The Subaru Coronagraphic Extreme-AO (SCExAO) system

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Christophe Clergeon (PhD student: ExAO wavefront sensing)
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+ HiCIAO team, AO188 team

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})

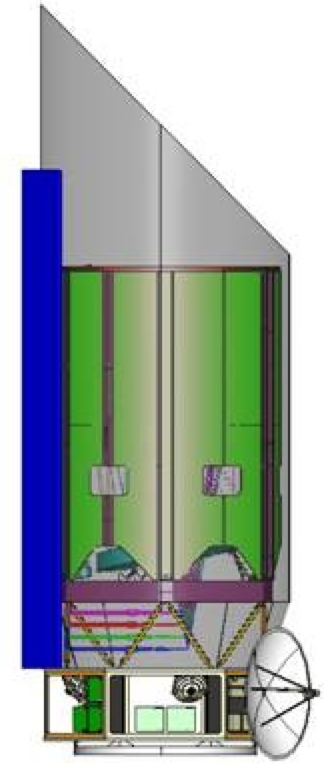
Coronagraphy:
High efficiency 1 λ/D PIAA coronagraph

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

PECO overview



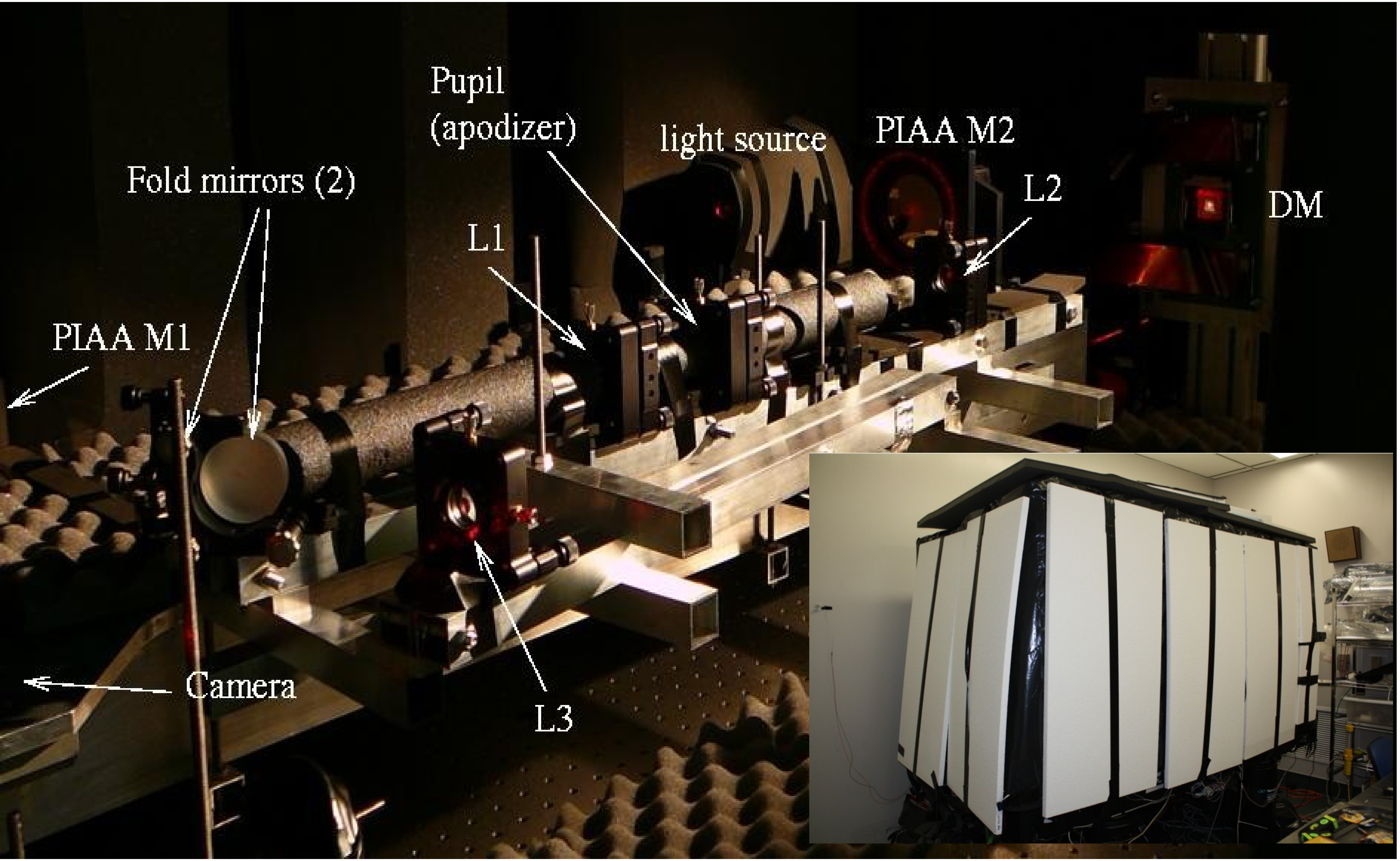
NASA-funded Advanced Strategic Mission Concept Study, medium class mission (~$800M cost cap)

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

Characterization of planets (including Earths/SuperEarths) and dust in habitable zone

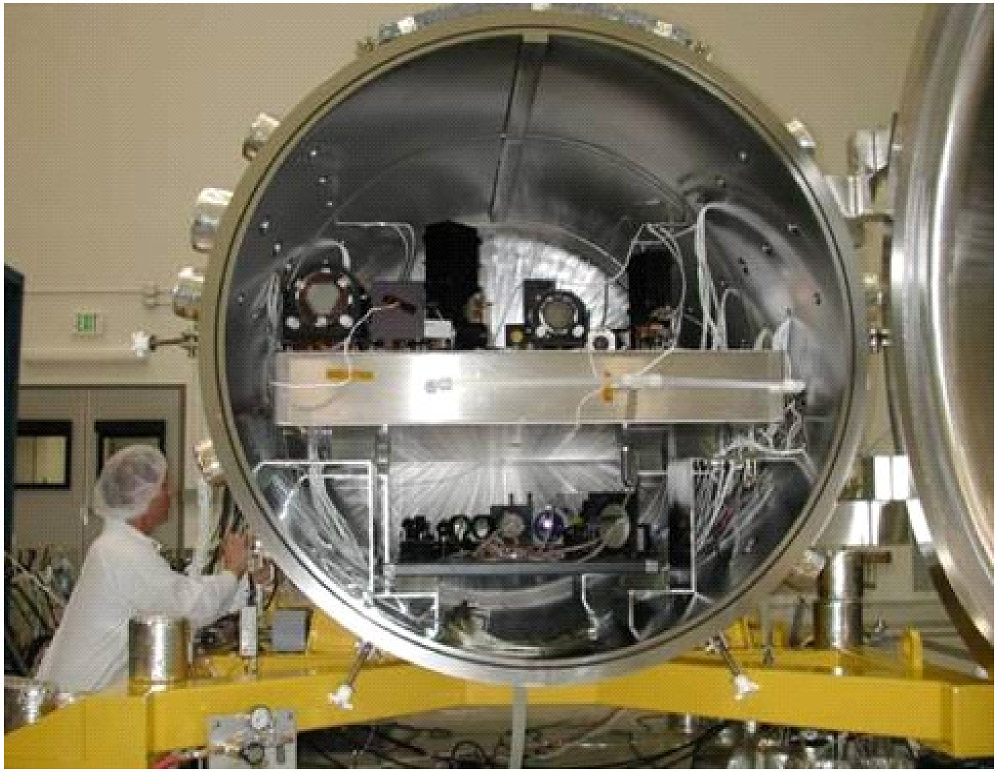
- 1.4m diameter off-axis telescope (sized for medium-class cost cap), 3 yr mission
- drift-away heliocentric orbit for maximum stability
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 – 0.9 micron spectral coverage / R~20, polarimetric imaging
- Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin

PIAA lab at Subaru Telescope

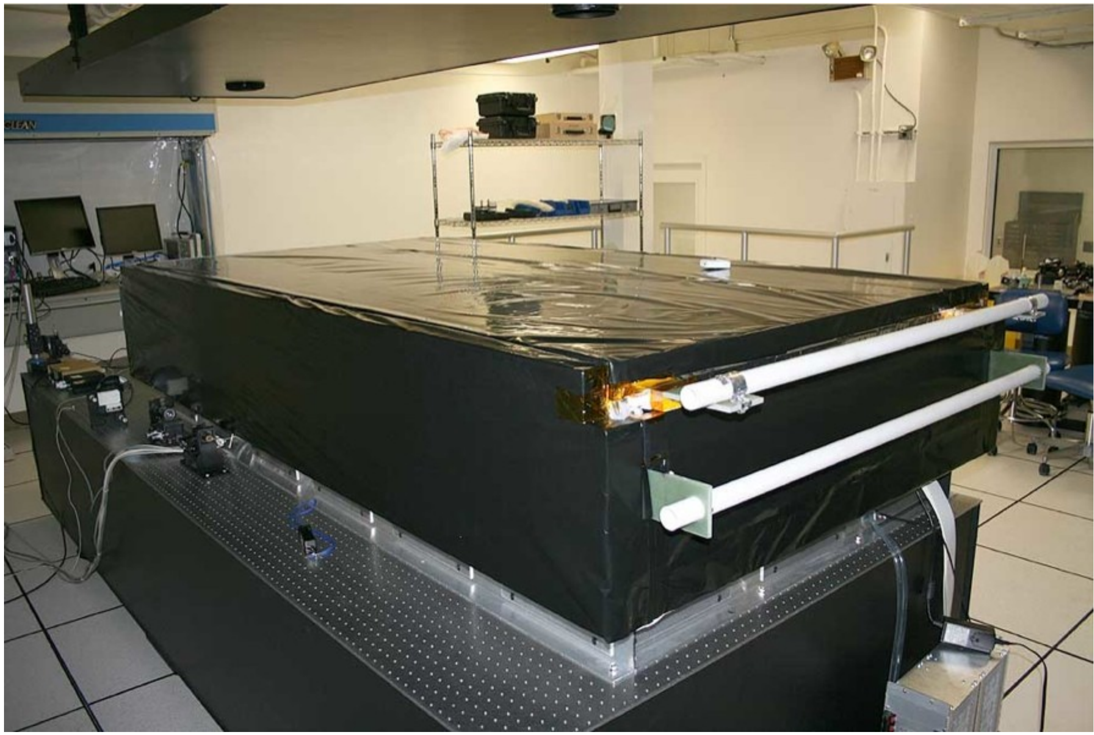


Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

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



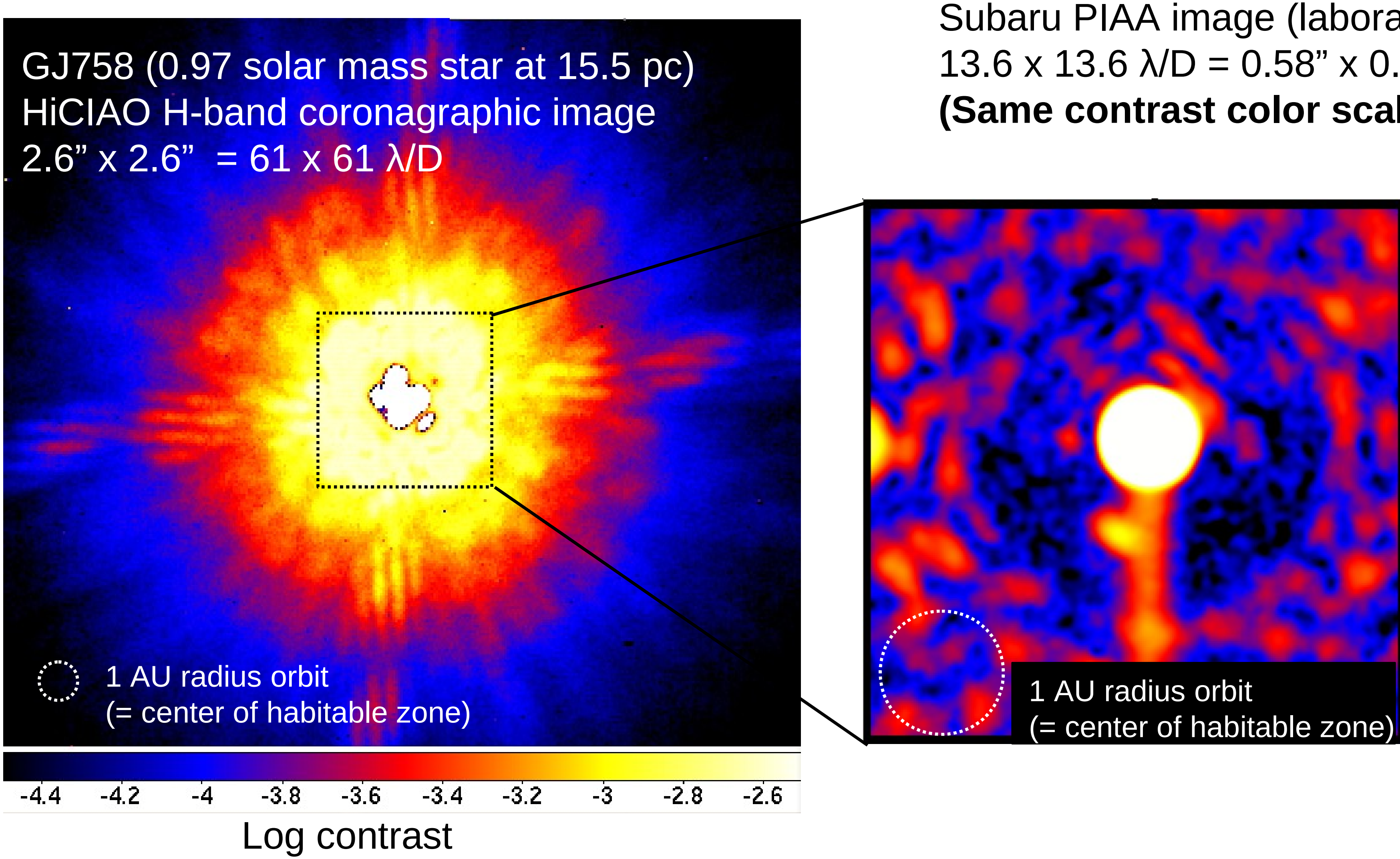
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



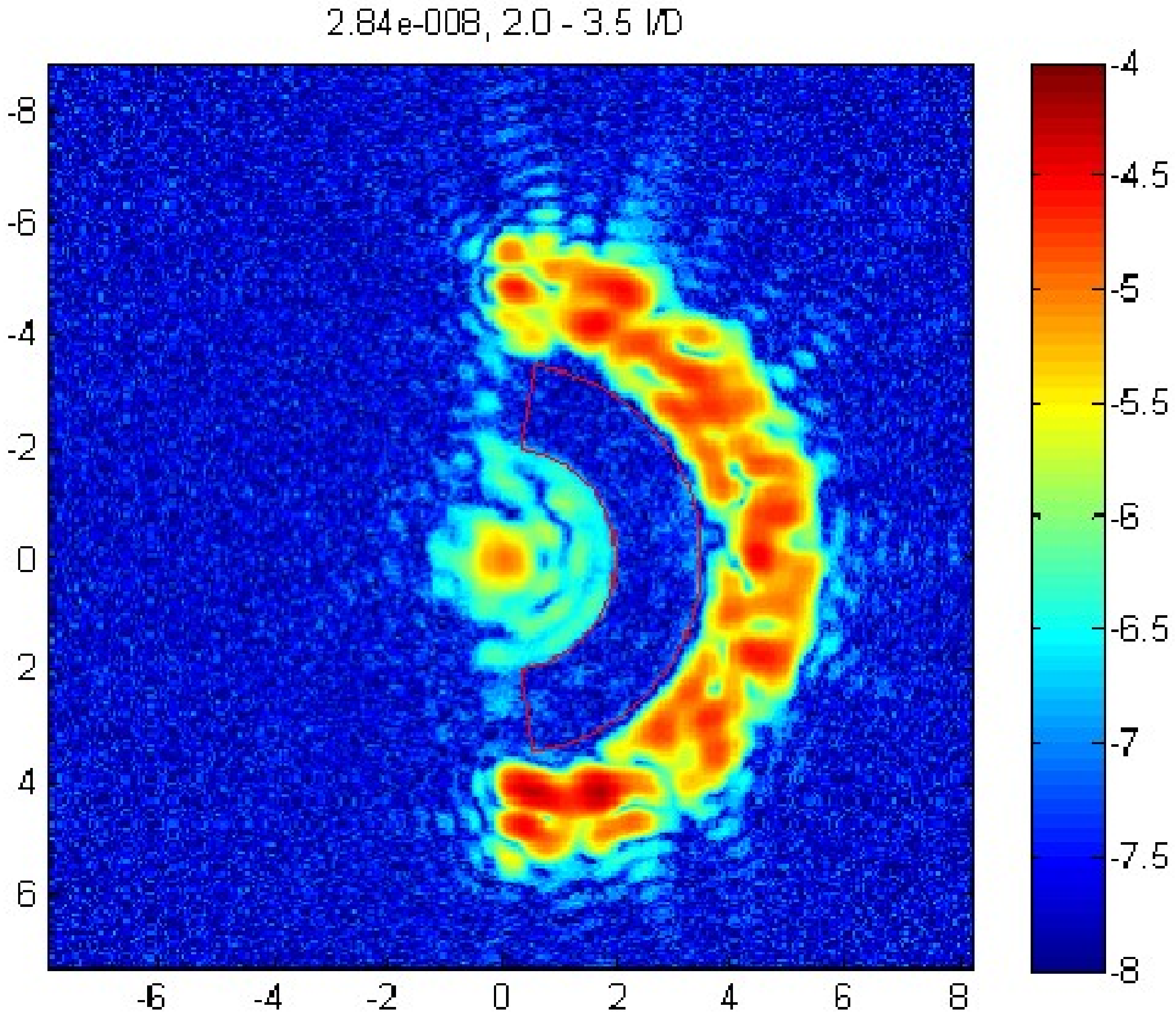
High contrast imaging in lab reaches much higher performance than what is currently achieved on-sky: newer technologies, more stable environment, better calibrations

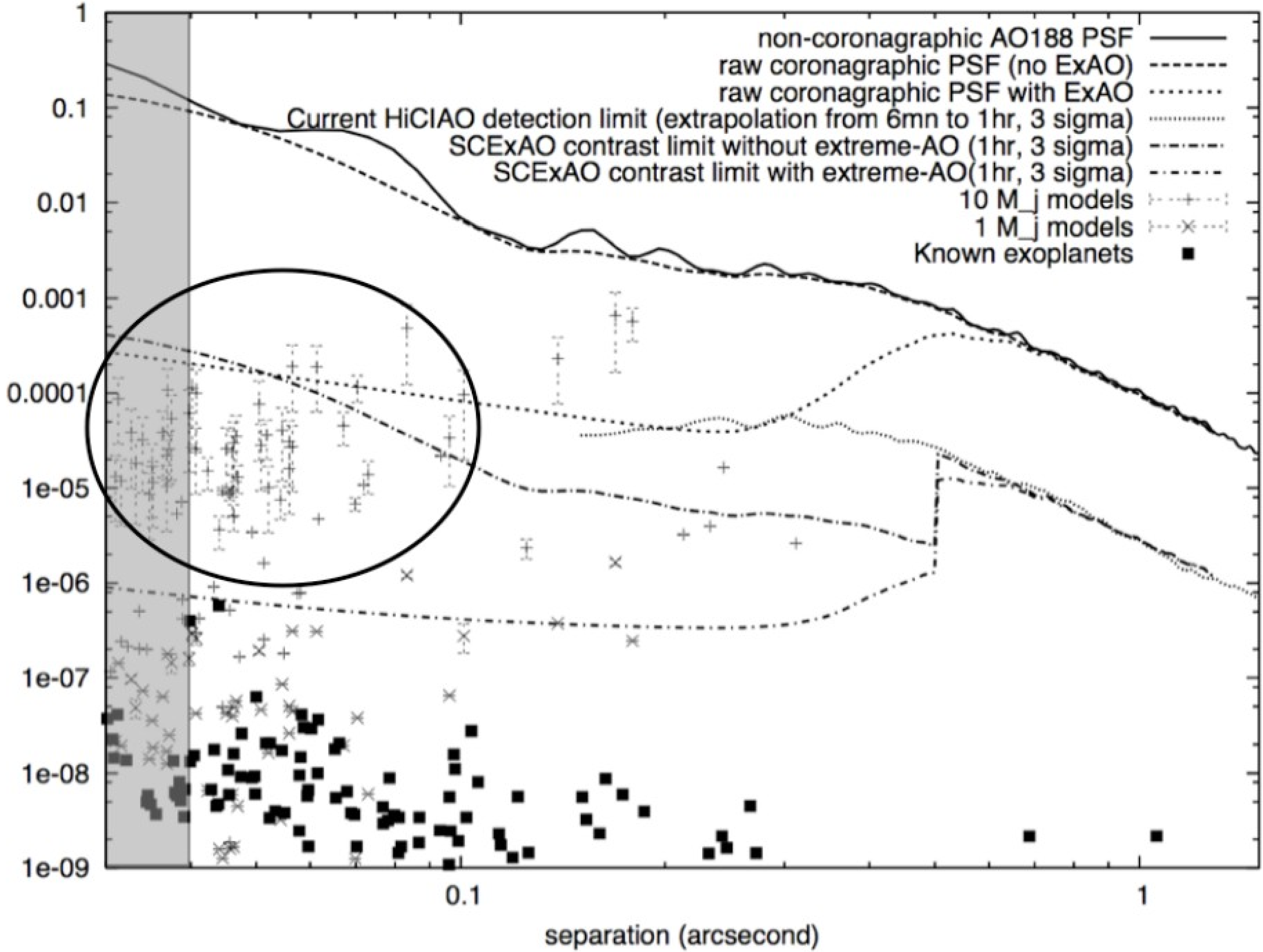
SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance

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

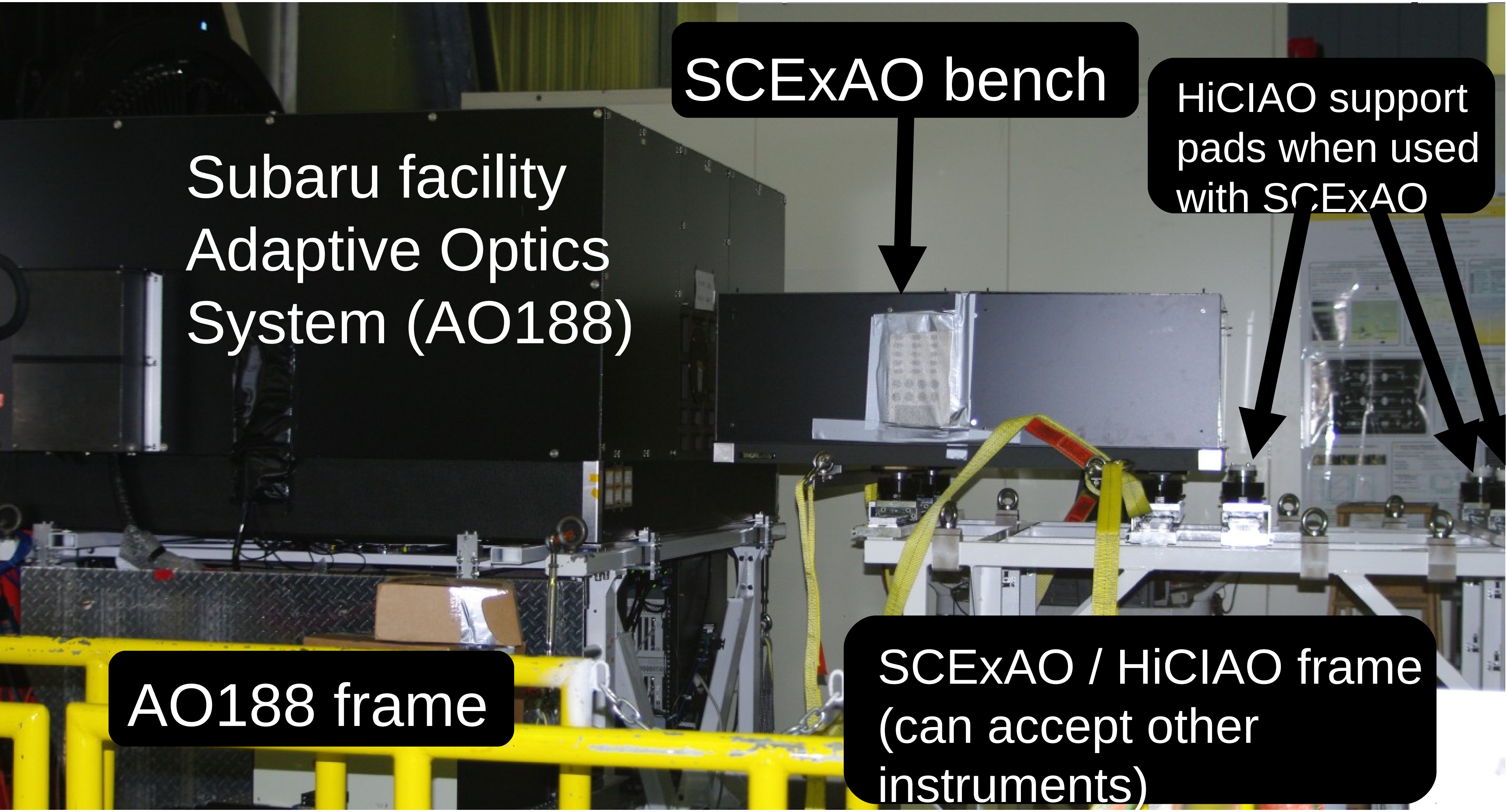


PIAA coronagraph image at NASA Ames testbed (R. Belikov group)

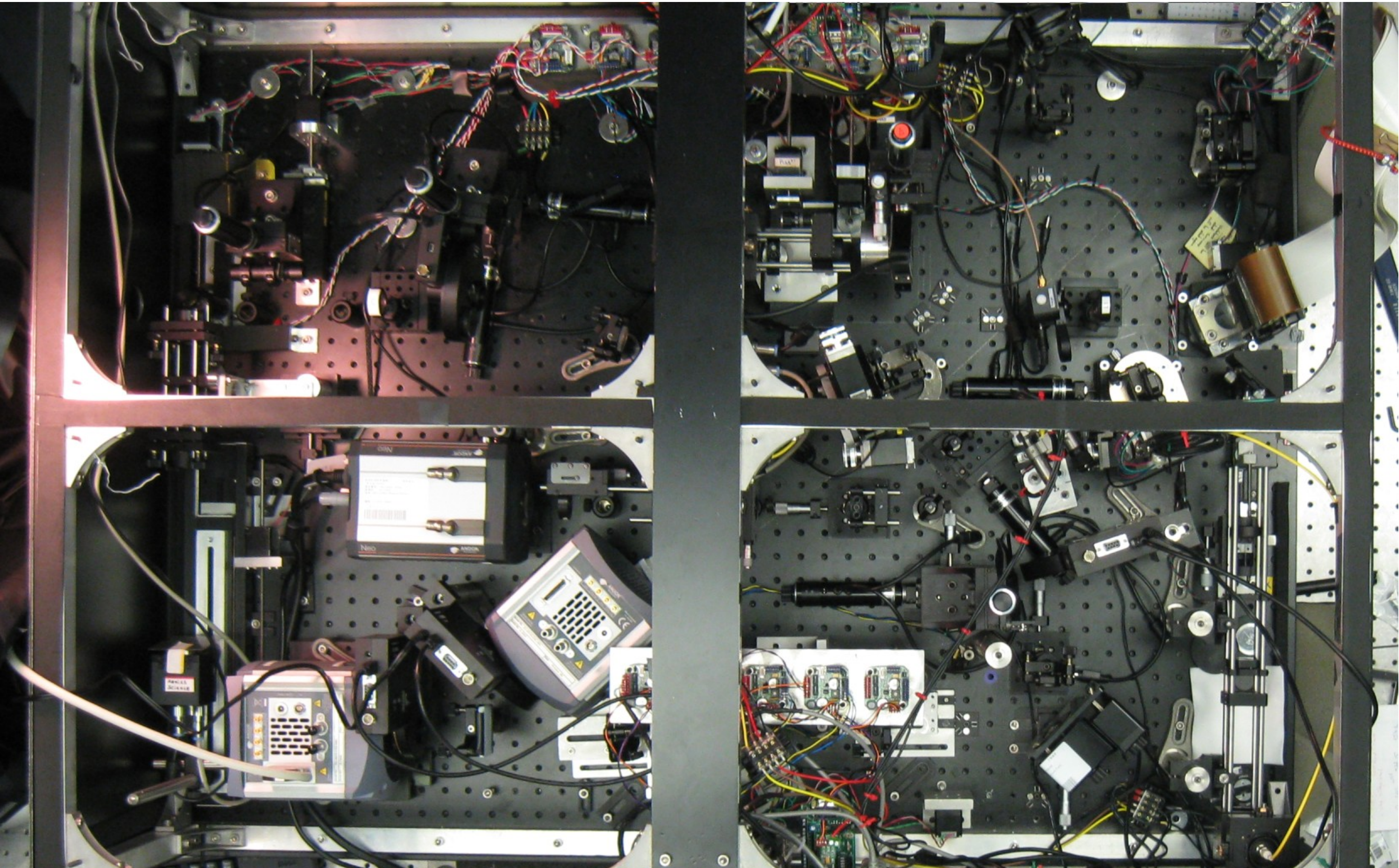



non-coronagraphic AO188 PSF
raw coronagraphic PSF (no ExAO)
raw coronagraphic PSF with ExAO
Current HiCIAO detection limit (extrapolation from 6mn to 1hr, 3 sigma)
SCExAO contrast limit without extreme-AO (1hr, 3 sigma)
SCExAO contrast limit with extreme-AO(1hr, 3 sigma)
10 M_j models
1 M_j models
Known 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)

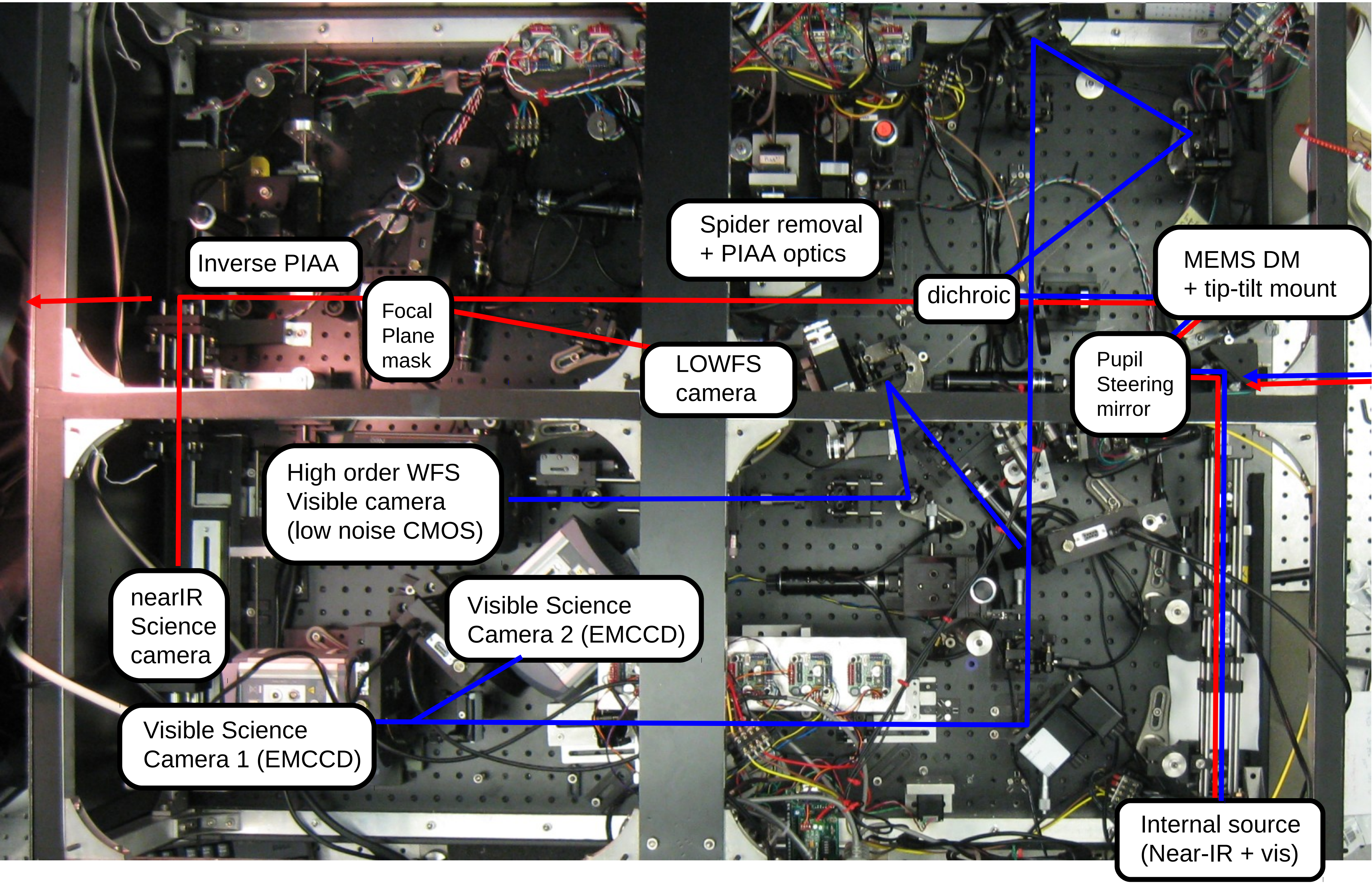
SCExAO at Subaru Telescope (Aug 2010)



The Subaru Coronagraphic Extreme-AO (SCExAO) system



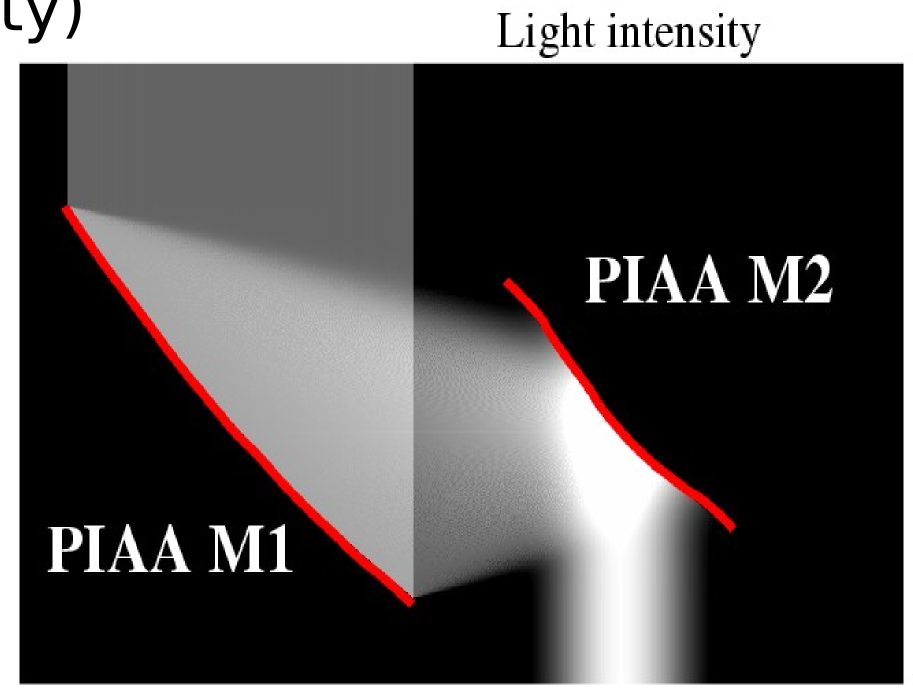
The Subaru Coronagraphic Extreme-AO (SCExAO) system



Phase-Induced Amplitude Apodization (PIAA) coronagraph

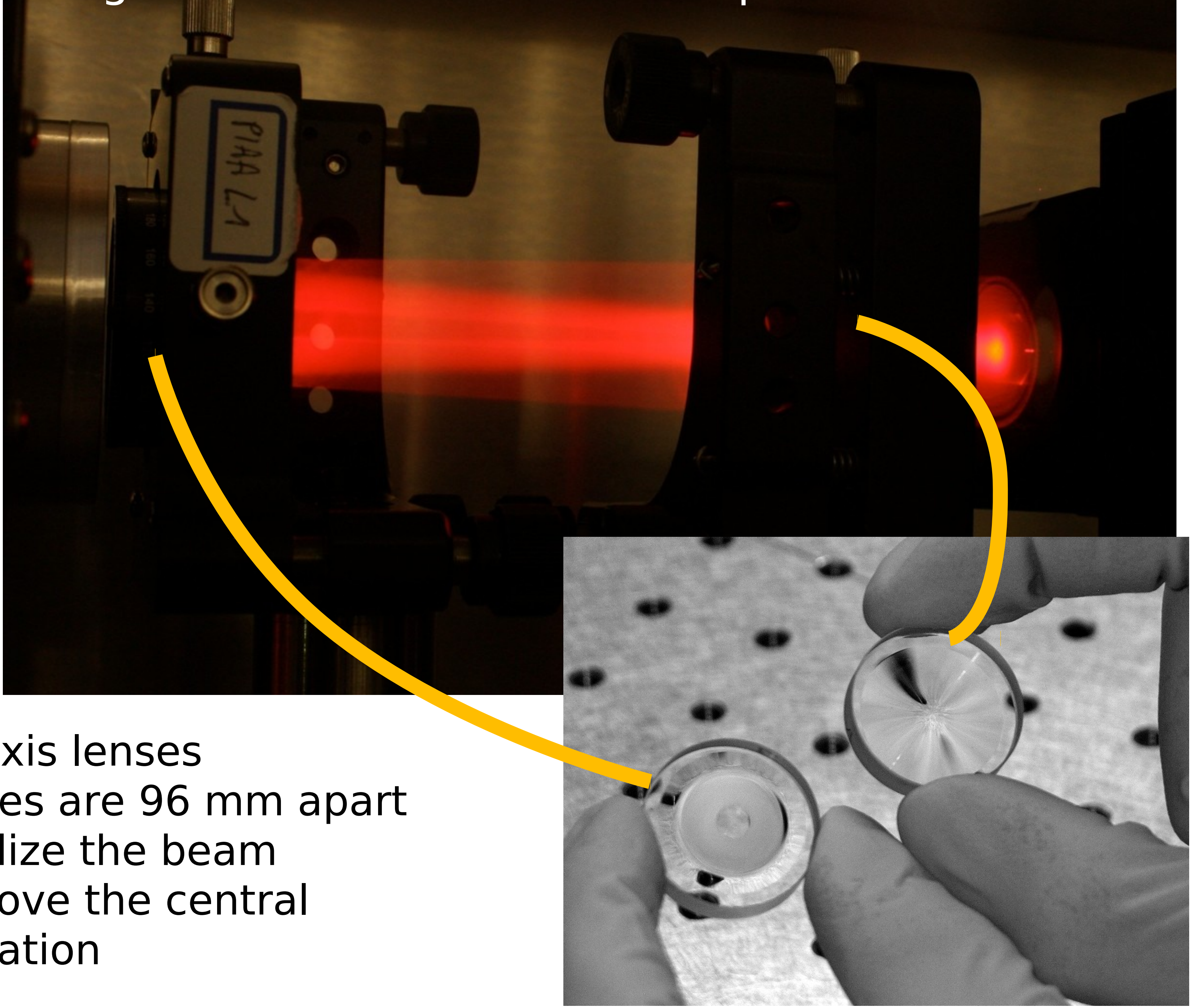
Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

- 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)



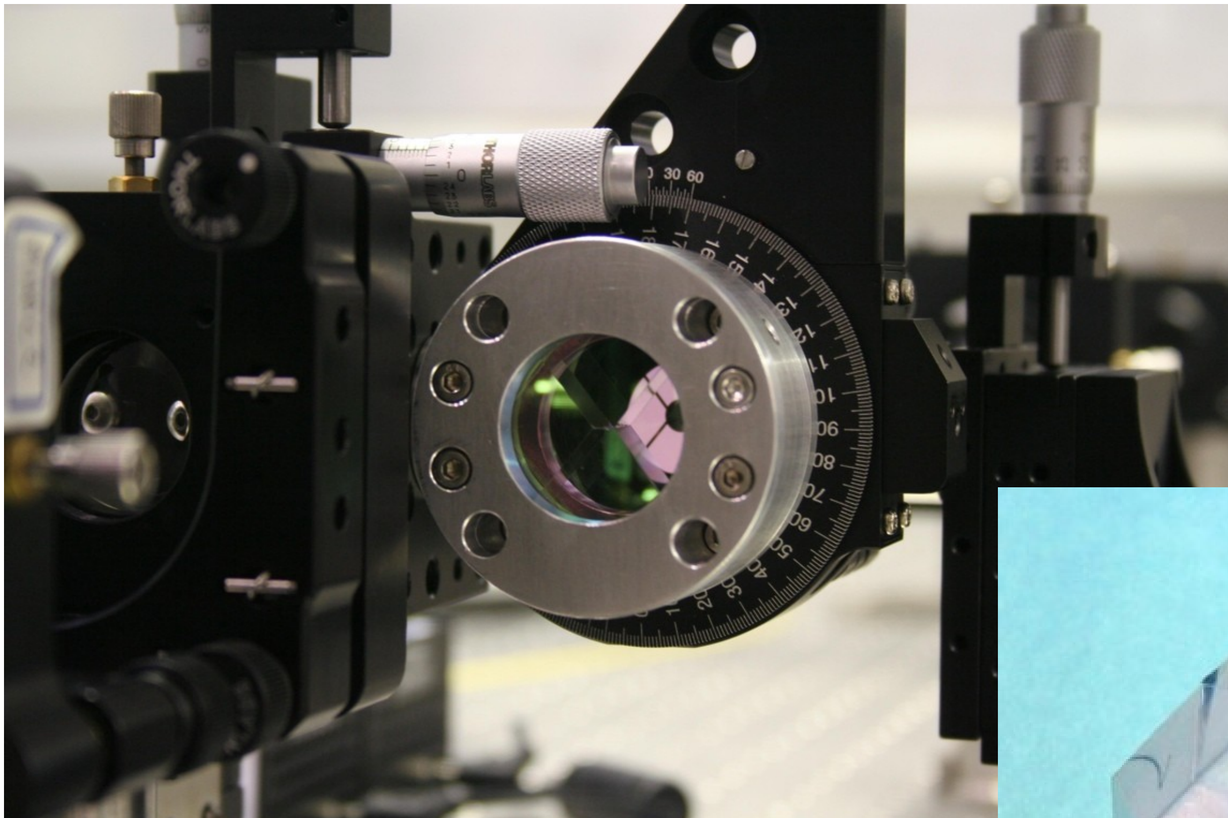
Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
Lab demos at NASA Ames, NASA JPL for space coronagraphy

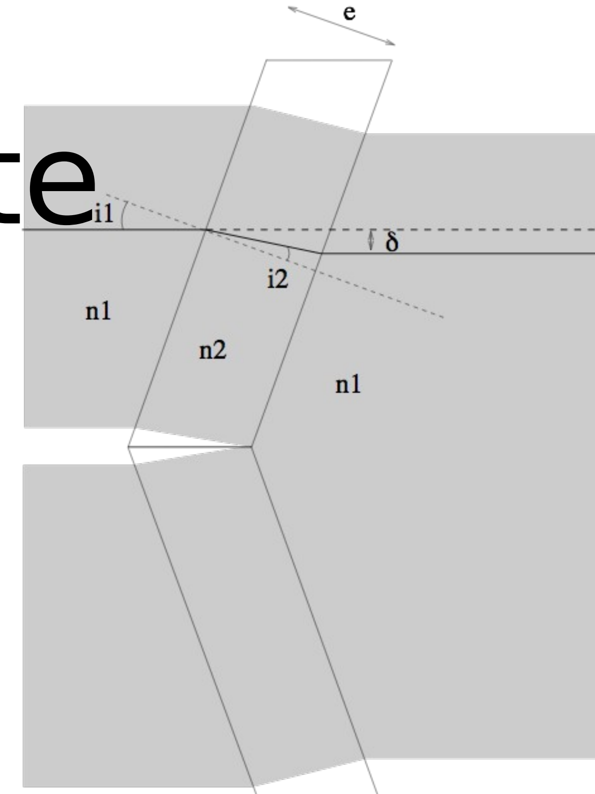
3rd generation refractive PIAA optics

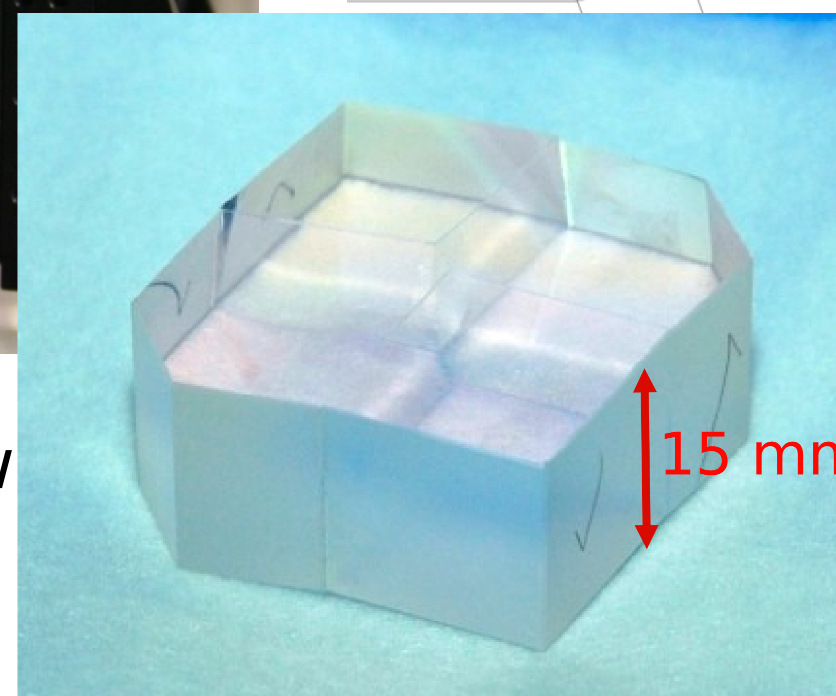


- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Spider Removal Plate

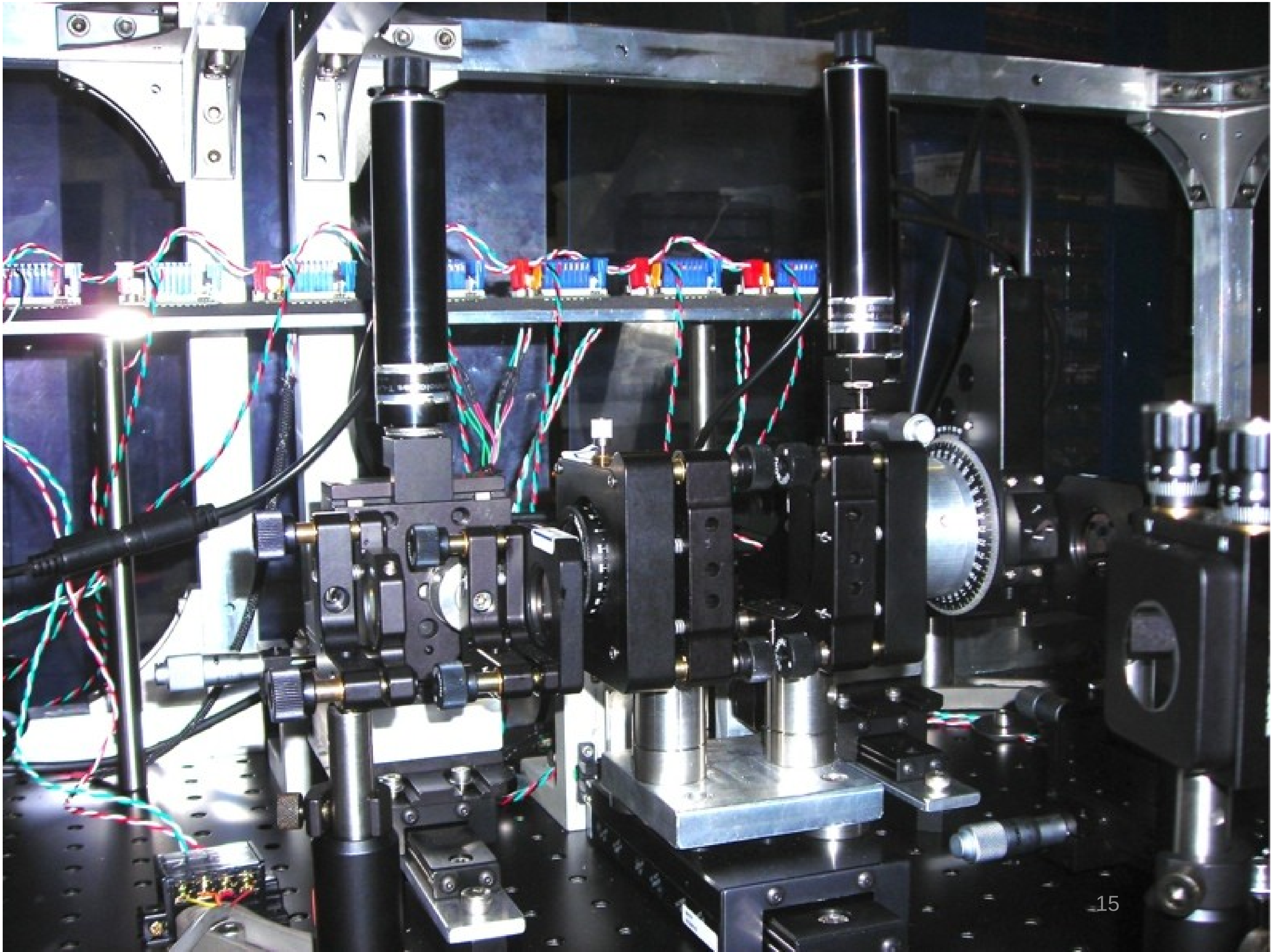


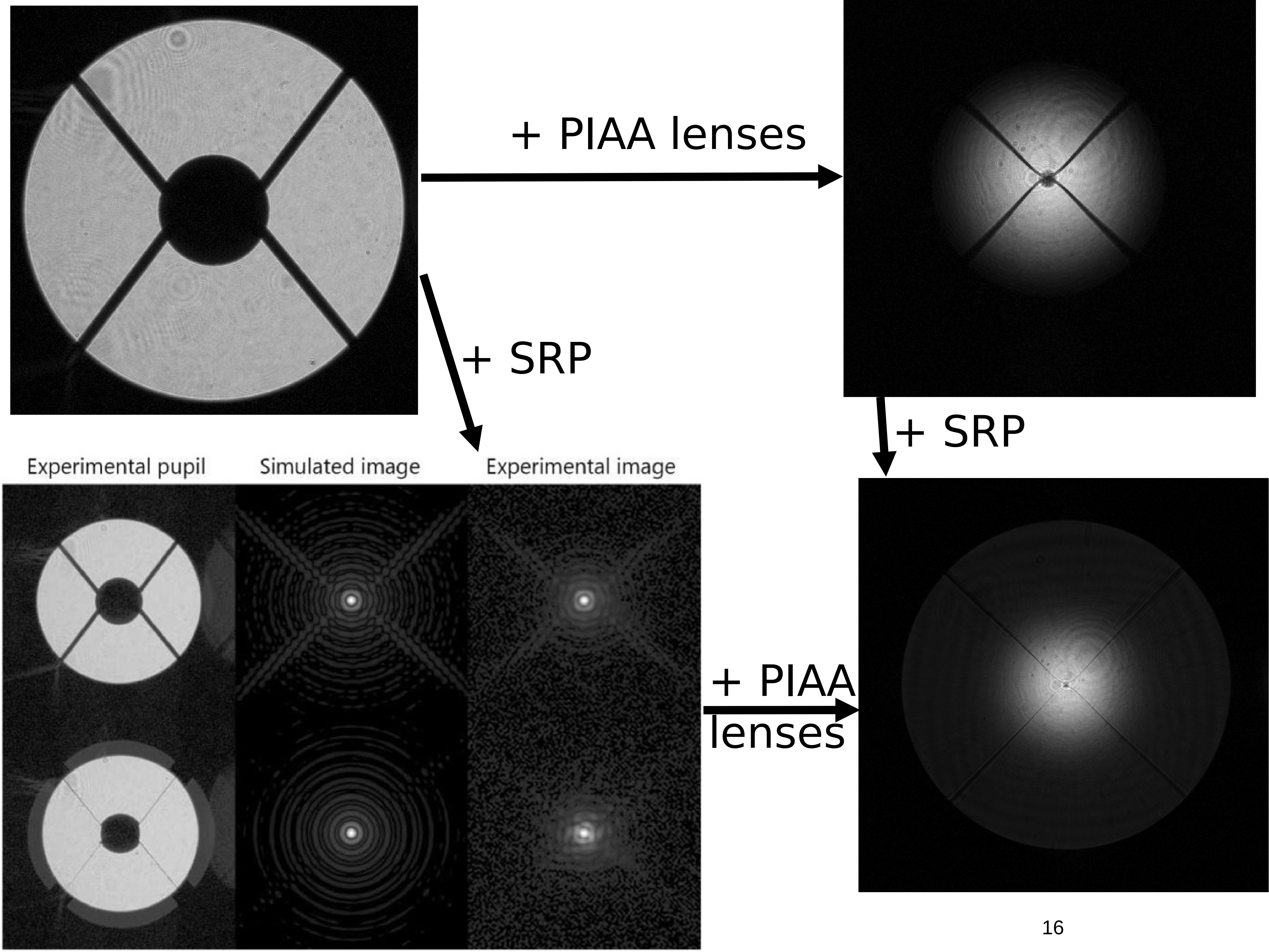




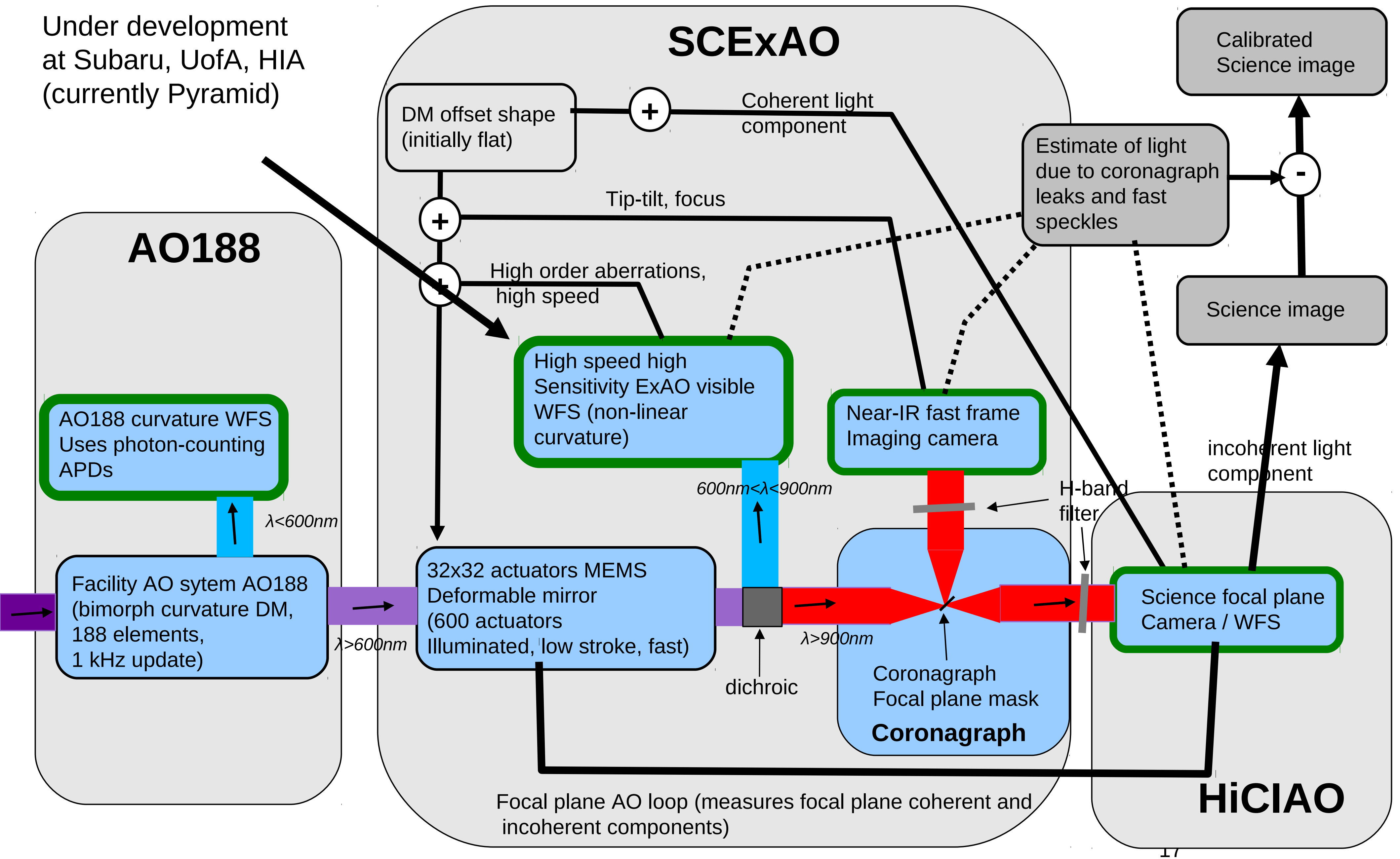
- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°

Beam shaping hardware

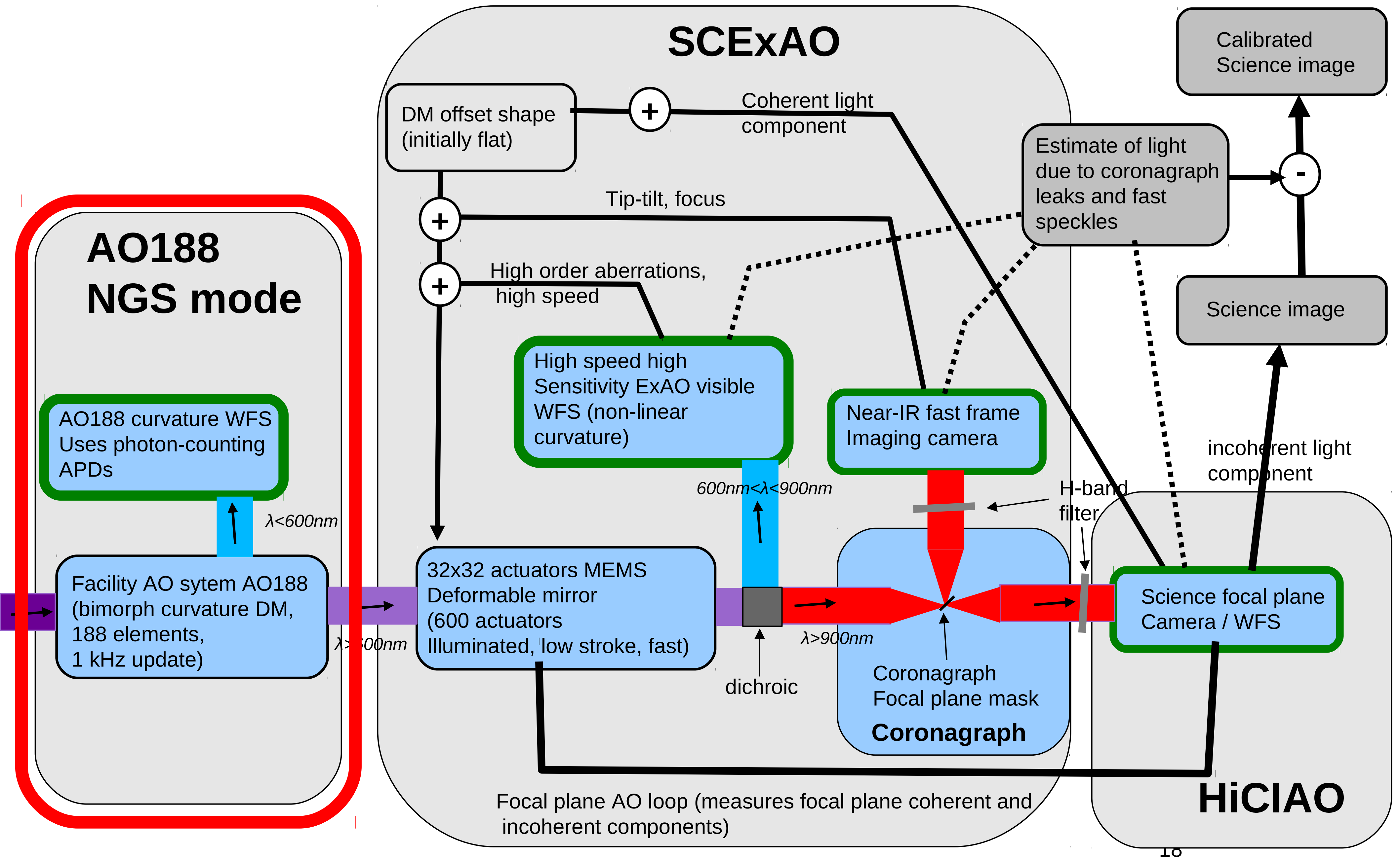



+ PIAA lenses
+ SRP
+ SRP
Experimental pupil
Simulated image
Experimental image
Without SRP
With SRP
+ PIAA lenses

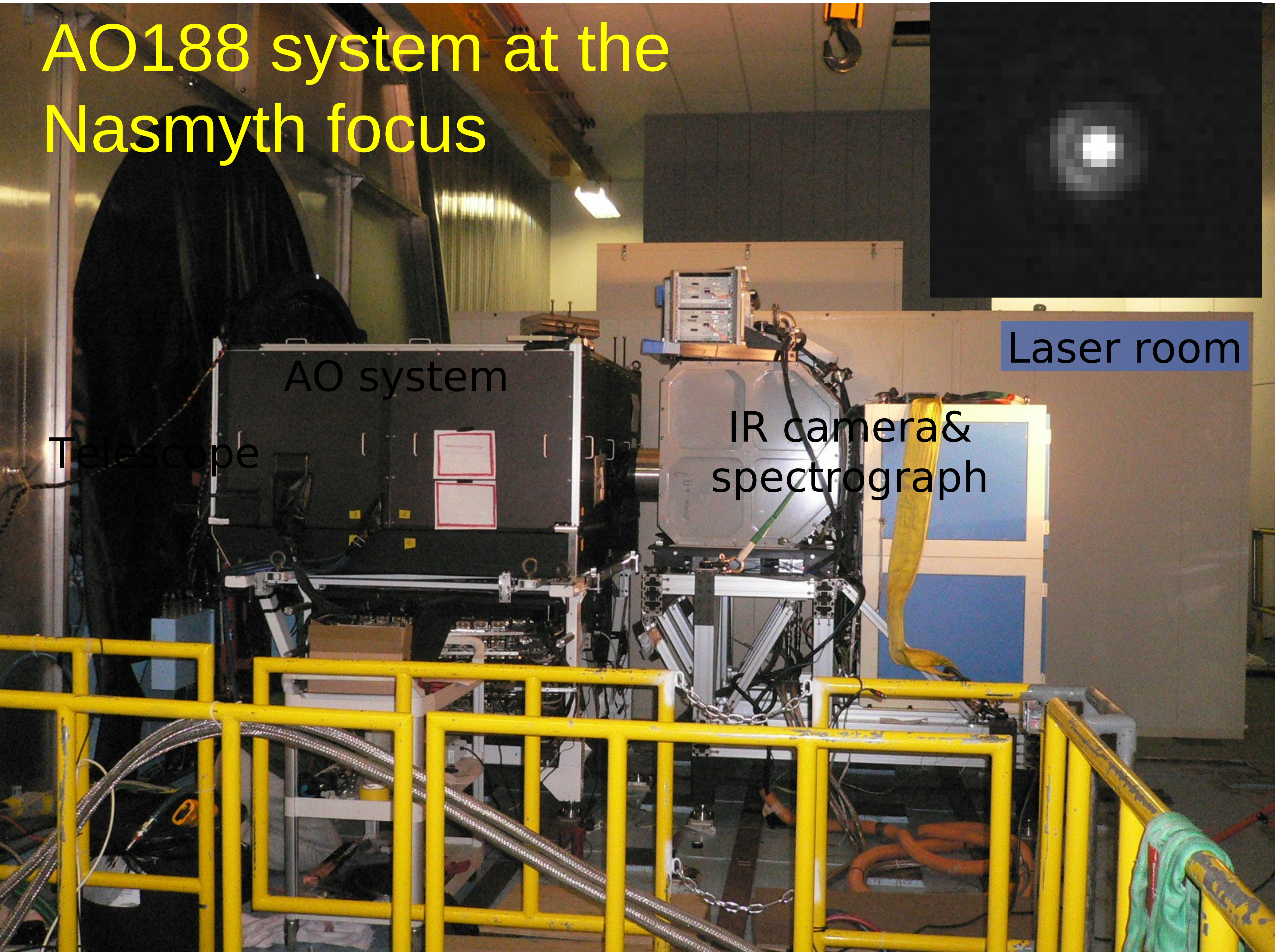
SCExAO Wavefront Control architecture and speckle calibration



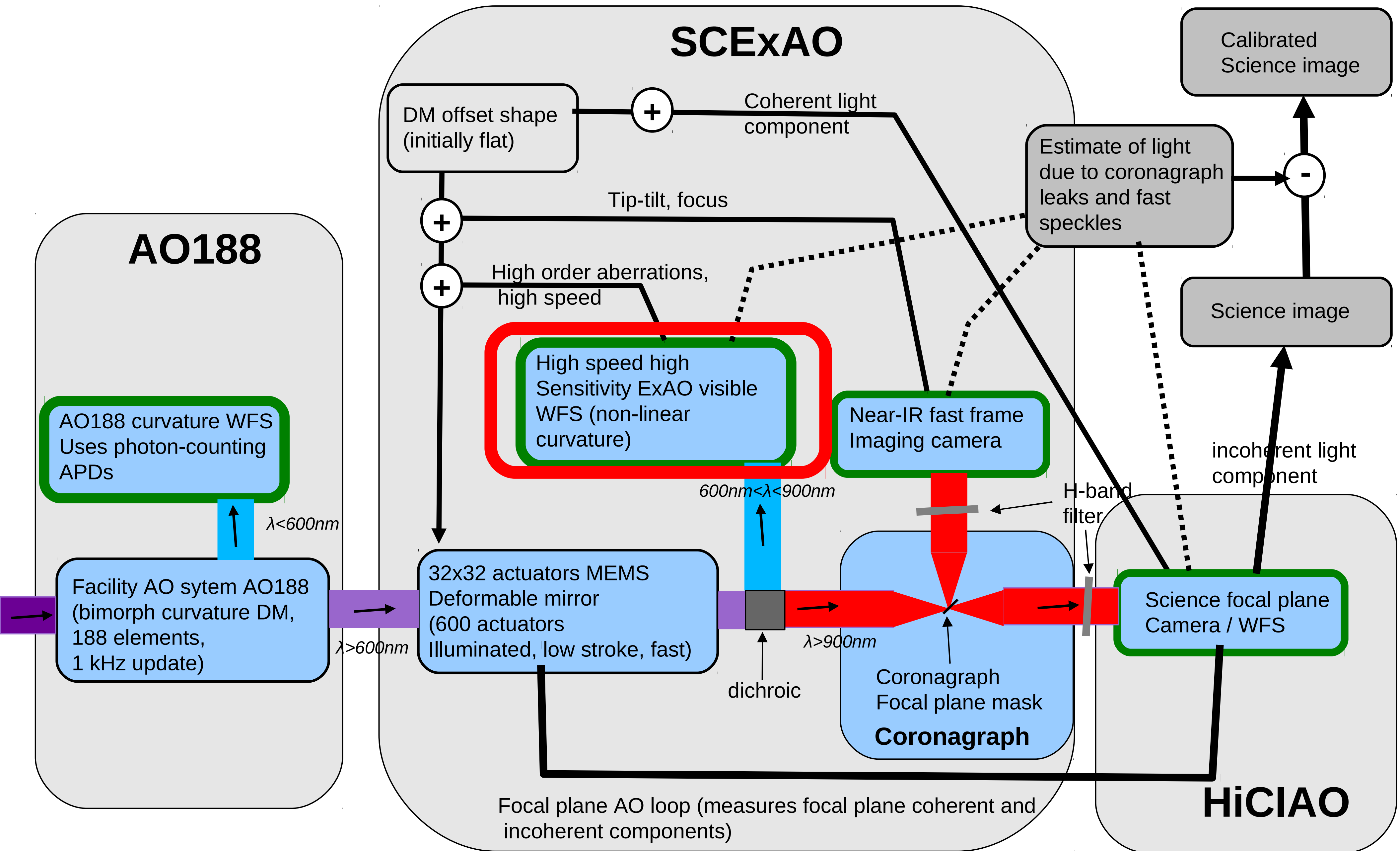
AO188 Woofer reduces WFE to ~200nm
AO188 is stand alone: no communication with SCExAO



AO188 system at the Nasmyth focus



SCExAO visible high speed WFS



Wavefront sensing at the diffraction limit of the telescope

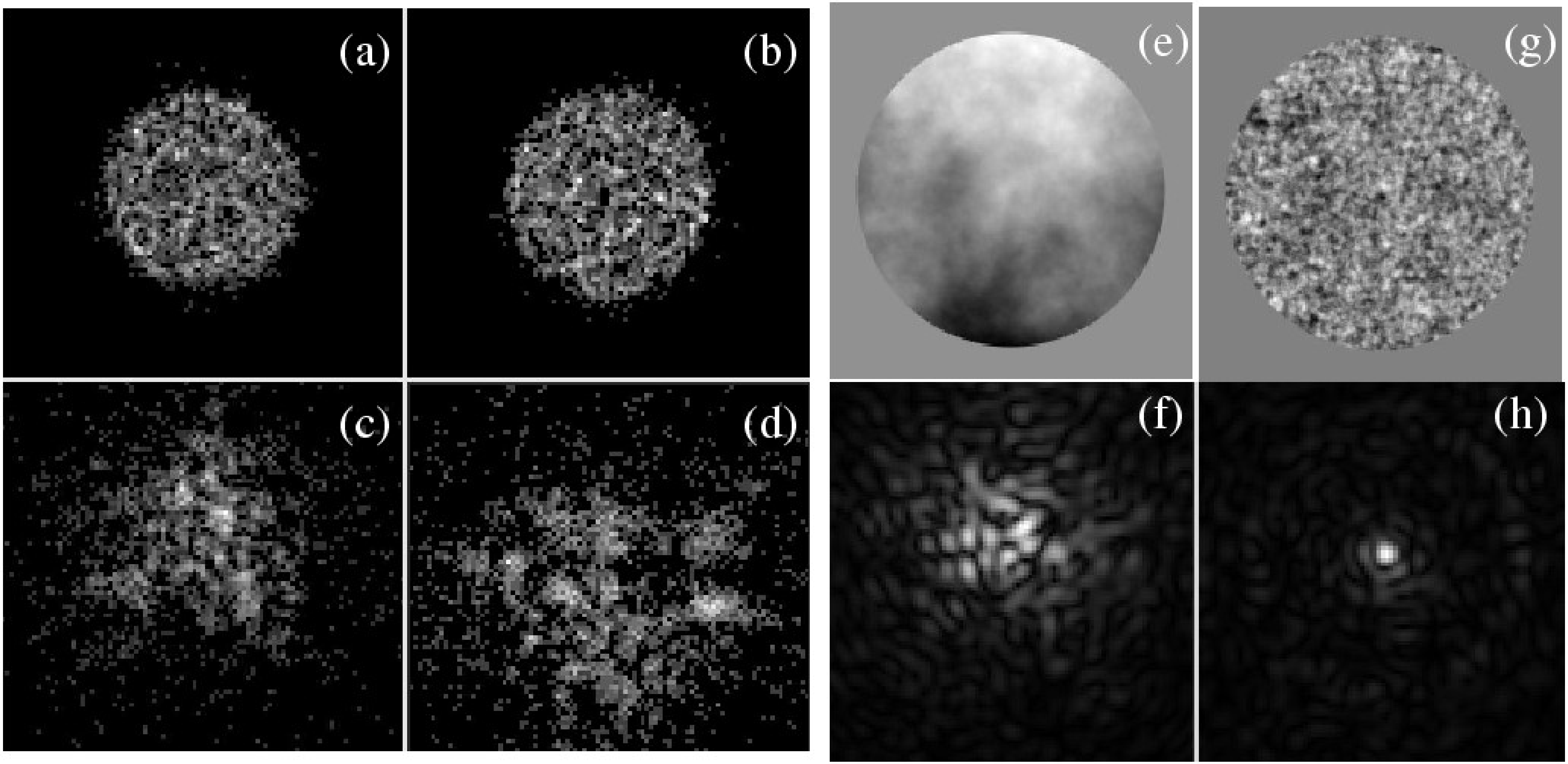
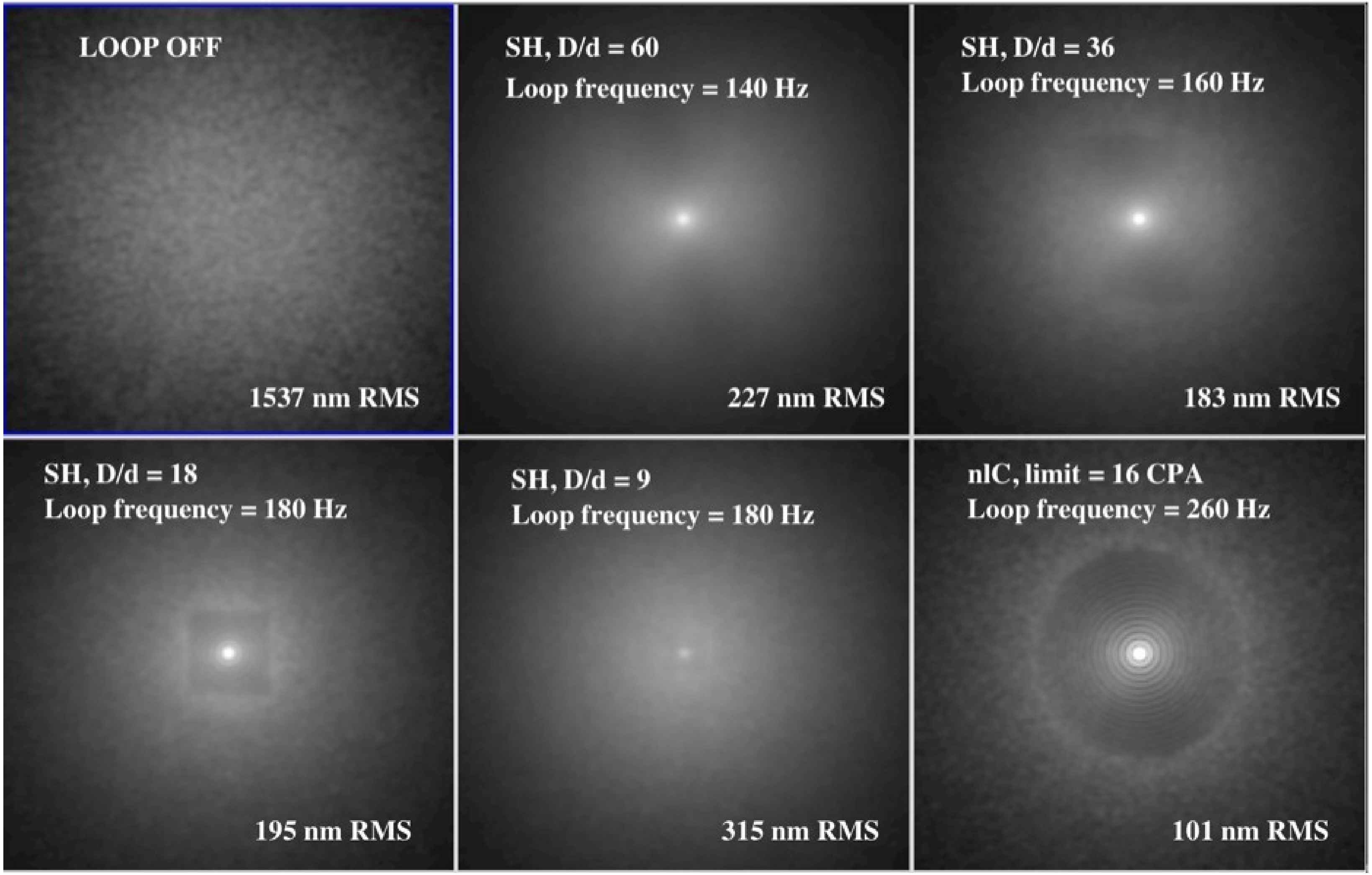


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

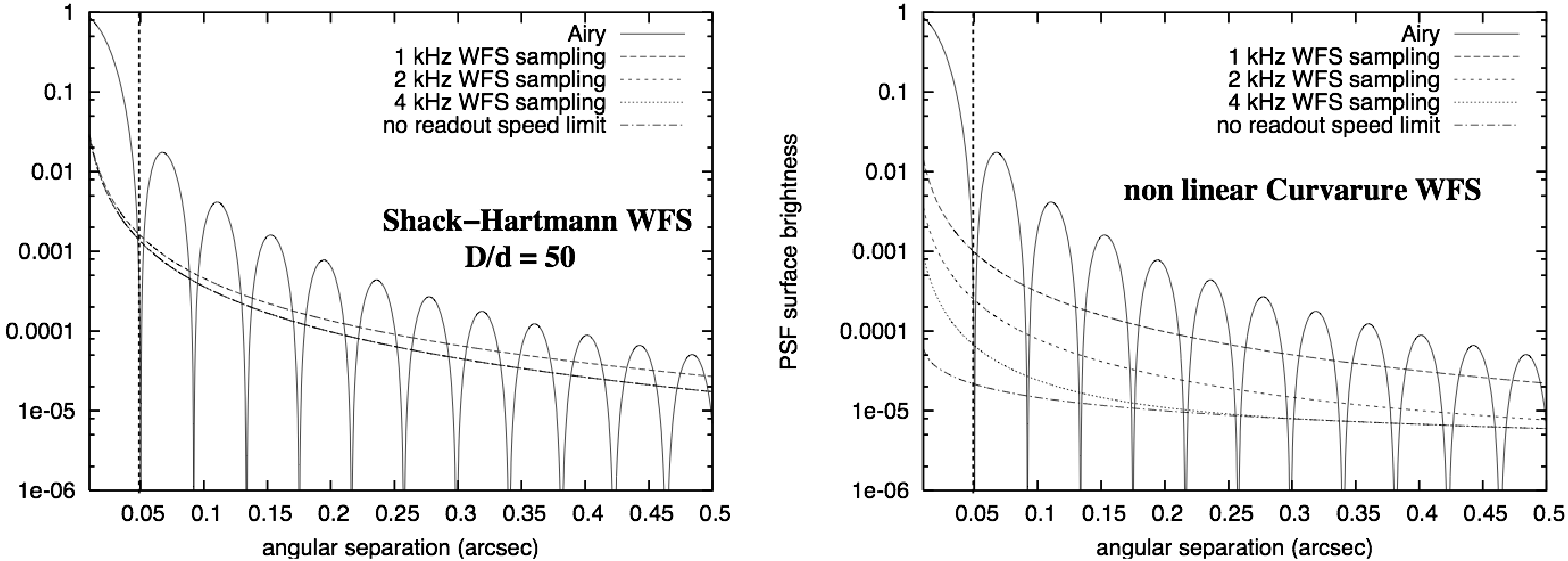
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

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%

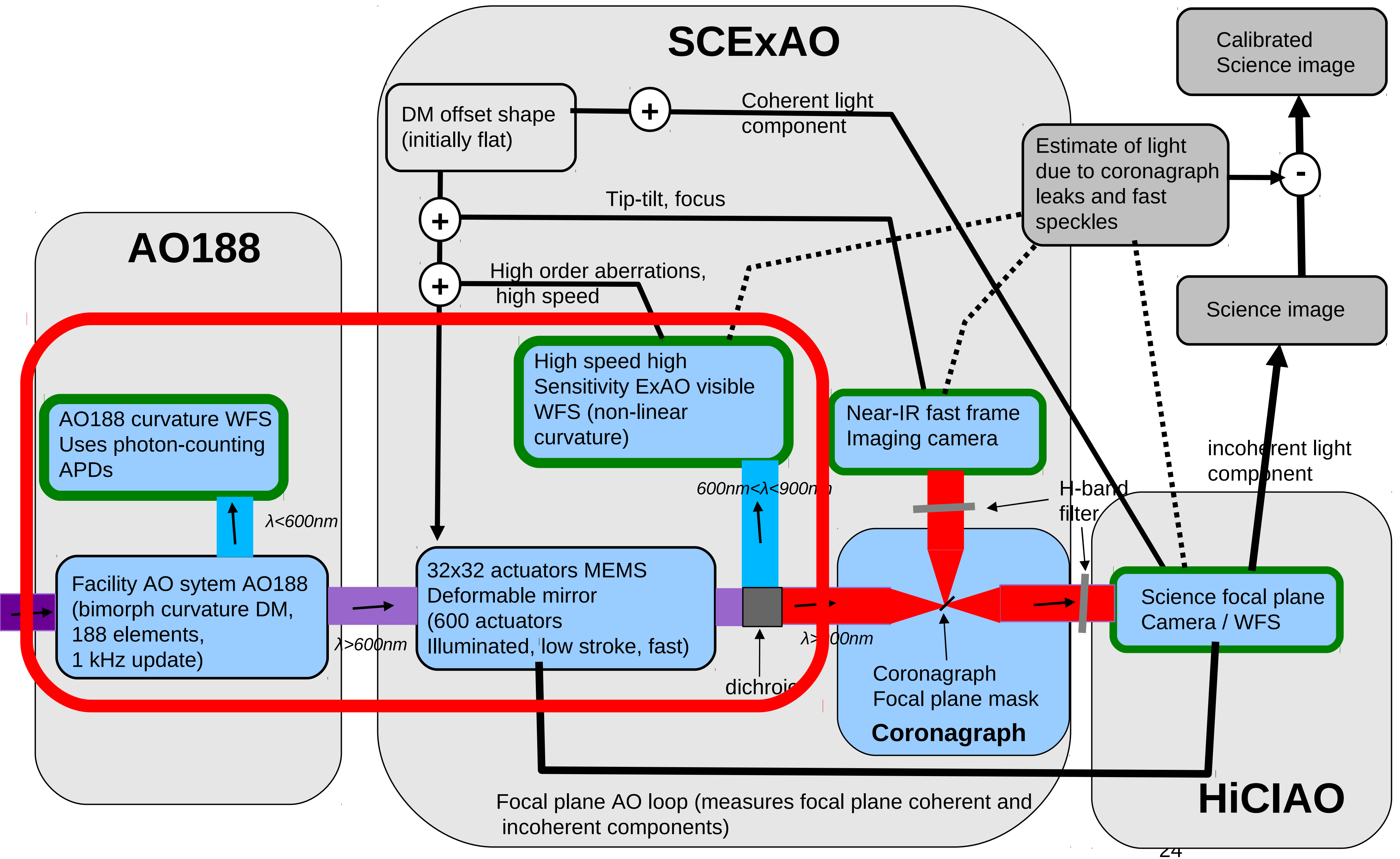
Performance gain for ExAO on 8-m telescopes



"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

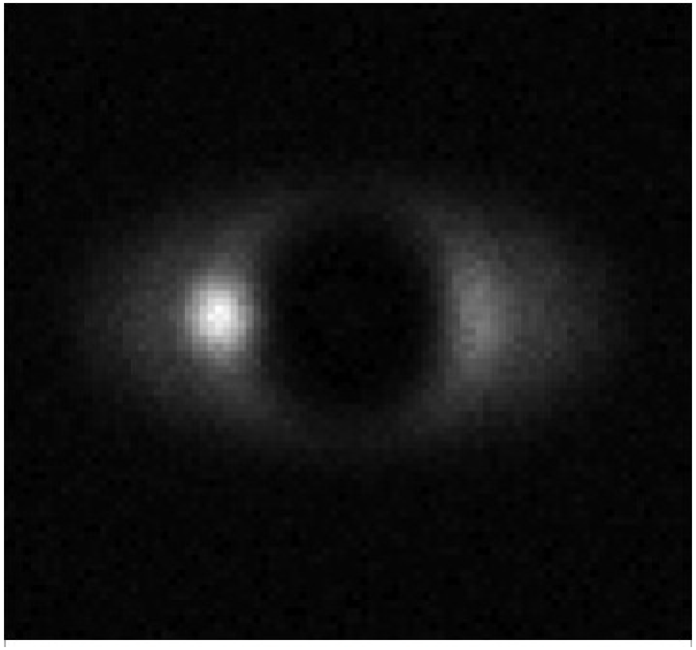
- differential atmospheric refraction (tip-tilt)
- chromatic propagation through atmosphere
- non-common path errors due to optics in SCExAO

→ **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

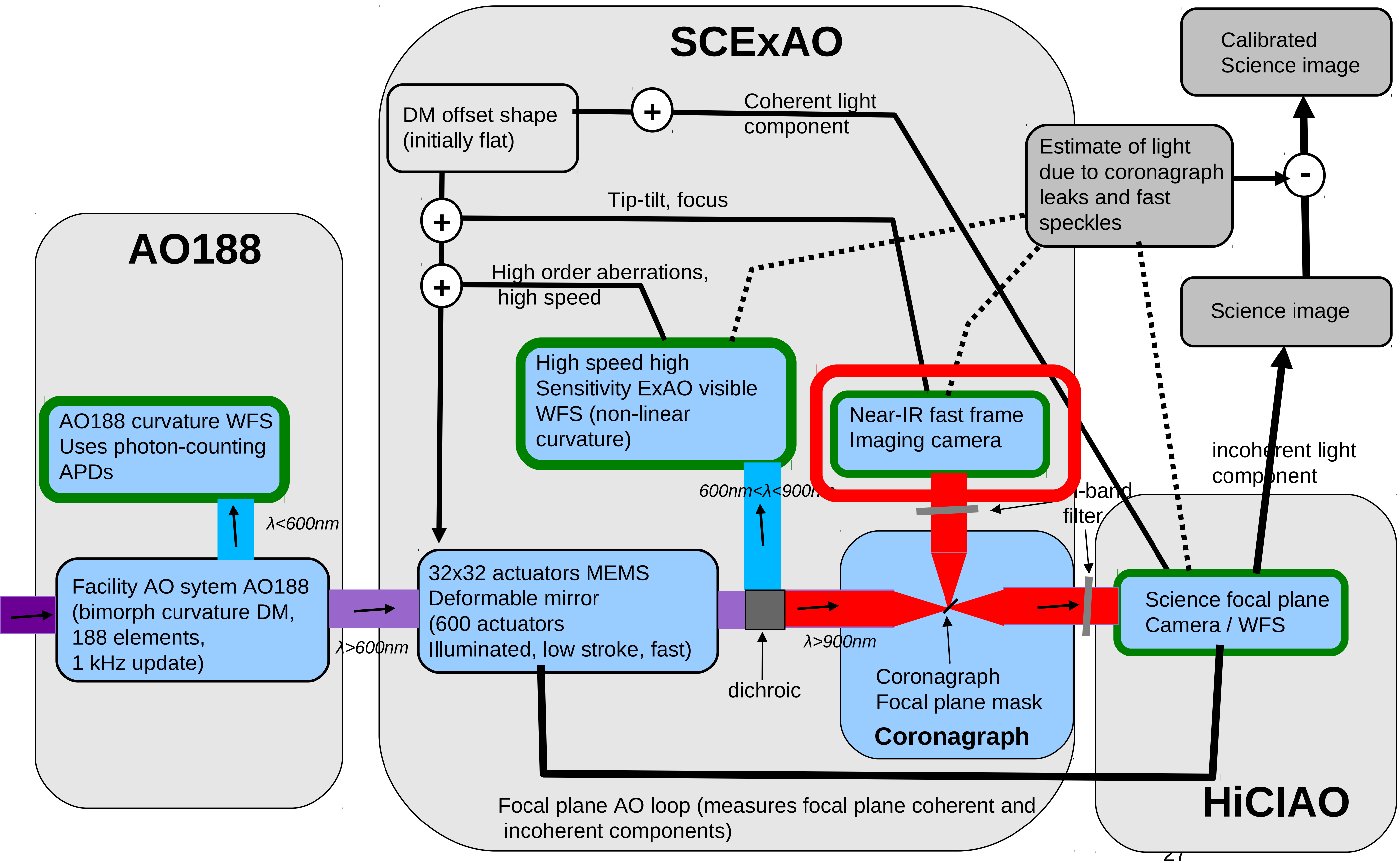
Pointing errors should be detected before they become large enough to induce a strong leak in the coronagraph

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)

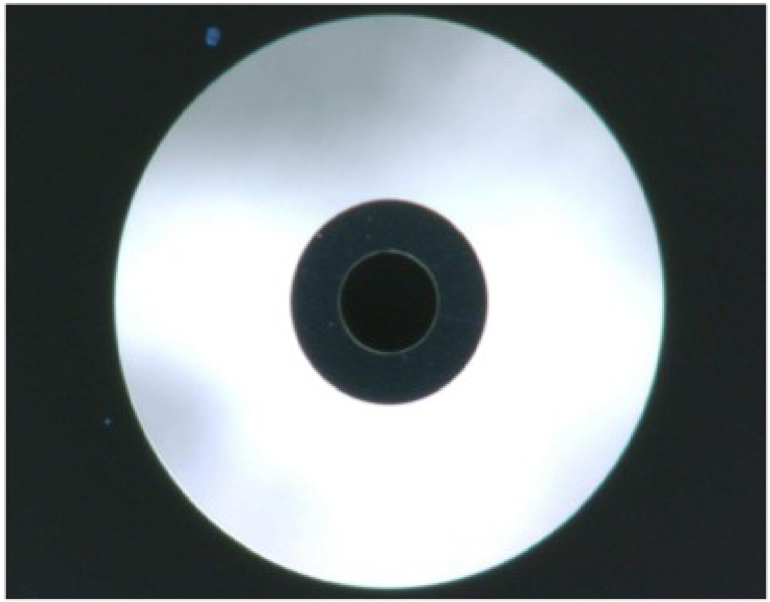
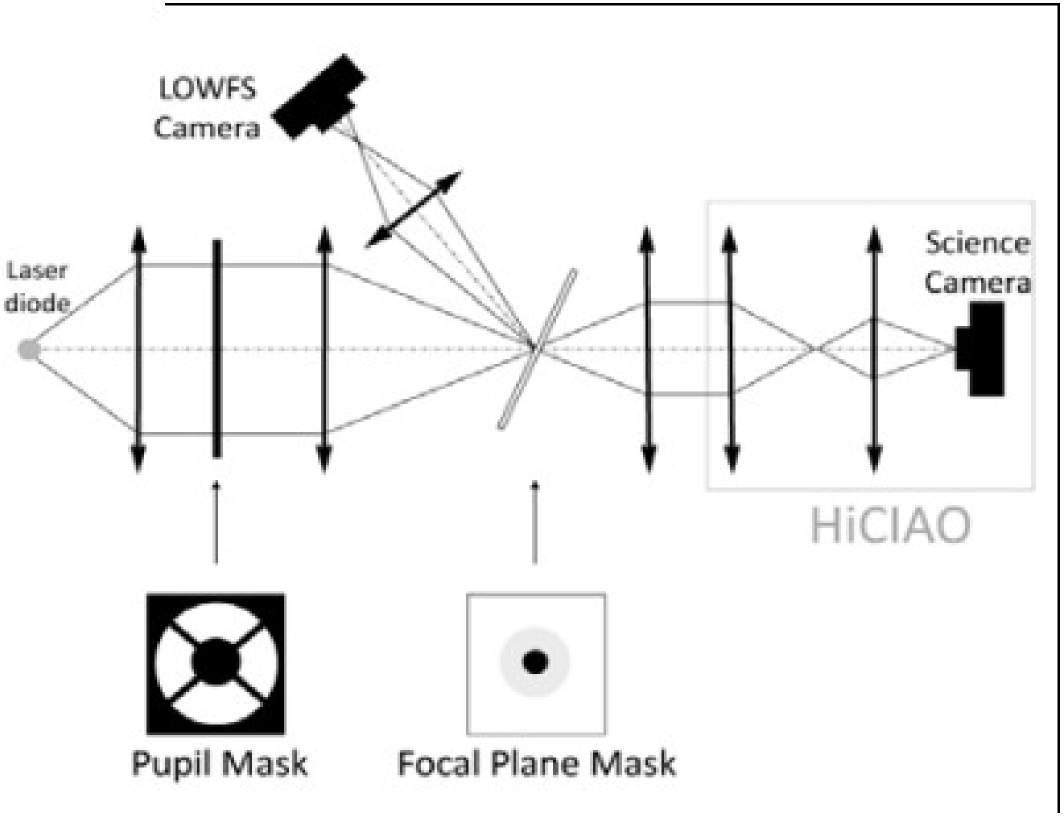
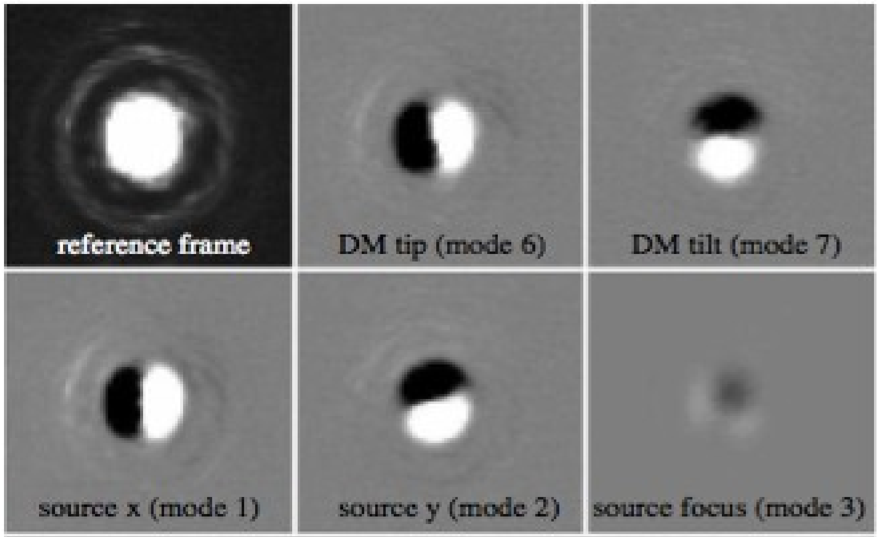
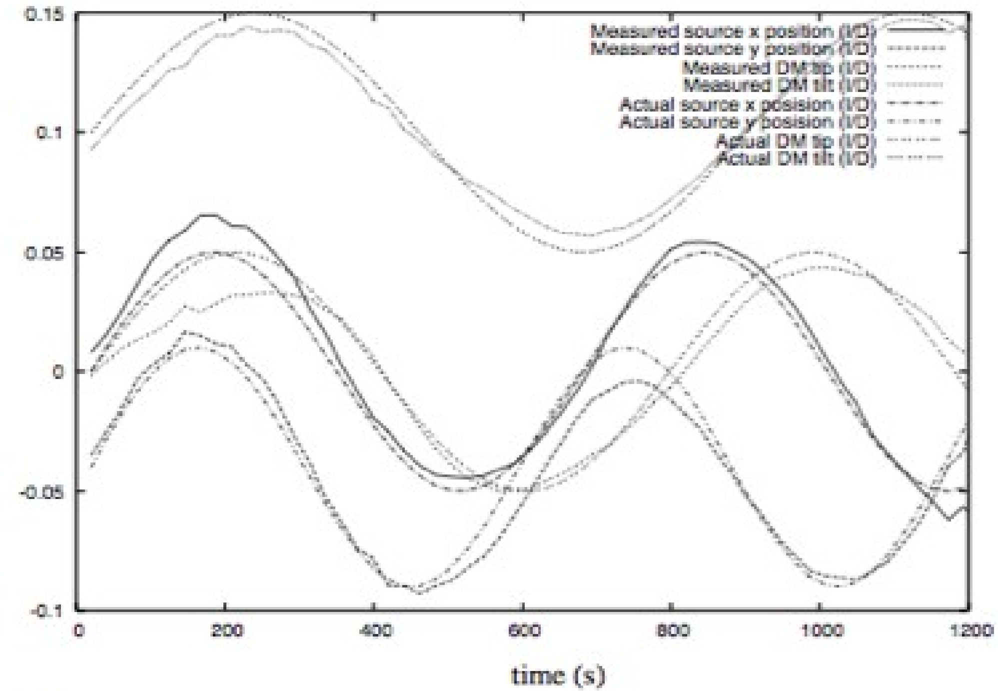


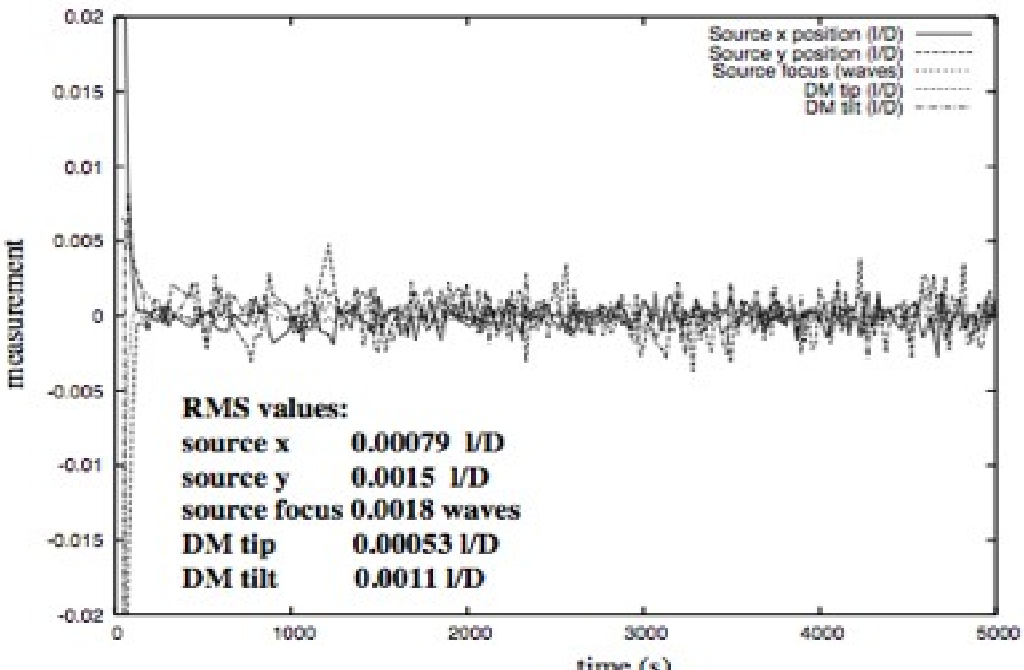
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

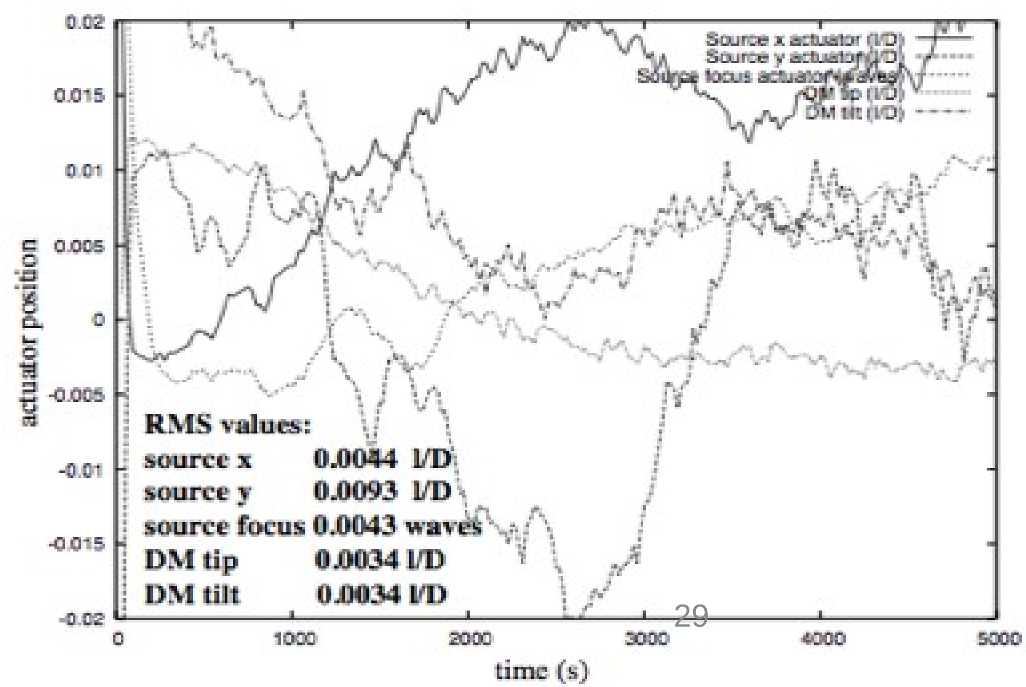


Pointing control demonstrated to 1e-3 λ/D in visible (this would be 0.02 mas on Subaru !!)

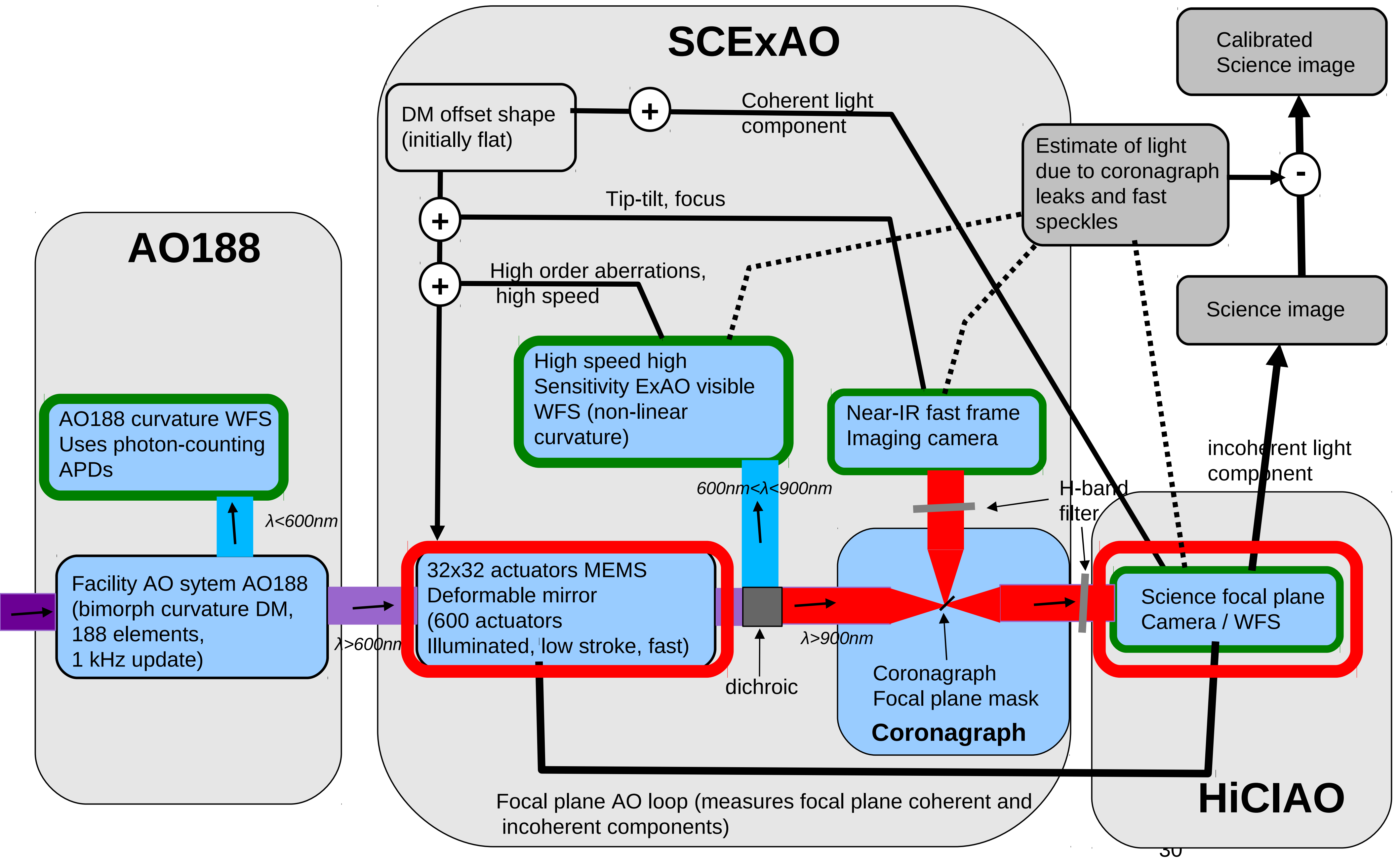




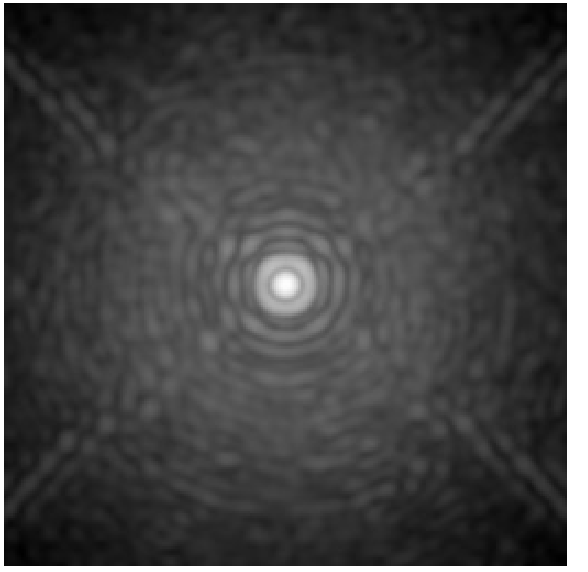




SCExAO focal plane WFS



Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

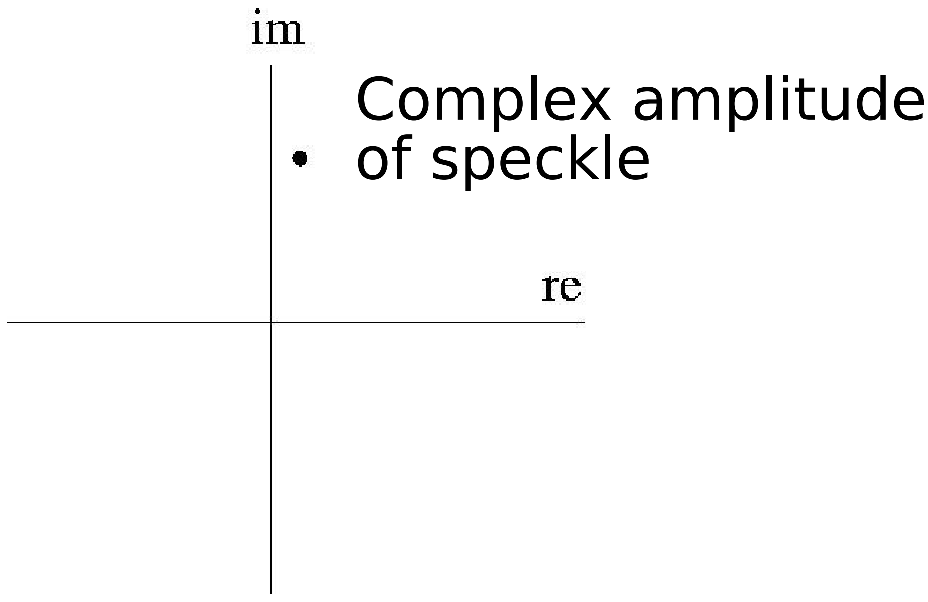
SENSING: Put “test speckles” to measure speckles in the image, watch how they interfere

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

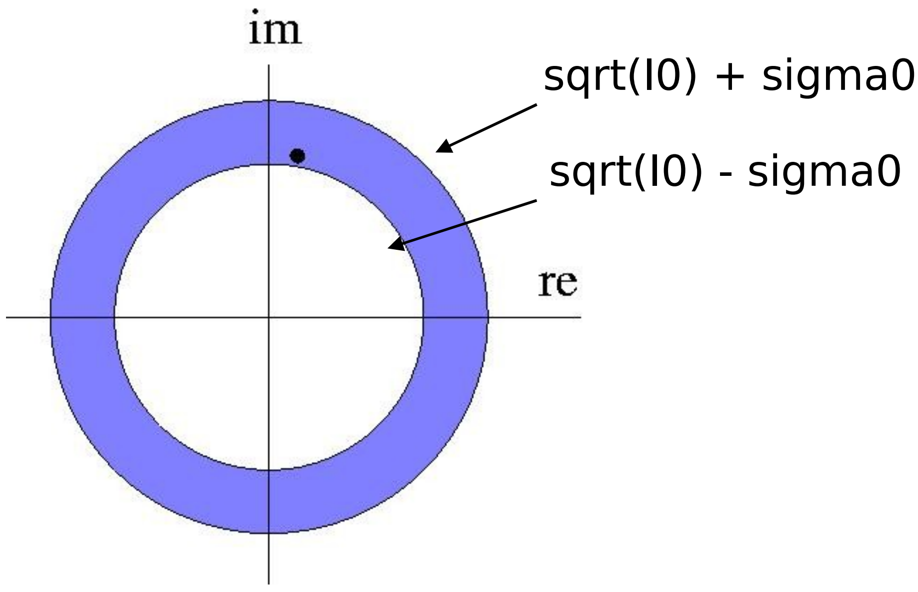
CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

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

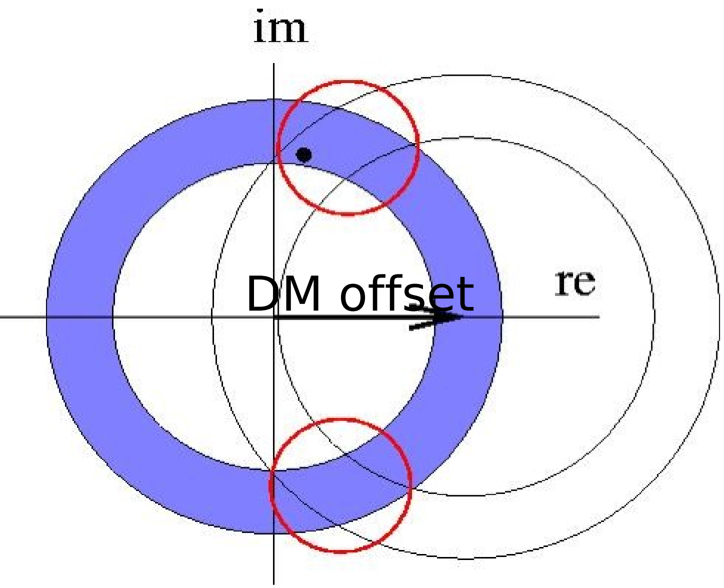
Initial problem

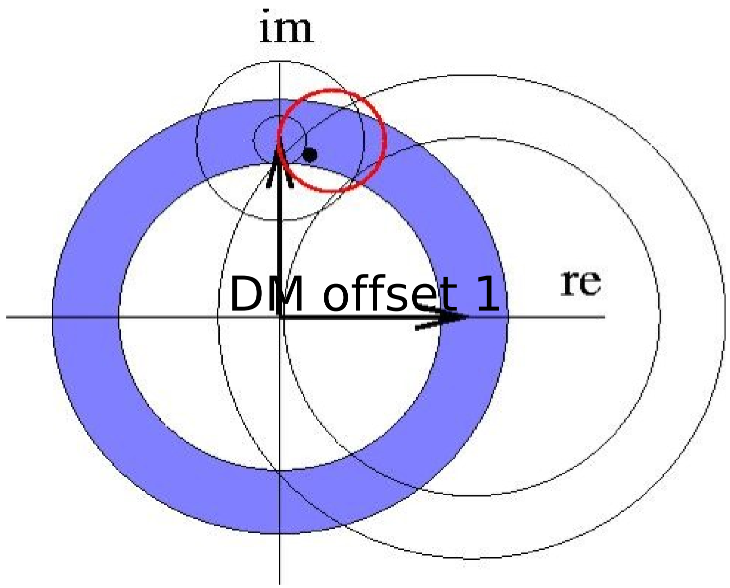


Take a frame -> measured speckle intensity = I0

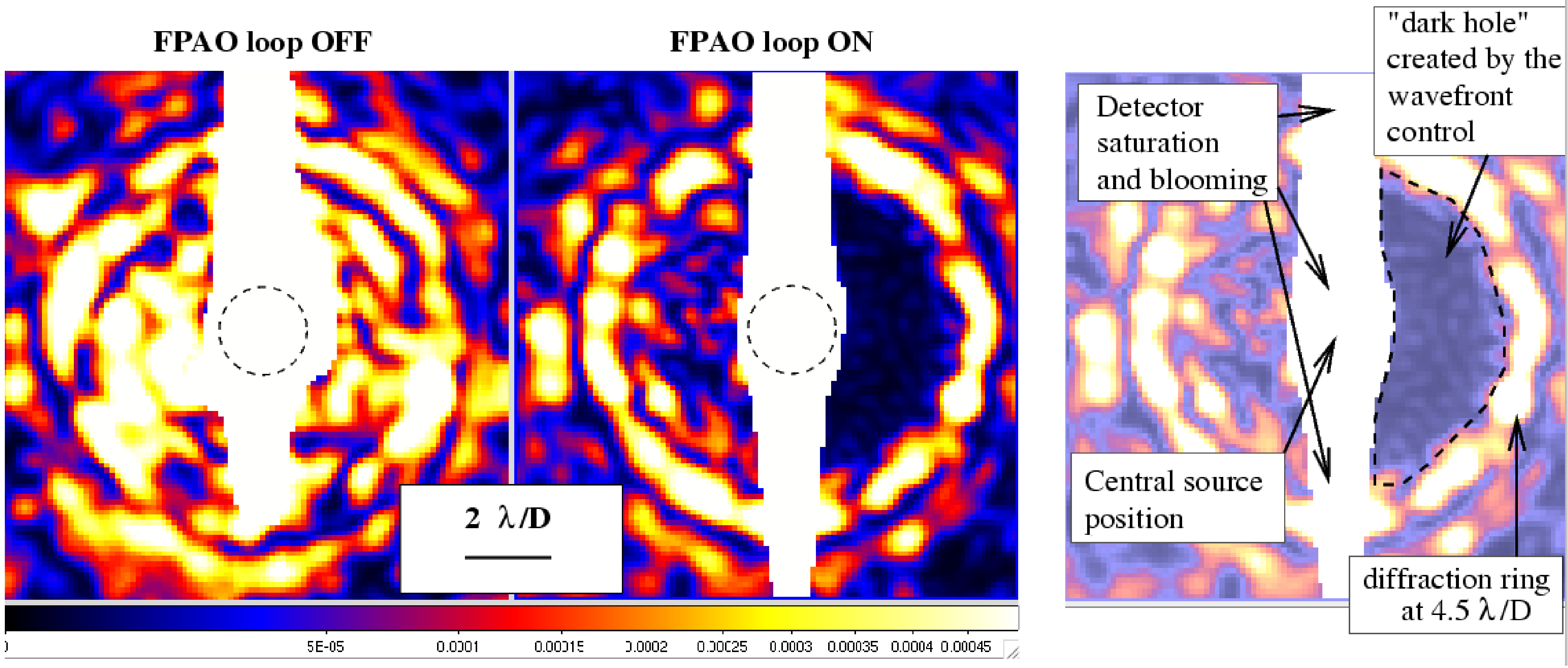


DM offset chosen to be ~ equal to speckle amplitude





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.

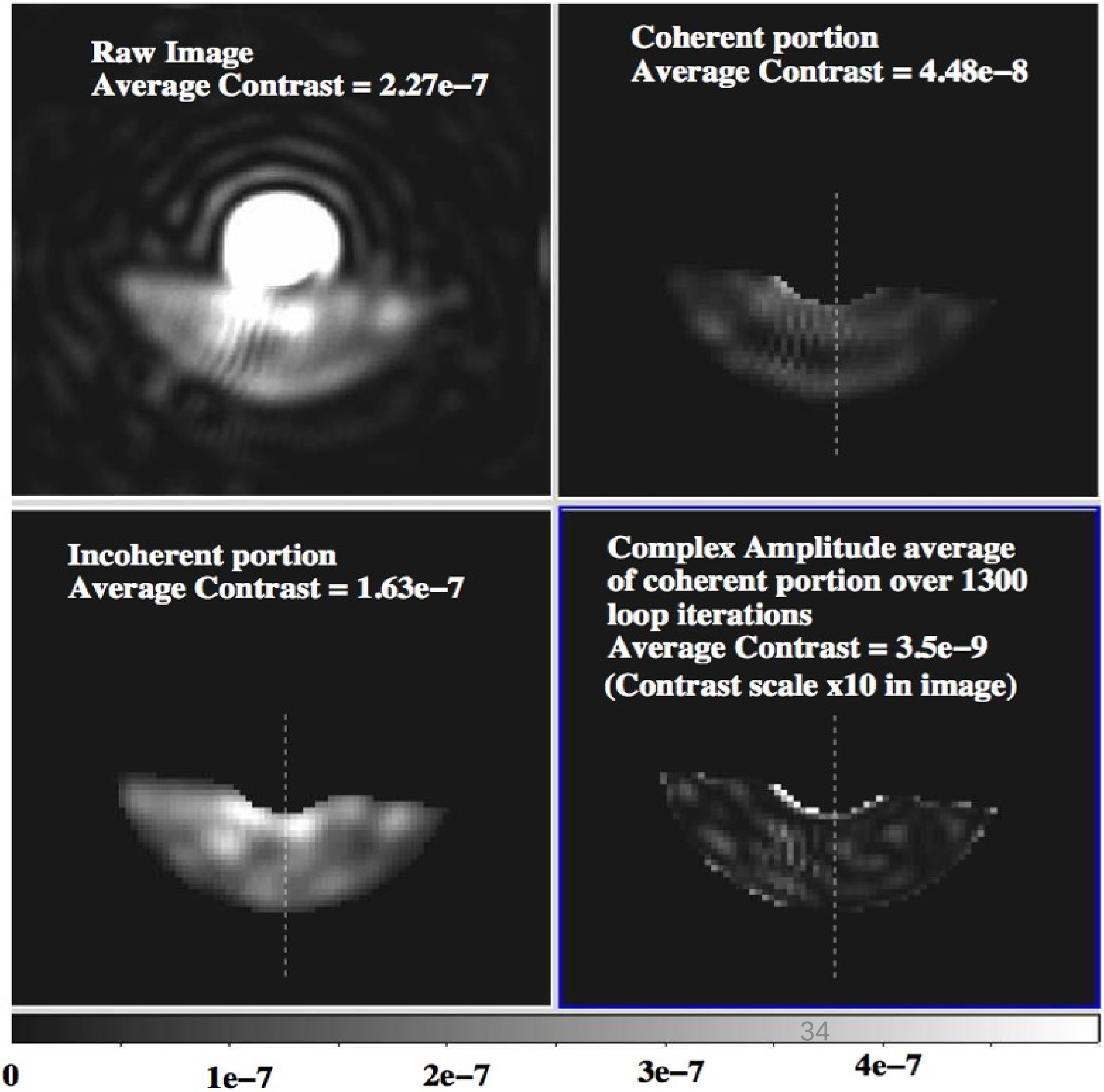
- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics

Focal plane WFS based correction and speckle calibration

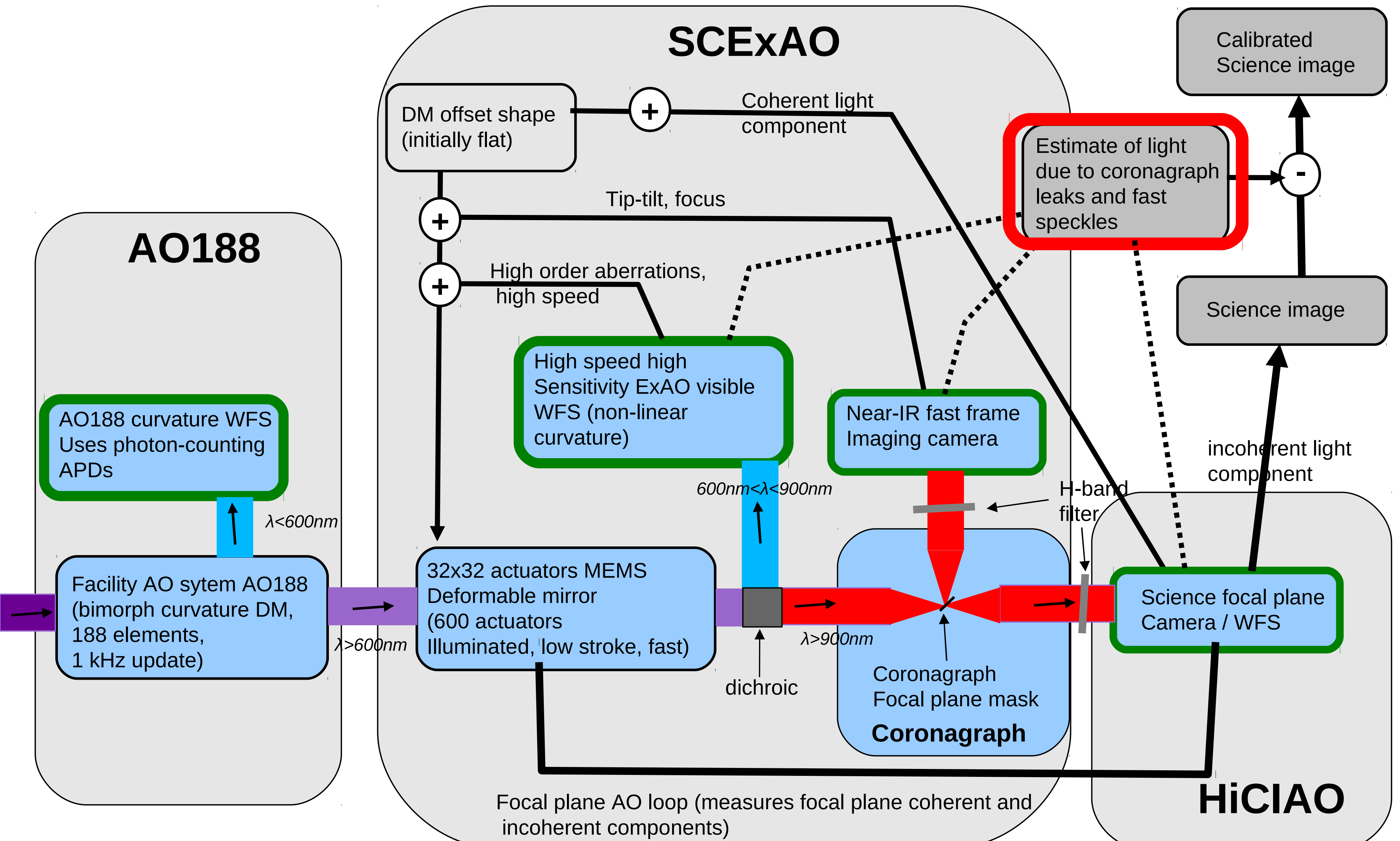
2e-7 raw contrast obtained at 2 λ/D

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



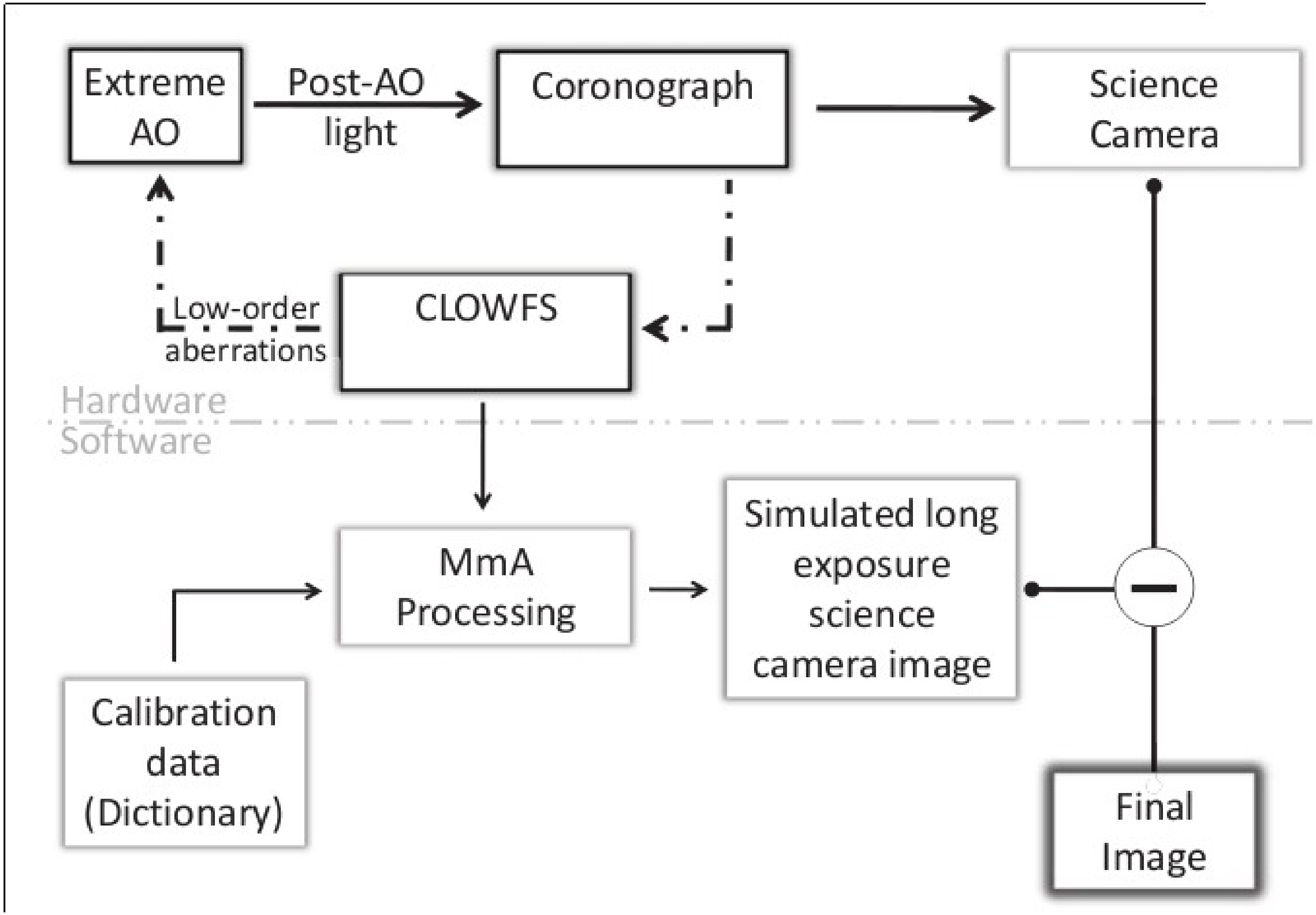
SCExAO residual light calibration



LOWFS post-processing: Principle

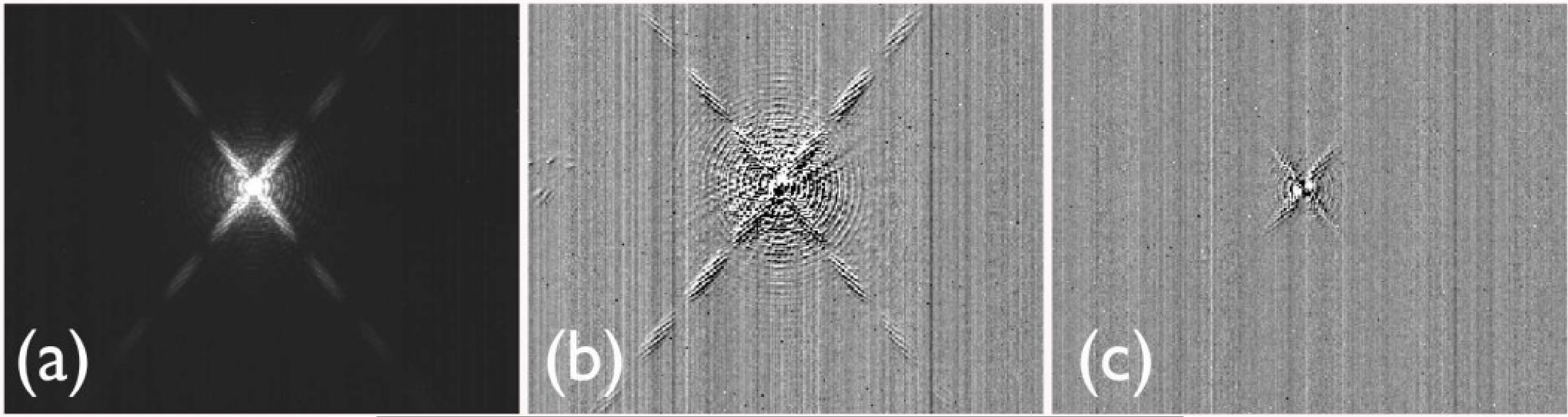
Use LOWFS data to estimate coronagraphic leaks in science image, and subtract them in post-processing
Challenge: how to model / link CLOWFS data with coronagraph leaks ?

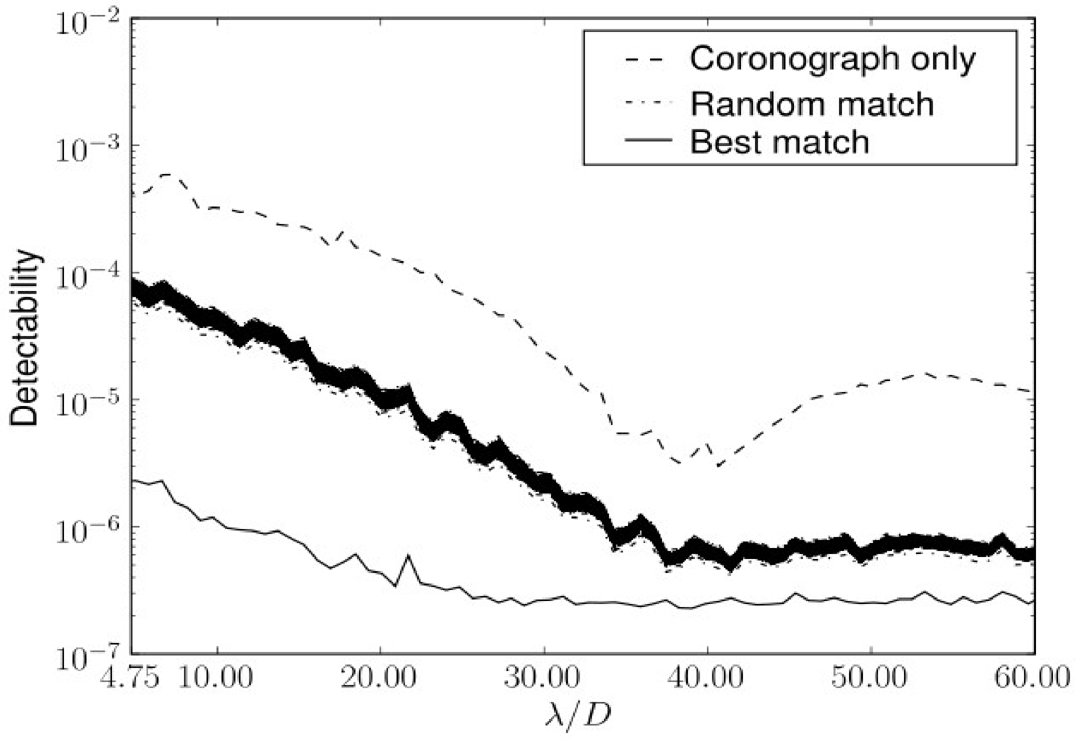
Solution:
Acquire and use a dictionary which stores the correspondance between LOWFS and science images



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

Co-added science image | Standard PSF subtraction | MMA





SCExAO schedule

SCExAO is currently in engineering phase

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

2[nd] nighttime engineering Jul 2011 (1 night): on-sky wavefront control, test coupling with HiCIAO

3[rd] nighttime engineering Sep 2011 (1 night): on-sky wavefront control + HiCIAO

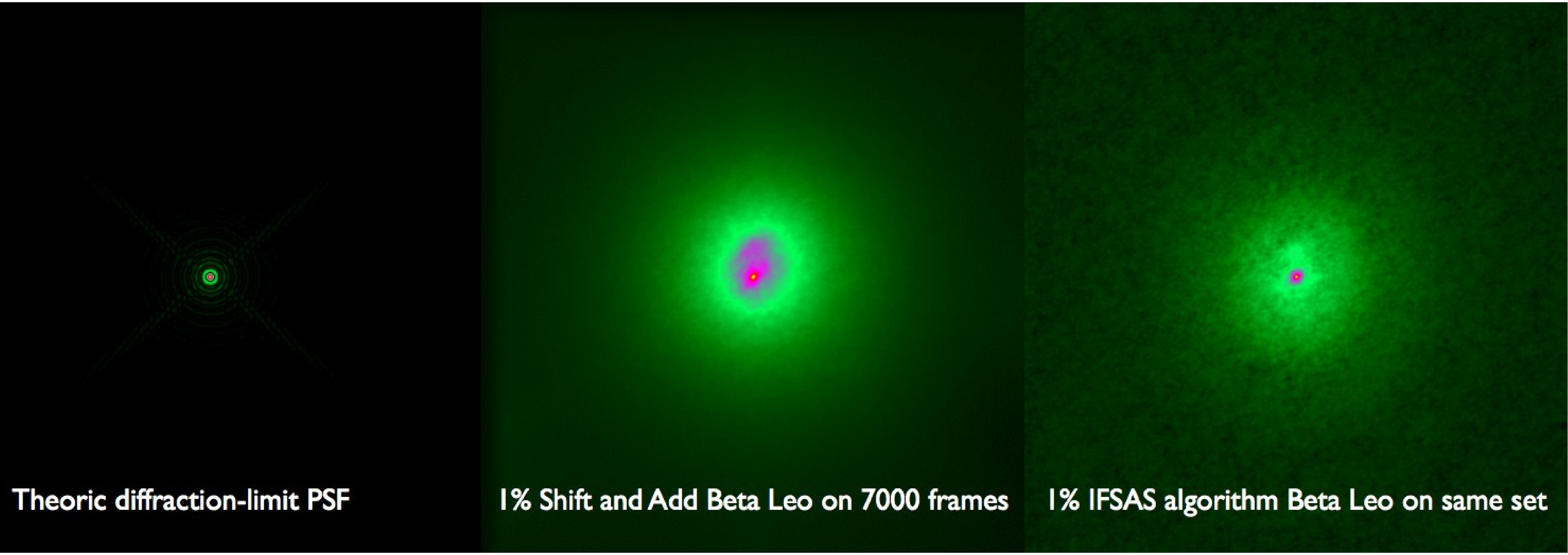
→ start of science observation with phase 1 system (no fast visible extreme AO WFS)

Detailed schedule uncertain due to Jul 2011 telescope hardware accident...

Phase 2: integrate ExAO visible WFS

SCExAO first visible images (V. Garrel PhD)

SCExAO acquired first visible light diffraction limited on Subaru in Feb 2011 run. Seeing was bad (variable from 1” to 2”) and some clouds, but selection + new Fourier-based reconstruction allowed diffraction-limited imaging.



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 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 ≠ static slow speckles + random halo which averages to a smooth halo in long exposures