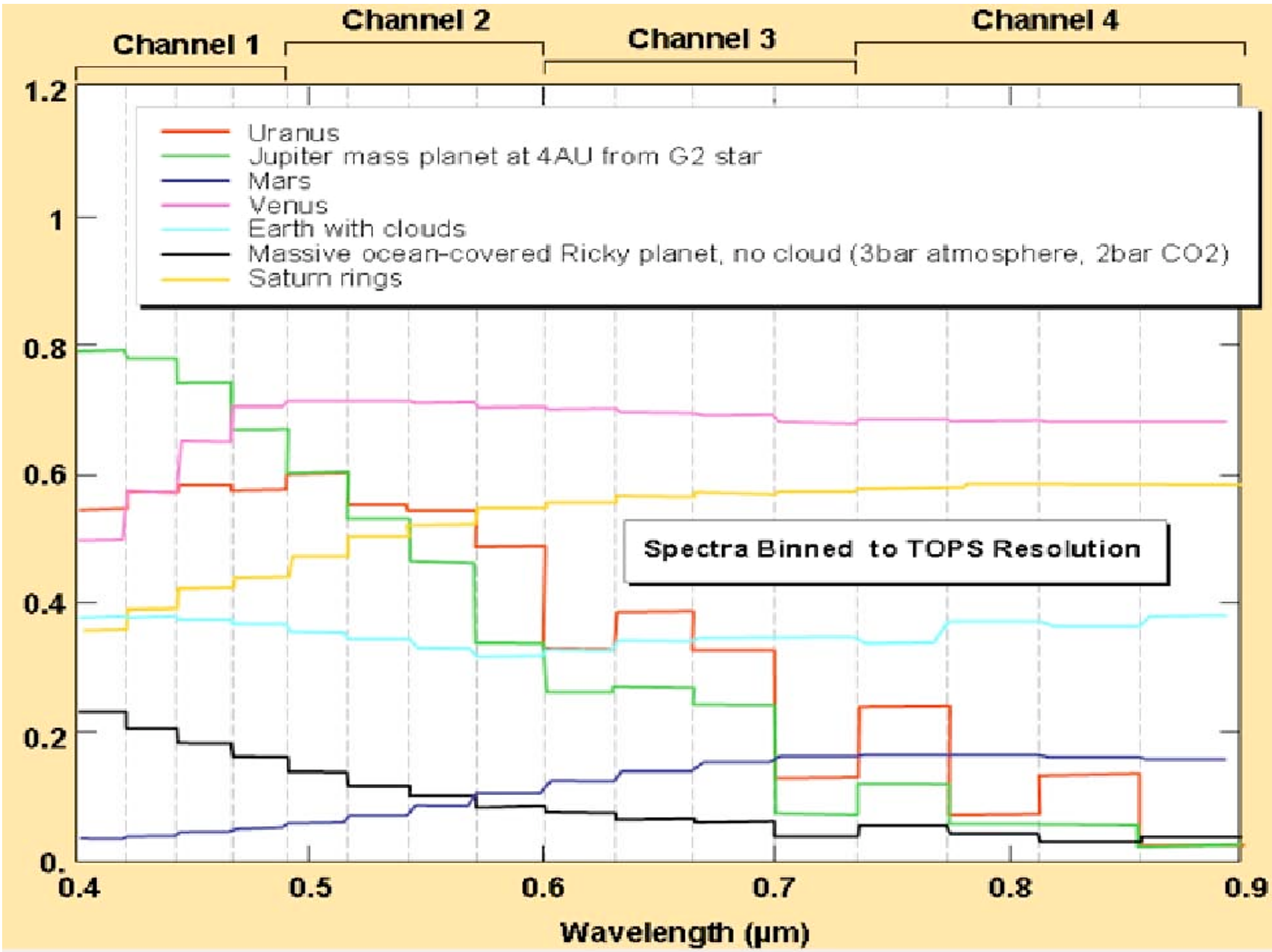
| | *TOPS (1.2-m)* | *PIAA (1.5-m)* | *TOPS2 (2-m)* | *PIAA (3-m)* | *PIAA (4-m)* |
|---|---|---|---|---|---|
| #Exo-Earths within 2 l/D | 10 | 23 | **67** | 212 | 476 |
| ... within 4 l/D | 2 | 2 | **6** | 23 | 67 |
| #Exo-Earths, t=1hr | 2 / 3 | 3 / 5 | **7 / 16** | 24 / 49 | 51 / 118 |
| #Exo-Earths, t=10hr | 3 / 7 | 7 / 17 | **22 / 40** | 65 / 147 | 172 / 299 |
| **Approximate cost** | **~$1B** | | **~$2B** | **~$??B** | |

Notes: Rows 3 and 4 list the number of Exo-Earths which would be detected at SNR=7 with respectively 1hr and 10 hr effective exposure times. Two numbers are given: the small number requires a 50% detection probability for a single observation; for the larger number, a 20% detection probability per observation is required. Alpha Cent A and B are included in this table, but may not be suitable targets due to their duplicity and the fact that Exo-Earths might lie beyond the Outer Working Angle of the instrument. If they are to be excluded, each number in this table should be reduced by two.
Costs estimates given in the table do not include the completion and operation of our 1-m PIAA telescope test-bed, required to bring up the TRL of key technologies.

50 % WFC overhead
50 % mission overhead
20 % Quantum Efficiency
x 6 observations

2 yr mission time
-> 260 hr effective time available
**40 targets @ > 74% detection**
**or 22 targets @ > 98.5% detection**

# Planet characterization with TOPS 16 spectral channels



## PIAA Coronagraph Technology Development

Testbed @ Subaru Telescope
Ground-based coronagraphic ExAO project
2nd generation PIAA design & manufacturing
Space projects studies: TOPS, TPF-C, SPICA

Main funding sources

**Ground-based**

**Space**

NASA JPL
Navigator program

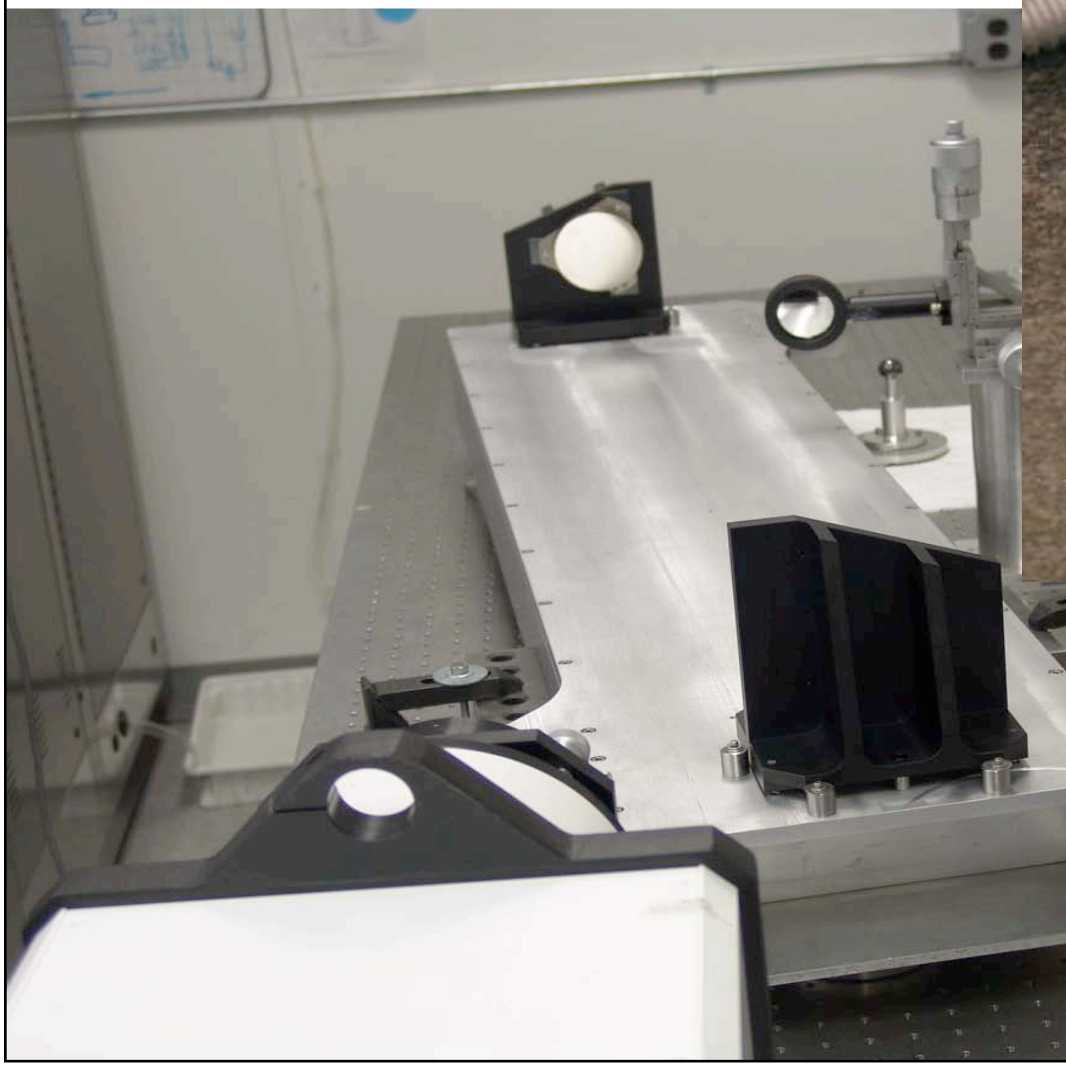
Subaru Telescope/NAOJ

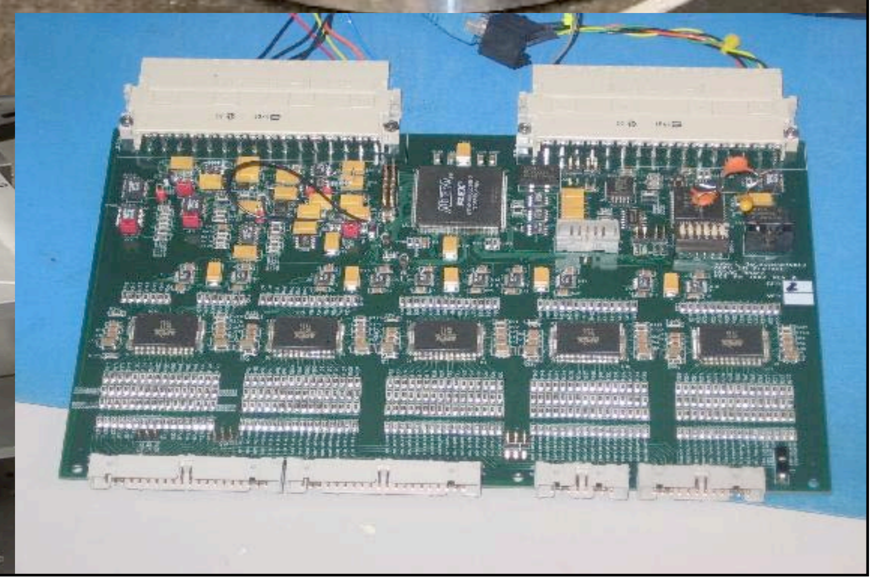
MEXT (Japan)

NASA Ames
TOPS partnership

# PIAA mirror lab demo (JPL & NAOJ funding)

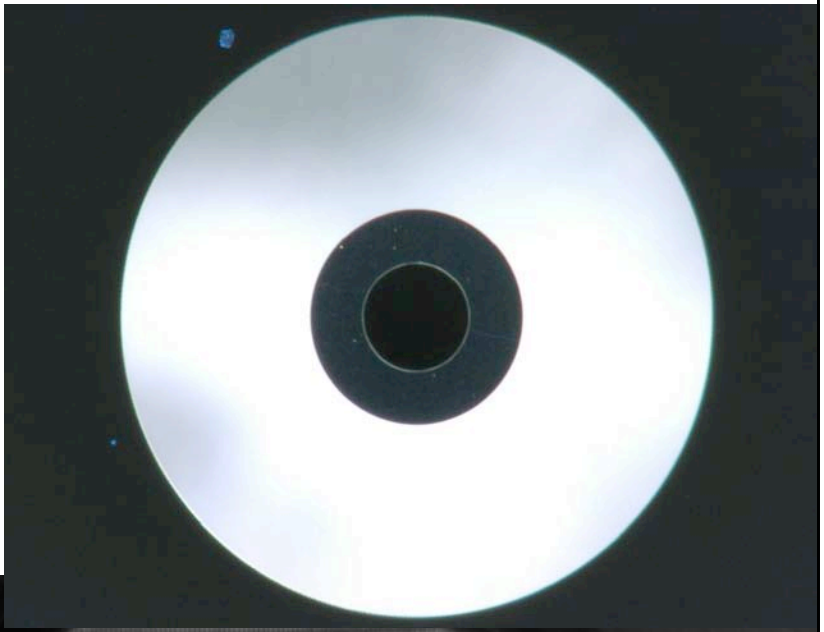
Extreme-UV lithography technology enables PIAA optics manufacturing

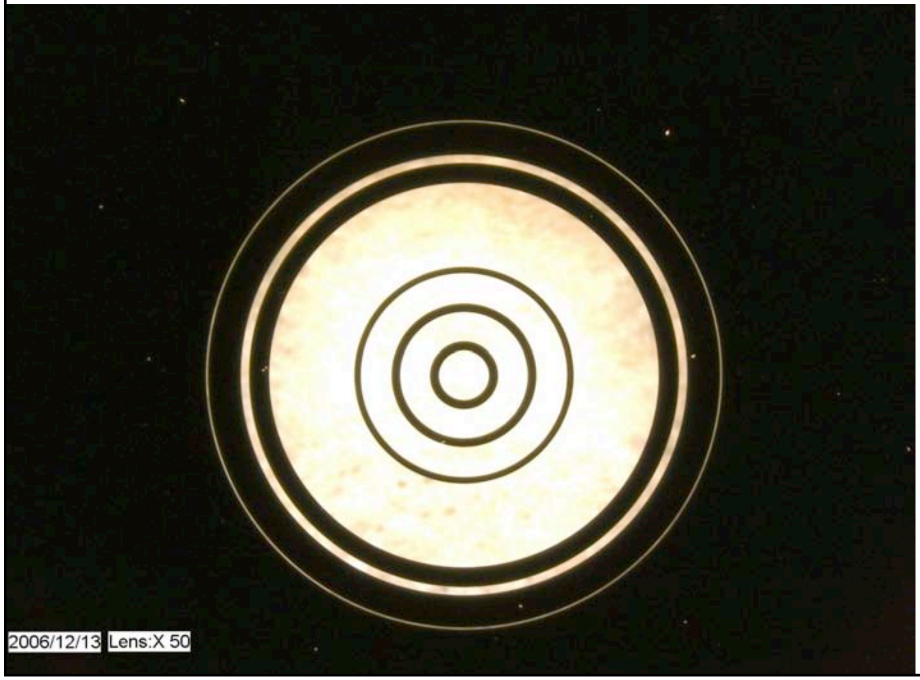


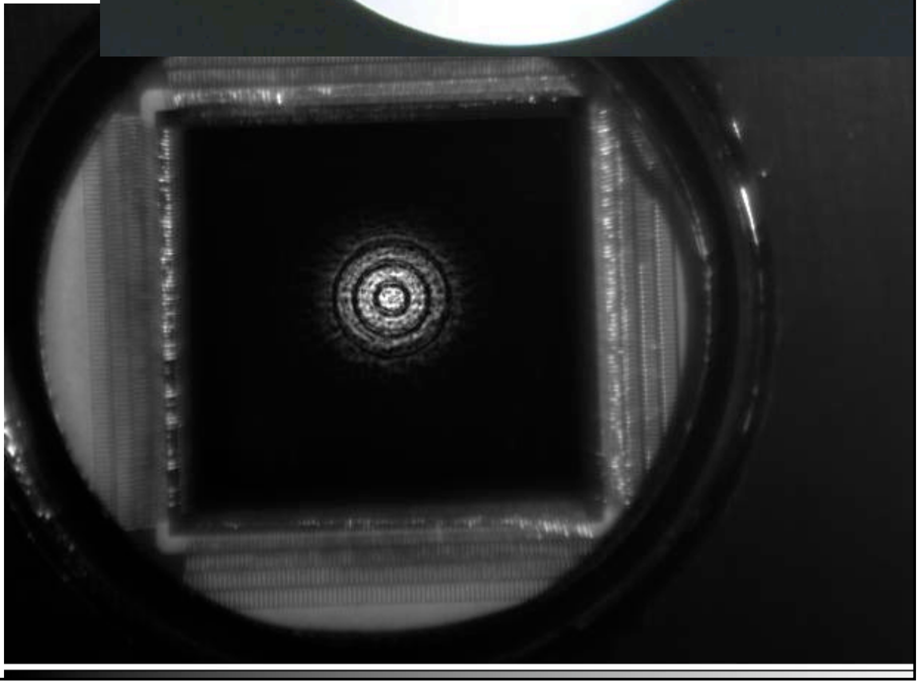


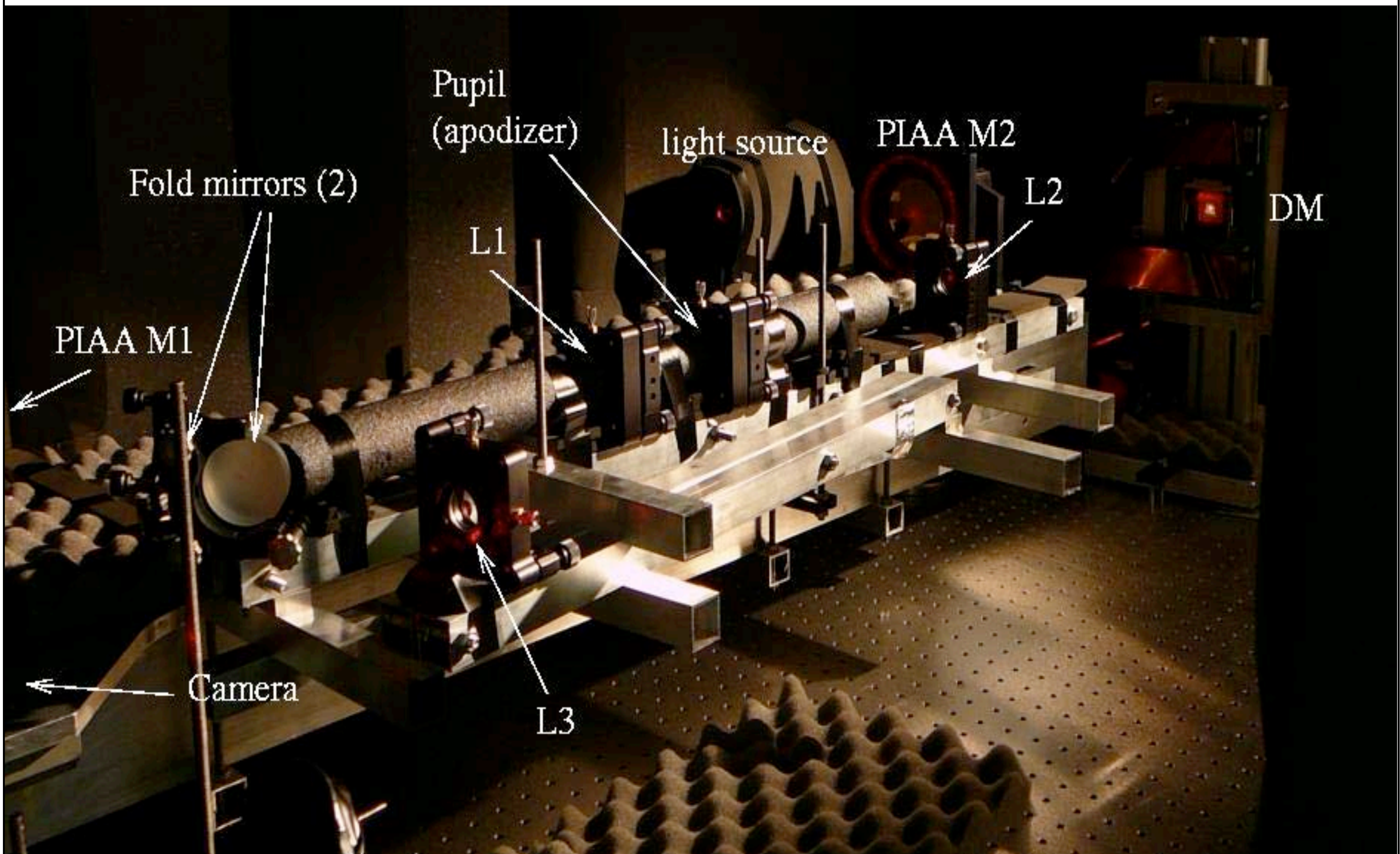
Hybrid PIAA/conventional apodization is best
-> Optics easier to manufacture
-> Good achromaticity

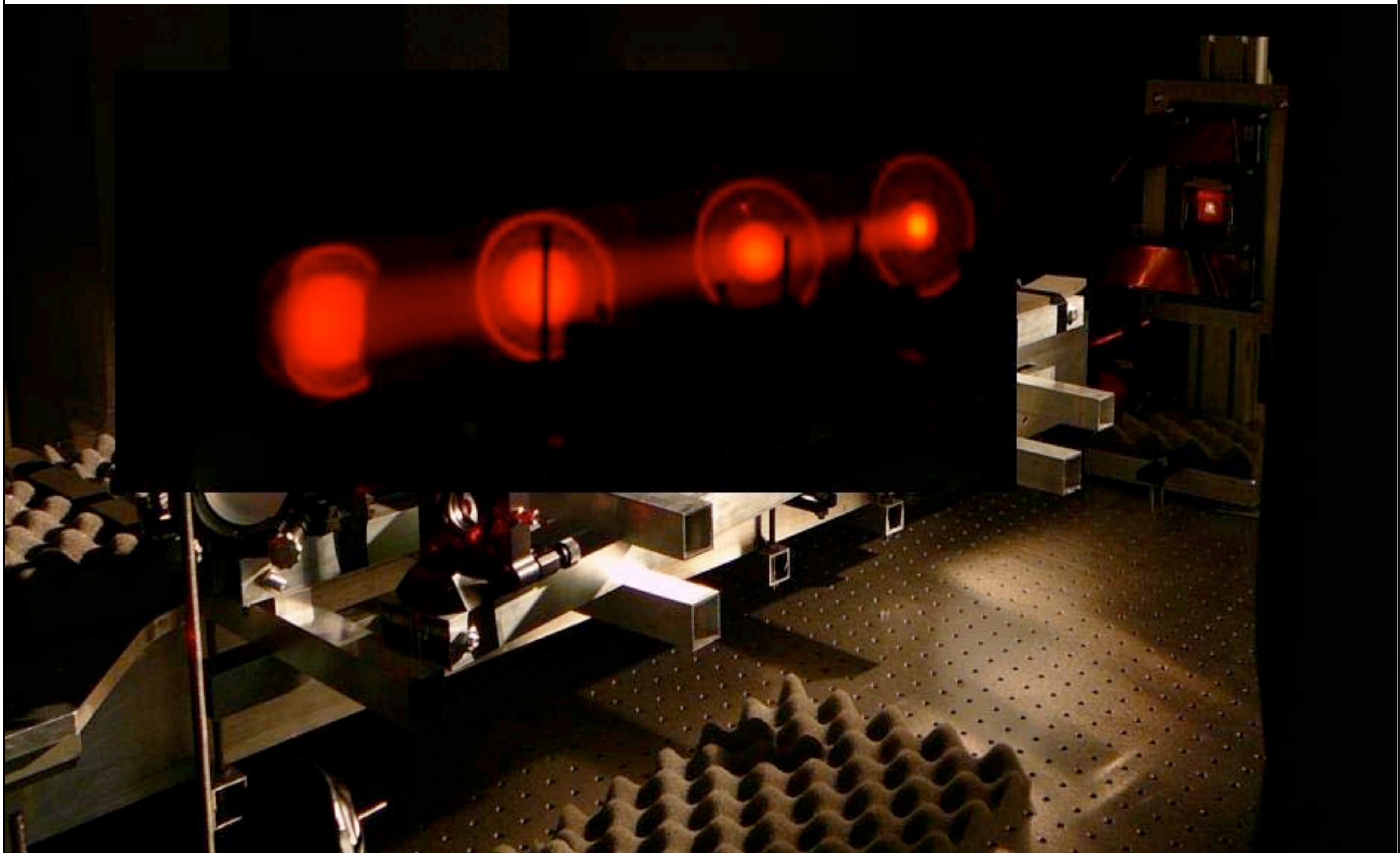
Pointing is critical
-> Continuous pointing corrections



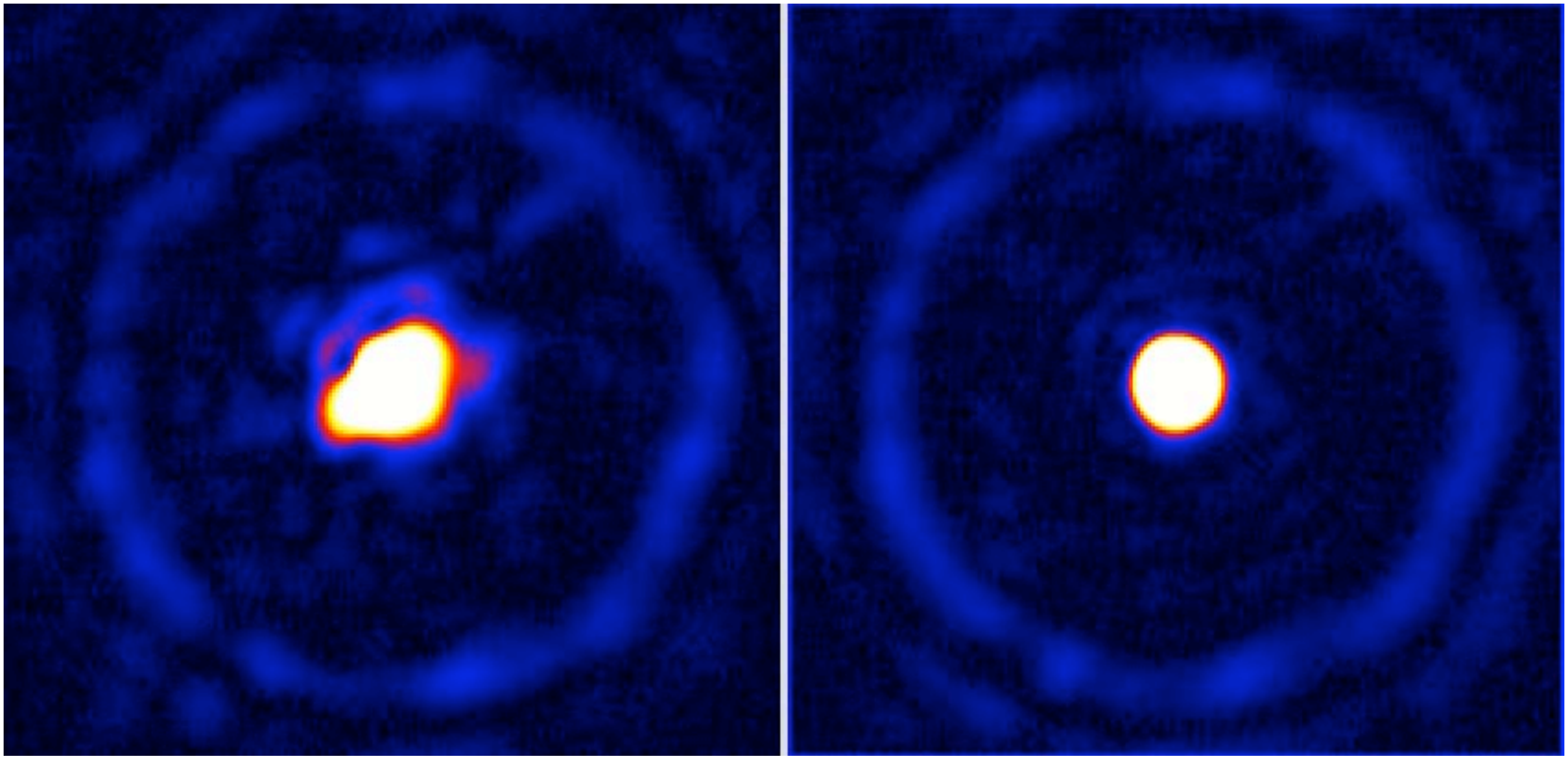



Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

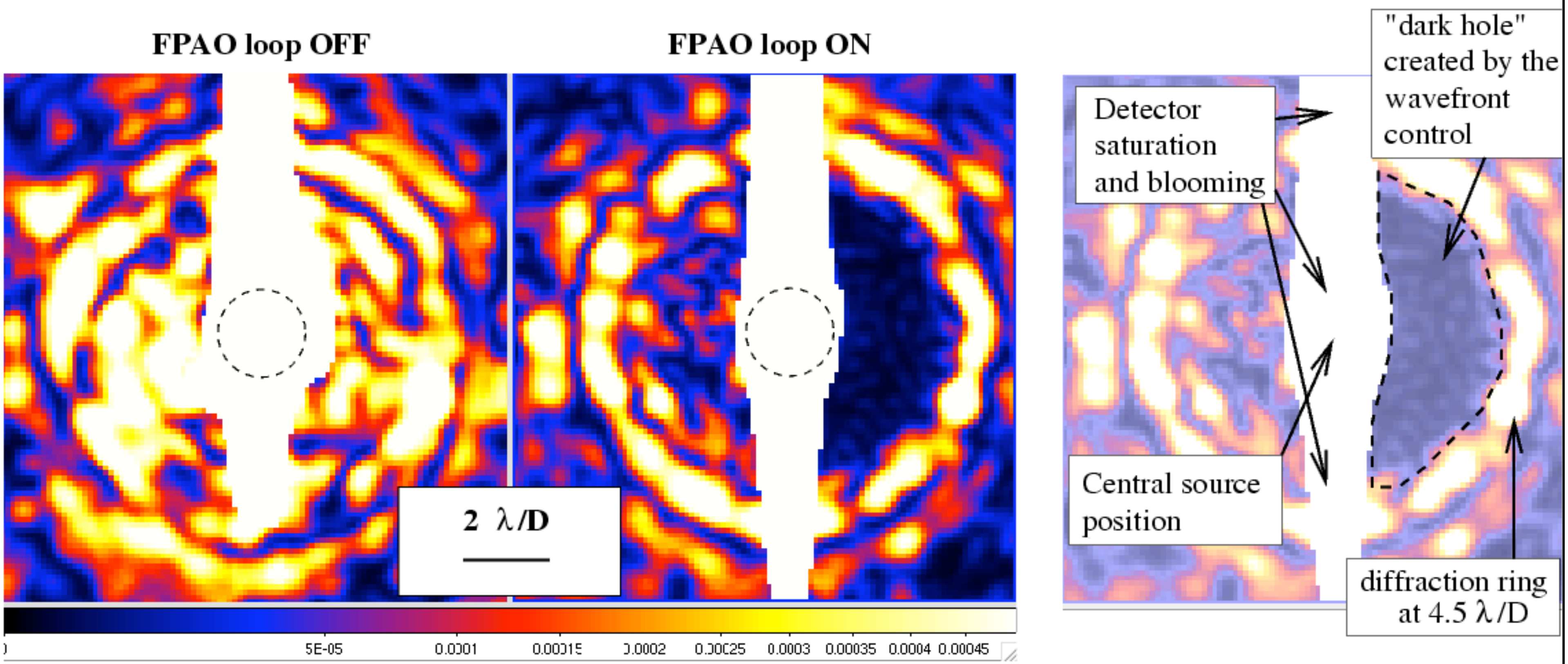


## Lab results with PIAA coronagraph + FPAO

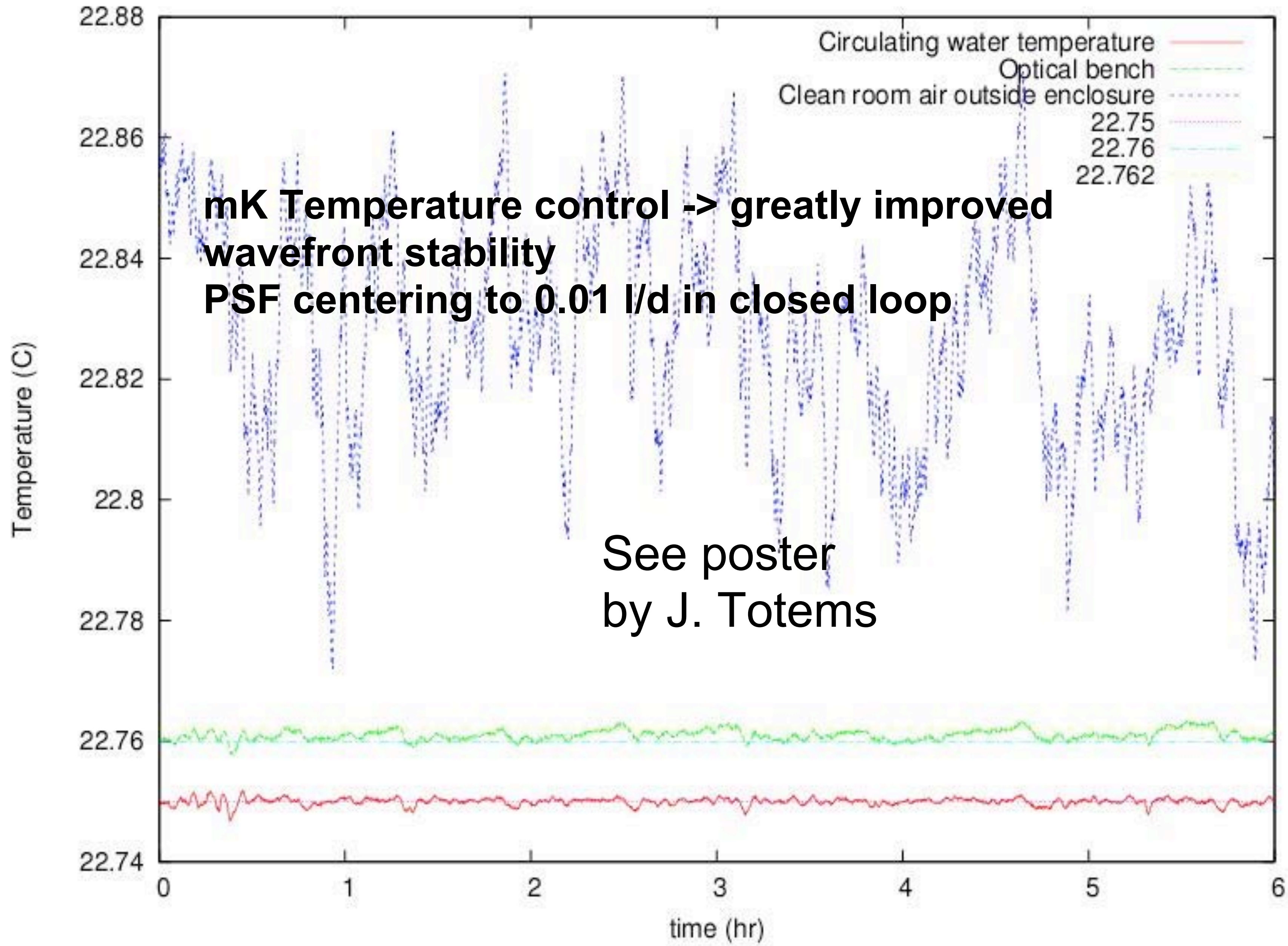


Step 1: phase diversity -> DM correction

# Lab results with PIAA coronagraph + FPAO




So far, ~6.5e-7 contrast


mK Temperature control -> greatly improved wavefront stability
PSF centering to 0.01 l/d in closed loop
See poster by J. Totems
Circulating water temperature
Optical bench
Clean room air outside enclosure
22.75
22.76
22.762
Temperature (C)
time (hr)
22.88
22.86
22.84
22.82
22.8
22.78
22.76
22.74
0
1
2
3
4
5
6

## Future tests & 2nd generation PIAA

NASA Ames / TOPS partnership / JPL

We are acquiring a 2nd generation PIAA

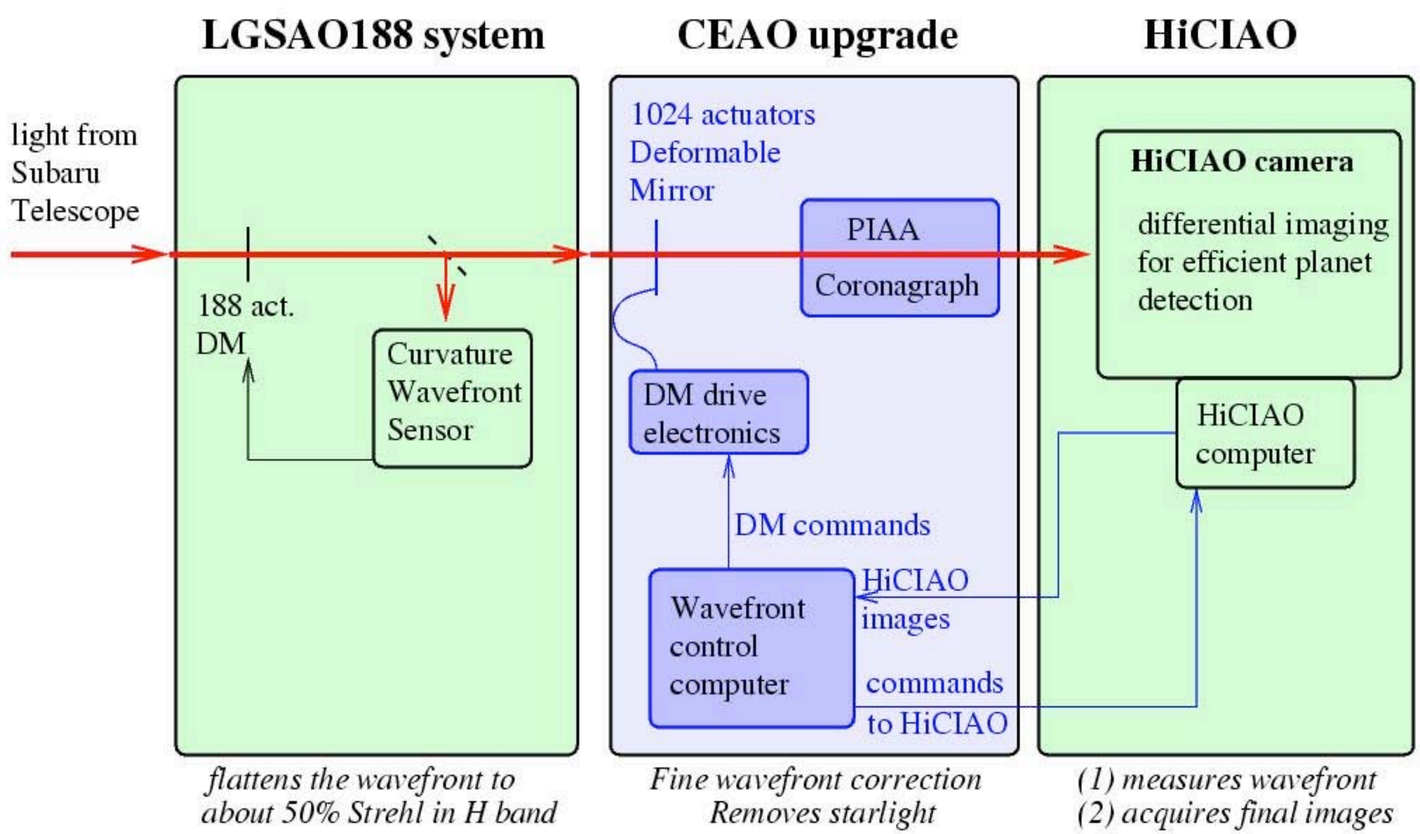
improved optical quality & better design (lessons learned with 1st generation PIAA)

improved achromaticity

Moving to tests in Vacuum – putting PIAA into HCIT

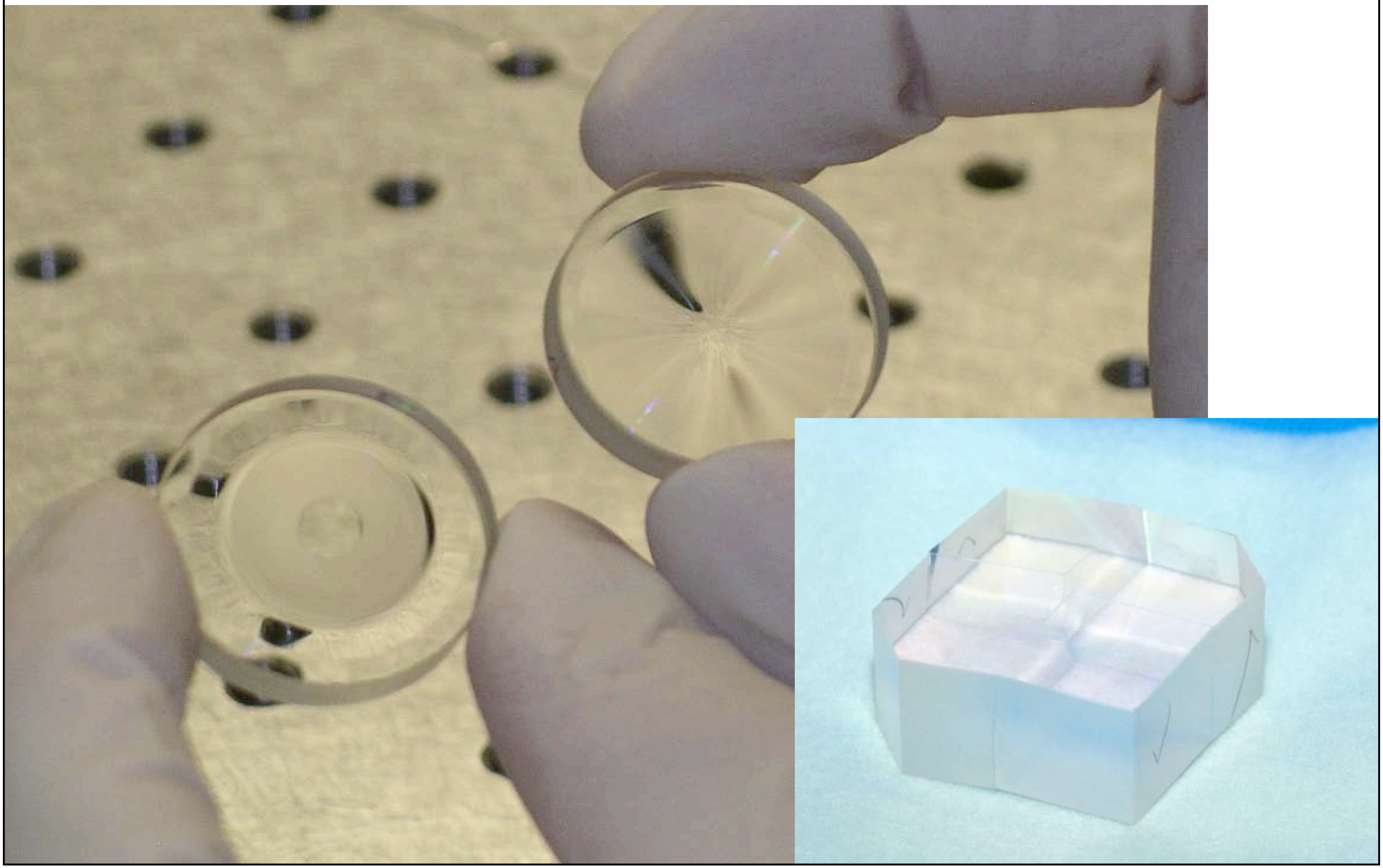
Testing PIAA fed by large mirror (~1m) in vacuum for end-to-end test at 1e-10 contrast

# Subaru Telescope Coronagraphic ExAO system




1 l/d IWA (50% throughput point)
~100% throughput except for coatings

# Subaru Telescope Coronagraphic ExAO system



## Wavefront control strategy

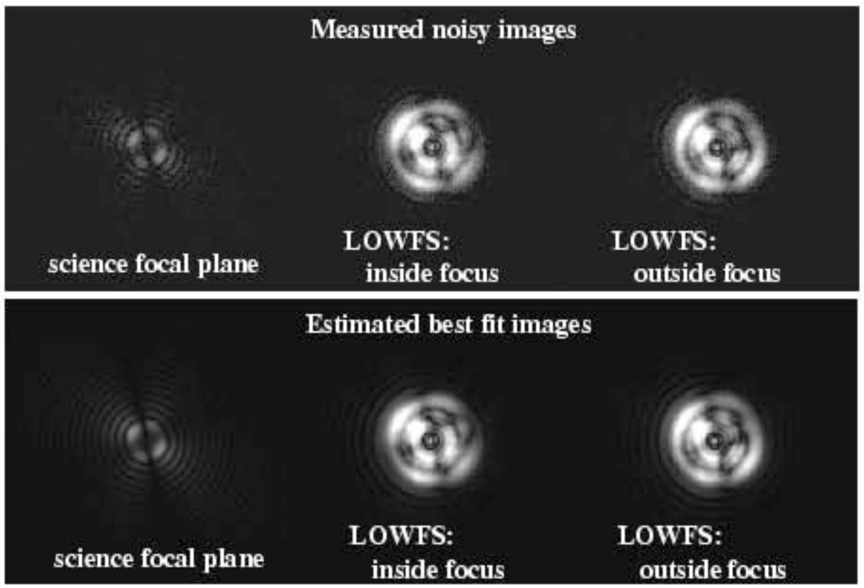
**Keep telescope as stable as possible**

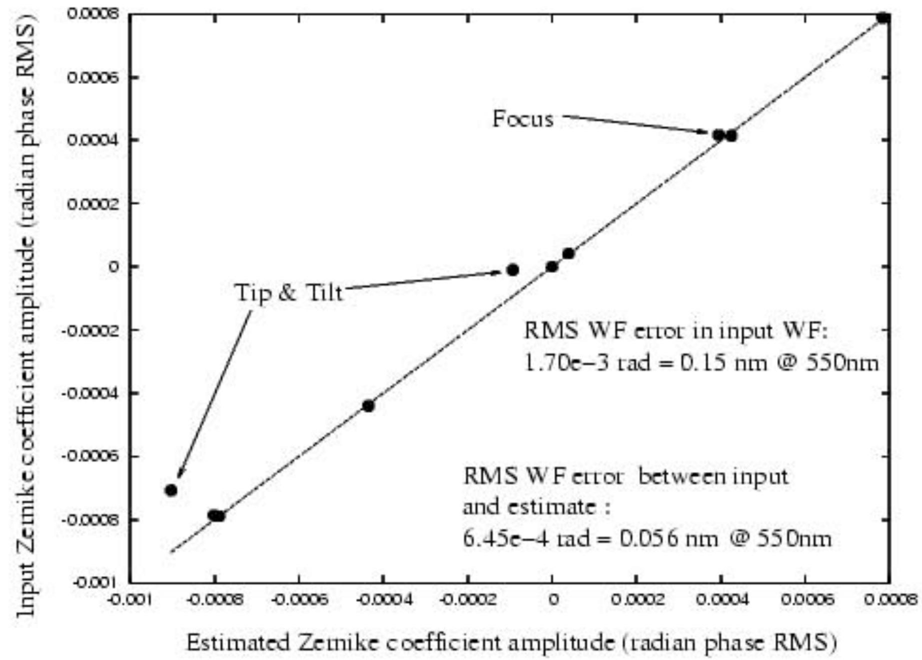
**Continuous correction (no roll subtraction)**
**USE EVERY PHOTON IN OPTIMAL WAY**
**(PIAA helps with high throughput and good angular resolution)**

**Use telemetry data to differentiate speckles from planet**
**-> smooth contrast vs. wavefront stability curve**

## Low Order Wavefront Sensor (LOWFS)

### LOWFS performance




Small (<<lambda) wavefront error produces large flux changes in the LOWFS images

# How good does it need to be ?

**Table 1.** Wavefront control requirements for $10^{10}$ contrast. Wavefront tolerances are given at the entrance of the PIAA. A coronagraph system including PIAA, focal plane occulter and inverse PIAA was simulated at 550 nm to derive these requirements. The sampling time necessary to measure the corresponding level of aberration at SNR=5 is given here for a $m_V = 5$ star.

| Mode | Required control accuracy | Sensor | SNR=5 sampling time |
|---|---|---|---|
| Tip / tilt | 0.9 nm rms/mode | LOWFS | 0.5 s |
| Focus | 43 pm rms | LOWFS | 1 s |
| Astigmatism | 70 pm rms/mode | LOWFS | 1 s |
| Mid spatial frequencies | 1.5 pm rms/mode [≈40 pm rms total, 15 pm per actuator] | Science CCDs & LOWFS | 5 min |
| High spatial frequencies | Strehl ratio > 0.98 | none, relies on optical quality of components | - |

Wavefront control **accuracy** : must be able to “dial” wavefront correction to <x> pm accuracy

Wavefront **stability**: within ~10x sampling time, wavefront must be stable to <x> pm (no vibrations or non-calibrated drifts)

Wavefront **chromaticity**: across each individual spectral band, wavefront chromaticity must be less than <x> pm (diffraction propagation between mirrors is a problem)

## Conclusions

**Science vs. Telescope size:**

TOPS at 1.2m can see a few “super-Earths” + colors
Hard to fit within Discovery class

“TOPS2”, at 2m, can detect Earth-like planets with some characterization (colors)

Spectroscopy to ~1 micron would require 4m with very high throughput

**Concepts exist to do this – ongoing active technology dev,**