The Subaru Coronagraphic Extreme-AO (SCExAO) system

Olivier Guyon *(Subaru Telescope & University of Arizona)*
Frantz Martinache

Vincent Garrel (PhD student: visible imaging)
Christophe Clergeon (PhD student: ExAO wavefront sensing)
Celia Blain (PhD student: MEMS deformable mirror models)

Jun-Ichi Morino (HiCIAO + SCExAO)
Tomoyuki Kudo (HiCIAO + SCExAO)

+ HiCIAO team, AO188 team

OUTLINE

INTRODUCTION

High contrast imaging at 1 l/D

SCExAO SYSTEM

Solutions to high contrast imaging at 1 l/D

- *coronagraphy*
- *wavefront control*
- *calibration*

SCExAO schedule and early results

SCExAO as a precursor to imaging habitable planets with ELTs

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})

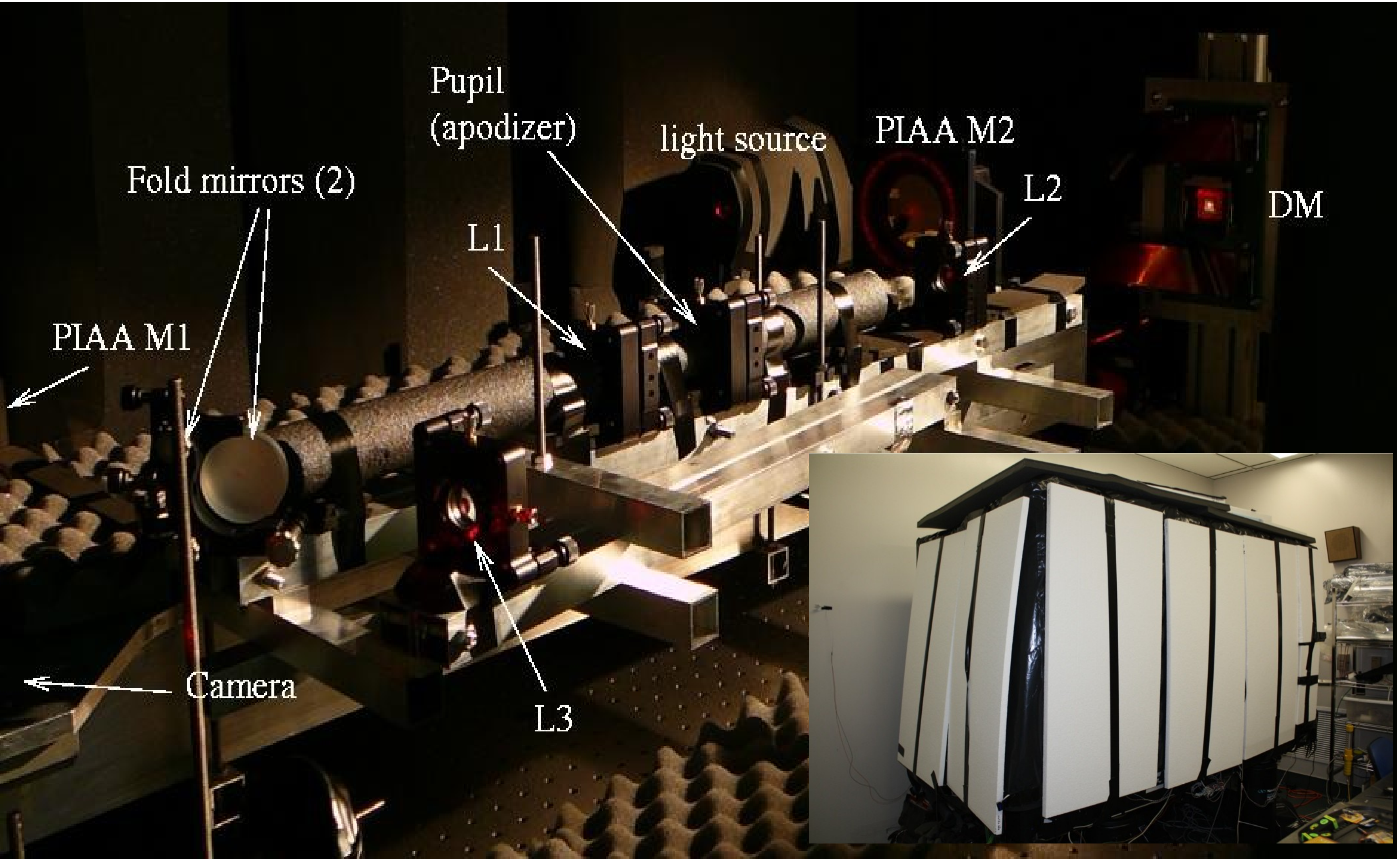
Coronagraphy:
High efficiency 1 λ/D PIAA coronagraph

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

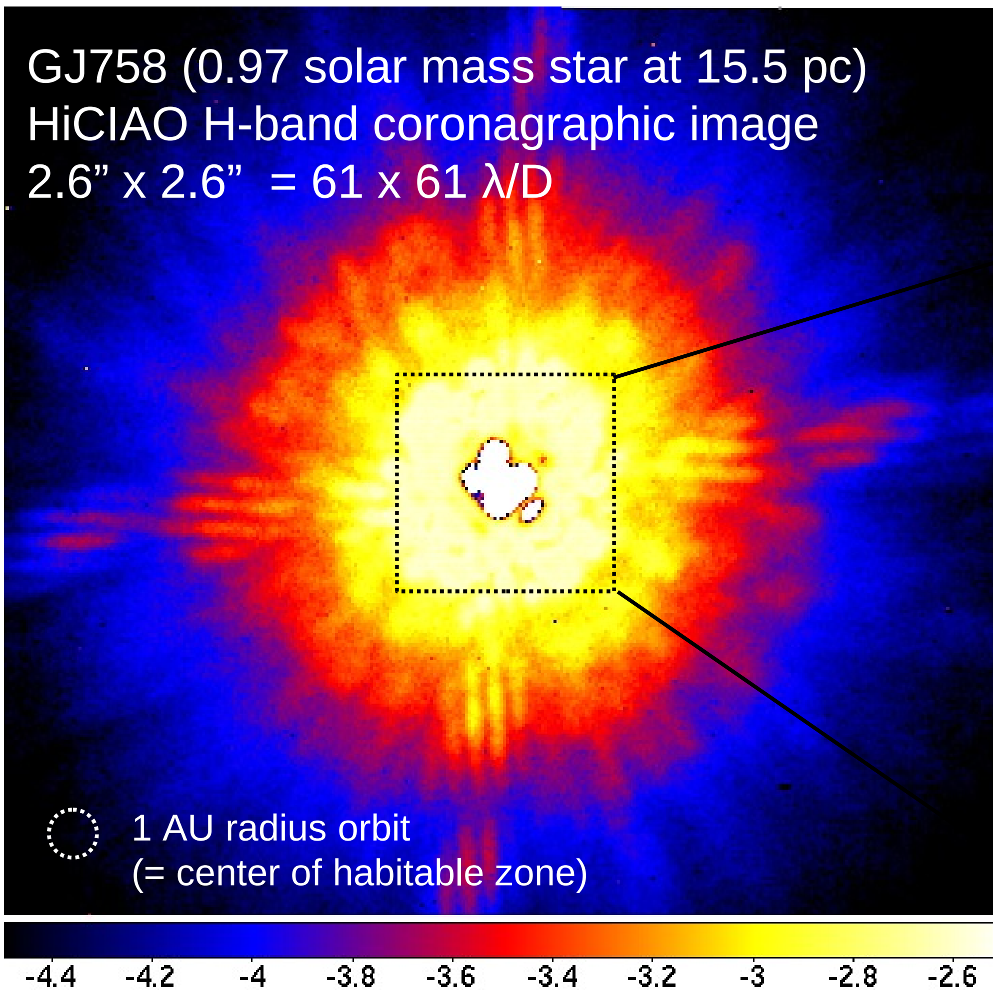
Designed as a **highly flexible, evolvable platform** (reduce time from lab demo to science)
Efficient use of AO188 system & HiCIAO camera
Technology development overlap with space coronagraphy

PIAA lab at Subaru Telescope



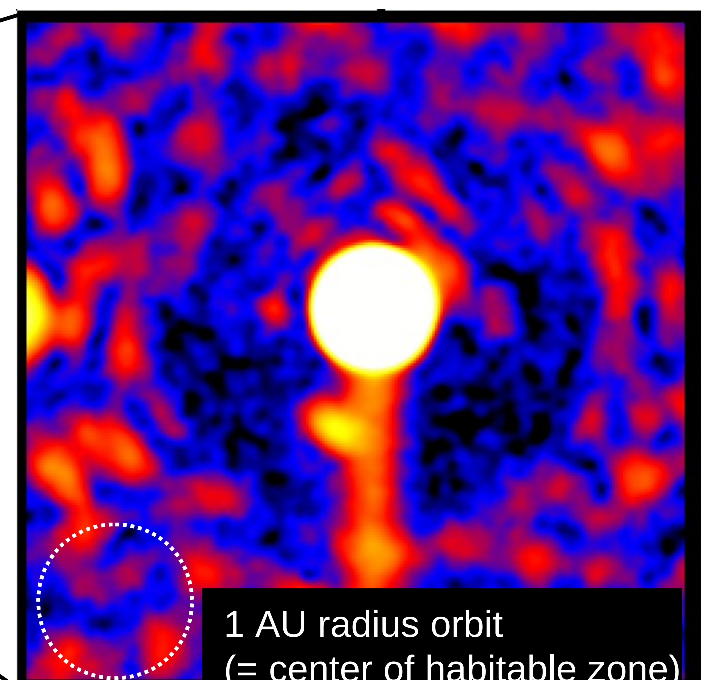
High contrast imaging in lab reaches much higher performance than what is currently achieved on-sky: newer technologies, more stable environment, better calibrations

SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance



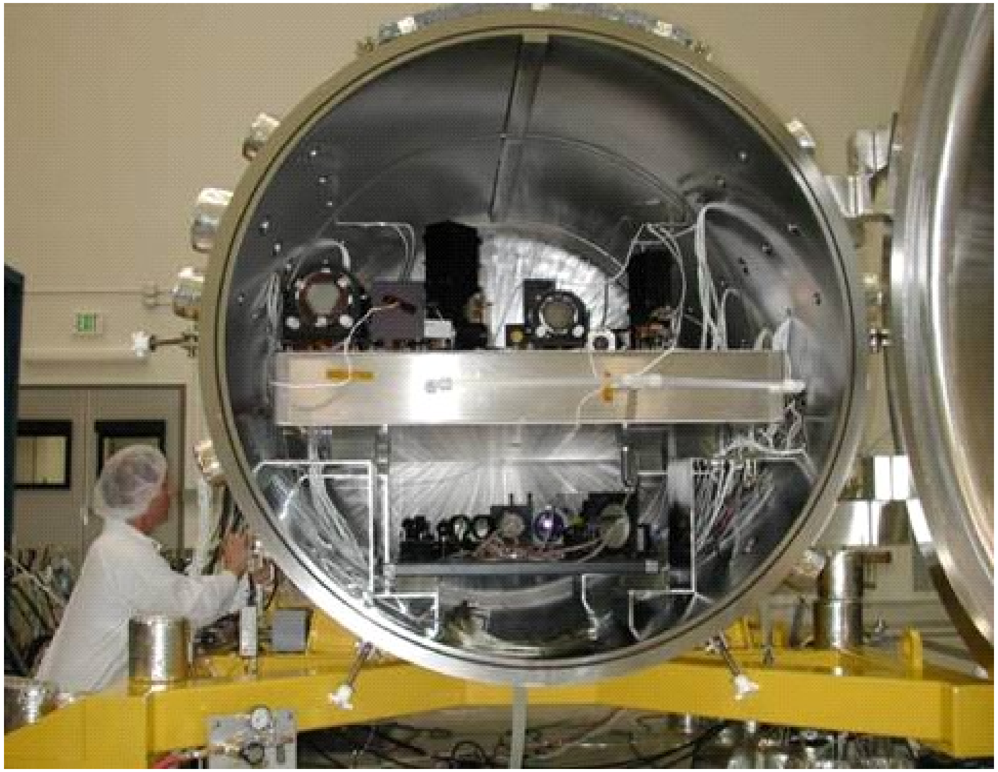
Log contrast

Subaru PIAA image (laboratory)
13.6 x 13.6 λ/D = 0.58" x 0.58"
(Same contrast color scale)

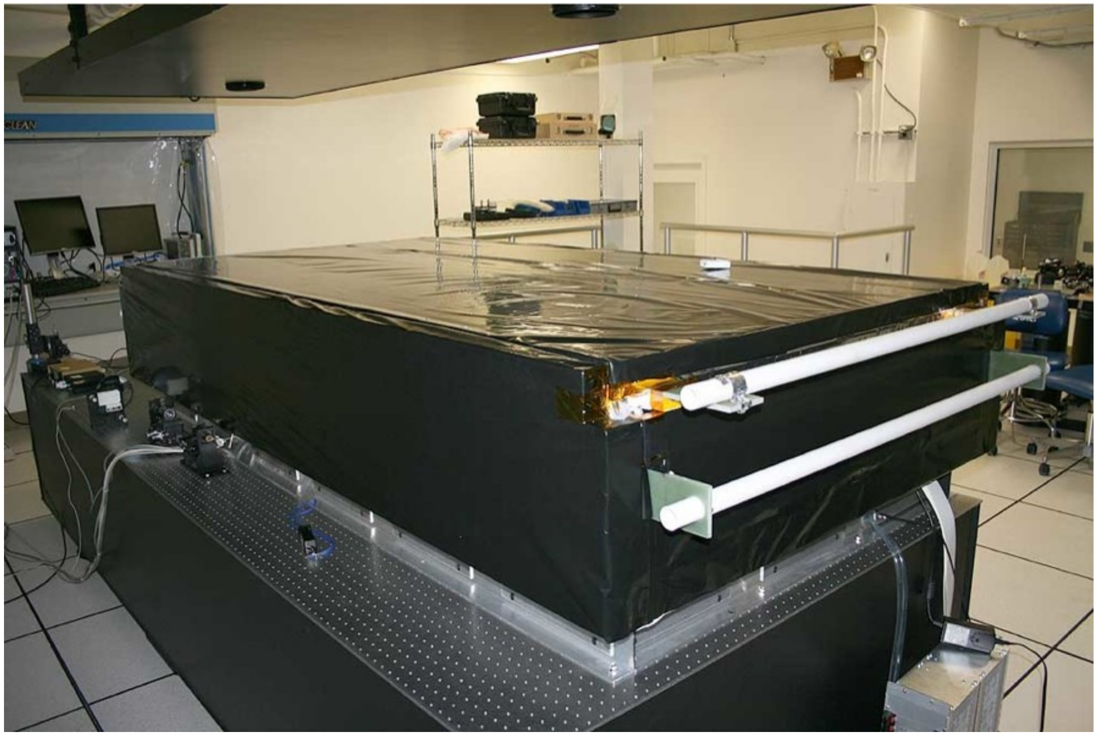


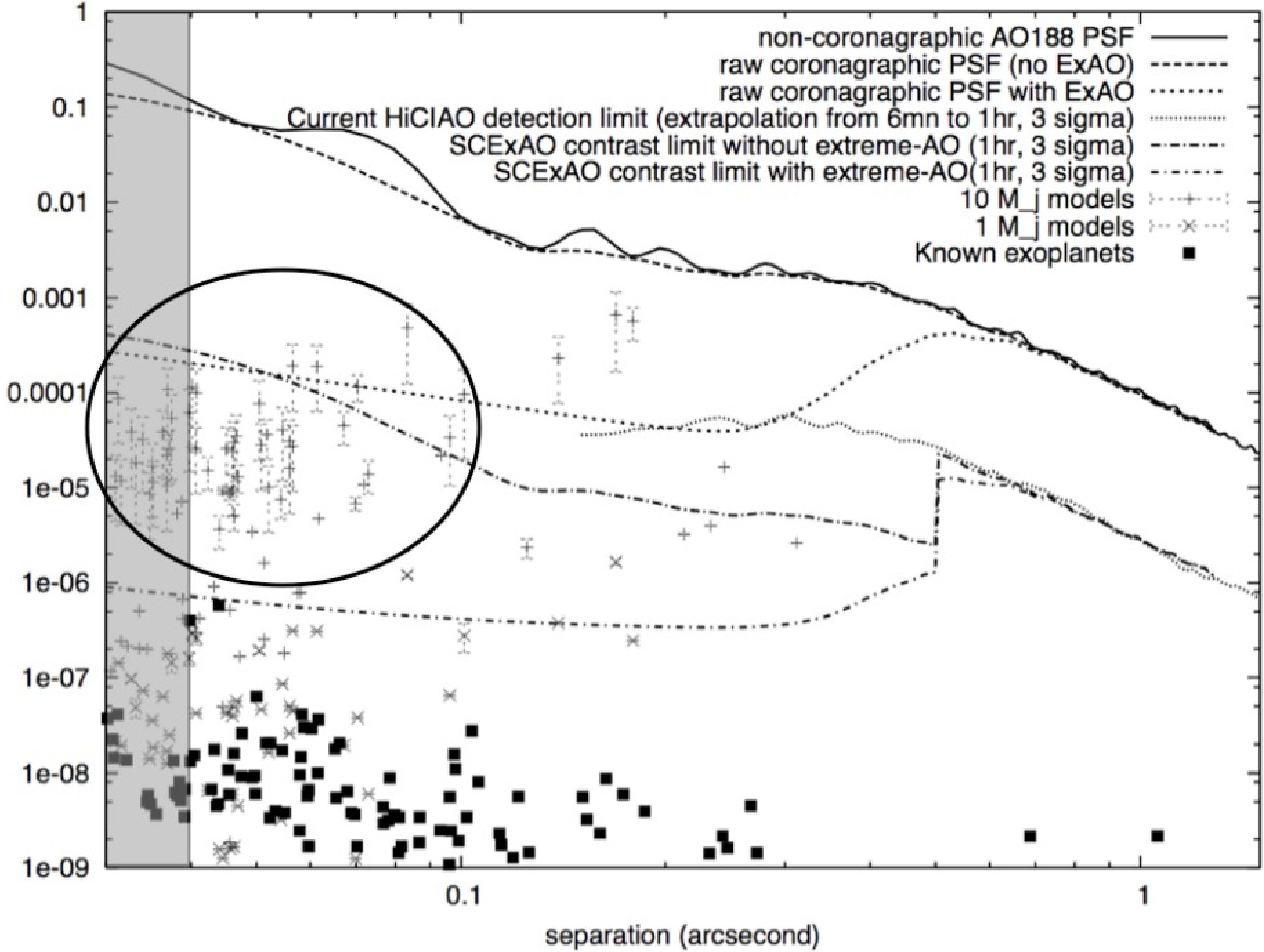
Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

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



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

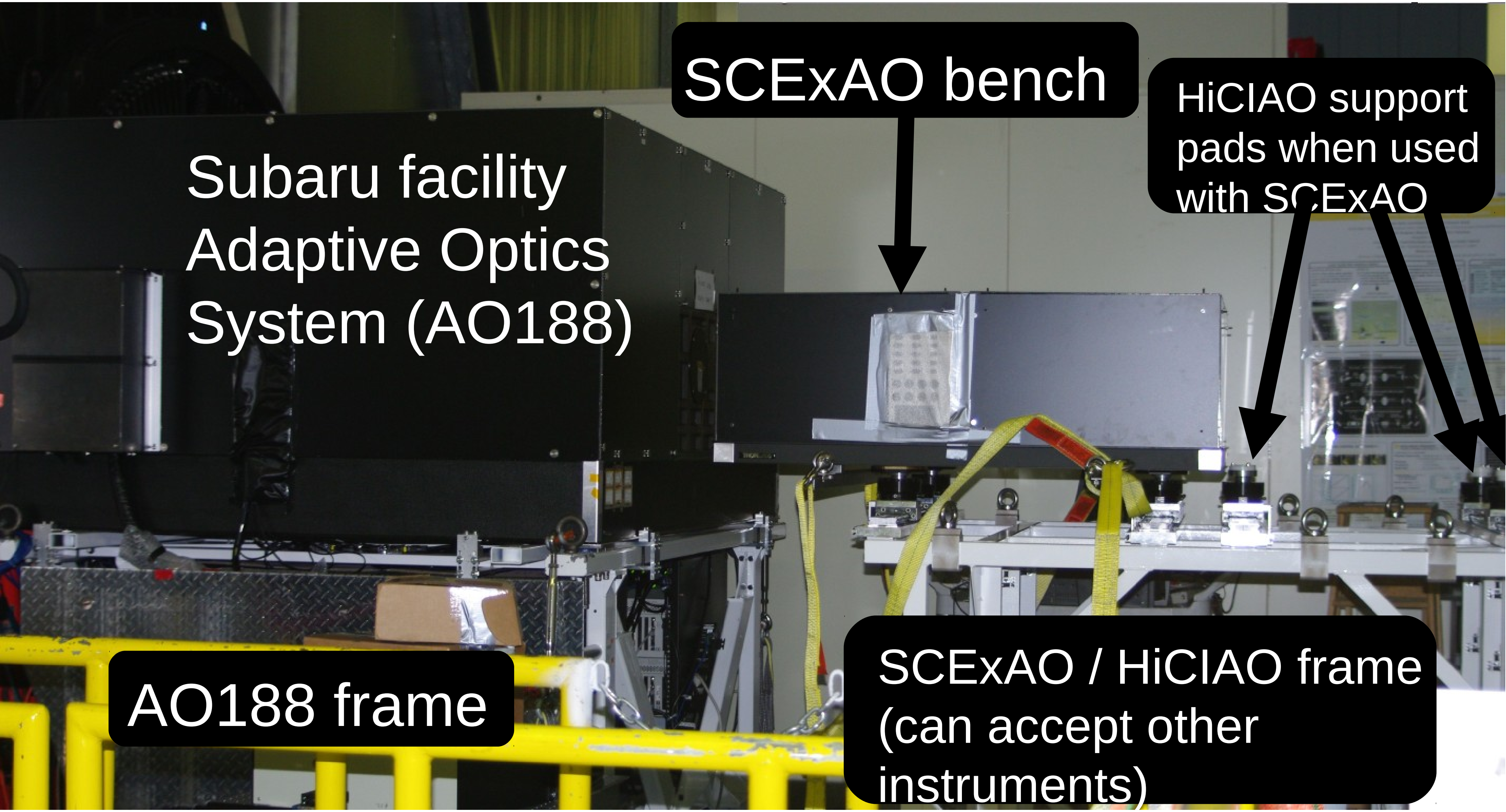




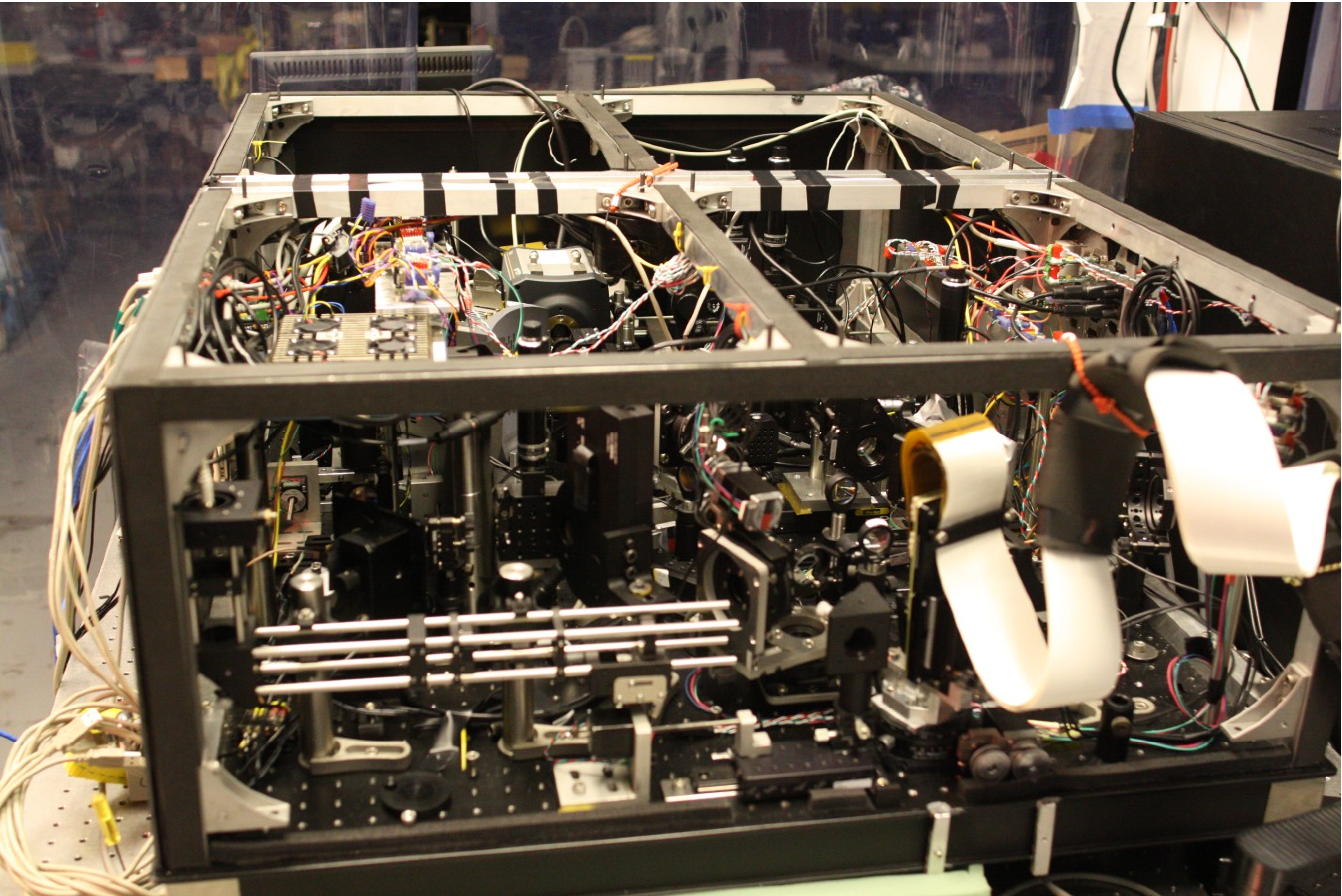
non-coronagraphic AO188 PSF
raw coronagraphic PSF (no ExAO)
raw coronagraphic PSF with ExAO
Current HiCIAO detection limit (extrapolation from 6mn to 1hr, 3 sigma)
SCExAO contrast limit without extreme-AO (1hr, 3 sigma)
SCExAO contrast limit with extreme-AO(1hr, 3 sigma)
10 M_j models
1 M_j models
Known exoplanets
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
0.1
1
separation (arcsecond)


EXIT

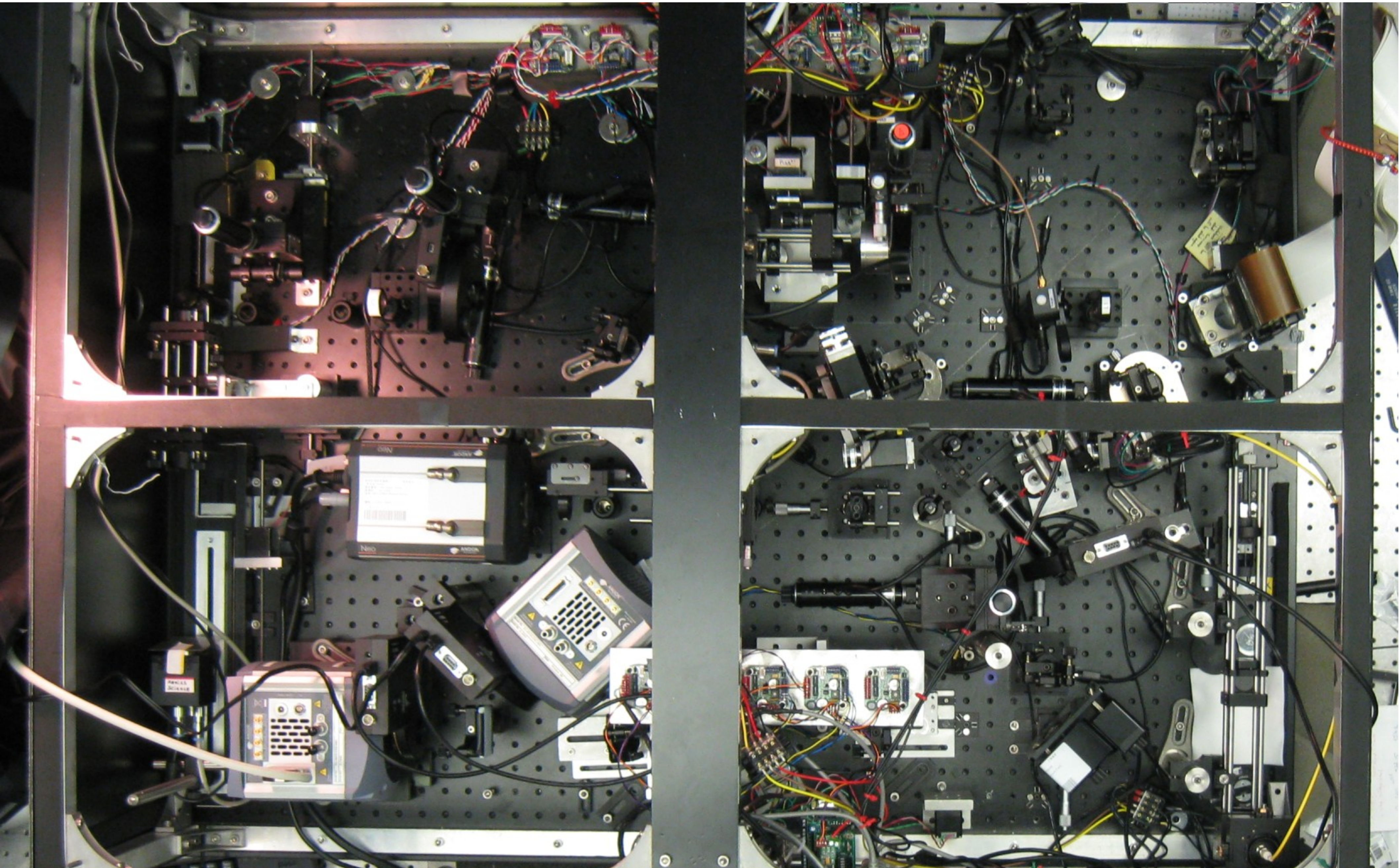
SCExAO at Subaru Telescope (Aug 2010)
[note: HiCIAO camera not in this image]
[note: IFS under design, built by Princeton]



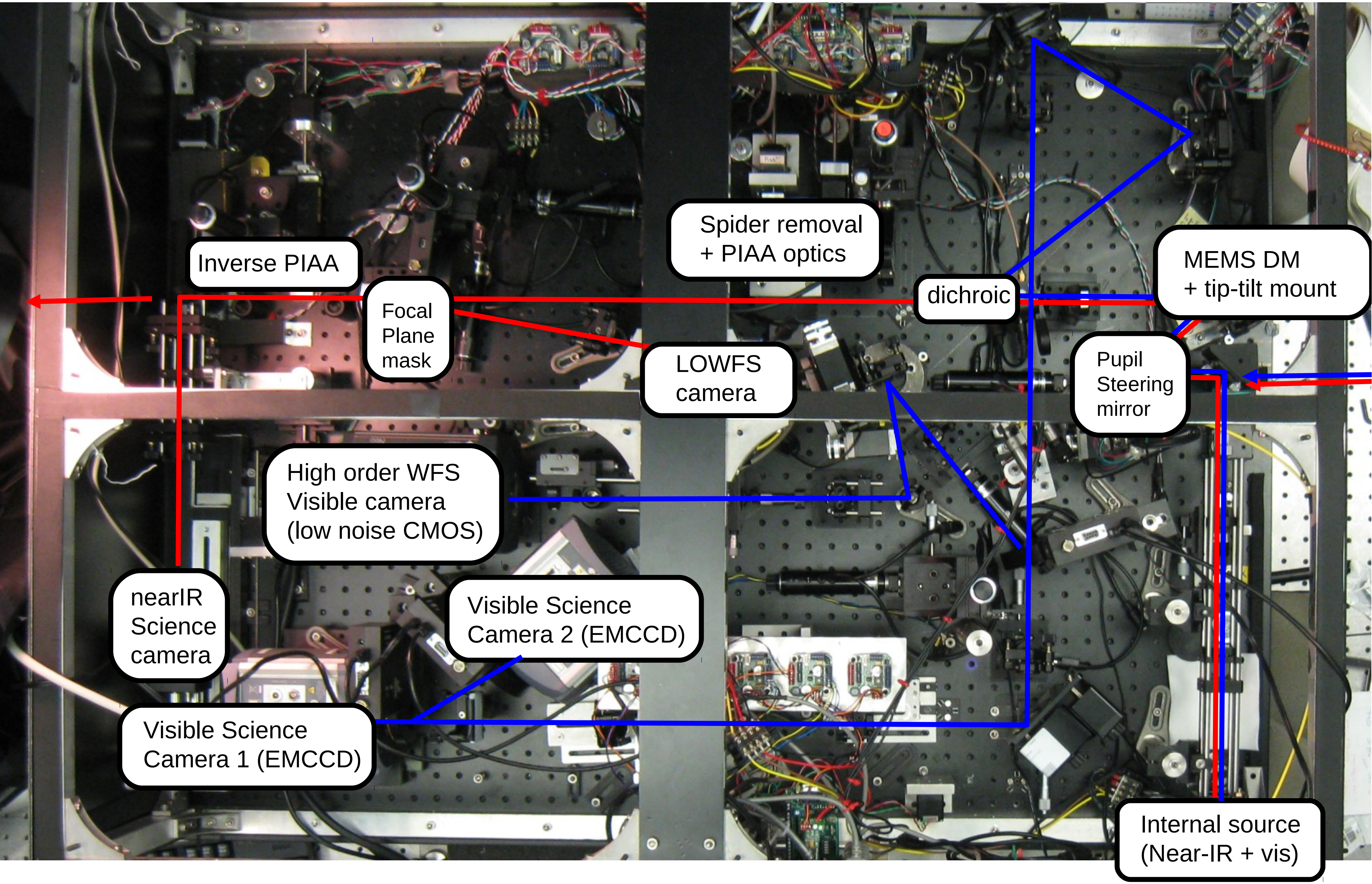
The Subaru Coronagraphic Extreme-AO (SCExAO) system



The Subaru Coronagraphic Extreme-AO (SCExAO) system



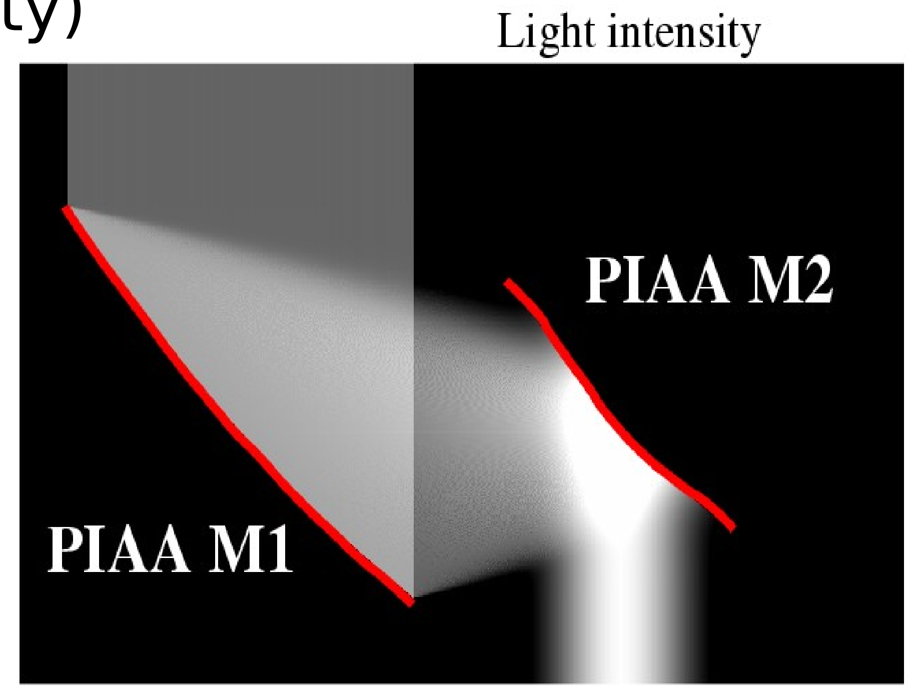
The Subaru Coronagraphic Extreme-AO (SCExAO) system



Phase-Induced Amplitude Apodization (PIAA) coronagraph

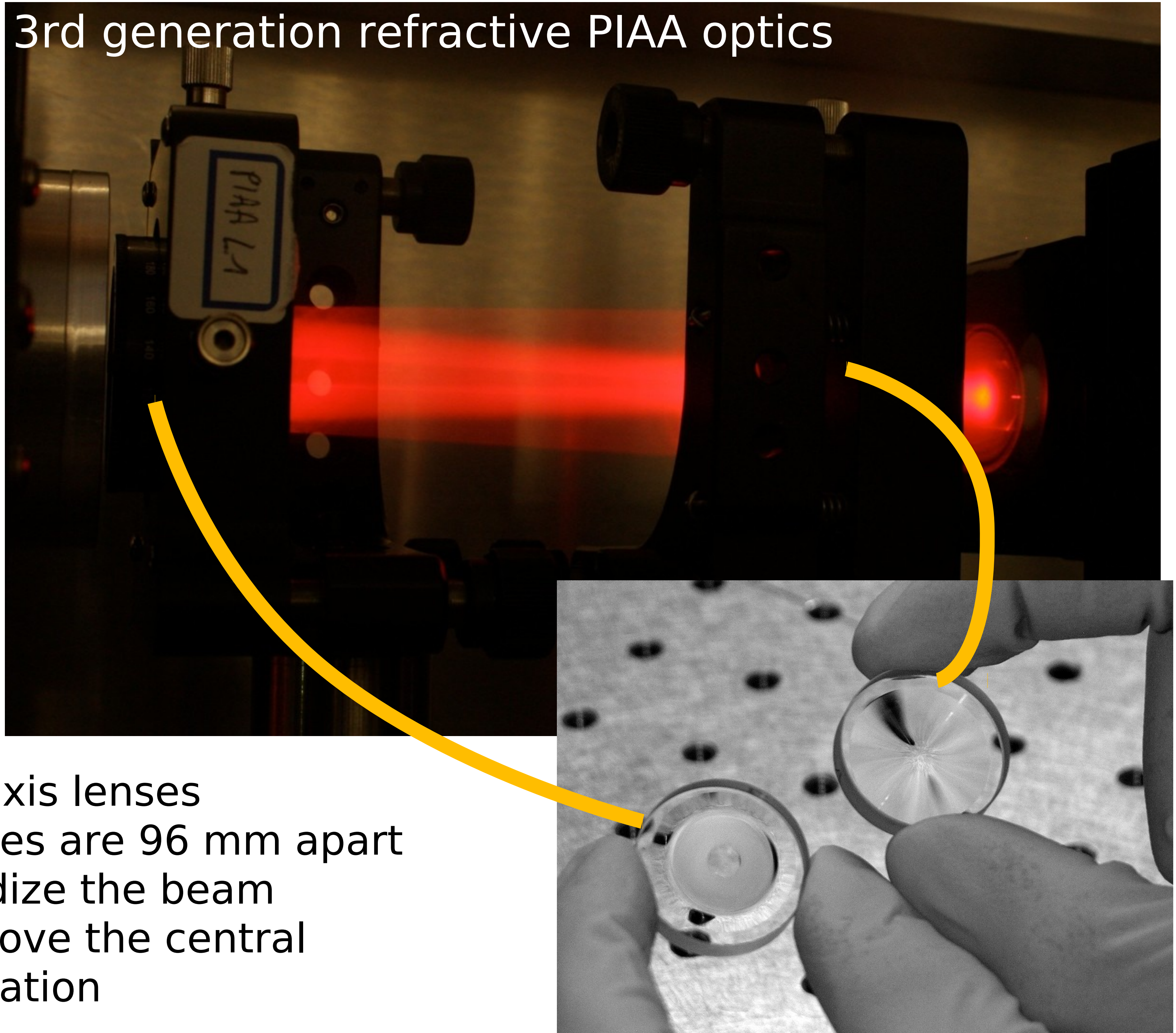
Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

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



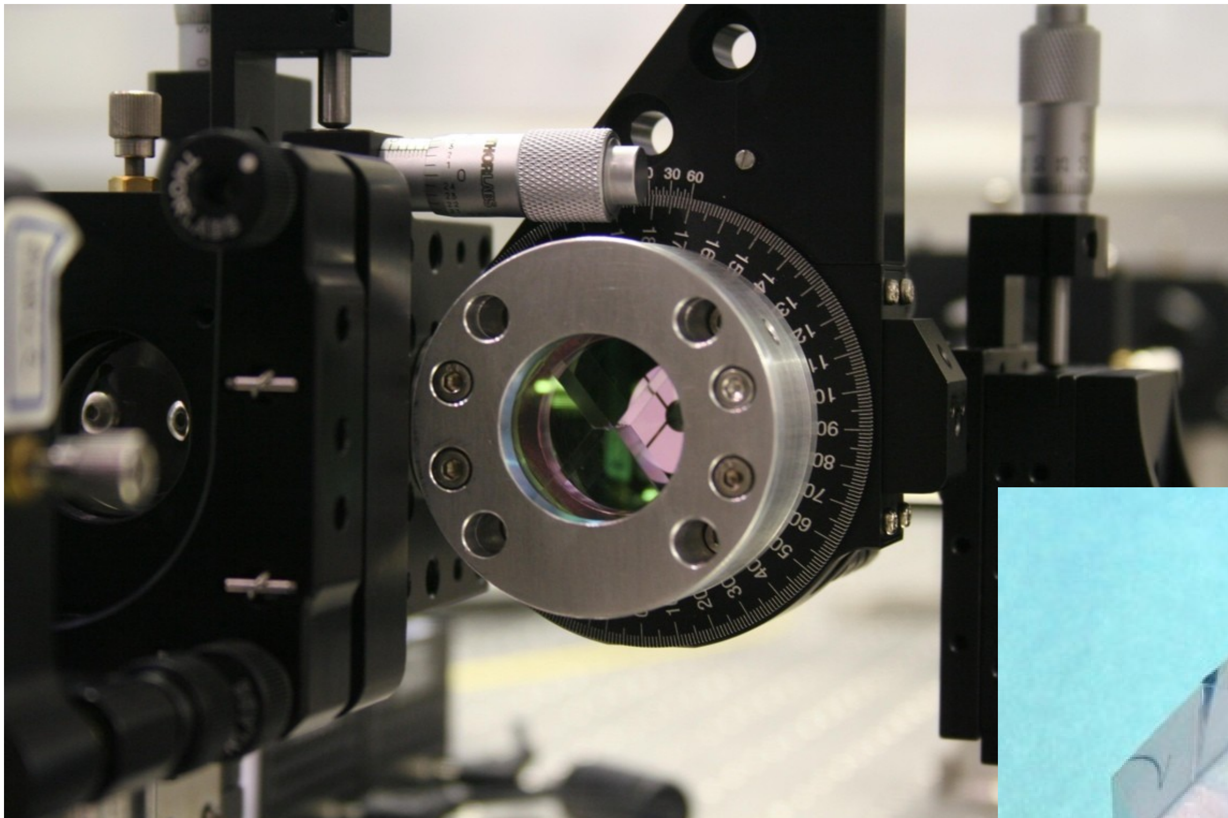
Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
Lab demos at NASA Ames, NASA JPL for space coronagraphy

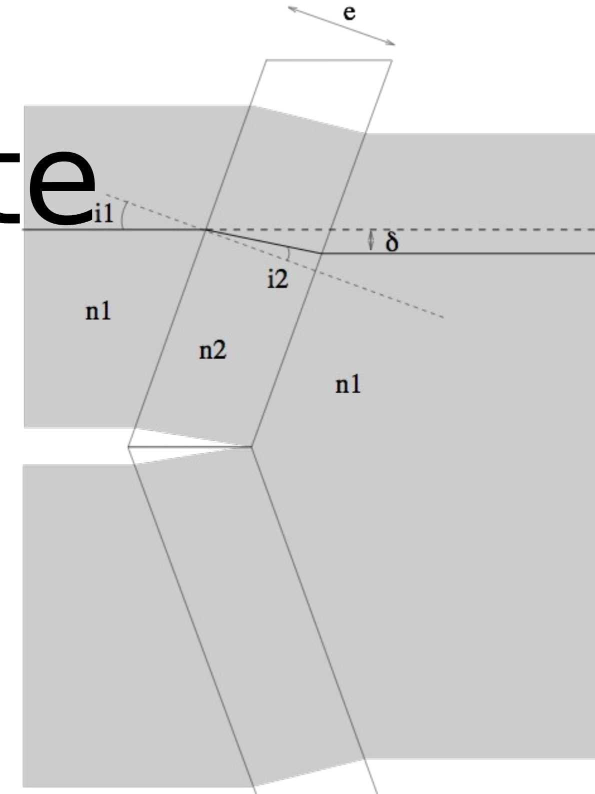
3rd generation refractive PIAA optics

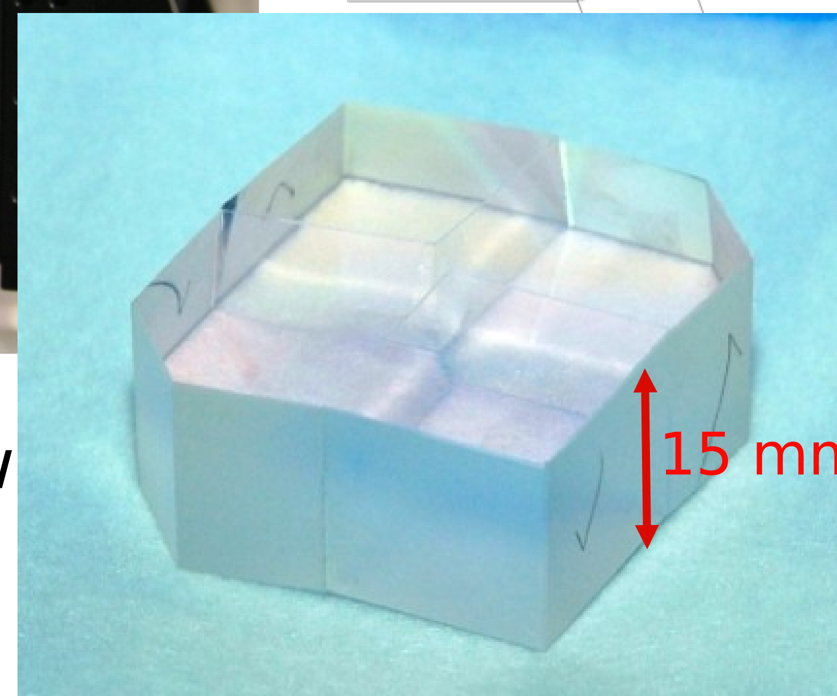


- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Spider Removal Plate

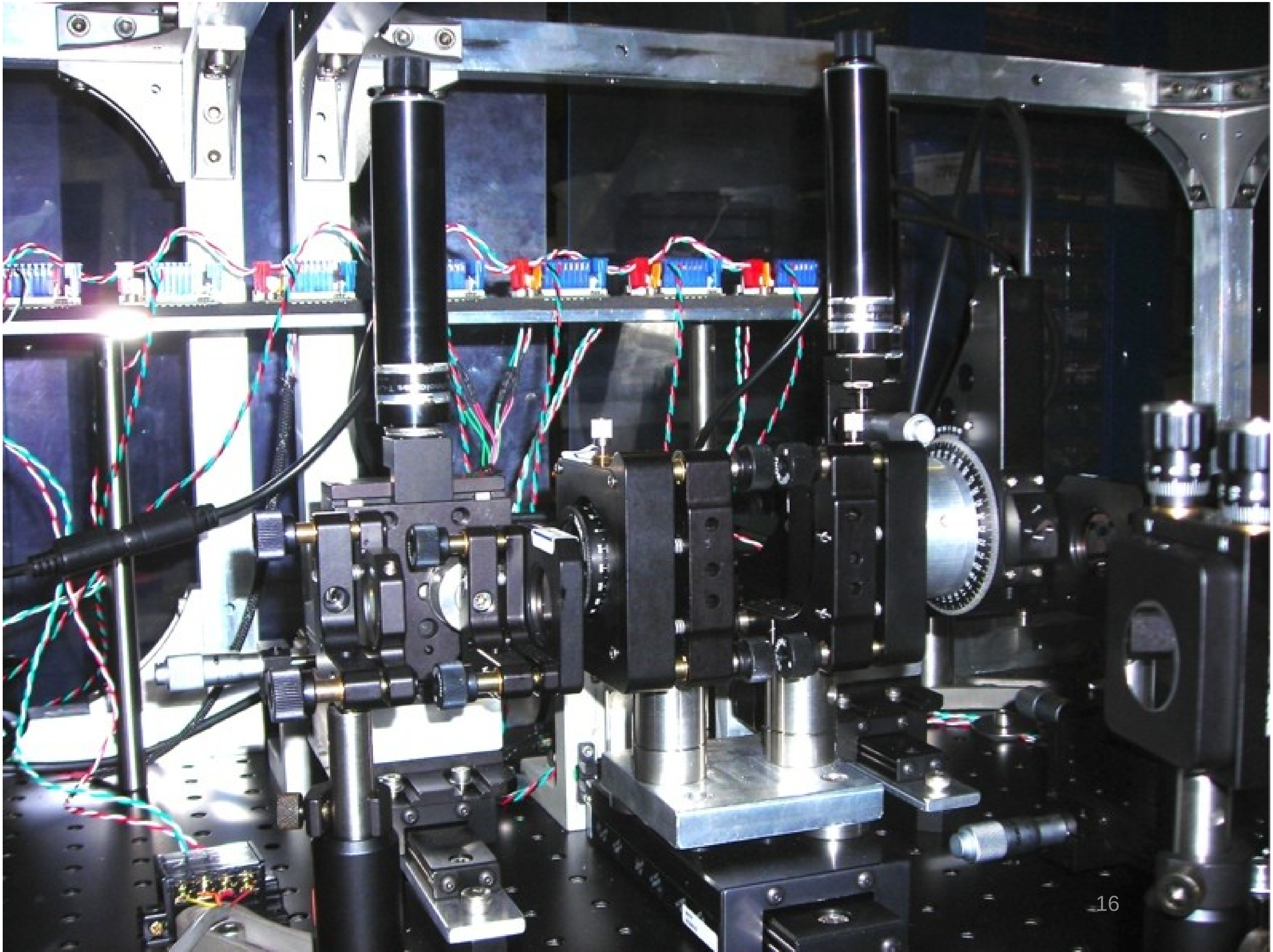


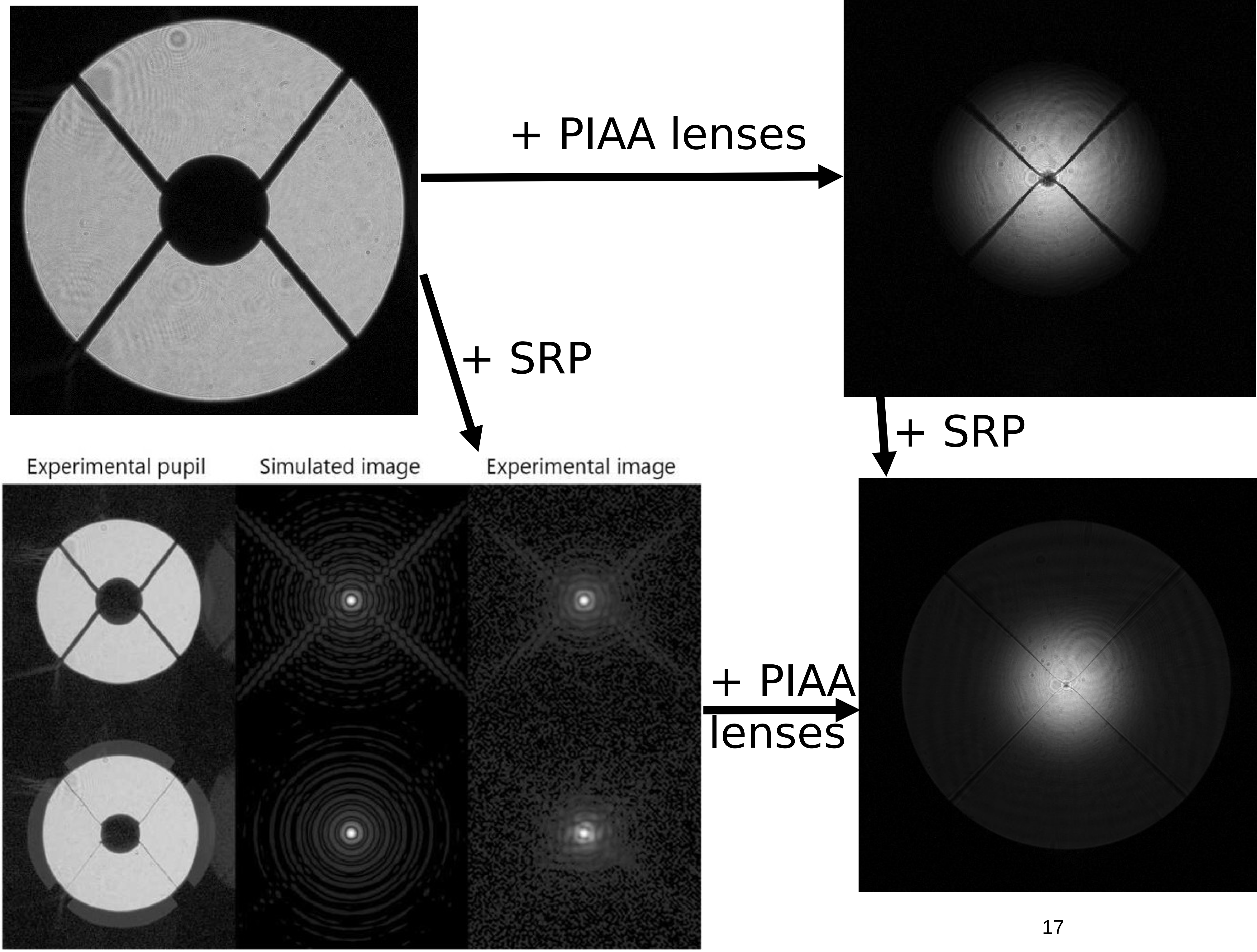




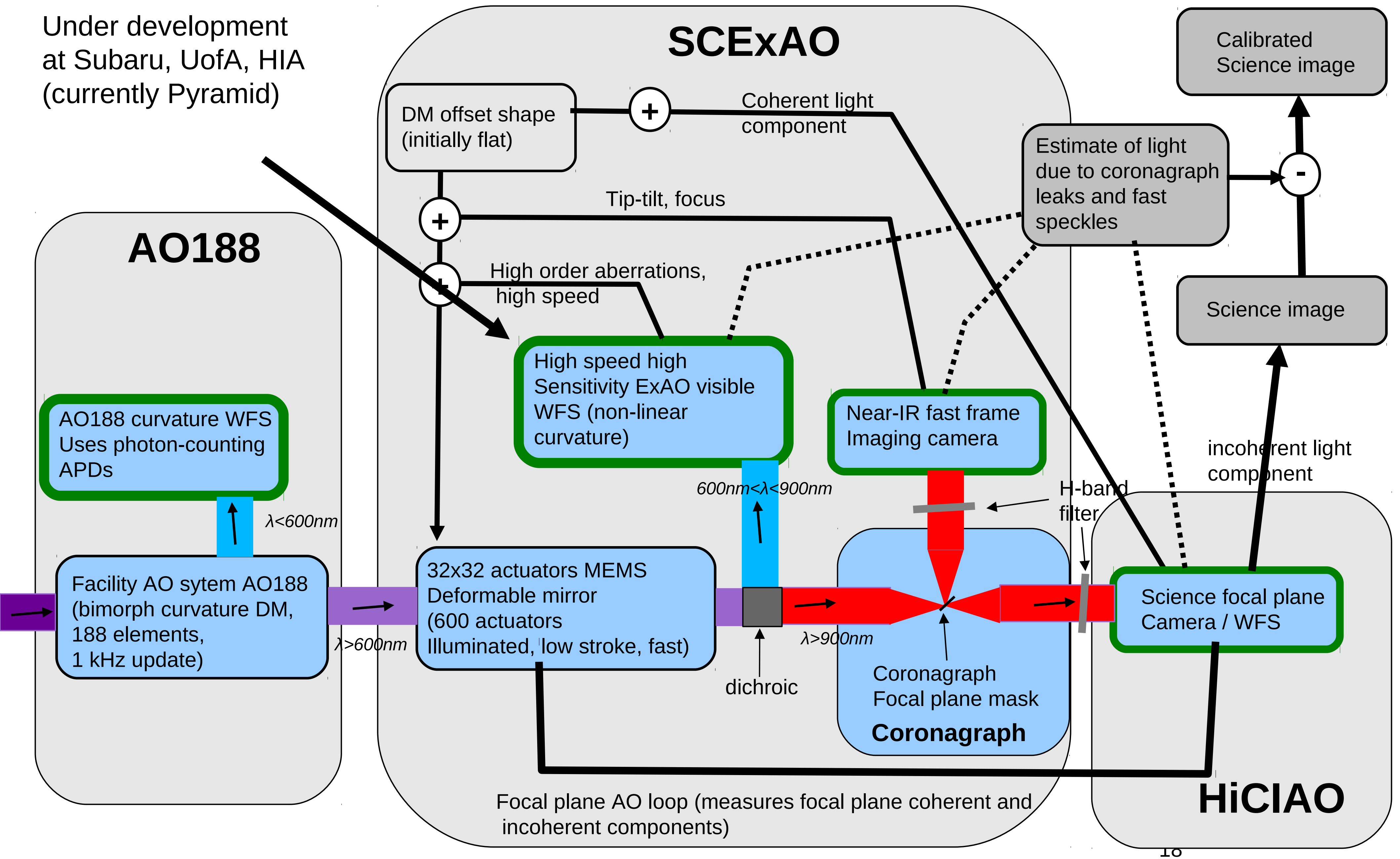
- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°

Beam shaping hardware

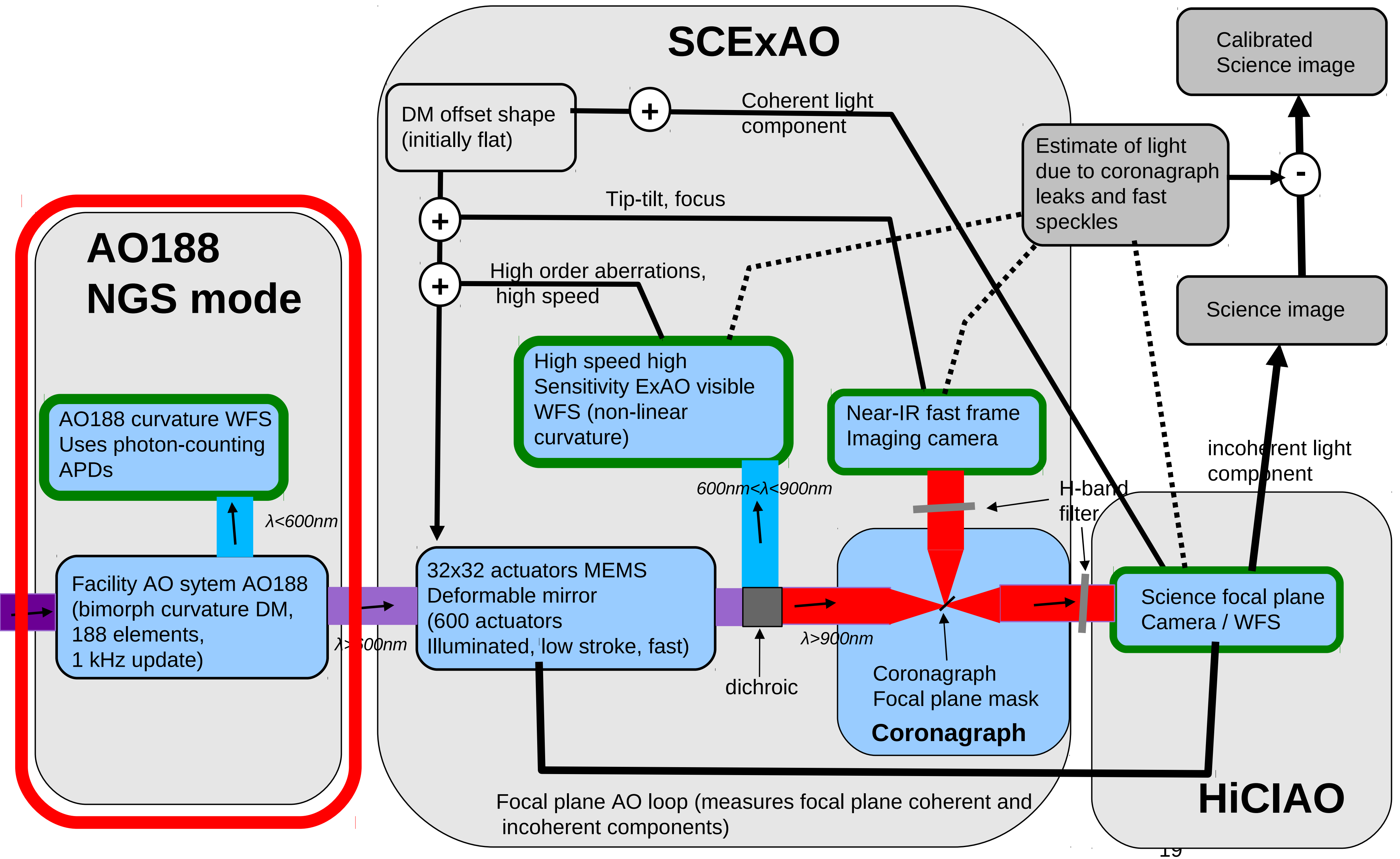



+ PIAA lenses
+ SRP
+ SRP
Experimental pupil
Simulated image
Experimental image
Without SRP
With SRP
+ PIAA lenses

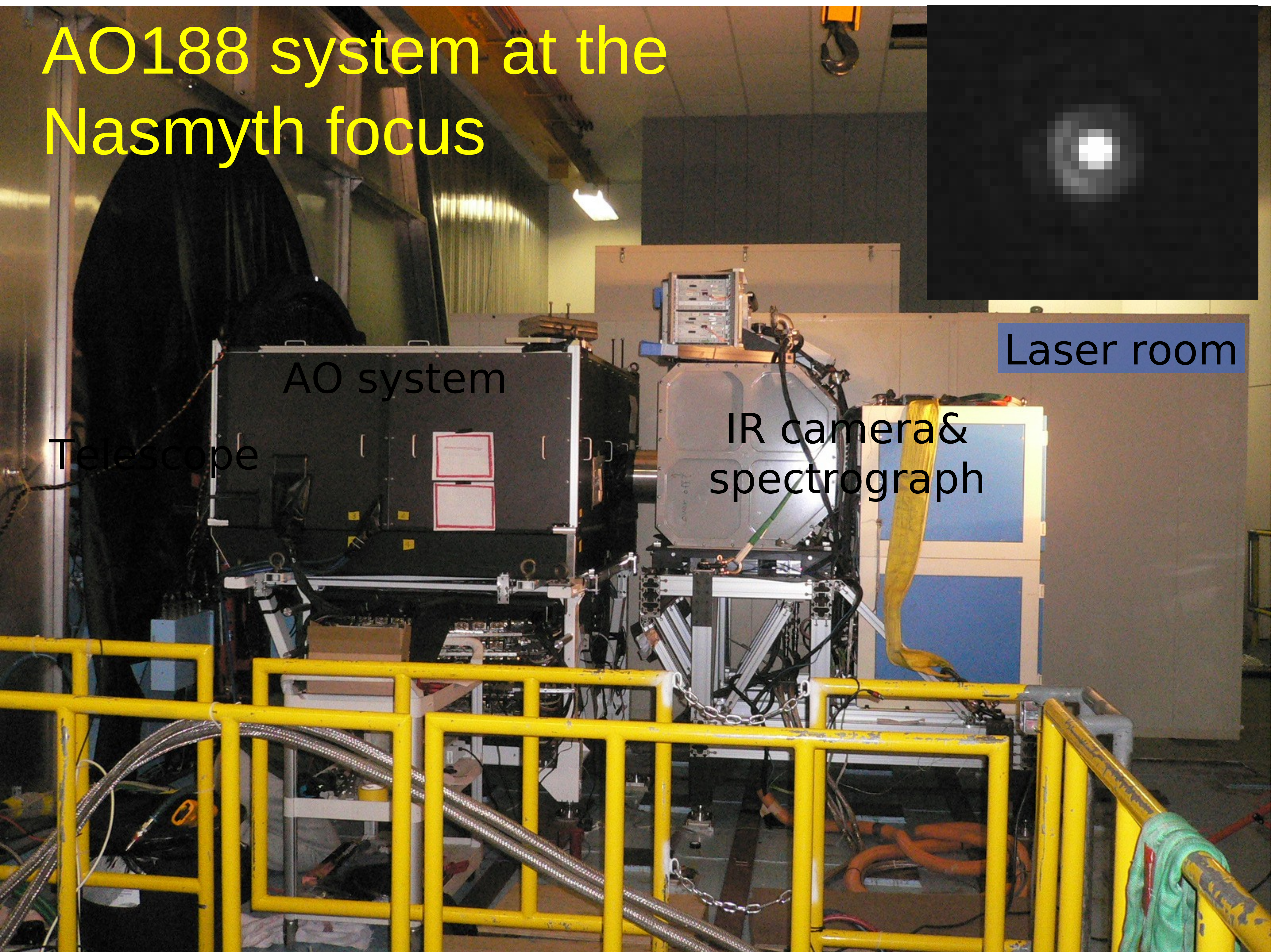
SCExAO Wavefront Control architecture and speckle calibration



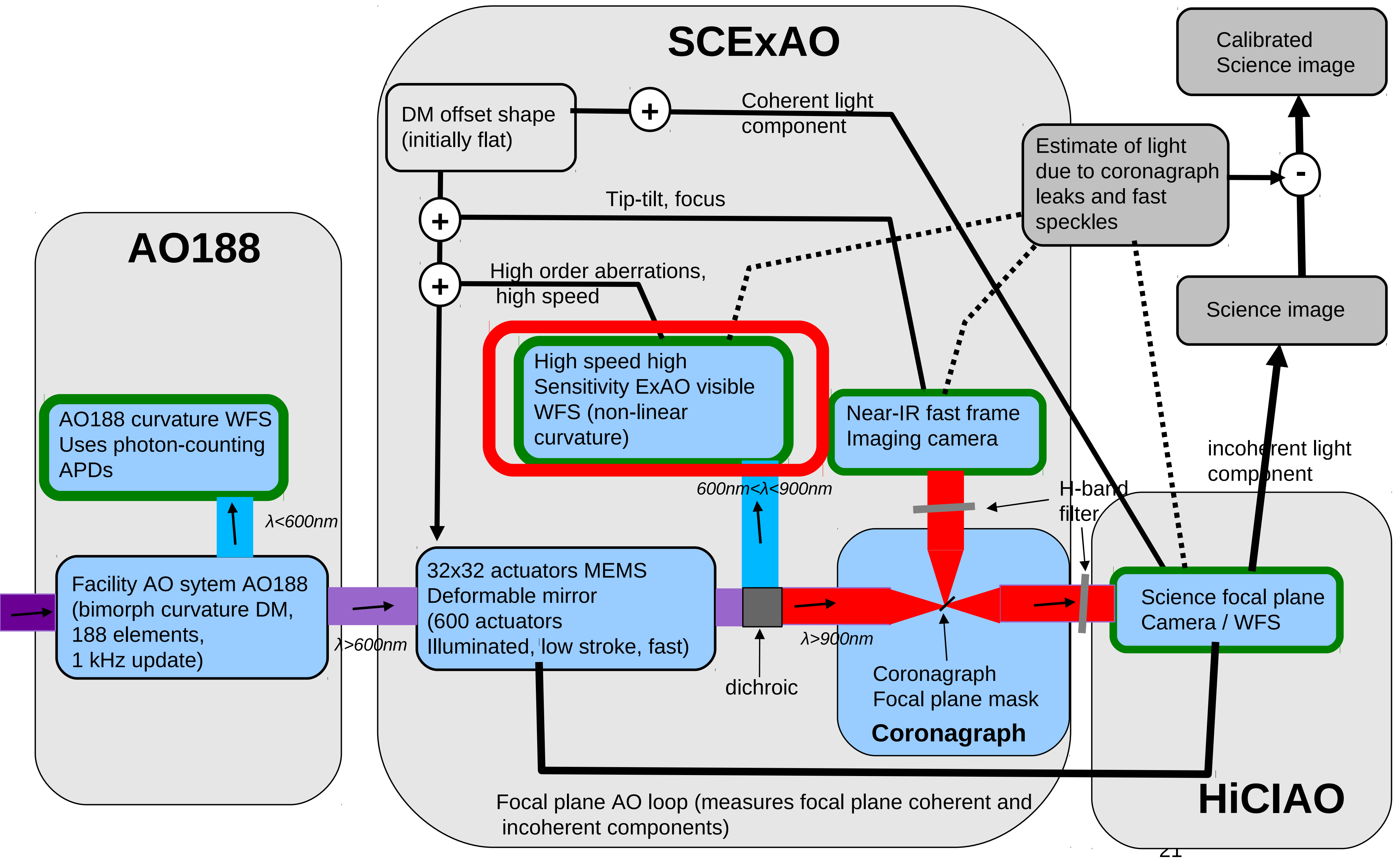
AO188 Woofer reduces WFE to ~200nm
AO188 is stand alone: no communication with SCExAO



AO188 system at the Nasmyth focus



SCExAO visible high speed WFS



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

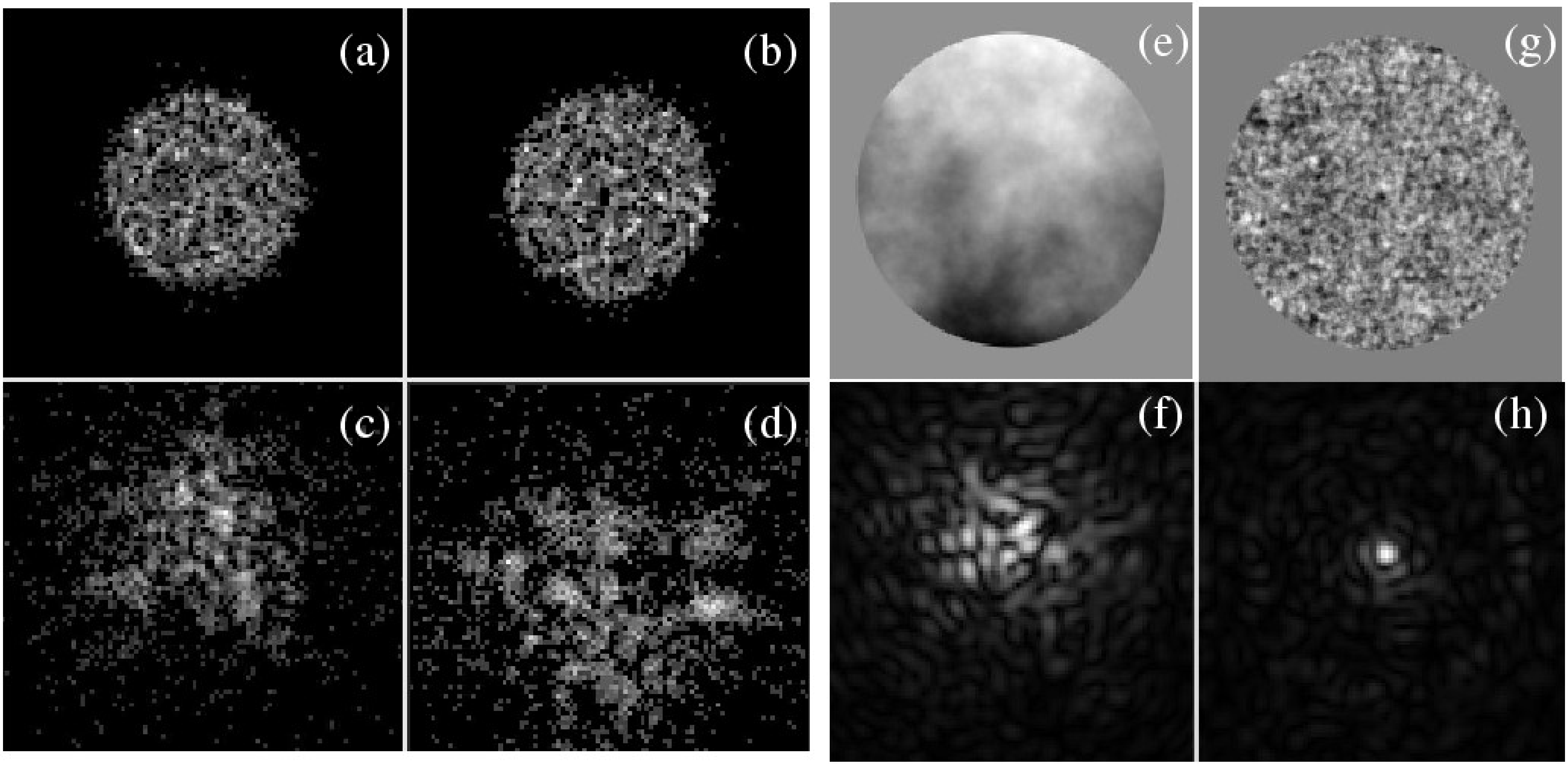
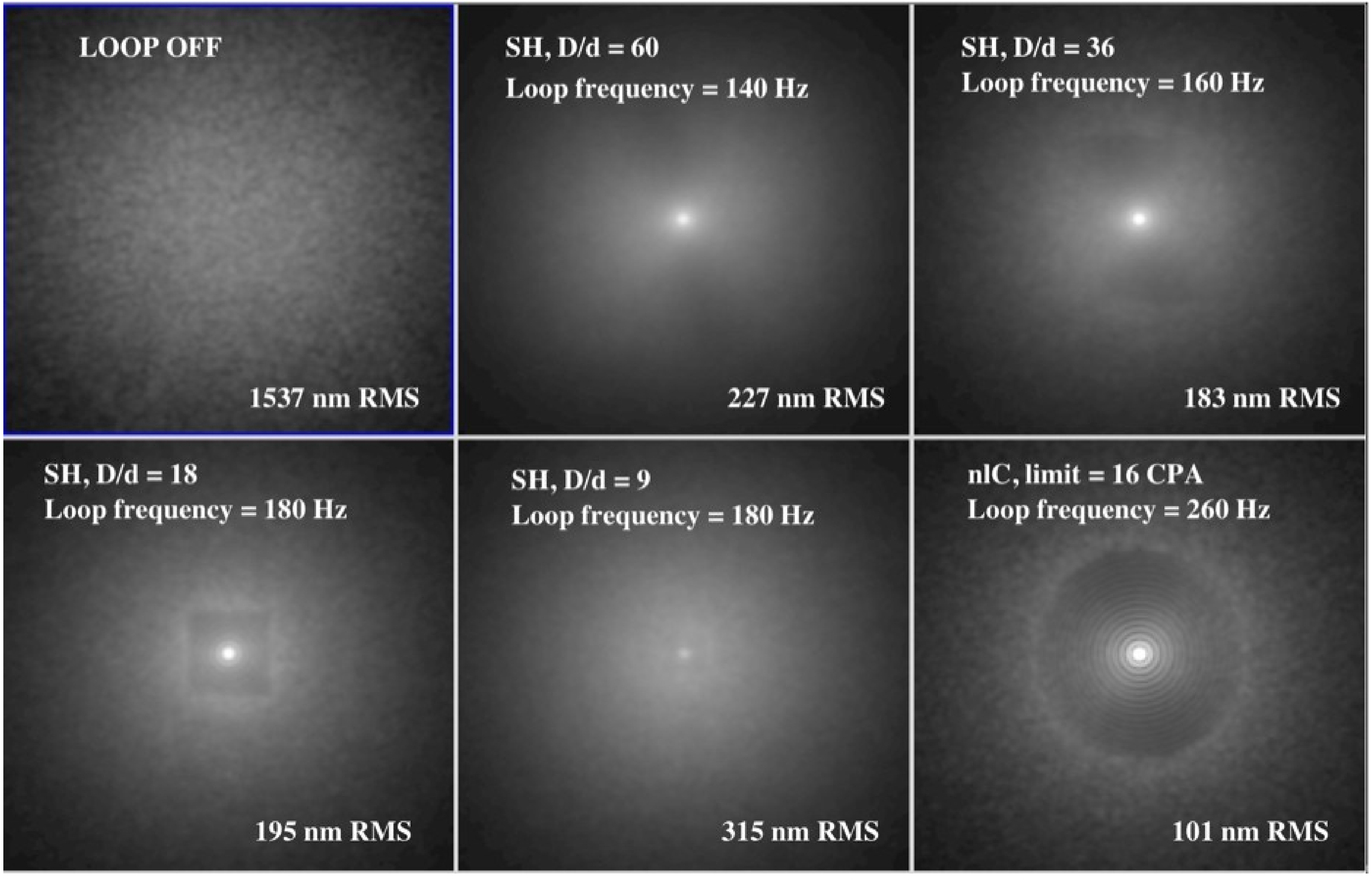


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After 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.

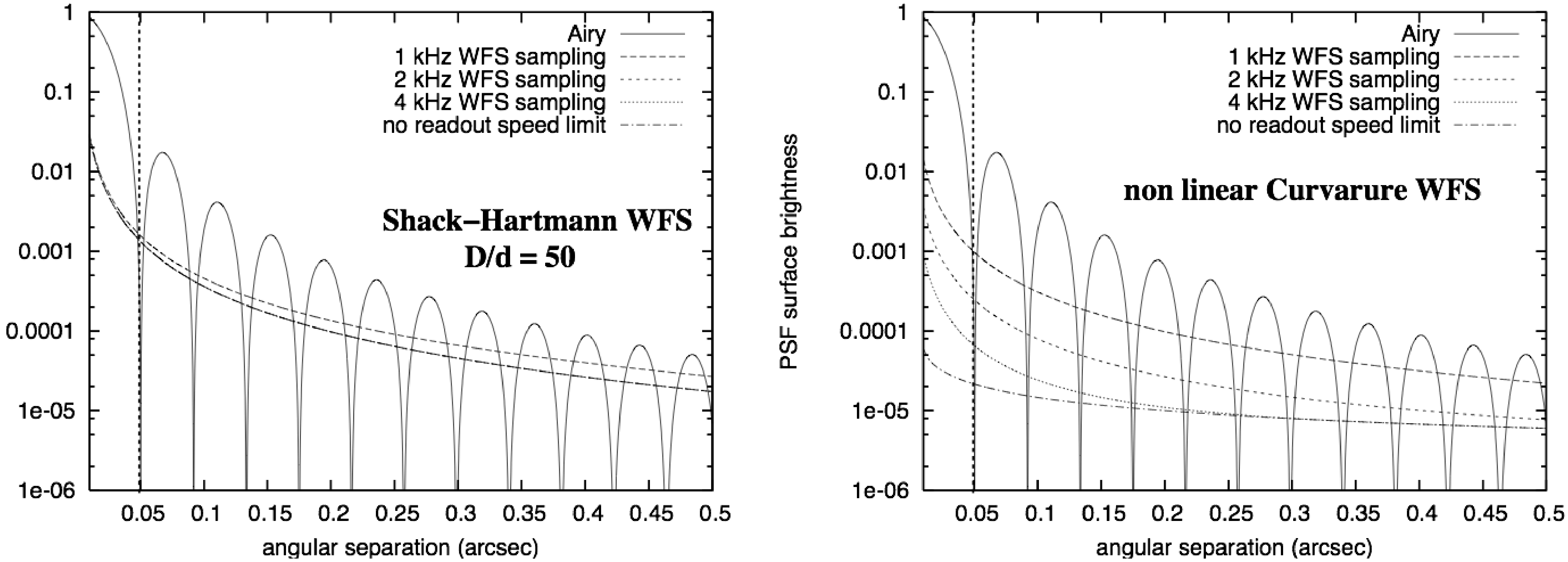
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)



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%
SH - D/60	140 Hz	227 nm	~6%	45%

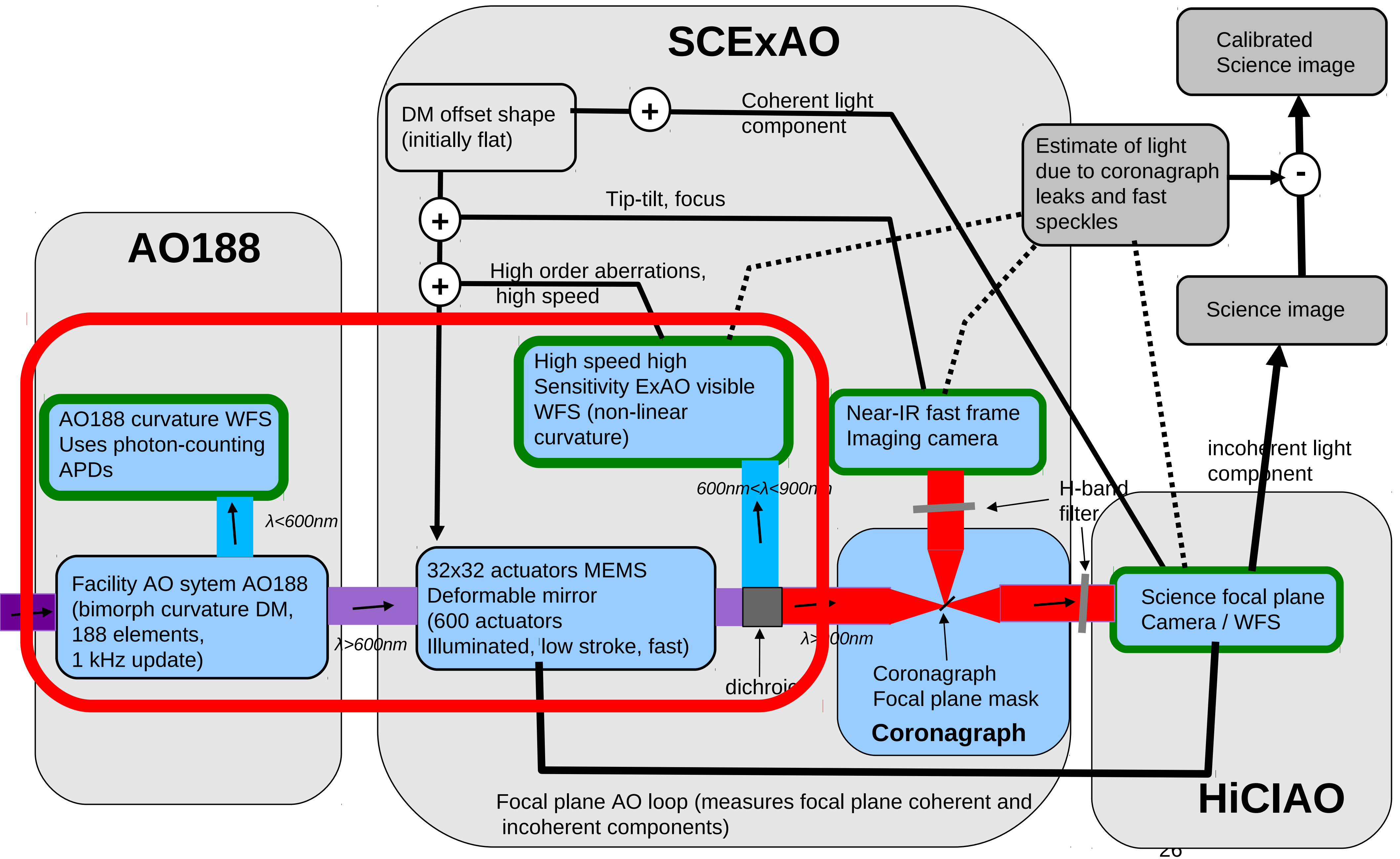
Performance gain for ExAO on 8-m telescopes



"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

SCExAO visible correction: woofer/tweeter
Optimal use of all visible light



Visible vs near-IR WFS

Visible is best for high speed high sensitivity WFS

- detectors are fast and cheap (photon counting APDs, EMCCD)
- optical gain is large: 1 nm is a larger phase in VIS than nearIR

→ SCExAO uses visible photons for fast WF sensing

Visible and near-IR wavefronts are slightly different

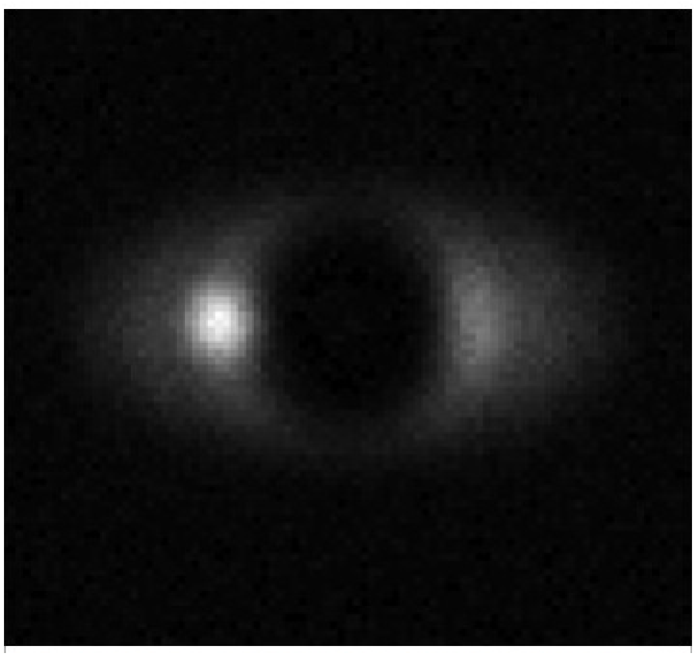
- differential atmospheric refraction (tip-tilt)
- chromatic propagation through atmosphere
- non-common path errors due to optics in SCExAO

→ **near-IR WF sensing and correction is required**

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

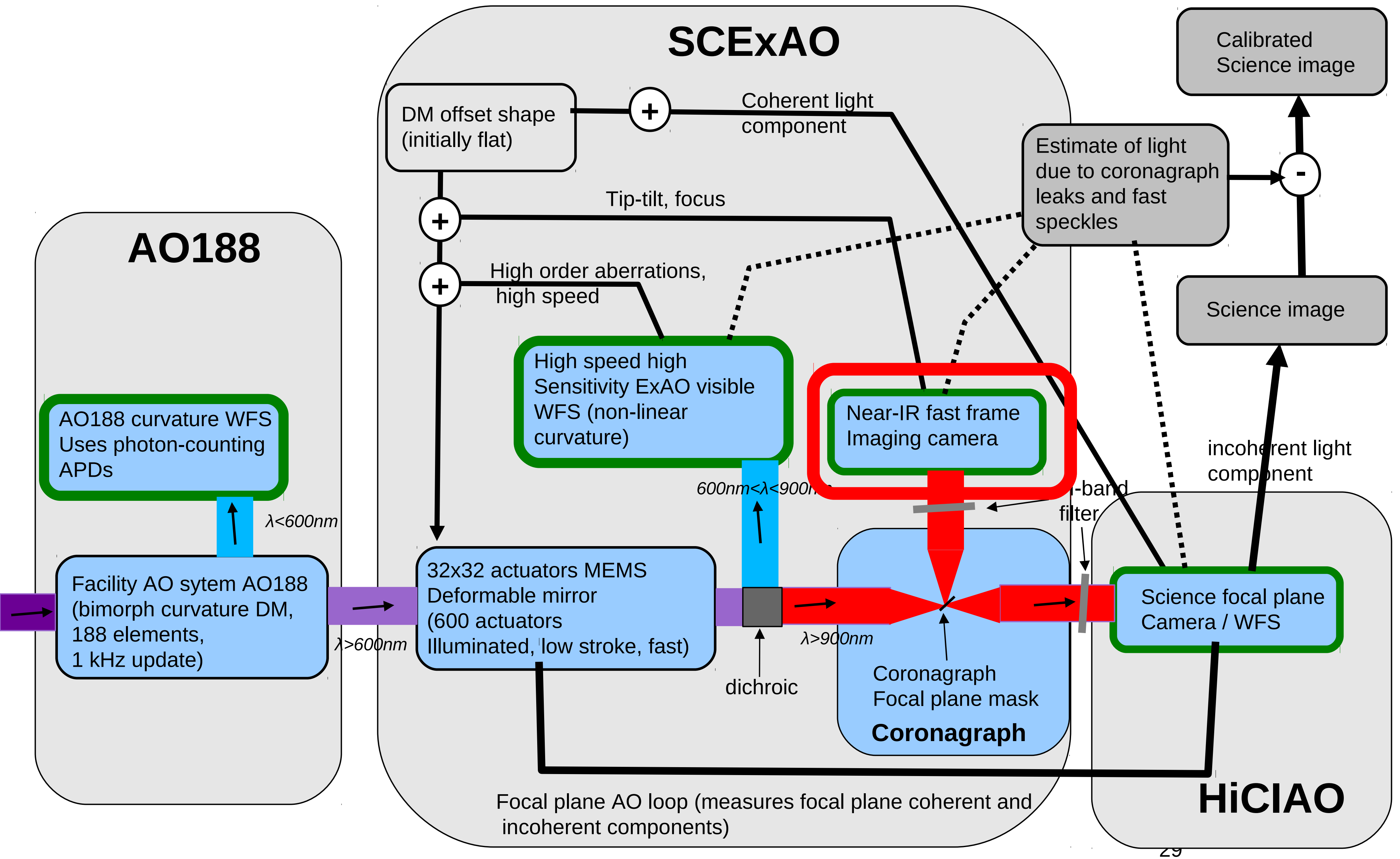
Pointing errors should be detected before they become large enough to induce a strong leak in the coronagraph

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

SCExAO Low Order WFS



Coronagraphic LOWFS

(Guyon et al. 2010)

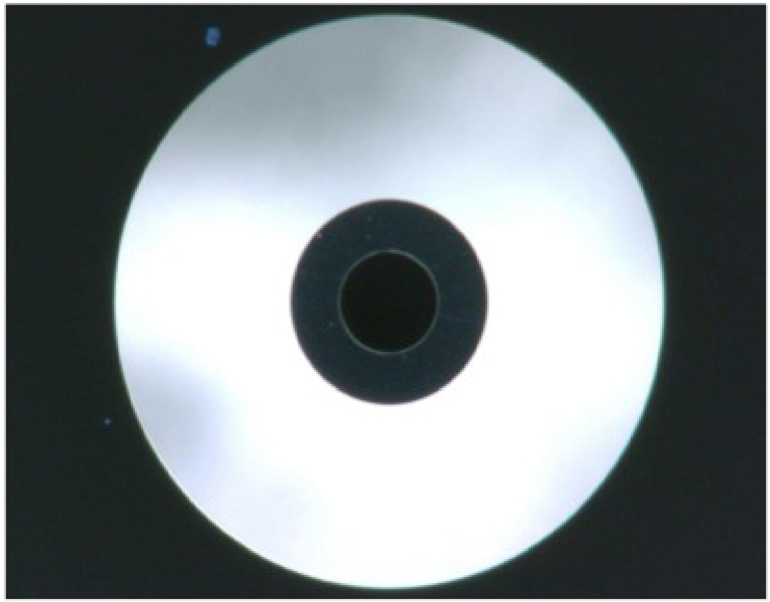
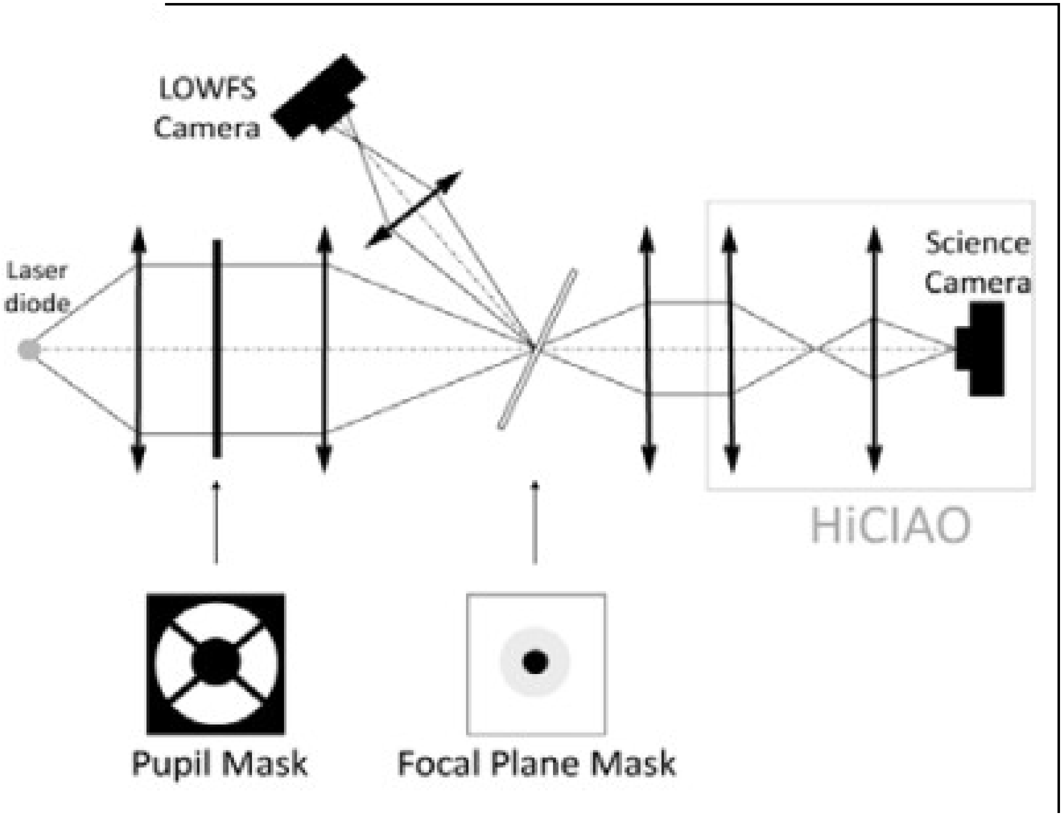
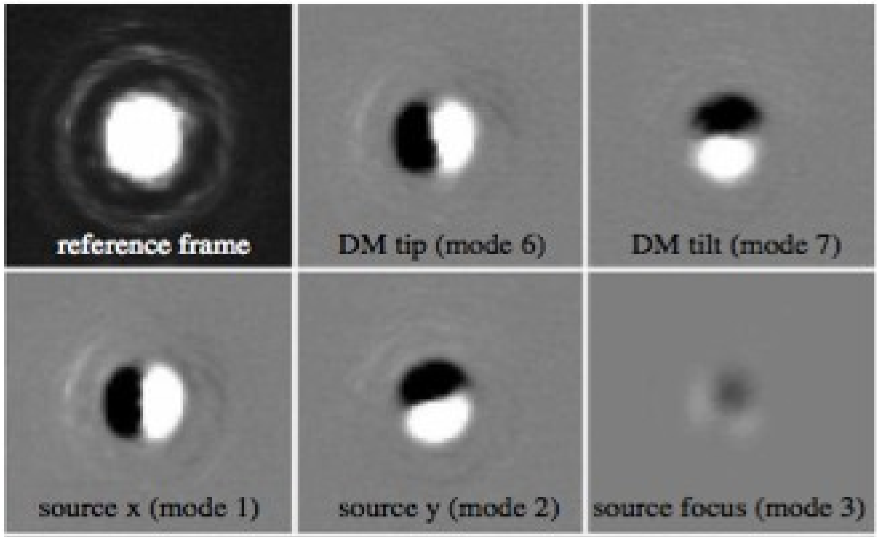
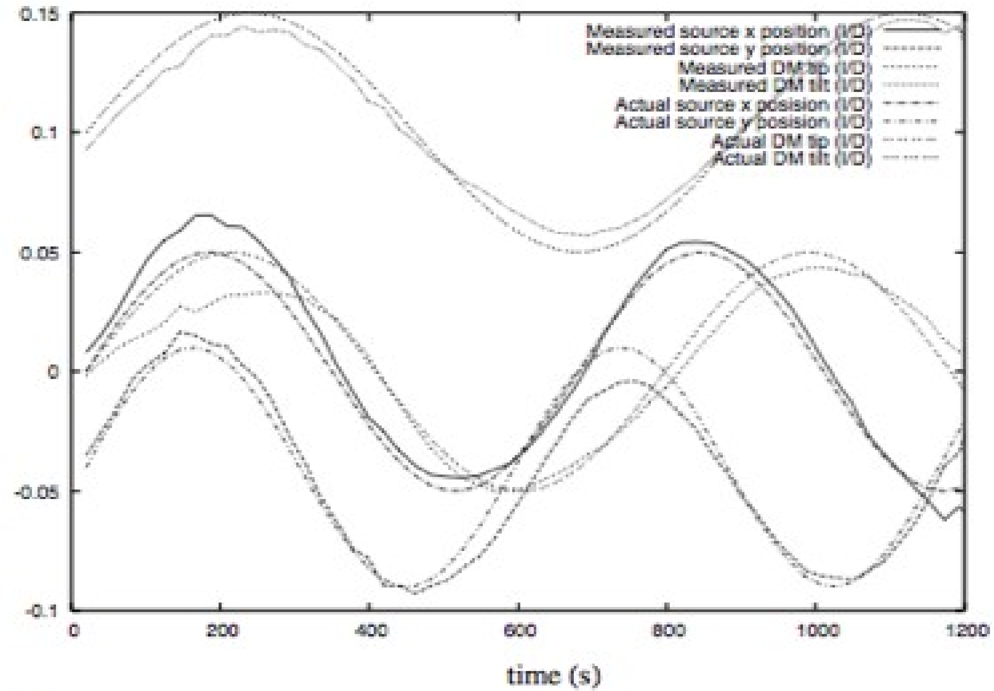


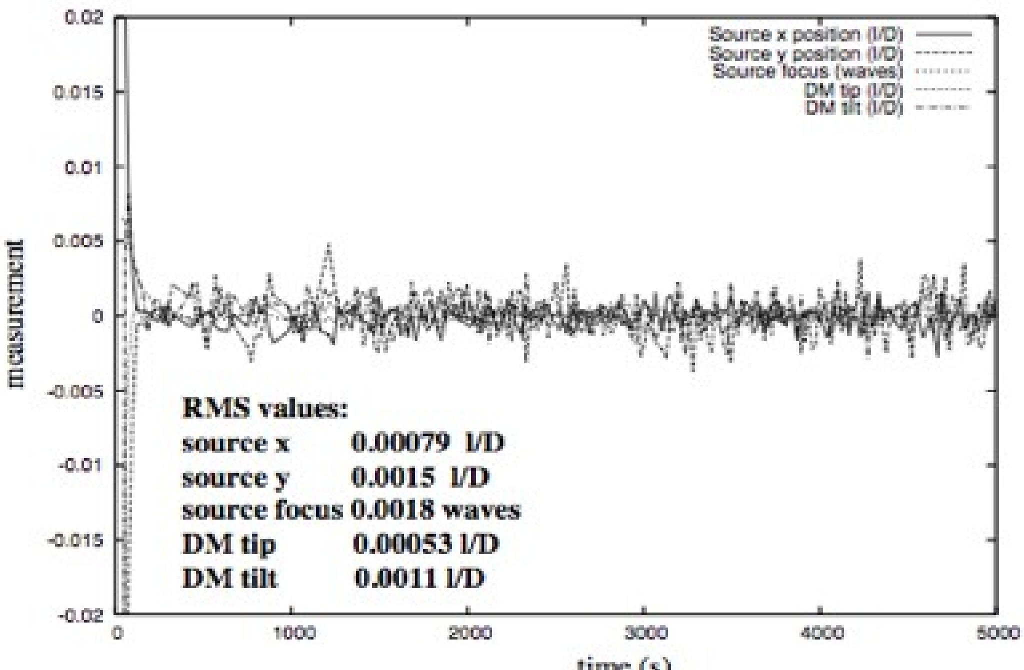
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

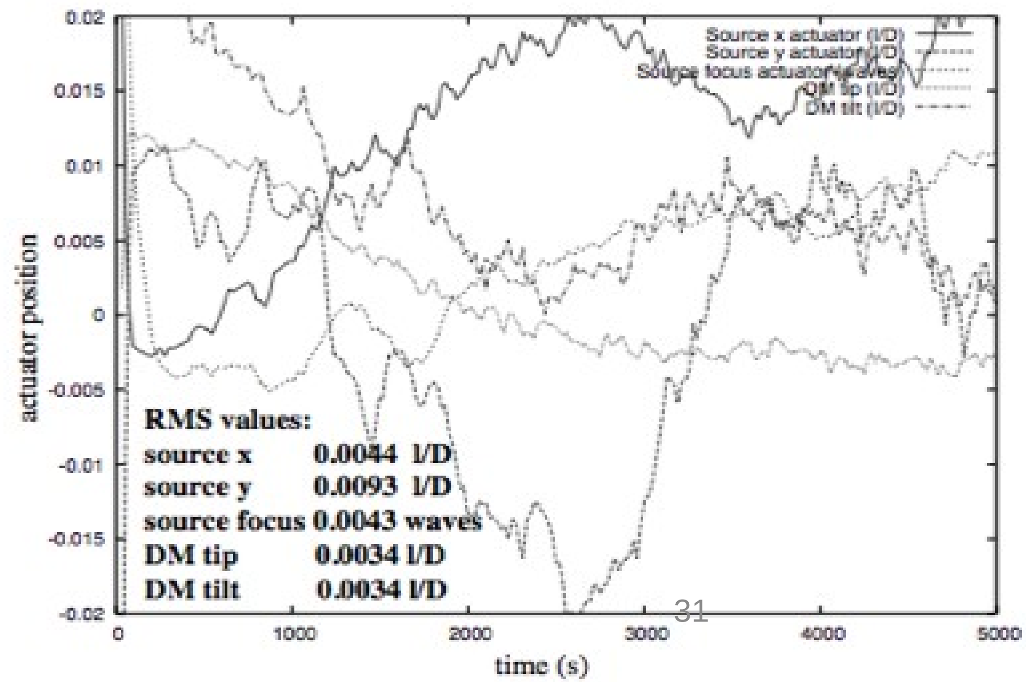


Pointing control demonstrated to 1e-3 λ/D in visible (this would be 0.02 mas on Subaru !!)

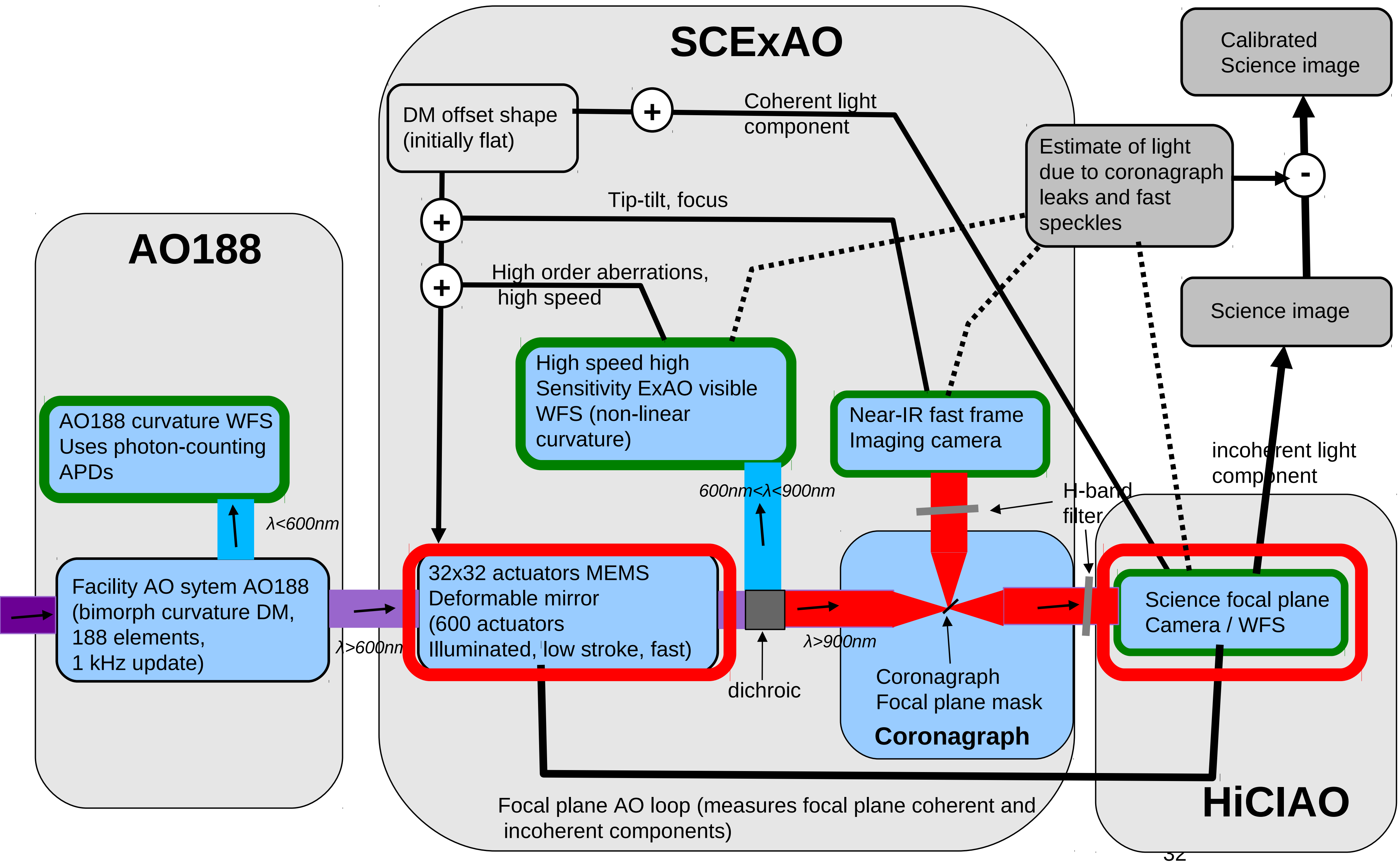




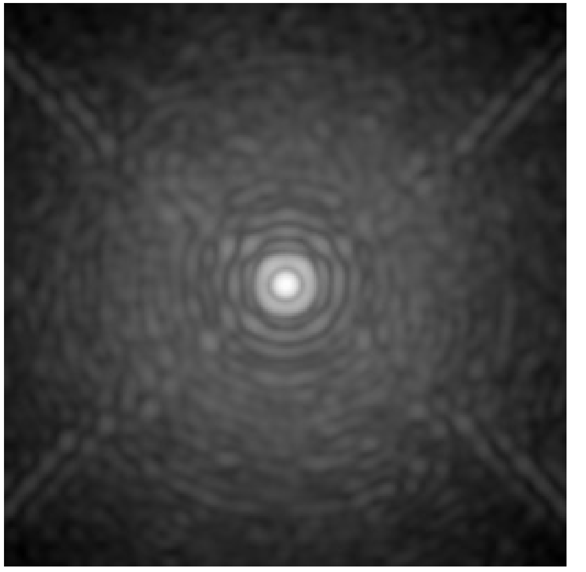




SCExAO focal plane WFS



Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

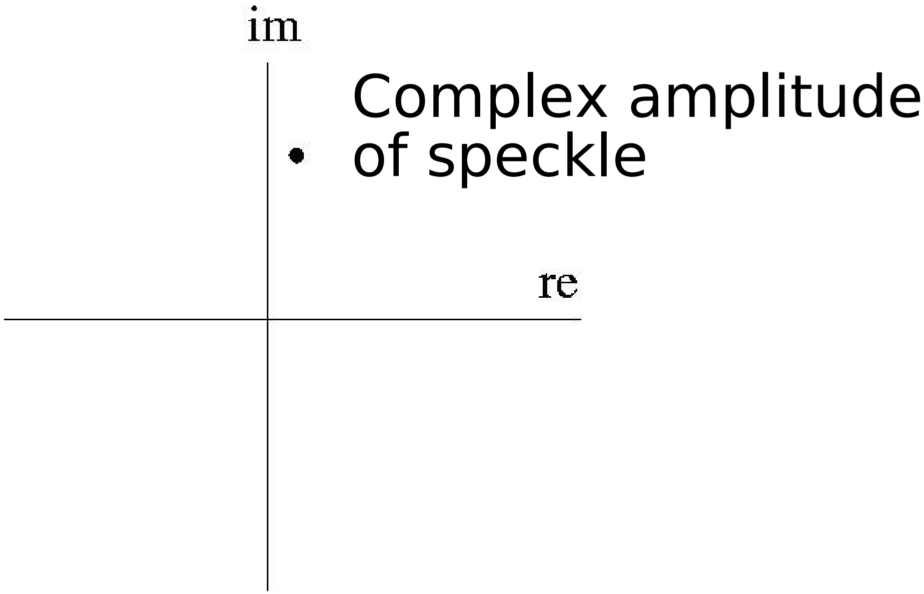
<u>SENSING</u>: Put "test speckles" to measure speckles in the image, watch how they interfere

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

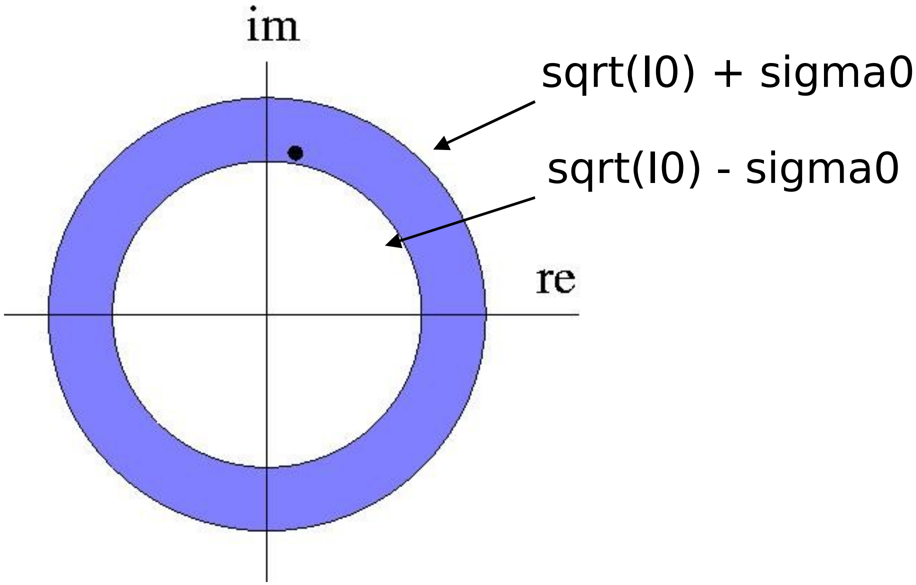
<u>CALIBRATION</u>: If there is a real planet (and not a speckle) it will not interfere with the test speckles

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

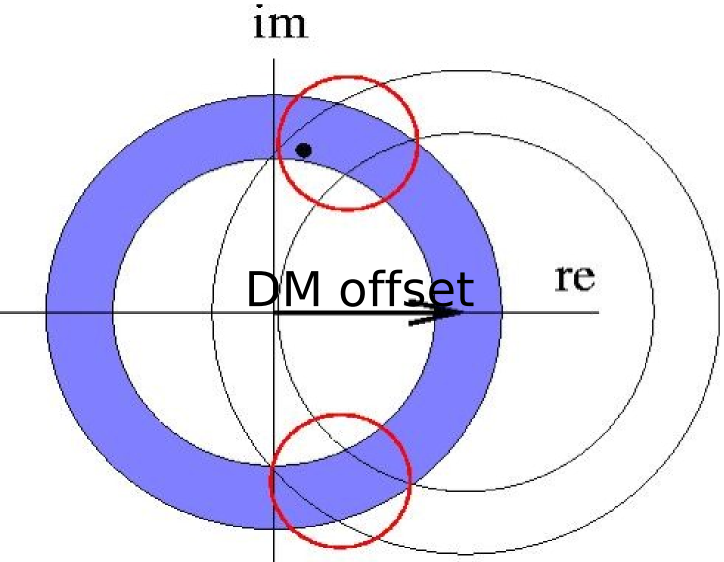
Initial problem

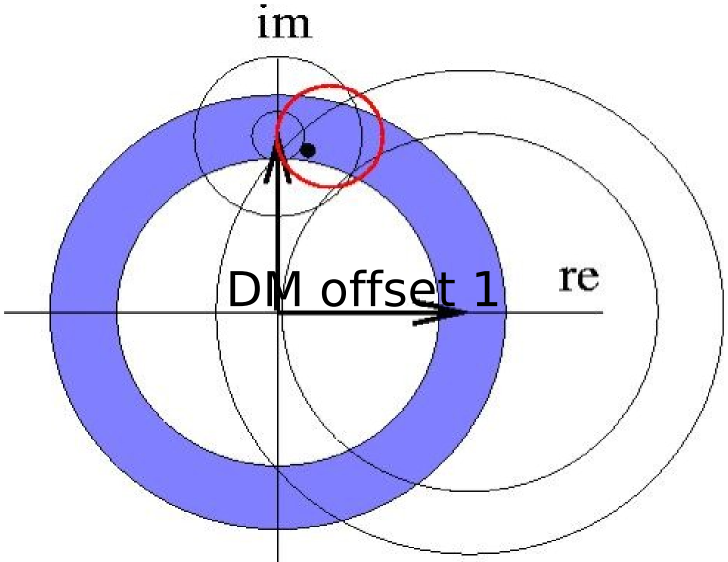


Take a frame -> measured speckle intensity = I0

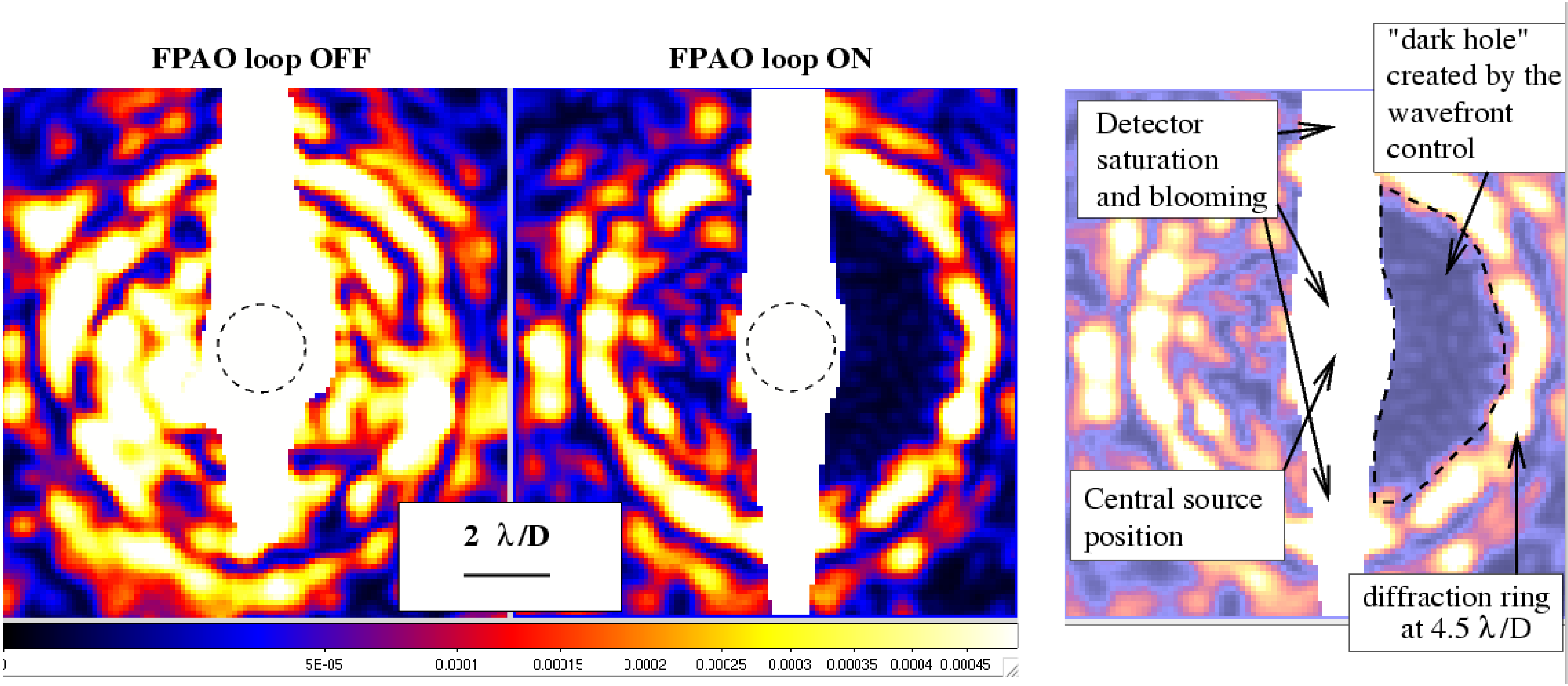


DM offset chosen to be ~ equal to speckle amplitude





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.

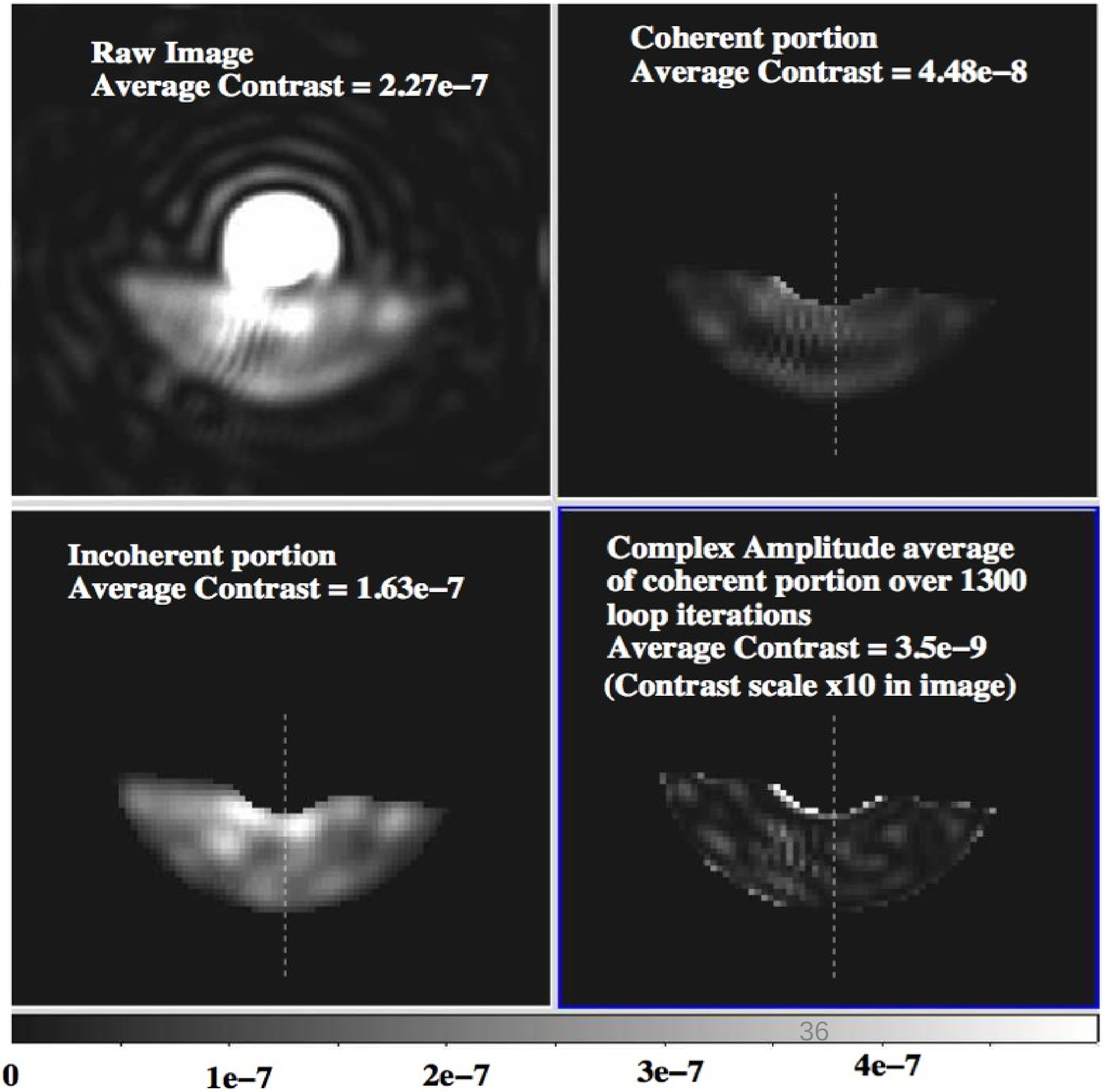
- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics

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



Focal plane WFS based correction and speckle calibration

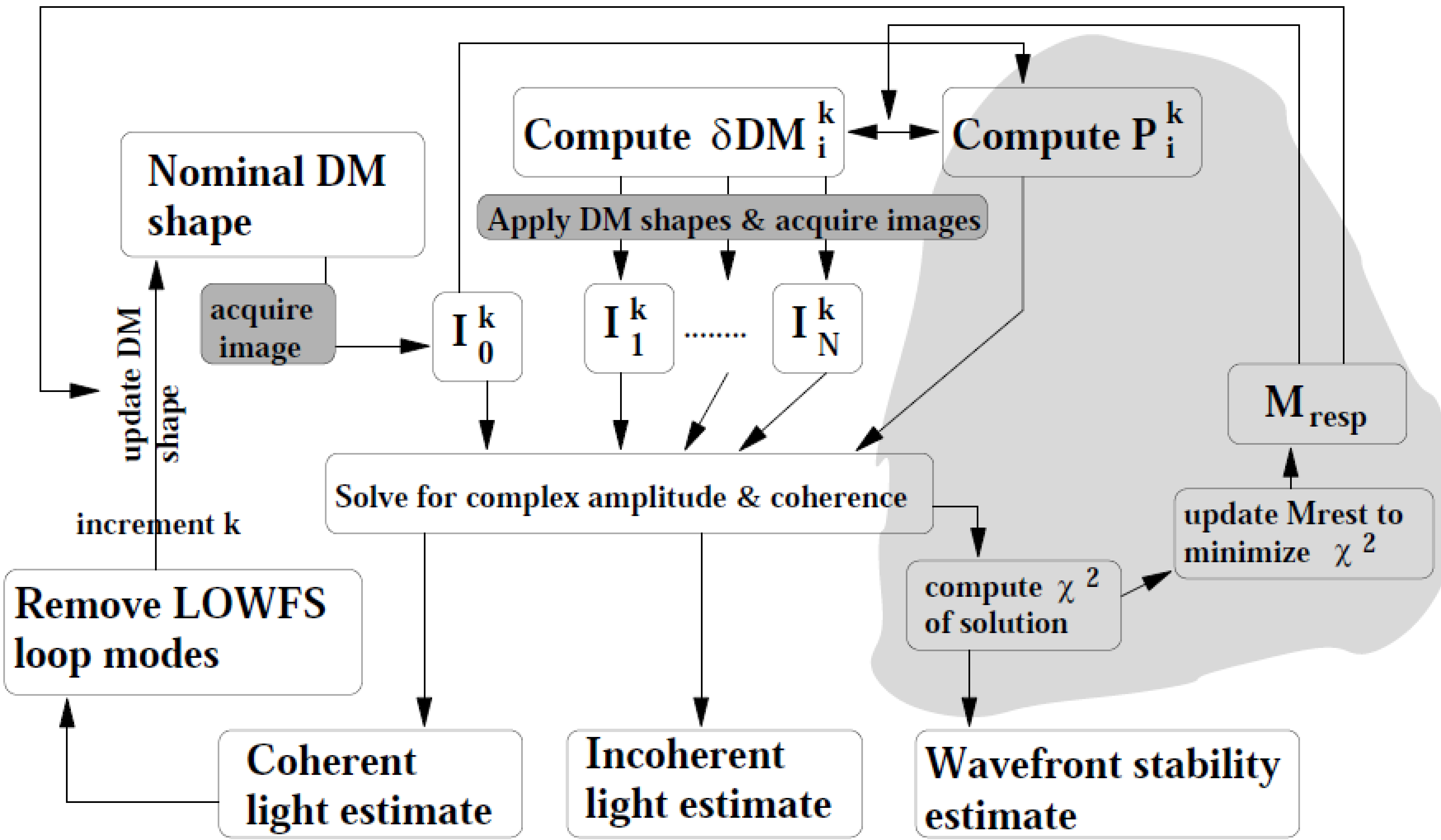
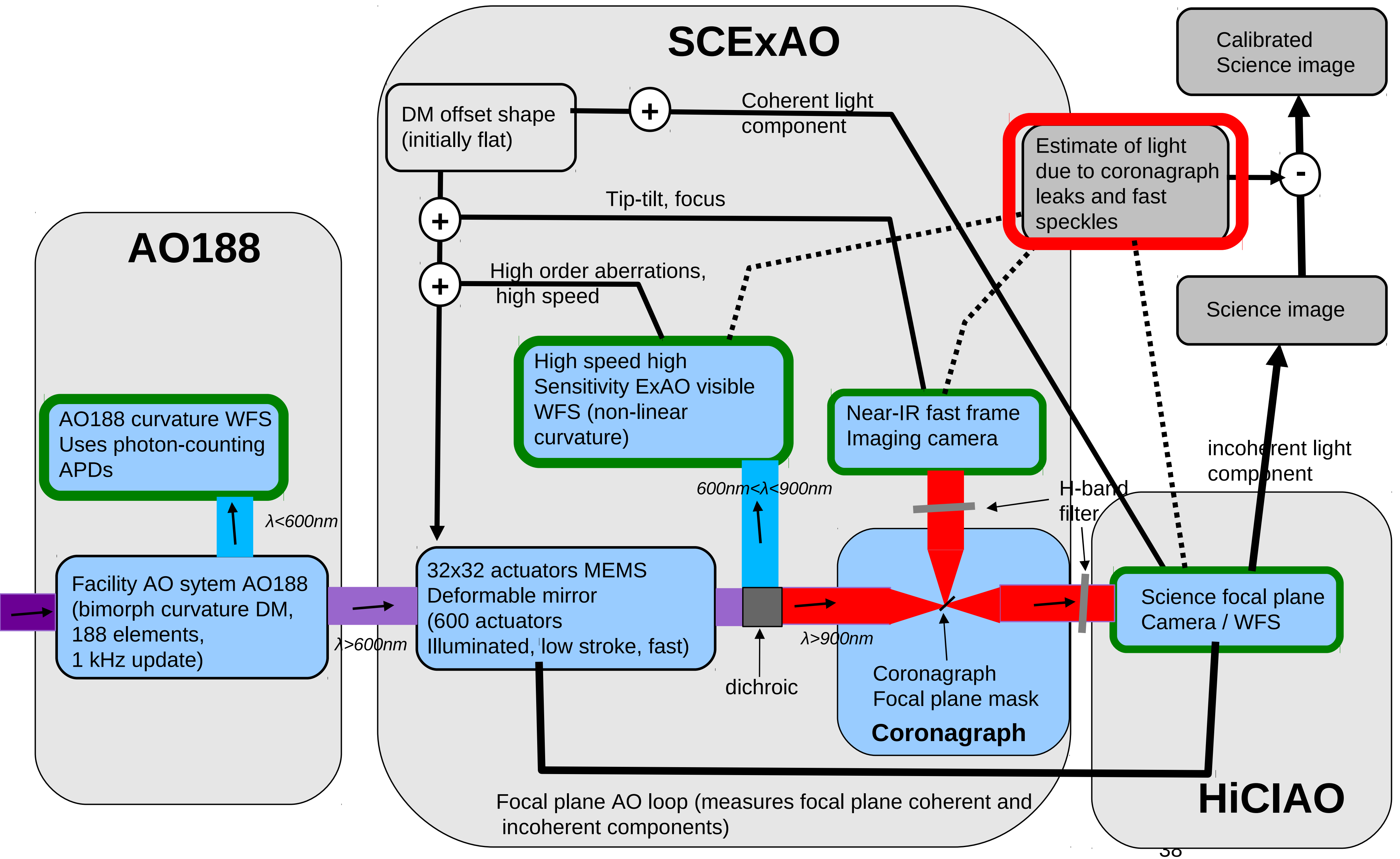


Fig. 8.— High order wavefront control loop, showing both the main loop and the system response matrix optimization loop (light shaded area). The two dark shaded boxes indicate image acquisition, which in the simulation mode, can be replaced with a simulated image acquisition using a model of the experiment and DM response.

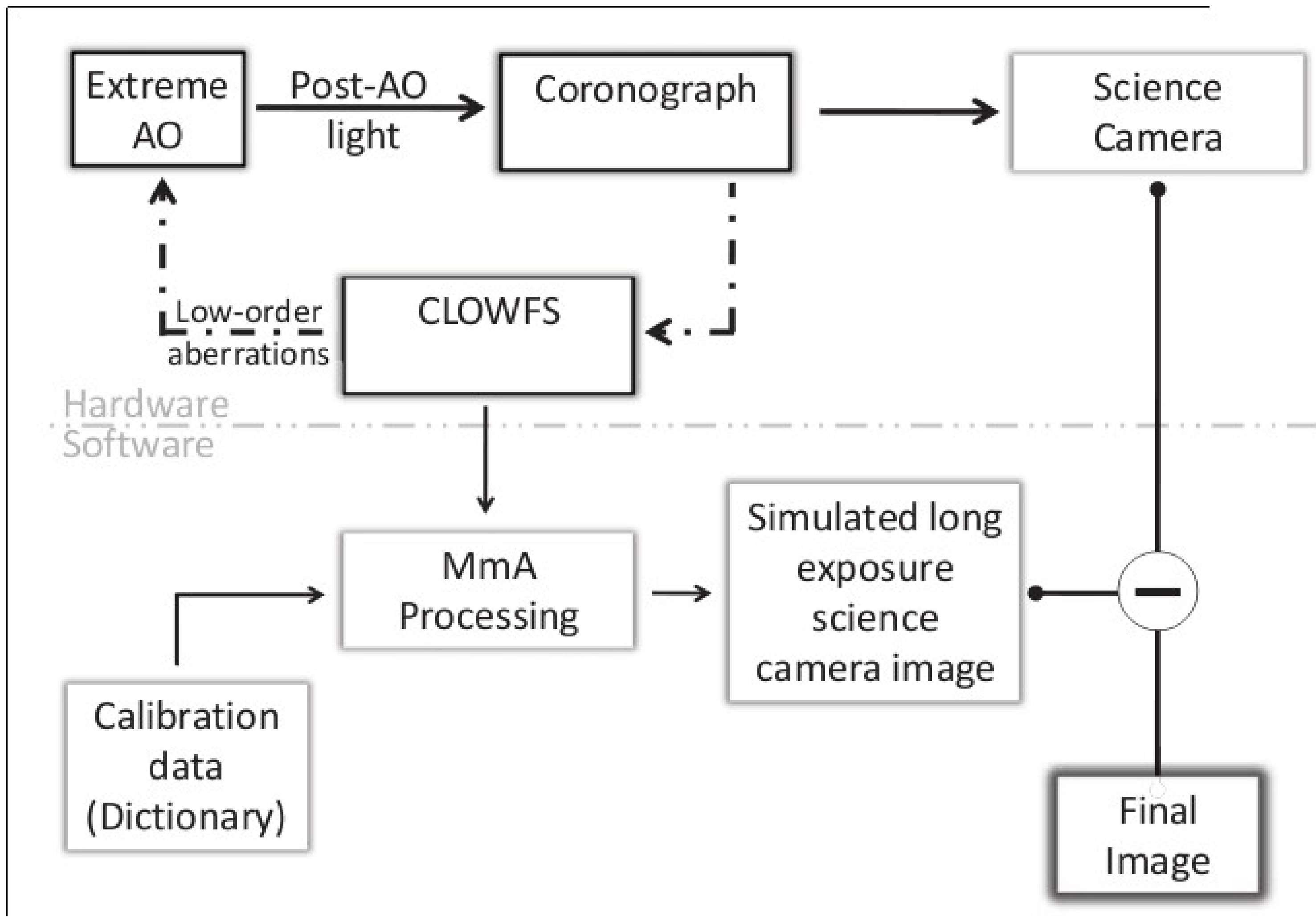
SCExAO residual light calibration



LOWFS post-processing: Principle

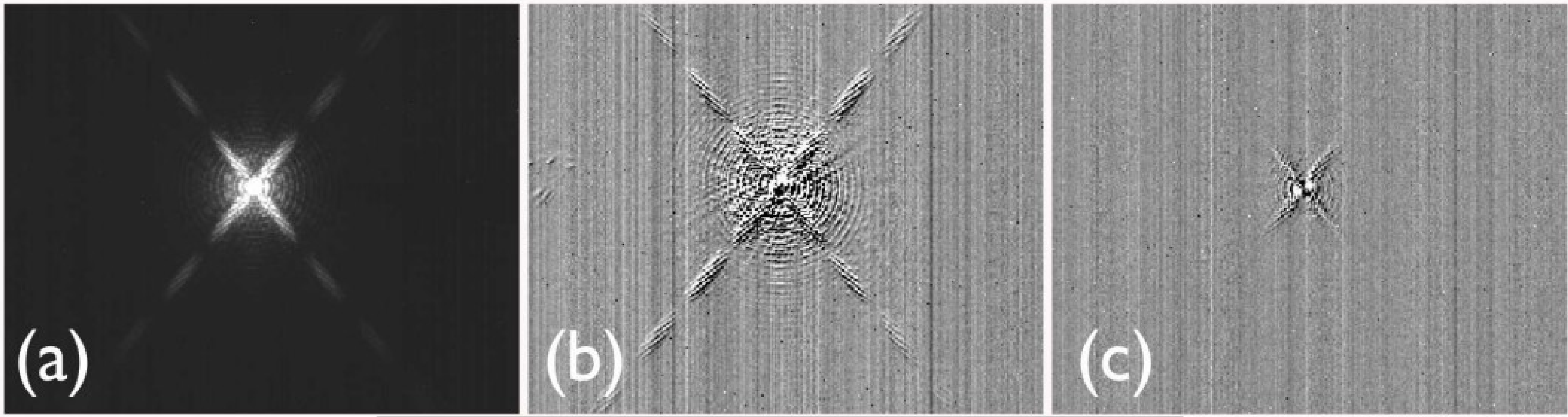
Use LOWFS data to estimate coronagraphic leaks in science image, and subtract them in post-processing
Challenge: how to model / link CLOWFS data with coronagraph leaks ?

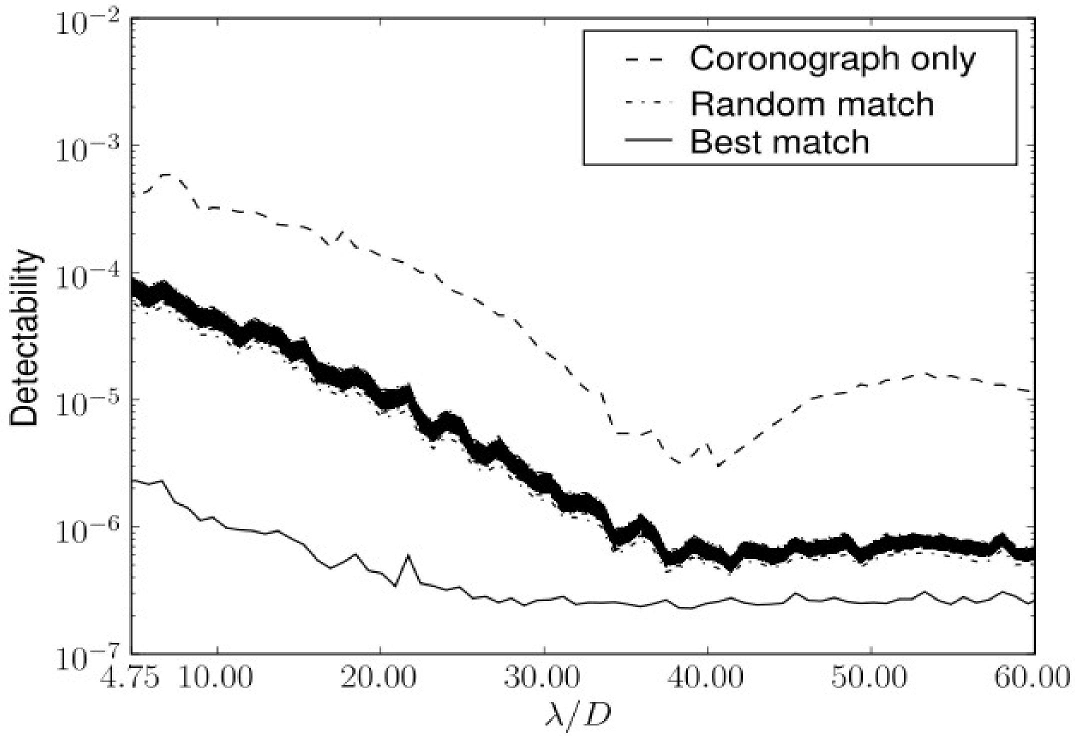
Solution:
Acquire and use a dictionary which stores the correspondance between LOWFS and science images



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

Co-added science image | Standard PSF subtraction | MMA





PSF calibration strategies

- **“classical” PSF subtraction**
- **Angular Differential Imaging**
  - works well at large angular separations, where aberrations have large static component
  - poor performance close in to the star
- **Spectral / Polarimetric differential imaging**
  - works great IF source has expected spectral signature or is polarized
- **Coherent differential imaging**
  - highly flexible, does not make any assumption about source
  - combined wavefront sensing / PSF calibration
  - works within control radius of DM

What sets the contrast limit ?

- **Purely random atmospheric speckles average with time**
  - AO correction removes slow atmospheric speckles, leaving fast component that averages down into a smooth halo fairly rapidly
- **Static and slow speckles are removed (or greatly attenuated) by focal plane WFC loop**
  - by design, there is **NO NON COMMON PATH ERROR**
  - coherence time of residual slow speckles is approximately equal to the focal plane WFC loop bandwidth → strong incentive to make focal plane WFC loop as fast and efficient as possible
- **Fast speckles (faster than focal plane WFC loop bandwidth) that have slowly varying statistics are not addressed → they set the contrast limit**
  - example: vibration creates a speckle at 2 l/d that varies in complex amplitude on ~ms timescale. As vibration comes and goes, so does the speckle → this speckle will look exactly like a planet !
  - Similar problem can be created by other effects creating loss in coherence (polarization, spectral effects)

Fundamental problem : wavefront cannot be accurately described by static/slowly varying term + fast zero-mean term with constant statistical properties

SCExAO schedule

SCExAO is currently in engineering, for phase 1

1st nighttime engineering Feb 2011 (2 nights): demonstrated coupling with AO188 system + basic functions (no science IR camera – using internal SCExAO video IR camera)

2nd nighttime engineering Sep 2011 (1 night): PIAA coronagraph, on-sky wavefront control: LOWFS, coupling with HiCIAO

May-June 2012: daytime engineering (2 weeks) to test and validate focal plane wavefront control + LOWFS

3rd nighttime engineering summer/early fall 2012 (1 night ?): on-sky wavefront control (focal plane WFC + LOWFS)+ HiCIAO

→ start of science observation with phase 1 system (no fast visible extreme AO WFS)

Phase 2: integrate ExAO visible WFS

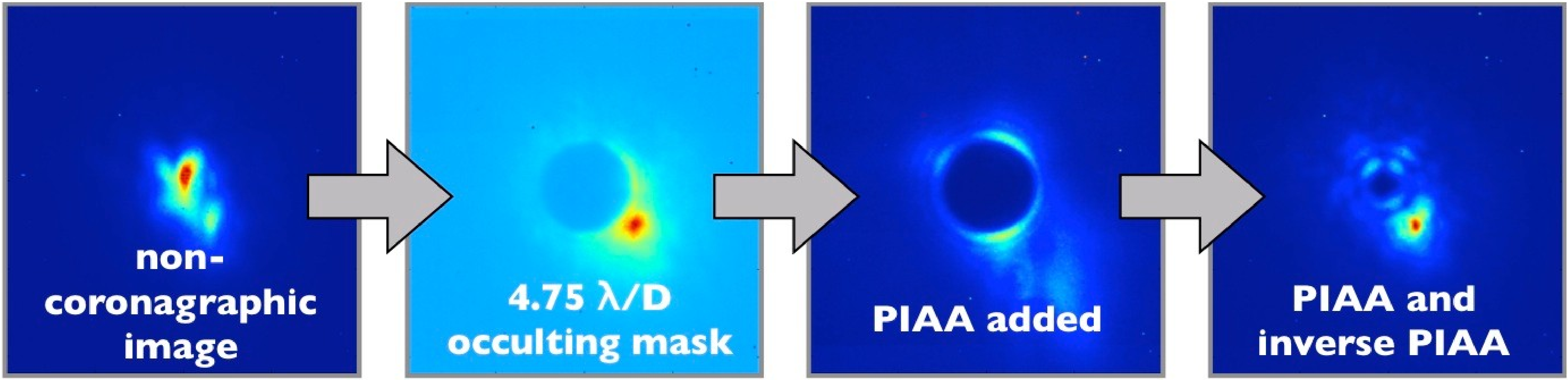
SCExAO Results

LOWFS validated on sky

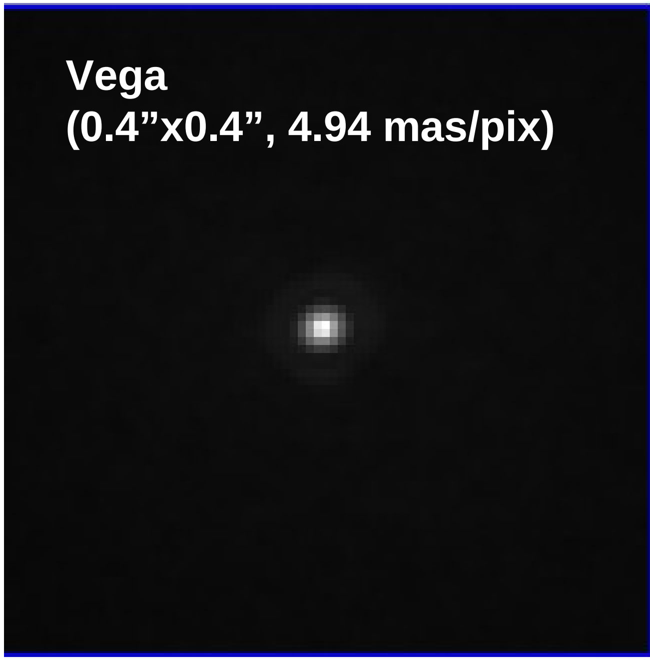
- robust performance at low gain (~0.1) in difficult conditions
- calibration can be time consuming

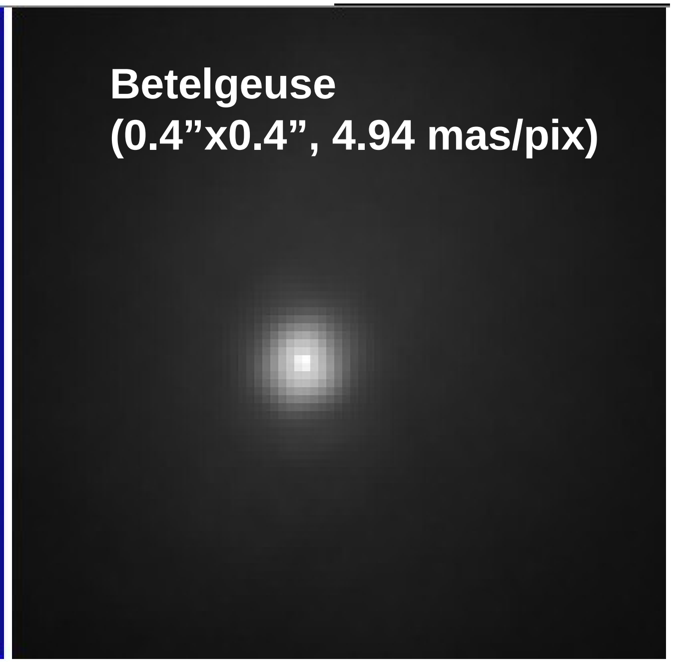
PIAA coronagraphy at 1.2 lambda/D validated

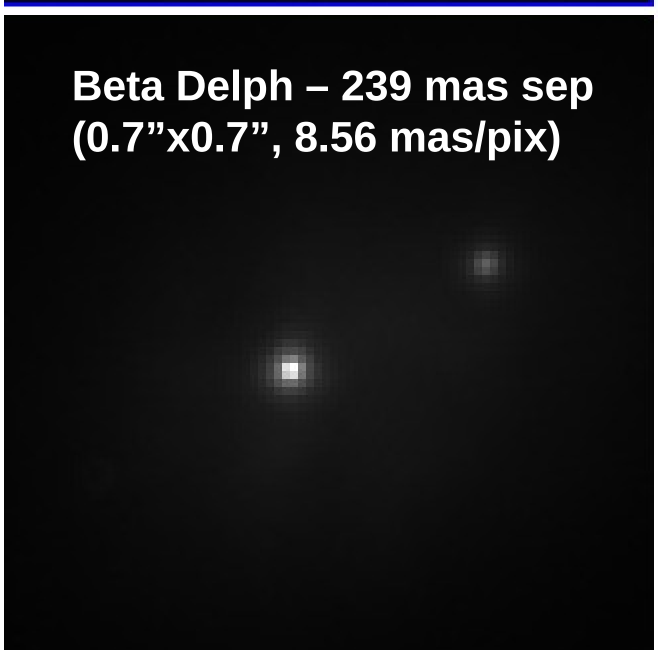
- Inverse PIAA image sharpening validated



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.

Achieving high contrast at 1 lambda/D: challenges & approaches

Coronagraphy

Requires a coronagraph with 1 lambda/D IWA, while maintaining nearly full sensitivity and angular resolution

Wavefront control

Exquisite control of low order aberrations, including tip-tilt

High sensitivity wavefront sensing for low order aberrations

Wavefront control loop should be bias-free (no static or slow speckles)

Calibration

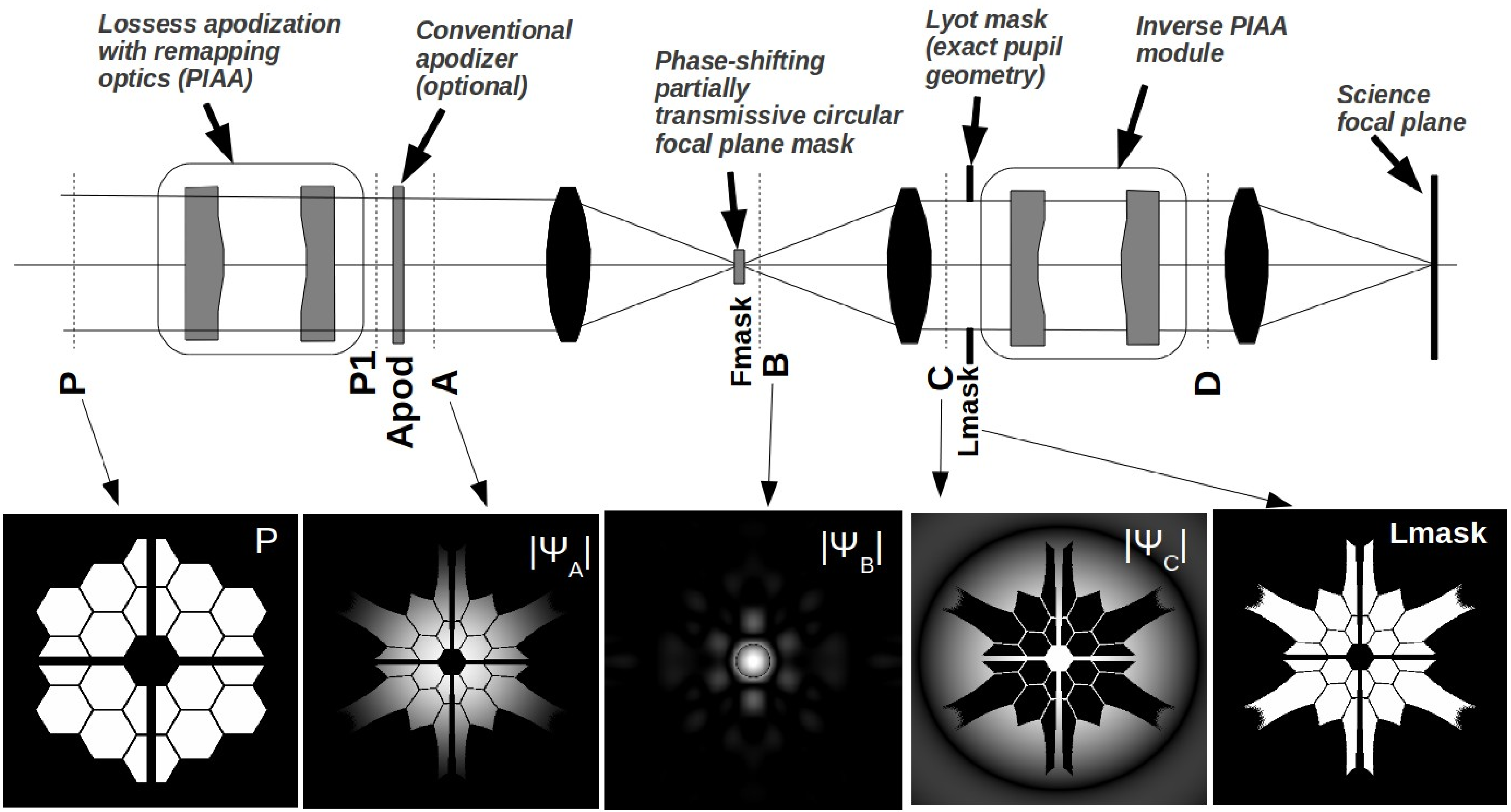
Need robust scheme to separate speckles from planet(s)

SDI, ADI will not work at 1 lambda/D

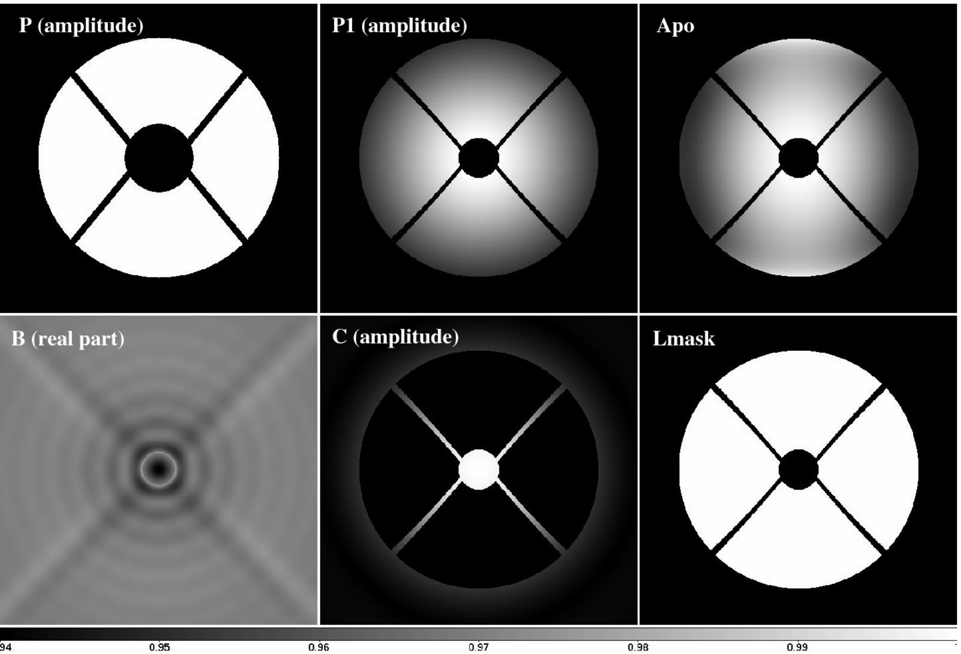
→ Solutions to these problems have been developed in the last ~10 yrs in several labs
Some of these techniques are part of the SCExAO instrument on Subaru, which is a precursor to an ELT ExAO system

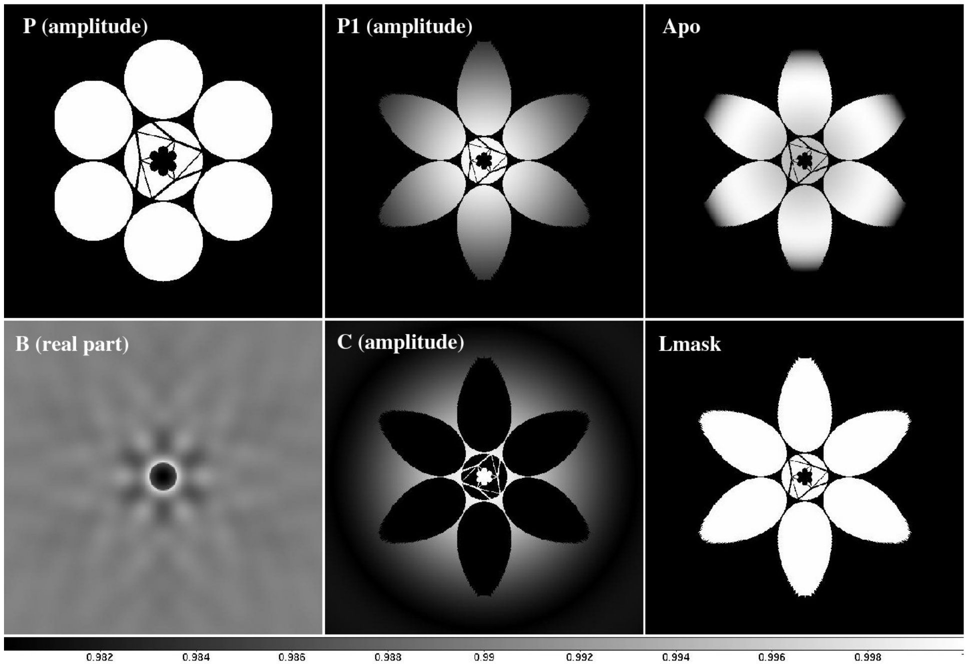
Is coronagraphy at < 1 lambda/D possible on ELTs ?

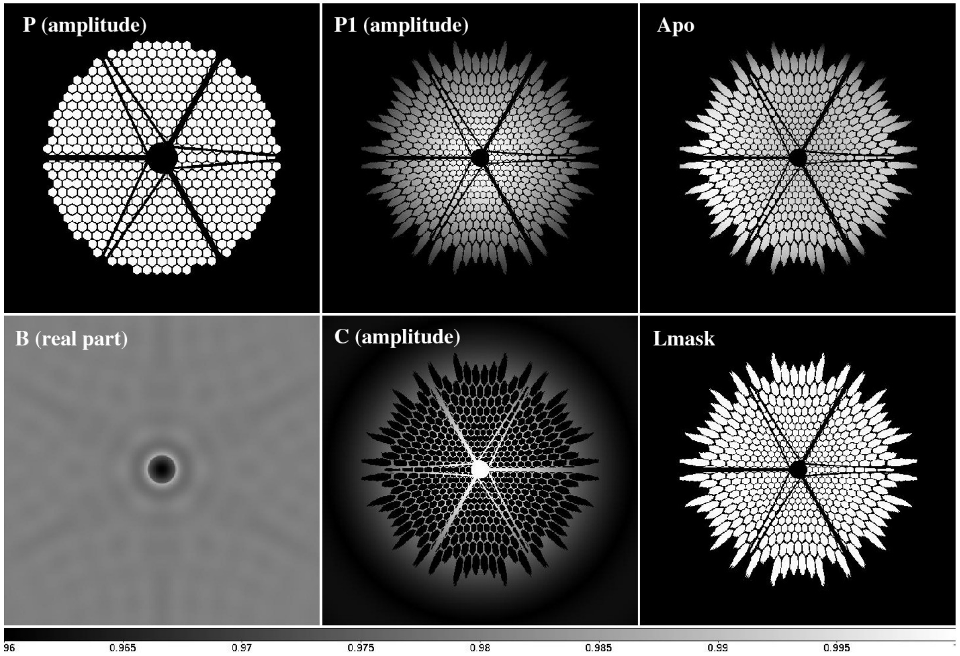
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

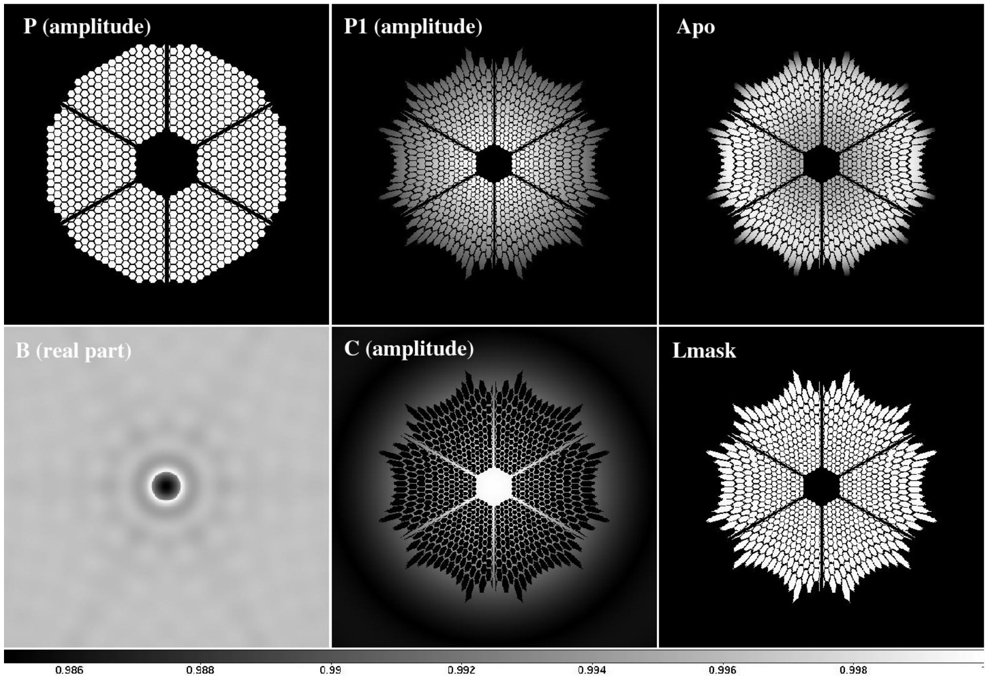


PIAACMC performance on various pupils

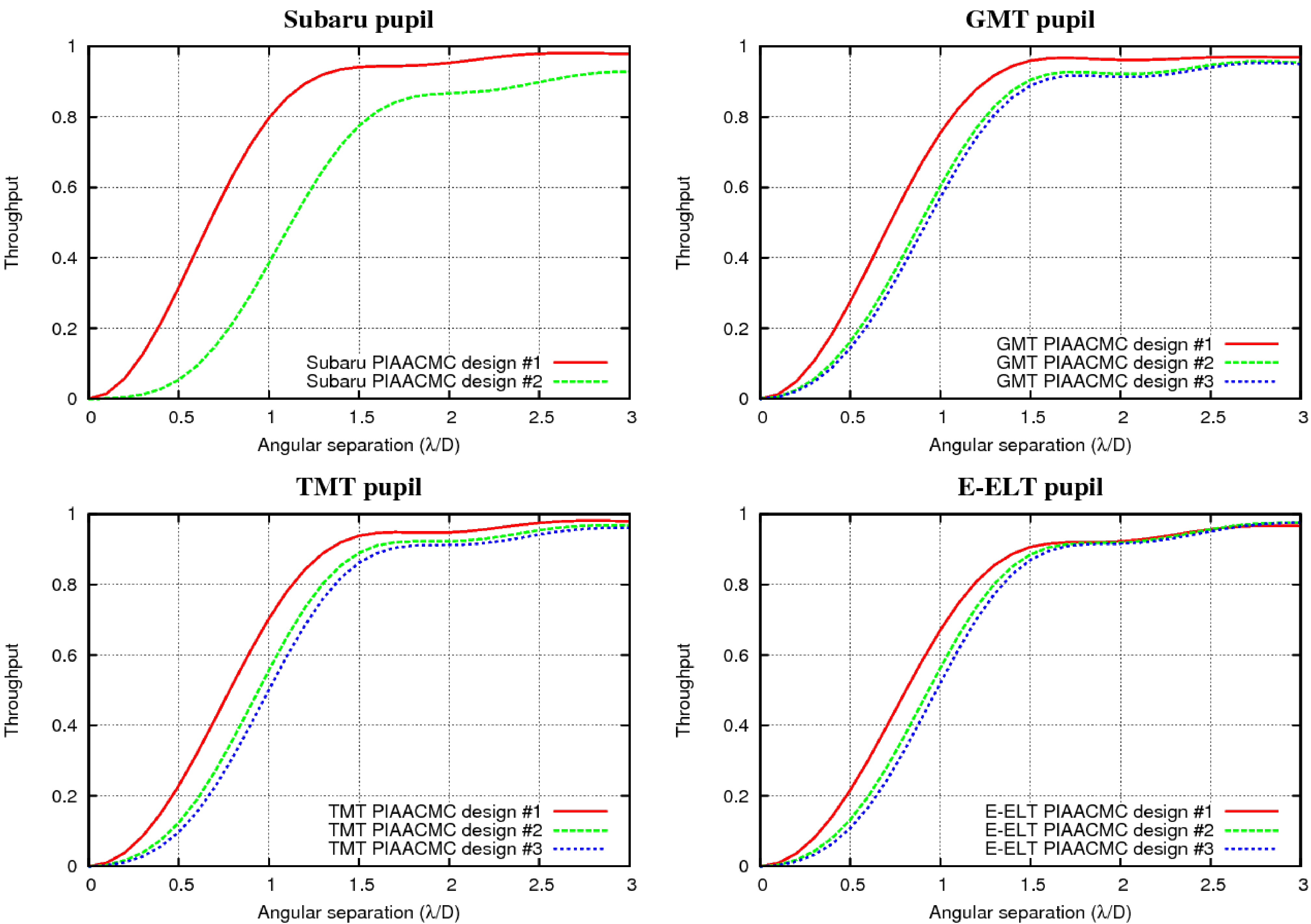








PIAACMC performance on various pupils



Science goals

ExAO instrument on ELT timescale for science return ~ 2030

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 ?)

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

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

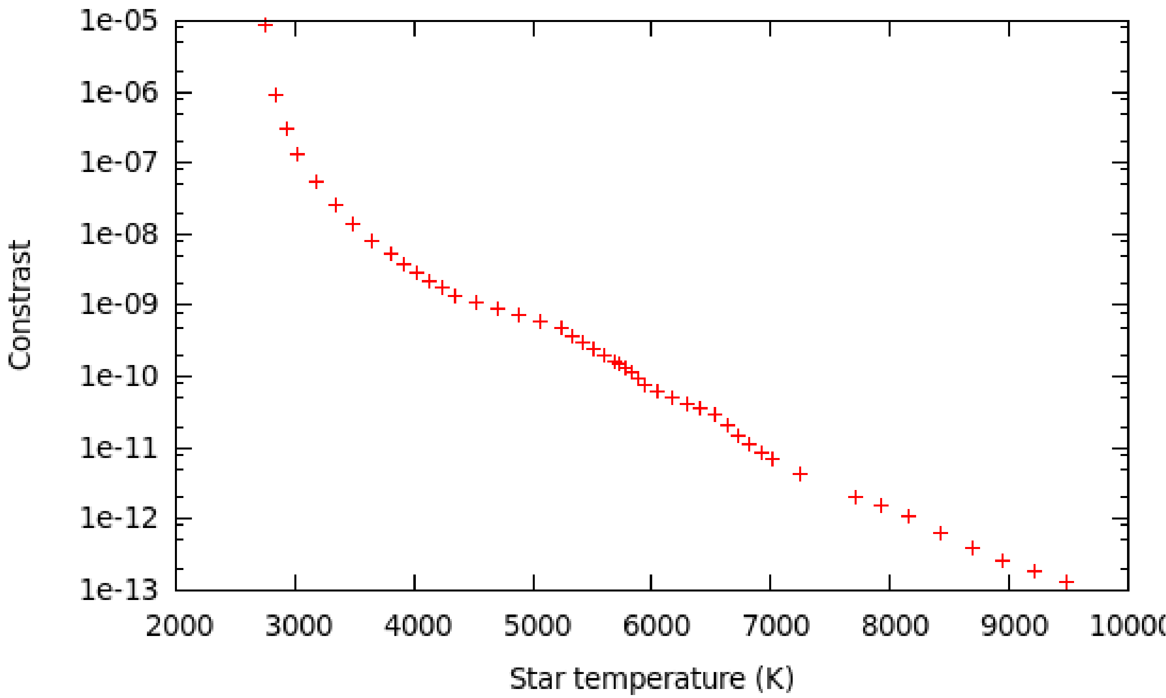
Reflected light imaging
Science vs instrument performance

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

Reflected light imaging: Contrast vs separation



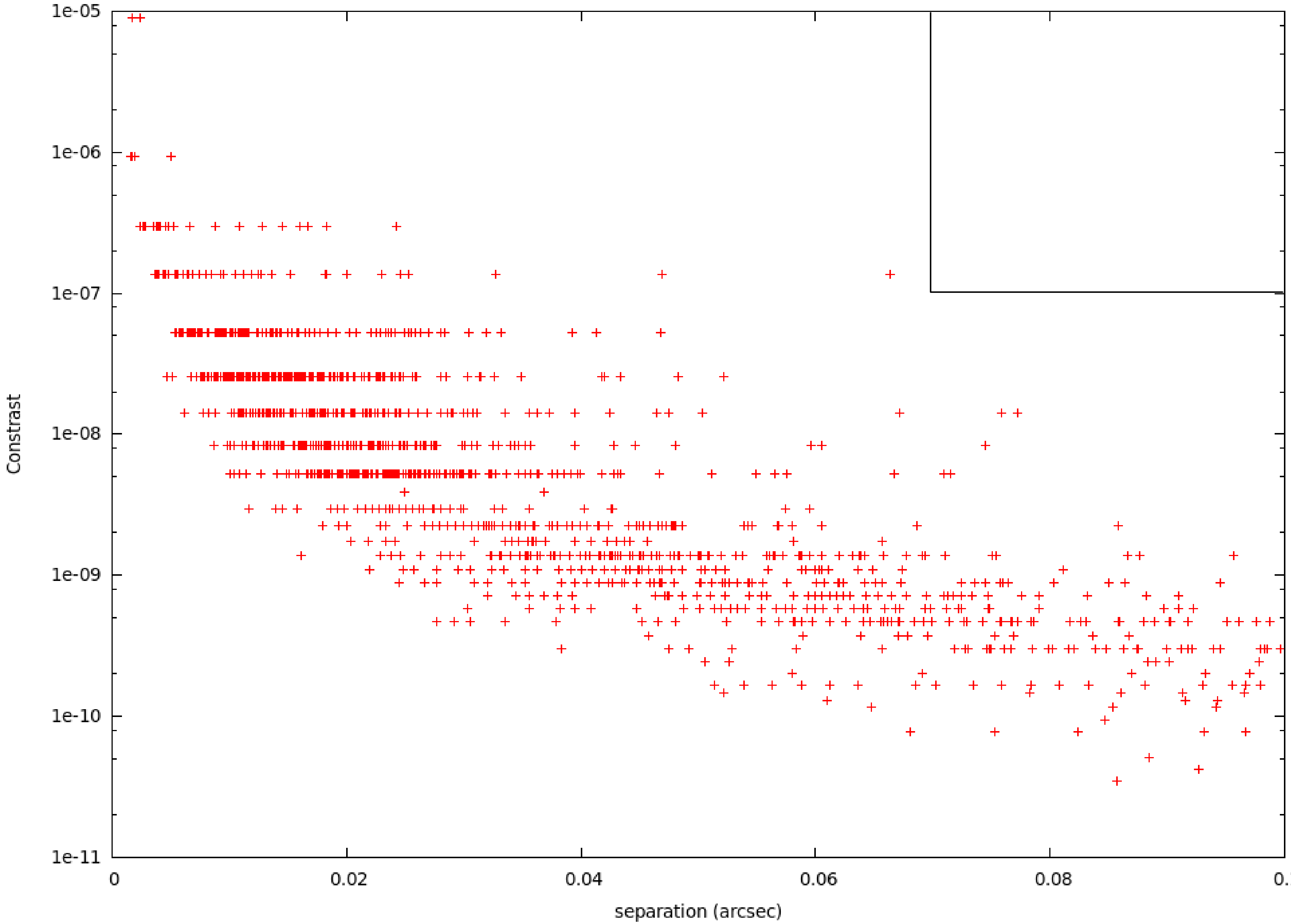
Gliese catalog of nearby stars
Kept only main sequence
→ 2347 stars within 25 pc

Each star characterized by :
- Distance (pc)
- Temperature (K)
- Absolute V magnitude

→ computed bolometric luminosity
→ computed location of habitable zone (1 AU equivalent)
→ placed a 2x Earth size planet, Earth albedo, at max elongation
→ Used main sequence colors (V-H) to compute apparent luminosity of star and planet at H band

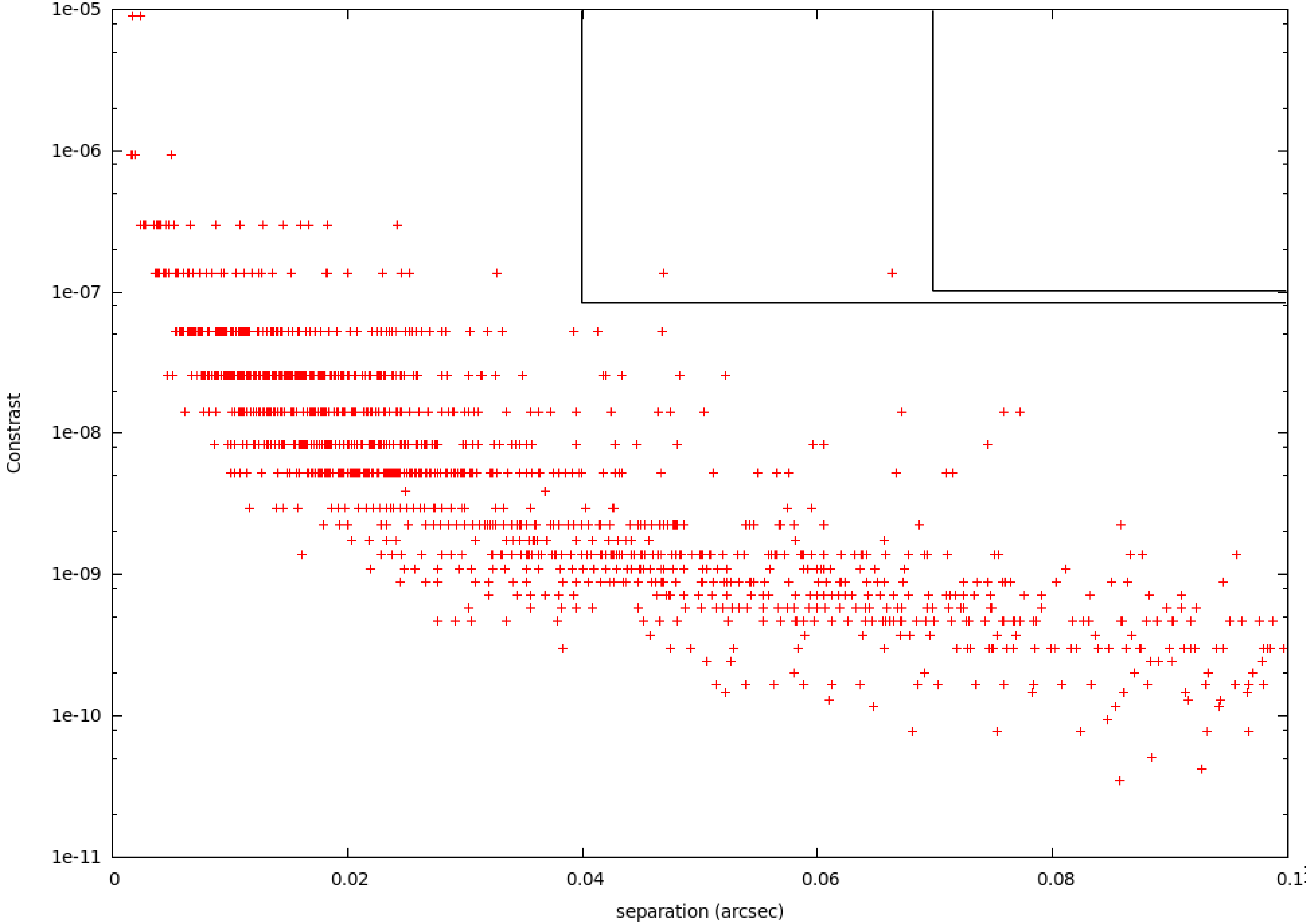
Reflected light imaging: Contrast vs separation

8-m telescope, 4 lambda/D



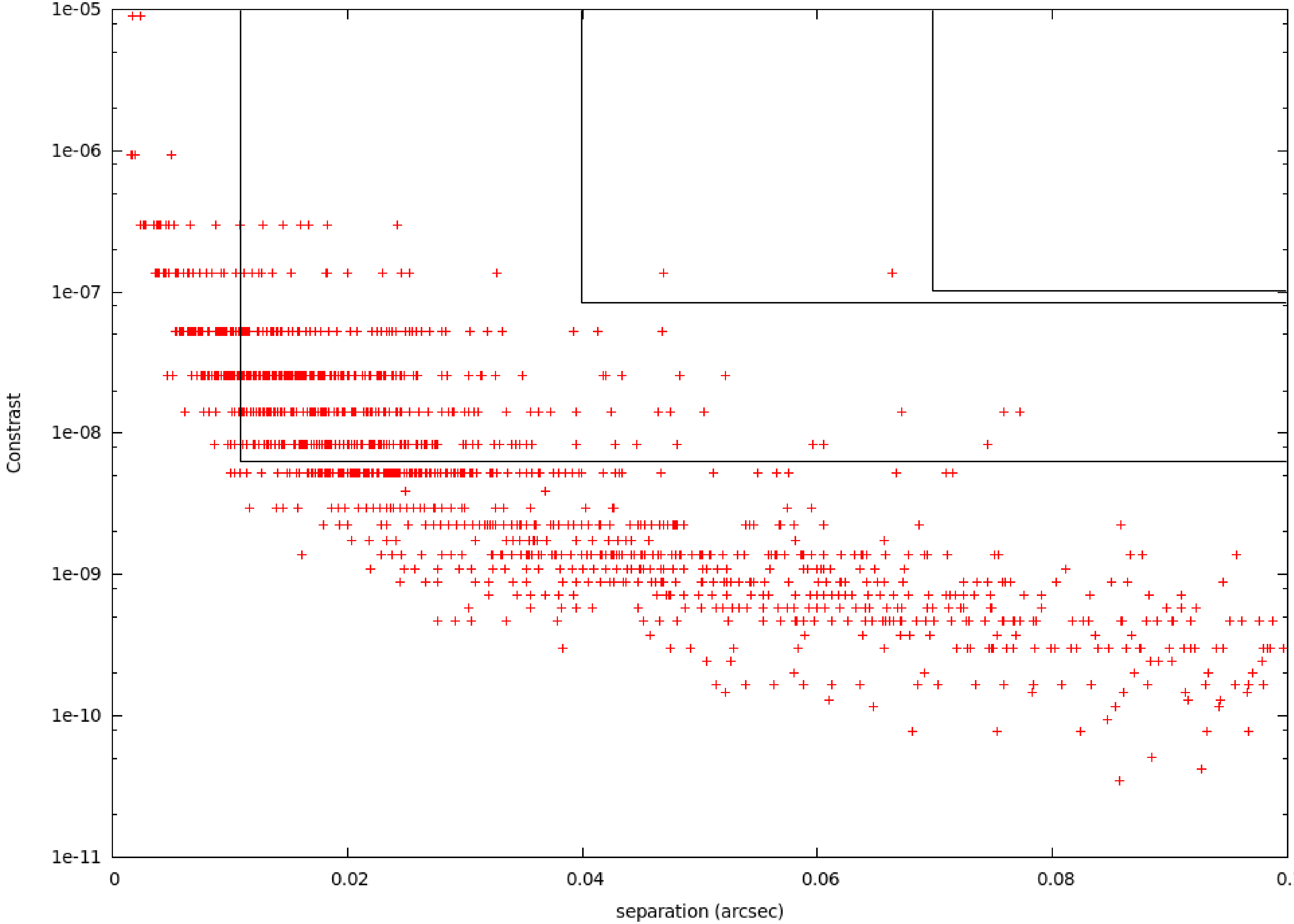
Reflected light imaging: Contrast vs separation

8-m telescope, 1 lambda/D



Reflected light imaging: Contrast vs separation

30-m telescope, 1 lambda/D

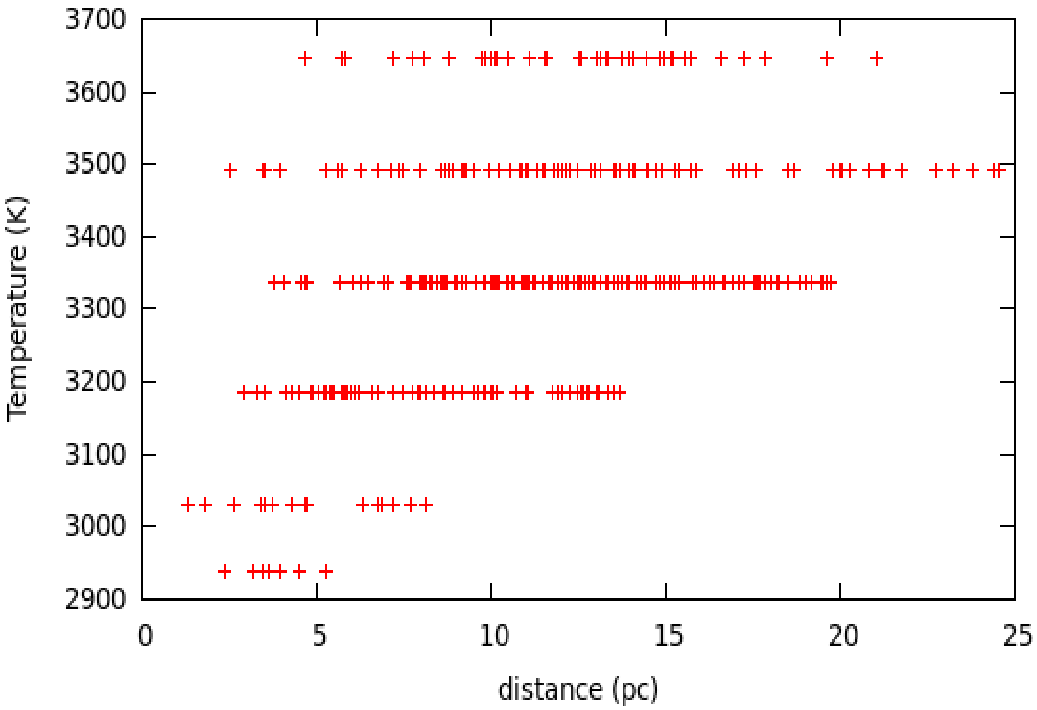


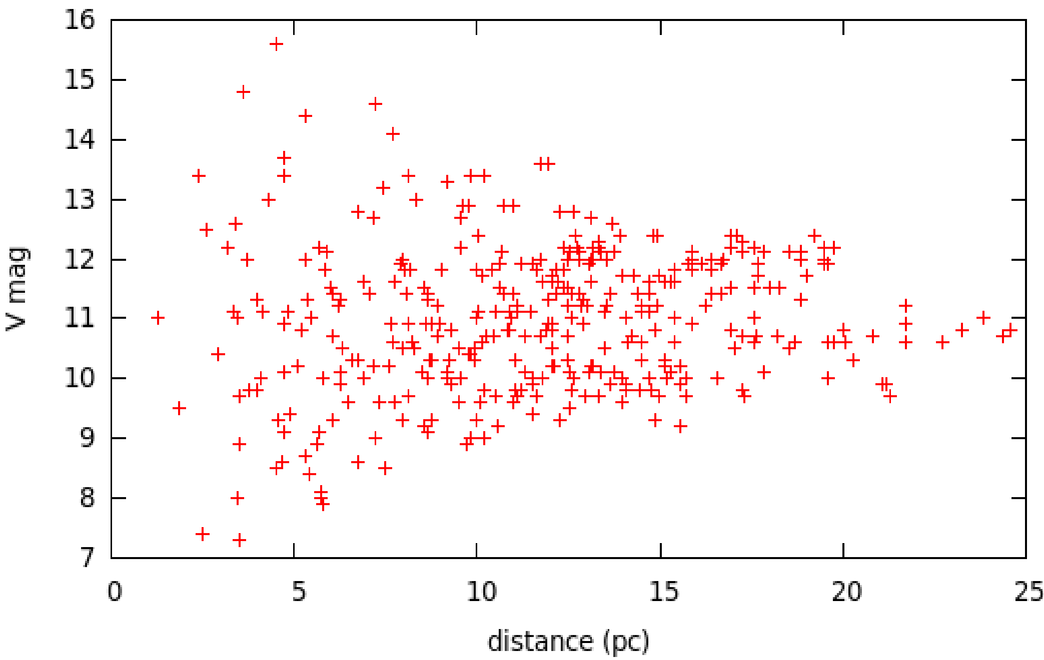
5000 K

Reflected light imaging: ELT targets

30-m telescope, 1 lambda/D: 365 targets within IWA and detection contrast limits
All are M-type stars, (T~3400K), nearby (d~10pc)

Fainter than conventional ExAO targets (mV ~ 10 to 11)





What kind of ExAO system is required ?

GPI-like system on ELT

Detection contrast: 7e-9 (equivalent to 1e-7 on 8-m)
Wavefront sensing: mV = 8 limit
Coronagraphy: 4 lambda/D
Sensitivity: mH = 26.5

→ 3 targets (0 for R=200 spectroscopy)

Increased WFS sensitivity

Same as above, but with mV = 12 limit for WFS

→ 23 targets (0 for R=200 spectroscopy)

Improved IWA

Same as above, but with 1 lambda/D coronagraph

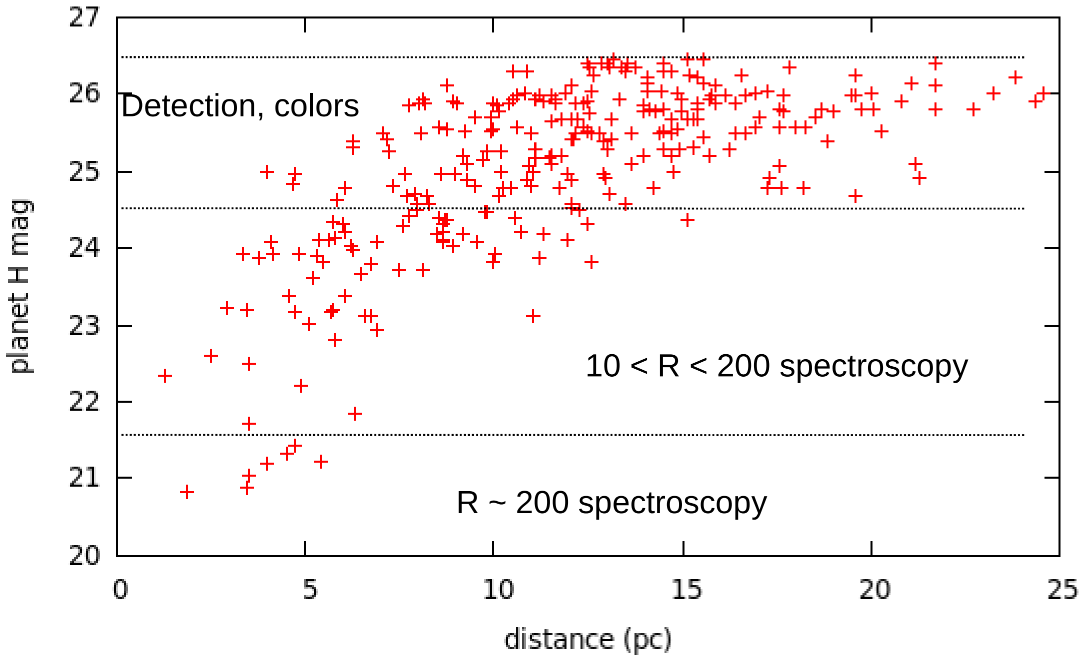
→ 287 targets (7 for R=200 spectroscopy)

R=200 spectroscopy targets

287 targets suitable for detection

7 prime targets on 30-m ELT, for which R=200 spectroscopy in near-IR can be done at SNR=5 in <1hr

Distance:	1.8 – 5.4 pc
Teff :	2900 K – 3200 K
Contrast:	3e-7 - 5e-8
Separation:	14 mas – 30 mas
Star V mag:	9.8 – 11.3
Star H mag:	3.0 – 4.9
Planet H mag:	20.8 – 21.4

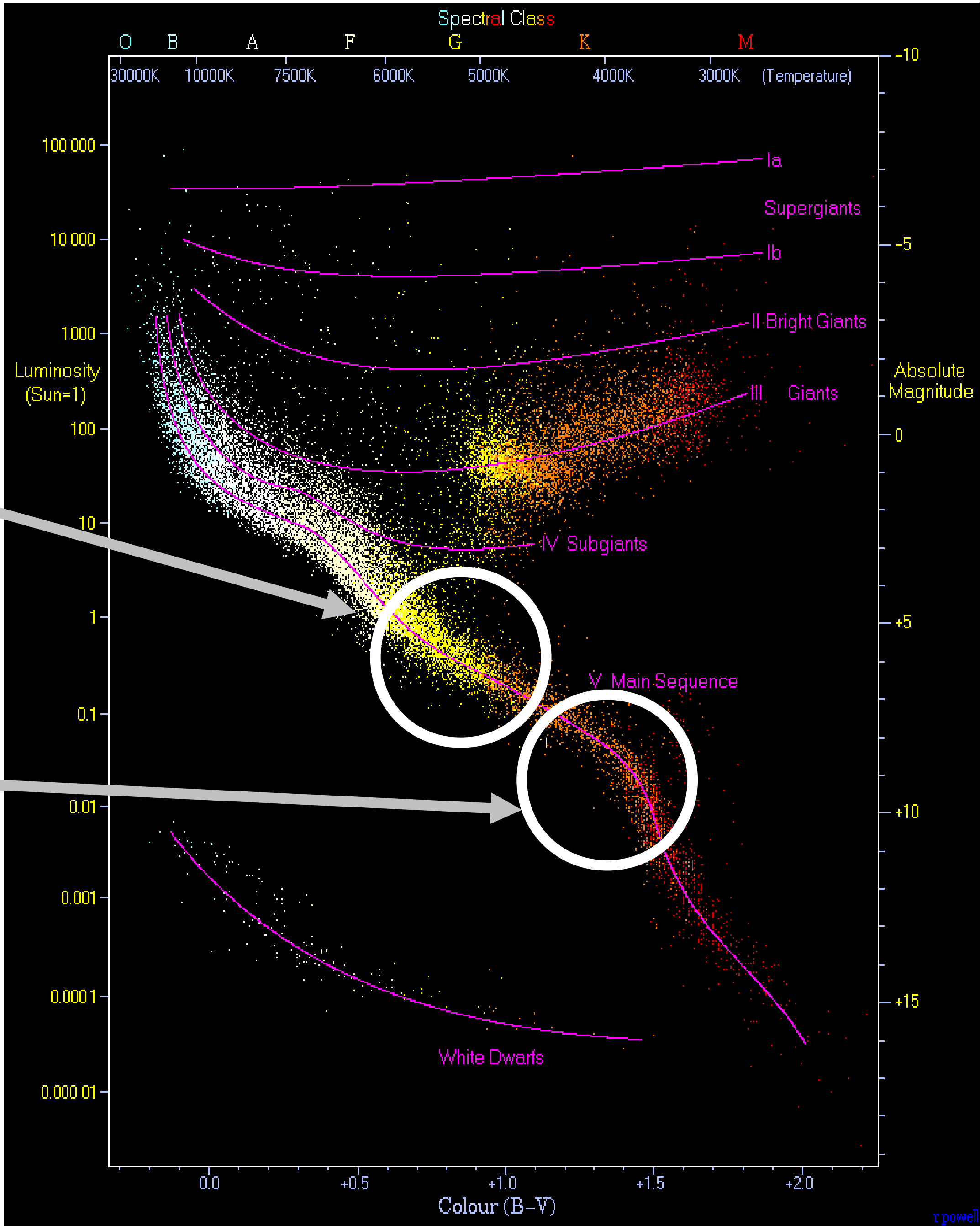


→ The targets are challenging because of their angular separation (& star V mag)

Habitable planets spectroscopy

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

Ground (ELT):
M type stars, nearIR



Conclusions

SCExAO WFC architecture combines several innovative technologies to provide both efficient wavefront control and high level of residual light calibration. These technologies have been and are developed in lab testbeds. SCExAO will be first system to test and combine several of these new concepts on sky.

→ much will be learned in the next year

SCExAO's flexible platform allows adaptive architecture, which can be quickly modified if required

SCExAO calibrated contrast limit will be set by incoherent speckles (due to polarization, fast temporal behavior or chromaticity) which “come and go”. It is a present difficult to estimate where this limit is.

PSF $\neq$ static slow speckles + random halo which averages to a smooth halo in long exposures

SCExAO is a precursor to an experiment that could image habitable planets around nearby M-type stars with ELTs

In ~15 yrs, we may have an opportunity to acquire spectra of habitable planets – we should think hard about this problem in the next decade.