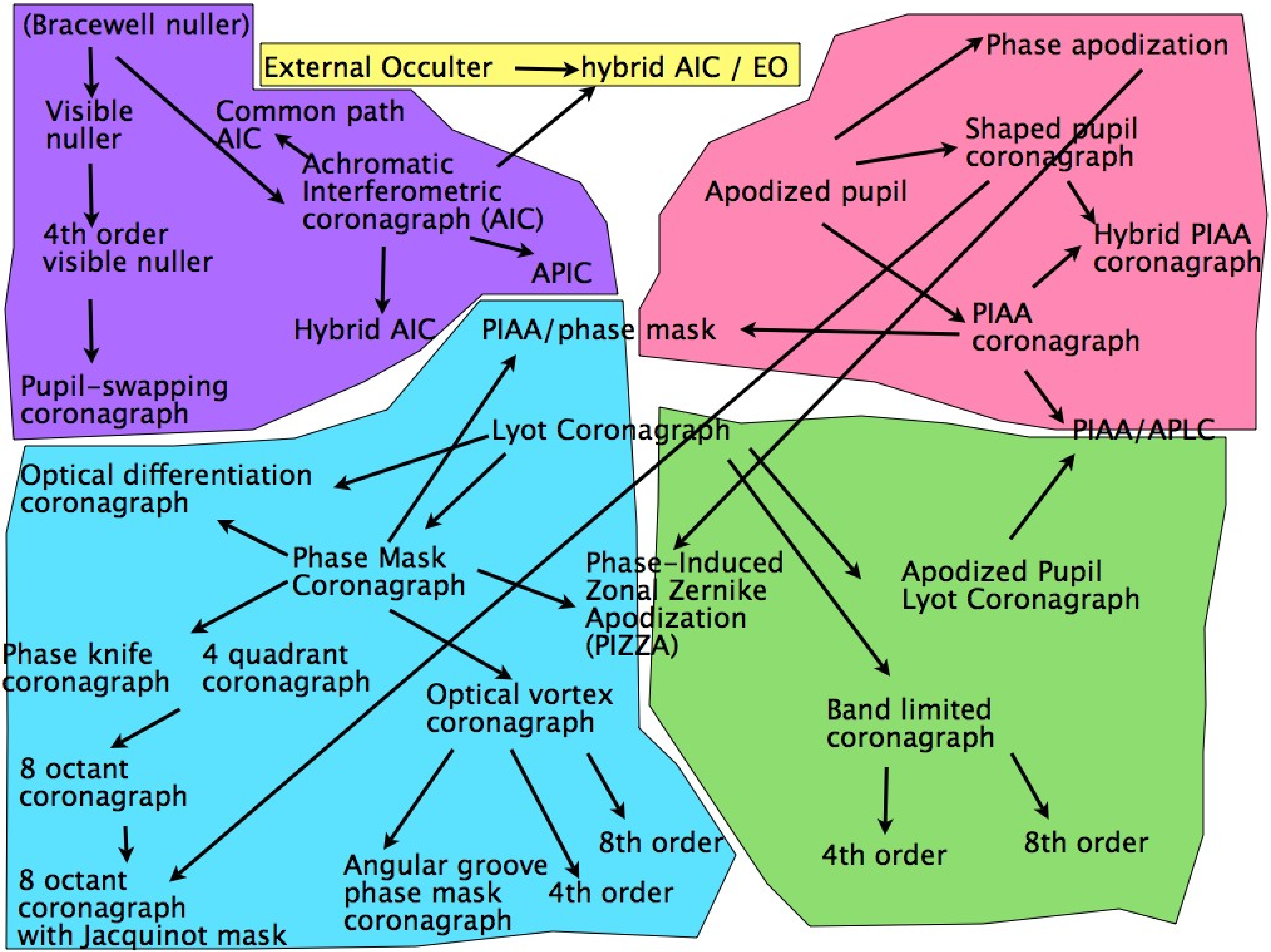
6 High contrast imaging

6.3 High contrast imaging systems

Coronagraphy: performance and fundamental limits

Laboratory developments

Ground based systems
Space based systems



(Bracewell nuller)
External Occulter
hybrid AIC / EO
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
4th order visible nuller
APIC
Hybrid AIC
Pupil-swapping coronagraph
Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
PIAA/APLC
Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
8th order
4th order
4th order
8th order

Coronagraph Performance

Contrast (raw): surface brightness in the coronagraphic image, normalized to the peak surface brightness of the central star (if it were not removed)

Throughput: how much of the planet light is left (depends on the planet-star angular separation)

Inner Working Angle: smallest angle at which a high contrast detection is possible
Usually, distance at which the contrast criteria above is met AND the throughput reaches 50% of peak throughput

Discovery angle: fraction of the field in which a detection is possible

What is the theoretical performance limit of coronagraphy ?

Every coronagraph in the previous chart except the classical Lyot can theoretically deliver 1e10 contrast at 4 l/D

New coronagraphs continuously appear, with higher perf.

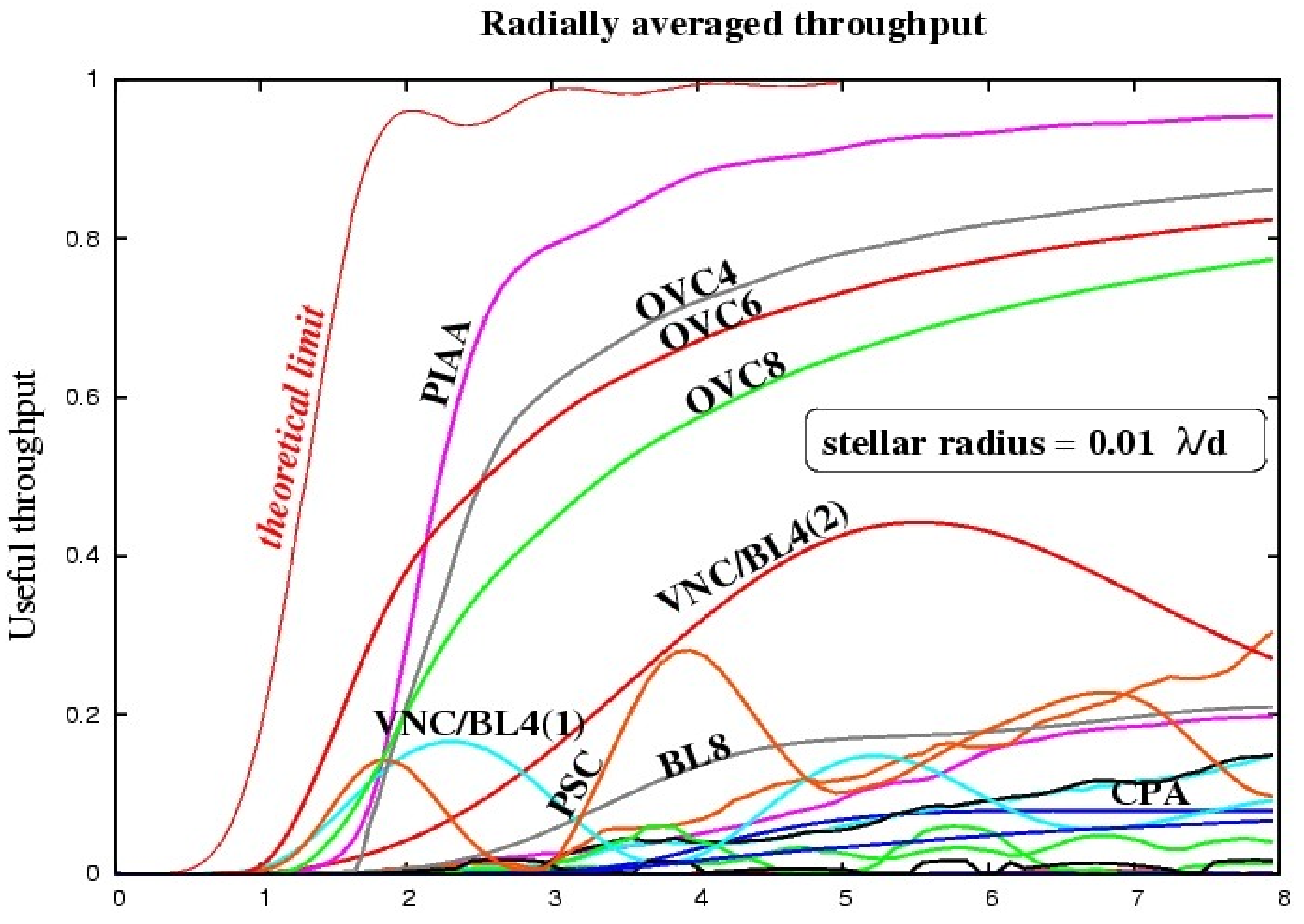
Is there a limit to coronagraph performance ?

Coronagraph is a linear filter in complex amplitude, and must remove starlight.
If :
planet wavefront Complex Amplitude =
0.2 x starlight wavefront + **0.8 x something else**
then:
coronagraph throughput for planet $< 0.8^2$

Problem: stars are not points !
Sun diameter ~1% of 1 AU
If 1AU=2 l/d, Stellar radius ~ 0.01 l/d
<u>Wavefront control cannot solve it</u>

Fundamental physics tells us limits of coronagraphy

Guyon, Pluzhnik, Kuchner, Collins & Ridgway 2006, ApJS 167, 81



Theoretical limit with increasing stellar radius (monochromatic light, 1e10 contrast)

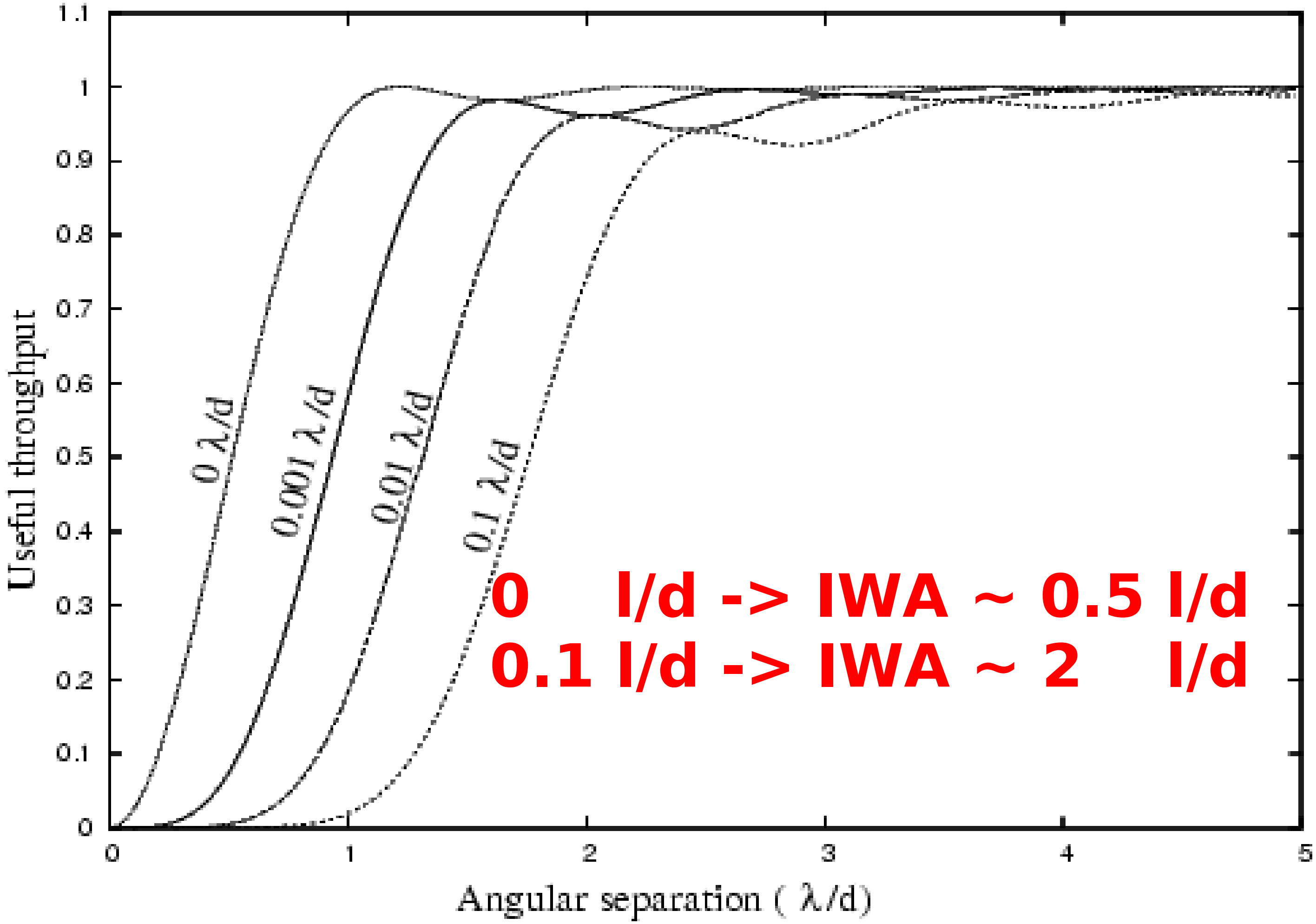


Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

Current limits to coronagraph performance are:

Coronagraph design and manufacturing (Only for contrasts < approximately 1e-8)

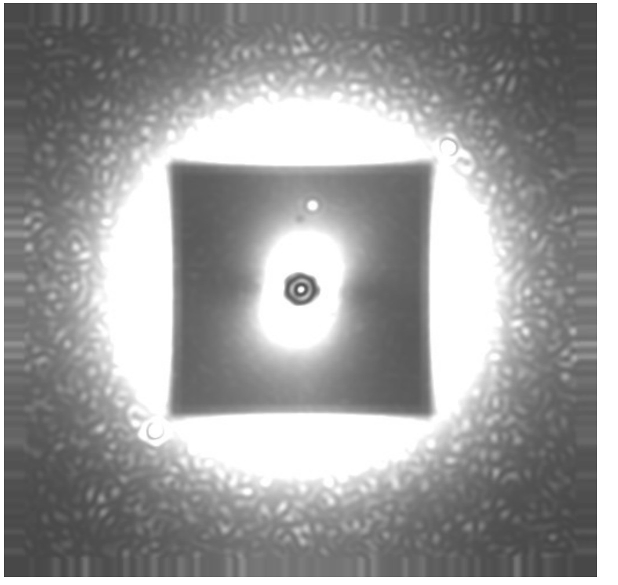
For moderate contrasts (up to ~1e-8), it is reasonably easy to manufacture a high performance coronagraph
→ ongoing lab development to push coronagraphic performance to ~1e-10 contrast in broadband light at small inner working angle

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



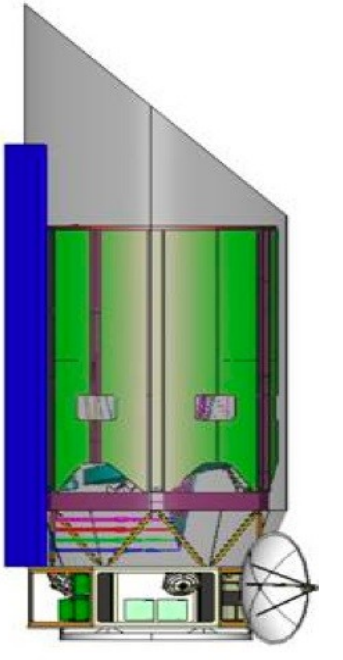
Ground-based systems

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

Wavefront control for High contrast imaging
Why is it difficult ?

pupil plane complex amplitude

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

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

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

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 !!)

Demonstration of 1e-3 l/D instrument pointing control with a coronagraphic low-order wavefront sensor at the Subaru Telescope laboratory

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

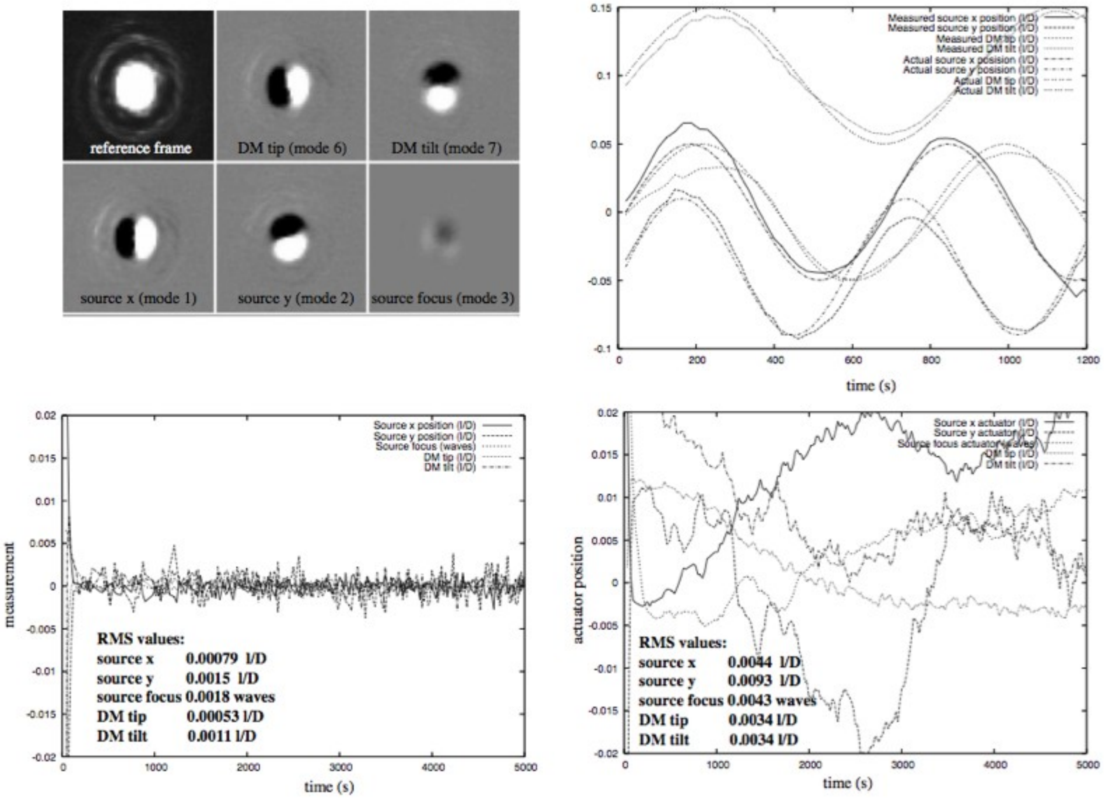


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about 10^{-3} λ/D for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

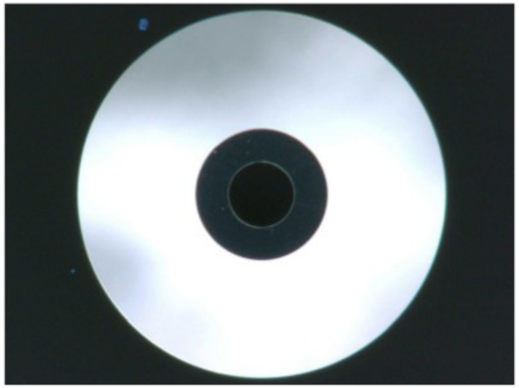
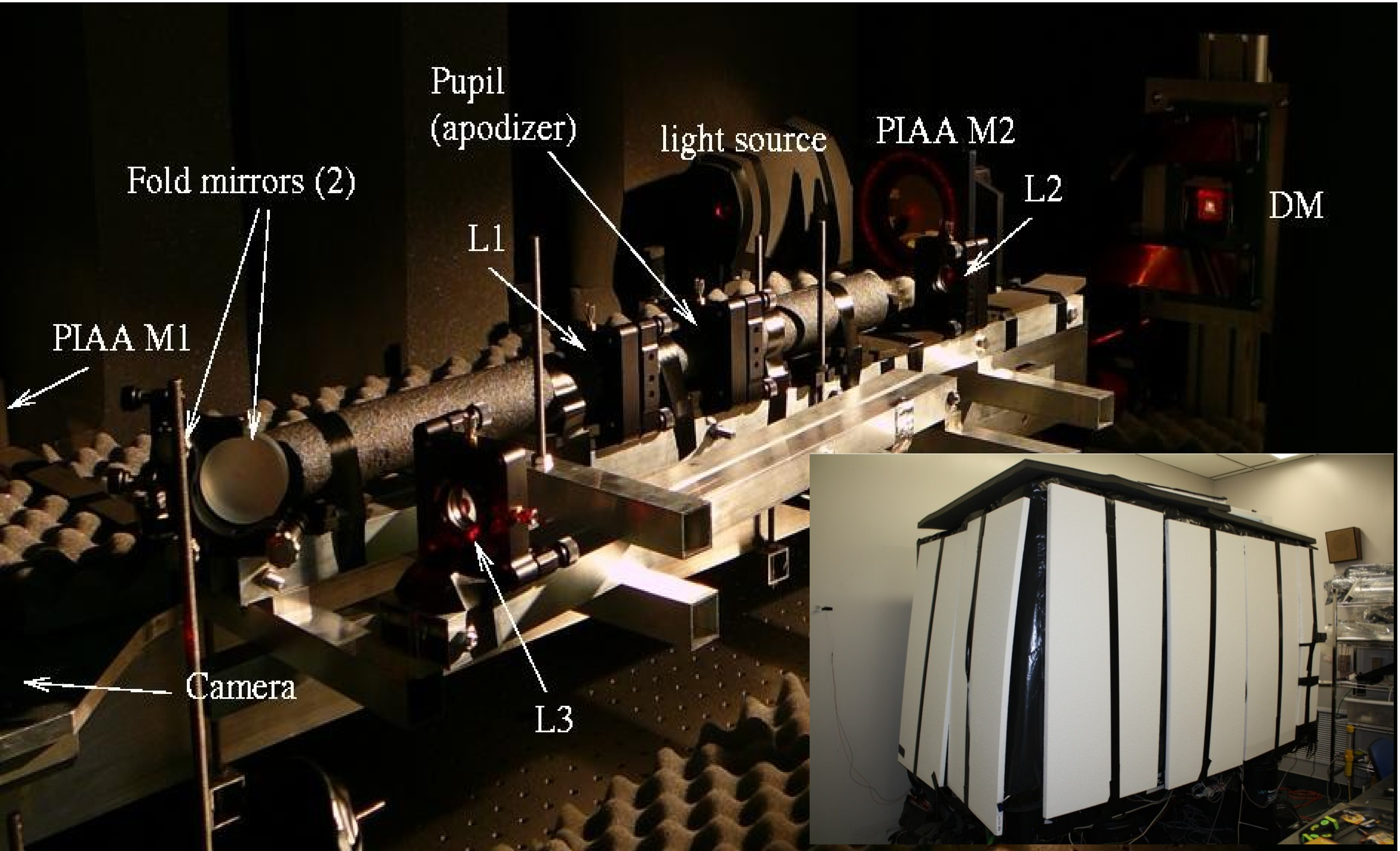


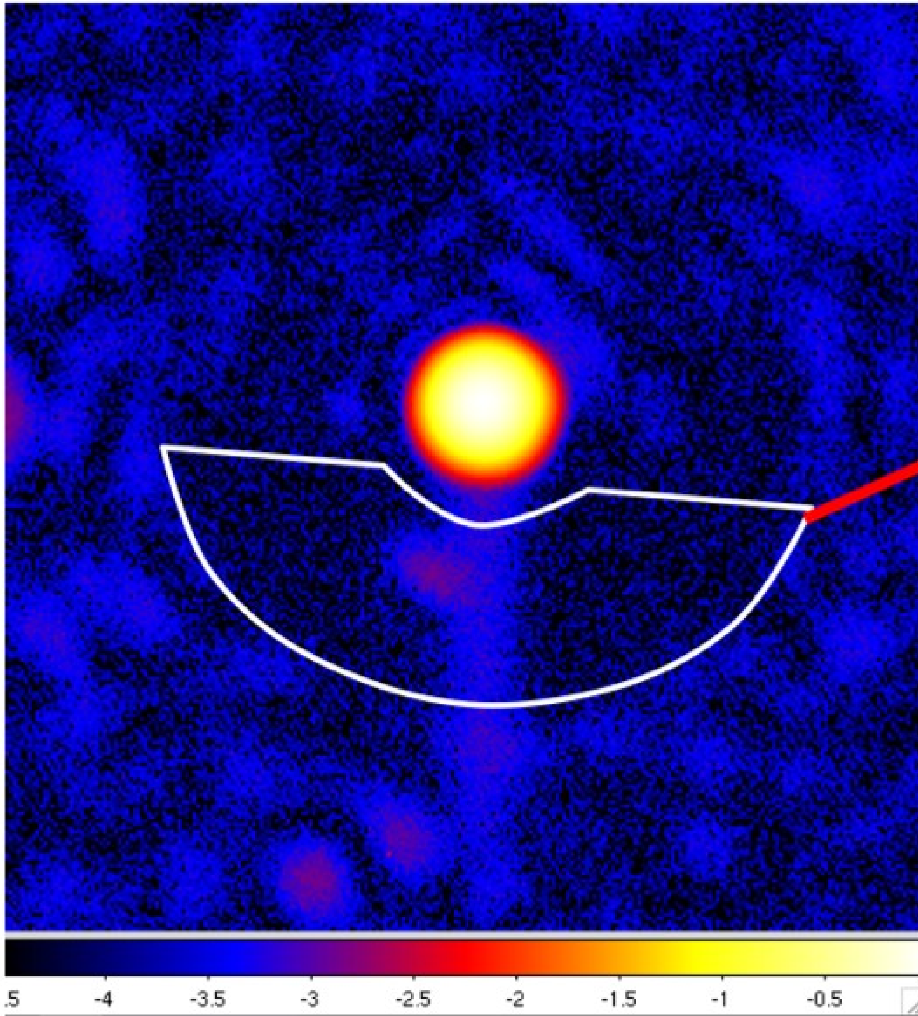
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

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

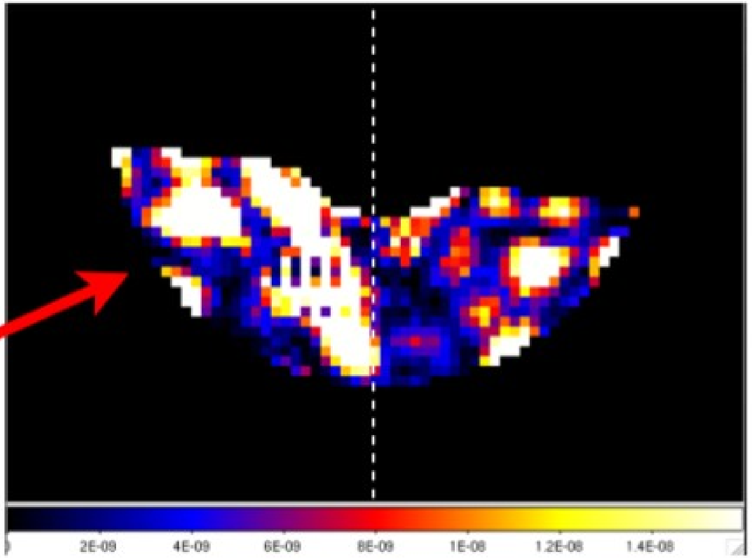


Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image



Coherent starlight

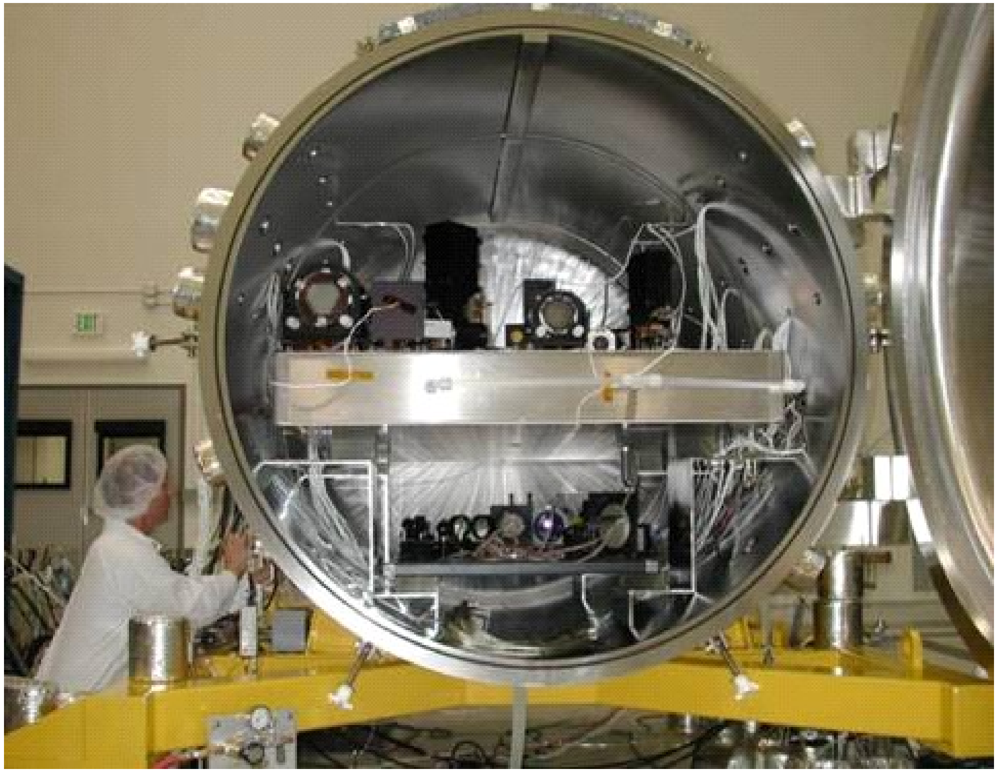


Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

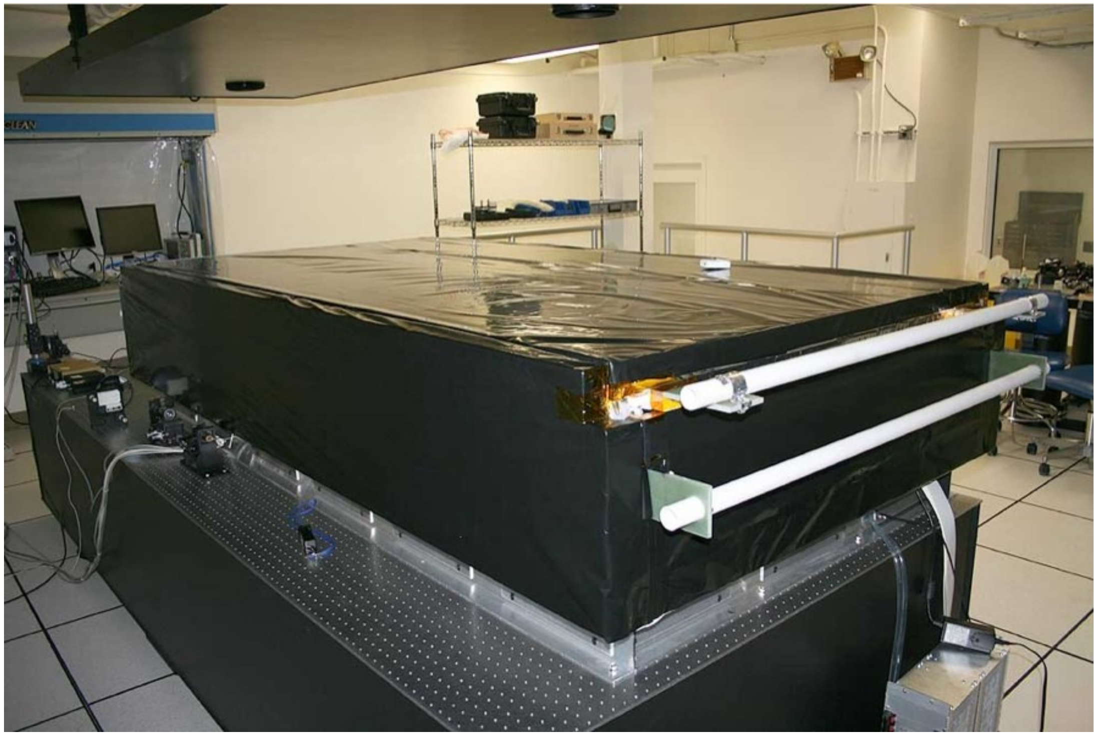
Contrast achieved in 1.6 to 4.5 l/D zone:
1.5e-7 incoherent halo ghost (equivalent to exozodi)
7e-9 coherent starlight speckles (turbulence, vibrations)

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

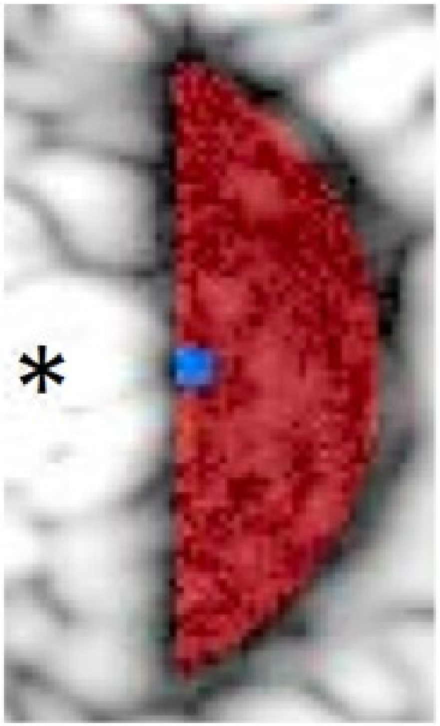


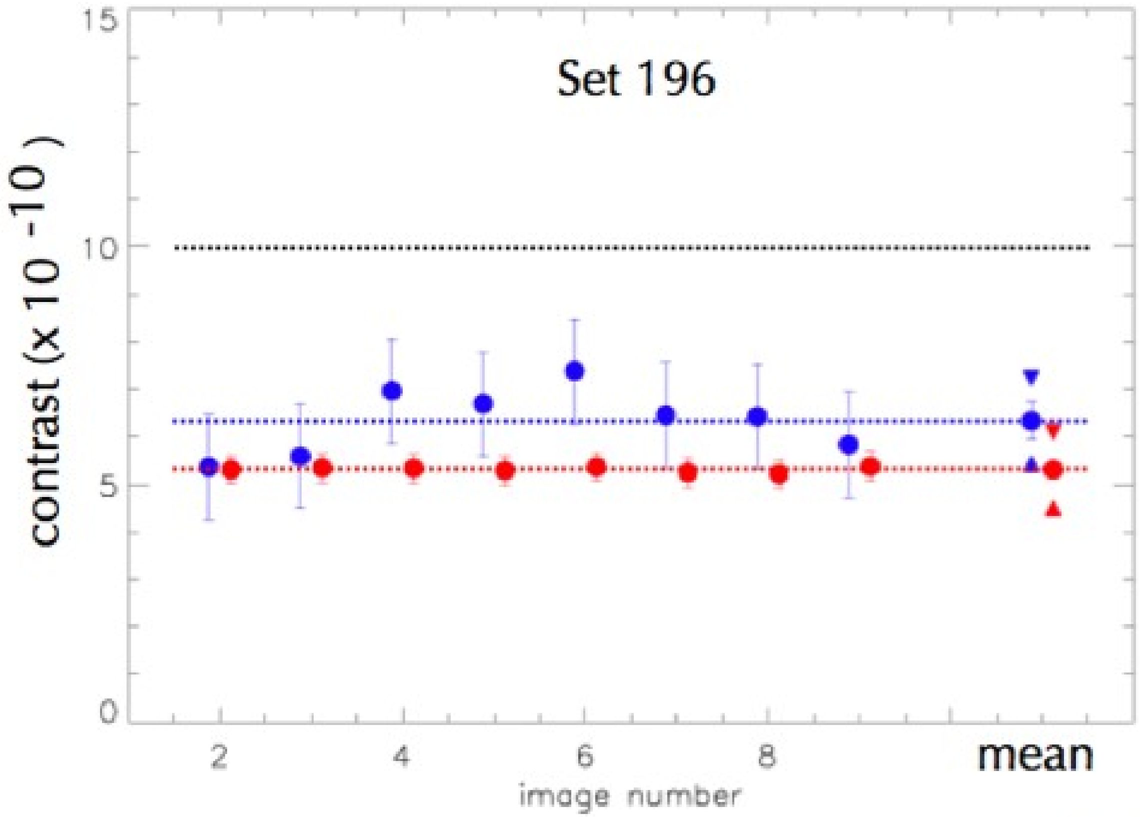
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



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) – start in 2011
- 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 – start in 2011
- 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 in ~2012
- 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 in ~2012
- ExAO system + coronagraph
- Highly stable bench
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra
- Includes differential polarimetric imager