A bright future for direct imaging of extrasolar planets & disks

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Subaru Telescope

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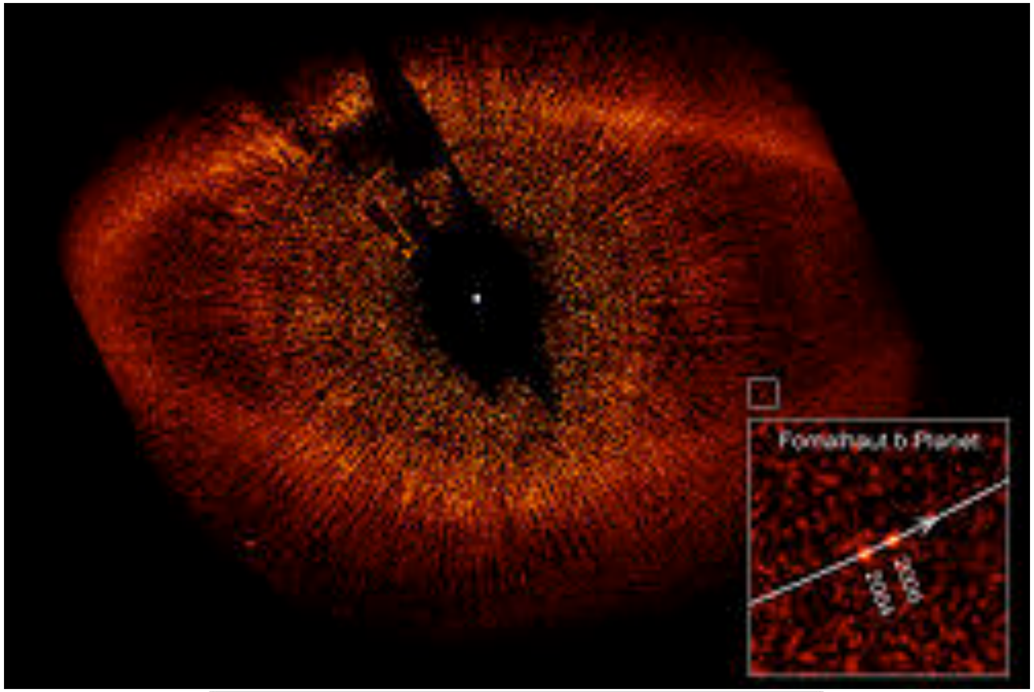
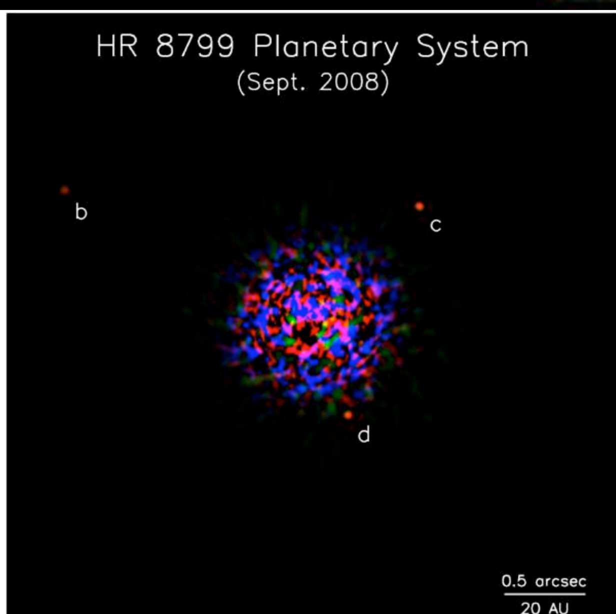
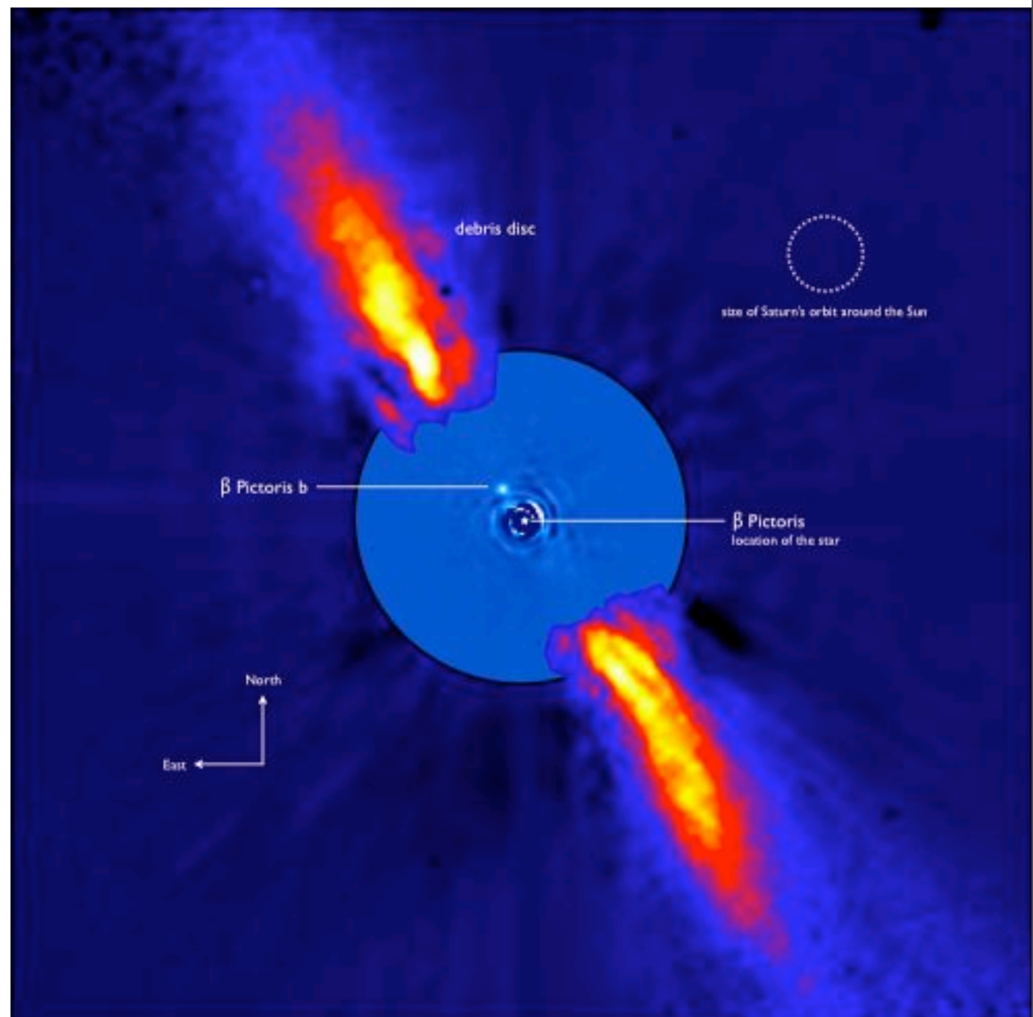
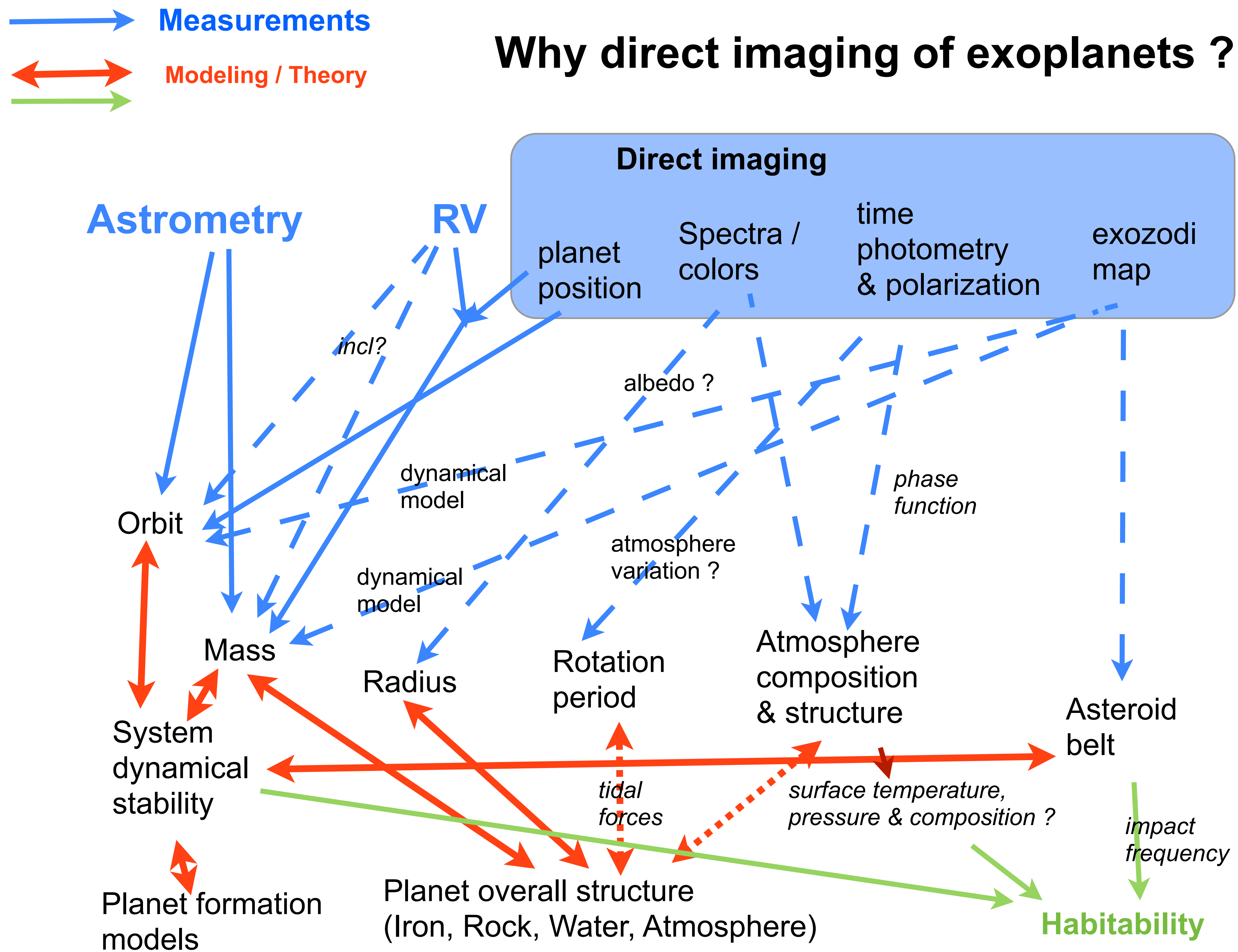
- understanding planetary systems formation & evolution
- Planetary atmospheres, physical properties









Measurements
Modeling / Theory
Why direct imaging of exoplanets ?
Direct imaging
planet position
Spectra / colors
time photometry & polarization
exozodi map
Astrometry
RV
incl?
albedo ?
dynamical model
phase function
atmosphere variation ?
dynamical model
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure & composition ?
impact frequency
Planet formation models
Planet overall structure (Iron, Rock, Water, Atmosphere)
Habitability

- Tools for high contrast imaging
  - **Coronagraphy** – optical system to remove starlight
  - **Wavefront control** – keep the image sharp and achieve high contrast
  - **PSF / speckles Calibration**

- Subaru Coronagraphic Extreme-AO (SCExAO)
- ExAO & coronagraphy on GMT

Coronagraphy

- R&D in coronagraph has extremely active in the last 10-15 yrs
- Many coronagraph designs now exist
- The theoretical limit imposed by fundamental physics is now approached by a few concepts
- Coronagraph performance achieved in labs is beyond requirements for ground-based systems

Coronagraphy: 1930 to ~15 yrs ago

Lyot Coronagraph

Lyot Coronagraph

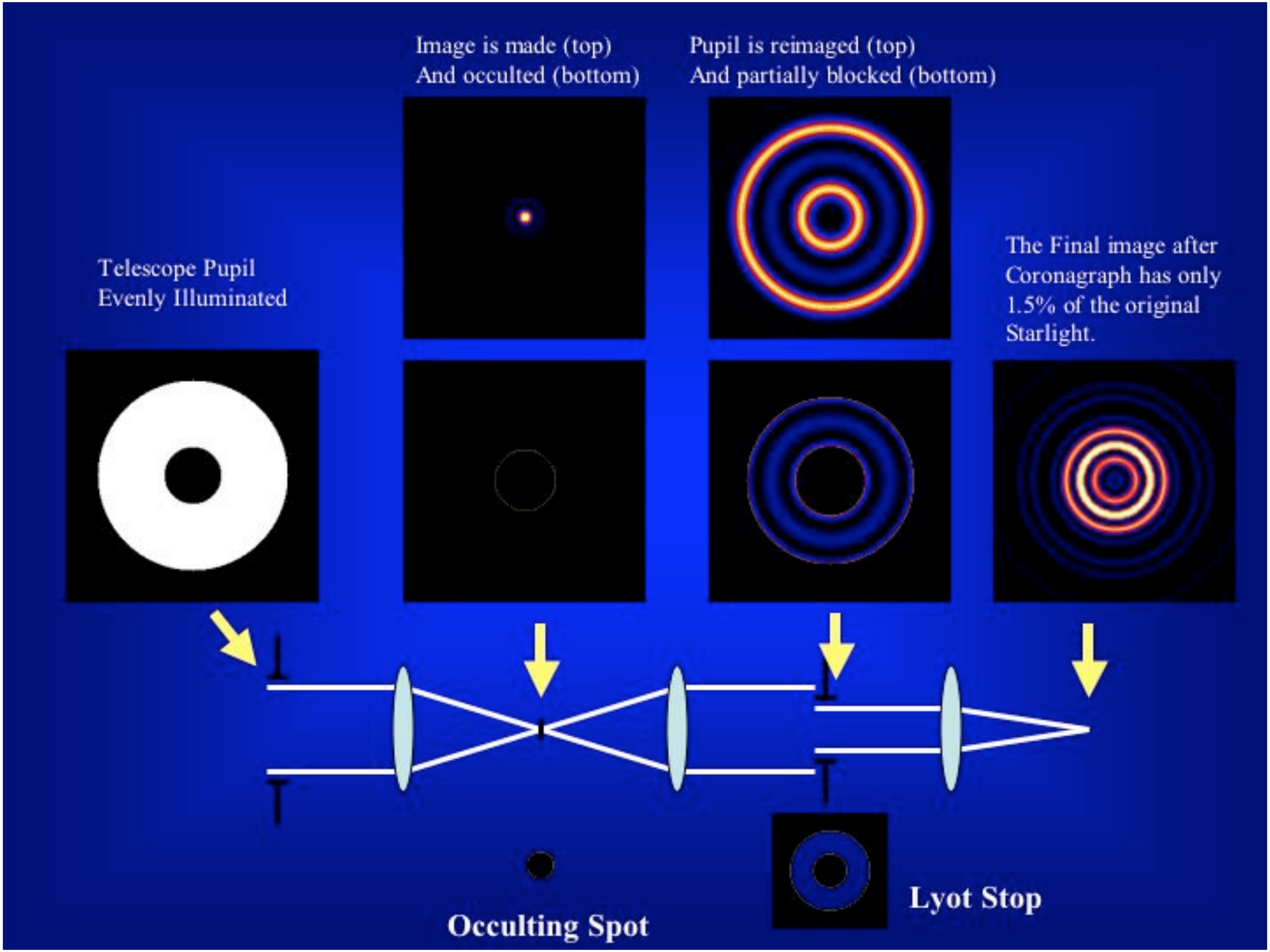
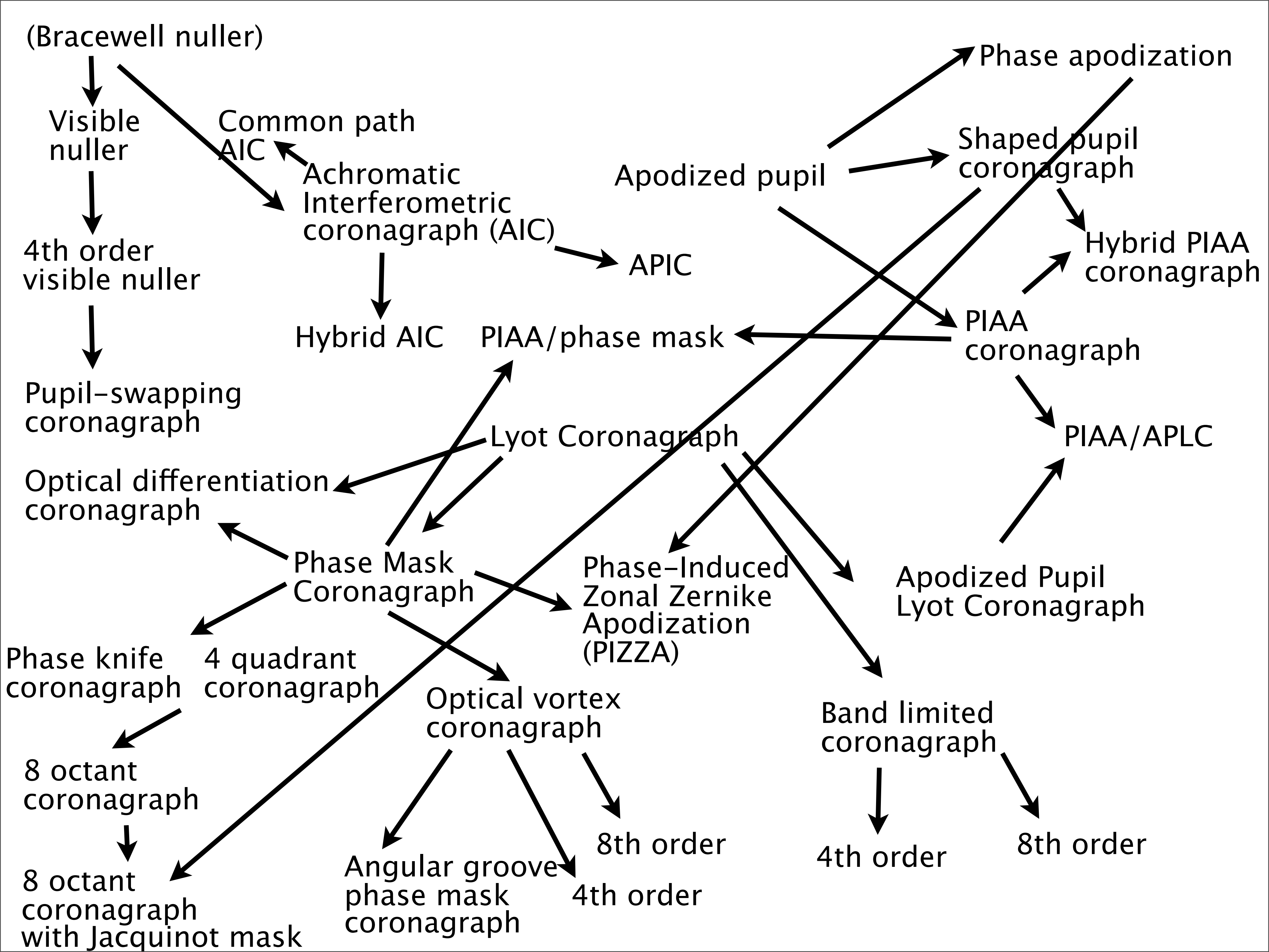
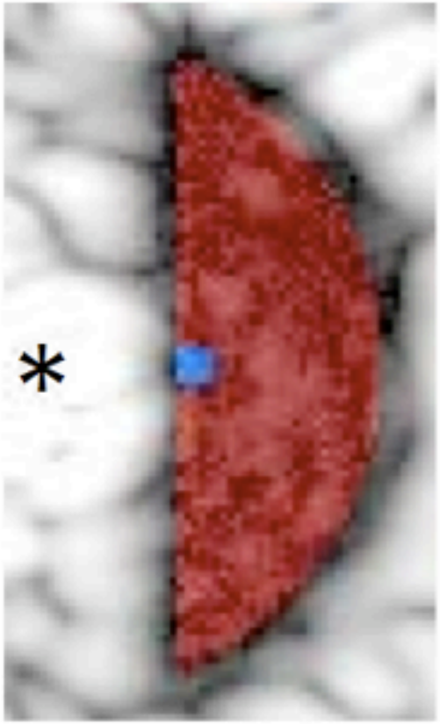


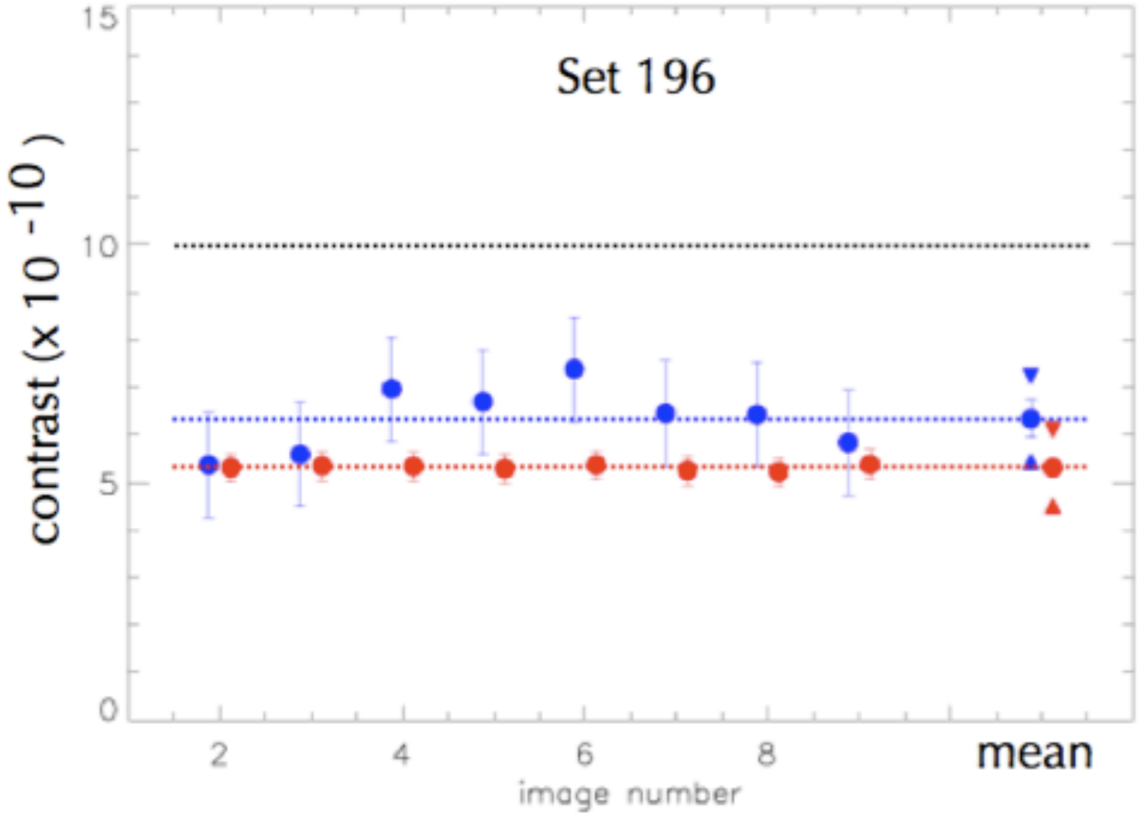
figure from Lyot project website


(Bracewell nuller)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
Common path AIC
Achromatic Interferometric coronagraph (AIC)
APIC
Hybrid AIC
PIAA/phase mask
Phase apodization
Apodized pupil
Shaped pupil coronagraph
Hybrid PIAA coronagraph
PIAA coronagraph
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

Vacuum tests at NASA JPL have reached close to 1e-10 contrast at 4 l/D with band-limited masks

"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.

What is the theoretical performance limit of coronagraphy ?

Coronagraph is a linear filter which removes starlight.
If :
planet = 0.2 x starlight wavefront + **0.8 x something else**
then:
coronagraph throughput for planet < 0.8

Theoretical limit would offer high contrast with little loss in throughput and inner working angle close to 1 lambda/D.

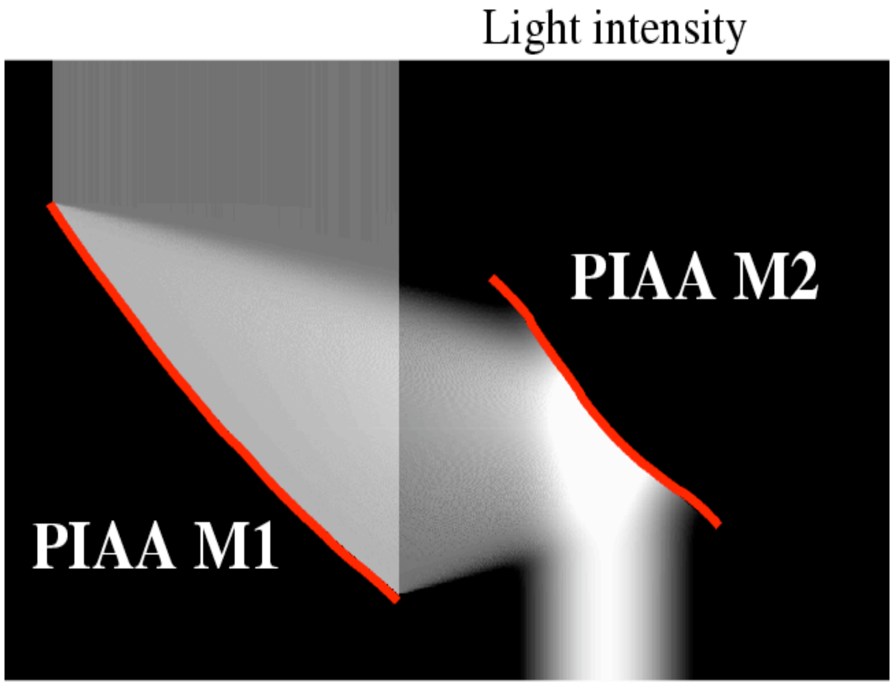
(Guyon, Pluzhnik, Kuchner, Collins & Ridgway 2006, ApJS 167, 81)

PIAA coronagraph development at Subaru

co-funded by Subaru/NAOJ, NASA JPL & NASA Ames

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

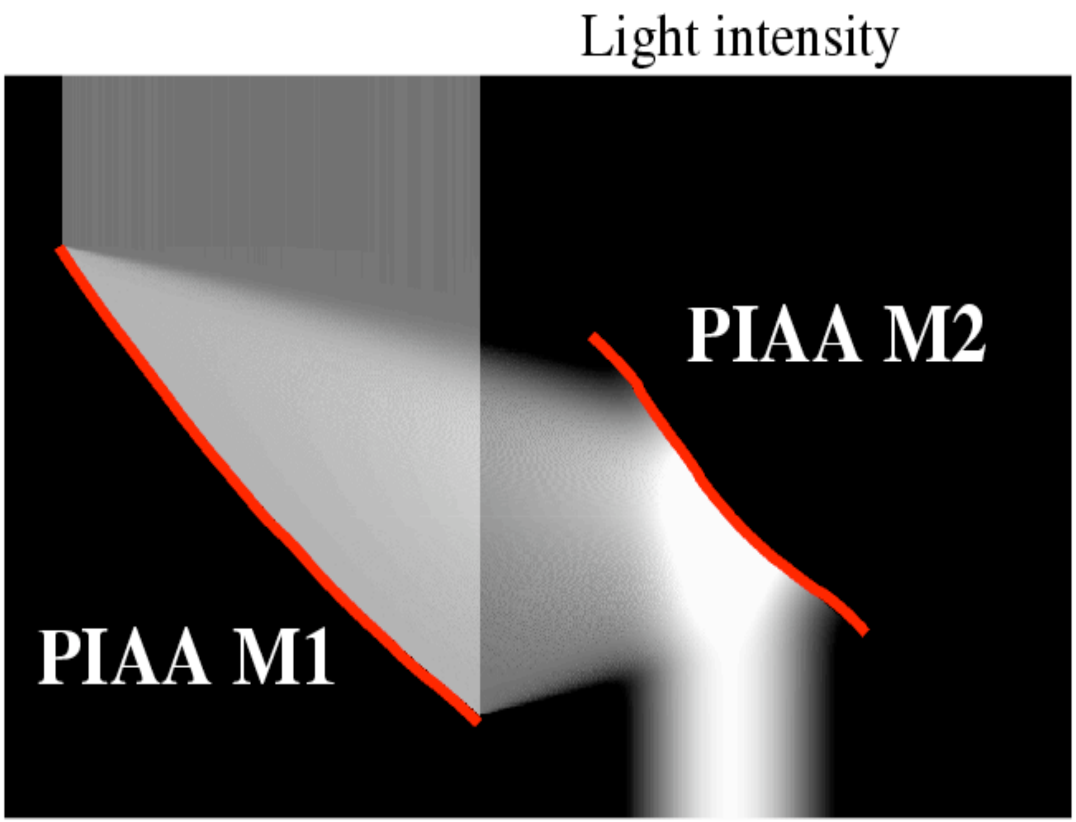
- high contrast
- Nearly 100% throughput
- IWA ~1 l/D to 2 l/D
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

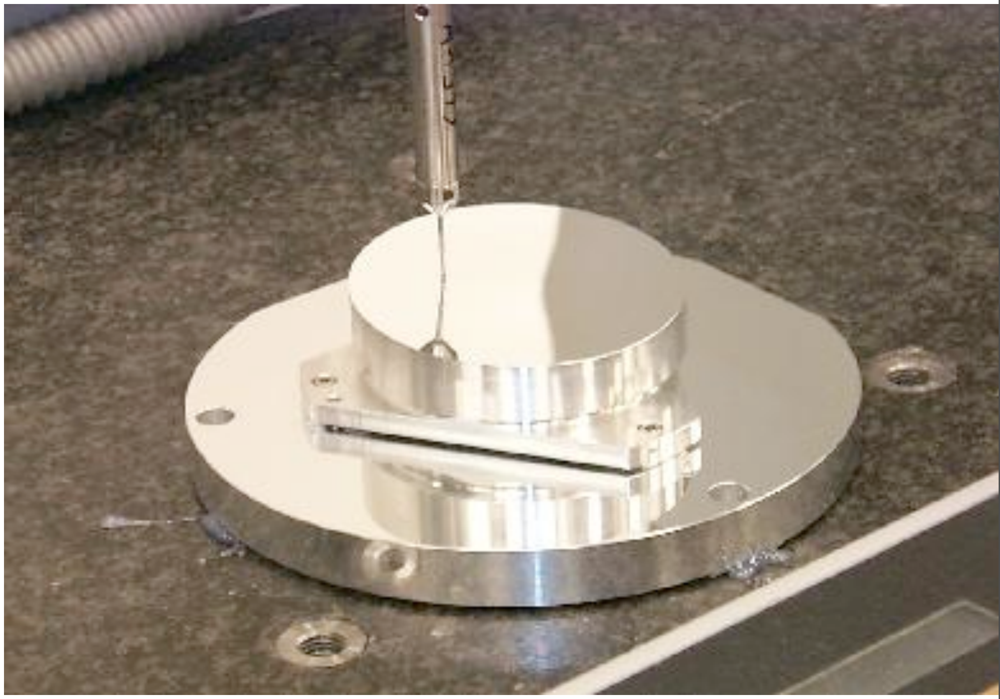


For Subaru, Lyot Coronagraph with PIAA- apodized input pupil. IWA ~ 1 lambda/d

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

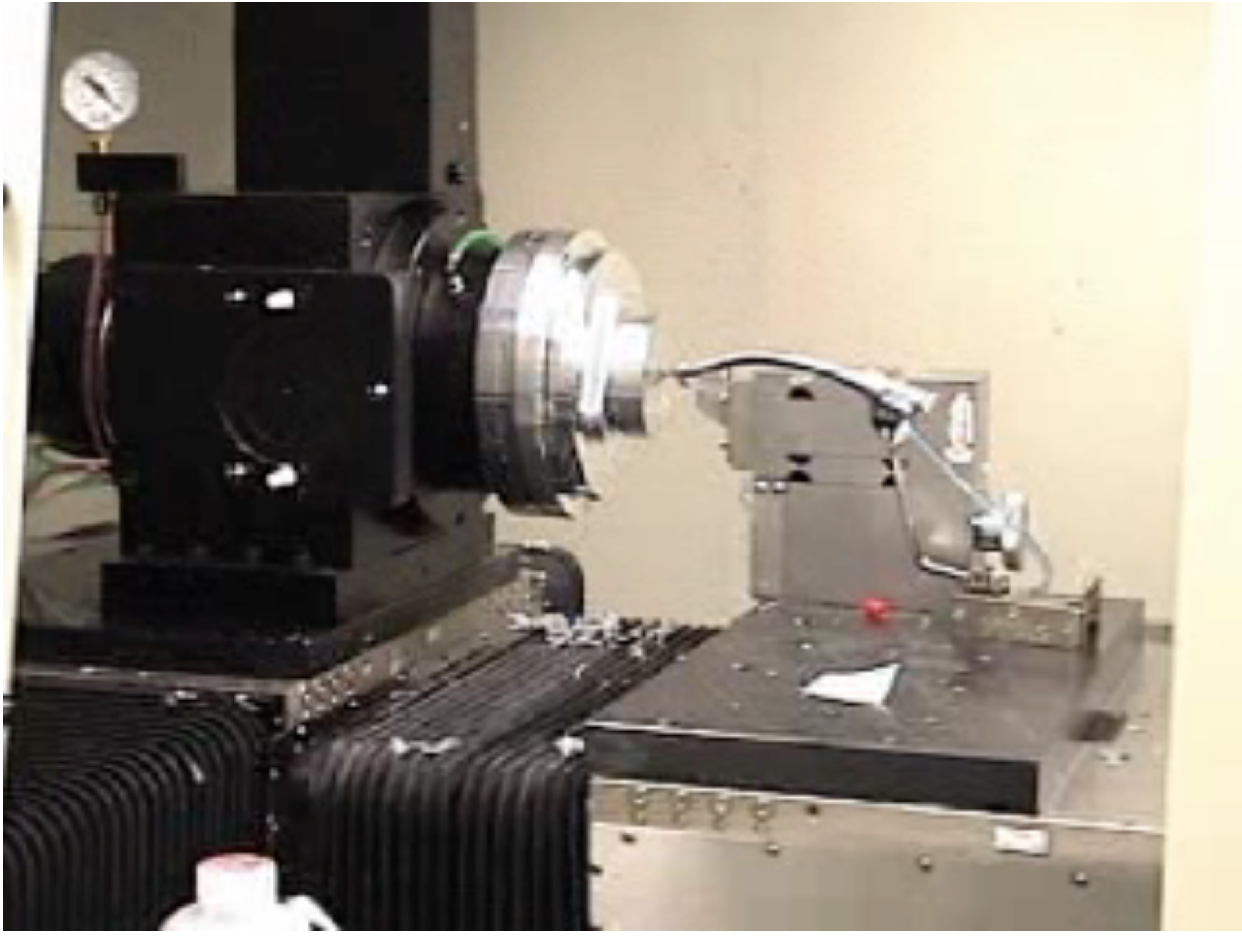
Lossless apodization by aspheric optics.

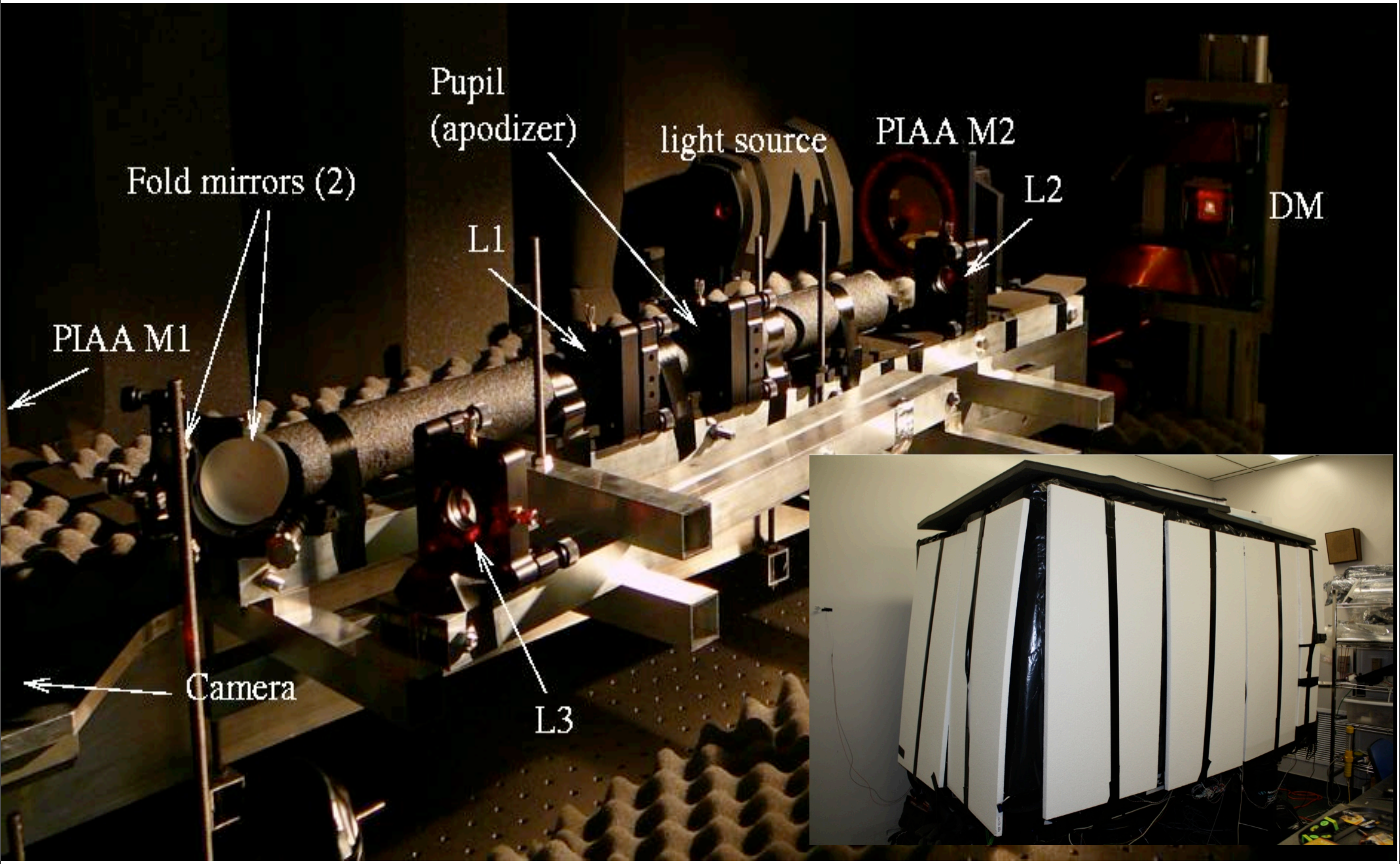




Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

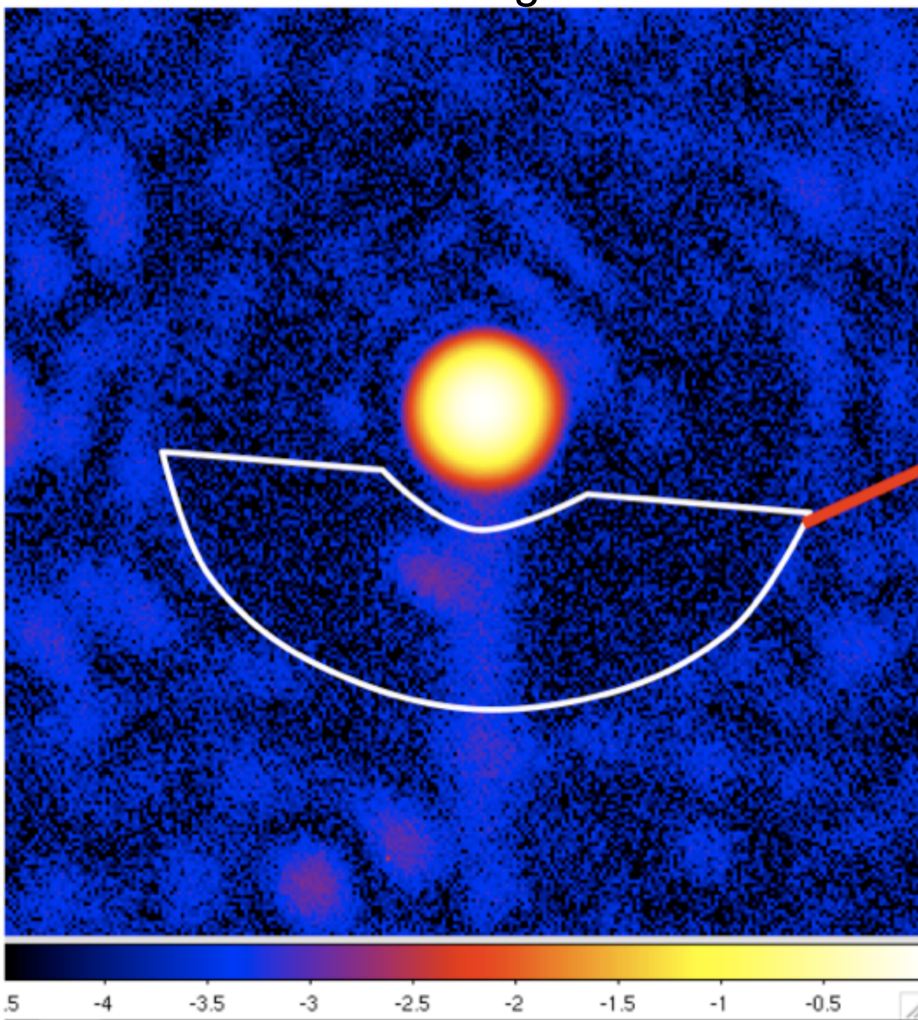
PIAA optics – Diamond turning



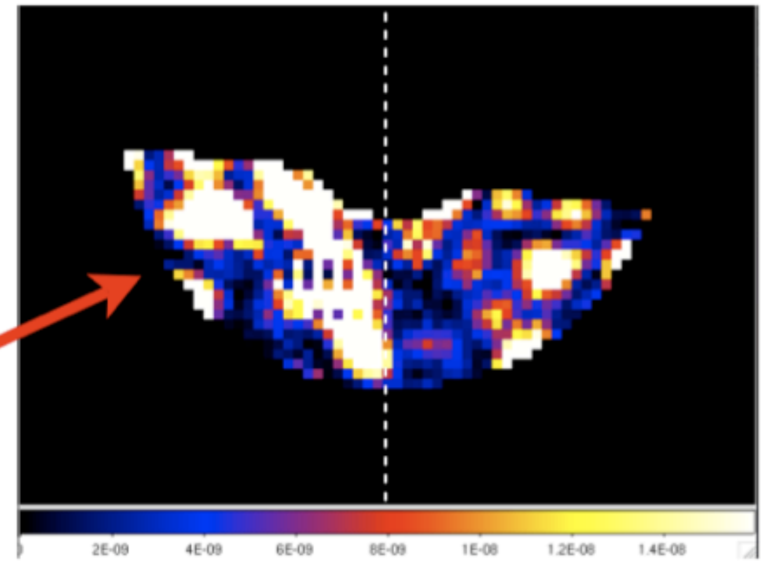

Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

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

Raw image



Coherent starlight



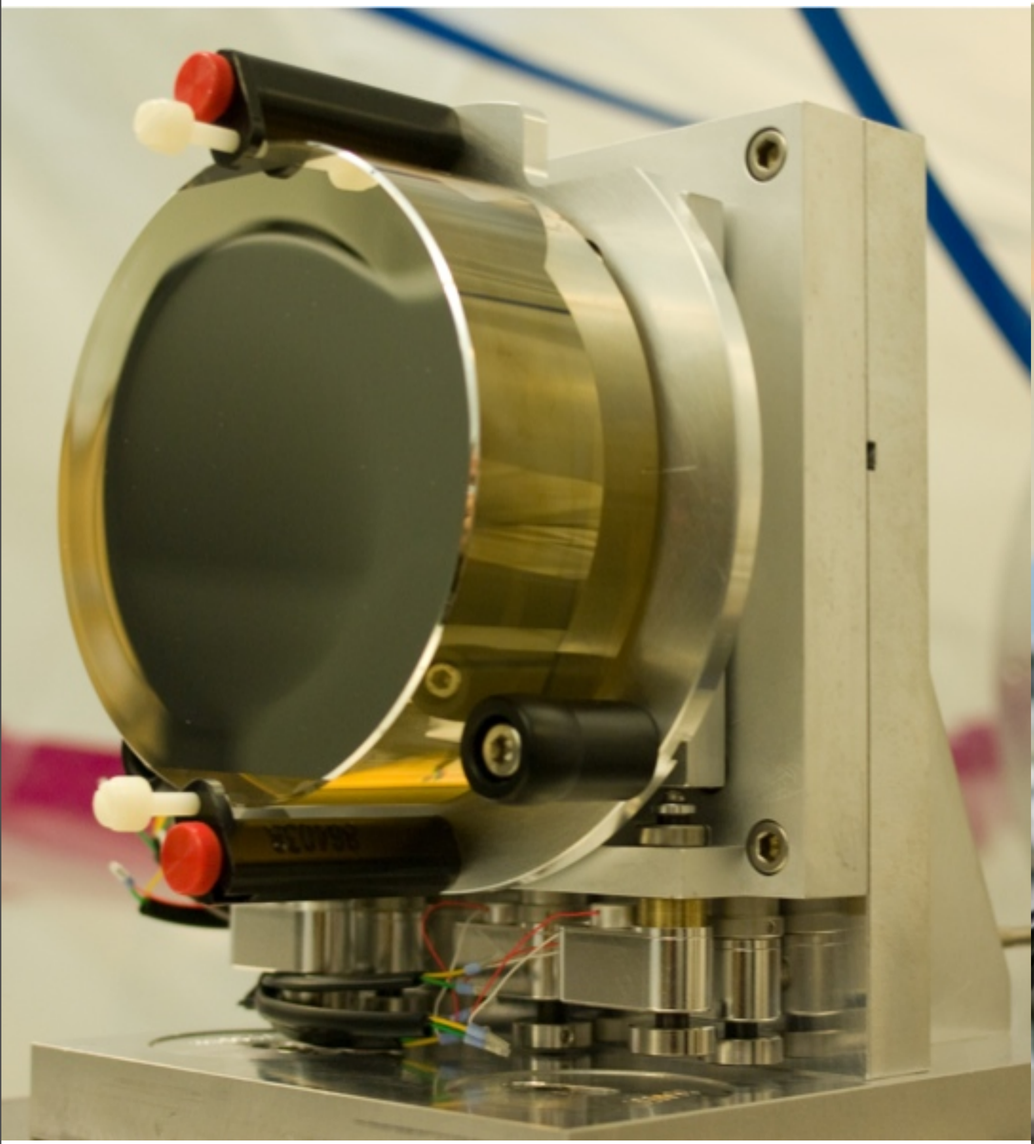
Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

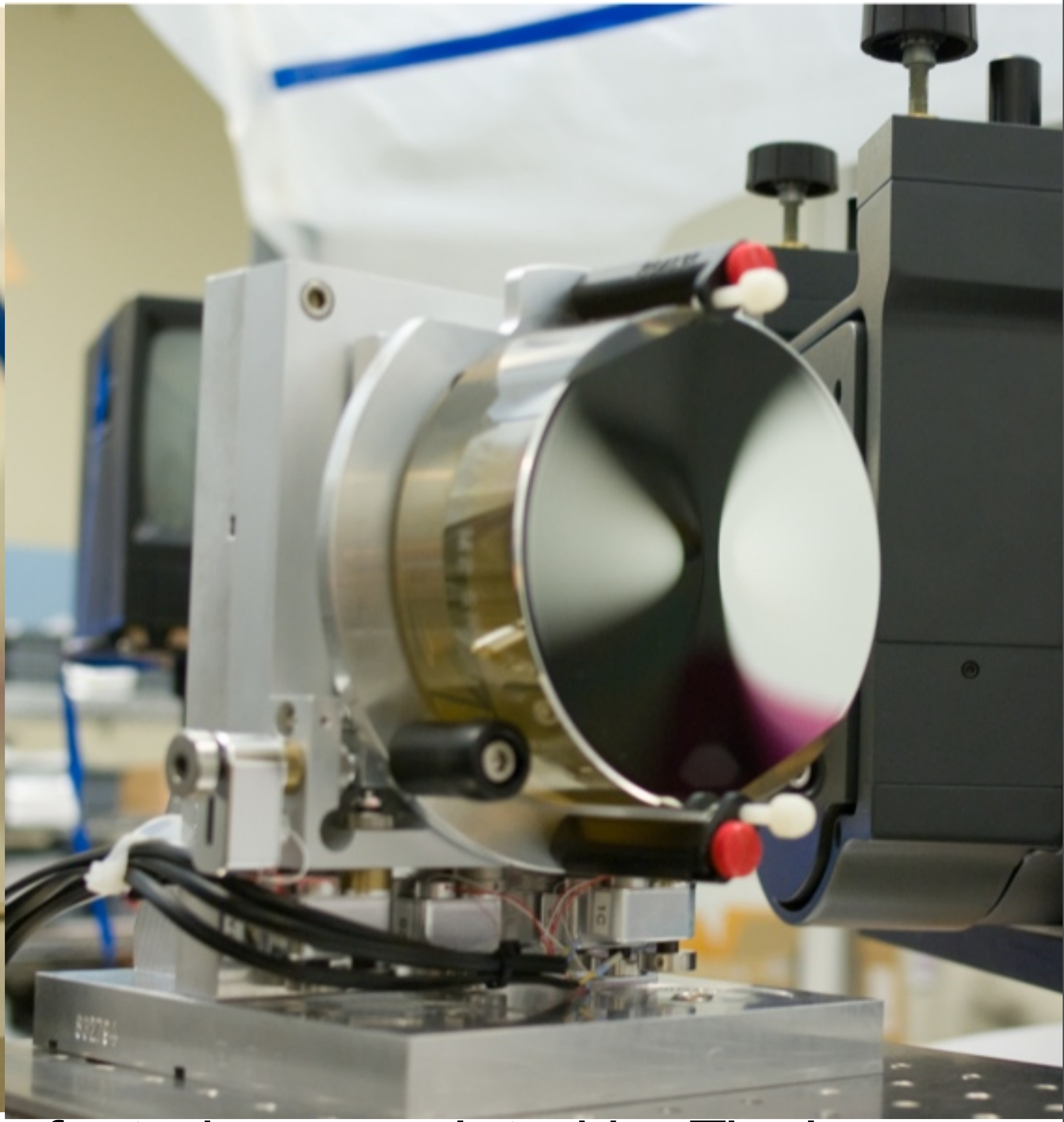
Contrast achieved in 1.6 to 4.5 l/D zone:

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

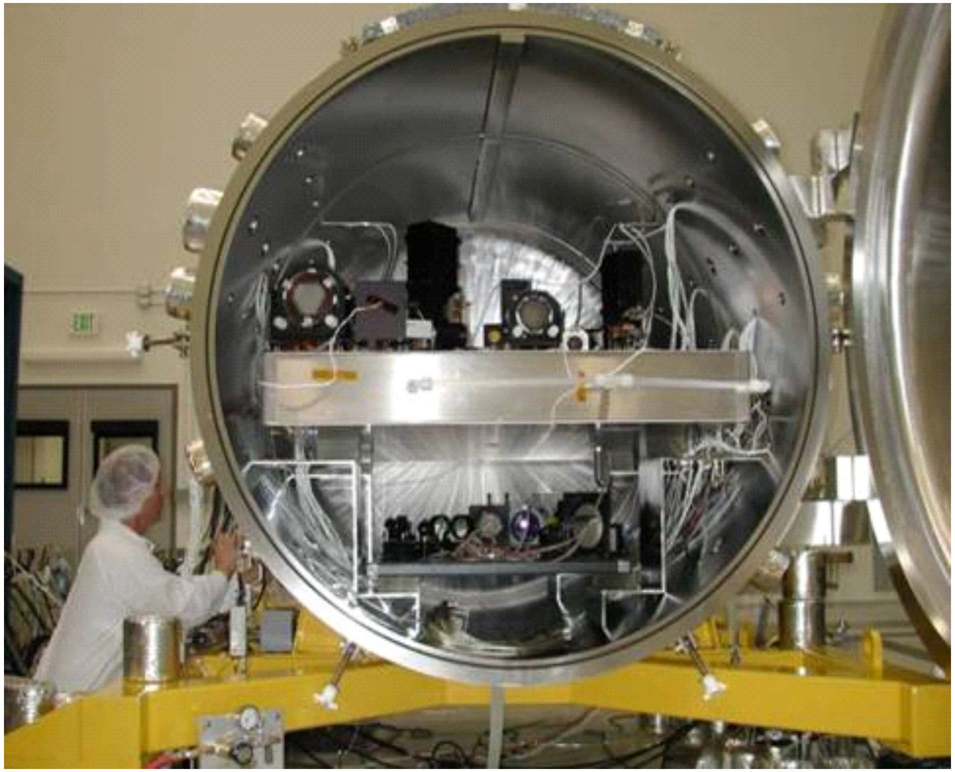
7e-9 coherent starlight speckles (turbulence, vibrations)

High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)

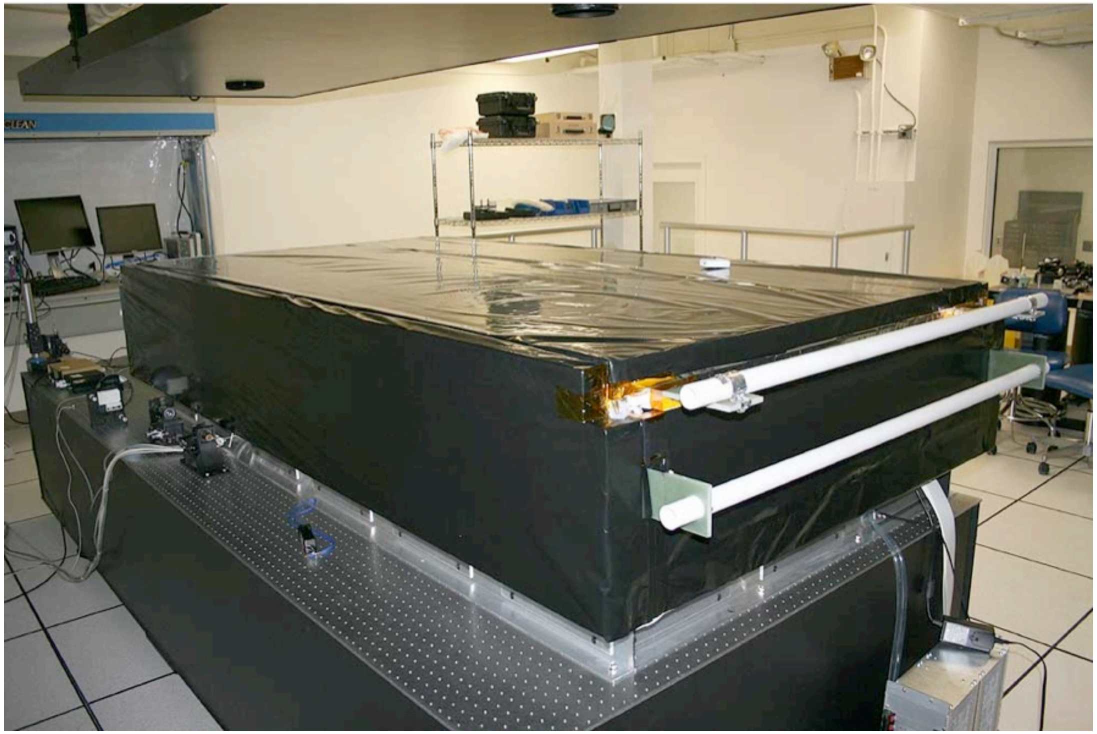




2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)



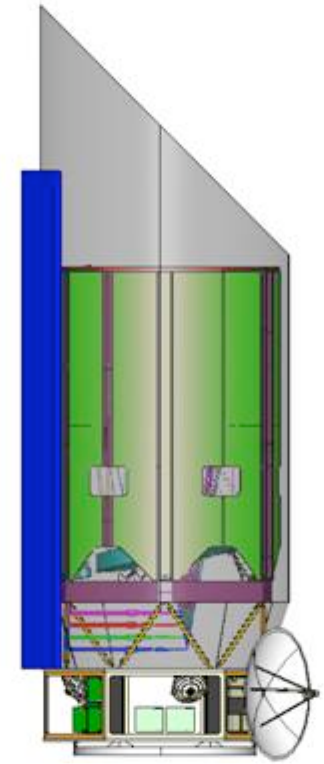
PIAA-dedicated testbed at NASA Ames testing WFC architectures & MEMs DMs.



Coronagraph labs in:
- NASA JPL (vacuum)
- NASA Ames
- Princeton Univ.
- Subaru Telescope
- Japan/ISAS (vacuum)

Pupil mapping Exoplanet Coronagraph Observer (PECO) *(caao.as.arizona.edu/PECO)*

- 1.4m diameter off-axis telescope
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 - 0.9 micron spectral coverage / R~20



- **Conduct a "Grand Tour" of 10 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.**
- **Study known RV planets, observing them at maximum elongation**
- **Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.**

Wavefront control for coronagraphy

Why do we need coronagraphs ?

Coronagraph can only remove known & static diffraction pattern
BUT:
- static & known diffraction can be removed in the computer
- coronagraphs don't remove speckles due to WF errors

Fundamental reasons:
(1) Photon Noise
(2) Coherent amplification between speckles and diffraction pattern

Practical reasons:
(3) Avoid detector saturation / bleeding
(4) Limit scattering in optics -> "stop light as soon as you can"

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.

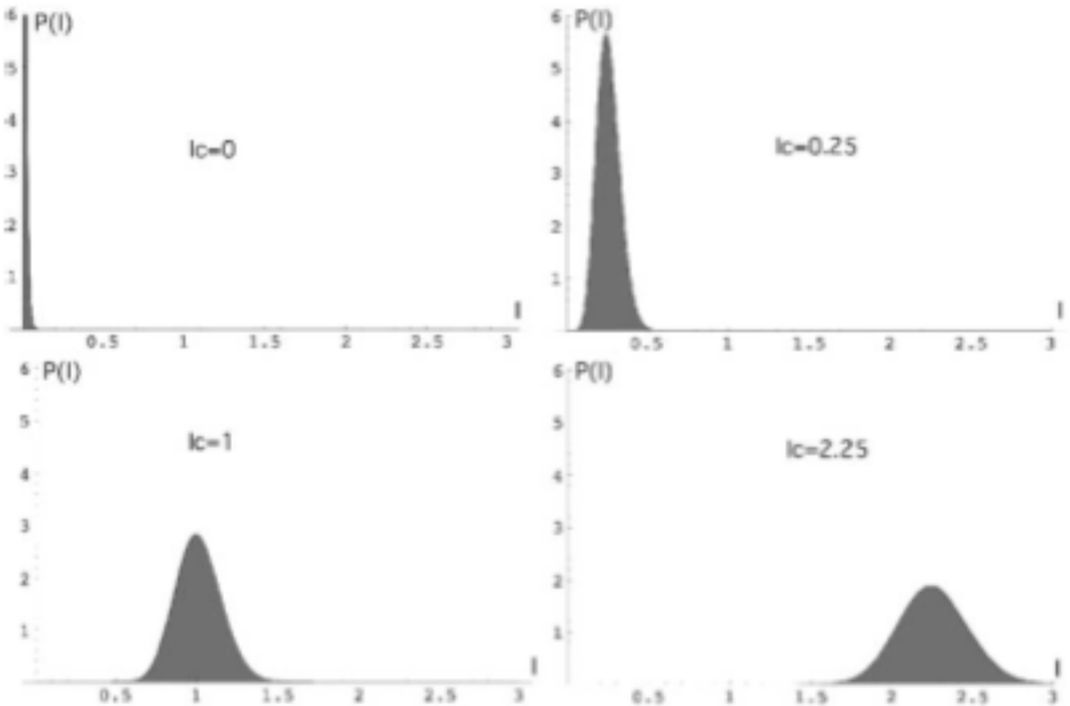


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from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

When do we need coronagraphs ?

Coronagraphs serve no purpose if dynamic speckle halo is > diffraction

-> Very important to keep in mind to **avoid over-designing the coronagraph**, as this usually would mean giving up something (usually throughput)

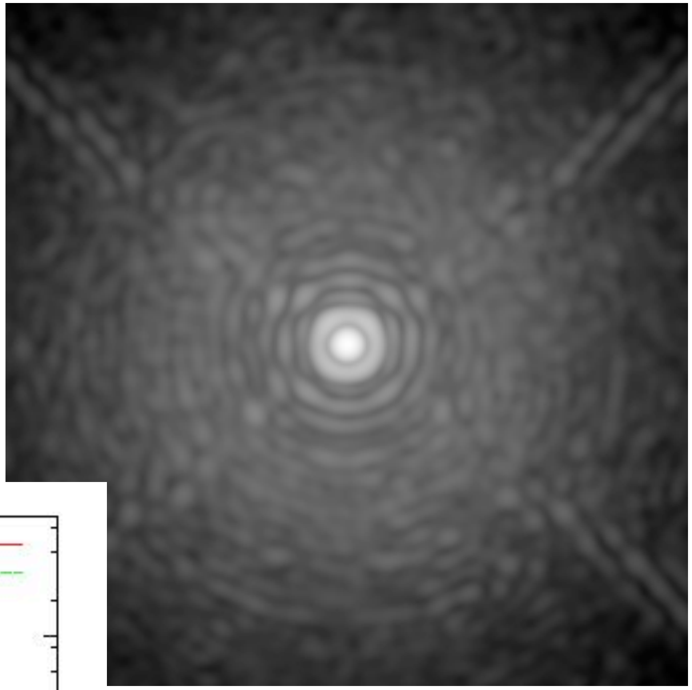
"Side effects" of coronagraphs :

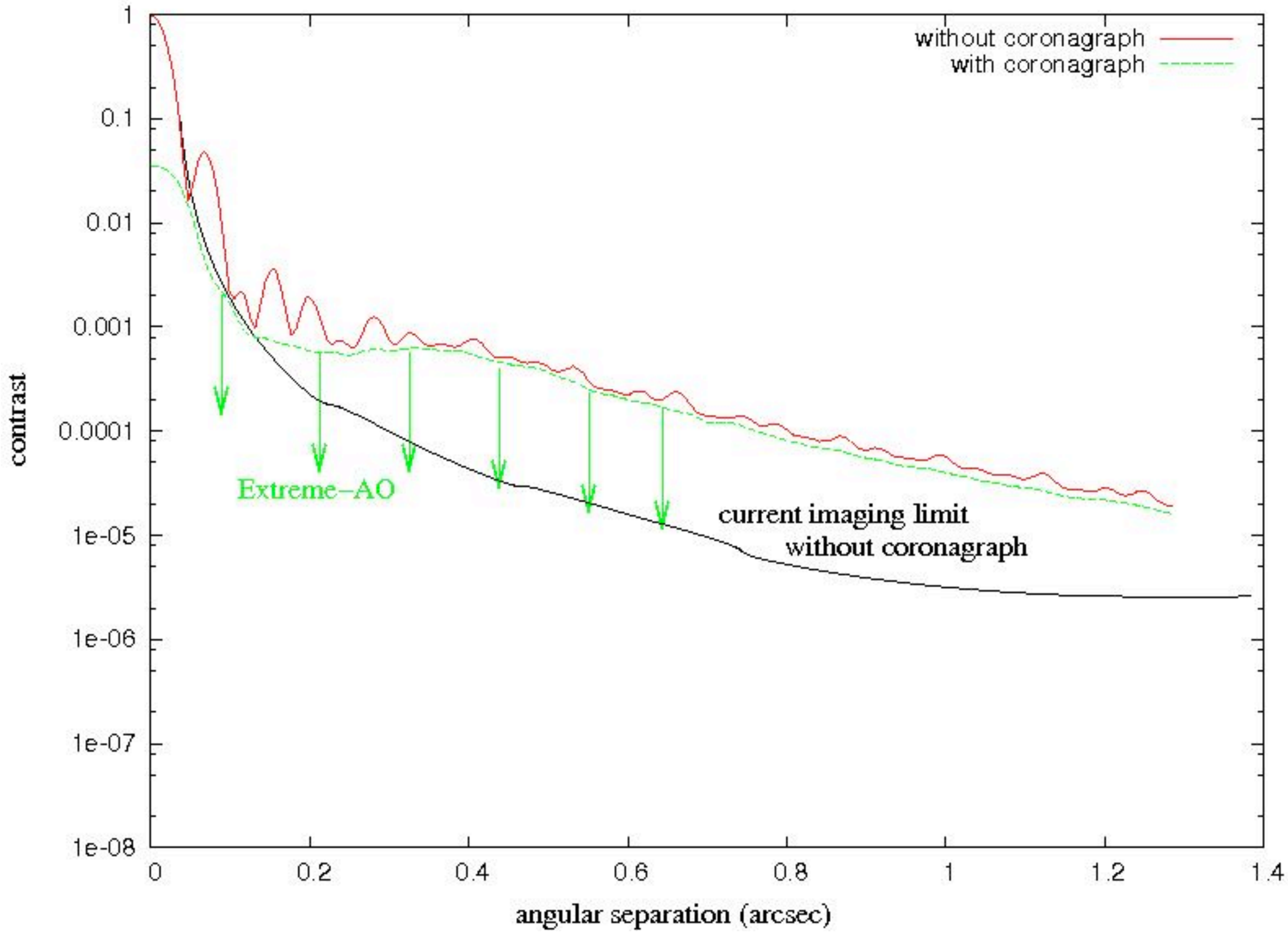
- (Usually) requires very good pointing. Risk of low order aberrations (for example pointing) creating additional scattered light in the region of interest

- data interpretation & analysis can be challenging (especially at inner working angle)

- Astrometry more difficult (solutions exist)

- None of the recent ground-based planet discoveries has been done with coronagraph
- With current Telescopes+AO systems, coronagraphs offer almost no help beyond ~0.3” in H band
- PSF calibration with coronagraphs is more complicated





ExAO systems currently under construction improve contrast with AO + coronagraphy

Wavefront Sensor Options...

Linear, large dynamical range, poor sensitivity:
Shack-Hartmann (SH)
Curvature (Curv)
Modulated Pyramid (MPyr)

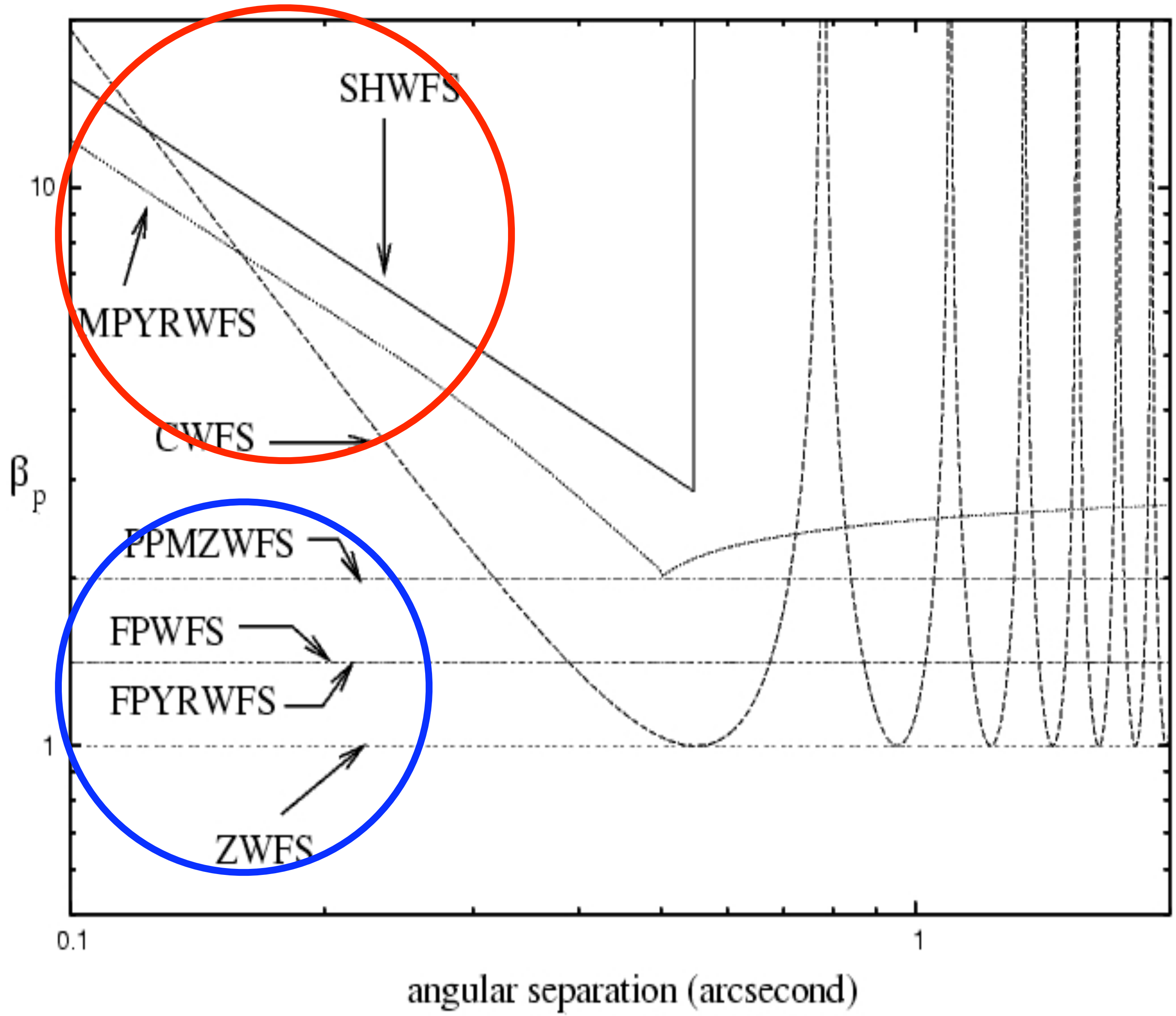
Linear, small dynamical range, high sensitivity:
Fixed Pyramid (FPyr)
Zernike phase constrast mask (ZPM)
Pupil plane Mach-Zehnder interferometer (PPMZ)

Non-linear, moderate to large dynamical range, high sensitivity:
Focal Plane (FP)
Non-linear Curvature (nlCurv)
Non-linear Pyramid (nlPyr) ?

Next slide compiles strengths and weaknesses of WFS options, and will be explained with simple but fundamental physics ...

	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
SH	serious noise propagation	Very good	Yes	Low	on sky	at least 4 pixels per subaperture
Curvature	serious noise propagation	Very good	Somewhat LGS OK	Low	on sky	1 pix/subaperture 2 reads
Pyramid (modulated)	noise propagation	very good	Somewhat LGS OK	Low	on sky	4 pix/subaperture
Pyramid (fixed)	Excellent	limited to < 1 rad in closed loop	No	Low	closed loop lab AO w turbulence	4 pix/subaperture
Zernike phase contrast	Excellent	limited to < 1 rad in closed loop	No	mask manufacturing	?	1 pix/subaperture
Mach-Zehnder	Excellent	limited to < 1 rad in closed loop	No	low if near zero OPD	?	2 pix/subaperture
Focal plane	Excellent	Good, can have > 1 rad error, but needs coherence	No	serious	closed loop lab AO no turbulence	4 pix/speckle
Non-linear curvature	Excellent	Good, can have > 1 rad error, but needs coherence	No	Low	in lab with no turbulence	4 pix/subaperture

Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)



Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5" from central star.

Why do SH, Curvature (& modulated pyramid) have bad sensitivity for low order aberrations ?

Good measurement of low order aberrations requires interferometric combination of distant parts of the pupil
FPWFS does it, but:
___- SH chops pupil in little pieces -> no hope !
- Curvature has to keep extrapupil distance small (see previous slides) -> same problem

Things get worse as # of actuators go up.
-> **This makes a big difference for ELTs**

Tip-tilt example (also true for other modes):
With low coherence WFS, sigma2 ~ 1/D^2 (more photons)
Ideally, one should be able to achieve:
sigma2 ~ 1/D^4 (more photons + smaller l/D)

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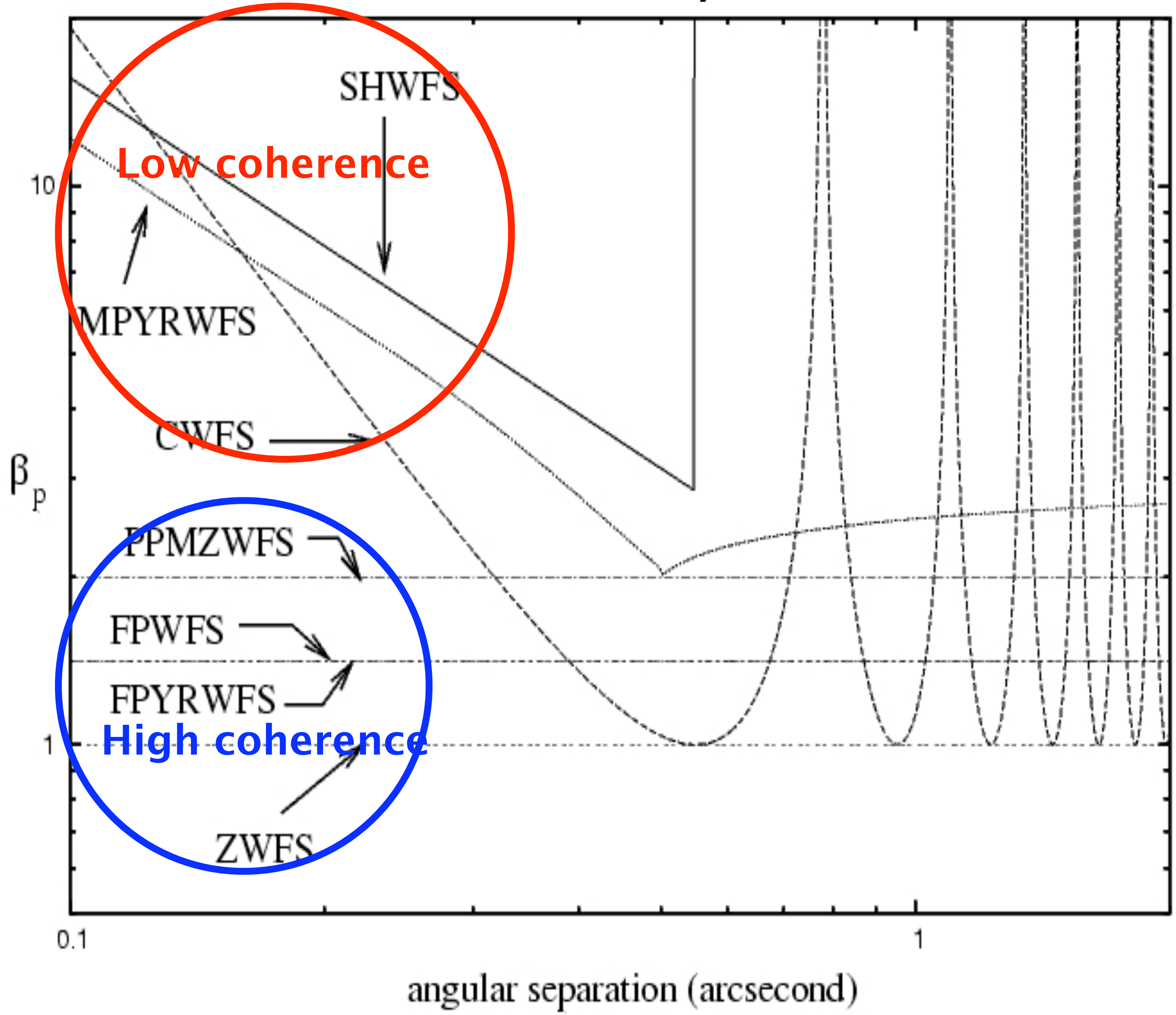
Good range/linearity but poor sensitivity

Good sensitivity over a small range

Non-linear reconstruction algorithm allows good sensitivity and larger range

Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)



Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for 0.5” separation.

	sensitivity	range	Extended target ? (LGS)	chromaticity	maturity	detector use
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Example: Possible Coronagraphic ExAO architecture

"Facility AO"

High speed AO in visible
"interferometric" WFS
non linear curvature
Pyramid

Near-IR

Coronagraph
Focal plane AO

Science frame acquired by the same camera as FPWFS

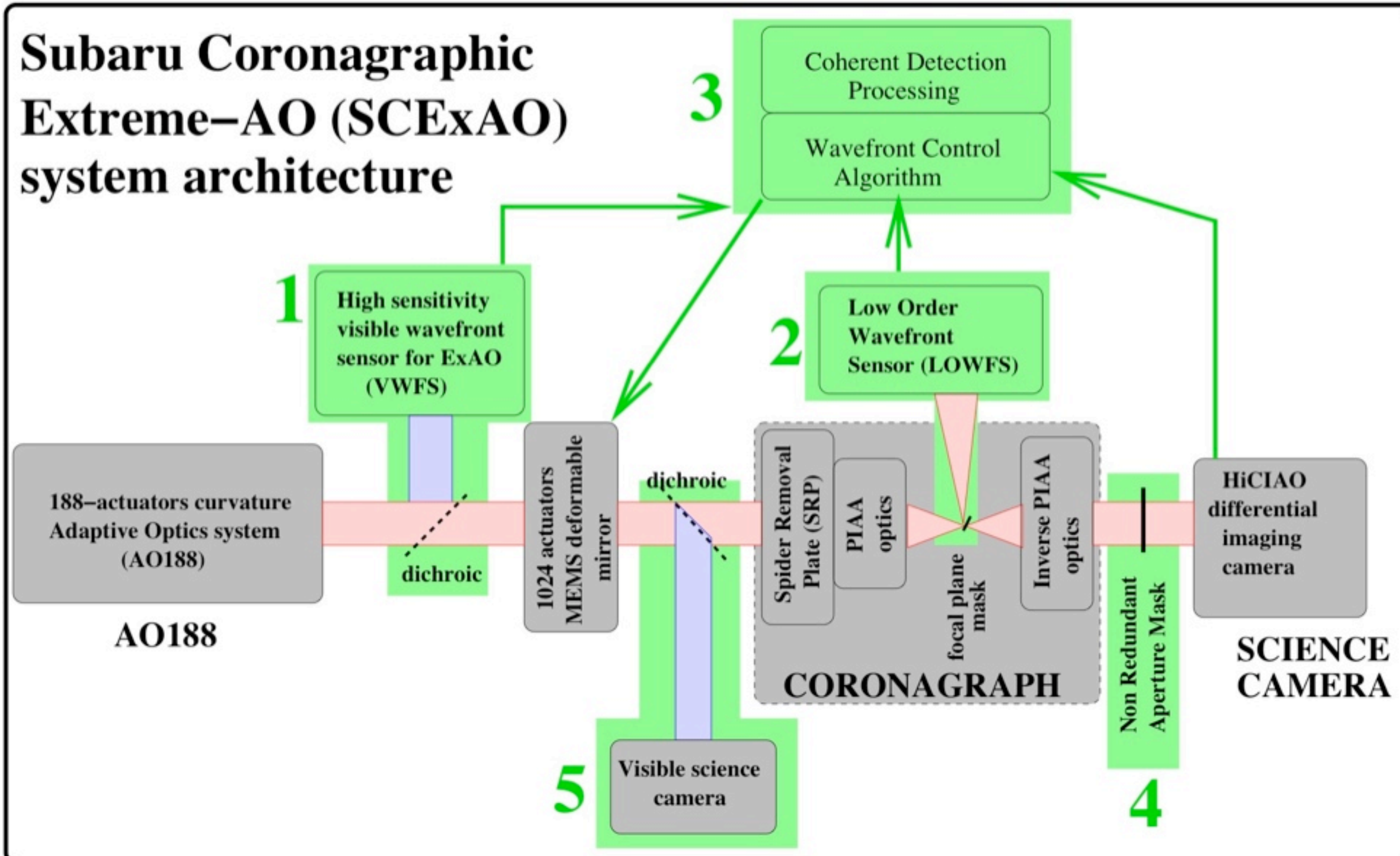
Fast camera for focal plane WFS after coronagraph

The first step is used to clean the wavefront within ~ 1 rad in Visible

The second step operates in the high coherence regime, and adopts a higher performance WFS

3rd step is a high coherence loop within coronagraph with NO non-common path errors & full sensitivity

Gemini Planet Imager (GPI) uses a similar strategy, with an interferometer to measure coherent residuals. Subaru ExAO will probe this architecture further.



Subaru Coronagraphic Extreme−AO (SCExAO) system architecture
3
Coherent Detection Processing
Wavefront Control Algorithm
1
High sensitivity visible wavefront sensor for ExAO (VWFS)
2
Low Order Wavefront Sensor (LOWFS)
188−actuators curvature Adaptive Optics system (AO188)
dichroic
1024 actuators MEMS deformable mirror
dichroic
Spider Removal Plate (SRP)
PIAA optics
focal plane mask
Inverse PIAA optics
CORONAGRAPH
Non Redundant Aperture Mask
HiCIAO differential imaging camera
AO188
SCIENCE CAMERA
5
Visible science camera
4

Non-linear Curvature WFS

High sensitivity WFS requires interferences between distant points in the pupil plane. Most current WFS schemes do not do that, and are therefore very insensitive at low spatial frequencies.

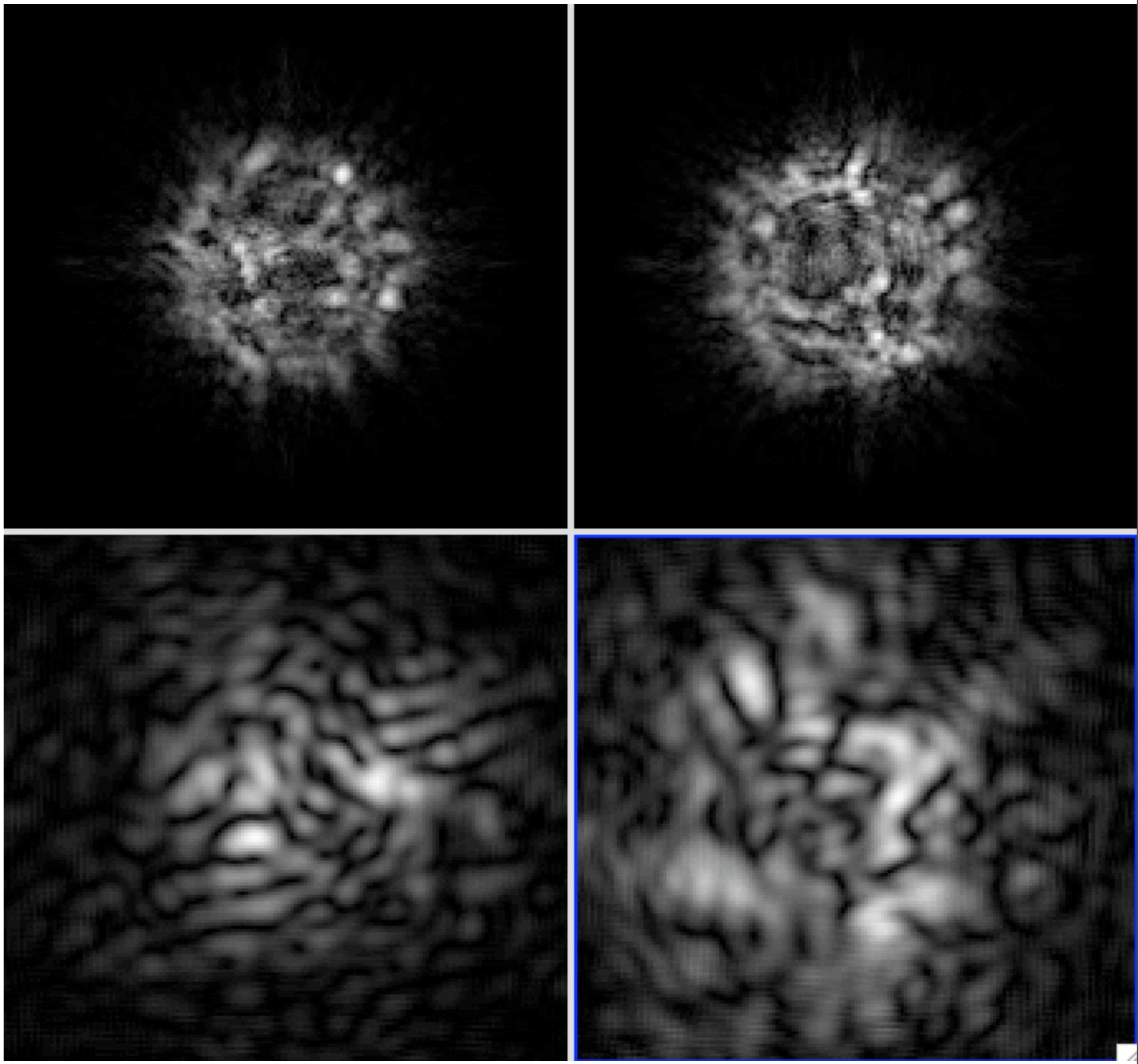
SH: Noise propagation limitation is introduced at the optical level (chopping the pupil in small pieces)

Curvature: Noise propagation comes from processing of WFS frames, which imposes linearity

-> possible to mitigate / solve ?

Defocused pupil images are full of lambda/D speckles

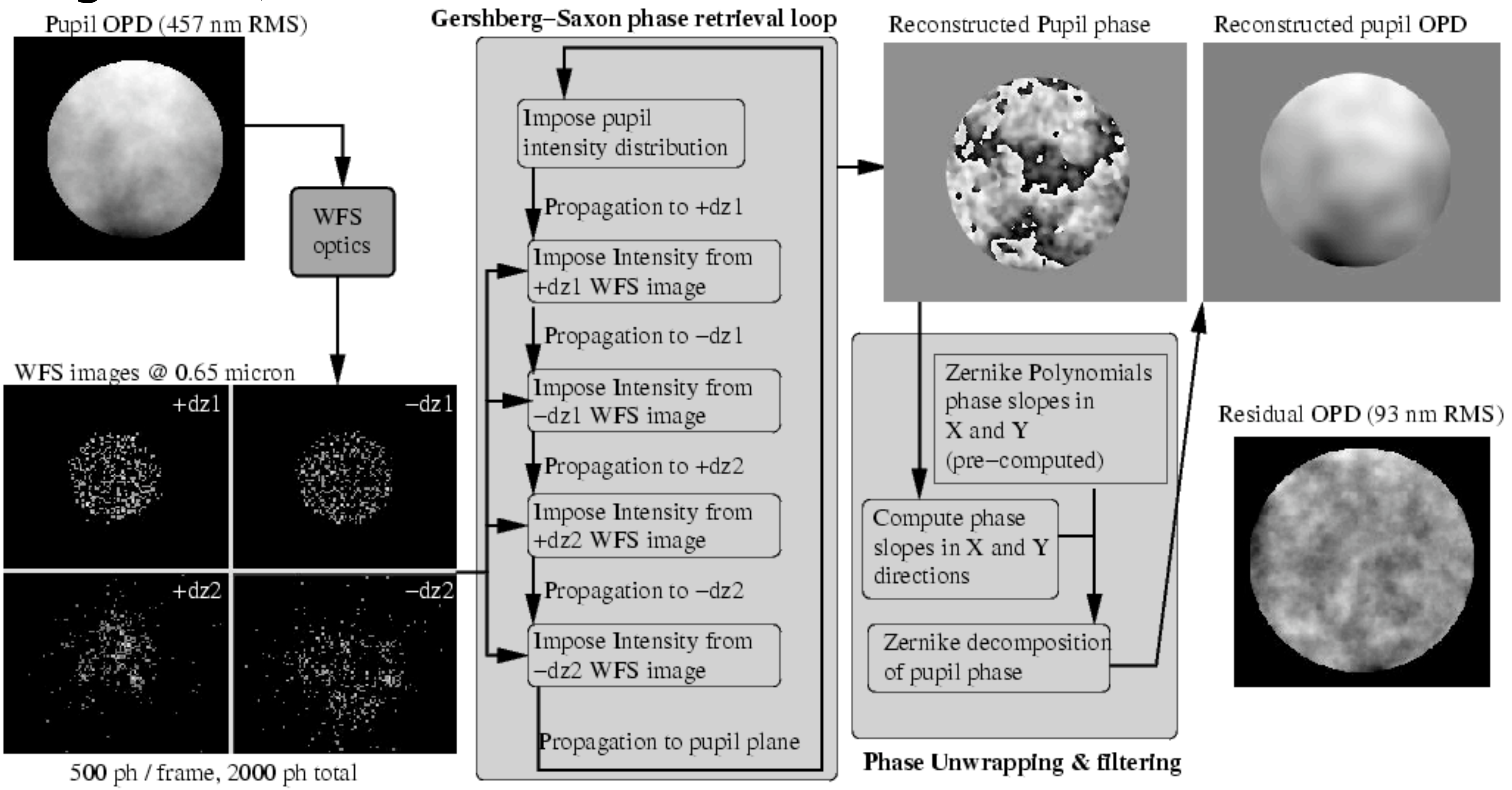
+/- 1000km



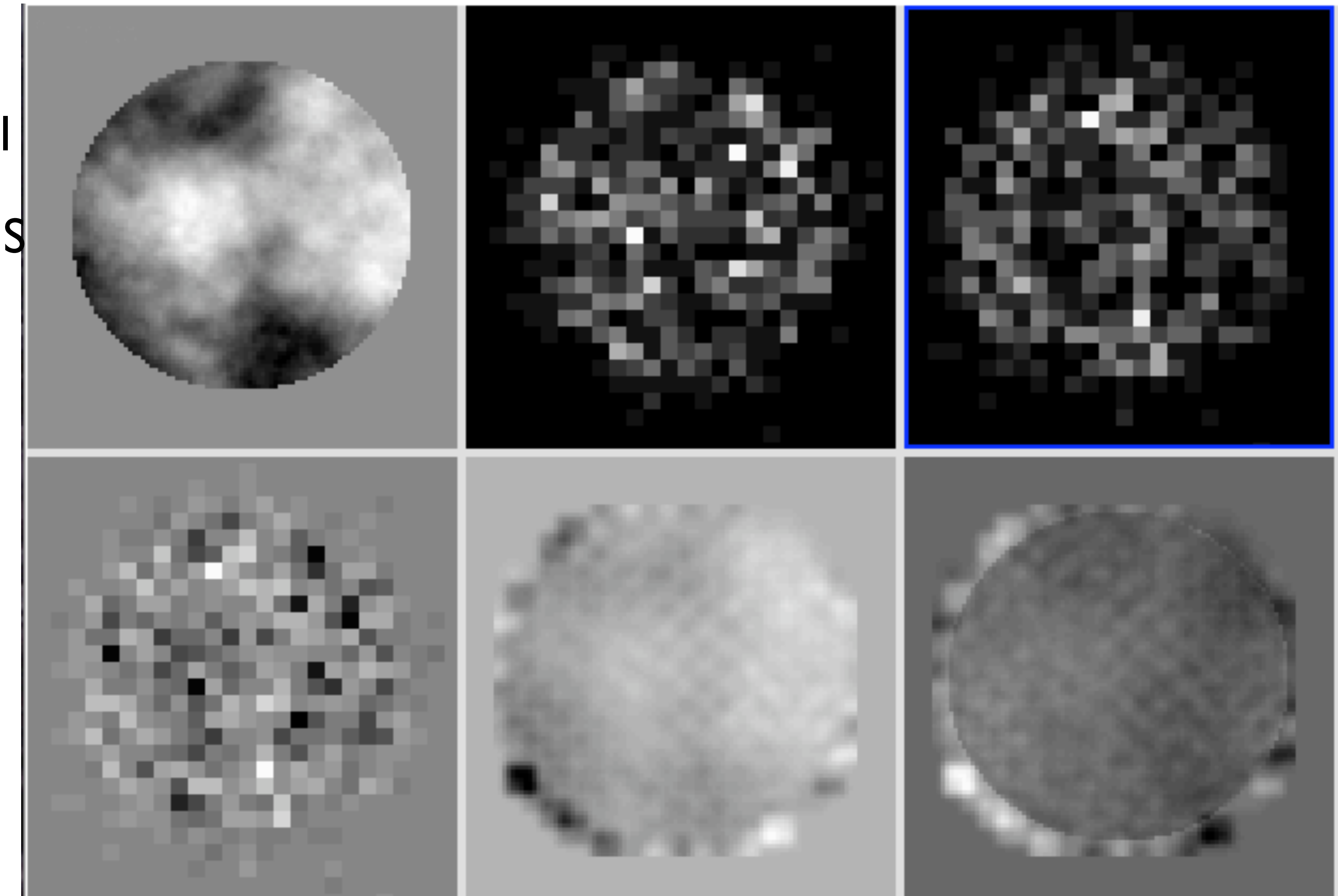
+/- 8000km

Standard phase diversity algorithm, working around pupil plane. There are probably better/faster algorithms (see for example: van Dam & Lane 2002, JOSA vol. 19)

kHz operation appears to be possible with current chips for few 100s actuators system (100 32x32pix FFT = 0.2ms on single CPU)



Linear single stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.



Input pupil phase 296nm RMS

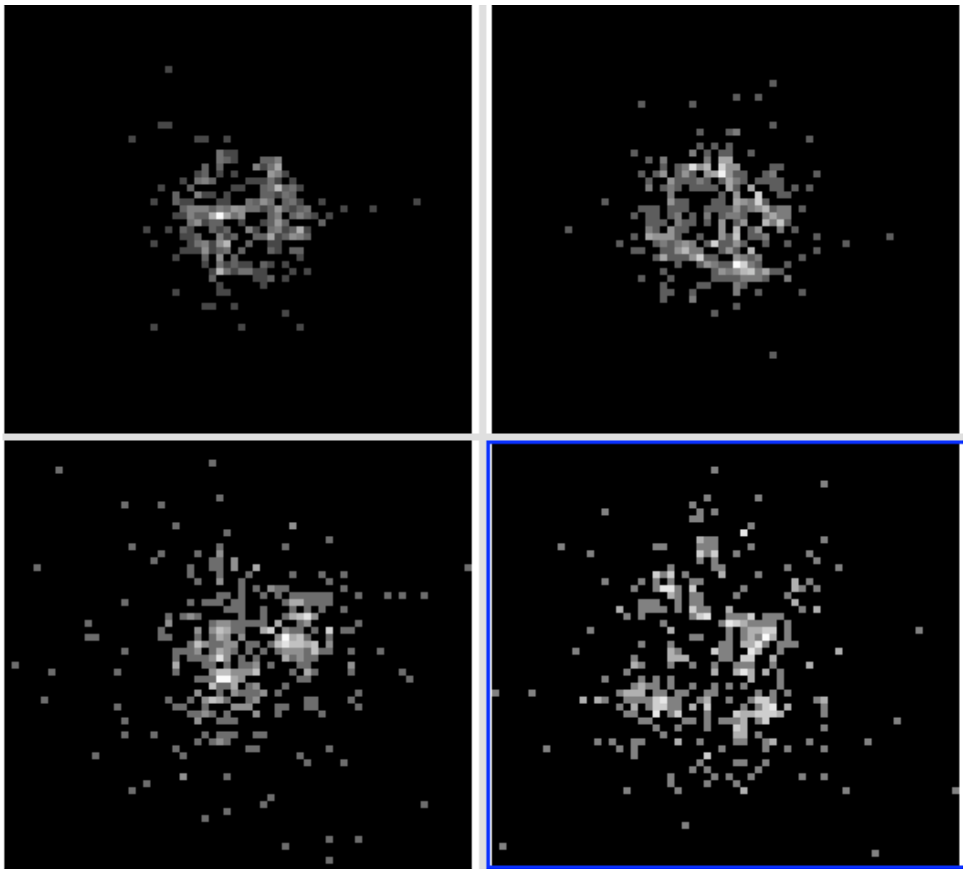
+/- 700km

Curv. signal

Reconstructed phase

Residual: 196nm RMS

Non linear dual stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.

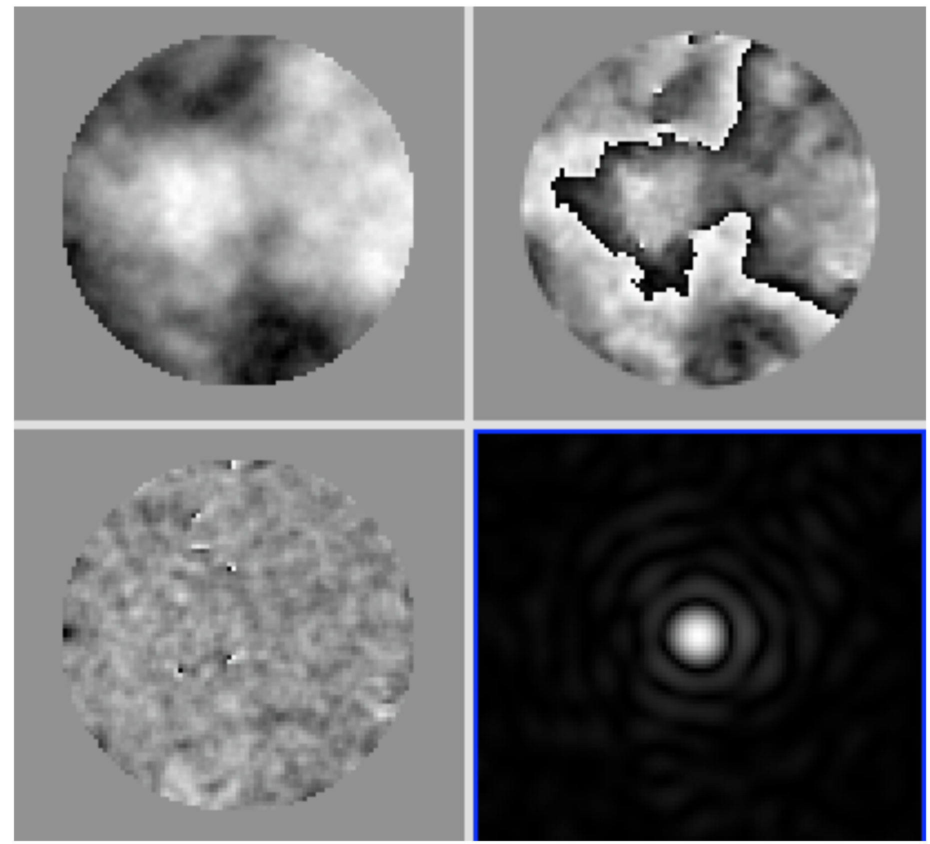


Defocused pupil images

500 ph / frame
Top : +/- 2000km
Bottom: +/- 8000km

Input pupil phase
296nm RMS

Reconstructed
phase



Residual: 55nm RMS

SR = 0.763
at 0.65 micron

Magn 16 source -> 2000 ph/ms on 8m telescope

Why is is so good ??? -> uses HSF to infer LSF

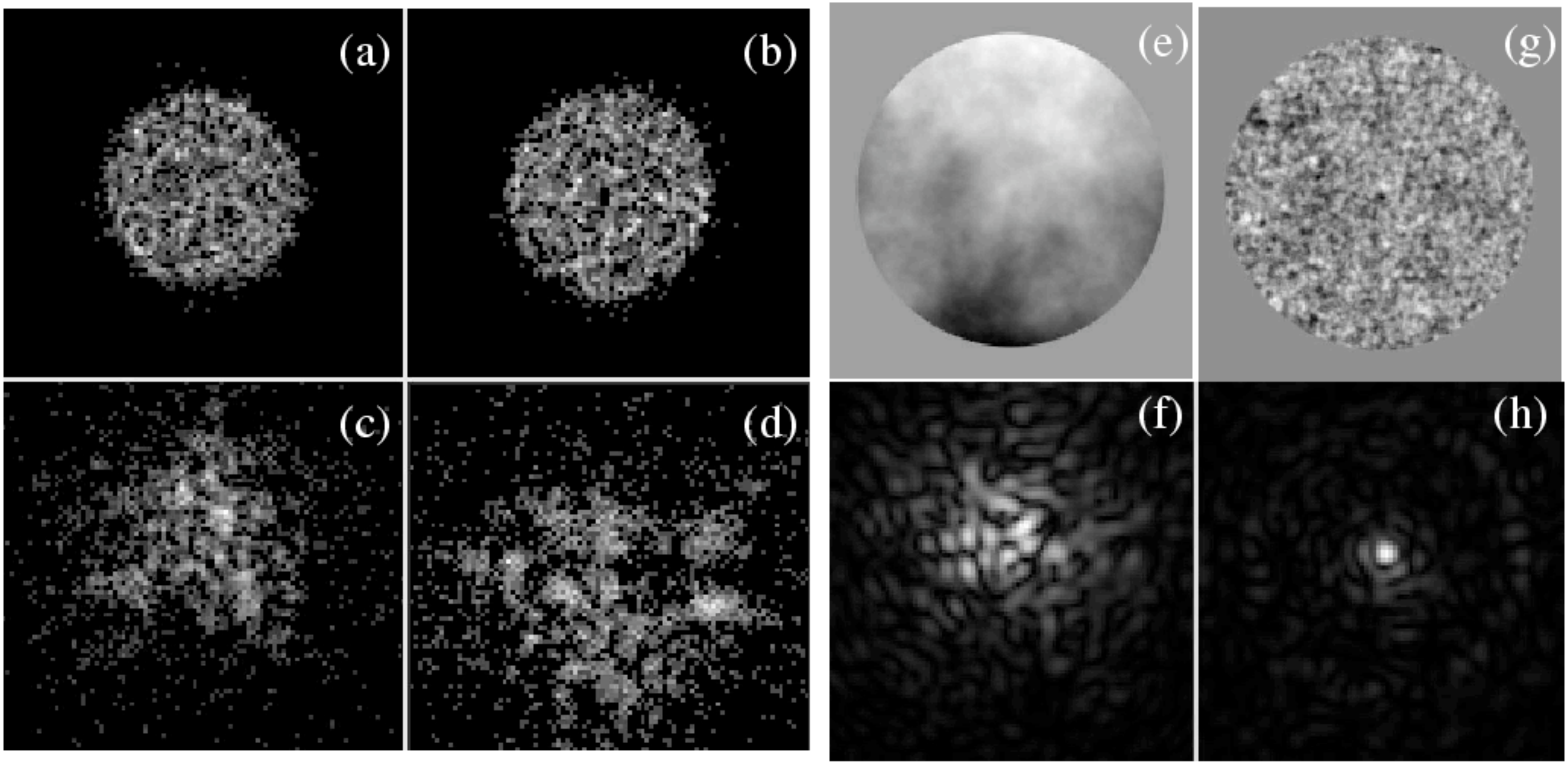
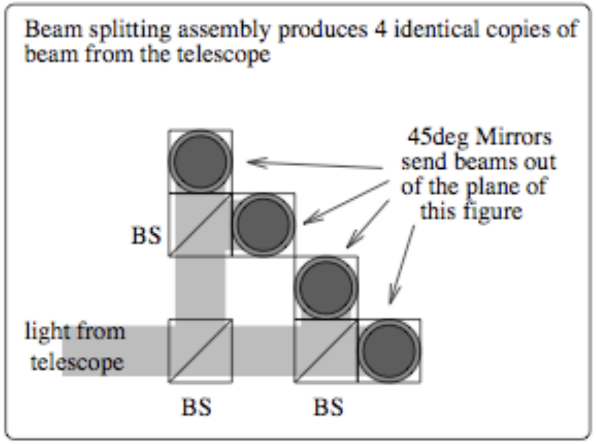
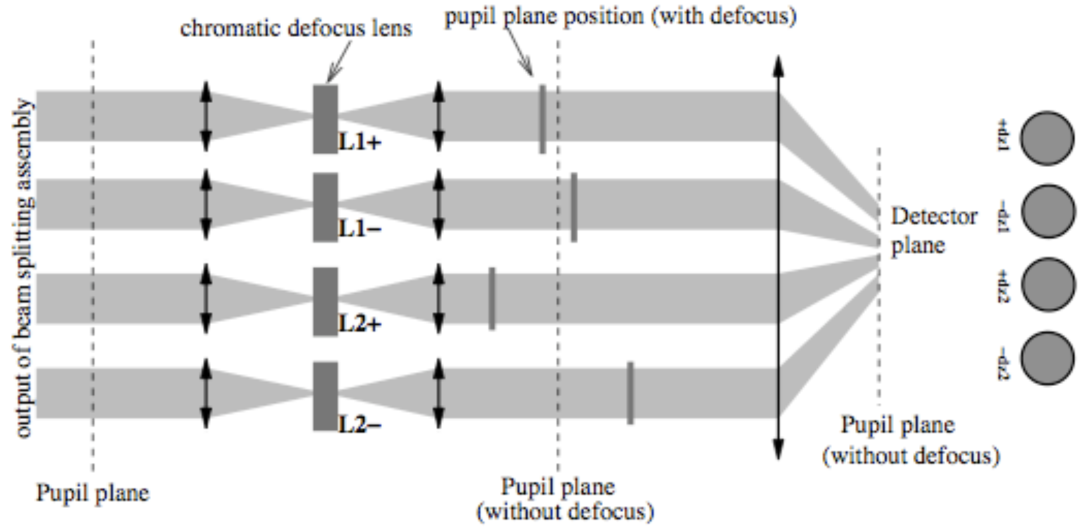
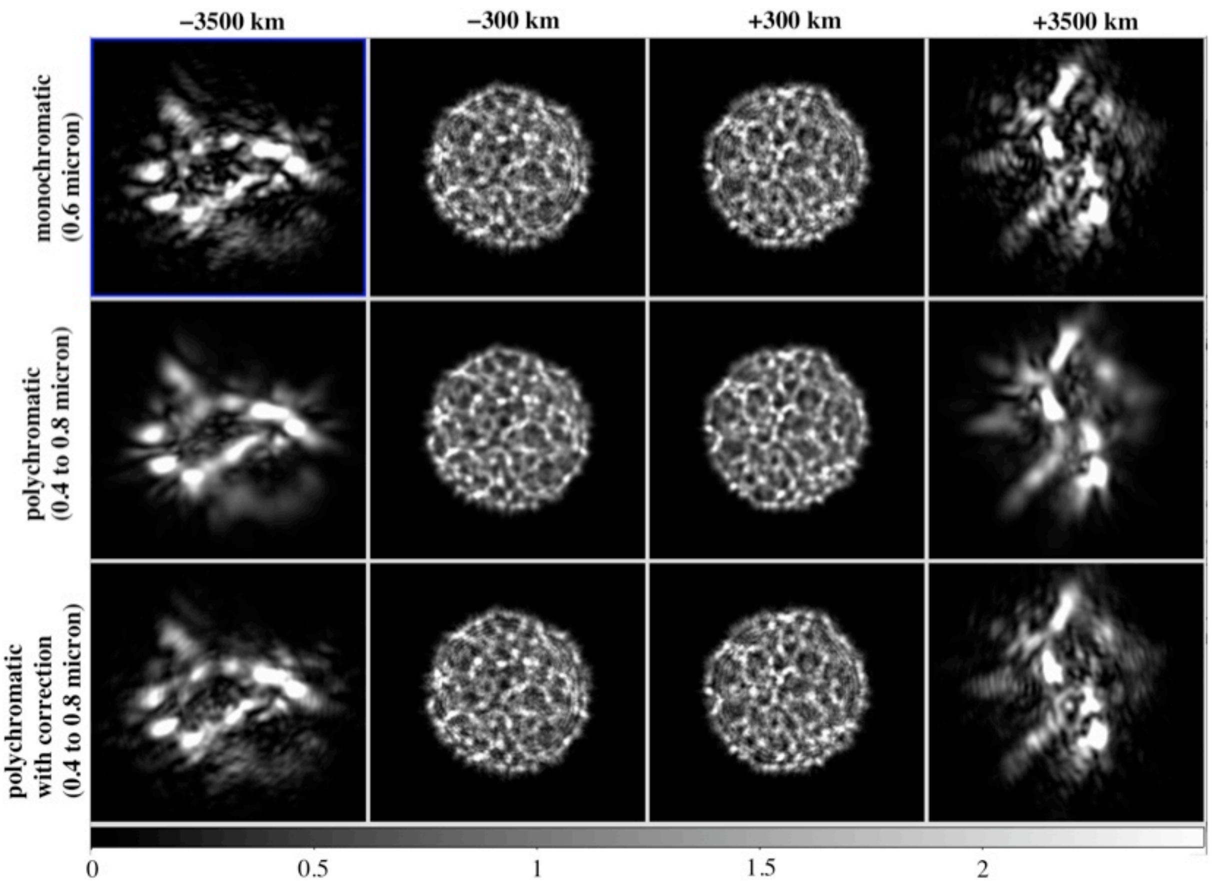


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After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

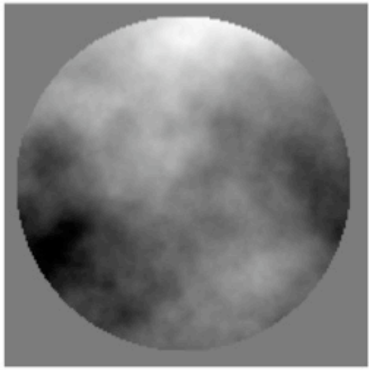


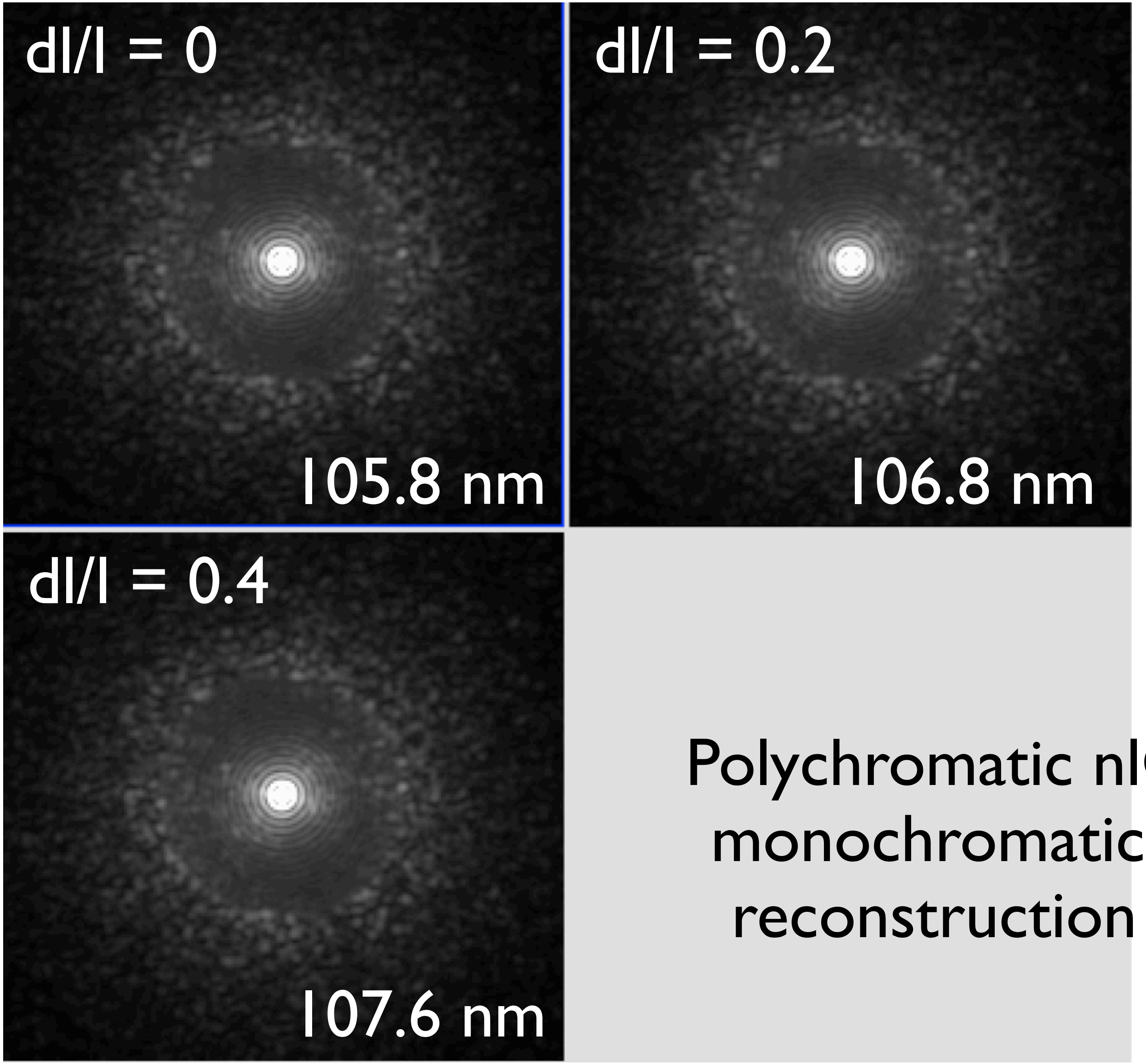




8 m diameter pupil

371 nm RMS

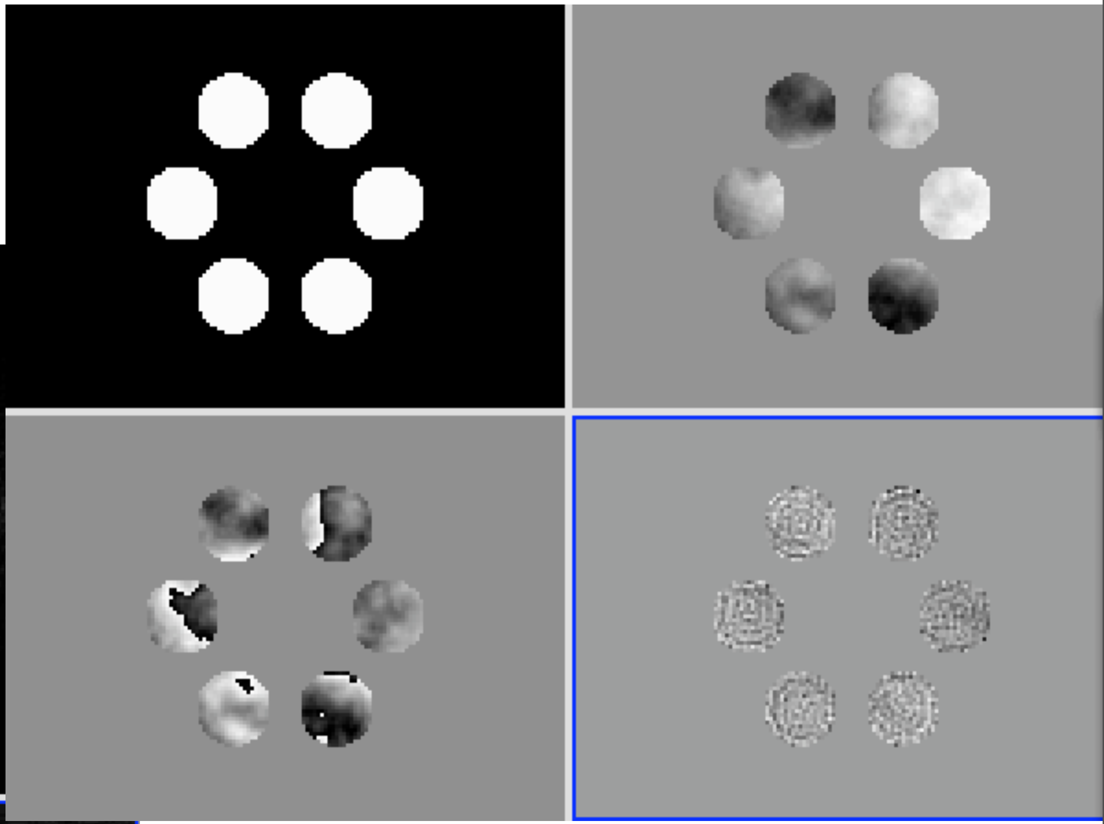


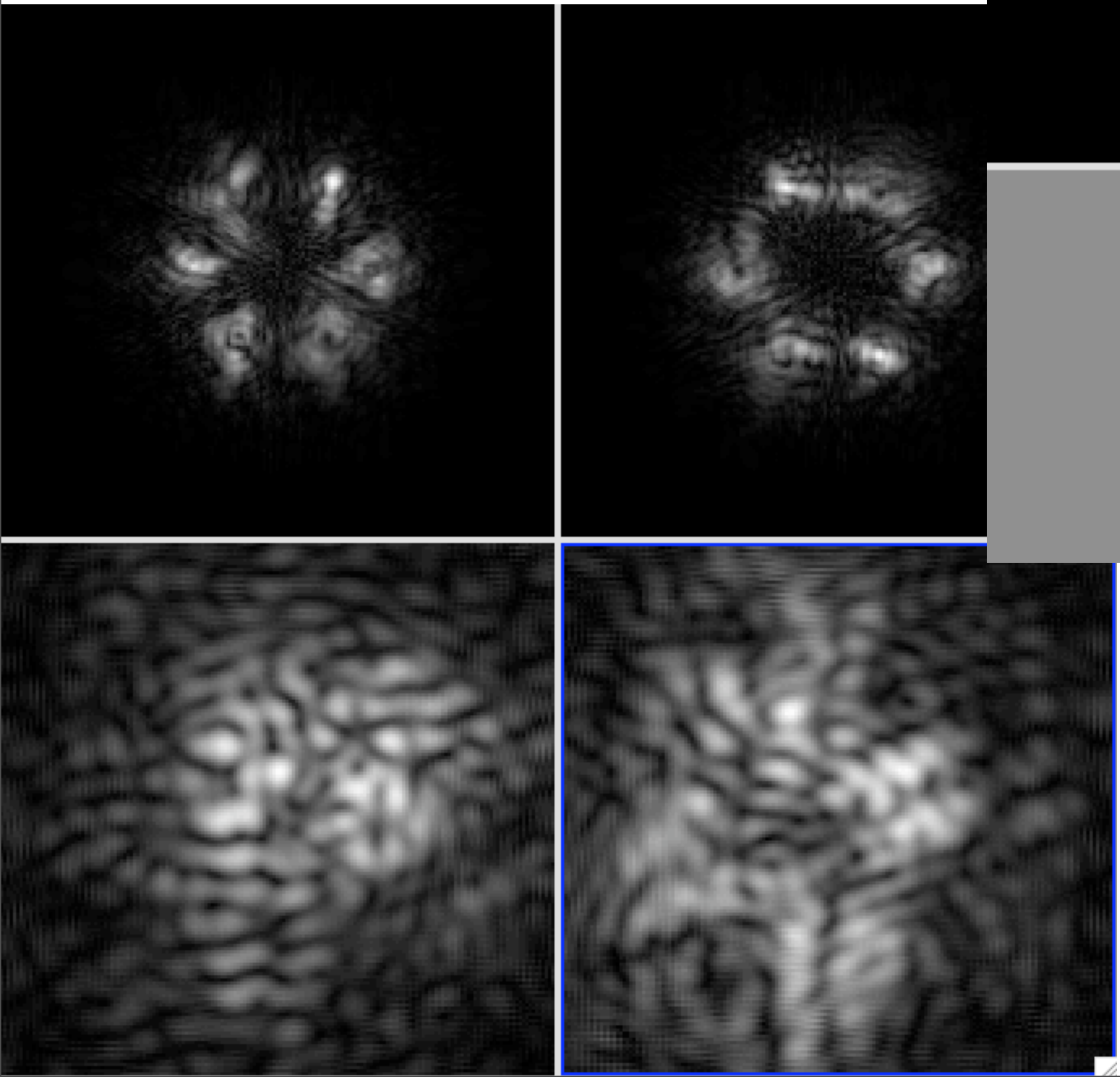


Polychromatic nlCWFS with monochromatic wavefront reconstruction algorithm

Very good for Sparse pupil or thick spiders

(well suited for GMT !)

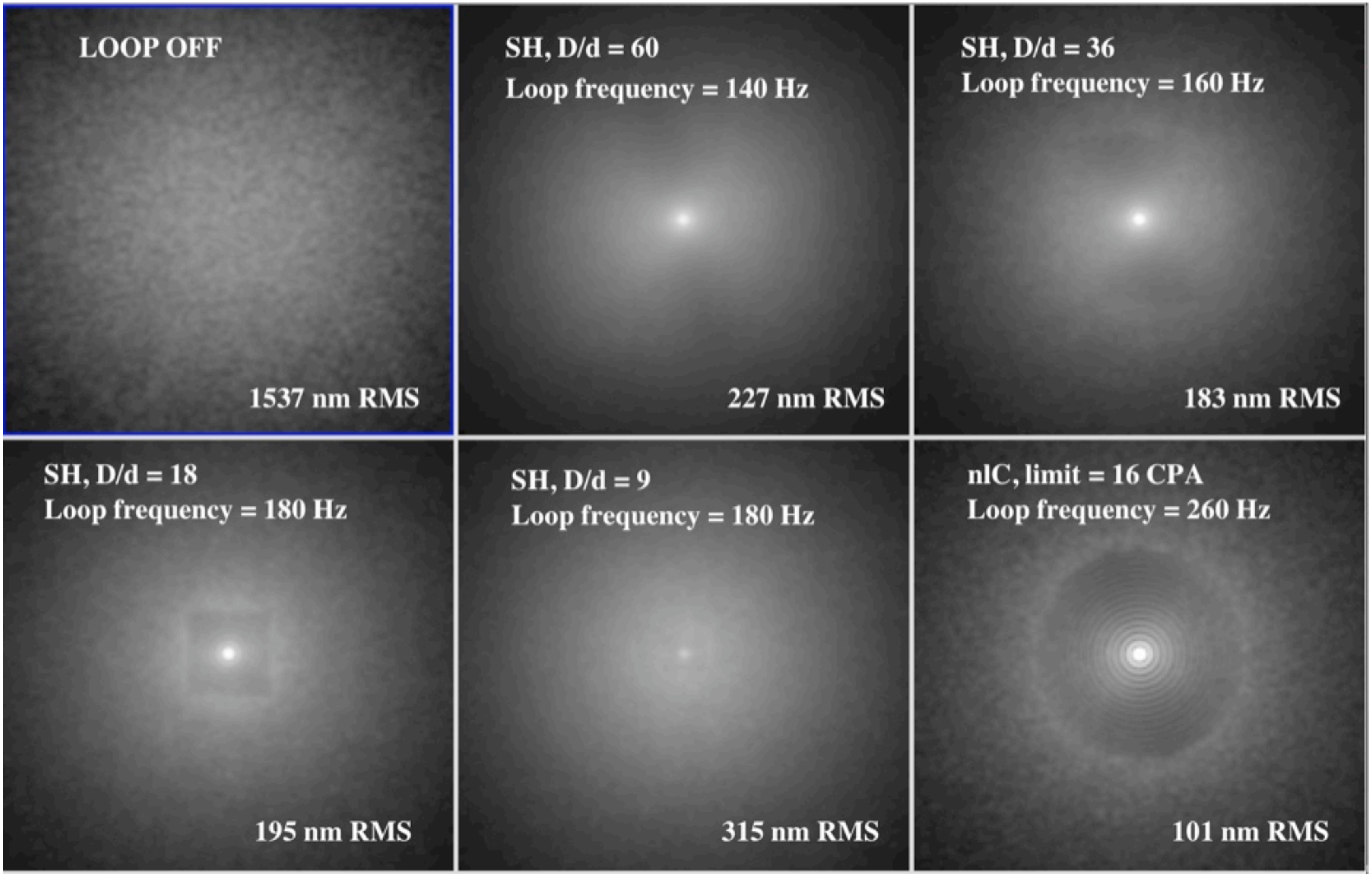




13nm RMS

2e8 ph

m ~ 13



WFS	Loop frequ	RMS	SR @ 0.85 mu	SR @ 1.6 mu
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%

Pointing control demonstrated to 1e-3 l/D at Subaru PIAA testbed

LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes.
Subaru Testbed has demonstrated closed loop pointing control to 1e-3 l/D ~ 0.1 mas on 1.4m PECO.
ref: Guyon, Matsuo, Angel 2009

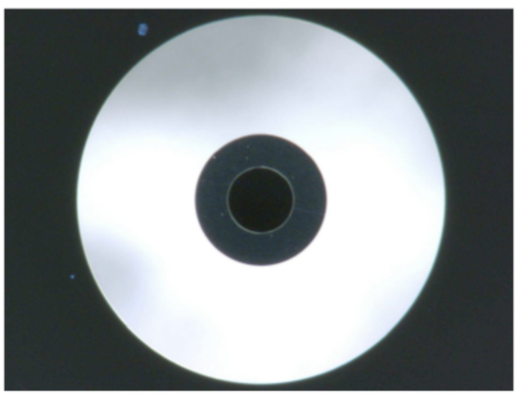


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

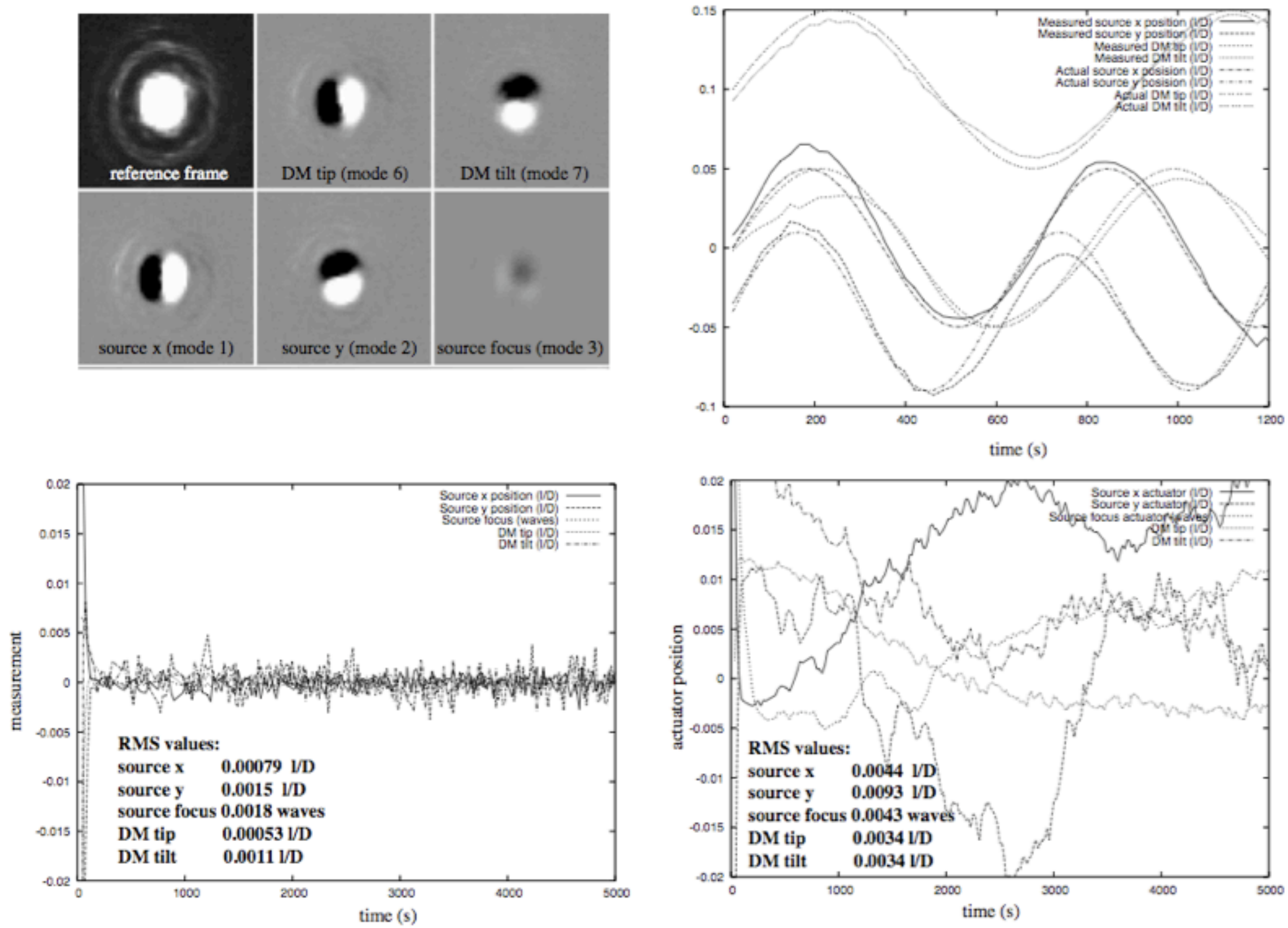


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. 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.

Focal plane WFS & calibration

Speckles vs. planet

Spectra differential imaging (SDI)
Optimized for methane-bearing giant planets
Will only detect planets with a given spectral feature
Polarization differential imaging (PDI)
Degree of polarization may be low (few %)
Only works on reflected light
Angular differential imaging (ADI)
Performs well if static speckles are strong
Does not work well at small angular separations

Coherent differential imaging (CDI)
Use DM to introduce a know variation in the WF to modulate speckle intensity
Can reach photon noise limit if system is very well calibrated and CDI is performed quickly (or simultaneously)

How to **optimally** measure speckle field complex amplitude ?

Use upstream DM to introduce phase diversity.
Conventional phase diversity: focus
With DM: freedom to tune the diversity to the problem

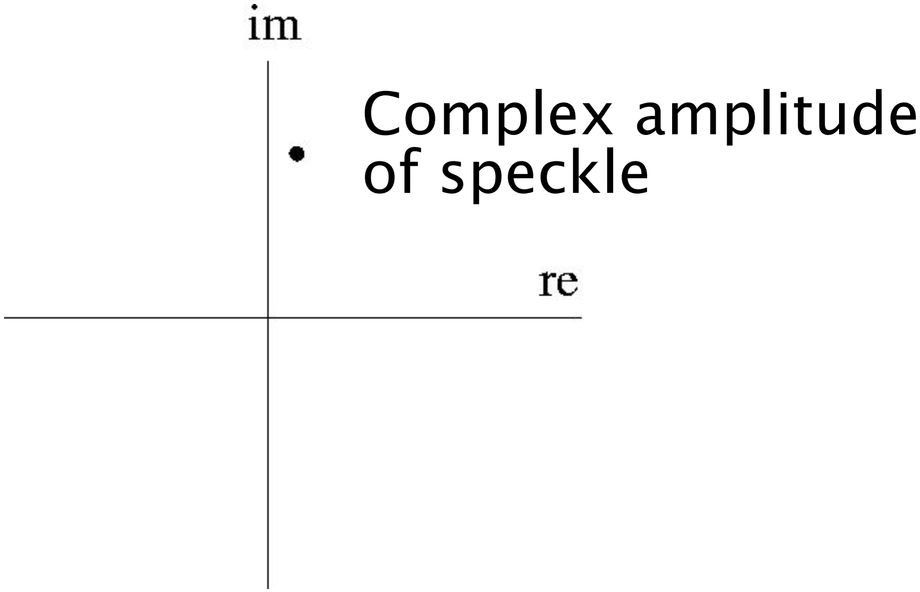
<u>Measure speckle field with no previous knowledge:</u>

- take one frame - this gives a noisy measure of the speckle field amplitude, but not phase

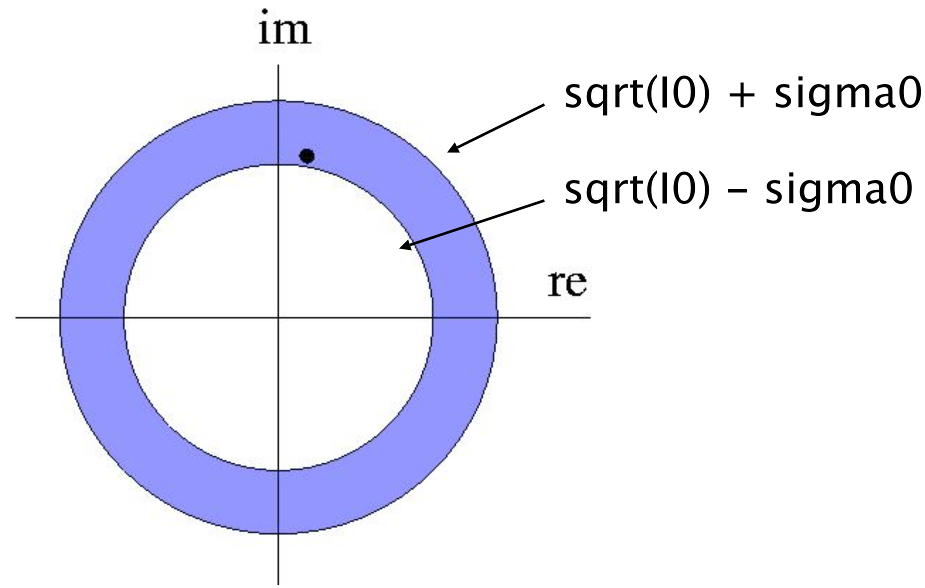
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

-> for each point in the focal plane, 3 intensities -> single solution for phase & amplitude of speckle field

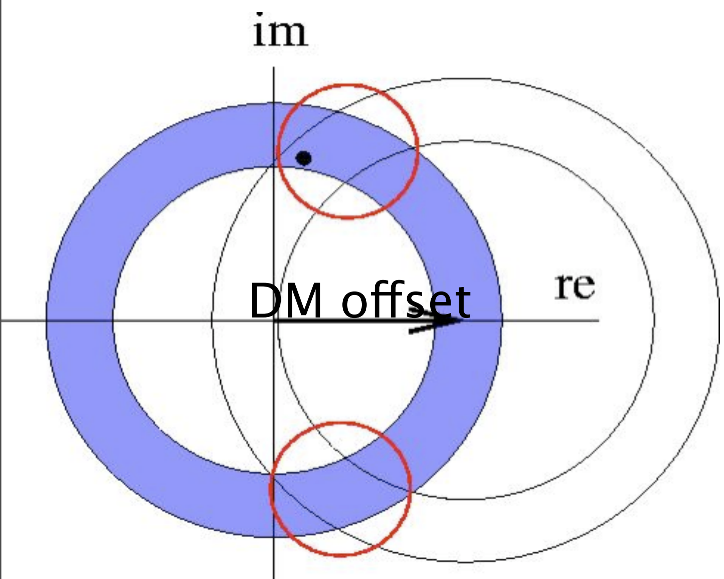
Initial problem

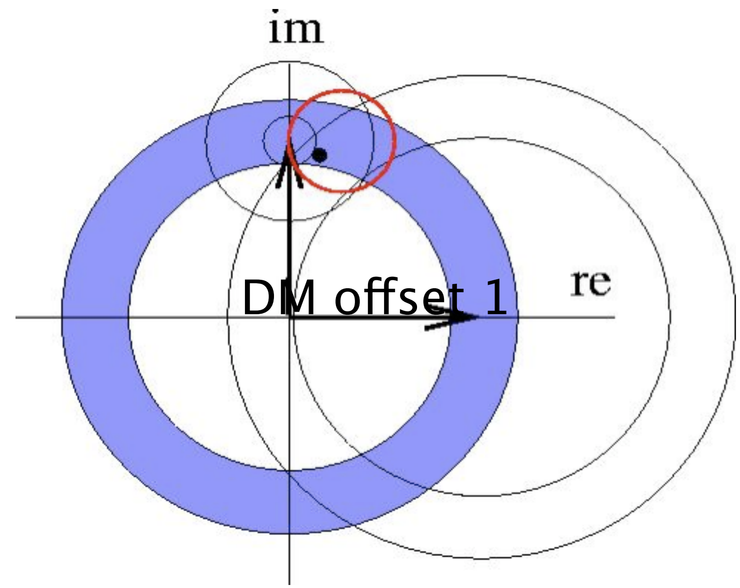


Take a frame -> measured speckle intensity = I0

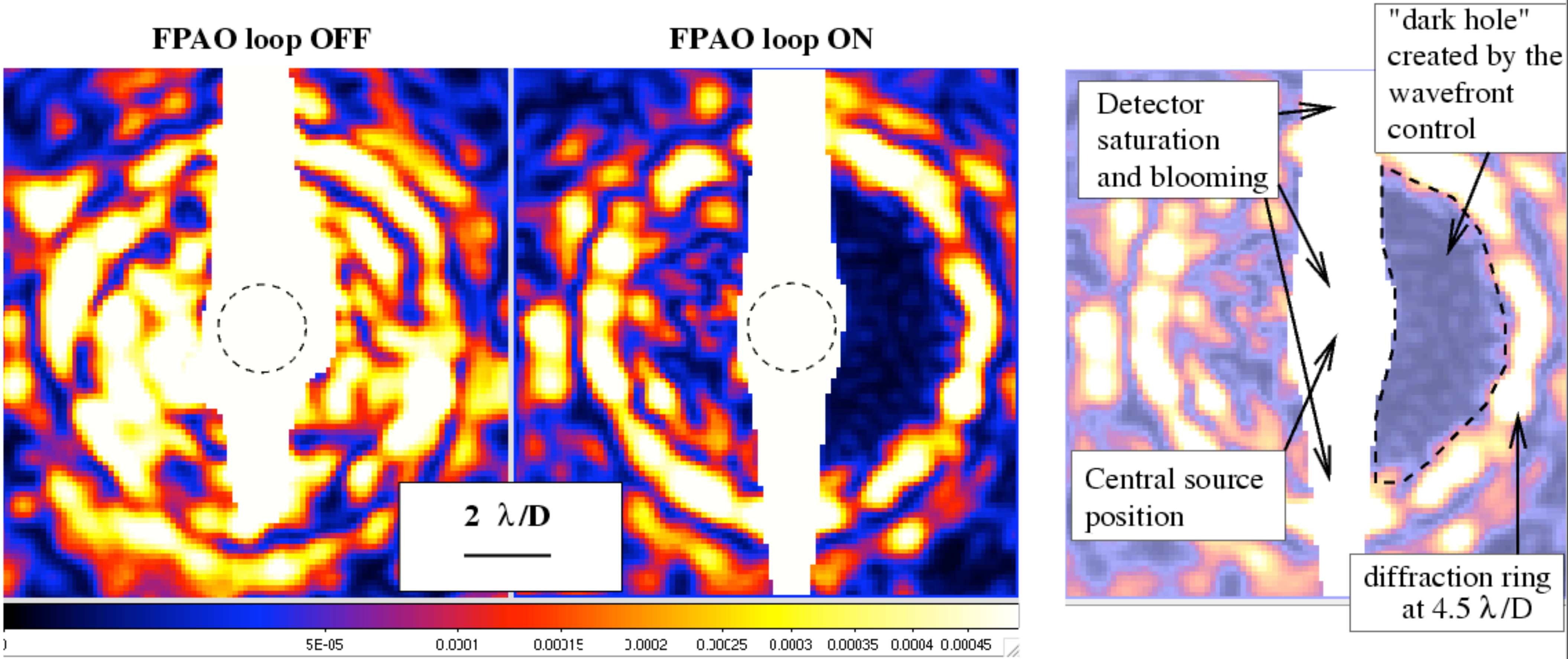


DM offset chosen to be ~ equal to speckle amplitude



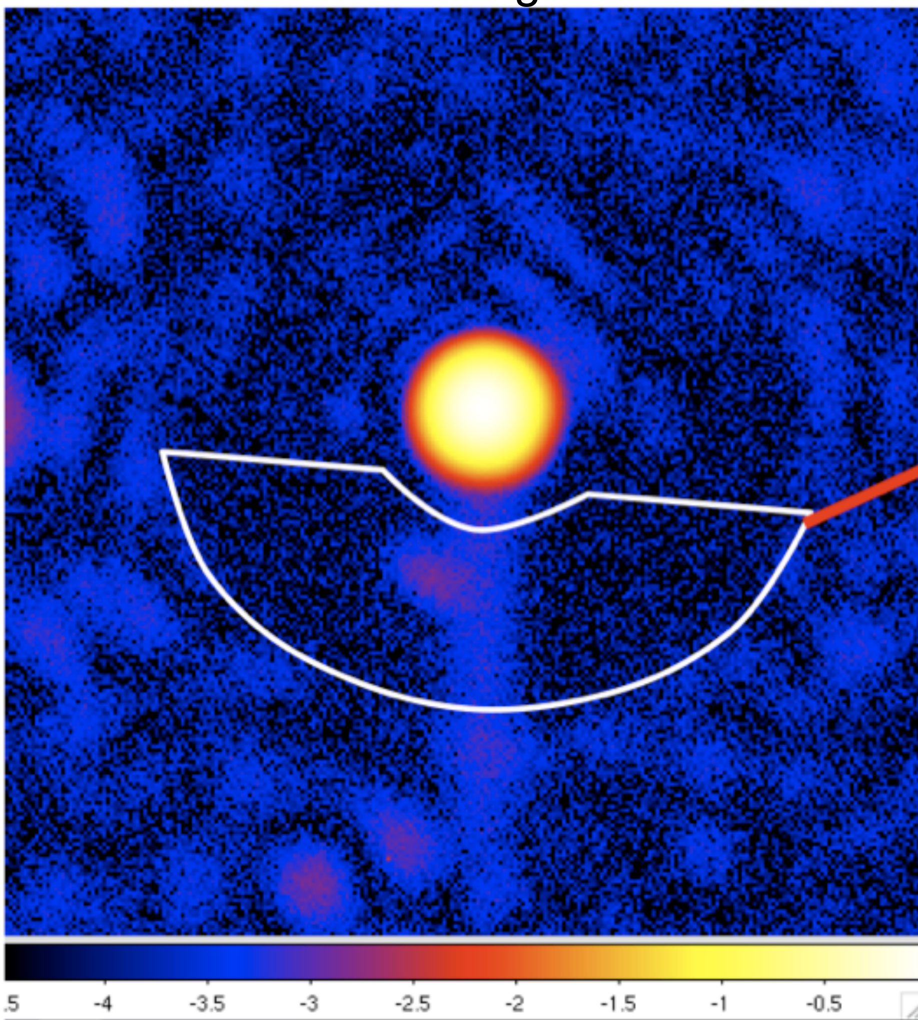


Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

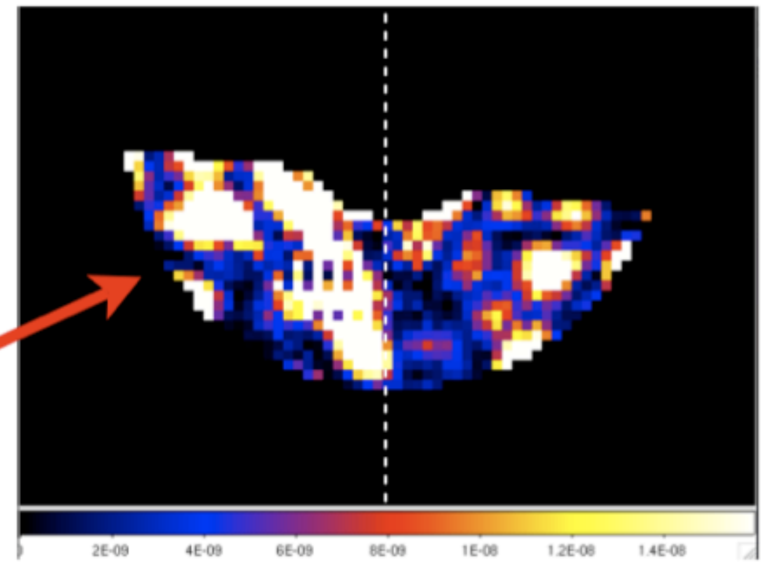


Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image



Coherent starlight



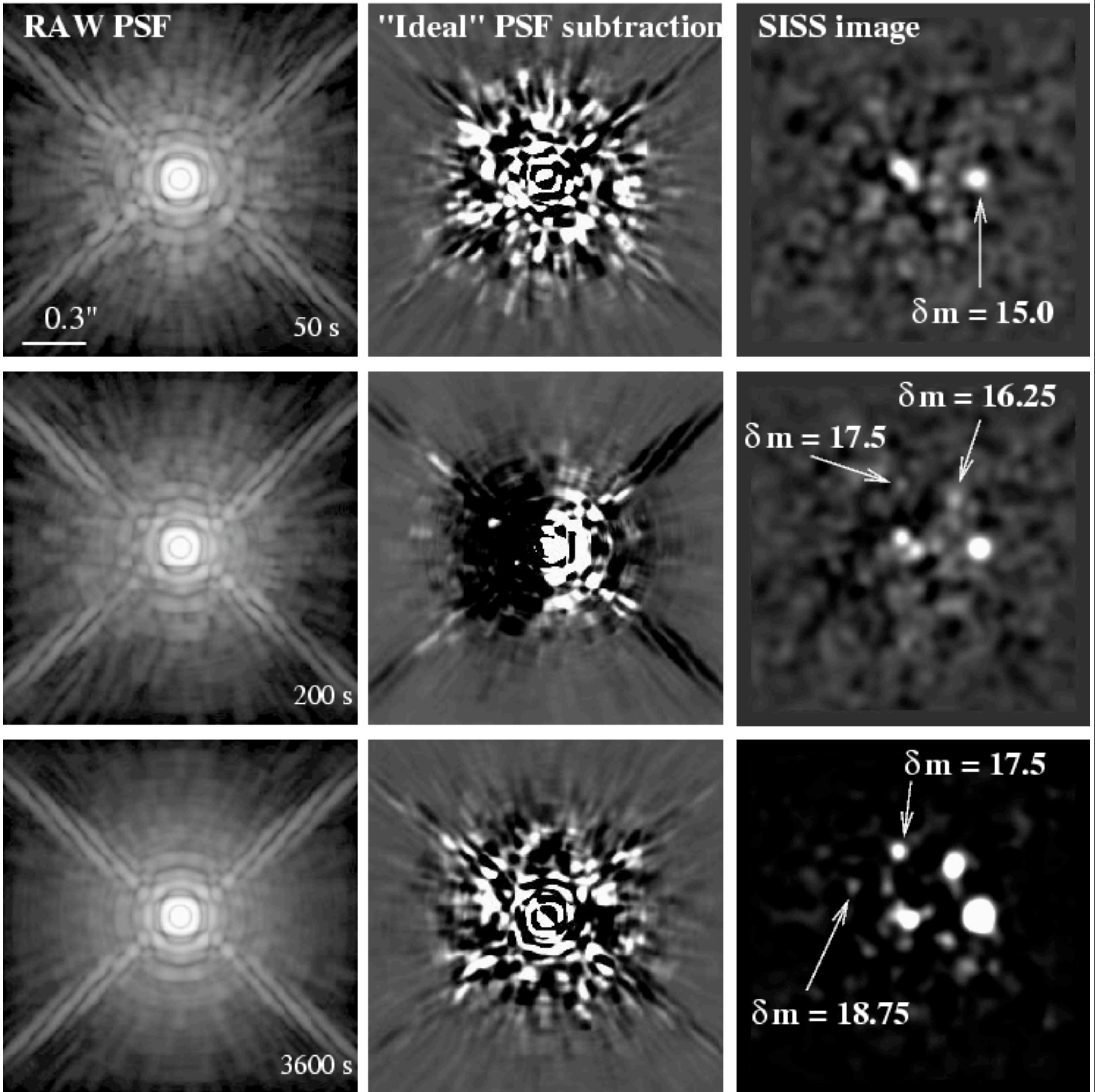
Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

Contrast achieved in 1.6 to 4.5 l/D zone:

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

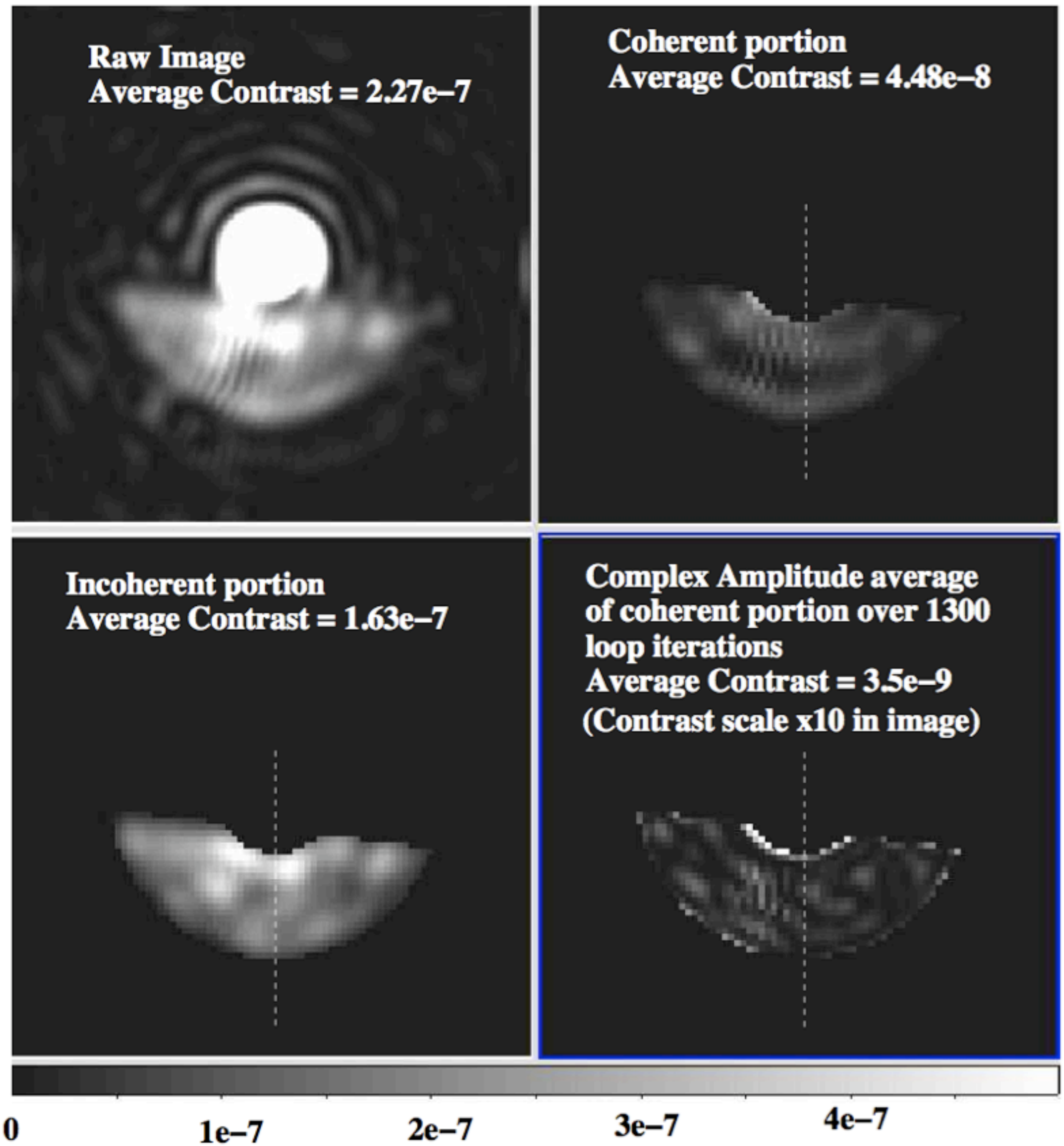
7e-9 coherent starlight speckles (turbulence, vibrations)

Speckle calibration with active coherent modulation



Coherent detection works in the lab alongside FPAO

Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the fly diagnostics
- CDI post-processing

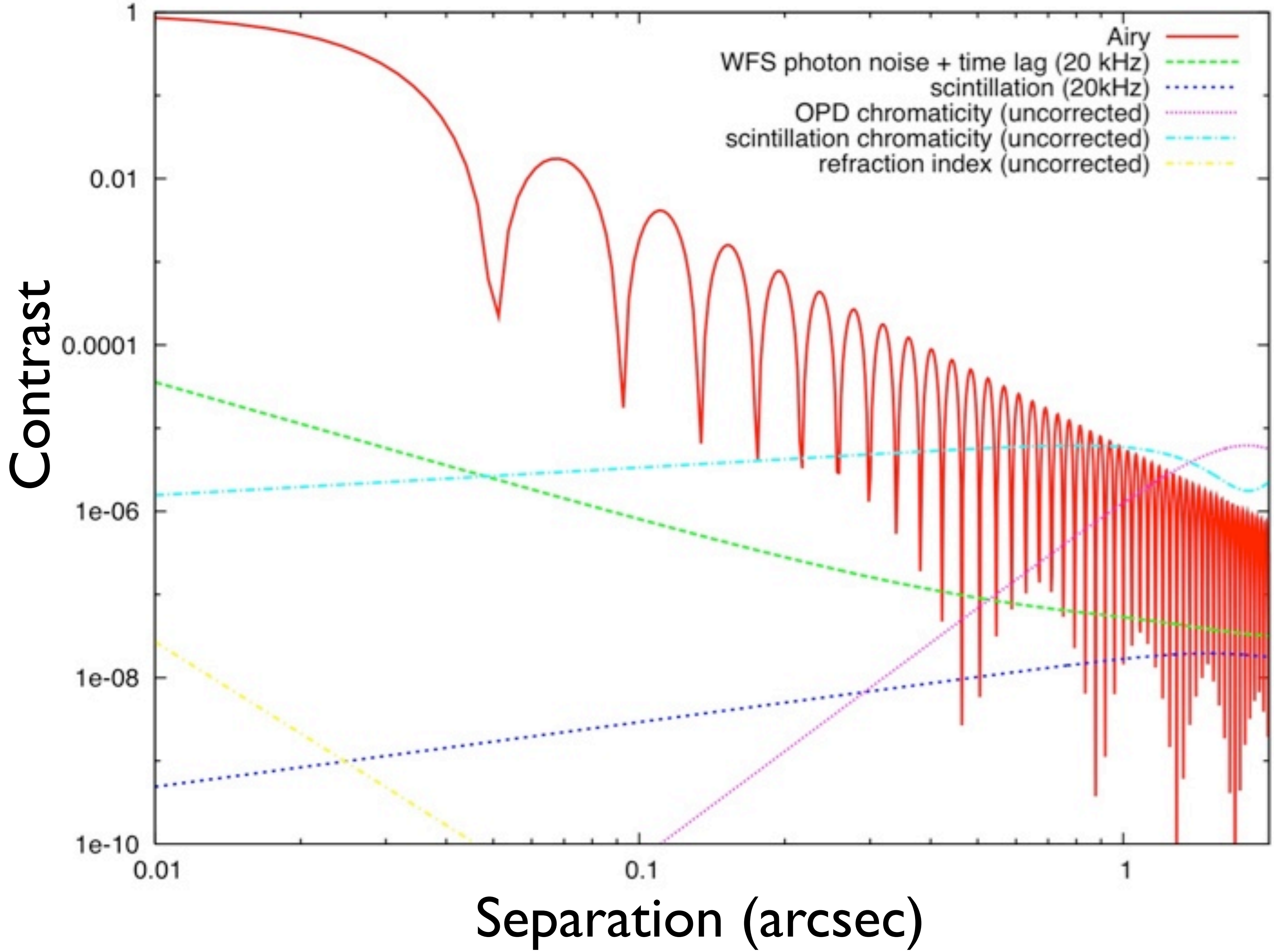


Can we image Earths with ground-based telescopes ?

Reflected light:

- Earth/Sun contrast ~ 1e-9
- SuperEarth ~ 4e-9
- Jupiter @ 1 AU: 2.5e-8

8-m telescope

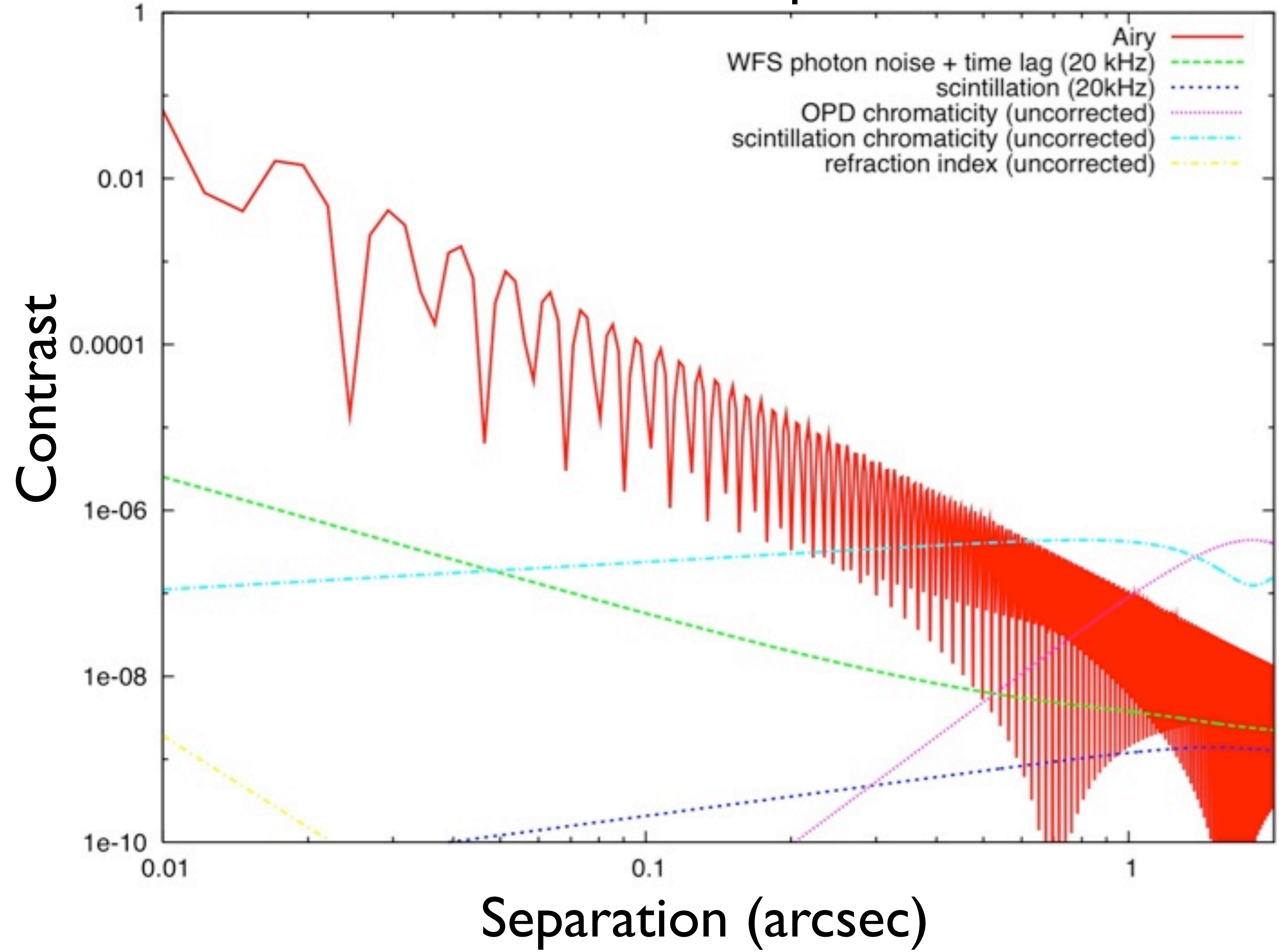


8m telescope, very good ExAO + slow near-IR correction

mV = 5, mH = 5
Contrast in H ~ 1e-5 ~ 1e4 ph/s/speckle (H band background ~1/2 of this)
with ~10 Hz residual speckle timescale
Photon noise from Halo = 1e-7 x 1/sqrt(t(s))
Speckle noise from Halo = 3e-6 x 1/sqrt(t(s))

in 1hr, 3-sigma detection limit =
1.5e-7 (no differential detection)
1e-8 (differential detection, 1/4 photons)

30-m telescope



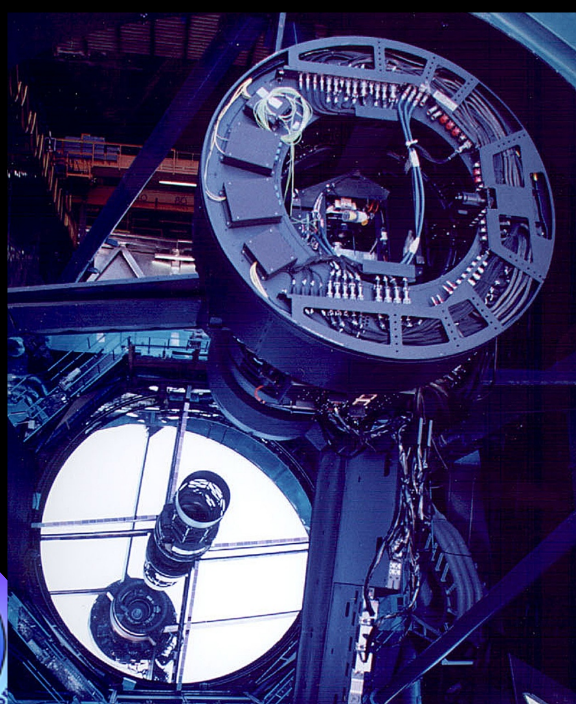
30m telescope, very good ExAO + slow near-IR correction

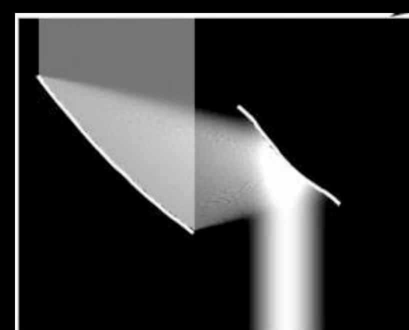
14x more photons in planet and star, contrast 14x better
still ~1e4 ph/s/speckle (7e-7 contrast)
Photon noise from Halo = 7e-9 x 1/sqrt(t(s))
Speckle noise from Halo = 2e-7 x 1/sqrt(t(s))

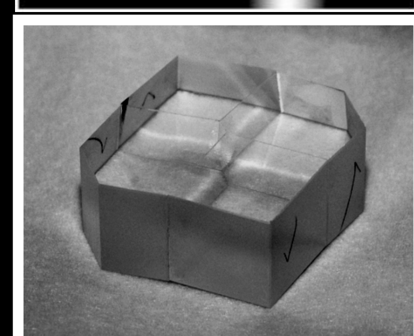
in 1hr, 3-sigma detection limit =
1.1e-8 (no differential detection)
7e-10 (differential detection, assuming 1/4 photons)

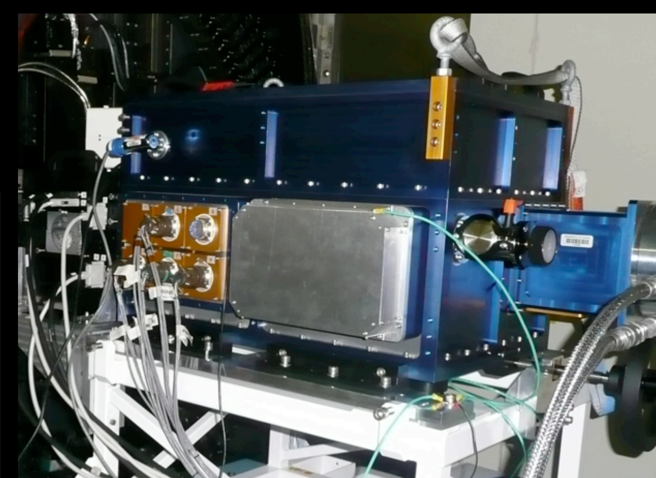
The Subaru Coronagraphic Extreme AO Project (SCExAO)

Olivier Guyon, Frantz Martinache,
Julien Lozi, Vincent Garrel

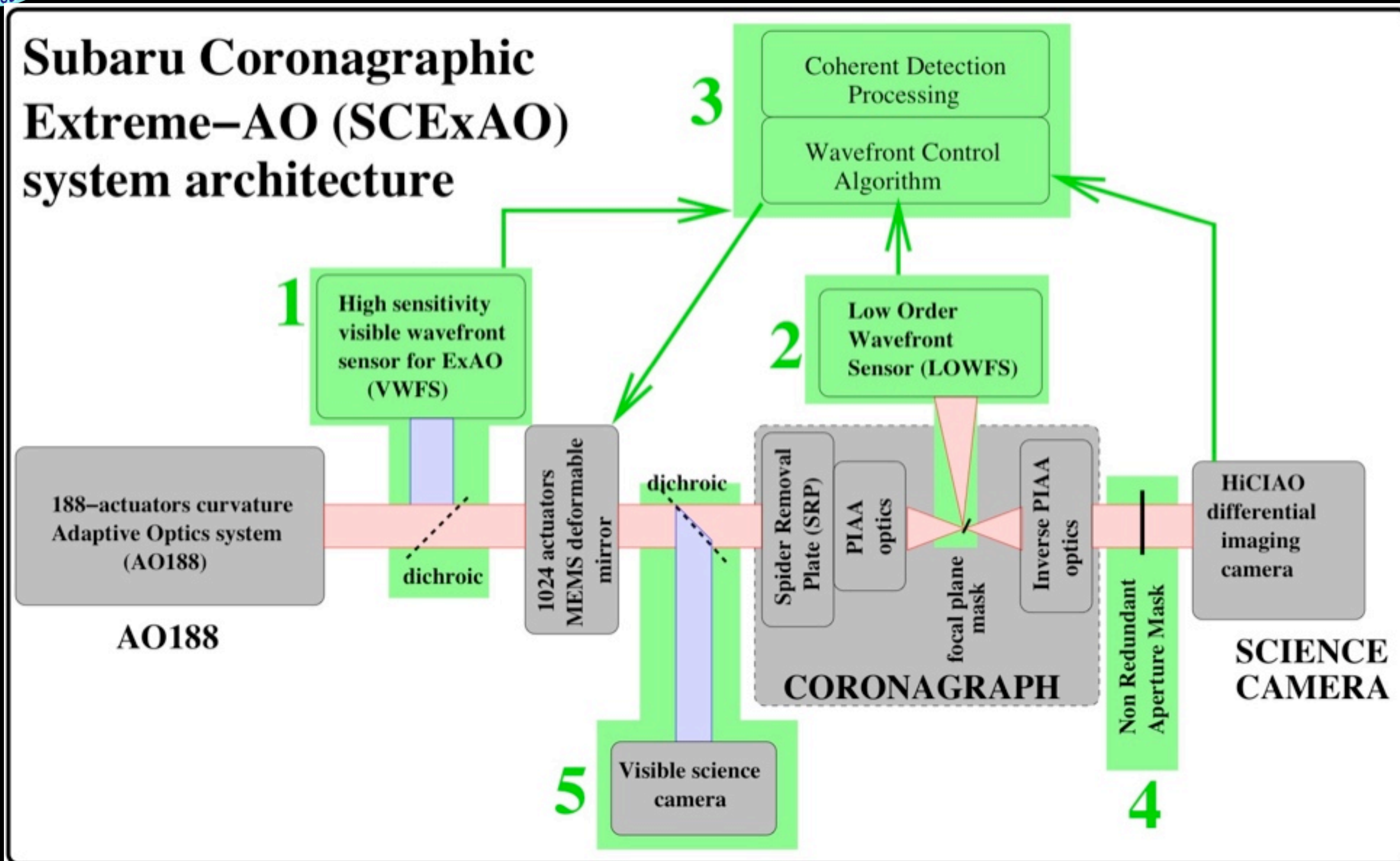




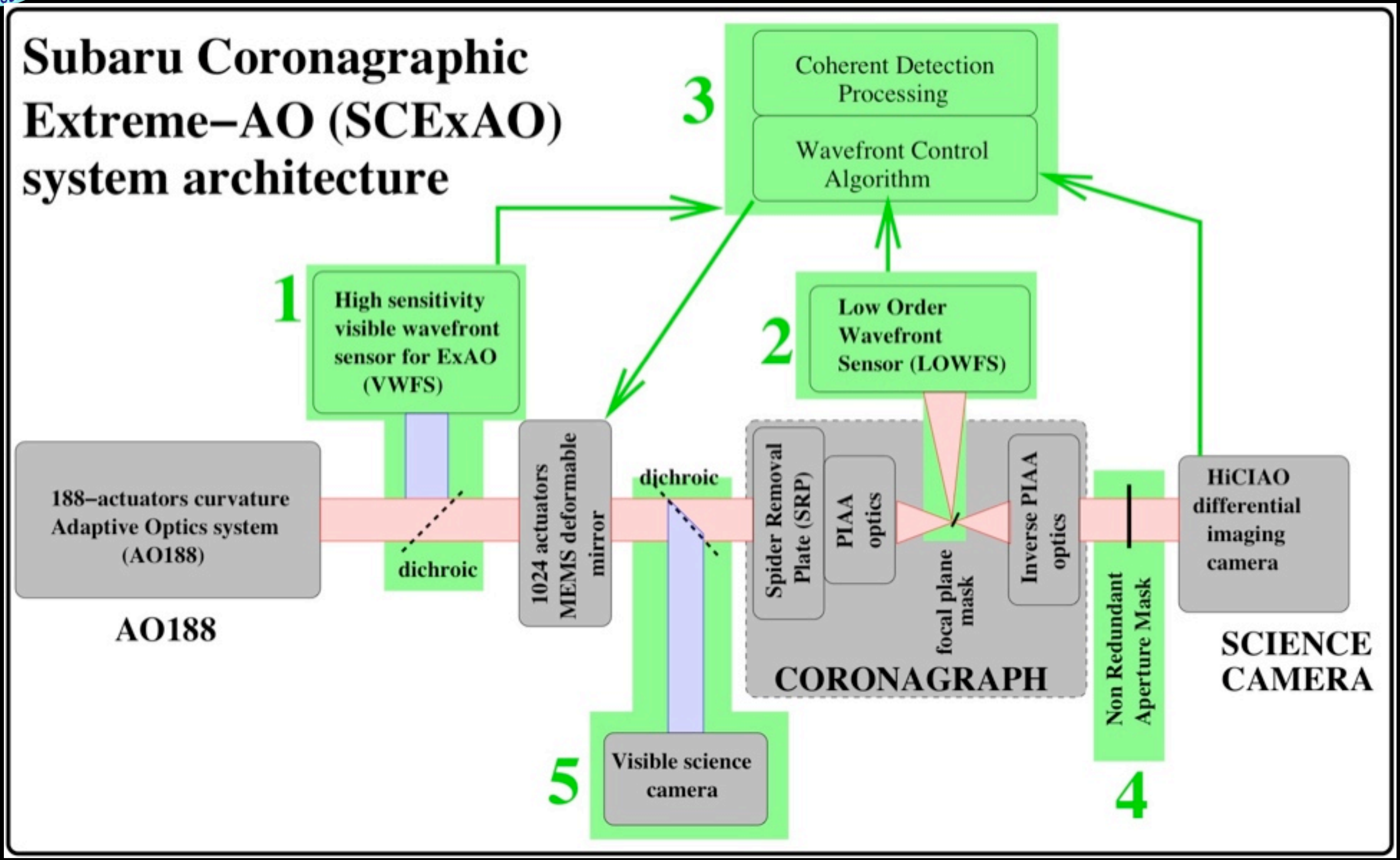




System architecture



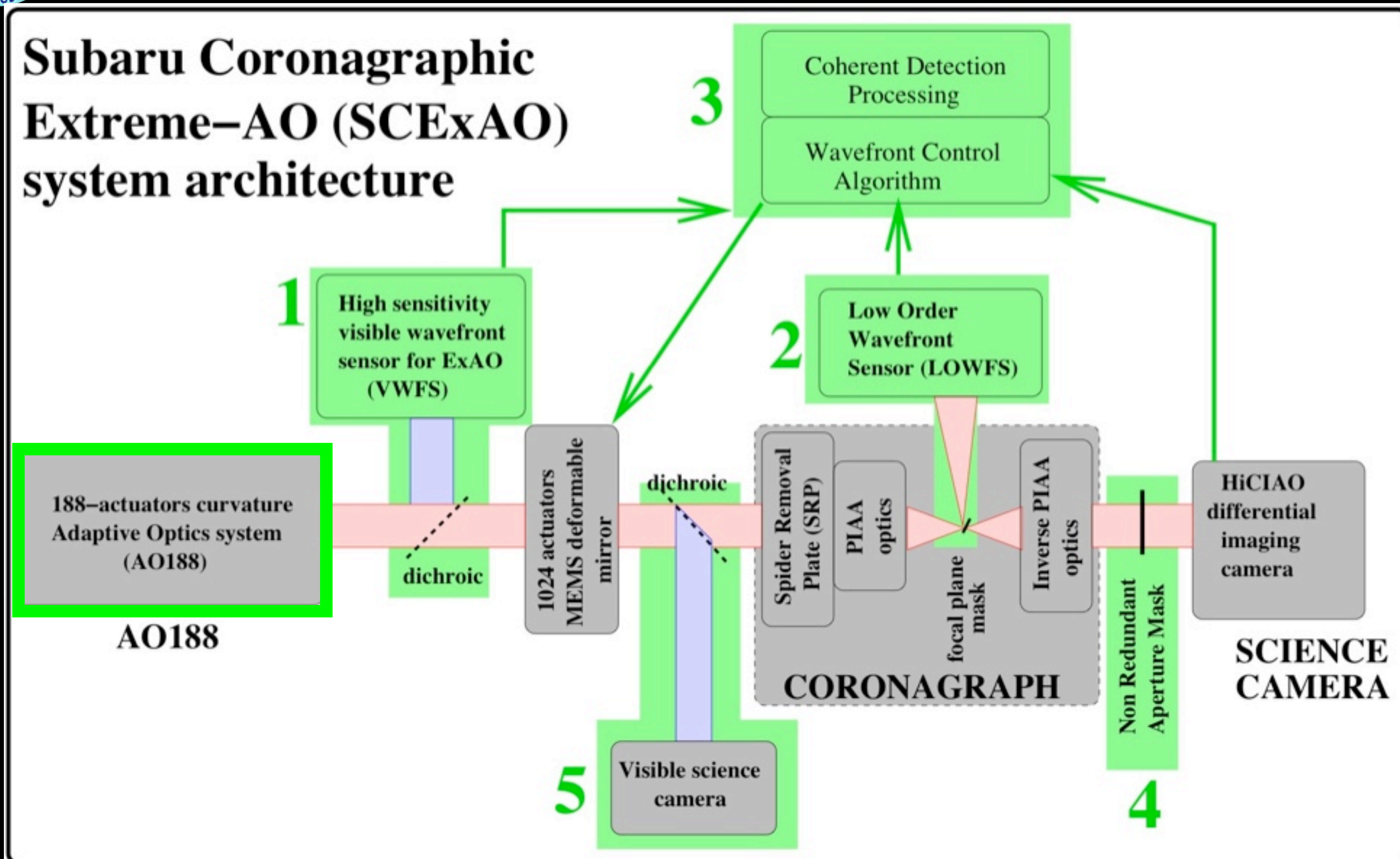
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

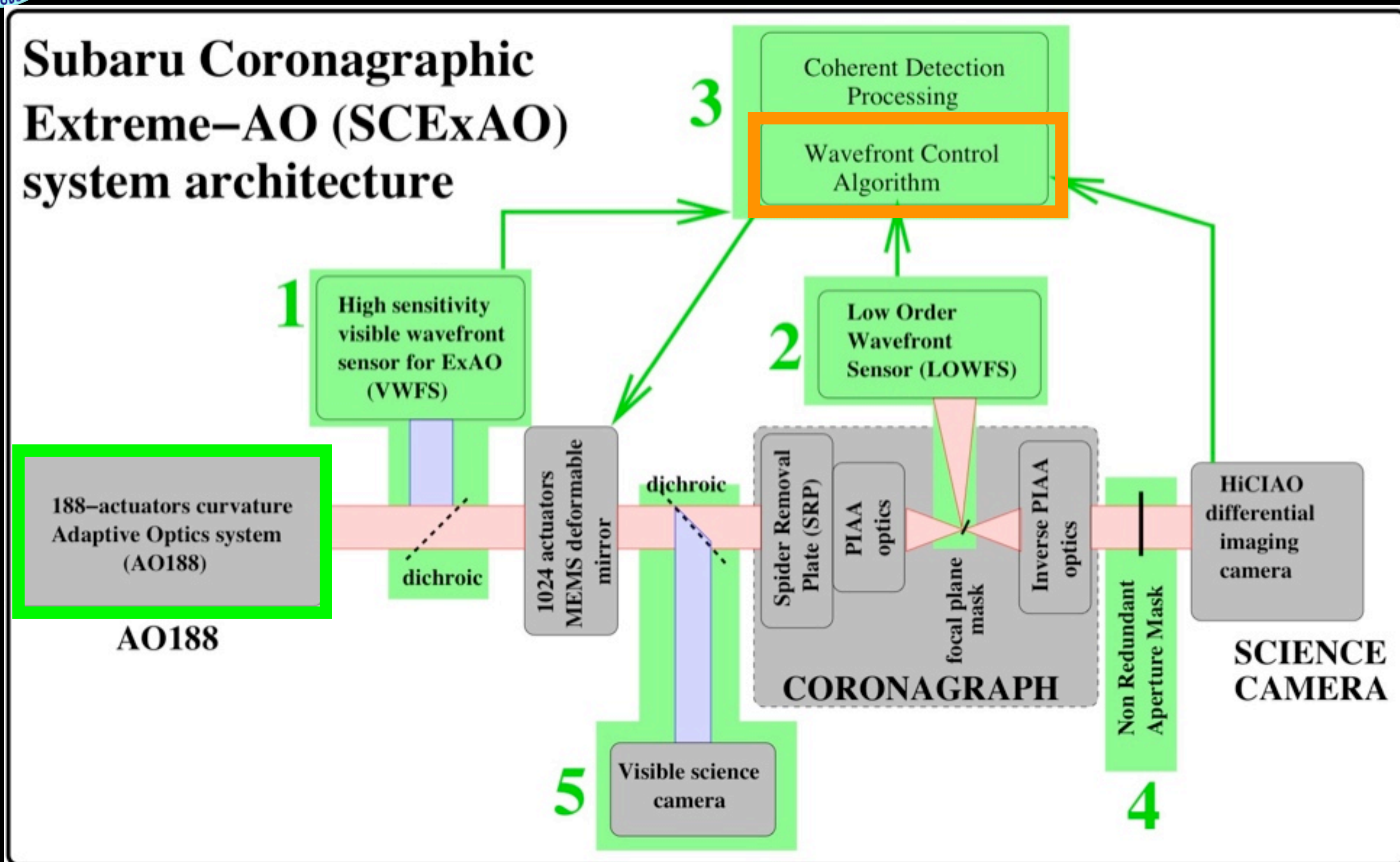
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

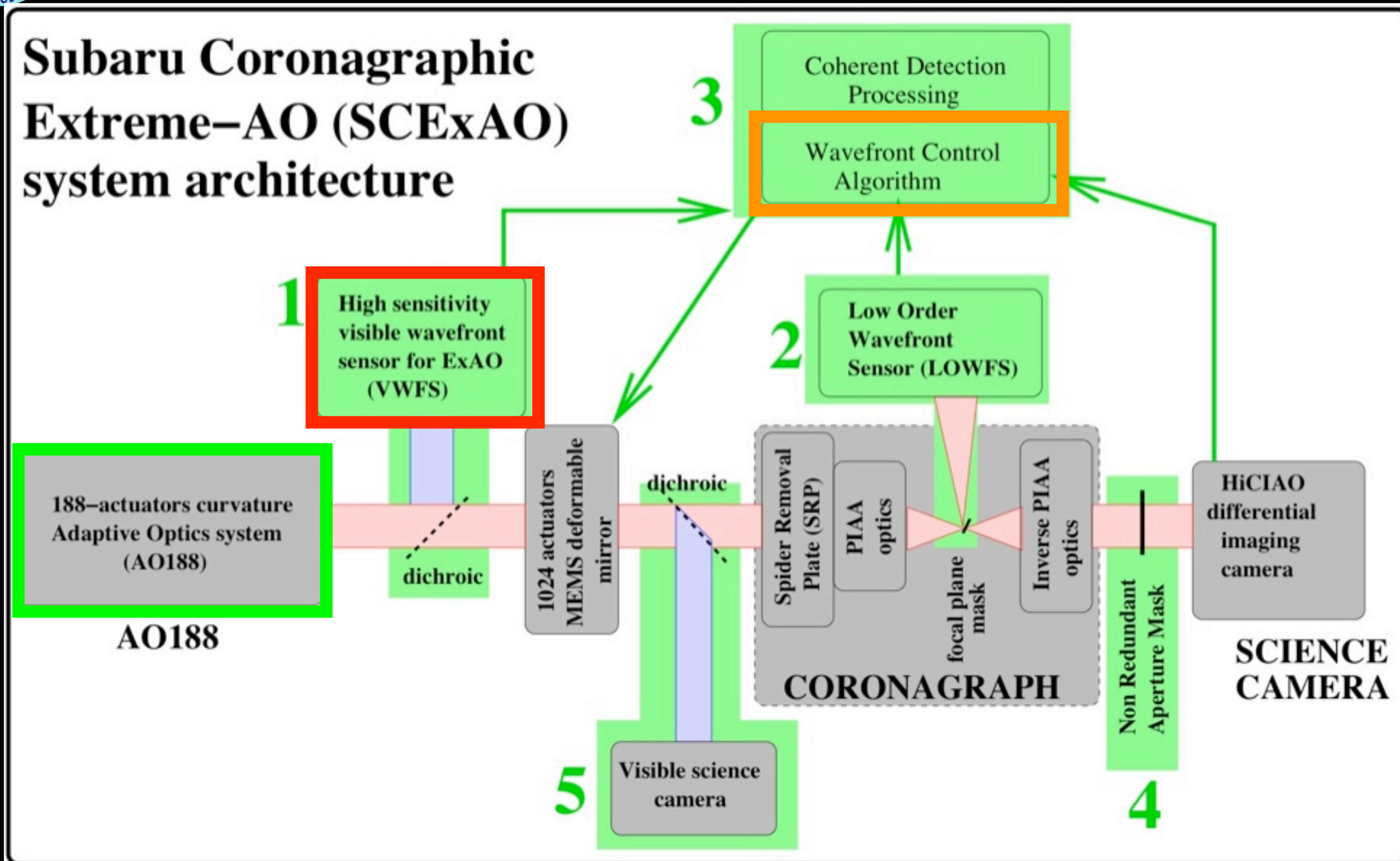
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

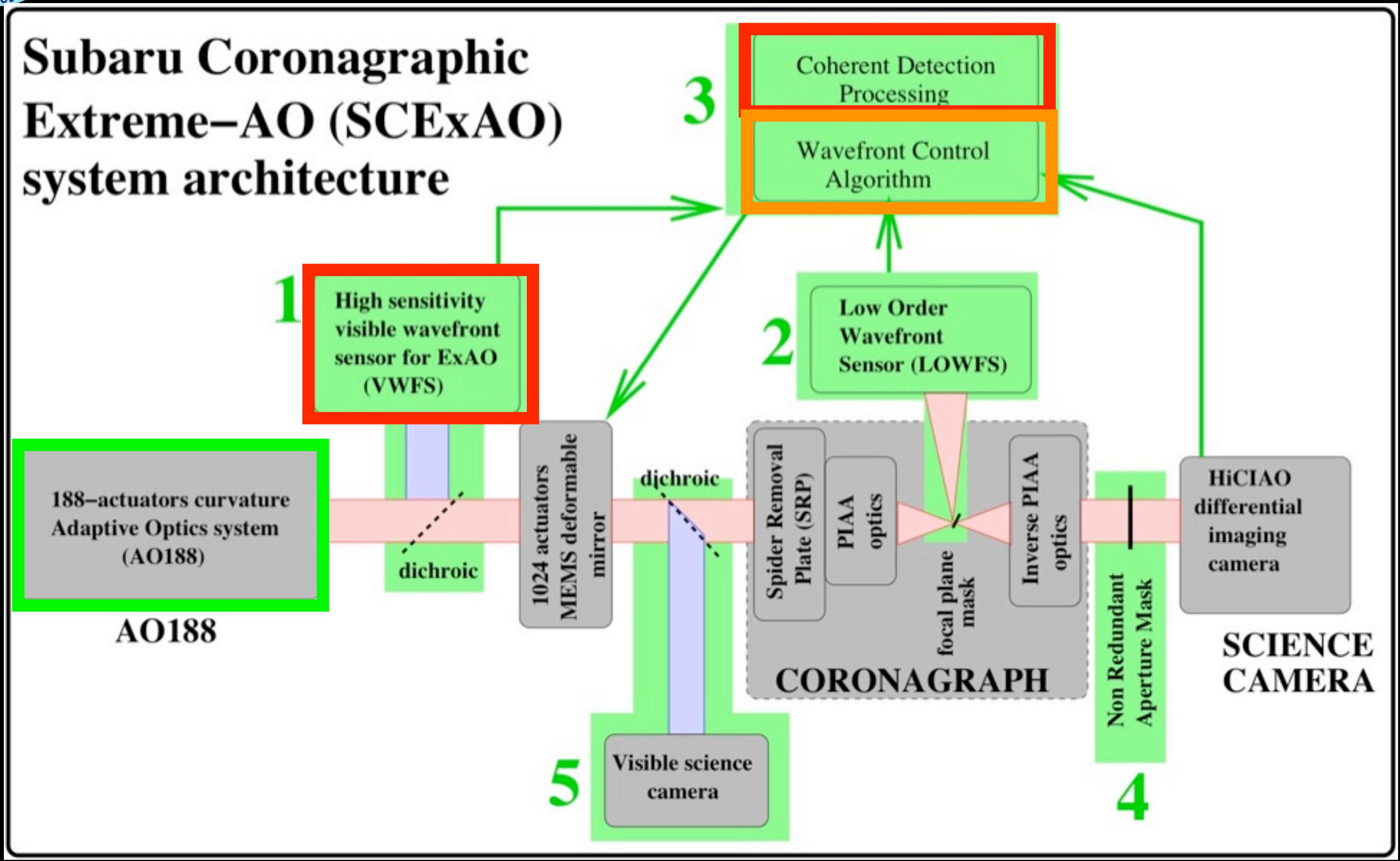
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

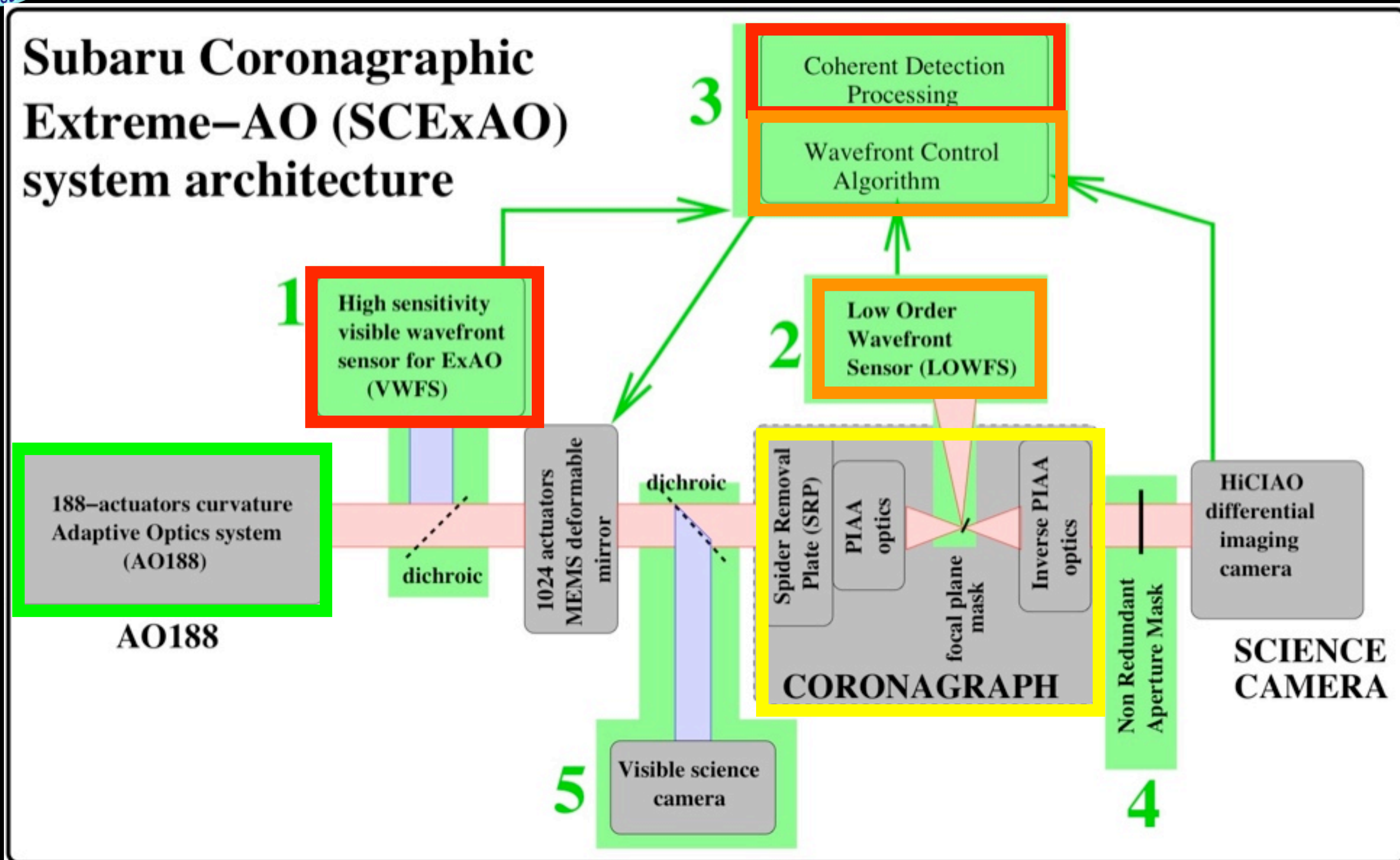
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

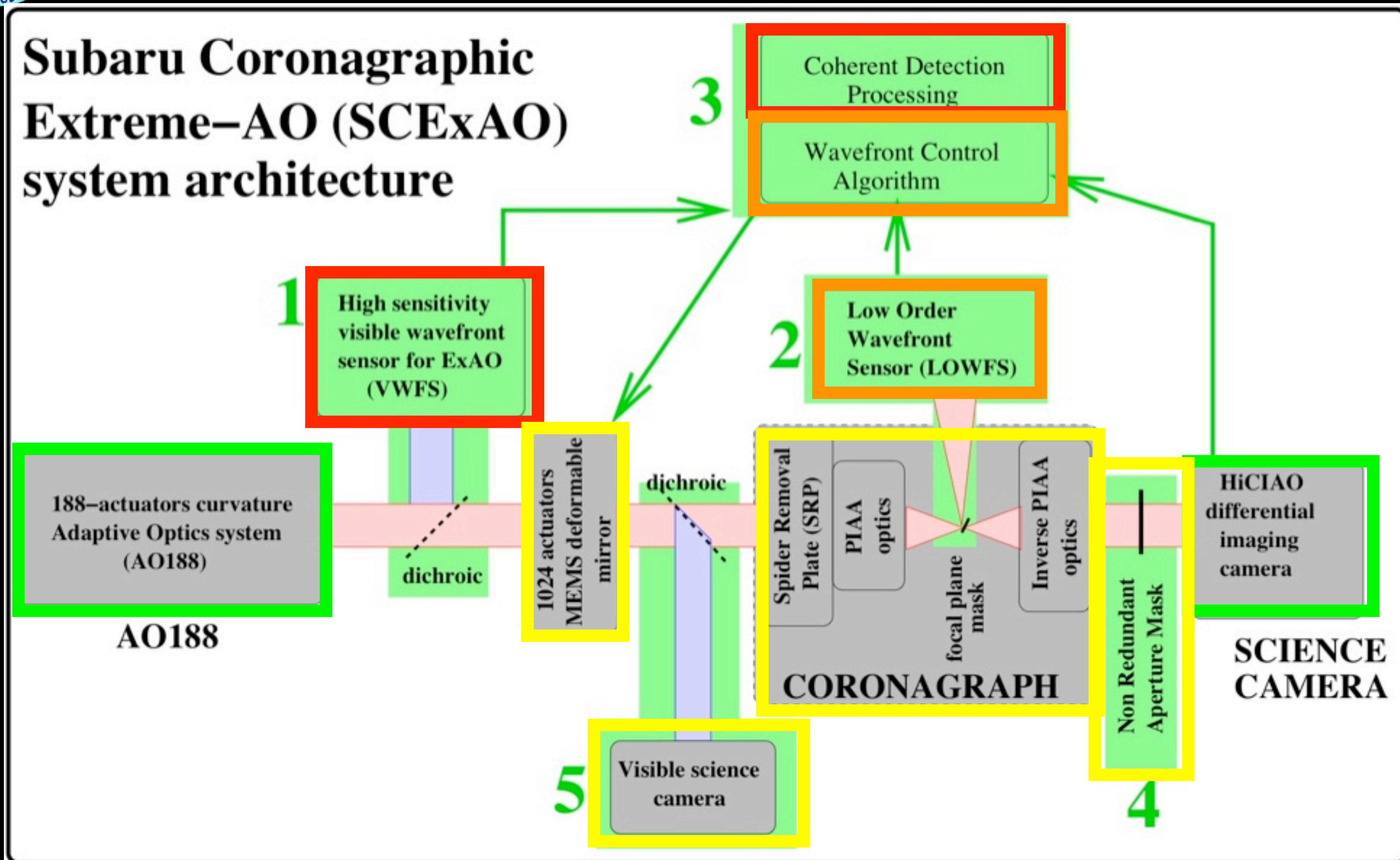
System architecture



Designed as a highly flexible, evolvable platform

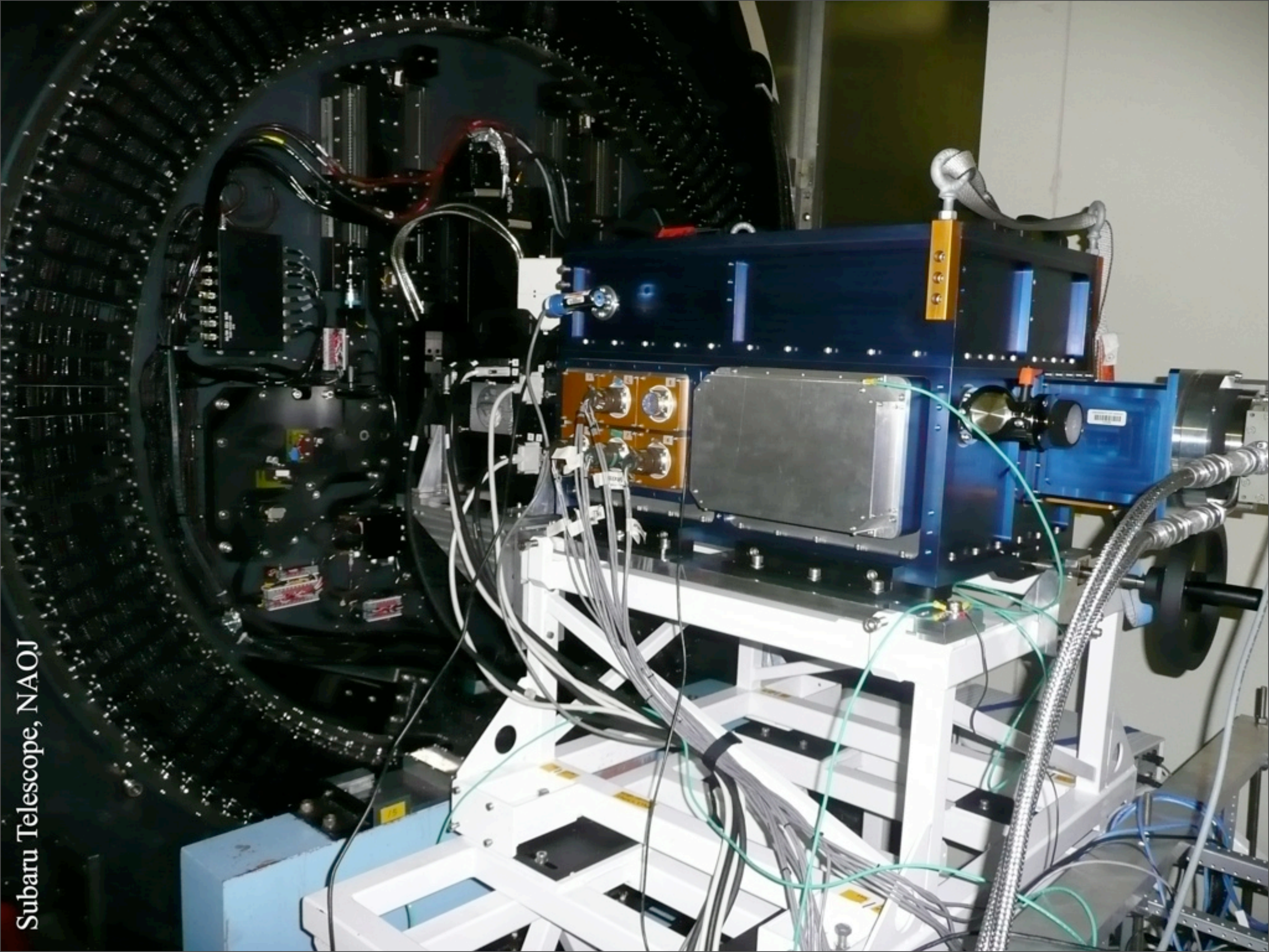
Efficient use of AO188 system & HiCIAO camera

System architecture

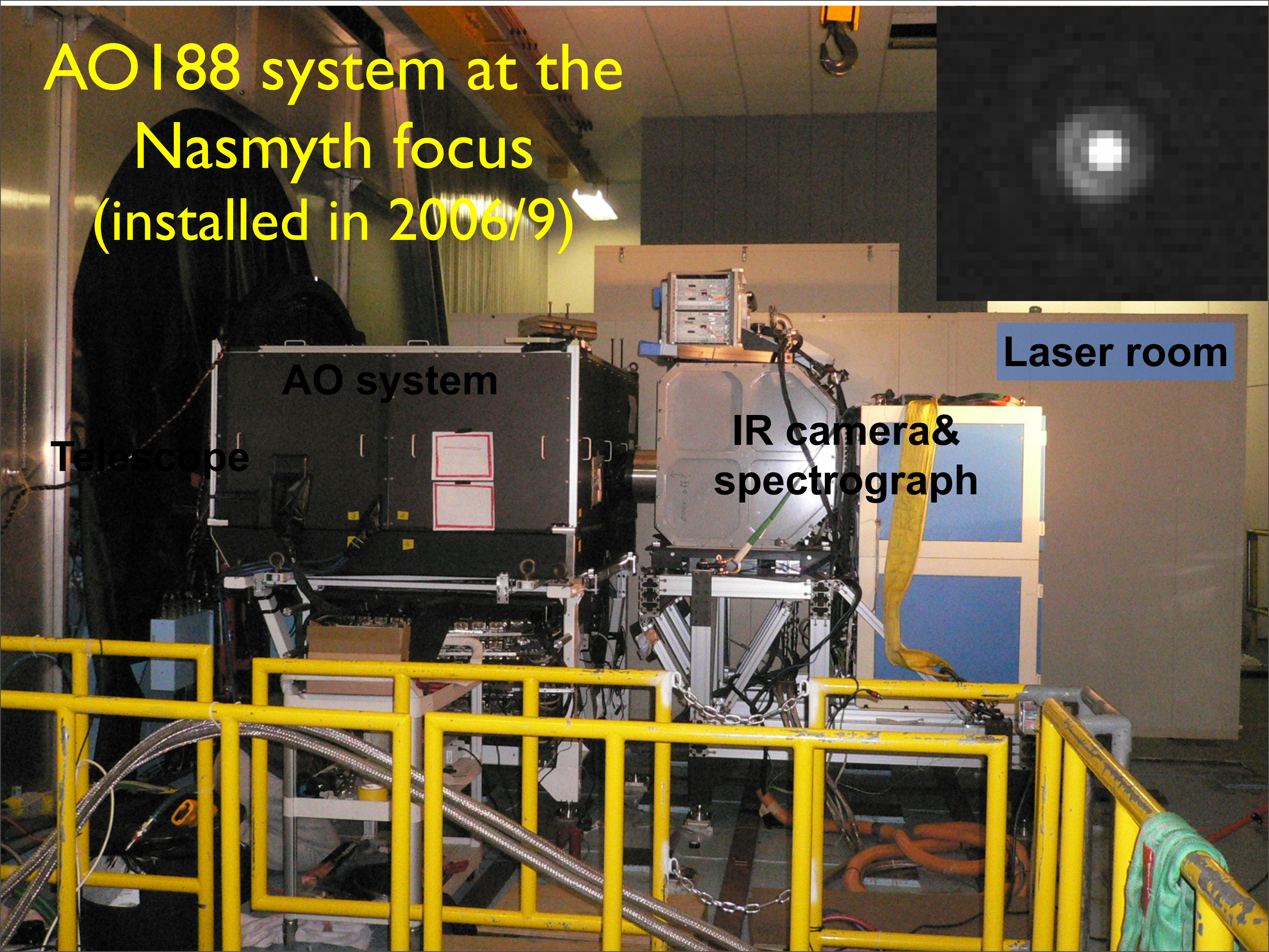


Designed as a highly flexible, evolvable platform

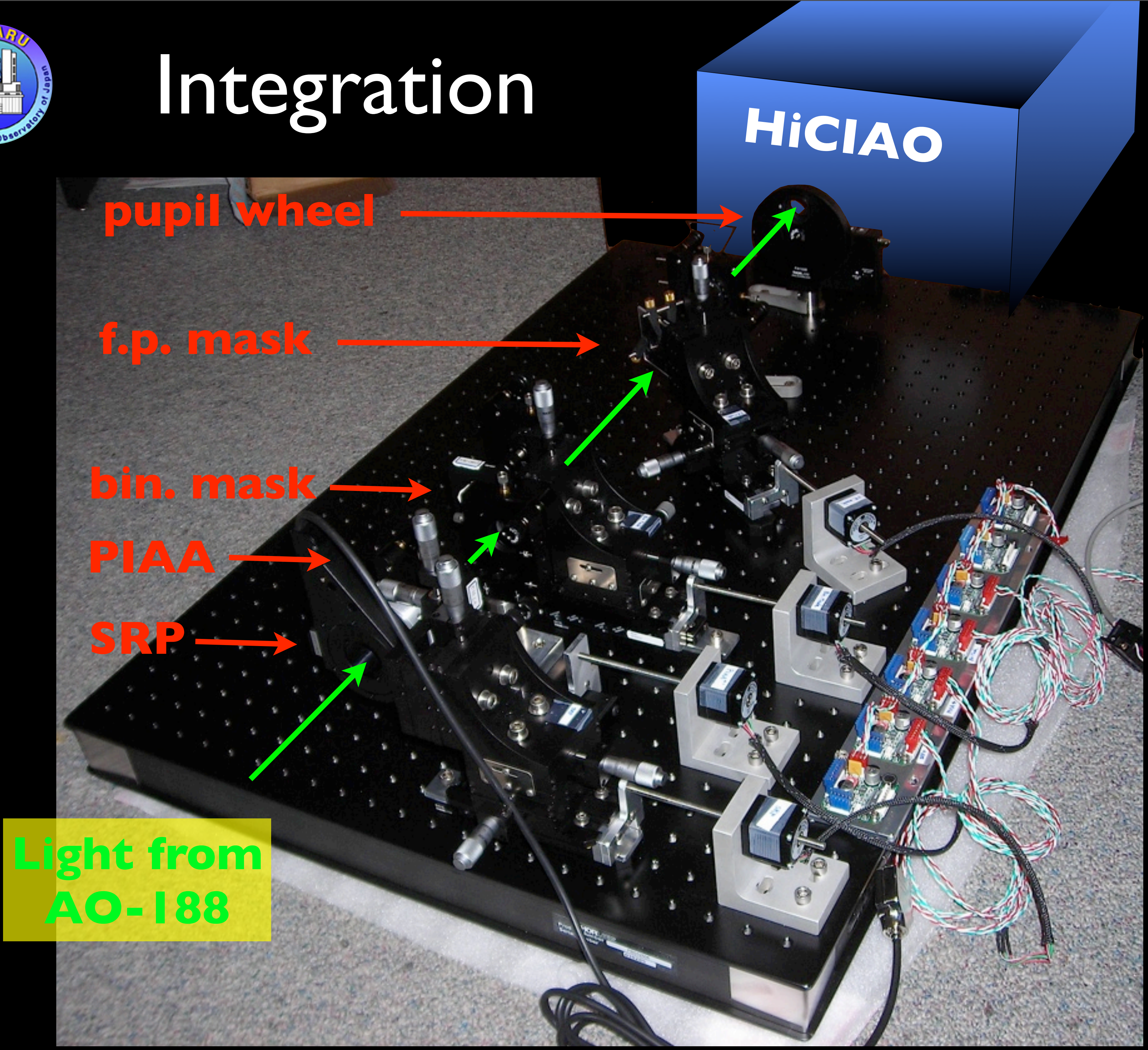
Efficient use of AO188 system & HiCIAO camera


Subaru Telescope, NAOJ

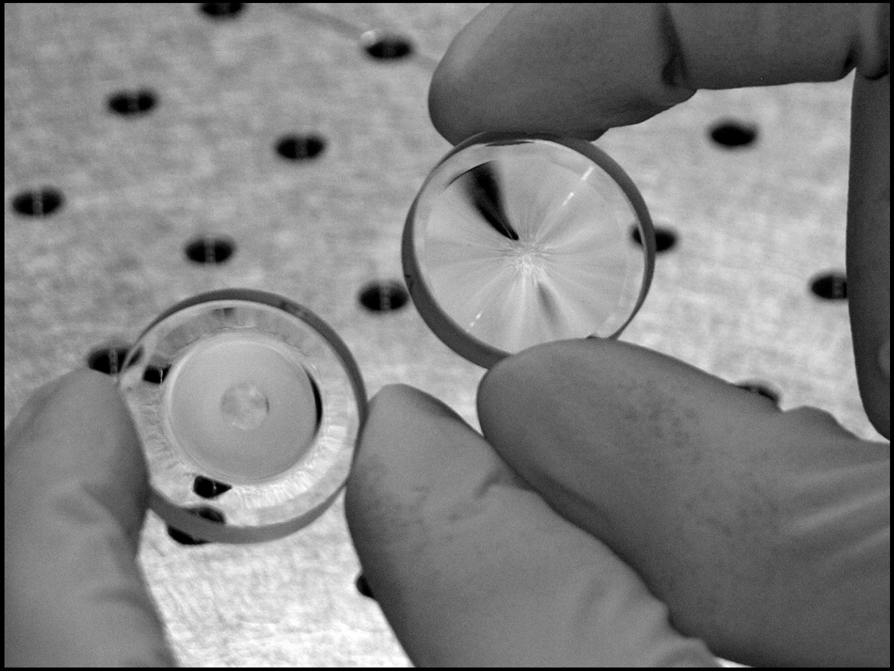
AO188 system at the Nasmyth focus (installed in 2006/9)



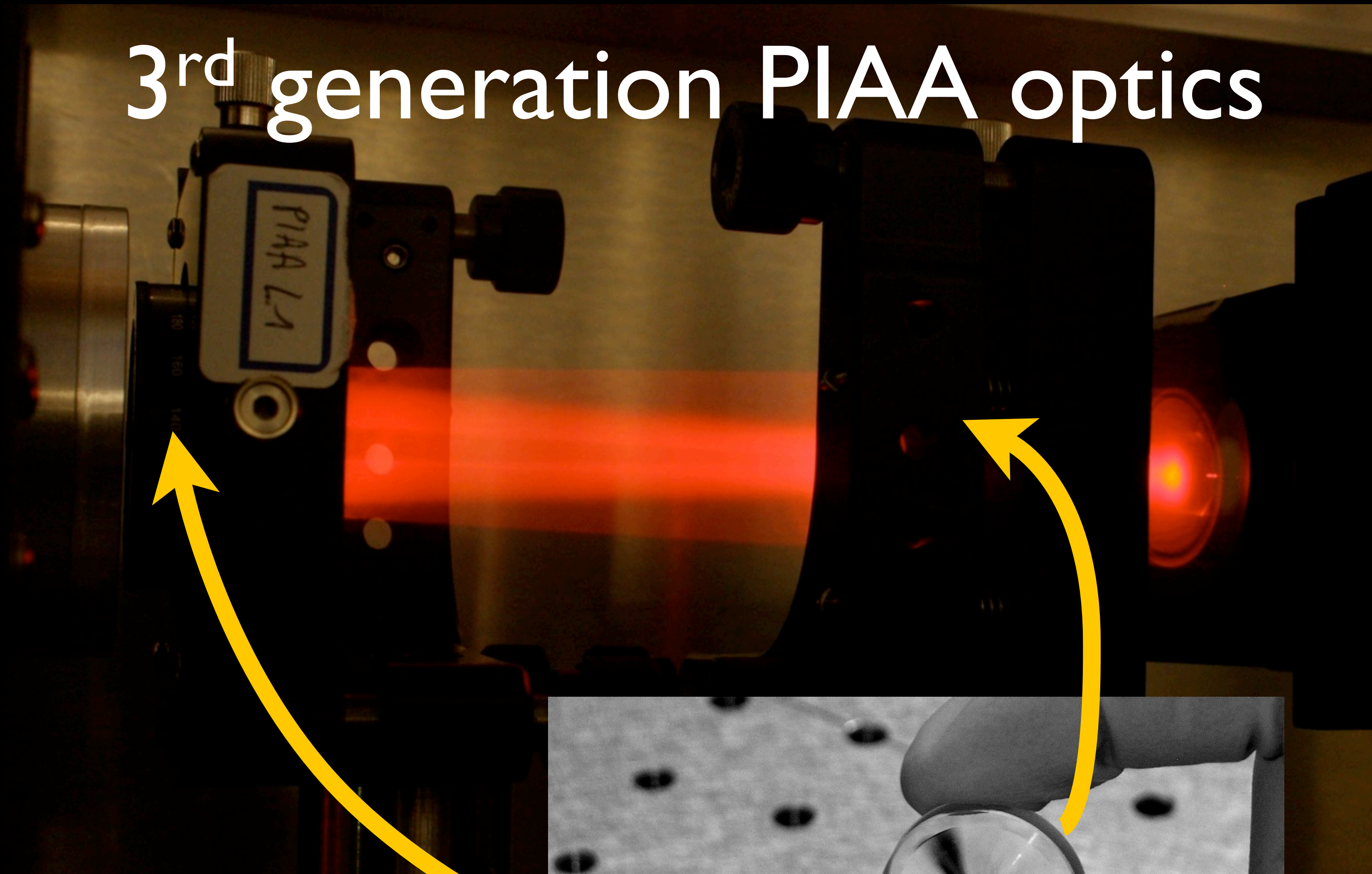
Integration

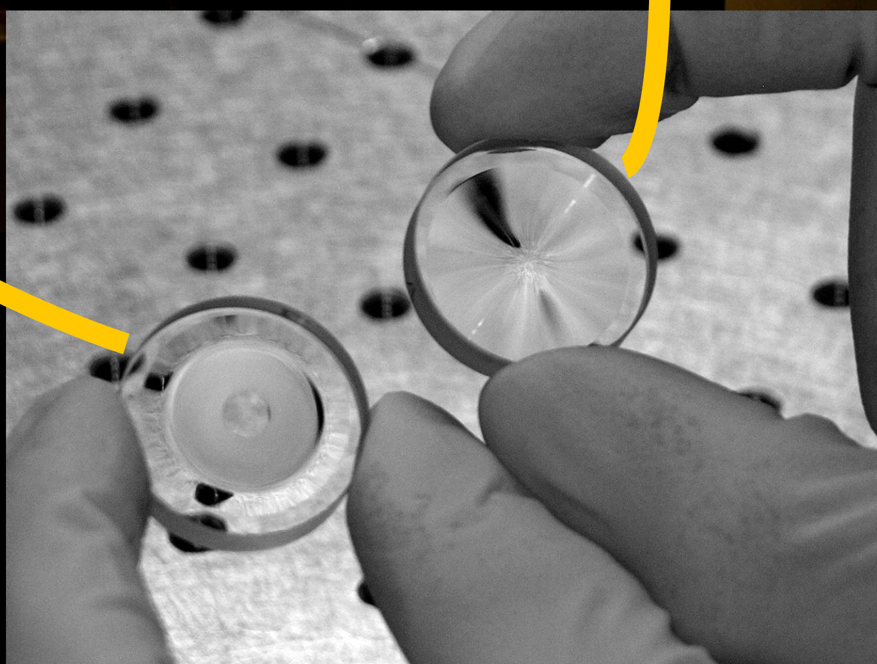


3rd generation PIAA optics



3rd generation PIAA optics

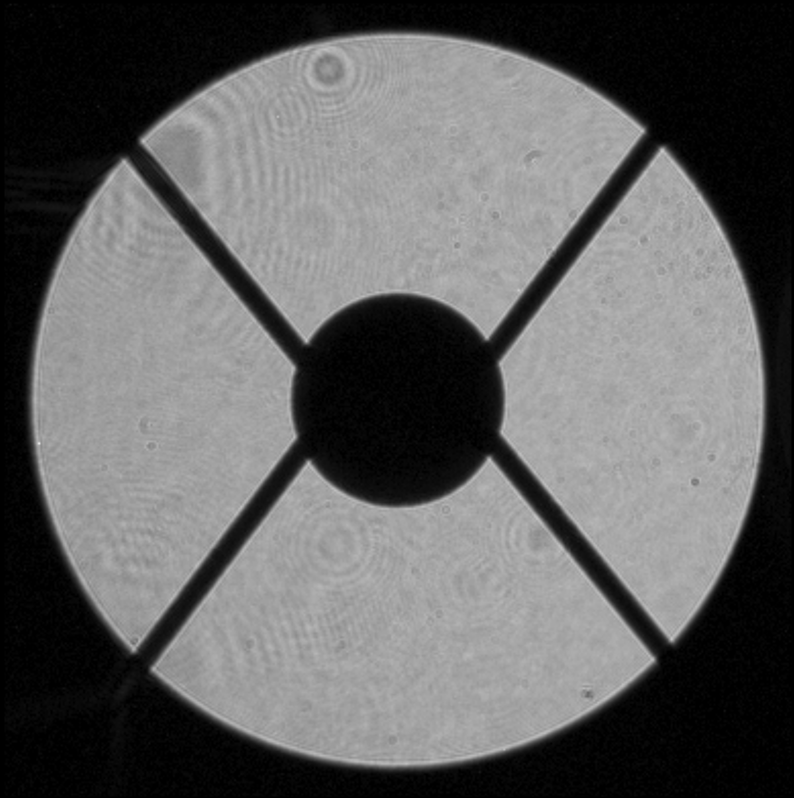




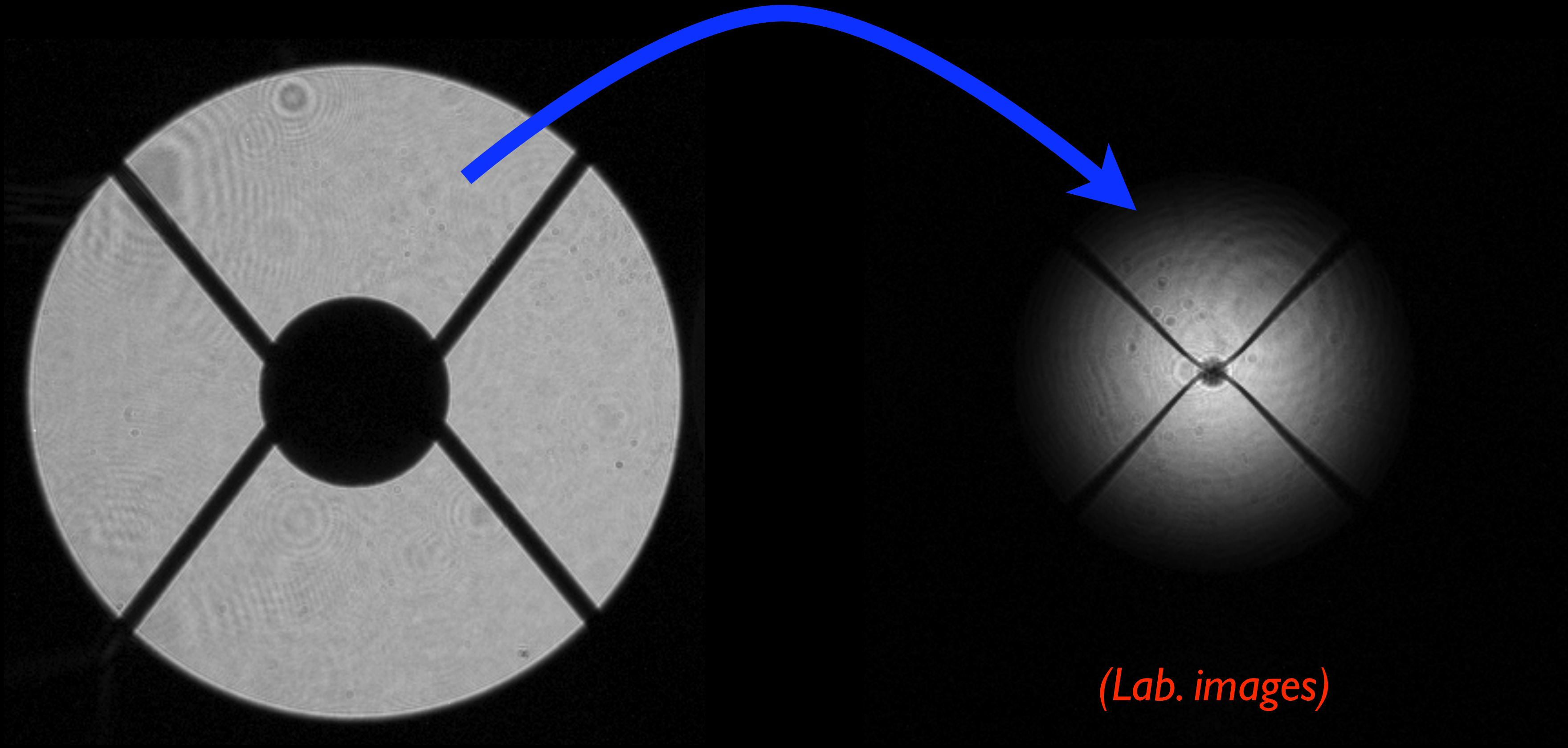
- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Optics tested, and good to go!

Apodized beam



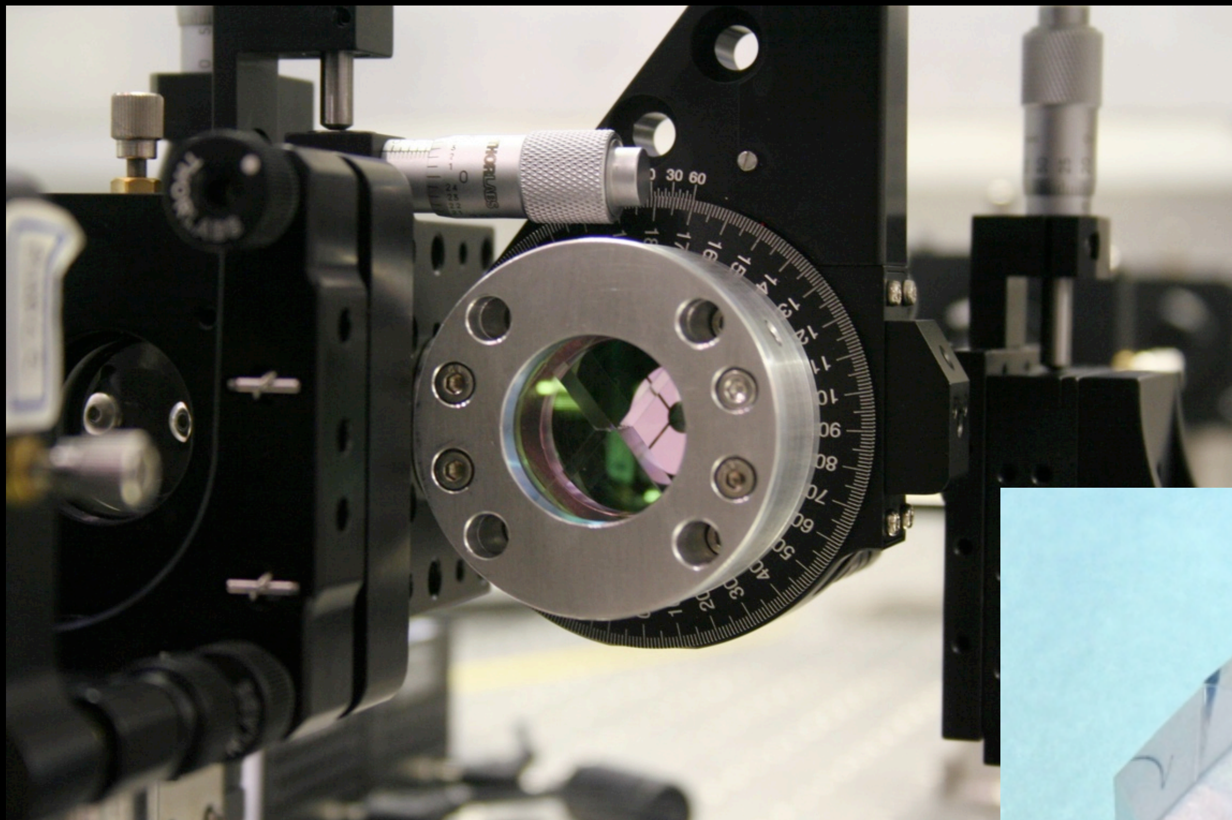
Apodized beam

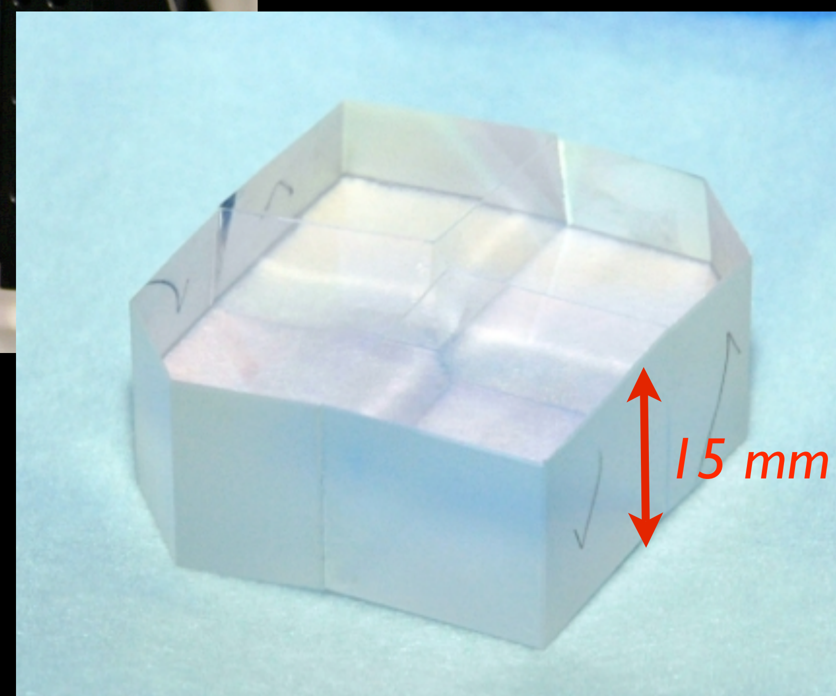


(Lab. images)

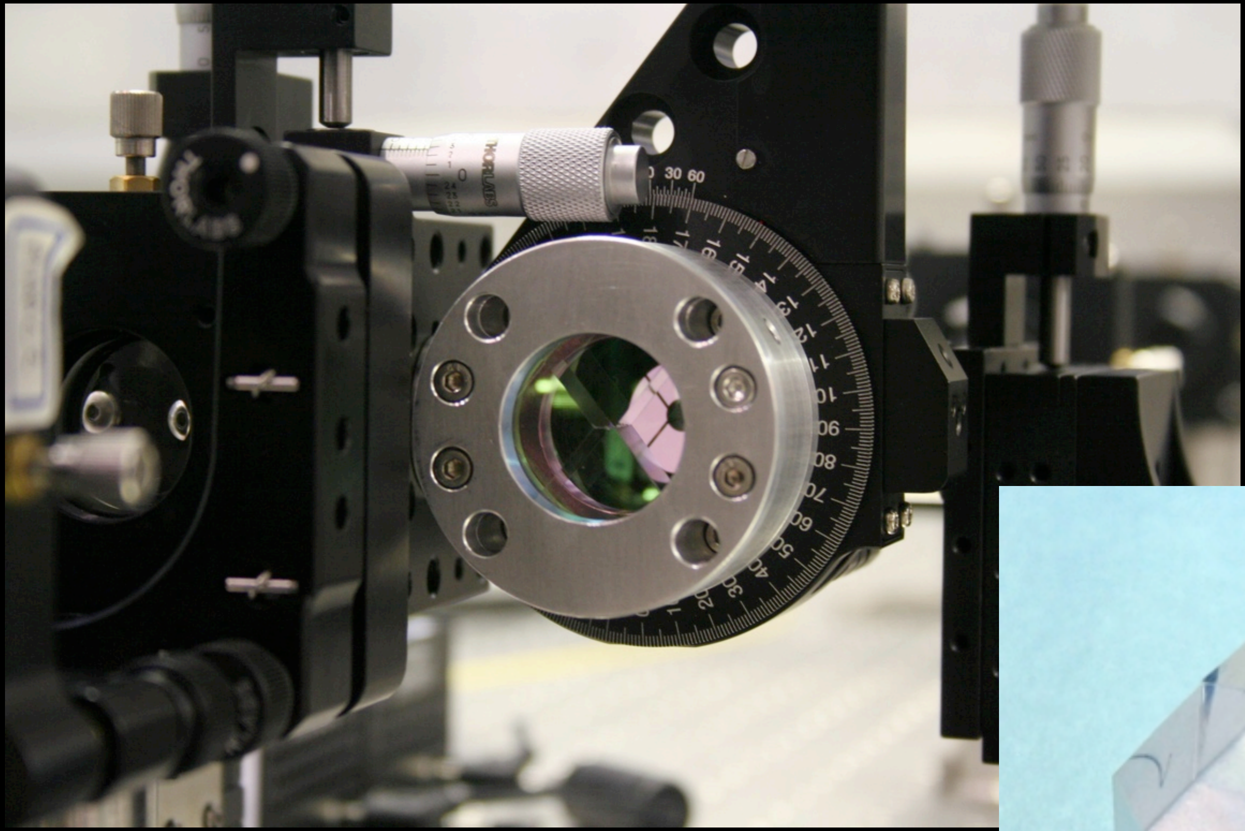
The PIAA does its job but spider vanes remain...

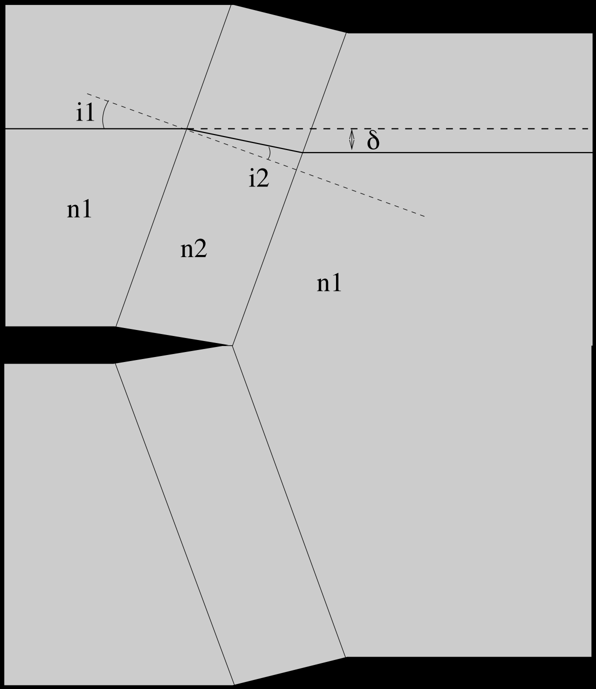
Spider Removal Plate

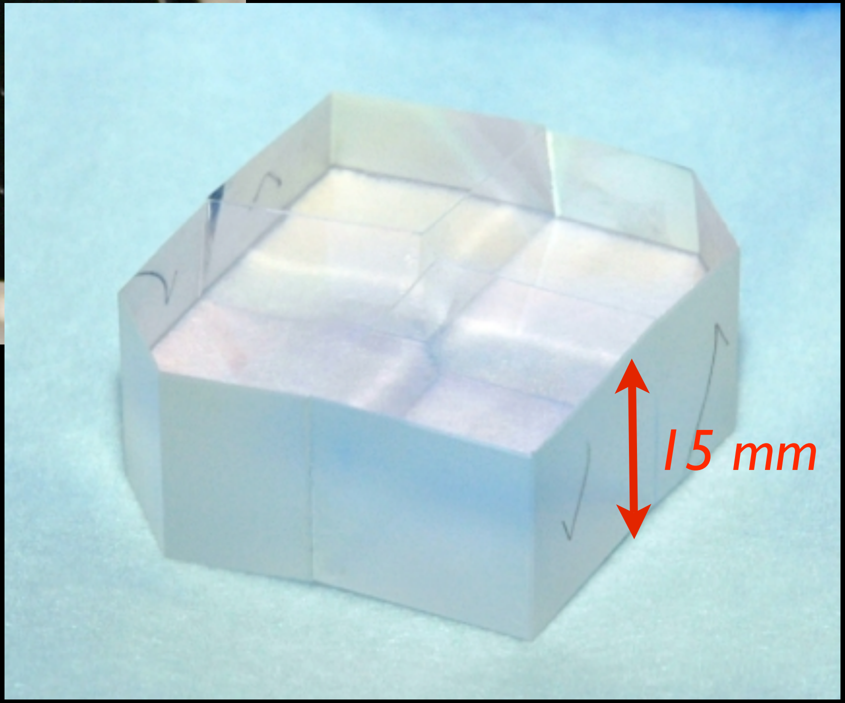




Spider Removal Plate







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

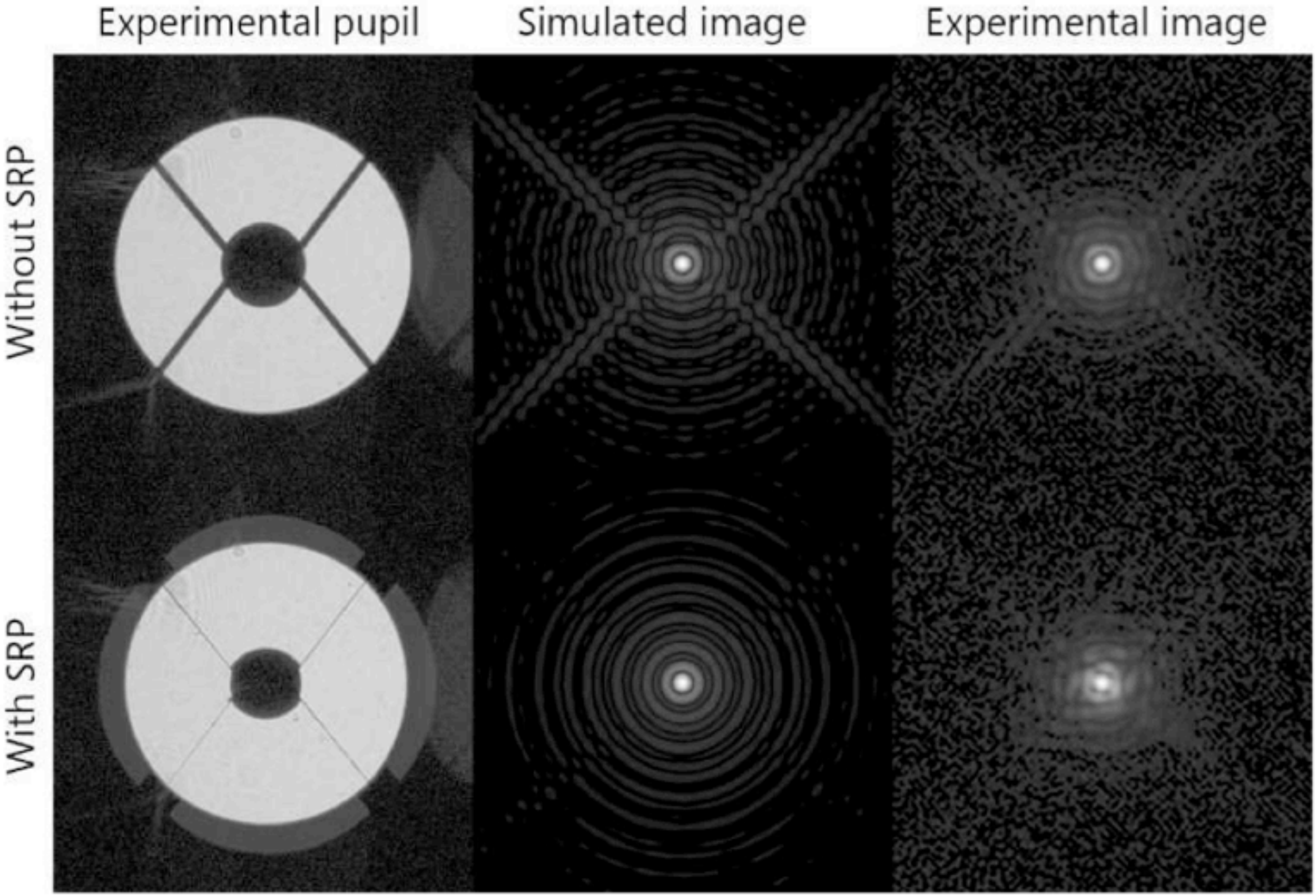
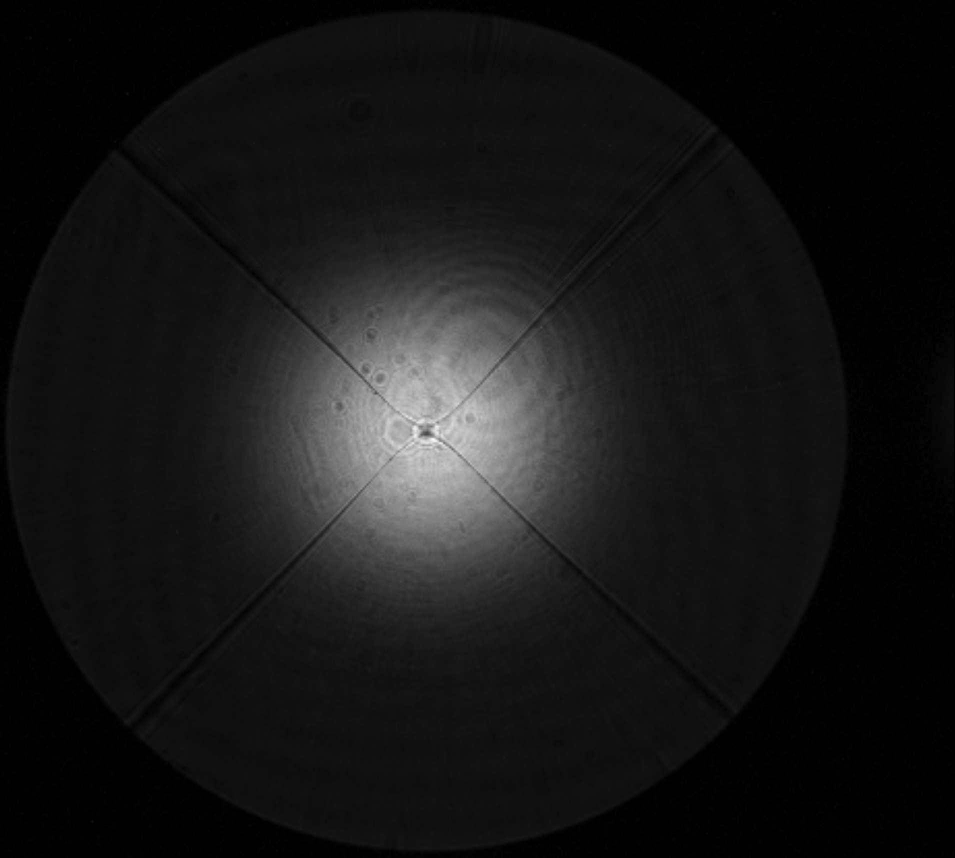


Fig. 8.— Effect of the SRP on the pupil. The three top panels show (from left to right): an image taken with the camera in a location conjugated with the pupil plane, showing the mask simulating the Subaru telescope pupil, as well as the corresponding simulated and experimental images. The three bottom panels show the same images when the SRP is inserted into the beam (cf. Sec. 3.3 for details).

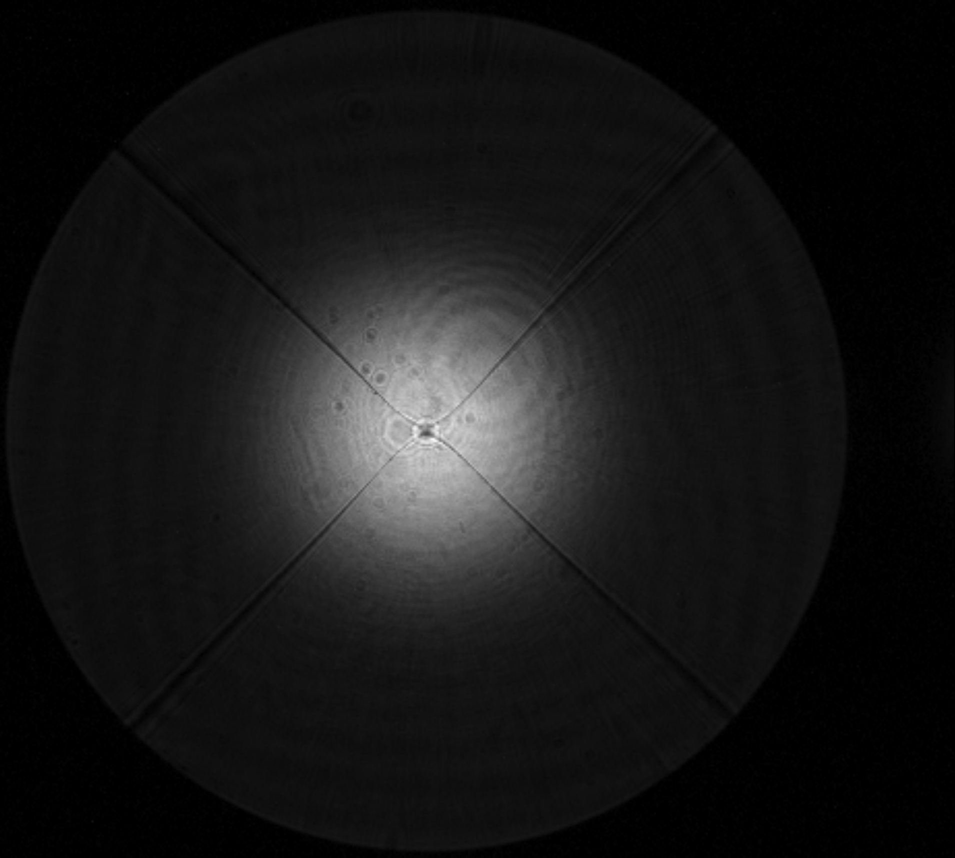
Putting things together: SRP+PIAA

Putting things together: SRP+PIAA



(Lab. image)

Putting things together: SRP+PIAA



(Lab. image)

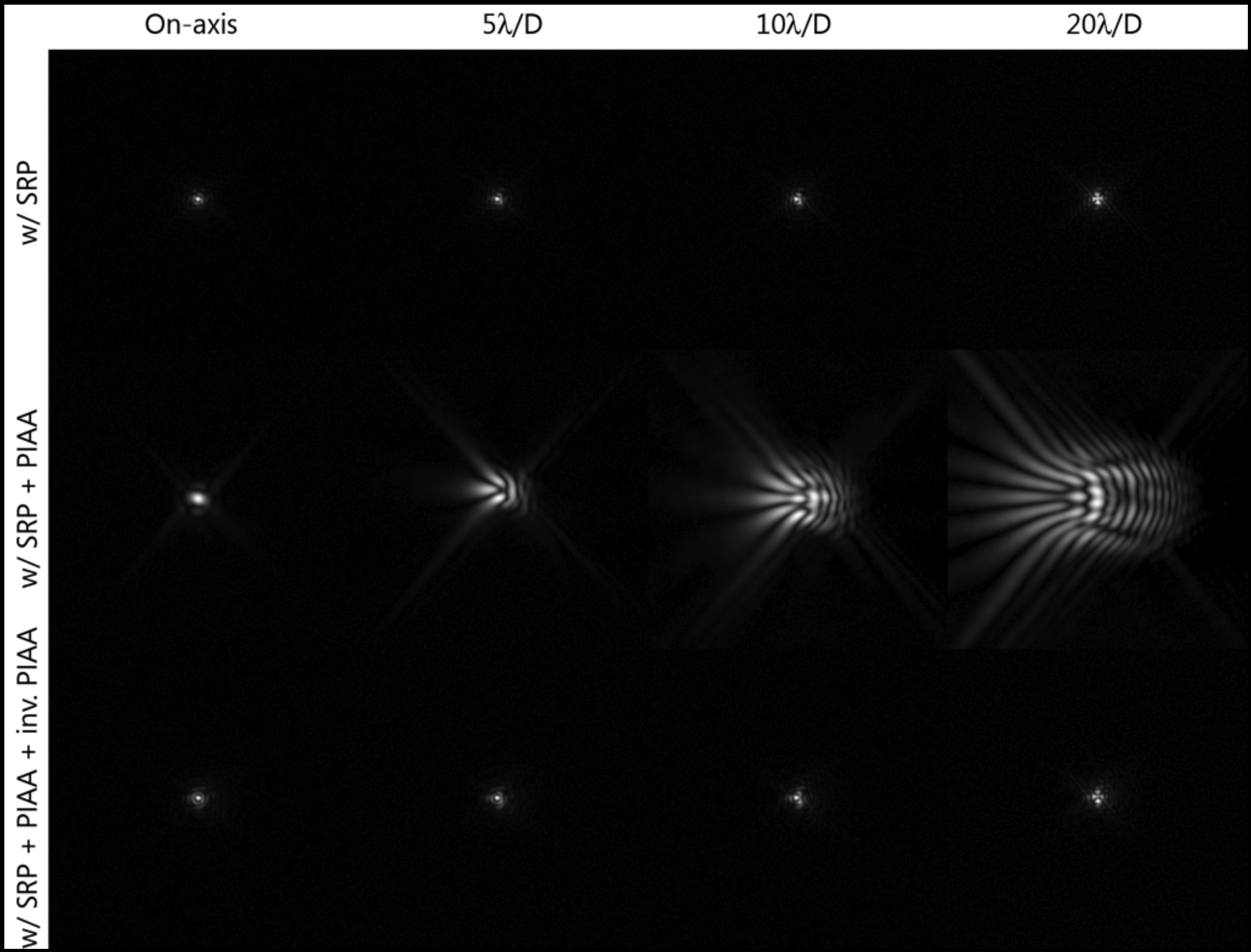
✓ Spider vanes gone

✓ Cent. obscur. gone

✓ Pupil apodized

-> coronagraphy with no losses with with inner working angle = 1 lambda/D

Recover the Field of view with "inverse PIAA" optics



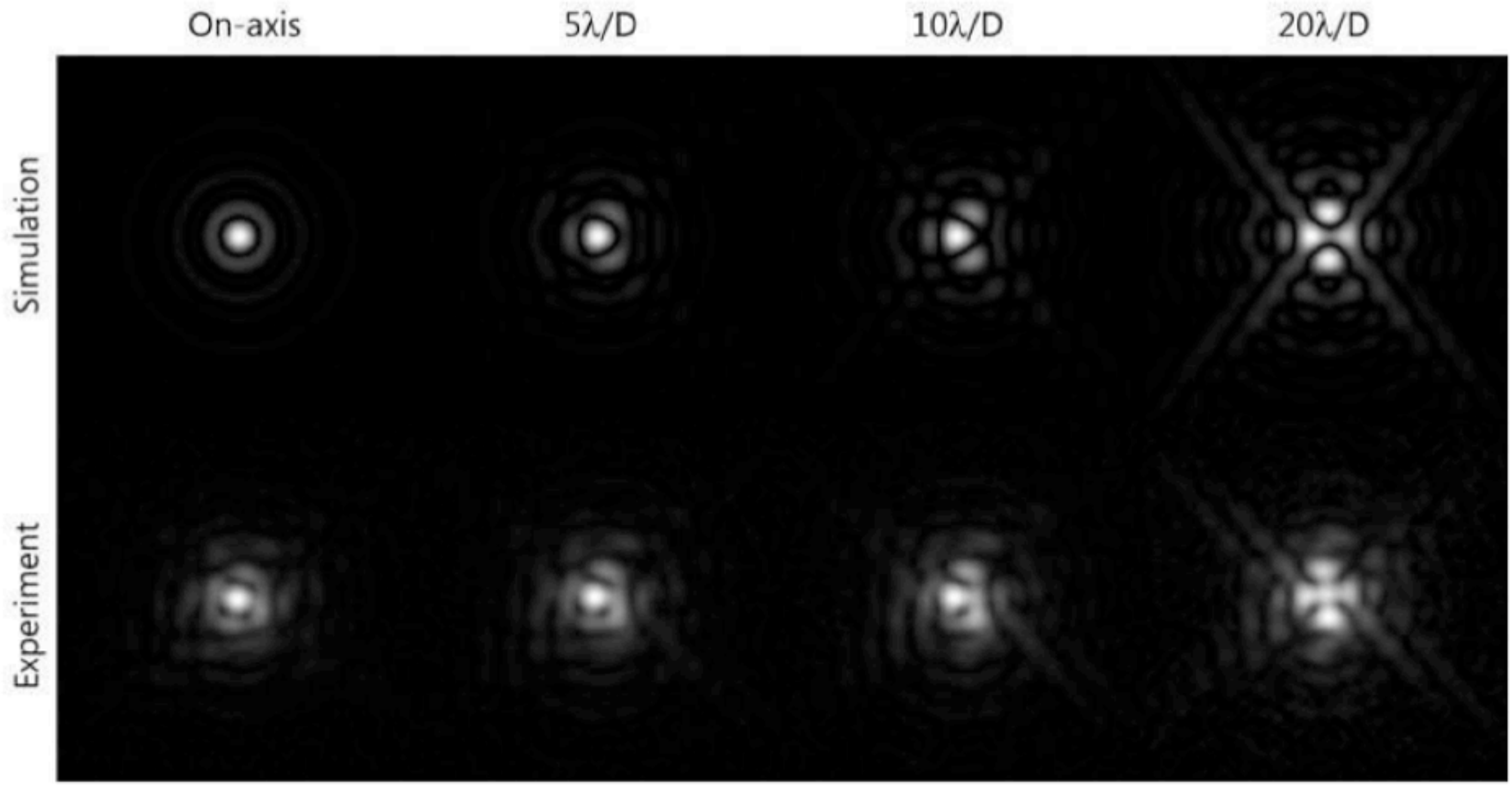
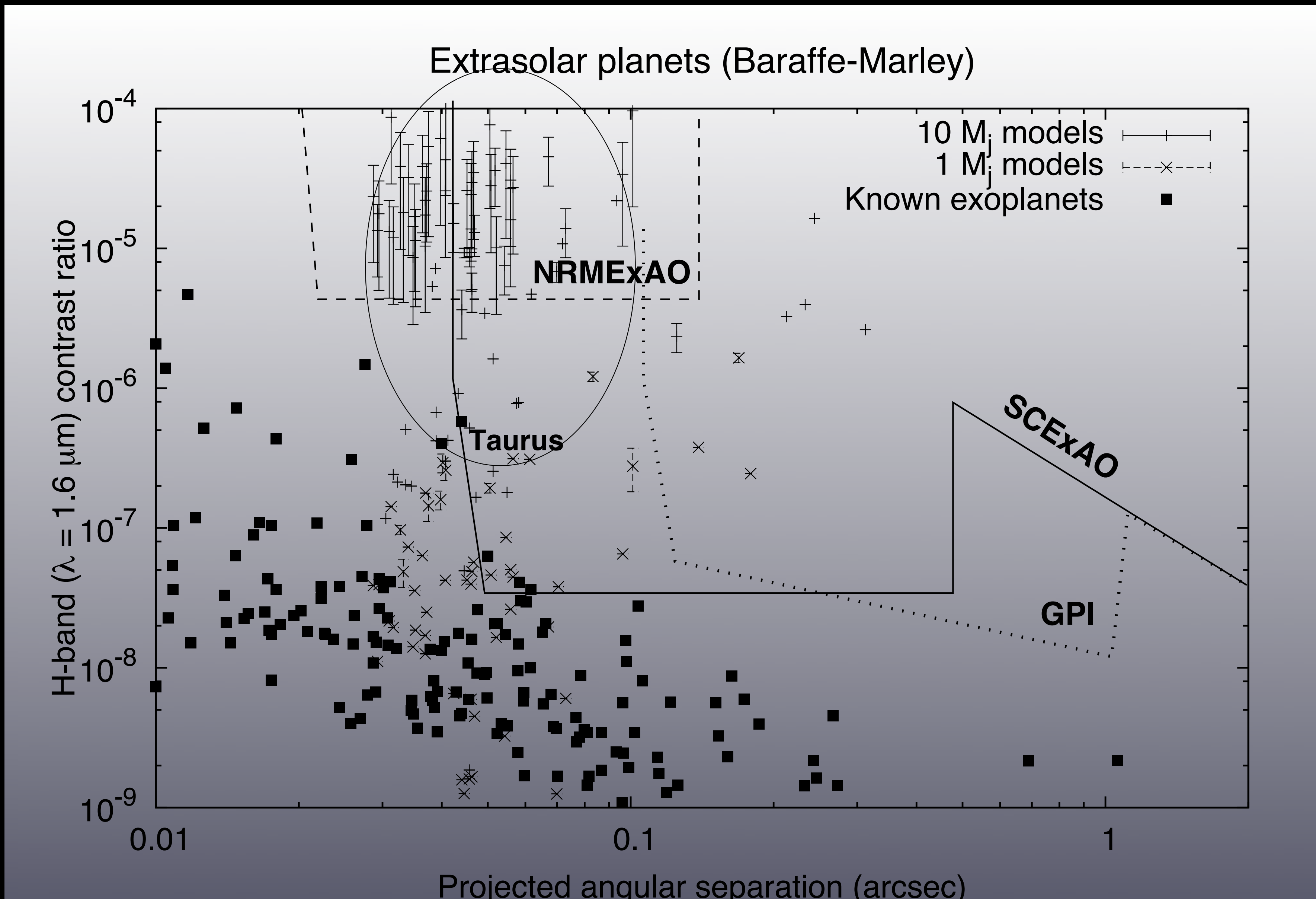


Fig. 12.— Comparison between simulated and experimental images of an off-axis source, from 0 to 20 λ/D with a 5 λ/D step. The field of view of each image is $\pm 12\lambda/D$.

Expected performance?

Expected performance?



High contrast imaging on GMT

Instrument strategy

- Make optimal use of subsystems available at the GMT (deformable secondary mirror, facility WFS)

- Initially adopt technologies & components which are already proven and does not require technology development. Resist temptation to be “too greedy” in order to secure the most accessible science
    - ang resol (# target goes as D^3)
    - flux -> play games in speckles vs. planets, contrast boost

- Adopt a modular streamlined instrument design which is initially quite simple but can later be expanded for higher performance. Subcomponents can also serve other instruments (example: WFS can be shared with TIGER)

This approach can bring ExAO science to GMT with a first-generation instrument at moderate cost (~$10M), and is sufficiently flexible to evolve both in performance (for example contrast) and capability (for example spectroscopy).

Scientific motivations

Huge scientific payoff can be obtained by using already validated technologies (on 8-m telescopes) on GMT:

- Reflected light planets accessible (down to rocky planets?)
- Planetary formation within 5 AU (constrain on planetary formation/evolution in habitable zone)
- Observation and characterization of giant planets, some known by radial velocity
- Resolve structures in circumstellar protoplanery disks and dusty debris
- TMT not planning to have first generation high contrast imaging instrument

Coronagraph options on GMT pupil

- Amplitude apodization
  low performance, but very simple. Can work with low WF quality

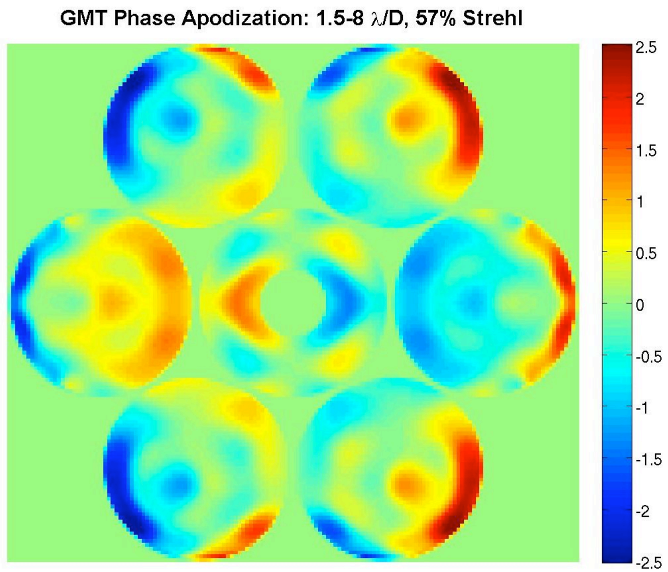
- **Phase plate apodization (Codona et al.)**
  Higher throughput than amplitude apodization. Also a low-risk option

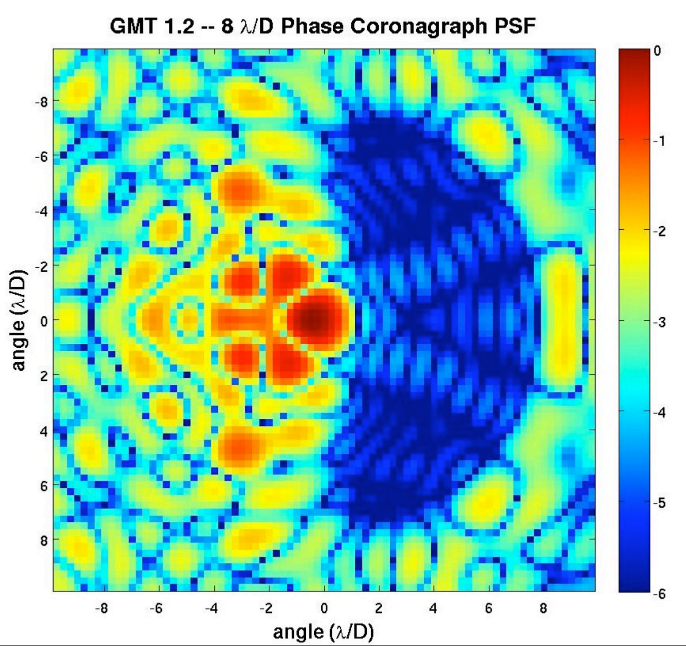
- PIAA coronagraph
  High performance & Throughput. Somewhat complicated optics.

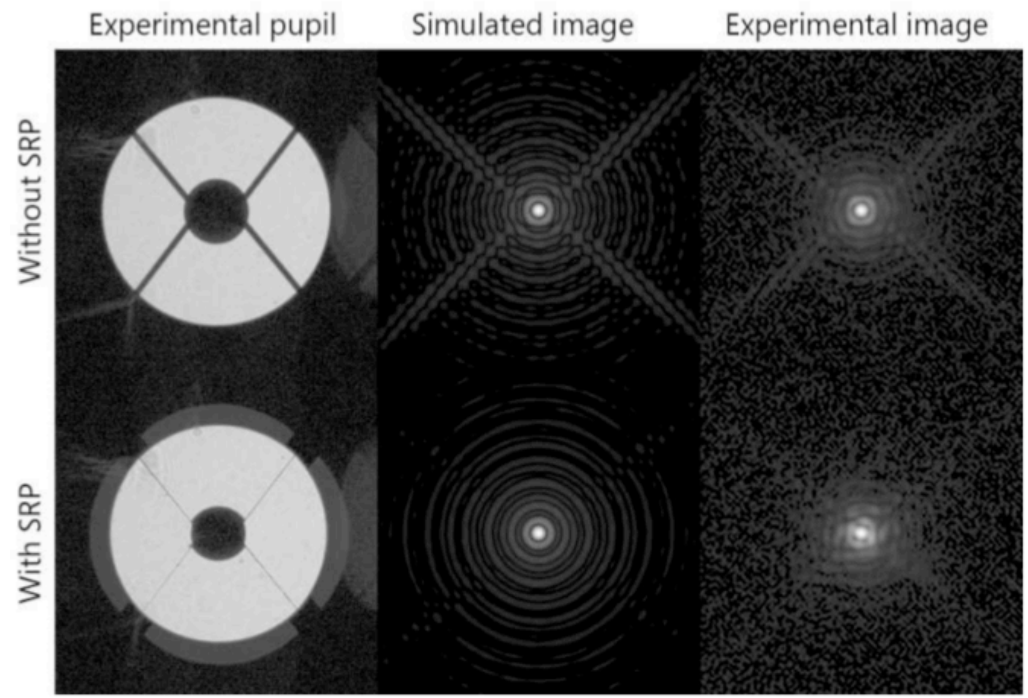
- **PIAA / Apodized Pupil Lyot hybrid coronagraph**
  Higher performance than simple PIAA. Remapping optics are simple (single set of radially symmetric lenses)

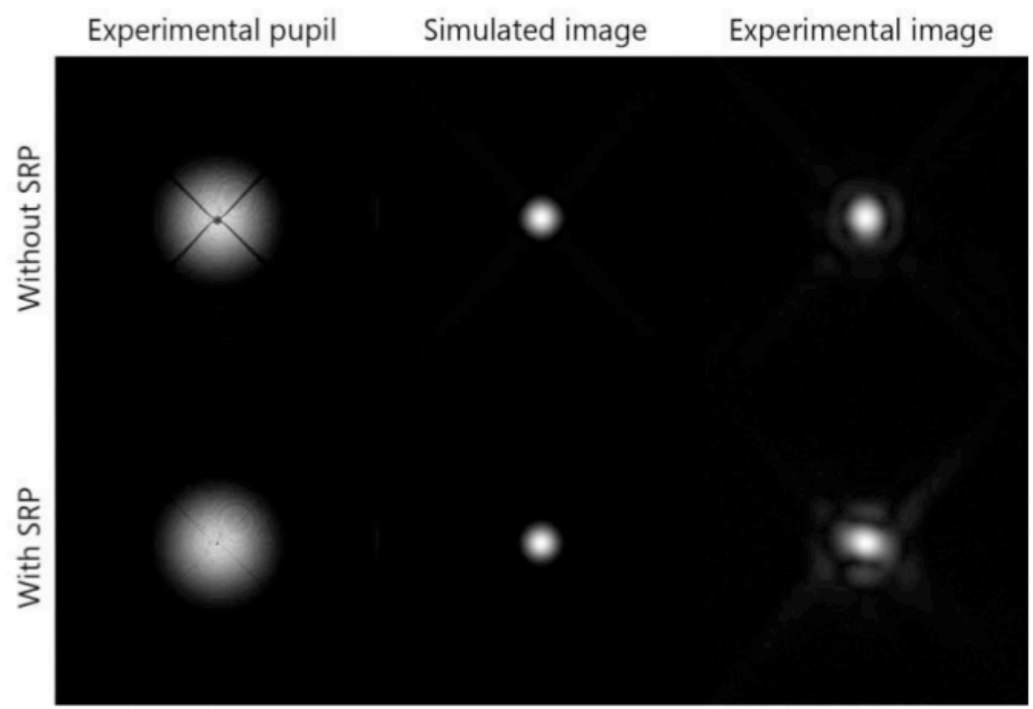
- **Nulling coronagraphs (Tolls et al.)**
  Nulling interferometer based approach. Potentially small IWA.

We know how to design coronagraphs for segmented pupils



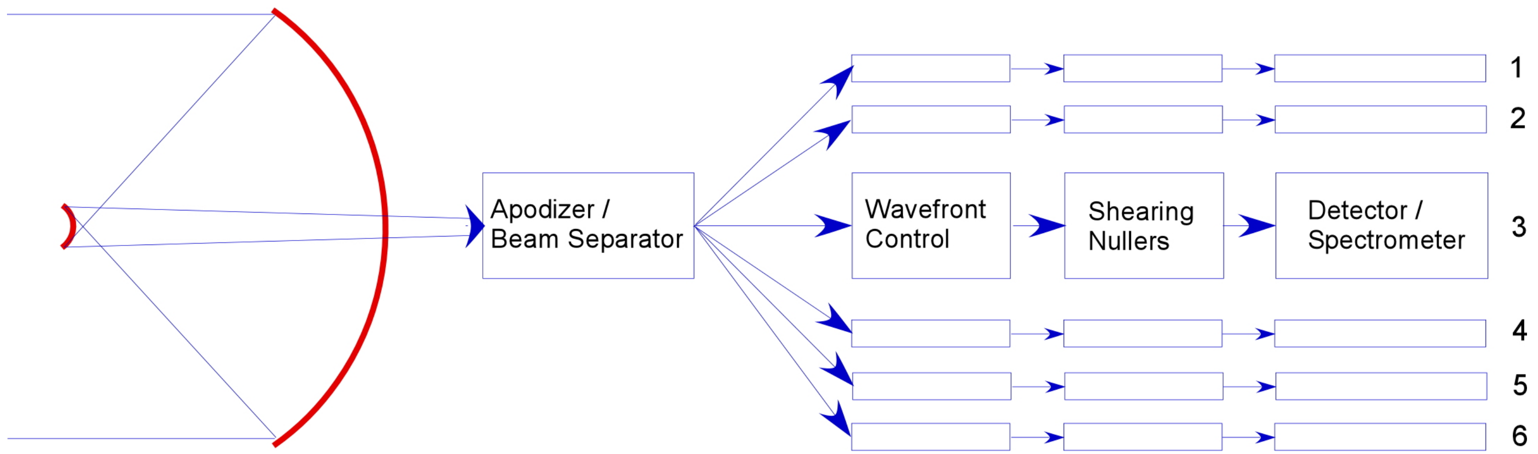




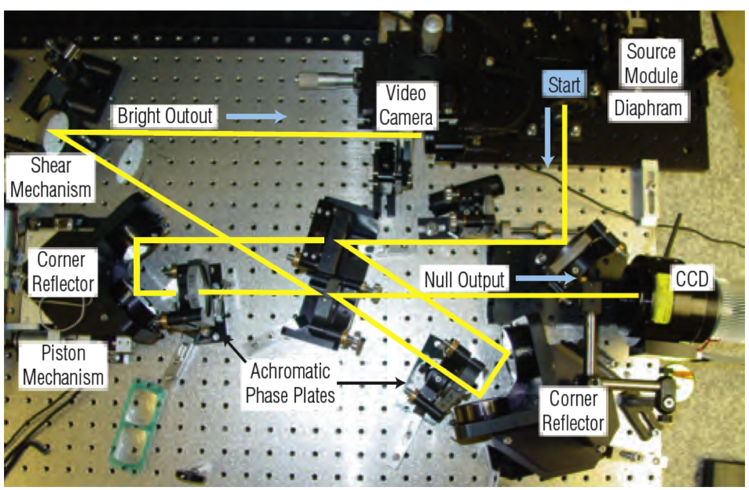


GMT Nulling Coronagraph

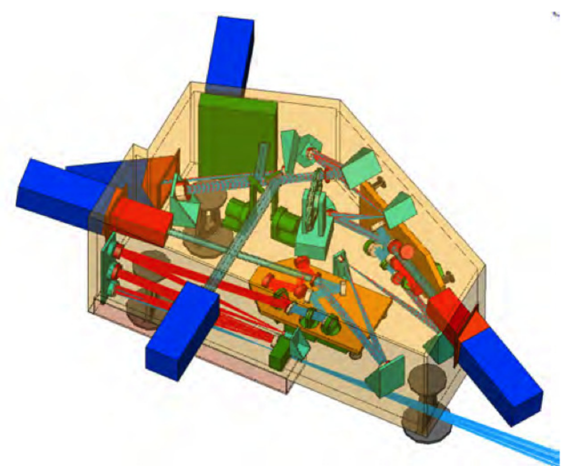
Preliminary Design Concept



Heritage from development for visible light nulling coronagraph



GSFC Laboratory Visible Nulling Coronagraph



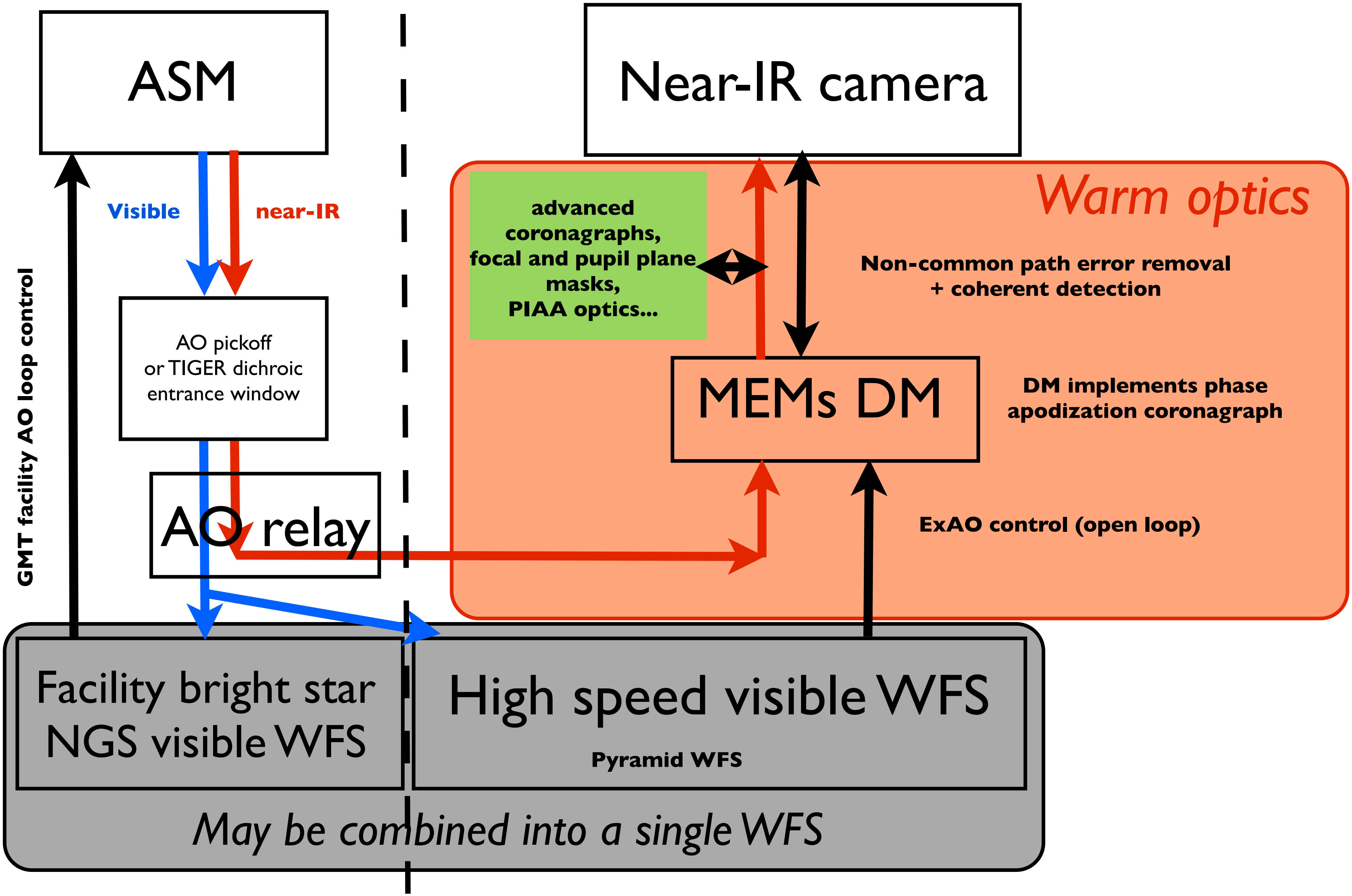
PIAA / Apodized Pupil Lyot Coronagraph

Apodized Pupil Lyot Coronagraph (adopted for GPI)
- Lyot coronagraph with entrance pupil properly apodized
- focal plane mask size and apodization chosen together to reach high suppression
- Can be designed for almost any pupil shape (including GMT, as shown in Soummer et al. 2009)

Problems/limitations:
- significant light is lost in apodization
- loss in angular resolution and inner working angle

Solution:
- perform apodization with PIAA optics (radially symmetric lenses)
- nearly ideal performance (1 lambda/D IWA, full throughput)

Possible system architecture (from ExAOcam proposal)



Conclusions

Low-risk / low cost path to ExAO science exists for GMT. 1st generation instrument can open unique science capabilities before other ELTs.

Modular & flexible architecture is key to make optimal use of rapidly improving ExAO technologies.

Segmented GMT pupil is not a limitation. Several validated coronagraph concepts can work very nicely on GMT pupil (phase plate, Apodized Pupil Lyot, PIAA, nullers).

Key to high performance is in wavefront sensing, control & calibration, where new techniques are rapidly being developed and will be tested on 8m telescopes.

Integrated modeling with AO important to evaluate options & design full system