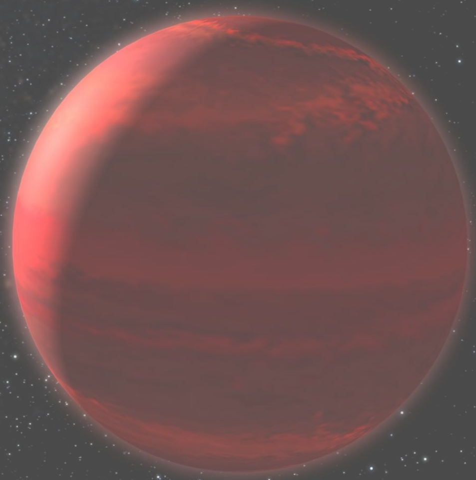
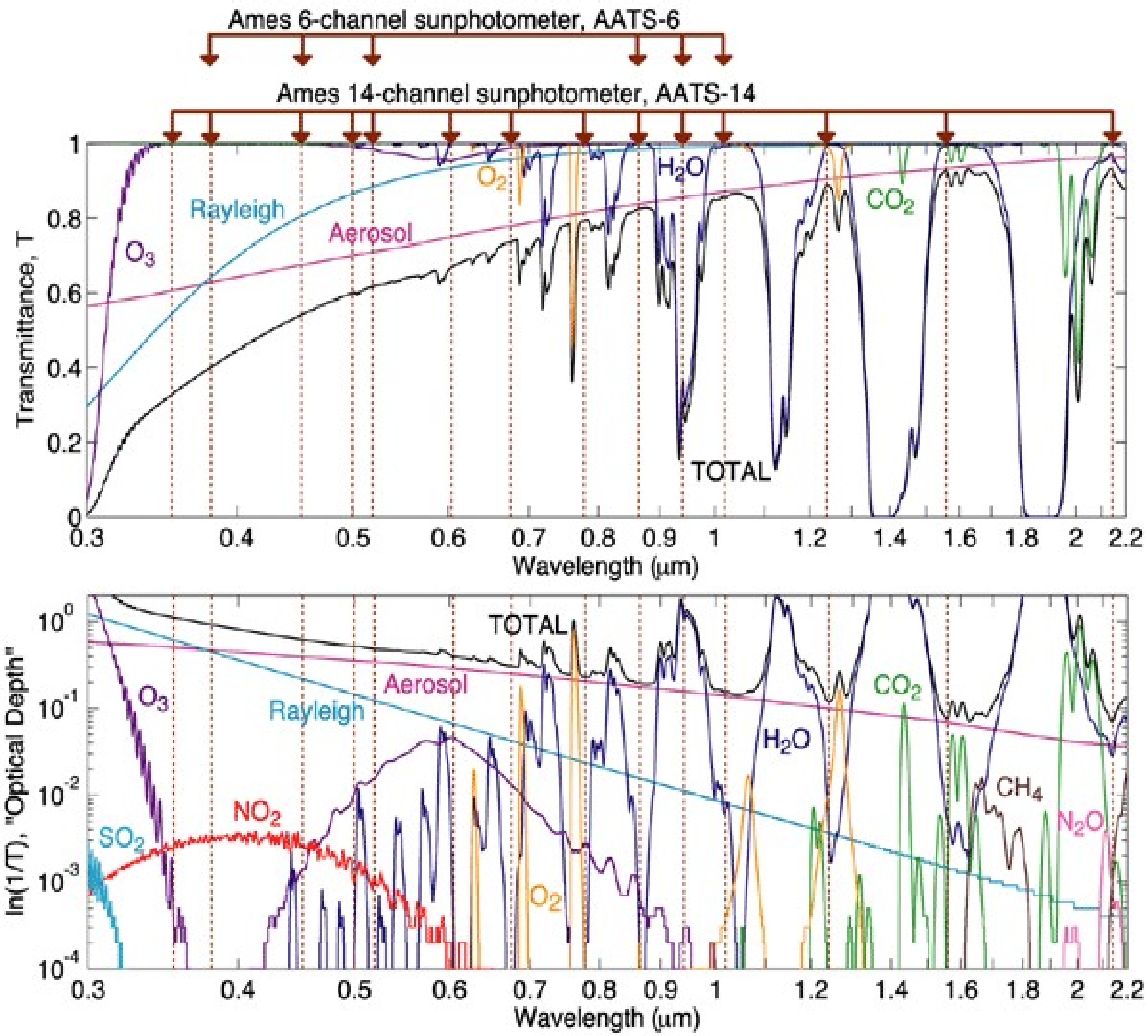
Direct imaging of habitable "Earth-like" planets with ELTs

SCExAO team
Olivier, Frantz, Nem



Contact: guyon@naoj.org

We would love to do Spectroscopy



Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

Atmosphere transmission:
O_2 (see Kawahara et al. 2012)
H_2O
CO_2
CH_4

Polarimetry

Cloud cover, variability
Rotation period

Reflectivity from ground in atmosphere transparency bands
(Ice cap, desert, ocean etc...)

Reflected light planets

First cut limits meant to exclude clearly impossible targets
→ used to identify potential targets → instrument requirements

FIRST CUT LIMITS

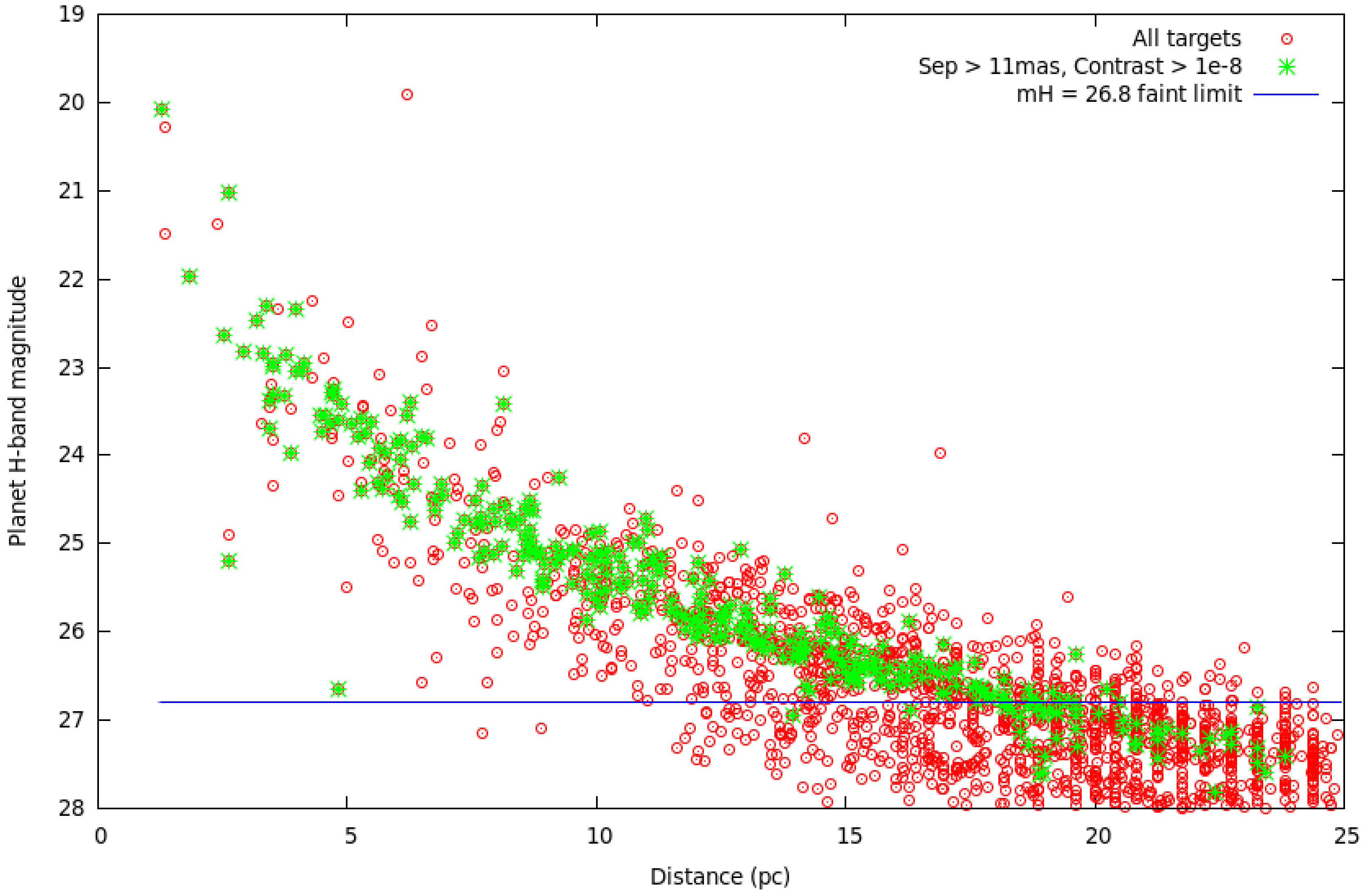
	Limit/constraints	Comments
Angular Separation	Must be > 1.0 λ/D	Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.
Contrast	Must be > 1e-8	High contrast imaging limit (see section 5)
Star brightness	Must be brighter than m_R = 15	Required for high efficiency wavefront correction (see section 5)
Planet Brightness	Must be brighter than m_H = 26.8	Faint detection limit

background-limited SNR > 10 in H band image in 1 hr on 30-m telescope (assuming 15% efficiency)

Reflected light planets

274 targets survive the first cut

Strong correlation between planet apparent brightness and system distance

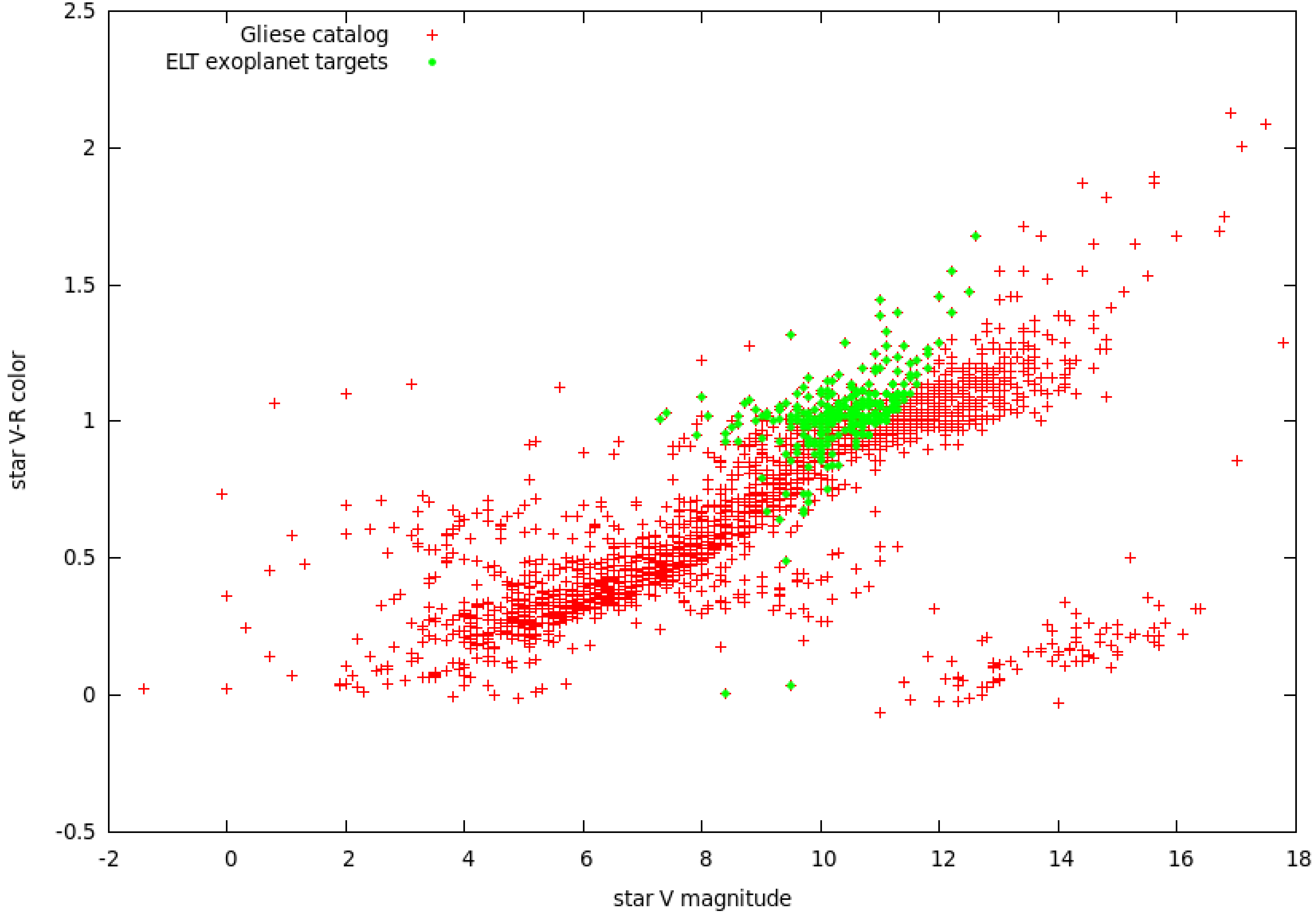


Reflected light planets

Most targets are red stars (M type), around V ~ 10, R ~ 9

2 white dwarfs : 40 Eri B and Sirius B

Early type stars → contrast too challenging



Easiest reflected light planets (2x Earth diameter)

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)

MOST FAVORABLE TARGETS

STAR							PLANET				
Name	**Type**	**Distance**	**Diameter**	L_{bol}	m_V	m_R	m_H	**Separation**	**Contrast**	m_H	**Notes, Multiplicity**
Proxima Centauri (Gl551)	M5.5	1.30 pc	0.138 R_{Sun} 0.990 +- 0.050 mas [1]	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	RV measurement exclude planet above 3 Earth mass in HZ [Endl & Kurster 2008]
Barnard's Star (Gl699)	M4	1.83 pc	0.193 R_{Sun} 0.987 += 0.04 mas [2]	4.96e-03	9.50	8.18	4.83	38.41 mas	1.40e-07	21.97	-
Kruger 60 B (Gl860B)	M4	3.97 pc	0.2 R_{Sun}[3]	5.81e-03	11.30	9.90	5.04	19.20 mas	1.20e-07	22.35	-
Ross 154 (Gl729)	M4.5	2.93 pc	0.2 R_{Sun}[3]	5.09e-03	10.40	9.11	5.66	24.34 mas	1.37e-07	22.82	-
Ross 128 (Gl447)	M4.5	3.32 pc	0.2 R_{Sun}[3]	3.98e-03	11.10	9.77	5.95	18.99 mas	1.75e-07	22.84	-
Ross 614 A (Gl234A)	M4.5	4.13 pc	0.2 R_{Sun}[3]	5.23e-03	11.10	9.82	5.75	17.51 mas	1.33e-07	22.95	Double star (sep=3.8 AU)
Gl682	M3.5	4.73 pc	0.26 R_{Sun}[3]	6.41e-03	10.90	9.70	5.92	16.93 mas	1.09e-07	23.33	-
Groombridge 34 B (Gl15B)	M6	3.45 pc	0.18 R_{Sun}[3]	5.25e-03	11.00	9.61	6.19	20.98 mas	1.33e-07	23.39	150 AU from M2 primary
40 Eri C (Gl166C)	M4.5	4.83 pc	0.23 R_{Sun}[3]	5.92e-03	11.10	9.88	6.28	15.93 mas	1.18e-07	23.61	35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1)
GJ 3379	M4	5.37 pc	0.24 R_{Sun}[3]	6.56e-03	11.30	10.06	6.31	15.09 mas	1.06e-07	23.75	-

[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI Demory et al. 2009
[2] Uniform disk angular diameter from Lane et al. 2001
[3] No direct measurement. Approximate radius is given. If possible, radius is extrapolated from photometry using K magnitude and radius vs. absolute K magnitude relationship in Demory et al. 2009

Requirement : ~1e-7 contrast, ~15mas, mR ~ 9.5 guide star

Why M dwarfs ?
… and why we should love them

Class	Surface temperature[8] (kelvin)	Conventional color	Apparent color[9][10][11]	Mass[8] (solar masses)	Radius[8] (solar radii)	Luminosity[8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[12]
O	≥ 33,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–33,000 K	white to blue white	blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	white to blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellowish white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,000–3,700 K	red	orange red	≤ 0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Planet to star contrast not too challenging (because star is faint)

Lots of them around → closest M dwarfs are quite close to us

→ ideal targets for planet spectroscopy

But also…

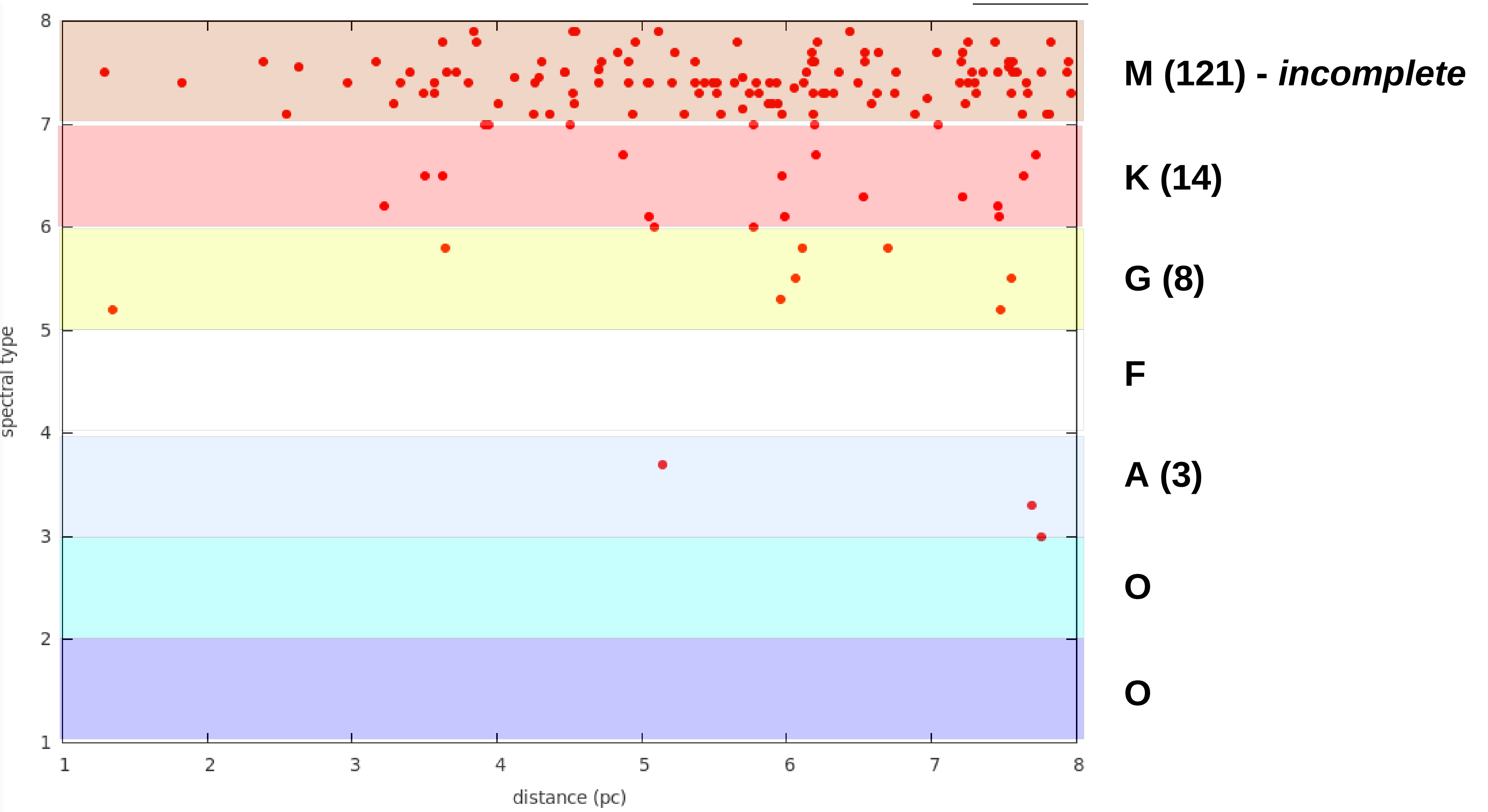
- some indication that rocky planets are more abundant around M dwarfs than Sun-like stars (Kepler)
- fast orbital period (~1 month) → quick measurement of orbit
- decent probability of transit (and short period), transit is deeper than for Sun-like stars thanks to small stellar size
- Radial velocity could reach required precision to measure masses of these planets (BUT: some M dwarfs are active…)

>3/4 of Main sequence stars are M type

174 stars within 8pc ...

168 Main sequence stars + 8 white dwarfs

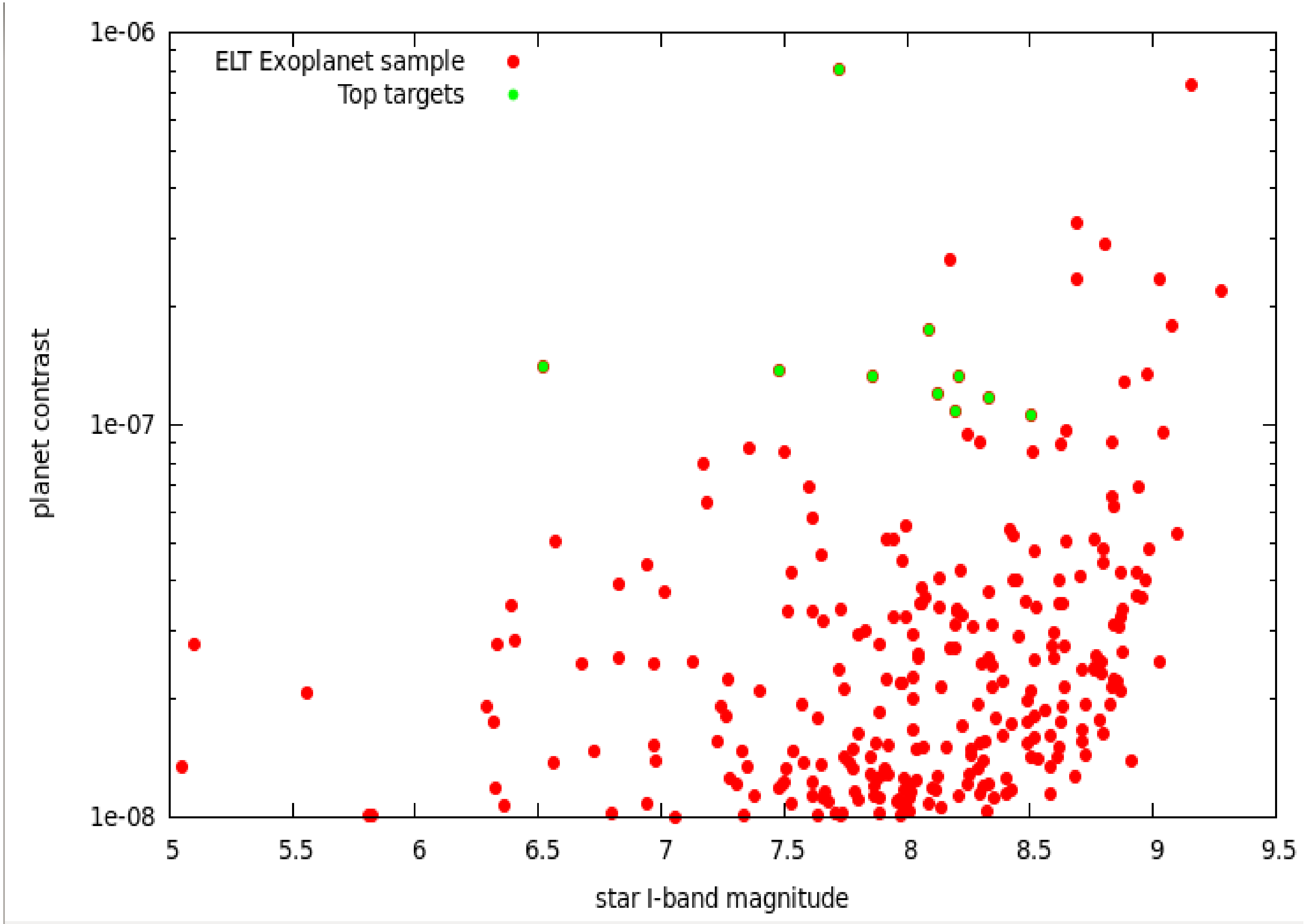
Data:
SUPERBLINK, CNS3, HIPPARCOS
multiple stars: only primary component kept



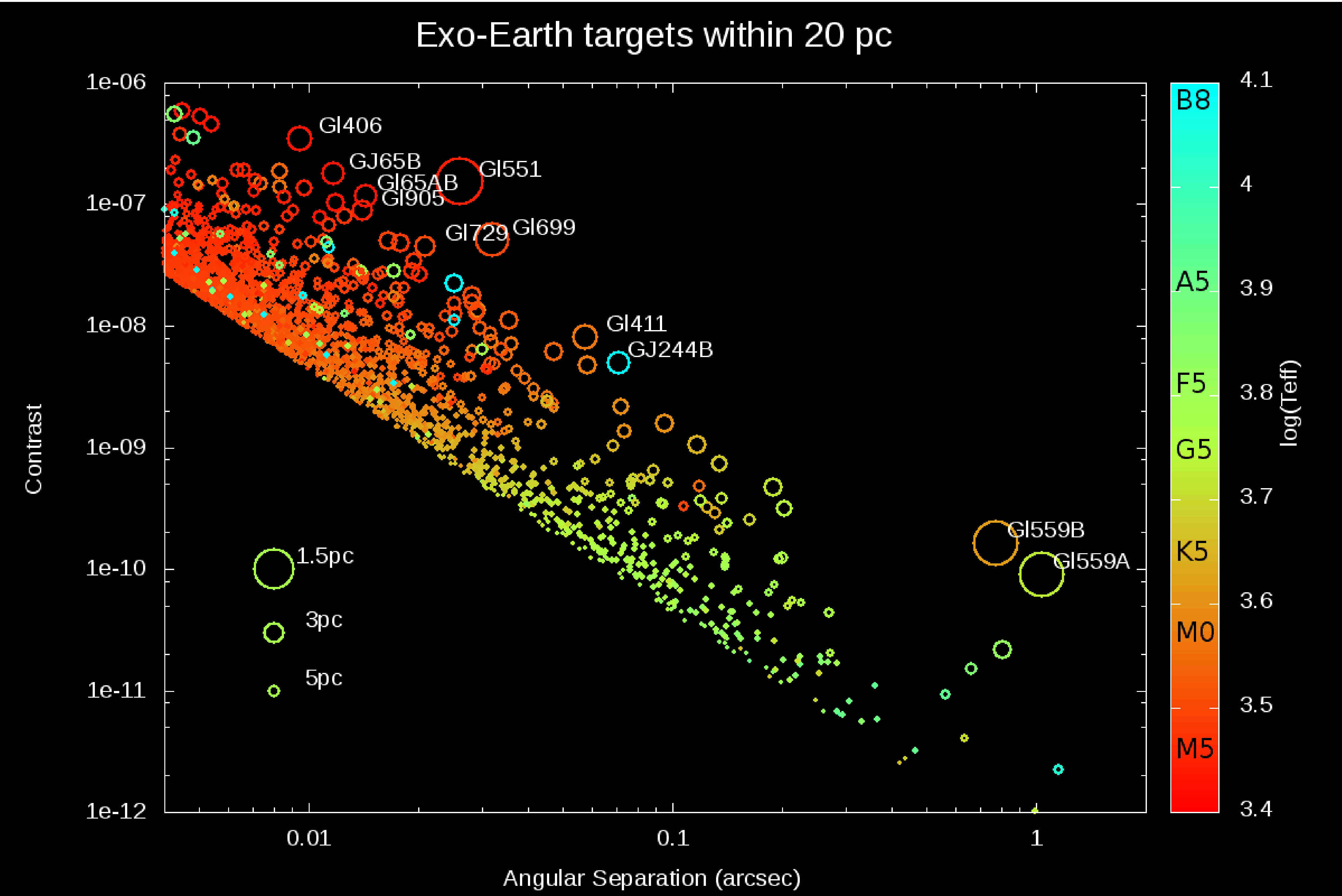
Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

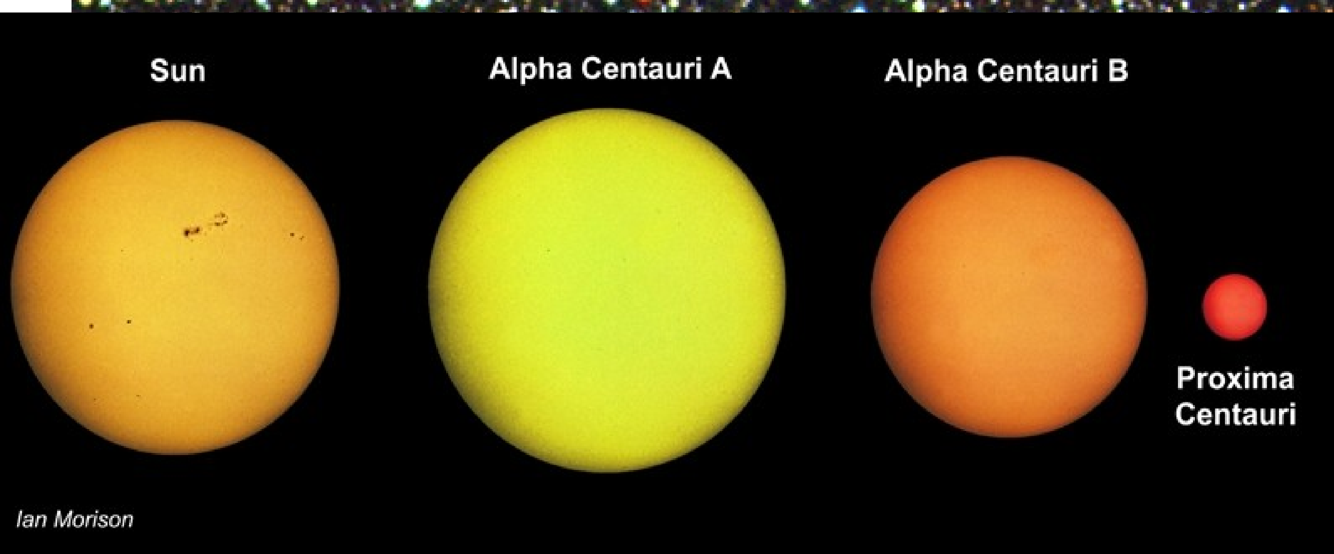
(assumes Earth albedo, contrast and separation for max elongation)



Earth analogs



Proxima Centauri



Interferometry or coronagraphy ?

Interferometry (aperture masking etc...):

Powerful calibration → contrast challenge mitigated

Demonstrated ability to work at separations around the telescope diffraction limit

Mixes planet and star flux → SNR limitation due to photon noise

Coronagraphy

Separates planet light from starlight, but:

- Must access close to 1 l/D with high efficiency
- Must be able to reach at least ~1e4 raw contrast, AND calibrate WF to ~1e-7 contrast

Interferometry or coronagraphy ?
→ only coronagraphs can offer SNR

Photon-noise limited SNR limit in H band

Earth like planet around M4 type star at 5pc

Assumptions:

- D = 30m telescope, m_H=14.4 $arcsec^{-2}$ background, 20mas aperture
- 15% efficiency (coatings, detector), 0.3 um bandpass (H band), 1 hr exposure
- planet mH = 25.2 (Earth at 5pc)

background = 230 ph/sec

Planet = 27.5 ph/sec

Star = 9.98e8 ph/sec (mH=6.3, M4 stellar type)

Star / Planet contrast = 3.6e7

SuperEarth at 5pc around M star (4x Earth flux, 2x diameter)

	Detection SNR H band (R~5)	Spectroscopy SNR R = 100
Imaging, no starlight	**102 [356]**	**23.5 [83]**
Imaging, 1e5 raw contrast	**16.31 [65]**	**3.8 [15]**
Imaging, 1e4 raw contrast	**5.16 [20.6]**	**1.2 [4.8]**
Interferometry, 100% efficiency	**0.05 [0.2]**	**hopeless...**

Transit spectroscopy ?
→ not competitive in SNR

Around M4 star, transit probability = 1.3% for a HZ planet

Statistically, closest transit target is 4.3x further than closest direct imaging target, and star is 18x fainter

M4 star diameter ~ 2.8e5km

12000km planet diameter, scale height = 8km → atmosphere is 5e-6 of stellar disk surface

Transit signal = 275 ph/sec

Star flux = 5.5e7 ph/sec

Detection SNR (1hr) = 2.2 (only during transit !!!)

Detection SNR if closest target transits = 9.4 (1.3% chance of being that lucky...)

Requirements, Top challenges

Efficient coronagraphy

… down to 1 l/D separation on segmented pupils

Coronagraph design

Chromaticity

Stellar angular size

Wavefront control

(getting raw contrast at or below 1e-4 at 1 l/D)

Efficient sensing of low order aberrations

Control and calibration of pointing errors

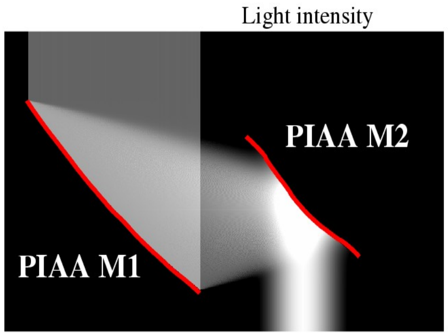
Wavefront calibration to 1e-7

(separating scattered light from planet light)

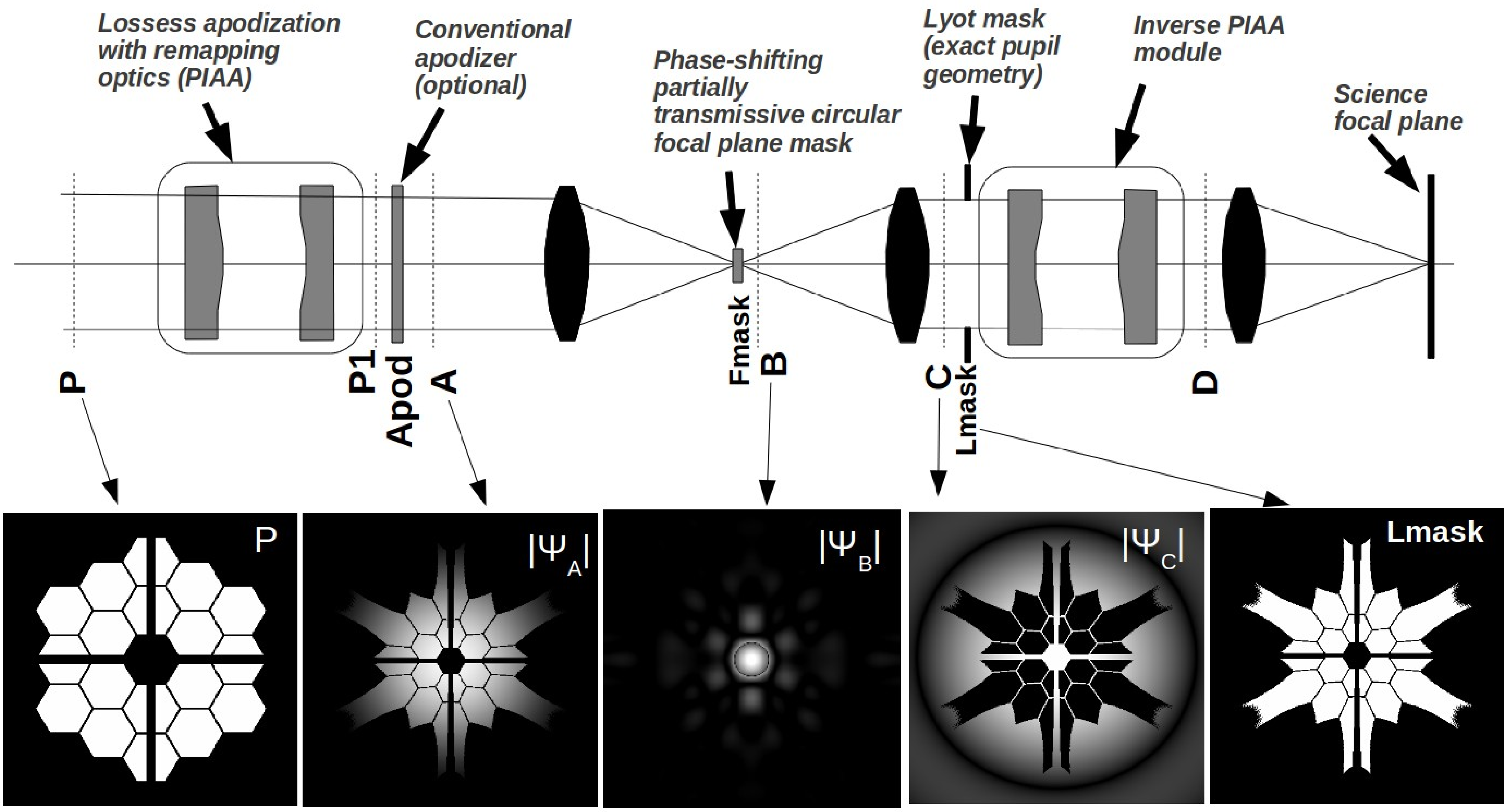
Main issues: time lag, chromatic effects, systematics

The need for nearIR wavefront modulation and correction

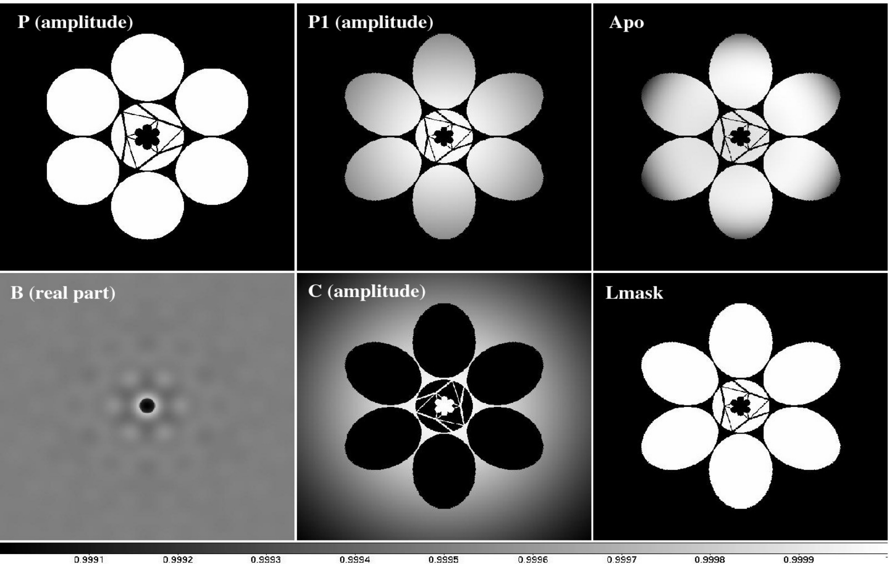
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



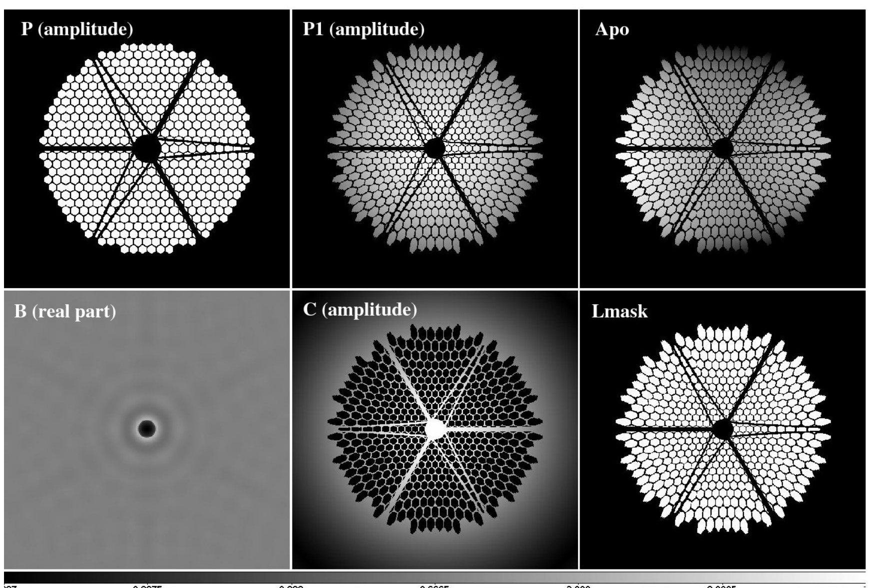
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

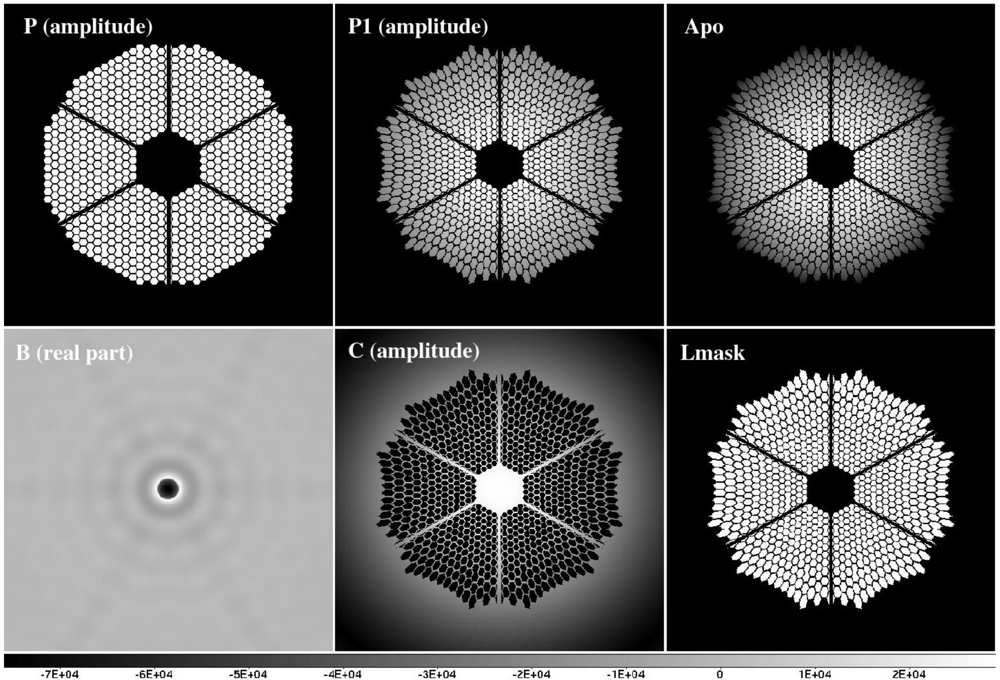


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

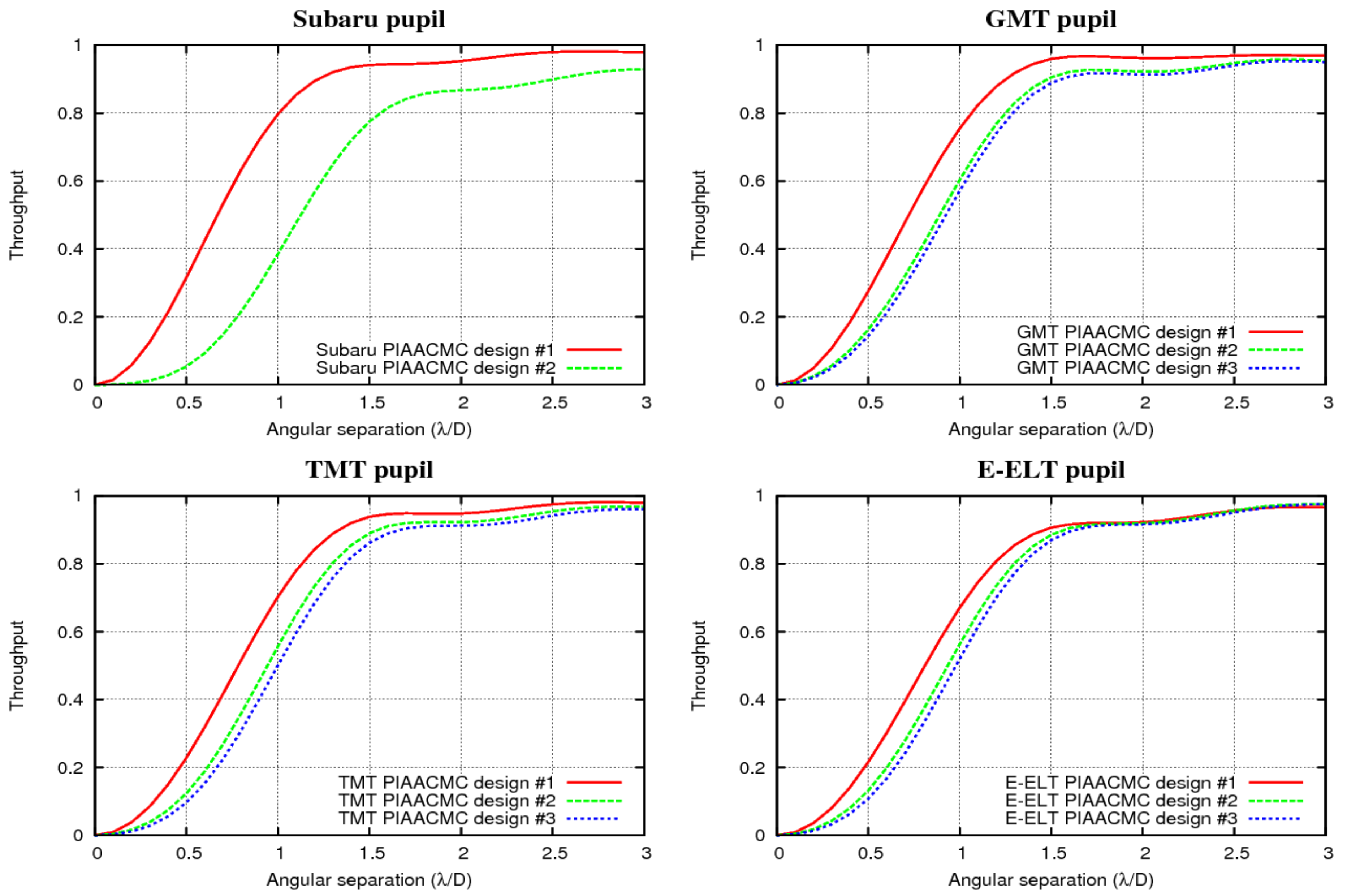


<u>Pupil shape does not matter !!!</u>

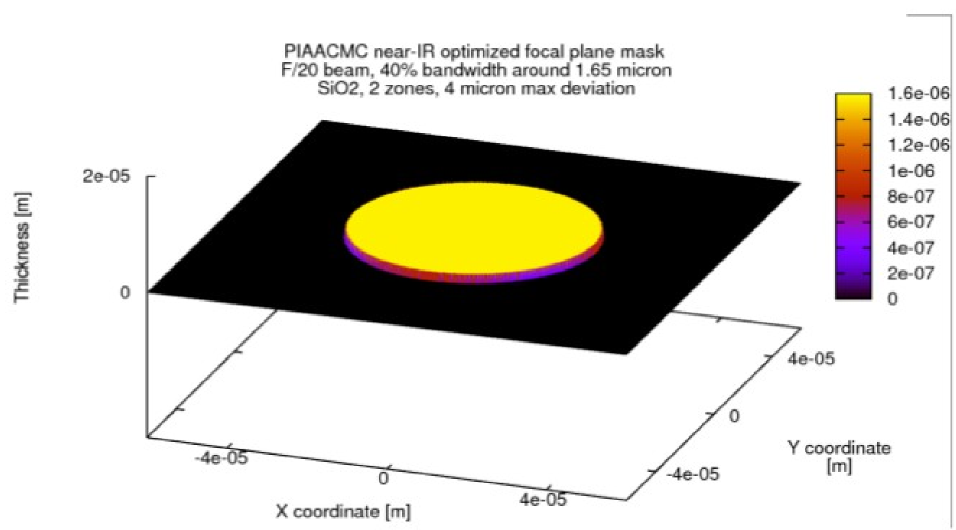


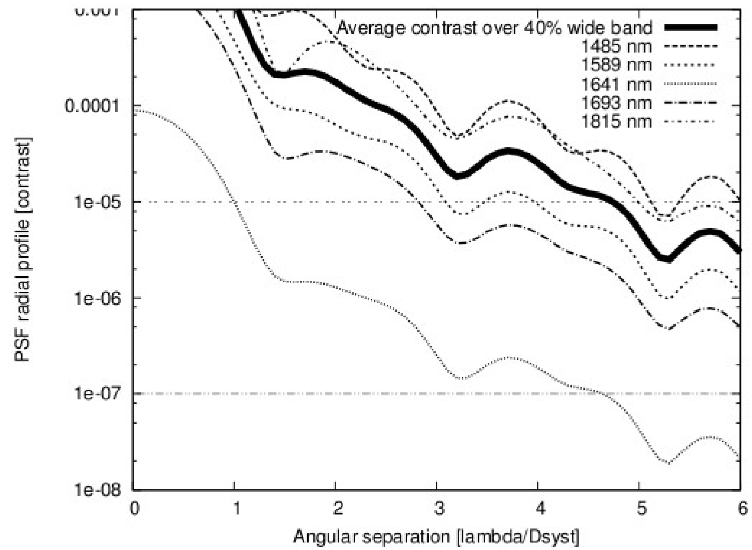


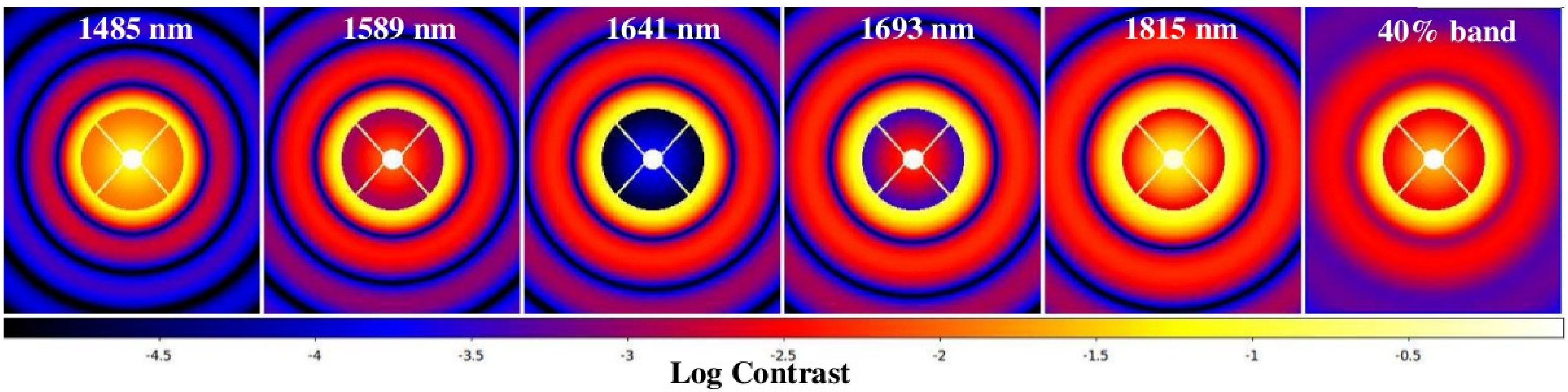
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

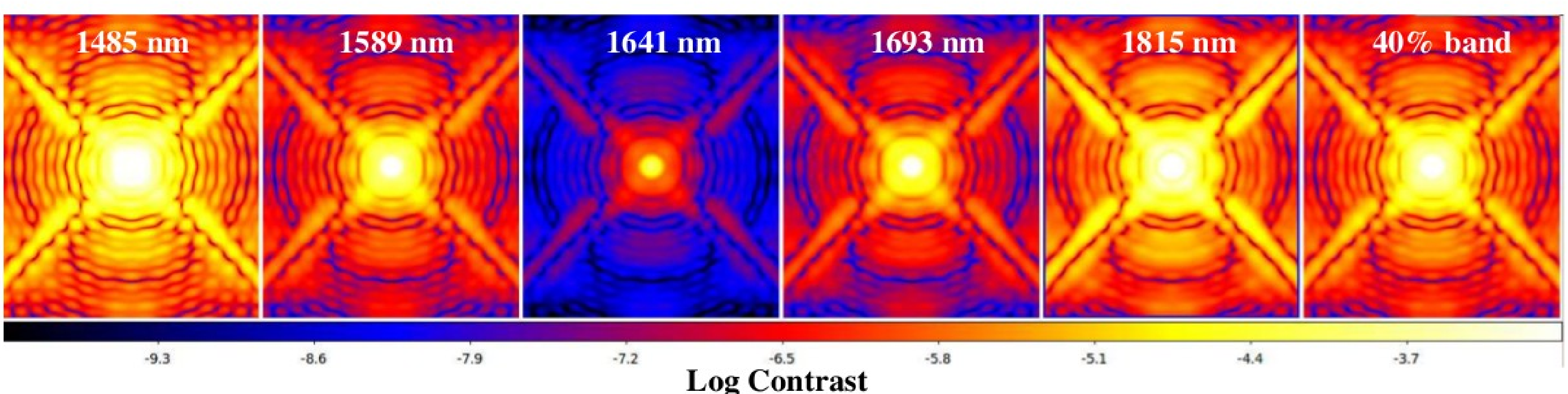


Chromatic effects are serious

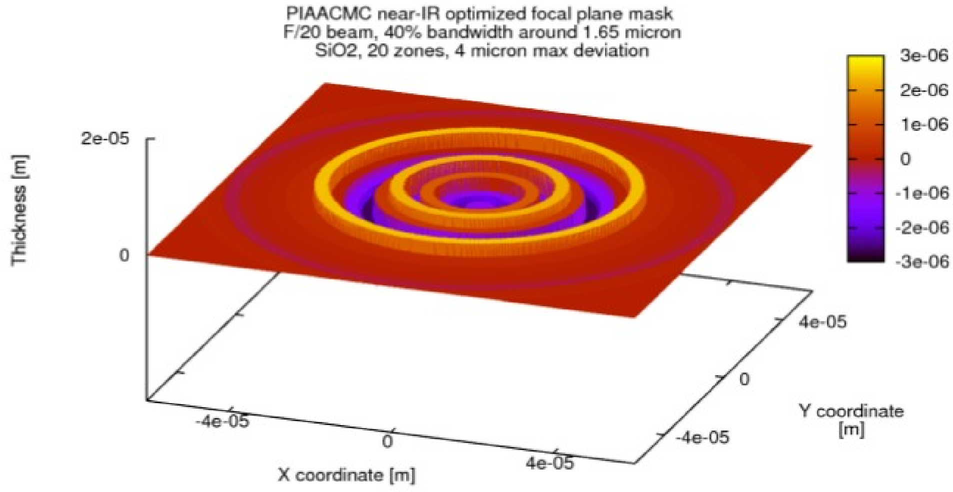


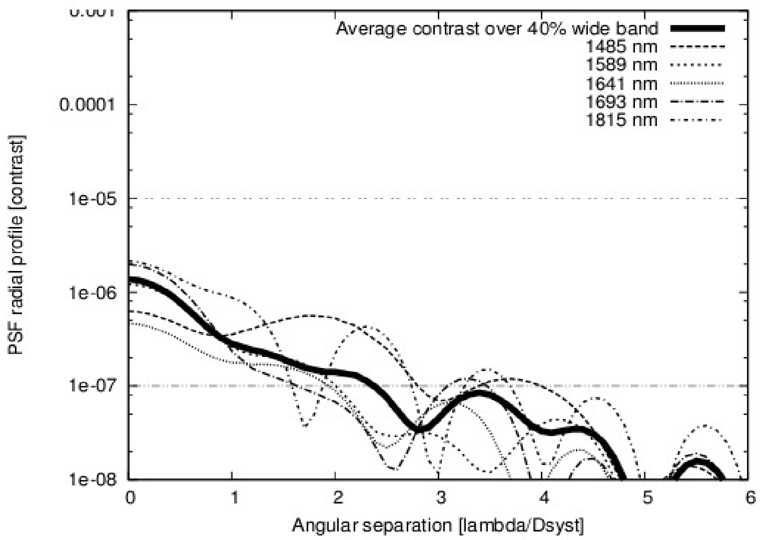


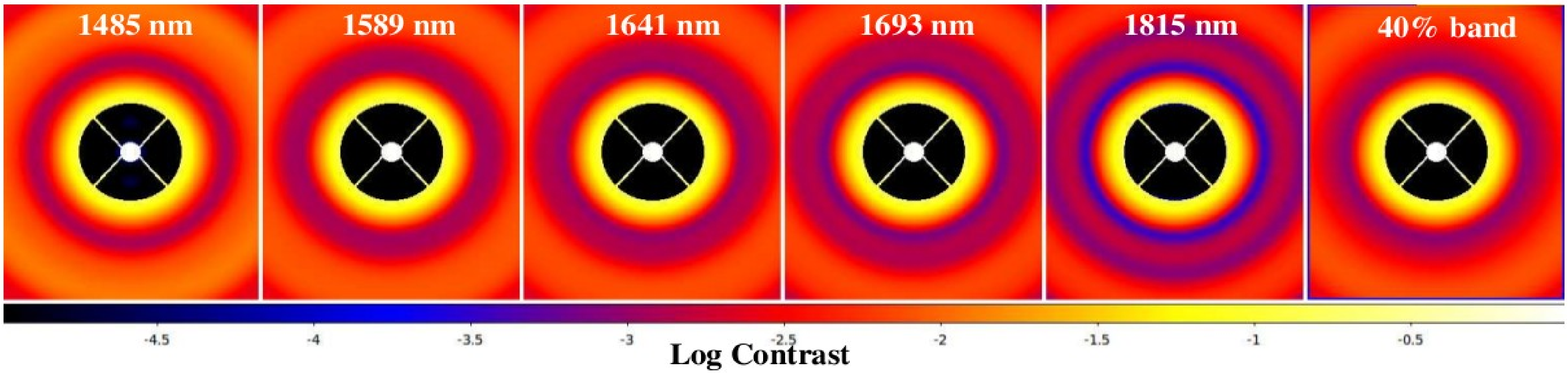


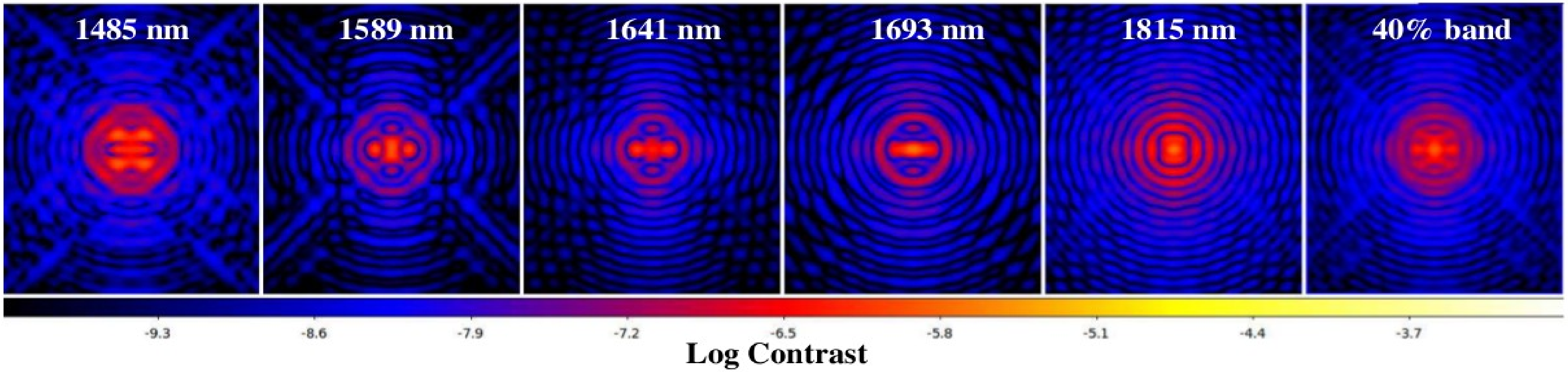


Achromatic design

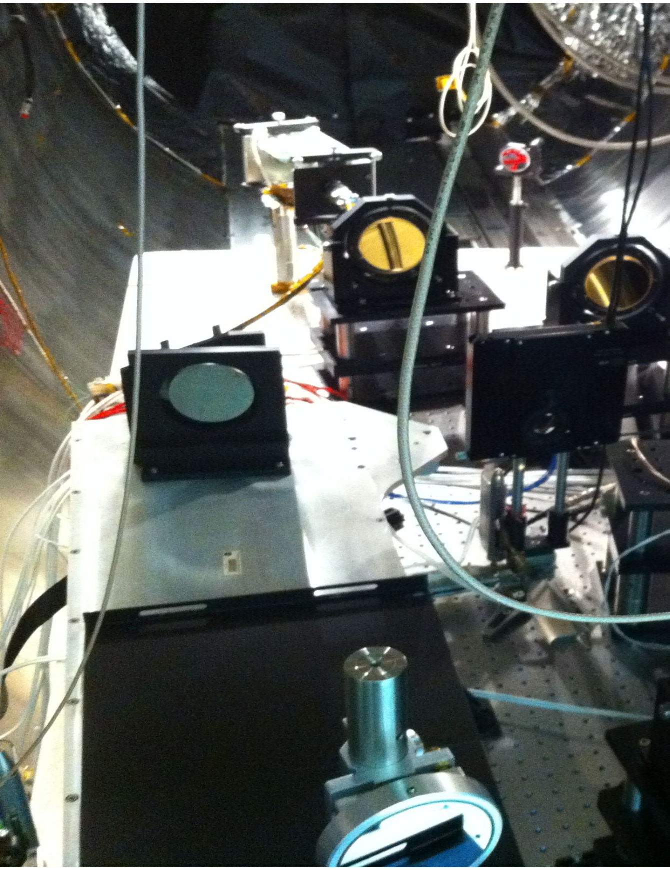


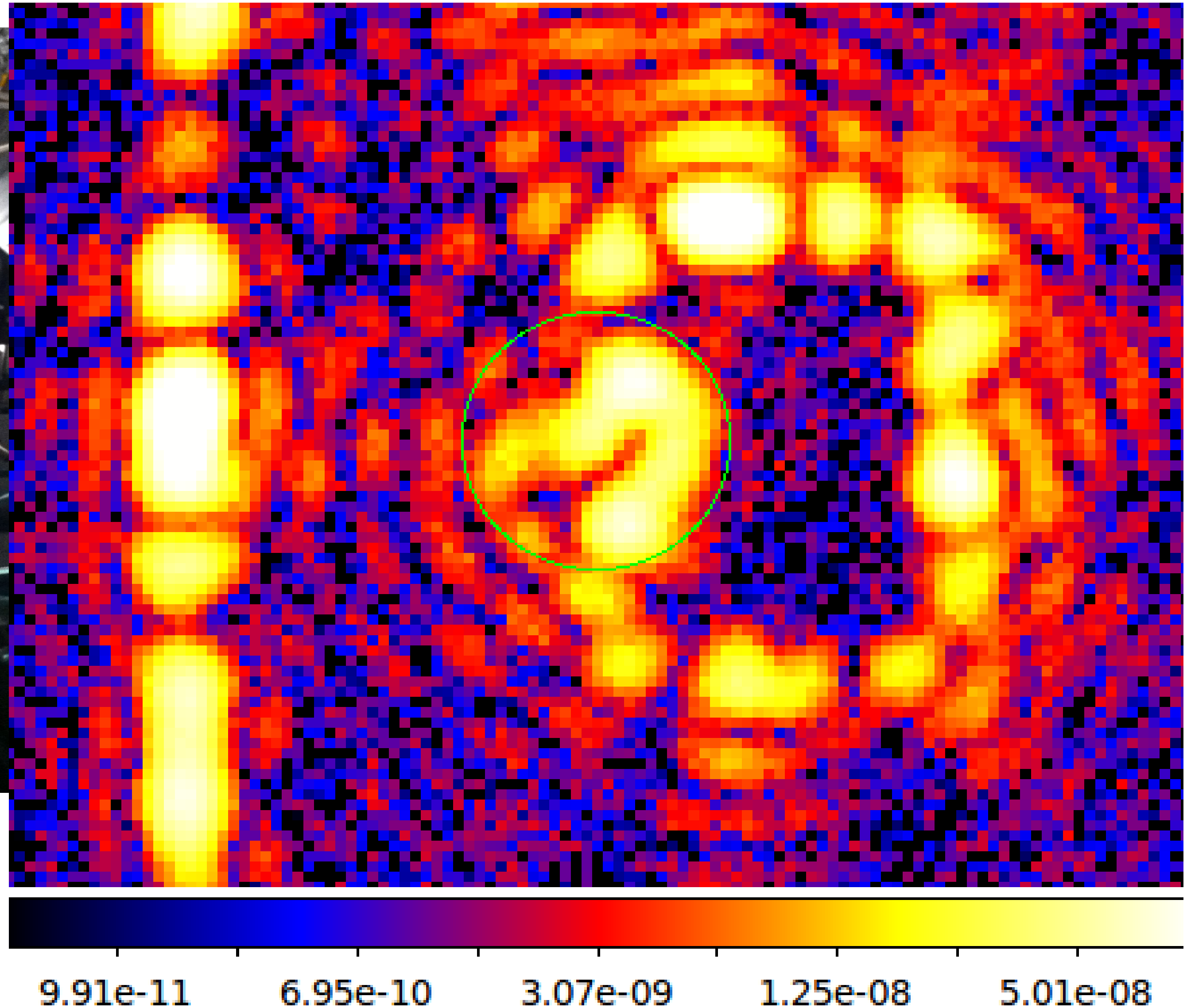






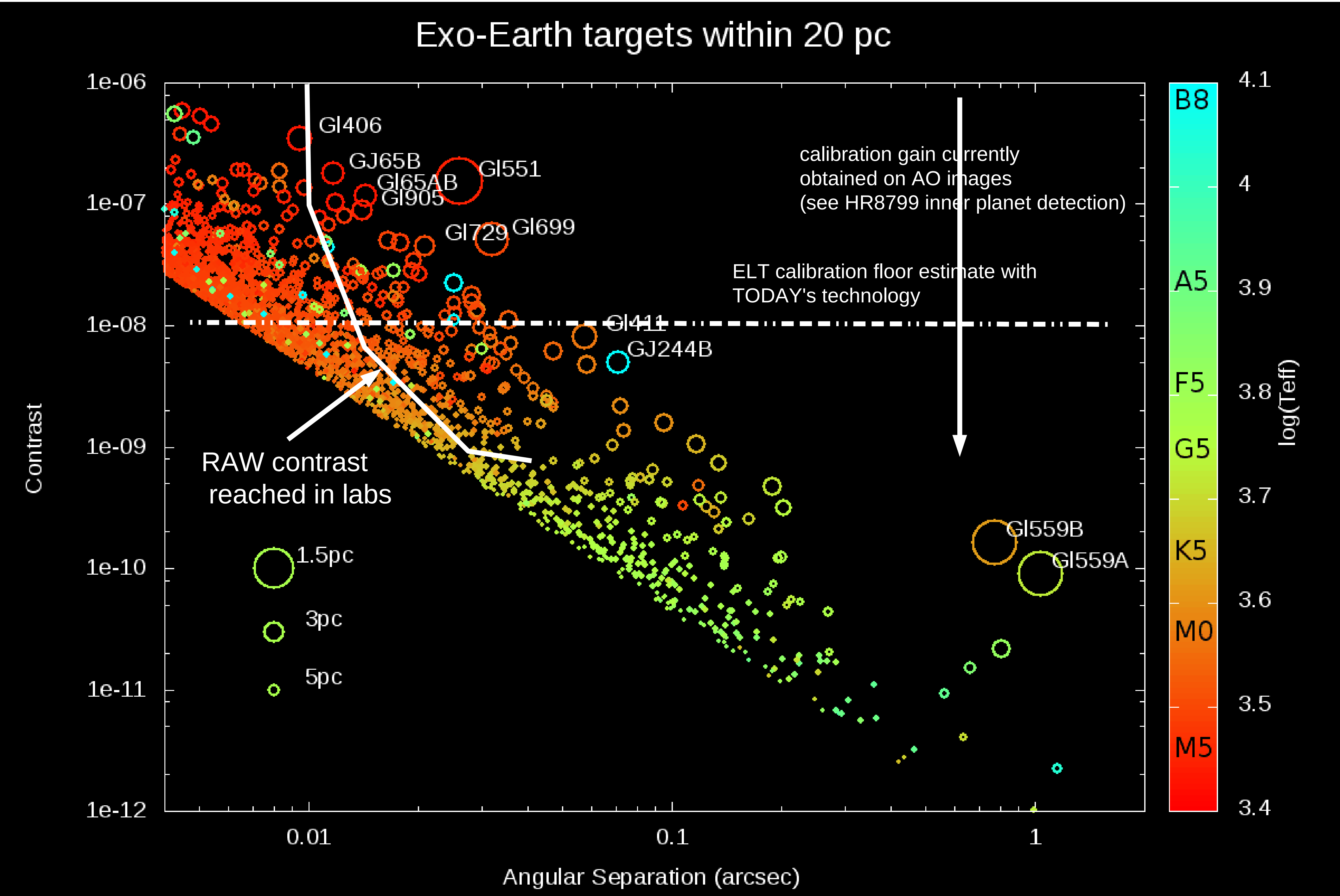
NASA JPL vacuum testbed





PIAA is reaching few <1e-9 contrast at 2-4 lambda/D separation (image above has IWA = 1.76 l/D, C=7e-9 at 1.76 l/D)

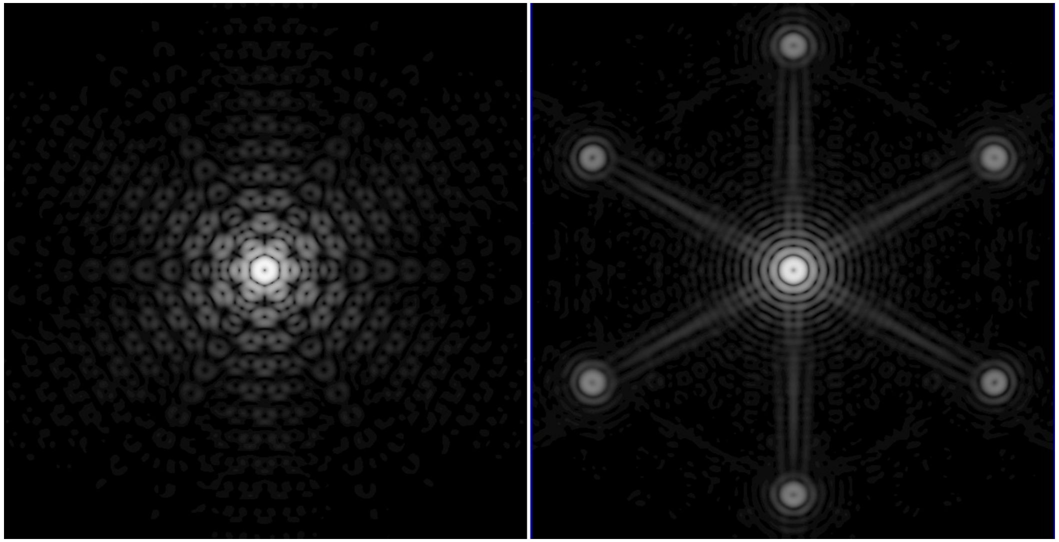
Earth analogs

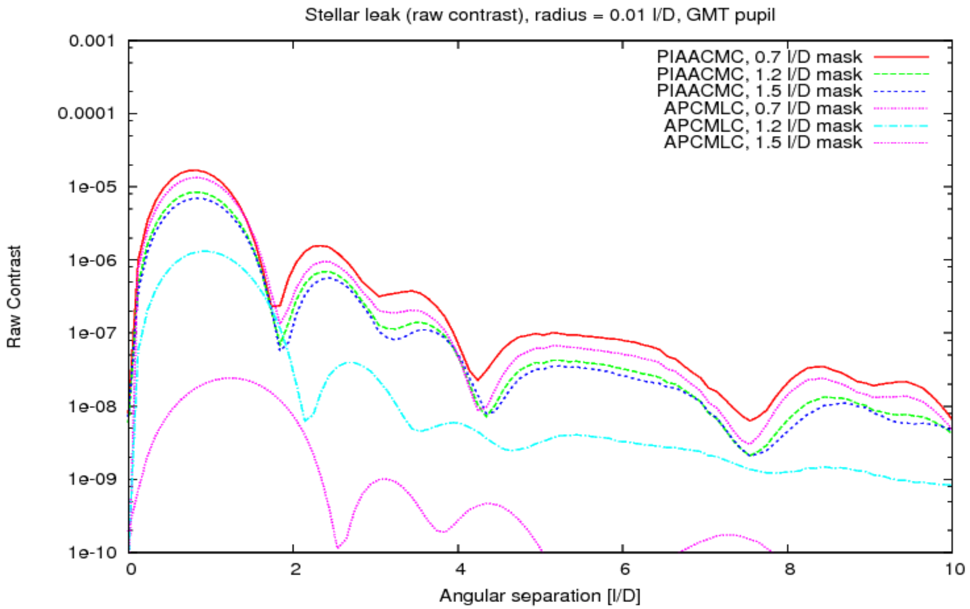


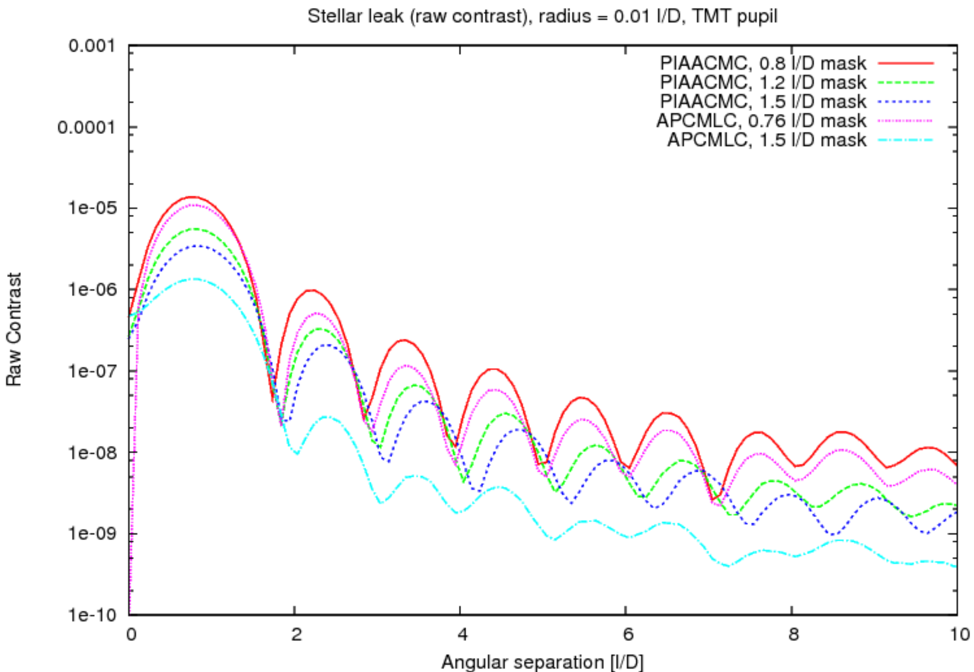
Coronagraphy: Stellar angular size

On ELT in near-IR, nearby M dwarf is about 0.1 to 0.5 mas radius = 0.01 to 0.05 l/D

→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5







Wavefront control

Can we reach 1e-4 RAW contrast in the 1 to 2 l/D range ?

Goal: ~1e-5 contrast at 1 l/D

We are not that far from it with current technology...

Conventional high order ExAO on 8-m class telescope achieves ~1e-3 contrast in near-IR at few l/D

Moving to 3x larger telescope diameter will help (dilute speckle halo) – at equal SR, 10x gain in contrast → 1e-4

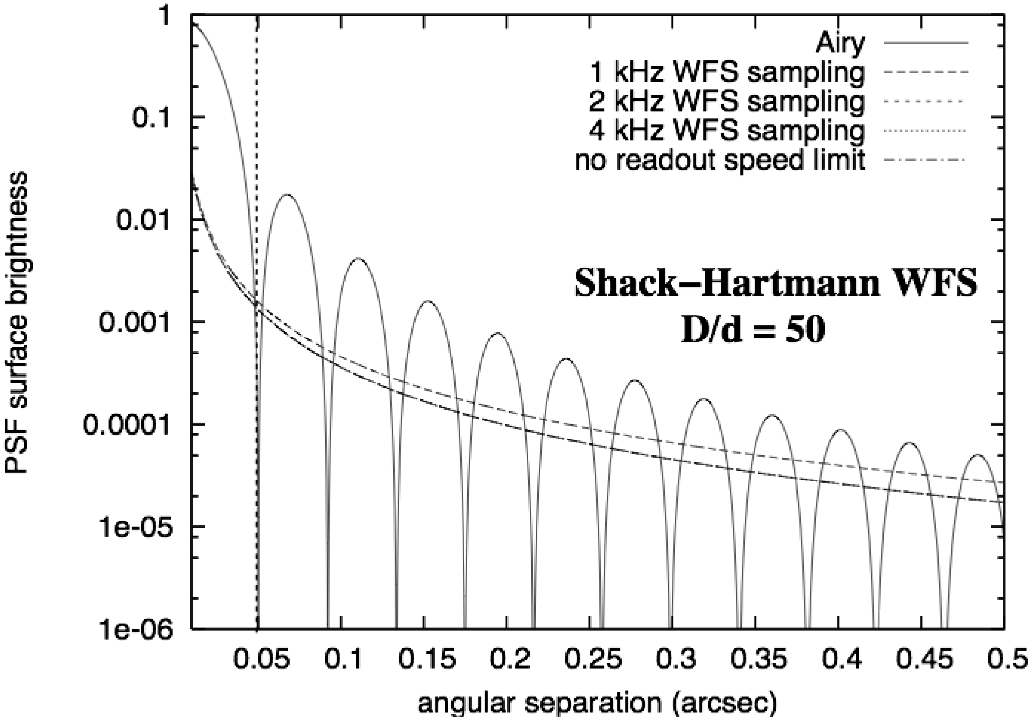
BUT **we can EASILY do much better** by :

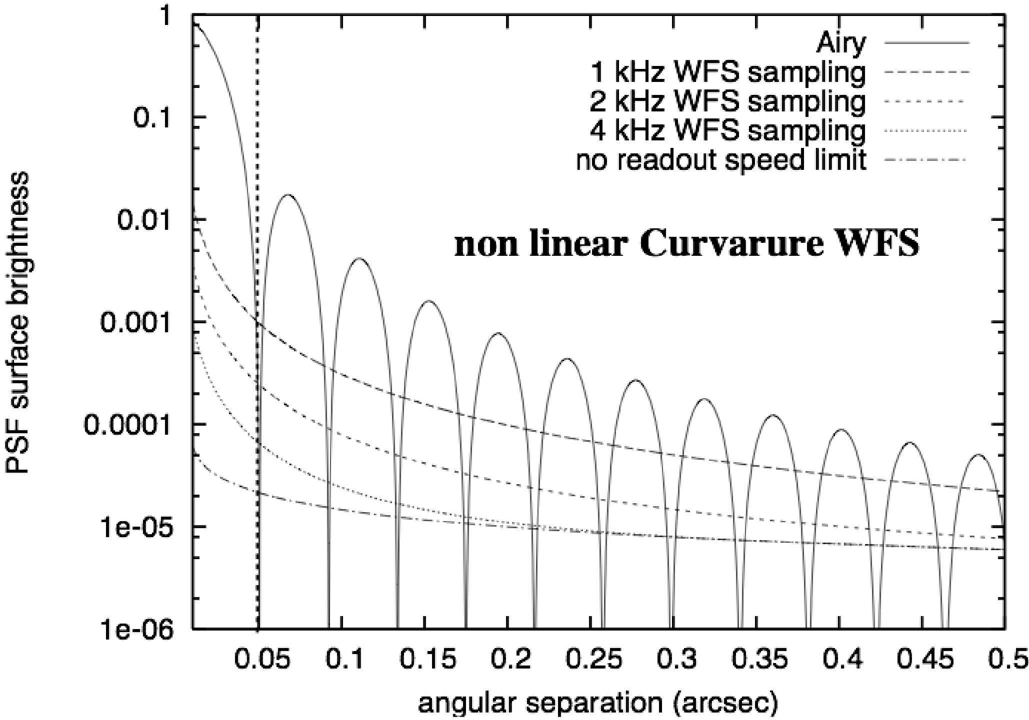
(1) Using diffraction-limited WFS (Pyramid with little or no modulation, nlCWFS, Zernike etc...)

For Tip-tilt, gain in flux is $(D/r_0)^2$ = 90,000 on 30m telescope (12.8 mag)

(2) Making use of predictive control in the control loop (inner PSF flux dominated by time lag)

Performance gain for ExAO on 8-m telescopes (10x better on 30-m)





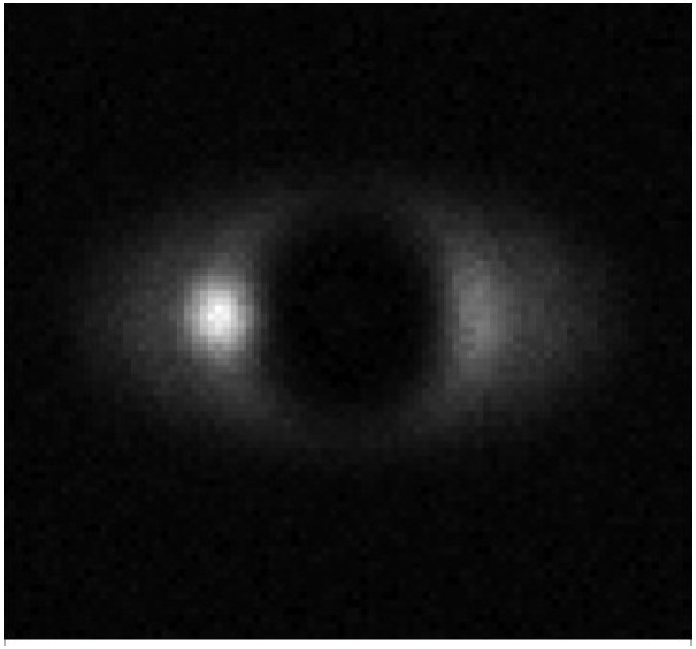
"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

Large gain at small angular separation: ideal for ExAO

Pointing and coronagraphy

Pointing errors put light in the 1 to 2 λ/D region of the focal plane, where planets should be seen

A pointing error and a planet at the inner working angle of the coronagraph look identical



Small IWA coronagraphy requires exquisite pointing control and knowledge

Pointing errors should be detected before they become large enough to induce a strong leak in the coronagraph

Pointing should be measured at the same λ as used for science

Should be measured at the diffraction limit of telescope

Should be measured at coronagraph focal plane mask

Coronagraphic LOWFS

(Guyon et al. 2010)

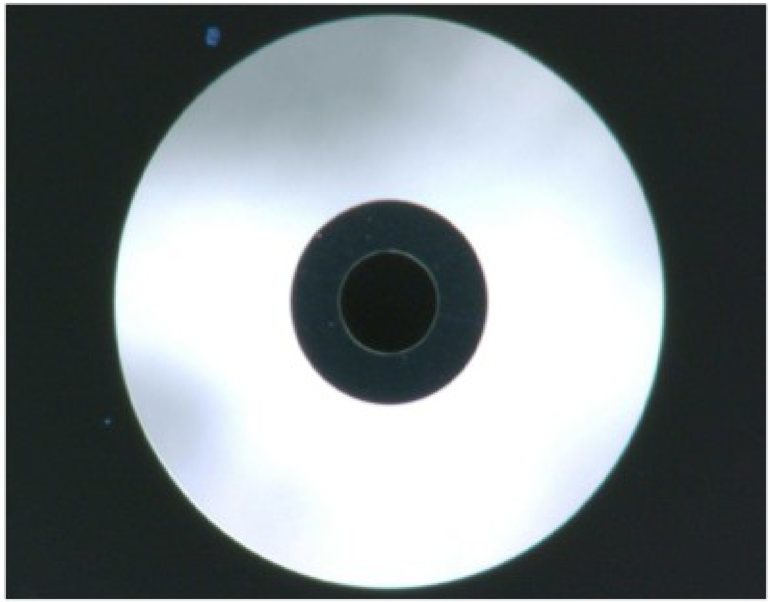
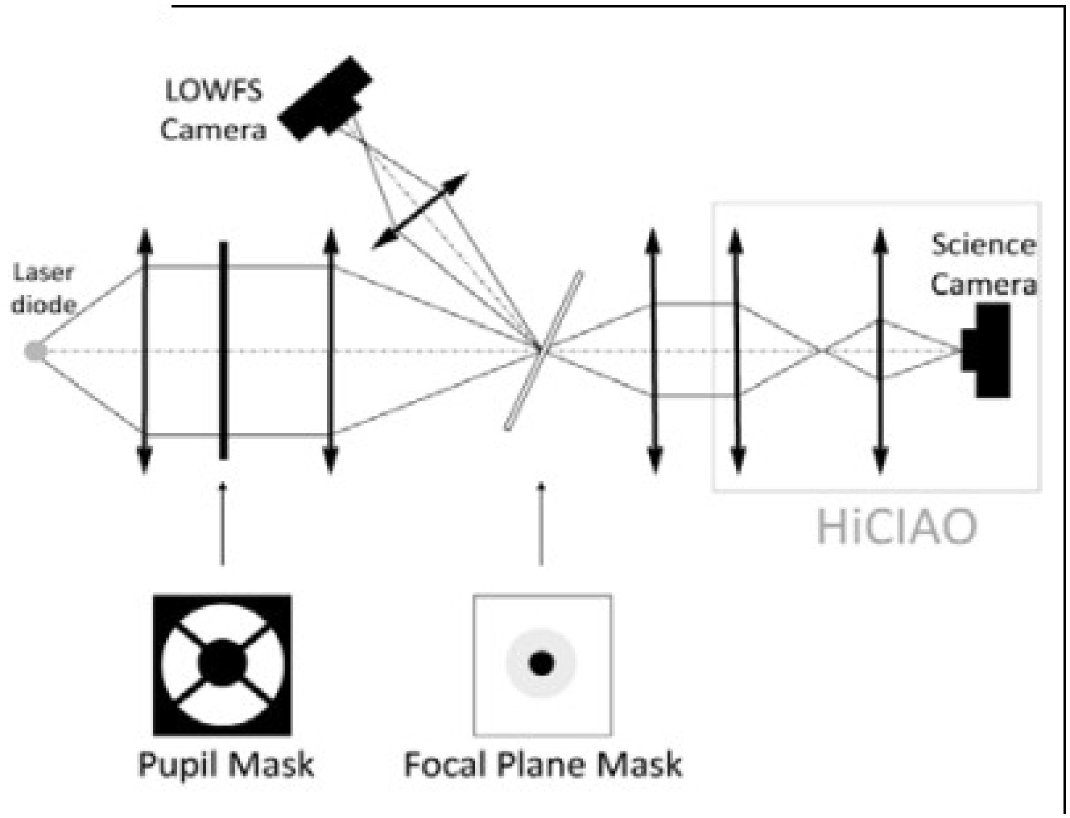
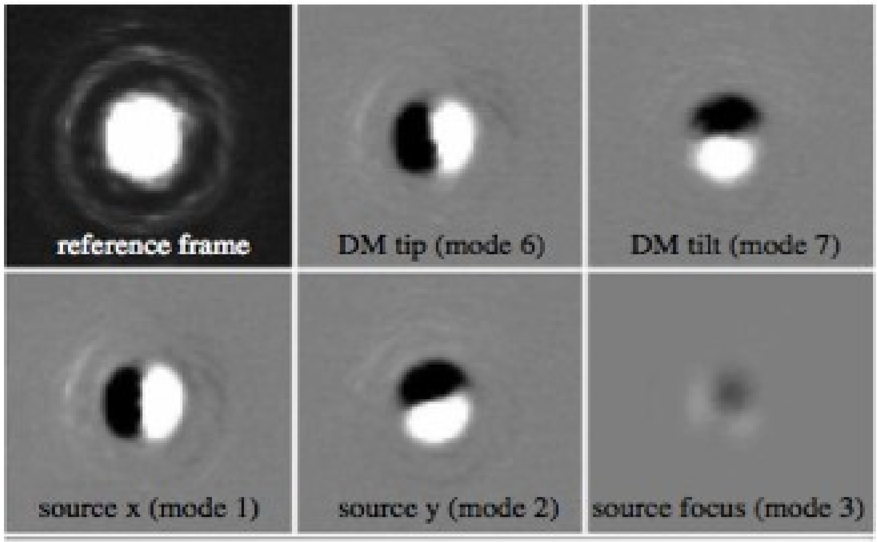
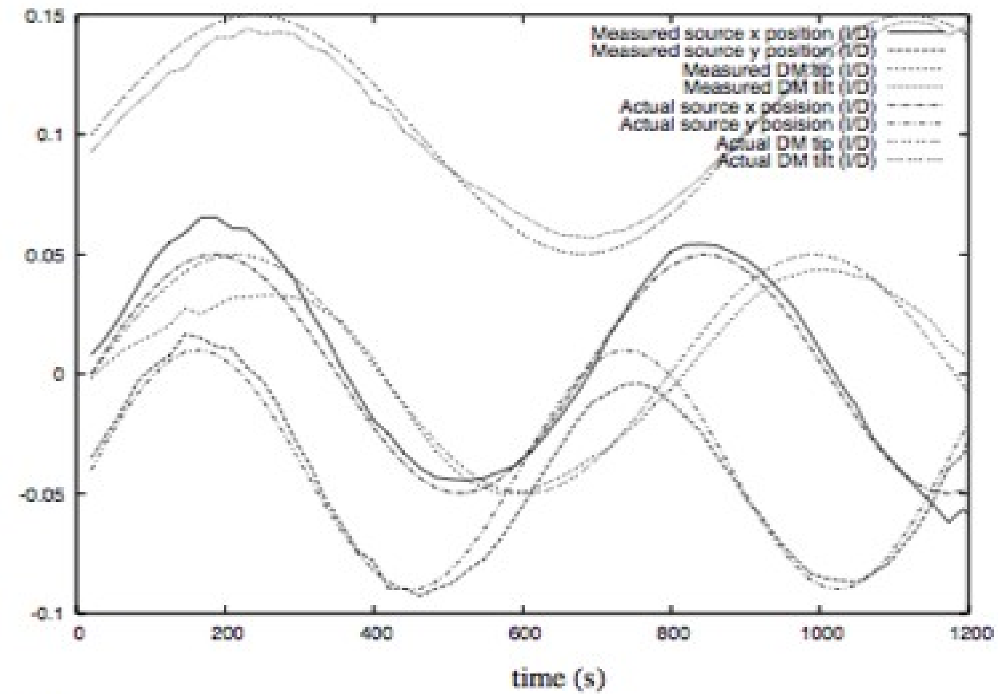


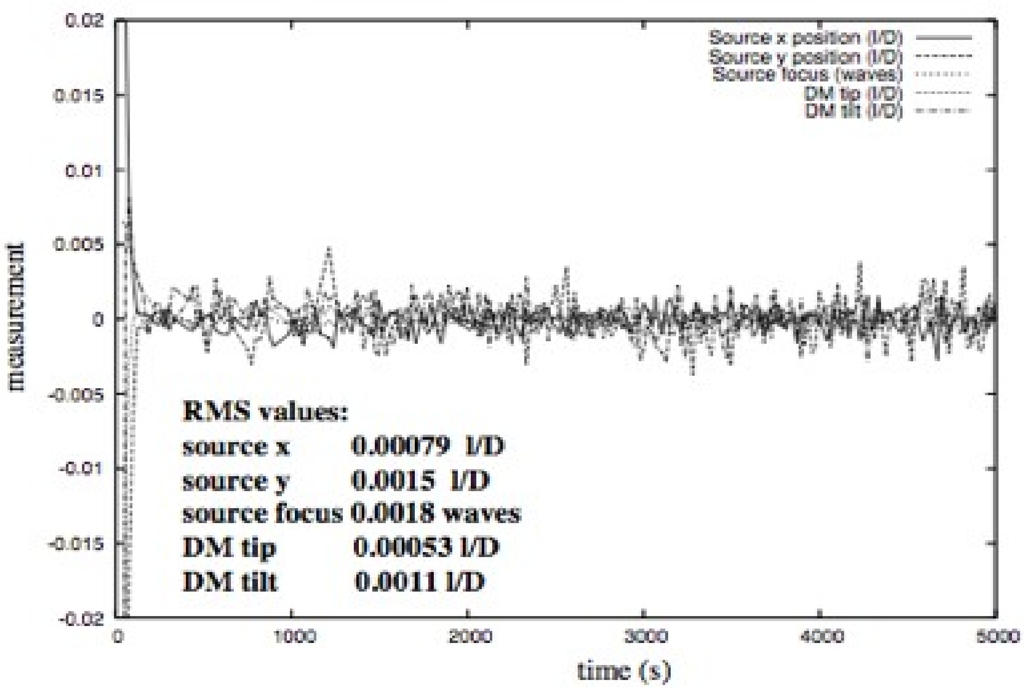
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

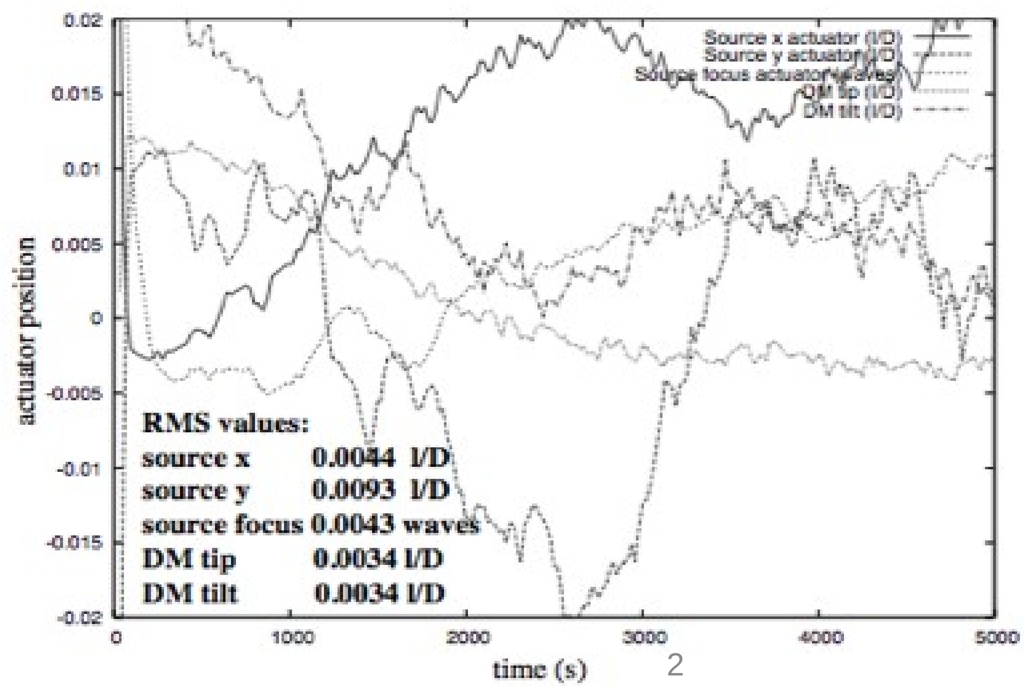


Pointing control demonstrated to 1e-3 λ/D in visible





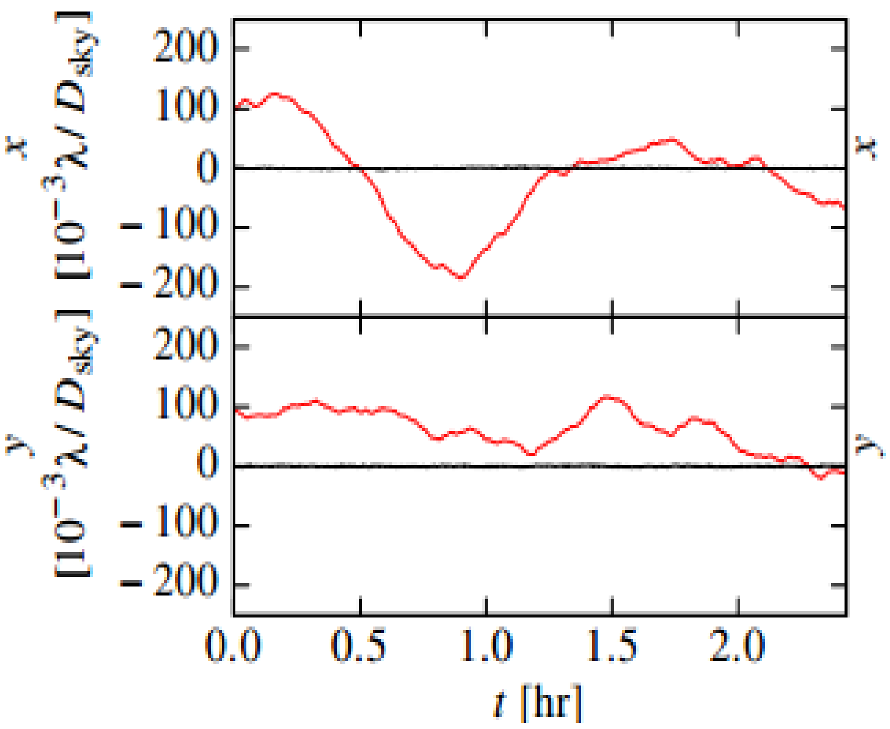




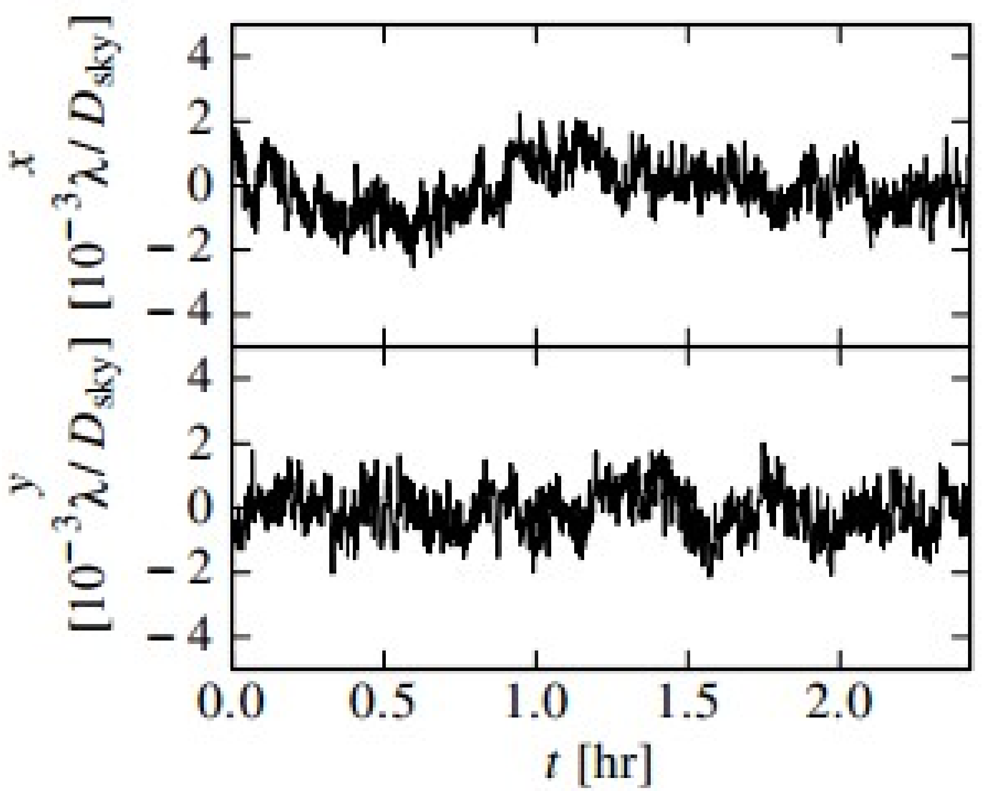
New results with CLOWFS at JPL demonstrate 3e-4 l/D control

At 10 kHz, ~1e4 ph per frame allows <1e-3 l/D measurement on ELT

No correction



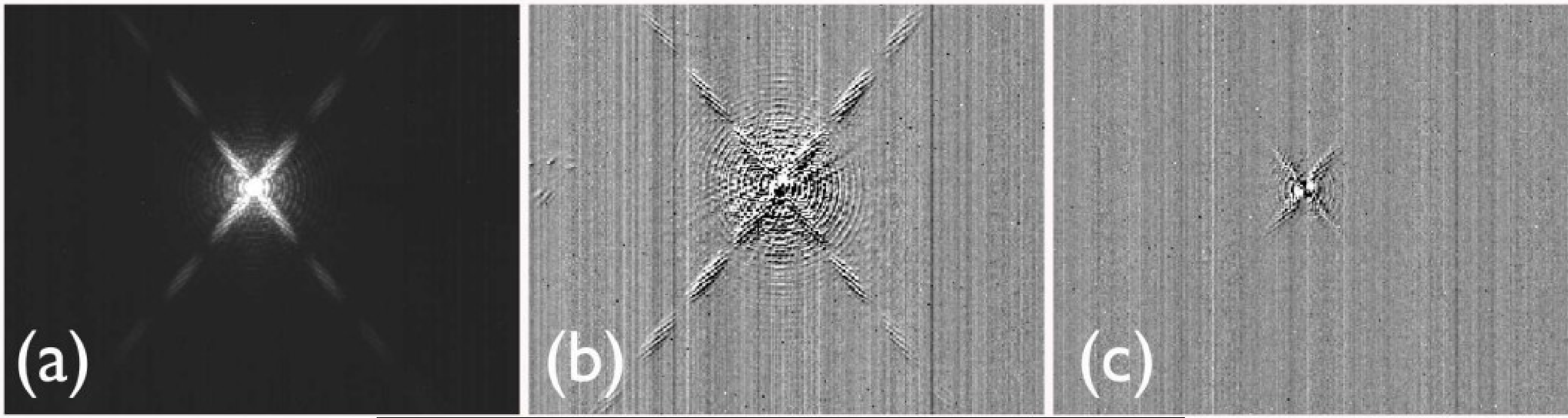
With correction

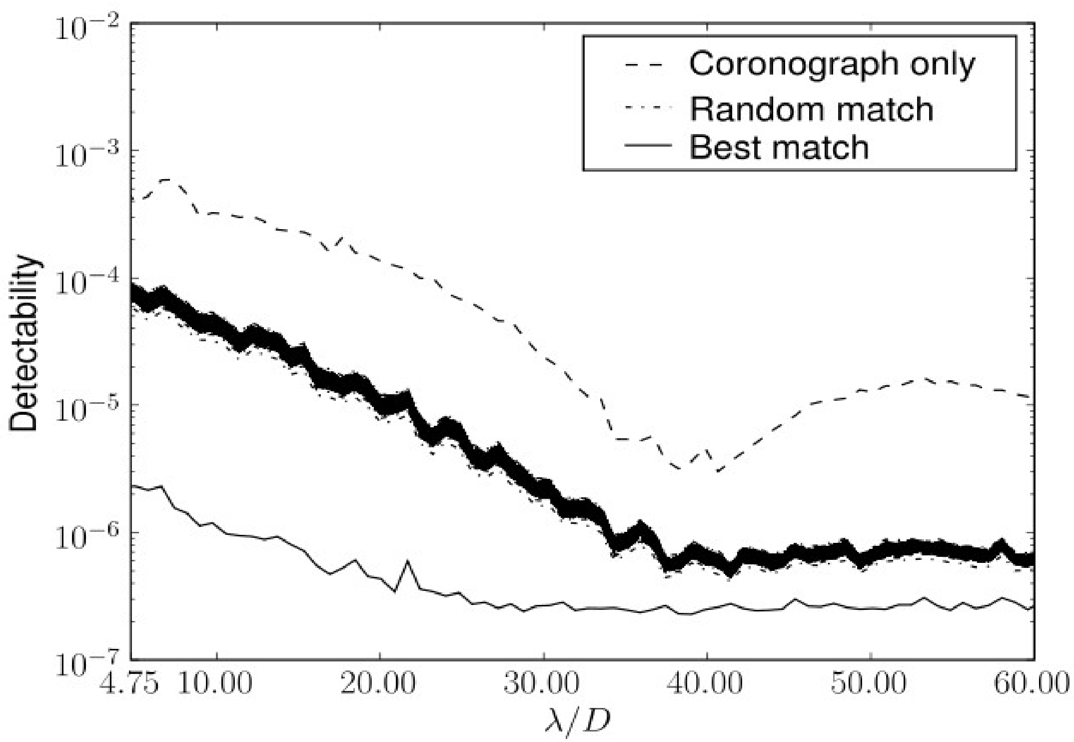


Vertical scale x50

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

Co-added science image Standard PSF subtraction MMA





Wavefront calibration to ~1e7 contrast

SDI, ADI WILL NOT WORK AT 1 l/D !!!

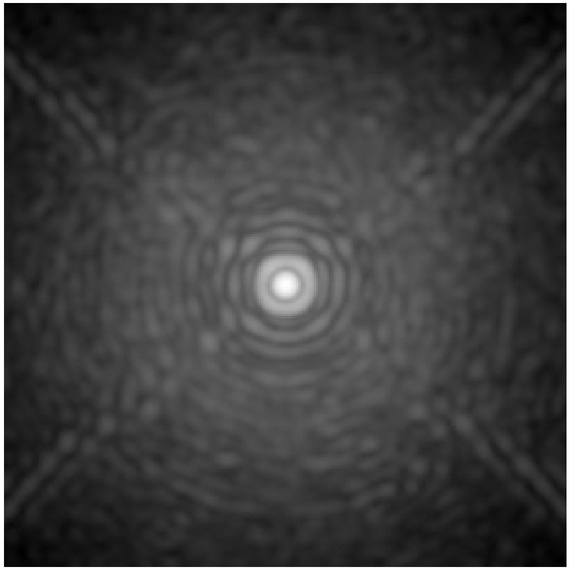
Focal plane speckle modulation appears to be very promising:

- no need for high optical quality
- non non-common path errors
- detectors now exist to do this efficiently

→ SCExAO (and others...) using this technique

Works well in the lab when things are stable... will it also work on sky with speckles moving around ?

Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

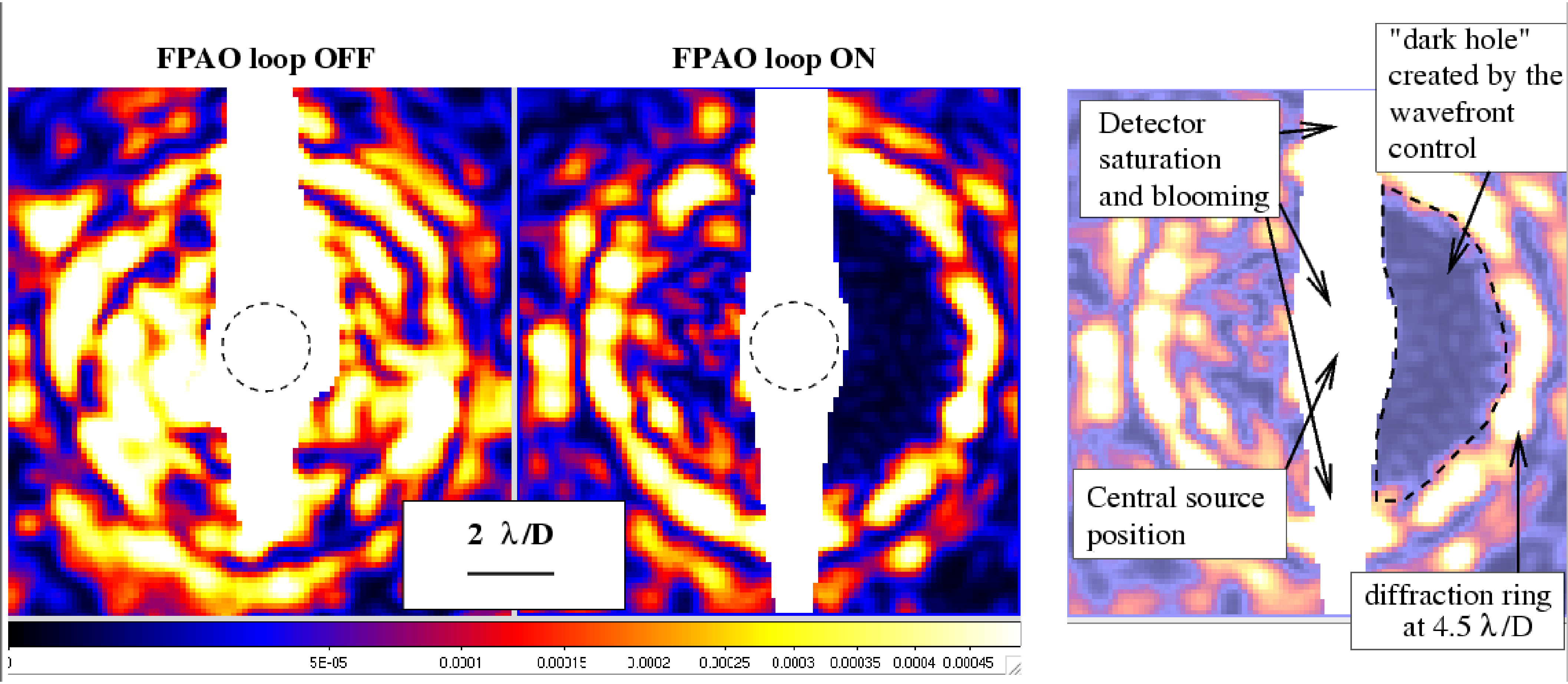
SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere

CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

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



See also results obtained at NASA JPL HCIT, NASA Ames & Princeton lab

All high contrast coronagraphic images acquired in lab use this technique.

- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics

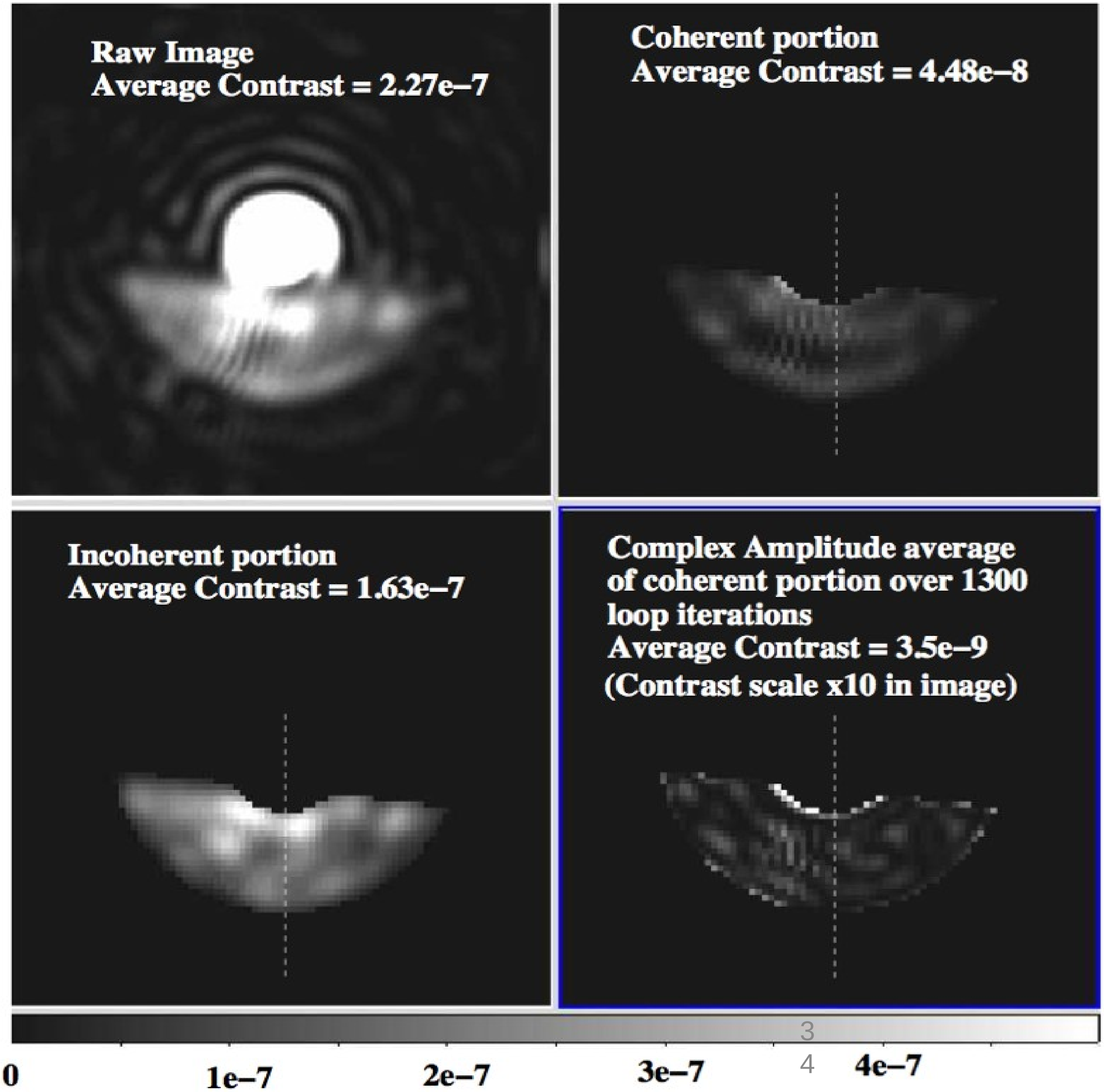
Focal plane WFS based correction and speckle calibration

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

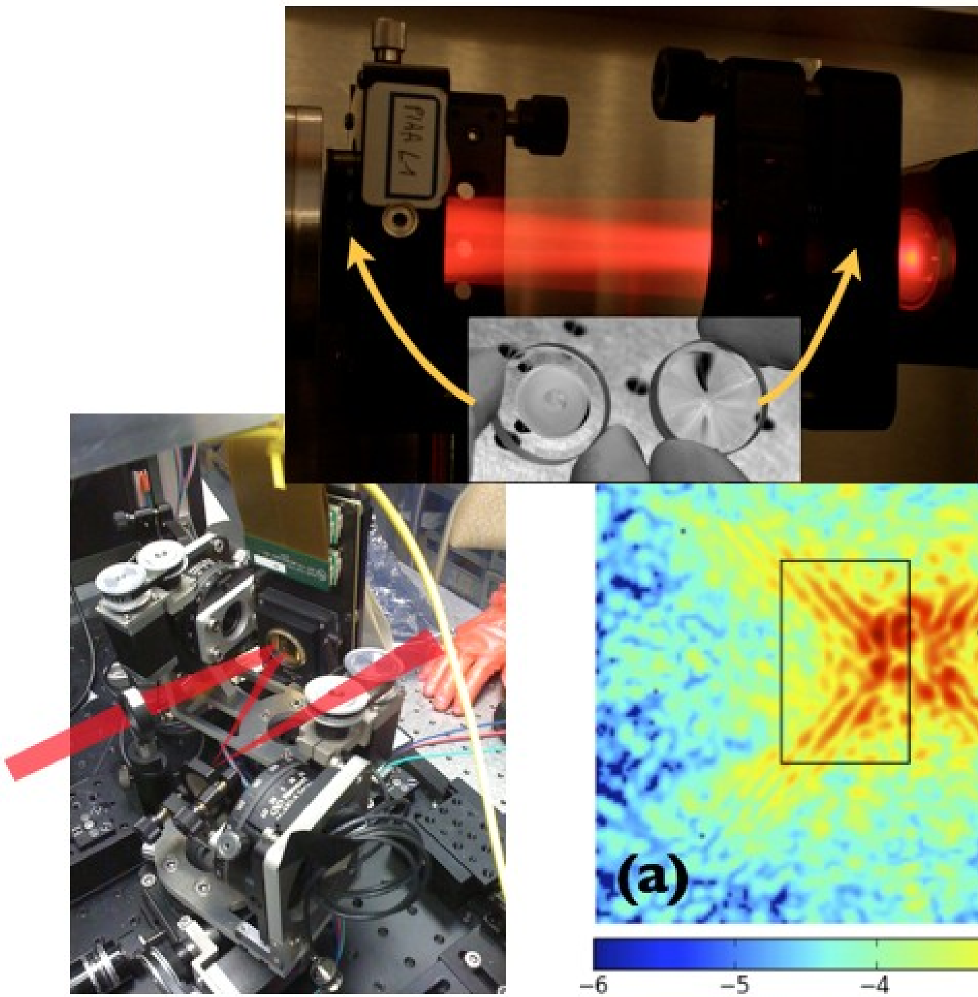
Guyon et al. 2010

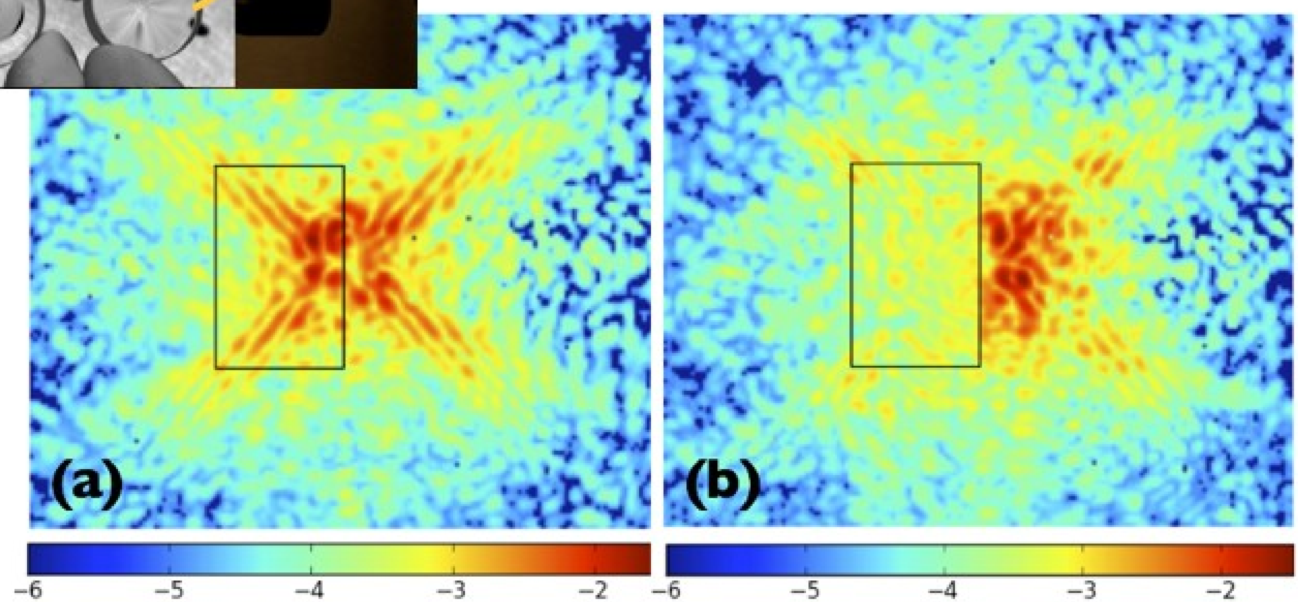


Active speckle control

Active MEMS DM to replace a passive ADI approach

Taking advantage of the full PIAA - focal plane mask - $PIAA^{-1}$ optical configuration



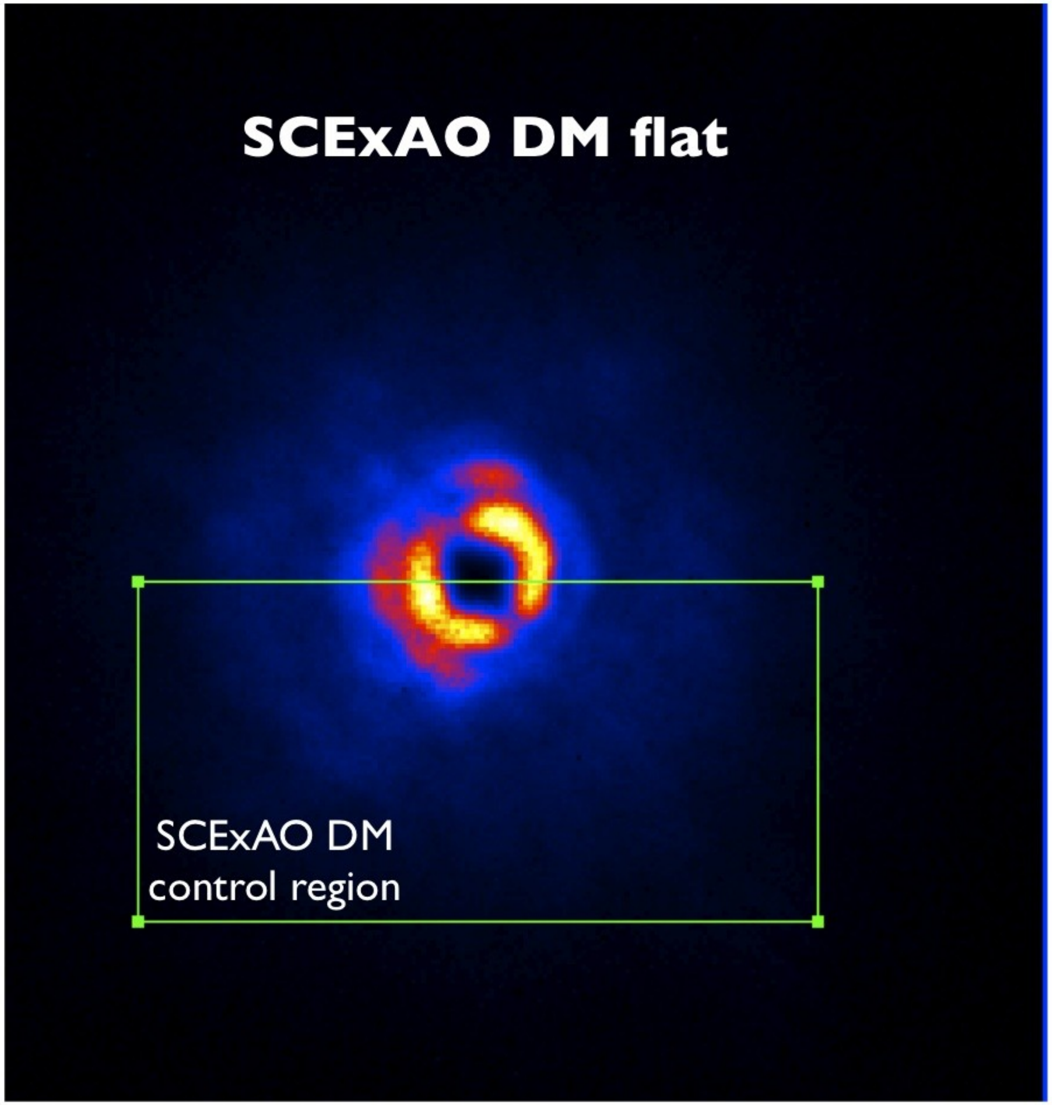


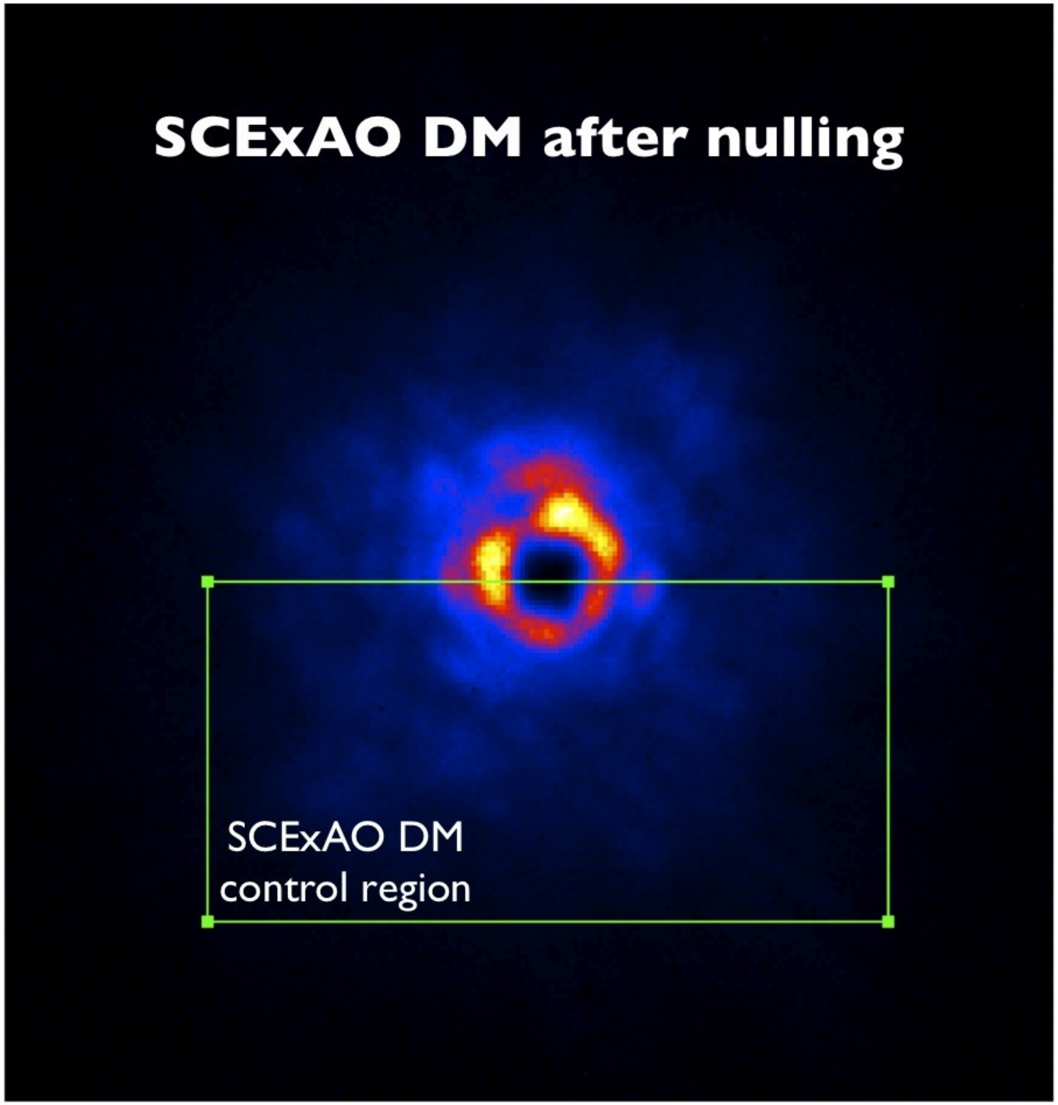
SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D
Raw contrast ~ 3e-4 inside the DM control region

Martinache et al, 2012, PASP, 124, 1288

http://www.frantzmartinache.com/subaru/02projects/04spkl_ctrl/04spkl_ctrl.html

On-sky speckle nulling with SCExAO (HiCIAO long exposure)





How to remove / calibrate static and slow speckles ?
→ case for near-IR speckle control

On ELTs, slow speckles ARE A PROBLEM

~1e-5 speckles with few sec lifetime due to large aperture

1hr exposure will only average 5sec speckles by 30x

Use predictive control in visible AO loop

→ mitigates time-lag slow speckles

Sense and correct speckles at >> 1 Hz in the nearIR (+ predictive control)

→ removes slow speckles due to time lag

→ removes slow speckles due to chromatic effects

→ removes static speckles due to optics

Detailed atmospheric WF modeling

1cm pixel scale, 40m x 40m size (4096x4096 pix)

250 us sampling (4 kHz) – linear interpolation between sample points

Multilayer frozen flow, Mauna Kea atmosphere model

0.6” seeing in visible

No inner scale, **outer scale = 25m**

Atmospheric refraction through atmosphere (**30 deg Z angle**)

Diffraction propagation between layers → **amplitude and phase**

Using 8192 x 8192 pix maps for all diffraction propagations, 16k x 16k screens for all frozen flow layers

Wavefronts unwrapped by comparison with 3D raytracing diffraction-free wavefront

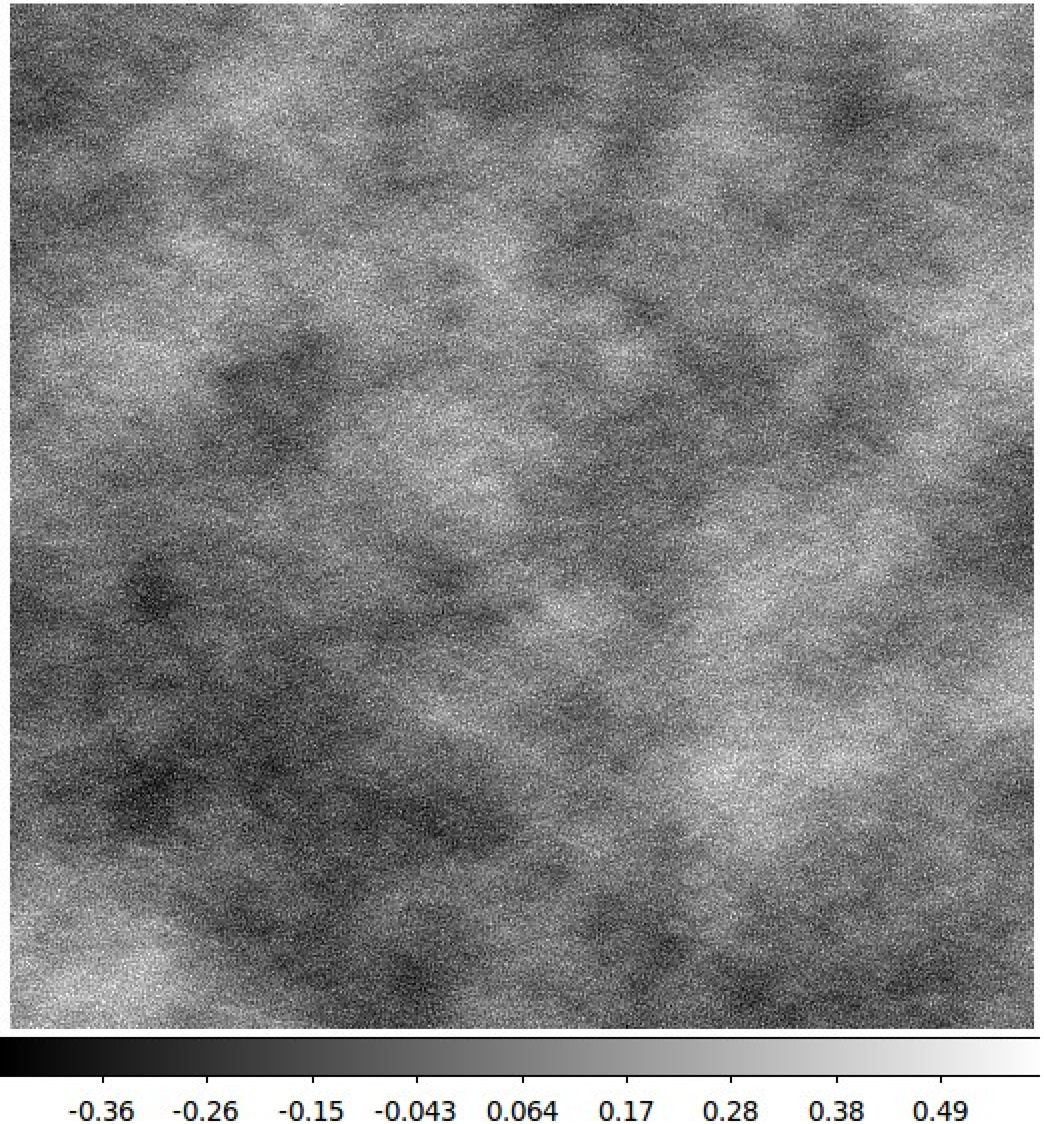
→ 240 GB / sec / wavelength (x3) = 0.72 TB / sec

→ 0.1 sec of WF data takes 1 day to compute

12 sec computed (= 30 days of CPU time, ~10 TB)

OPD chromaticity

Scintillation chromaticity (nearIR[1.6um] OPD – visible[0.6um] OPD), 40x40m



Due to :
(1) change in refactive index (gain factor)
(2) atmospheric refraction
(alt-dependent translation)

(also, diffraction propagation to lesser degree)

~0.1 rad RMS → 1% SR loss

But:
Dominated by low spatial frequencies
Slow (speckle lifetime up to few sec on ELT)

Creates ~1e-6 speckles with
~1 to ~5 sec lifetime
→ ~1e-7 speckles in 1hr exposure

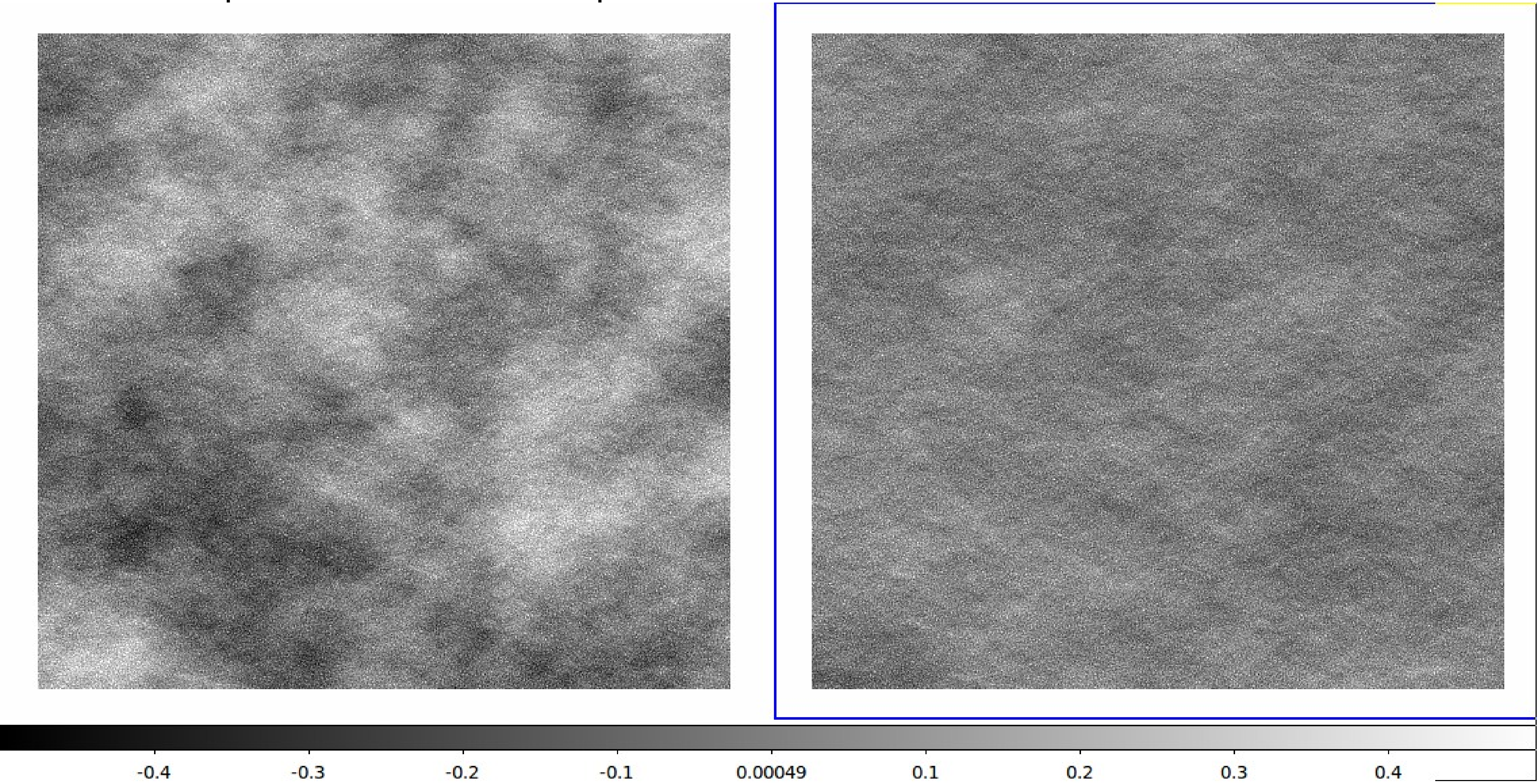
Optimal OPD scaling

0.6 um vs 1.6 um: 1.4% difference in (n-1)

0.8 um vs 1.6 um: 0.7% difference in (n-1)

Scaling removes most of the low order OPD chromaticity

Multiplicative coefficient (here 1.017) can be computed, but difficult to separate telescope errors from atmosphere



Why fast near-IR sensing ?

Low noise near-IR detectors are becoming available

- 2e- RON, 2kHz frame rate available (RAPID, SELEX + others)
- << e- RON photon counting array available soon (works in labs with 32x32 pixels, large format under dev.)

1e-5 speckle = 1e4 ph/s in H on ELT → sensing & control possible at ~100 Hz with low-noise detector

100 Hz sensing, 10 Hz control of 1 Hz speckle → ~x10 attenuation

→ 1e-6 residual with 0.1 sec lifetime → x100 gain in contrast

(conservatively assumes no predictive control)

Without near-IR sensing & control > 1 Hz → ~1e-7 contrast limit due to chromatic effects

With 100Hz sensing (10Hz control) → chromatic effects pushed to ~1e-9 contrast

SCExAO as a precursor

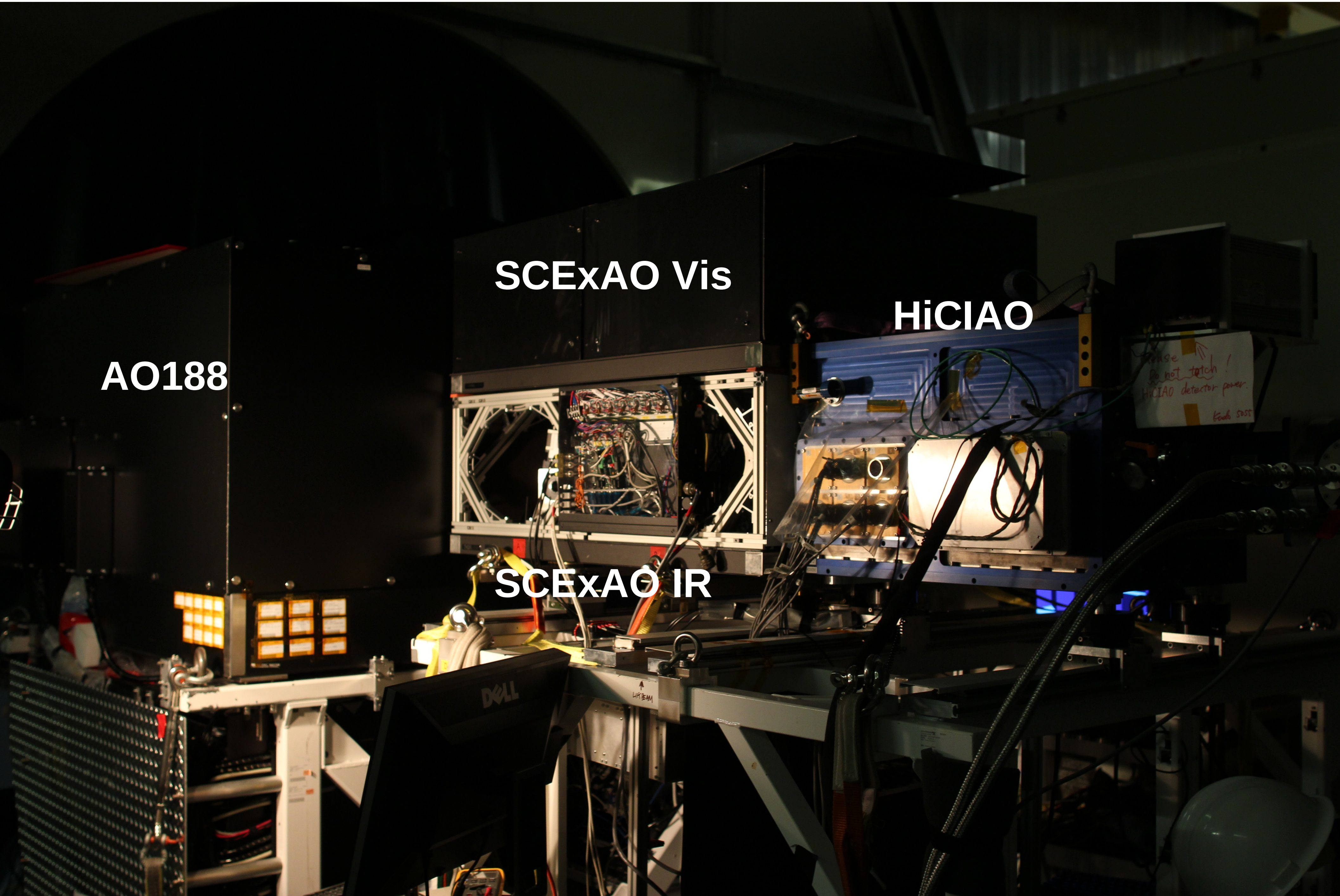
SCExAO is a precursor to an ELT system for direct imaging of exo-Earths. A SCExAO-like system could be placed on an ELT in a short time, as optical interfaces for narrow FOV system are relatively easy

SCExAO will not image Earth-like planets, but it will demonstrate the performance required to do so with ELTs

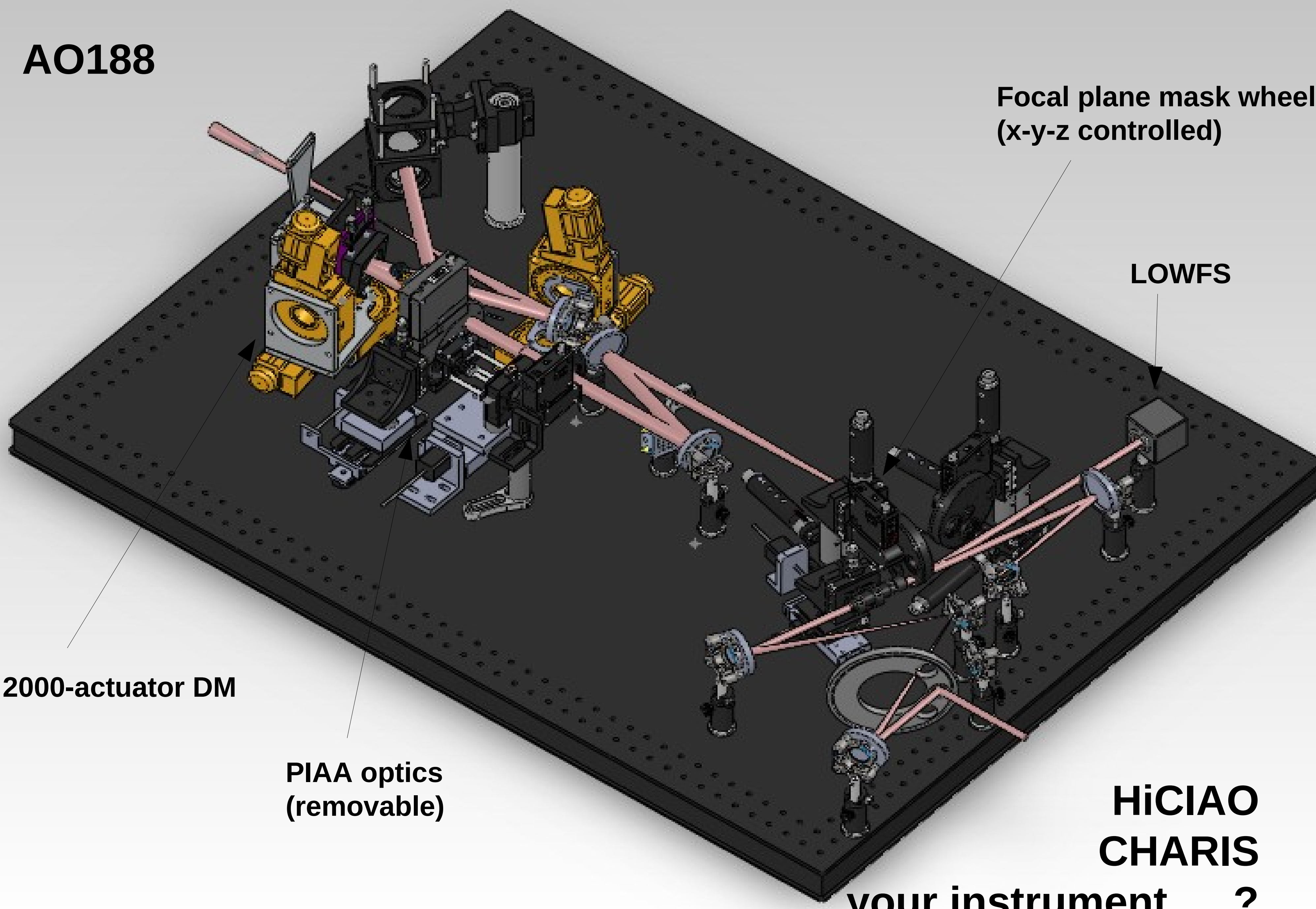
SCExAO provides a platform well-suited for technology development and on-sky testing / scientific use.

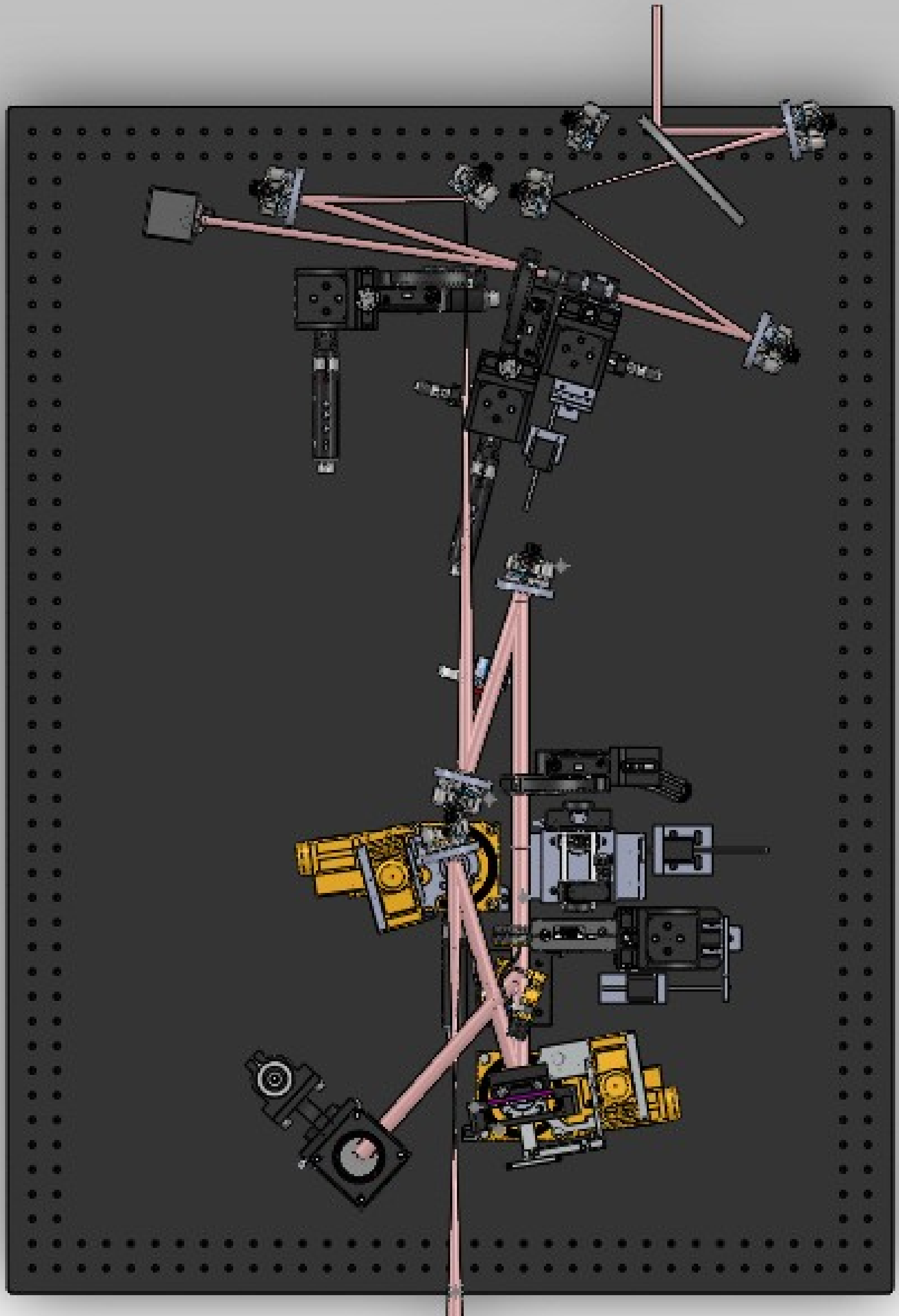
- SCExAO team can work with scientists & engineers to bring new techniques & instruments to sky
- SCExAO provides wavefront control and calibration required to test new techniques
- Such ongoing tests already happening (8 octants, vortex, VAMPIRES and FIRST modules)

SCExAO at Subaru



SCExAO near-IR bench





Conclusions

Habitable planets can be imaged with ELTs around low-mass stars. Spectroscopy of several targets could also be done at a very useful R~100 → <u>this is the easiest quickest way to characterize habitable planets</u>

This requires aggressive IWA system able to work at 1 lambda/D and somewhat unusual (but not particularly challenging) technical choices

Technologies are being matured now, and should be ready in 10yrs **ASSUMING WE WORK ON IT**

This should be a focused experiment for <100 targets. Can be deployed quickly and cheap → great science per $!!!!

SCExAO is a precursor to such a system. A SCExAO-like system could be placed on an ELT in a short time, as optical interfaces for narrow FOV system are relatively easy

Related work: Crossfield 2013, Kawahara et al. 2012, SEIT

Habitable planets spectroscopy

Space (2m<D<4m telescope):
F-G-K type stars, visible light

Ground (ELT):
M type stars, nearIR