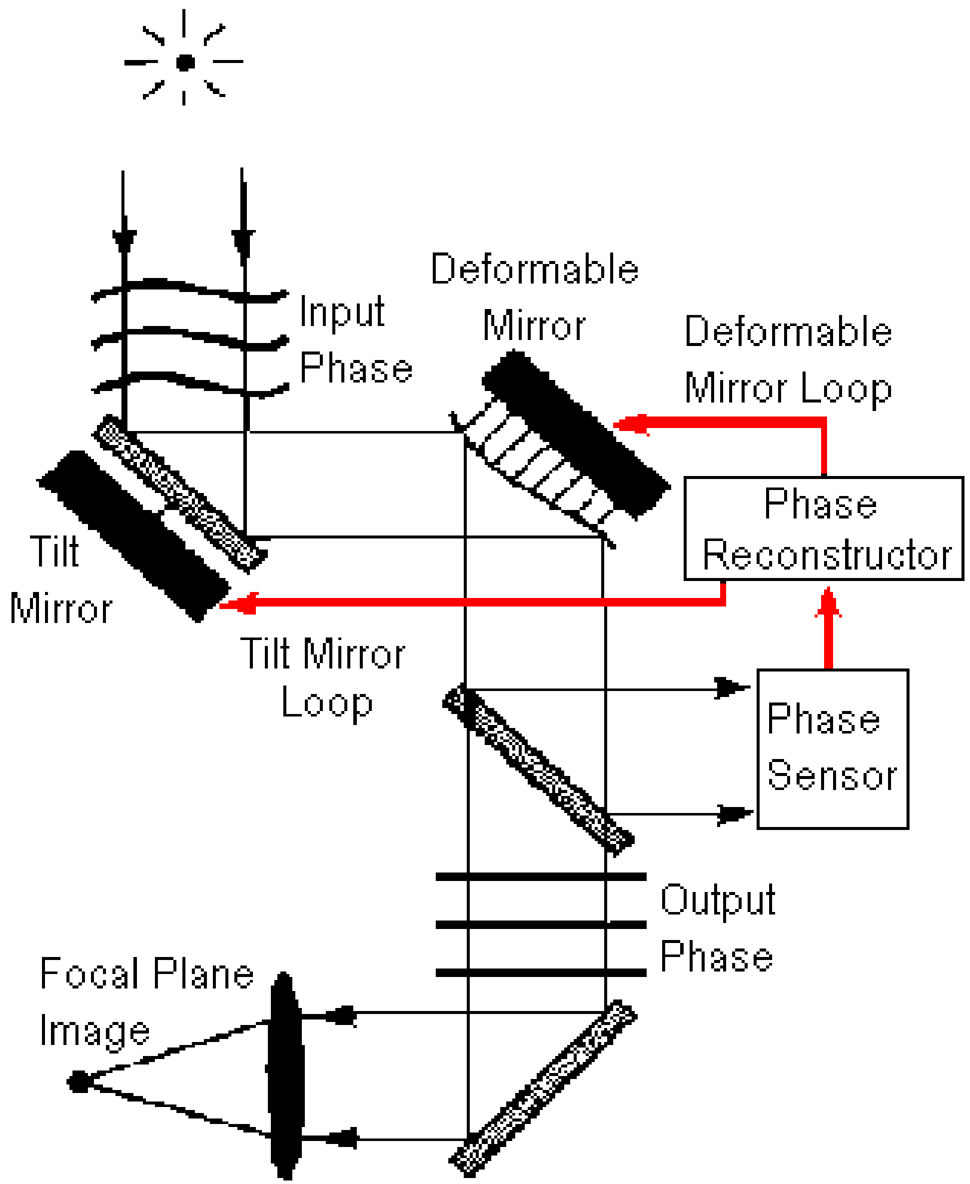
# What is Adaptive Optics ?




Main components of an AO system:

**Guide star(s)**: provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

**Deformable mirror(s)** (+ tip-tilt mirror): corrects aberrations

**Wavefront sensor(s)**: measures aberrations

**Computer, algorithms**: converts wavefront sensor measurements into deformable mirror commands

# Adaptive Optics for High contrast imaging
# ("extreme AO")

Goals

System architecture

Wavefront sensing and control techniques

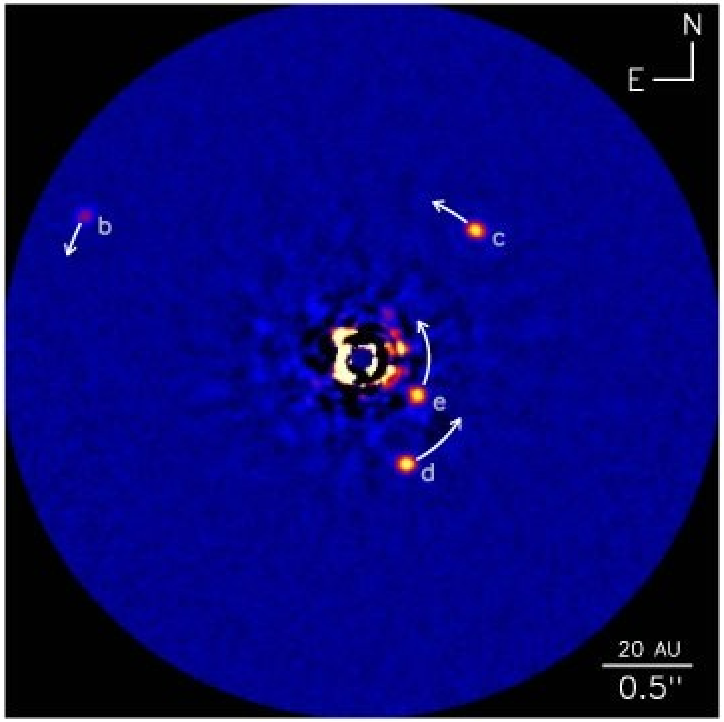
Example systems: ground and space missions/projects

# Goals

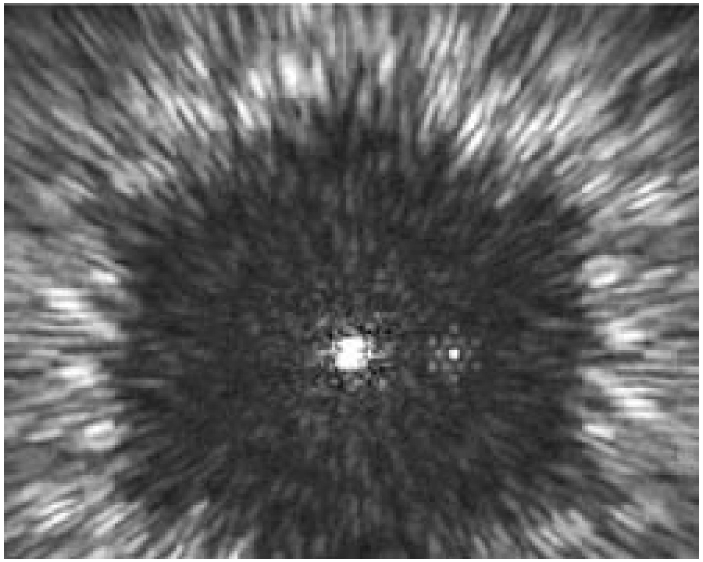
*Direct imaging of planets and disks around other stars = separating planet light from starlight*

- *required for high quality spectroscopy of planet light*
- *allows relative astrometry and flux measurement for planet*
- *direct imaging can reveal multiple planets, planet/disk interactions*

***→ Requires Imaging system optimized to provide high contrast at small angular separation.***




Giant planets around HR8799 imaged in near-IR
(current large ground based telescopes)



Simulated Earth-like planet image with space telescope optimized for high contrast imaging
(Courtesy NASA JPL-Caltech)

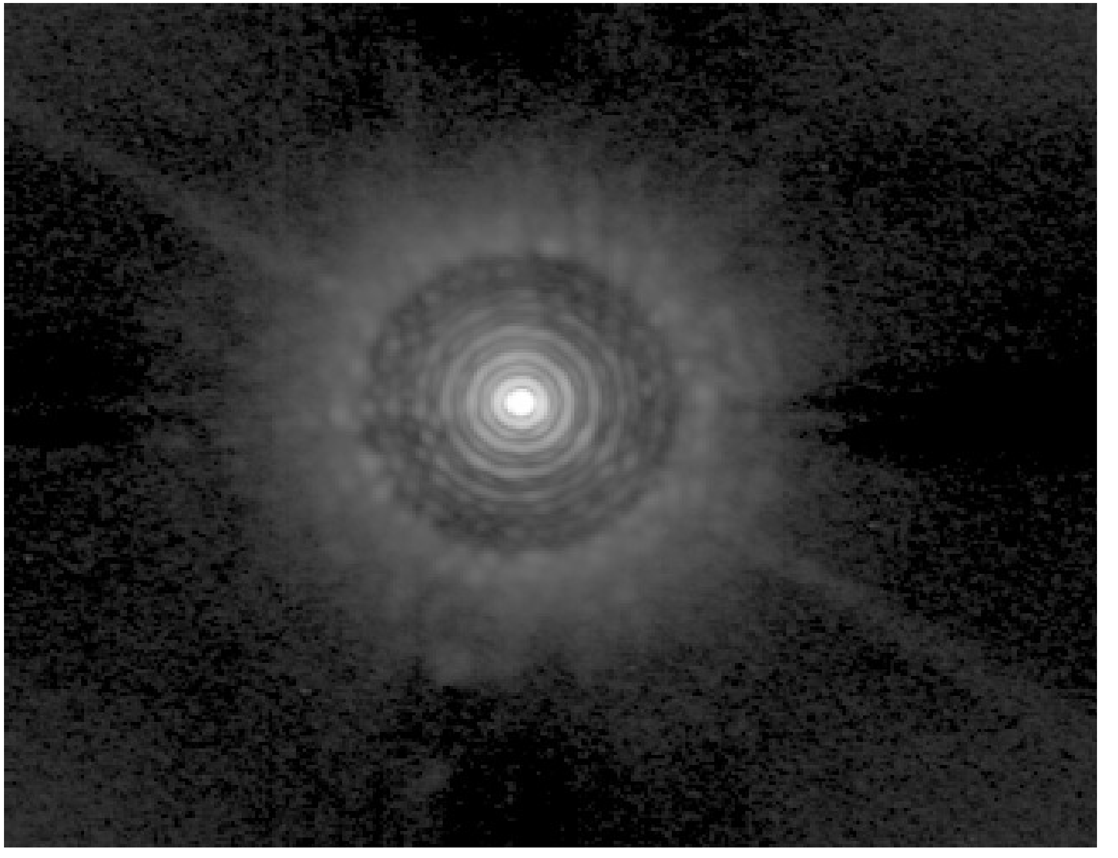
# Goals and Challenges

***Imaging system optimized to provide high contrast at small angular separation***
***→ suitable performance metric is CONTRAST (how dark is it next to the star image)***

***RAW contrast:*** surface brightness in PSF, normalized to central peak

***DETECTION contrast:*** detection limit after calibration

*DETECTION contrast is better than RAW contrast:*
*by ~100x on ground-based telescopes observing bright stars with AO in the near-IR*
*only by ~1x to ~10x for space-based detection of Earth-like planets (photon noise imposes a strong limit on detection)*



LBT AO image of a star
Raw contrast = PSF surface brightness
Detection contrast = how faint can a planet be detected
note challenge: how to differential speckles from actual sources ?

# What is a high contrast imaging system (ground or space) ?

*Imaging system optimized to provide high contrast at small angular separation.*

**Key elements:**

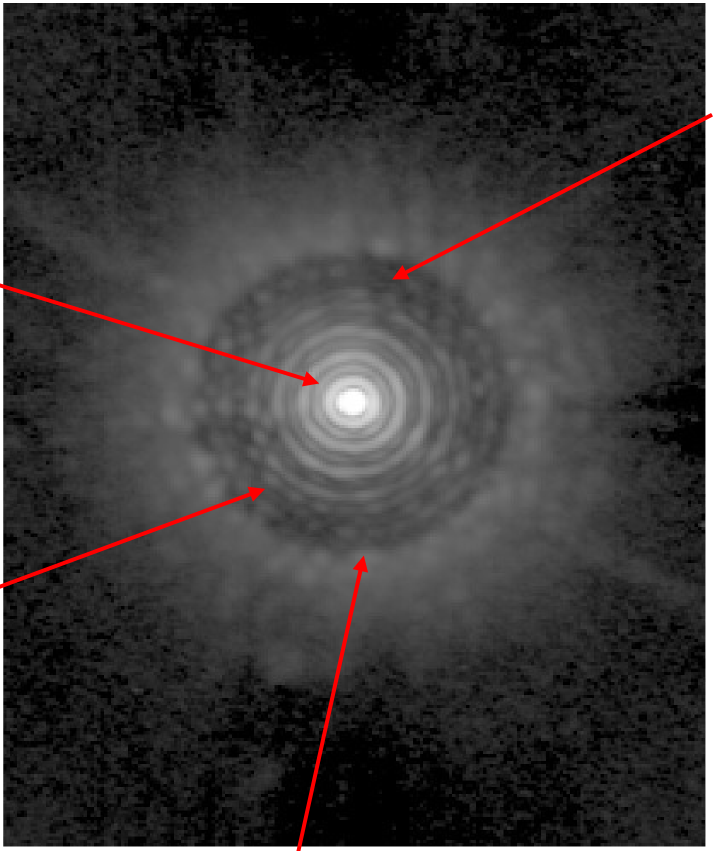
**- Coronagraph** or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

**- Wavefront correction system** to reduce and calibrate residual wavefront errors
For coronagraphs: Extreme-AO system to flatten wavefront
For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

**- Science detector (+ differential detection technique)** for imaging, spectroscopy and polarimetry
(note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)

# From conventional AO to Extreme-AO: illustration

We use a non-extreme AO system image as starting point
Example of a very good PSF with a current AO system: LBT AO image



Residual atmospheric speckle halo

**REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM**

PSF diffraction (Airy rings, spiders)

**REMOVED BY CORONAGRAPH**

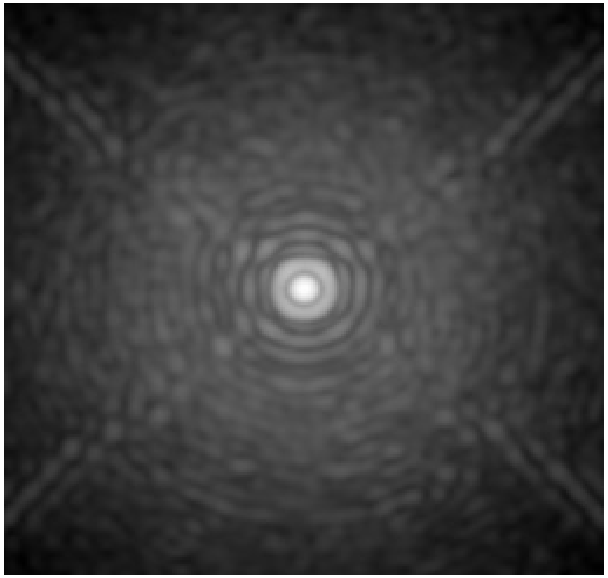
Static and slow speckles

**MUST BE REMOVED BY CALIBRATION SYSTEM OR DIFFERENTIAL IMAGING (actively or in post processing)**

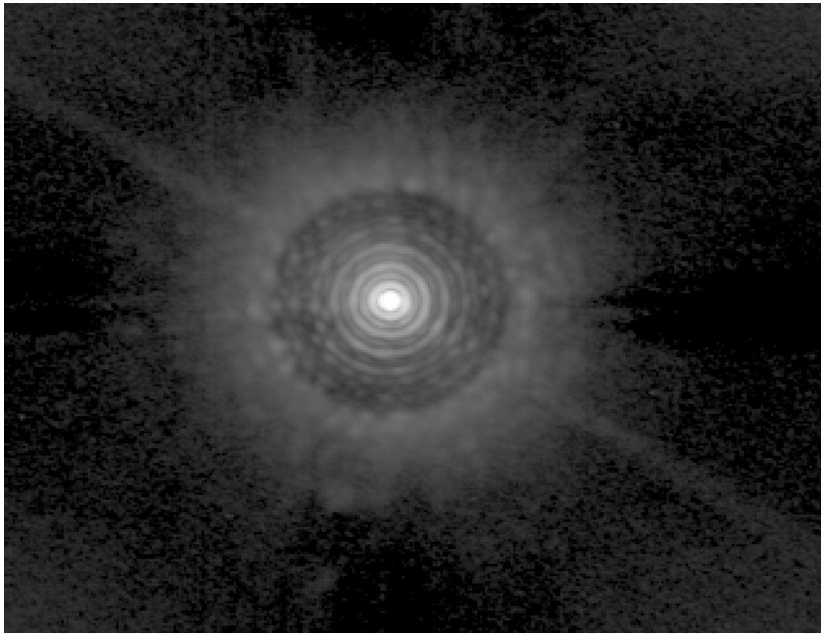
Control radius of AO

**DEFINED BY NUMBER OF ACTUATORS IN DM: MAY BE INCREASED WITH MORE ACTUATORS IF REQUIRED**

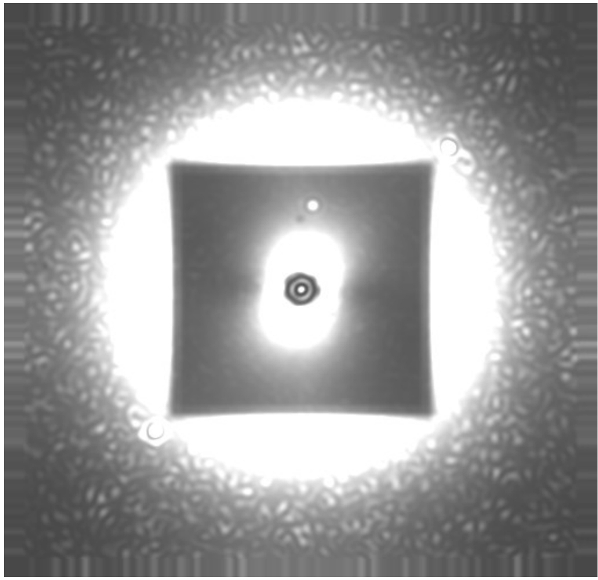
# From conventional AO to Extreme-AO



**Conventional AO system**

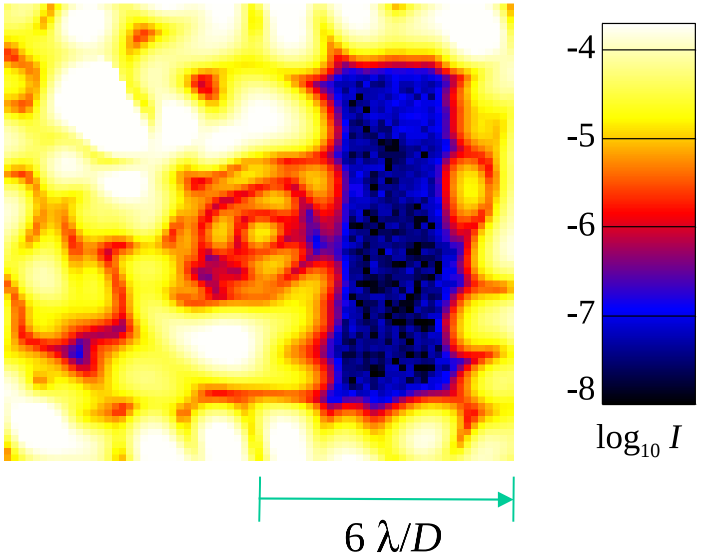


**Very good conventional AO system (LBT)**



**Ground-based Extreme-AO system (GPI - simulation)**

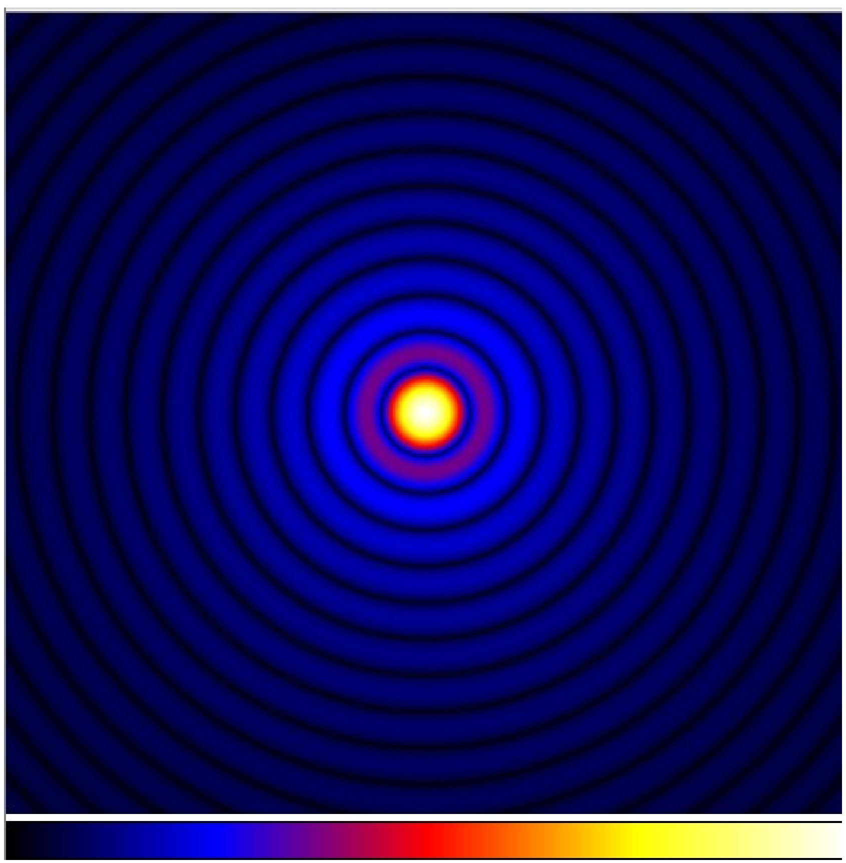
**High contrast imaging systems are specifically designed to produce dark areas in the image**
**Use:**
- **coronagraphy**
- **contrast-optimized wavefront control**
- **calibration / differential imaging**

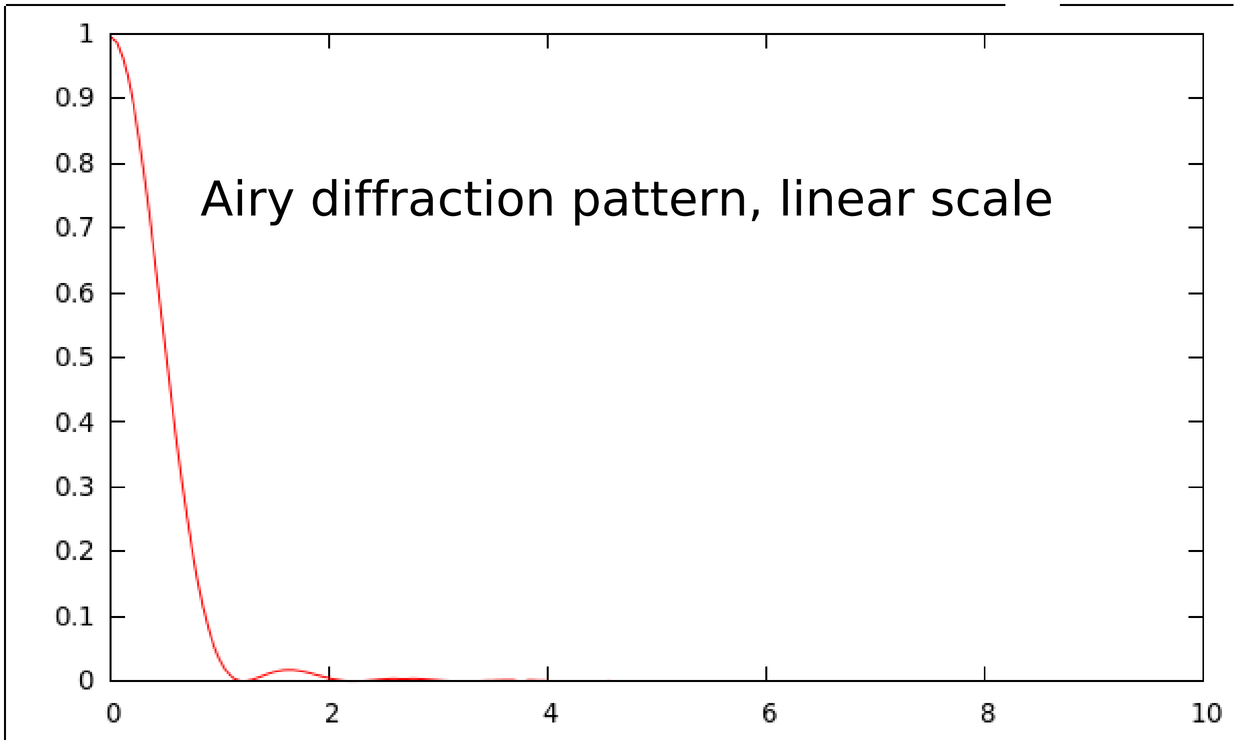


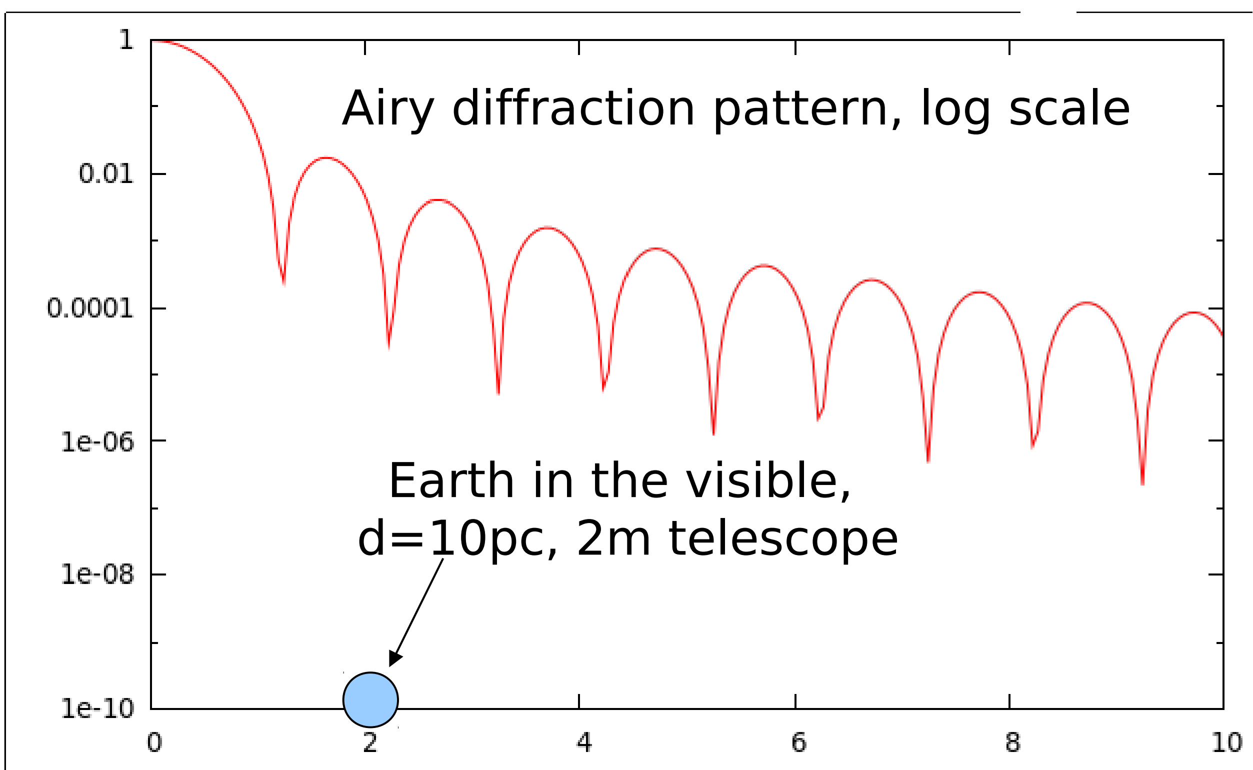

**Space-based high contrast imaging system (lab)**

# Why coronagraphy ?

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





# 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.

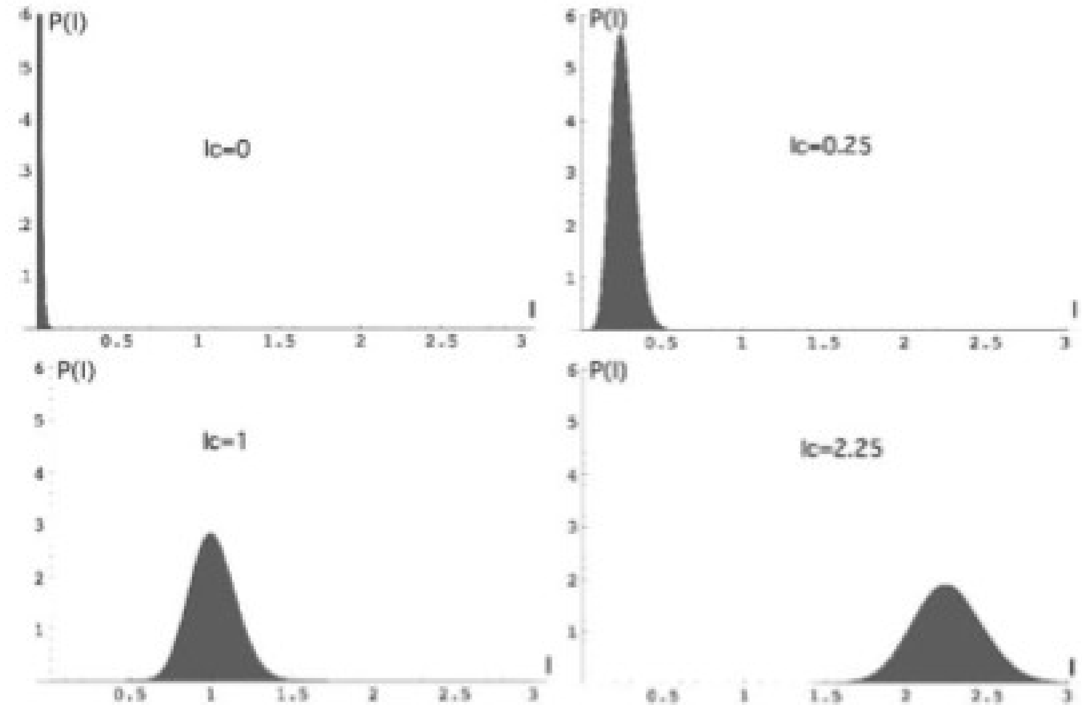



FIG. 3.—PDF of the light intensity at four different constant background intensity levels $I_c$ and a single value of $I_s = 0.1$. High values of $I_c$ correspond to locations near the perfect PSF maxima (rings), and low values of $I_c$ correspond to locations near the zeros of the perfect PSF or far 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

# Current limits to coronagraph performance are:

**Coronagraph design and manufacturing (Only for contrasts better than approximately 1e-8)**

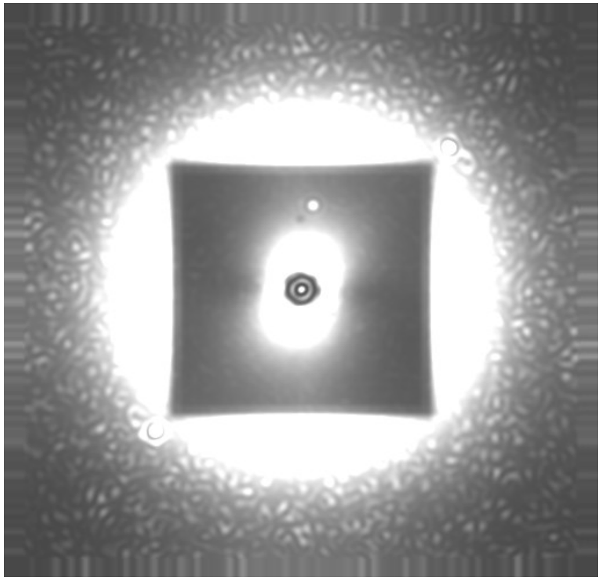
For moderate contrasts (up to ~1e-8), it is reasonably easy to manufacture a high performance coronagraph
→ ongoing lab development to push coronagraphic performance to ~1e-10 contrast in broadband light at small inner working angle

**Wavefront quality and stability (including calibration)**

For ***high contrast space systems*** (aiming at 1e-10 contrast), wavefront should be good to << nm, and stable over long period of time
→ design of very stable optical system, with efficient (but slow) wavefront correction & calibration

For ***ground-based system***, Extreme AO system can reduce wavefront errors to a few x 10nm at best
→ efforts to develop Extreme-AO systems, and calibrate residual light

# Wavefront control for High contrast imaging



**Ground-based systems**

Residual speckle field is brighter than planets(s)

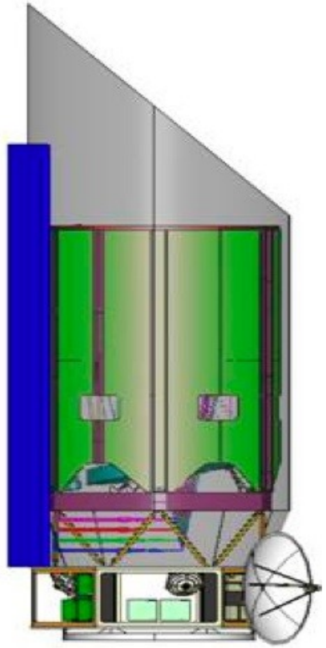
Systems often operate in **speckle noise limited regime**

→ calibrating speckles is extremely important

**Space-based ultra-high contrast systems**

Detection is close to the **photon noise limit** of the planet(s)

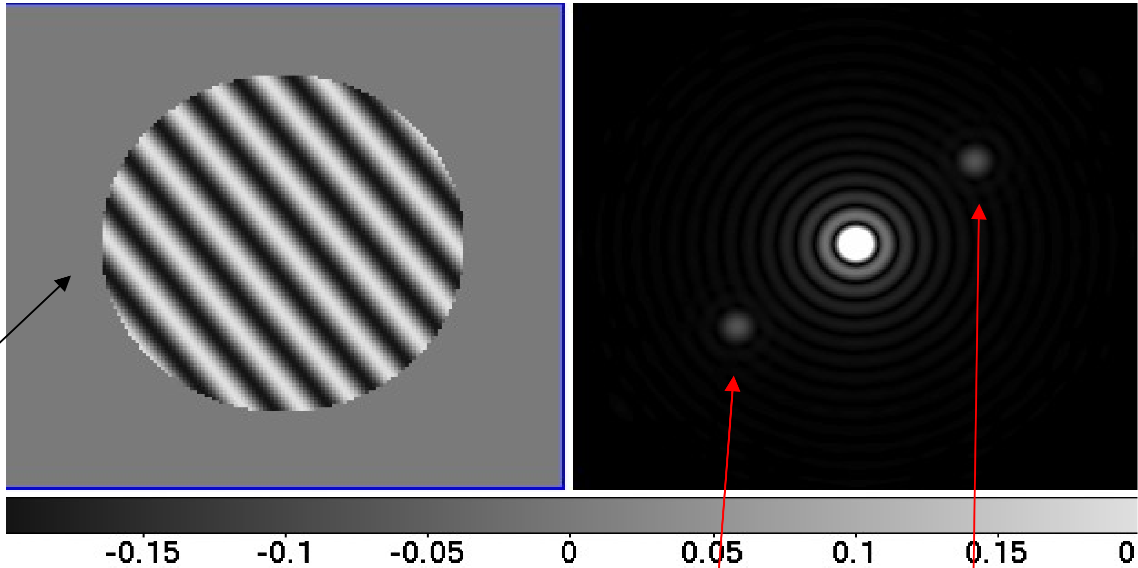
→ speckles need to be reduced at or below the planet image surface brightness level



Wavefront control is essential, and differential imaging/calibration will not work if speckle halo is brighter than planet

→ need to build extremely stable system

# Relationship between speckle and wavefront errors




pupil plane complex amplitude

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

Cosine aberration in pupil phase

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

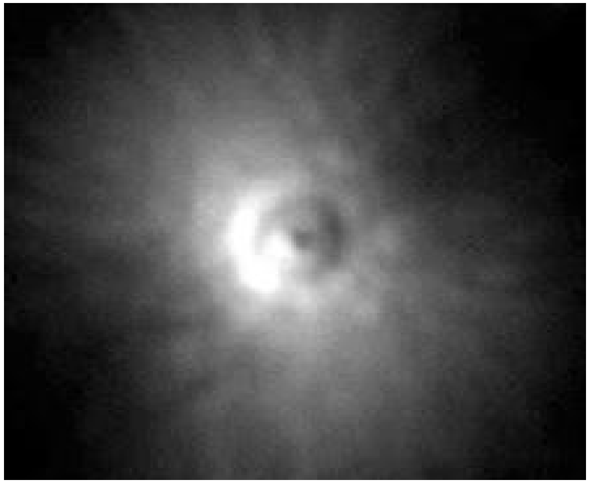
$$I(\vec{\alpha}) = PSF(\vec{\alpha}) + \left(\frac{\pi h}{\lambda}\right)^2 \left[PSF(\vec{\alpha}+\vec{f}\lambda) + PSF(\vec{\alpha}-\vec{f}\lambda)\right]$$

**EXAMPLE:**
Earth-like planet around Sun-like star is ~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 needs to be stable to 1/1000 nm over ~ minute**

# Pointing control is critical for small inner working angle

**Small error in pointing = coronagraphic leak around the focal plane mask (can look like a planet !!)**



on-sky coronagraphic image (Lyot Project)

Solution: **use starlight falling on coronagraph mask to measure tip tilt** and a few other low order modes.

Example coronagraphic focal plane mask designed for this purpose: starlight is reflected into fast camera for measurement of low order aberrations (pointing, focus)

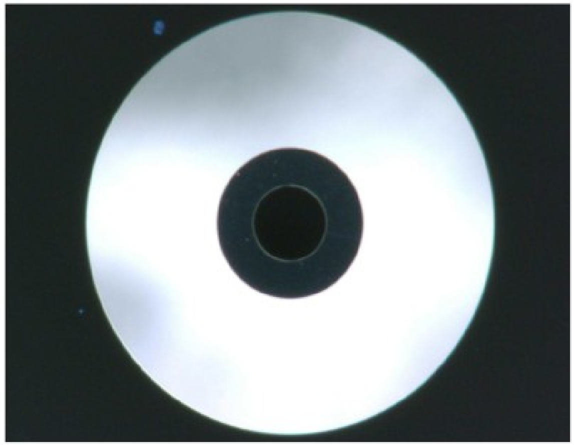
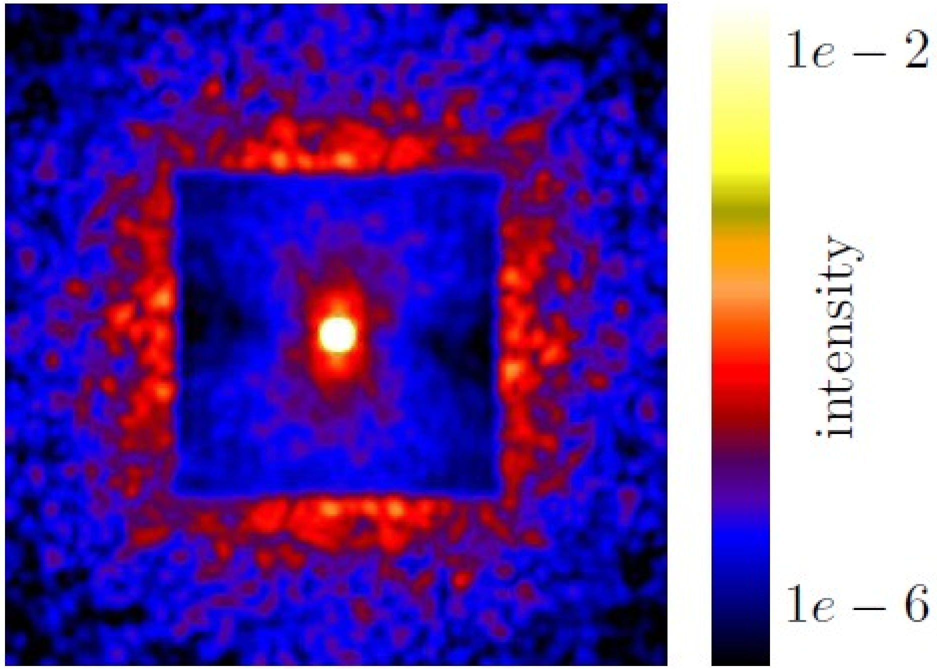


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

# Static and slow speckles

**Problem:**
Fixed aberrations create static speckles that look like planets. Slow speckles (some of them due to atmosphere) take a long time to average down, and look like planets.
→ ExAO systems need to calibrate/remove static and slow speckles




GPI PSF simulation (Macintosh et al. 2006)

**Proposed solutions:**

**Pupil plane interferometry:** interfere residual light (after coronagraph) with starlight (extracted by coronagraph focal plane mask) to measure static aberrations after AO system

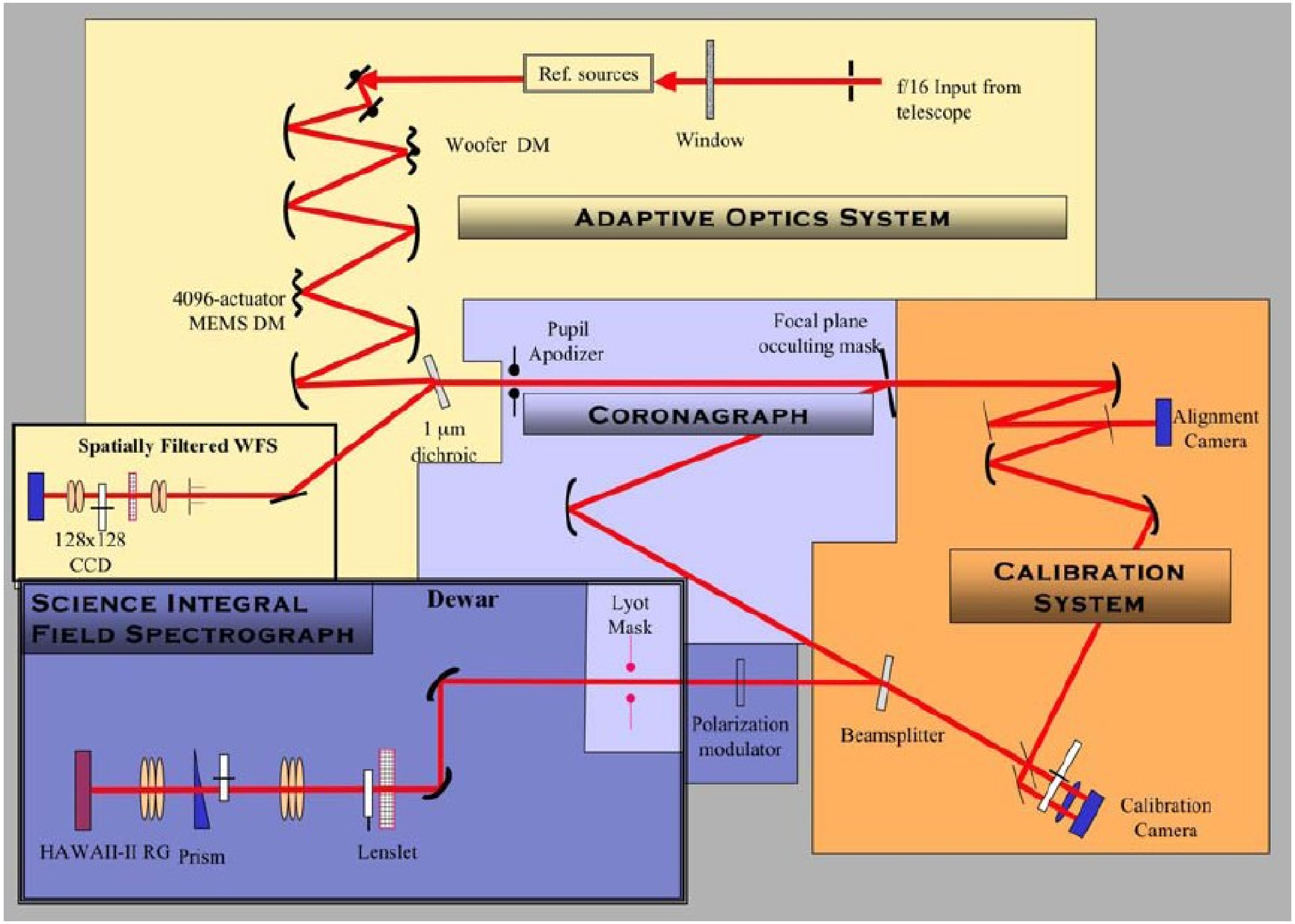
**Self-coherent camera:** interfere focal plane with reference wave extracted from central star

**Focal plane wavefront control with DM:** modulate (=probe) focal plane speckles by issuing commands to the deformable mirror

# Pupil plane calibration interferometer (Gemini Planet Imager)

Pupil-plane interference between light at the output of the coronagraph and starlight extracted in coronagraph.

*Any residual starlight will be detected, and then removed by inducing an offset to the upstream AO system*




(Macintosh et al. 2006)

# Differential detection techniques

**How to separate speckles from planet(s) ?**

**PSF subtraction**

*Observe another star, subtract the 2 images*

Observation time overhead, reference PSF is different from target PSF

**Angular Differential Imaging (ADI)**

*On alt/az telescope, use field rotation to differentiate between speckles (fixed on PSF) and planet(s) rotates according to known field rotation*

Efficient use of observing time, ideal reference PSF

Does not work well very close to star (little rotation)

**Spectral Differential Imaging (SDI)**

*Use spectral signature(s) to differential planet from speckles: speckle spectra = star spectra, while planet is expected to show methane spectral signature*

Works at all separations, no need for separate reference PSF

Can only detect planets with the expected spectral feature

**Polarimetric Differential Imaging (PDI)**

Planet reflected light is polarized, speckles are not

Works at all separations, no need for separate reference PSF

Can only detect reflected light planets

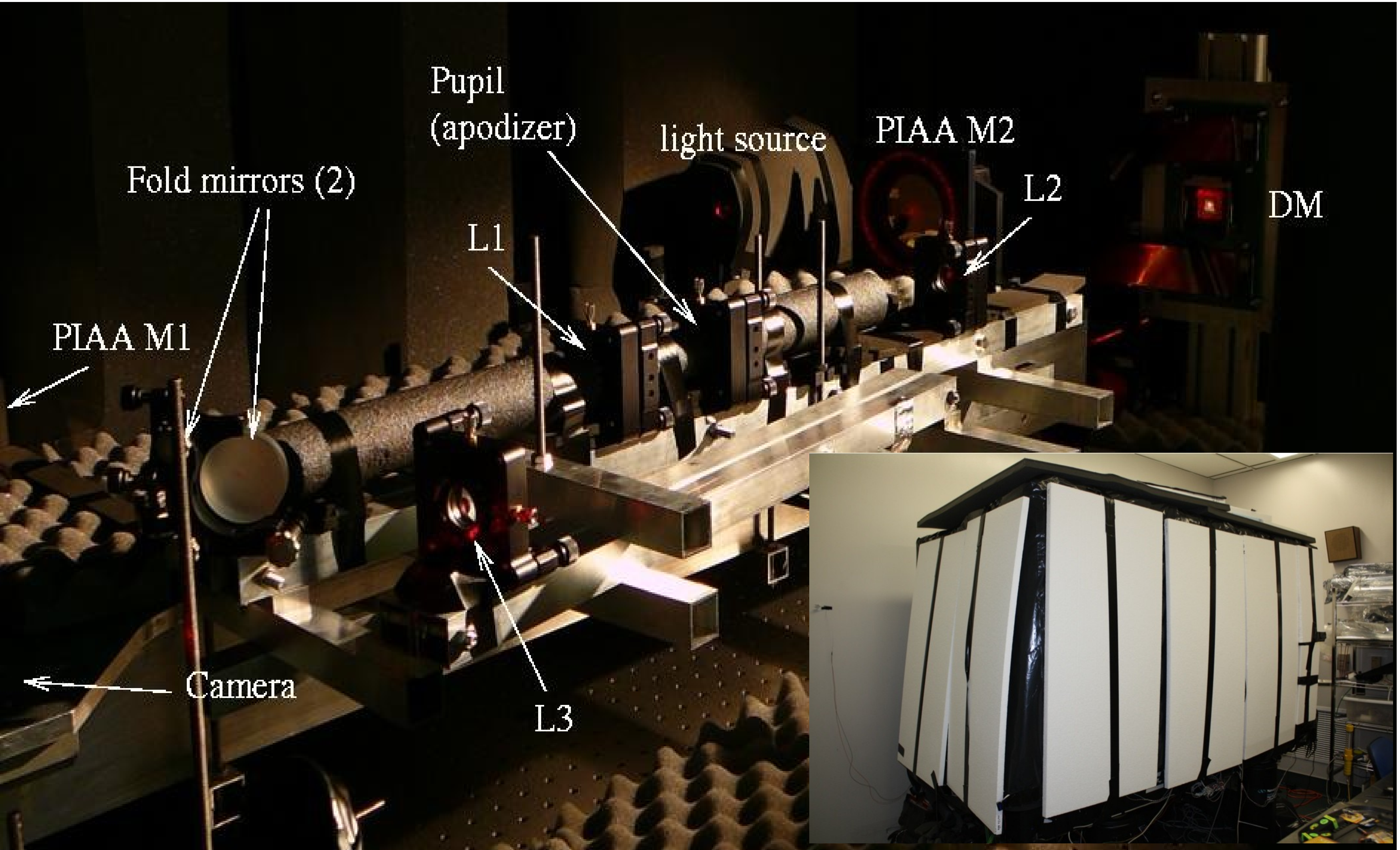
**Coherent Differential Imaging (CDI)**

Planet incoherent with starlight, while speckles are coherent → modulate speckle field by issuing commands to deformable mirror

Works at all separations, no need for separate reference PSF, well matched to focal plane WFC

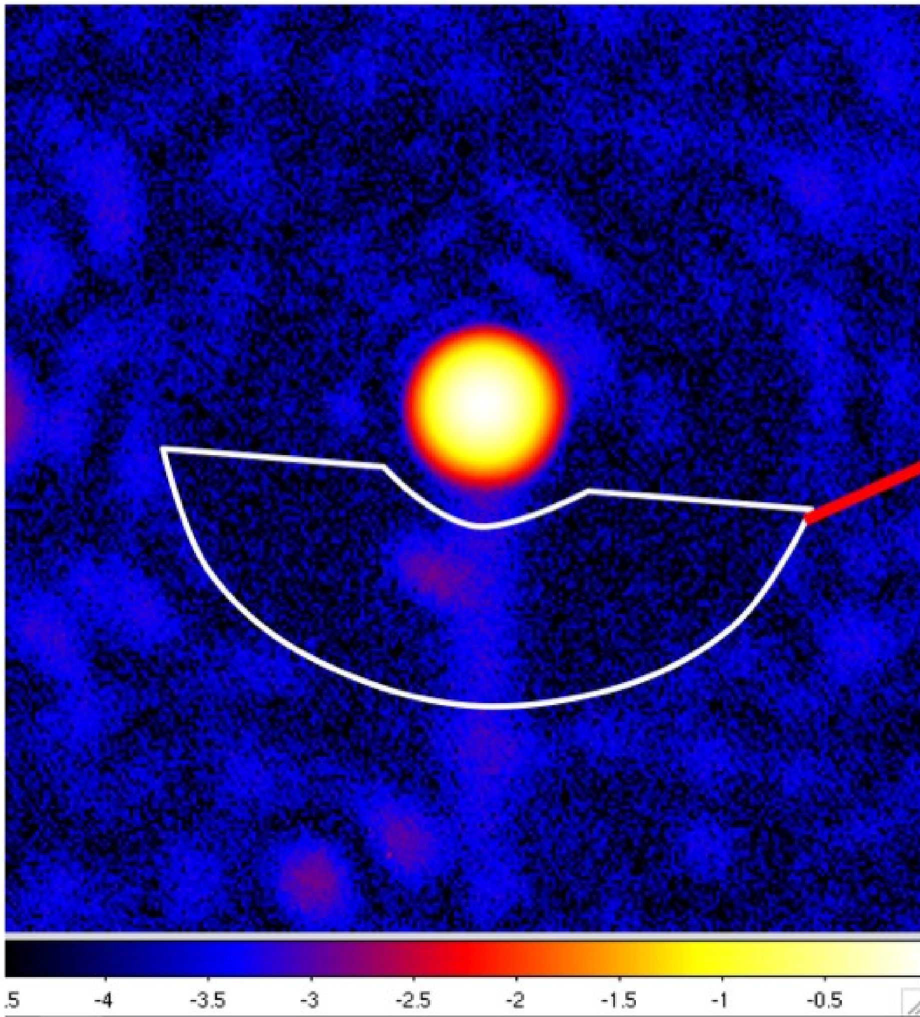
Needs fast detector as speckles loose coherence in long exposures

# Laboratory testing of coronagraphs: example of PIAA testbed at Subaru Telescope lab

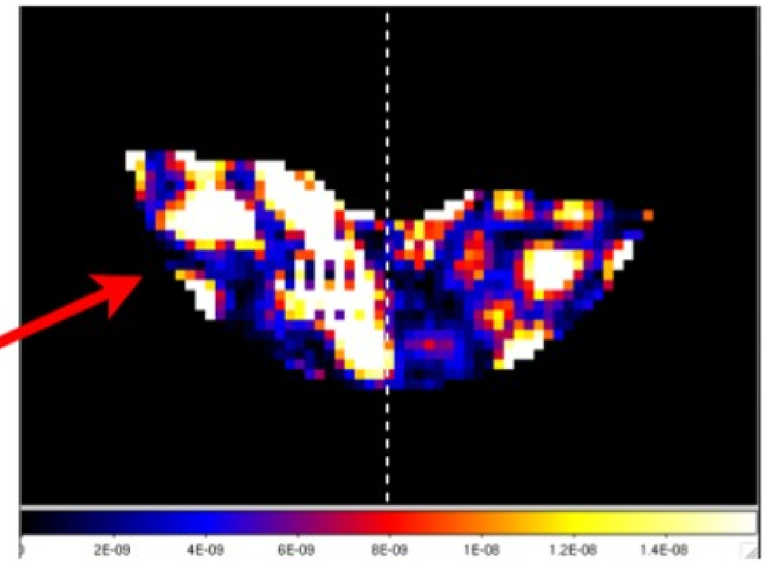


## Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image




Coherent starlight




Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

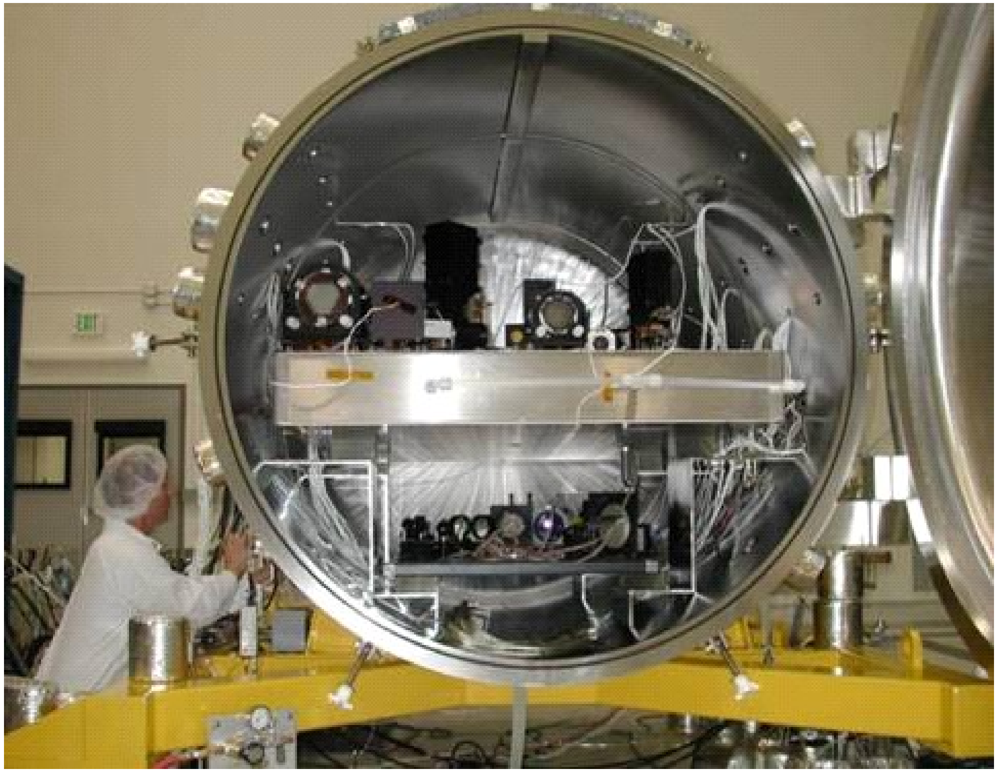
Contrast achieved in 1.6 to 4.5 l/D zone:

1.5e-7 incoherent halo ghost (equivalent to exozodi)

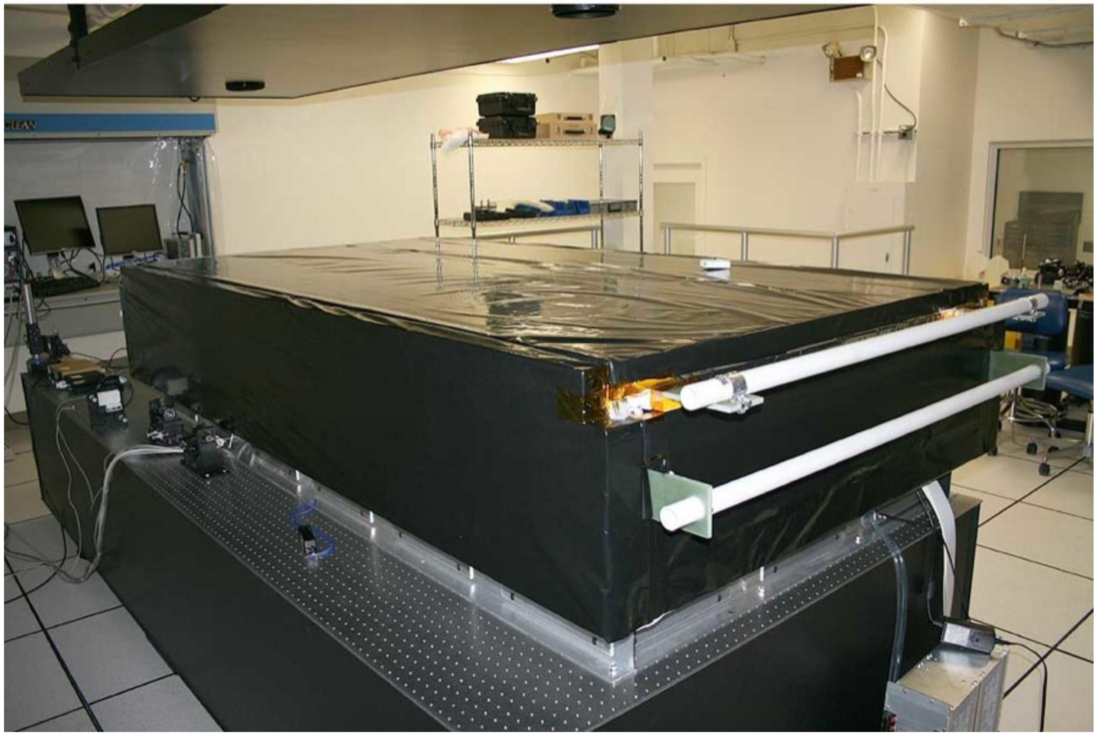
7e-9 coherent starlight speckles (turbulence, vibrations)

# 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*

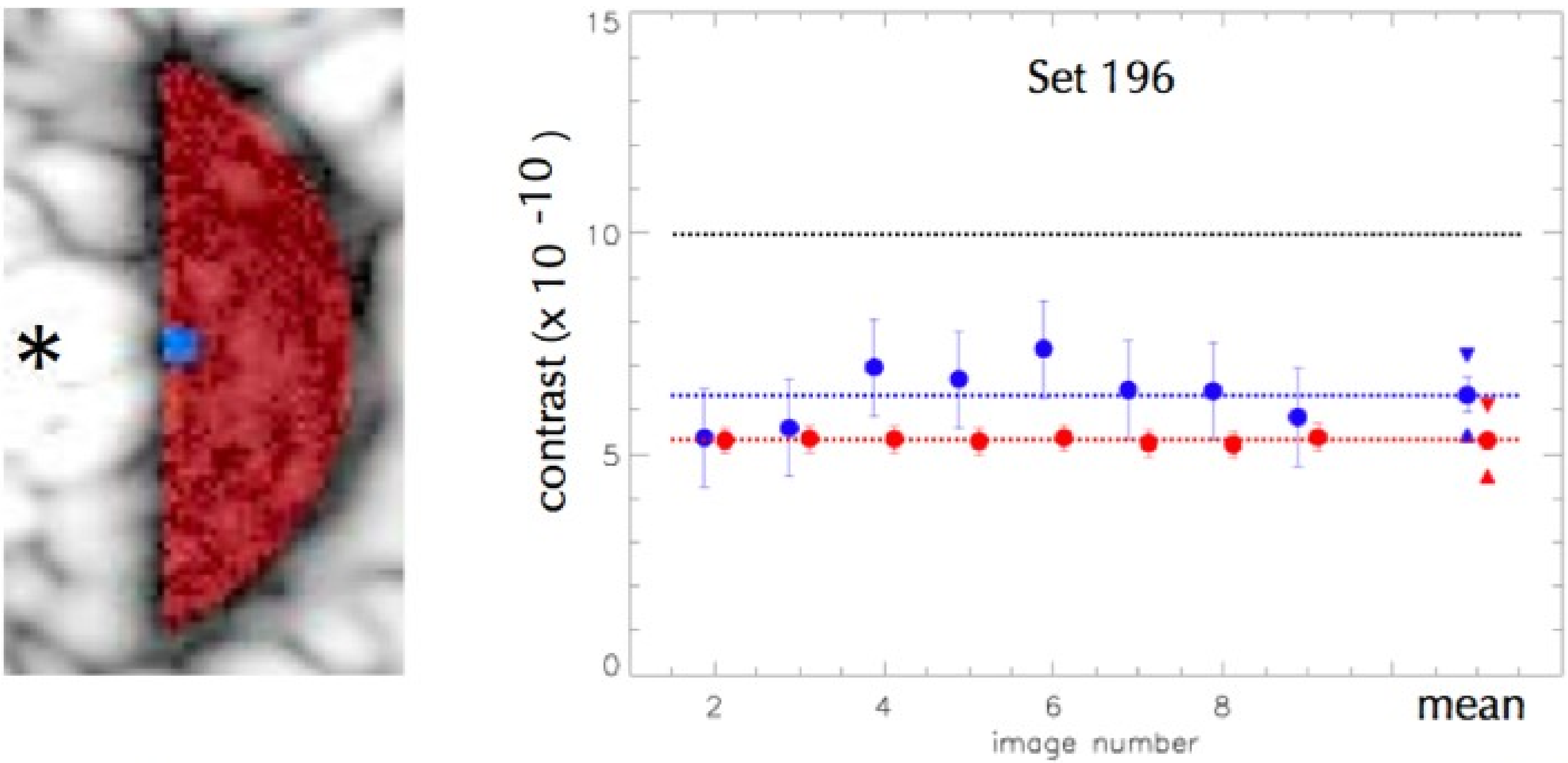


*NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.*



# Vacuum tests at NASA JPL have reached close to 1e-10 contrast at 4 l/D with band-limited masks (Trauger et al.)

*"Classical" speckle nulling with the HCIT*




Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. 1-σ error bars indicate the measurement noise estimated from pairwise data.

# Current and future high contrast systems - ground

**NICI on Gemini South telescope** – ongoing survey
85-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)

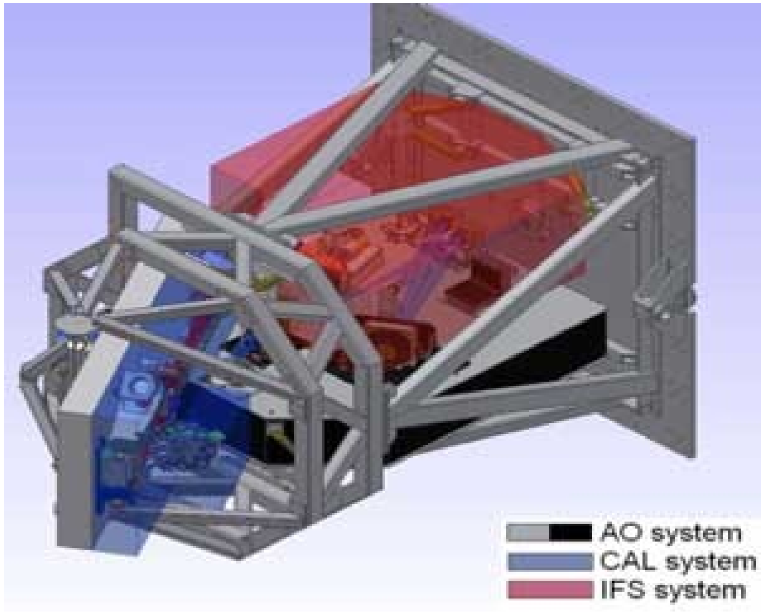
**HiCIAO on Subaru Telescope** – ongoing survey
188-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)
**→ Subaru Coronagraphic Extreme AO (upgrade of HiCIAO)** – on sky in 2012
Small inner working angle PIAA coronagraph
Pointing sensing and control with coronagraphic low order WFS
Speckle control using focal plane image as sensor
32X32 MEMS deformable mirror

**P1640 + Palm300 on Palomar 5-m telescope** – on sky in 2011/2012
3000 element high order AO system + Lyot coronagraph
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

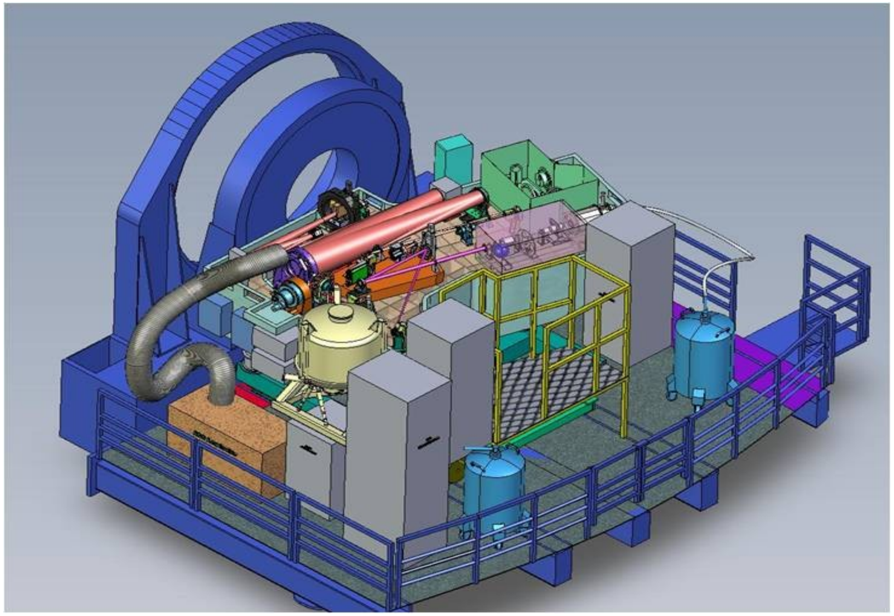
**Gemini Planet Imager (GPI)** – large survey will start observations in ~2013
ExAO system using 64x64 MEMS DM + coronagraph
Includes calibration interferometer to accurately measure residual speckles
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

**ESO's SPHERE on VLT** – large survery will start observations in ~2013
ExAO system + coronagraph
Highly stable bench
Includes Integral Field Spectrograph to help remove speckles and acquire spectra
Includes differential polarimetric imager

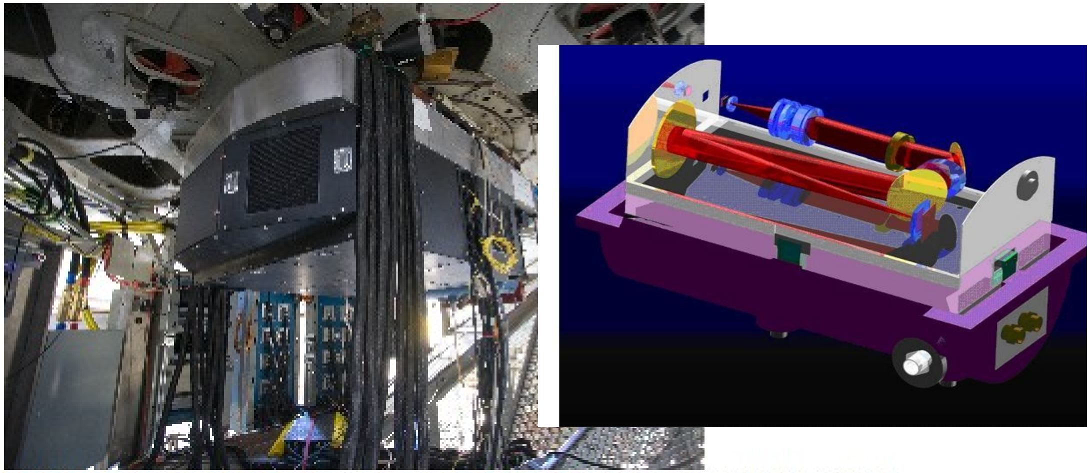
# Current and future high contrast systems - ground




Gemini Planet Imager

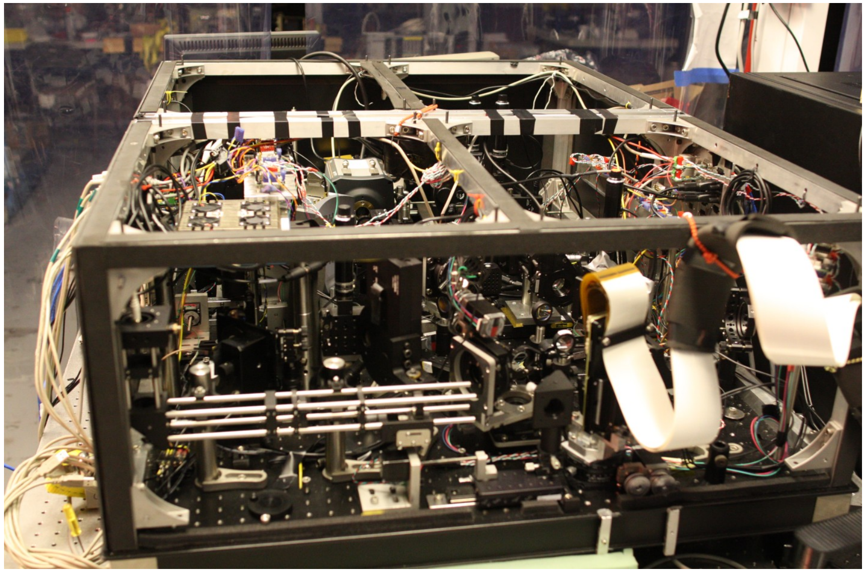


SPHERE (European Southern Observatory)



PALM-3000 installed at the Cass focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel.

PALM3000/P1640 (Palomar 5-m Telescope)



Subaru Coronagraphic Extreme-AO