Survey of Present and Future Ground-Based Imaging Systems

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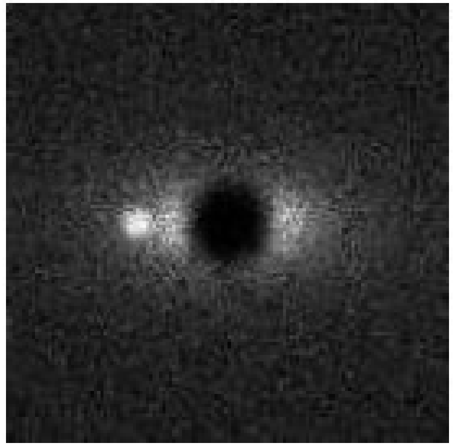
Subaru Telescope

With material from :
Rich Dekany, Ben Oppenheimer (Palm 3000, P1640)
Bruce Macintosh (Gemini Planet Imager)
+ HiCIAO, NICI, SPHERE

Direct imaging of Exoplanets allows extensive characterization



Orbit

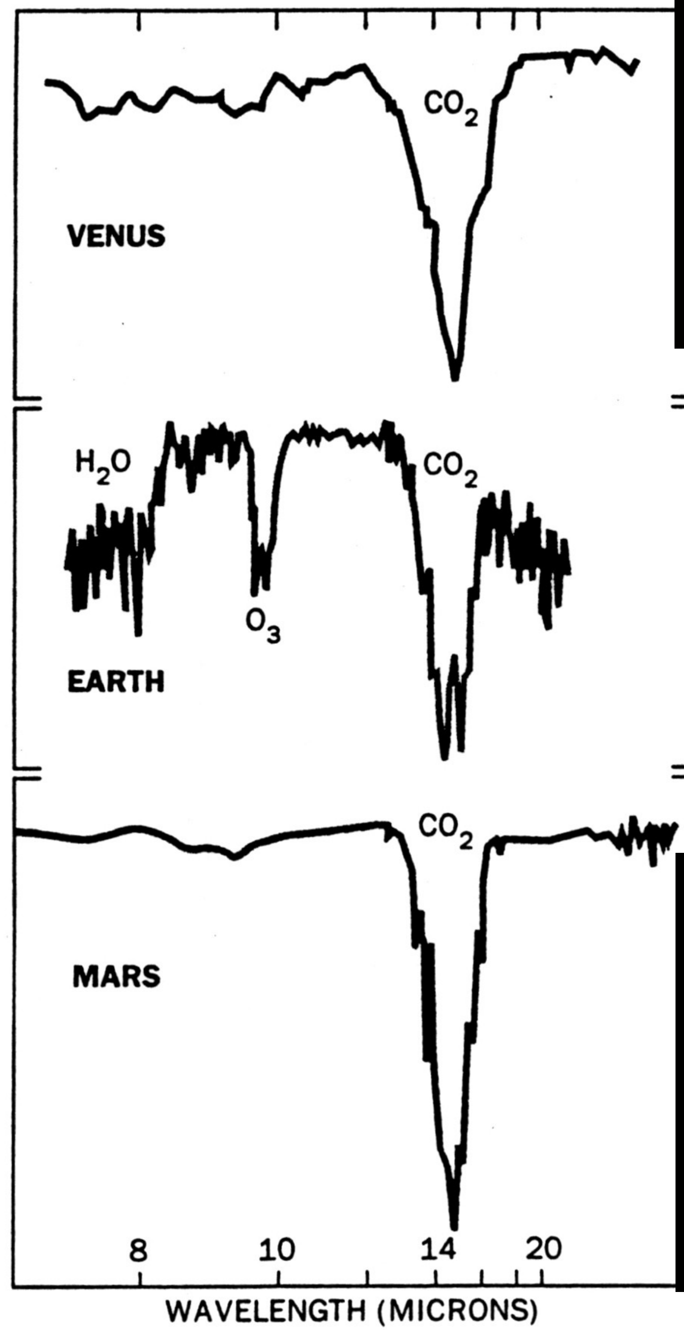
Atmosphere composition

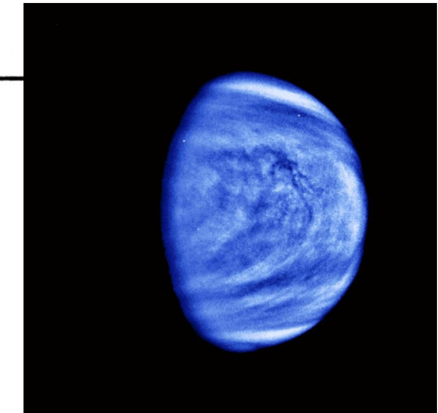
Continents vs. Oceans ?

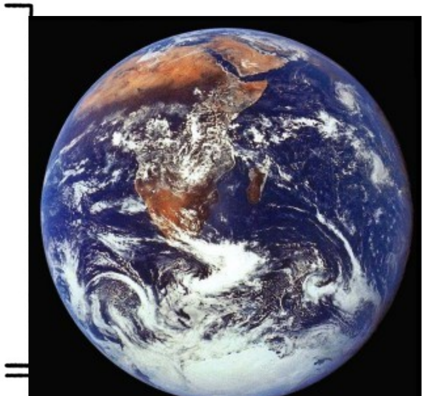
Rotation period

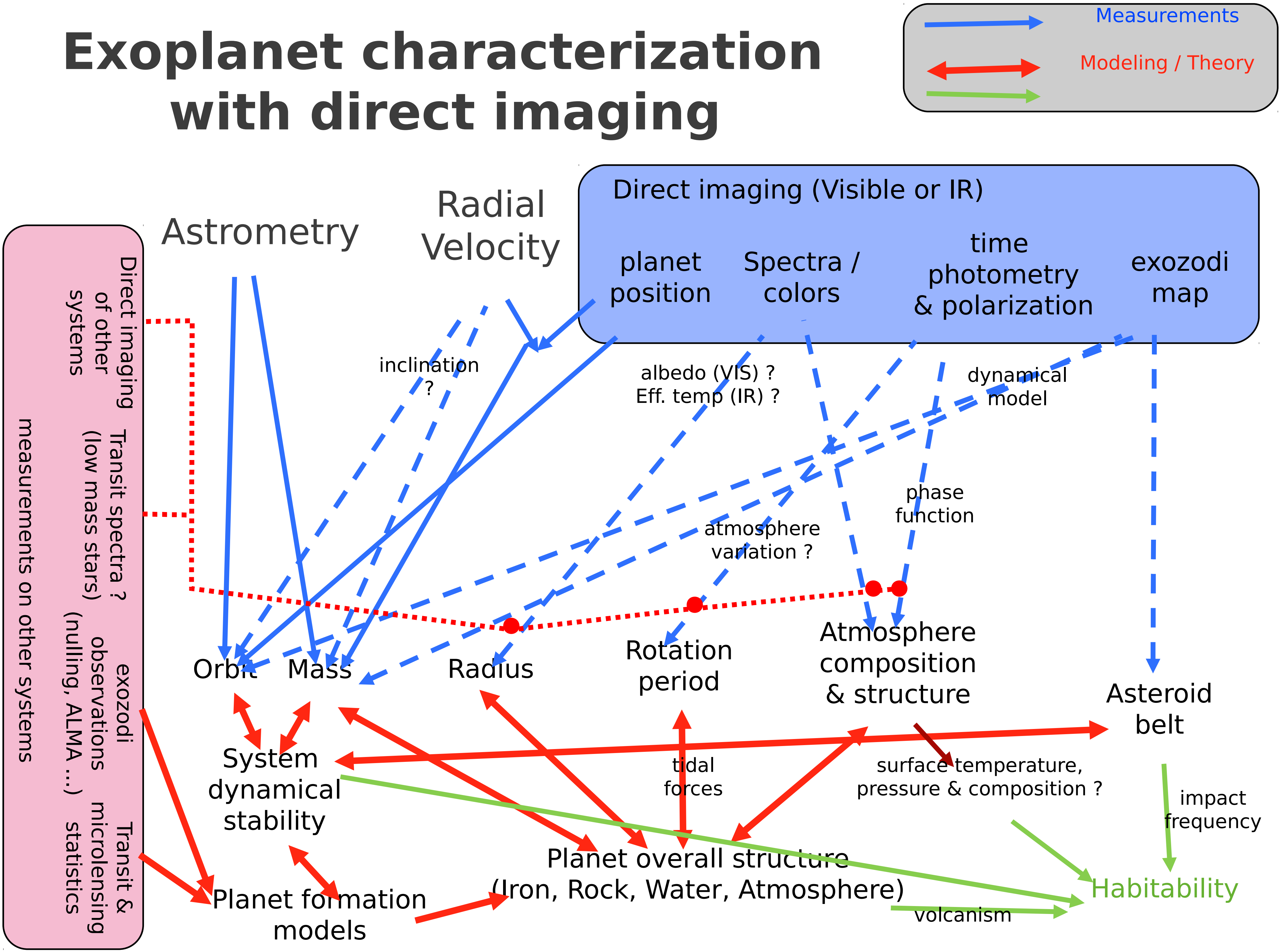
Weather patterns

Planetary environment :
Planets + dust





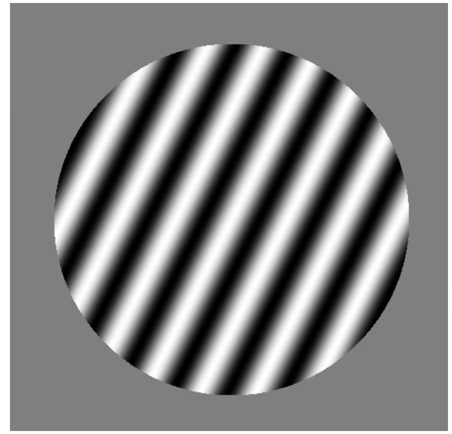



Exoplanet characterization
with direct imaging
Measurements
Modeling / Theory
Direct imaging (Visible or IR)
planet position
Spectra / colors
time photometry & polarization
exozodi map
Astrometry
Radial Velocity
Direct imaging of other systems
Transit spectra ? (low mass stars)
exozodi observations (nulling, ALMA ...)
Transit & microlensing statistics
measurements on other systems
inclination ?
albedo (VIS) ?
Eff. temp (IR) ?
dynamical model
phase function
atmosphere variation ?
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure & composition ?
impact frequency
Planet overall structure
(Iron, Rock, Water, Atmosphere)
Planet formation models
Habitability
volcanism

Why is it difficult ?
(even in space)

pupil plane complex amplitude

$$W(\vec{u}) = A(\vec{u})\, e^{i\phi(\vec{u})}$$



Cosine aberration in pupil phase

$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

… creates 2 speckles

$$I(\vec{\alpha}) = PSF(\vec{\alpha}) + \left(\frac{\pi h}{\lambda}\right)^2 \left[PSF(\vec{\alpha}+\vec{f}\lambda) + PSF(\vec{\alpha}-\vec{f}\lambda)\right]$$

High Contrast

Small angular separation

Low Flux

What would it take to image an Earth-like planet around Sun-like star at 10pc ?

~1e-10 contrast in visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

1e-10 speckle (or 1e-10 contrast planet) around Sun at 10pc = 0.1 ph/sec/m^2/um

On a 4-m telescope, with 10% efficiency and a 0.5 um spectral band:

Earth = 0.6 ph/sec

To measure phase and amplitude of speckle requires ~10 photon

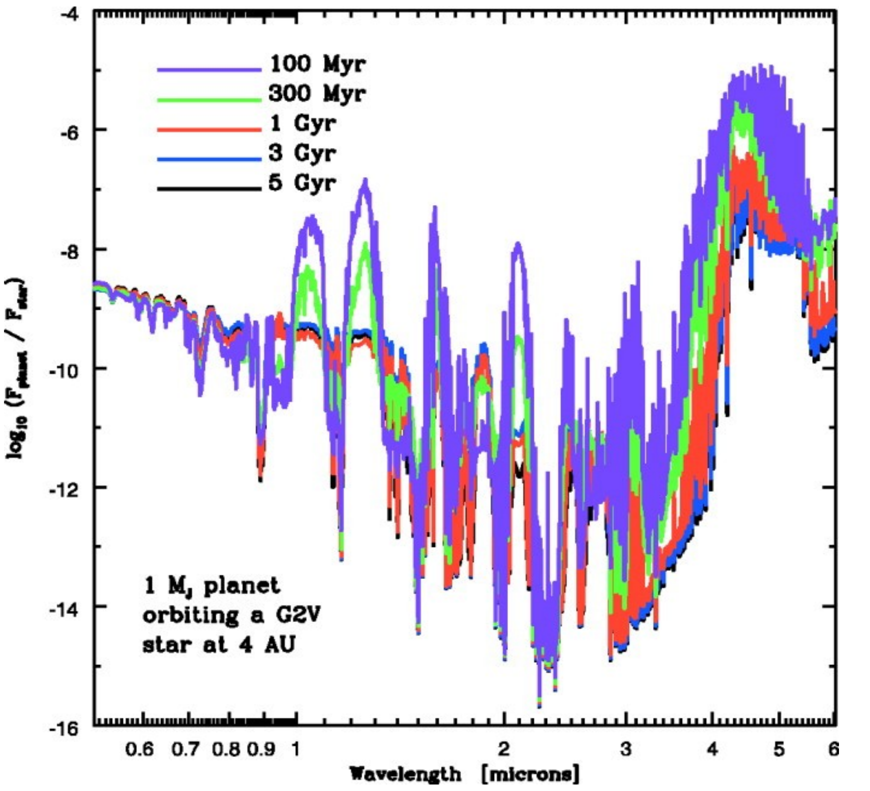
10 photon = 16 sec

→ This spatial frequency would need to be stable to 1/1000 nm over ~ minute

(in near-IR, 1e-7 contrast → h = 0.16 nm)

Exoplanets: Contrast ratio, visible vs. infrared

In the visible, the contrast is very challenging unless the exoplanet is very close to the star (luminosity goes as d^{-2})
Required wavefront quality cannot be achieved from the ground. Habitable planets cannot be imaged from the ground, and will likely require dedicated space telescope+instrument.



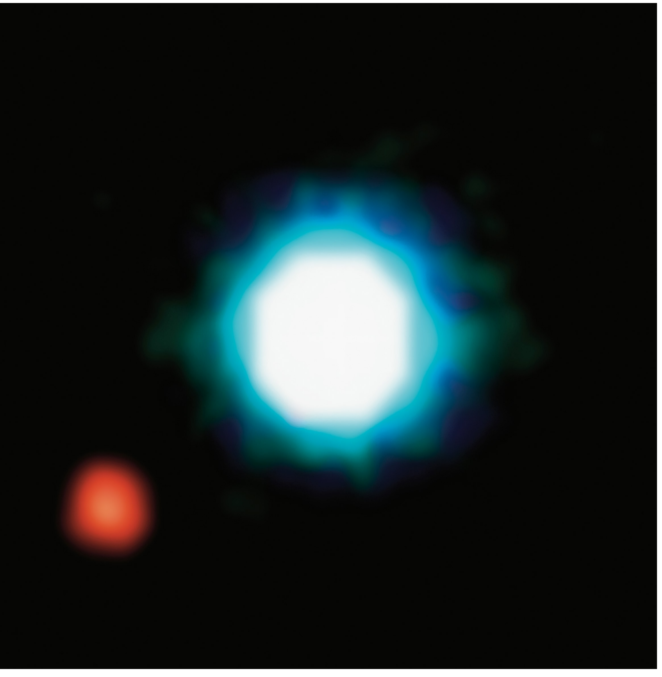
Burrows et al. 2004

In the near-IR (1-5 um), giant and young planets
•(“young Jupiters”) can be imaged:
• Adaptive Optics systems work well in the near-IR
• Giant planets emit their own light (thermal emission)
• Young planets are still very hot, and cool slowly after formation

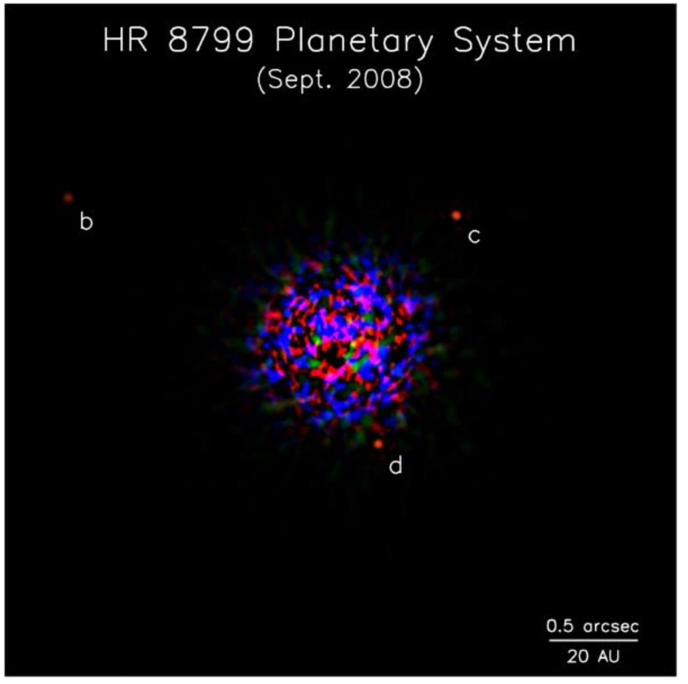
Best strategy for Ground-based imaging

In the Thermal IR (~10 um & longer), contrast is even more favorable, and older giant planets can be imaged (this is one of the key science goals of JWST)

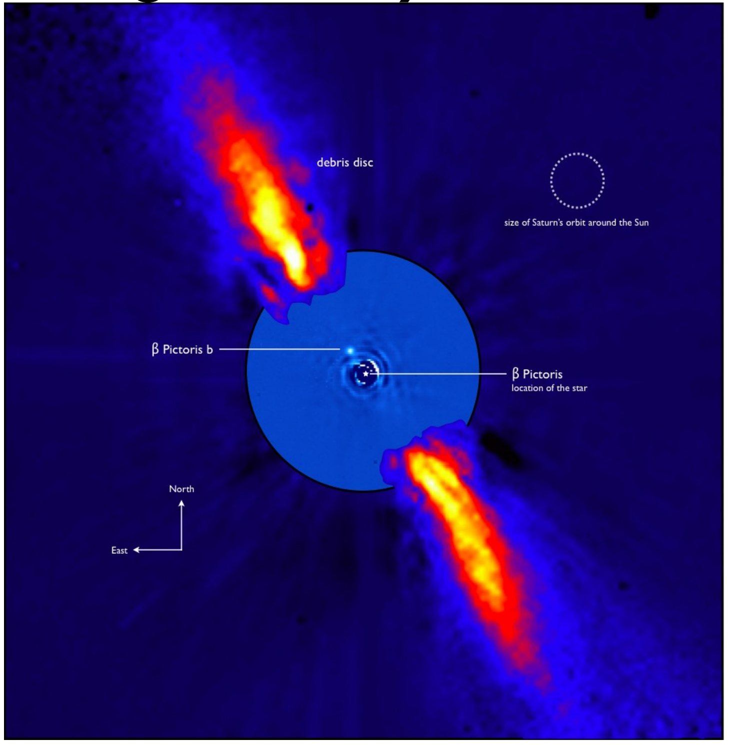
Exoplanets imaged with ground-based telescopes
… tip of the iceberg (Young, massive, and large orbits)



2M1207 exoplanet (Chauvin et al., ESO, 2004)
Possibly the first direct image of an exoplanet



HR8799: first image of exoplanetary sytem with multiple planets
(Marois et al. 2009)



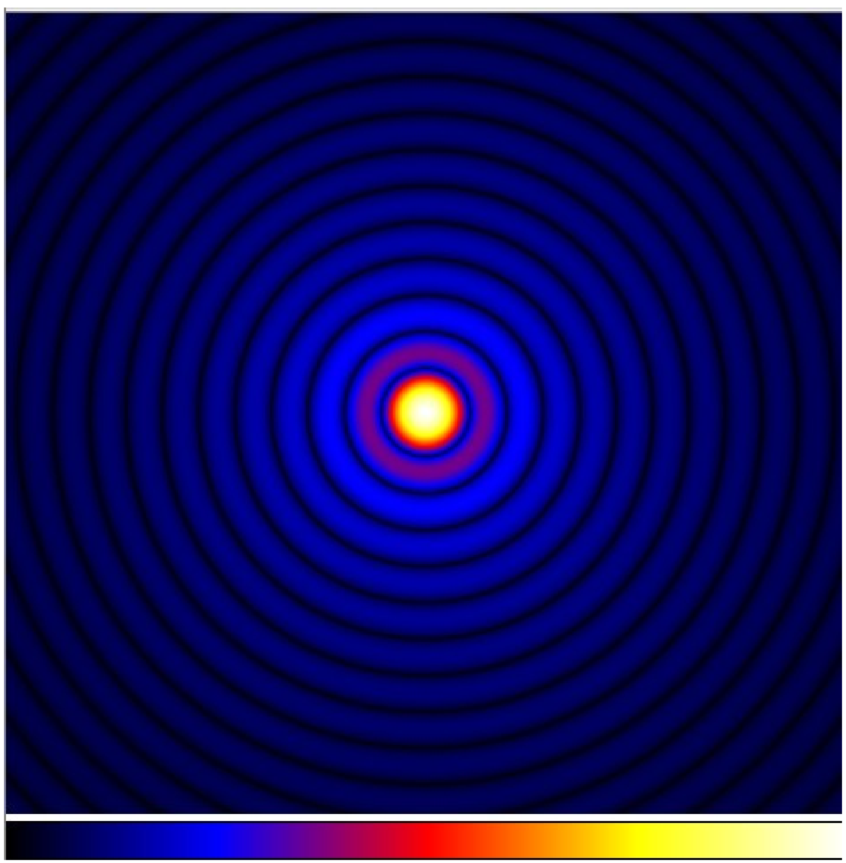
Beta Pic exoplanet and dust disk (Lagrange et al. 2009)

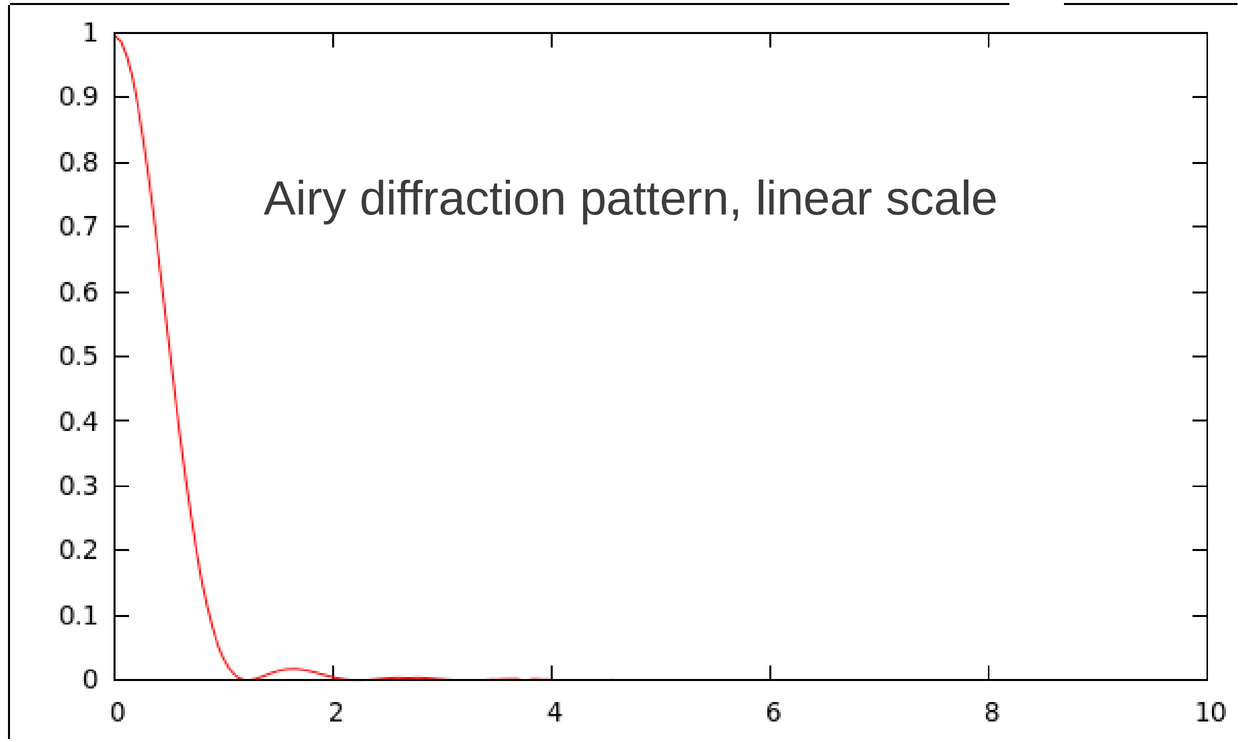
… using AO systems and camera which were not specifically designed for high contrast imaging (but often using optimized data acquisition and reduction techniques)

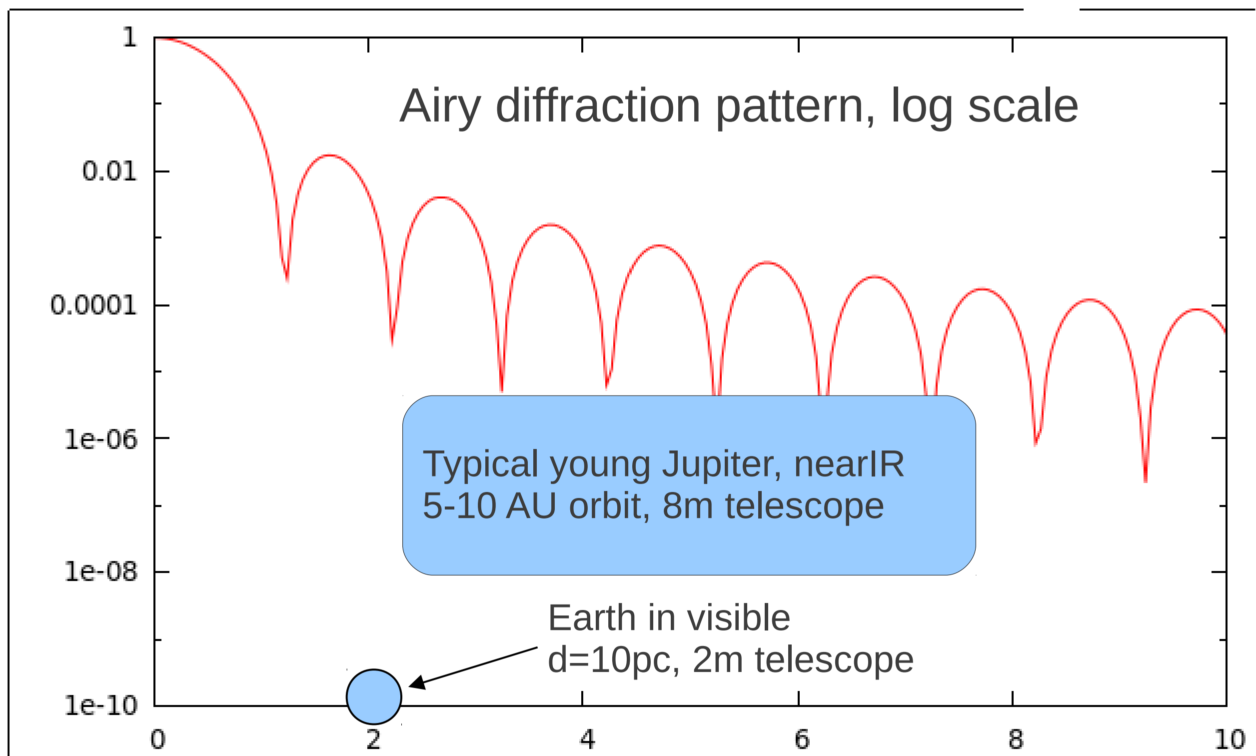
No coronagraph was used (in fact, coronagraphs are mostly useless on current AO systems)

Why coronagraphy ?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction





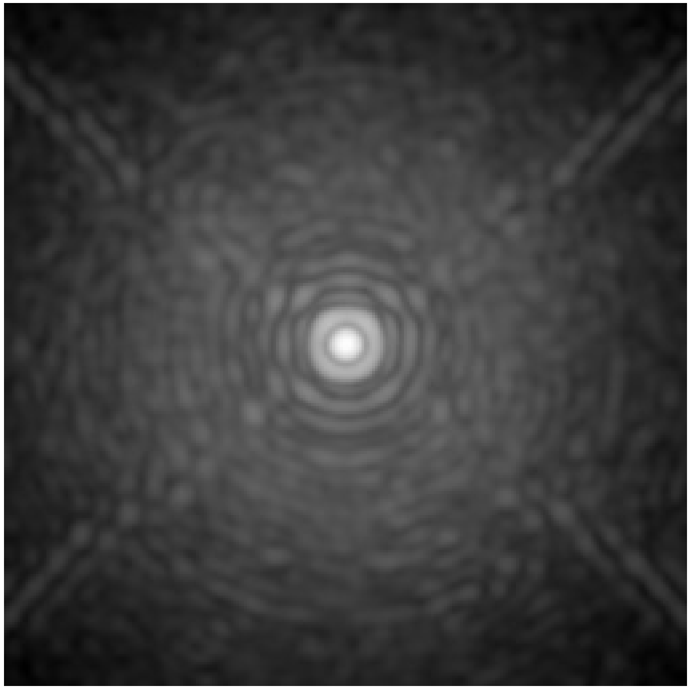


Why are coronagraphs (mostly) useless ?

A coronagraph can only remove a known & static diffraction pattern
Coronagraphs can’t remove unknown (when the coronagraph is designed) diffraction (including speckles due to WF errors)
BUT static & known diffraction can be removed in the computer ?

Two fundamental reasons why a coronagraph is useful:
(1) Reduce photon noise from diffraction
(2) Avoid coherent amplification between speckles and diffraction pattern

Coronagraphs serve no purpose if the dynamic speckle halo (due to residual wavefront errors) is higher than the static diffraction (due to pupil shape)
... which is the regime under which most current AO systems operate.



Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

This equation is true in complex amplitude, not in intensity.

Intensity image will have product term → speckles are amplified by the PSF diffraction.

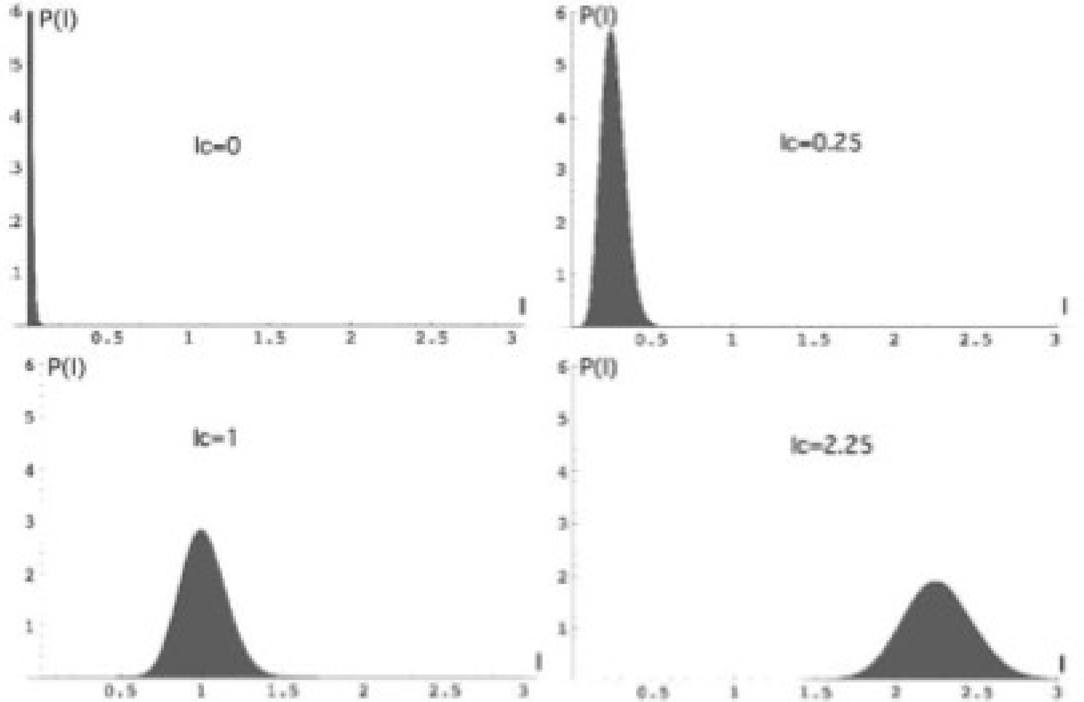
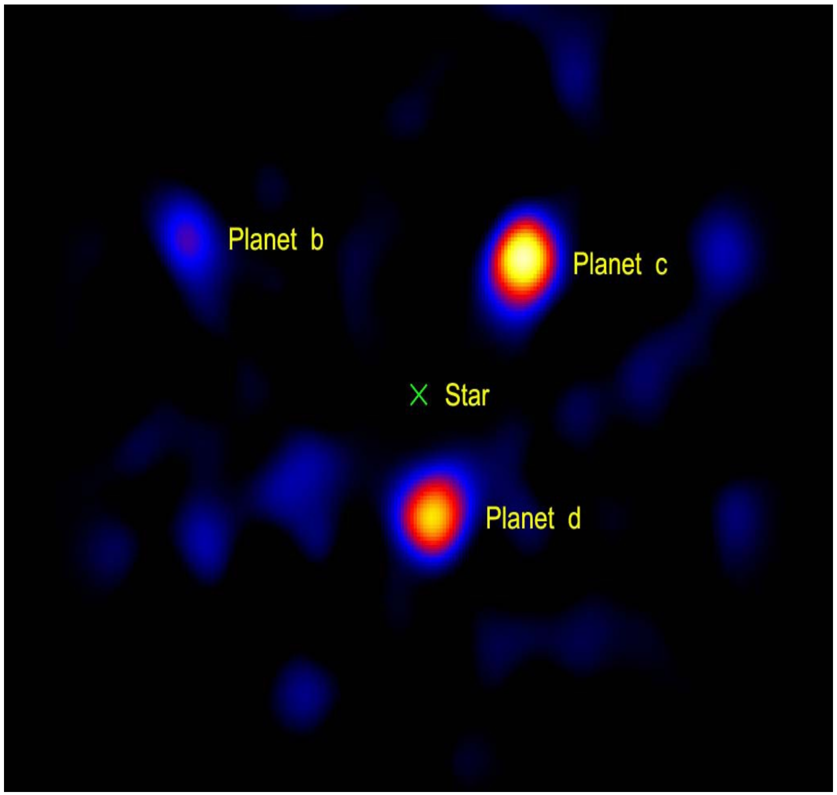
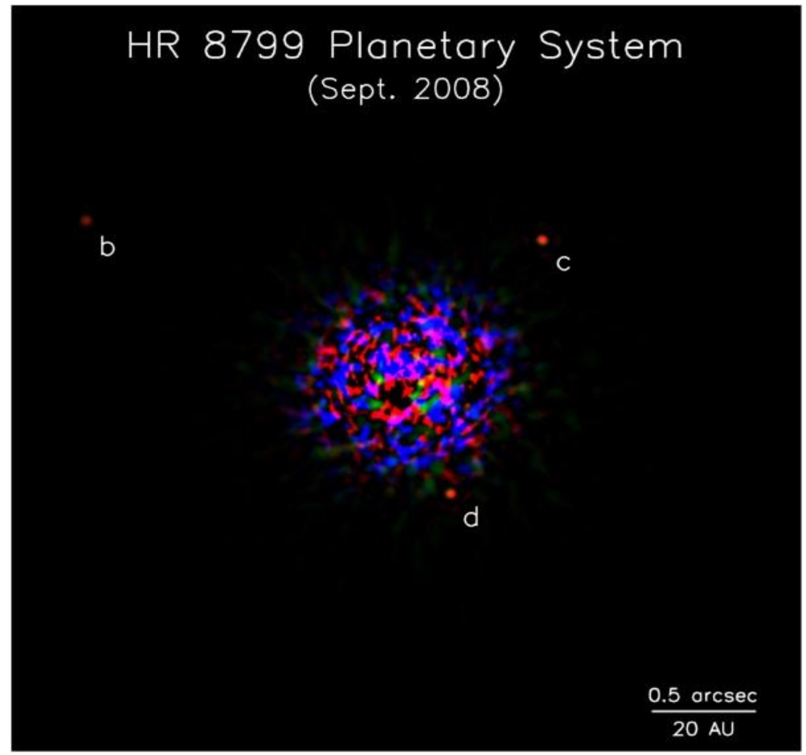


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from the core. For $I_c = 0$ we have the pure speckle exponential statistics. The width of the distribution increases with an increase in the level of I_c. This explains speckle pinning; speckle fluctuations are amplified by the coherent addition of the perfect part of the wave.

Aime & Soummer 2004

Need for good AO correction and good coronagraphs

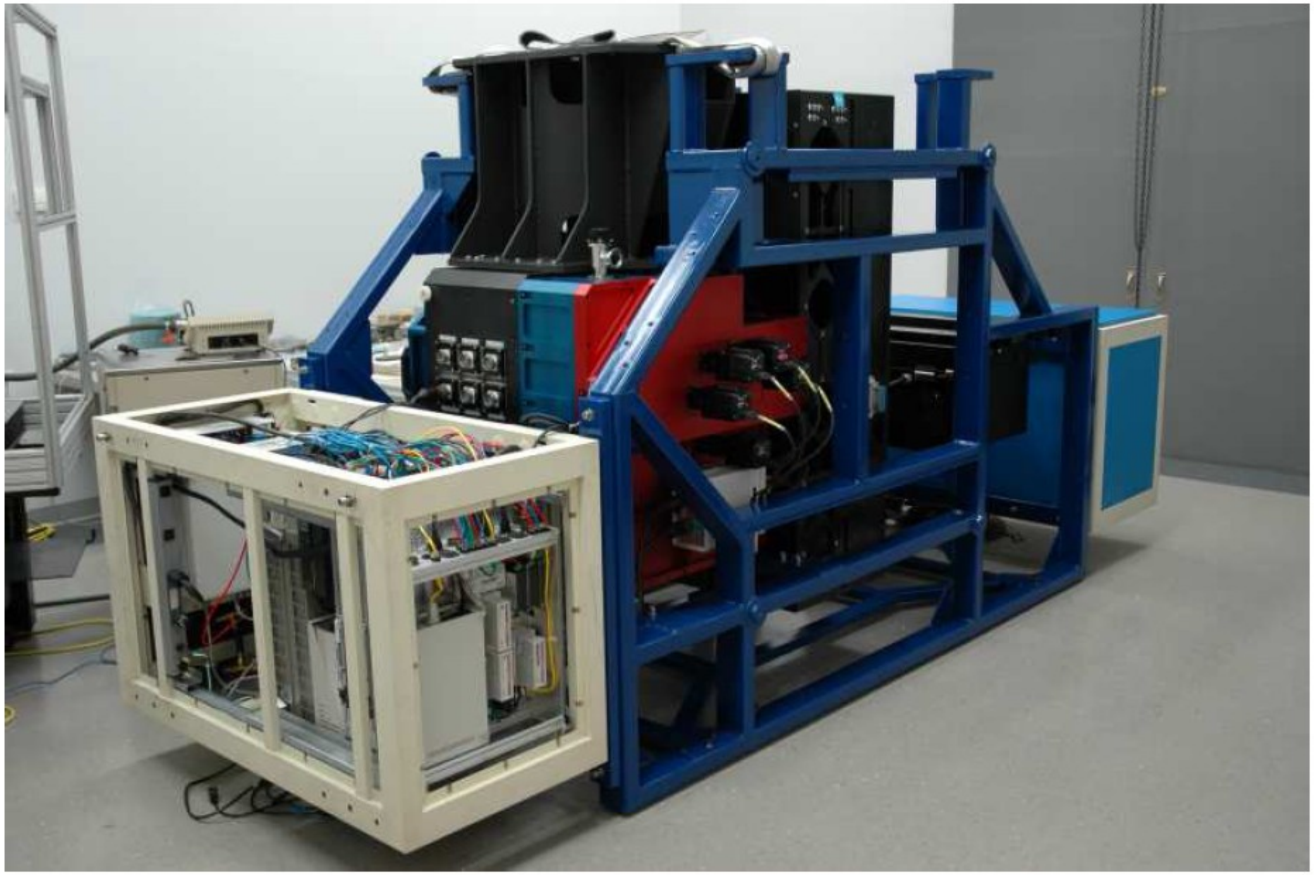


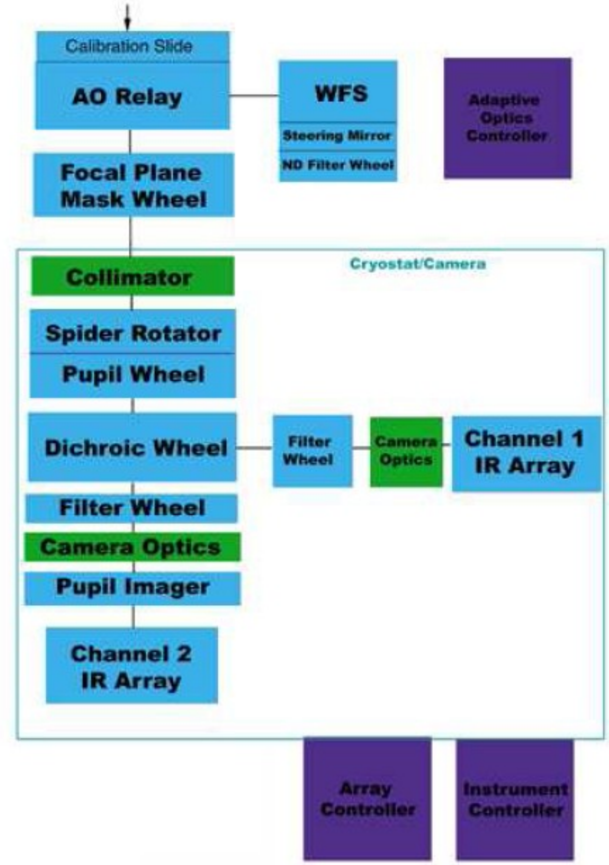


1.5-m subaperture of Palomar
+ AO system + high perf coronagraph
(Serabyn et al.)

Full aperture (10-m)
No coronagraph, standard AO system
(Marois et al.)

NICI system (Gemini South)





Liu et al., 2010

85-element curvature AO system
Lyot type coronagraph
Simultaneous dual band imaging (inside / outside methane abs. Band)

Currently surveying ~300 nearby young stars

NICI system (Gemini South)

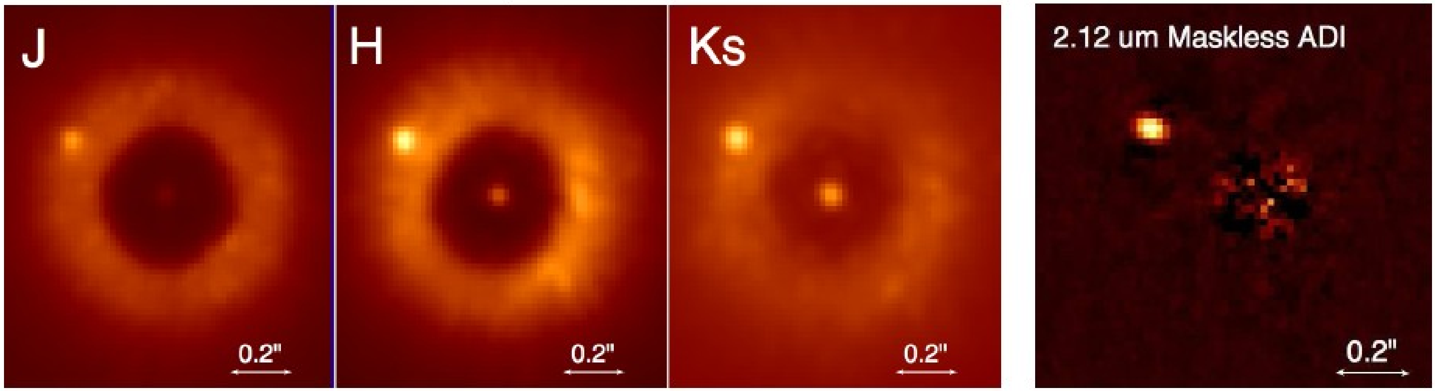


Fig. 1.— Left: J, H, and K_s-band images of the PZ Tel system obtained with NICI in direct imaging mode at the Gemini-South Telescope in May 2010. North is up, east is left. The primary resides at the center of the translucent 0.22" radius focal plane mask and is attenuated by a factor of 329 in J, 214 in H, and 131 in K_s-band. The confirmed companion is at 0.36" separation and PA=59.4° with flux ratios of $\Delta J = 5.40 \pm 0.13$, $\Delta H = 5.38 \pm 0.09$, and $\Delta K_s = 5.04 \pm 0.10$ mag. Right: Maskless ADI H_2 2-1 (2.12 μm) image from May 2010. Light from the primary has been removed by ADI processing.

Biller et al. 2010

NICI is the first system (coronagraph + AO) designed for a high contrast imaging survey of nearby young stars deployed on a 8-m class telescope

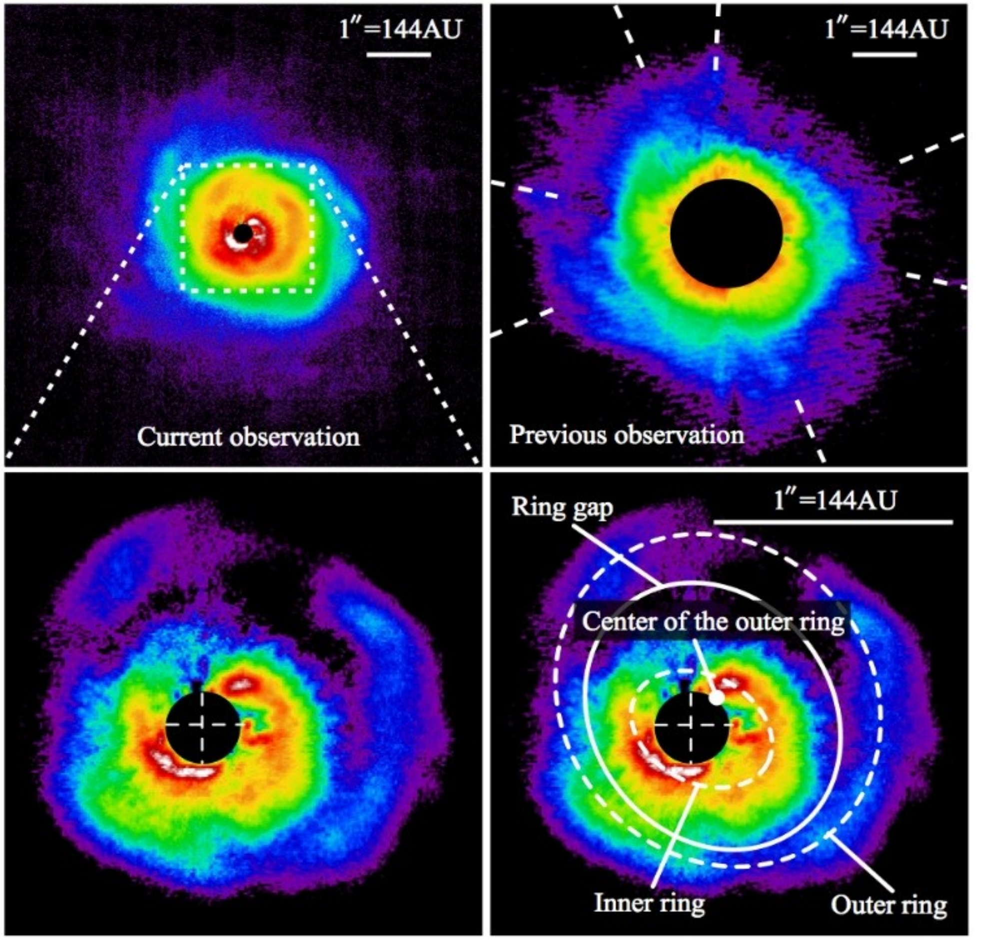
Combines together well-proven technologies:

- Curvature AO, 85 elements
- Lyot coronagraphy
- Spectral differential imaging

HiCIAO system (Subaru Telescope)

(see presentation by M. Tamura in this conference)

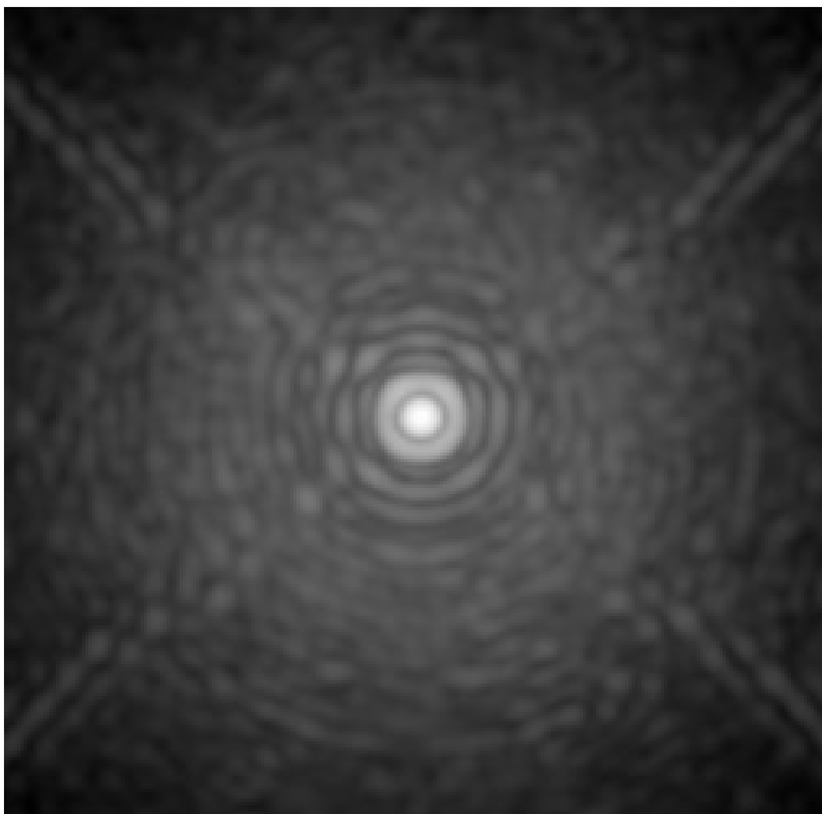
HiCIAO combines:
- Curvature AO, 188 elements
- Lyot coronagraphy
- Spectral differential imaging



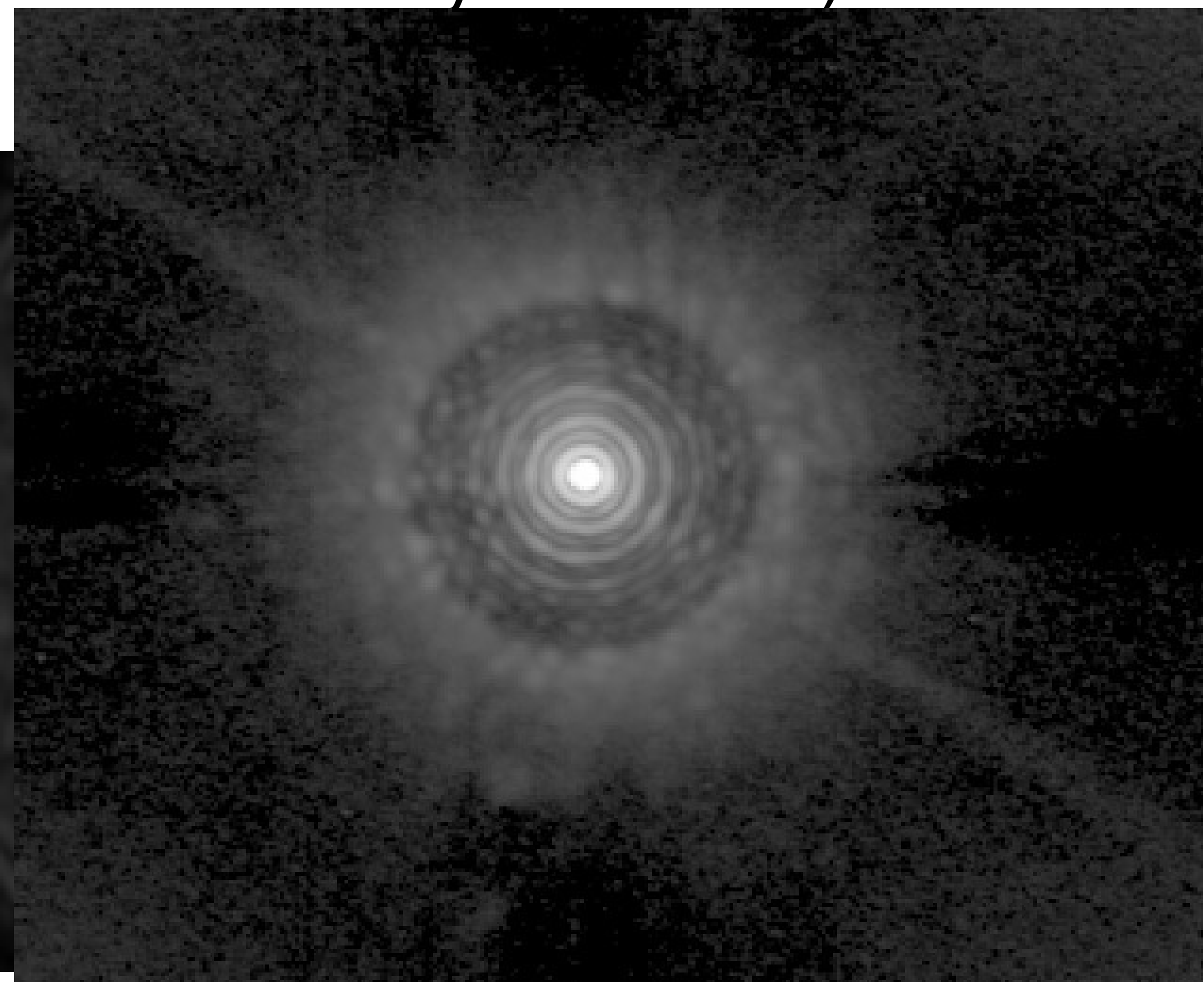
AB Aur disk imaged with HiCIAO

Higher quality AO correction (Extreme-AO) is becoming available, and will make efficient use of coronagraphs

(Coronagraphs will soon become very useful !!!)

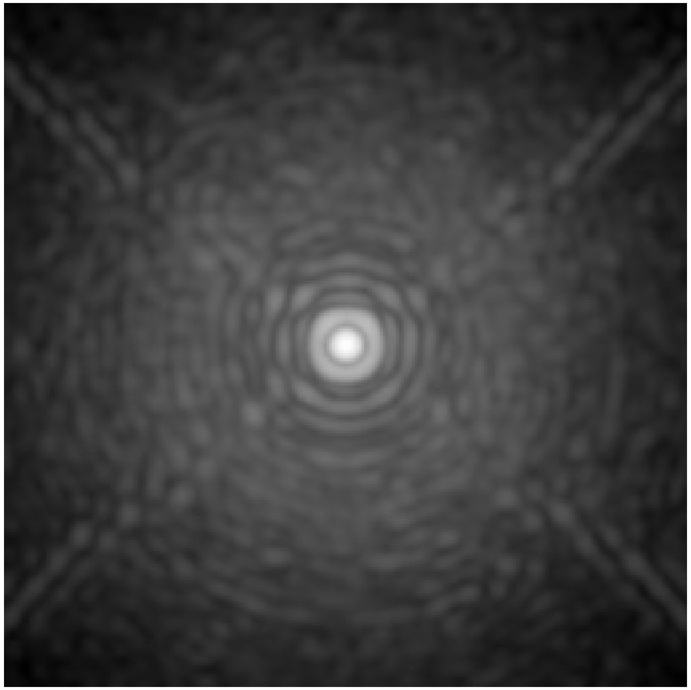


High quality PSF for HiCIAO (simulation)



LBT H-band PSF (~80% SR)
Credit: Esposito et al., SPIE vol 7736

Higher quality AO correction (Extreme-AO) is not sufficient: **calibration and stability** are important



Removing bias in AO correction

It is essential to minimize slow and static speckles that may look like planets.
There are the limiting factor in current systems
Fast atmospheric speckles are OK, as they average out very rapidly into a smooth PSF halo

Bias can come from non-common path error, bias in the wavefront sensor, uncorrected mode that is not detected by the WFS.

Calibrating residual speckle halo in the PSF

Using differential measurements, looking for:
- ways to change/modulate the speckle field without changing the planet image, or
- ways to change the planet image without changing the PSF halo

PSF calibration strategies

- **“classical” PSF subtraction: observe reference PSF, subtract**
- **Angular Differential Imaging: same-star subtraction thanks to sky rotation**
  - works well at large angular separations, where aberrations have large static component
  - poor performance close in to the star (not enough rotation)
- **Spectral differential imaging (dual band or IFS)**
  - Speckle calibration works well at large angular separations, where speckles are spectrally elongated, but does not work as well close in to the star
  - Science (spectra) + speckle calibration from same data
  - IFS is more powerful and efficient than simultaneous differential imaging
- **Polarimetric differential imaging**
- **Coherent differential imaging: speckles are coherent with starlight, real sources are not**
  - Does not make any assumption about source (spectra, polarization)
  - combined wavefront sensing / PSF calibration
  - Works well very close to the star
  - works only within control radius of DM, requires good detector (fast readout favored)

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From past/present to future instruments

“Conventional” AO imaging, ususally without coronagraph

→

First Systems designed for high contrast imaging, combining existing techniques

HiCIAO

NICI

Lyot coronagraph
Differential spectral imaging
Good AO system

→

Extreme-AO coronagraphic systems designed

PALM3000+P1640:
First ExAO with IFS
GPI, SPHERE:
Large survey with high performance systems
SCExAO:
Pushing close in to the star

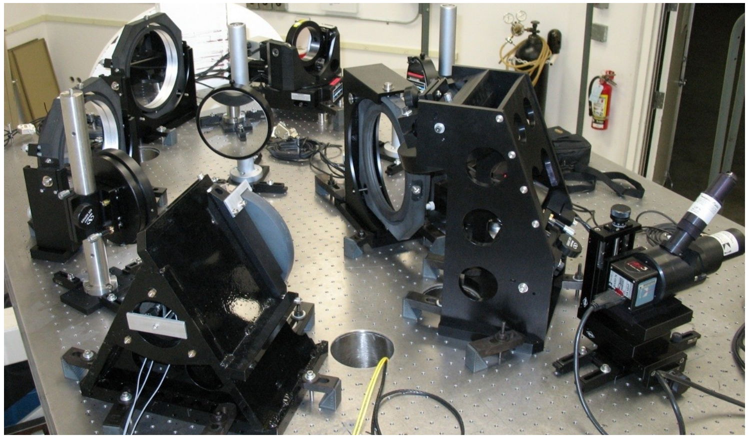
Better AO correction:
- More actuators
- Better WFSs

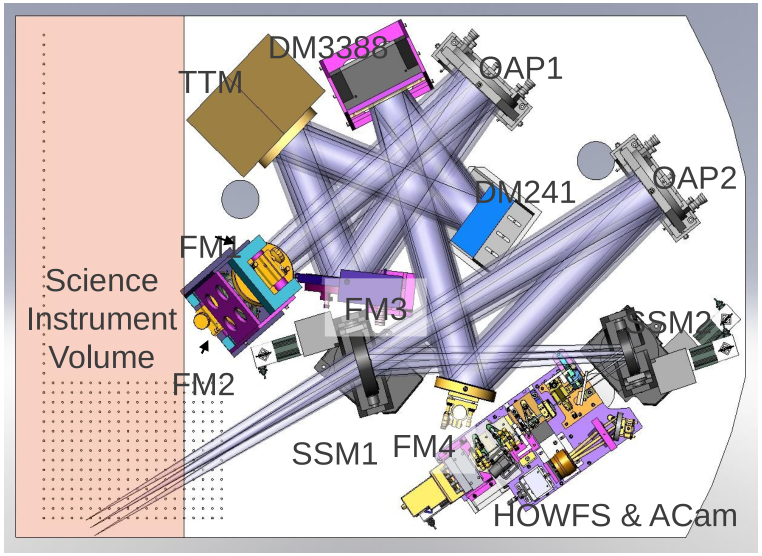
Improved PSF calibration:
- IFS, coherent PSF detection

Better coronagraphs:
- APLC, PIAA, 4 quadrant

The PALM-3000 upgrade to Palomar AO

- Science goals:
  - Comparative exoplanet and disk studies in the near-IR
  - Visible-light science at the diffraction-limit
- Deformable mirrors
  - 3388-actuator, 1µm stroke “tweeter”
  - 241-actuator, 5 µm stroke “woofer”
- Selectable WFS pupil sampling
  - 63x63, 32x32, 16x16, or 8x8
  - Up to 2kHz WFS frame rate
- Science instruments:
  - Project 1640 near-IR APLC coronagraphic IFS & CAL (AMNH & JPL)
  - PHARO near-IR Lyot and vortex coronagraph / spectrograph / imager (Cornell & JPL)
  - SWIFT visible-light IFS (Oxford)
  - Visible light imager and ‘red’ vortex coronagraph (Caltech & JPL)
  - Future option: Echelle fiber feed (Caltech)



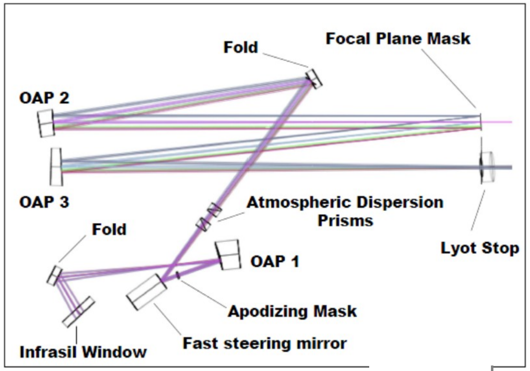


PI: Richard Dekany

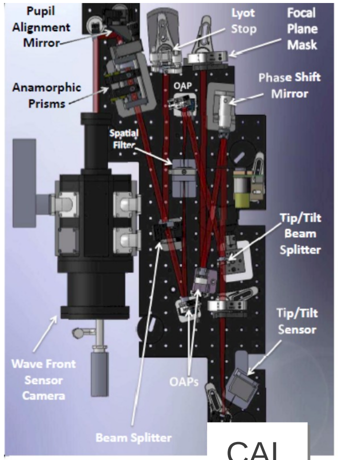
Project 1640

(AMNH, CIT, JPL: Ben Oppenheimer, PI)

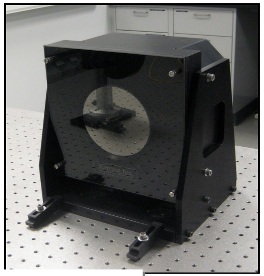
- Palomar 5m Telescope
- Apodized pupil Lyot coronagraph
- 200 x 200 spaxel JH IFS
  - R ~ 30; 20 mas / pixel
- < 5 nm RMS CAL
  - Currently 15 nm RMS
- Performance goals
  - 10^{-6} raw contrast (SNR = 1, 30s)
  - 10^{-7} post-LOCI (SNR = 5, 30m)
- Schedule
  - First high-order lock: July 2011
  - 99-night Survey 2011-2014



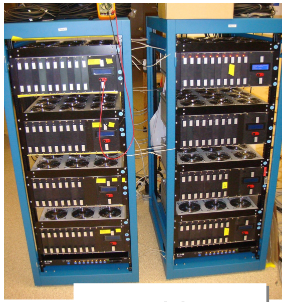
APLC



CAL

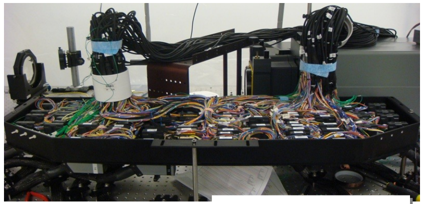


DM3388

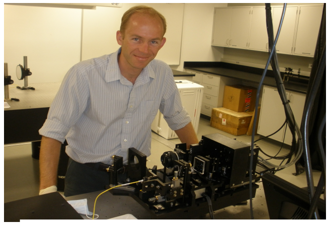


DM drivers

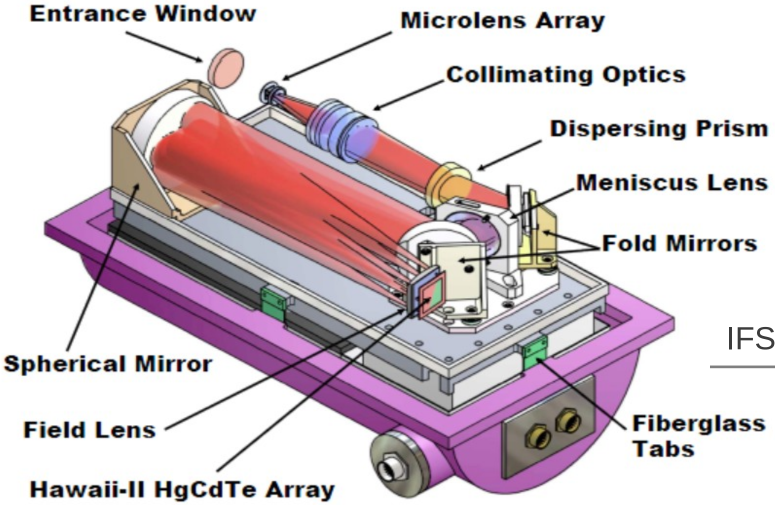
RTC



DM cabling

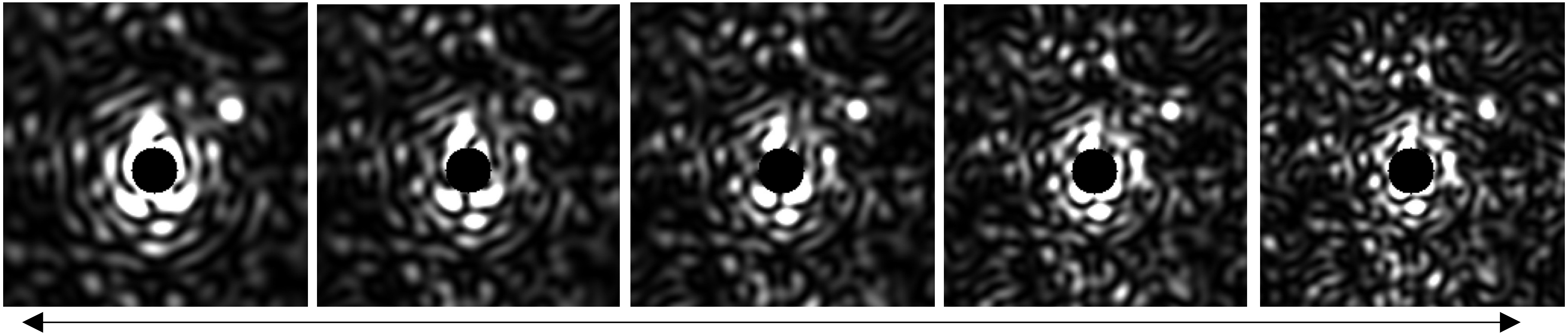


Antonin & the HOWFS



IFS

Speckle Suppression Through Chromaticity



RED (1.8 μm)

BLUE (1.0 μm)

Automatically provides spectra of any companions.

Plan: Utilize the chromatic nature of speckles with a IFS.

Credit: B. Oppenheimer

Wavelength diversity enables differentiation between speckles and companions

PSF calibration with Integral Field Spectrograph

Speckle spatial scale and contrast changes with lambda
IFS data can be used to fit speckle field image with a residual OPD error in the pupil plane

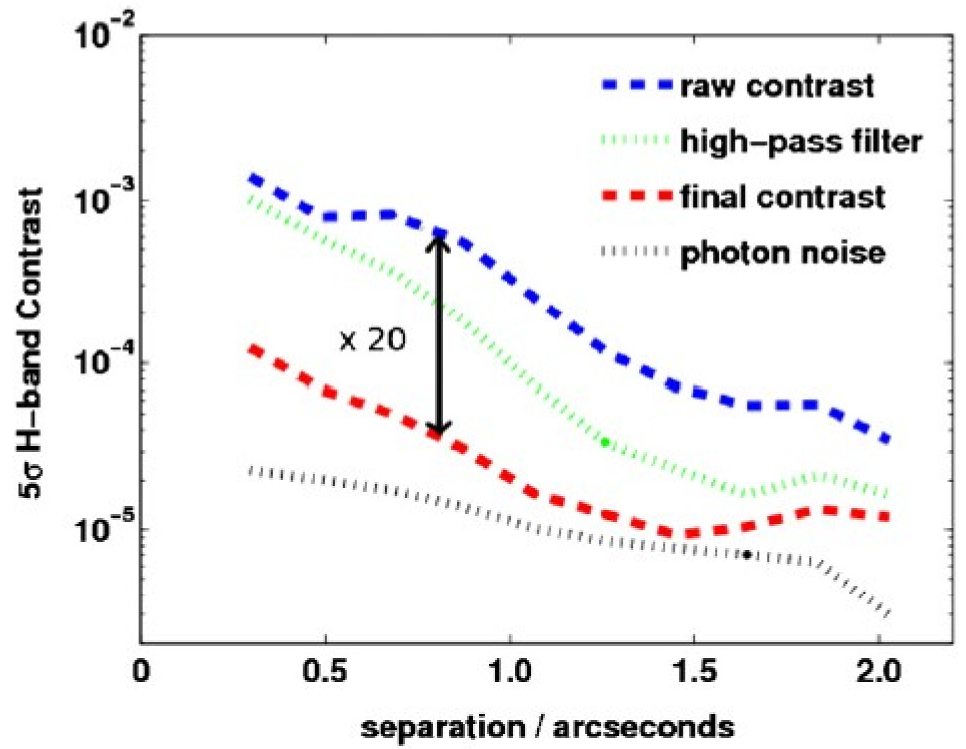
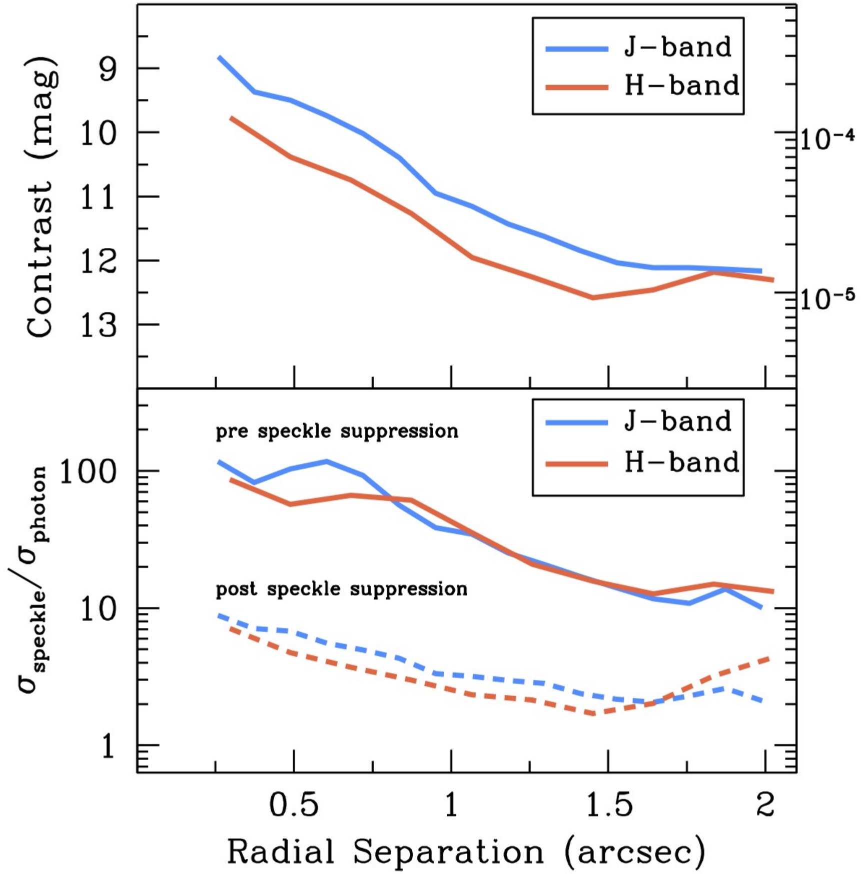


Figure 9. P1640 contrast levels in the *H* band for the star HD 204277 taken on 2009 June 28 UT. The star is occulted by the apodized pupil Lyot coronagraph. PSSP consistently provides a gain of at least one order of magnitude in sensitivity at subarcsecond separations.

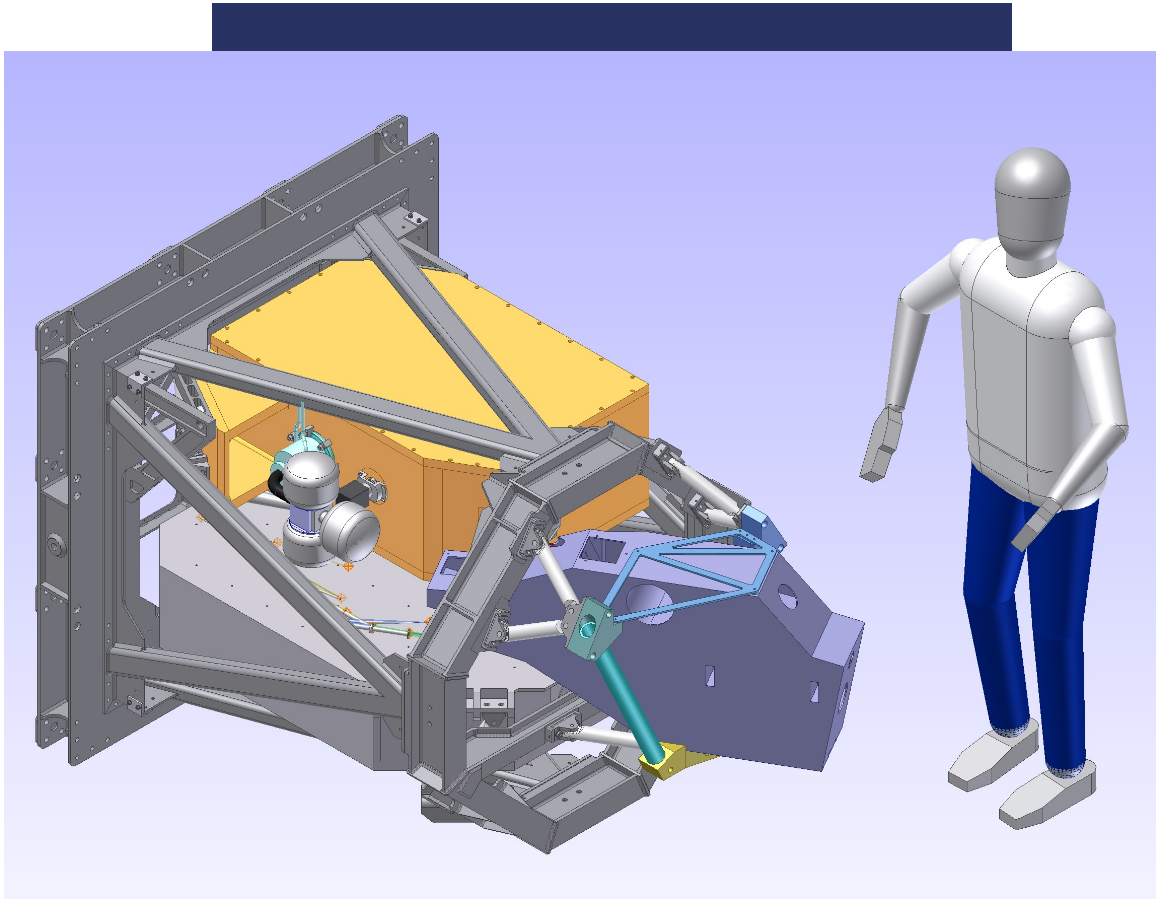


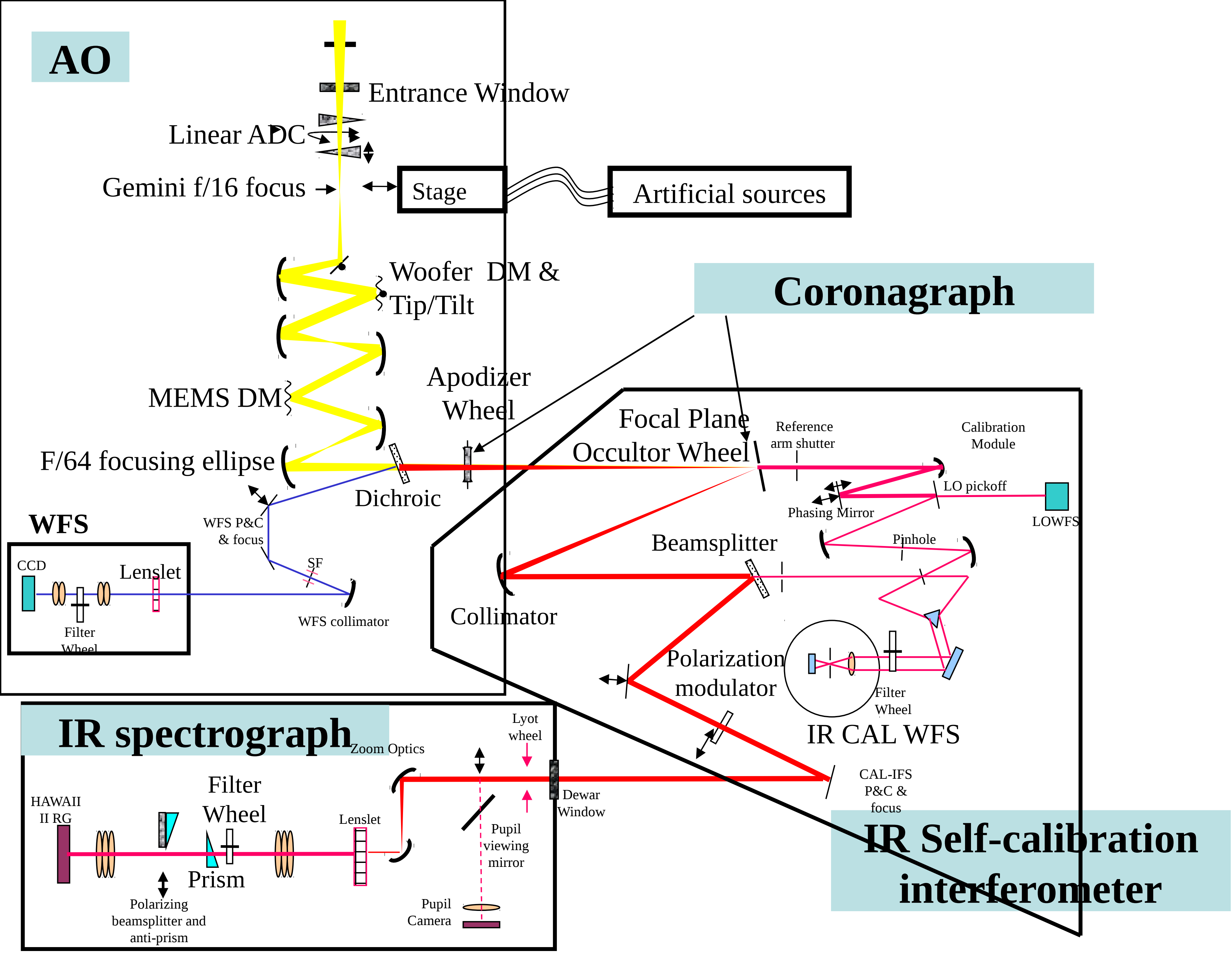
Hinkley et al. 2011

Crepp et al. 2011

Gemini Planet Imager (GPI)

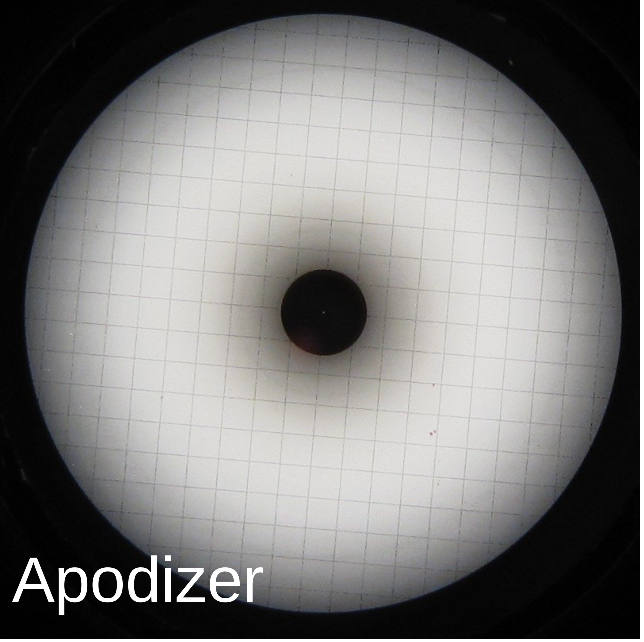
- 44x44 MEMS AO system
- Static speckles minimized
  - Precision optics
  - Daytime speckle nulling calibration
  - On-sky IR interferometer WFS
- APLC
- IR integral field spectrograph

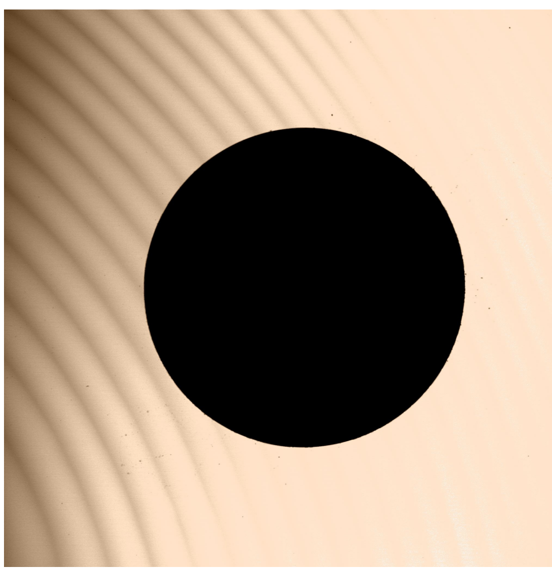




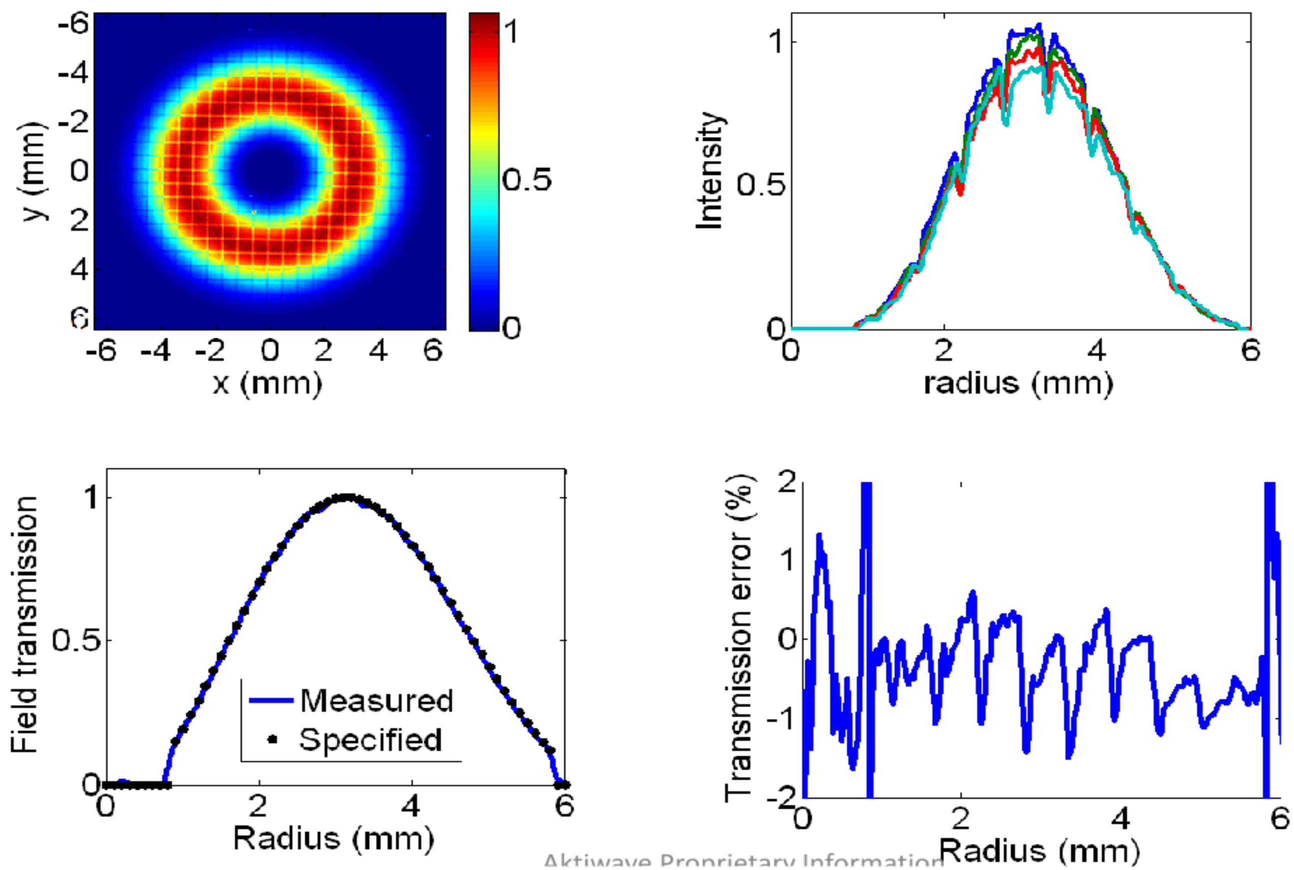
AO
Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
Woofer DM &
Tip/Tilt
Coronagraph
Apodizer
Wheel
MEMS DM
Focal Plane
Occultor Wheel
Reference
arm shutter
Calibration
Module
F/64 focusing ellipse
LO pickoff
Dichroic
Phasing Mirror
LOWFS
WFS
WFS P&C
& focus
Beamsplitter
Pinhole
CCD
Lenslet
SF
Filter
Wheel
WFS collimator
Collimator
Polarization
modulator
Filter
Wheel
IR CAL WFS
IR spectrograph
Zoom Optics
Lyot
wheel
Dewar
Window
CAL-IFS
P&C &
focus
HAWAII
II RG
Filter
Wheel
Lenslet
Pupil
viewing
mirror
IR Self-calibration
interferometer
Prism
Polarizing
beamsplitter and
anti-prism
Pupil
Camera

APLC coronagraph masks



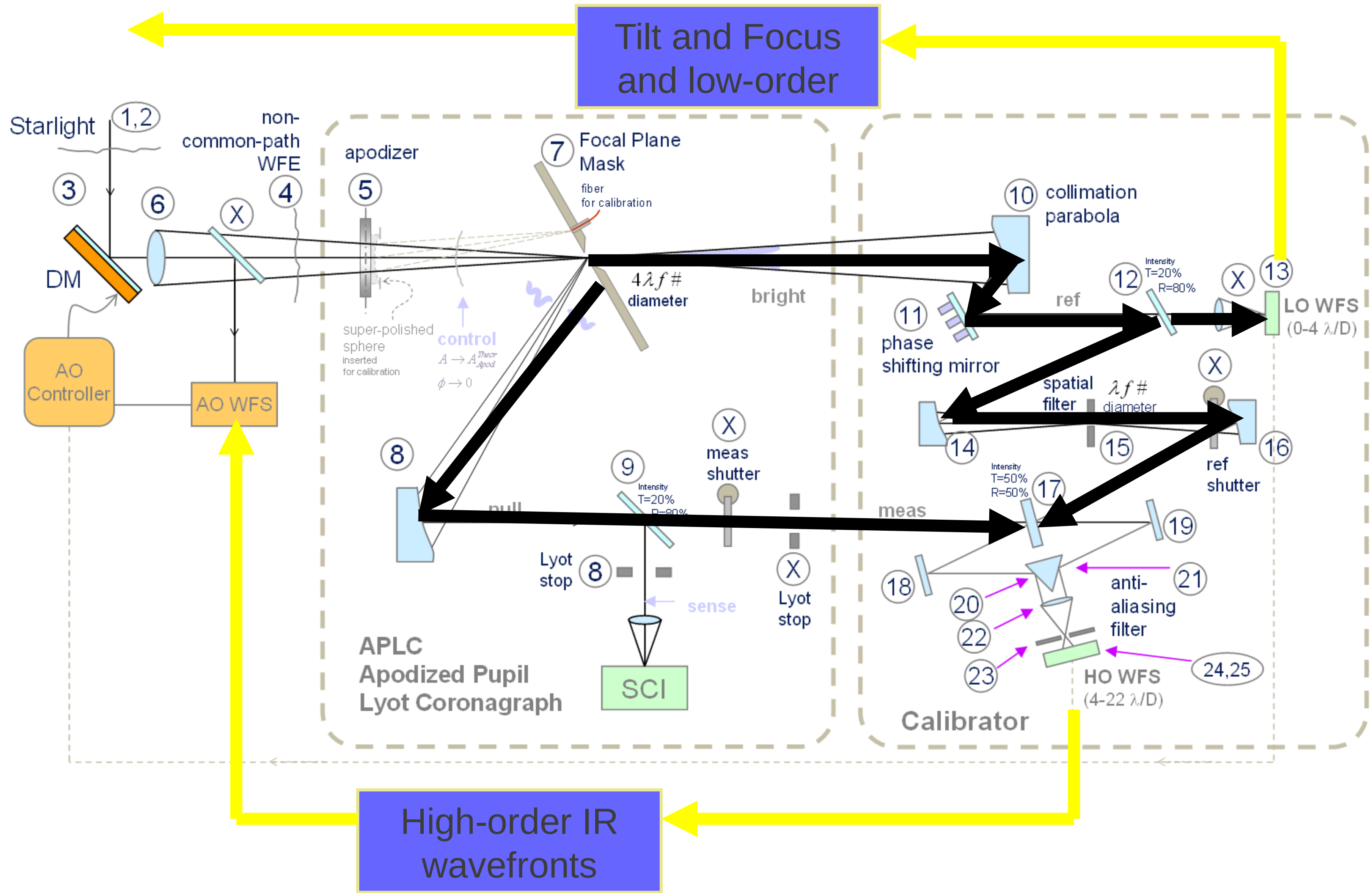


Focal plane mask

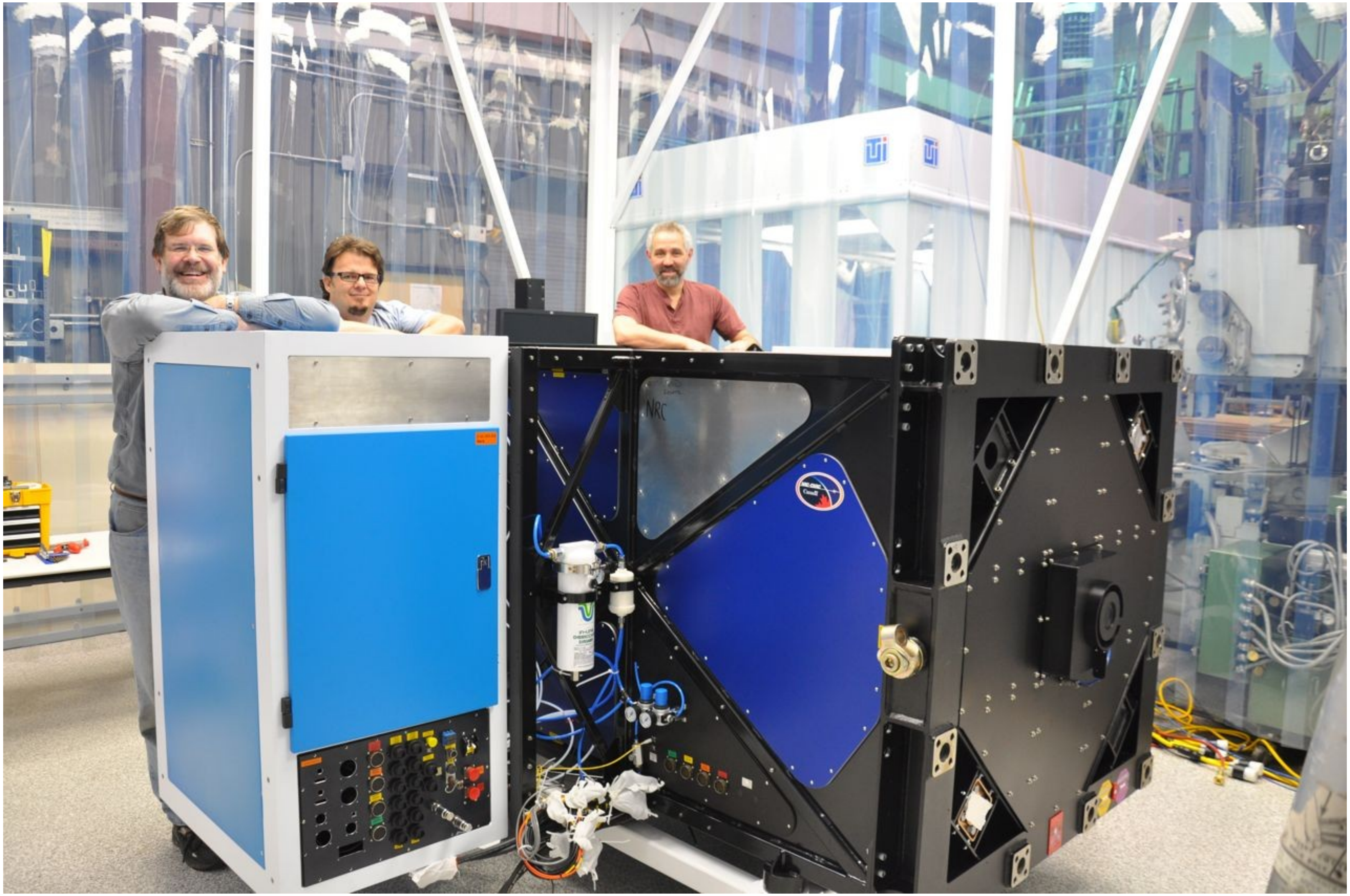


Apodizer profile

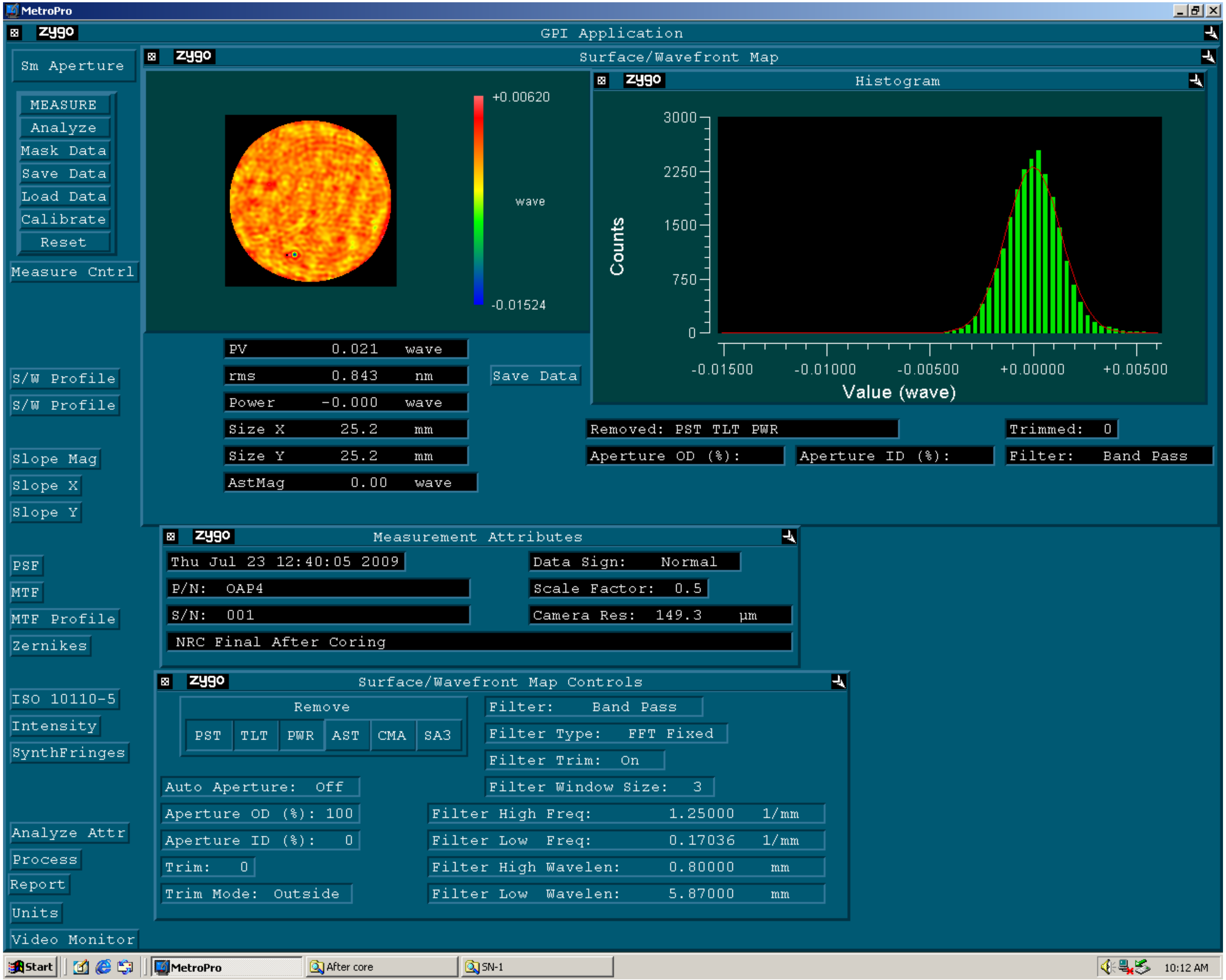
Calibration interferometer (JPL) measures slow aberrations to nanometer accuracy



UCSC clean room
December 18 2010



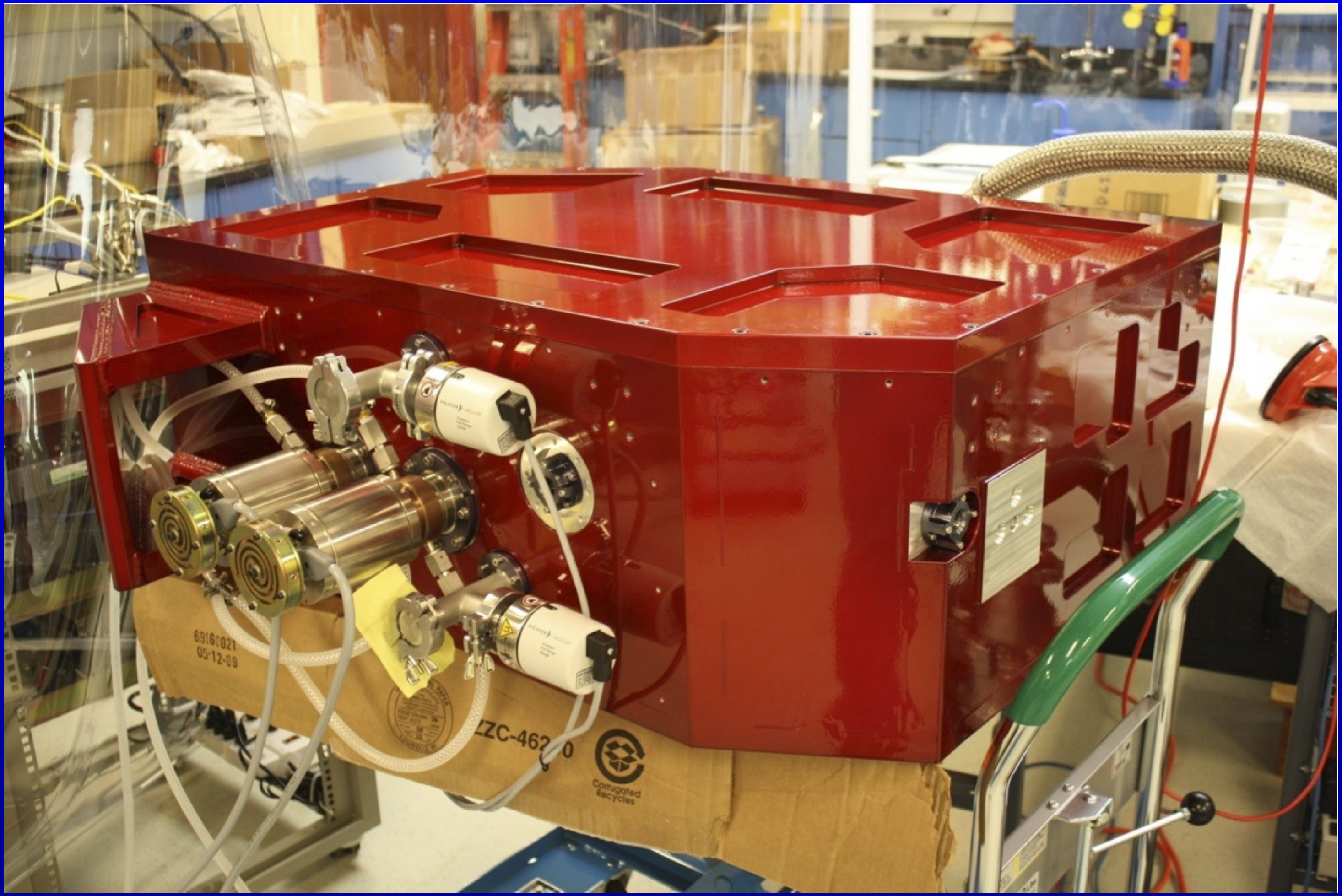
Individual optics < 1 nm



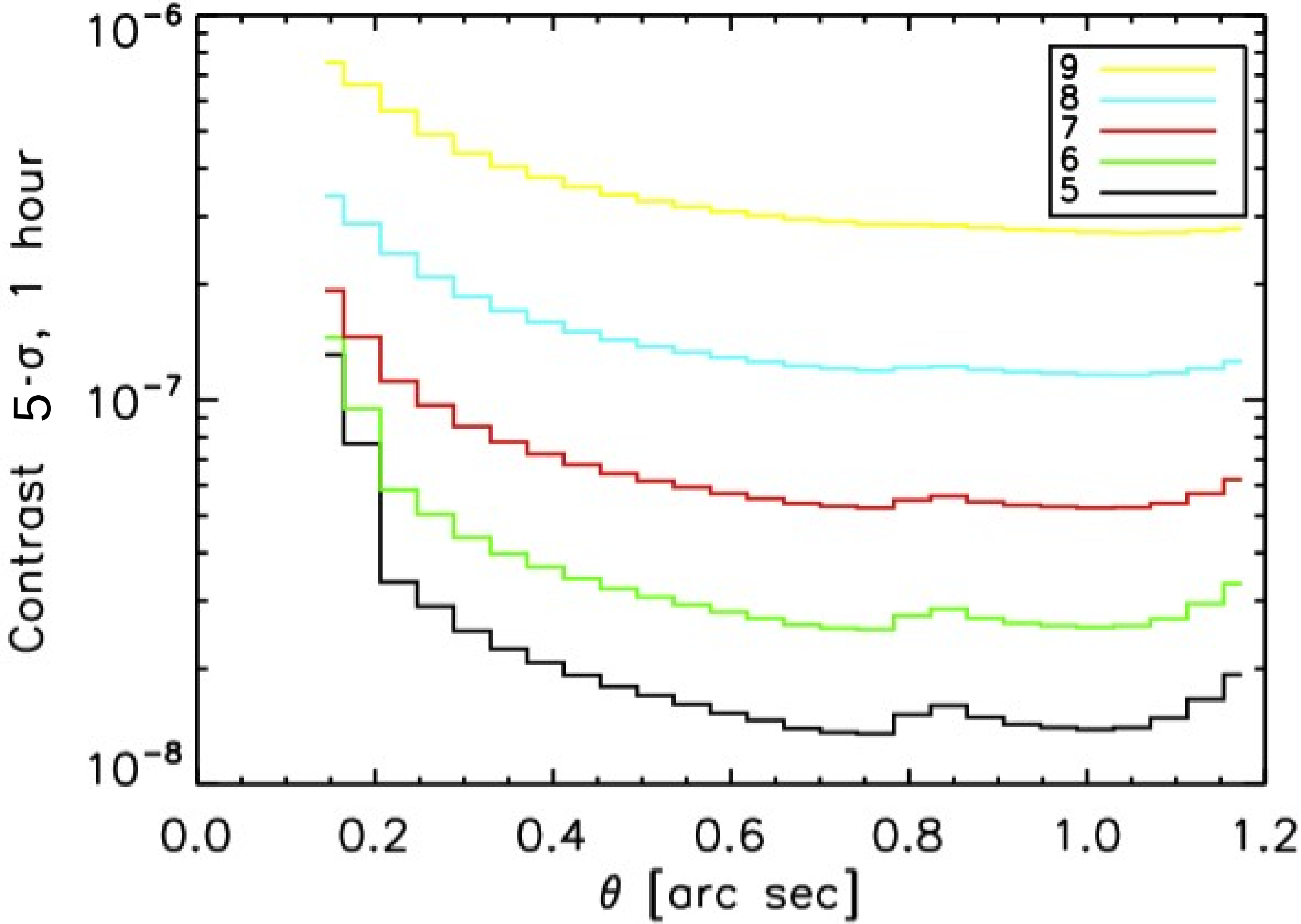
UCLA
U Montreal,
Immervision

Integral field spectrograph

Gemini Planet Imager



Performance models now on http://planetimgaer.org



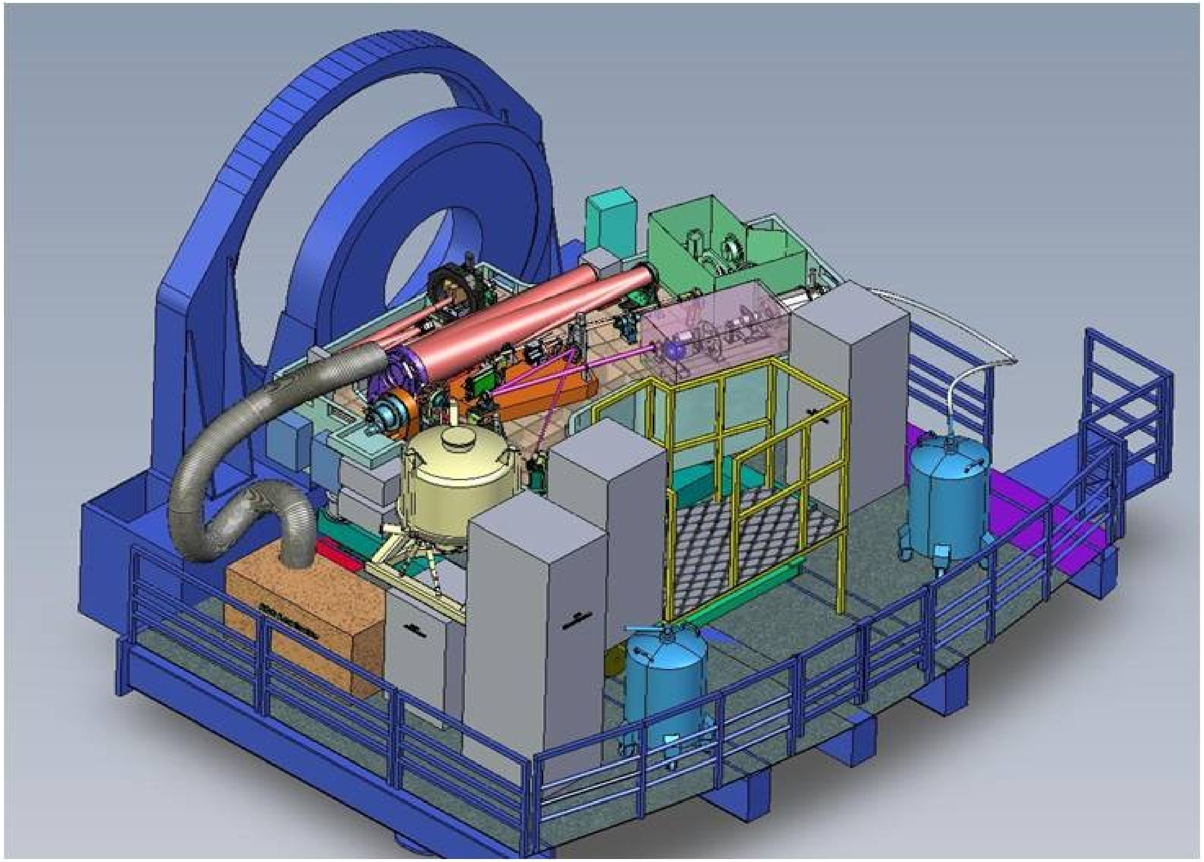
Spectro-Polarimetric High Contrast Exoplanet REsearch (SPHERE)

High order AO correction (SAXO)
    41X41 actuators DM
    ~90% Strehl in H band

Dual band near-IR imaging (IRDIS)
    <10 nm differential error

Integral Field Spectrograph (IFS)

Visible differential polarimetric imager (ZIMPOL)
    Direct imaging of disks and evolved planets (reflected light)



Large survey will start in ~2012
    Schedule and science goals similar to GPI

SPHERE & GPI:
high performance systems
+ large telescopes in good sites
+ large observing programs

Statistics: SPHERE & GPI will observe a large sample of stars to few MJ sensitivity
→ good planet statistics for >MJ planets at >5AU
Complementary to RV and transits, which favor close in planets
Will provide strong test for planetary formation theories (formation + migration)
Sample will be sufficiently large for comparative planetary system architecture studies
How do planetary systems change as function of stellar mass ?

Characterization: SPHERE & GPI will obtain spectra of exoplanets
→ contrain planetary atmosphere models, cooling rate → better mass estimates

The Subaru Coronagraphic Extreme-AO (SCExAO) system

O. Guyon, F. Martinache, V. Garrel, C. Clergeon, J. Morino, T. Kudo, P. Stewart, T. Groff

1 λ/D PIAA coronagraph

NIR focal plane WF control/calibration

Coronagraphic low order WFS

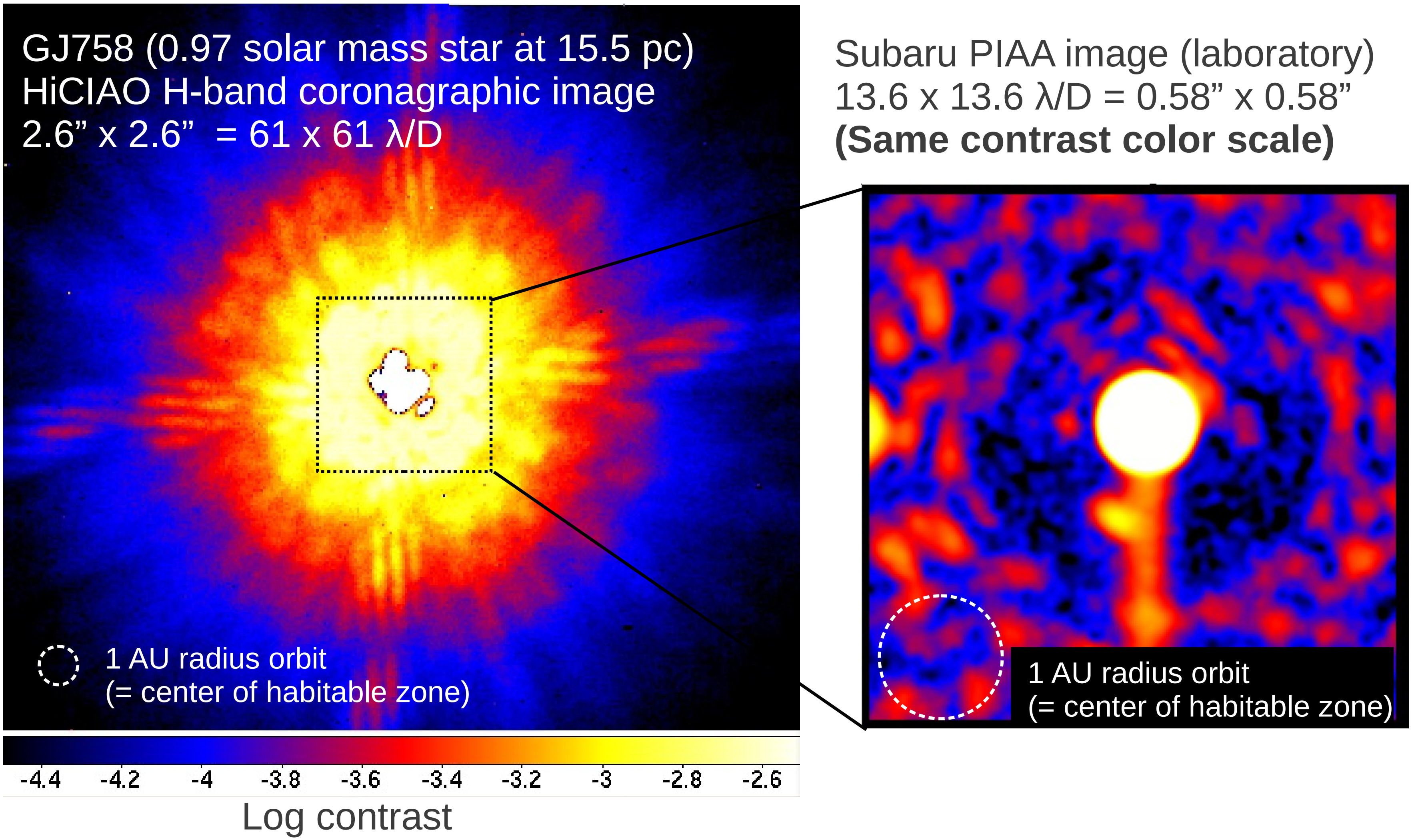
ExAO-optimized visible WFS

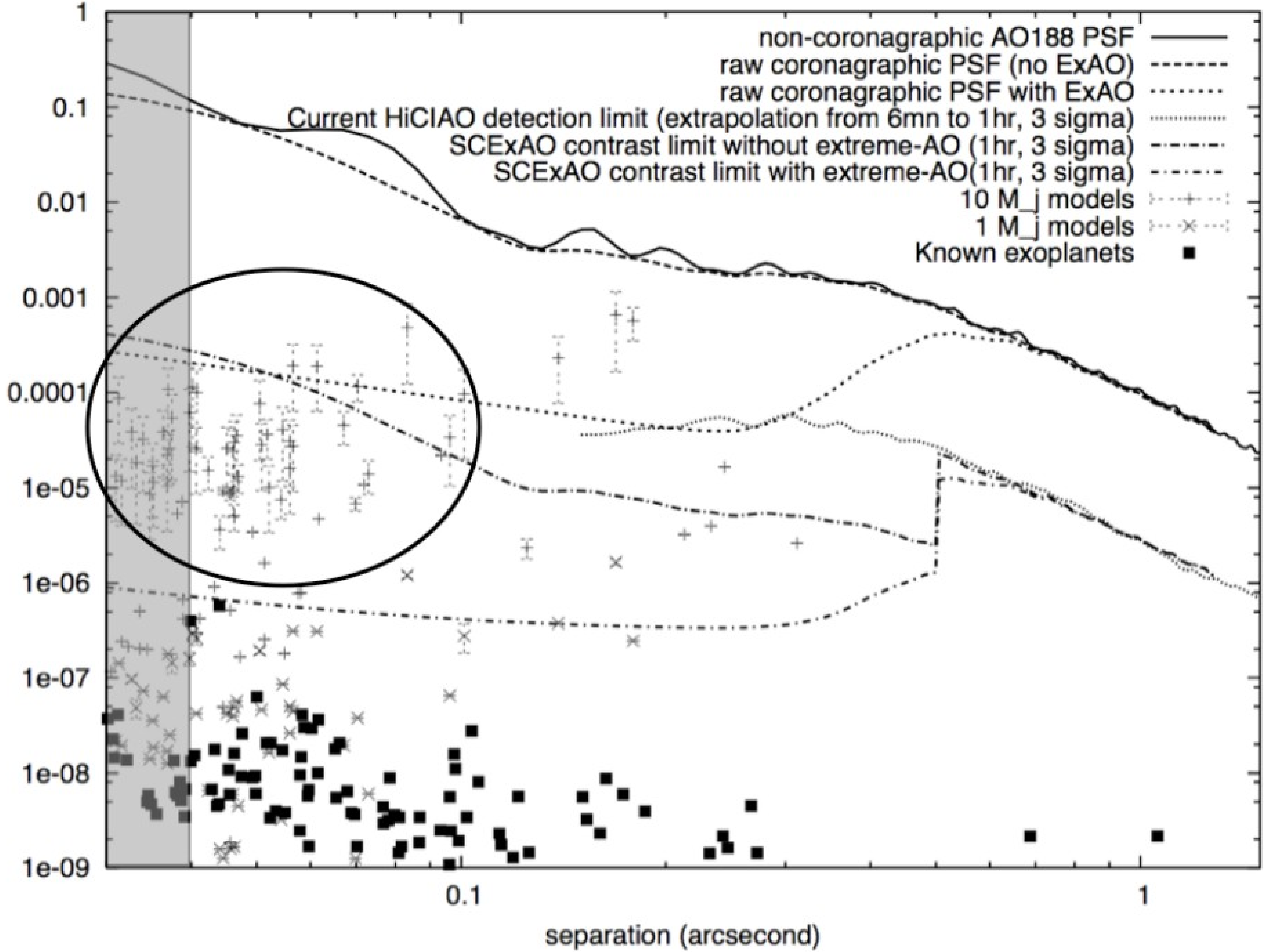
High contrast imaging at small angular separation is scientifically extremely valuable:
- allows sytem to probe **inner parts of young planetary systems** (<10 AU)
- constrain planet formation in the **habitable zone** of stars
- **direct imaging** of reflected light planets may be possible (reflected flux goes as a^{-2})
- number of planet accessible scales as IWA^{-3}

Designed as a highly flexible, evolvable platform
→ uses new (more risky) techniques than GPI and SPHERE
Efficient use of AO188 system & HiCIAO camera
Ongoing telescope engineering runs (Feb 2011, Jul 2011)

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

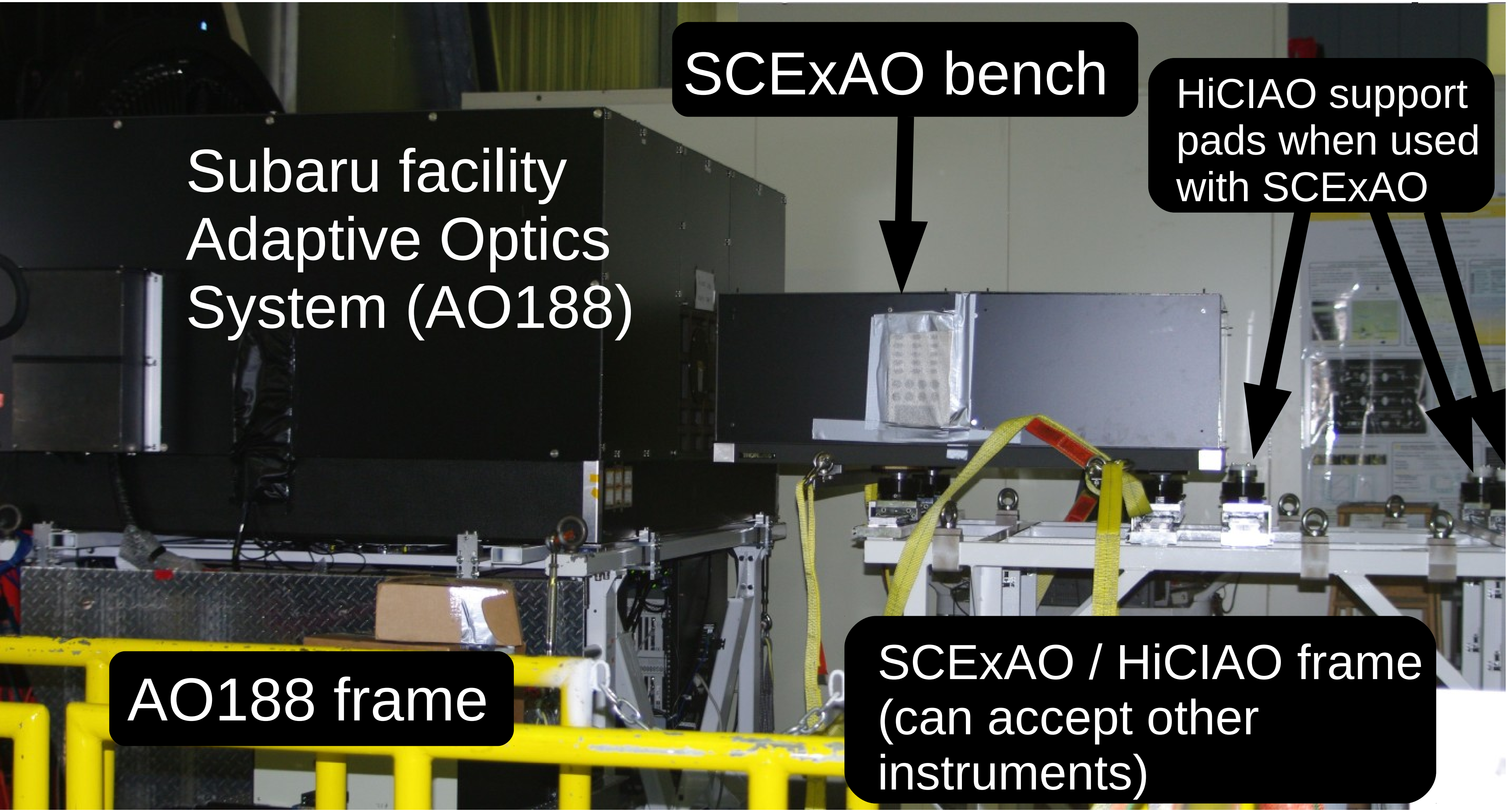
SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance



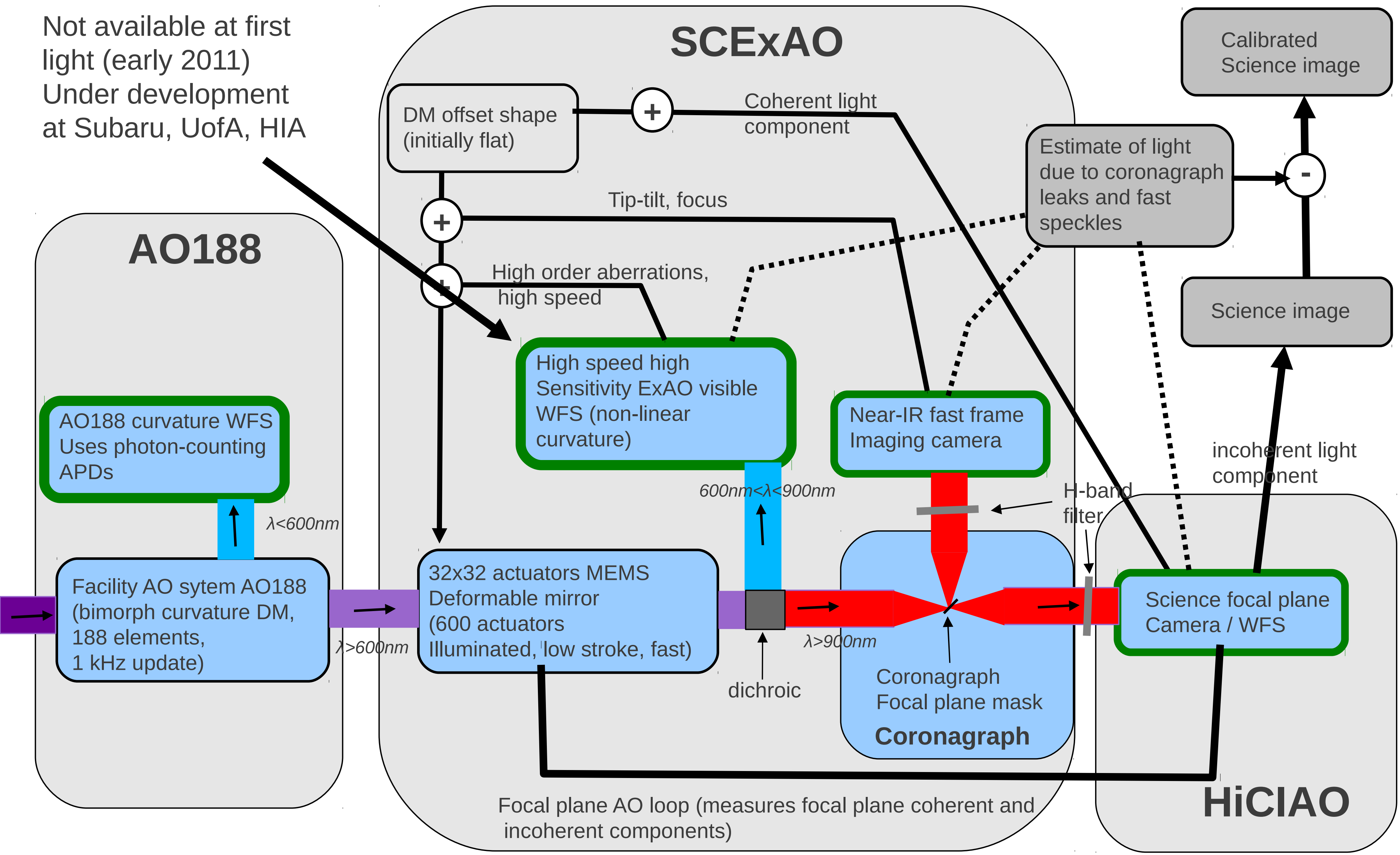


non-coronagraphic AO188 PSF
raw coronagraphic PSF (no ExAO)
raw coronagraphic PSF with ExAO
Current HiCIAO detection limit (extrapolation from 6mn to 1hr, 3 sigma)
SCExAO contrast limit without extreme-AO (1hr, 3 sigma)
SCExAO contrast limit with extreme-AO(1hr, 3 sigma)
10 M_j models
1 M_j models
Known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

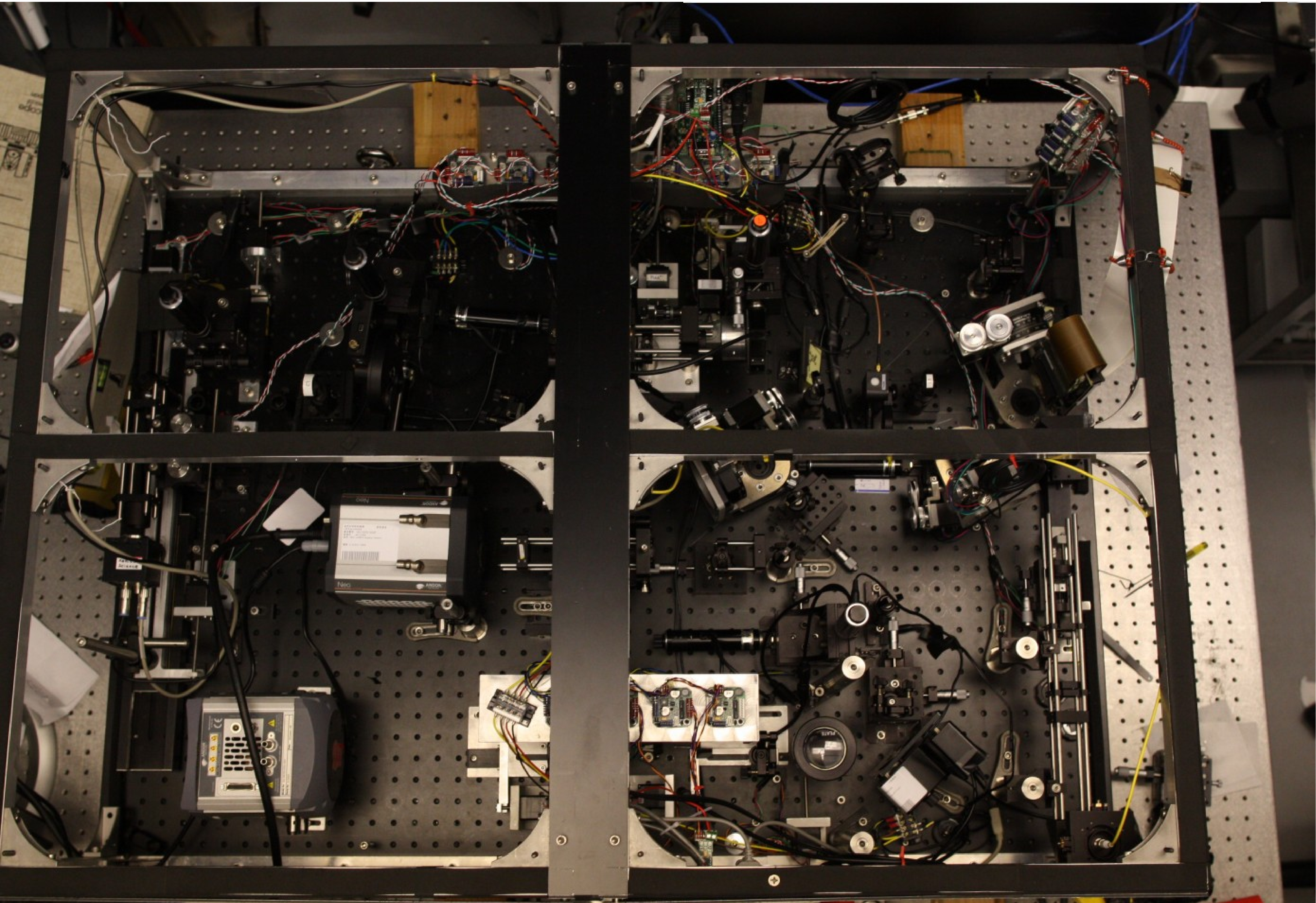
SCExAO at Subaru Telescope (Aug 2010)



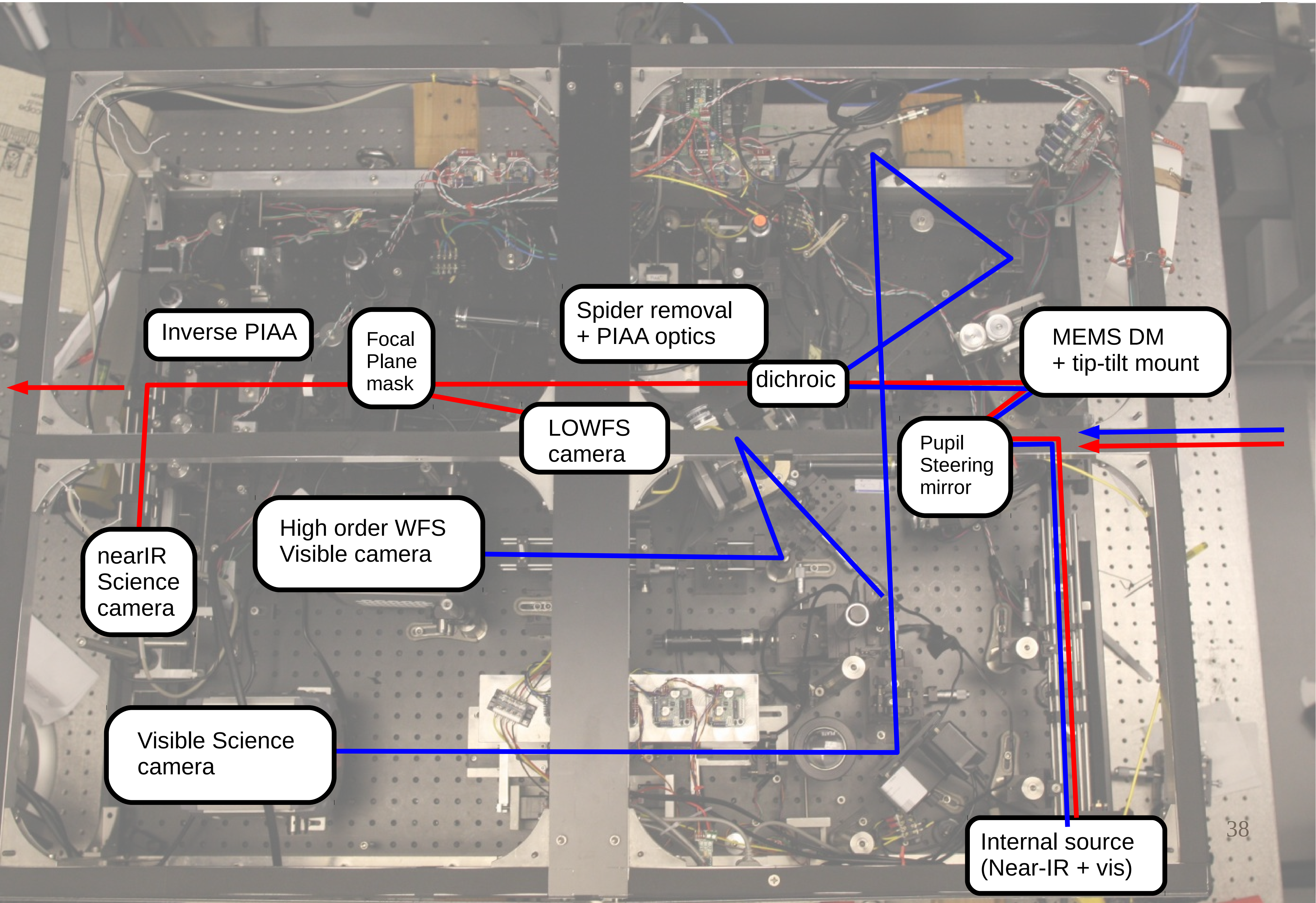
SCExAO Wavefront Control architecture and speckle calibration



The Subaru Coronagraphic Extreme-AO (SCExAO) system



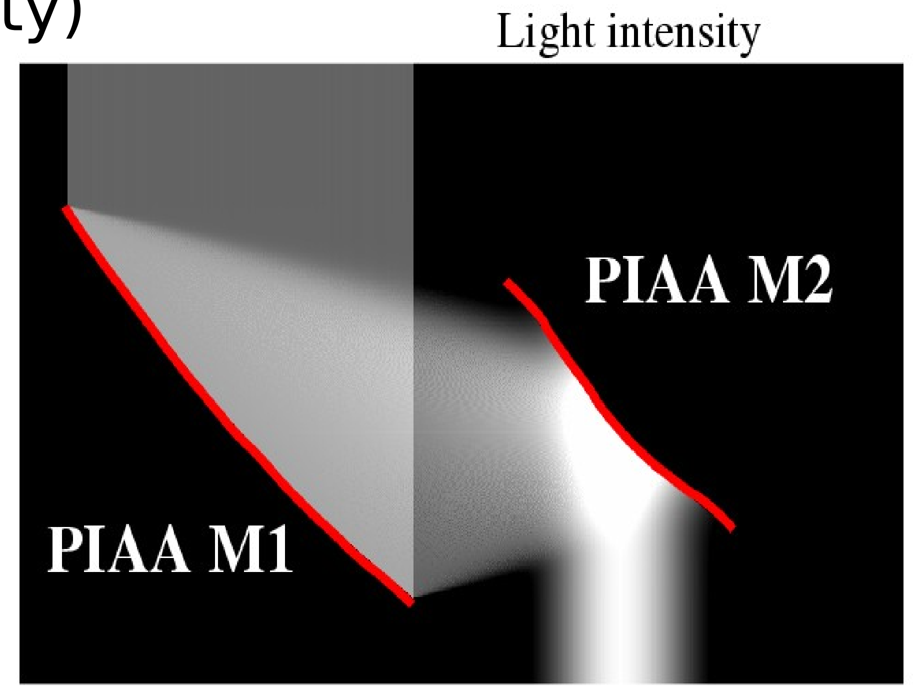
The Subaru Coronagraphic Extreme-AO (SCExAO) system



Phase-Induced Amplitude Apodization (PIAA) coronagraph

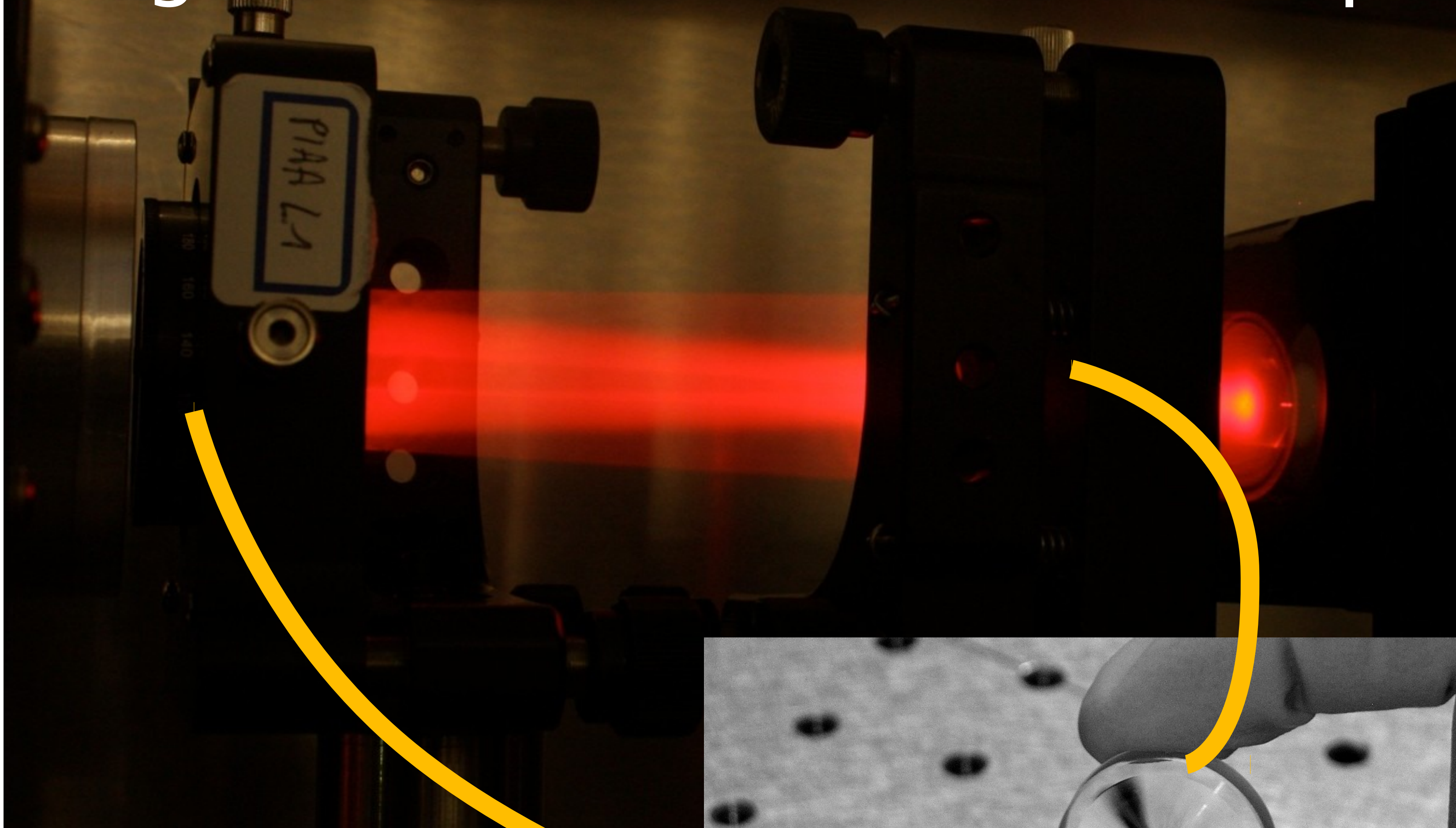
Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

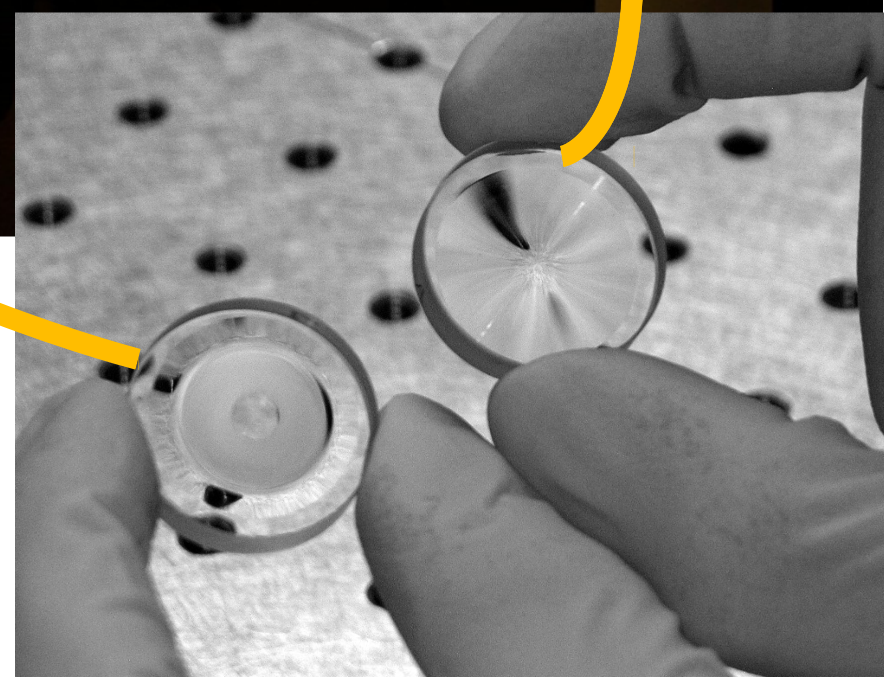
- high contrast (limited by WF quality)
- Nearly 100% throughput
- IWA 0.64 λ/D to 2 λ/D
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)



Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

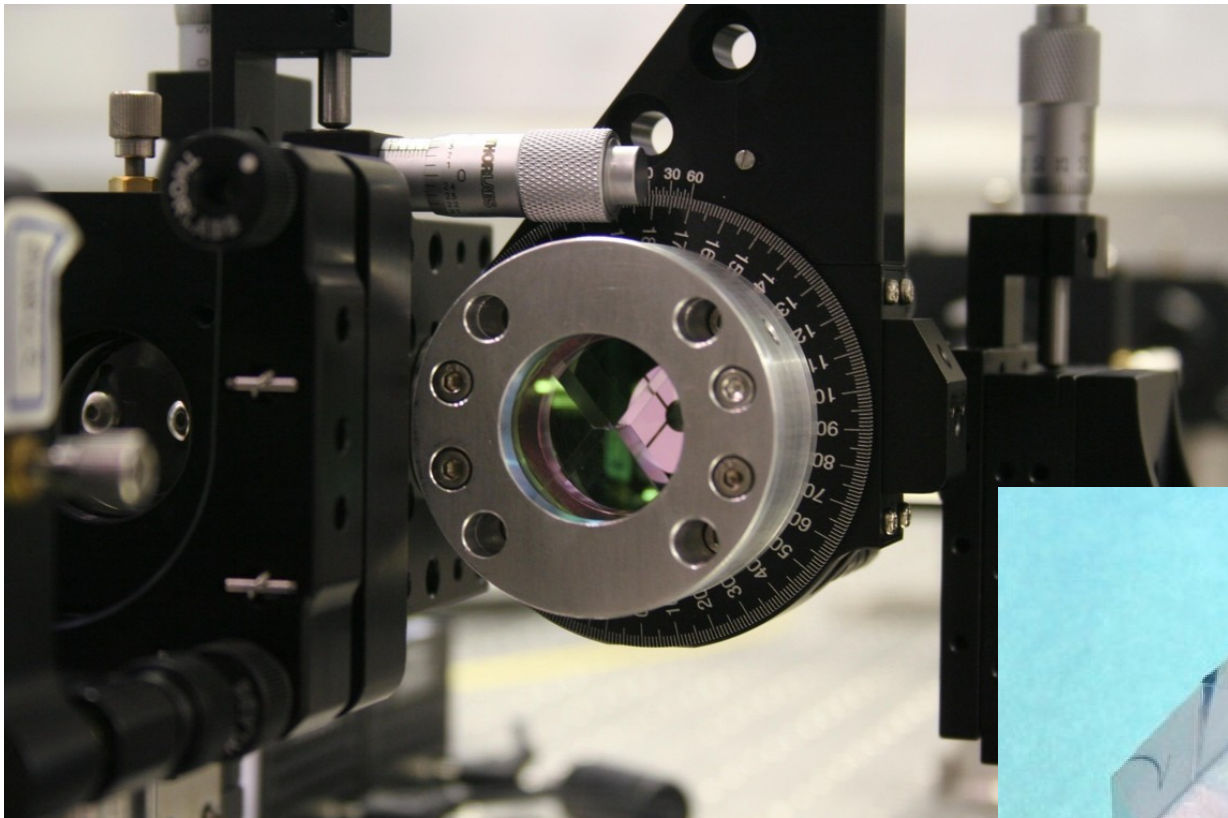
3rd generation refractive PIAA optic

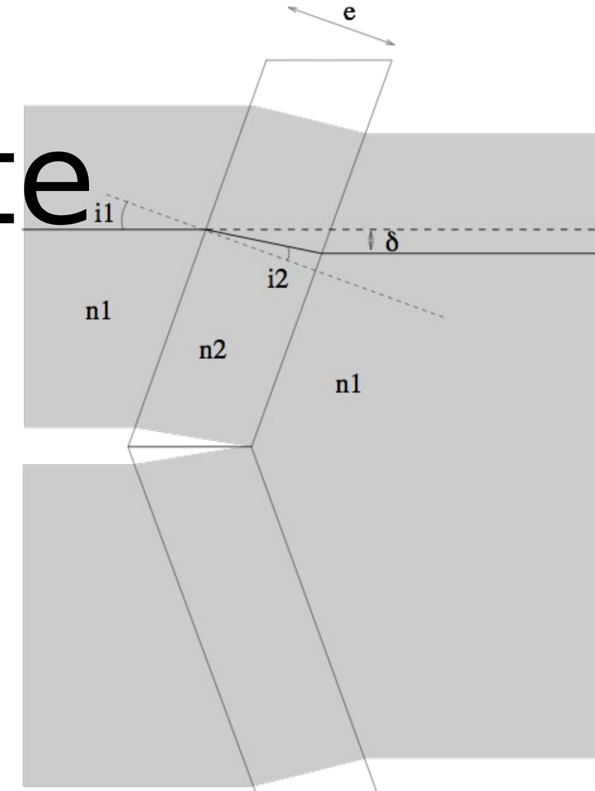




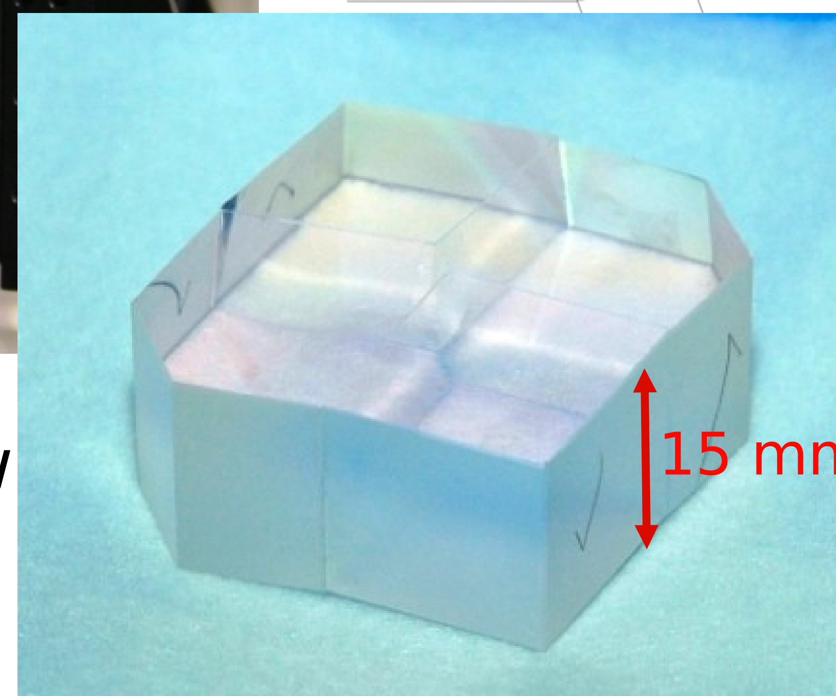
- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Spider Removal Plate



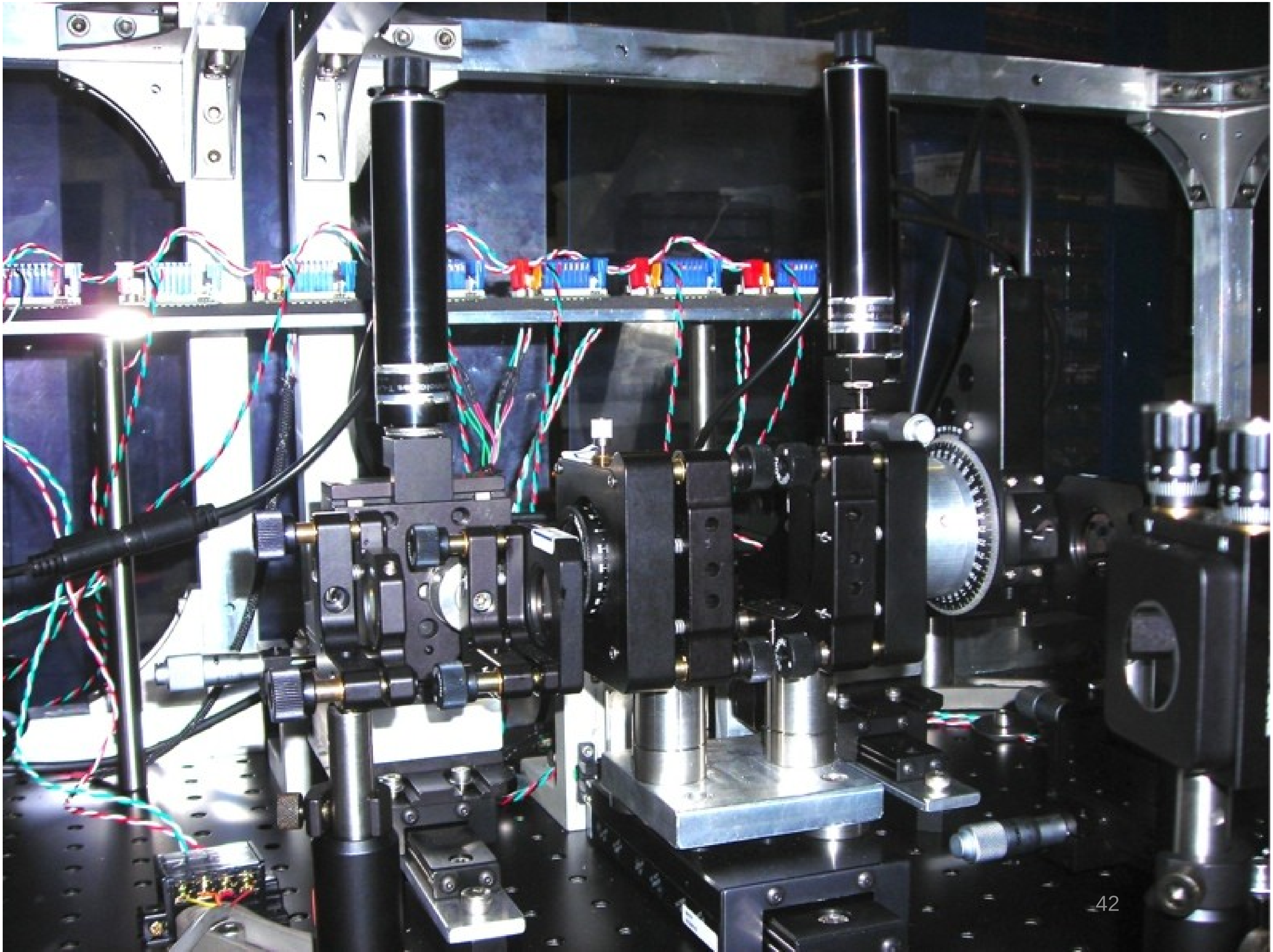


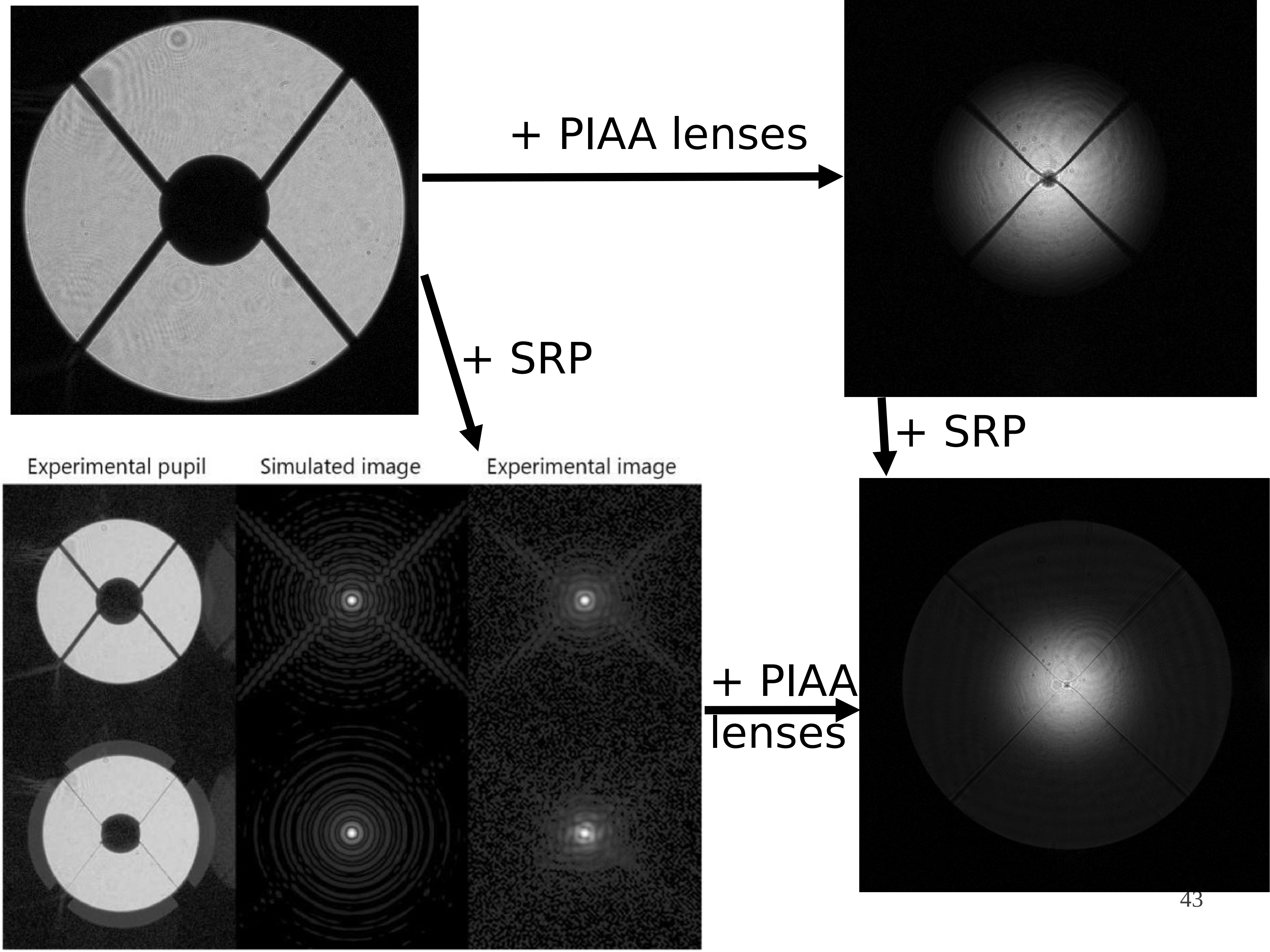
- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°



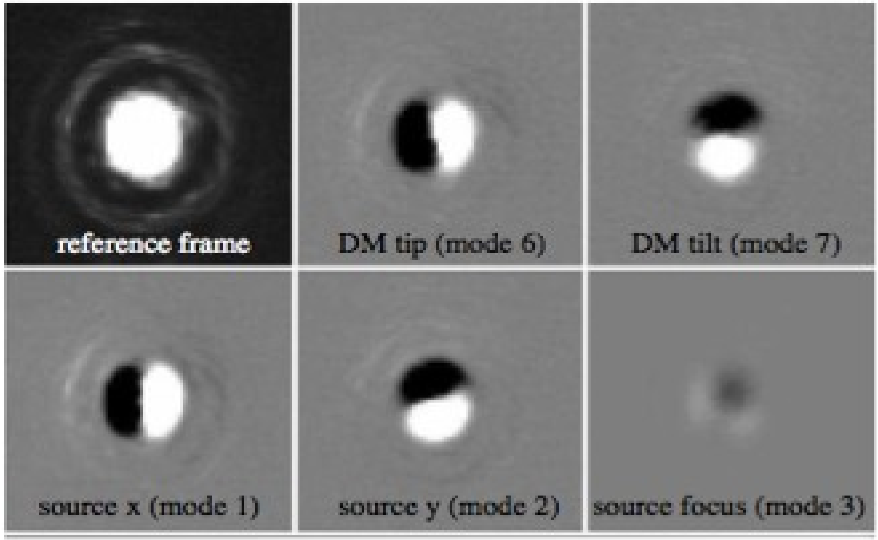
1

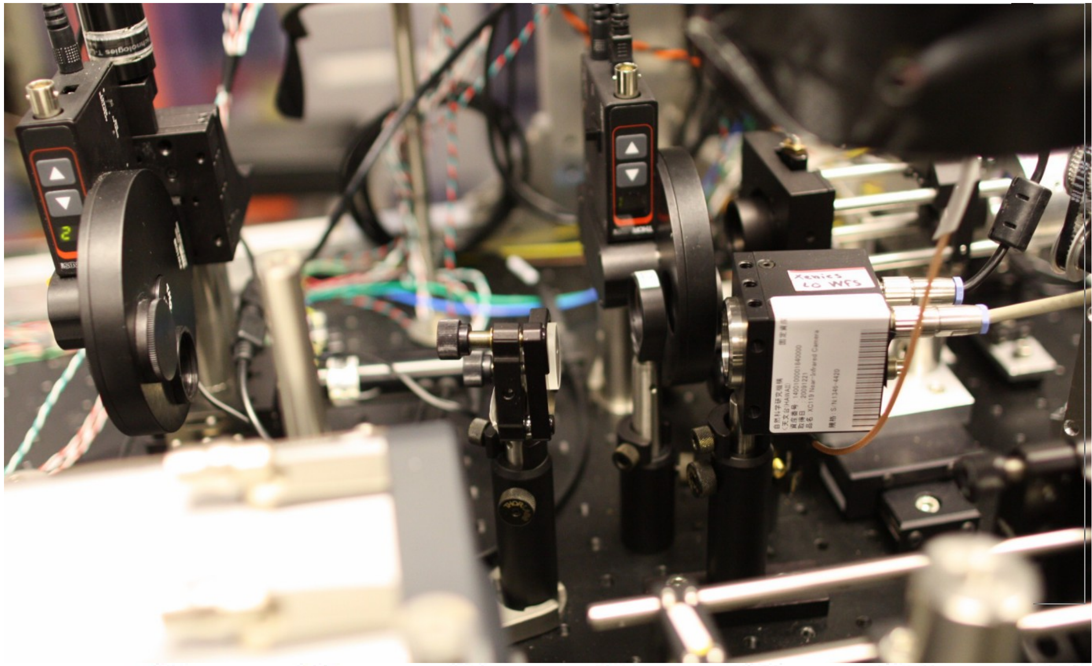
Beam shaping hardware

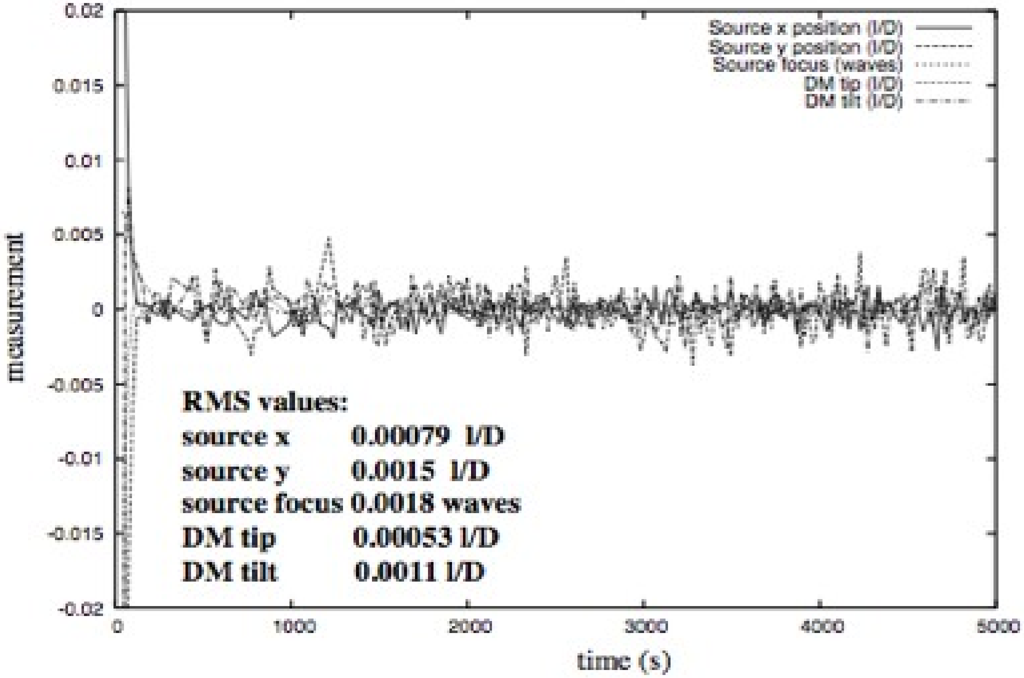


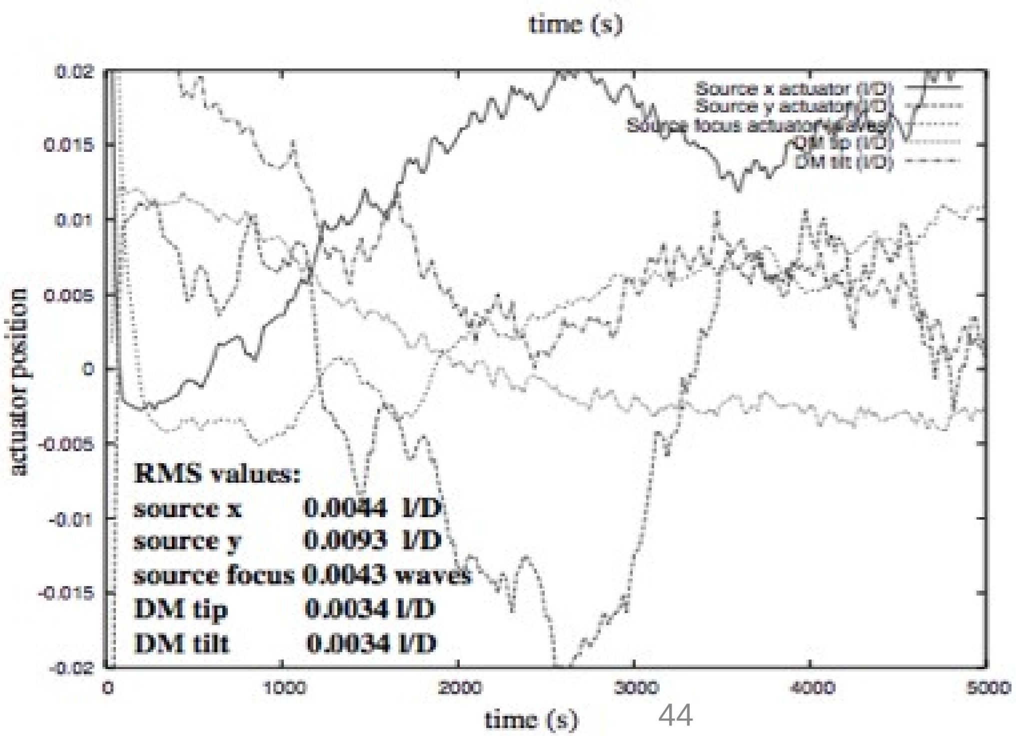

+ PIAA lenses
+ SRP
+ SRP
Experimental pupil
Simulated image
Experimental image
Without SRP
With SRP
+ PIAA lenses

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



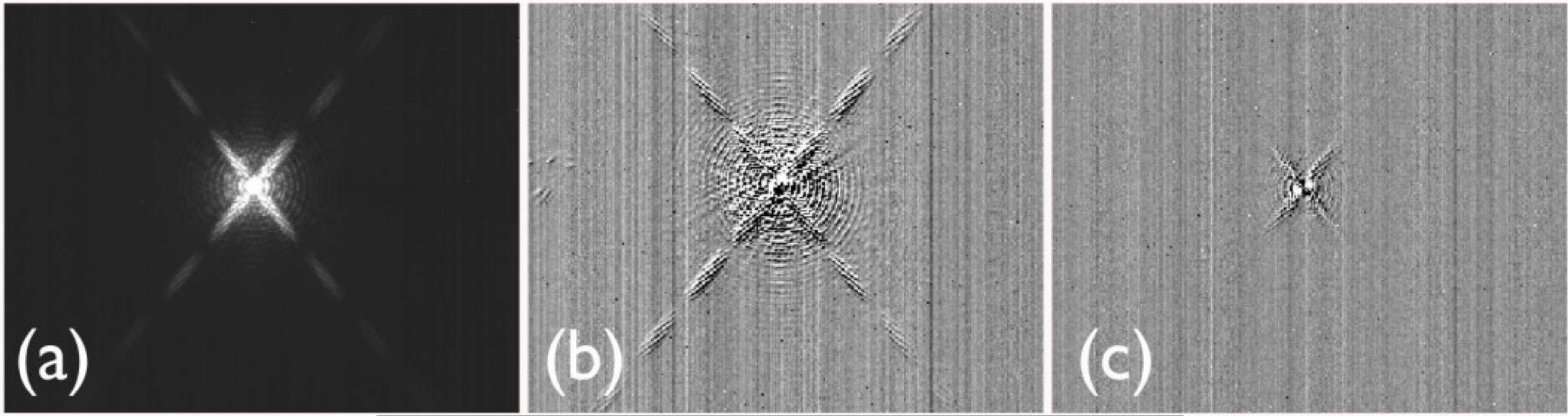


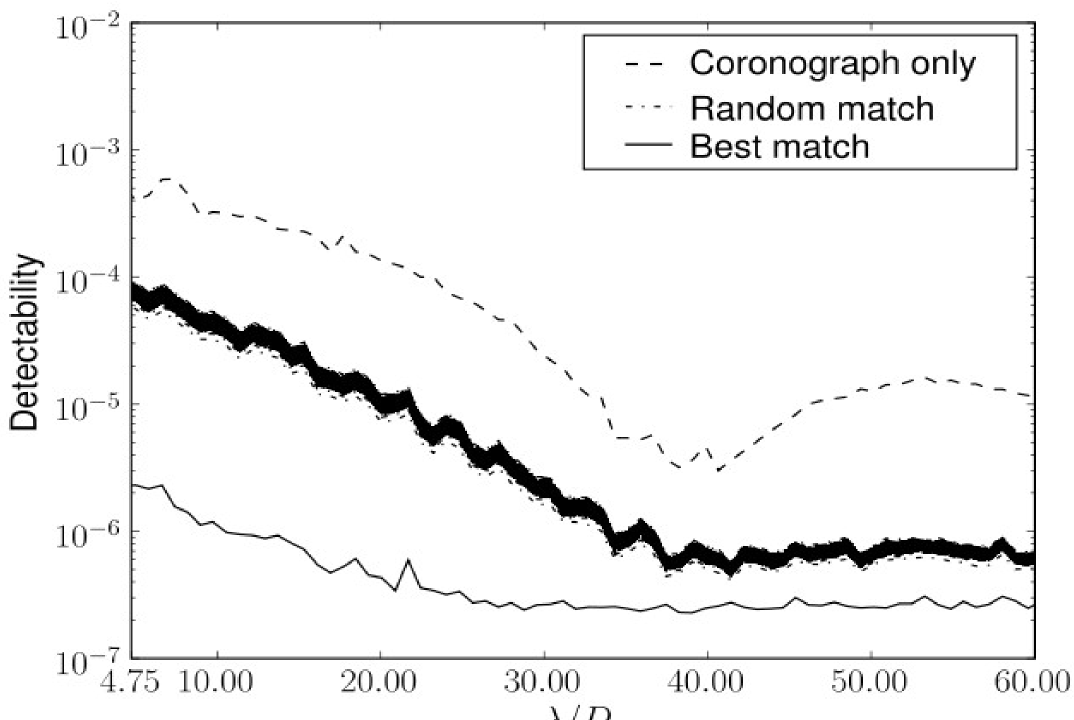




Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011, submitted)

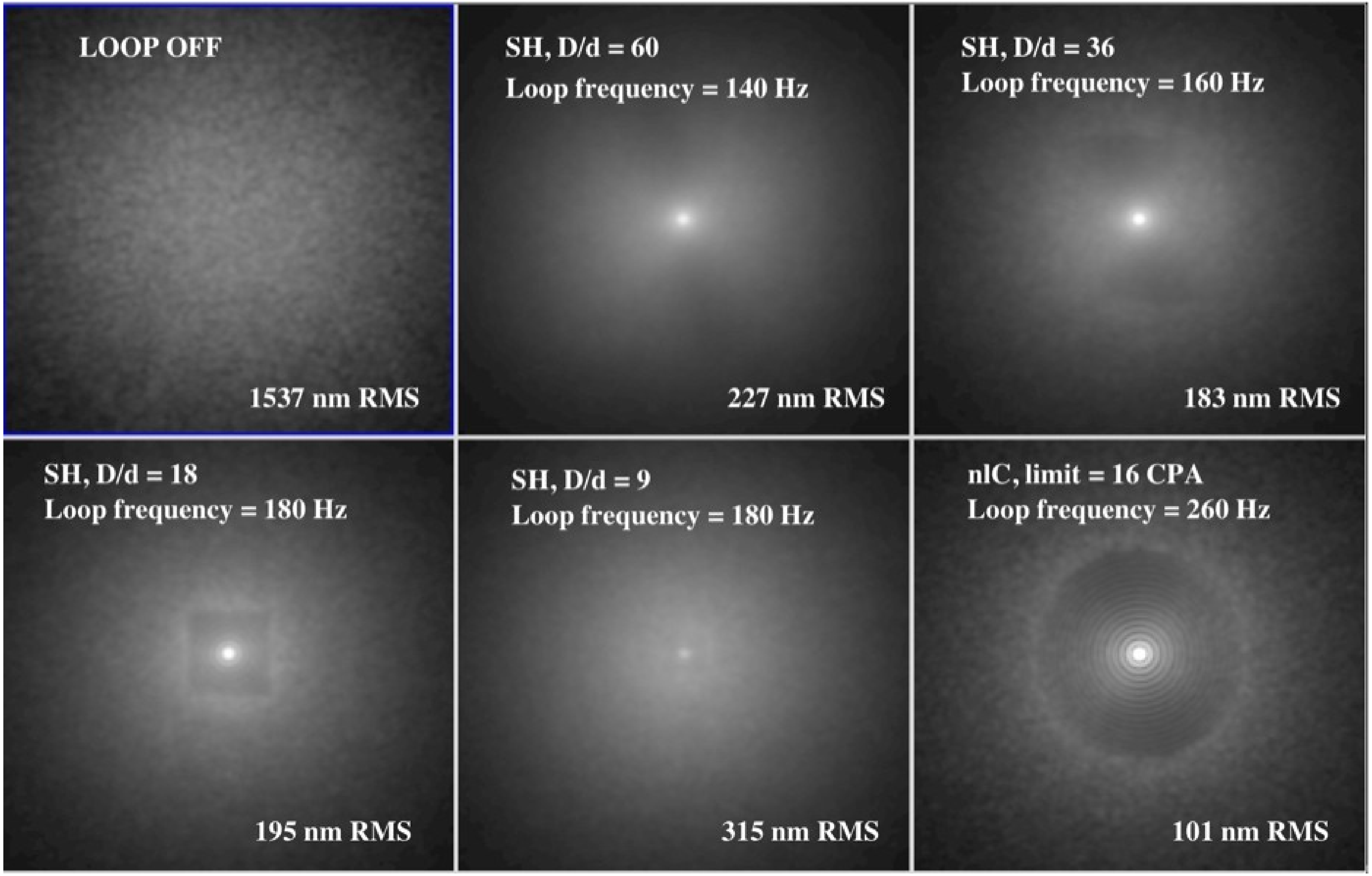
Co-added science image | Standard PSF subtraction | MMA





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%

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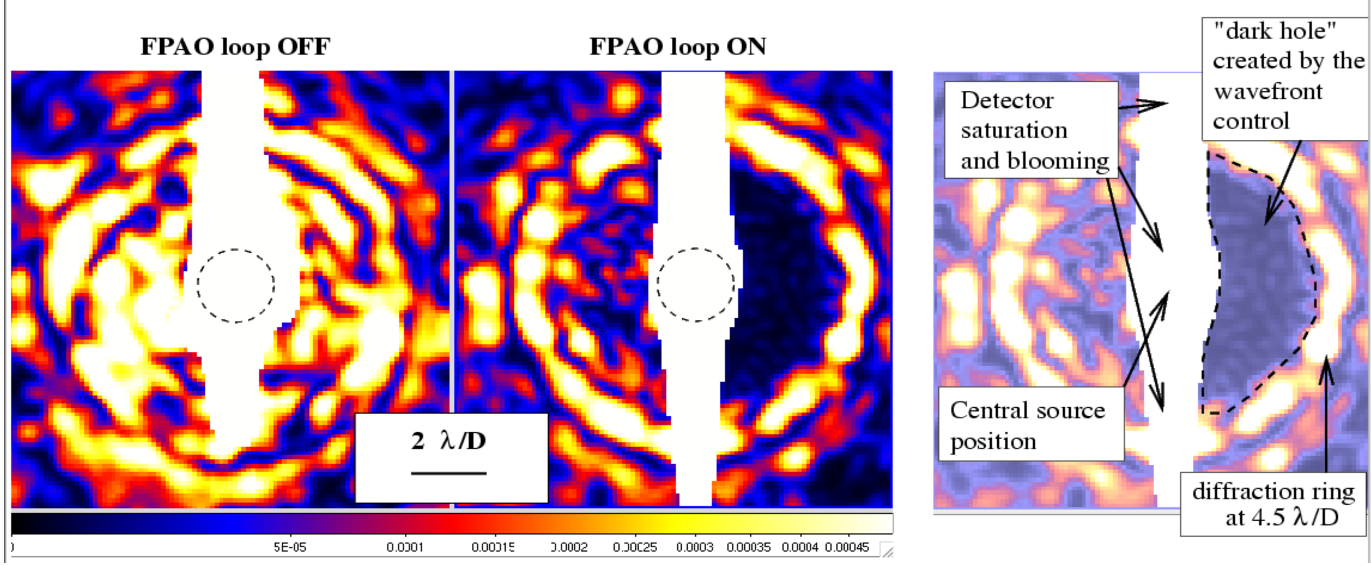
Focal plane AO and speckle calibration



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

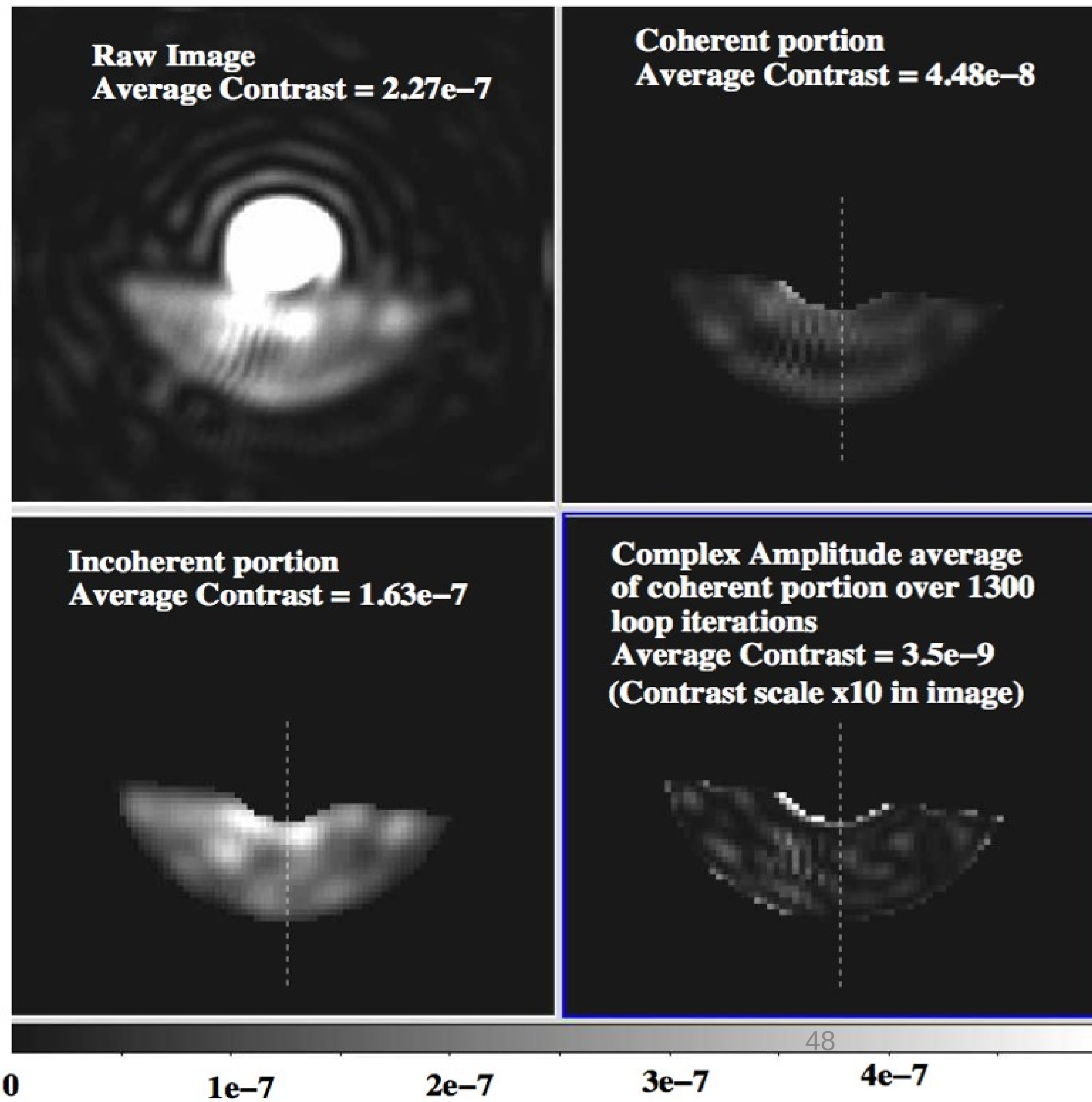
Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

Focal plane WFS based correction and speckle calibration: lab demo

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



Reflected light imaging

Initially very hard – requires ~1e-7 contrast and small inner working angle

Contrast is not a steep function of planet mass → small gains in contrast performance can lead to large science gain

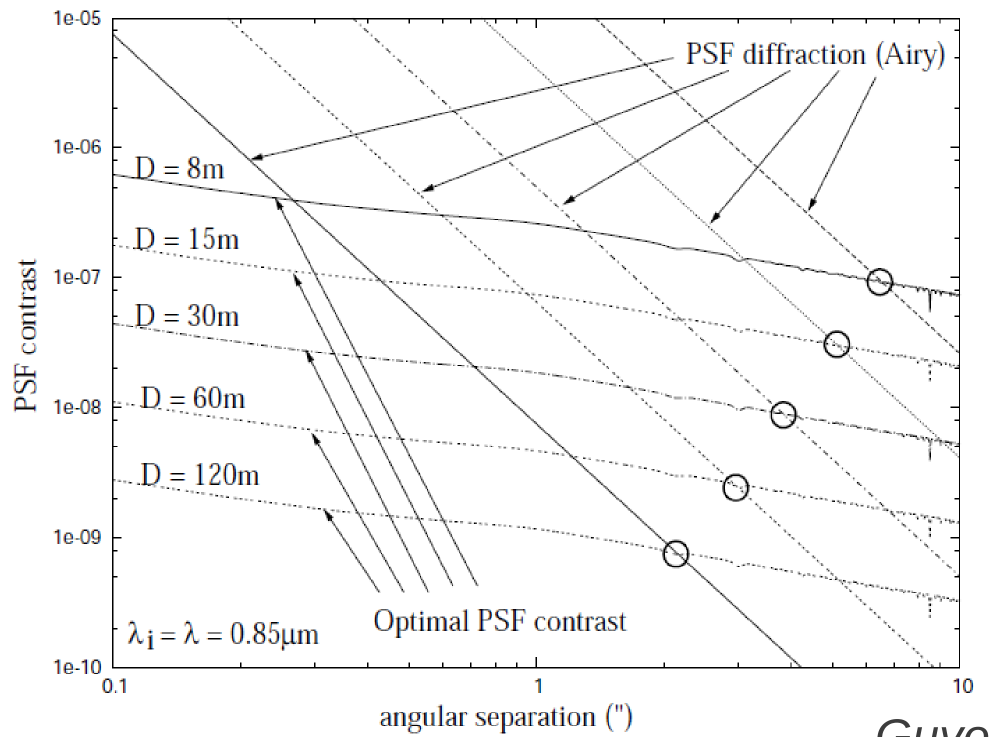
Easiest targets are the closest stars (few pc) – stars can be old

High performance system on 8-m telescope can detect reflected light from a few of the known RV planets
This will be an important science case for ELTs

Upcoming ExAO systems will validate technologies for reflected light imaging on larger telescopes

Ultimate performance limit

Could Earth-like planets be imaged from the ground ?



Guyon 2005

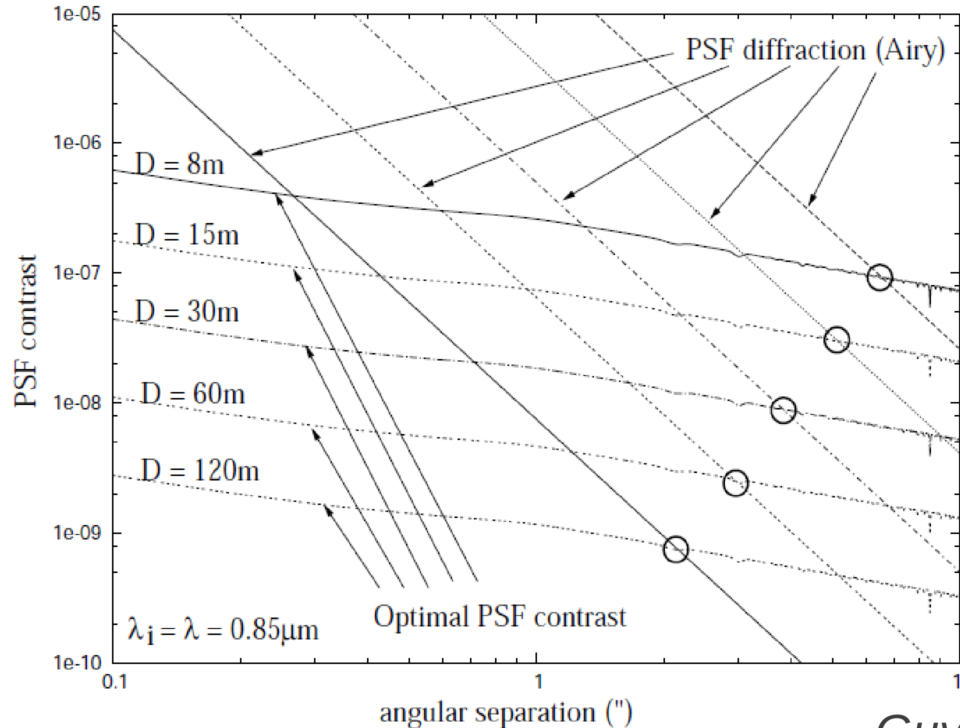
Assuming:

- perfect AO system, limited by photon noise in the WFS and speed of turbulence
- perfect coronagraph (to the contrast level reached by AO system)

At 0.85 um:
8-m telescope can reach better than ~1e6 RAW contrast
30-m telescope can reach better than ~1e7 RAW contrast

m_I=5 source, 0.05 um effective bandwidth, 1 hr exposure
Planet contrast = 1e10
8-m telescope: 452 ph/hr for planet, 4.5e6 ph/hr from speckles → $SNR_{ph\ noise}$ = 0.2
30-m telescope: 6356 ph/hr for planet, 6.4e6 ph/hr from speckles → $SNR_{ph\ noise}$ = 2.5

Could Earth-like planets be imaged from the ground ?



Guyon 2005

At nearIR (1.6 um), PSF contrast is x2 better, number of planet photon similar
30-m telescope: 6356 ph/hr for planet, 3.2e6 ph/hr from speckles → $SNR_{ph\ noise}$ = 3.5

→ Earth-like planets cannot be imaged from ground with 30m telescope

Super-Earths ?
Radius x3, contrast can be 10x better → $SNR_{ph\ noise}$ = 35

Highly optimized system on ELT could image Super-Earth in habitable zone of nearby star. Low resolution spectroscopy would be possible is the planet is around a nearby star (d < 10pc), but mid-resolution spectroscopy would not be possible at high SNR

With broader definition of "Earth" (nearby K, M? type main sequence star), SNR is much better, and target can be closer