Direct imaging of habitable planets from ground and space

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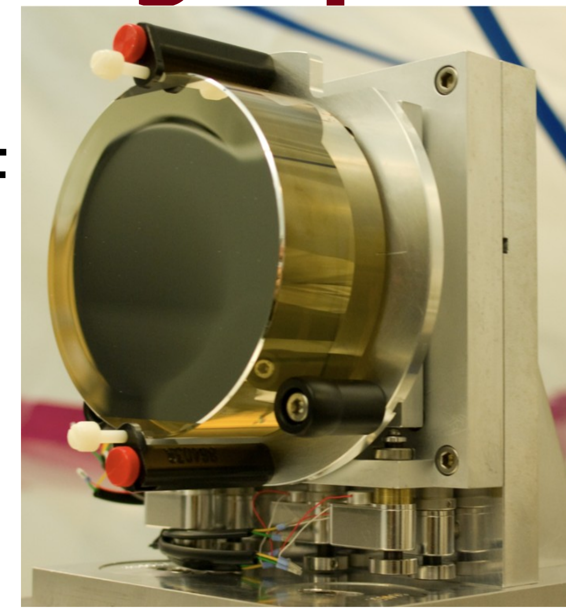
Direct imaging of habitable exoplanets with space telescopes

- New technologies: coronagraphy, wavefront control
- Scientific opportunities – what size telescope ?
- The case for a multi-purpose mission
  Wide field imaging, coronagraphy and astrometry ?

Direct imaging of habitable exoplanets with ELTs

Why M dwarfs ?
Why ELTs may be the first to find evidence of extraterrestrial life ?
The SCExAO system: a precursor on an 8-m telescope
Complementarity with space projects

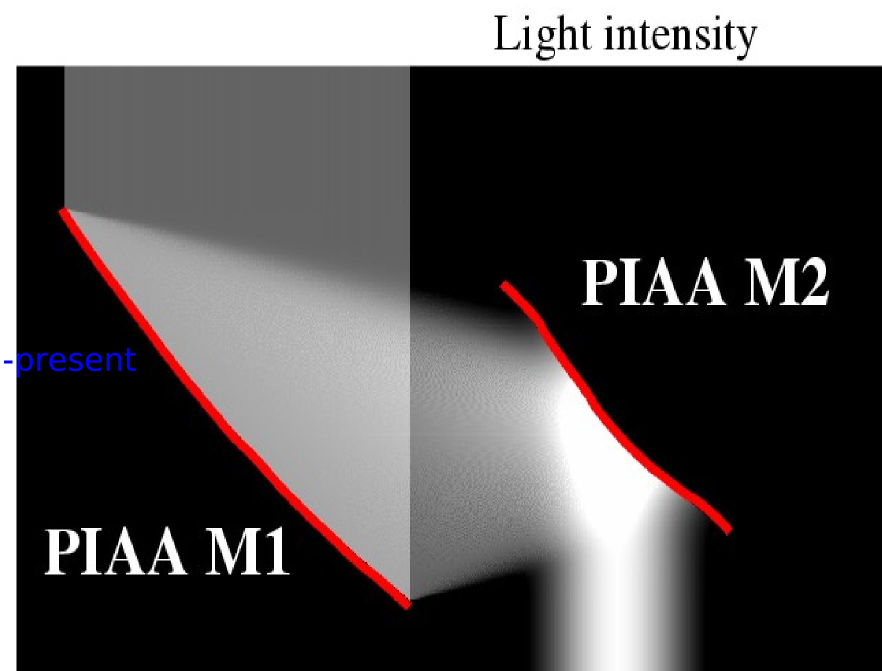
Phase-Induced Amplitude Apodization (PIAA) coronagraph



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 (PIAACMC) 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
Lab demos at NASA Ames, NASA JPL for space coronagraphy

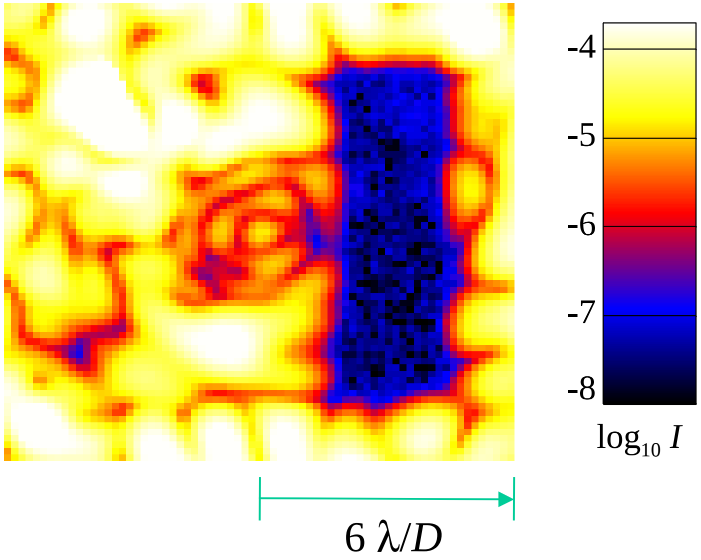


Focal plane wavefront sensing (speckle nulling, EFC, SCC ...)

Use focal plane science image as wavefront sensor:

No non common path errors → the required 1e9 raw contrast can be obtained with conventional optics

High sensitivity → nearly optimal use of star photons (as opposed to SHWFS for example)



Current lab raw contrast ~1e-9

PIAA achieved 4e-9 at 2 l/D [JPL/Ames/UofA]

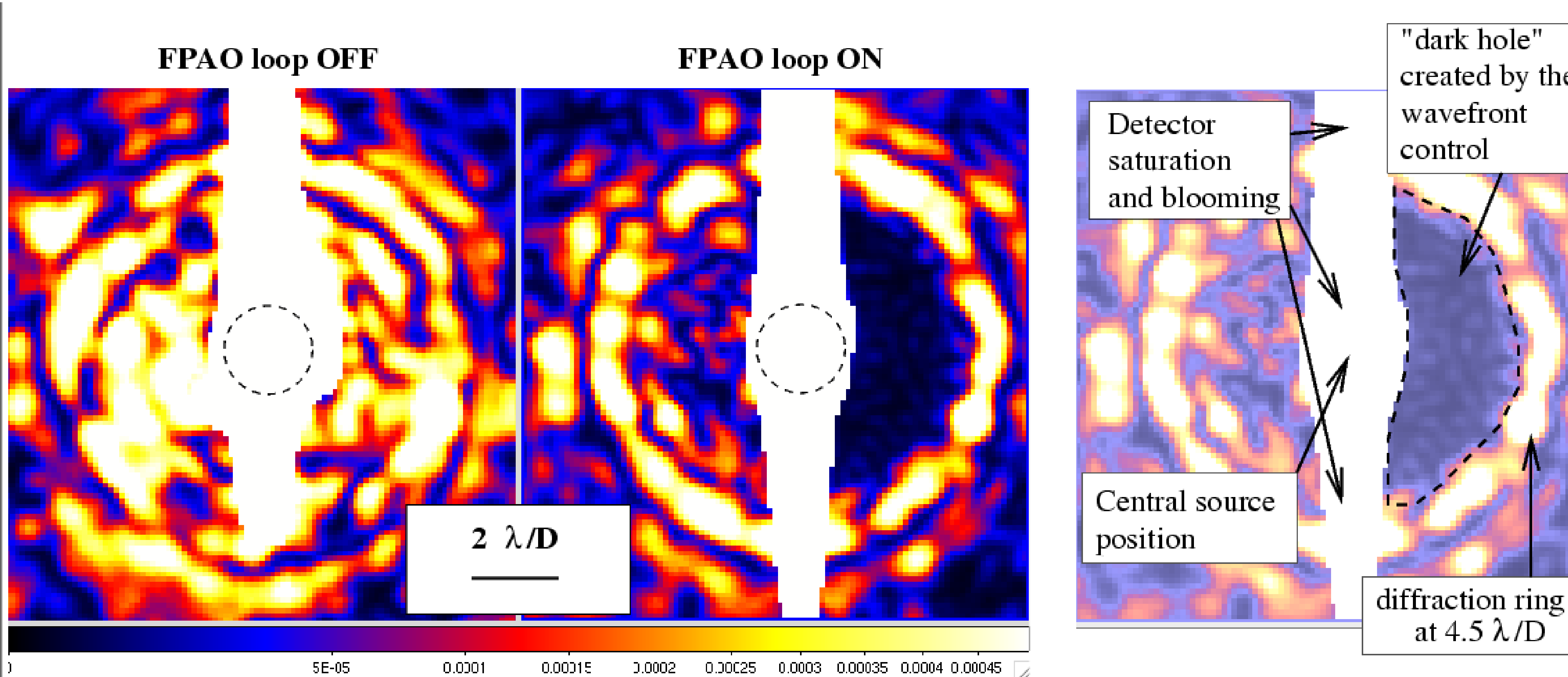
OVC achieved 4e-9 at 2.5 l/D [Serabyn et al., JPL]

Lyot achieved <1e-9 at 4 l/D [Trauger et al., JPL]

Ongoing work to :

- improve contrast to <1e-9
- achieve contrast in polychromatic light (promising results with Lyot)
- pointing control to <mas jitter, <0.1mas calibration
- system level work to simultaneously combine high contrast, low IWA, pointing control and polychromatic WFC

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

Coronagraphic LOWFS

(Guyon et al. 2010)

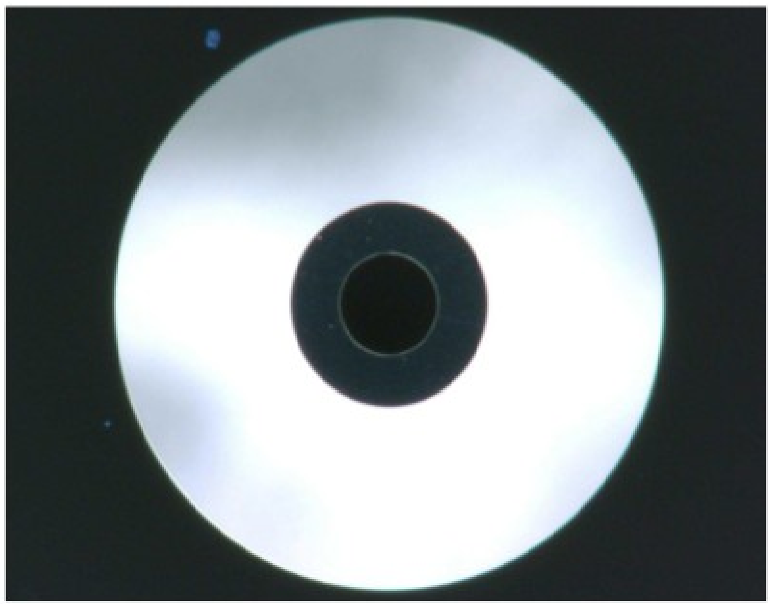
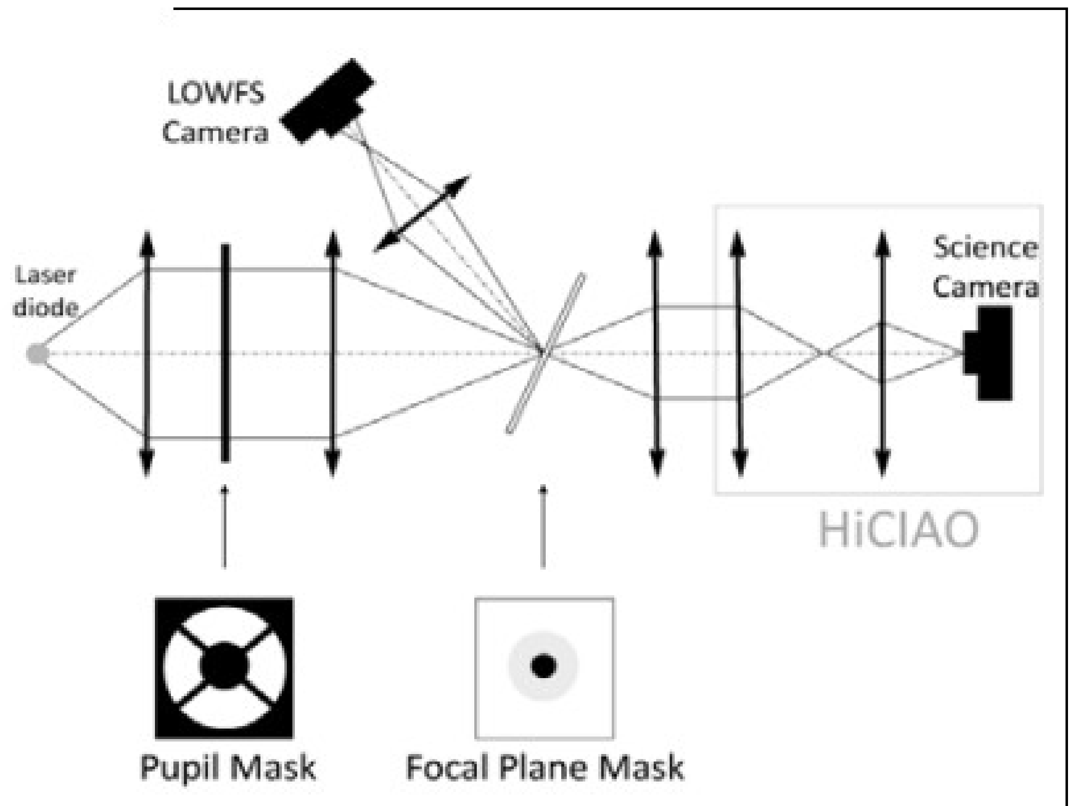
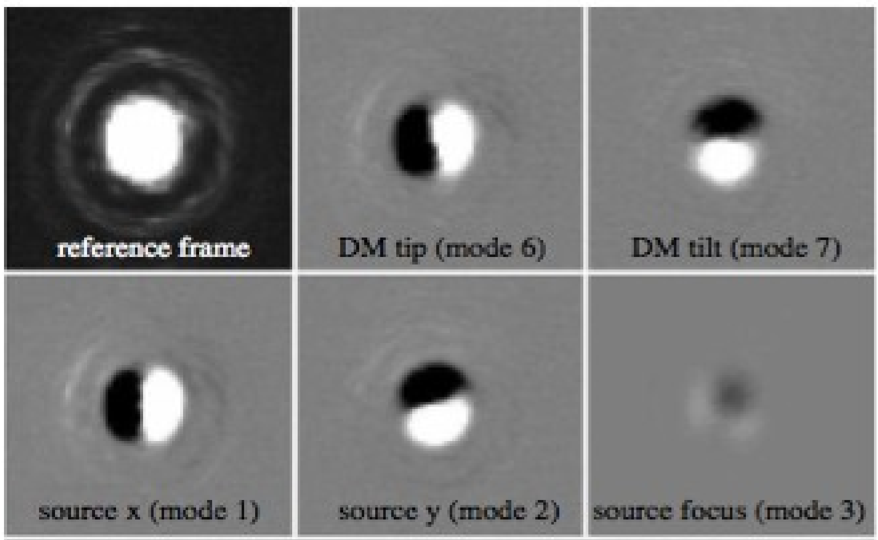
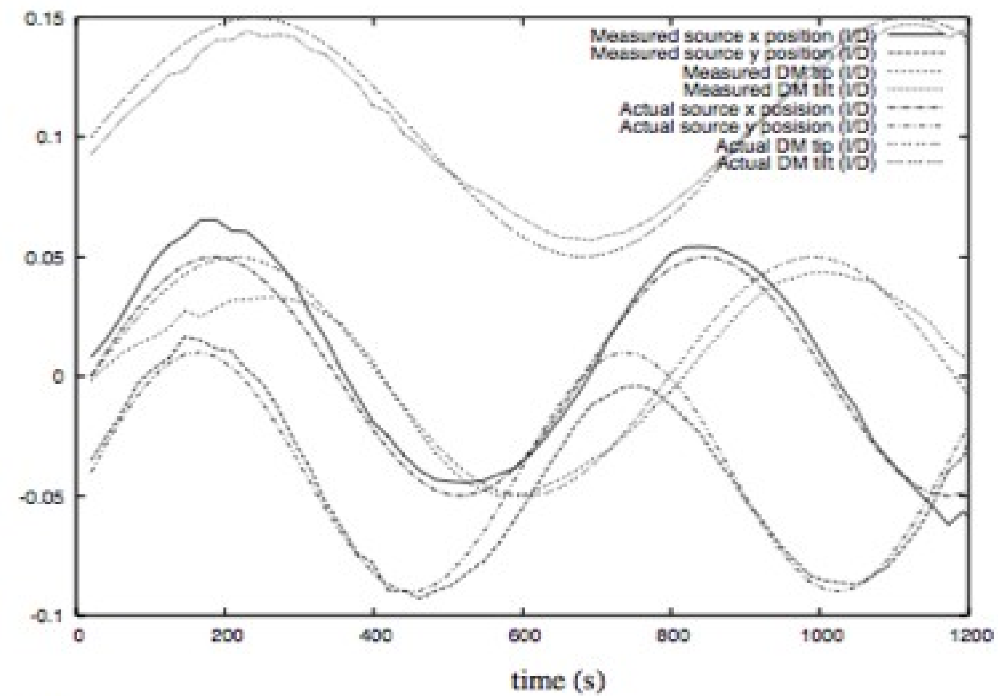


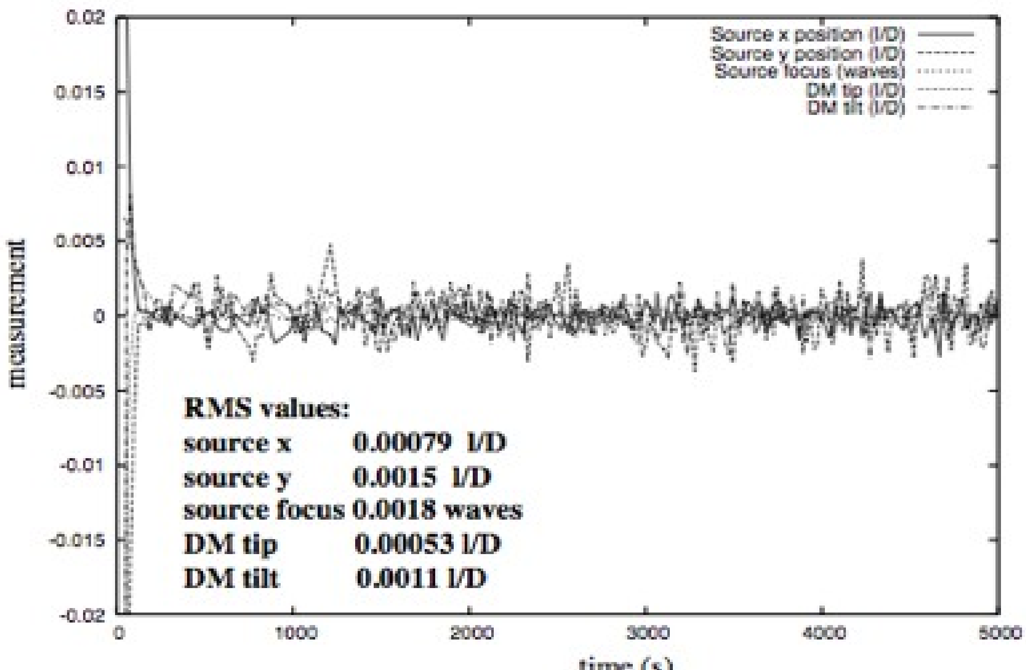
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

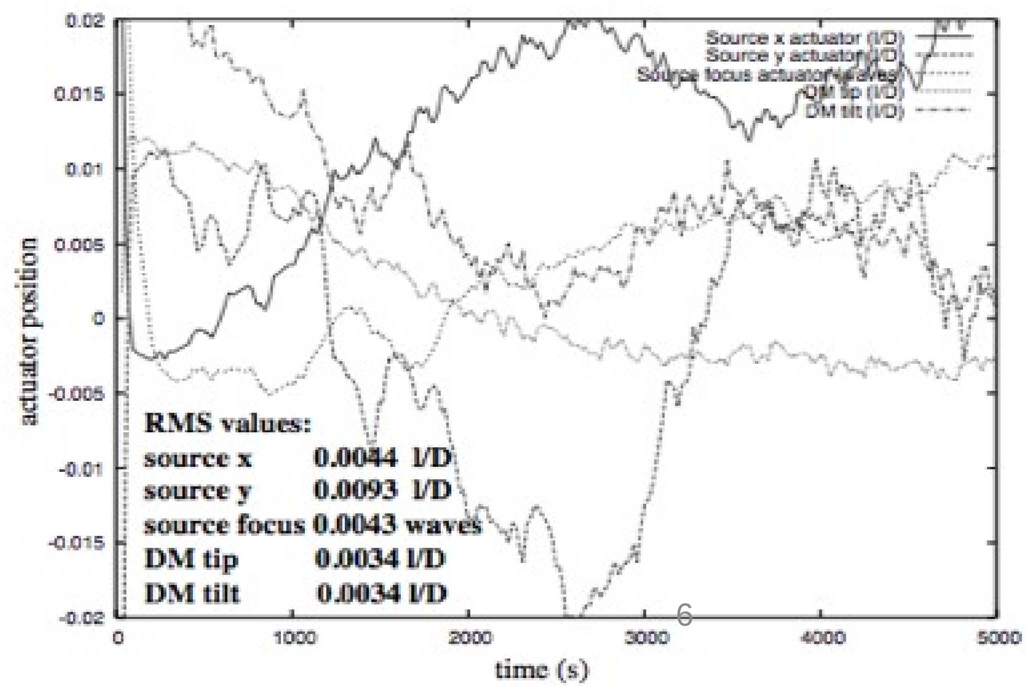


Pointing control demonstrated to 1e-3 λ/D in visible (3x better in vacuum at JPL)









Mission opportunities

Sub-orbital (balloon, sounding rocket)
low cost, but limited focused science: Exozodi disks (& giant planet(s) ?)
Technology maturation for larger missions
PICTURE MISSION ONGOING

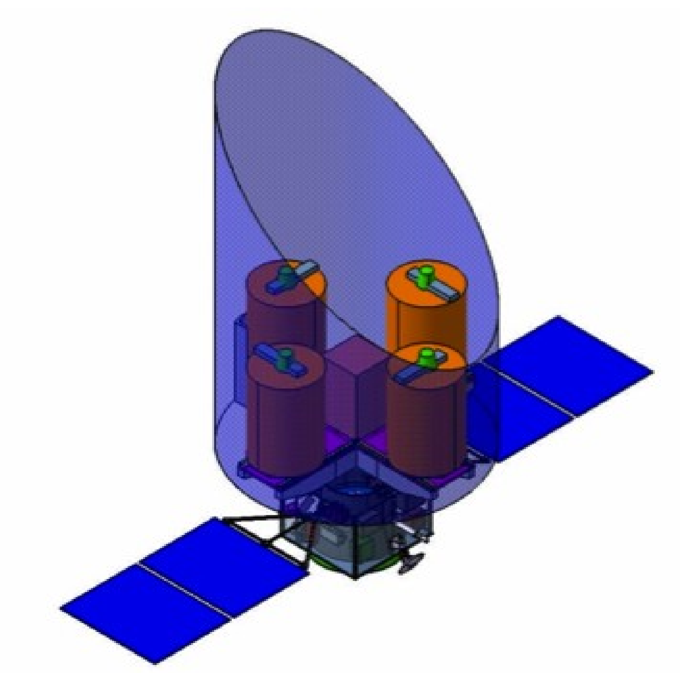
Small mission (Explorer size) – few $100Ms
<1-m telescope, relatively simple instrument
Example: EXCEDE's 0.7-m telescope with PIAA coronagraph in optical
Solid exozodi/disks science case, few giant planets
EXCEDE FUNDED FOR TECHNOLOGY DEV

Probe-class mission – $1B to $2B
~1.5-m telescope, dedicated to direct imaging of exoplanets
Great for Jupiters. Could image few super-Earths ?
Examples: EPIC, ECLIPSE, PECO, some external occulter mission
TOO COSTLY (~$1.6B for 1.5m according to astro2010) FOR THIS DECADE

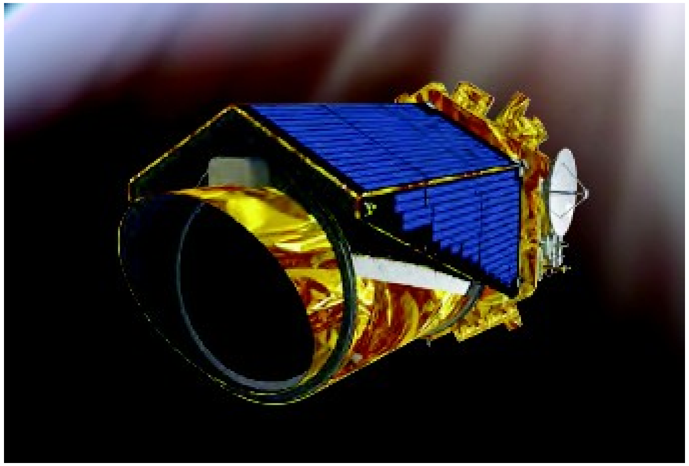
Flagship - > $2B - REQUIRED FOR SPECTROSCOPY OF EXOEARTHs
2-m to 4-m general purpose telescope in 2030s ? Larger 4-m to 8-m beyond 2030s ?
Coronagraph would be one instrument in a large flagship mission
Other likely instrument is wide field diffraction limited imaging in optical (nearUV, nearIR ?)
DEDICATED EXOPLANET MISSION (TPF, DARWIN) UNLIKELY DUE TO COST
TOO COSTLY FOR THIS DECADE, COULD GAIN COMMUNITY SUPPORT FOR MISSION IN 2030s

Probe class missions – internal coronagraphs

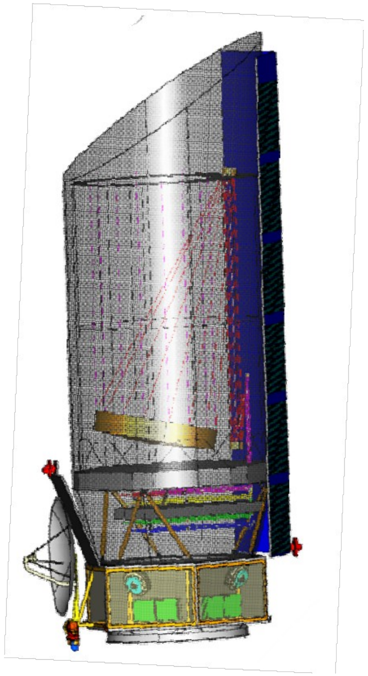
ACCESS



DAViNCI



EPIC



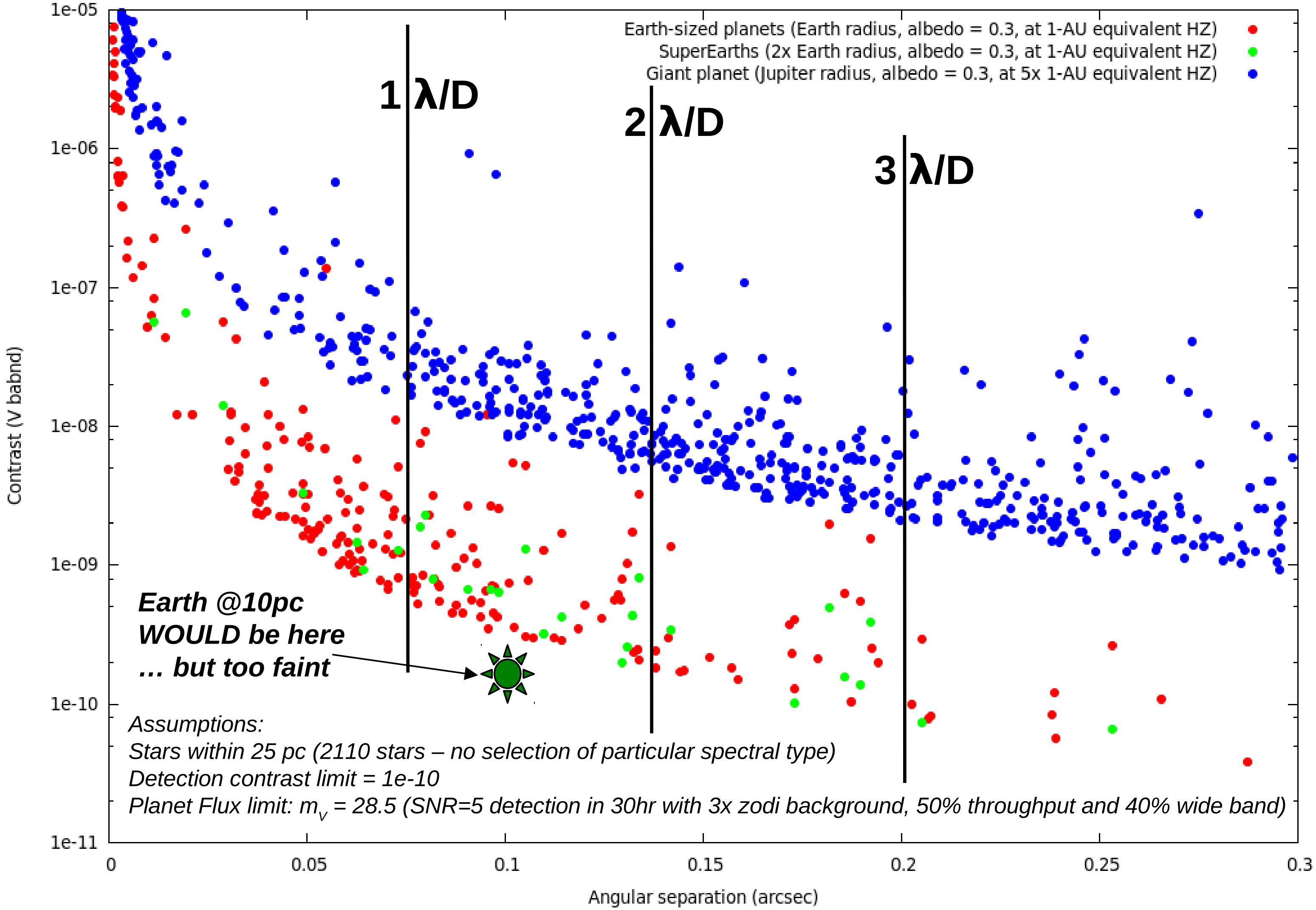
PECO

Performance Requirements (D=1.5m)

Inner Working Angle, Contrast and Sensitivity

	1 λ/D (0.069")	1.5 λ/D (0.103")	2 λ/D (0.137")	2.5 λ/D (0.172")	3 λ/D (0.206")	3.5 λ/D (0.241")	4 λ/D (0.275")
1e-8	2 152	94	52	29	26	20	11
1e-9	4 35 574	1 10 514	4 435	3 348	1 287	1 219	1 160
1e-10	22 102 778	15 49 718	8 26 639	7 18 552	2 7 491	2 5 423	2 3 364

D = 1.5m, λ = 500nm



Earth-like planet
Albedo = 0.3
1 Earth radius
At 1AU-scaled HZ

SuperEarth
Same as above
2 Earth radius

Giant planet
Jupiter size
Albedo = 0.3
At 5x HZ

Technology Status

Contrast & IWA

	1 λ/D (0.069")	1.5 λ/D (0.103")	2 λ/D (0.137")	2.5 λ/D (0.172")	3 λ/D (0.206")	3.5 λ/D (0.241")	4 λ/D (0.275")
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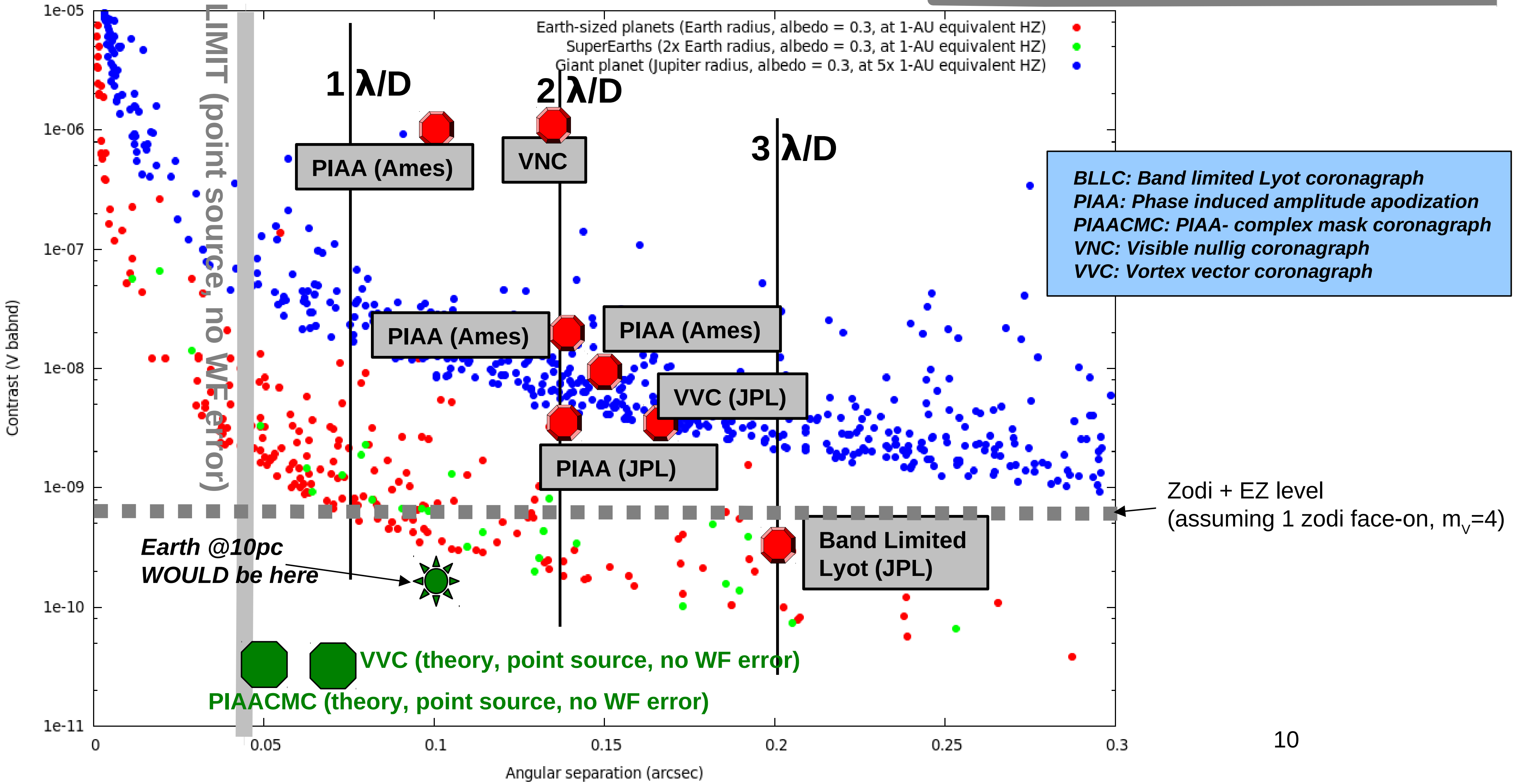


Exoplanet direct imaging mission: what should we aim for ?

Spectra of Jupiters in 2030s will not be attractive at the >$1B level
JWST transit spectroscopy in IR
Competition from smaller missions and ground-based transit spectroscopy
Direct imaging with ELTs will do spectroscopy (in near-IR) of giant planets 2030s

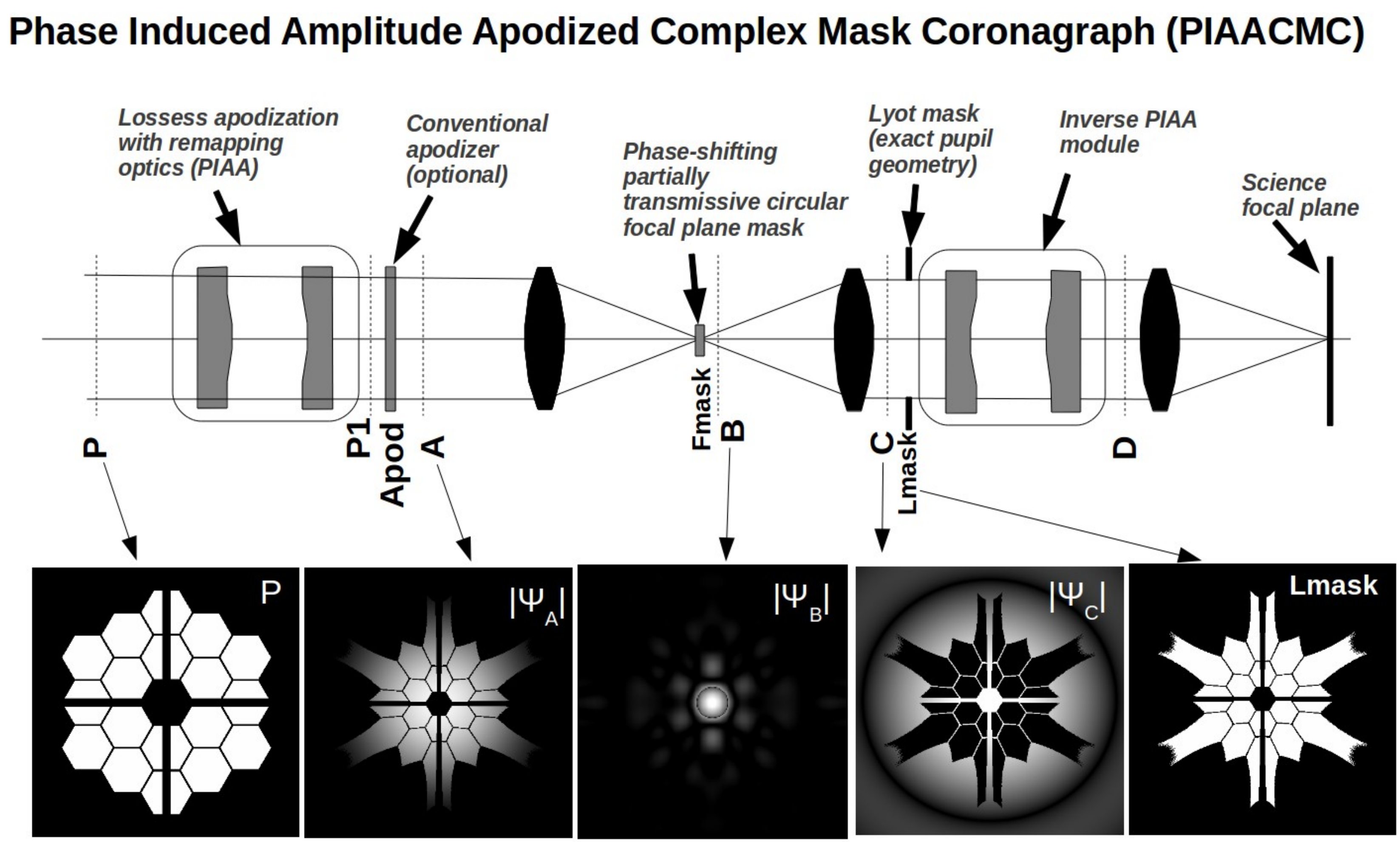
exoEarth spectra will require flagship (2-m or larger)
mission performance is a very steep function of aperture: sample size grows as 3^{rd} power of telescope diameter. Spectroscopy requires collecting area

Flagship would eat up large part of astrophysics budget for > decade
→ will require broad community support, multiple science goals/instruments

Science return per $ is much higher by building instrument for flagship (>2-m) than paying for full mission
Coronagraph instrument may cost $100Ms, as part of a multi-$B mission

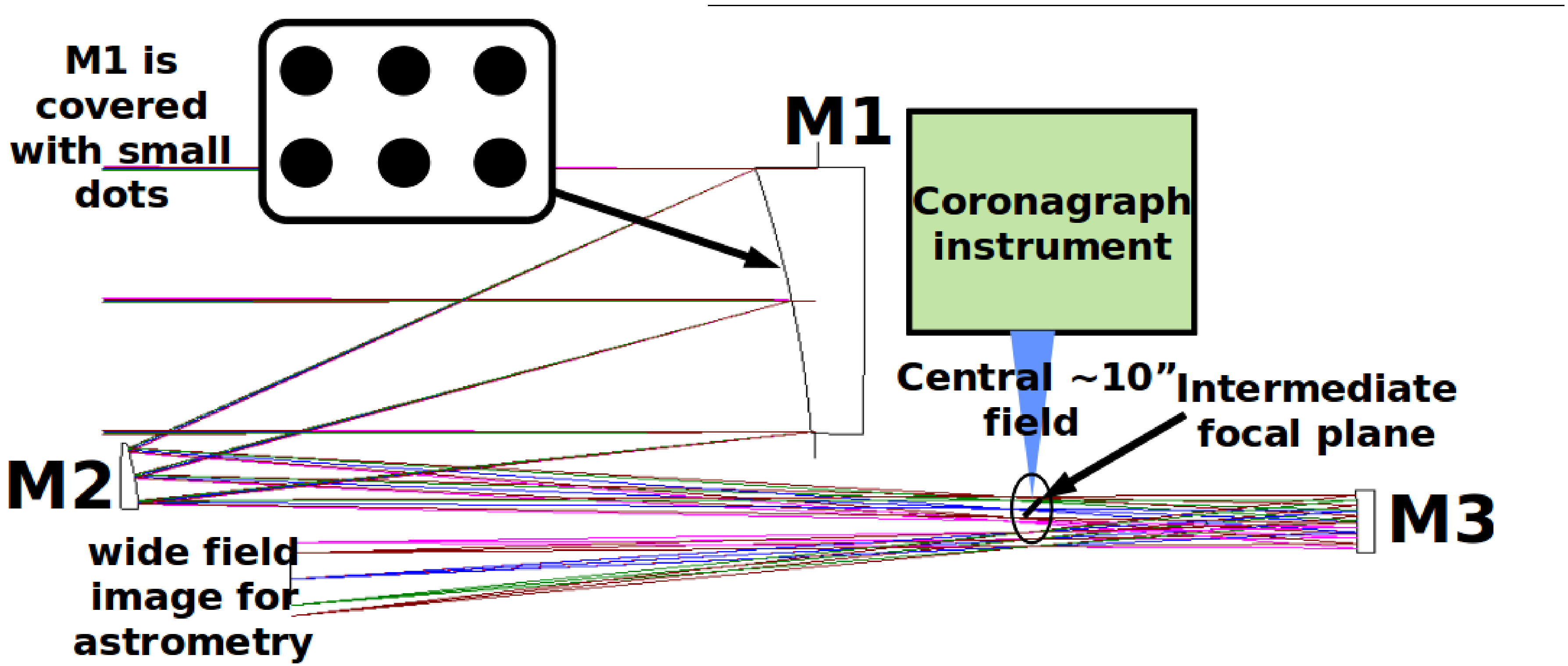
→ we need to think very hard about building a coronagraph instrument that is not driving the telescope cost (central obstruction, wavefront quality)
→ we need to look very hard into combining several measurements into a single mission (detection, spectroscopy, astrometry ?) instead of queuing missions over several decades

High performance coronagraphy on complex apertures is possible



IWA < 1 l/D
100% throughput
No stellar residual light
Polychromatic light focal plane mask under fabrication

Astrometry with a general purpose wide field telescope ?



Single telescope with coronagraph instrument and wide field camera working simultaneously

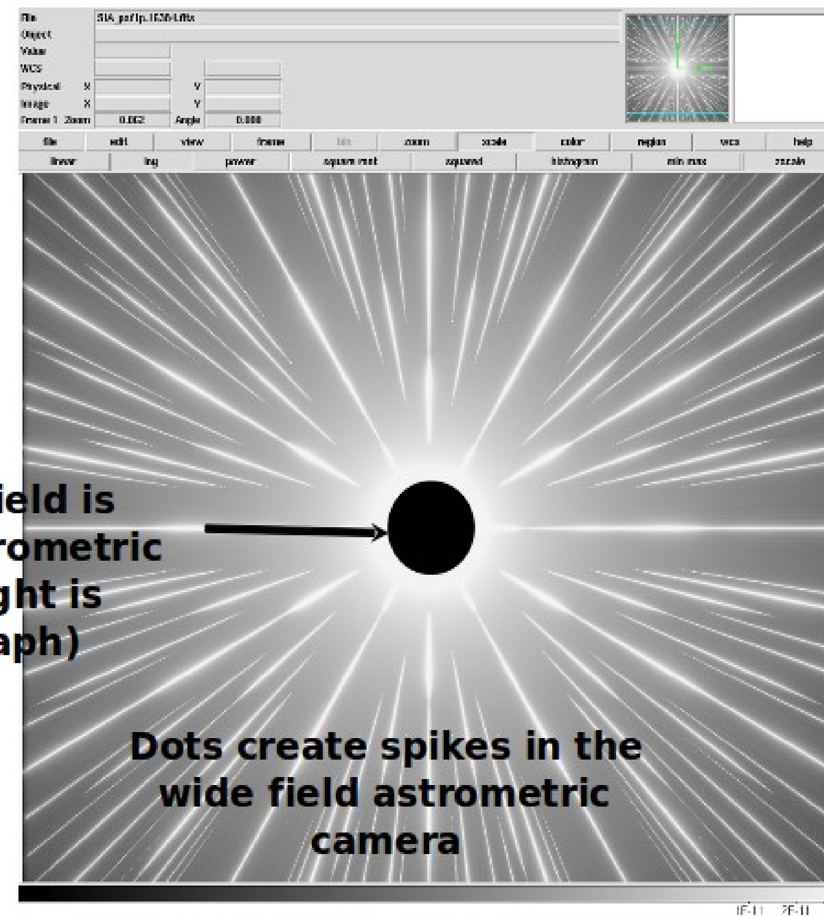
Diffractive pupil (dots on primary mirror)

Astrometry with a general purpose wide field telescope ?

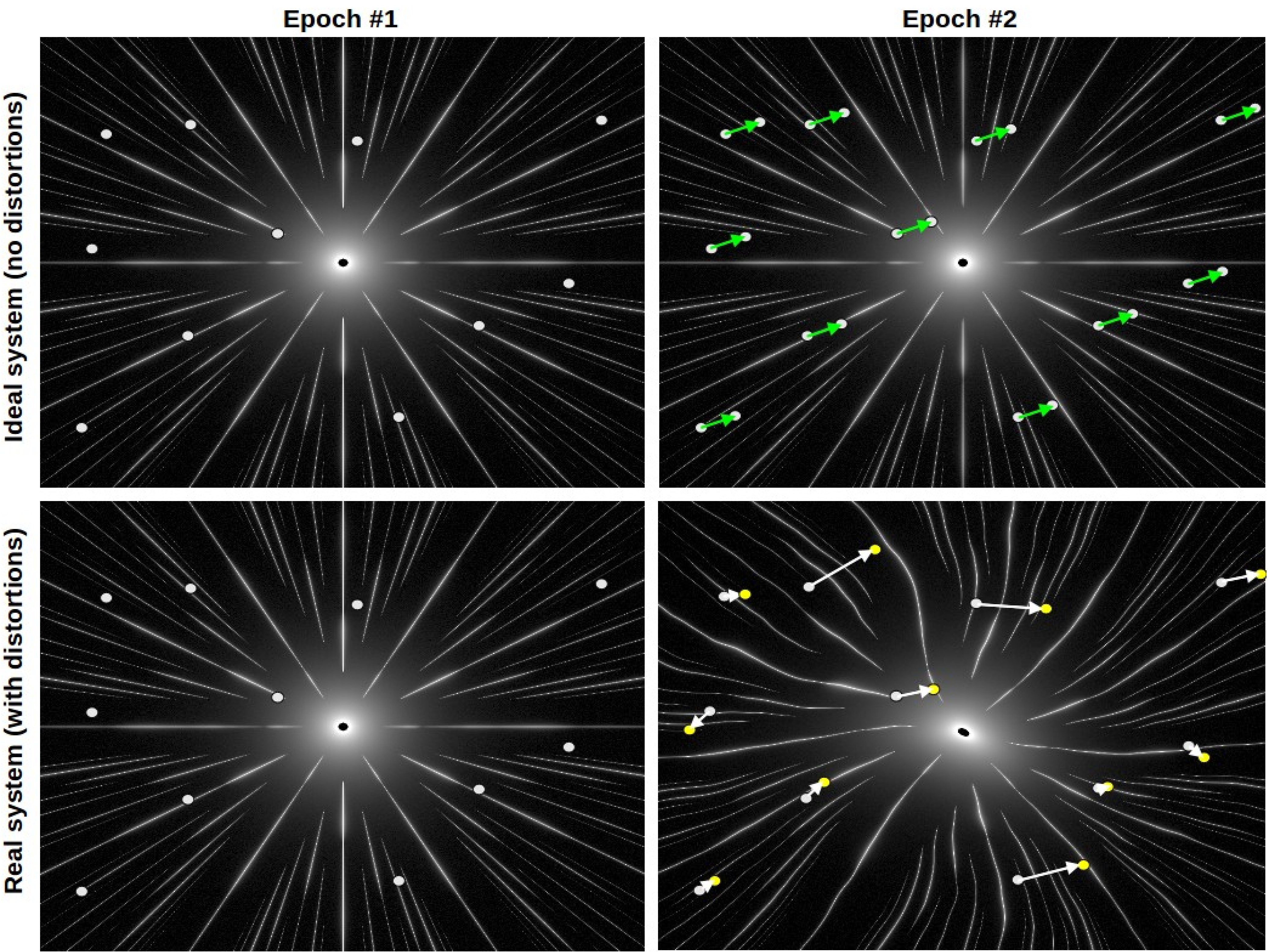
Dots on primary mirror create a series of diffraction spikes used to calibrate astrometric distortions

Primary mirror is covered with small dots

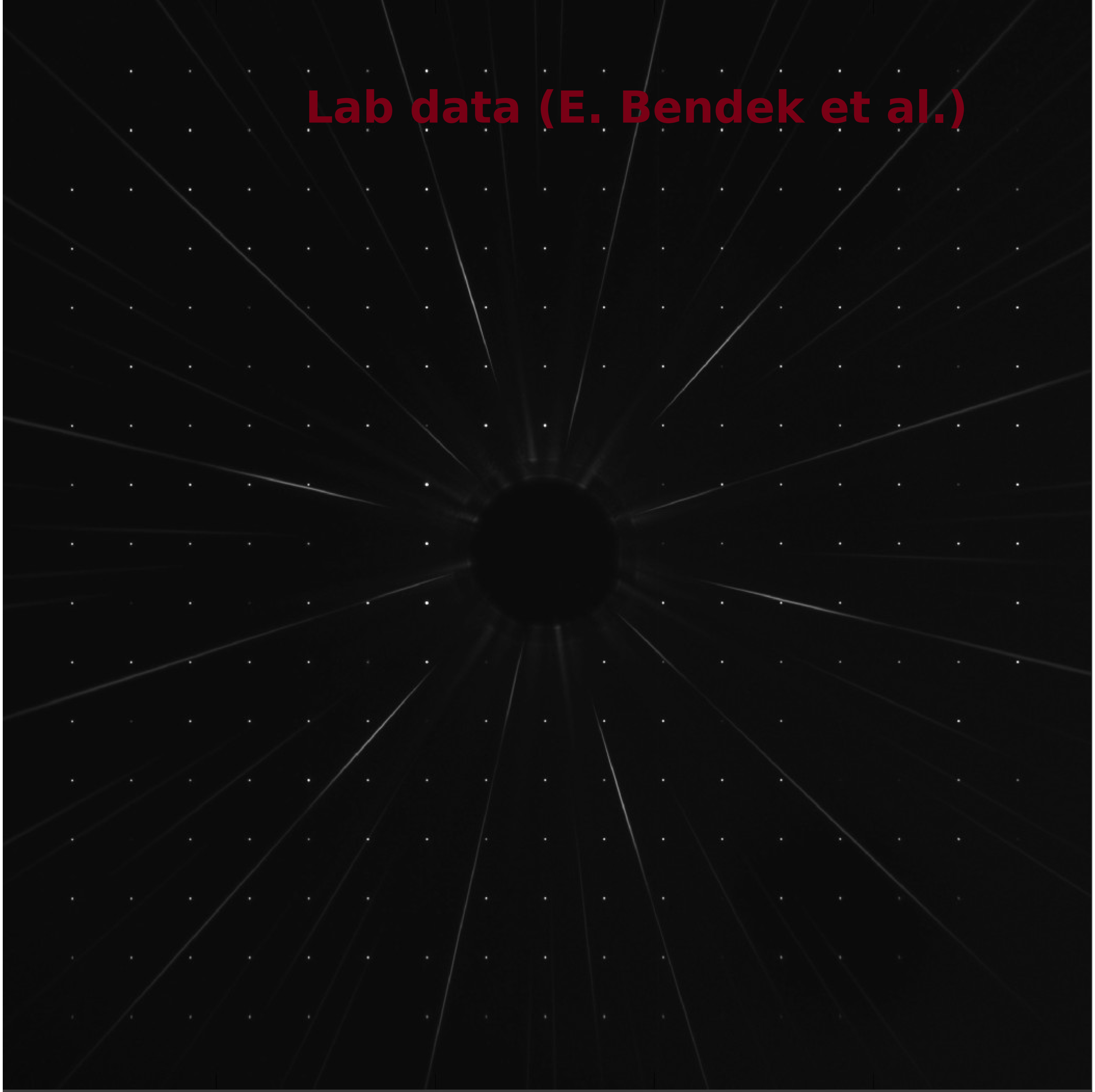
The center of the field is missing from the astrometric camera (central light is sent to coronagraph)



Dots create spikes in the wide field astrometric camera



Epoch #1
Epoch #2
Ideal system (no distortions)
Real system (with distortions)


Lab data (E. Bendek et al.)

Lab data (E. Bendek et al.)

Direct imaging with ELTs: Science goals

ExAO instrument on ELT timescale for science return
~ 2020s

Detection of Jupiter-like giants
Good science (statistics), but not Earth-shattering
Competition from indirect techniques and space (JWST?)

Spectroscopy of Jupiter-like giants

Planet formation
ELT well suited for this science goal

Imaging and low resolution spectroscopy of rocky planets
In habitable zones
Unique to ELTs for low-mass stars
May also be first opportunity to image
Habitable planets (timing of space mission ?)

Challenges and strategy

Earth twin at 10pc (nominal system for space-based mission studies)
NOT DETECTABLE WITH ELTs
Too faint, contrast too extreme (~1e10)

Thermal emission from young planets
Young = not habitable ...
NOT DETECTABLE WITH ELTs
Strategy works well for massive young planets, but:
(1) luminosity drops rapidly with lower mass
(2) young systems are not very close to us (~50 - 100 pc ?)
→ Rocky planets too faint

OPTIMAL STRATEGY:
Reflected light imaging around nearby low mass stars
Key advantage of ELTs is IWA
Reduced contrast challenge
Nearby stars → apparent luminosity is more favorable

Reflected light imaging
Science vs instrument performance

Thermal emission:
Flux is steep function of planet mass
0.5 MJ is much harder than 1 MJ
Increased science return (lower mass) requires significant instrument performance improvement

Reflected light:
Flux is shallow function of planet mass
0.5 MJ is about as hard as 1 MJ
Large increase in science return (lowe mass) obtained by moderate instrument performance improvement

Prediction:
Once the first planets are imaged in reflected light, steady and fast progress expected

Science goals, targets
Key assumptions, absolute limits

Fundamental limits of ExAO system:

(1) Raw contrast

- Expected to be 14x better than on 8-m telescope
- 1e-5 on 8-m telescope → 7e-7 on 30-m telescope

(2) Detection contrast

- Expected to be 14x better than on 8-m telescope
- 1e-7 on 8-m telescope → 7e-9 on 30-m telescope

(3) IWA ~ 1 lambda/D

- Scales as 1/D: 40mas on 8-m, 10mas on 30-m

(4) Background-limited sensitivity (1hr, SNR=5)

- mH: 23.5 on 8-m telescope → mH = 26.5 on 30-m

Assuming Super-Earths (~2x Earth diameter)

- Still potentially habitable
- Easier than Earths: 1e9 contrast at 1 AU separation (Earth ~ 2e10)
- Abundant (HARPS results: ~30% occurrence)

Detection, colors: mH = 26.5 limit on planet
Spectroscopy (R=200, SNR = 5): mH = 21.5 limit on planet
→ ability to analyze atmosphere composition, biological activity

Reflected light imaging: Contrast vs separation

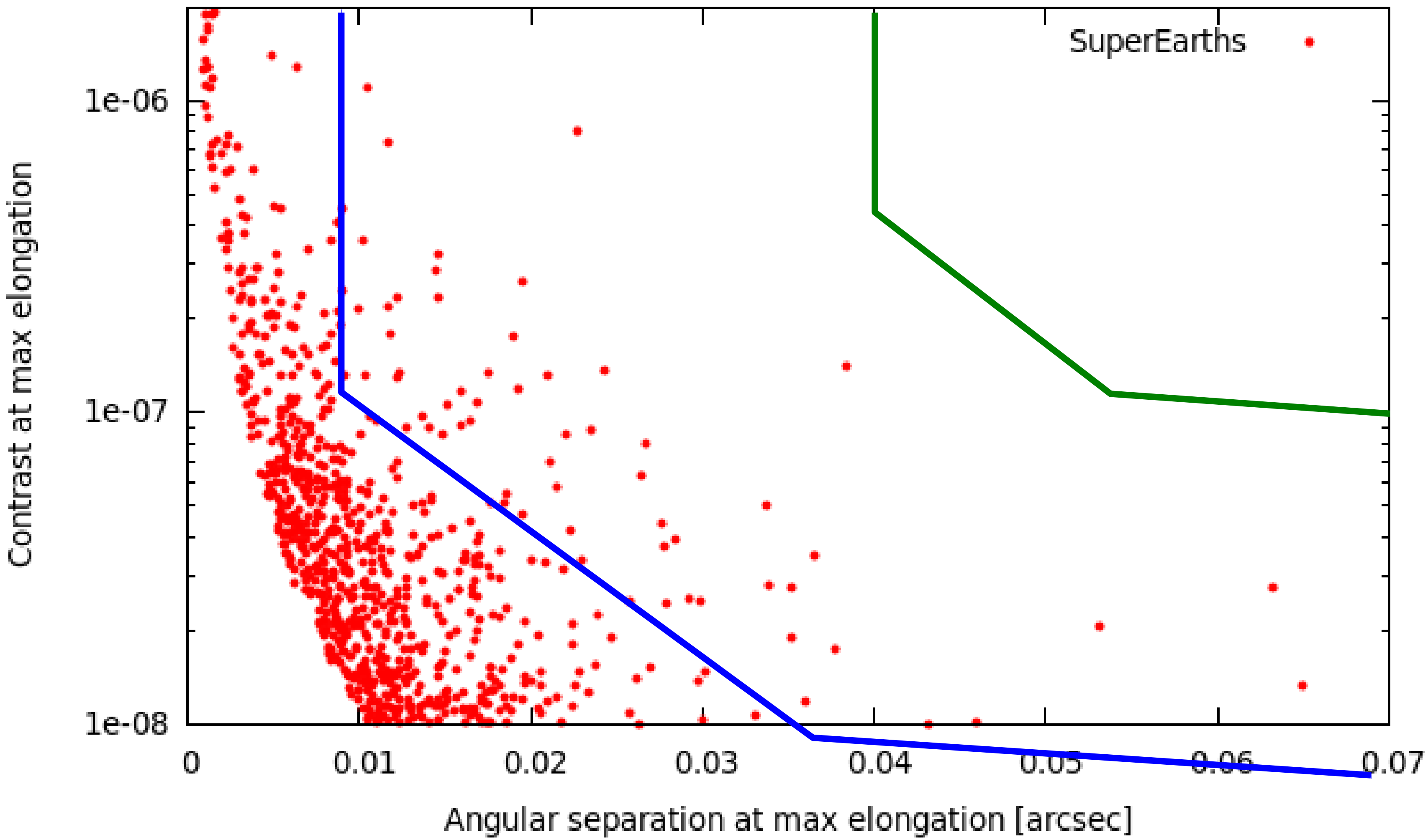
Known stars within 25pc
→ computed bolometric luminosity
→ computed location of habitable zone (1 AU equivalent)
→ placed a 2x Earth size planet, Earth albedo, at max elongation

2MASS for near-IR colors

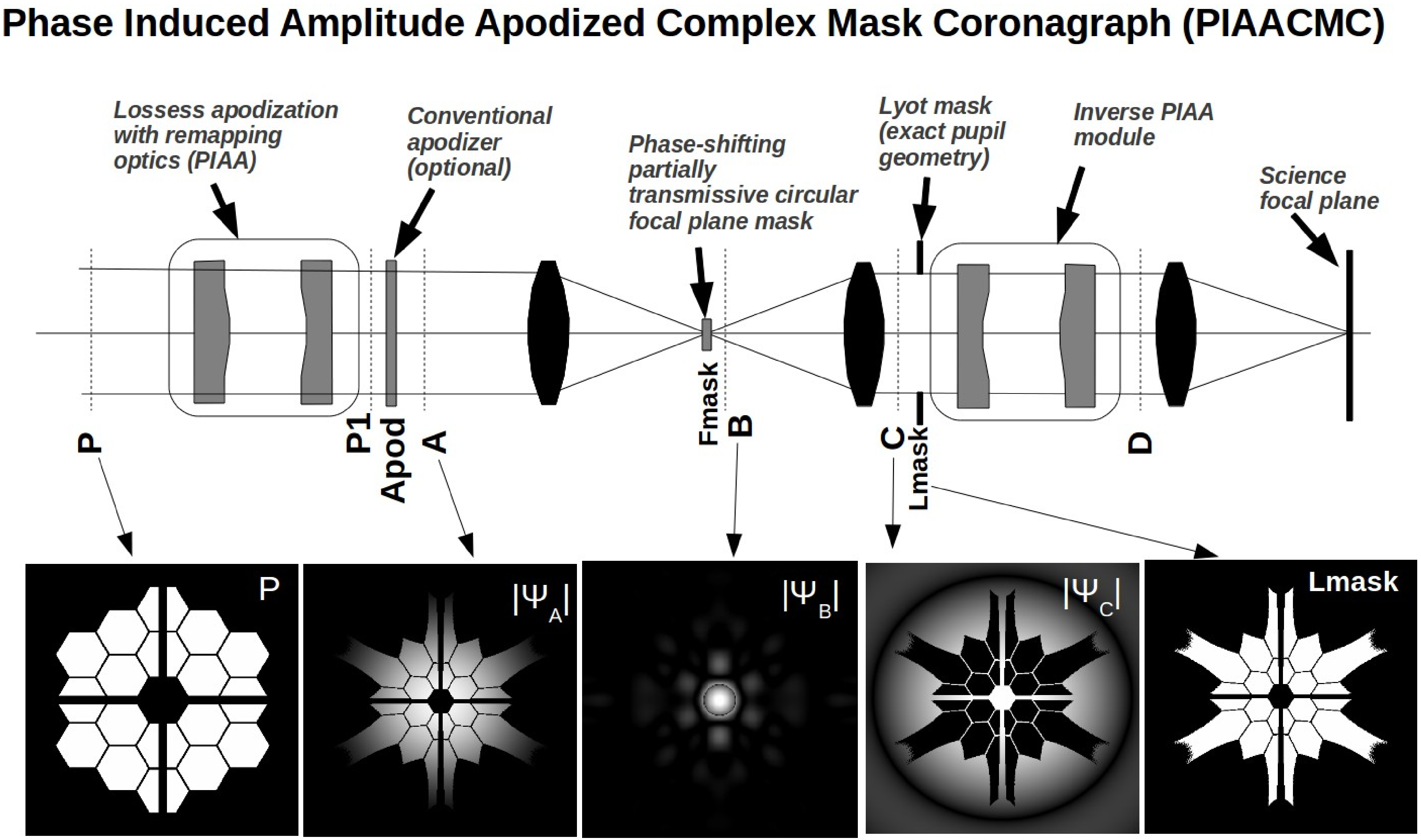
Reflected light imaging: Contrast vs separation (H band)

8-m telescope, 1 lambda/D

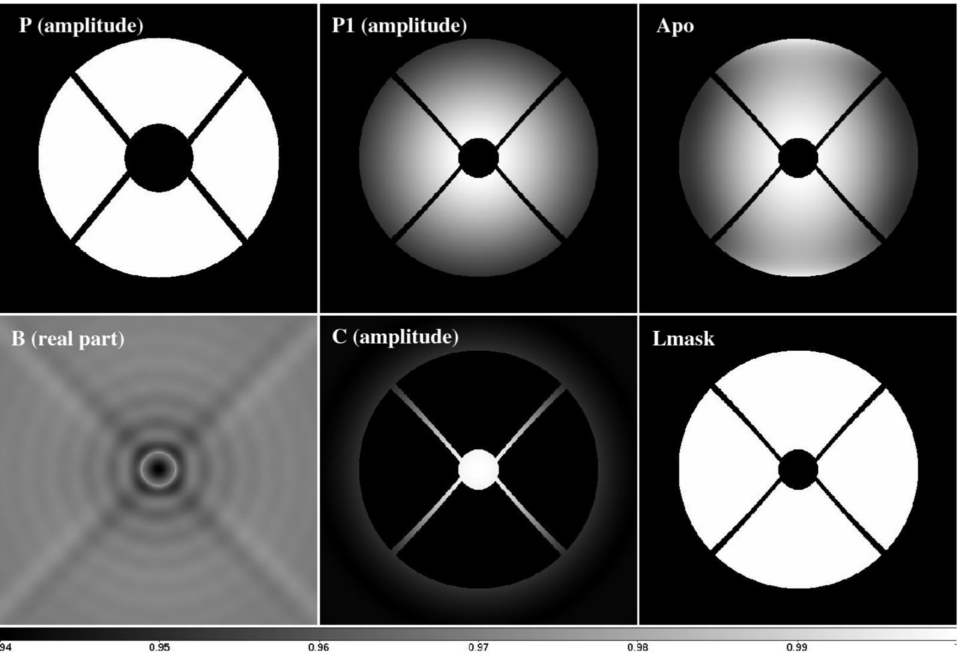
30-m telescope, 1 lambda/D

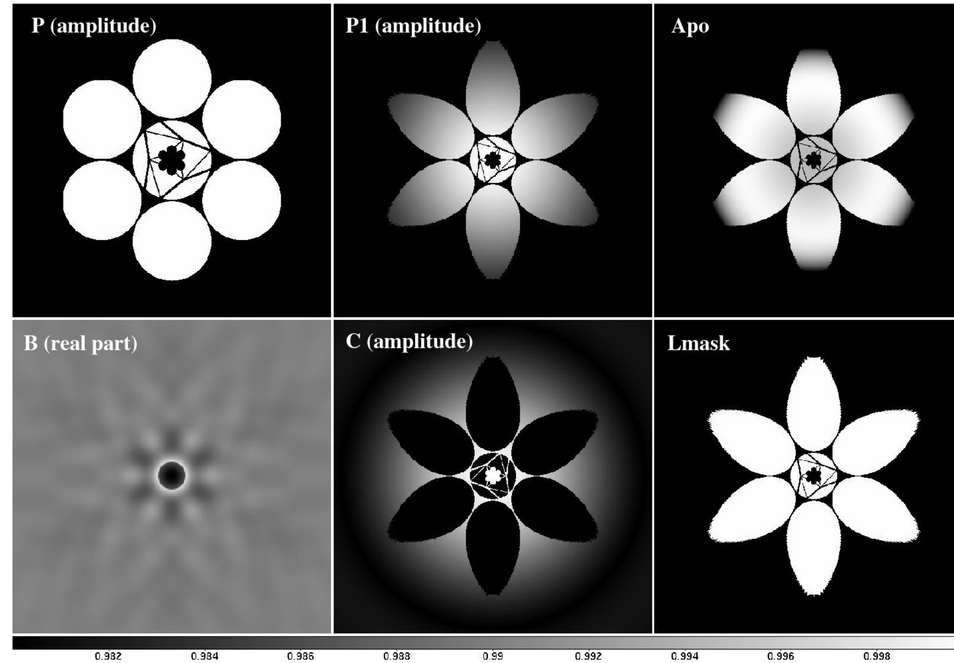


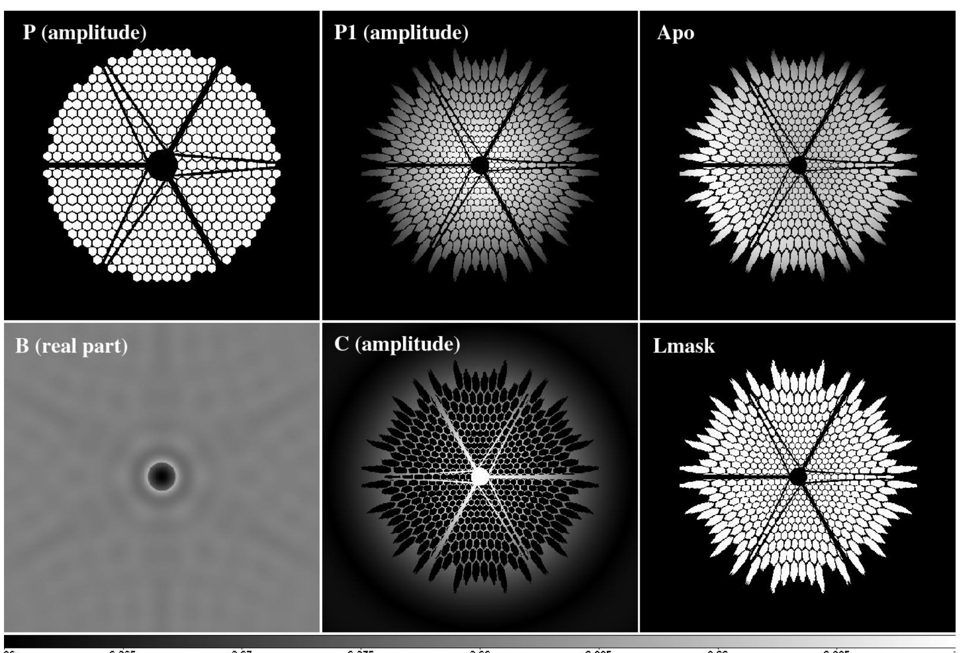
Is coronagraphy at < 1 lambda/D possible on ELTs ?

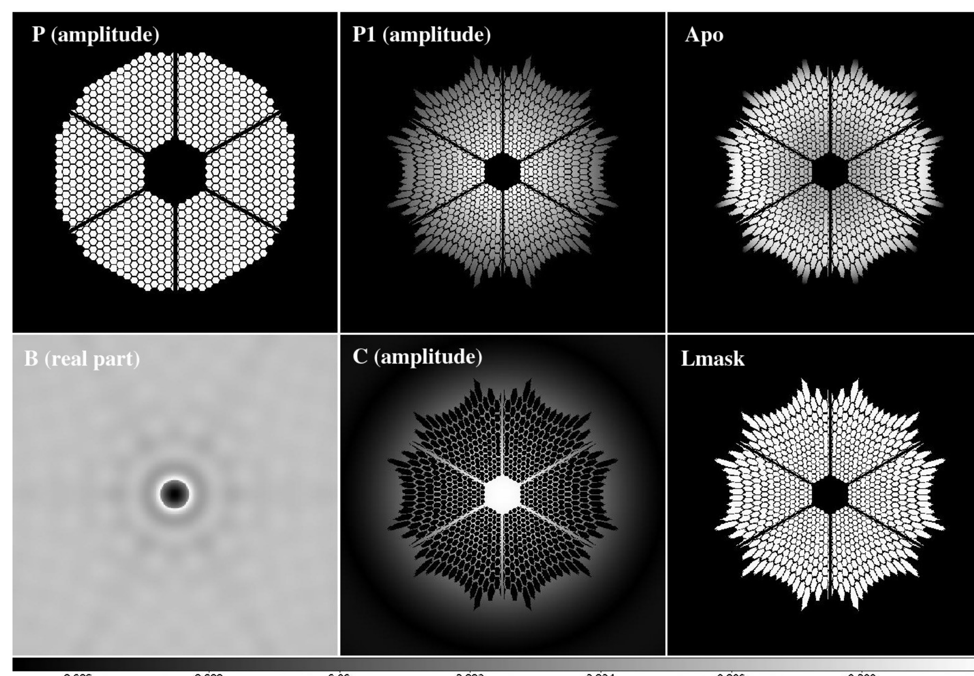


PIAACMC performance on various pupils

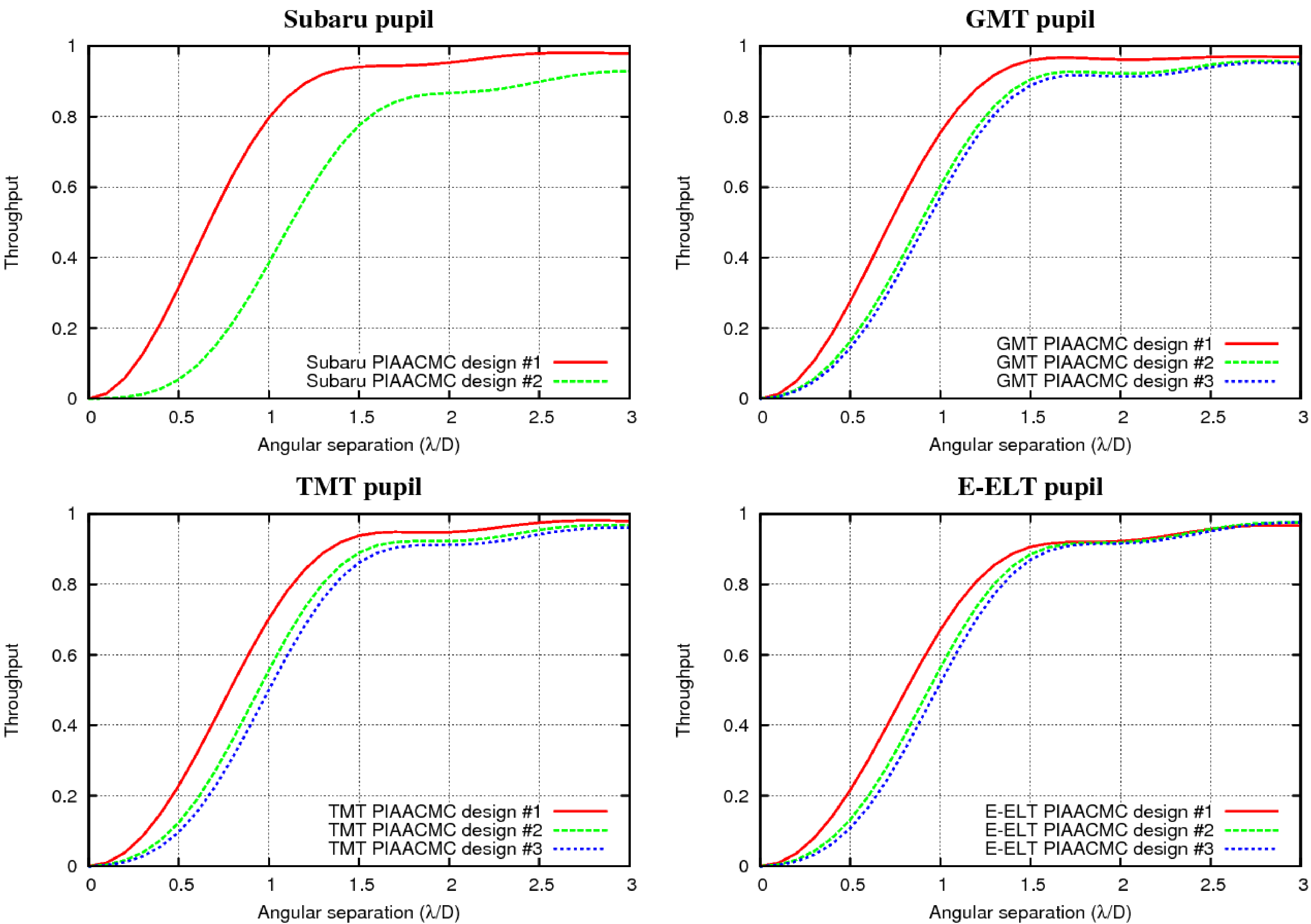








PIAACMC performance on various pupils



Reflected light imaging: ELT targets first cut

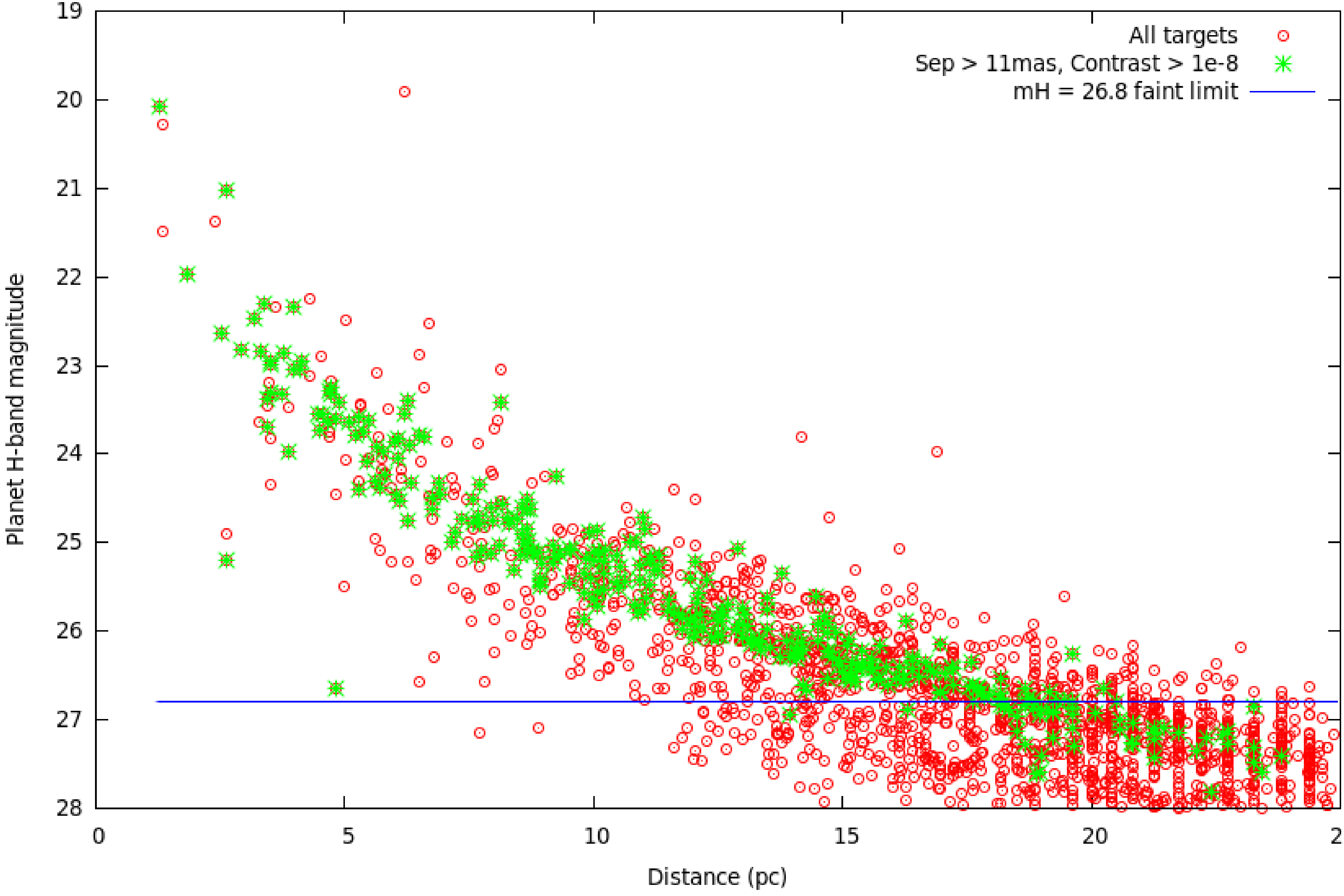
FIRST CUT LIMITS

	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

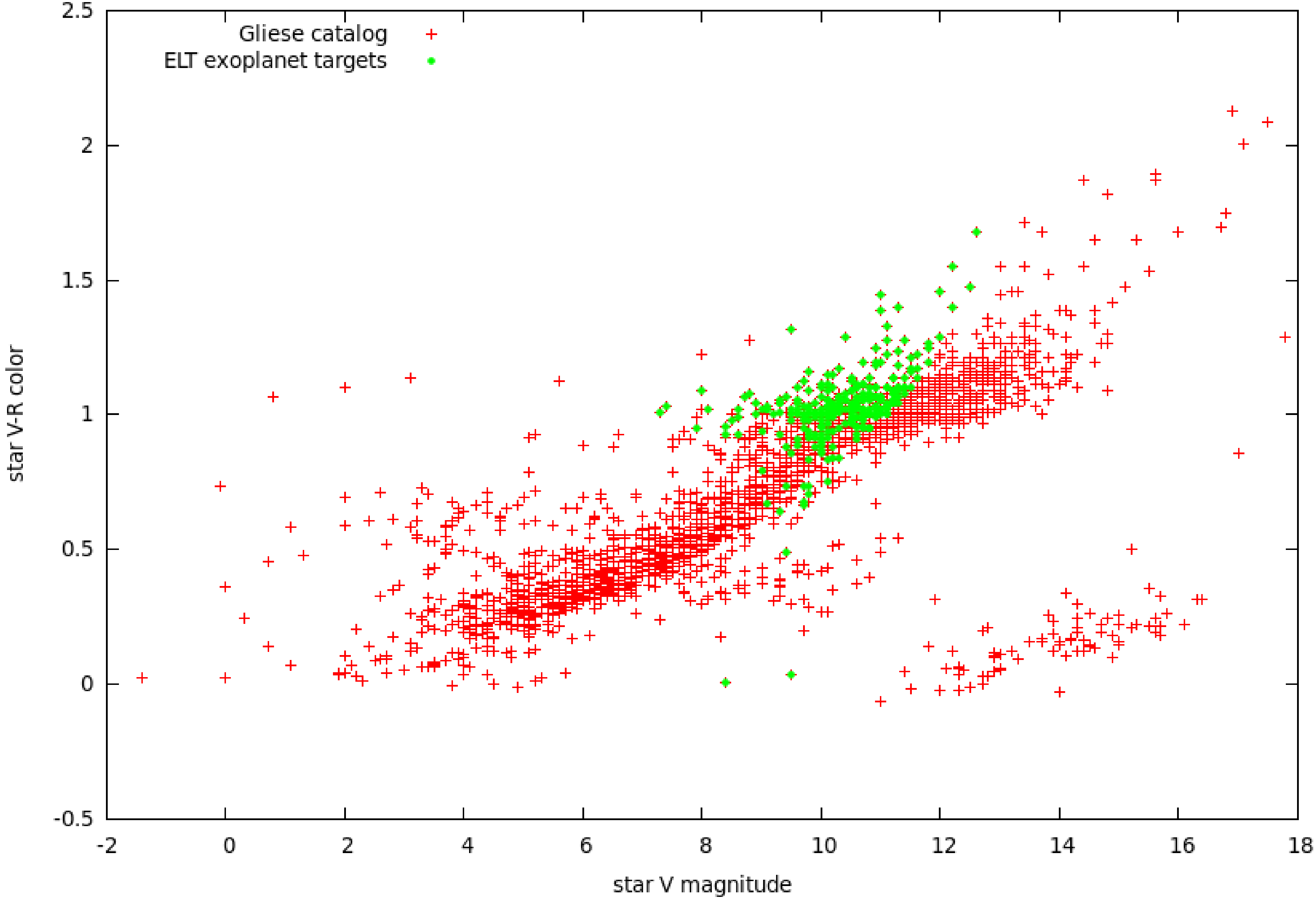
The first cut limits are shown in the table above. The number of targets kept is mostly driven by the contrast and separation limits, and to a lesser extent by the planet brightness limit. The planet brightness limit is derived from a required SNR=10 detection in 10mn exposure in a 0.05 µm wide effective bandwidth (equivalent to a 15% efficiency for the whole H-band) on a 30-m diffraction limited telescope, taking into account only sky background and assuming all flux in a 20mas wide box is summed. The assumed sky background (continuum + emission) is $m_H = 14.4$ mag/arcsec^2 [E-ELT sky background model, ESO] and [Cuby et al. 2000].

```
D=30 -> 700 m2
background = 16412 ph / sec / um / m2 / arcsec2 -> 230 ph/sec on the 20mas box
With N photon/sec from source: SNR(t) = N sqrt(t) / sqrt(N + 230)
With t = 600 sec -> SNR = 24.5 N / sqrt(N+230)
SNR = 10 ->  N = 6.3 ph/sec
flux = 6.3 ph/sec = 0.18 ph/sec/um/m2 -> mH = 26.8
```

Reflected light imaging: ELT targets first cut



Reflected light imaging: ELT targets first cut → 274 targets



Top targets for ELTs

The most favorable target, listed in the table below, were selected with the following criteria:

- Angular separation at maximum elongation > 15 mas
- Contrast > 1e-7
- Planet brightness m_H < 24, allowing spectroscopy

MOST FAVORABLE TARGETS

STAR							PLANET			
Name	**Type**	**Distance**	L_{bol}	m_V	m_R	m_H	**Separation**	**Contrast**	m_H	**Notes, Multiplicity**
Proxima Centauri (Gl551)	M5.5	1.30 pc	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	-
Barnard's Star (Gl699)	M5	1.83 pc	4.96e-03	9.50	8.18	4.83	38.41 mas	1.40e-07	21.97	-
Kruger 60 B (Gl860B)	M6	3.97 pc	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	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	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	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	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	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	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)
Gl 3379	M4	5.37 pc	6.56e-03	11.30	10.06	6.31	15.09 mas	1.06e-07	23.75	-

What kind of ExAO system is required ?

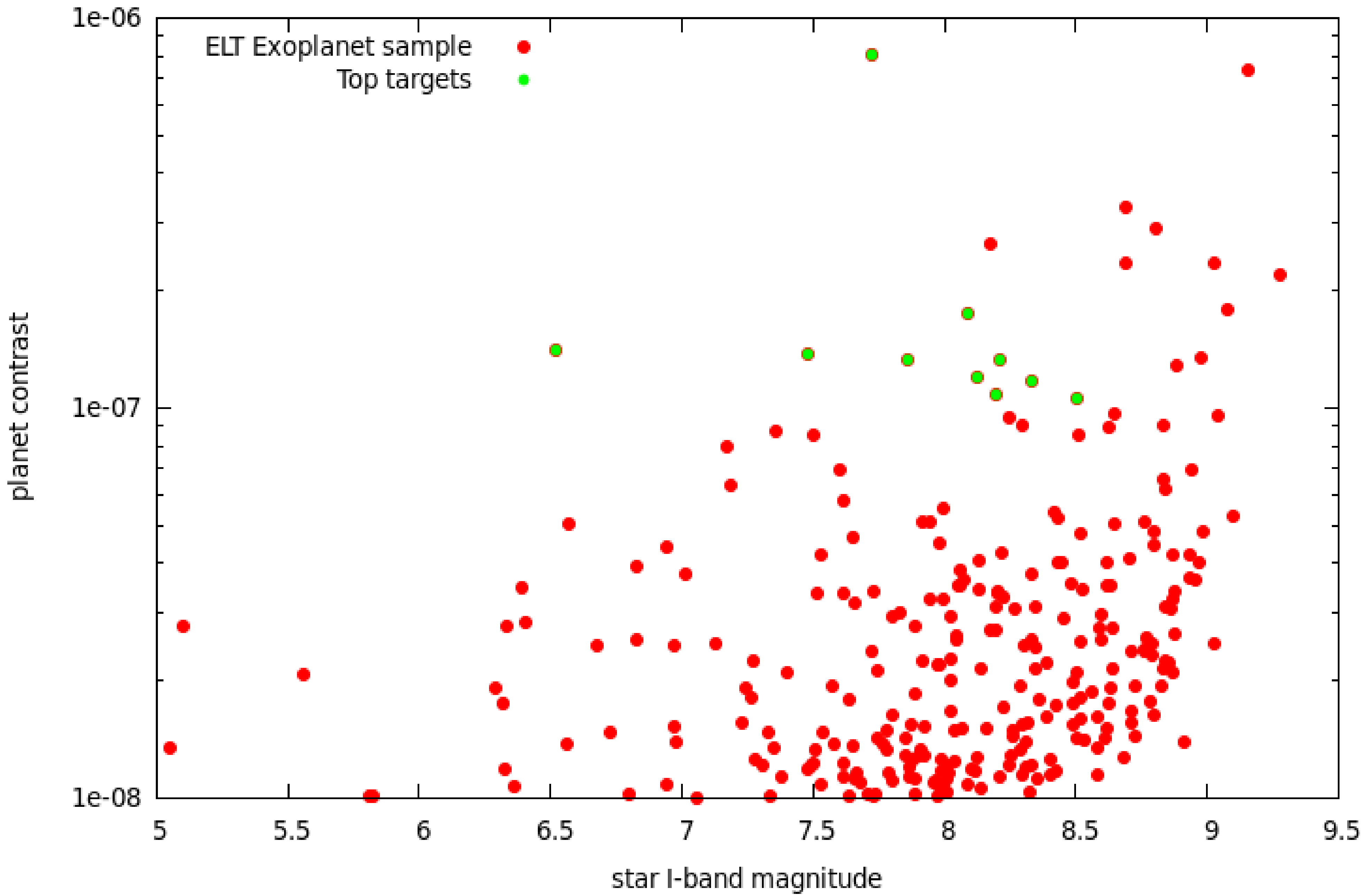
Small IWA coronagraph

Good WFS sensitivity, working in I (or R) band
→ need diffraction-limited WFS (pyramid, nlCWFS)

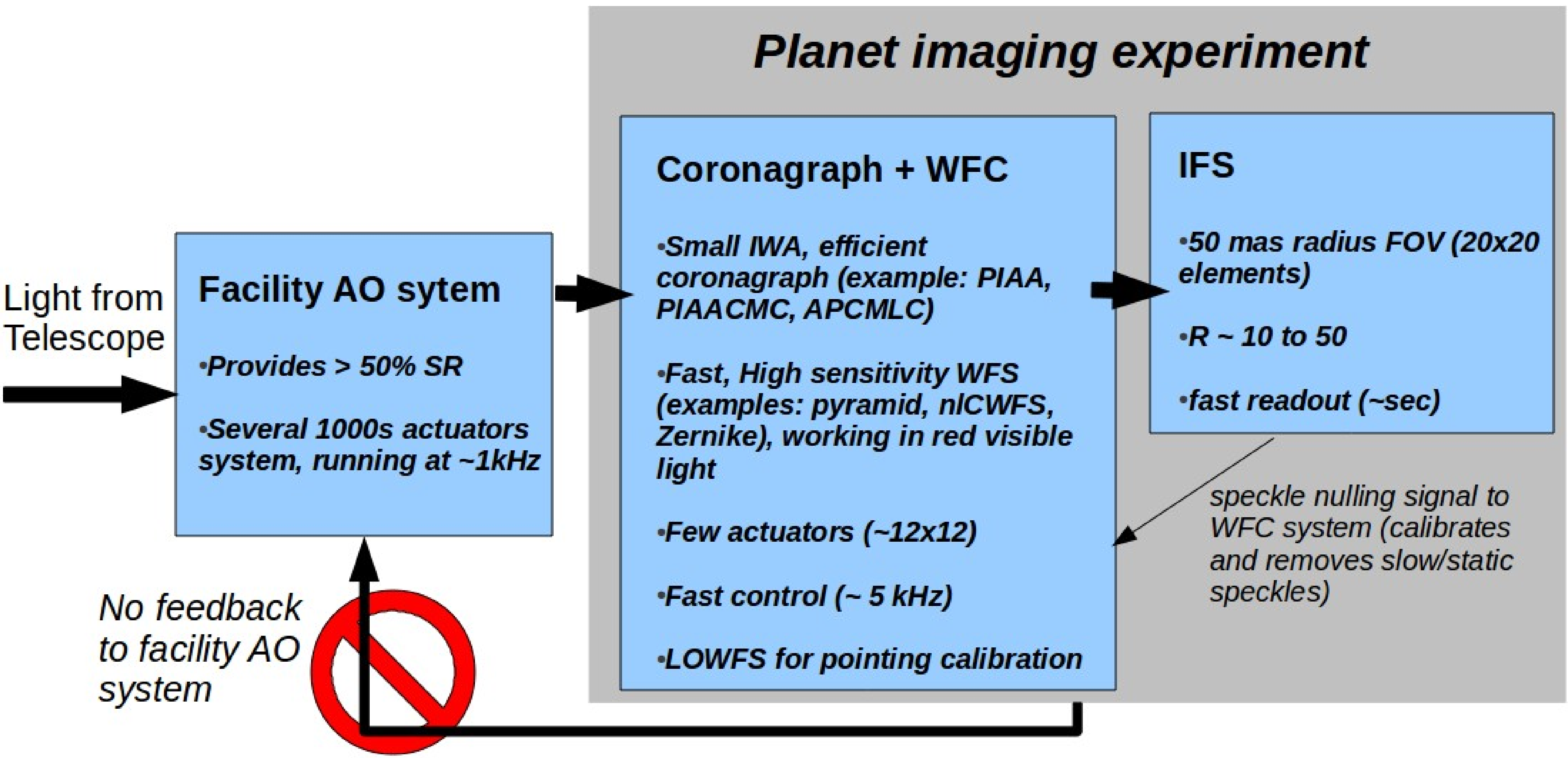
~50 mas OWA → 12x12 actuators required

Fast AO control (>kHz)

I-band magnitude



Possible system architecture



Wavefront sensing at the sensitivity limit imposed by the telescope diffraction limit

Seeing limited wavefront sensing (what we do now)

Example: SH WFS

Diffraction limited wavefront sensing (what needs to be done for ExAO)

Examples: Pyramid (non-modulated), non-linear curvature

Tip-tilt example (same argument applicable to other modes):

With low coherence seeing-limited WFS, $\sigma^2 \sim 1/D^2$ (more photons)

Ideally, one should be able to achieve: $\sigma^2 \sim 1/D^4$ (more photons + smaller λ/D)

This makes a big difference for Extreme-AO on large telescopes

For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than diffraction-limited WFS (11.5 mag)

Similar gain on other low order modes

Wavefront sensing at the diffraction limit of the telescope

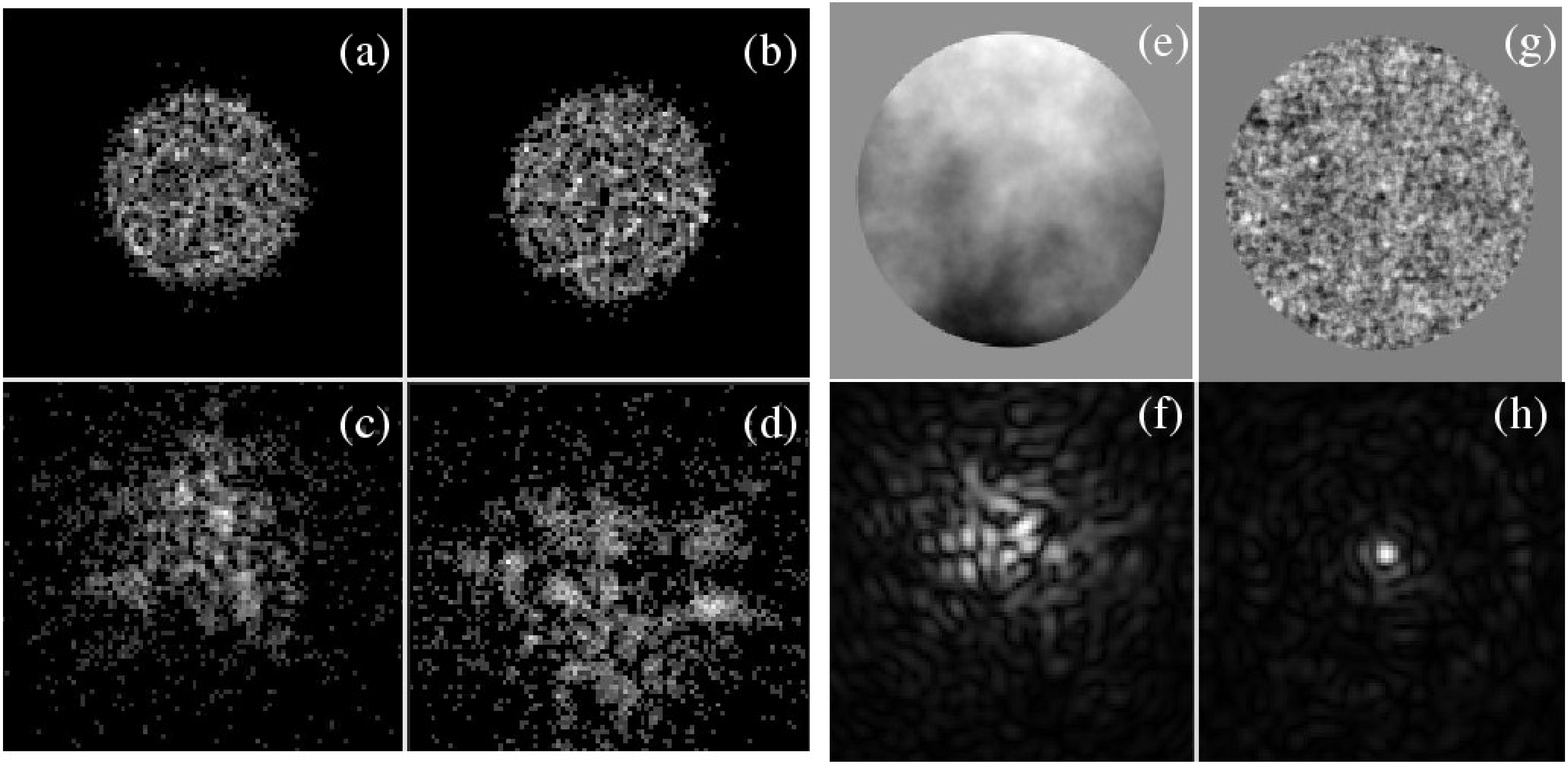
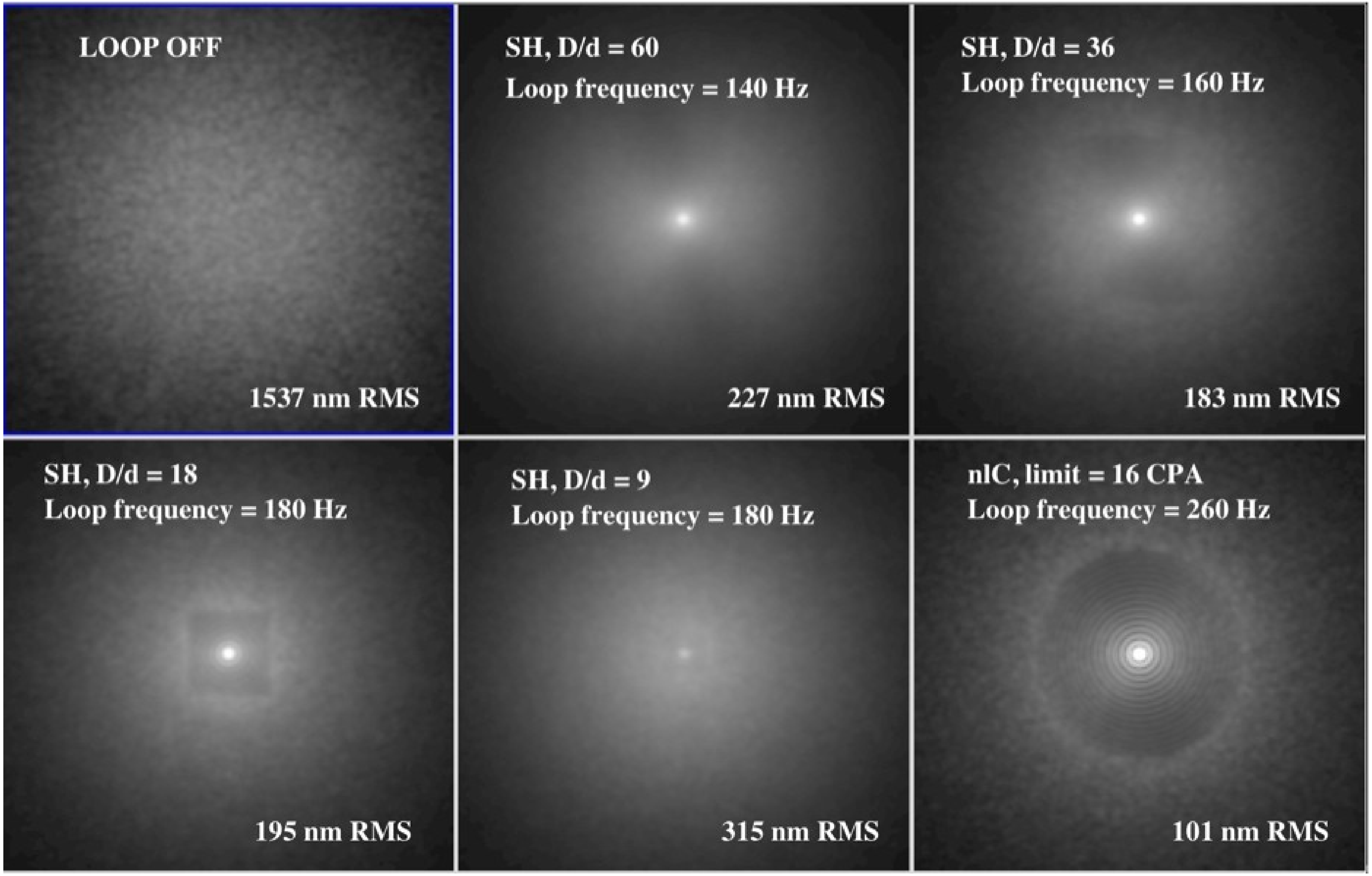


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.

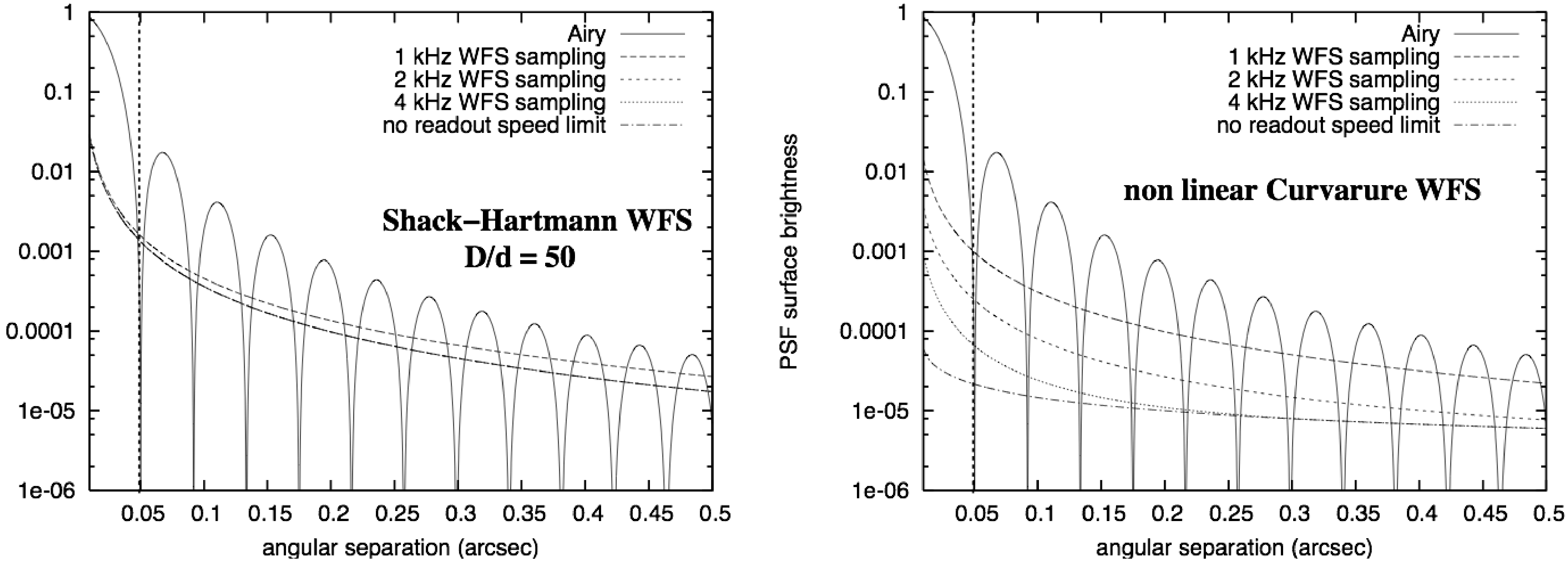
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)



m ~ 13

WFS	Loop frequ	RMS	SR @ 0.85 um	SR @ 1.6 um
nlCurv	260 Hz	101 nm	57%	85%
SH - D/9	180 Hz	315 nm	~4%	22%
SH - D/18	180 Hz	195 nm	~13%	56%
SH - D/36	160 Hz	183 nm	~16%	60%

Performance gain for ExAO on 8-m telescopes

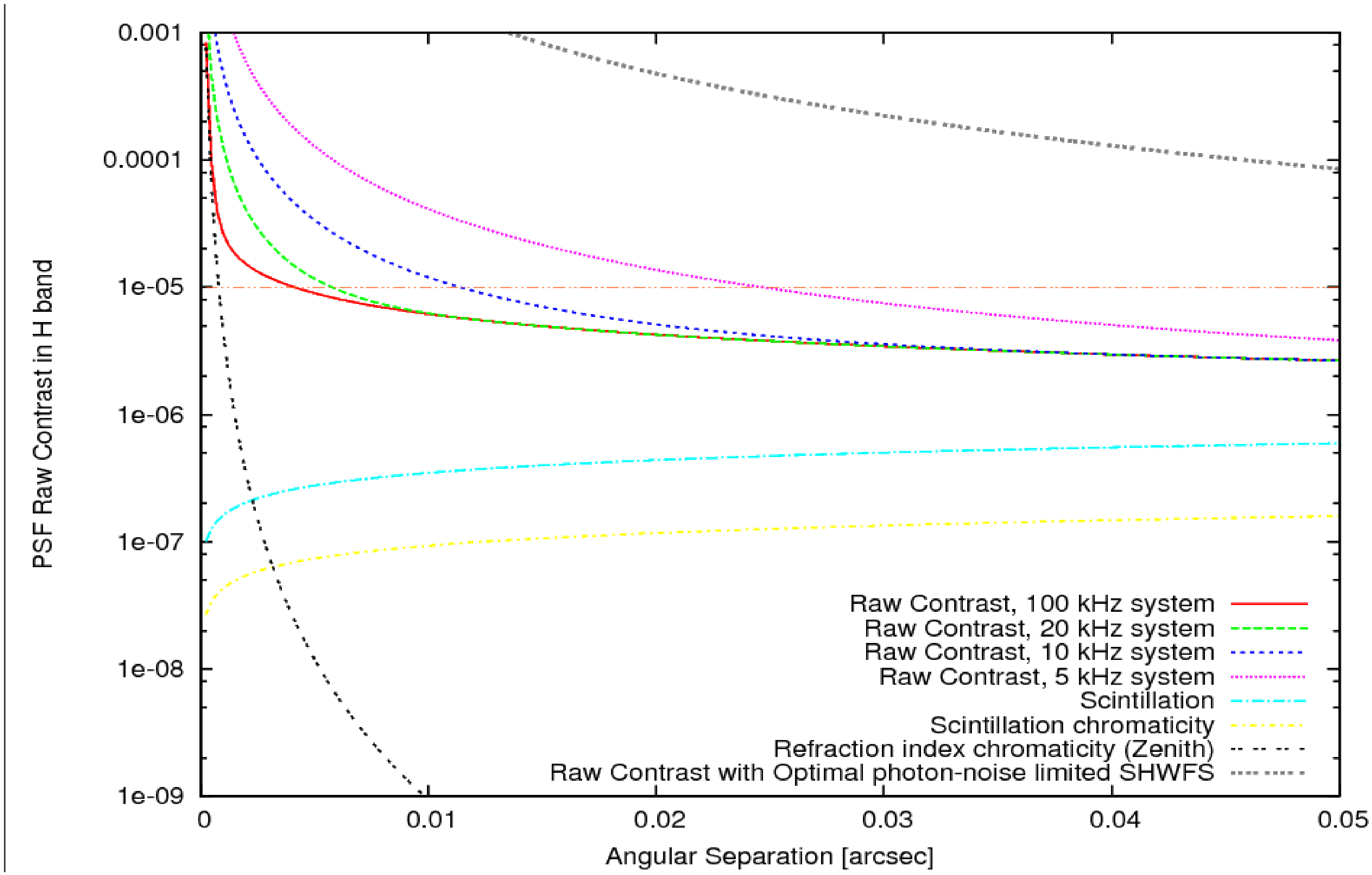


"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

Large gain at small angular separation: ideal for ExAO

Expected AO contrast

~1e-5 raw contrast, diffraction-limited WFS
→ ~1e-8 detection contrast in 1hr (limited by speckle noise)



The Subaru Coronagraphic Extreme-AO (SCExAO) system

High contrast imaging at small angular separation is scientifically extremely valuable:

- allows sytem to probe **inner parts of young planetary systems** (<10 AU)
- constrain planet formation in the **habitable zone** of stars
- **direct imaging** of reflected light planets may be possible (reflected flux goes as a^{-2})

Coronagraphy:
High efficiency 1 λ/D PIAA coronagraph

Wavefront control:
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS visible channel
- Exquisite pointing control

Aux. Science modes:
- Non-redundant masking
- Visible light imaging

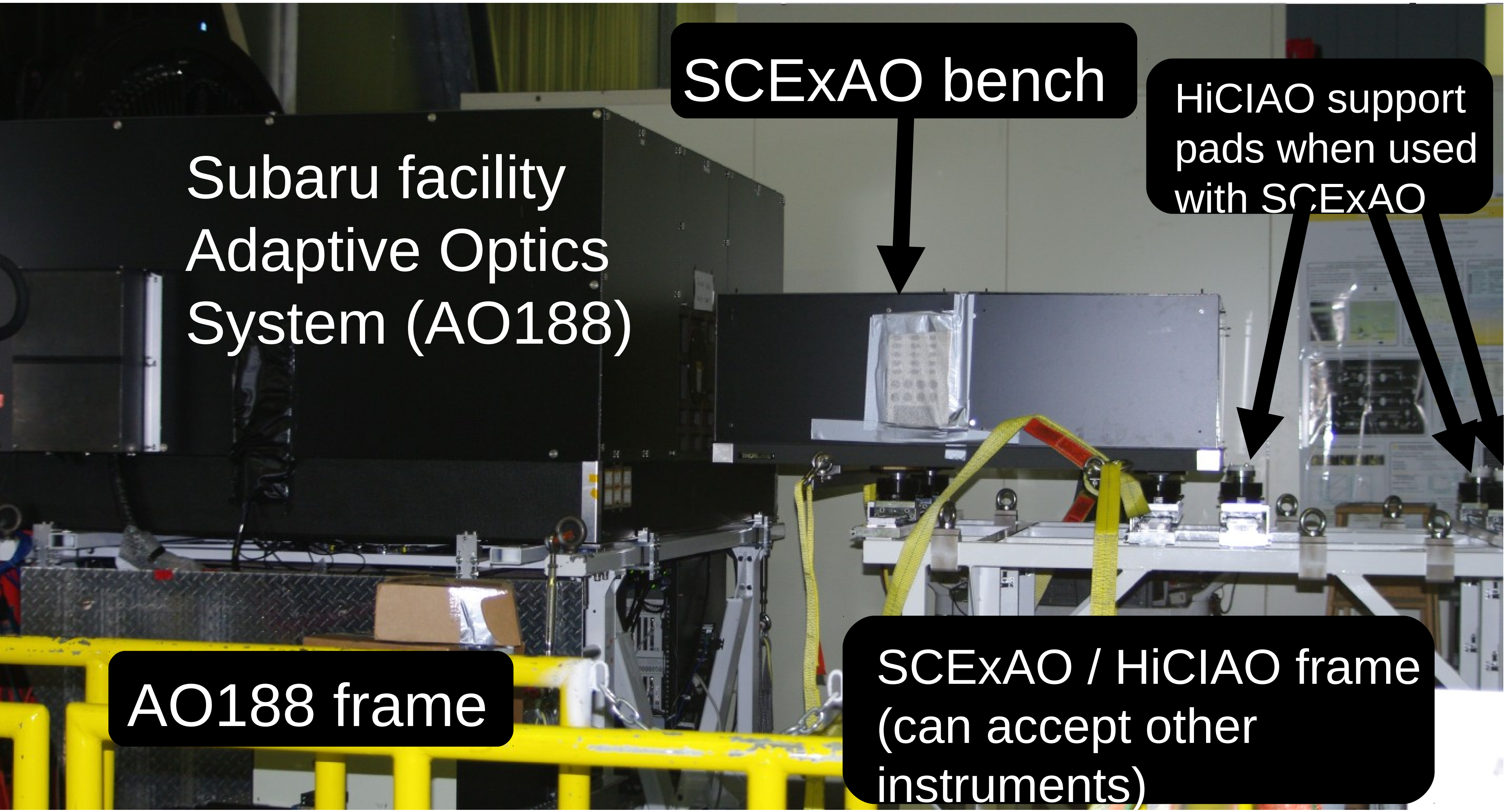
Designed as a **highly flexible, evolvable platform** (reduce time from lab demo to science)
Efficient use of AO188 system & HiCIAO camera
Technology development overlap with space coronagraphy


EXIT

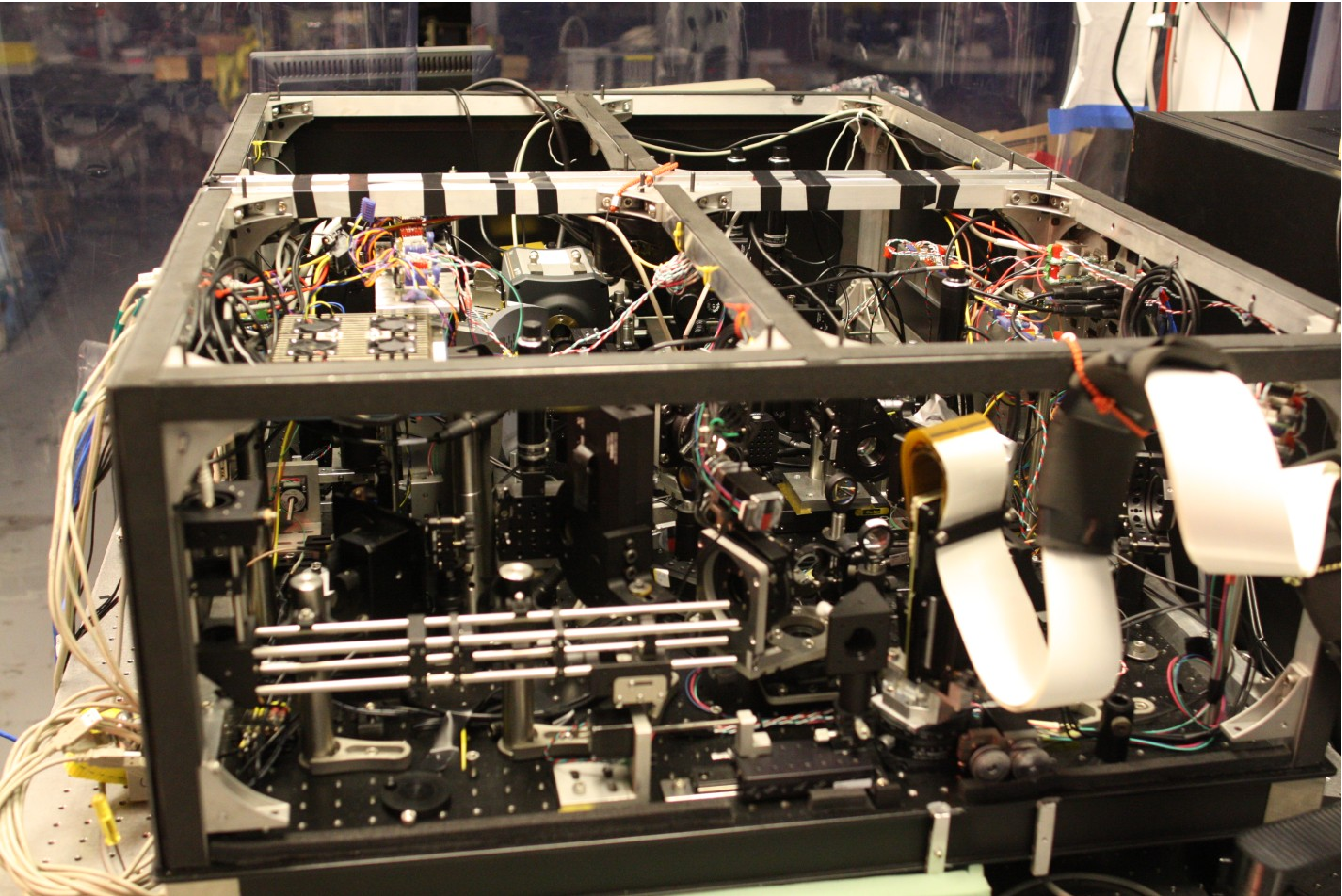
SCExAO at Subaru Telescope (Aug 2010)

[note: HiCIAO camera not in this image]

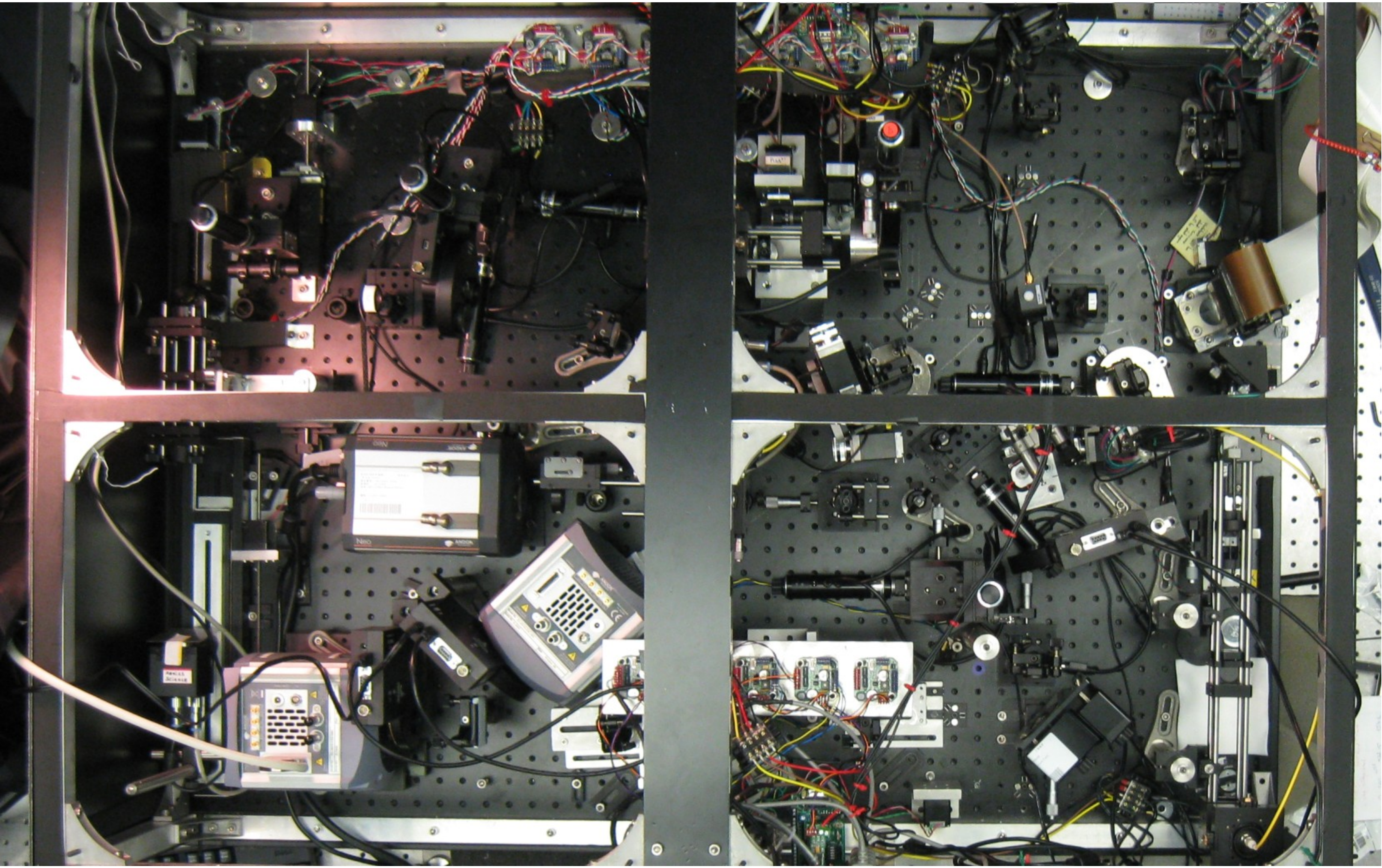
[note: IFS under design, built by Princeton]



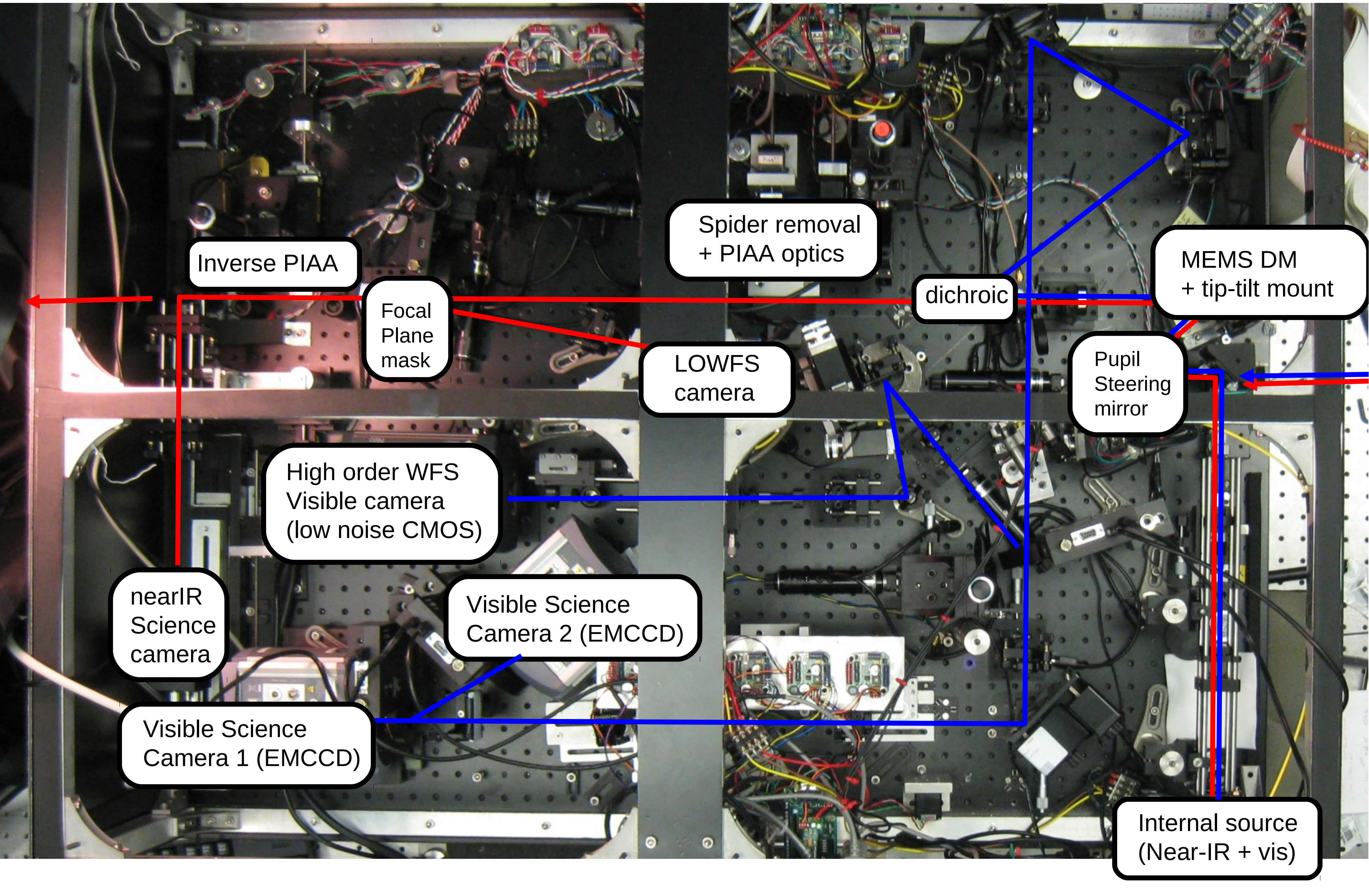
The Subaru Coronagraphic Extreme-AO (SCExAO) system

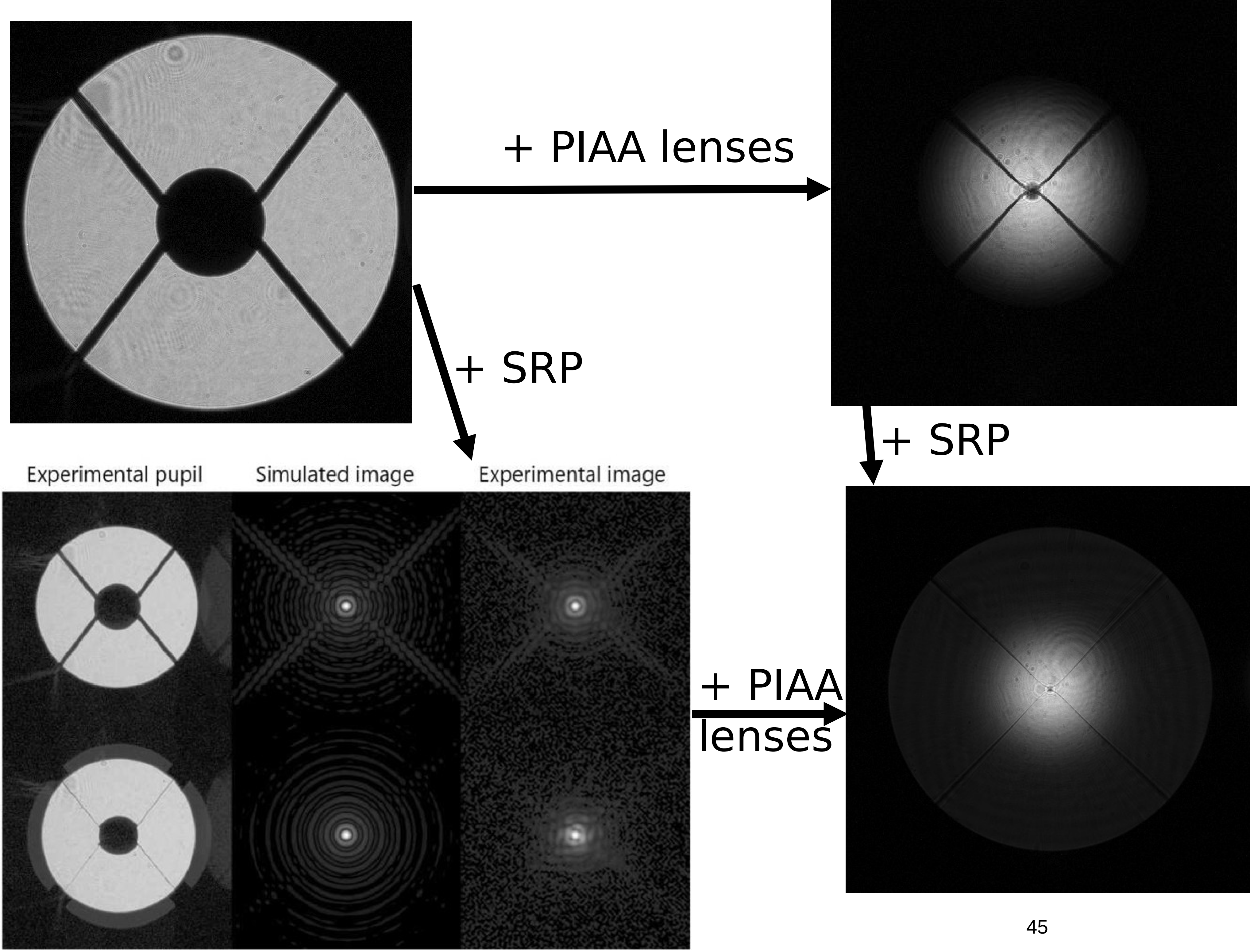


The Subaru Coronagraphic Extreme-AO (SCExAO) system

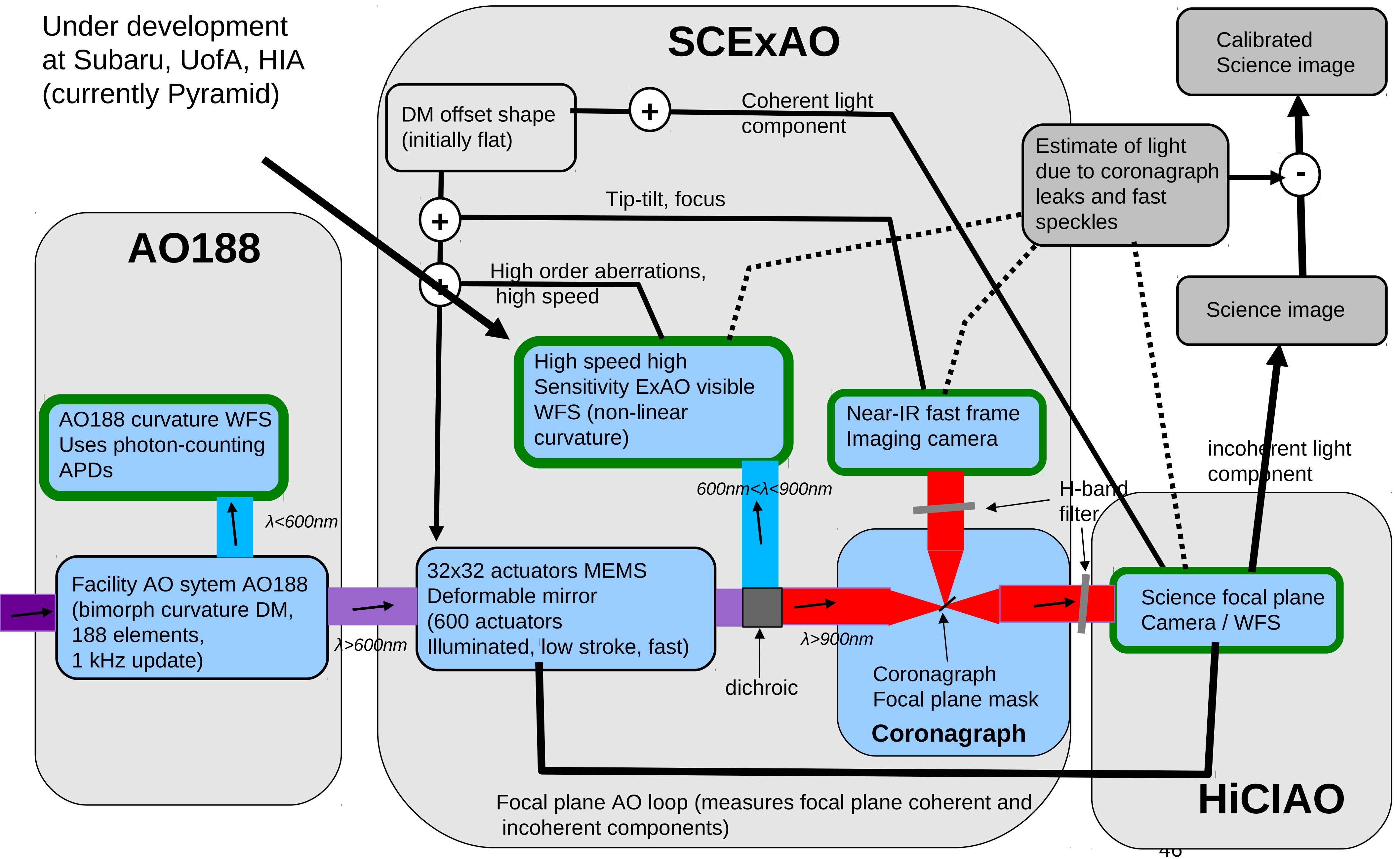


The Subaru Coronagraphic Extreme-AO (SCExAO) system




+ PIAA lenses
+ SRP
+ SRP
Experimental pupil
Simulated image
Experimental image
Without SRP
With SRP
+ PIAA
lenses

SCExAO Wavefront Control architecture and speckle calibration



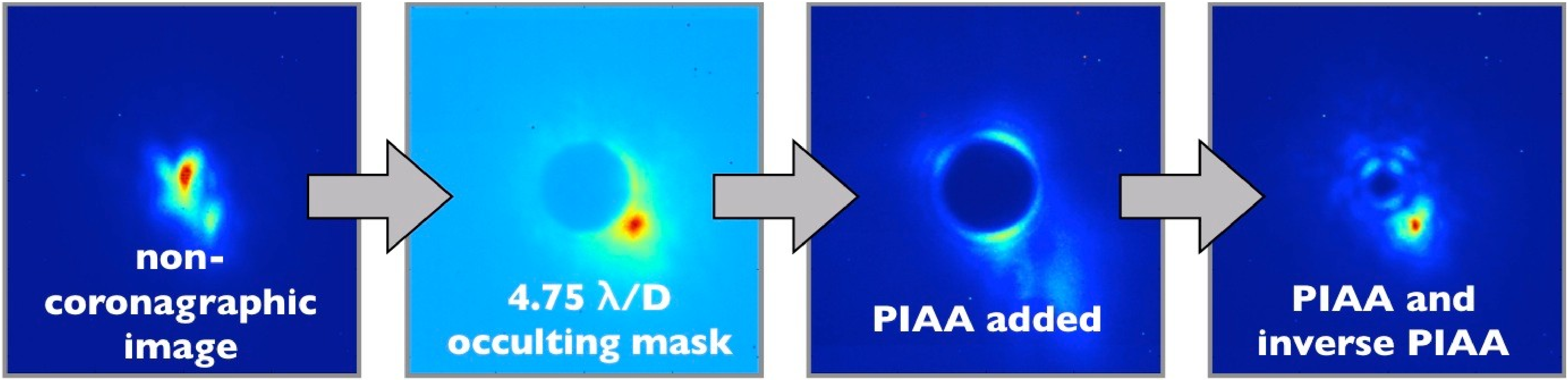
SCExAO Results

LOWFS validated on sky

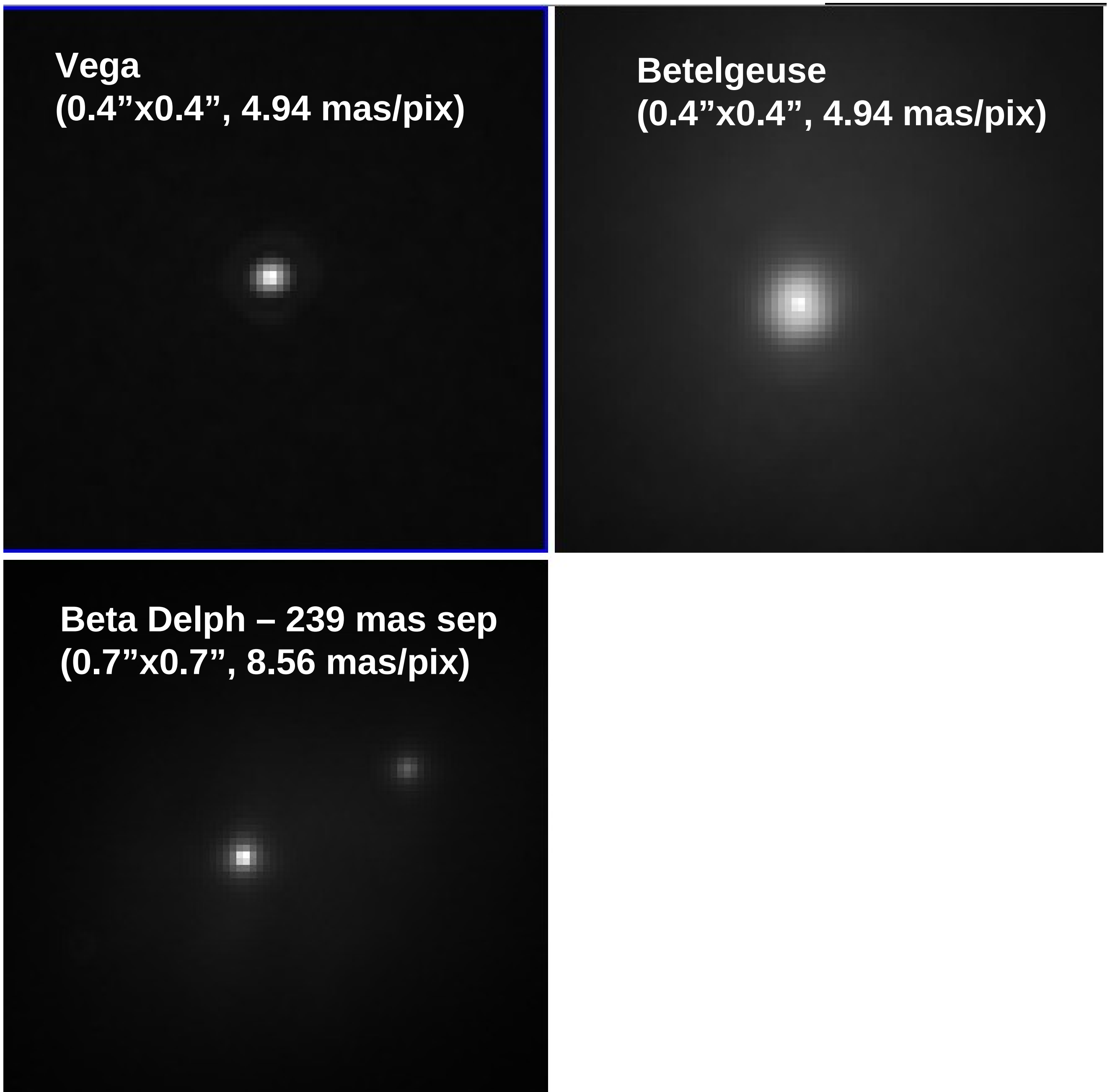
- robust performance at low gain (~0.1) in difficult conditions
- on-sky calibration can be time consuming

PIAA coronagraphy at 1.2 lambda/D validated

- Inverse PIAA image sharpening validated



SCExAO first visible images (V. Garrel PhD)



SCExAO acquired first visible light diffraction limited on Subaru in Feb and Sept 2011

Despite moderate AO performance (seeing 1” to 2” + clouds in Feb, poor AO perf in Sept) selection + new Fourier-based reconstruction allowed diffraction-limited imaging.

Habitable planets spectroscopy

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

Ground (ELT):
M type stars, nearIR