ExAO for GMT

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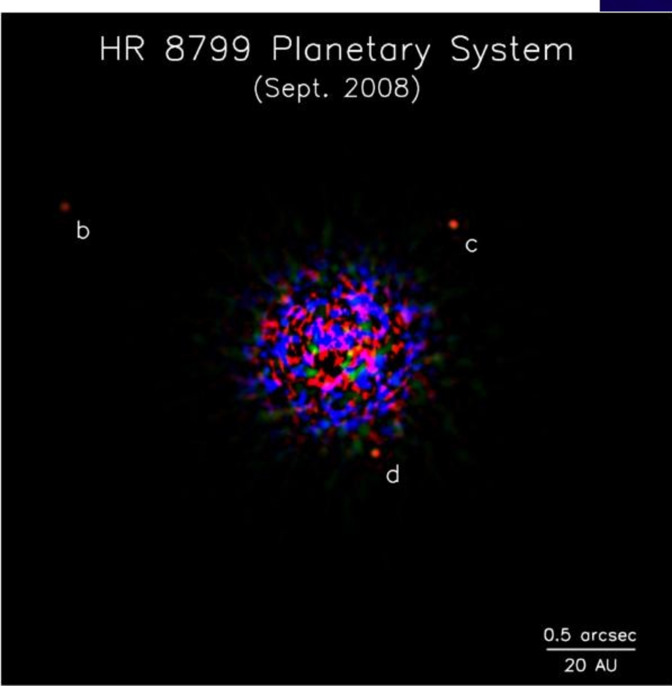
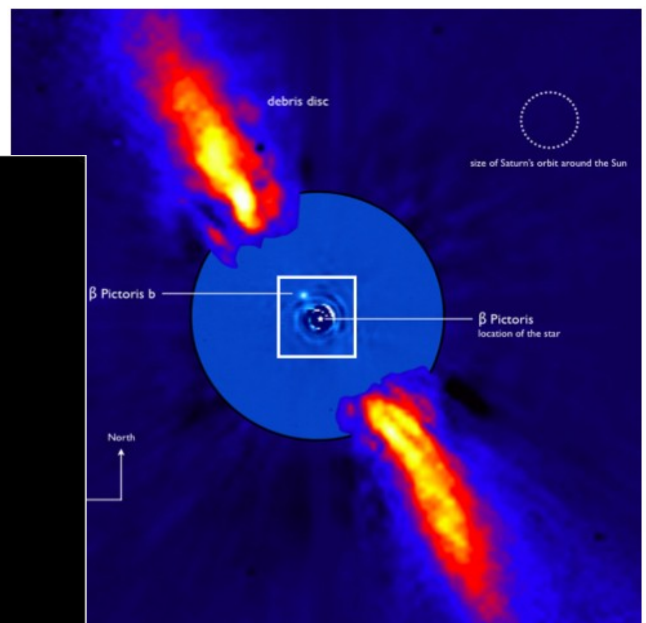
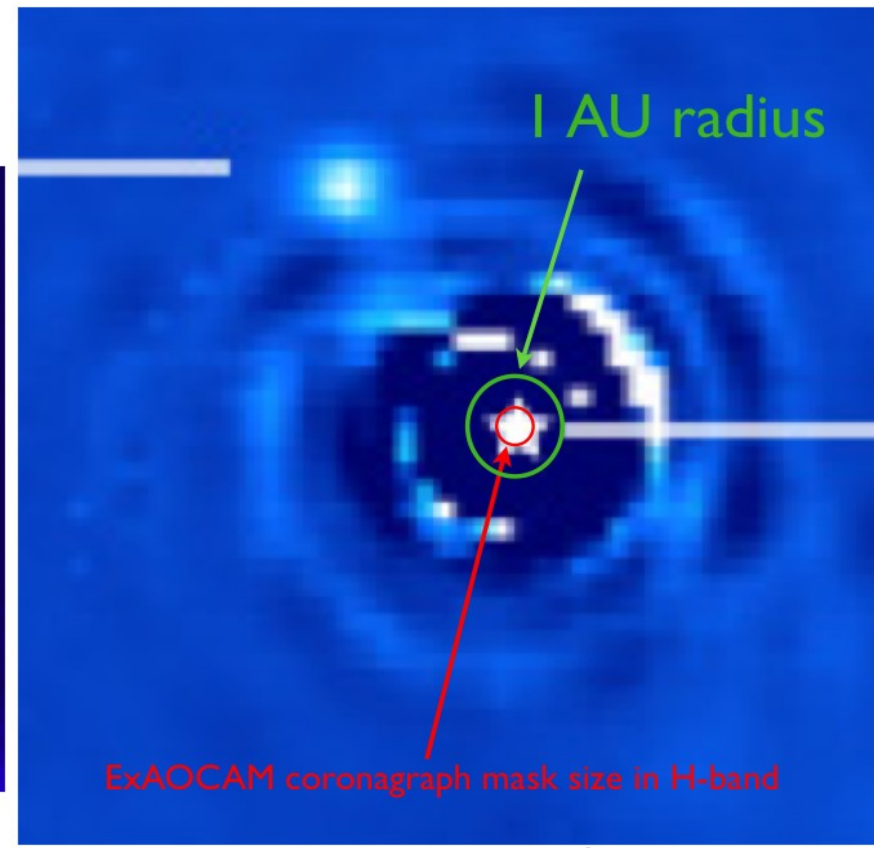




Marois et al. 2008



Lagrange et al. 2009

ExAO and coronagraphy myths

ExAO is what you call something that used to be an AO system but is not anymore

ExAO and coronagraphy myths

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No: it means Extreme-AO

ExAO and coronagraphy myths

Extreme-AO means Extremely difficult AO

ExAO and coronagraphy myths

Extreme-AO means Extremely difficult AO

No: lots of things are as easy as they get in an extreme-AO system:

Small field of view

Bright on-axis natural guide star (makes GMT segments cophasing easy)

ExAO doesn't care about vertical distribution of turbulence

ExAO is not demanding on facility AO (just needs to lock on star)

ExAO and coronagraphy myths

Extreme-AO means Extremely costly AO

ExAO and coronagraphy myths

Extreme-AO means Extremely costly AO

No: Extreme-AO system can be small and cheap – does not scale up with telescope size

BUT: instrument suite can drive up the cost
(IFU, polarization camera etc...)

ExAO and coronagraphy myths

Extreme-AO needs more and more actuators to get better

ExAO and coronagraphy myths

Extreme-AO needs more and more actuators to get better

No: the number of actuator only affects the field of view of ExAO system, not its contrast

Exisiting MEMS type DM would be sufficient for GMT

ExAO and coronagraphy myths

Coronagraphy only works in the lab – it's totally useless on a real telescope !

ExAO and coronagraphy myths

Coronagraphy only works in the lab – it's totally useless on a real telescope !

Yes (but not for much longer).
Putting a coronagraph on a non-ExAO system which
was build for general purpose science doesn't work well.

Pairing a coronagraph with ExAO will pay off.

ExAO and coronagraphy myths

Self-proclaimed ExAO "experts" have no clue how to do their job: they change techniques faster than the time it would take them to build anything that would work on a telescope.

By the time they build something, it won't work and they will say:
"ah, but I know why, I used old techniques...
give me more money and I'll build it right this time"

ExAO and coronagraphy myths

Self-proclaimed ExAO “experts” have no clue how to do their job: they change techniques faster than the time it would take them to build anything that would work on a telescope.

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Yes (and we need to keep this in mind).
We are still learning how to do things right.

We should avoid over-designing a rigid system right now for GMT, and leave flexibility to evolve during design and operation.

Extreme-AO for GMT: Key science goals

Planetary formation in the inner parts (1 to 10 AU) of planetary systems

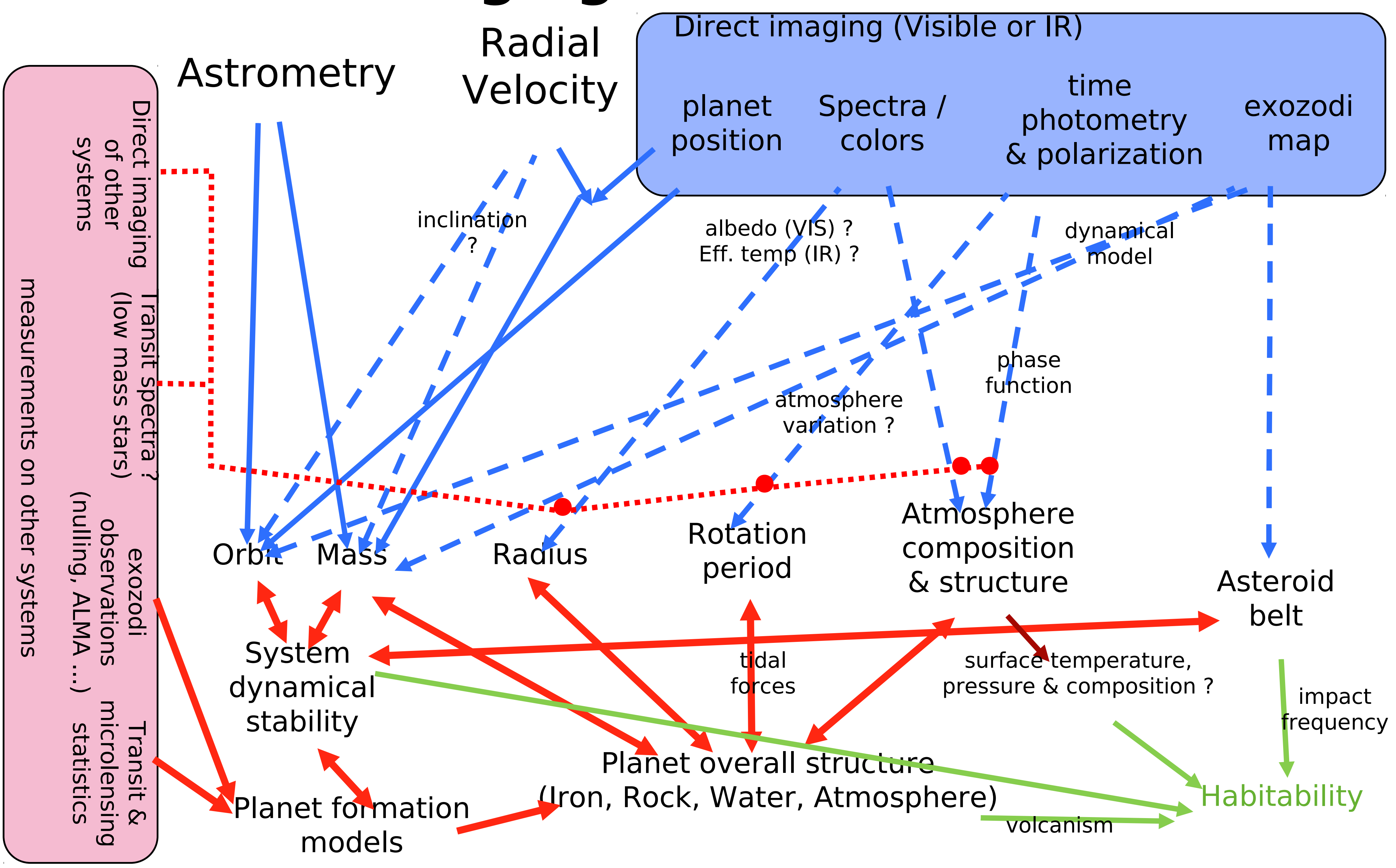
- GMT angular resolution is key to access this separation range for a large number of young stars
- GMT should acquire high resolution images of disks and planets: dust disk structure shaped by planets
- GMT's sensitivity will allow large number of thermal near-IR planets to be imaged, at ~ Jupiter mass (age-dependant)

Direct imaging of reflected light from planets

- Allowed by GMT's angular resolution and sensitivity
- Large (Jupiter-size to possibly Super-Earth size) could be imaged in the habitable zone around any nearby star

Spectral characterization of exoplanets

Habitable exoplanet characterization with direct imaging

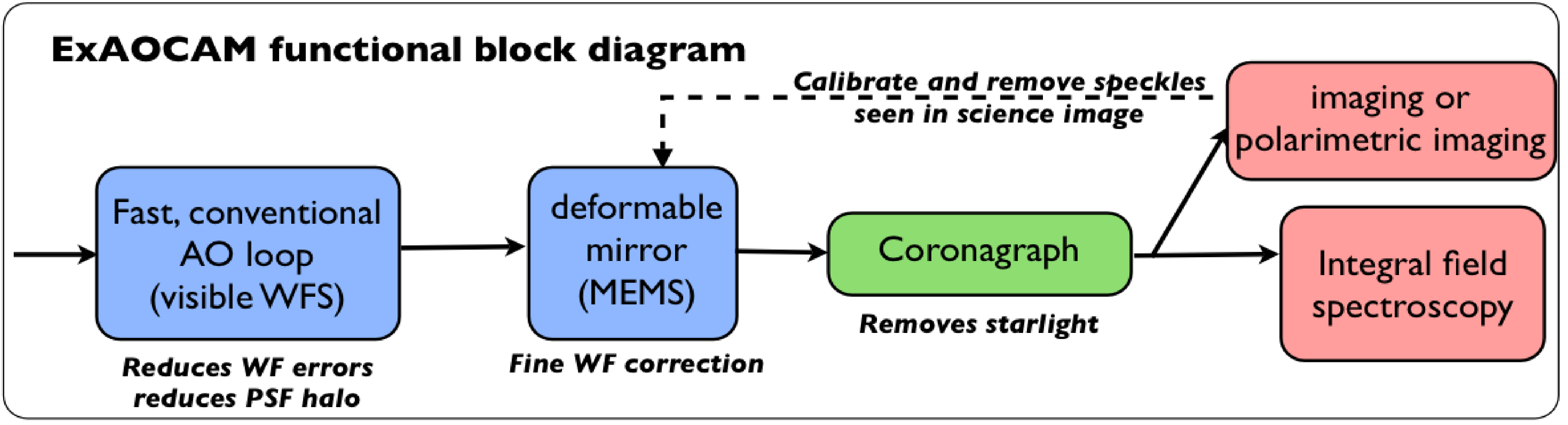


What is an Extreme-AO system ?

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

Key elements:
- **Coronagraph** to remove starlight
- **Wavefront correction system** to recude and calibrate residual wavefront errors
  (note: the ExAO wavefront correction may consist of a second stage tweeter following the facility AO)
- **Science detector** for imaging, spectroscopy and polarimetry
  (note: the science detector is ideally part of the wavefront control system, at is measures residual scattered light to be removed)

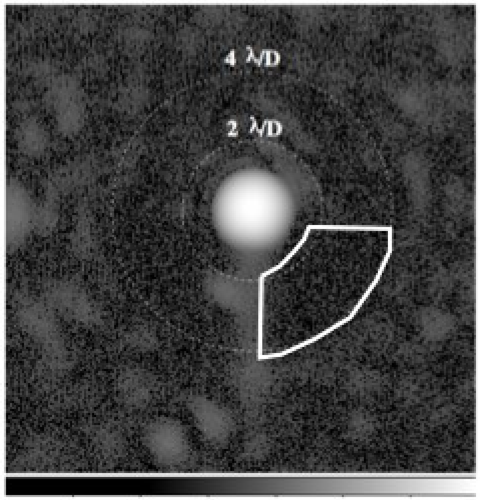
Coronagraph + WFC system can bring speckle halo to 1e-4 to 1e-6 ***raw contrast*** *level due to residual atmospheric turbulence.*
Using good calibration of residual light + differential imaging tricks, the ***detection contrast*** *is 100x to 1000x lower.*



Coronagraphy

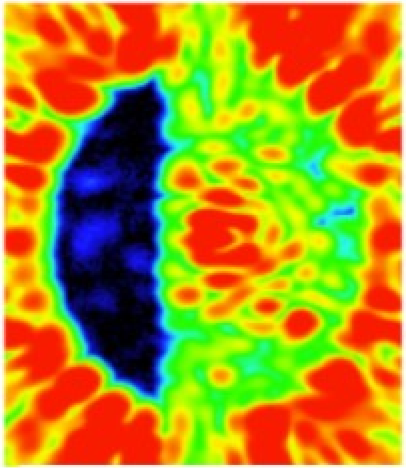
The field of coronagraphy is extremely active, and many solutions now exist for high performance coronagraphy.

PIAA coronagraph, monochromatic light, Subaru lab. Average contrast in white area (from 1.65 to 4 l/D)= 2.27e-7



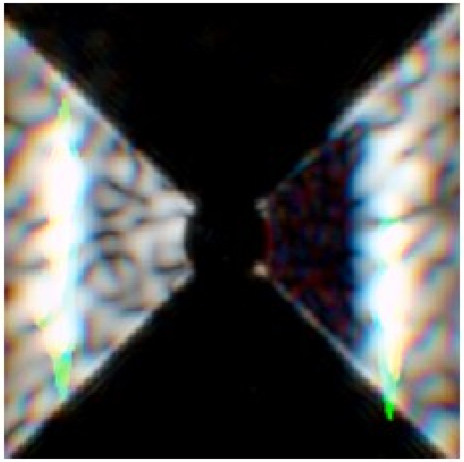
ref: Guyon et al. 2009

Lyot type coronagraph, 10% bandwidth High Contrast Imaging Testbed (HCIT), NASA JPL Ave. contrast in 4-10 l/D box = 7.5e-10



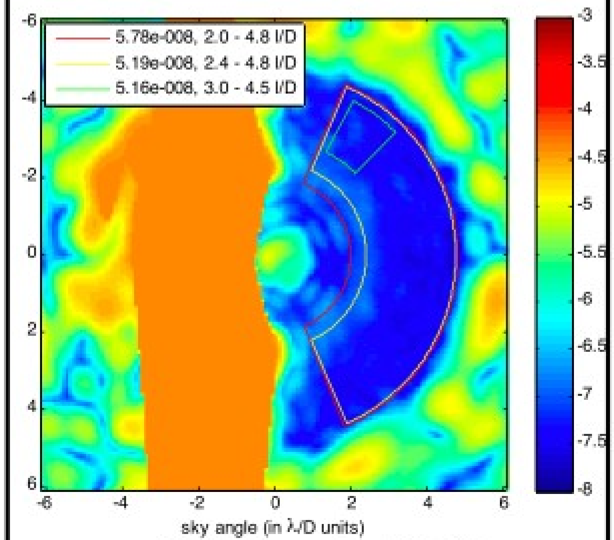
ref: Moody et al. 2008

Princeton/HCIT experiment shaped pupil coronagraph contrast = 2.5e-9 10% bandwidth @800nm IWA = 4 l/D



ref: Belikov et al. 2007

NASA Ames coronagraph lab PIAA coronagraph, monochromatic light Contrast ~ 7e-8 in 2-4 l/D window



ref: Belikov et al. 2009

Coronagraphs in lab already work to 1e-7 to 1e-9 raw contrast at a few l/D from the optical axis (and they are often limited by wavefront stability). This is several orders of magnitude better than required for a ExAO system on GMT.

Coronagraphy: does the GMT pupil make it challenging ?

GMT pupil shape restricts coronagraph choice, but several high performance options remain, with various degrees of technological maturity:

- **Pupil apodization** works for GMT (safe and easy architecture, but efficiency is below 50%.

  Pupil apodization works well in labs, and has been installed on MMT.

- The **PIAACMC**, the coronagraph design with the highest known raw performance, can be used on the GMT pupil with essentially no loss in performance over a full aperture.

  PIAACMC works well in lab, and can be continuously tuned from a moderate performance apodized Lyot-like coronagraph to a high performance apodized phase mask coronagraph.

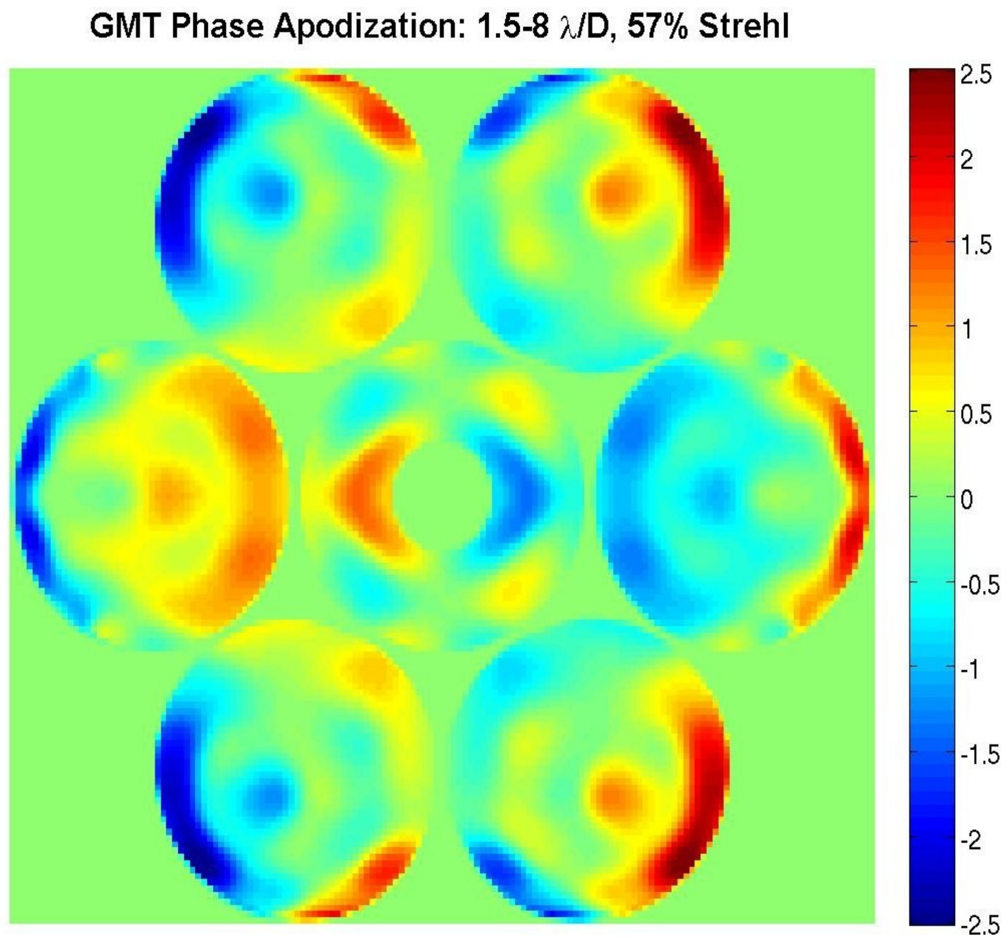
  Note: A flavor of PIAACMC is adopted for the Subaru Coronagraphic ExAO System, to be on sky in early 2011.

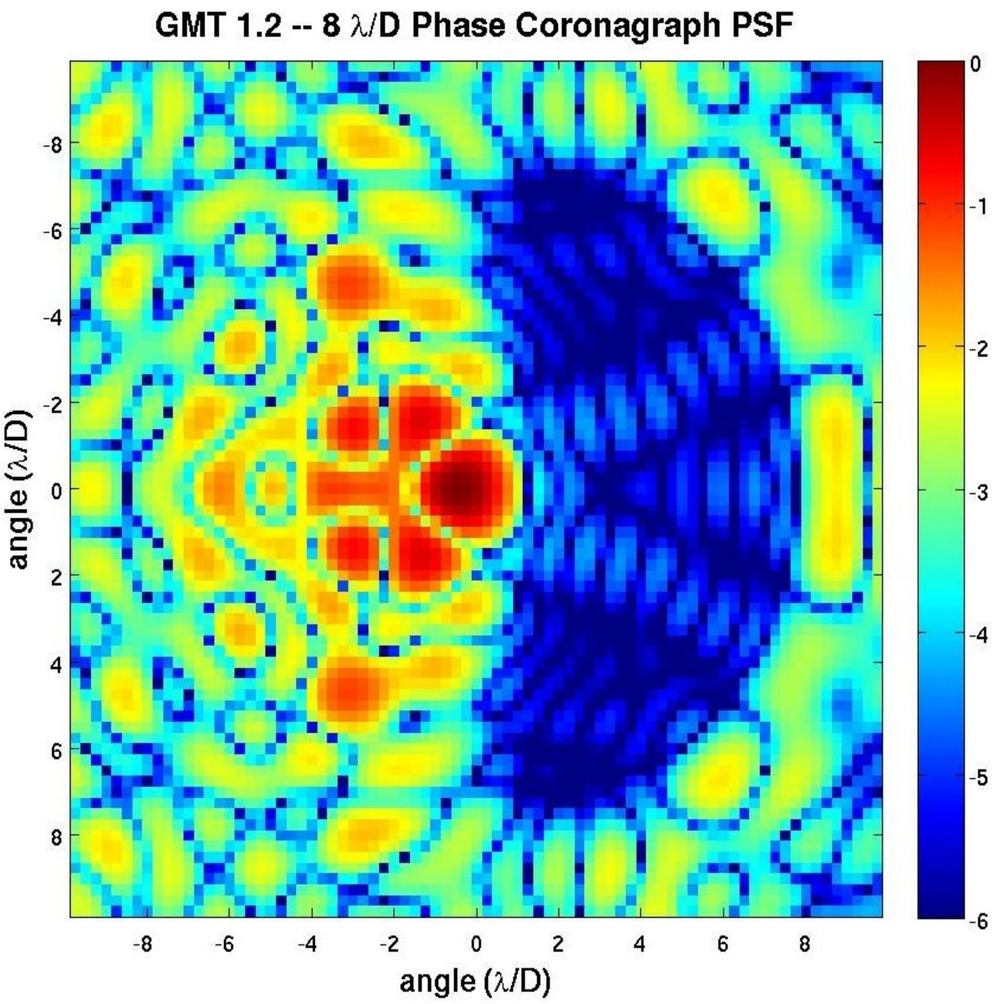
- **Pupil shaping** to feed a coronagraph which doesn't like the GMT pupil

What will not work is to take a coronagraph designed for a single aperture and use it on GMT !

Pupil Apodization for GMT

- (Design by J. Codona)

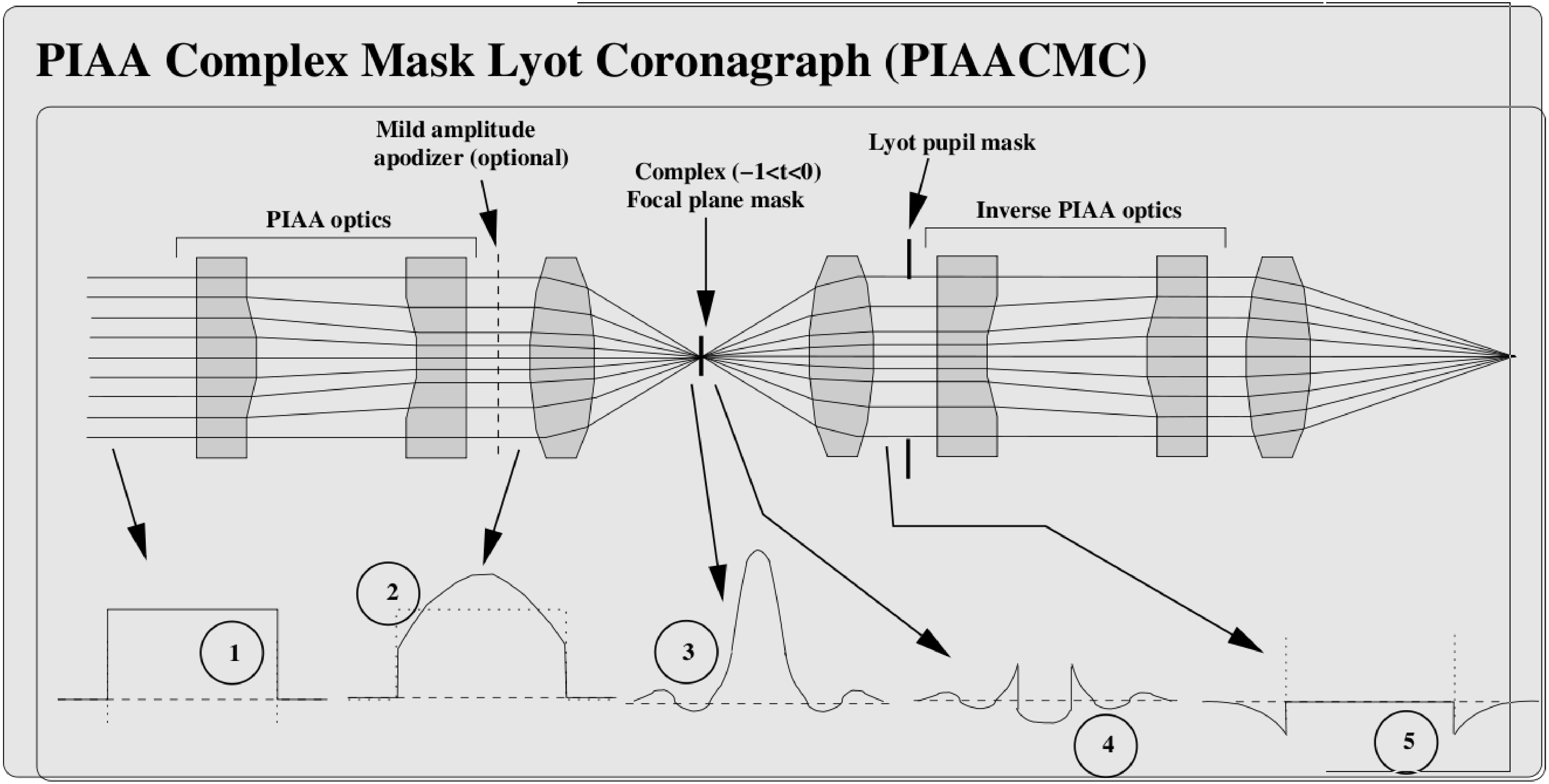




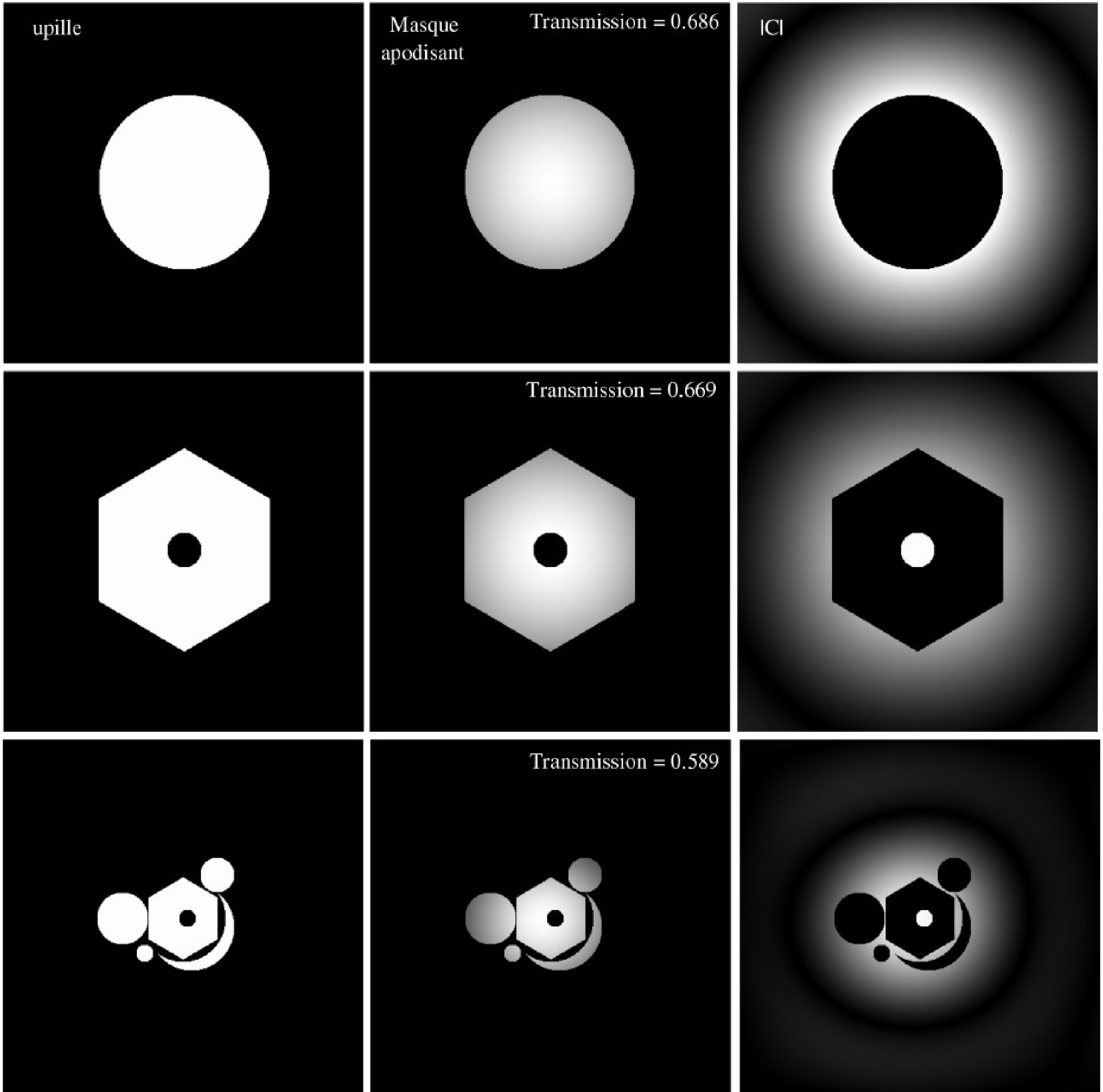
PIAACMC coronagraph GMT

PIAA complex mask coronagraph (PIAACMC) combines 2 techniques:

- PIAA: Phase-Induced Amplitude Apodization
- Phase mask Lyot coronagraphy with apodized pupil



Phase mask Lyot coronagraphy with apodized pupil



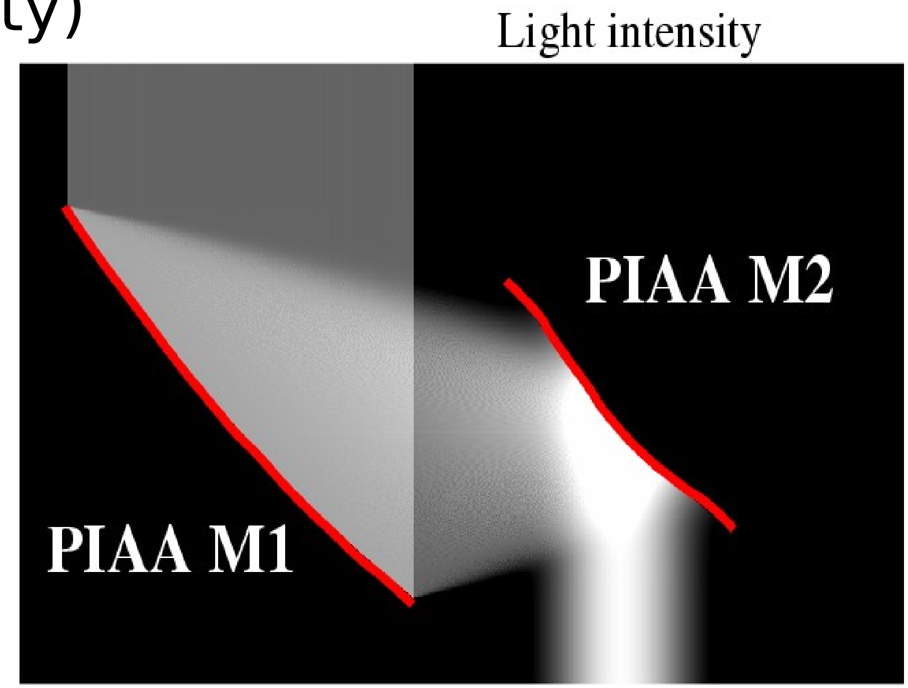
Concept works on any pupil shape

Guyon PhD thesis, 2002

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 l/D to 2 l/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

PIAACMC coronagraph

Fully removes starlight (if unresolved and no WF error)

Very close to ideal coronagraph limit derived from fundamental physics

Can be designed for GMT pupil and other non-circular geometries.

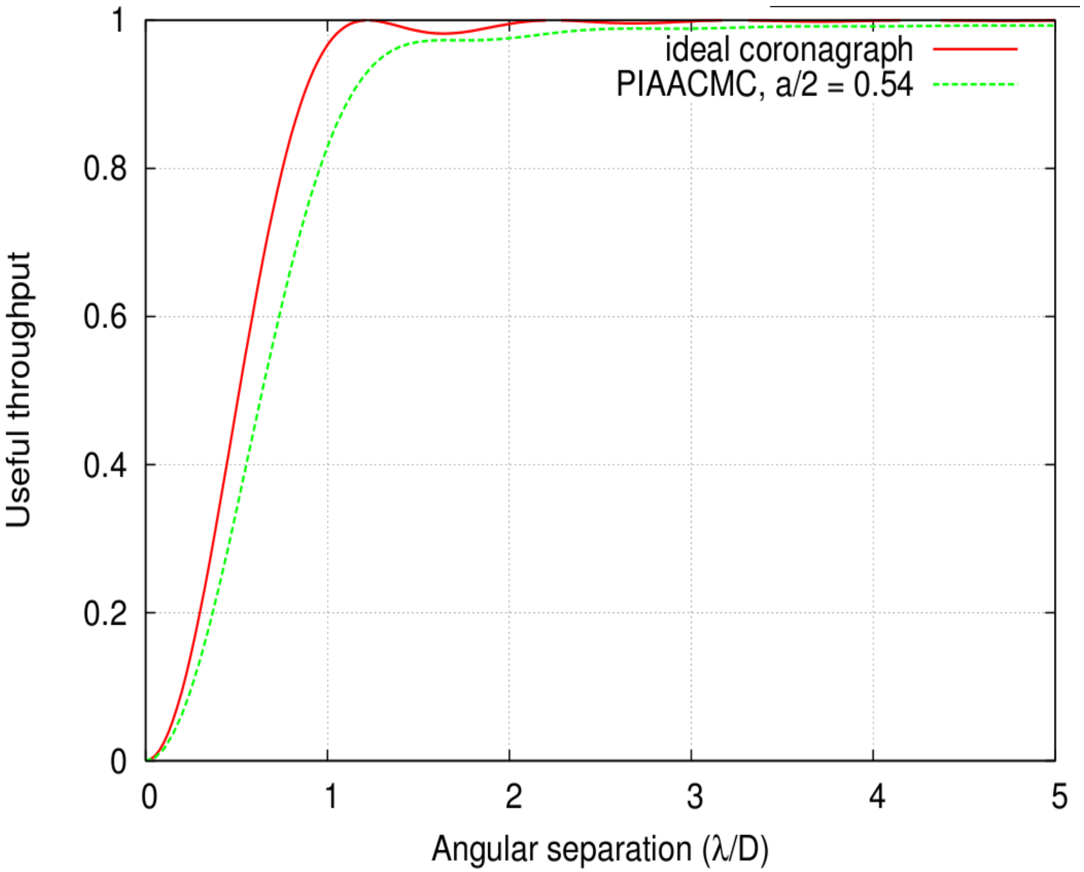
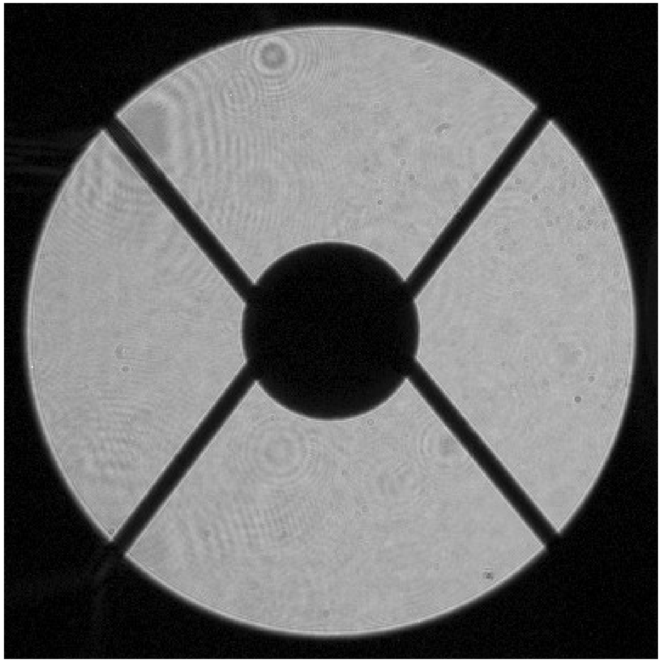


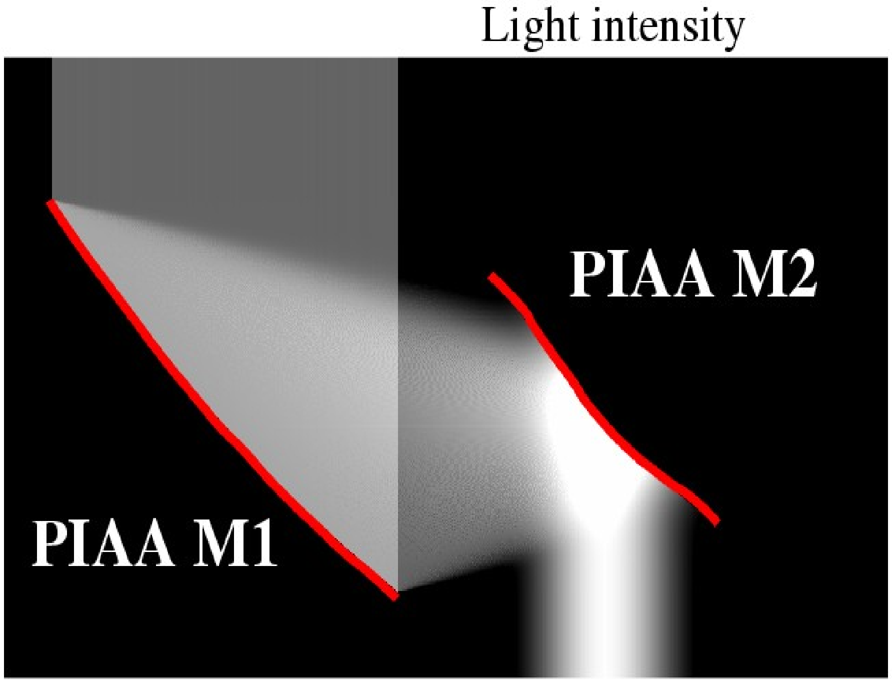
FIG. 6.— Comparison between the useful throughput of the PIAACMC with $a/2 = 0.54\lambda/D$ (apodized pupil phase mask coronagraph) and the theoretical ideal performance limit of coronagraphy on a point source.

Ideal coronagraph curve derived in:

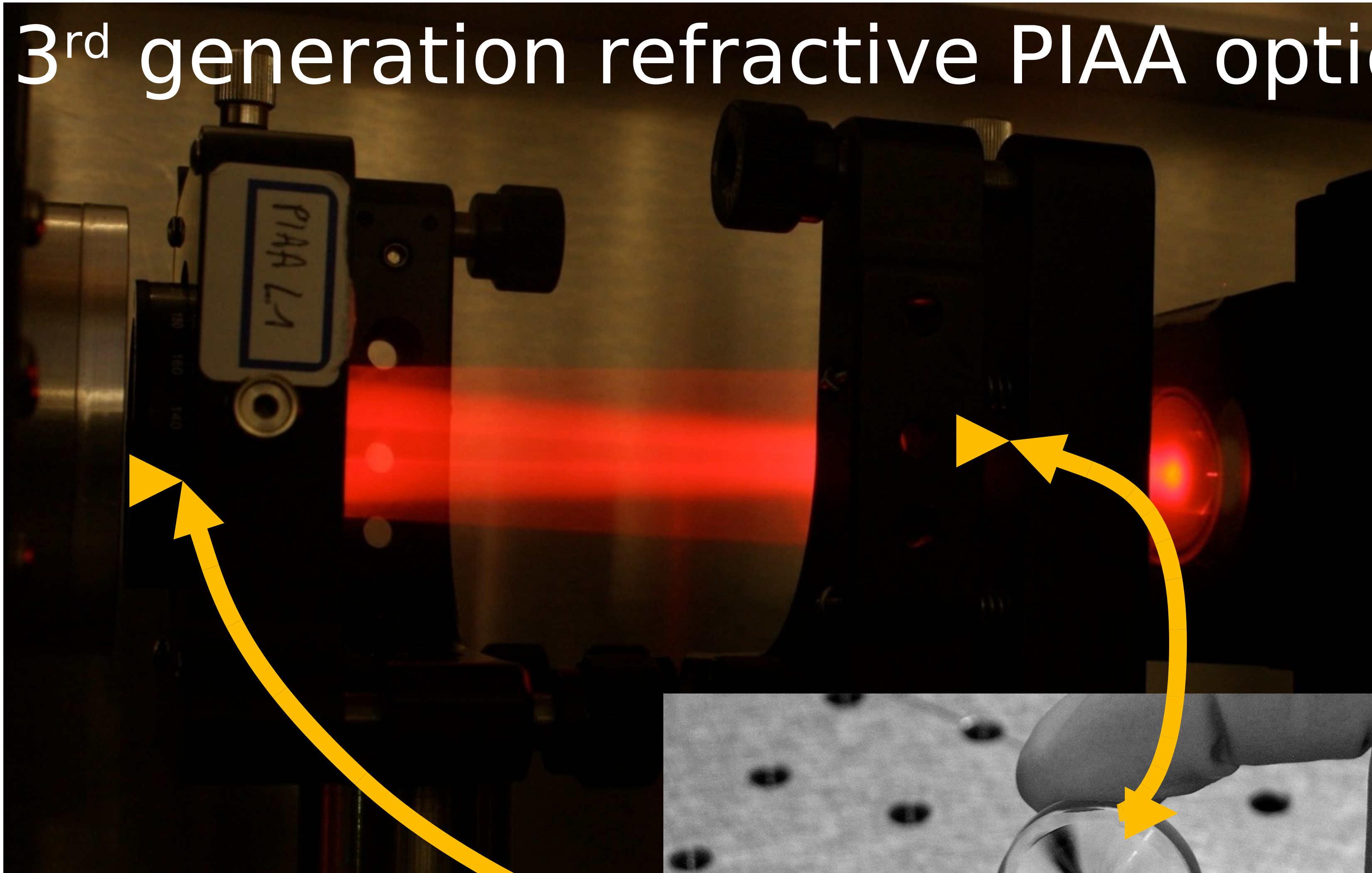
"Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs" Guyon, O., Pluzhnik, E.A., Kuchner, M.J., Collins, B., Ridgway, S.T., ApJ Suppl, 167, 81-99 (2006)

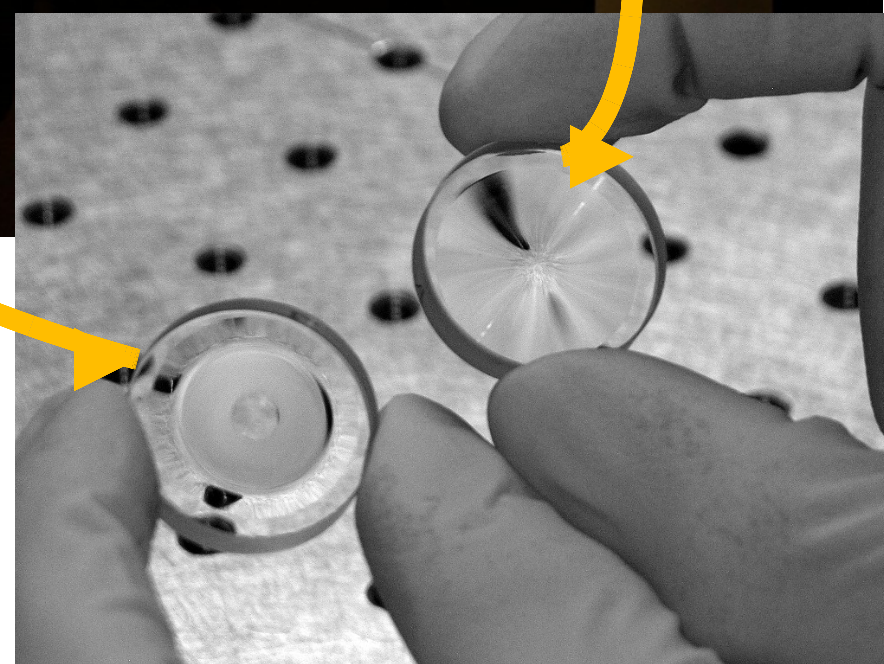
Pupil shaping





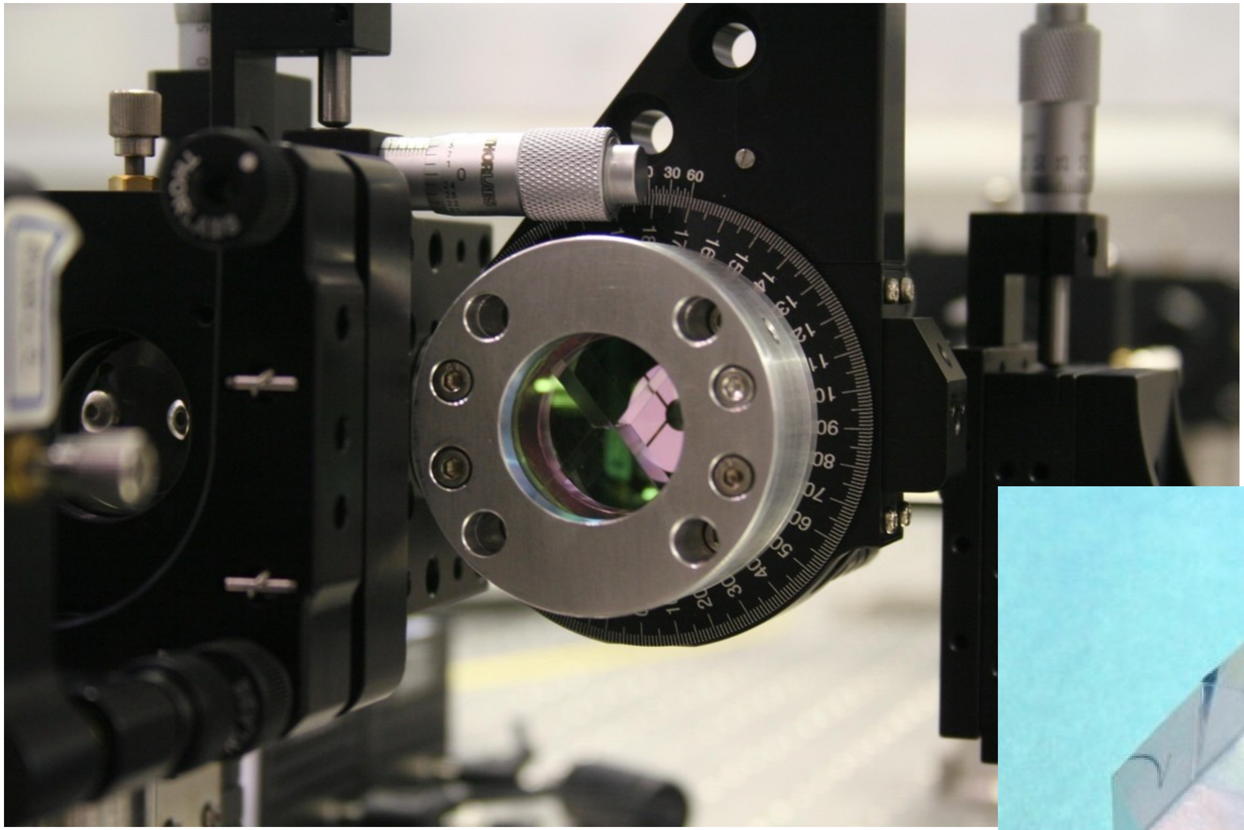
3rd generation refractive PIAA optic

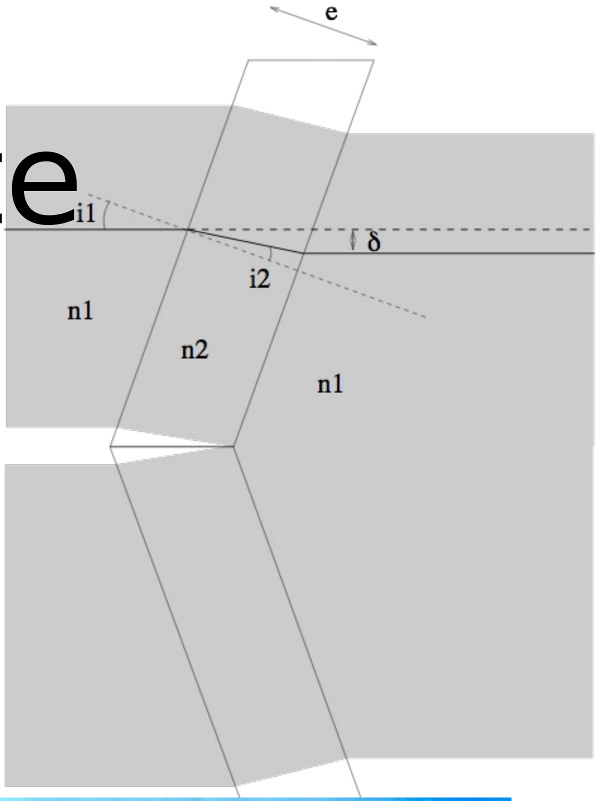


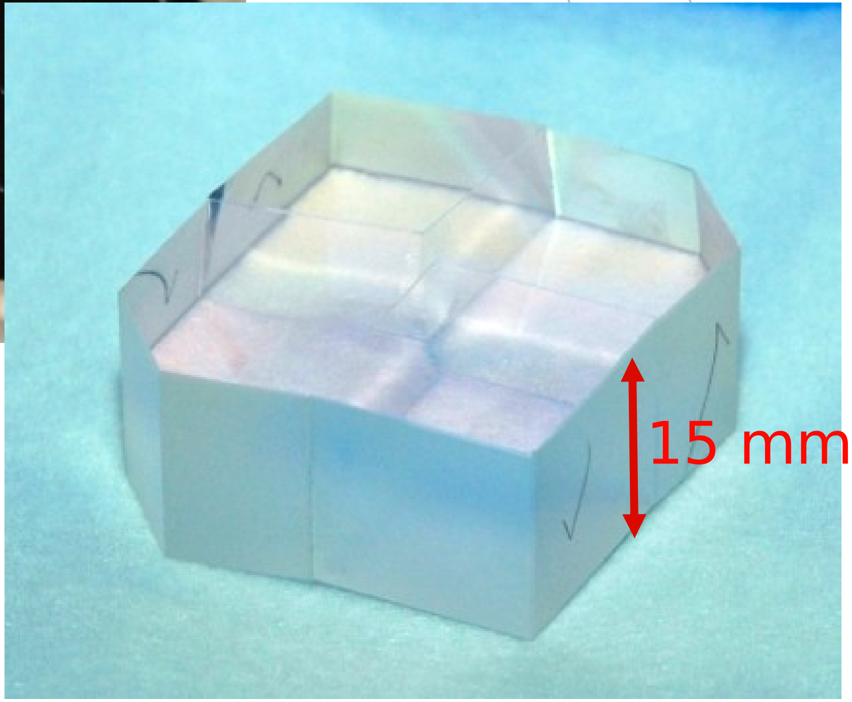


- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

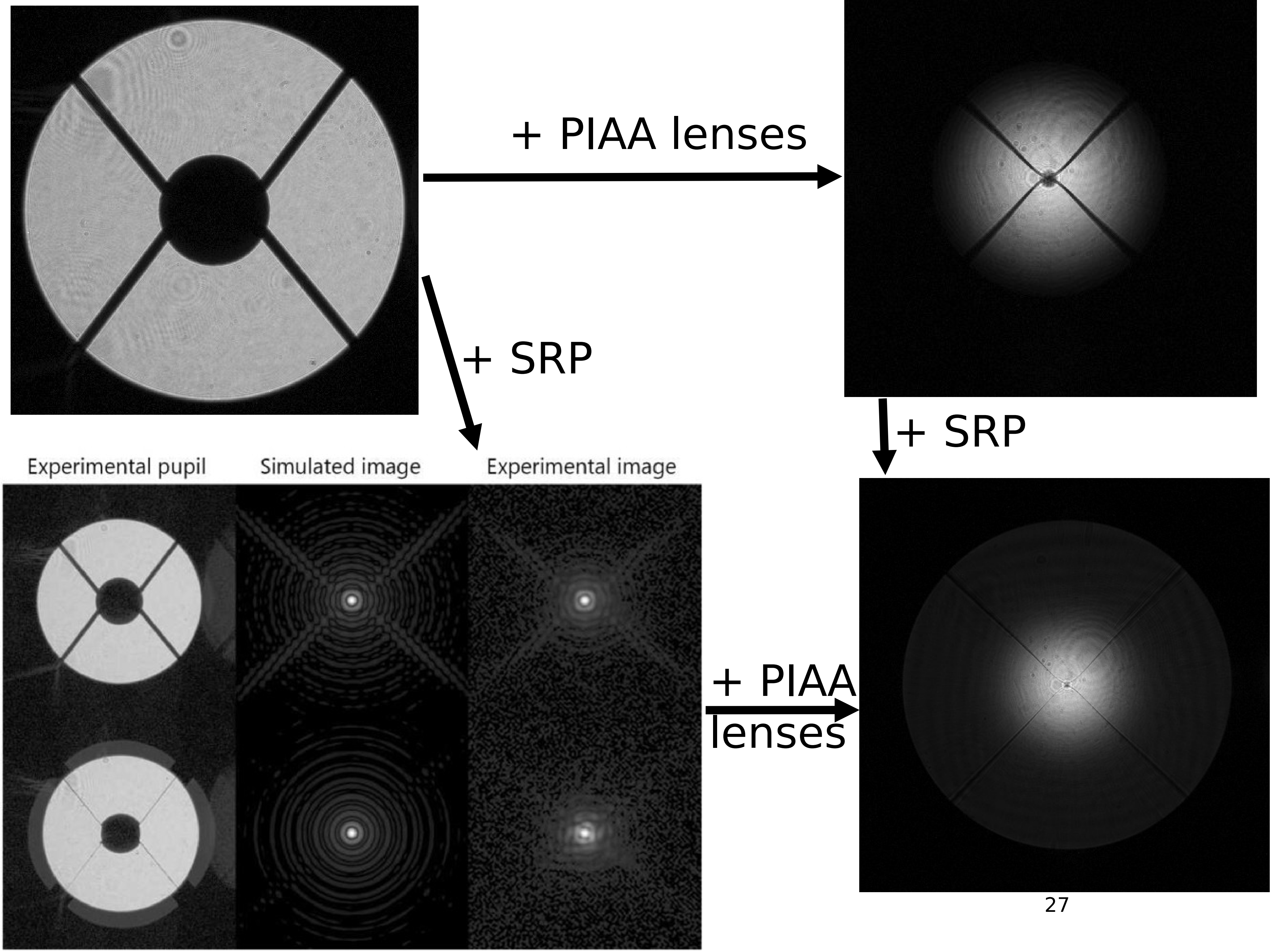
Spider Removal Plate







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


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

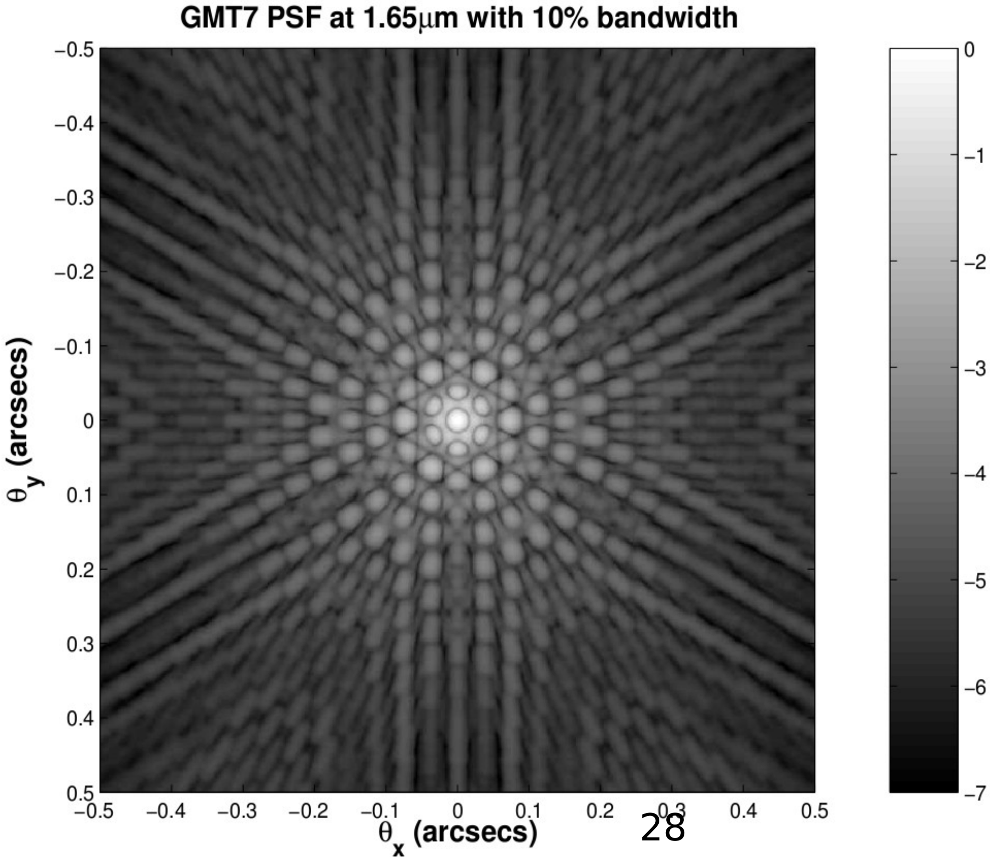
Fundamental effect of segmented pupil on coronagraphy

What happens if planet is located on top of a 10% level speckle ?

10% side lobe = 10% coupling between the wavefront of the planet and the wavefront of the star

The coronagraph, by removing 100% of the starlight, will also remove 10% of the planet light → this is a very small loss in efficiency !

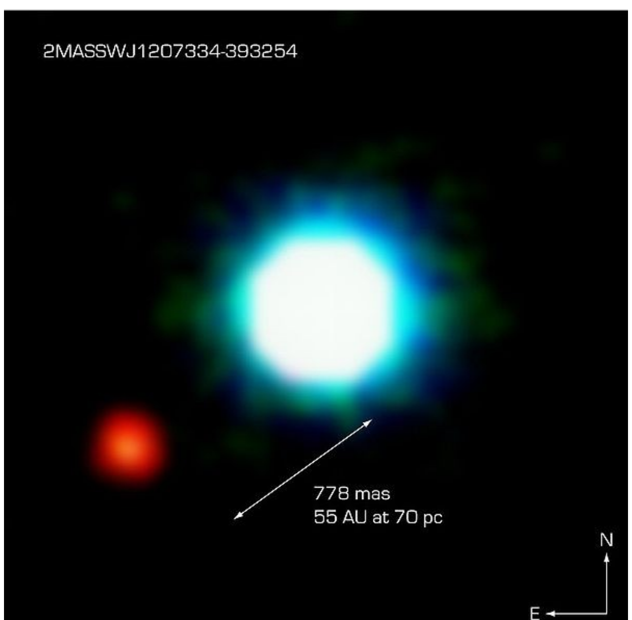
With properly designed coronagraph, the GMT pupil does not reduce ExAO sensitivity for detecting faint sources.



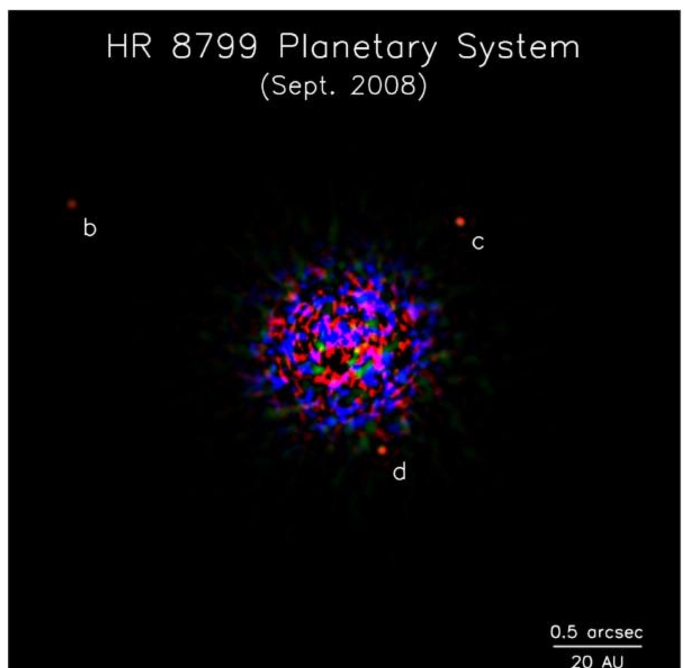
Coronagraphy on GMT: conclusions

Coronagraphy on GMT is not particularly challenging. Coronagraphs for the GMT pupil can be designedand built with current technology to deliver the required contrast in the absence of wavefront aberrations.

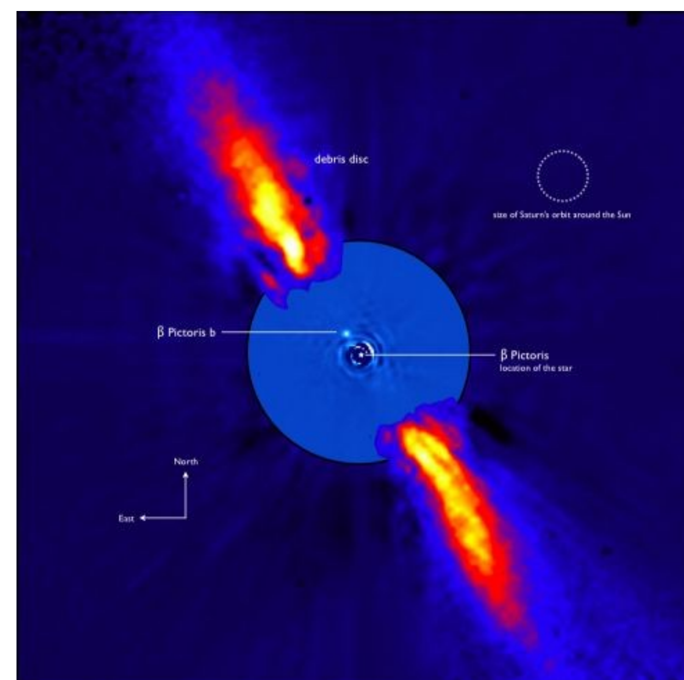
Coronagraph performance will be limited by wavefront quality. This is the most challenging aspect of ExAO systems. This is why we have very good coronagraphs in the lab but they don't work all that well on ground based telescopes (yet): putting a coronagraph on a conventional AO system doesn't work very well.



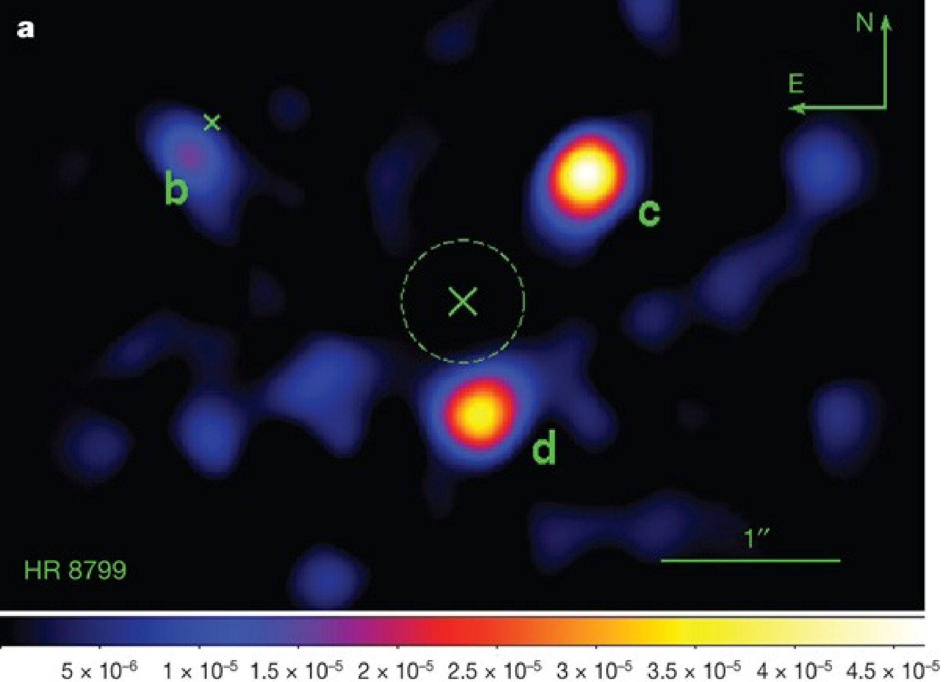
Chauvin et al. 2004

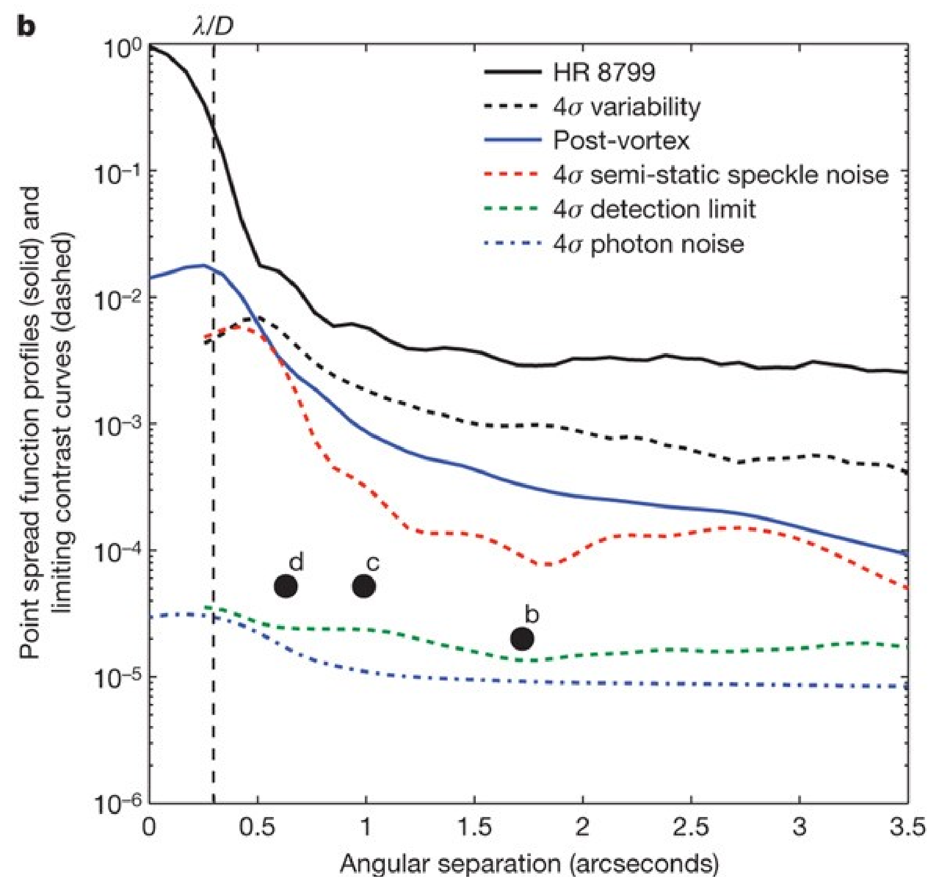


Marois et al. 2008



Lagrange et al. 2009





Example: imaging HR8799 with a 1.5m telescope

(Serabyn et al. 2010, Nature)

System with 3 planets, discovered with conventional 8-m and 10-m telescopes equipped with non-ExAO AO systems and no coronagraph. Observations were challenging and required careful calibration and data analysis.

Using an efficient coronagraph + high degree of correction + good calibration, planets can be imaged on 1.5-m telescope.

Extreme-AO vs “conventional” AO

In may respects, Extreme-AO is simple:

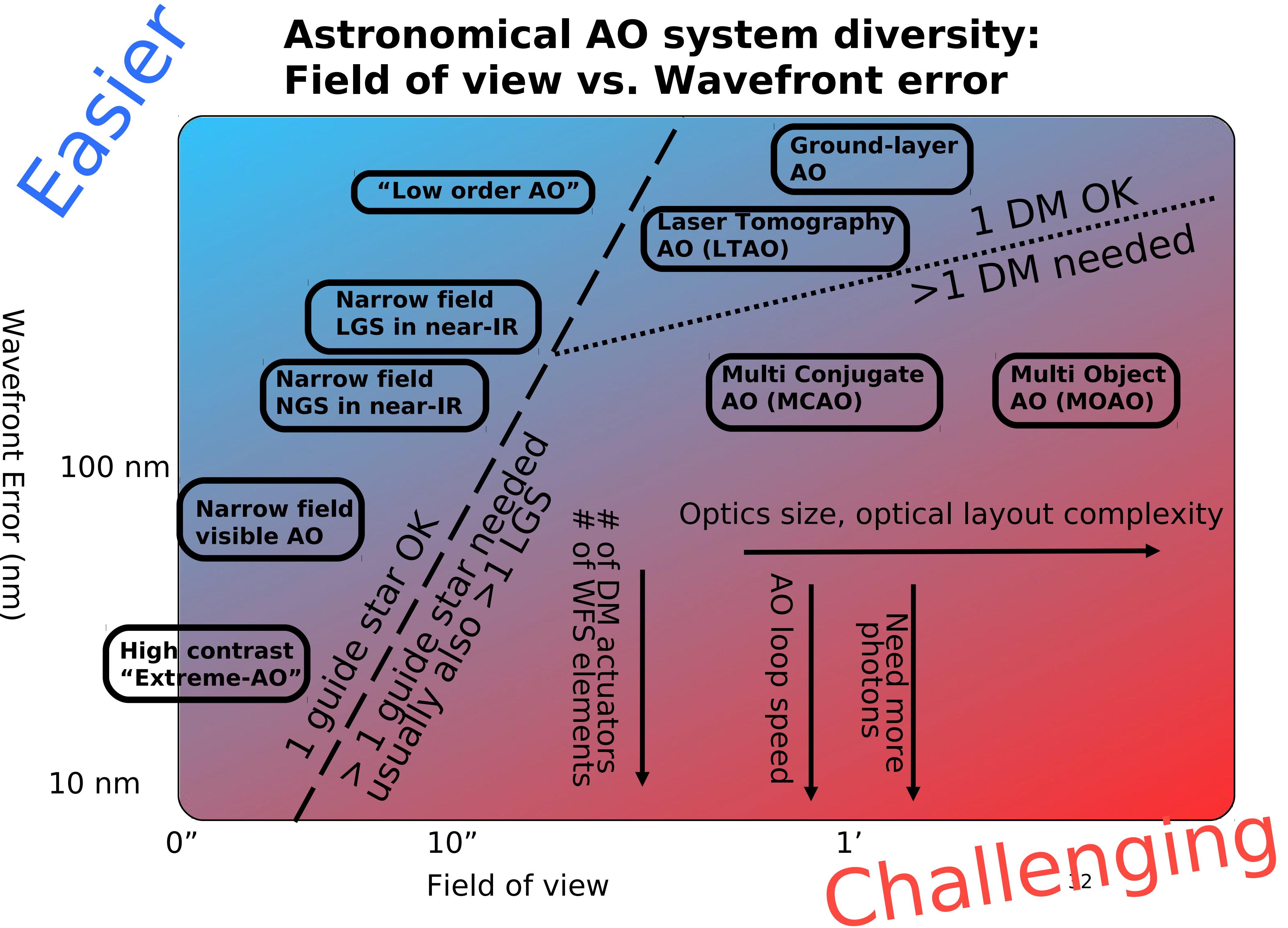
Natural guide star (no laser guide star)
Guide star is bright and on-axis
ExAO does not require field of view
→ Small optics OK, instrument can be small
→ Single guide star, no LGS(s), simple reconstruction (no tomography)
→ Single DM may be OK (if sufficient stroke, speed and actuator count)

What is unconventional in ExAO is:

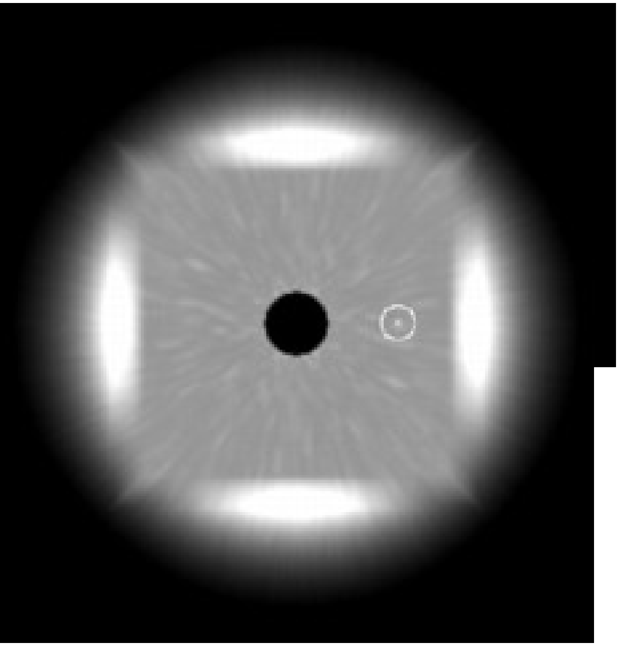
(1) Need for low wavefront residual
→ high speed correction
→ efficient WFS
(2) Good control of low order aberrations necessary for coronagraph
→ fast pointing control necessary
(3) Good calibration of residual light in PSF halo
→ design architecture needs to provide a mean to calibrate speckles

A good ExAO system design needs to address these 3 requirements.

Astronomical AO system diversity: Field of view vs. Wavefront error

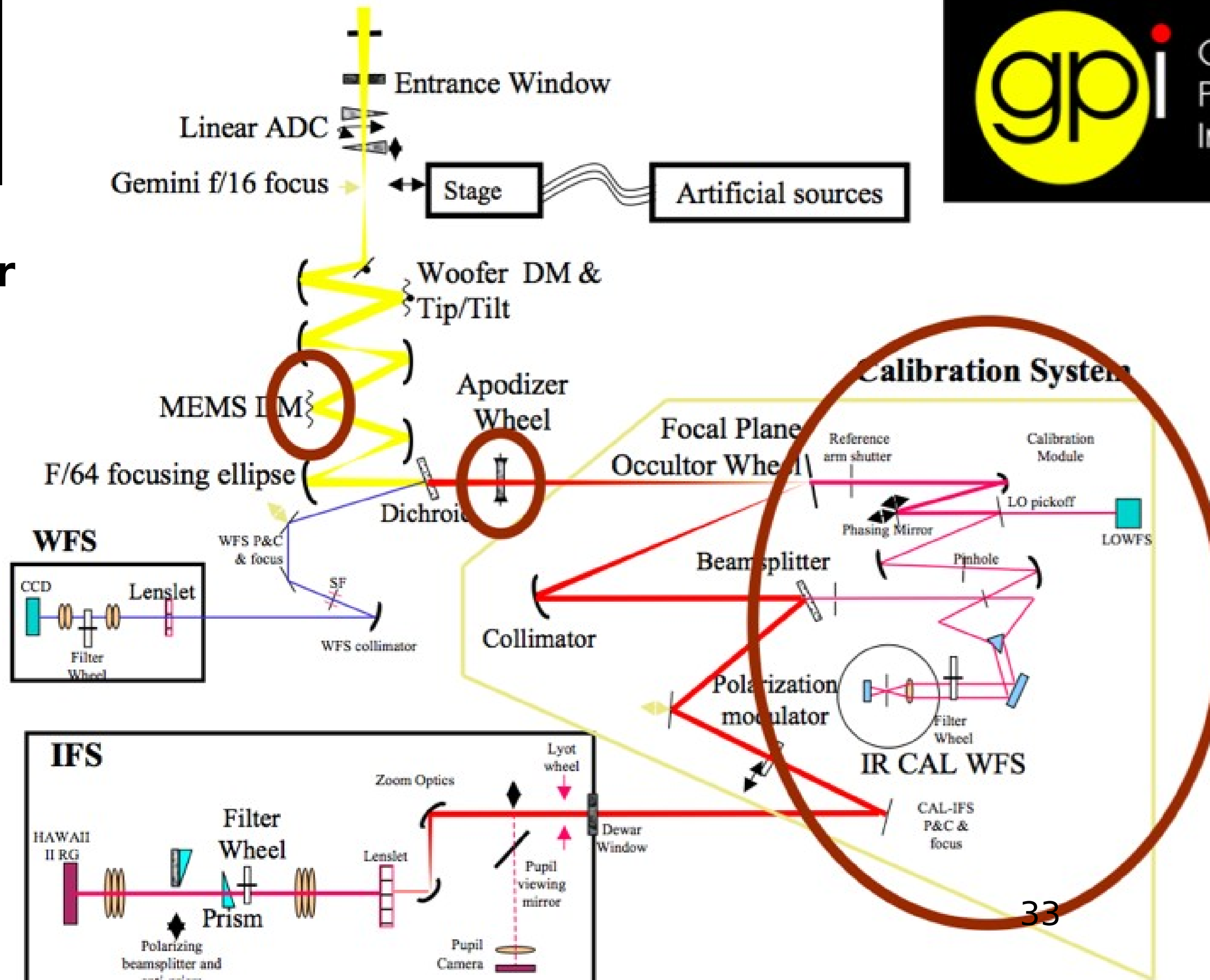


Extreme-AO systems are quite different from conventional AO systems



Gemini Planet Imager
SPHERE (ESO)
SCExAO (Subaru)

Also under study: space-based ExAO systems



Coronagraphic Extreme-AO on large telescopes: Why does it make sense ? How should it be done ?

Even without technology improvement (highly conservative) over current generation of ExAO systems on 8-m telescopes, deploying ExAO on large telescope greatly improves performance over 8-m telescopes:

- The **increased angular resolution** allows observation of planets 3x closer to their host star

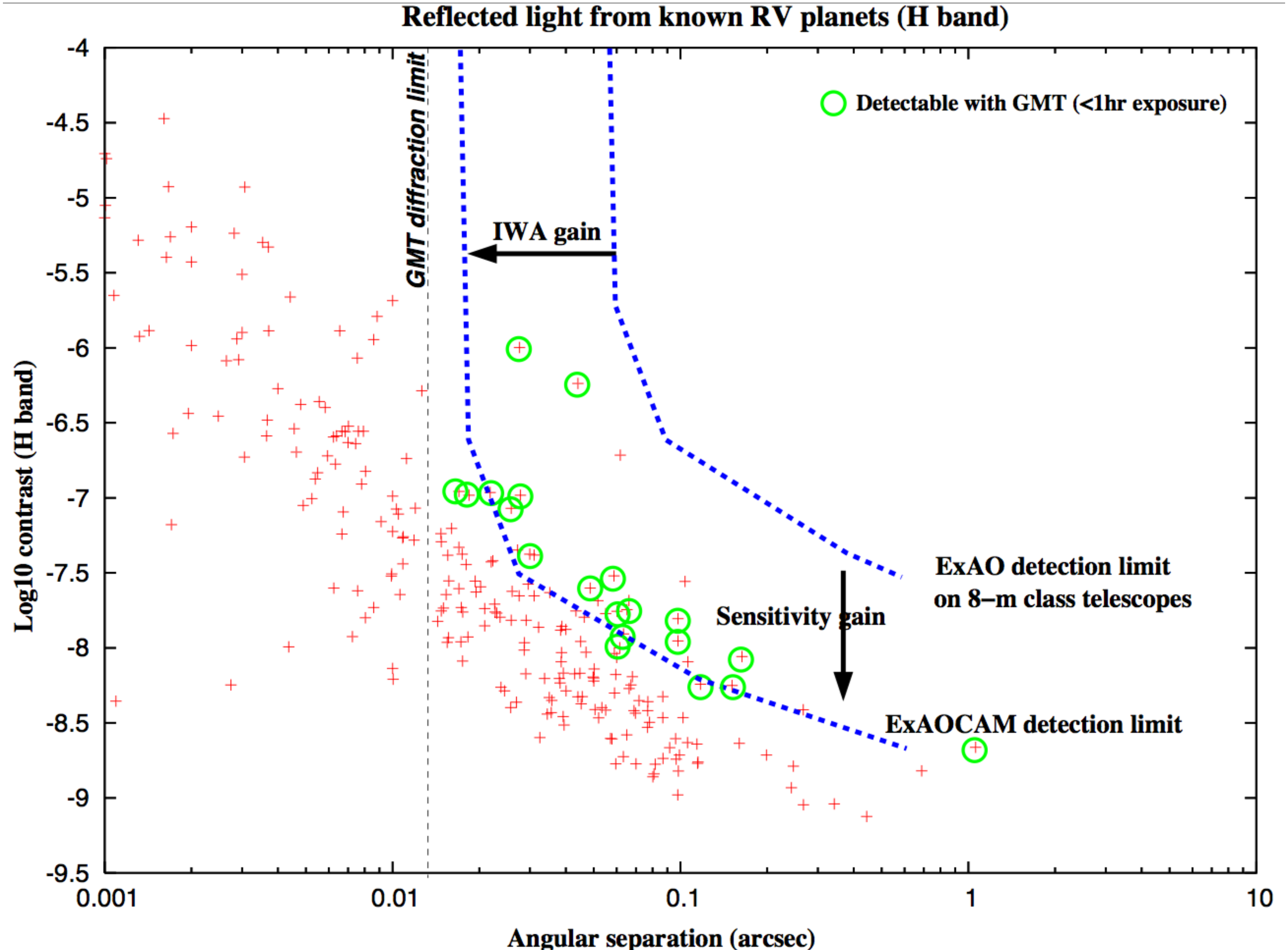
- At constant PSF Strehl ratio and angular separation, a 3x increase in telescope diameter yields a **9x increase in PSF contrast**: the planet light is more peaked against the PSF halo and thermal background

This provide a very good starting point: take what works on 8-m telescopes and quickly deploy it on GMT for a very compelling science case. Risks are kept low.

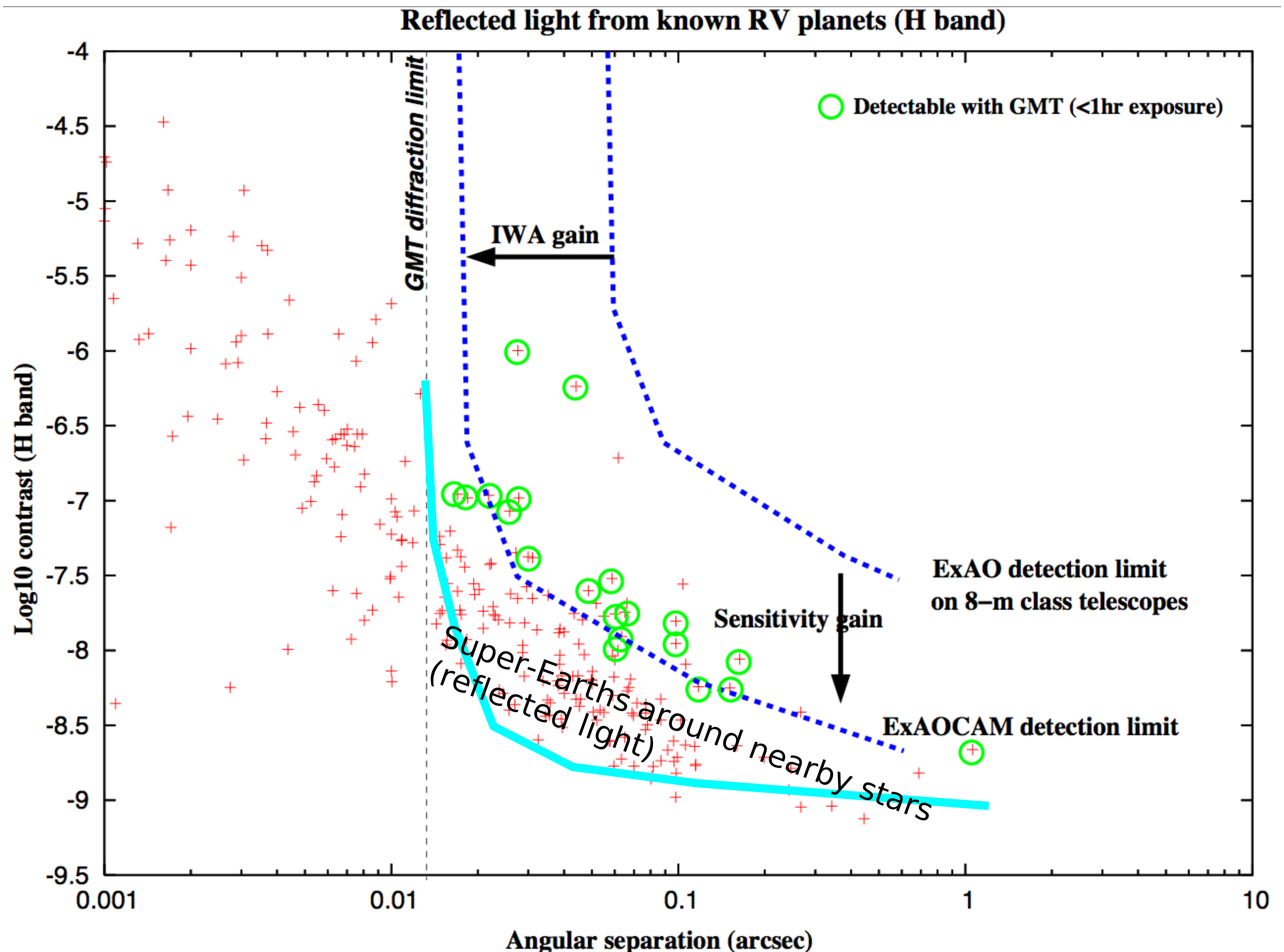
There are (and always will be) game-changing techniques appearing regularly in ExAO. They should be deployed when ready to keep the system scientifically unique.

ExAO system should be flexible and should be able to evolve from a low risk first light configuration to a high performance system employing the best techniques of the time.

Expected performance (conservative estimate using ~5 yr old technology)



Potential GMT performance (high efficiency WFS and coronagraph)



Game-changing techniques for ExAO:
(1) Wavefront sensing at the diffraction limit of the telescope

Conventional wavefront sensors are optimized to be :
- **robust** (need to close the loop, guide on extended source)
- **linear** even with > 1 rad aberration

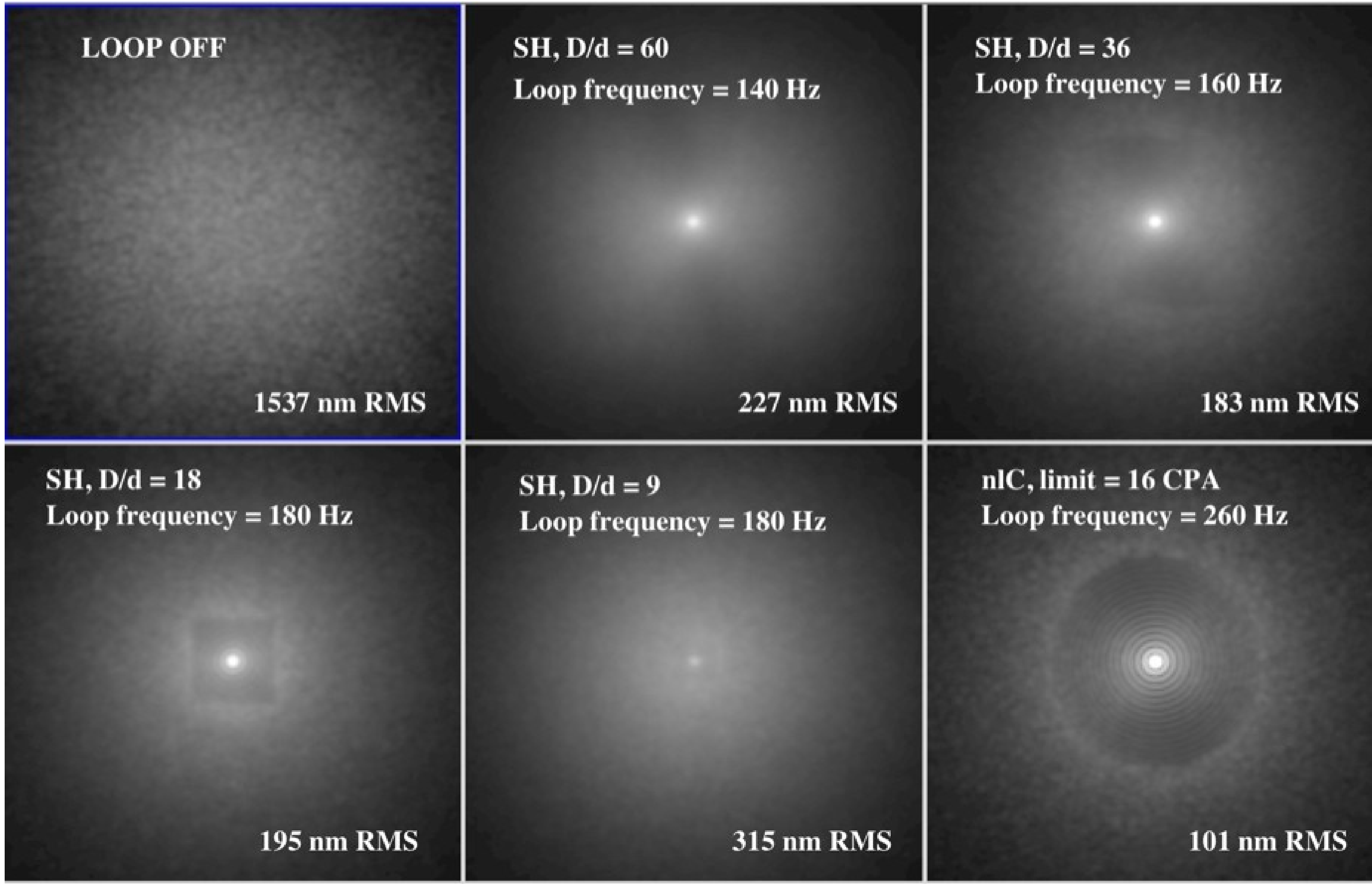
But they are **extremely inefficient**
[efficiency = wavefront measurement accuracy with a limited number of photons]

Example: SH WFS
Works at the seeing limit (does not take advantage of angular resolution of telescope)

Efficient WFS should take advantage of GMT diffraction limit (even if PSF is not diffraction limited !) in visible
For tip-tilt (most important for coronagraphy) gain in flux is:
$(D/r_0)^2$: 2500 for 8-m telescope, 30000 for GMT

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

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%

38

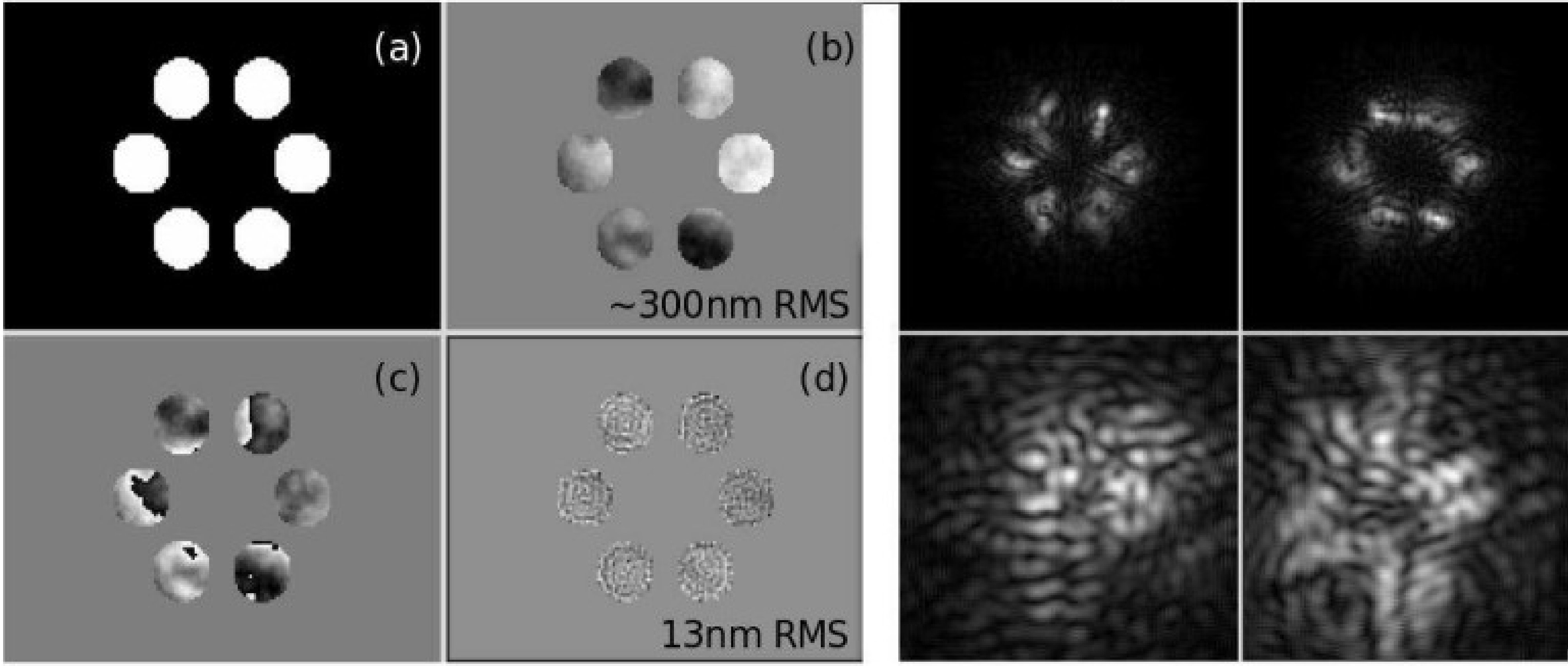
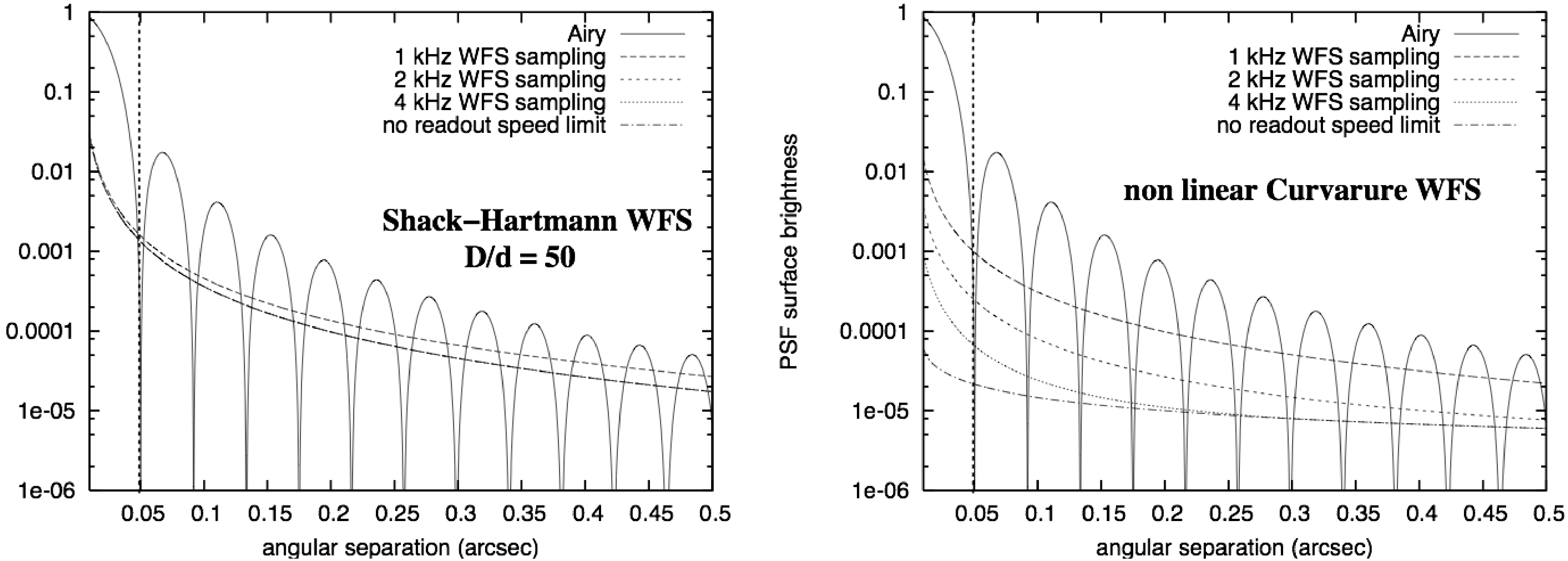


Fig. 9.— Wavefront reconstruction with dual stroke non-linear CWFS on a sparse pupil. The pupil amplitude (a) and phase (b) yield the four defocused pupil images shown on the right. The recovered pupil phase (c) and the residual phase error (d) demonstrate that dual stroke non-linear CWFS can simultaneously measure OPD within and across segments. This polychromatic simulation was performed with 2e8 photons in a $d\lambda/\lambda = 0.5$ wide band centered at 0.65 μm.

"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

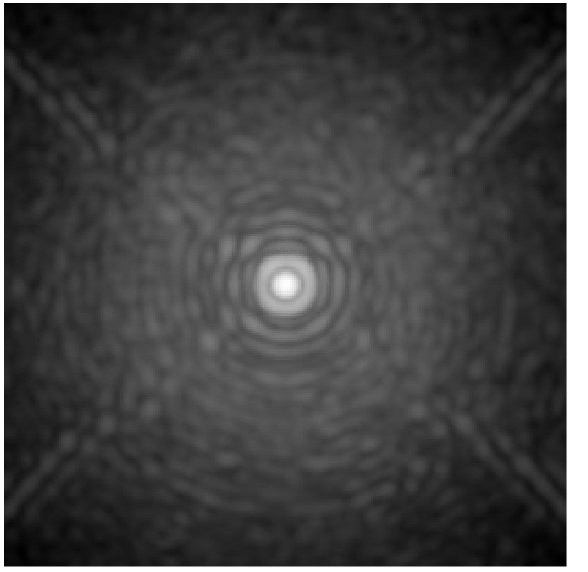
Performance gain for ExAO on 8-m telescopes



"High Sensitivity Wavefront Sensing with a non-linear Curvature Wavefront Sensor", Guyon, O. PASP, 122, pp.49-62 (2010)

Large gain at small angular separation: ideal for ExAO
Gain for GMT is larger.

Game-changing techniques for ExAO:
(2) 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”

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

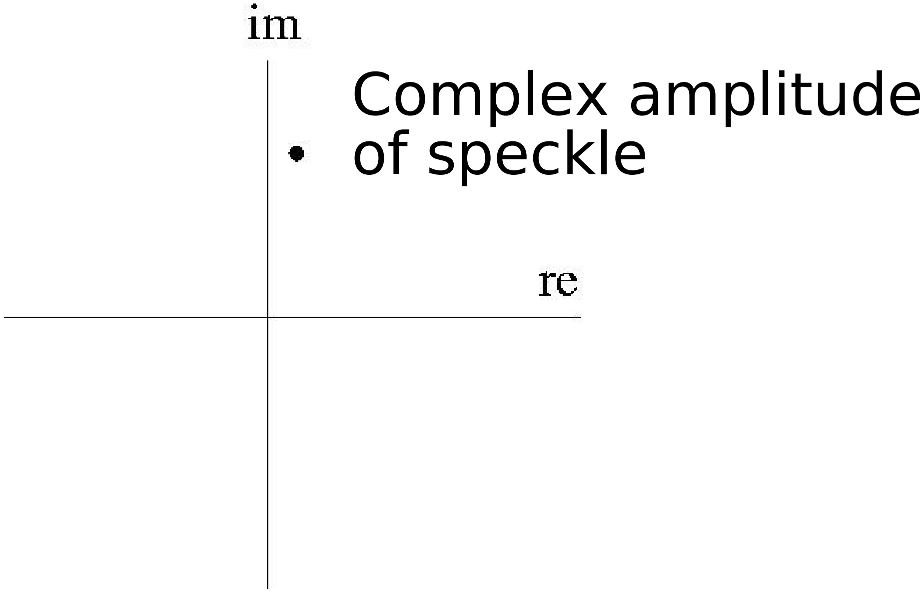
Measure speckle field with no previous knowledge:

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

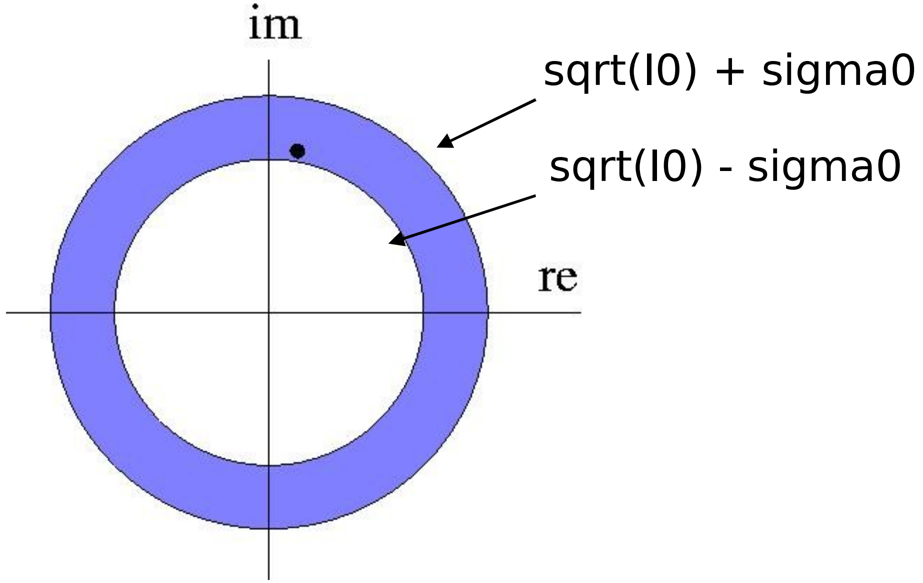
- compute 2 DM shapes which will add known speckles on top of existing speckles. These 2 “additive” speckle field have same amplitude as existing speckles, and the phase offset between the 2 additive speckle fields is PI/2

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

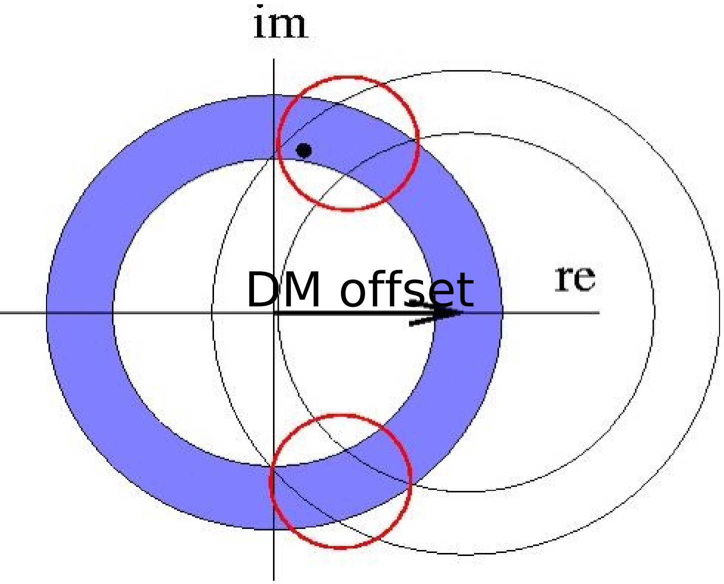
Initial problem

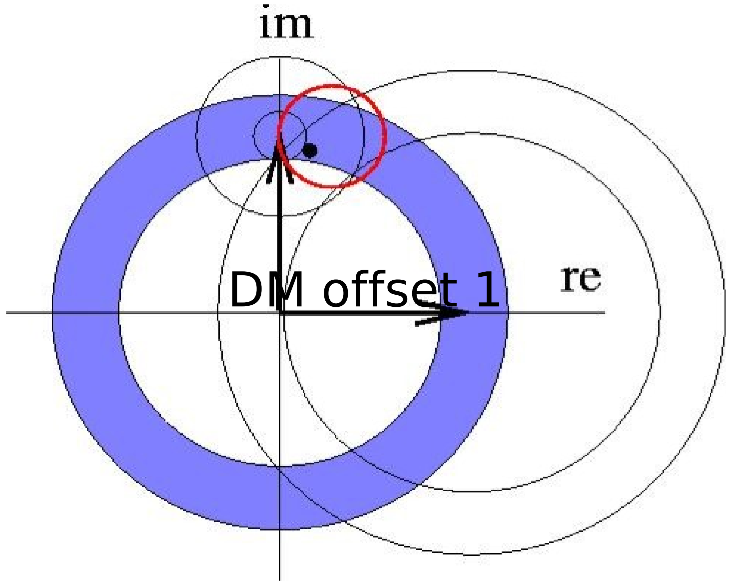


Take a frame -> measured speckle intensity = I0

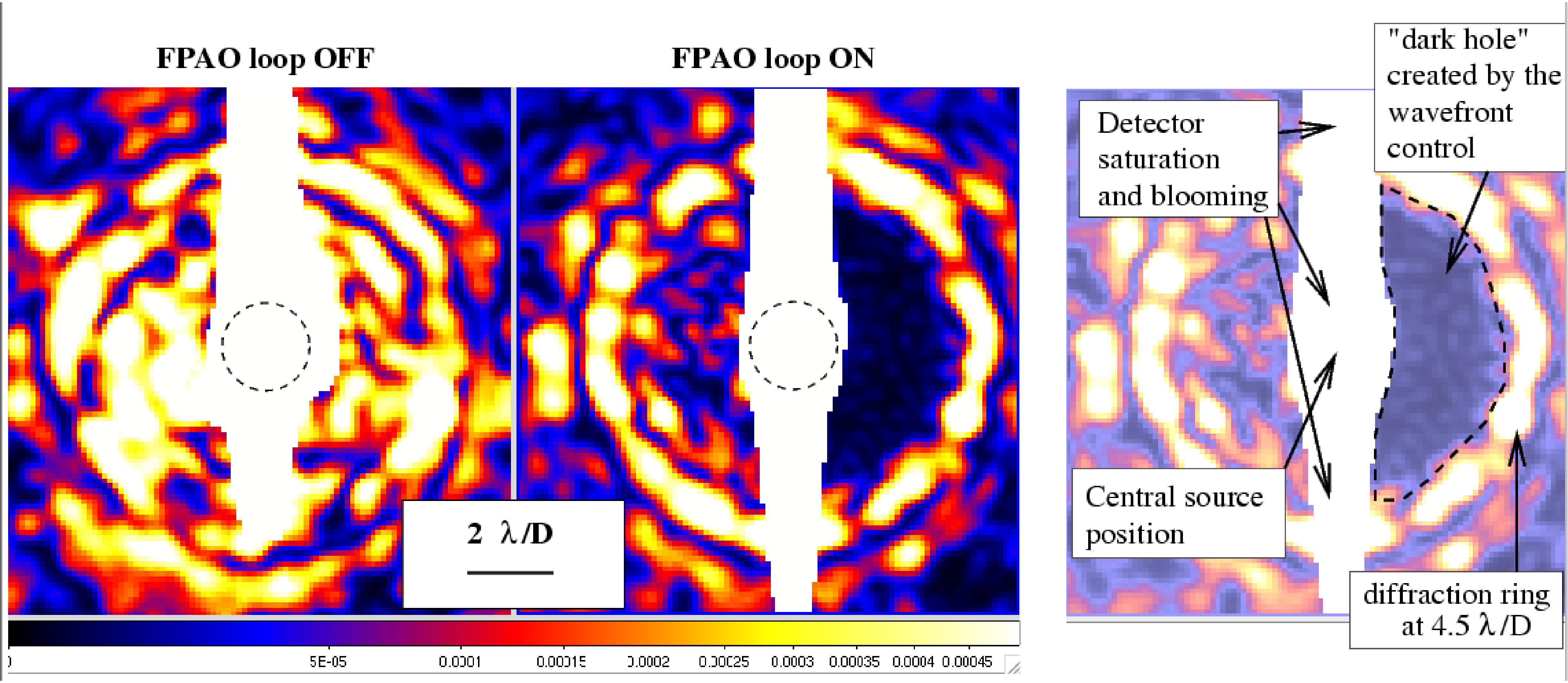


DM offset chosen to be ~ equal to speckle amplitude





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



See also results obtained at NASA JPL HCIT, NASA Ames & Princeton lab

All high contrast coronagraphic images acquired in lab use this technique.
- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics

Game-changing techniques for ExAO:
(3) Low Order Wavefront Sensor with coronagraph

(Guyon et al. 2010)

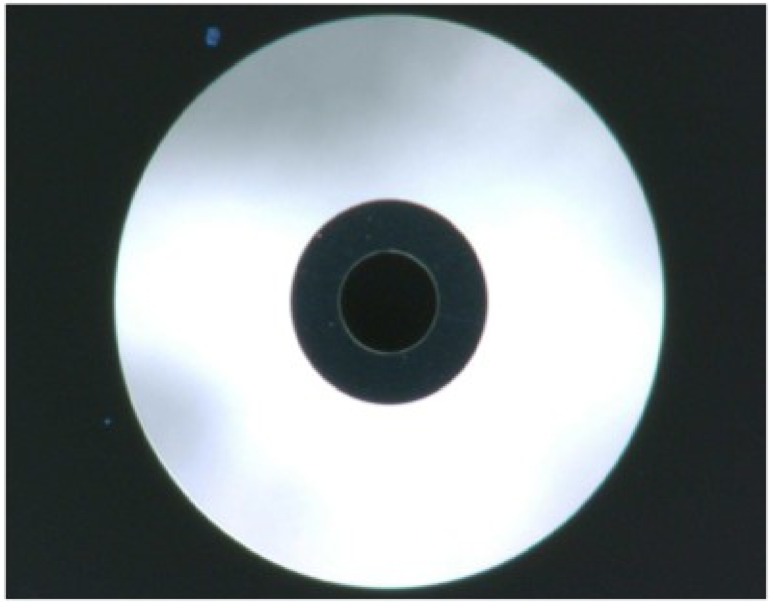
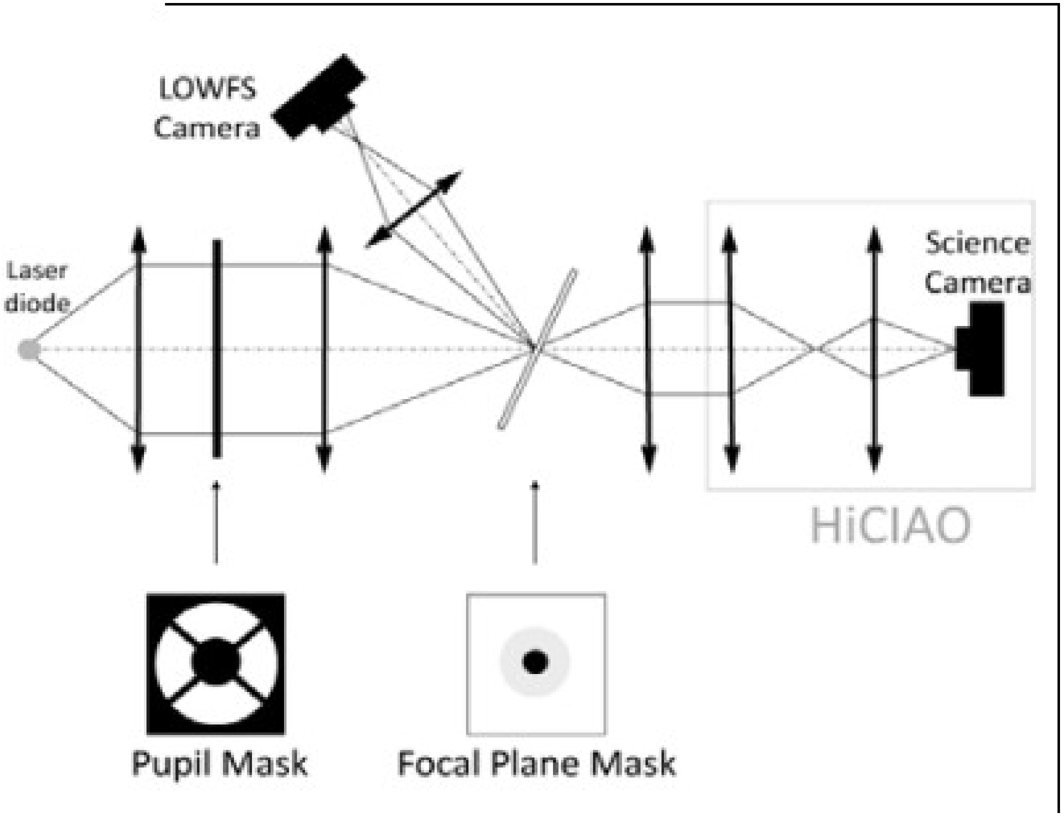
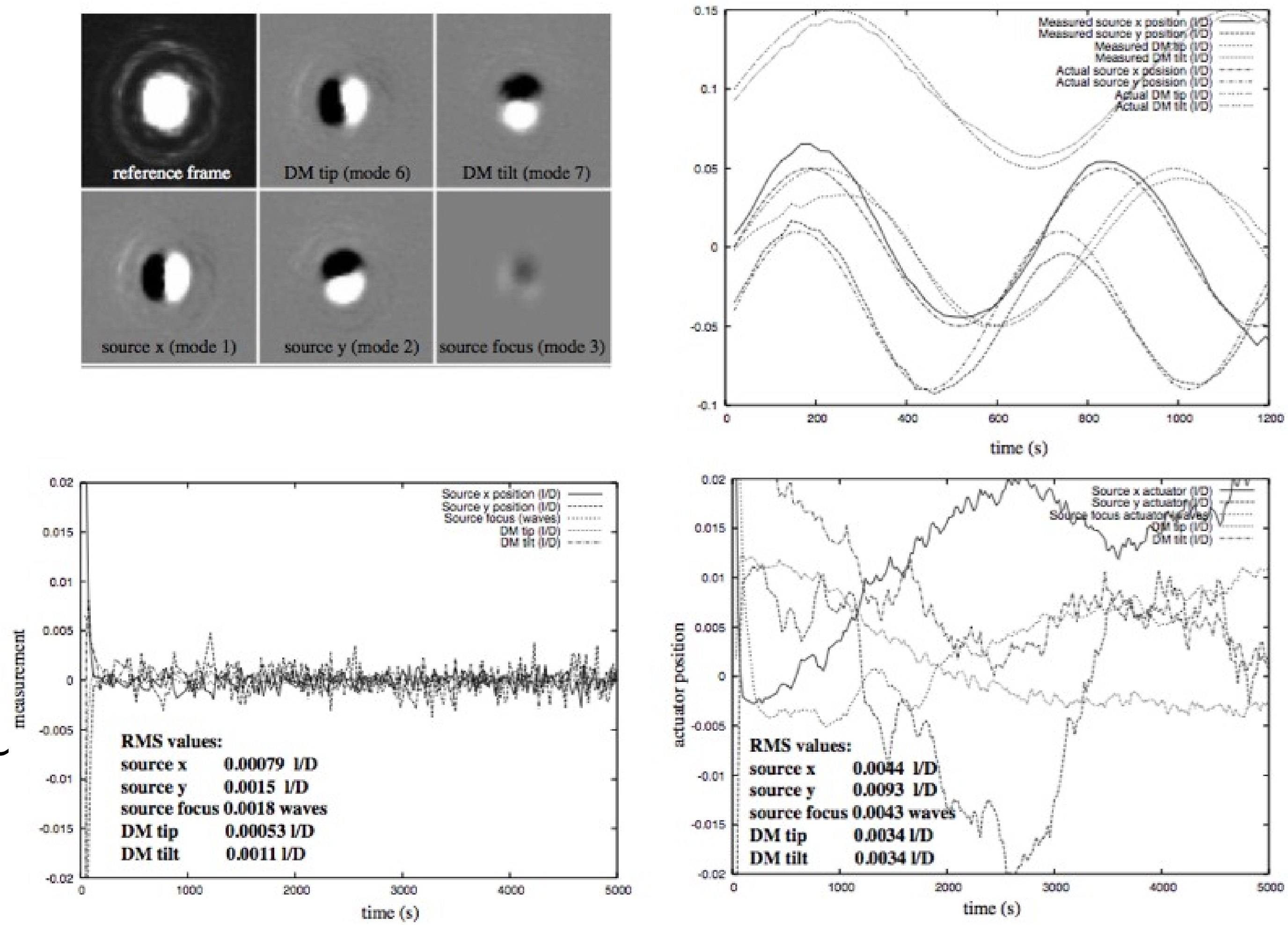


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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



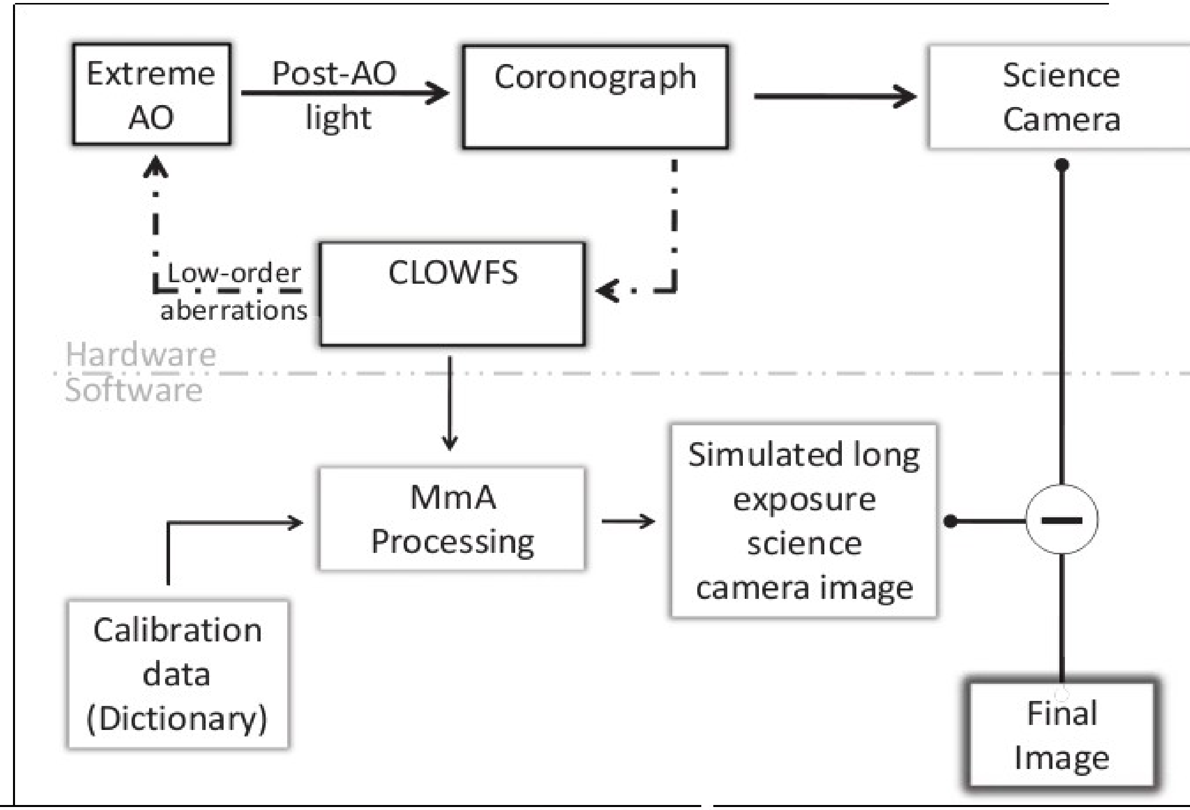
Pointing control demonstrated to 1e-3 l/D at Subaru PIAA testbed

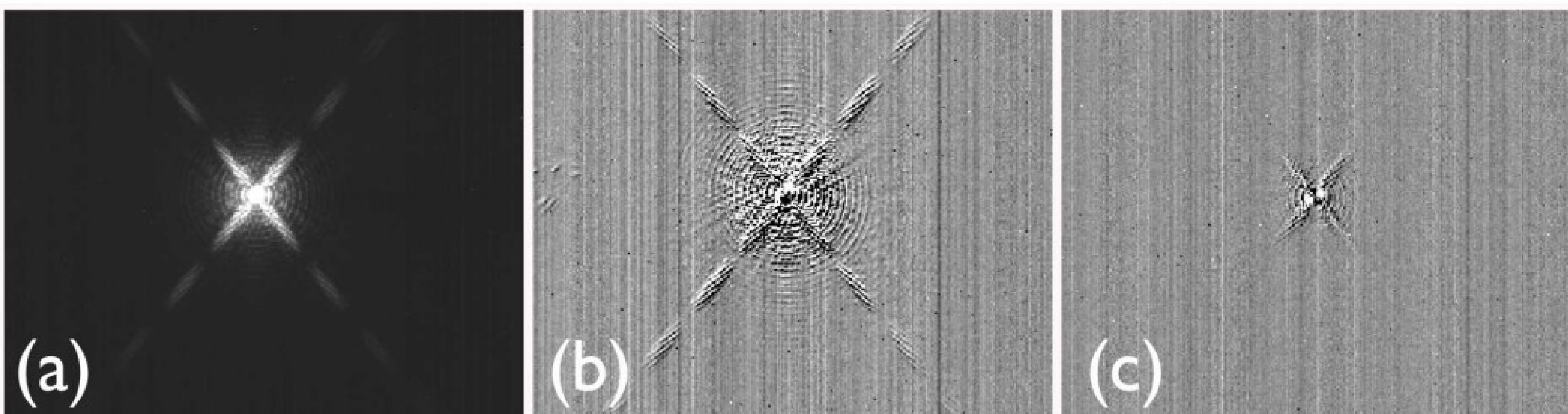


LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes.
Subaru Testbed has demonstrated closed loop pointing control to 1e-3 l/D ~ 0.1 mas on 1.4m PECO.
New "lookup table" algorithm removes residual low order coronagraphic leaks.
ref:
Guyon, Matsuo, Angel 2009
Vogt et al. 2010

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 $10^{-3}\ \lambda/D$ for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

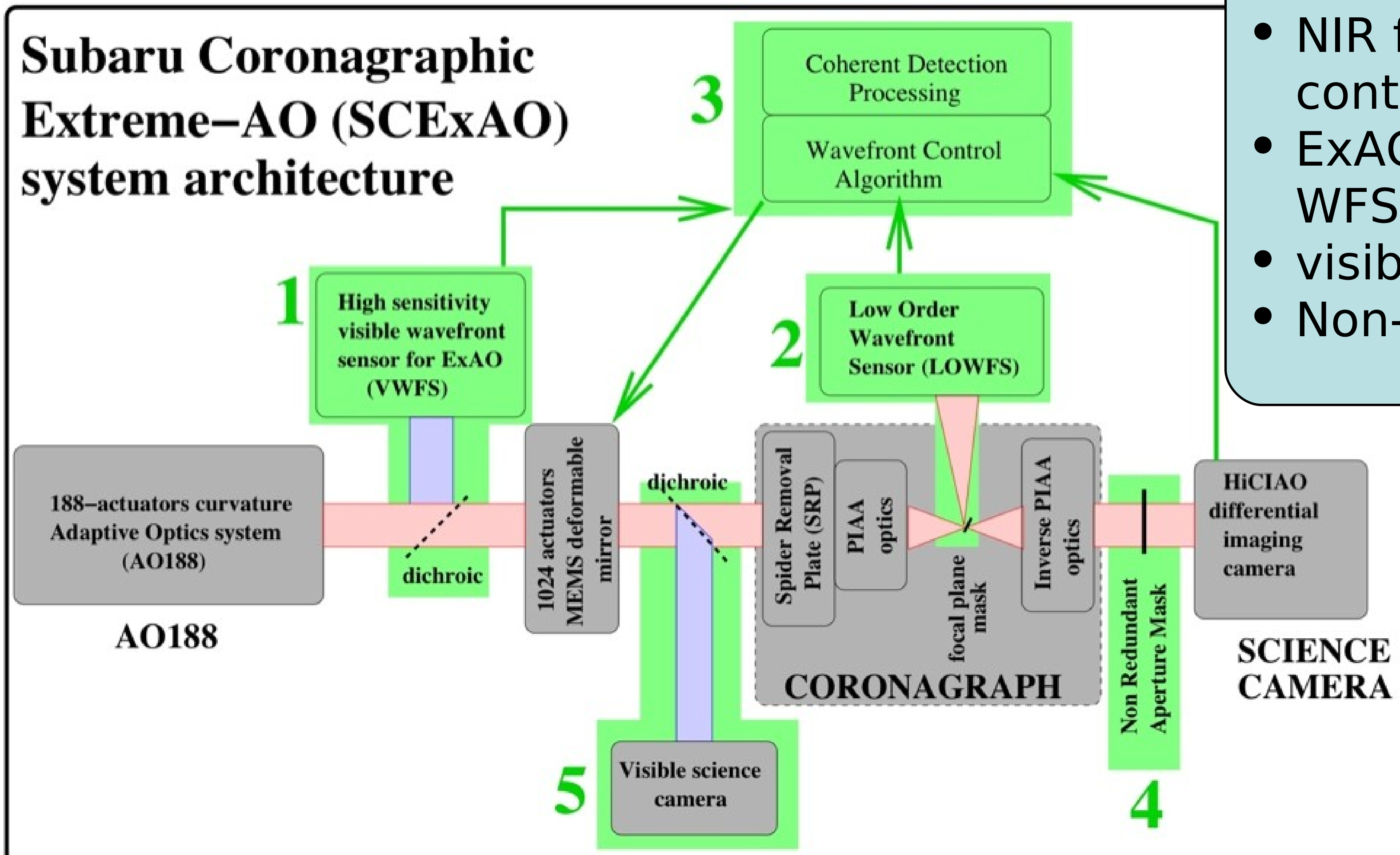
Coronagraph leaks calibrated to 1% (Vogt et al. 2010, in prep)





Subaru Coronagraphic Extreme-AO (SCExAO) system

http://www.naoj.org/Projects/SCEXAO/



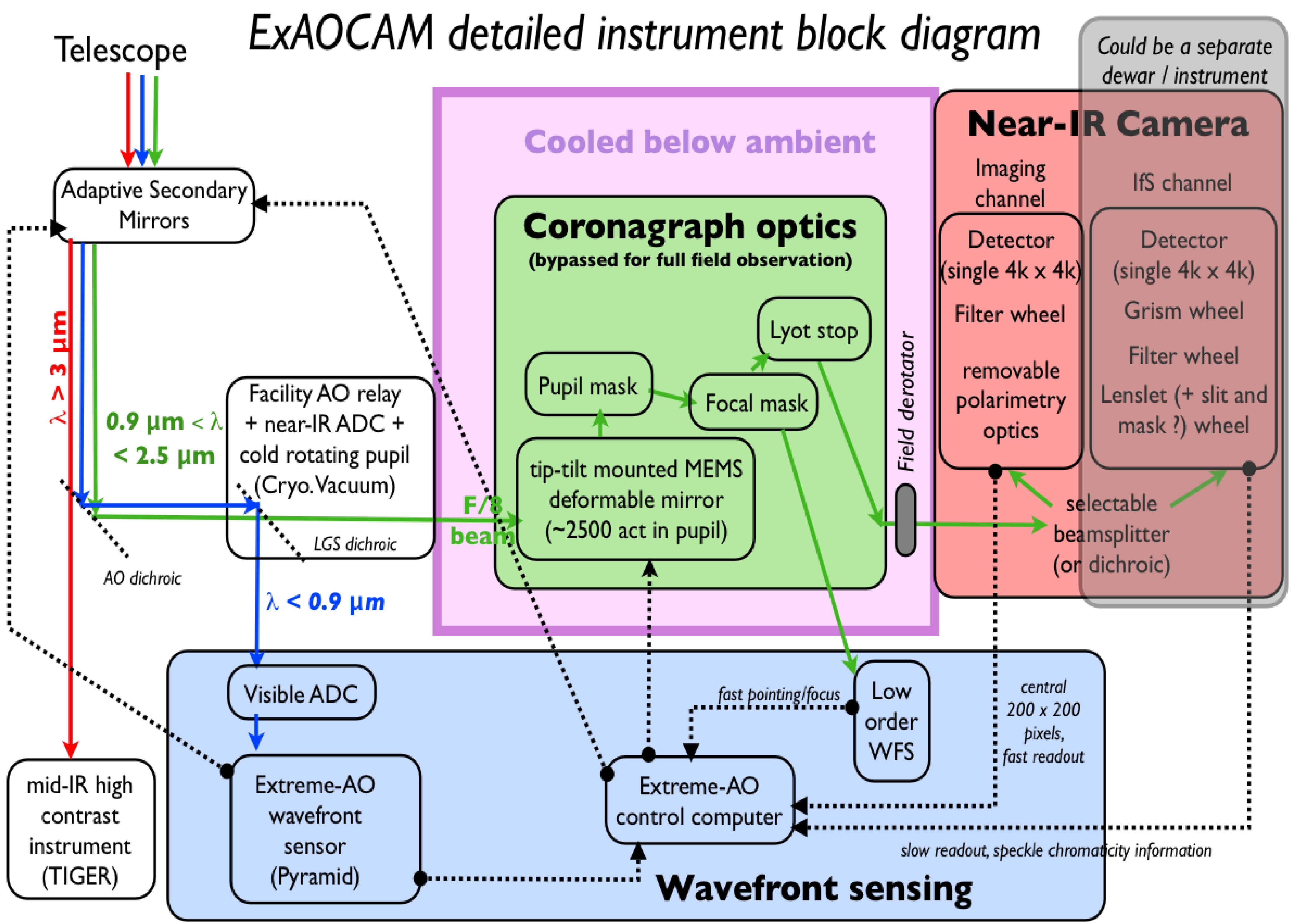
- 1 l/D PIAA coronagraph
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS
- visible channel
- Non-redundant masking

Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
First light in early 2011

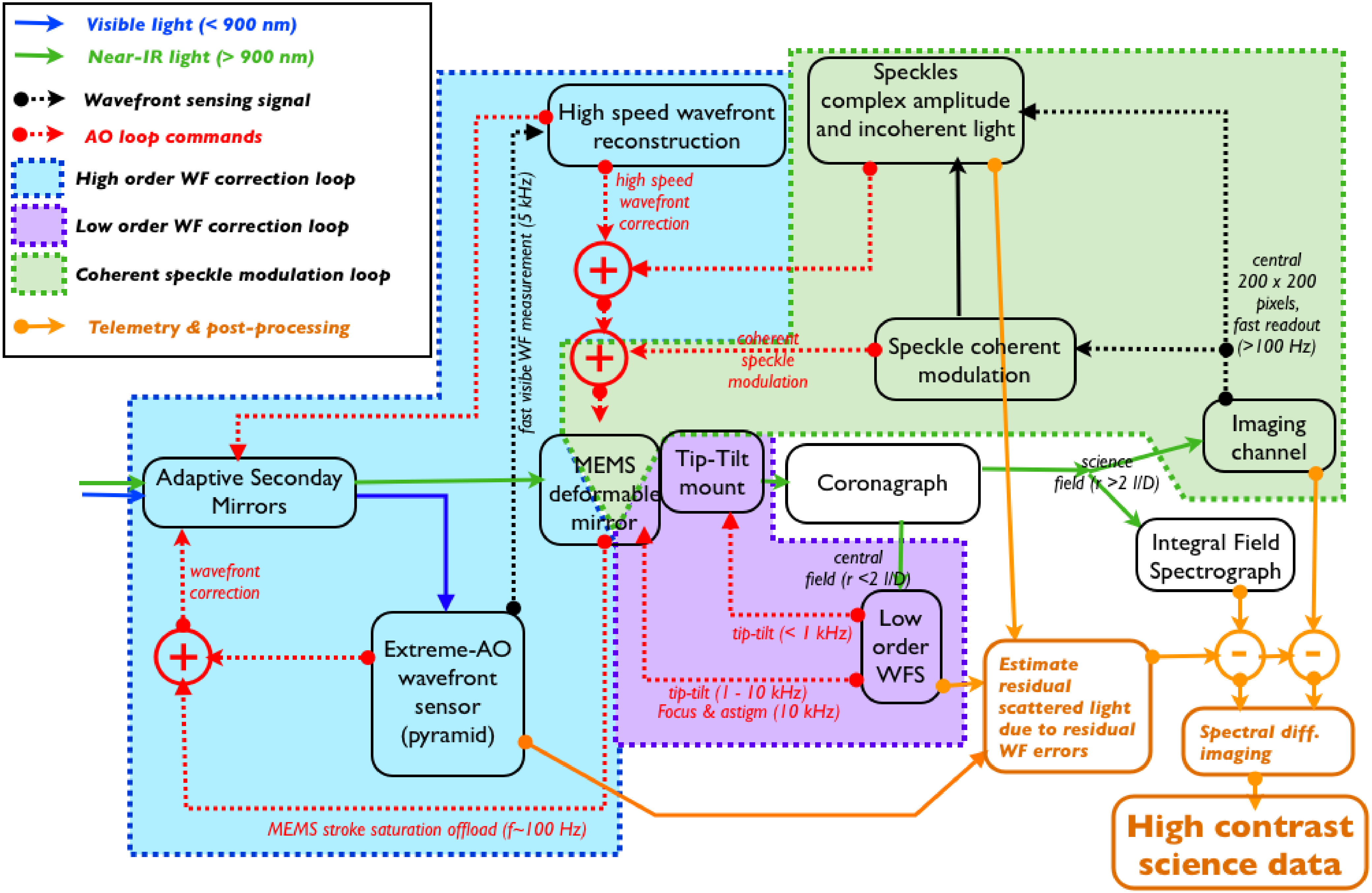
The next 2 slides show how a coronagraphic ExAO system might be implemented on GMT

Material is taken from the ExoCAM proposal for the study of a high contrast imaging instrument for GMT.

Note:
Adaptive Secondary Mirrors allow a simpler design: the ExAO system only includes the “fine correction” layer of the wavefront with a small MEMS type DM.


ExAOCAM detailed instrument block diagram
Telescope
Adaptive Secondary Mirrors
λ > 3 µm
0.9 µm < λ < 2.5 µm
AO dichroic
Facility AO relay + near-IR ADC + cold rotating pupil (Cryo.Vacuum)
LGS dichroic
λ < 0.9 µm
F/8 beam
Cooled below ambient
Coronagraph optics
(bypassed for full field observation)
Pupil mask
Focal mask
Lyot stop
tip-tilt mounted MEMS deformable mirror (~2500 act in pupil)
Field derotator
Could be a separate dewar / instrument
Near-IR Camera
Imaging channel
Detector (single 4k x 4k)
Filter wheel
removable polarimetry optics
IfS channel
Detector (single 4k x 4k)
Grism wheel
Filter wheel
Lenslet (+ slit and mask ?) wheel
selectable beamsplitter (or dichroic)
mid-IR high contrast instrument (TIGER)
Visible ADC
Extreme-AO wavefront sensor (Pyramid)
Extreme-AO control computer
fast pointing/focus
Low order WFS
central 200 x 200 pixels, fast readout
slow readout, speckle chromaticity information
Wavefront sensing

ExAOCAM: AO loop & signal extraction



Conclusions

With ExAO system, GMT can image and characterize disks and planets in and near the **habitable zones of nearby stars**:

- This is critical to understand planet formation and evolution in the habitable zone
- Ability to image reflected light planets will potentially allow study of Super-Earths around nearby stars

ExAO on GMT is no harder (or easier) than on other ELTs. The most challenging aspect of ExAO will be **wavefront control** and calibration, not coronagraphy itself.

Much will be learned in the next few years on 8-m class telescopes with ExAO systems such as GPI, SPHERE, SCExAO. This will provide a very good starting point for ExAO on GMT (take what works on 8-m telescopes and put it on GMT).

A **flexible system** will pay off: it will allow to stay ahead of the competition in this rapidly evolving field. With a focused instrument the cost and complexity can be kept low.