

# High-Contrast Imaging with the Astrophysics Focused Telescope Assets

N. Jeremy Kasdin

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Bob Vanderbei, Alexis Carlotti, Erin Elliot, Tyler Groff, Elizabeth Young

## AFTA SDT Charge:

- i. Use of the telescope assets “as is” to advance the science priorities described in the 2010 Decadal Survey for a Wide Field Infrared Survey Telescope; and
  - ii. Use of the telescope assets “as is” plus a coronagraph<sup>^</sup> defined in a parallel study to advance the science priorities described in the 2010 Decadal Survey for the detection and study of exoplanets.
- and wavefront control*

# Objectives of Talk

- What led to considering a coronagraph on the AFTA?
- What is the possible performance and what are the limitations?
- What exoplanet science might be accomplished?
- What is the state of coronagraph technology for an on-axis telescope?

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A more careful and thorough analysis is planned as part of the AFTA SDT.

# Boundary Conditions:

A game-changing opportunity to accomplish priority science programs of “New Worlds New Horizons” . . . the potential exists to have greater capability for the WFIRST science, enable additional scientific opportunities, match or reduce cost, and improve schedule.

–Alan Dressler, 9/4

With the 2.4 m AFTA used for WFIRST and a robust GO program, there is room for a narrow field imager with high-contrast capability. Preliminary design work shows that with < 60 nm wavefront error and existing optics, a 2 to 10 arcsec system in 400-1100 nm band is easily accommodated. Wavefront error is a factor of 2 or more better than Hubble and JWST and within capability of deformable mirror based control. Telescope is stable with closed loop thermal and dynamic control.

A coronagraph or occulter with AFTA-1 “as-is” could . . .

1. Directly detect and *characterize* in visible light giant planets down to Neptune size that are 1-10 AU from their host star. (Complementary to ground systems.)
2. Perform excellent disk science.
3. Characterize the exozodi around typical systems down to 5x the local zodi.
4. Perform critical technology development and demonstration in space.

. . . at less than the cost of a SMEX!

# Constraints:

“Since the telescope assets come to us as-is and free, it seems inappropriate to use first quality new hardware to develop a science driven system that costs as much as a new (if somewhat smaller) mission capability . . . focus on what can be done for science at the lowest price.”

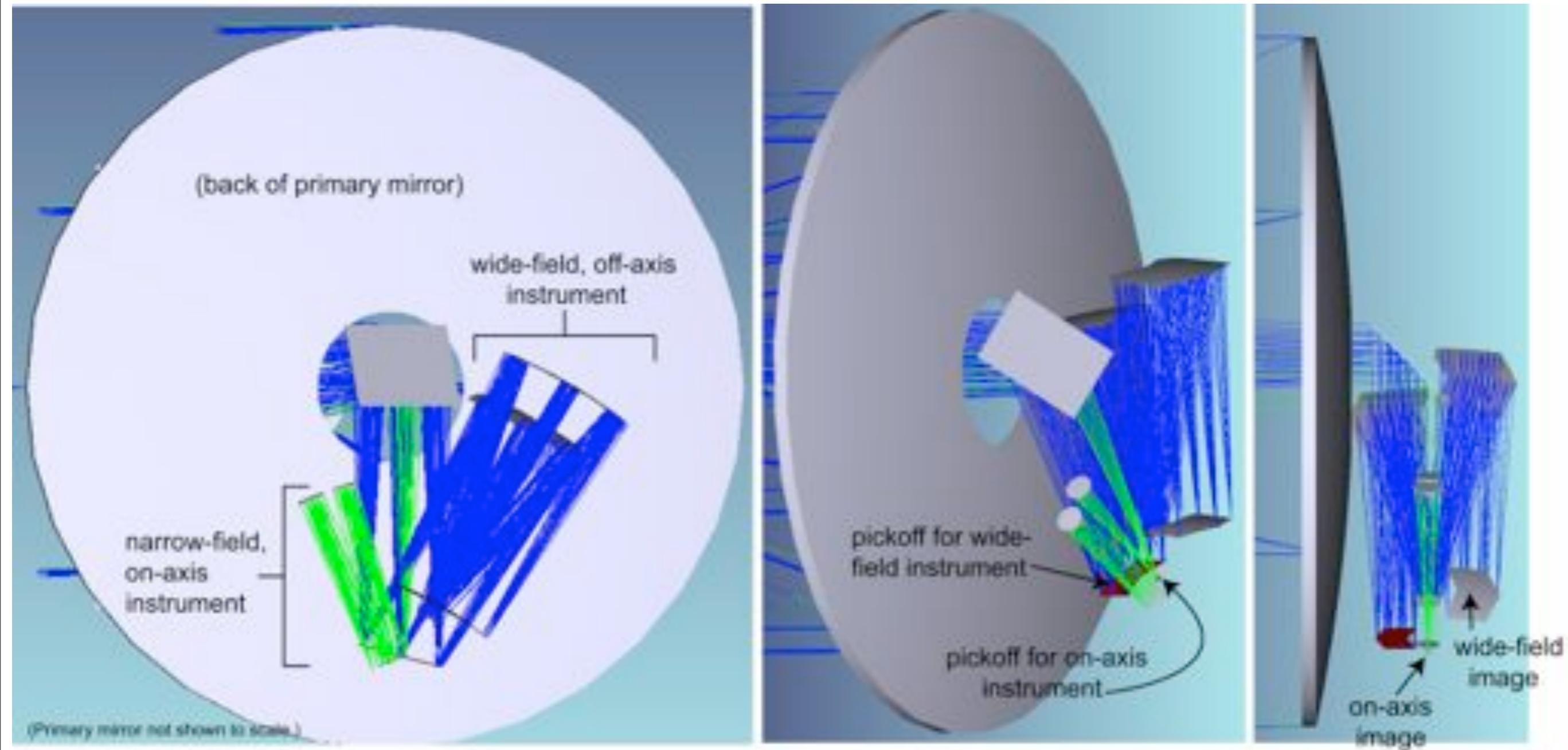
–Michael Moore, 9/4

Meaning, no changes to telescope to accommodate high-contrast imager, use simple, lab proven coronagraphs, keep cost and risk down, and possibly limit mission to HEO or GEO (for robotic servicing).

- Earth orbit constrains instrument to some type of coronagraph (no occulter).
- Likely limited to a single narrow (10-20%) band channel (2 or 3 DMs) with filter wheel due to cost and space constraints.
- Goal for spectrograph, but may be limited to filter photometry by cost and space constraints.
- Ultimate performance will be limited by telescope stability.

Nevertheless, still an outstanding opportunity for exoplanet science and technology pathfinding that would enable a future mission. Coronagraphs exist that could be made flight ready almost immediately.

# AFTA-I with On-Axis Narrow-field Instrument:



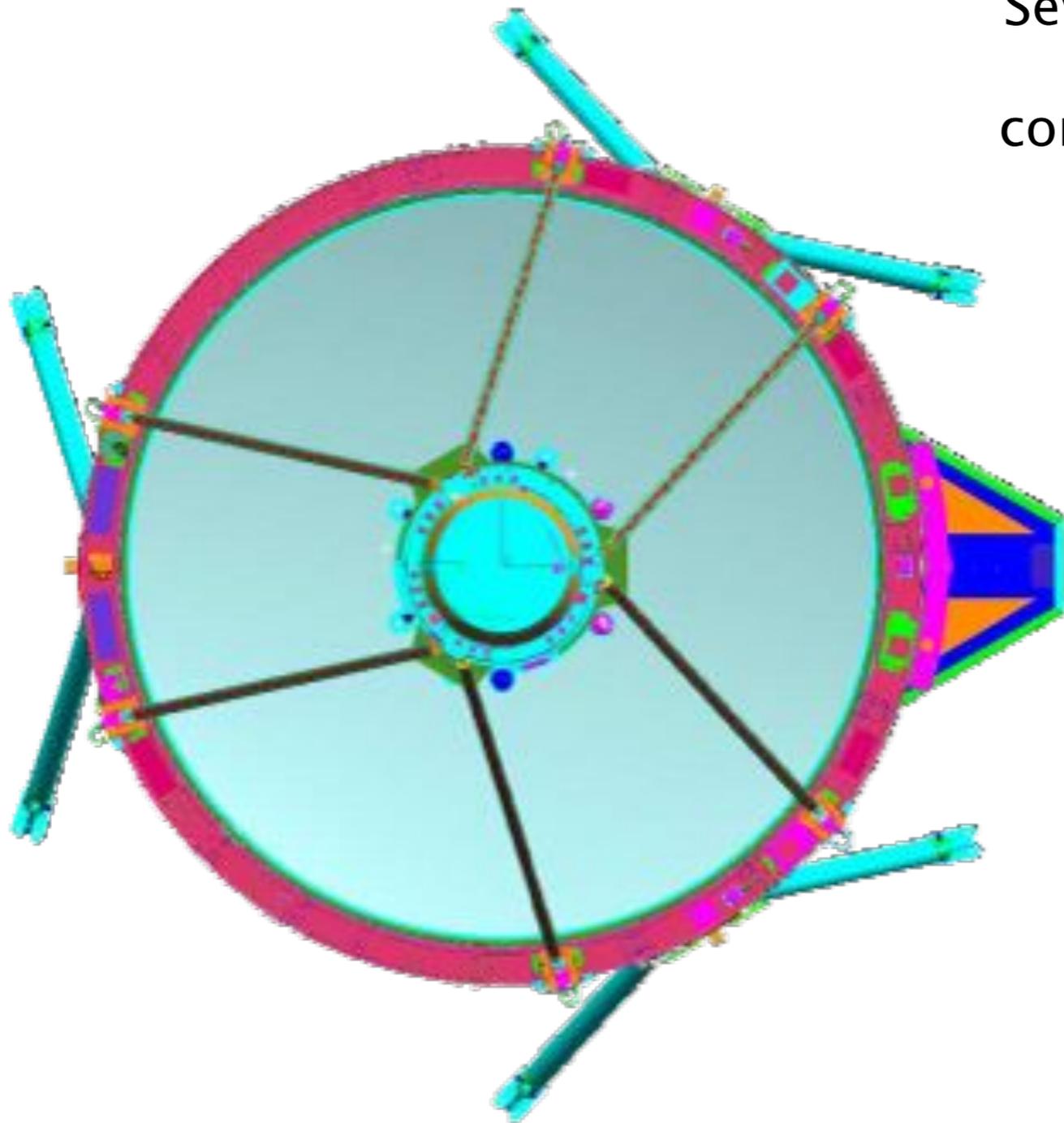
courtesy Erin Elliot, STScI



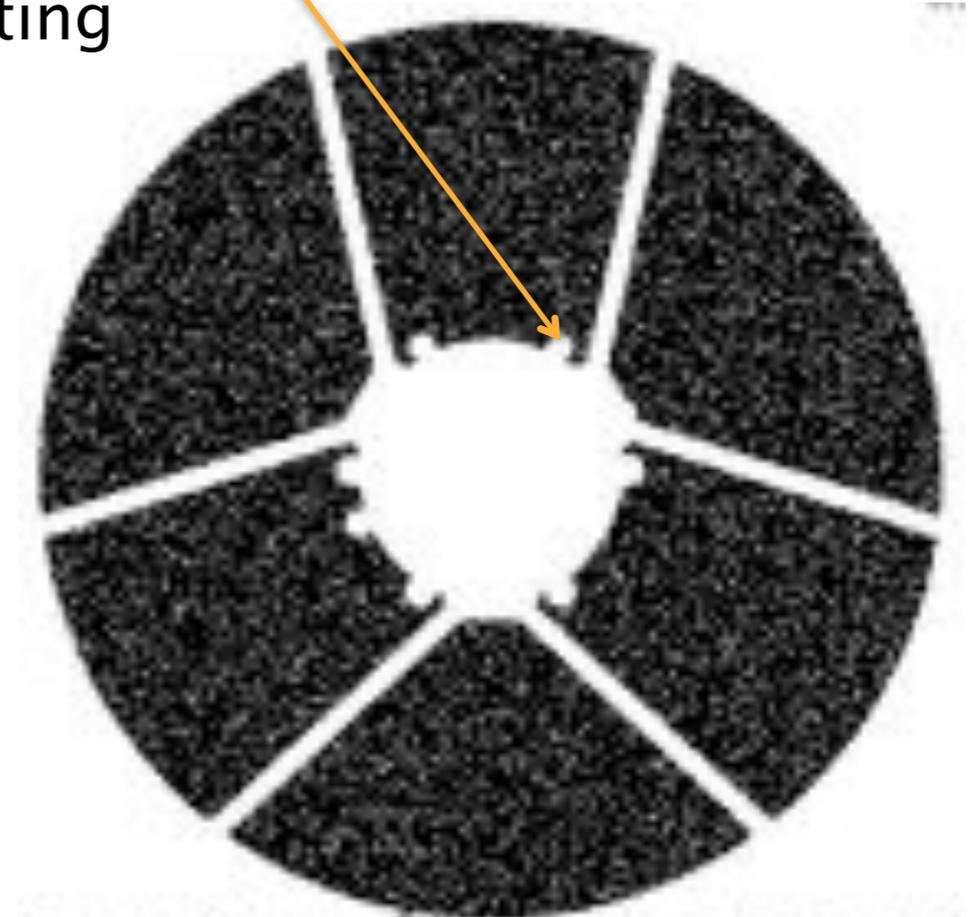
# System Obstruction

courtesy Gary Mathews, Exelis

Complicated pupil makes high-performance coronagraphy challenging.



Seven coating artifacts correctable by recoating



## On Axis Pupil

17% Obstructed

Strut Mean Width: 41mm

Strut Obstruction Length: 881mm

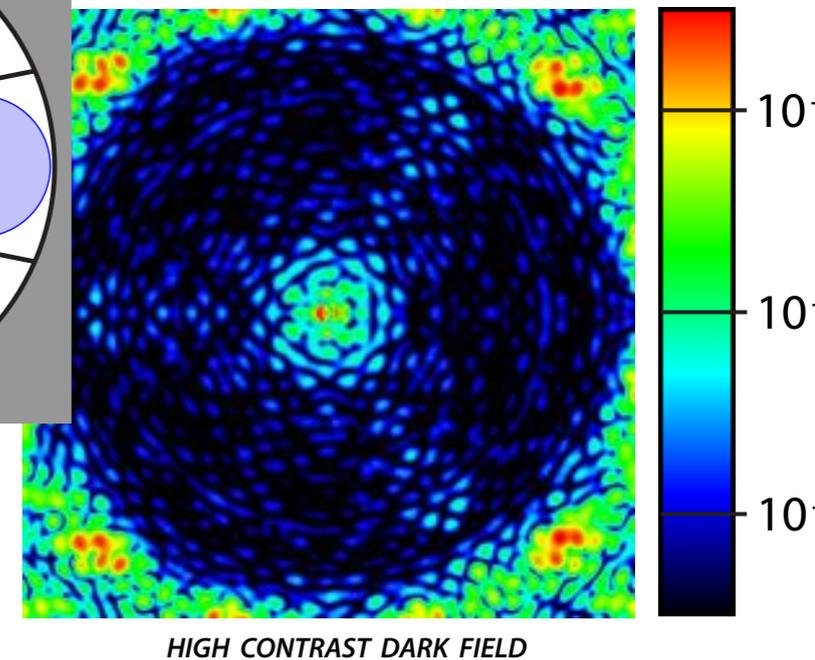
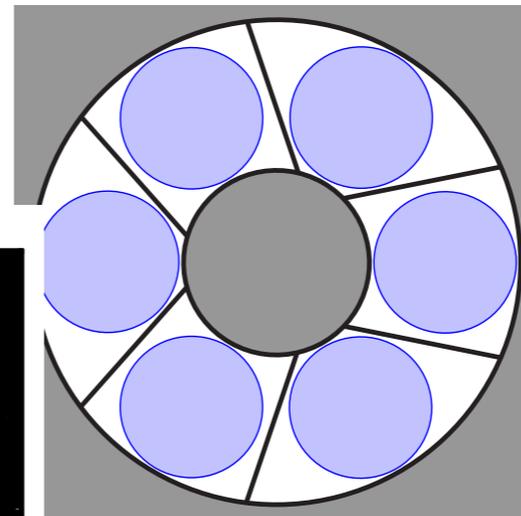
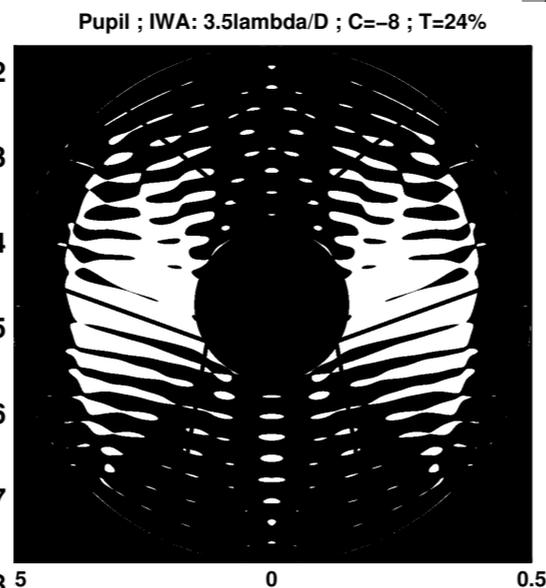
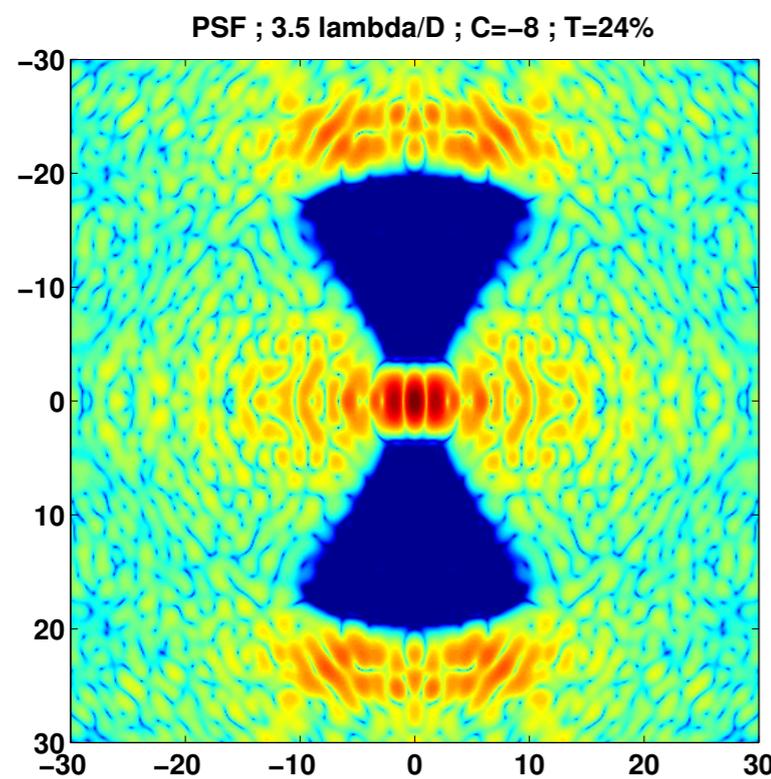
# Coronagraph + WFC Design & Performance:

The usual metrics:

- Contrast
- Inner working angle
- Throughput
- Outer working angle
- Discovery space
- Bandwidth/chromaticity
- Complexity

New approaches exist for on-axis systems with spiders

- Shaped pupils
- Complex Lyot
- PIAA-CMC
- Visible Nuller



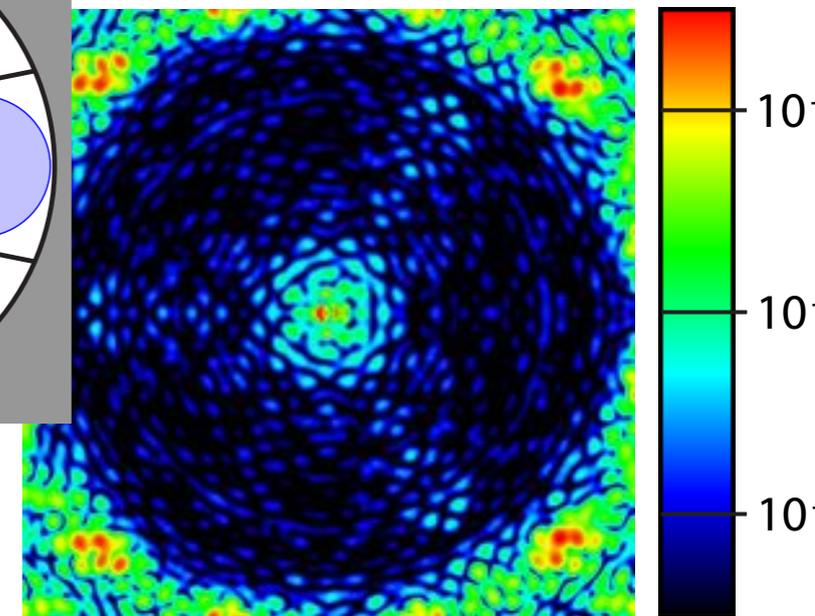
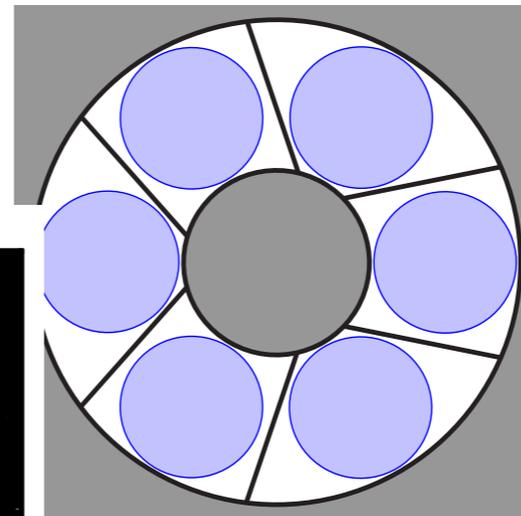
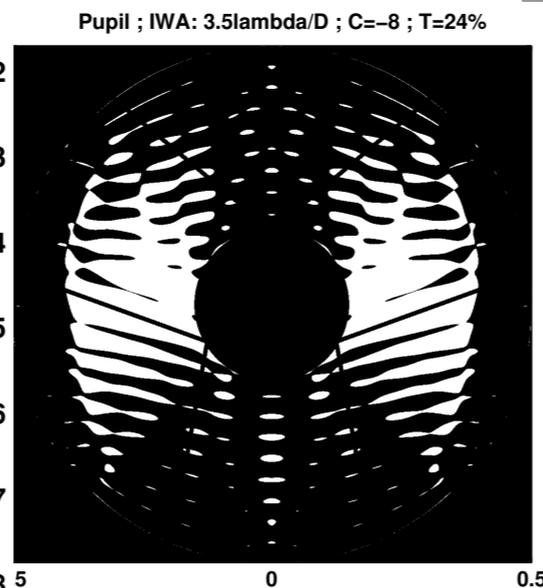
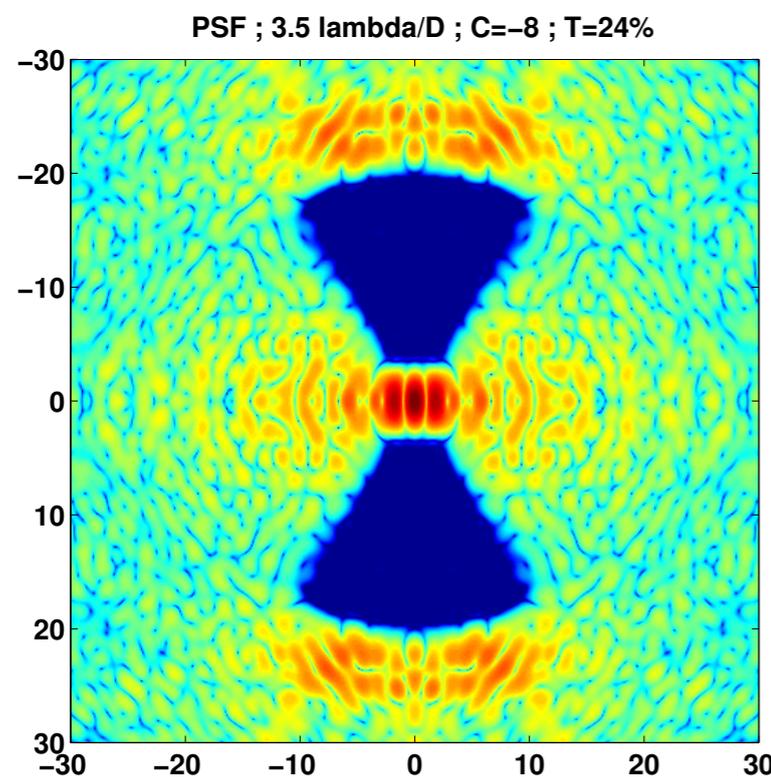
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HIGH CONTRAST DARK FIELD

**AFTA mission would be ideal testbed to compare performance and realizability of different coronagraphs.**

# Telescope stability will be limiting factor on contrast

- Coronagraphs differ widely in sensitivity to low-order aberrations.
- Controlled contrast likely limited to  $10^{-8}$  with inner working angles of  $\geq 3 \lambda/D$ .
- Optimistic bound is  $10^{-9}$ , probably requiring low-order wavefront sensor and closed loop control and/or post-processing.
- Weak lensing places tight requirements on stability of low order aberrations.
- Further analysis of telescope thermal/mechanical stability is essential

Table 5. Key requirements for systematic noise floor, radial masks, at 2, 2.5, and 3  $\lambda/D$ .

Shaklan, et al. 2011

Allocation	2 $\lambda/D$ radial complex		2.5 $\lambda/d$ radial complex		3 $\lambda/d$ radial amplitude	
	Reqmnt.	$\Delta$ Contrast	Reqmnt.	$\Delta$ Contrast	Reqmnt.	$\Delta$ Contrast
PM x-coma drift, picometers	1.00	2.0E-12	2.50	2.0E-12	5.00	2.7E-12
PM y-coma drift, picometers	1.00	2.0E-12	2.50	2.0E-12	5.00	2.7E-12
Secondary Mirror z-motion drift, nm	0.40	1.9E-12	0.80	2.0E-12	1.60	1.8E-12
Secondary Mirror y-motion drift, nm	0.80	1.7E-12	1.60	2.0E-12	3.00	1.4E-12
PM spherical aberration drift, picometers	1.00	1.1E-12	2.00	1.3E-12	4.00	4.8E-13
Secondary Mirror x-motion drift, nm	0.80	7.6E-13	1.60	4.1E-13	3.00	6.1E-13
Pointing zero-point x-offset drift, milliarcsec	0.10	4.5E-13	0.14	6.4E-13	0.30	7.5E-13
Pointing zero-point y-offset drift, milliarcsec	0.10	4.5E-13	0.14	6.4E-13	0.30	7.5E-13
PM focus drift, picometers	2.00	3.7E-13	4.00	4.9E-13	8.00	3.3E-13
Secondary Mirror x-tilt drift, milliarcsec	0.17	2.6E-13	0.34	1.4E-13	0.62	2.2E-13
Secondary Mirror y-tilt drift, milliarcsec	0.17	2.2E-13	0.34	1.2E-13	0.62	1.9E-13
Line-of-sight x-drift, milliarcsec	2.00	1.5E-13	2.00	2.2E-13	2.00	2.8E-13

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Ex.: Off-axis telescope with 4th order Lyot and  $10^{-10}$  overall contrast requires picometer stability.

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**AFTA mission would provide critical in-situ information on dynamic and thermal performance**

# AFTA Potential High-Contrast Science

Thanks to Bruce Macintosh, Dmitry Savransky, Karl Stapelfeld, Aki Roberge, Olivier Guyon, Glenn Schneider, Marshall Perrin

## Baseline Assumption:

A robust coronagraph at  $10^{-8}$  to  $10^{-9}$  contrast with 3 to 3.5  $\lambda/D$  inner working angle at 800 nm and 20% to 50% throughput.

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That performance level should be achievable with current technology.

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## ○ Protoplanetary and debris disk imaging

1. Evolution of disk structure = constraints on planet formation
2. Disk multi-color imaging & polarimetry = dust properties
3. Debris disk structure characterization = indicators of planets
4. Exozodi dust measurements in visible = prepare for terrestrial planet direct imaging

## ○ Gas and ice giant exoplanet detection & characterization

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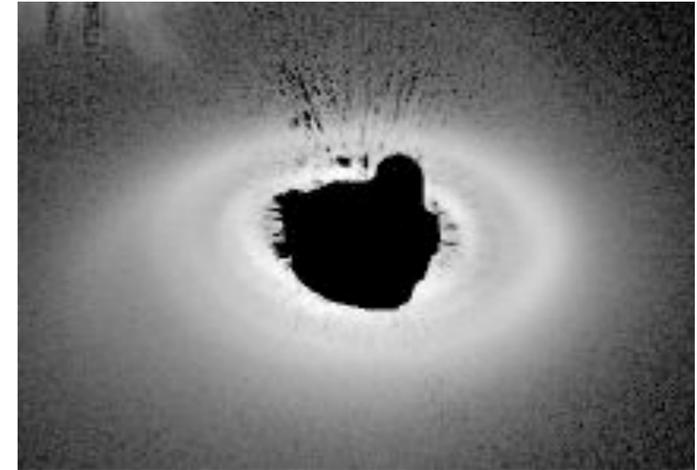
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**Consistent with Small Explorer Science Mission.**

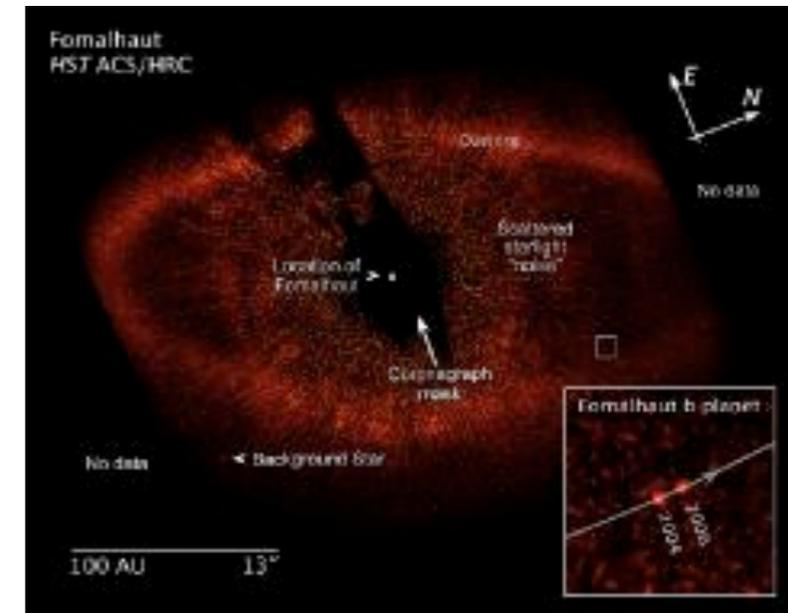
# Protoplanetary & Debris Disk Imaging

At short wavelength (400 nm), AFTA could reach into 0.1" (1 AU at 10 pc).

- Evolution of circumstellar disk properties, from early protoplanetary stages through mature main sequence debris disks
  - ALMA will have exceptional performance for protoplanetary disk thermal imaging. The niche for optical imaging is to measure **scattered light**, then calculate dust properties (e.g. albedos) in conjunction with ALMA. Important for probing dust composition as planetary material grows.
- Measure the distribution of dust particles around nearby stars, in order to develop a comparative understanding of planetary **system architectures** (including asteroid and Kuiper belts).
  - Imaging disk structures around stars known to have IR excess from Herschel & Spitzer. Accessible targets range from dozens to hundreds, depending on contrast and outer working angle. HZ dust accessible in only a few systems.
- Characterize disk-planet and disk-ISM interactions to understand how substructures within dusty debris can be used to infer the presence of planets.
  - Requires imaging on 0.1" scales to measure disk asymmetries, sharpness of their edges, and dynamical relationship to planets measured in the systems.
  - Cannot be done by ALMA, as most debris disks are too faint in the submillimeter to allow imaging at this resolution.
  - Important to prepare for possible confusion issues in optical wavelength **direct imaging of terrestrial planets**.



HD 141569 : HST/ACS  
Clampin et al. (2003)



Fomalhaut b : HST/ACS  
Kalas et al. (2008)

[Yes, it's probably a planet (Currie et al. 2012).]

# Exozodiacal Dust & Planet Imaging

Roberge et al. (2012)

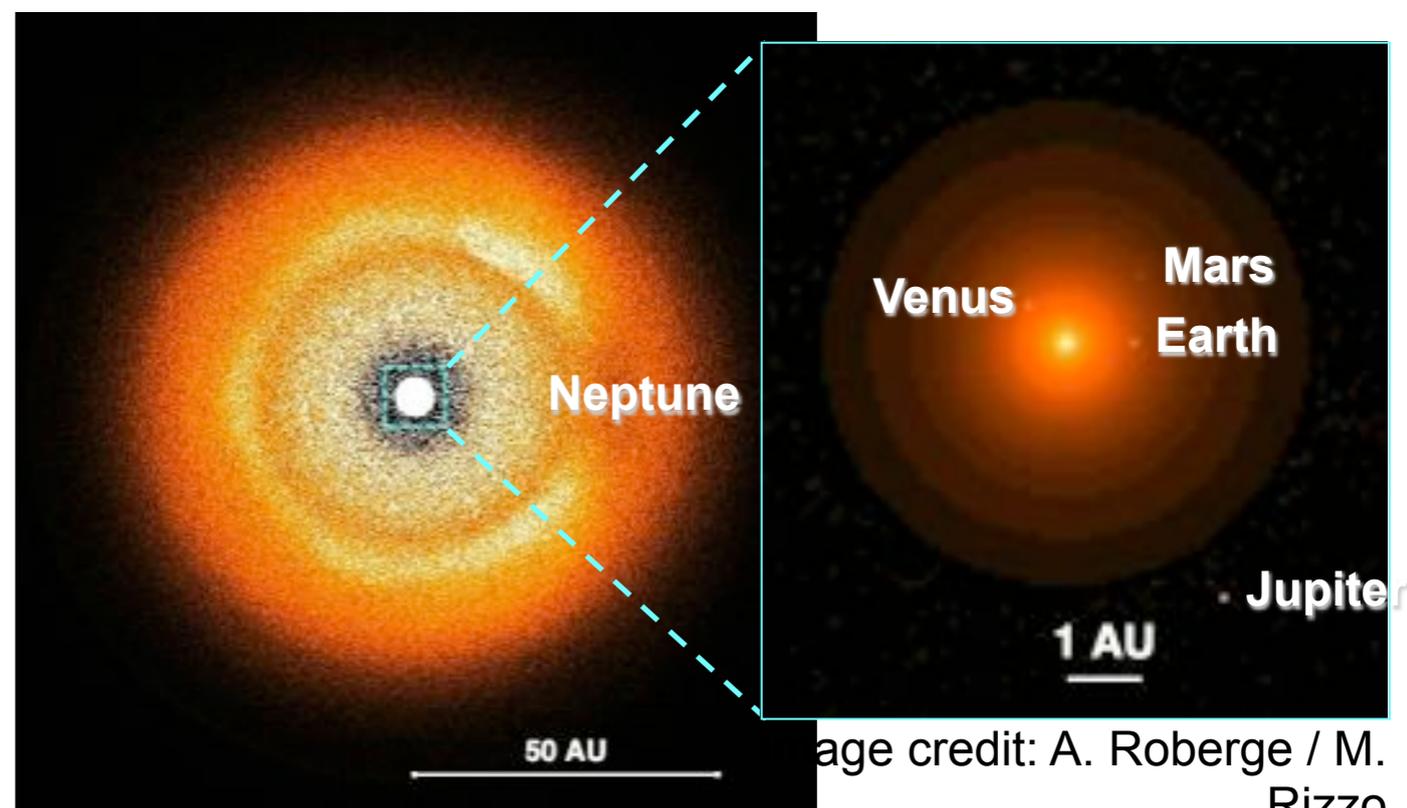
**Decadal Survey ASTRO2010: “... need to characterize the level of zodiacal light present so as to determine, in a statistical sense if not for individual prime targets, at what level starlight scattered from dust will hamper planet detection”.**



1 zodi  $\sim 10^{-9}$  at 1 AU for 2.4 m telescope (10x Earth brightness, decreases as distance<sup>2</sup>).

AFTA at  $10^{-9}$  could measure a few zodi at 1 AU, 5-10 zodi out to 4 AU.

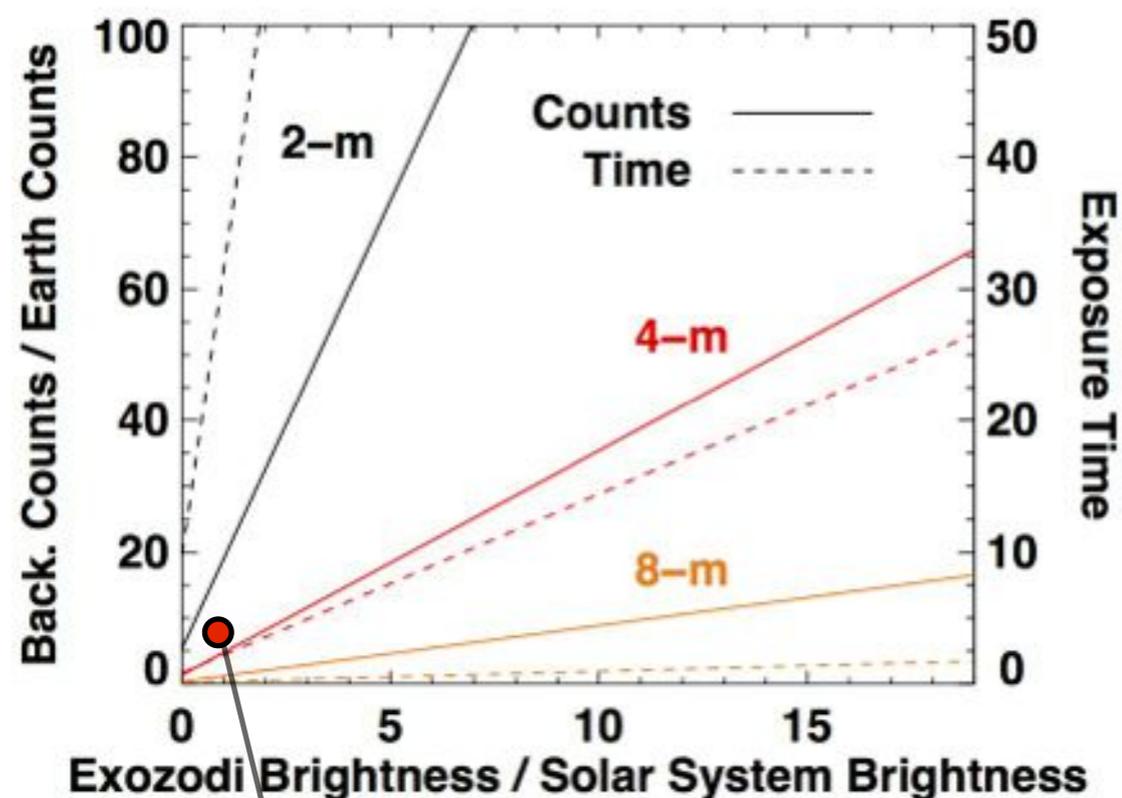
Optical imaging removes ambiguity extrapolating from LBTI thermal emission.



High-resolution simulation of Solar System without Sun at 0.6 micron

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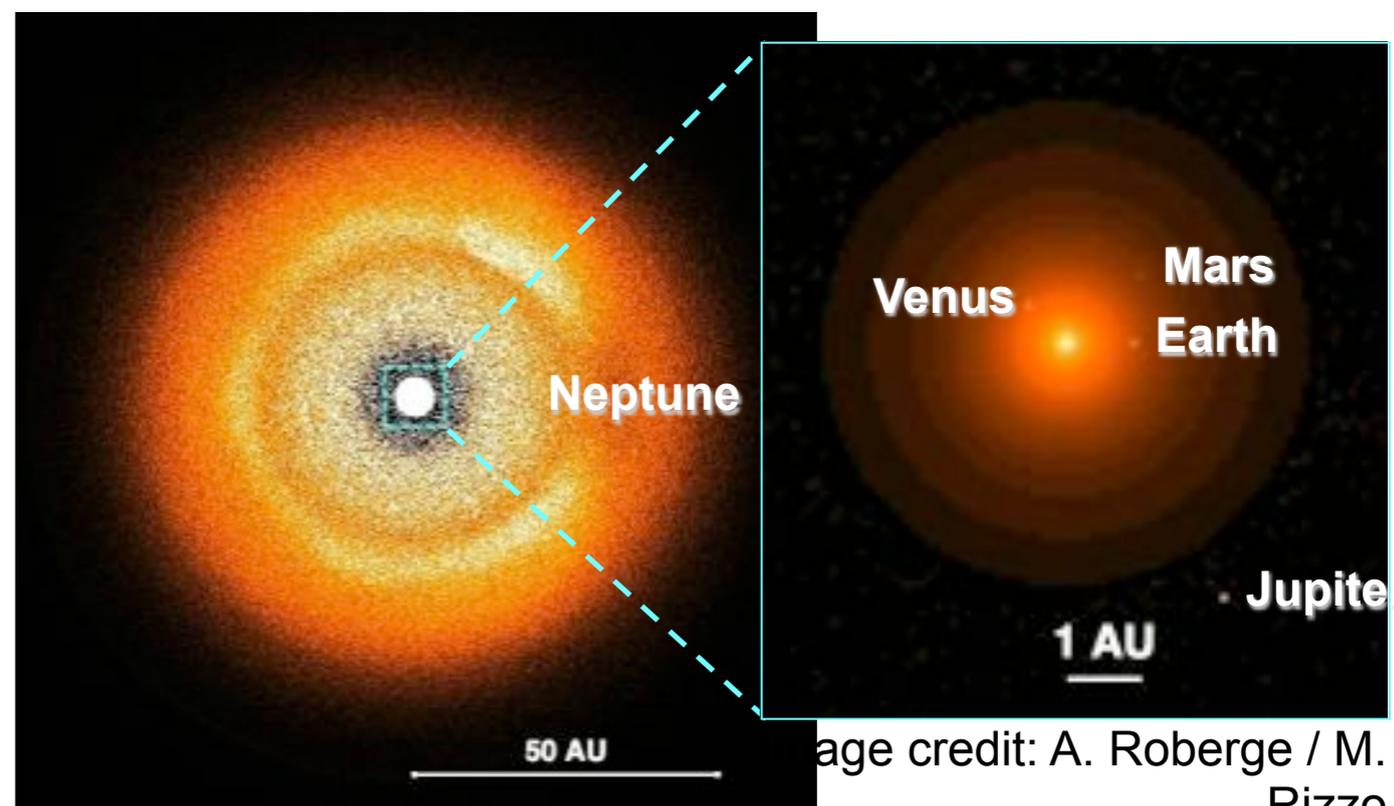


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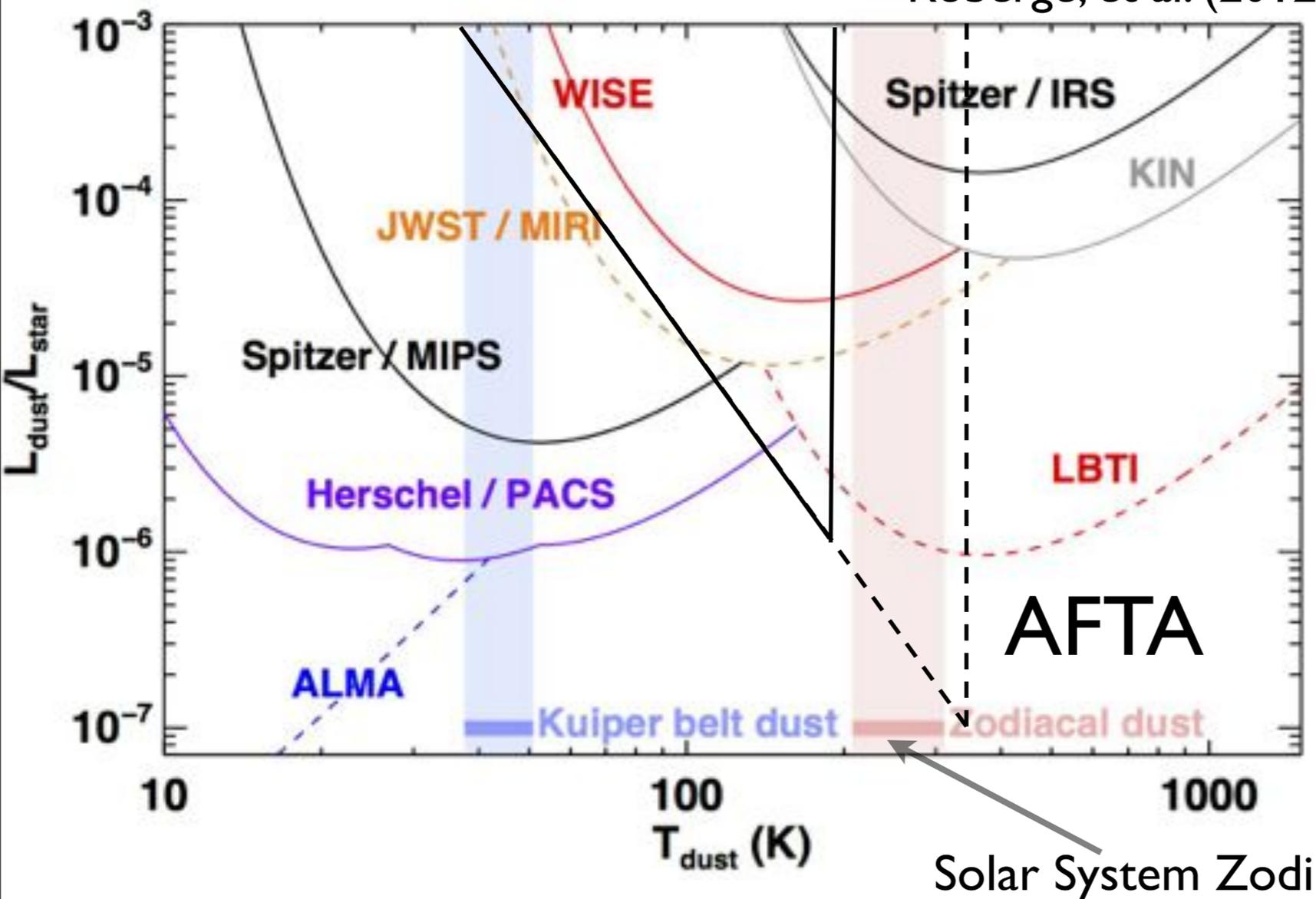


High-resolution simulation of Solar System without Sun at 0.6 micron

# Exozodical Disk Characterization

- G-star at 10 pc
- - - G-star at 3-5 pc

Roberge, et al. (2012)



Sensitivity limits for detection of debris dust around nearby Sun-like stars, for various recent (Spitzer, WISE), current (KIN, Herschel) and near-term facilities (LBTI, JWST, ALMA). The curves show  $3\sigma$  detection limits in terms of the fractional dust luminosity ( $L_{\text{dust}}/L_{\text{star}}$ ) versus its temperature. Recent and current facilities are plotted with solid lines, near-term ones with dashed lines. The temperature ranges for dust in two zones around the Sun are shown with vertical bars, calculated assuming blackbody grains. The habitable zone (0.8 AU – 1.8 AU) is shown in pink, the Kuiper belt (30 AU – 55 AU) is shown in light blue. The modeled  $L_{\text{dust}}/L_{\text{star}}$  values for the Solar System's Kuiper belt dust are marked with horizontal light blue and pink bars.

**Optimized coronagraph on the AFTA could detect & characterize visible scattered light from dust with  $L_{\text{dust}}/L_{\text{star}} \sim 10^{-6}$  at  $T_{\text{dust}} \sim 200$  K ( $r \sim 2$  AU) for small number of stars.**

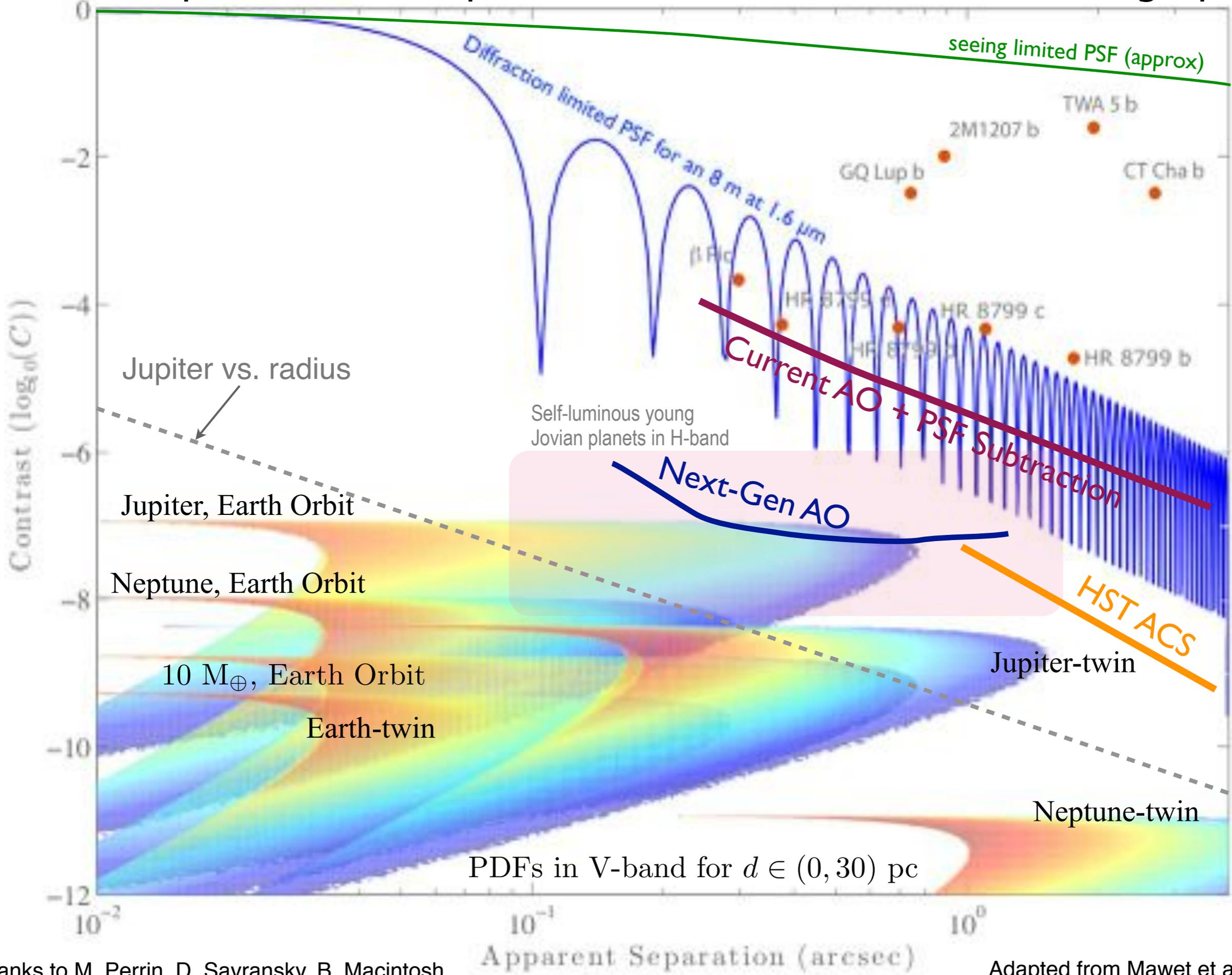
# Exoplanet Detection & Characterization

The next few slides explore the space of reachable planets by a 2.4 m telescope with  $3 \lambda/D$  inner working angle at 800 nm.

Not included is consideration of integration time affected by stellar (planet) magnitude and background. This will necessarily limit the number of planets that could be imaged in a given fraction of the mission. A careful monte carlo simulation needs to be performed.



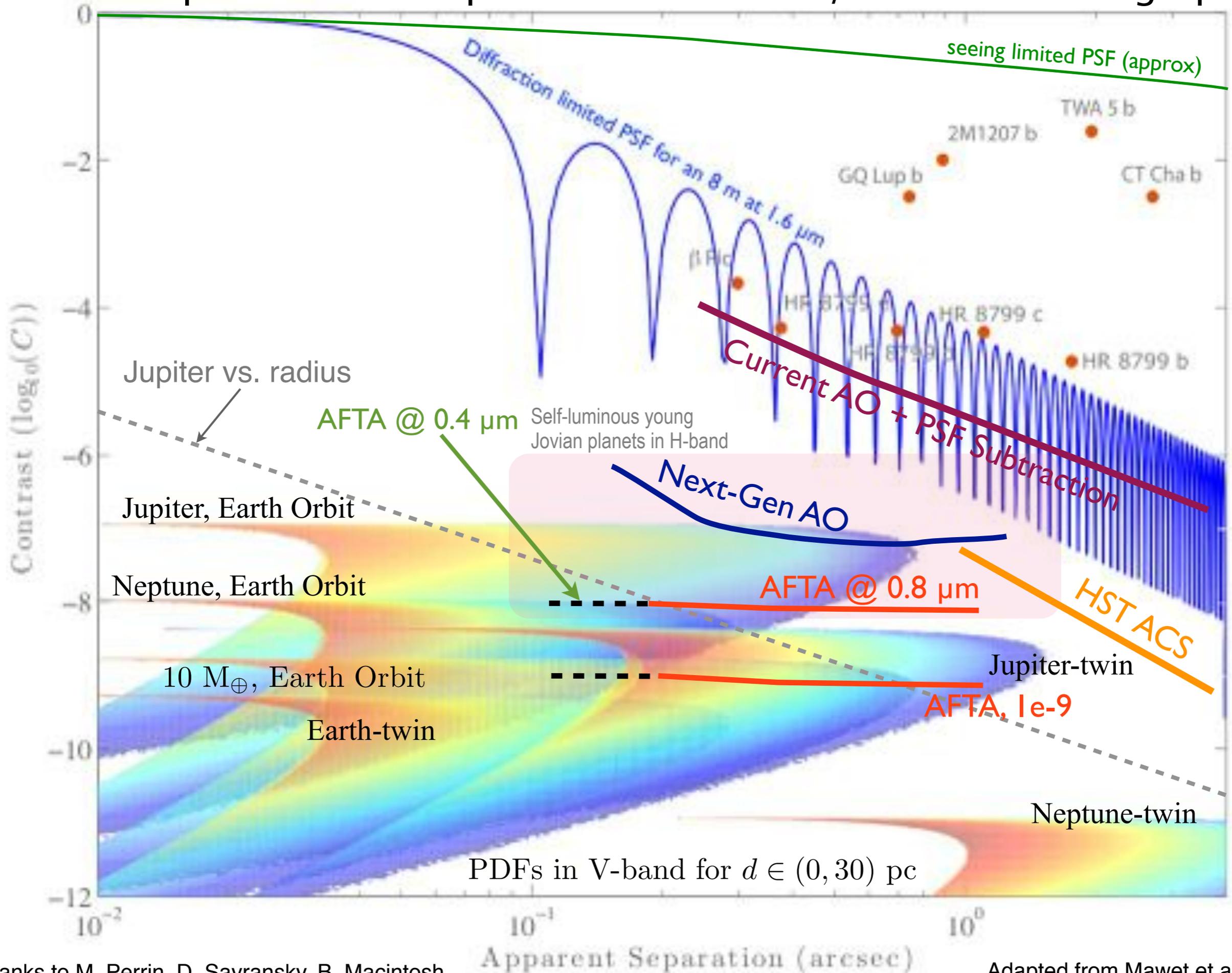
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Thanks to M. Perrin, D. Savransky, B. Macintosh

Adapted from Mawet et al. 2012

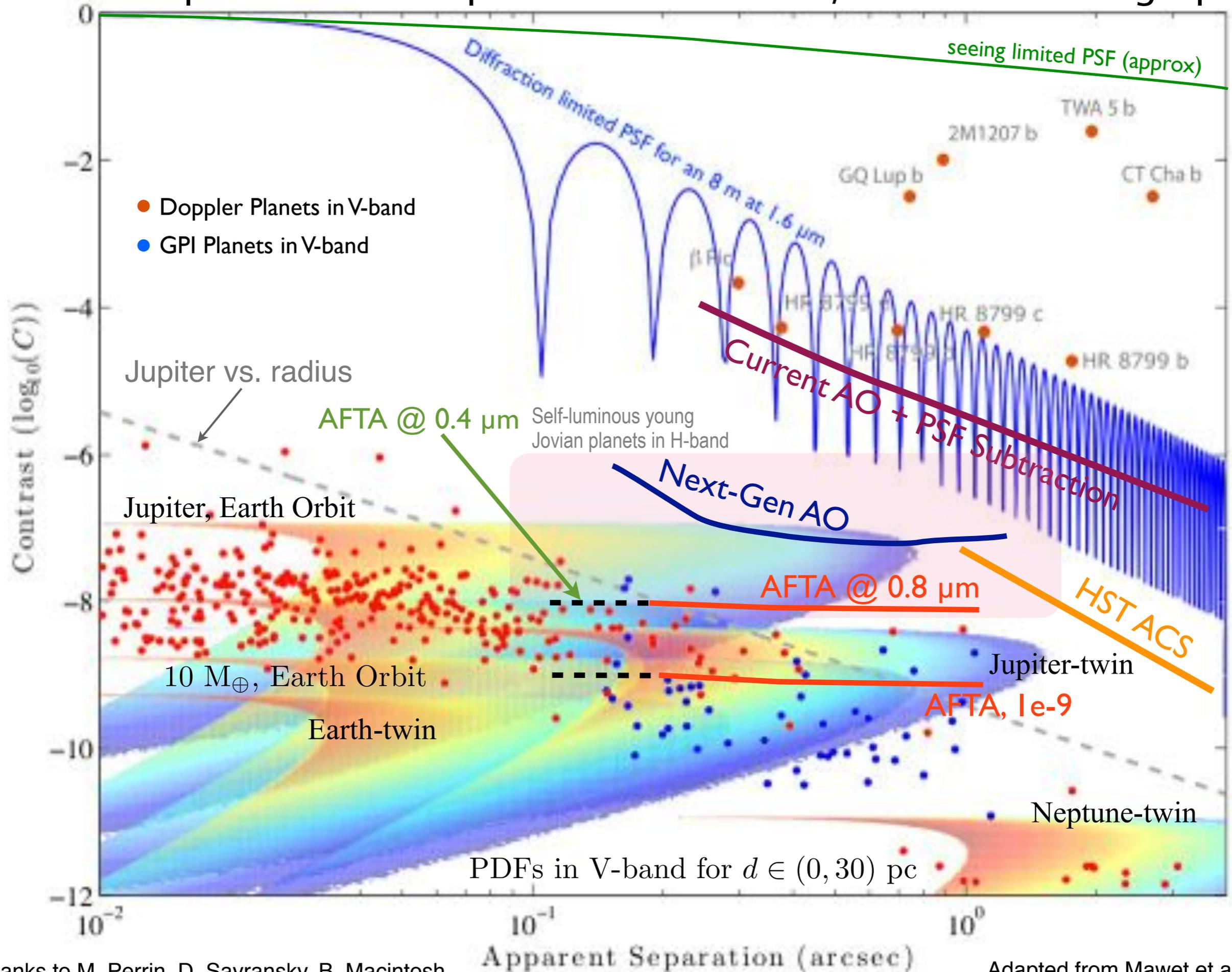
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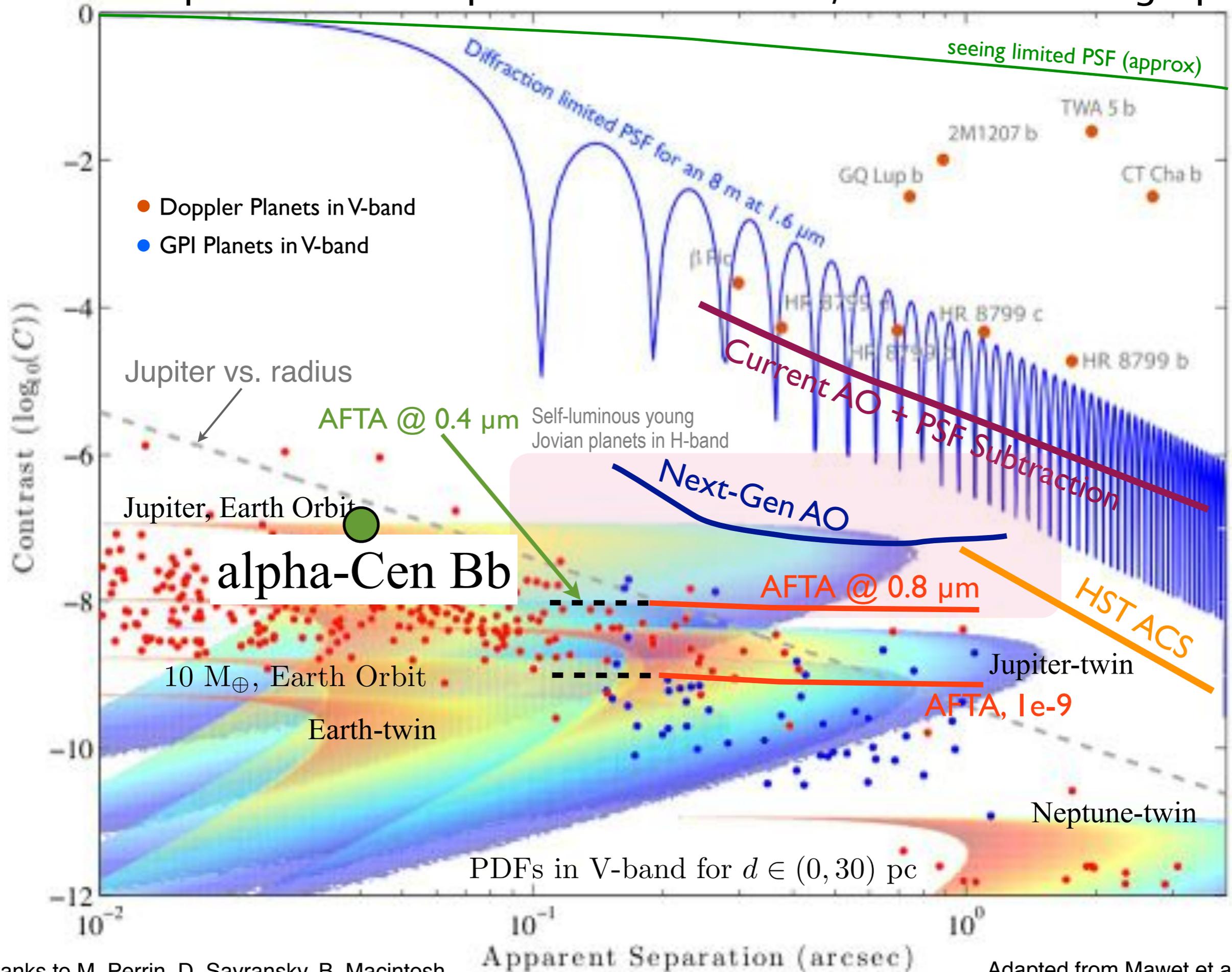
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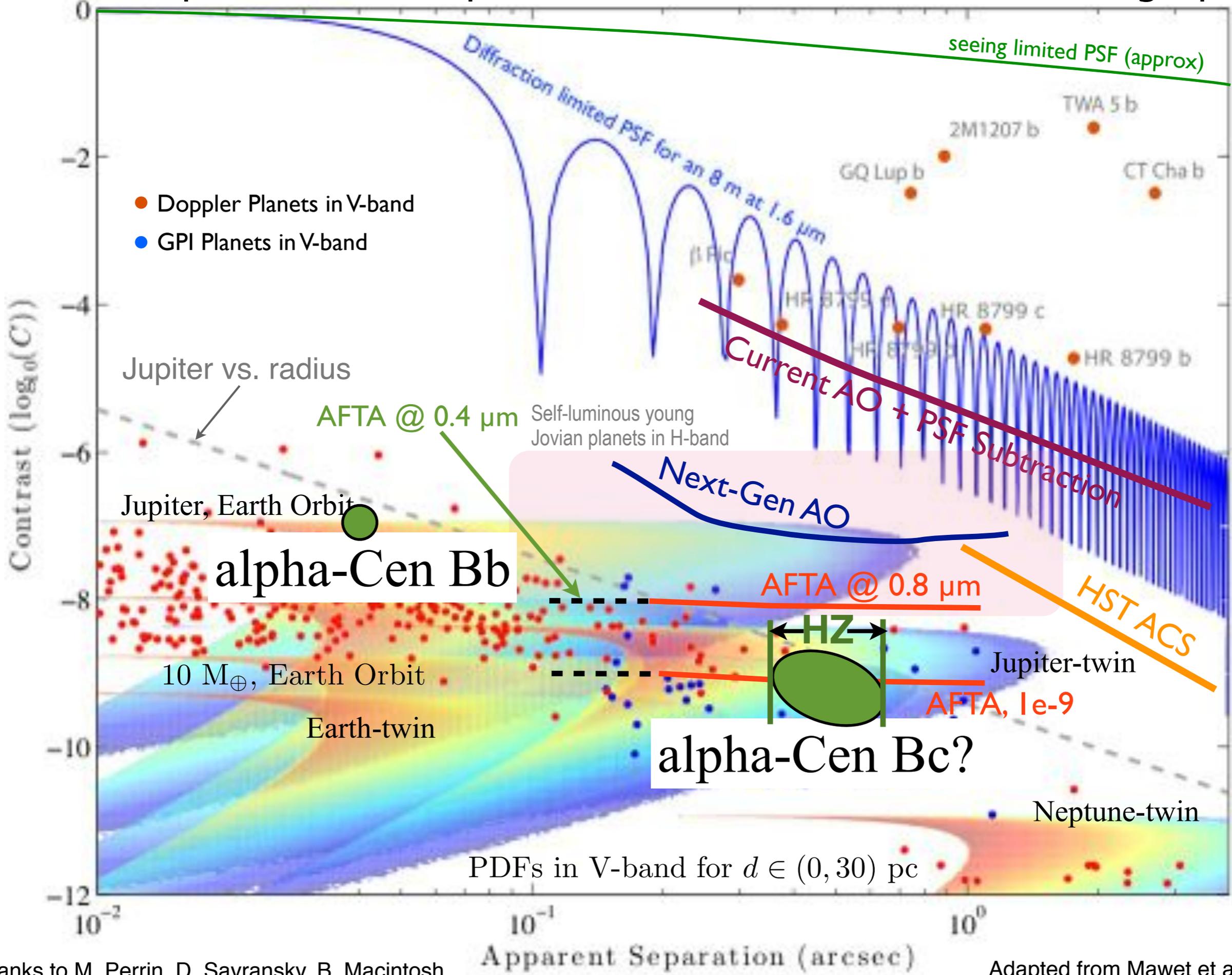
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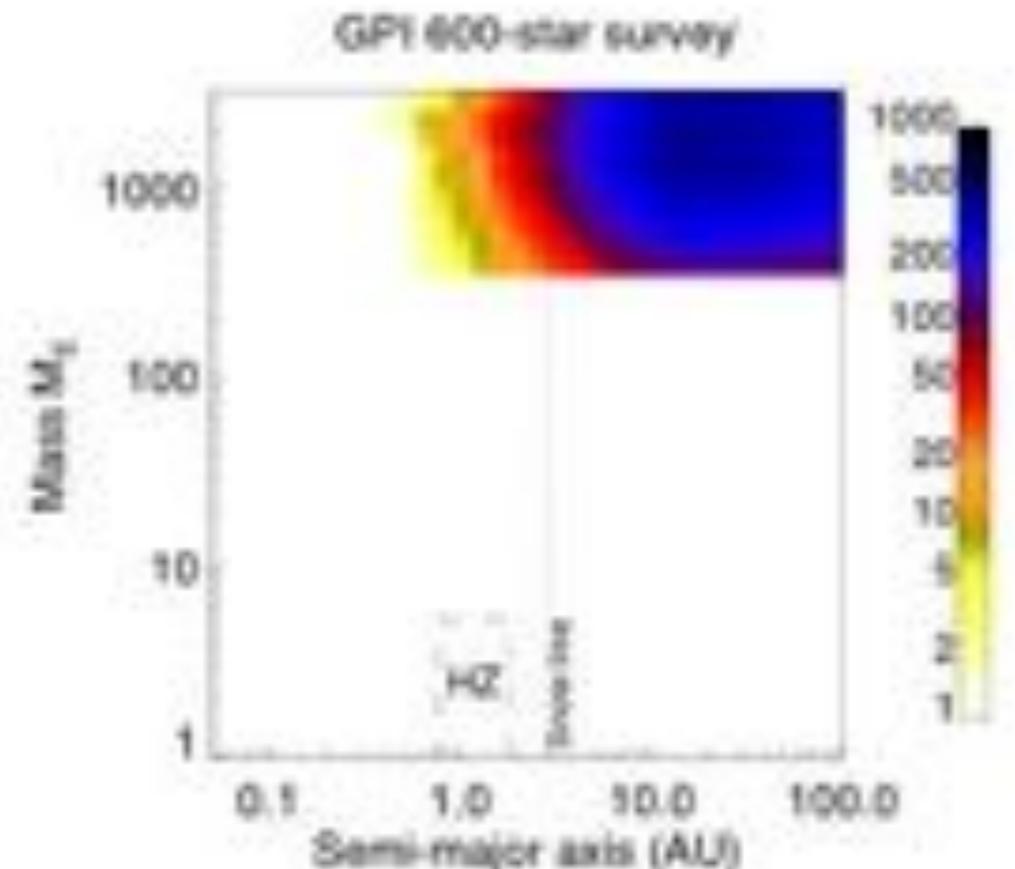
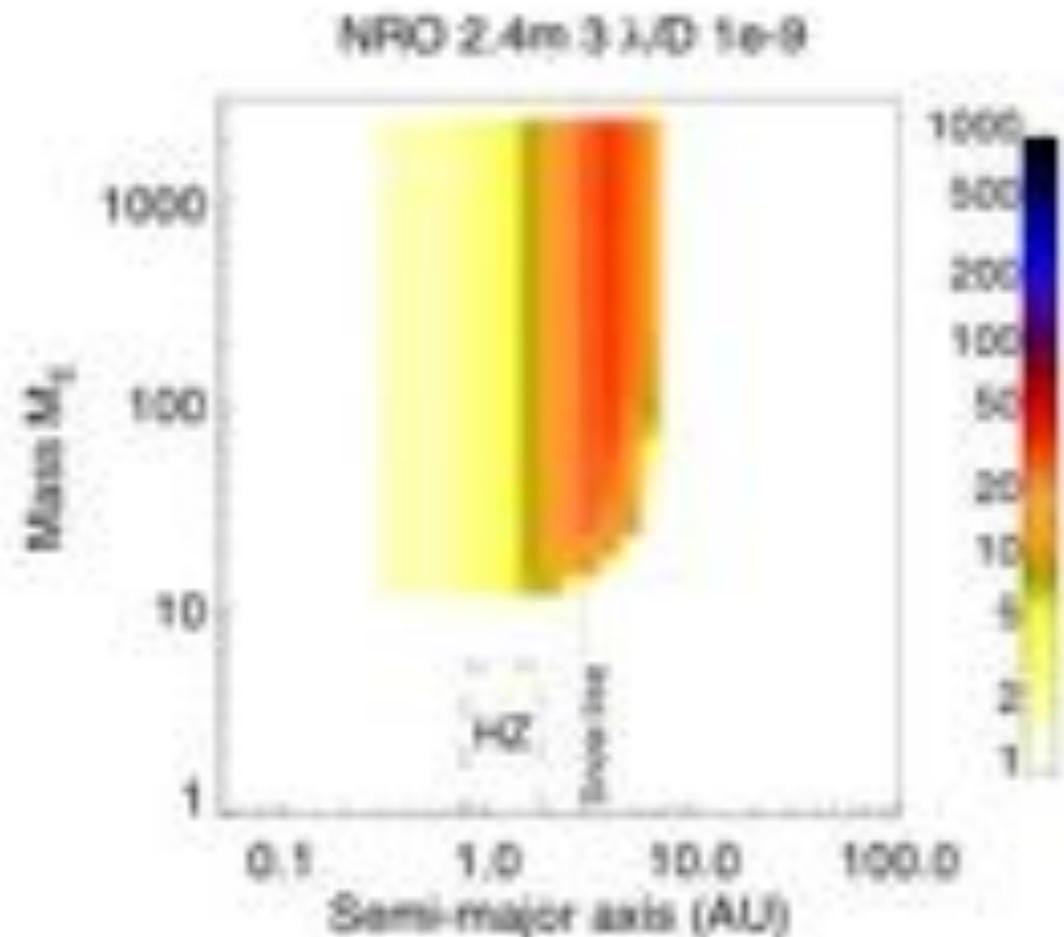
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Adapted from Mawet et al. 2012



# Depth of Planet Search in Visible

Giant Planet Imaging at  $10^{-9}$  at 800 nm.



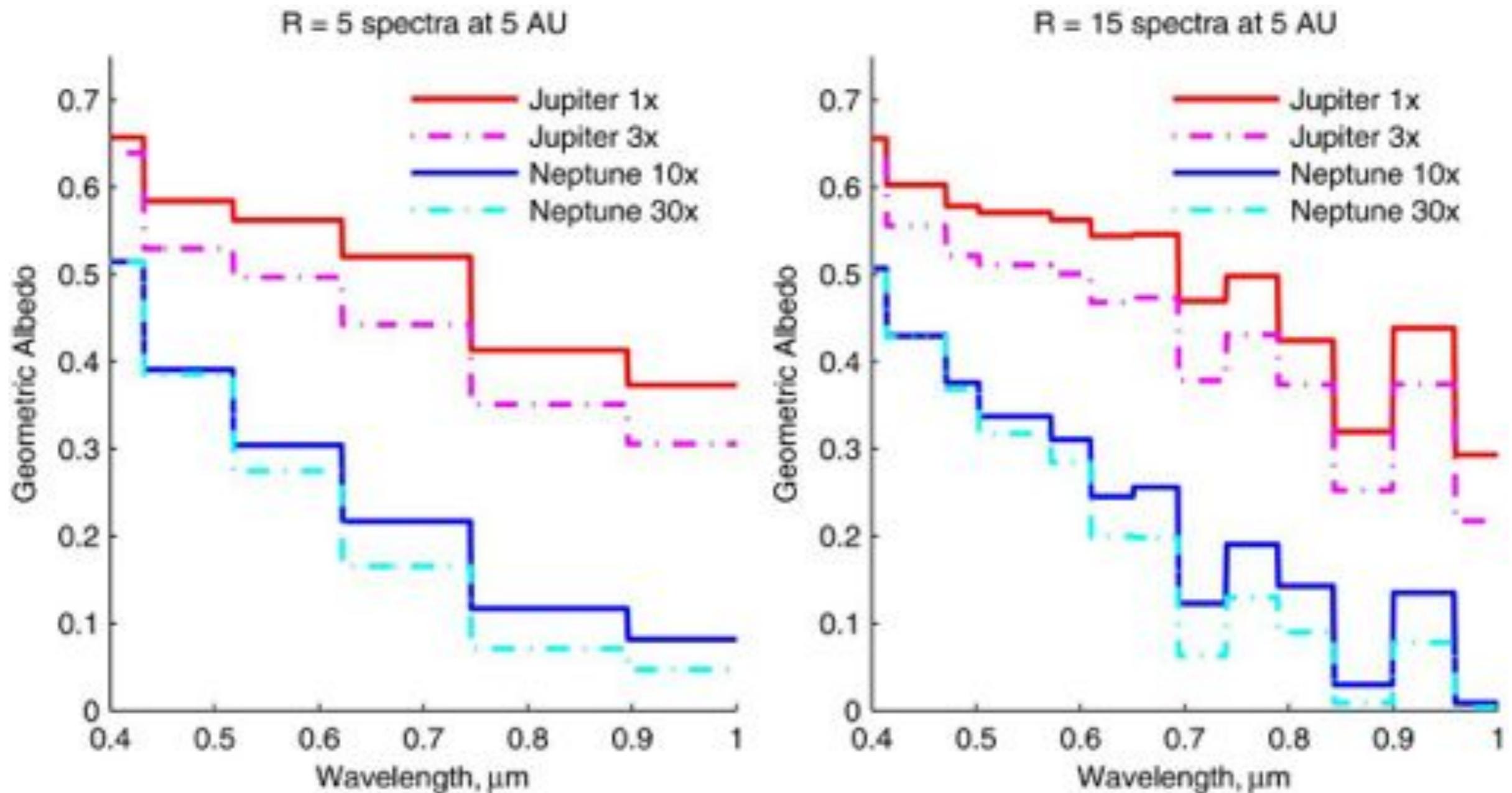
**Sensitivity comparison between a 2.4m space coronagraph and the Gemini Planet Imager for a notional survey of nearby stars with mass 0.5-1.5 solar masses. The quantity plotted is the ExoPTF “depth of search” (Lunine et al). This is the sum of the completeness of a survey for all targets – it can be thought of as the number of planets of a given mass and semi-major axis that would be discovered if all targets had such a companion. GPI has a much larger potential target sample, but since it detects self-luminosity which declines steeply with mass and age it is sensitive only to high-mass planets. Also able to characterize in visible a subset of GPI planets.**

B. Macintosh

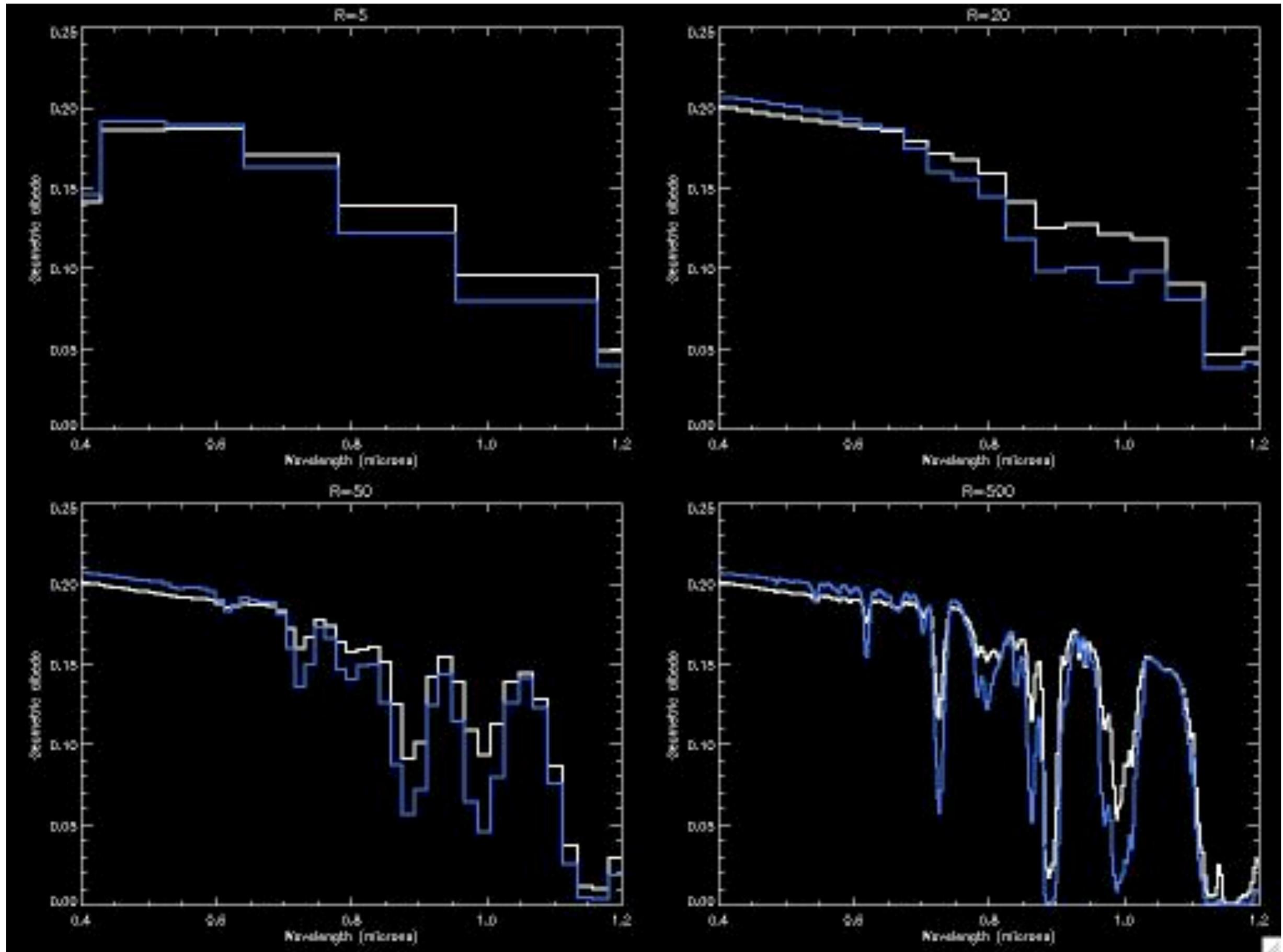
# Exoplanet spectra can distinguish formation mechanisms

Spectra from Cahoy et al. 2010

for Jupiter and Neptune analogs at 5 AU and different metallicities



# The advantage of higher resolution



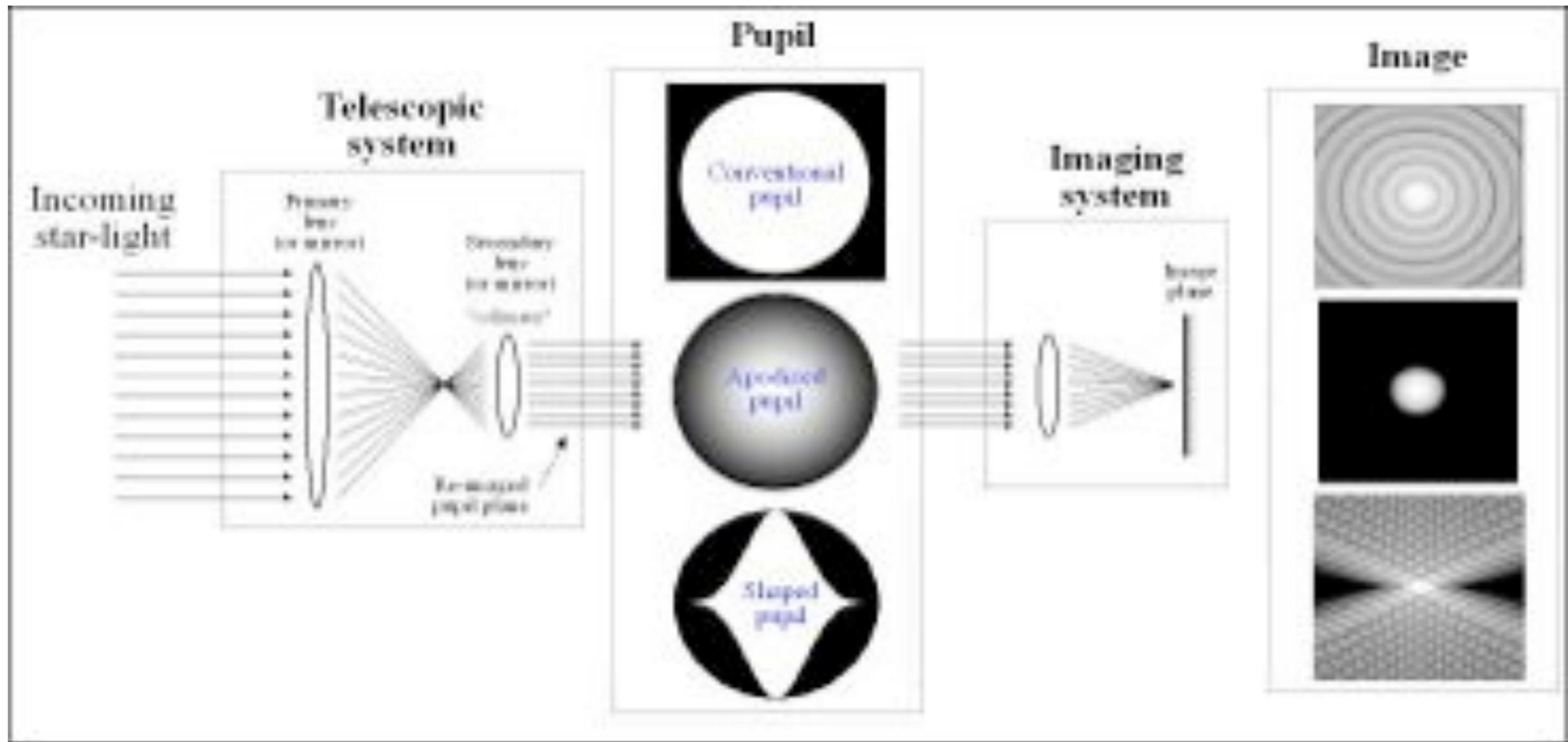
# Possible coronagraph approaches for NRO Telescope

No proven  $10^{-8}$  or  $10^{-9}$  broadband coronagraph with wavefront control exists yet for the AFTA pupil. What follows are potential technological pathways.

*Detailed design and aberration **sensitivity** studies will be performed as part of SDT process.*

There will be a clear trade between robustness/complexity and high performance. AFTA may be an excellent platform for multiple coronagraphs.

# Pupil Apodization to Reshape PSF

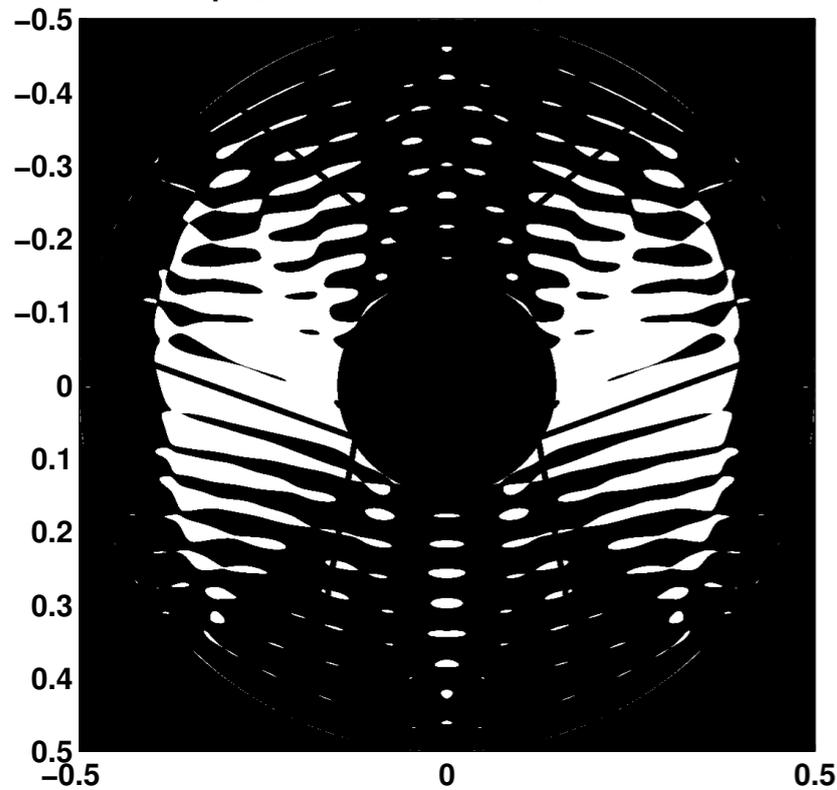


$$E(\xi, \zeta) = \iint e^{i(x\xi + y\zeta)} A(x, y) dy dx$$

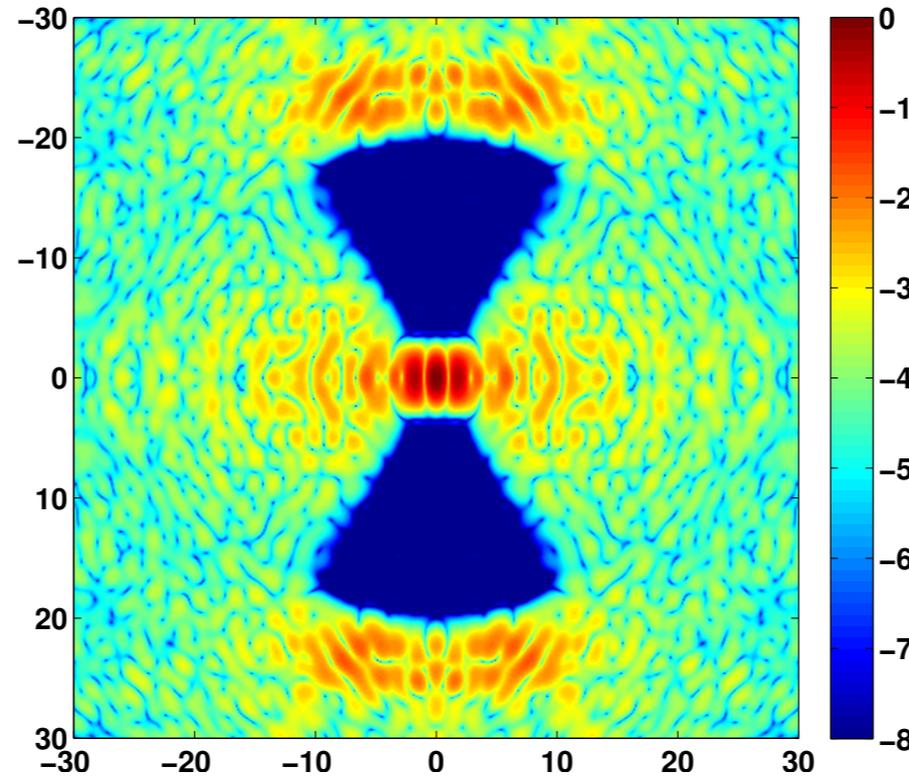
Shaped pupils are achromatic and robust.

# 2-D Shaped Pupil Mask Tailored for Telescope Aperture

Pupil ; IWA:  $3.5\lambda/D$  ; C=-8 ; T=24%

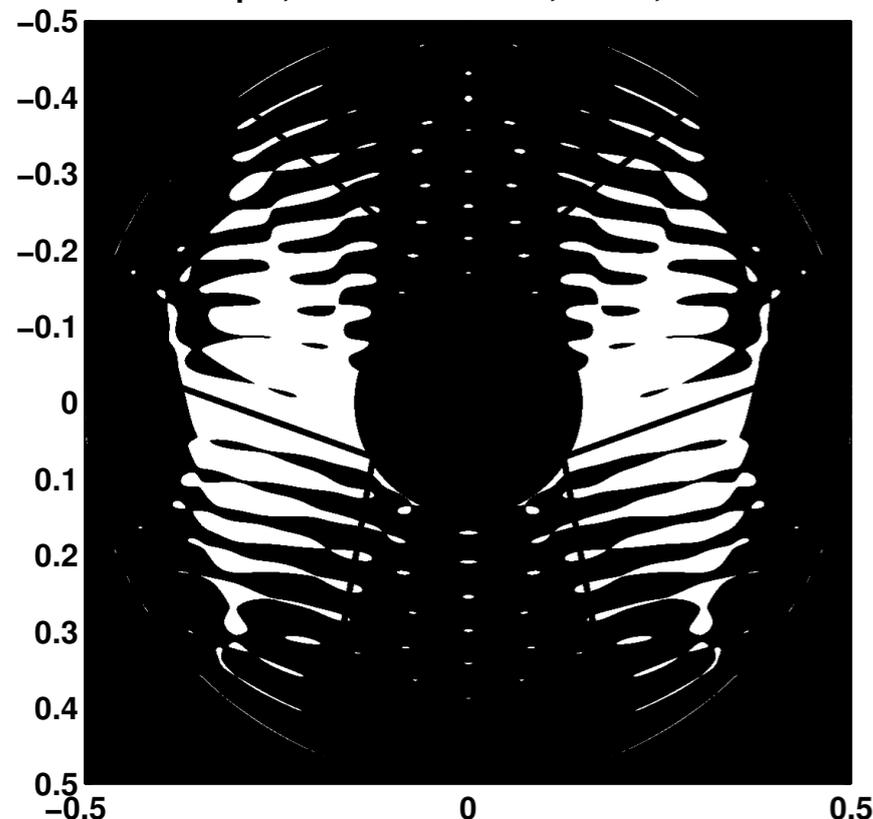


PSF ;  $3.5\lambda/D$  ; C=-8 ; T=24%

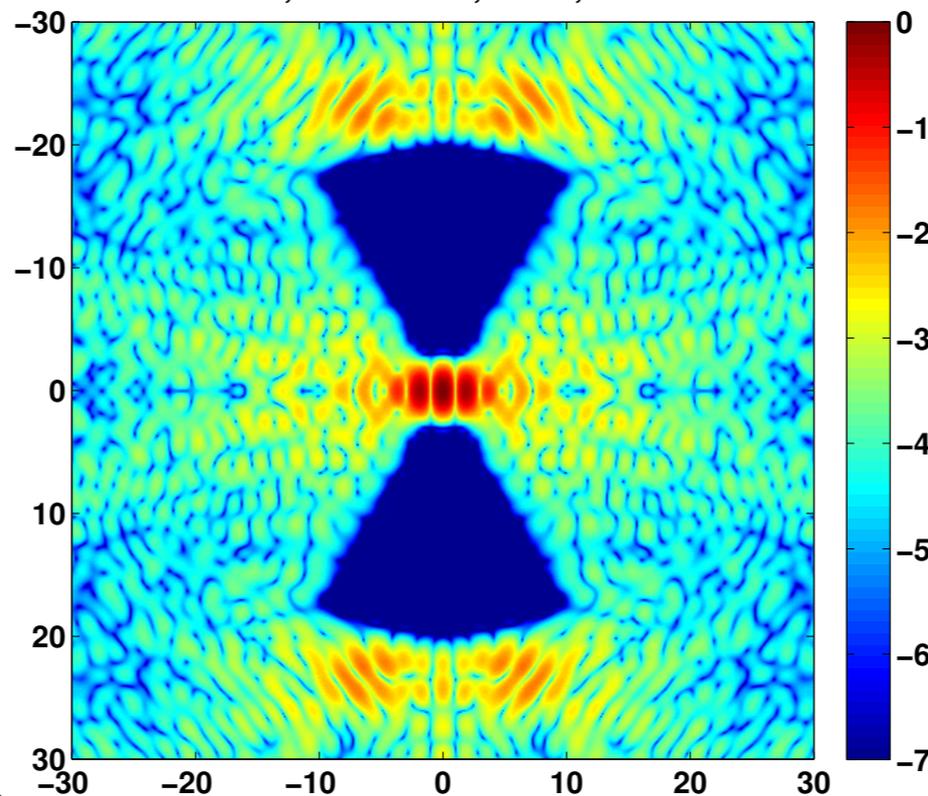


Working Angles  $3.5$  to  $20\lambda/D$   
Contrast:  $10^{-8}$   
Throughput: 24%

Pupil ; IWA:  $3\lambda/D$  ; C=-7 ; T=23%



PSF ;  $3\lambda/D$  ; C=-7 ; T=23%



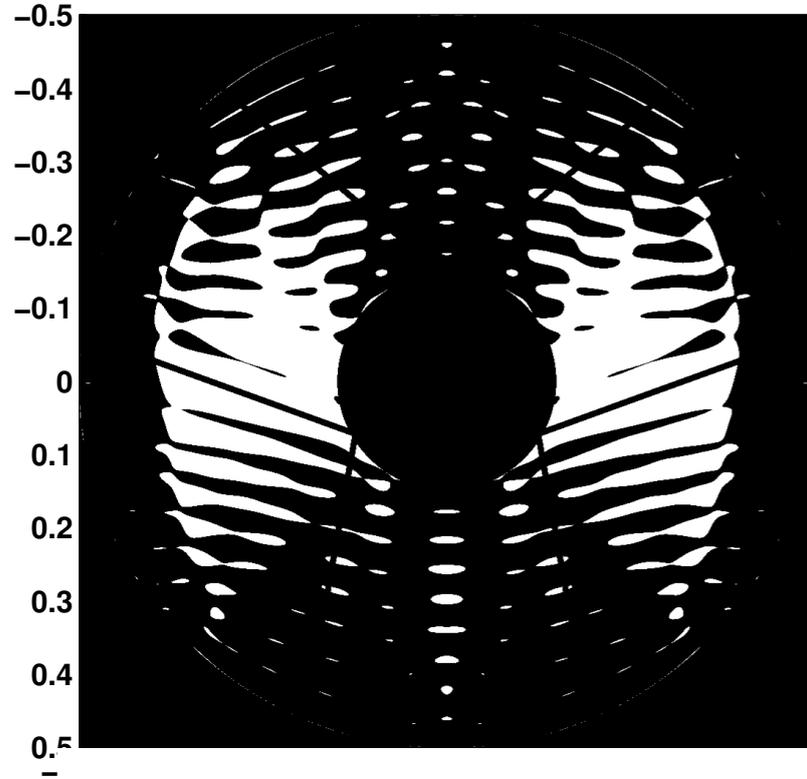
Working Angles  $3$  to  $20\lambda/D$   
Contrast:  $10^{-7}$   
Throughput: 23%

$3\lambda/D$  is  $\sim 0.2''$  at  
800 nm for a 2.4 m  
telescope

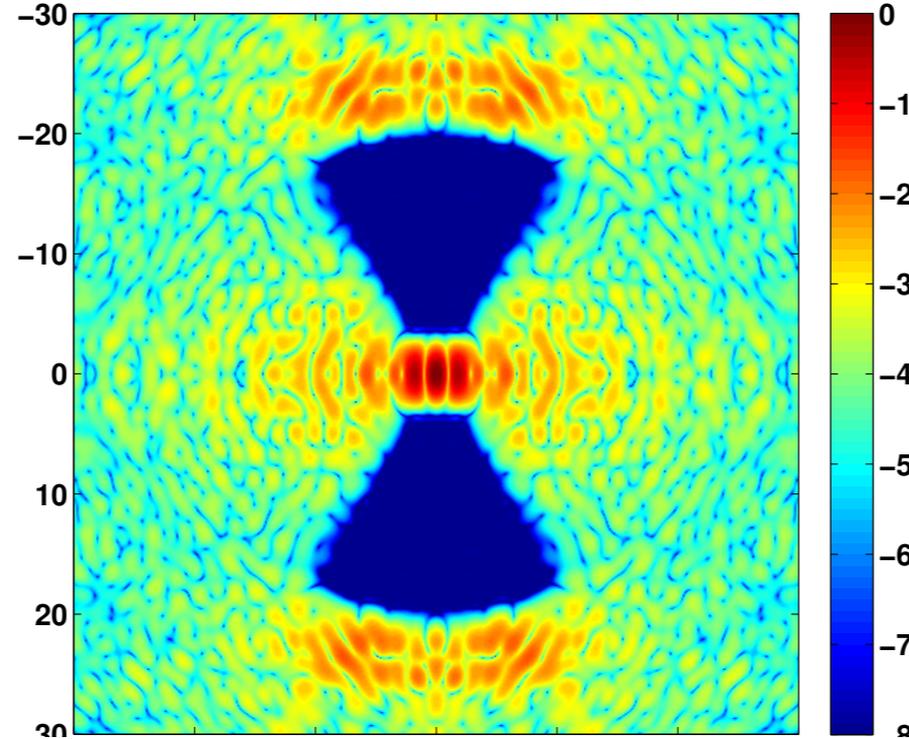
R. Vanderbei, et al., 2011  
A. Carlotti, et al., 2012

# 2-D Shaped Pupil Mask Tailored for Telescope Aperture

Pupil ; IWA:  $3.5\lambda/D$  ;  $C=-8$  ;  $T=24\%$



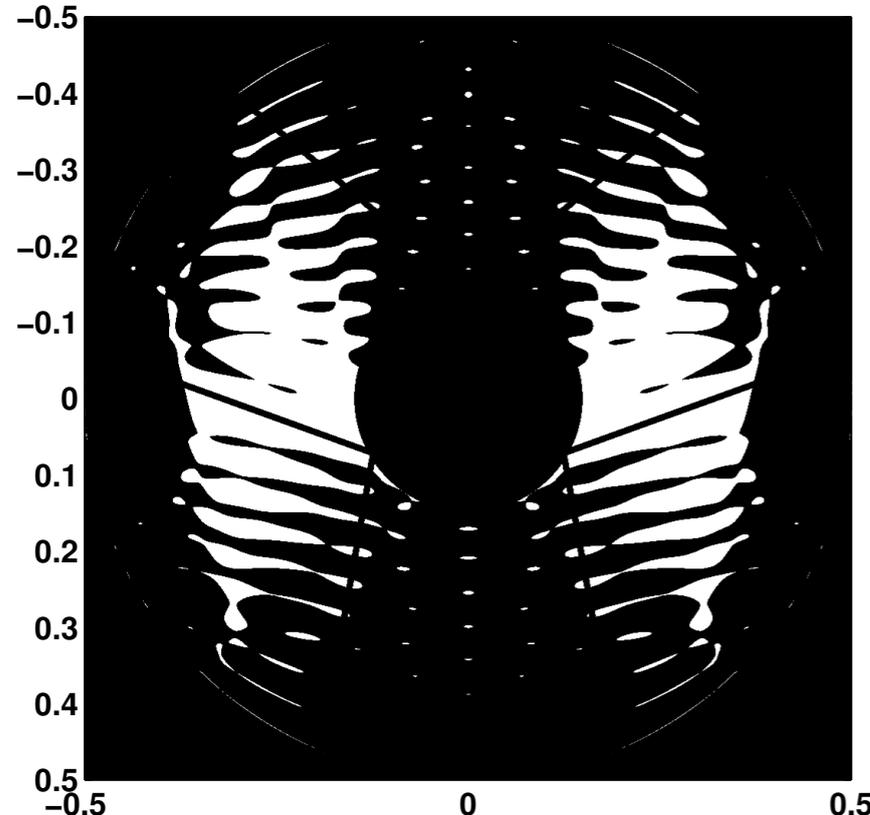
PSF ;  $3.5\lambda/D$  ;  $C=-8$  ;  $T=24\%$



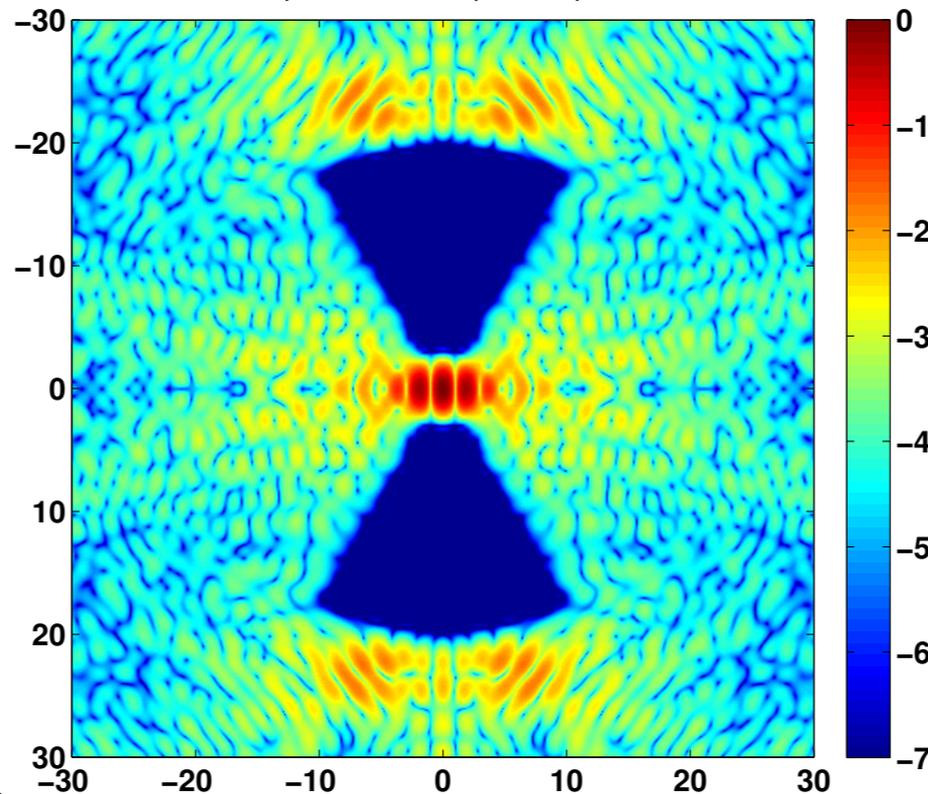
Working Angles 3.5 to  $20\lambda/D$   
Contrast:  $10^{-8}$   
Throughput: 24%

Will most likely need to be hybridized with DMs.

Pupil ; IWA:  $3\lambda/D$  ;  $C=-7$  ;  $T=23\%$



PSF ;  $3\lambda/D$  ;  $C=-7$  ;  $T=23\%$



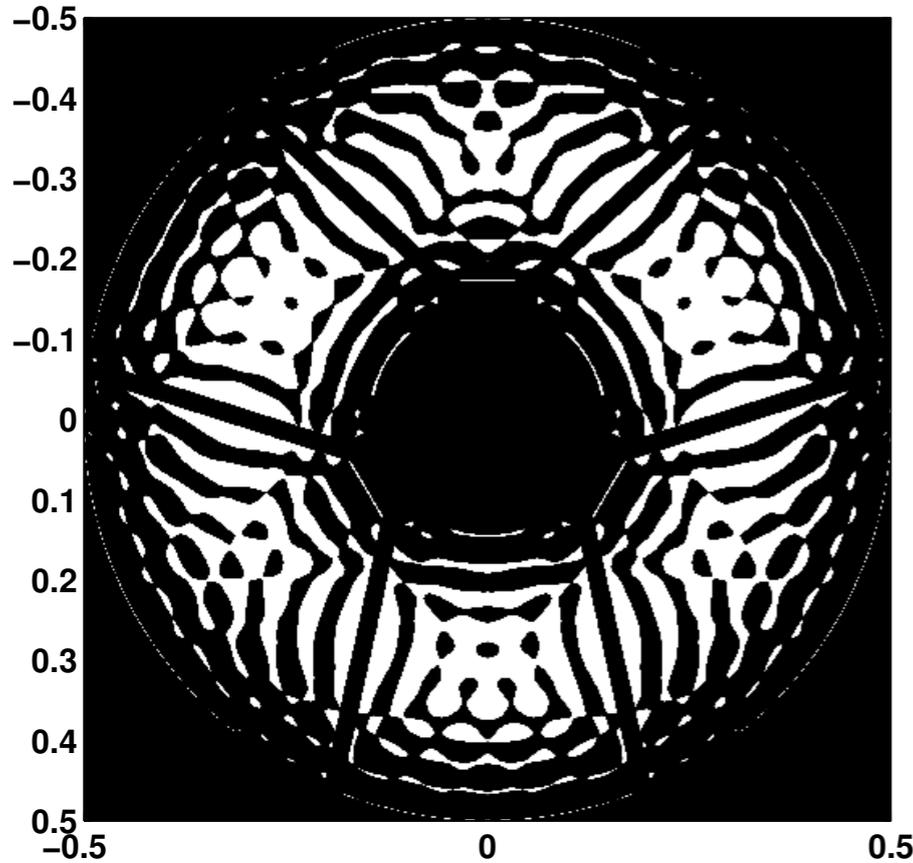
Working Angles 3 to  $20\lambda/D$   
Contrast:  $10^{-7}$   
Throughput: 23%

$3\lambda/D$  is  $\sim 0.2''$  at  
800 nm for a 2.4 m  
telescope

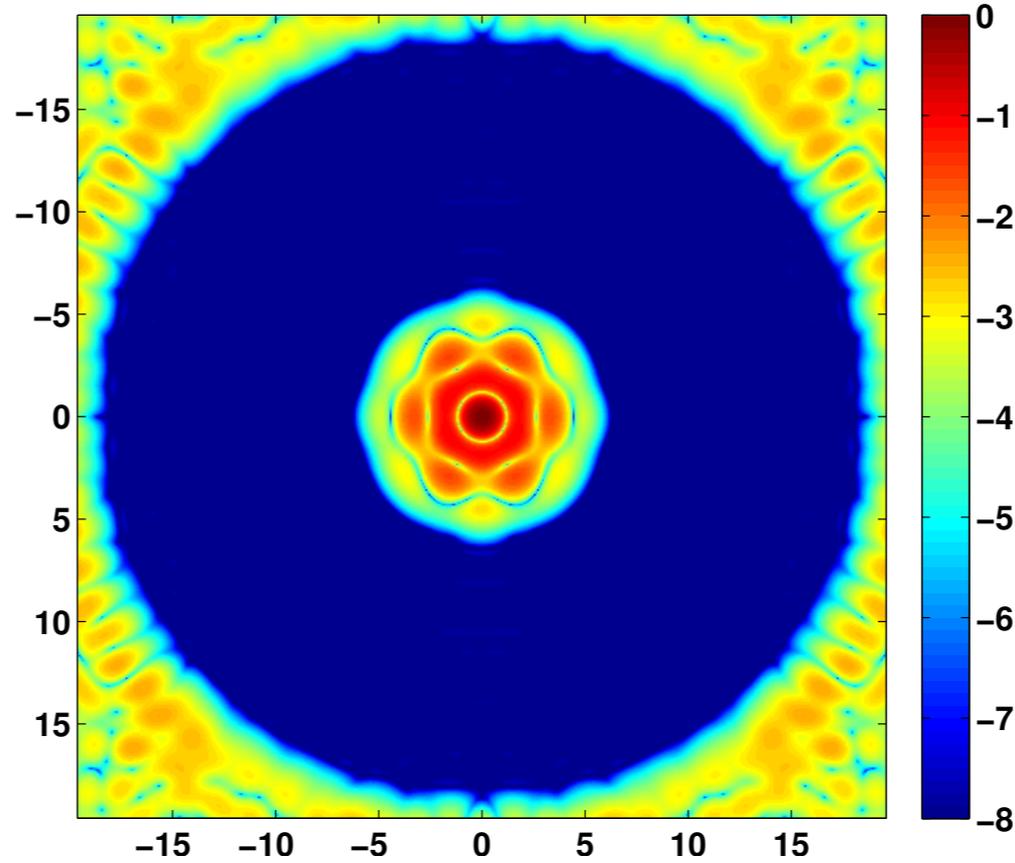
R. Vanderbei, et al., 2011  
A. Carlotti, et al., 2012

# Discovery and Characterization Masks

Pupil ; IWA: 6 I/D ; C=-8 ; T=37%

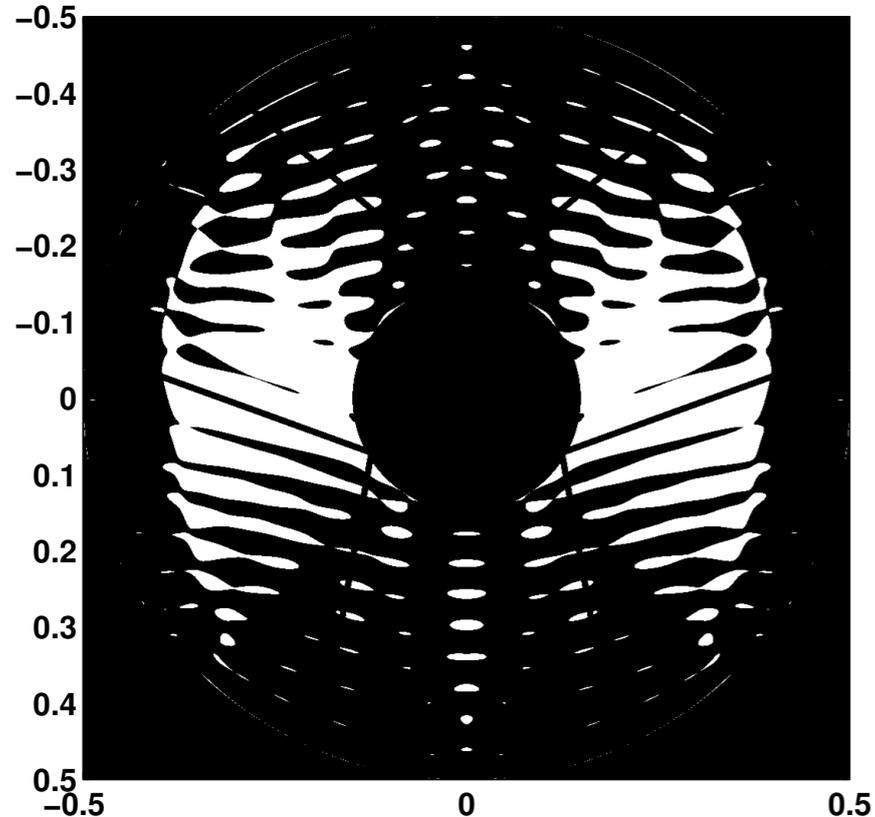


PSF ; 6 I/D ; C=-8 ; T=37%

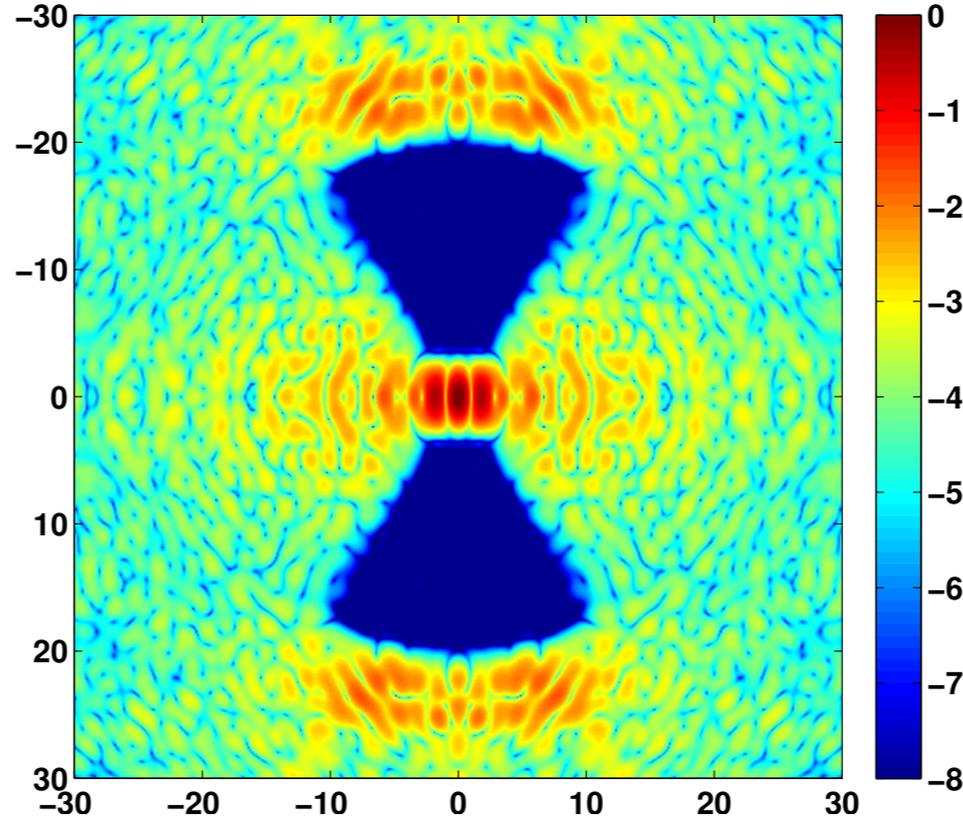


6 lambda/D iwa  
for discovery at  
400 nm.  
Throughput =  
37%.

Pupil ; IWA: 3.5lambda/D ; C=-8 ; T=24%



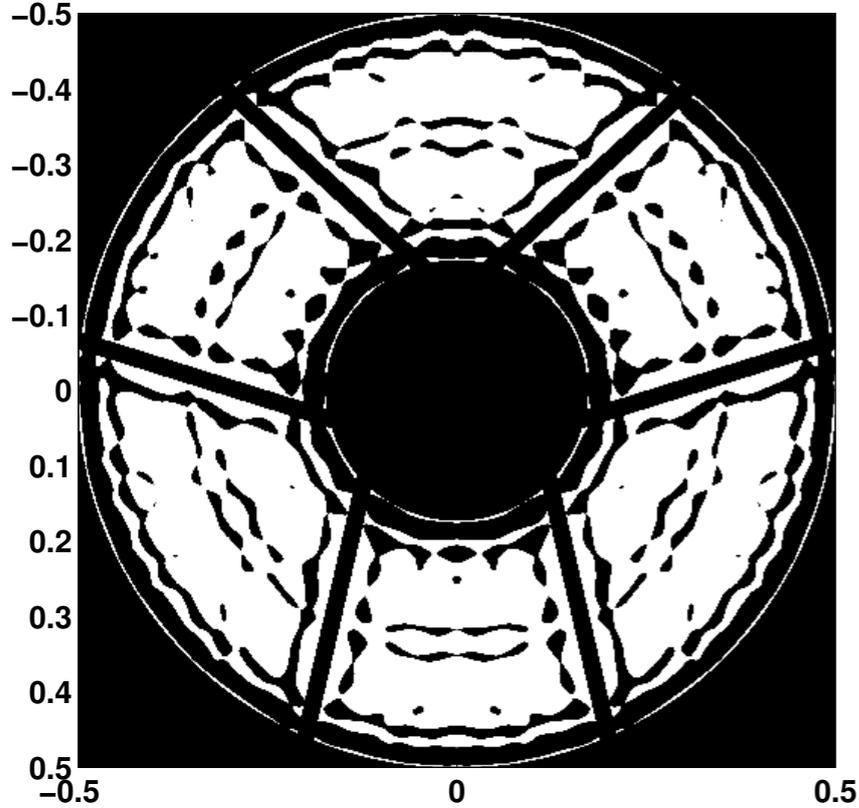
PSF ; 3.5 lambda/D ; C=-8 ; T=24%



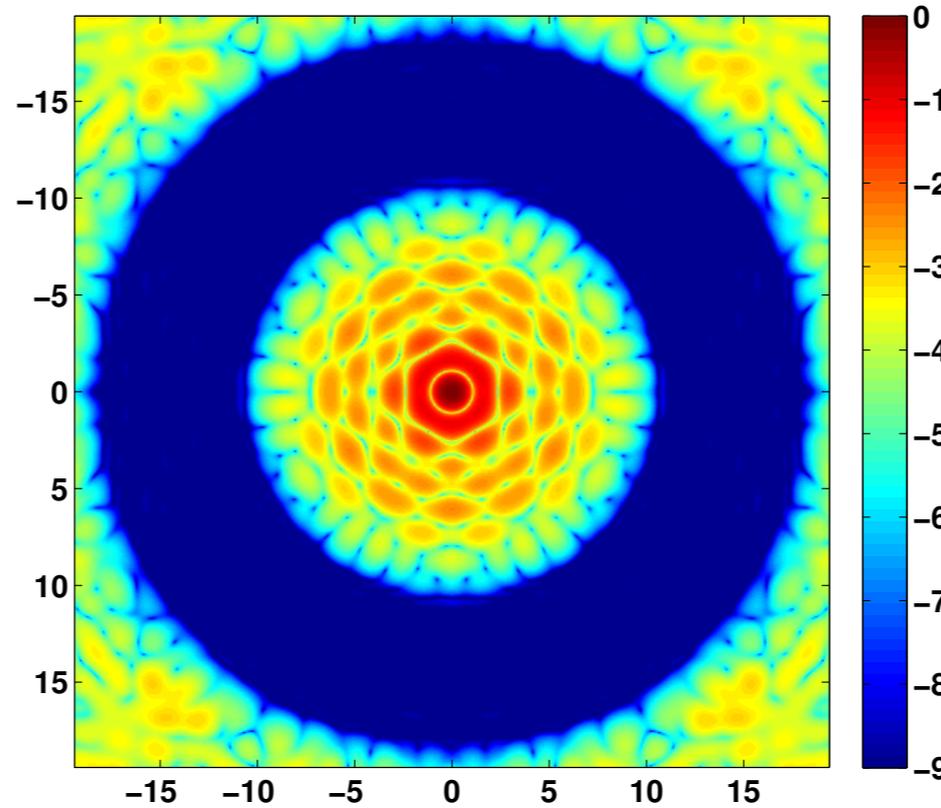
3.5 lambda/D iwa  
for characterization  
at 400-800 nm.  
Throughput = 24.

# Imaging Alpha Centauri Bc in the Habitable Zone

Pupil ; IWA: 10.5 I/D ; C=-9 ; T=67%



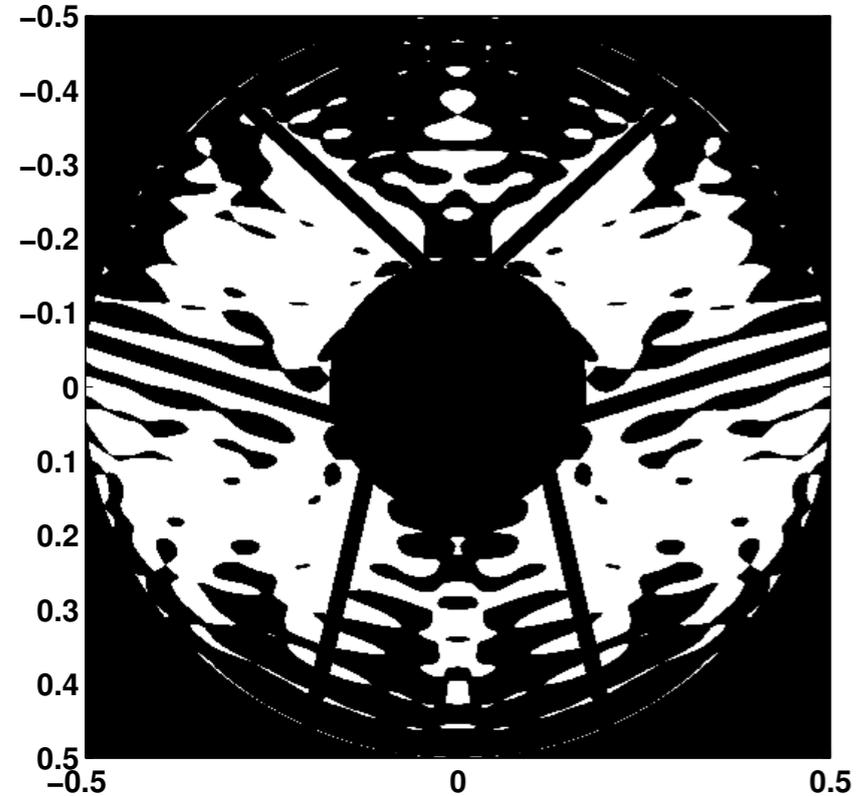
PSF ; 10.5 I/D ; C=-9 ; T=67%



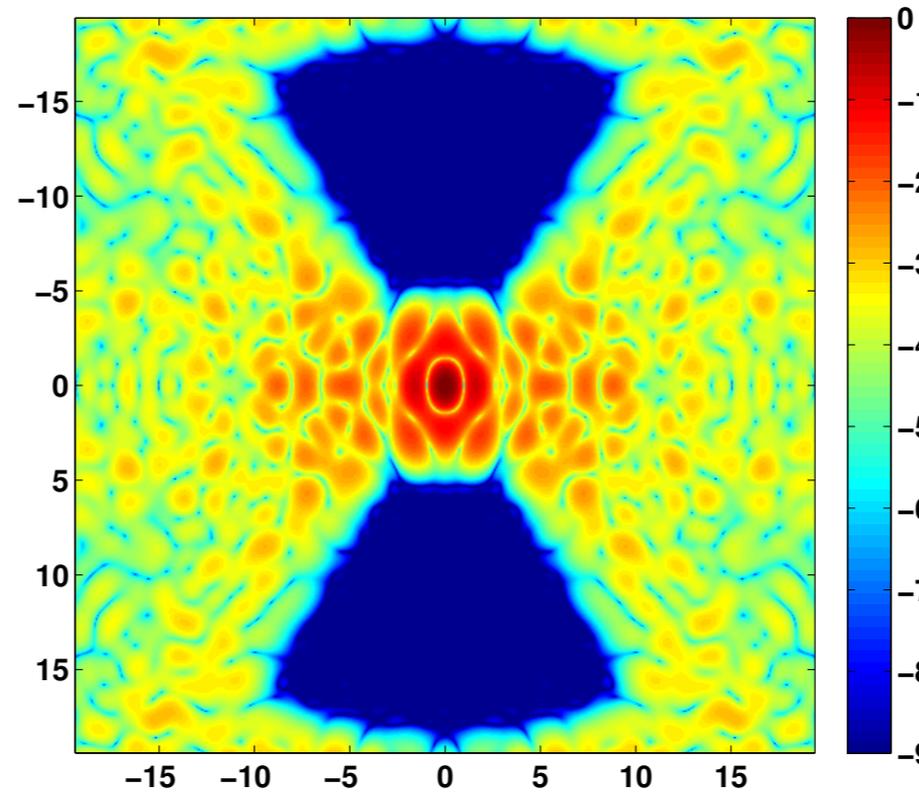
Wide discovery band with large iwa at 400 nm.

$10^{-9}$  contrast with  $>50\%$  throughput

Pupil ; IWA: 5.3 I/D ; C=-9 ; T=52%



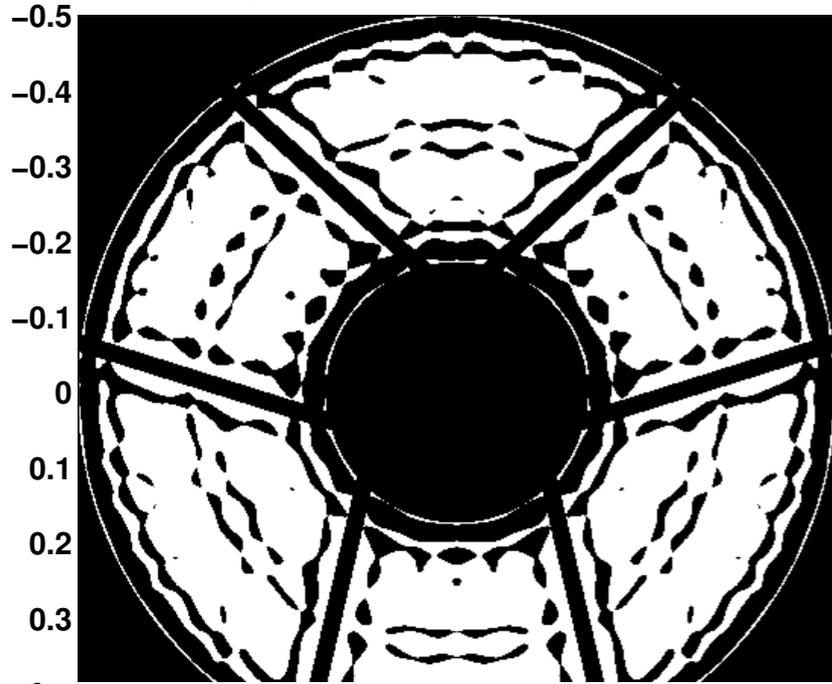
PSF ; 5.3 I/D ; C=-9 ; T=52%



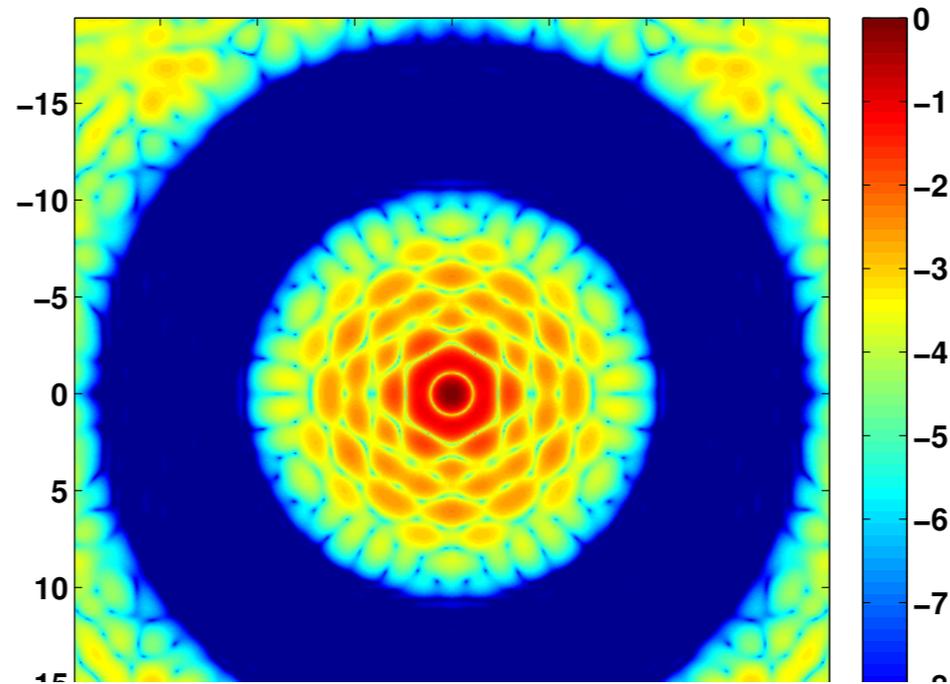
Narrow characterization region band with small iwa (400 to 800 nm).

# Imaging Alpha Centauri Bc in the Habitable Zone

Pupil ; IWA: 10.5 I/D ; C=-9 ; T=67%



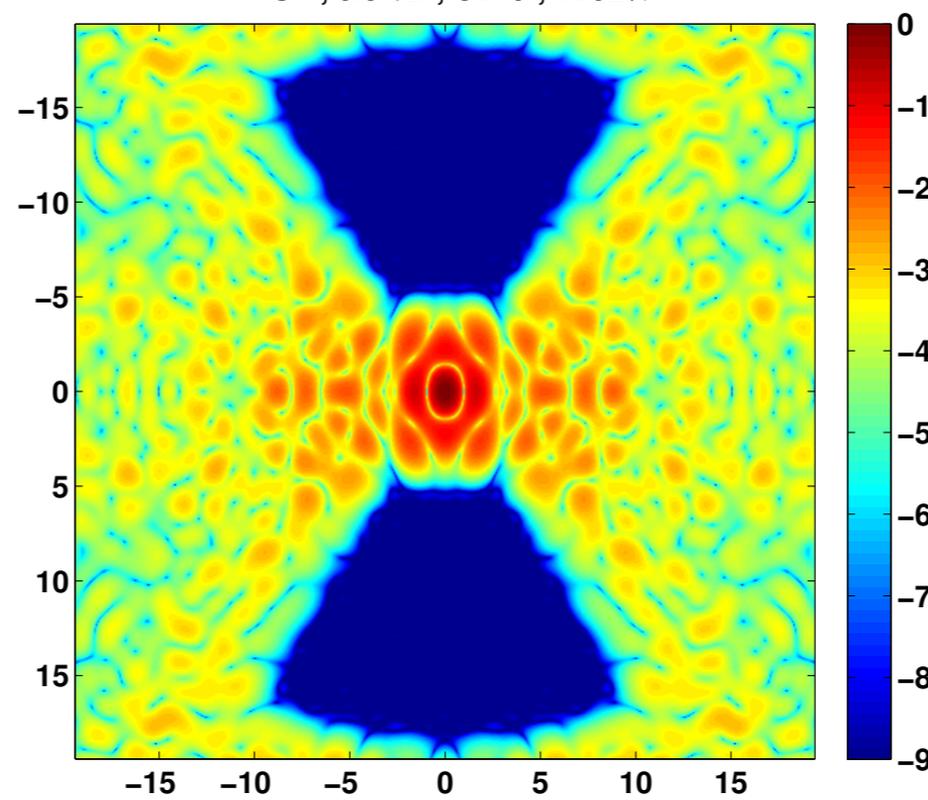
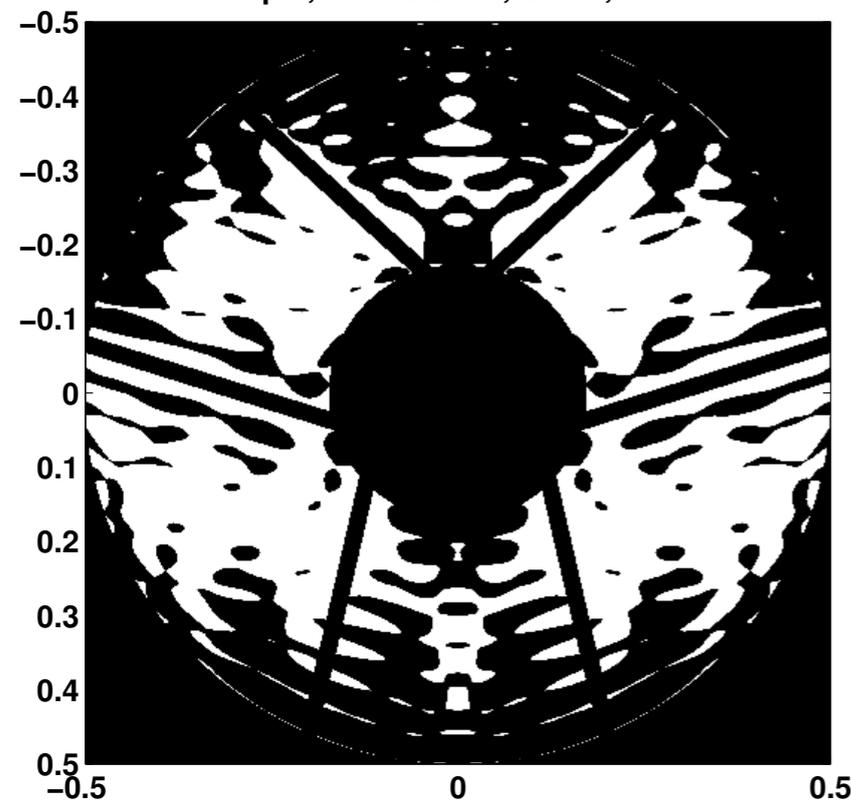
PSF ; 10.5 I/D ; C=-9 ; T=67%



Wide discovery band with large iwa at 400 nm.

Can tailor wings of PSF to have additional suppression at Alpha Cen A separation.

$0^{-9}$  contrast with  $>50\%$  throughput



Narrow characterization region band with small iwa (400 to 800 nm).

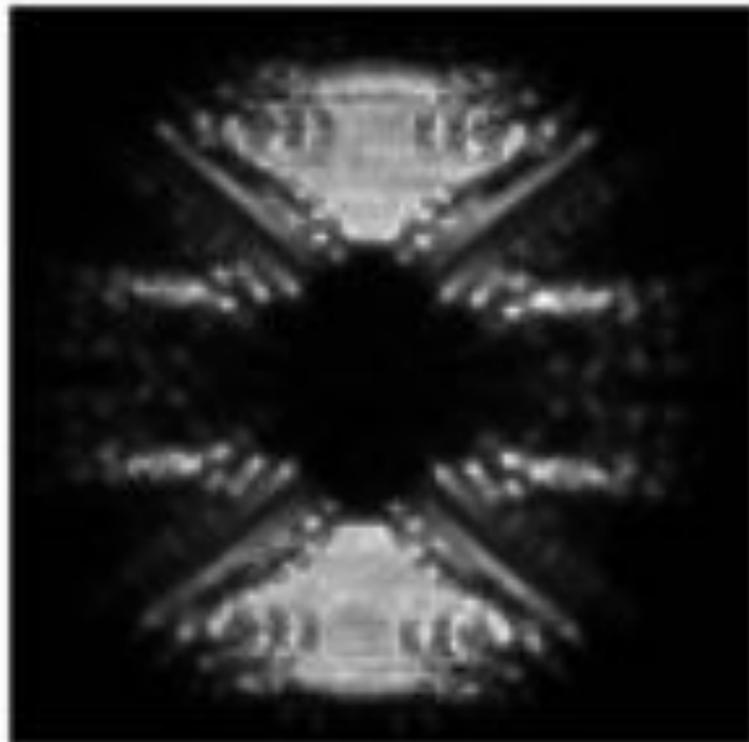
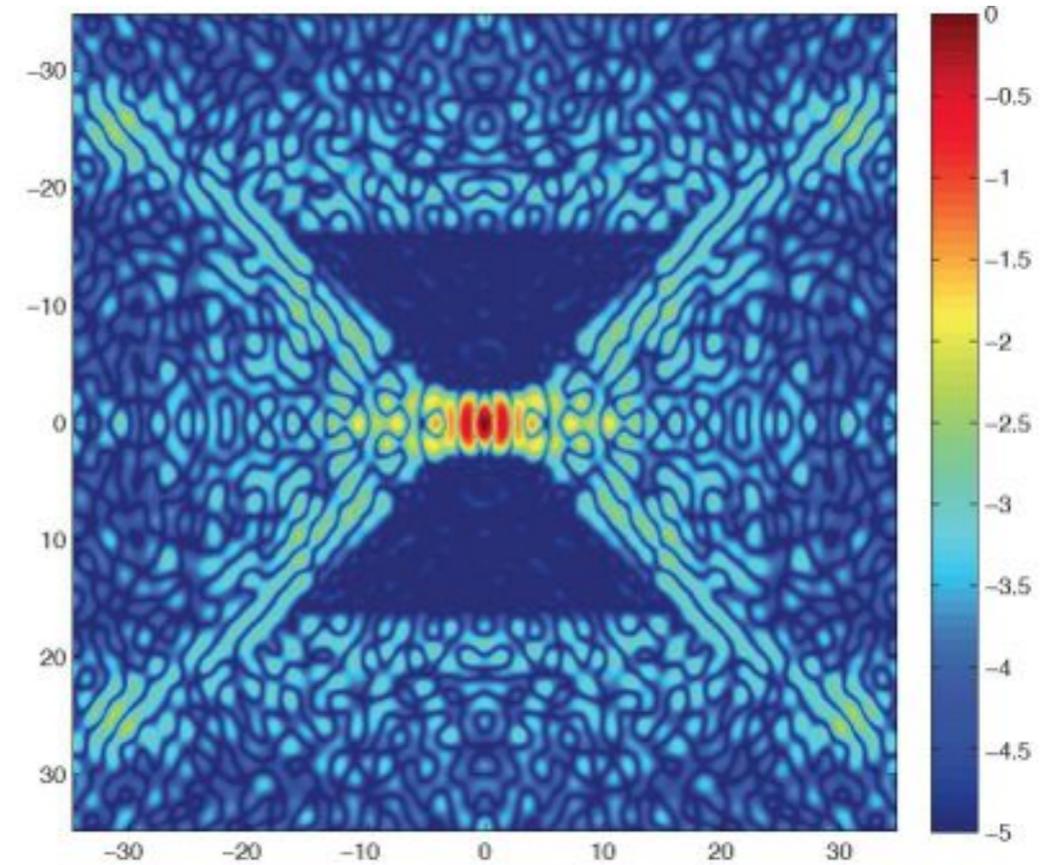
# Shaped Pupil for Subaru SCExAO

Lab test from 2/2012; on-sky July 2012.

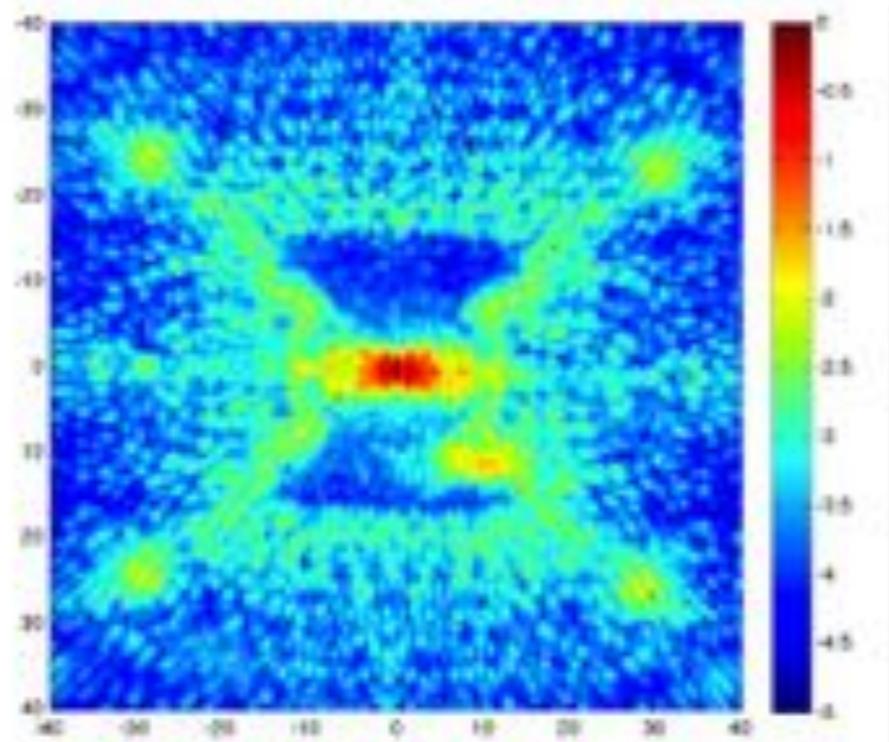


Al deposited on glass substrate ( $\lambda/10$ )

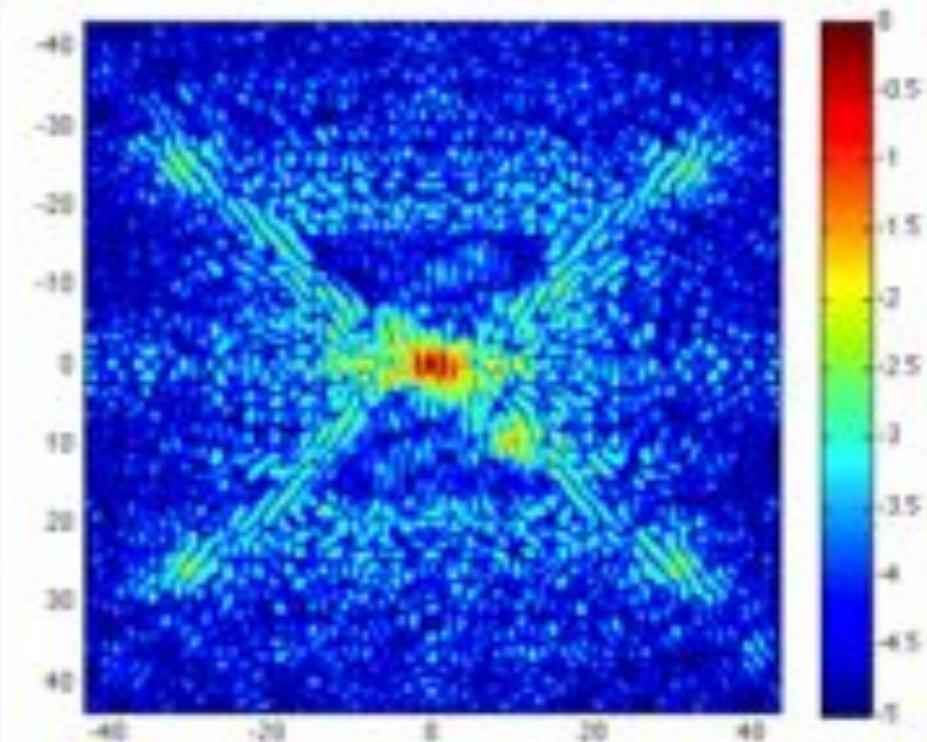
10 $\mu\text{m}$  precision



Pupil Image

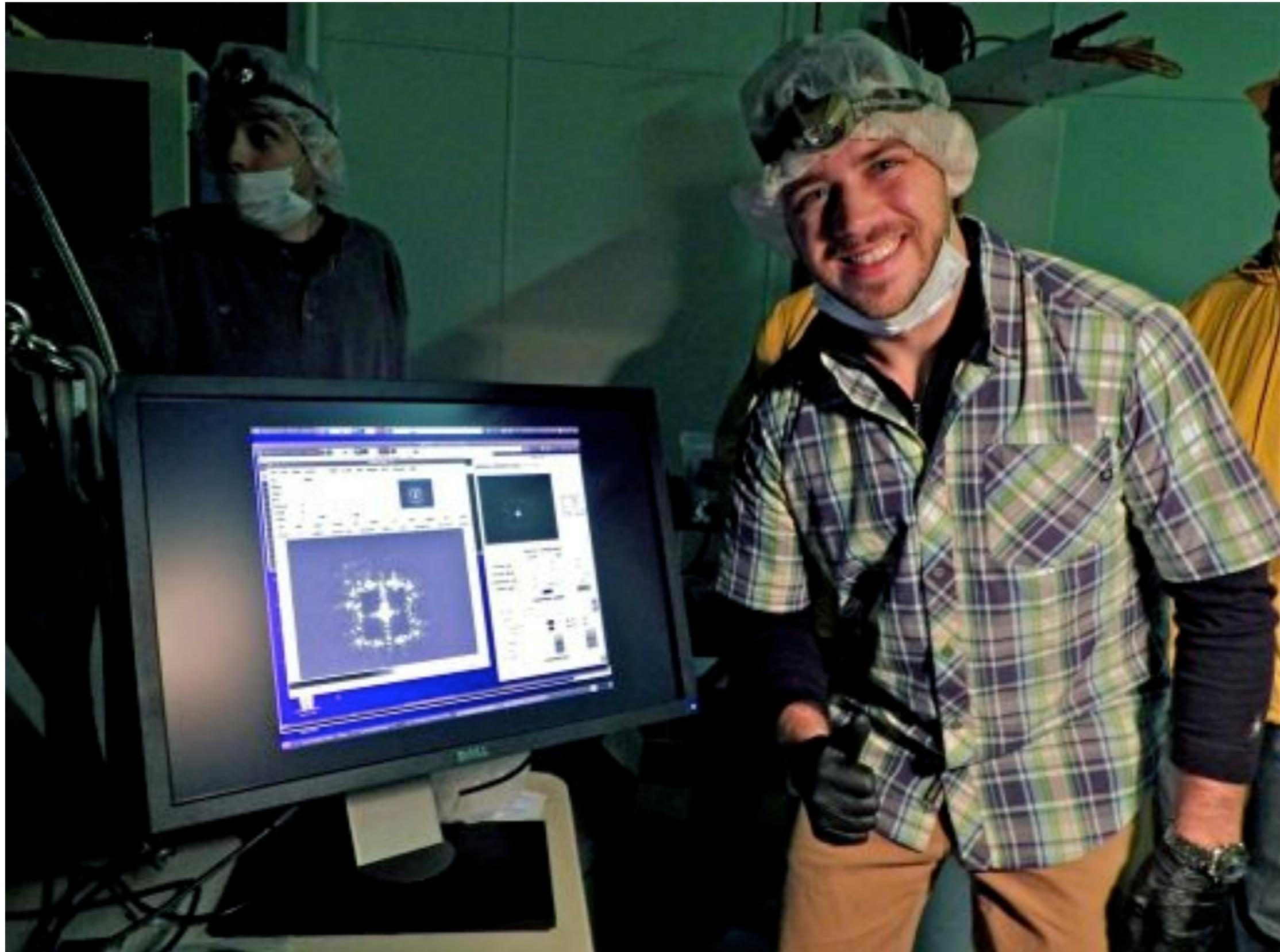


Experimental PSF

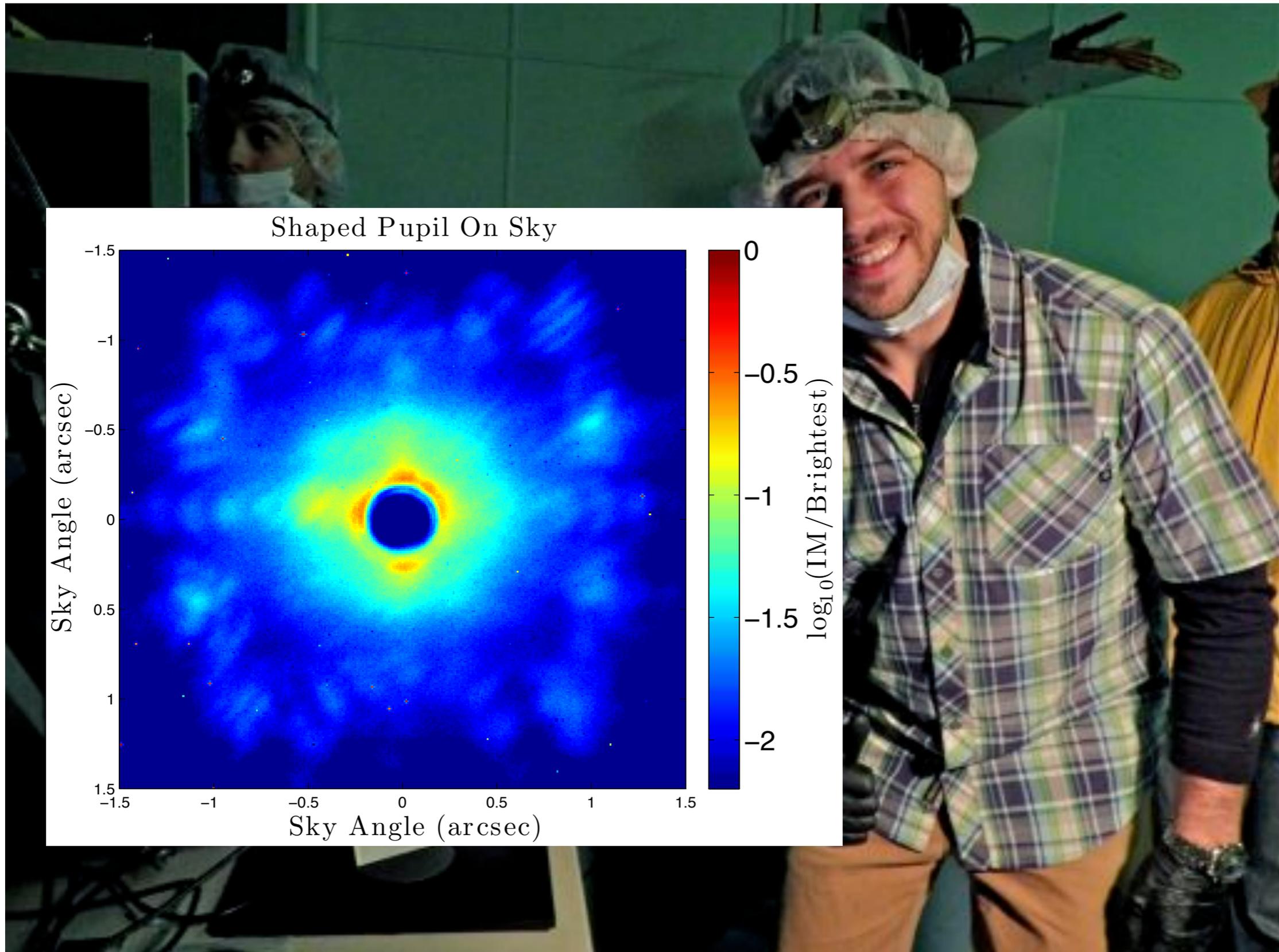


Simulated PSF

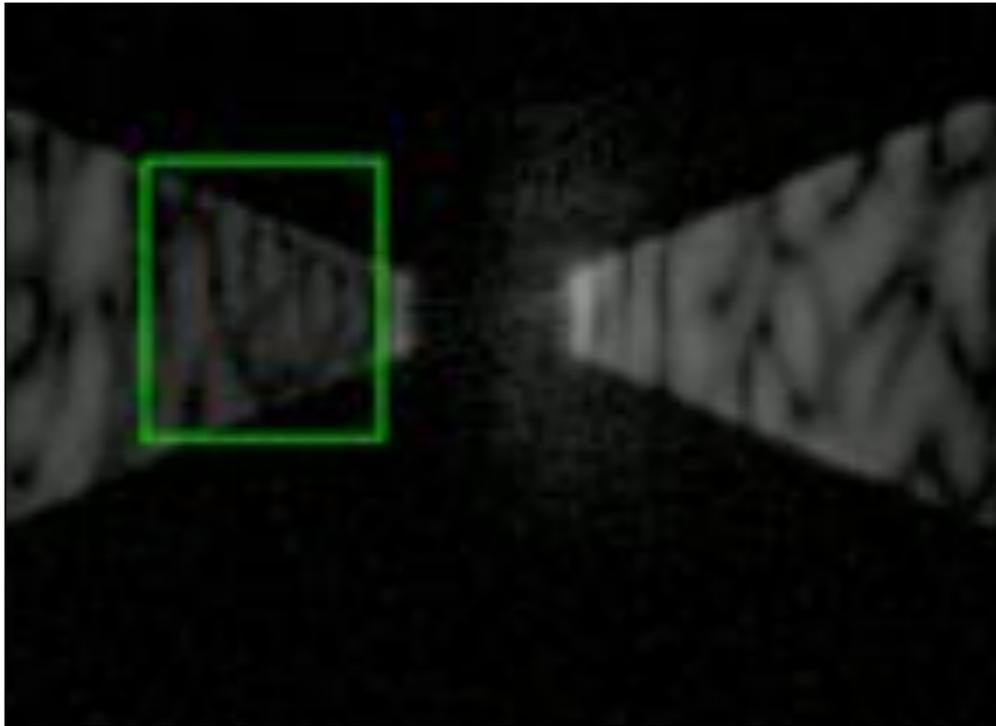
# Shaped Pupil Test on Subaru in Early September



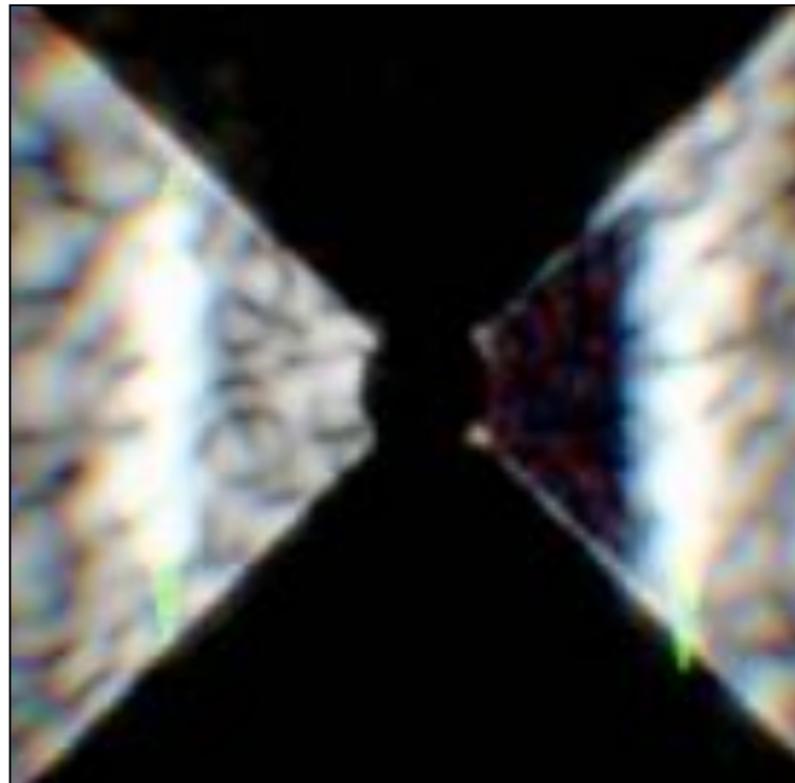
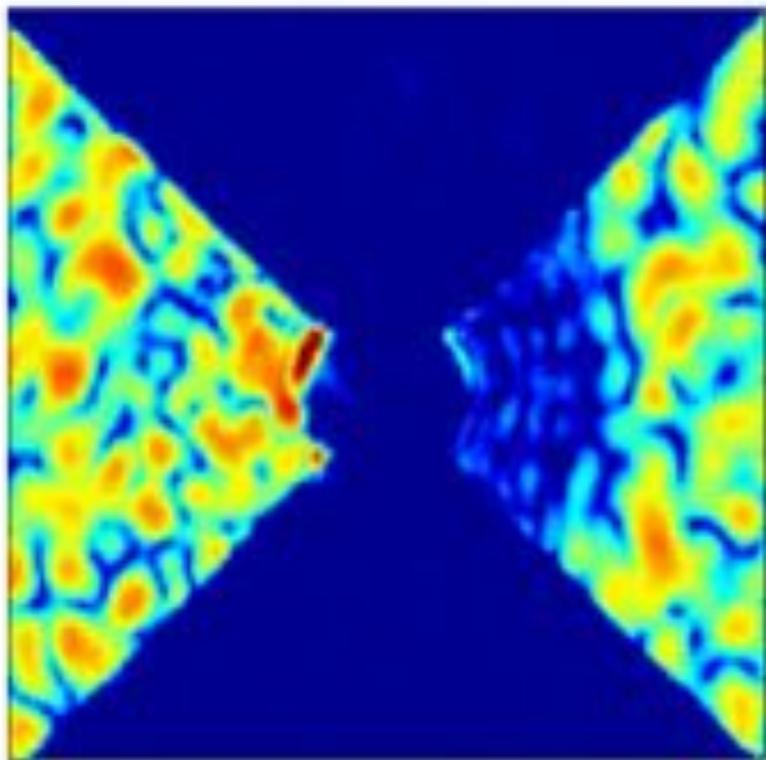
# Shaped Pupil Test on Subaru in Early September



# Shaped Pupil with Wavefront Control at HCIT, 2007



Single DM,  
Single-  
sided Dark  
Hole.

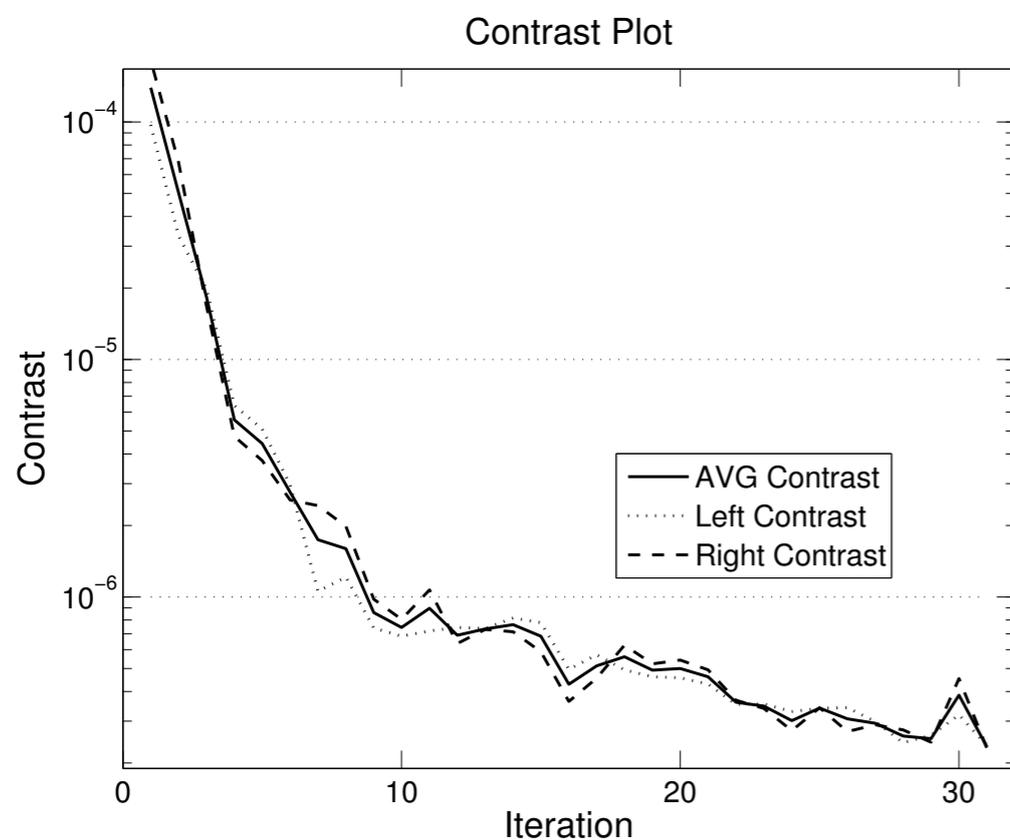
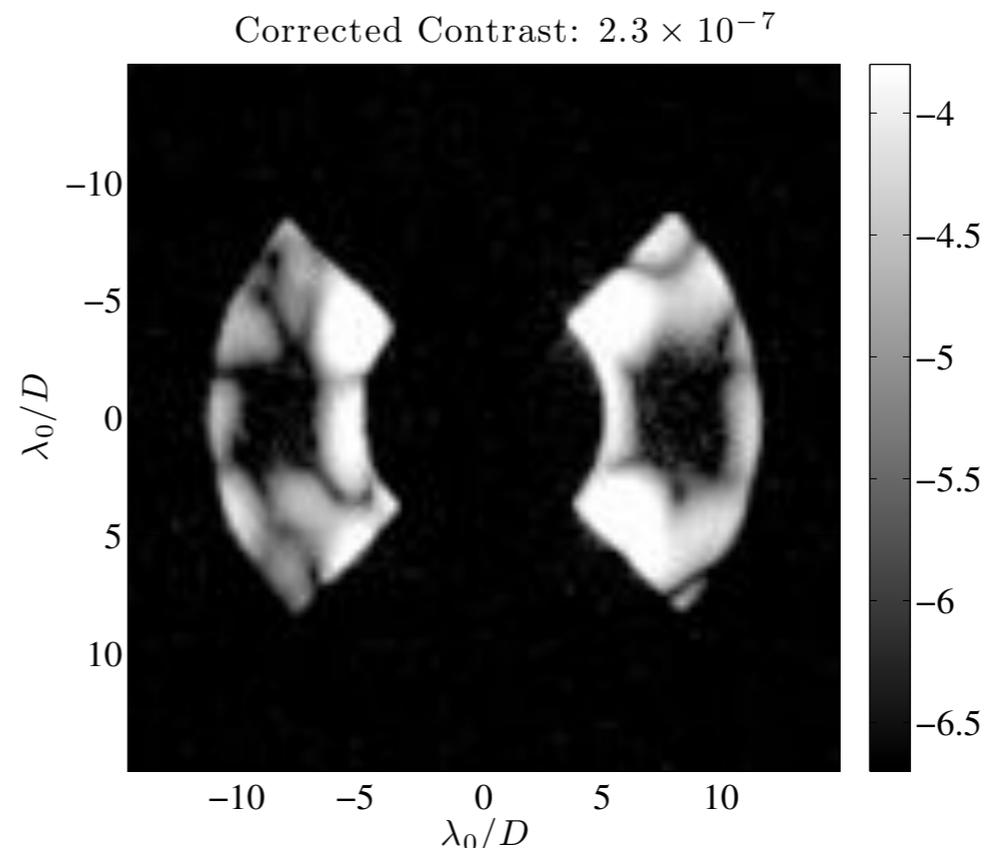
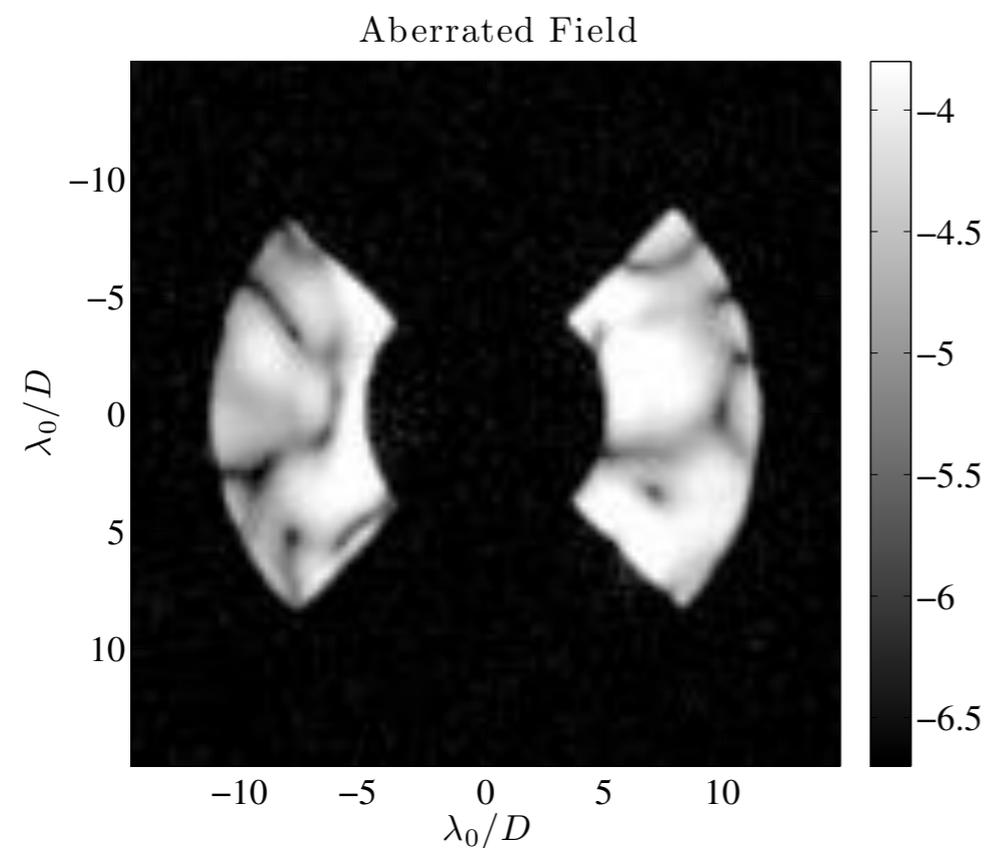


$2.4 \times 10^{-9}$   
in 10% band

Kasdin et. al 2003  
Kasdin et. al 2005  
Belikov et. al 2007

Already achieved lab contrast at expected level for AFTA coronagraph.

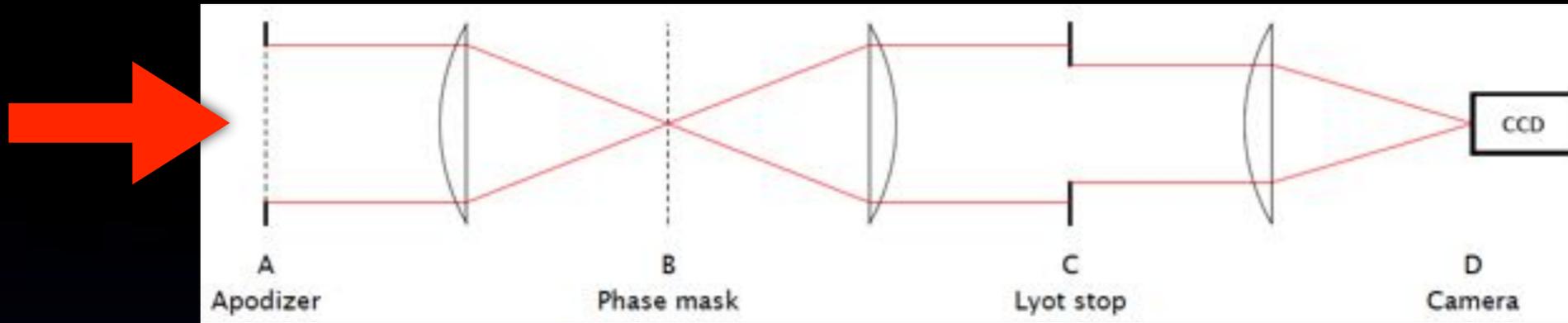
# Two-Sided Dark Hole in Princeton HCIL



Experimental results of sequential MEMS DM correction using a discrete time extended Kalman filter with 2 image pairs to build the image plane measurement. The dark hole is a square opening from 7–10 x -2–2  $\lambda/D$  on both sides of the image plane. Final contrast is  $2.3 \times 10^{-7}$  on both sides of the image plane. Image units are  $\log(\text{contrast})$ .

Groff et, al.

# Hybrid Shaped pupil + Four-quadrants phase mask

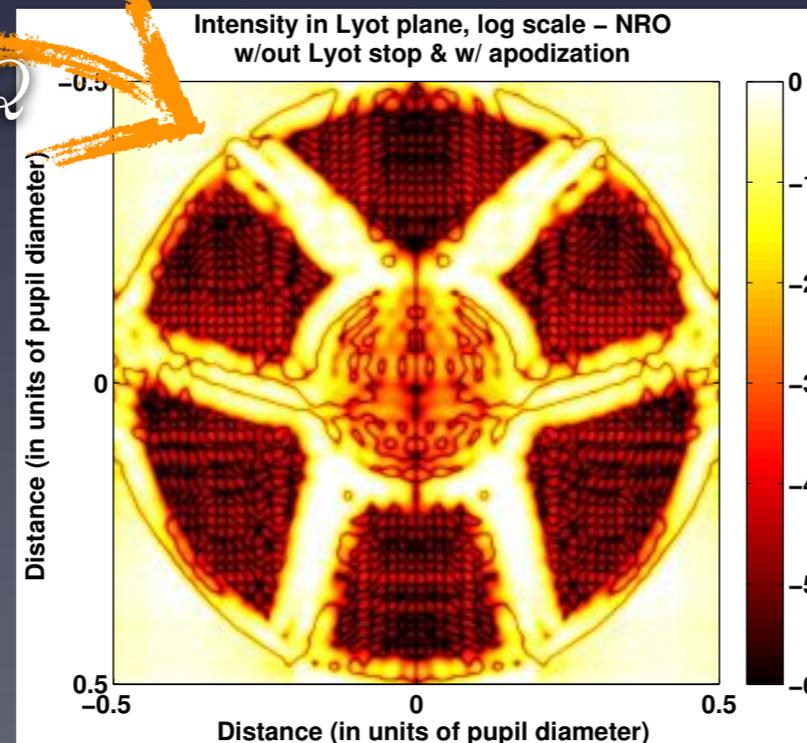
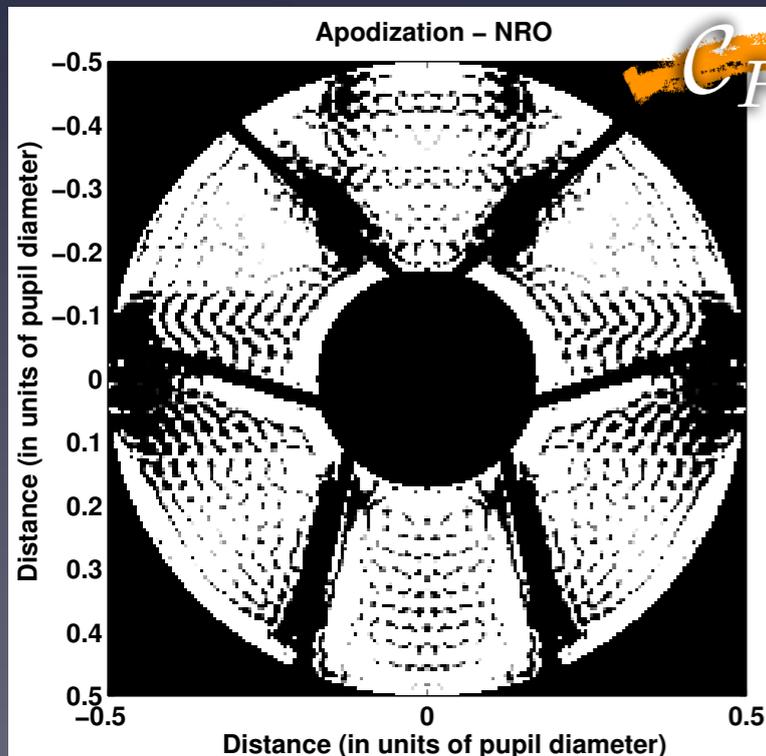


$$P(\tilde{x}, \tilde{y}) = \mathcal{C}_{FQ}[A(x, y)] \quad \text{with } \mathcal{C}_{FQ}: \text{ coronagraphic operator}$$

P: EF in Lyot plane      A: Apodization in 1<sup>st</sup> pupil plane

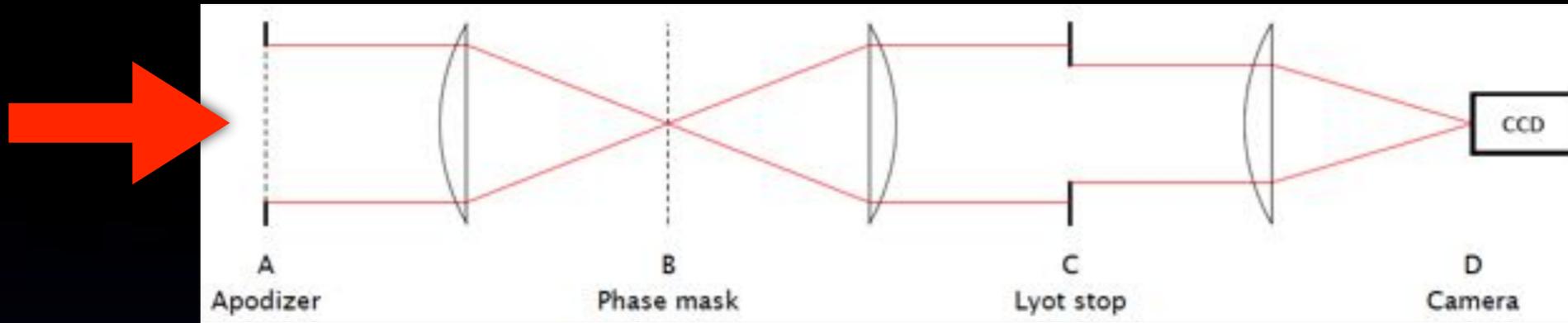
First pupil plane  
Apodizer

Lyot plane  
Intensity is reduced  
by the FQPM



$\mathcal{C}_{FQ}$

# Hybrid Shaped pupil + Four-quadrants phase mask

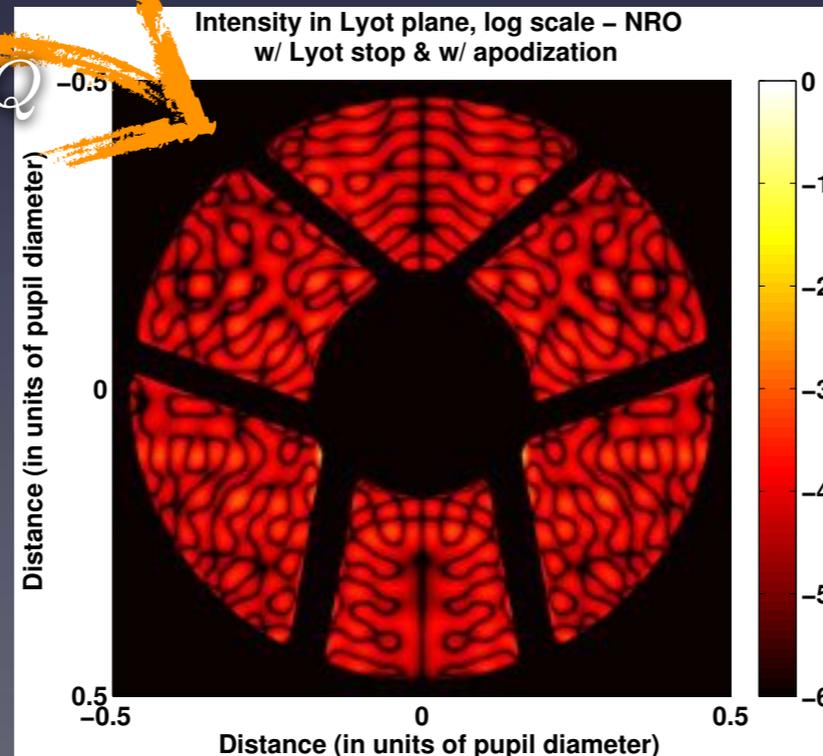
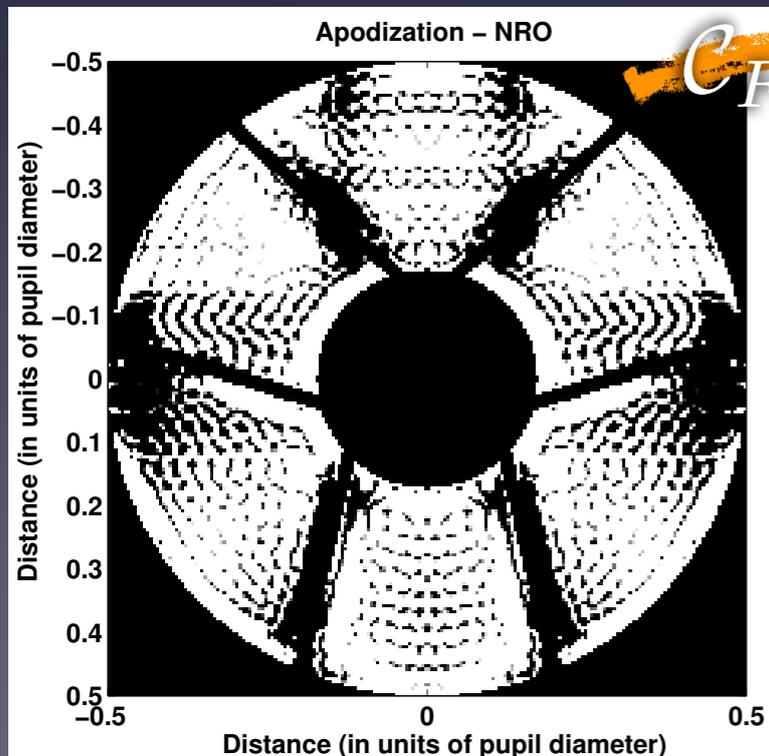


$$P(\tilde{x}, \tilde{y}) = \mathcal{C}_{FQ}[A(x, y)] \quad \text{with } \mathcal{C}_{FQ} : \text{coronagraphic operator}$$

P: EF in Lyot plane      A: Apodization in 1<sup>st</sup> pupil plane

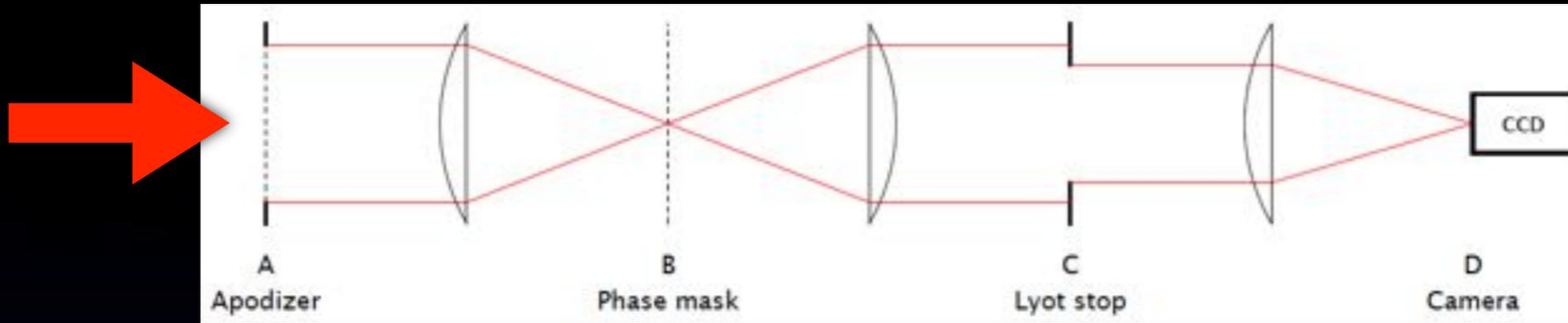
First pupil plane  
Apodizer

Lyot plane  
Intensity is reduced  
by the FQPM



$\mathcal{C}_{FQ}$

# Hybrid Shaped pupil + Four-quadrants phase mask



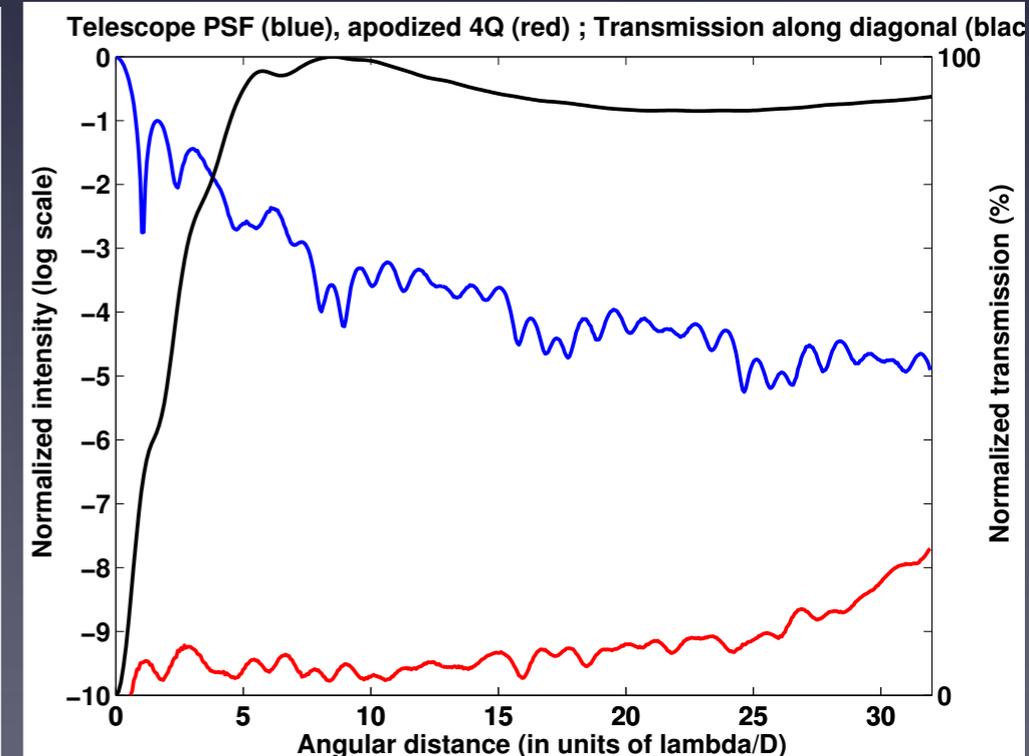
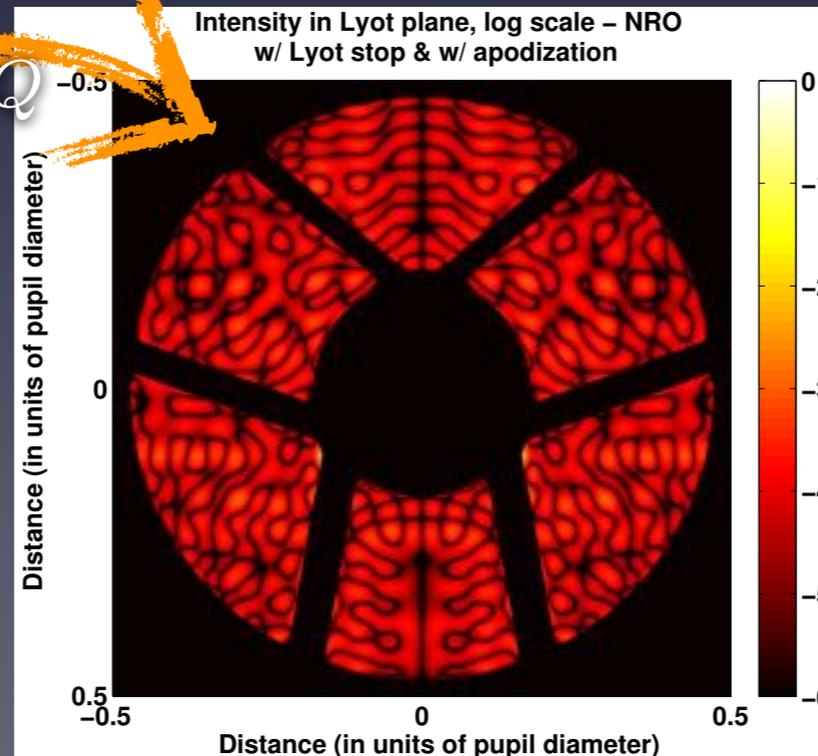
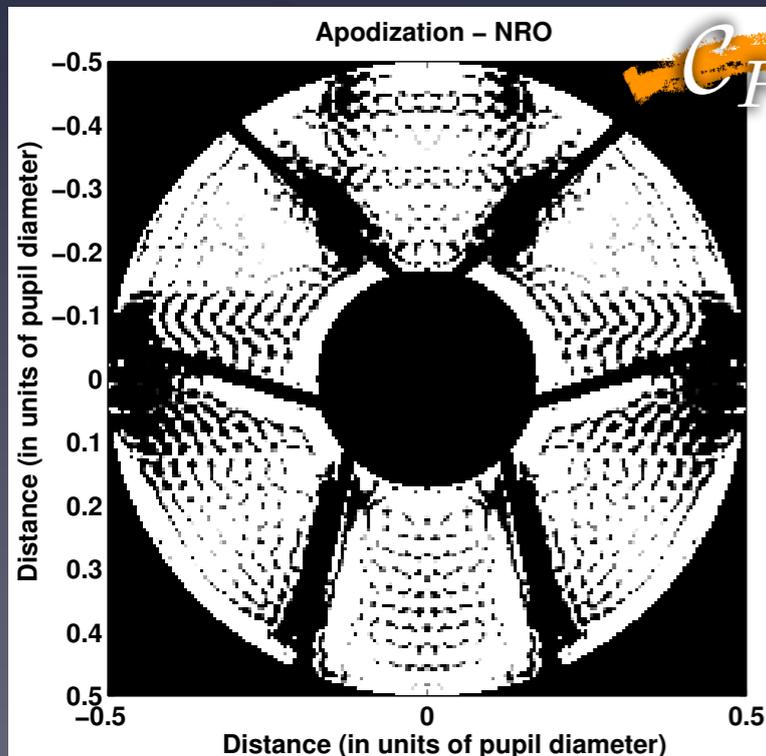
$$P(\tilde{x}, \tilde{y}) = \mathcal{C}_{FQ}[A(x, y)] \quad \text{with } \mathcal{C}_{FQ} : \text{coronagraphic operator}$$

P: EF in Lyot plane      A: Apodization in 1<sup>st</sup> pupil plane

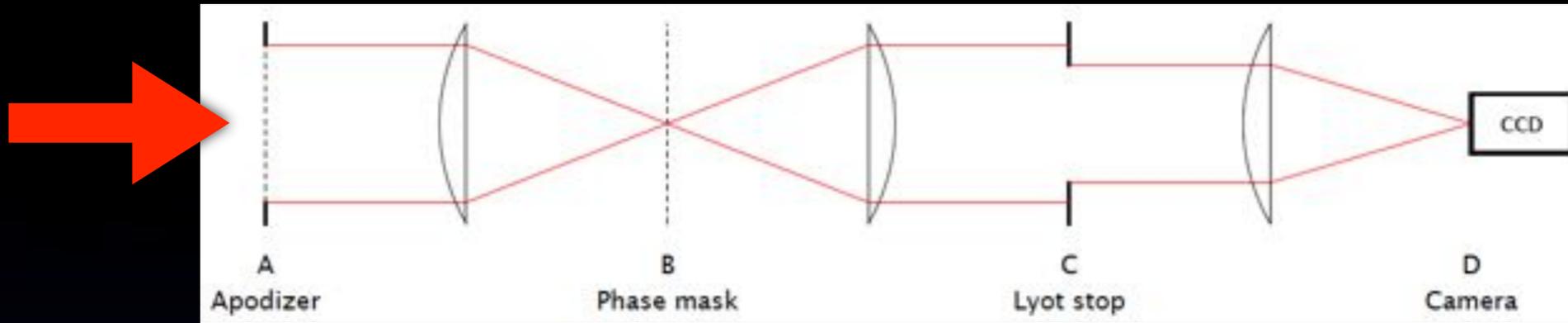
First pupil plane  
Apodizer

Lyot plane  
Intensity is reduced  
by the FQPM

Final PSF  
**>10<sup>-9</sup> contrast, 2 I/D iwa**  
**40% throughput**



# Hybrid Shaped pupil + Four-quadrants phase mask



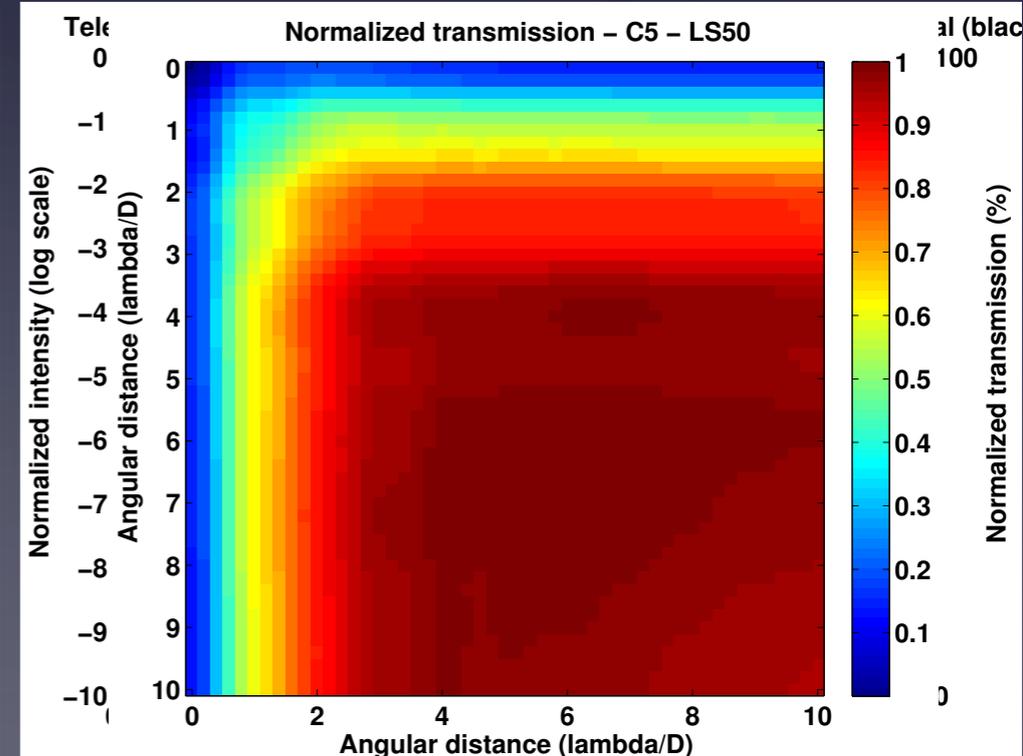
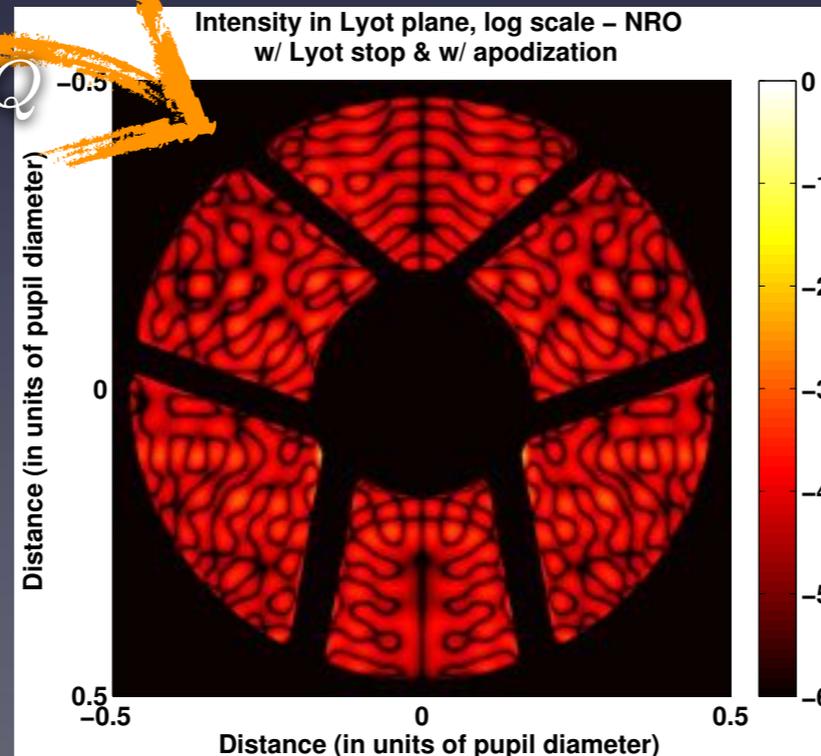
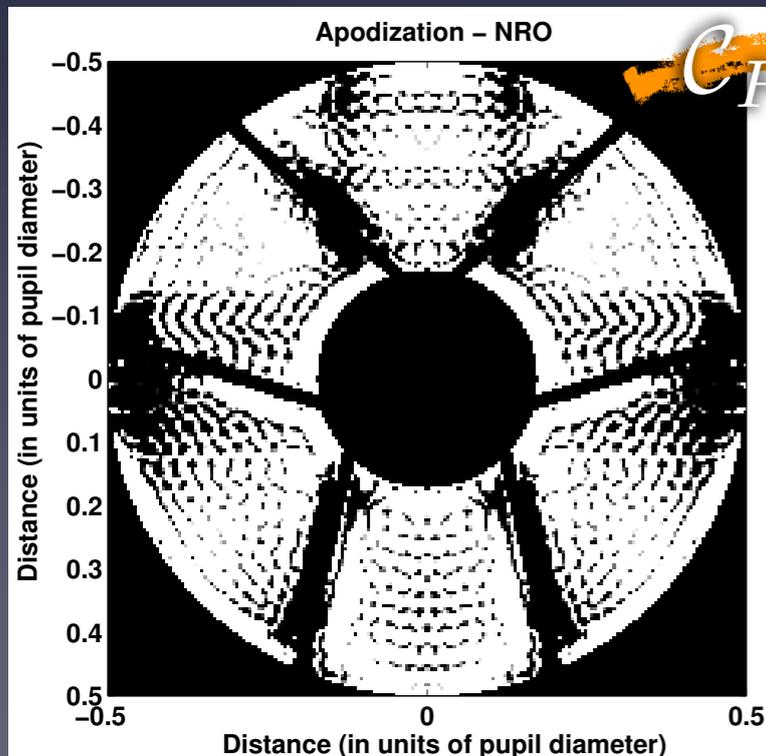
$$P(\tilde{x}, \tilde{y}) = \mathcal{C}_{FQ}[A(x, y)] \quad \text{with } \mathcal{C}_{FQ}: \text{ coronagraphic operator}$$

P: EF in Lyot plane      A: Apodization in 1<sup>st</sup> pupil plane

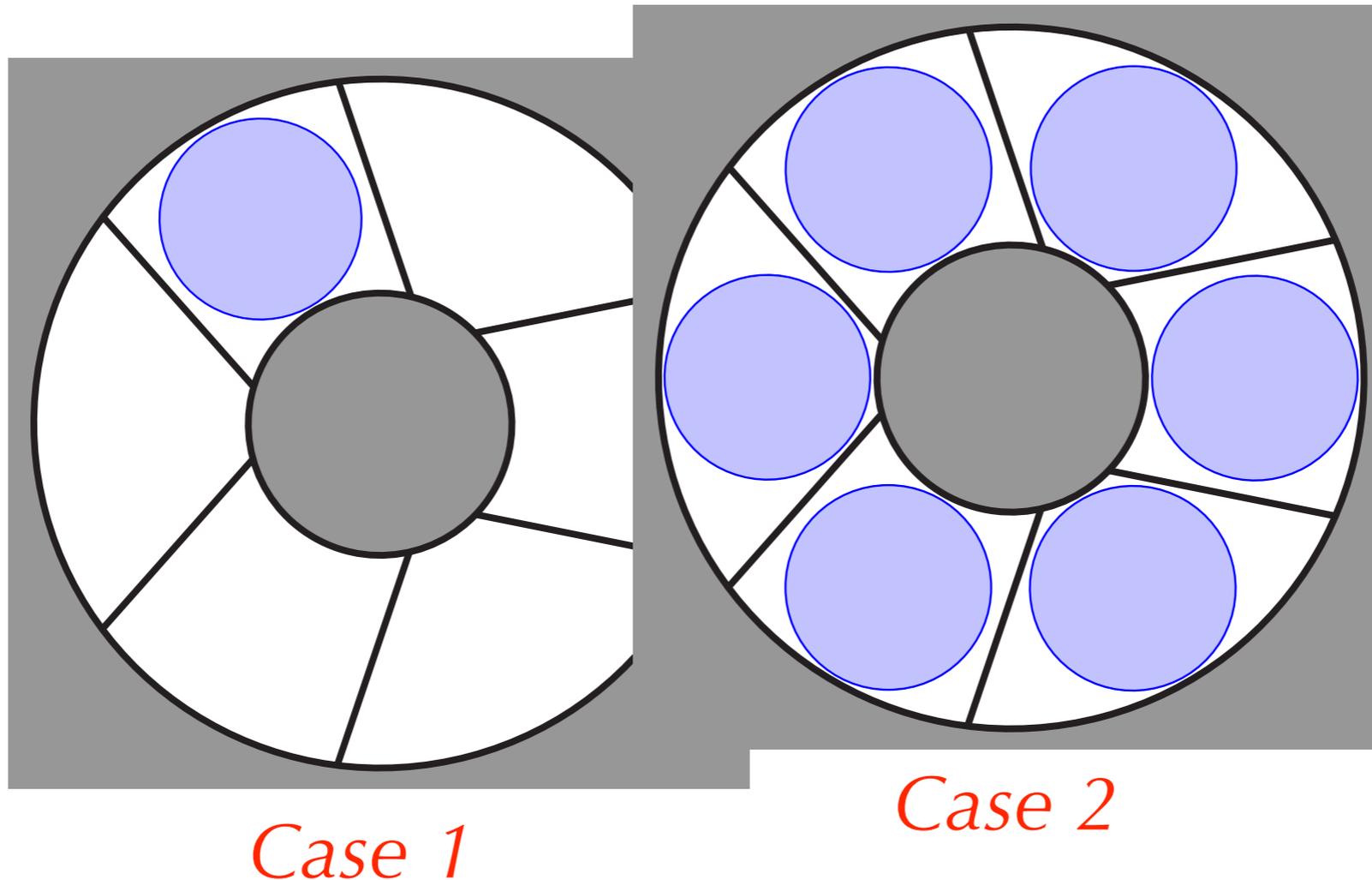
First pupil plane  
Apodizer

Lyot plane  
Intensity is reduced  
by the FQPM

Final PSF  
>10<sup>-9</sup> contrast, 2 I/D iwa  
40% throughput

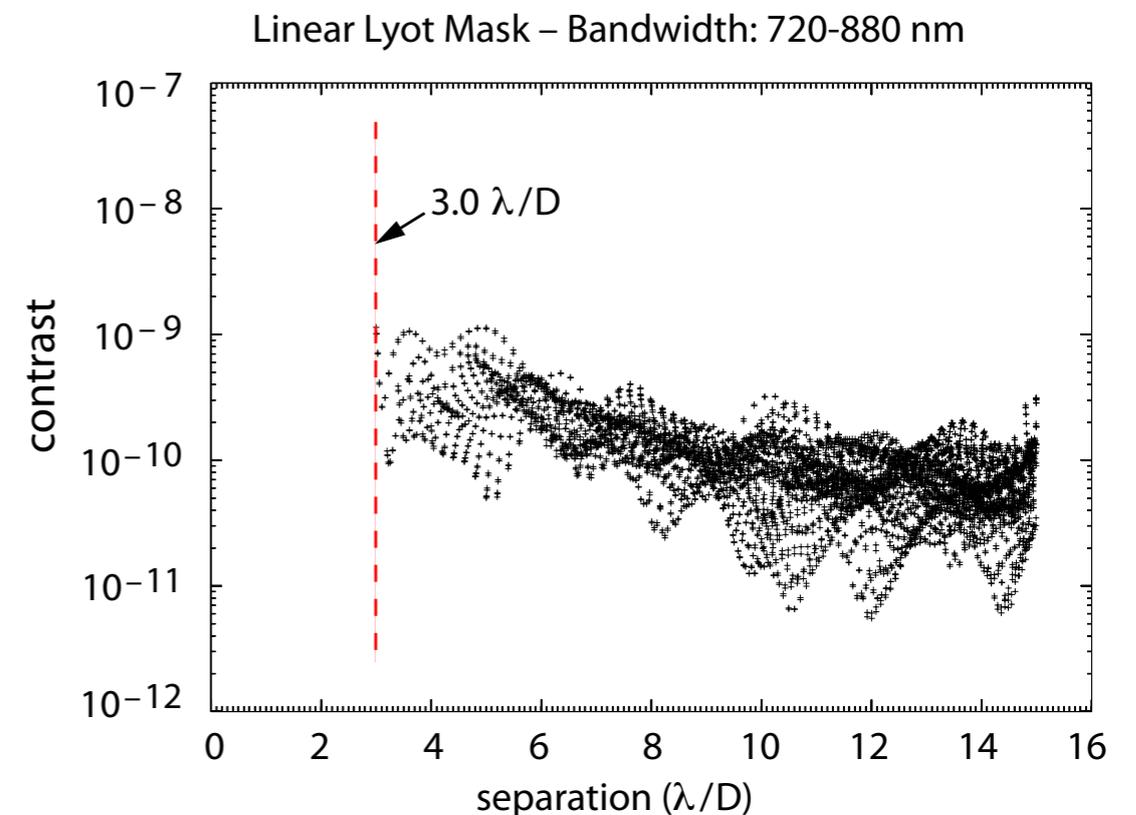
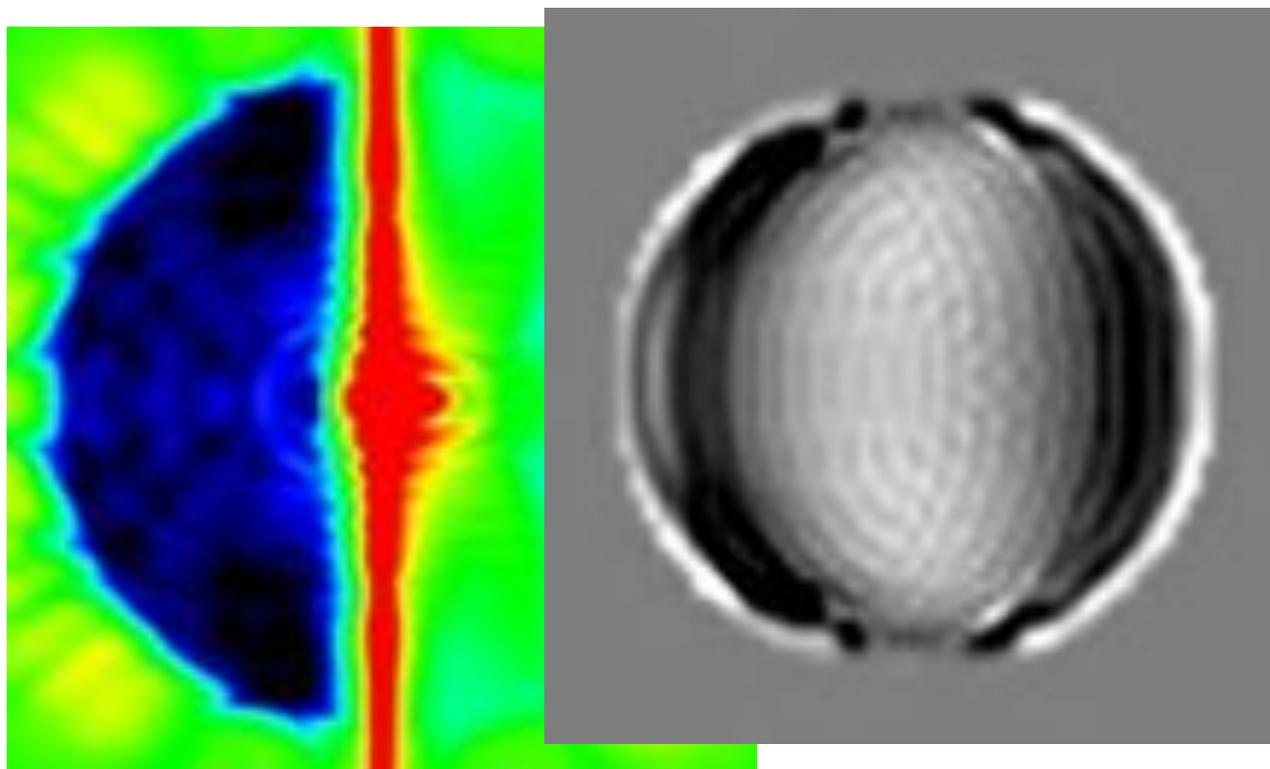


*Lyot coronagraph solutions can be found for either a subaperture or the full aperture of the NRO telescope*



- *The Lyot coronagraph has performed well in laboratory demonstrations (as validated by the NASA/SAT/TDEM program) with high contrast, throughput, bandwidth, and small inner working angle, and it is among the simplest technologies to implement.*
- *Have looked at subaperture and full aperture solutions for the NRO.*

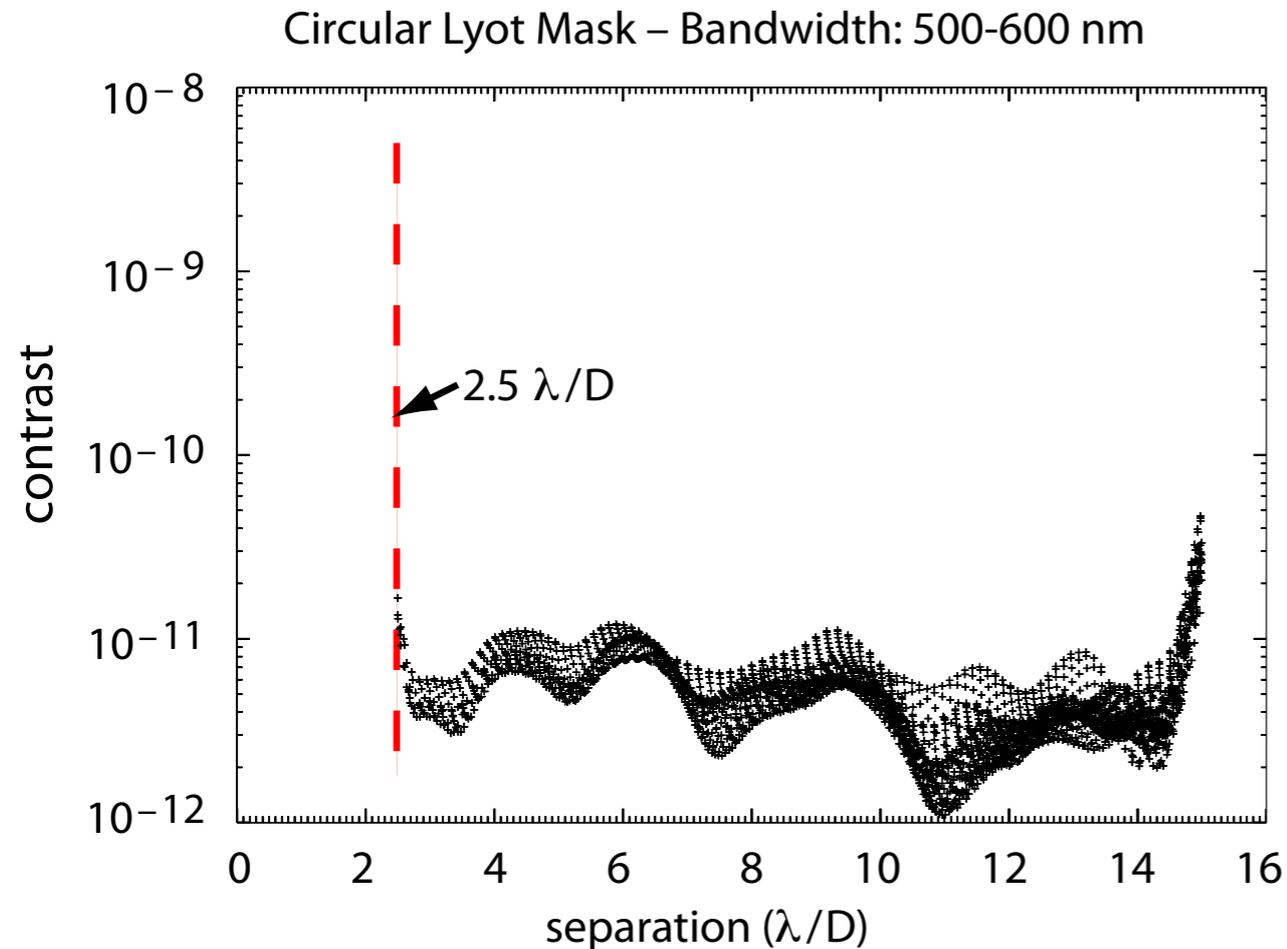
# State of the art for the Lyot coronagraph



- A complex apodized Lyot coronagraph (with focal plane mask of superimposed metal and dielectric layers) has been developed and tested in the laboratory under NASA's SAT TDEM program.
- With an unobscured aperture, **raw coronagraph contrast of  $5e-10$  is routinely achieved over a 10% spectral bandwidth with a 3 lambda/D inner working angle**, a robust result from the TDEM demonstrations.
- Linear Lyot coronagraph (shown above), **provides contrast better than  $5e-10$  over a 20% bandwidth**. It has been manufactured and awaits vacuum testbed time.
- Next step is the implementation of a circular Lyot mask with better limiting contrast and smaller inner working angle (next slide).

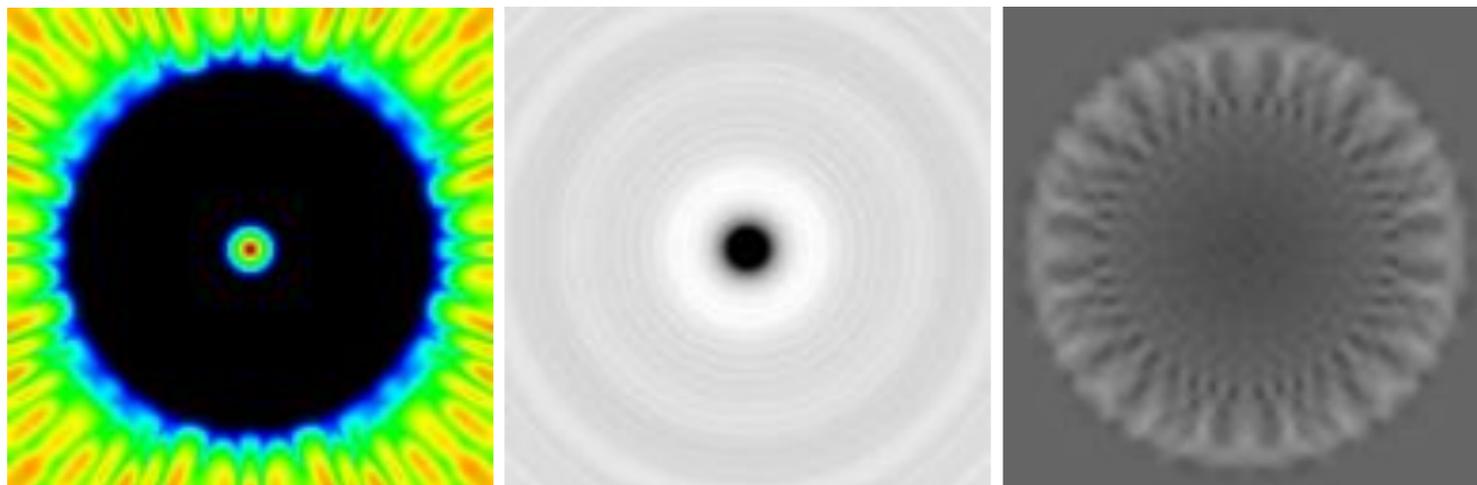
# COMPLEX APODIZATION LYOT CORONAGRAPHY

John Trauger, Brian Gordon, John Krist, Dimitri Mawet, Dwight Moody (Proc.SPIE 8442-04, 2012)



## Computed performance for a newly designed circular complex apodized Lyot mask:

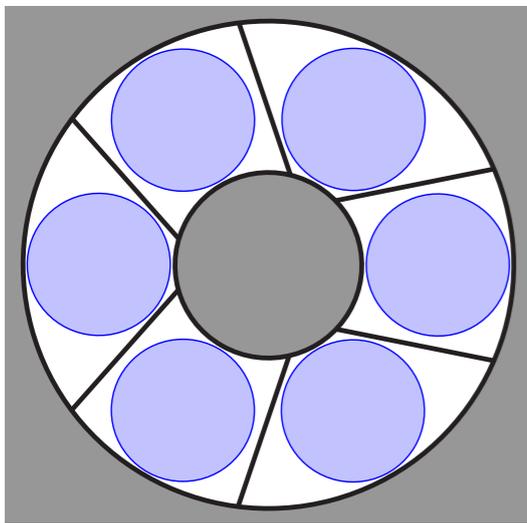
- As for previous linear mask designs, the thickness profiles of the metal and dielectric layers are optimized simultaneously with the wavefront phase control of a single 48x48 DM.
- Focal plane mask is a layer of nickel plus a layer of cryolite superimposed on a fused silica substrate.
- These two layers provide the degrees of freedom to control both the real and imaginary parts of the optical wavefront.
- Inner working angle is  $2.5 \lambda_0/D$ . Note that a full  $360^\circ$  dark field has been created with a single deformable mirror.
- Contrast in the 500-600 nm ( $\delta\lambda/\lambda_0 = 18\%$ ) spectral band is  $5.3 \times 10^{-12}$  in both the inner  $2.5\text{--}3.5 \lambda_0/D$  annulus and averaged across the entire dark field extending from radii of 2.5 to  $15 \lambda_0/D$ .



Left: Raw contrast in the dark field is displayed with a logarithmic stretch from  $10^{-11}$  to  $10^{-7}$ .

Center: Intensity transmittance profile of the complex apodized focal plane mask is displayed with a linear stretch from zero to 1.

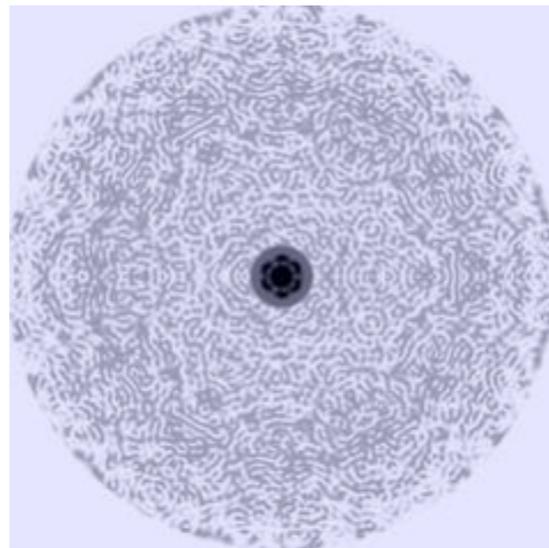
Right: Corresponding surface setting on the deformable mirror is displayed with a linear black-to-white stretch of 40 nm.



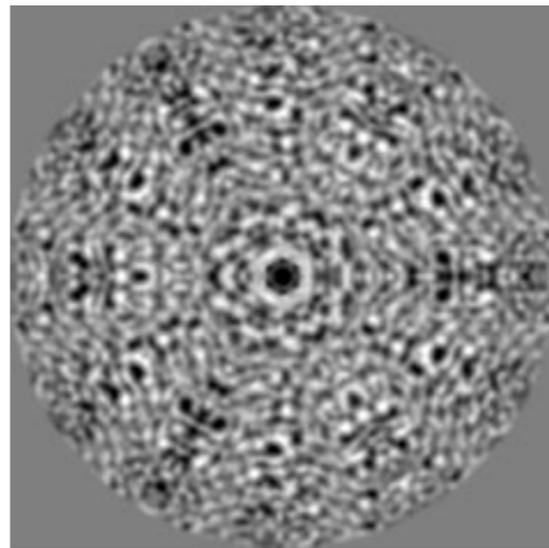
*Case 2: complex apodization Lyot coronagraph for the full AFTA aperture  
– early analysis –*



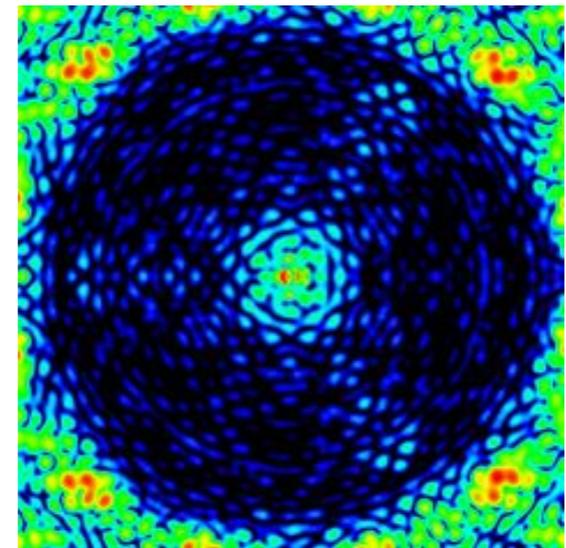
TELESCOPE APERTURE & LYOT MASK



LYOT FOCAL PLANE MASK (TRANSMITTANCE)



LYOT FOCAL PLANE MASK (PHASE SHIFT)



HIGH CONTRAST DARK FIELD

- *As in foregoing Lyot coronagraph designs, the focal plane mask controls both real and imaginary parts of the complex wavefront, using one metal and one dielectric layer on a glass substrate.*
- *We begin our design optimization with an idealized solution assuming perfect optics, no wavefront corrections, and monochromatic light.*
- *In the example shown above, raw contrast averages  $6e-10$  from 2.5 to 24  $\lambda/D$ .*
- *Next step, now in progress, is to introduce deformable mirror(s) and further adjustments of the focal plane mask to extend spectral bandwidth from a few% to as broad as 20% while maintaining high contrast.*

# Phase-Induced Amplitude-Apodization Complex-Mask Coronagraphy

The PIAACMC concept offers high performance coronagraphy on a centrally obscured (e.g., ex-NRO) telescope.

PIAACM Coronagraphy combines:

- Very high to unity throughput and uncompromised angular resolution of a PIAA Coronagraph
- Small Inner Working Angle (IWA) of a Phase-Mask Coronagraph
- Design Flexibility of an Apodized Pupil Lyot Coronagraph

PIAACM + ex-NRO Coronagraphy offers:

- small ( $\sim 1 \lambda/D$ ) IWA with very high throughput (e.g., 80% throughput at  $1 \lambda/D$ ) for  $1e-9$  contrast at visible wavelengths →

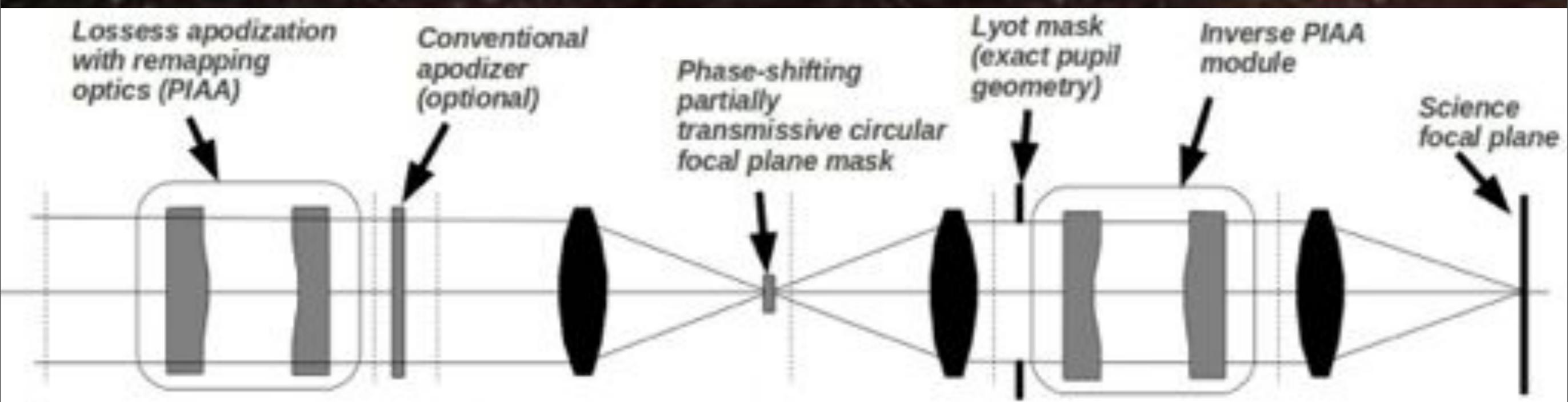
PIAACM Coronagraph with 2.4m ex-NRO telescopes could provide:

**IWA of  $1 \lambda/D = 43 \text{ mas}$  (0.43 AU at 10 pc) at  $0.5 \mu\text{m}$**

# Phase-Induced Amplitude-Apodization Complex-Mask Coronagraph

**PIAACMC is a particularly efficient hybrid (PIAA, Roddier Phase Mask, Apodized Lyot) coronagraph with starlight suppression achieved by:**

- 1. A mild entrance pupil apodization with a lossless PIAA**
- 2. A small circular complex (amplitude/phase shift) focal plane mask**  
(with partial transmission of sub- $\lambda/D$  PSF core)
- 3. A pupil-optimized Lyot stop**



N.B.: Closed-loop wavefront sensing & control with Low Order WFS and Science Camera using Fast Steering Mirror (tip-tilt) and Deformable Mirrors (mid-spatial frequencies)

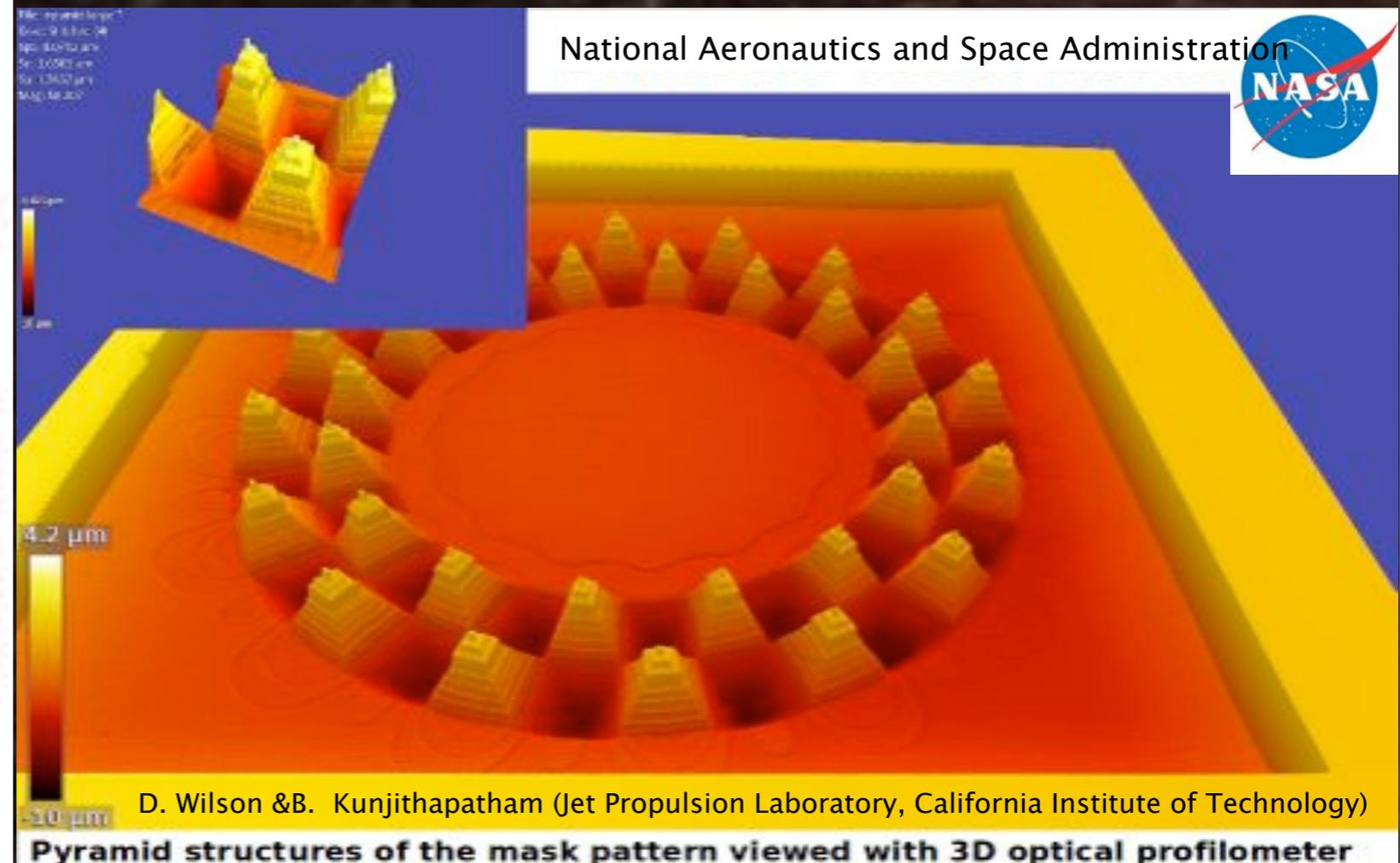
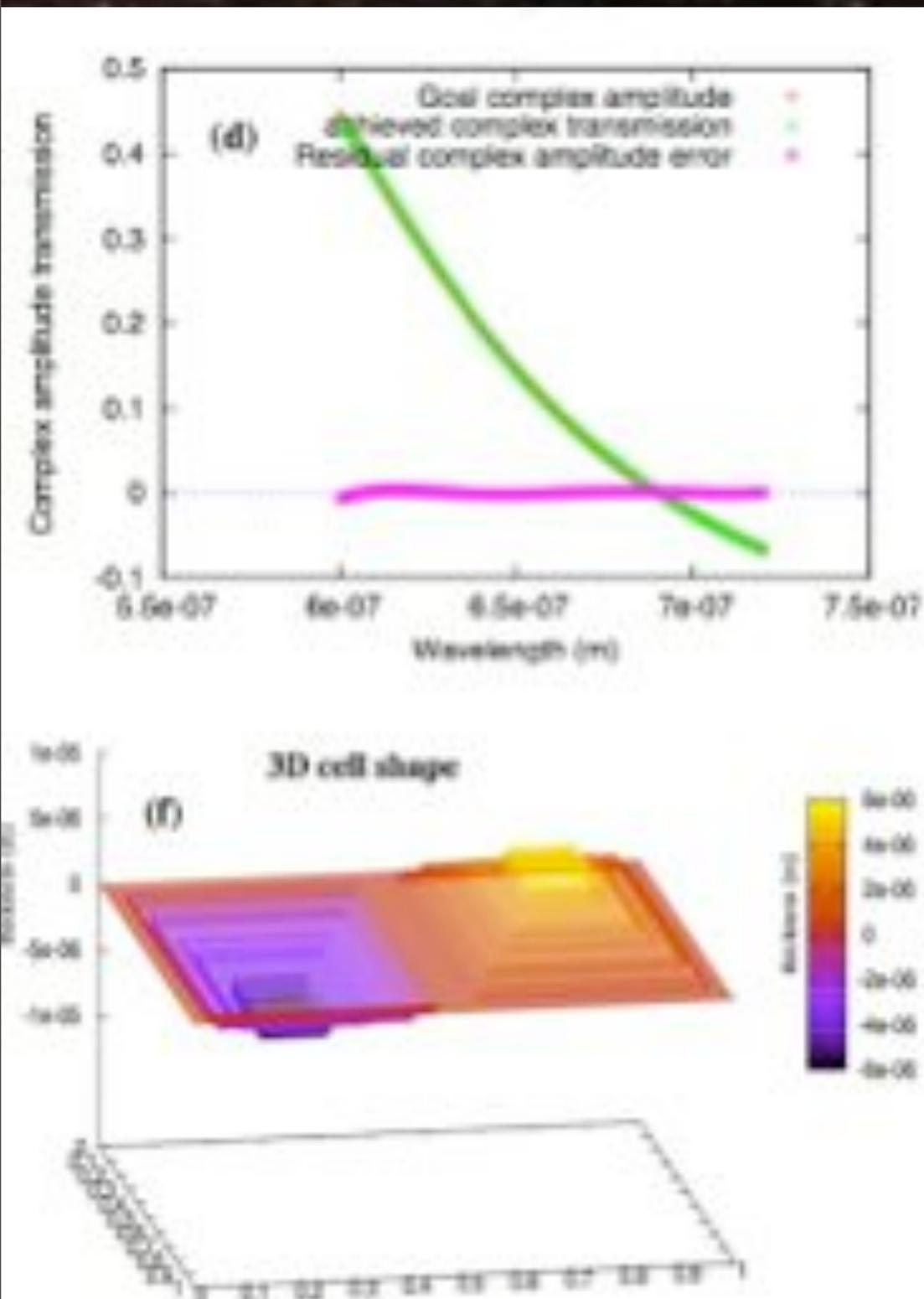
High-efficiency PIAA provides more light into science camera for faster WFE sensing/control

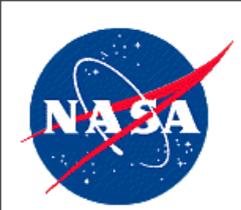
# Complex (phase & amplitude focal plane Mask (CM)

Diffractive focal plane mask for high performance (throughput) coronagraphy in broadband light

Initial Development for  $\sim 1e-9$  contrast work to date funded by NASA (PI: Belikov, NASA Ames)

Prototype Diffractive Focal Plane Mask (JPL MDL)





# Visible Nulling Coronagraph (VNC): Overview

- **VNC Approach is inherently flexible:**

- Conform instrument to Telescope; lower instrument significance as mission driver
- In-principle VNC works w/ *filled, segmented* and *interferometric* apertures
- Differential Wavefront Control (photon conserving)
- EPIC / VNC studied under NASA Astrophysics Strategic Mission Concept (ASMC)
- VNC / technologies supported under IRAD, SBIR's & SAT/TDEM:

Includes: DM, spatial filter arrays, achromatic phase shifters, wavefront control, cameras

- **VNC selected under NASA ROSES SAT/TDEM (FY10/11 & FY12/13)**

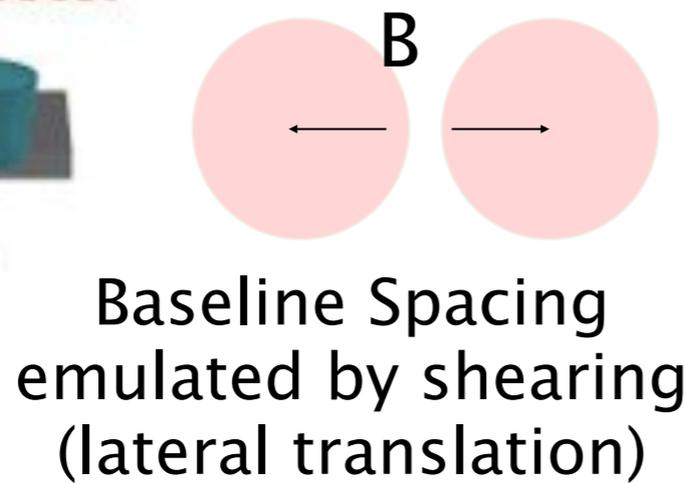
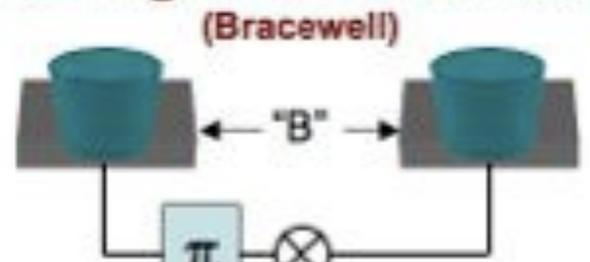
- Milestones: Advance Technology Readiness; reviews by Technical Advisory Committee (TAC)
  - Milestone #1:  $10^8$  contrast at  $2 \lambda/D$ , narrowband, to 90% confidence
  - Milestone #2:  $10^9$  contrast at  $2 \lambda/D$ , narrowband, to 90% confidence
  - Milestone #3:  $10^9$  contrast at  $2 \lambda/D$ , with  $\Delta\lambda = 40$  nm centered on  $\lambda = 633$  nm ( $R \sim 16$ ) to 90% confidence
- Milestones traceable to contrasts of  $10^9$  & IWA of 125 mas (Jovians / Dust disks)

- **Testbeds => will show lab data achieves  $10^9$  at  $2 \lambda/D$ , dark hole from 1 – 4  $\lambda/D$**

- Incremental sequence of visible nulling testbeds
  - Assess VNC and associated technologies
- Earlier Testbed demonstrated closed-loop nulling w/ less segments on DM
- GSFC Vacuum Nuller Testbed (VNT) used for current milestone achievement

# Visible Nulling Coronagraph–Basic Principle

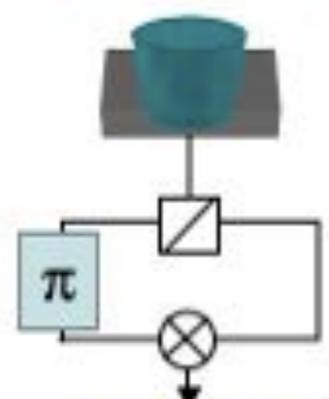
## Nulling Interferometer (Bracewell)



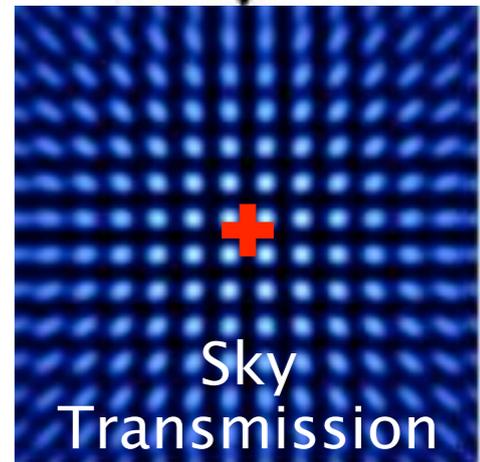
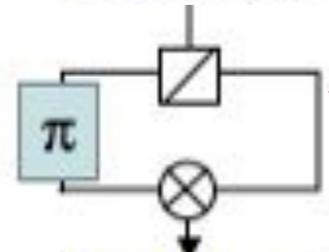
$$T^{2} \sim \theta^2$$



## Nulling Coronagraph



$$T^{2} \sim \theta^2$$

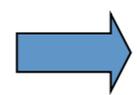


- On-axis starlight on dark fringe
  - Destructive interference
- Off-axis planetlight on bright fringe
  - Constructive interference

$$T^{4} \sim \theta^4$$

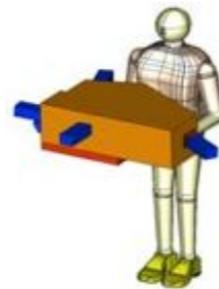
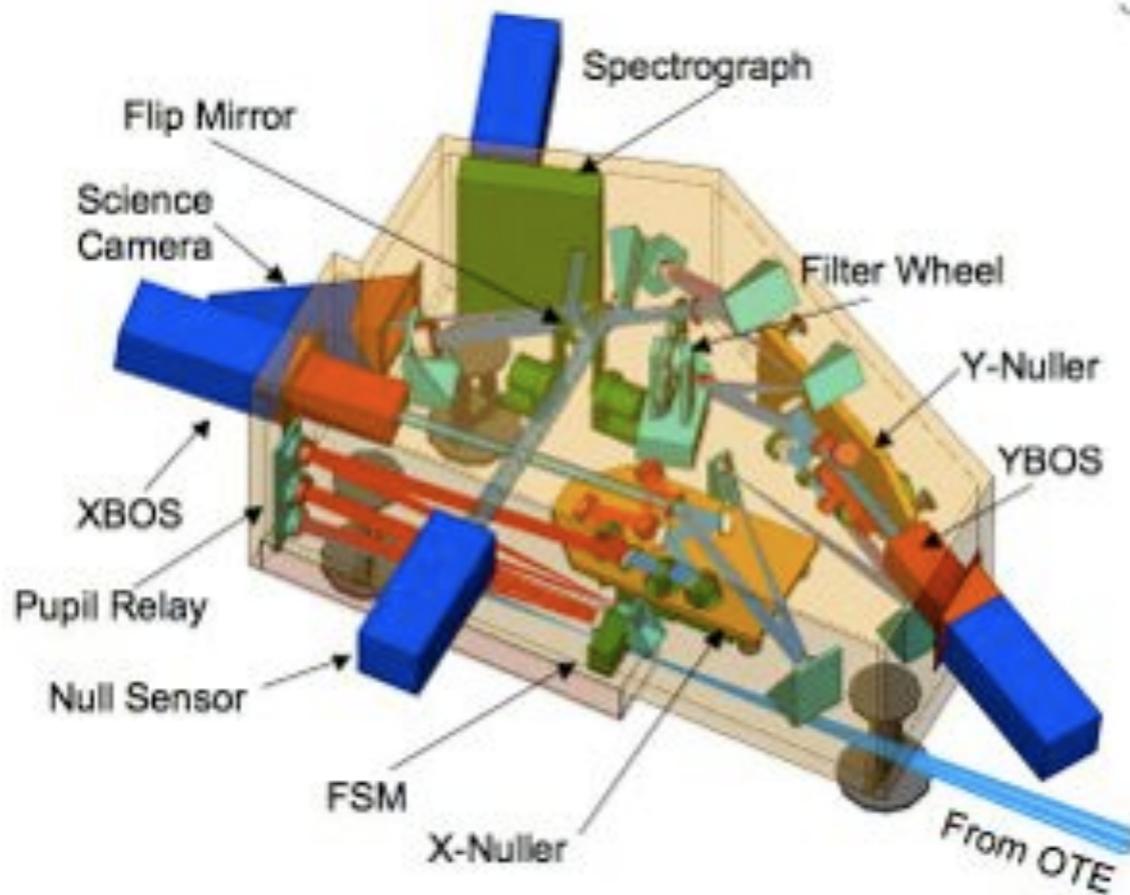
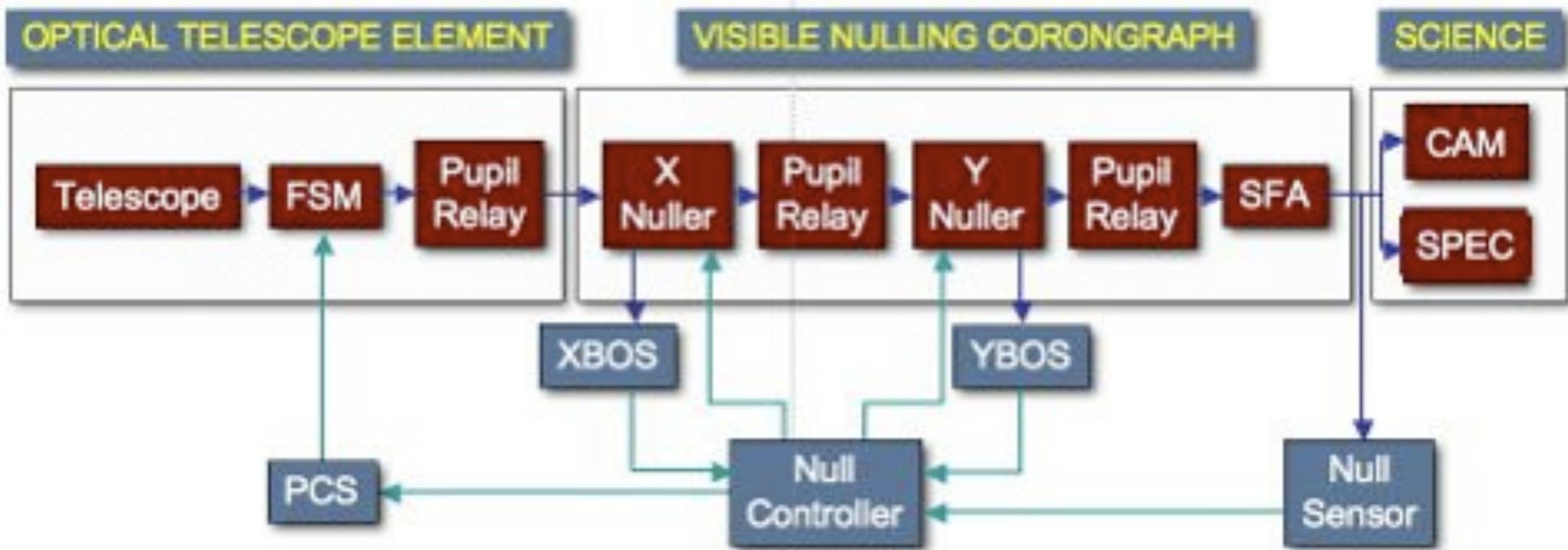
$$IWA = \frac{1}{s}$$

$$s = 0.25 \Rightarrow IWA = 2 \frac{\lambda}{D}$$



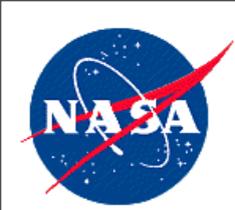


# Architecture Overview



- XBOS used for fine pointing
- XBOS, YBOS, Null Sensor used for coarse & fine null control
- YBOS & Science Cam used for in-situ null control monitoring

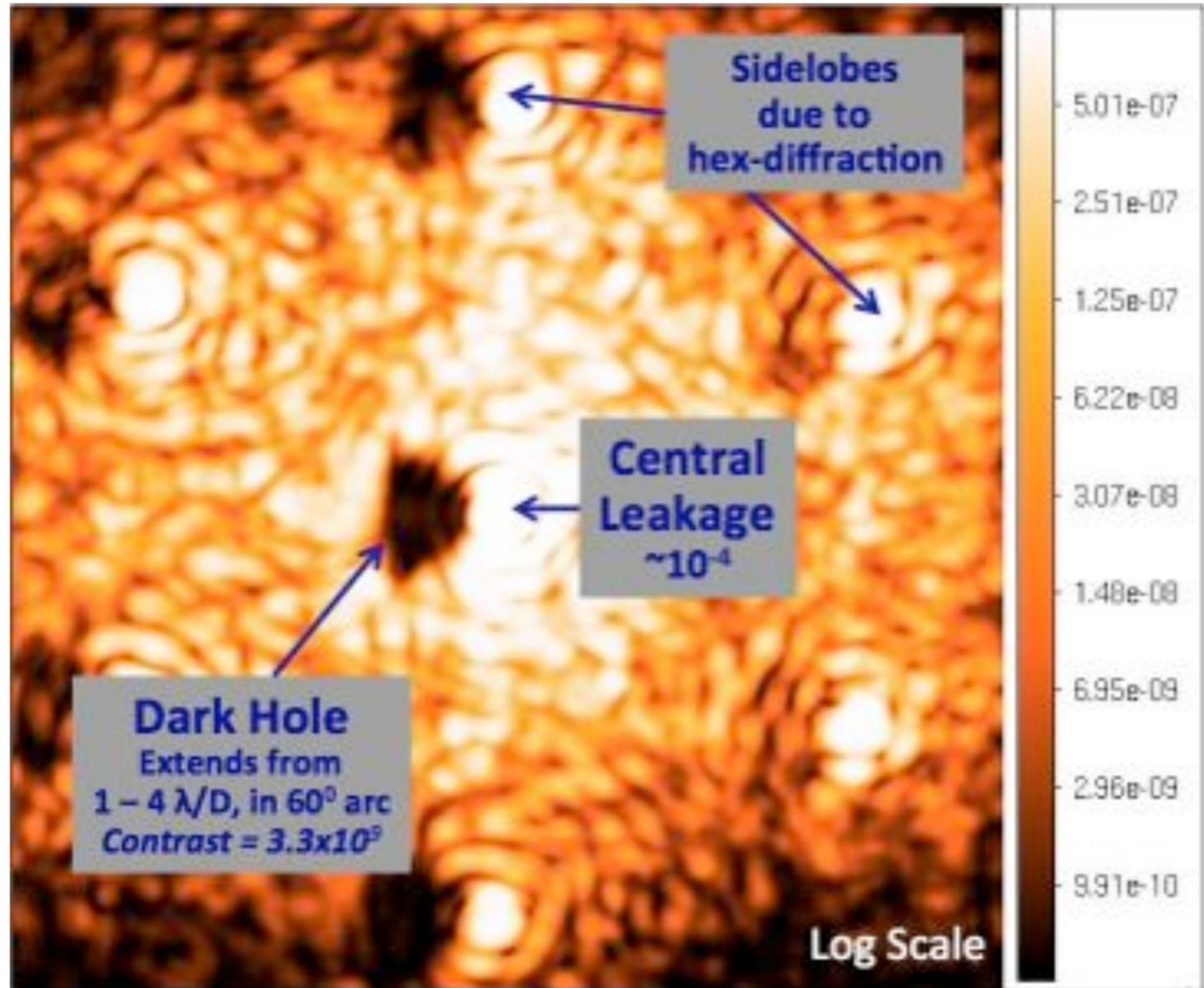
Most optics within VNC are Flats  
<2 cm diameter  
Size limited by DM technology



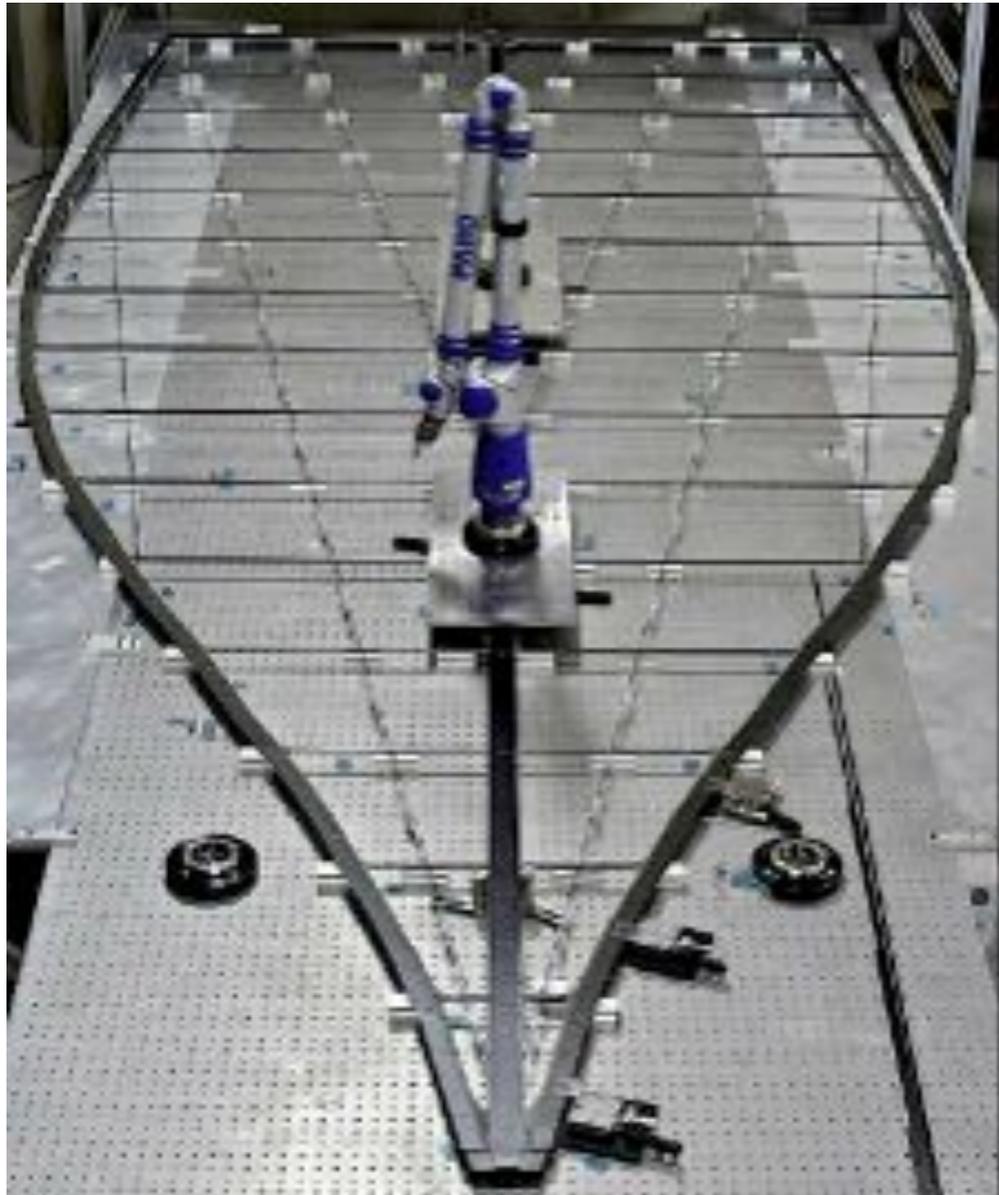
# 10<sup>9</sup> Contrast @ IWA 1 - 4 λ/D Results

## GSFC VNC Testbed on 06/09/12

- GSFC/Visible Nulling Coronagraph Testbed
- 4 Data Collection Events (DCE)
  - 50,000 frames per DCE
  - Average last 3,800 frames
  - Closed-loop at 40 Hz / 4 Hz in vacuum tank
  - $(\lambda, \Delta\lambda) = (633, 1.2)$  nm
- **~10<sup>9</sup> Contrast averaged over 1-4 λ/D, 60° arc region**
- 1<sup>st</sup> Demo using segm DM
  - hex-packed segment MEMs DM
- FY12/13 TDEM broadband
  - increase spectral bandpass from  $\Delta\lambda = 1.2$  nm to  $\Delta\lambda = 40$  nm



# Should AFTA-WFIRST go to L2, consider an occulter!



- Contrast and Inner working angle independent of telescope.
  - No wavefront control needed, only on-axis camera.
  - Could detect Earth's in habitable zone.
  - Full band (400-1100) spectroscopy at once.
  - Recently completed prototype petal compatible with  $10^{-10}$  mission.
- 
- Requires second spacecraft in addition to narrow-field camera.
  - Telescope must be equipped for cooperative sensing and control.

It would be prudent to include the capability on AFTA (RF-link and NIR tracking camera).

## Summary

A narrow field camera with coronagraph can be included on AFTA-WFIRST at low cost with no changes to telescope:

- Jupiter and Neptune detection and characterization in the visible.
- Exozodiacal dust characterization down to 5x zodi in visible, specific recommendation of NWNH.
- Technology testing and demonstration of coronagraphs with precision wavefront control in space

This was just a preliminary look.

- What is WFE and thermal and dynamic stability of telescope?
- How will low-order aberrations affect contrast for different coronagraphs?
- Is there room for a spectrograph or just filter photometry?
- What is available mission time for observations?
- What is observing band and how many channels?

**Opportunity to perform science and advance the state of the art!**

Next step is careful study of coronagraph design space, wavefront control, technology readiness, and potential science

# Backup Slides

# Mass Radius Relationship

