High-Contrast Imaging with the Astrophysics Focused Telescope Assets

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

<u>AFTA SDT Charge:</u>

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 [and wavefront control] defined in a parallel study to advance the science priorities described in the 2010 Decadal Survey for the detection and study of exoplanets.

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."

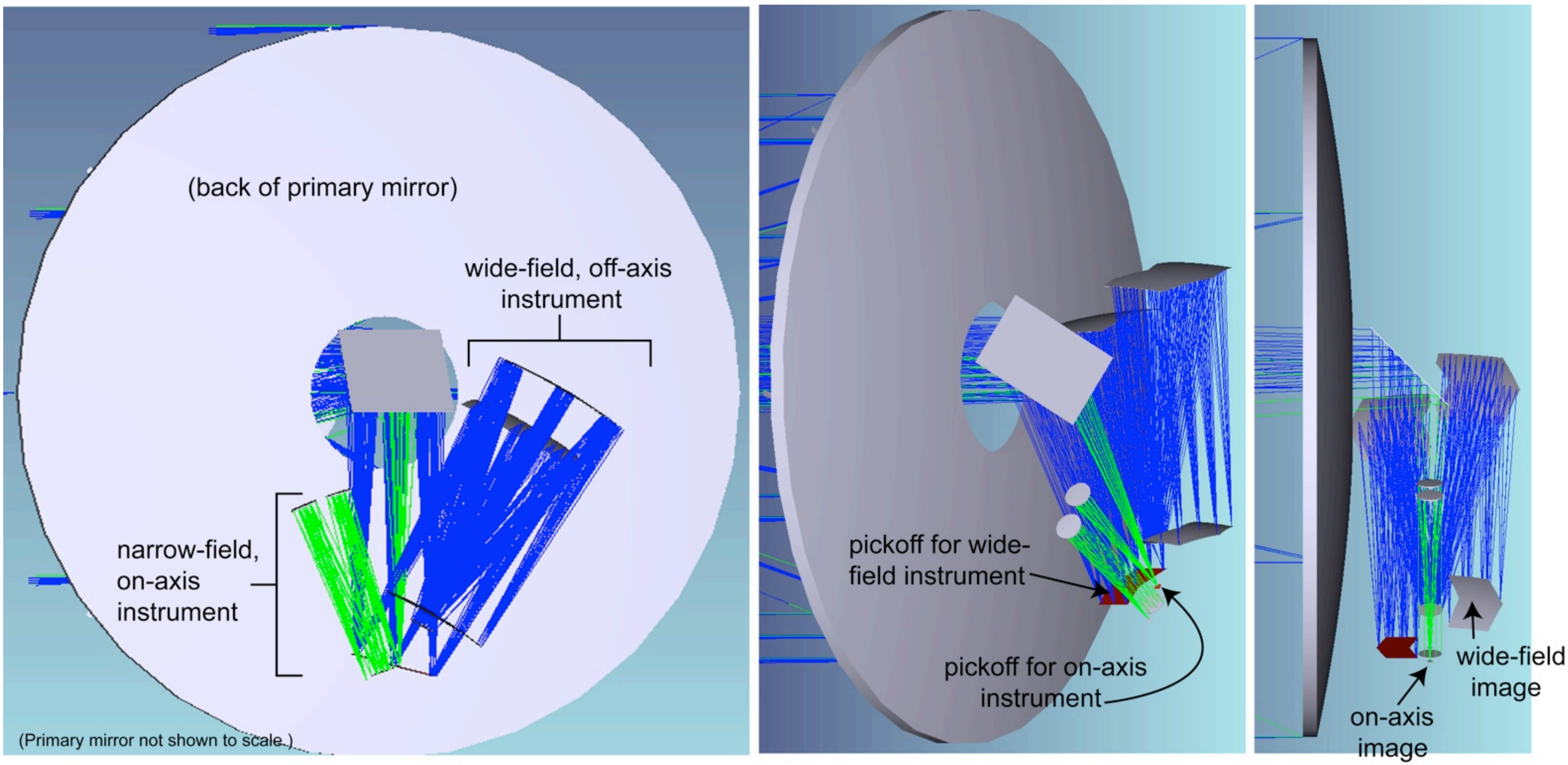
–Michael Moore, 9/4

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-1 with On-Axis Narrow-field Instrument:

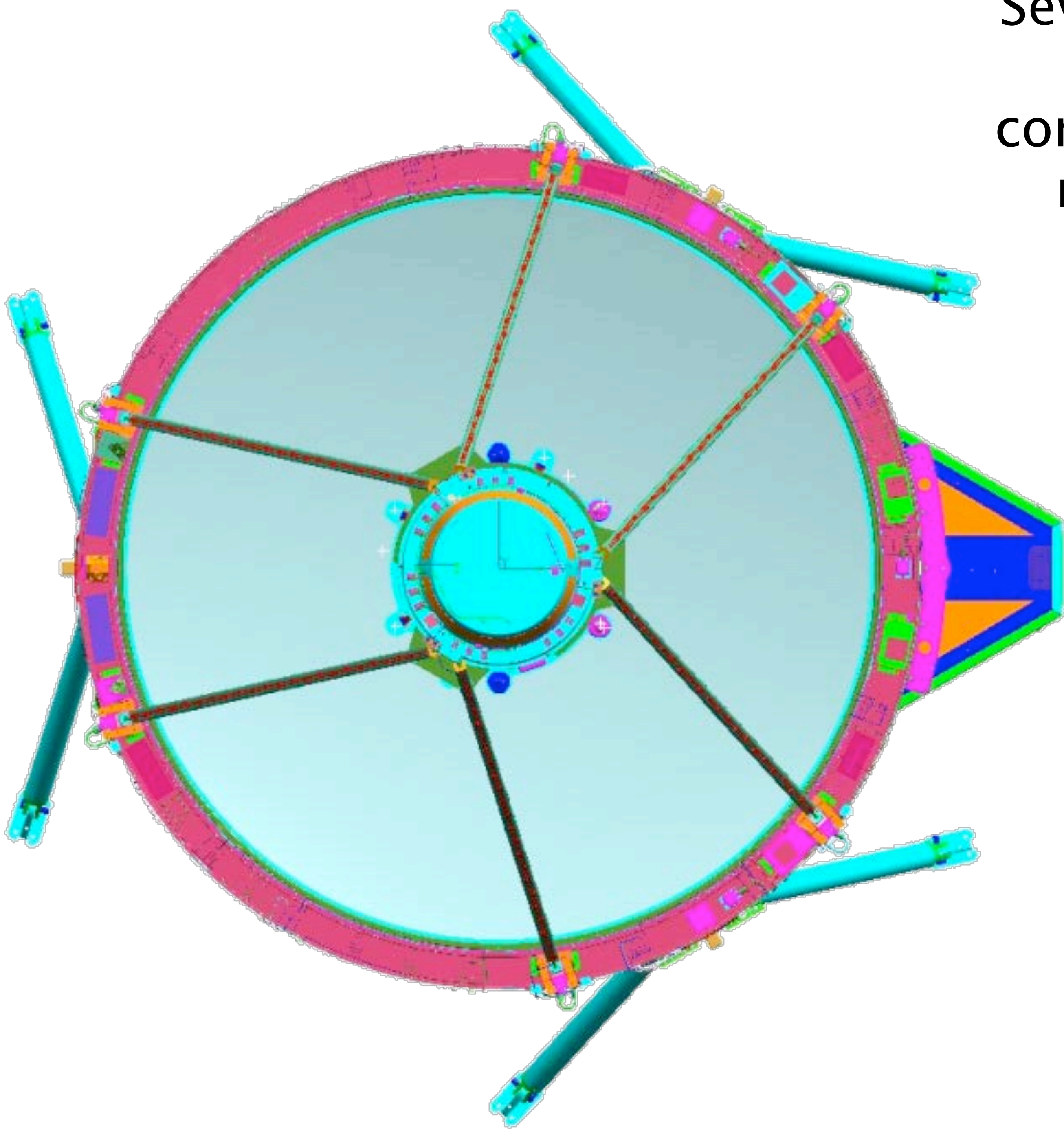


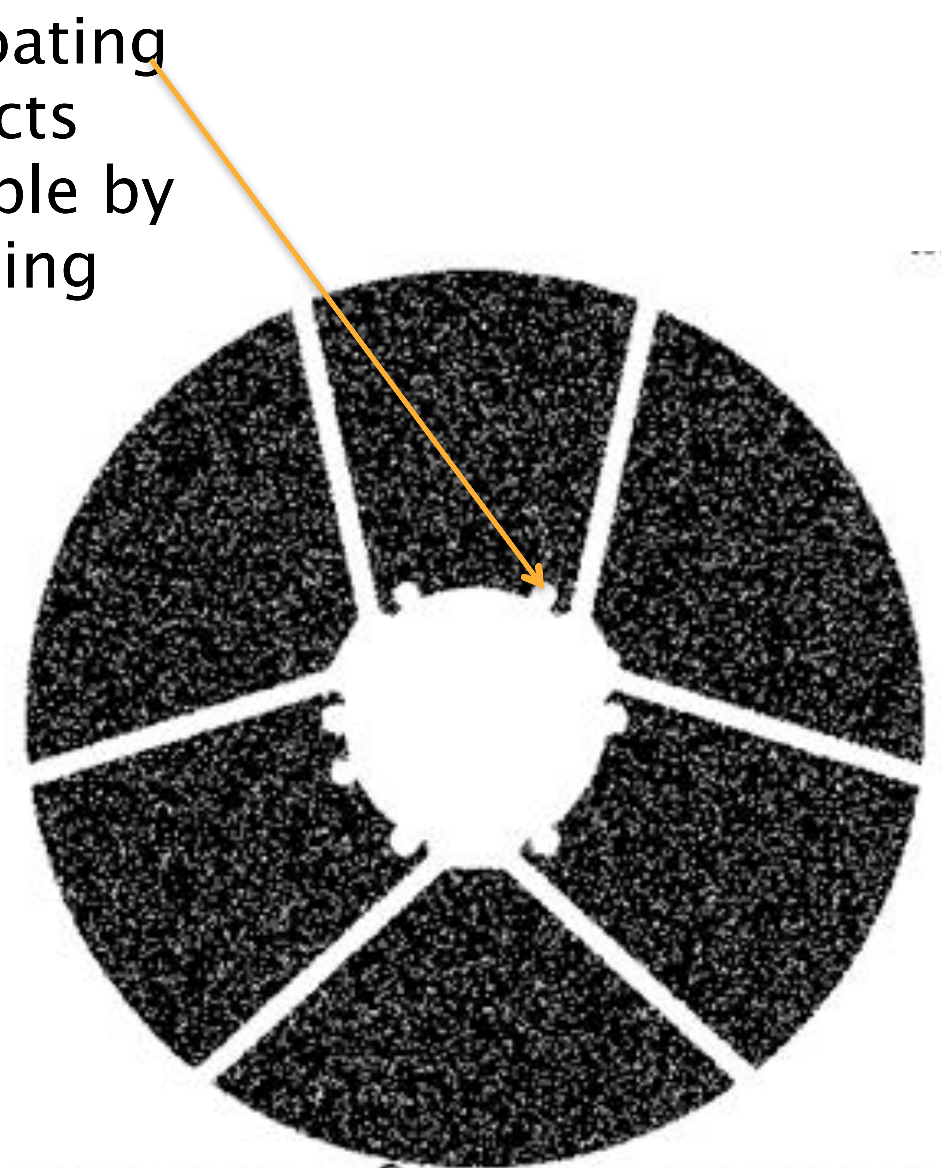
courtesy Erin Elliot, STScI

System Obstruction

courtesy Gary Mathews, Exelis

Complicated pupil makes high-performance coronagraphy challenging.





On Axis Pupil

17% Obstructed

Strut Mean Width: 41mm

Strut Obstruction Length: 881mm

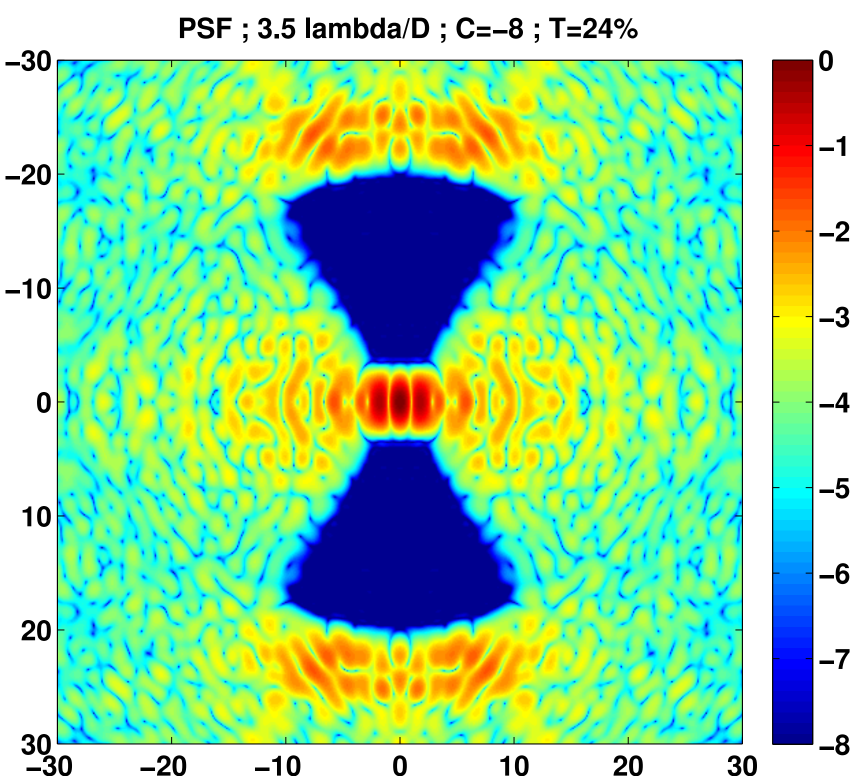
Coronagraph + WFC Design & Performance:

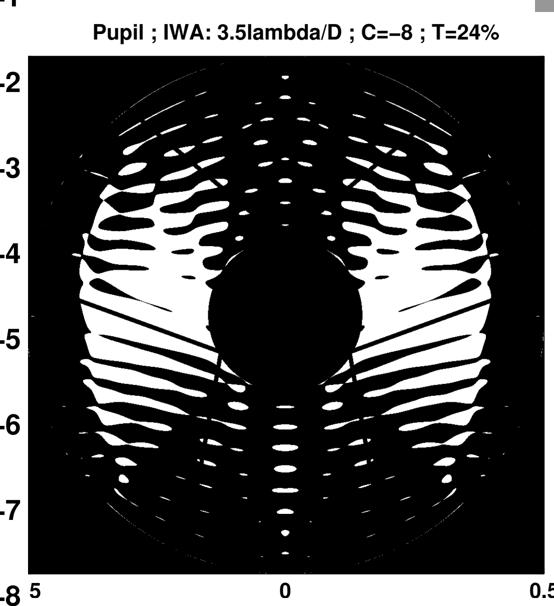
The usual metrics:

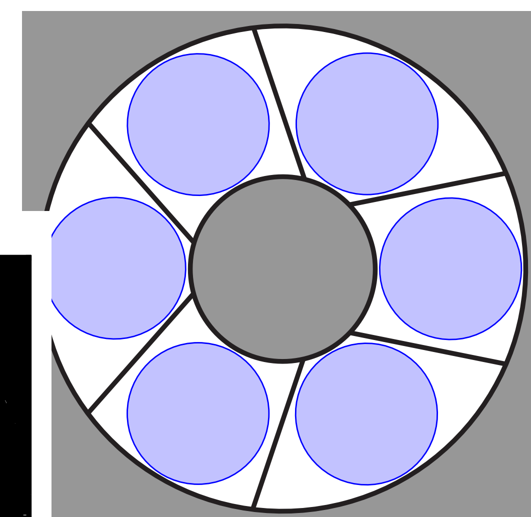
- Contrast
- Inner working angle
- Throughput
- Outer working angle
- Discovery space
- Bandwidth/chromaticity

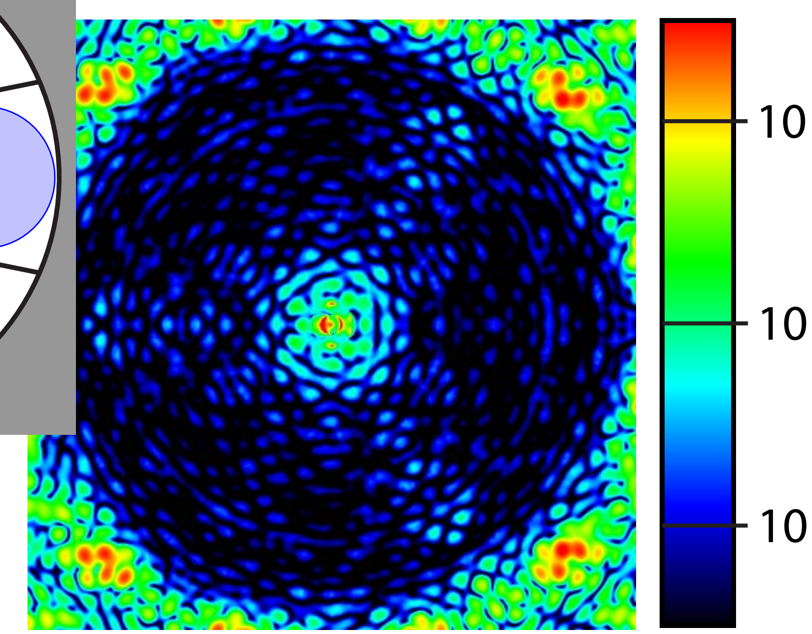
New approaches exist for on-axis systems with spiders

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









HIGH CONTRAST DARK FIELD

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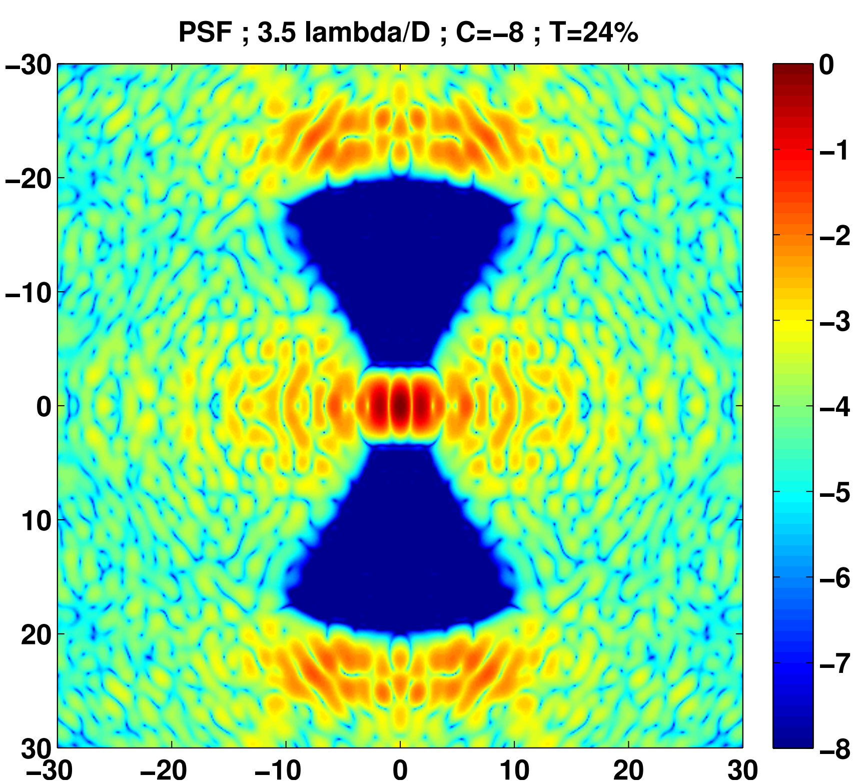

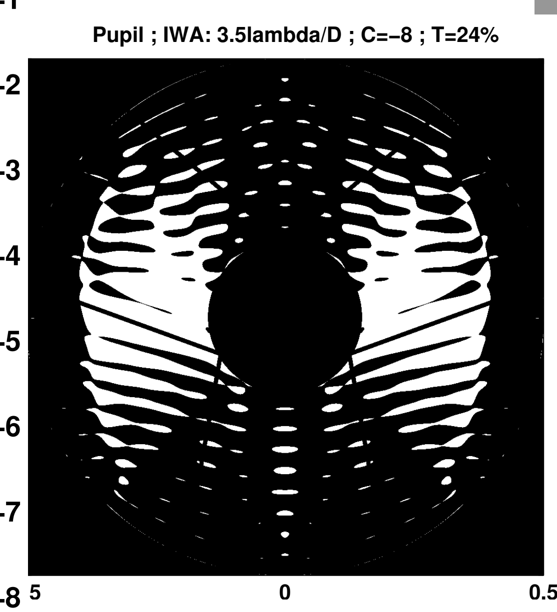

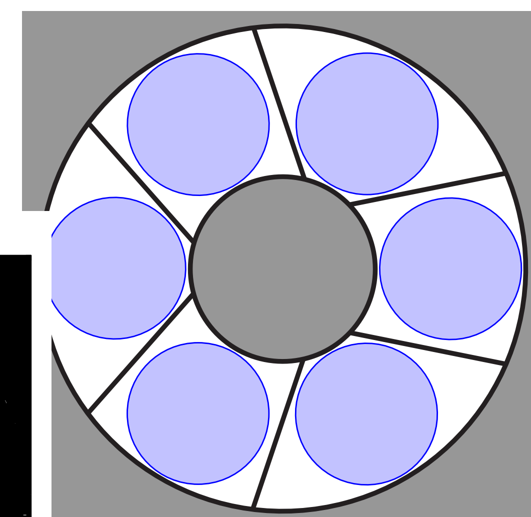

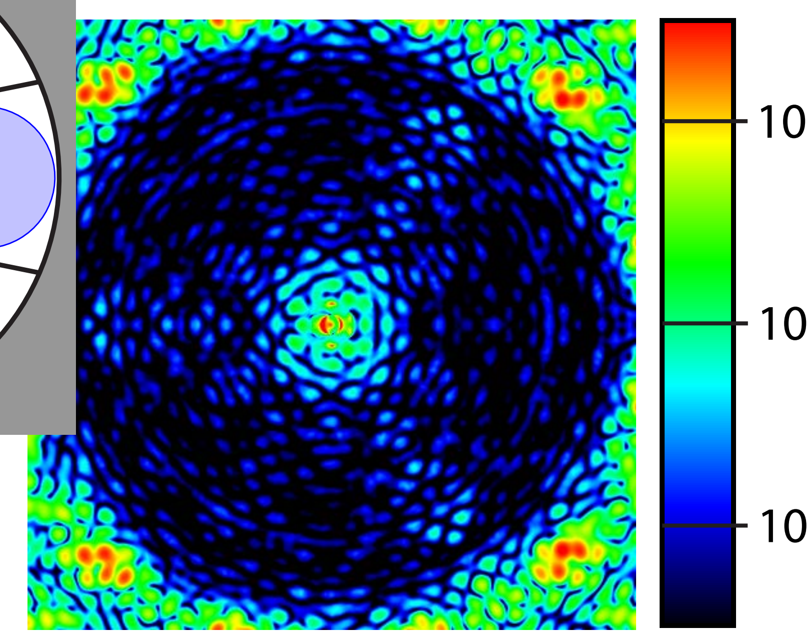

HIGH CONTRAST DARK FIELD

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 ≥3 l/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

Shaklan, et al. 2011

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

	2 λ/D radial complex		2.5 λ/d radial complex		3 λ/d radial amplitude	
Allocation	Reqmnt.	ΔContrast	Reqmnt.	ΔContrast	Reqmnt.	ΔContrast
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
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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

What science could be done with AFTA-I assuming these performance values?

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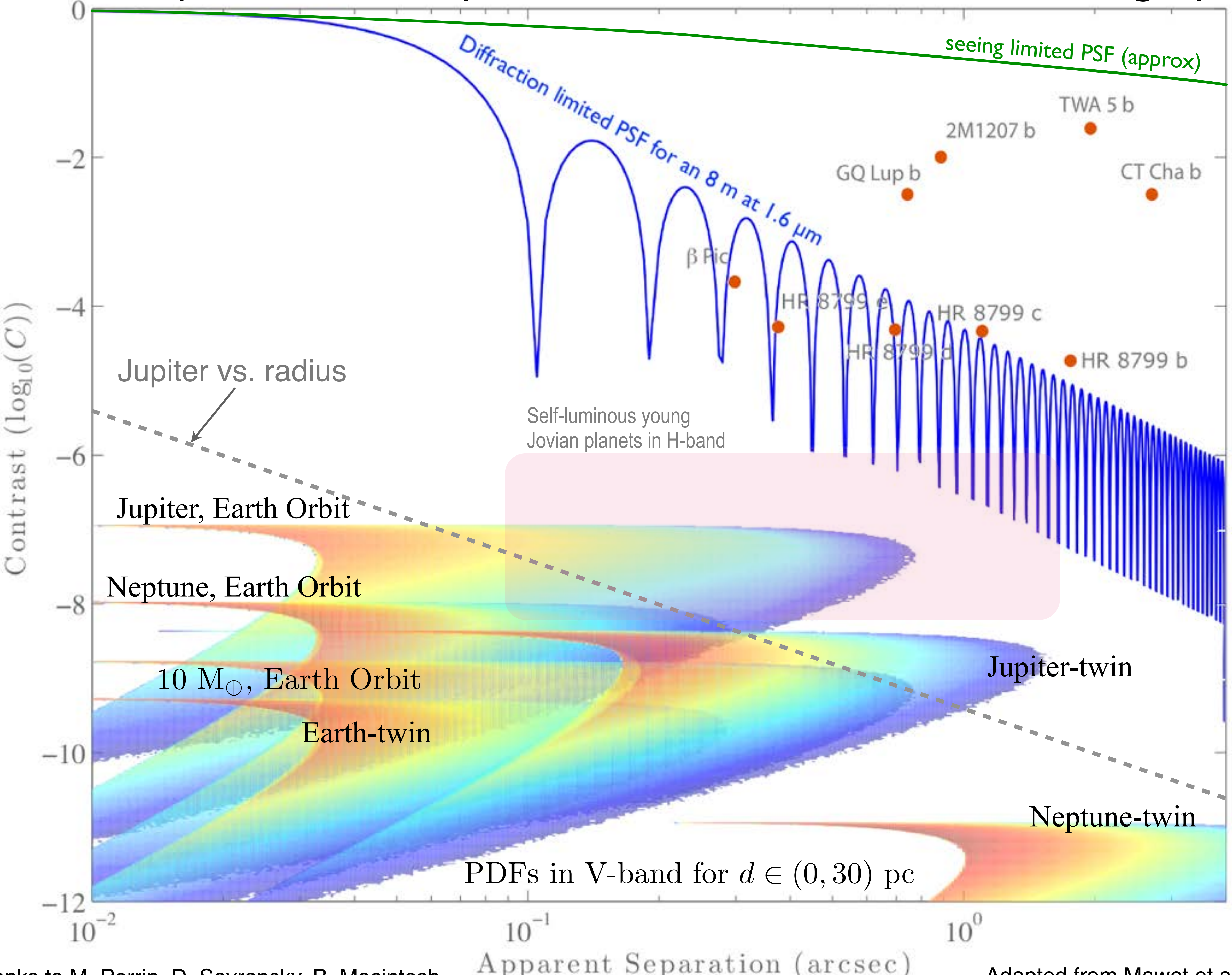
- Giant exoplanet detection and characterization
- Circumstellar disk characterization
- Exozodi dust measurements in visible
- Dust density variations

Exoplanet Search Space with 3 lambda/D AFTA Coronagraph



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

Adapted from Mawet et al. 2012

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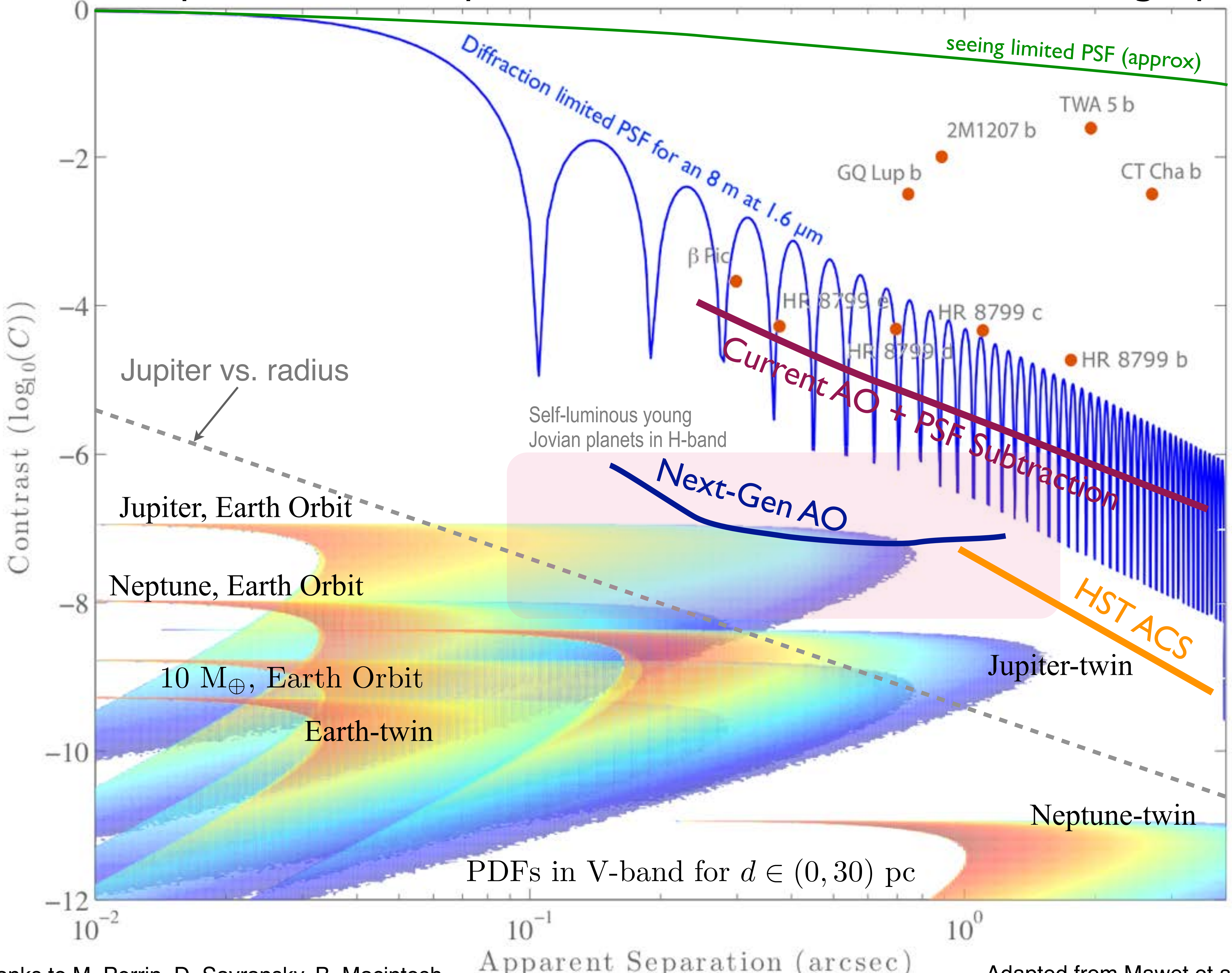

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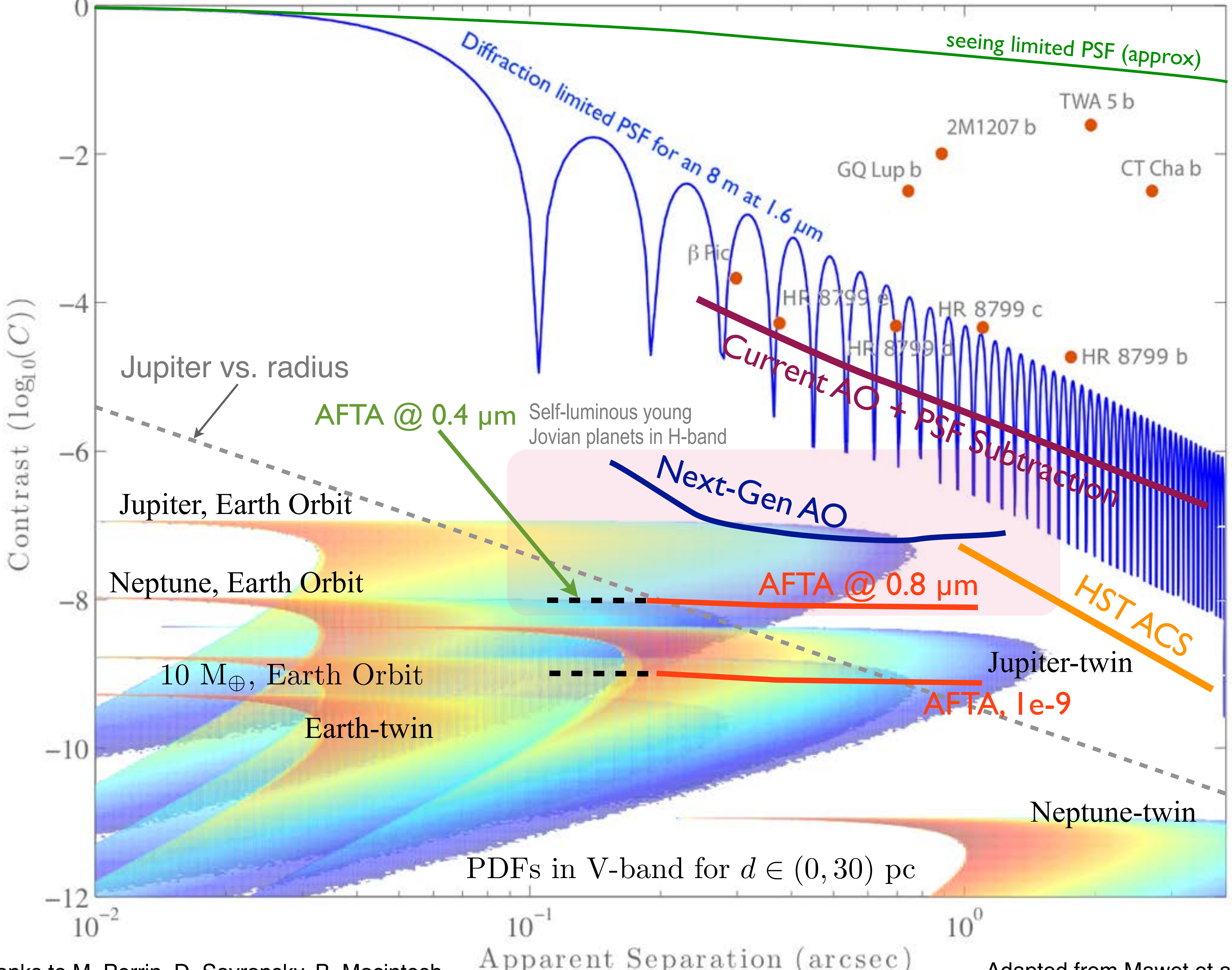

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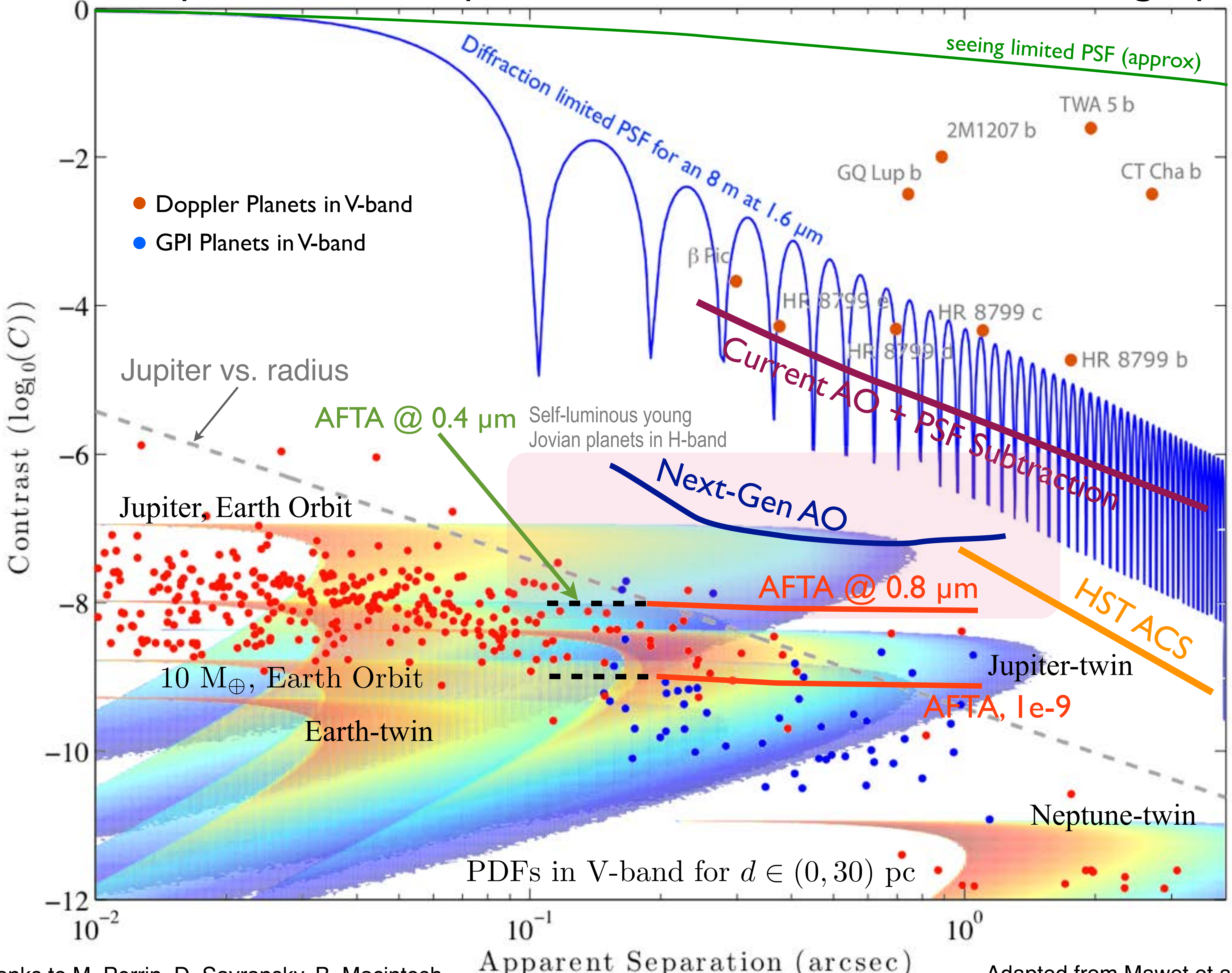

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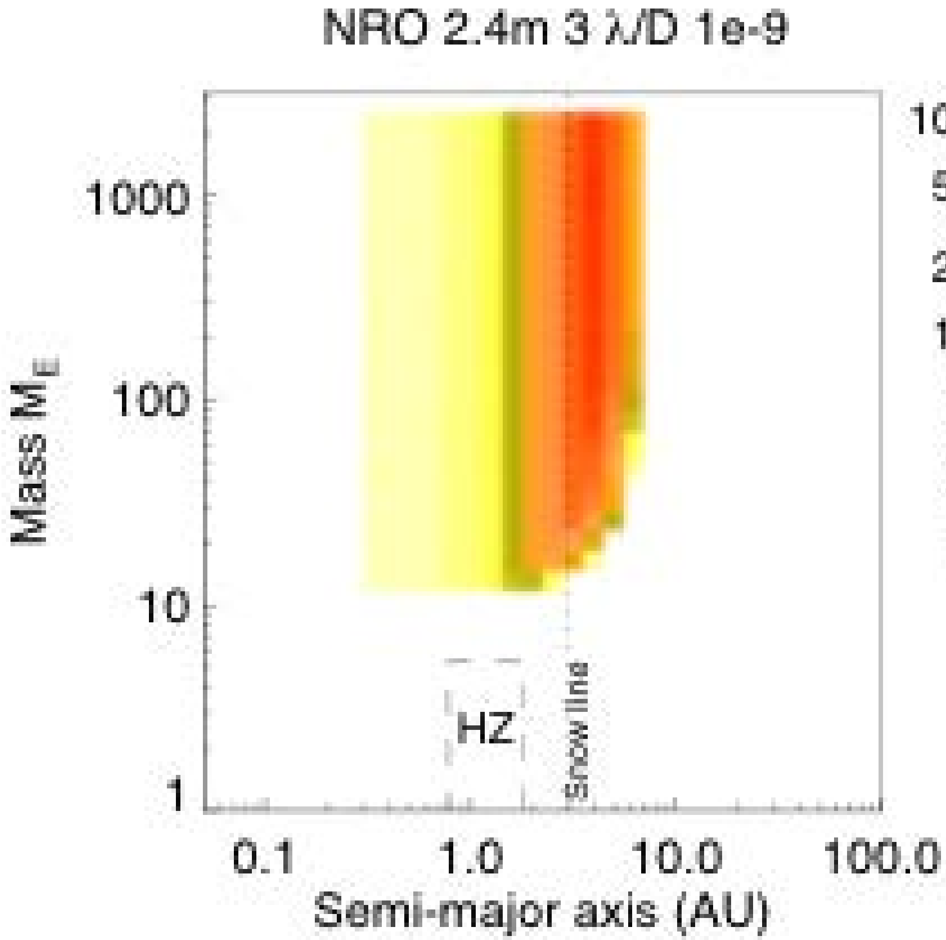
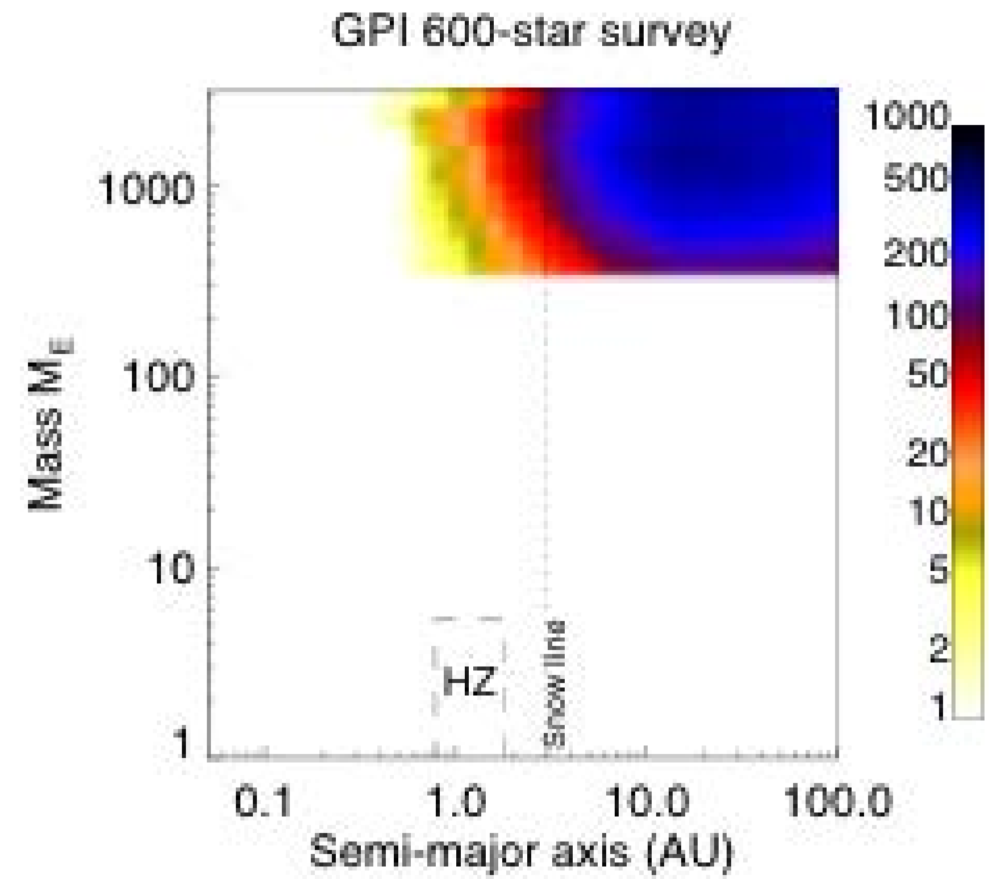
Depth of Planet Search in Visible

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



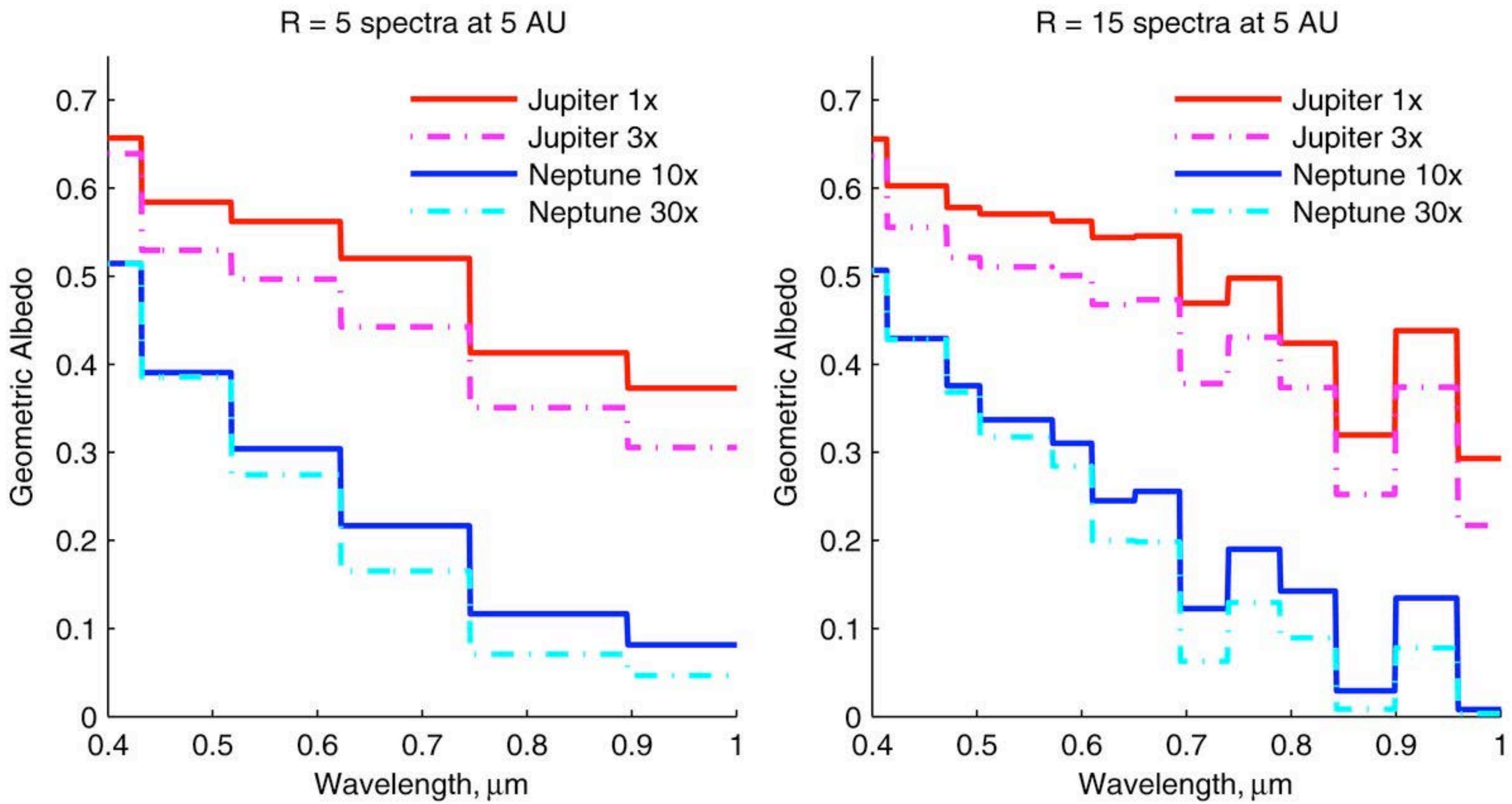


Sensitivity comparison between a 2.4m space coronagraph and the Gemini Planet Imager for a notional survey of nearby stars with mass 0.5-1.5 solar masses. The quantity plotted is the ExoPTF "depth of search" (Lunine et al). This is the sum of the completeness of a survey for all targets – it can be thought 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.

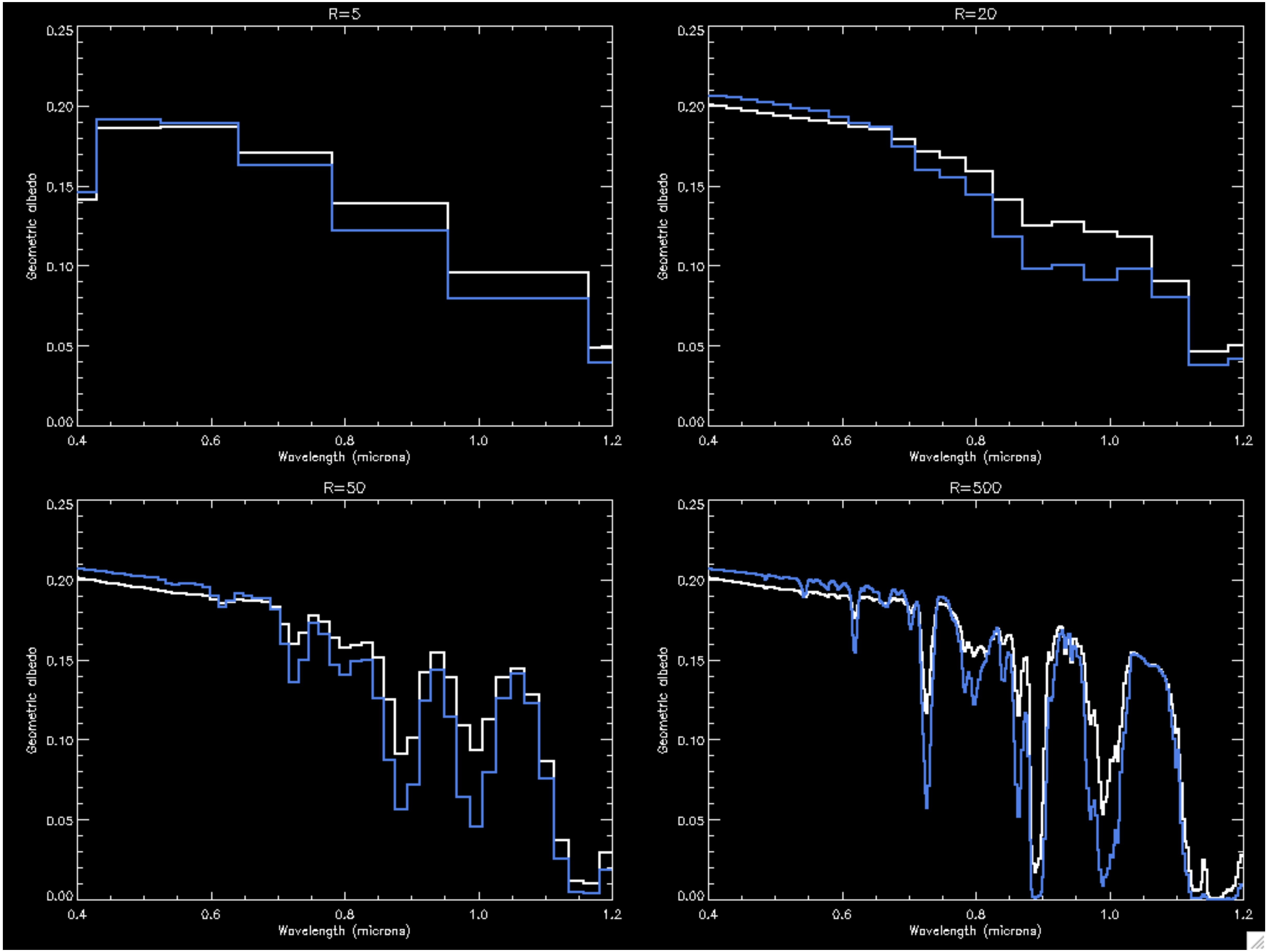
B. Macintosh

Exoplanet spectra can distinguish formation mechanisms

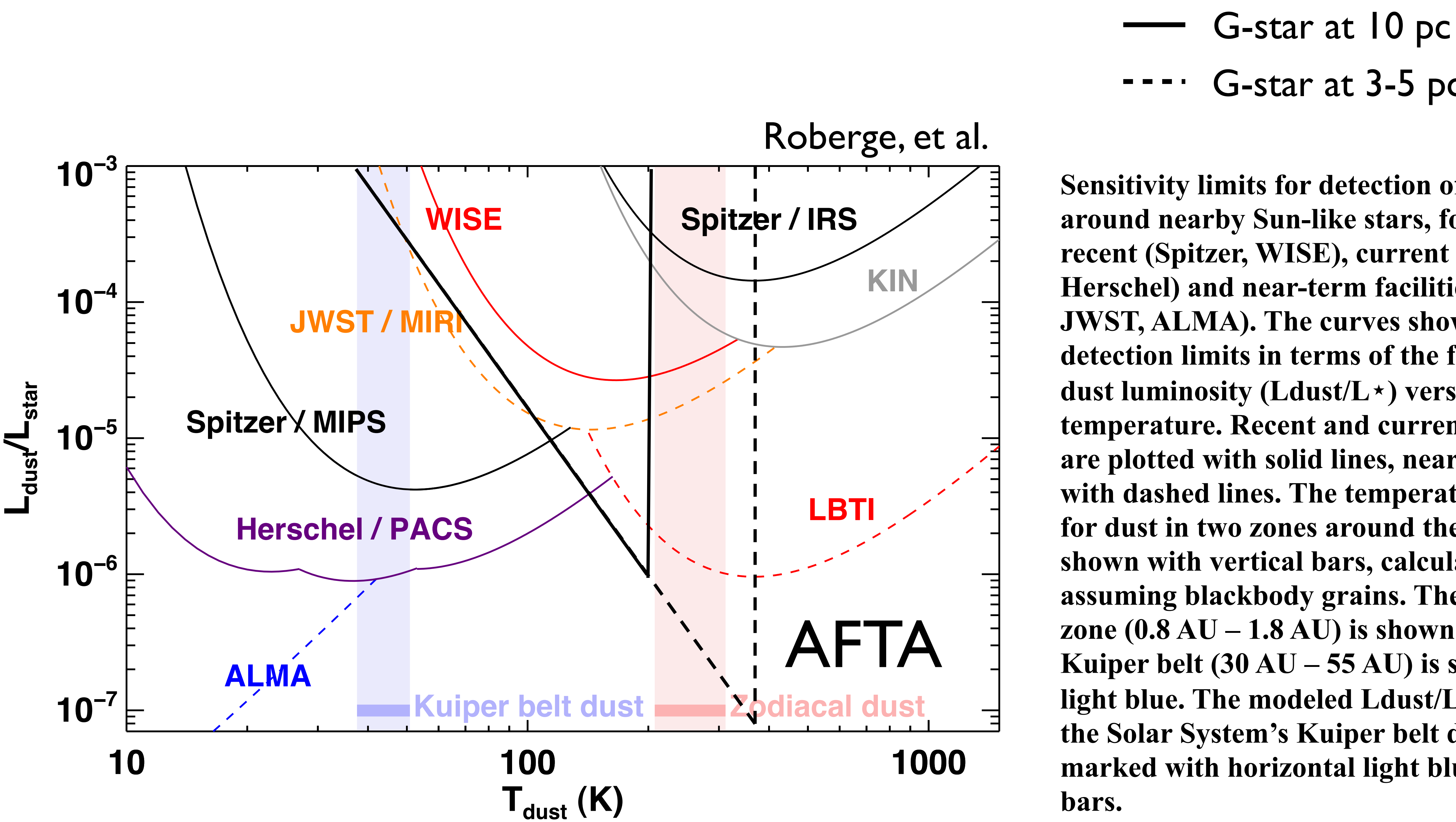
Spectra from Cahoy et al. 2010
for Jupiter and Neptune analogs at 5 AU and different metallicities



The advantage of higher resolution



Exozodical Disk Characterization



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 3σ detection limits in terms of the fractional dust luminosity (Ldust/L⋆) 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 Ldust/L⋆ values for the Solar System's Kuiper belt dust are marked with horizontal light blue and pink bars.

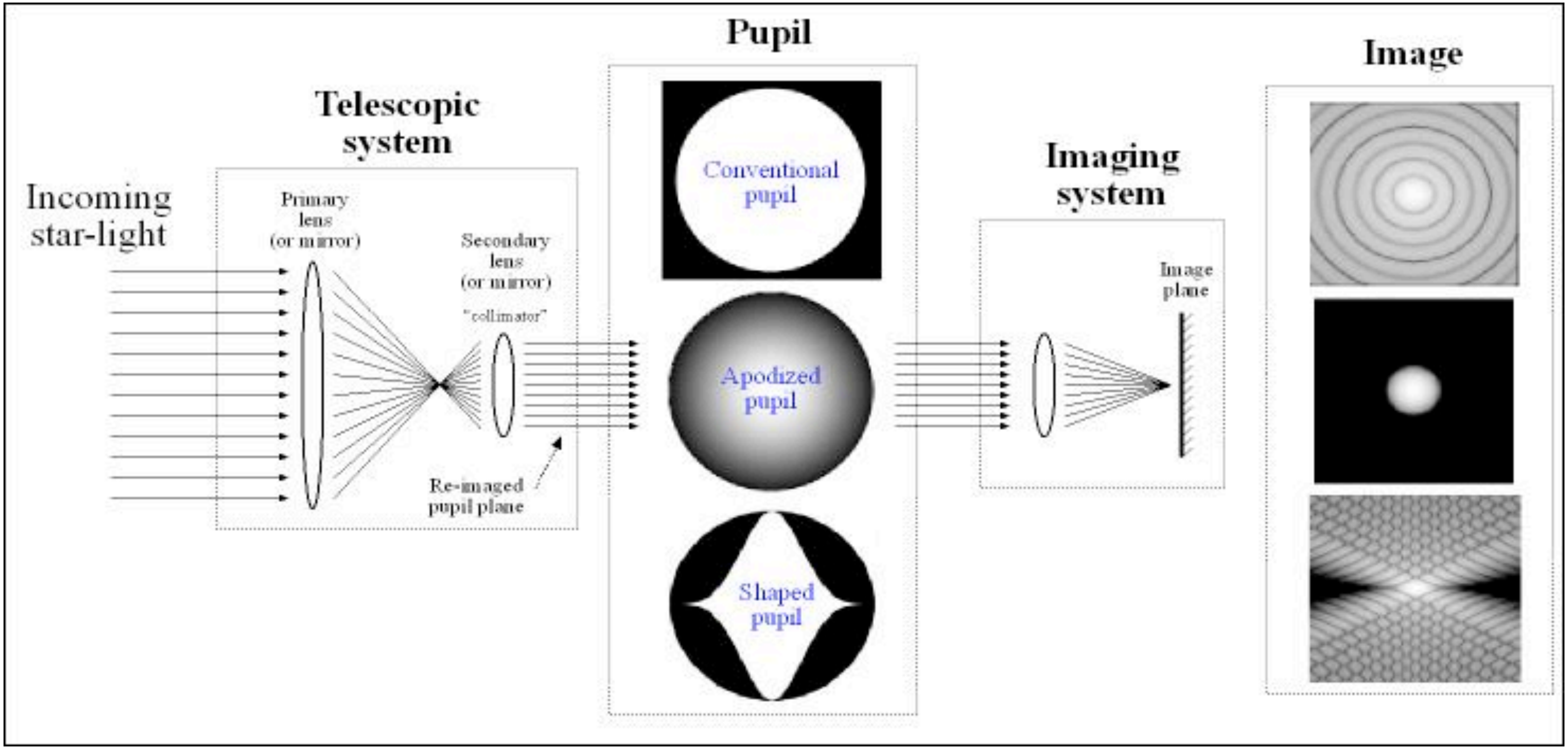
An optimized coronagraph on the AFTA could be sensitive to Ldust/L* ~ 10^{-6} at Tdust ~200 K and characterize in the visible.

Sample of possible coronagraphs for NRO Telescope

Note: No 10^{-8} or 10^{-9} broadband coronagraph yet exists for the AFTA pupil. What follows are potential technological pathways.

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

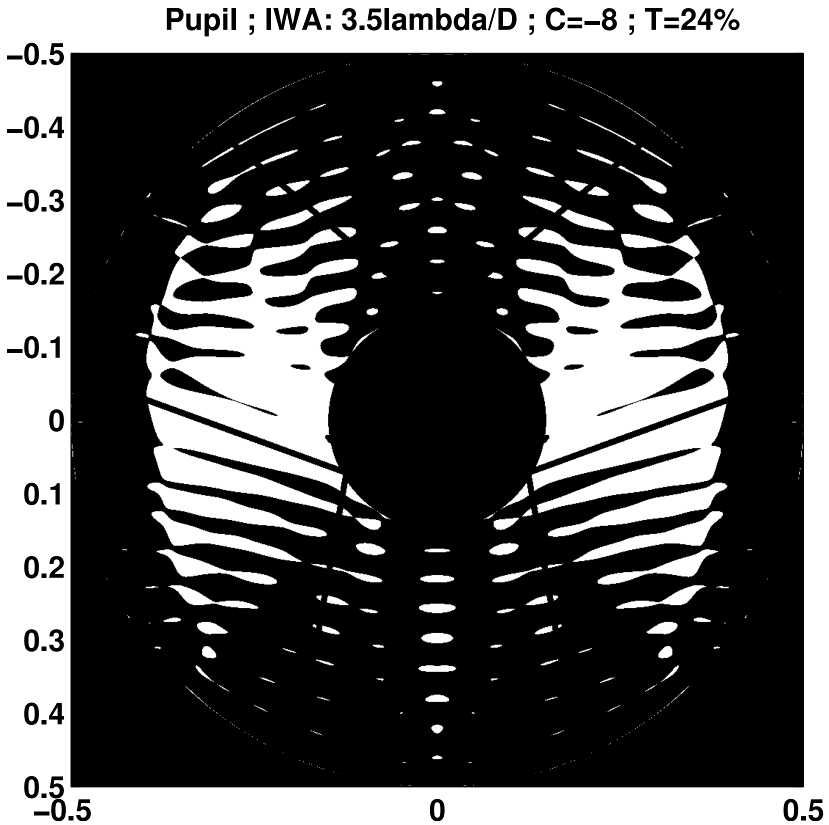
Pupil Apodization to Reshape PSF

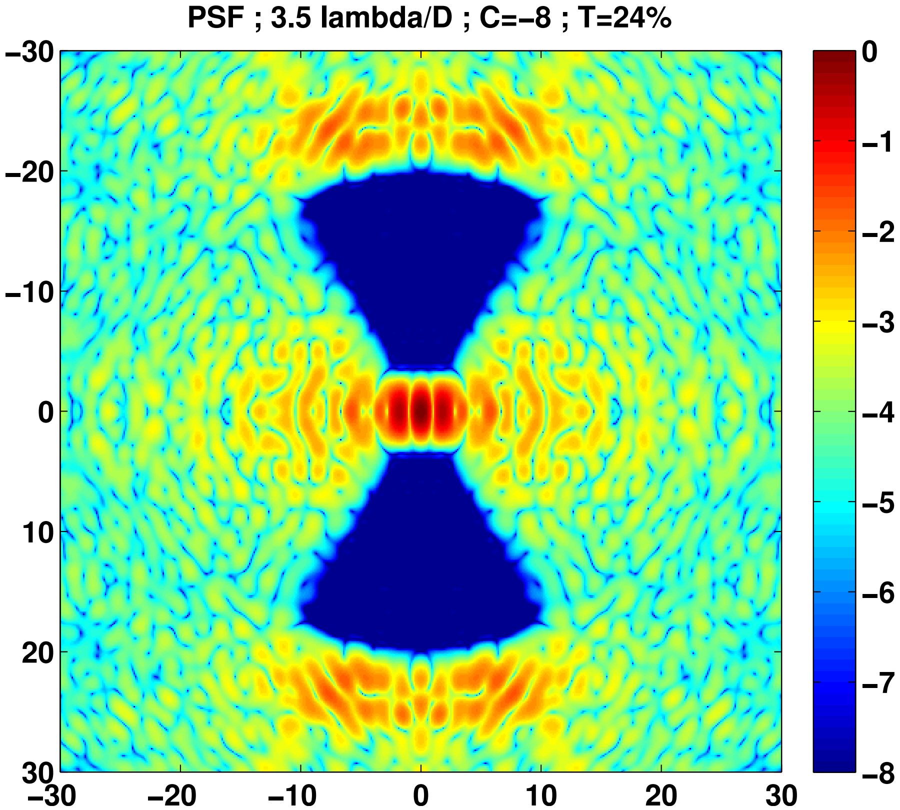


$$E(\xi, \zeta) = \int \int e^{i(x\xi + y\zeta)} A(x, y) dy dx$$

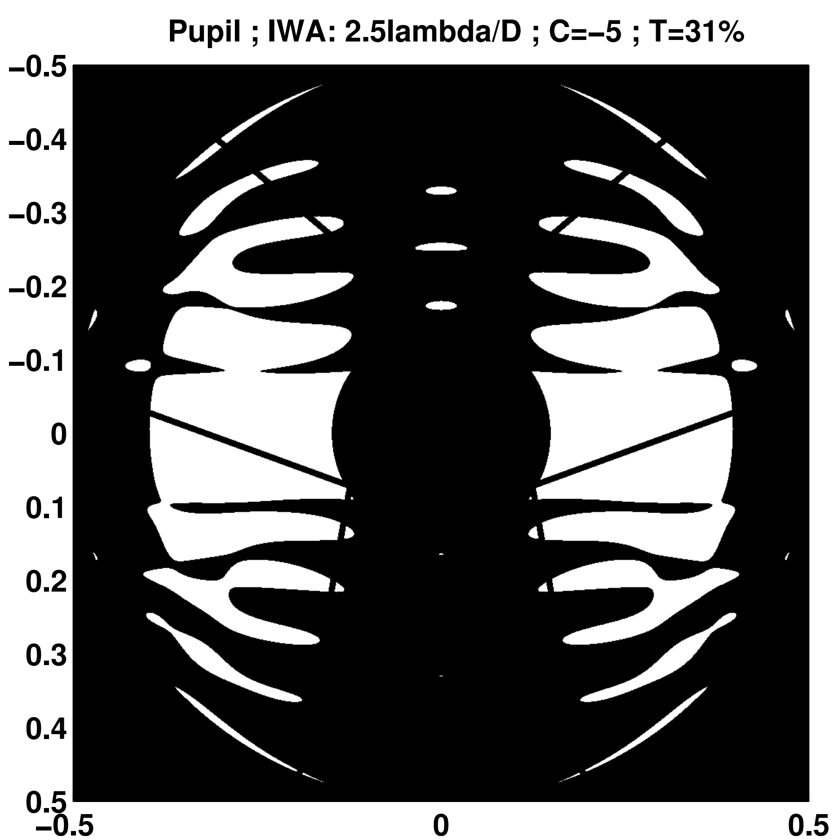
Shaped pupils are achromatic; PSF same at all wavelengths.

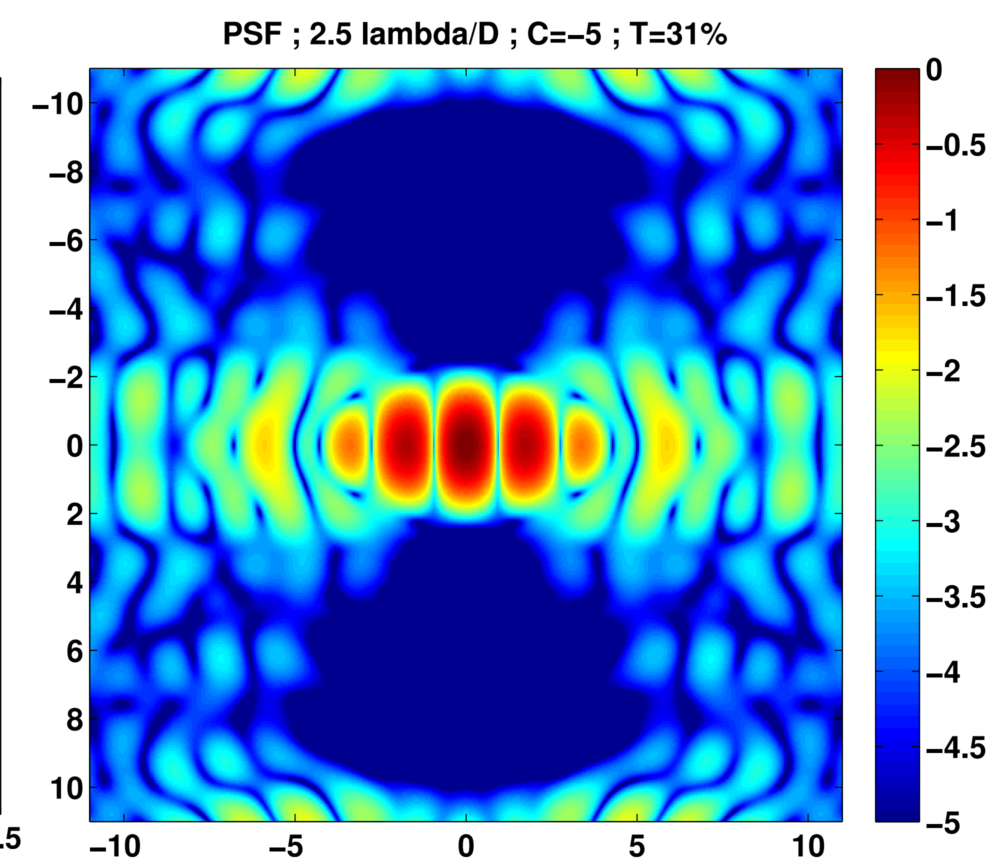
2-D Shaped Pupil Mask Tailored for Telescope Aperture





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



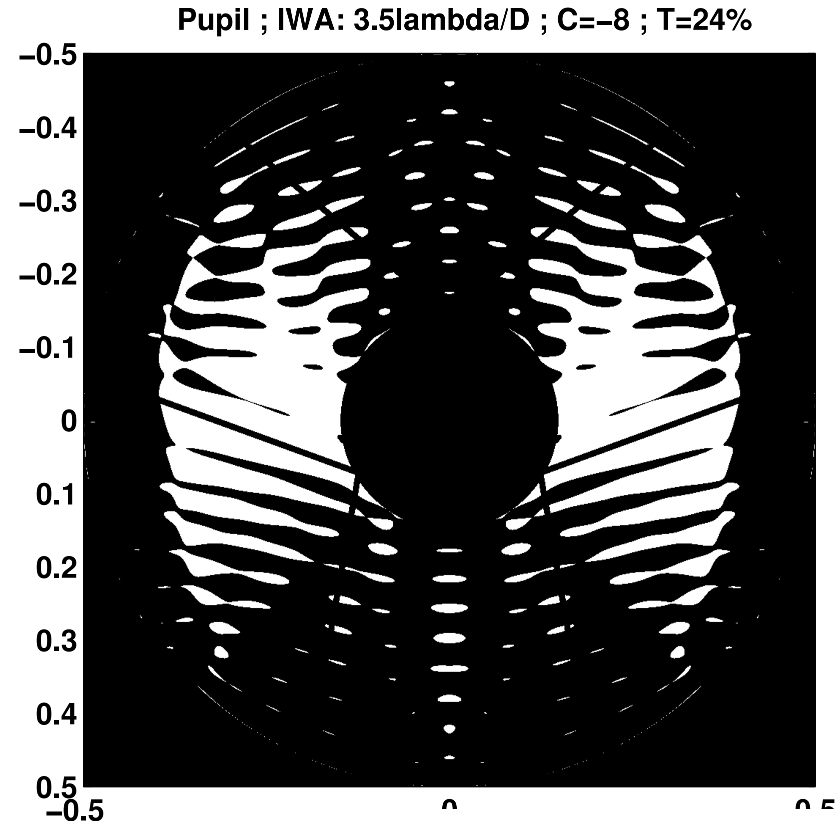


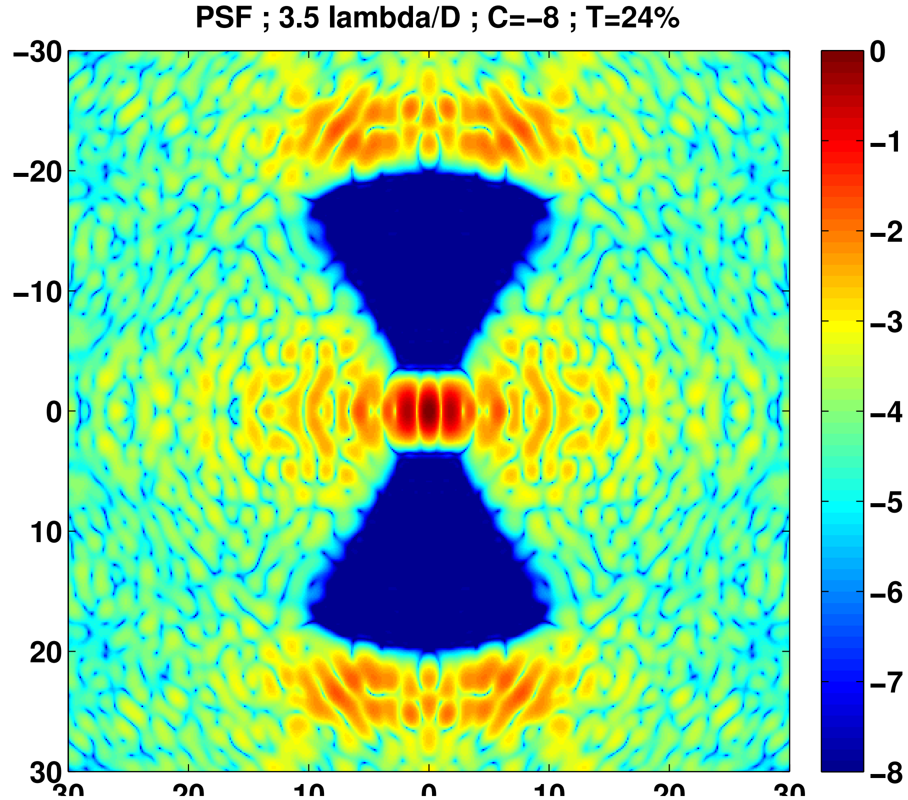
Working Angles 2.5 to 10 λ/D
Contrast: 10^{-5}
Throughput: 31%

3 λ/D is ~ 0.2” at 800 nm for a 2.4 m telescope

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

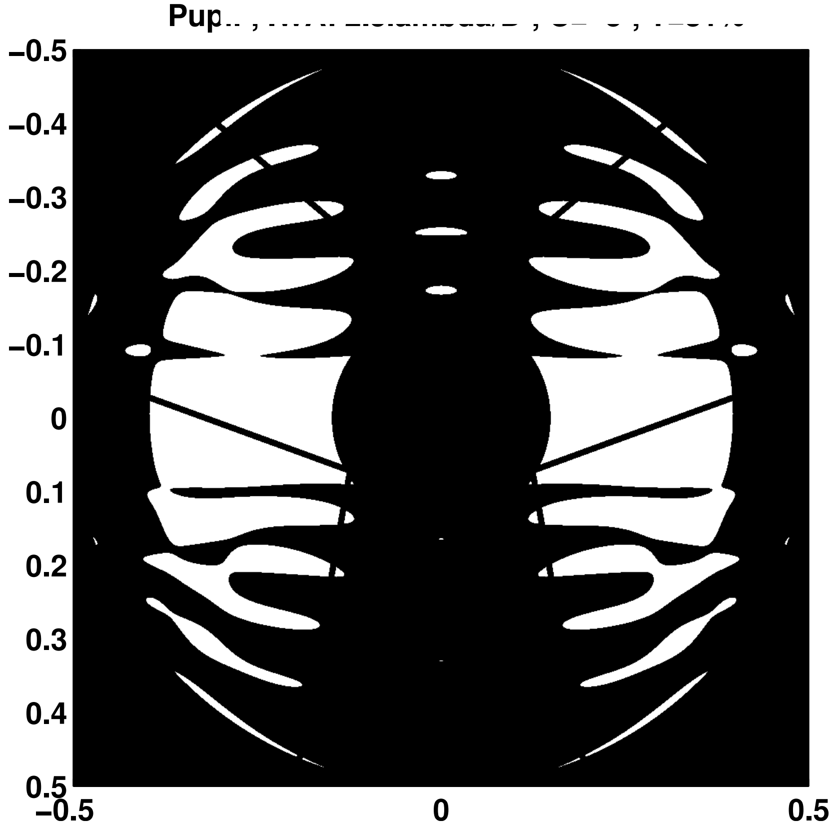
2-D Shaped Pupil Mask Tailored for Telescope Aperture

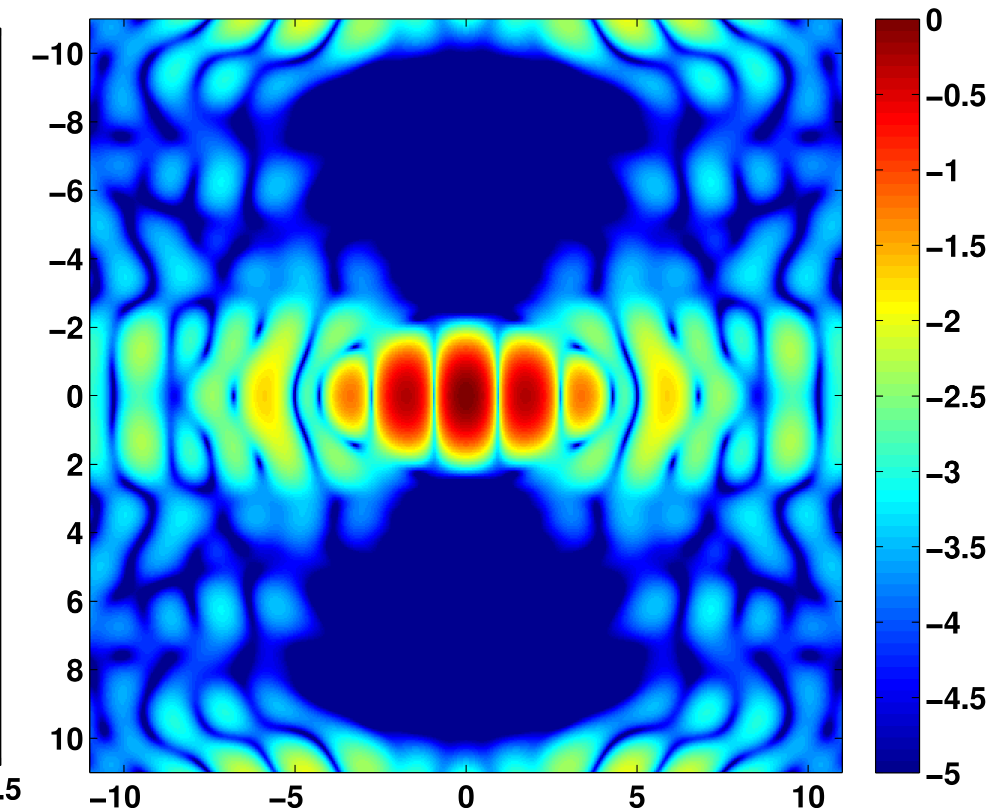




Working Angles 3.5 to 20 λ/D
Contrast: 10^{-8}
Throughput: 24%

Will most likely need to be hybridized with DMs.





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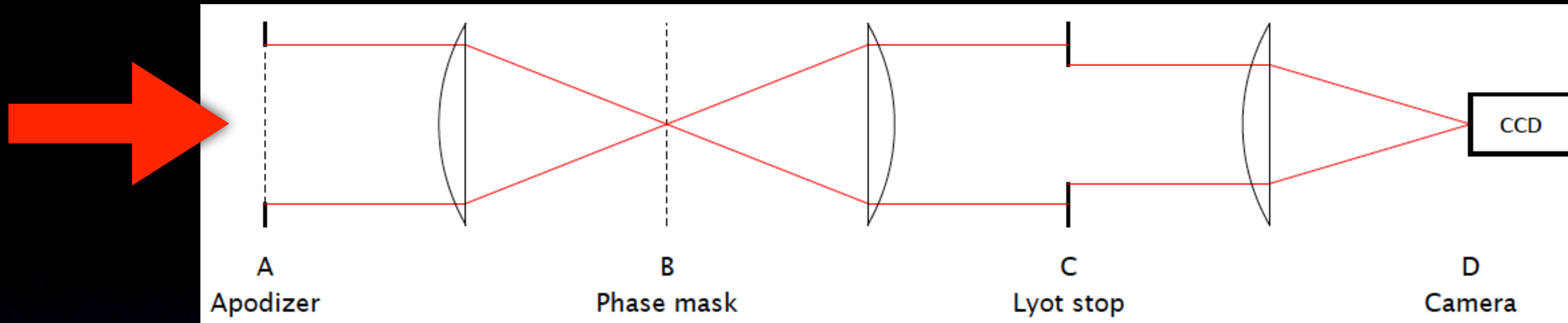
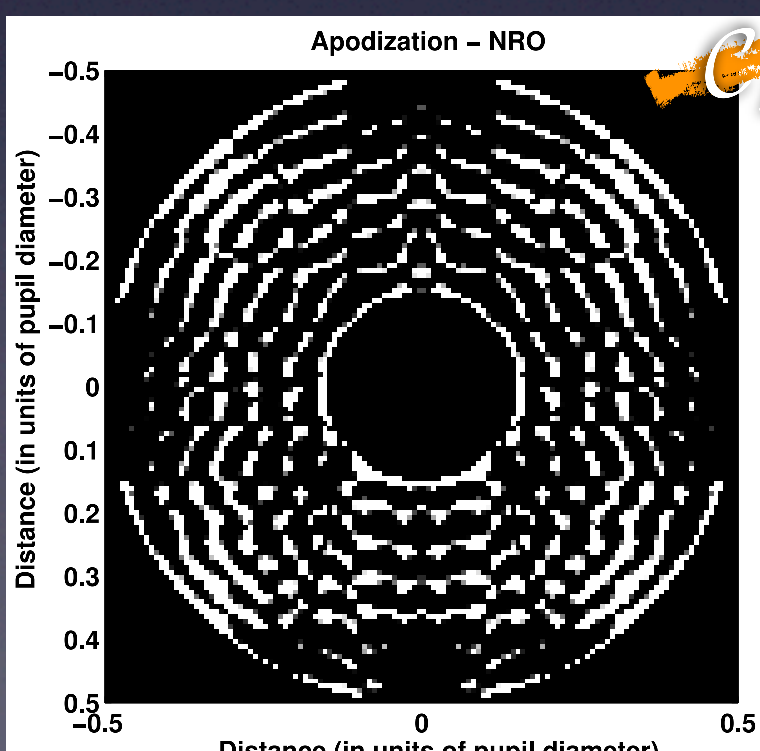
Hybrid Shaped pupil + Four-quadrants phase mask



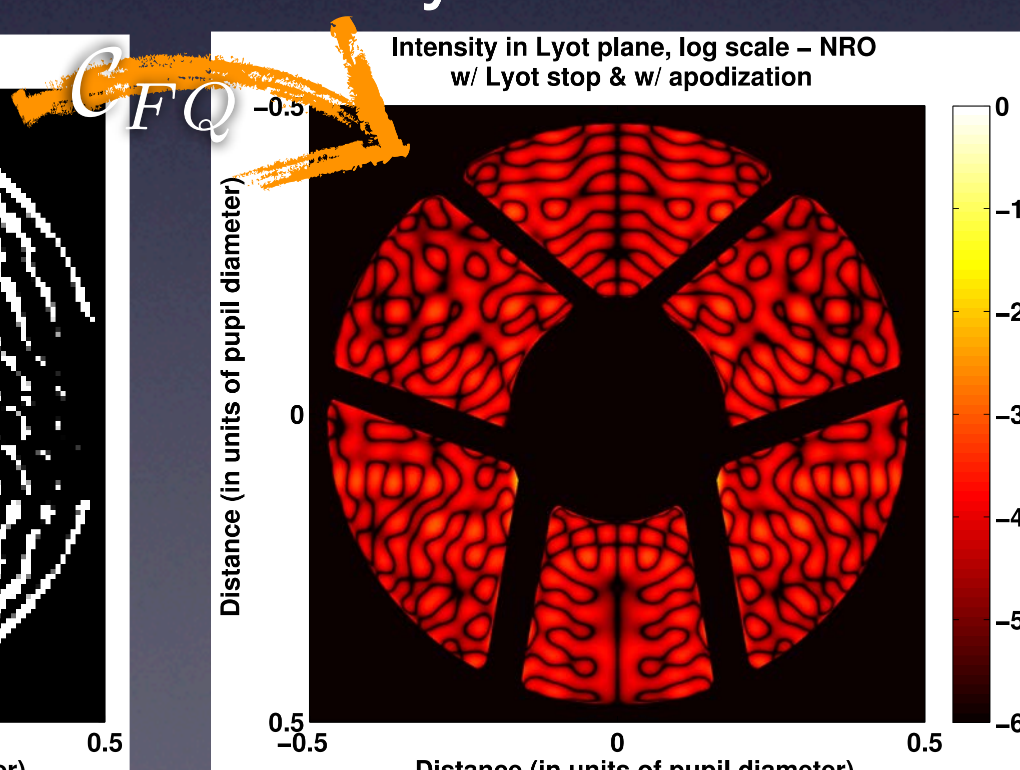
$$P(\tilde{x}, \tilde{y}) = \mathcal{C}_{FQ}[A(x, y)]$$ with $\mathcal{C}_{FQ}$: coronagraphic operator

P: EF in Lyot plane A: Apodization in 1st pupil plane

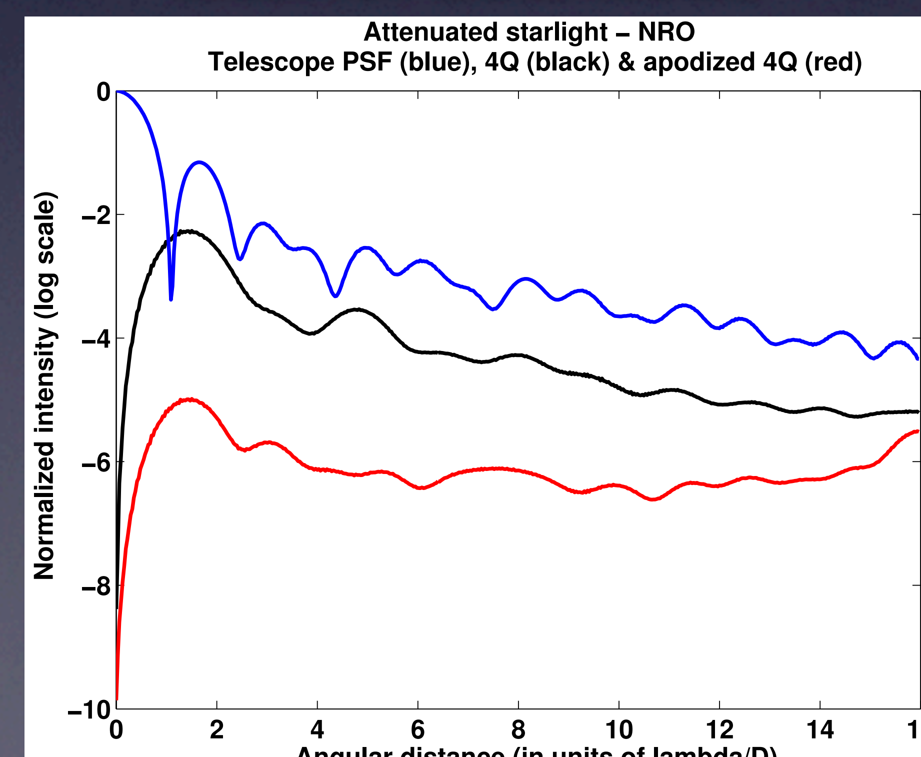
First pupil plane
Apodizer



Lyot plane
Intensity is reduced
by the FQPM



Final PSF
10^{-8} with MORE POINTS
wait for next week

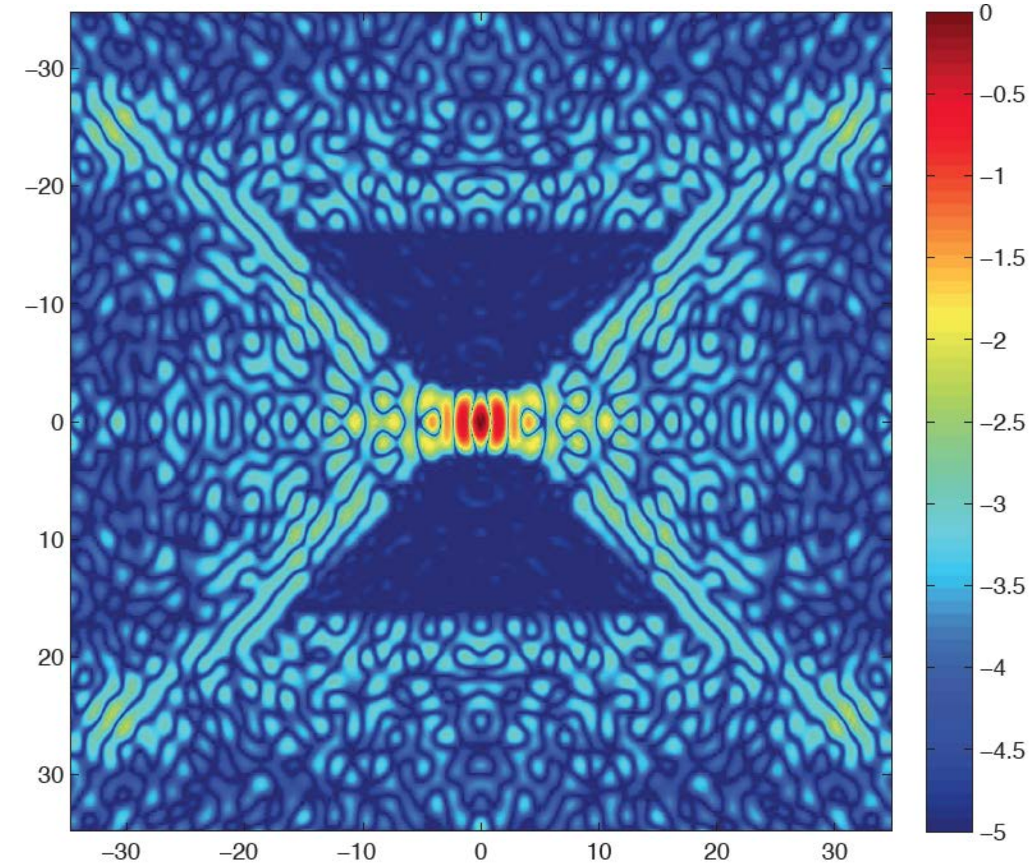


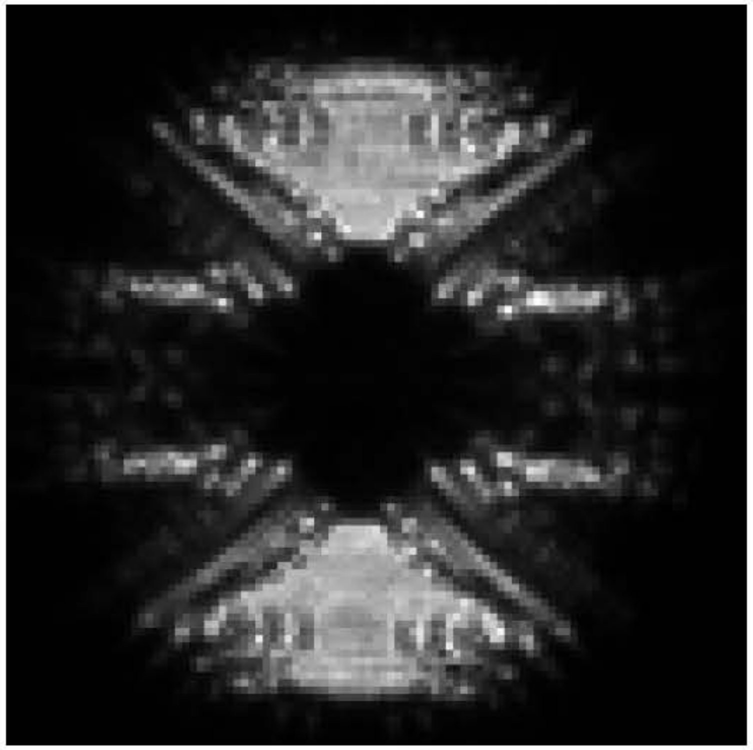
Shaped Pupil for Subaru SCExAO

Lab test from 2/2012; on-sky test tonight!

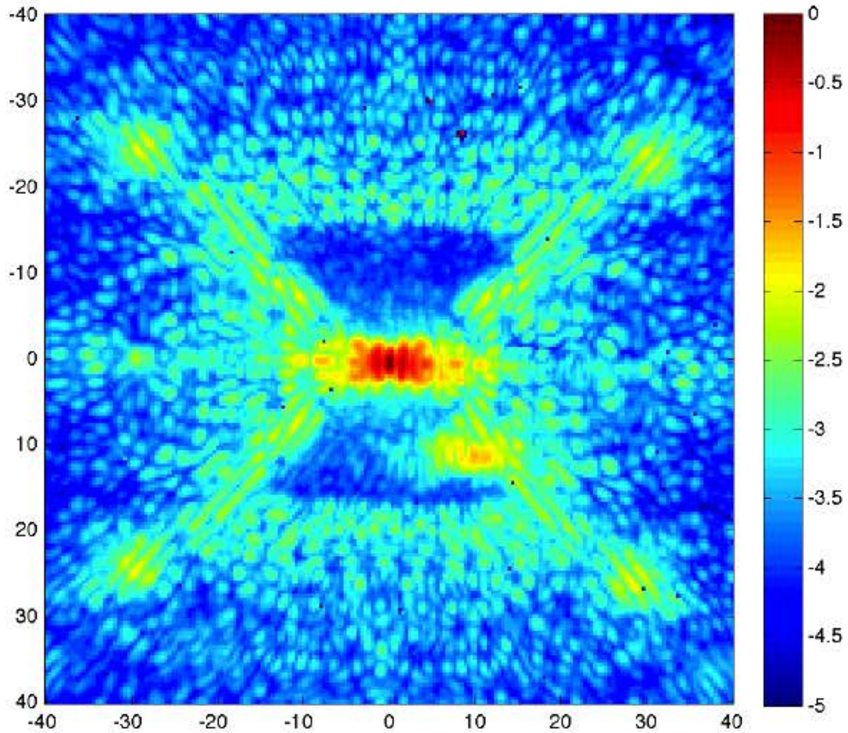
Al deposited on glass substrate (λ/10)

10μm precision

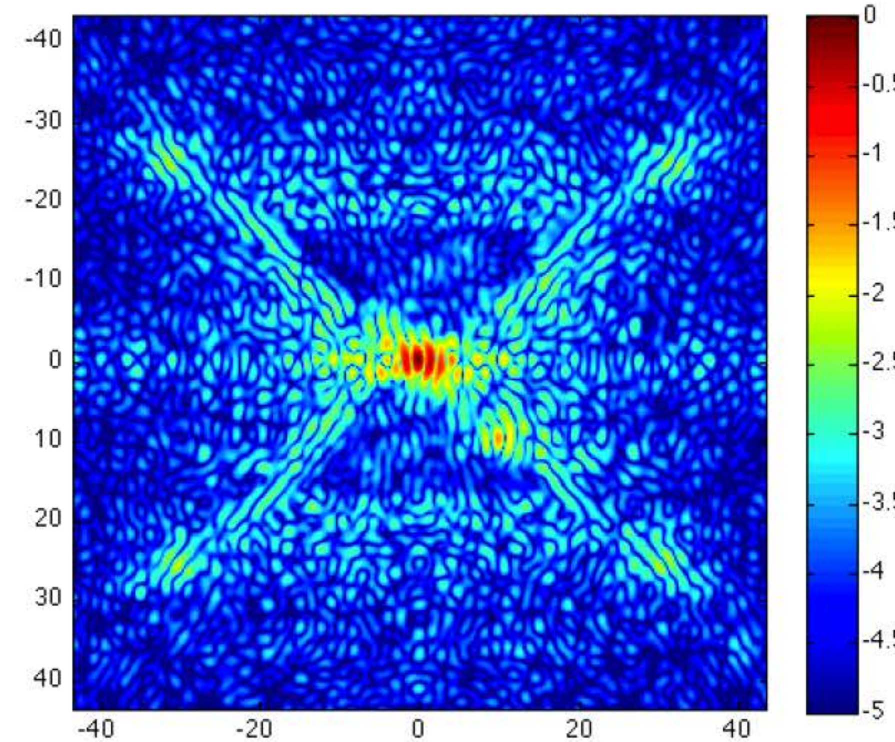




Pupil Image

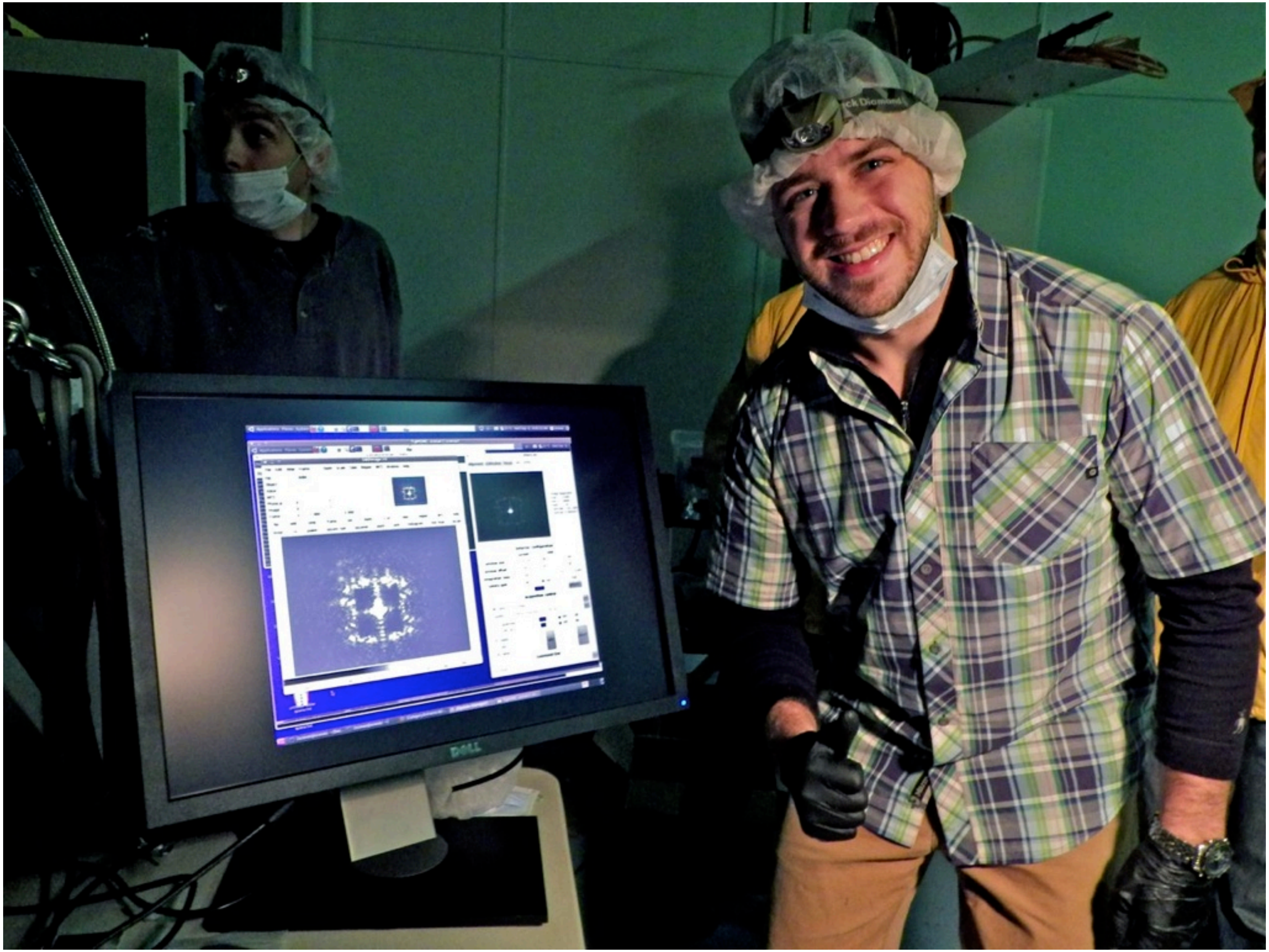


Experimental PSF

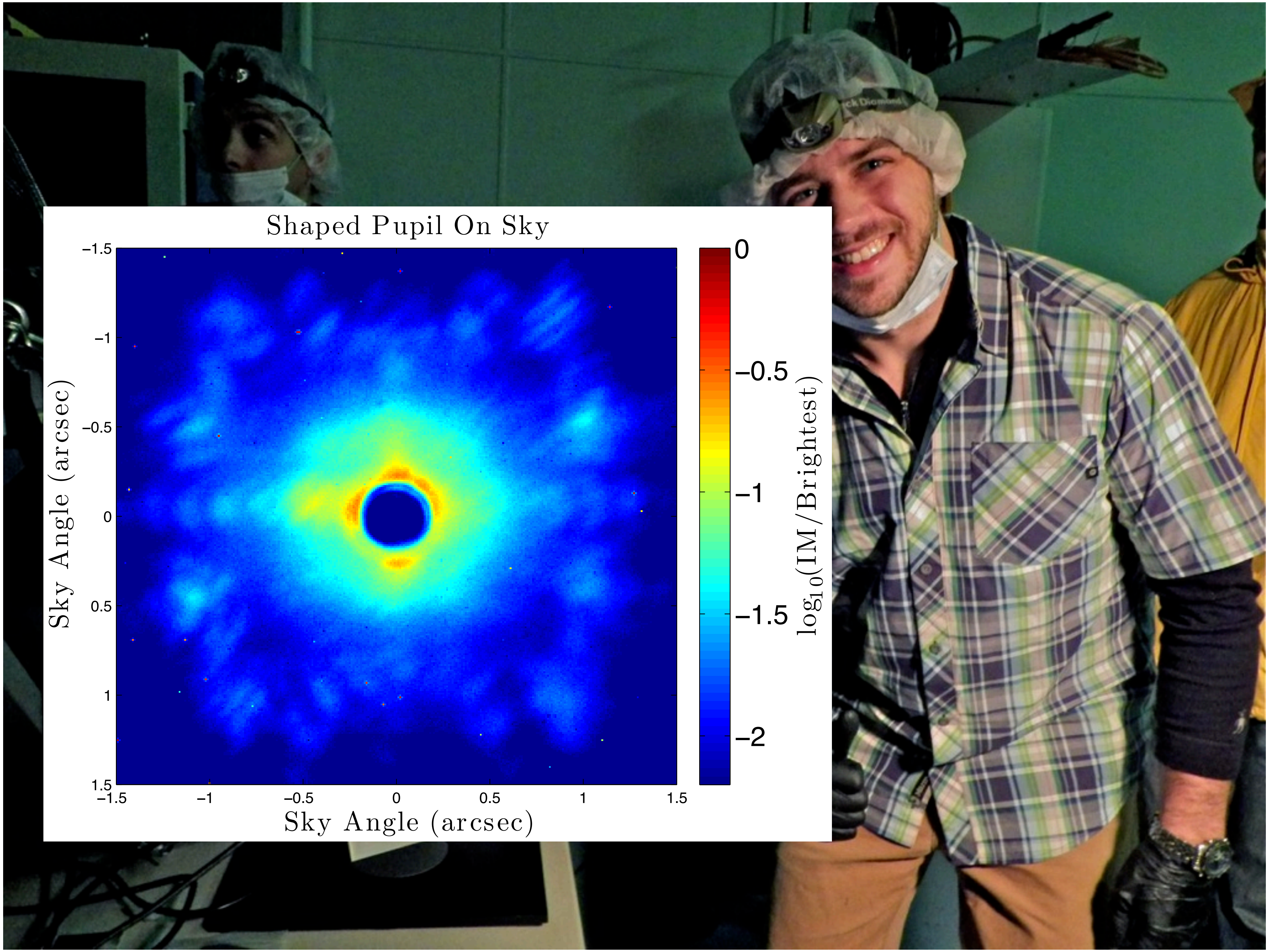


Simulated PSF

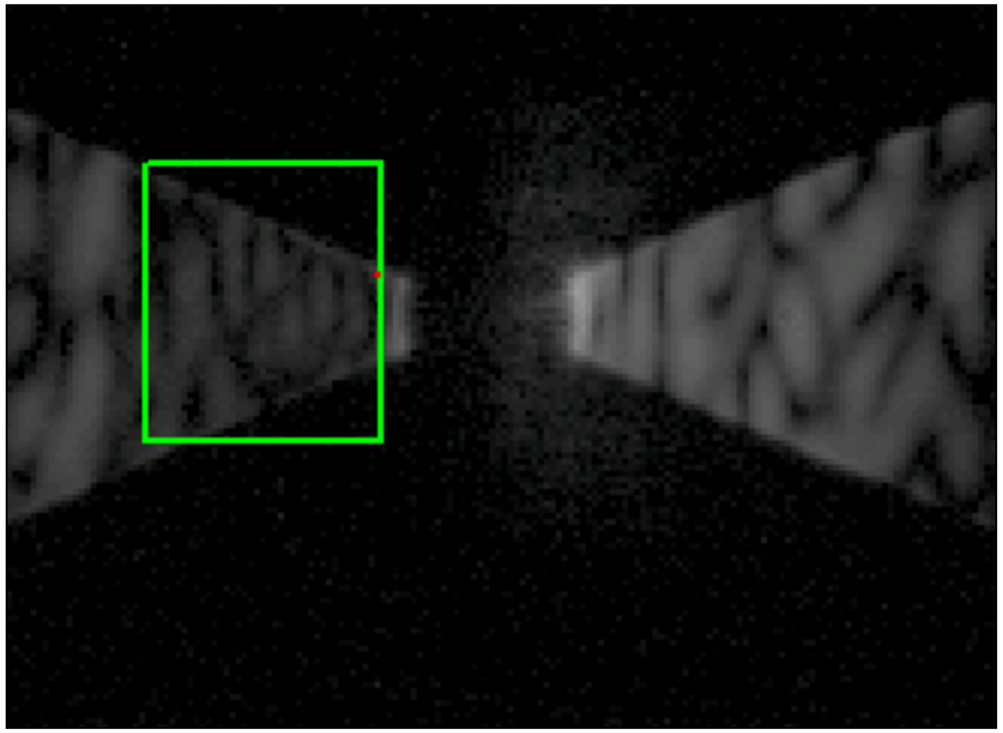
Shaped Pupil Test on Subaru in Early September

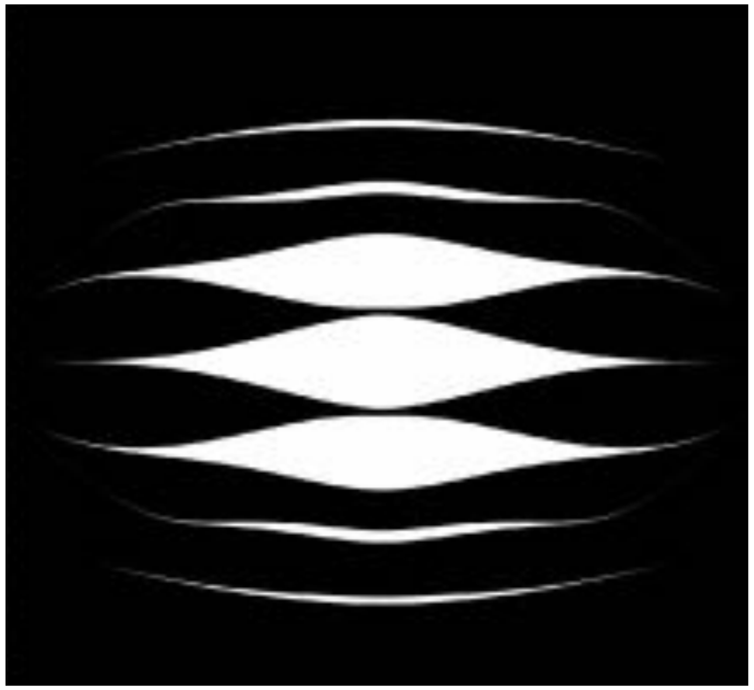


Shaped Pupil Test on Subaru in Early September

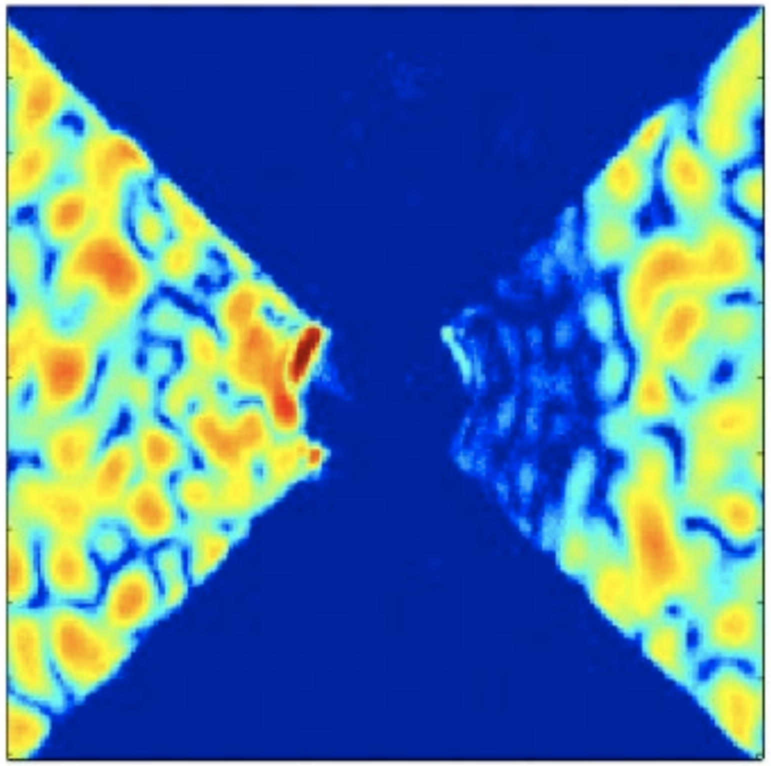


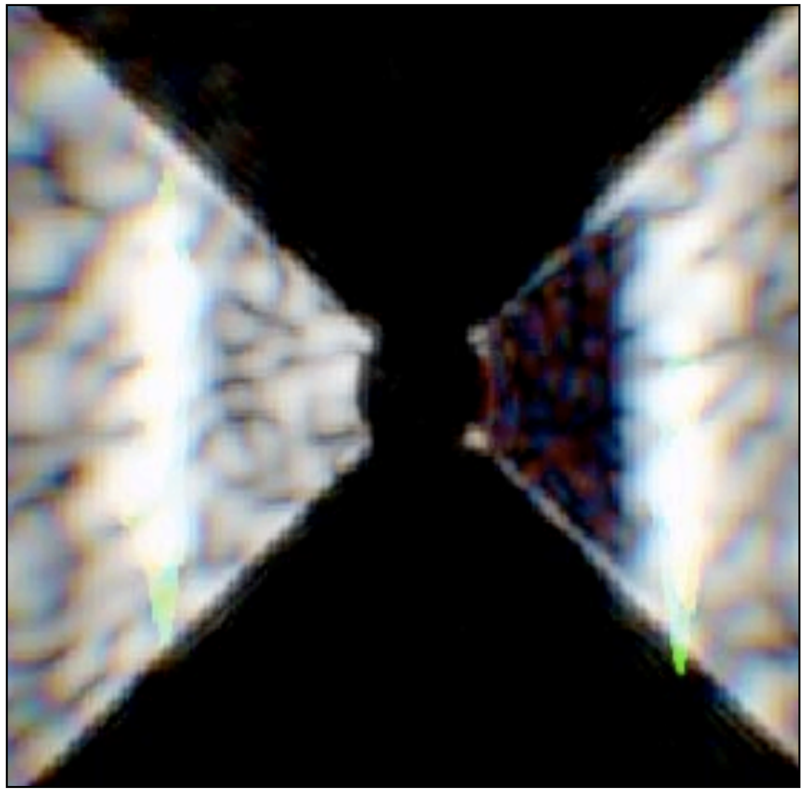
Shaped Pupil with Wavefront Control at HCIT, 2007





Single DM, Single-sided Dark Hole.



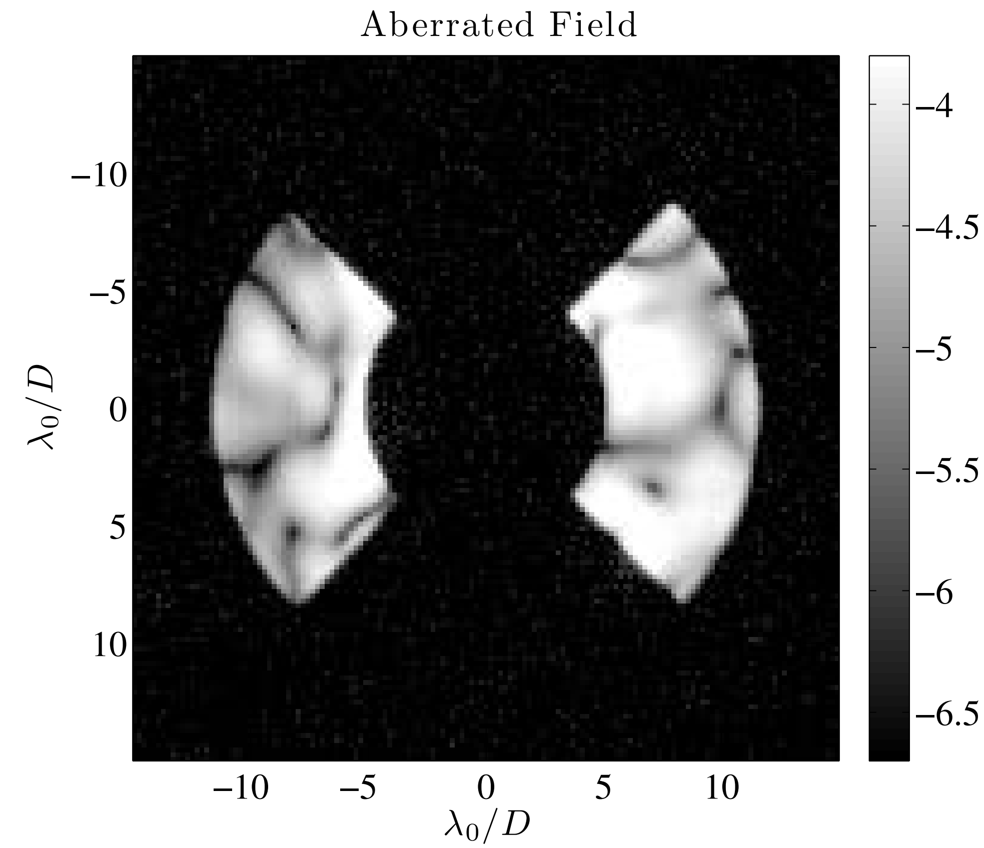


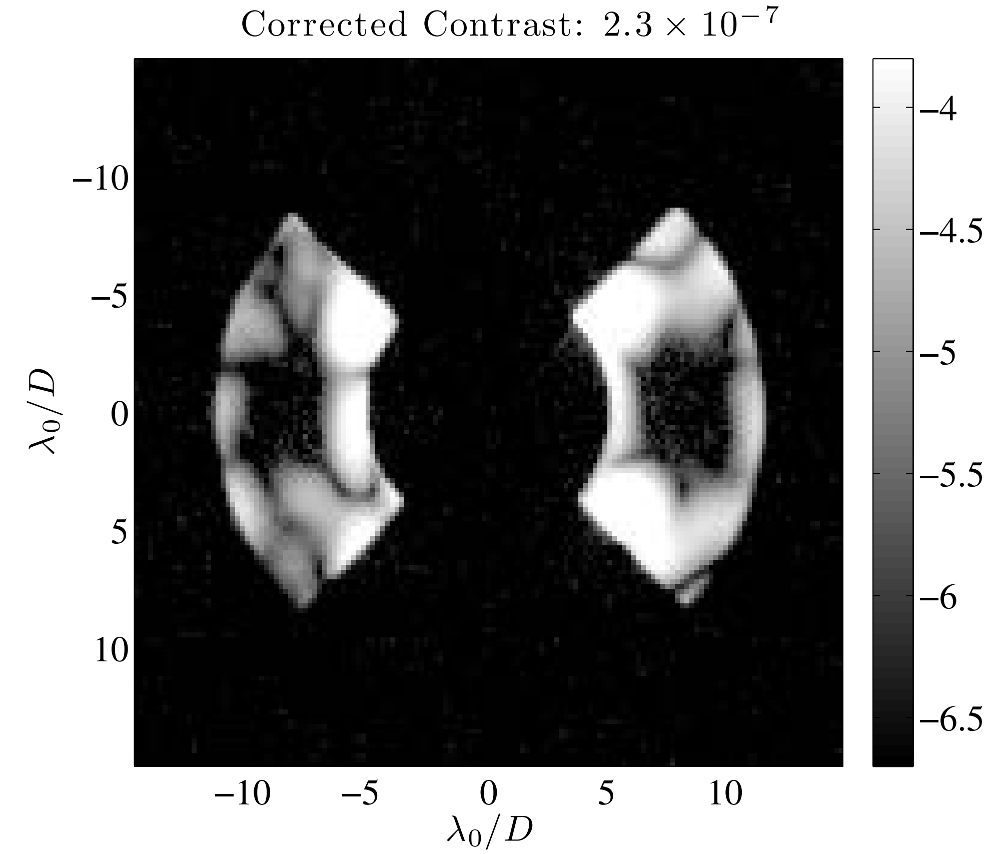
2.4×10^{-9} in 10% band

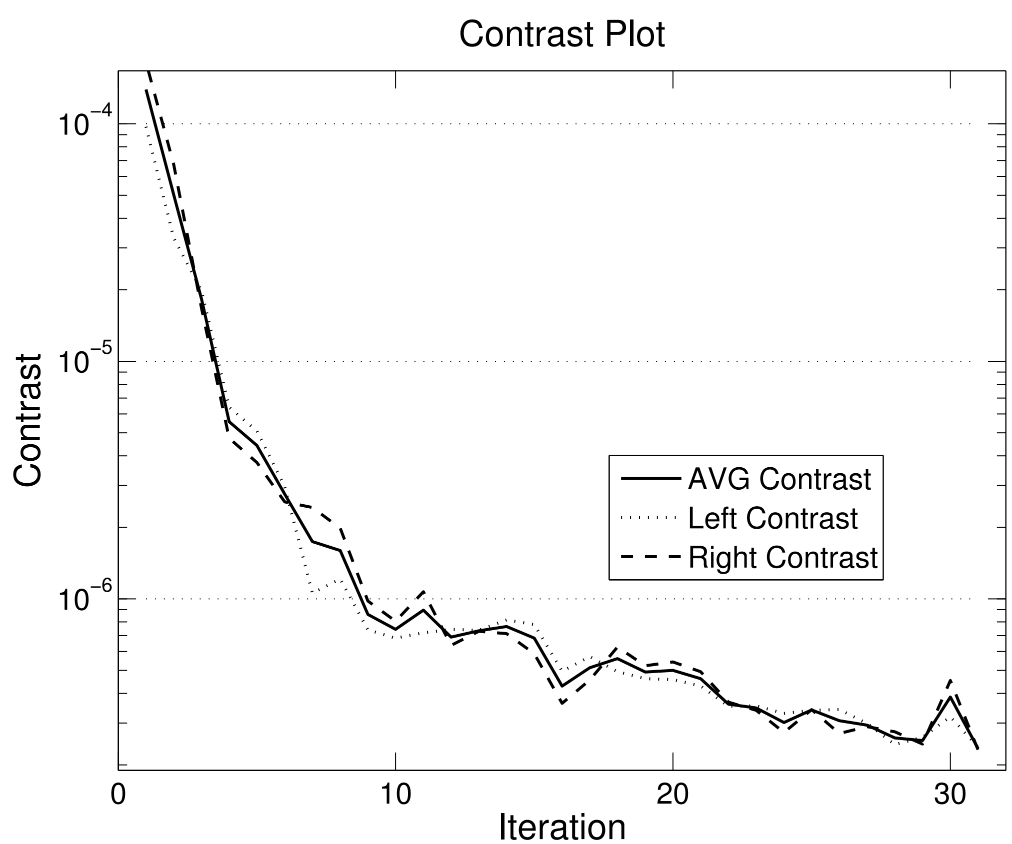
Kasdin et. al 2003
Kasdin et. al 2005
Belikov et. al 2007

Already achieved lab contrast at expected level for AFTA coronagraph.

Two-Sided Dark Hole in Princeton HCIL



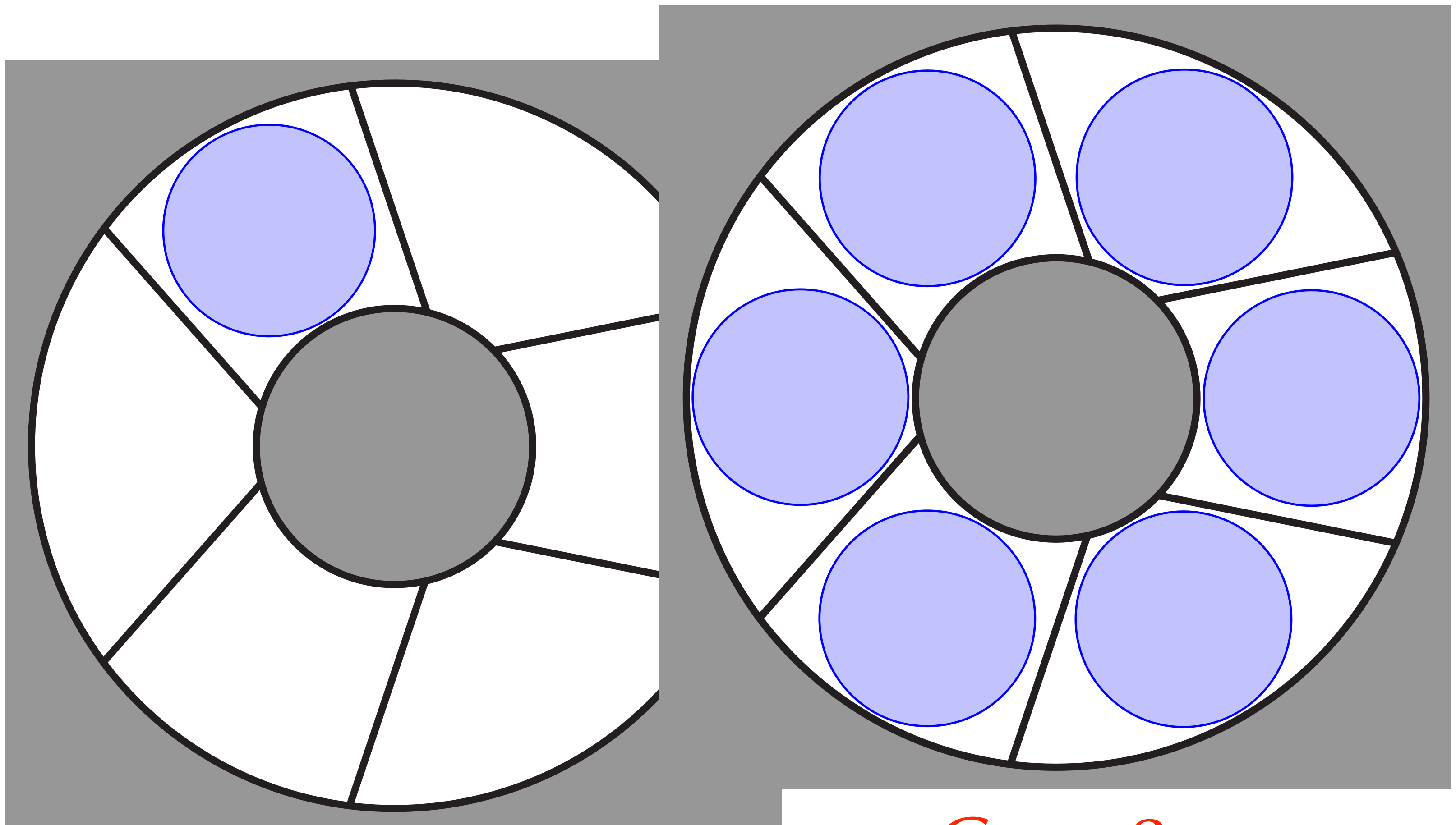




Experimental results of sequential MEMS DM correction using a discrete time extended Kalman filter with 2 image pairs to build the image plane measurement. The dark hole is a square opening from 7–10 x -2–2 lambda/D on both sides of the image plane. Final contrast is 2.3 x10^{-7} on both sides of the image plane. Image units are log(contrast).

Groff et, al.

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

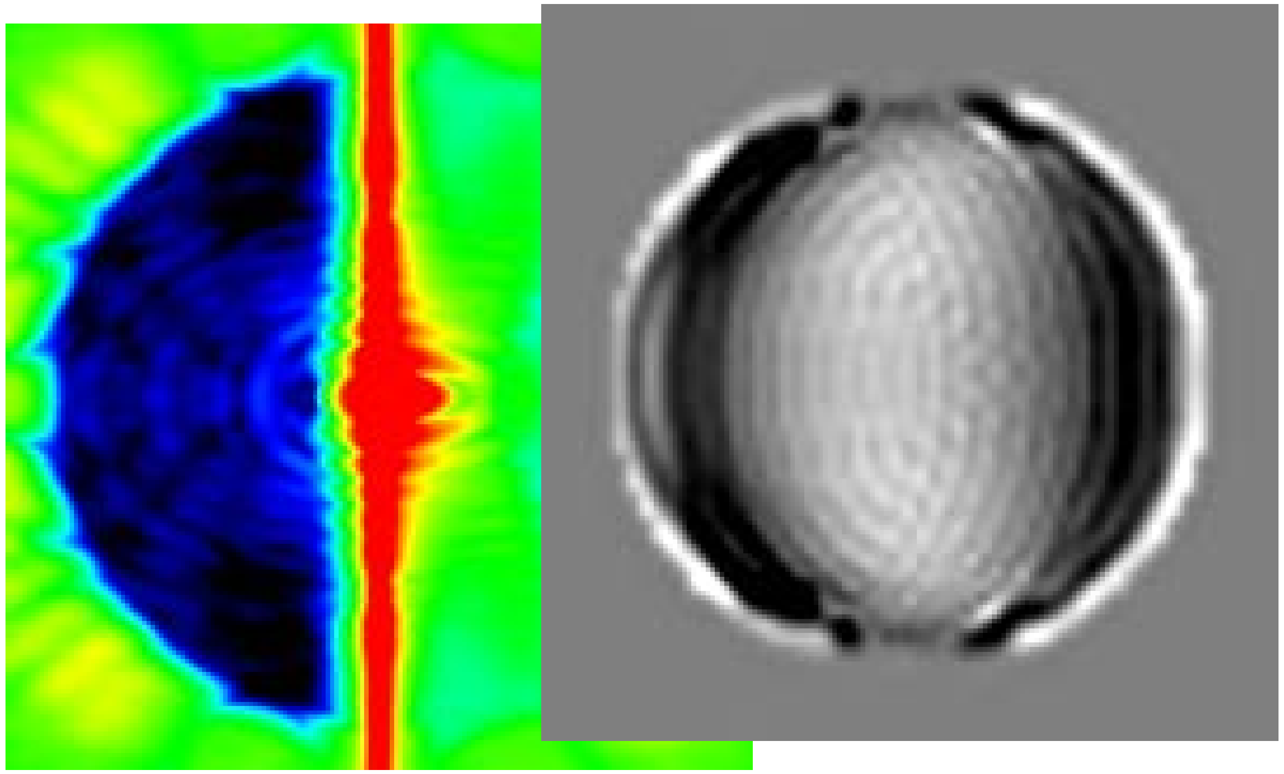


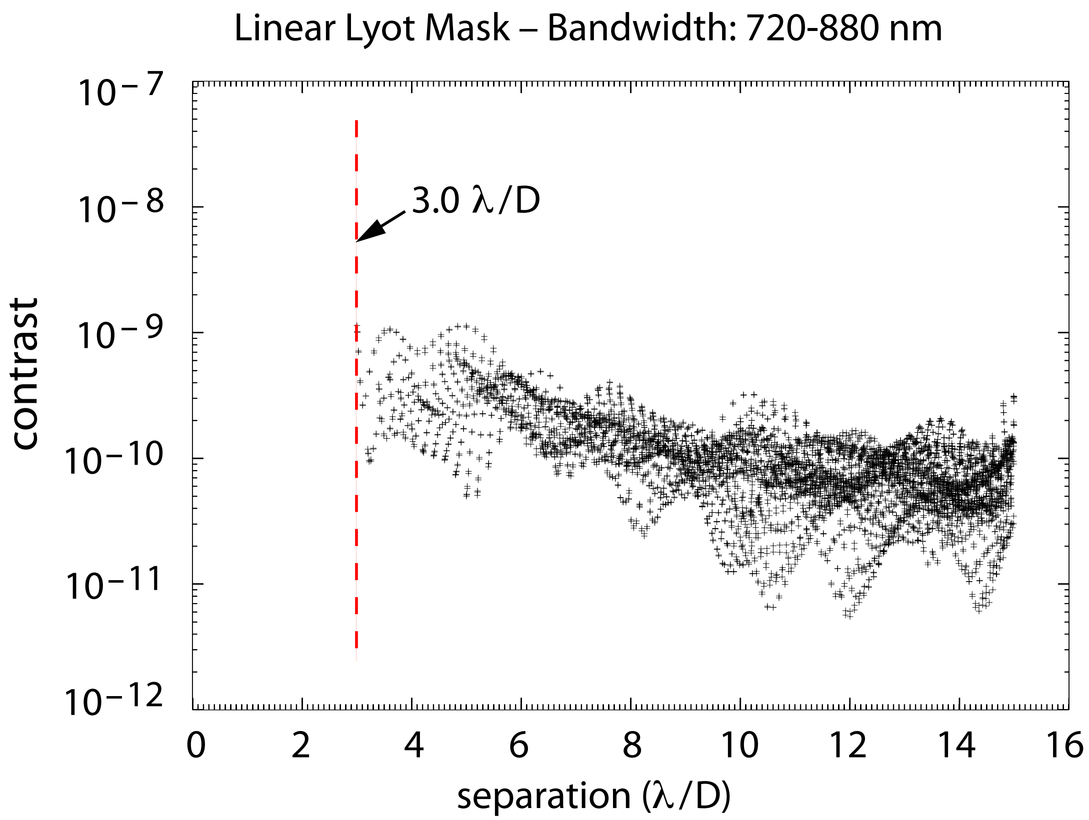
Case 1

Case 2

- *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.*
- *We compare subaperture and full aperture solutions for the NRO.*

State of the art for the Lyot coronagraph

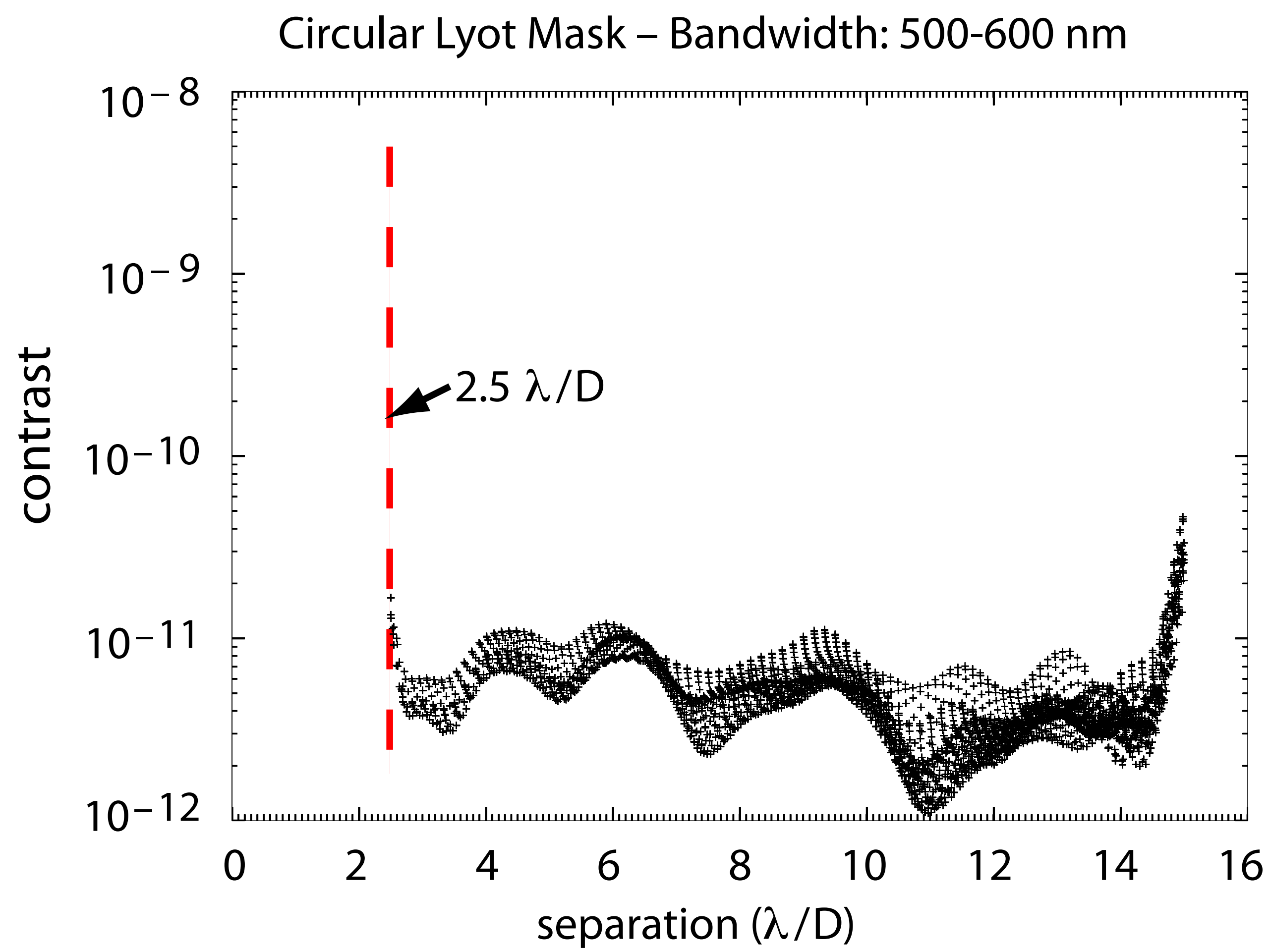




- *A complex apodized Lyot coronagraph (with focal plane mask of superimposed metal and dielectric layers) has been developed and tested in the laboratory under NASA's SAT TDEM program.*
- *With an unobscured aperture,* ***raw coronagraph contrast of 5e-10 is routinely achieved over a 10% spectral bandwidth 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).*

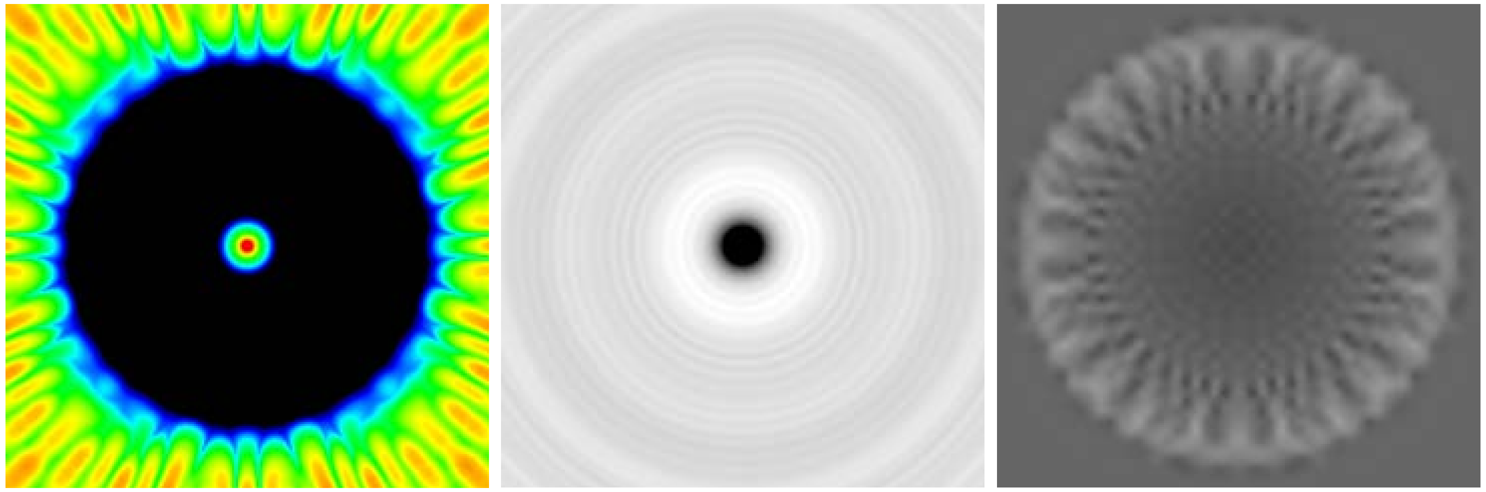
Complex Apodization Lyot Coronagraphy

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:

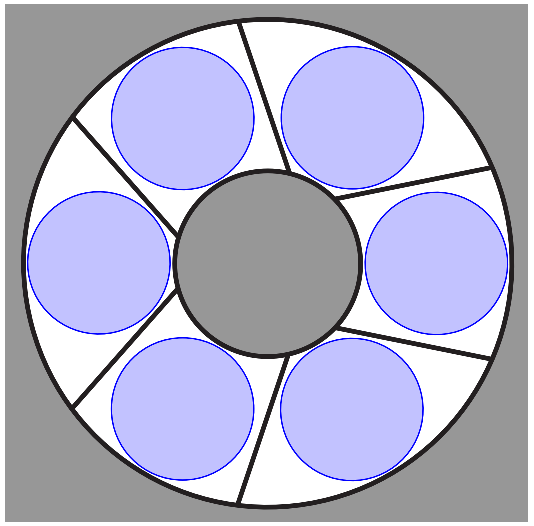
- *As for previous linear mask designs, the thickness profiles of the metal and dielectric layers are optimized simultaneously with the wavefront phase control of a single 48x48 DM.*
- *Focal plane mask is a layer of nickel plus a layer of cryolite superimposed on a fused silica substrate.*
- *These 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 λ_0/D. Note that a full 360^O dark field has been created with a single deformable mirror.*
- *Contrast in the 500-600 nm ($\delta\lambda/\lambda_0 = 18\%$) spectral band is 5.3×10^{-12} in both the inner 2.5–3.5 λ_0/D annulus and averaged across the entire dark field extending from radii of 2.5 to 15 λ_0/D.*



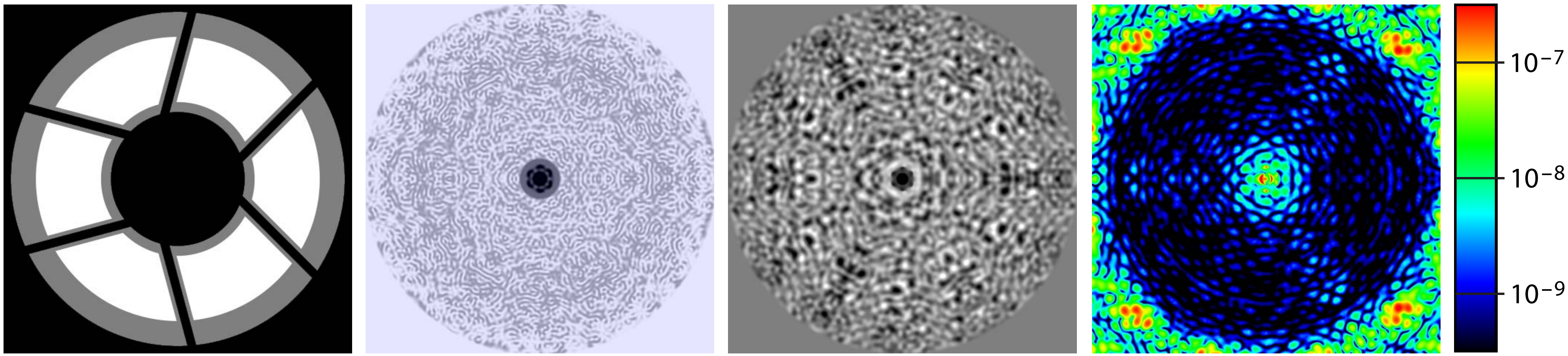
Left: Raw contrast in the dark field is displayed with a logarithmic stretch from 10^{-11} to 10^{-7}.

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 Coronagarphy offers:

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

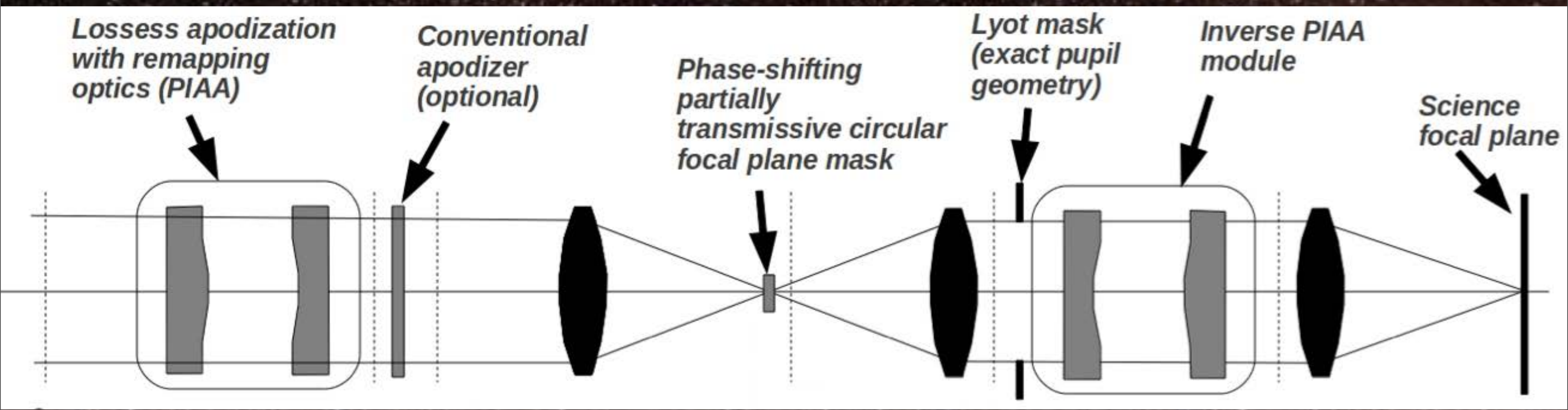
PIAACM Coronagraph with 2.4m ex-NRO telescopes could provide:

IWA of 1 λ/D = 43 mas (0.43 AU at 10 pc) at 0.5 μm

Phase-Induced Amplitude-Apodization Complex-Mask Coronagraphy

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-λ/D PSF core)
3. **A pupil-optimized Lyot stop**

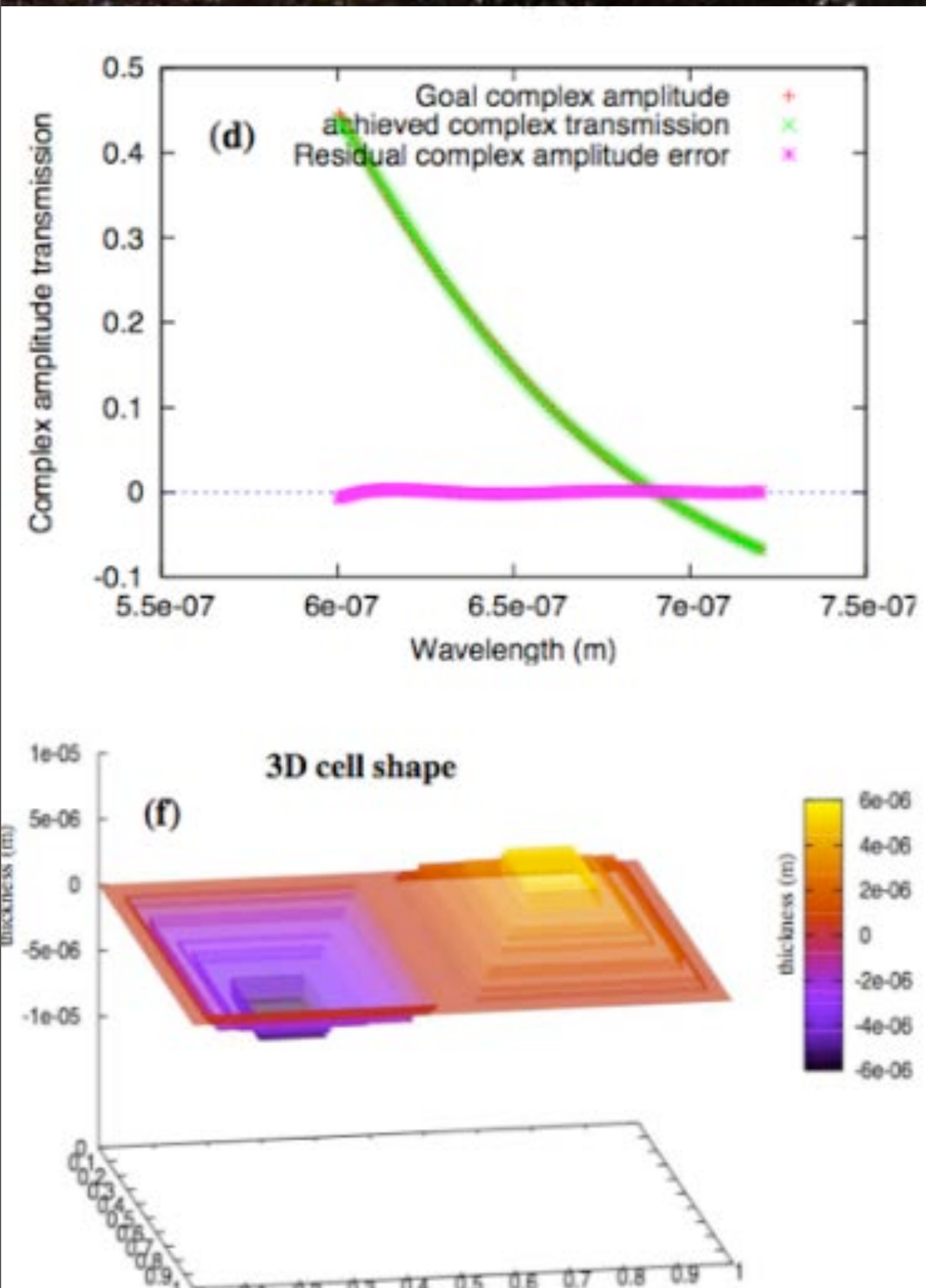


N.B.: Closed-loop wavefront sensing & control with Low Order WFS and Science Camera using Fast Steering Mirror (tip-tilt) and Deformable Mirrors (mid-spatial frequencies)

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

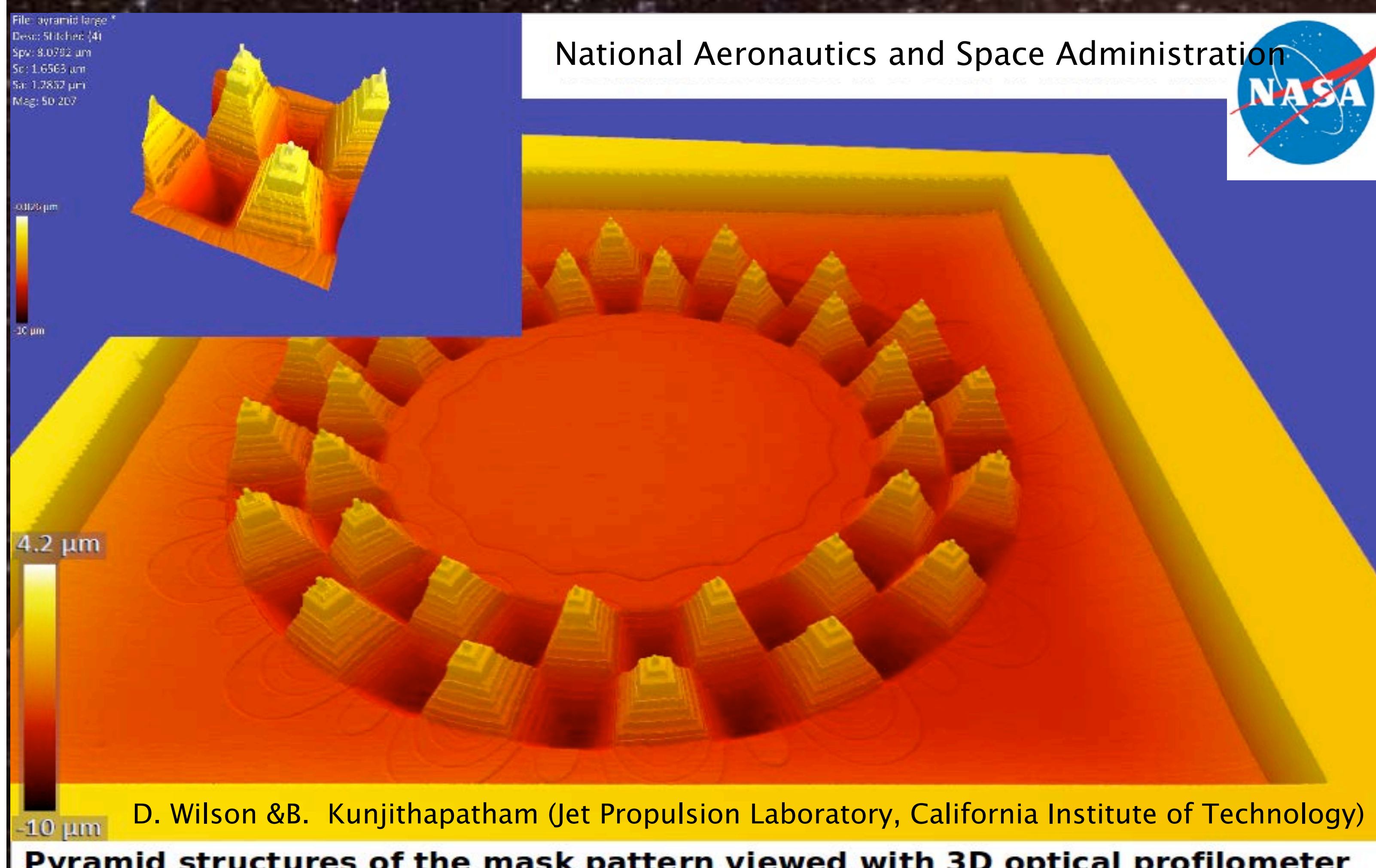
Complex (phase & amplitude focal plane Mask (CM)

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



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

Prototype Diffractive Focal Plane Mask (JPL MDL)

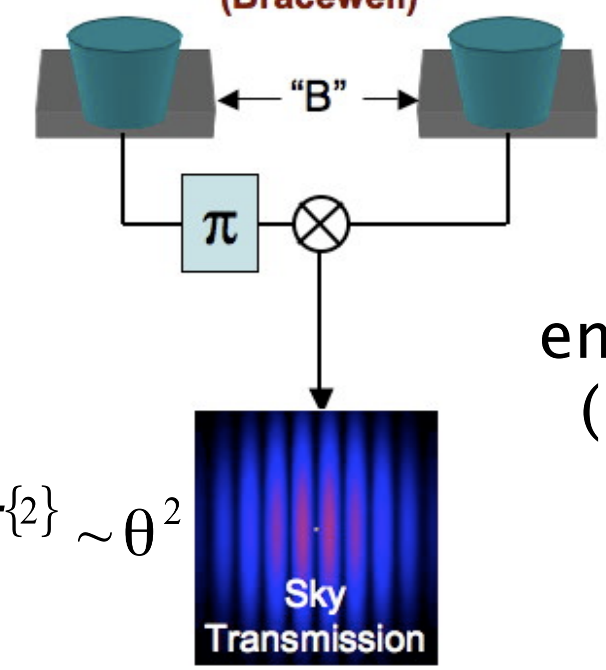


Visible Nulling Coronagraph (VNC): Overview

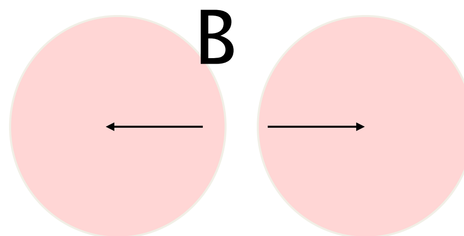
- ***VNC Approach is inherently flexible:***
  - *Conform instrument to Telescope*; lower instrument significance as mission driver
  - In-principle VNC works w/ *filled, segmented* and *interferometric* apertures
  - Differential Wavefront Control (photon conserving)
  - EPIC / VNC studied under NASA 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)**
  - Miletstones: Advance Technology Readiness; reviews by Technical Advisory Committee (TAC)
    - Milestone #1: 10^8 contrast at 2 λ/D, narrowband, to 90% confidence
    - Milestone #2: 10^9 contrast at 2 λ/D, narrowband, to 90% confidence
    - Milestone #3: 10^9 contrast at 2 λ/D, with Δλ = 40 nm centered on λ= 633 nm (R ~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 λ/D, dark hole from 1 – 4 λ/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



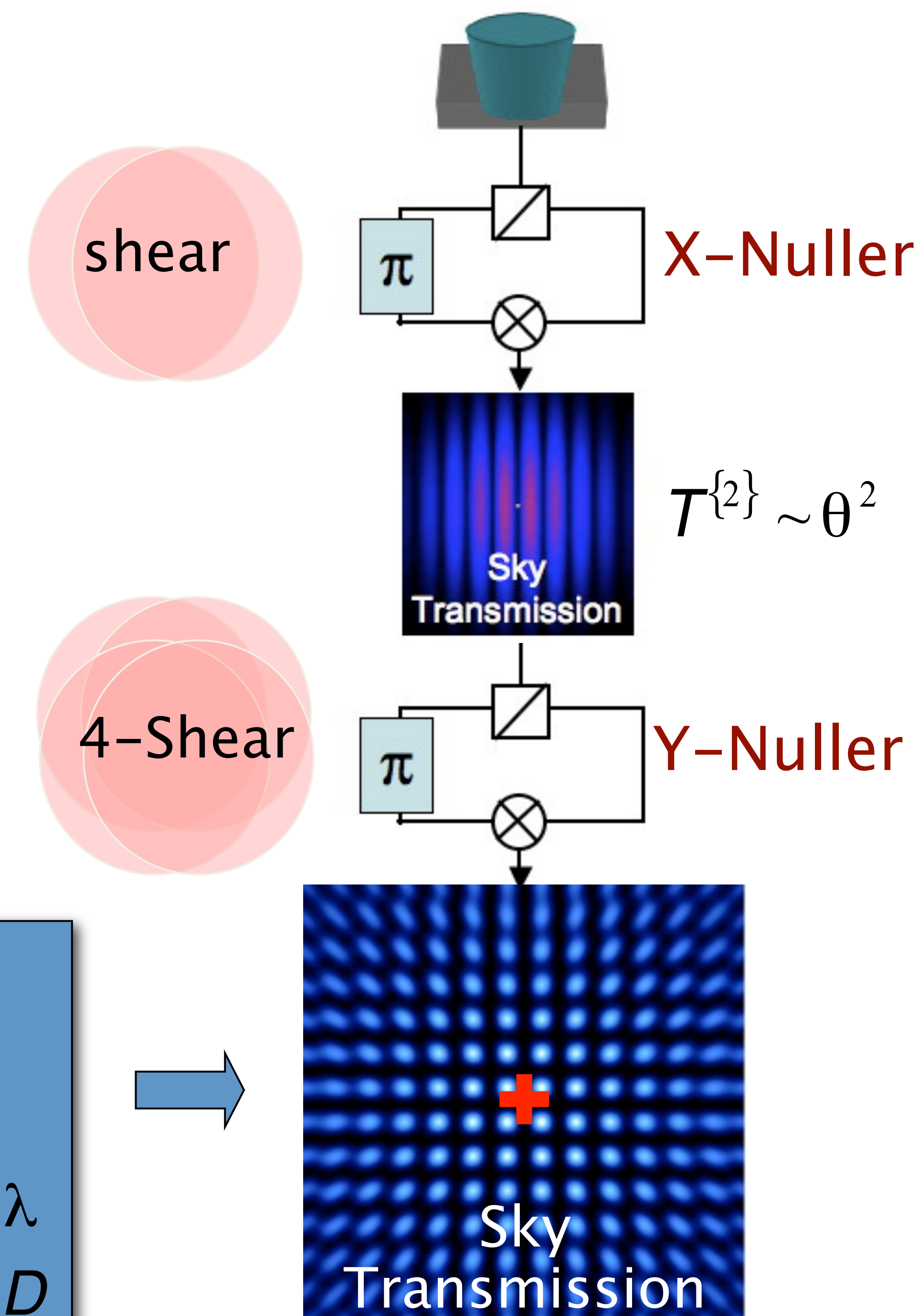
$T^{\{2\}} \sim \theta^2$



Baseline Spacing emulated by shearing (lateral translation)

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

Nulling Coronagraph



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

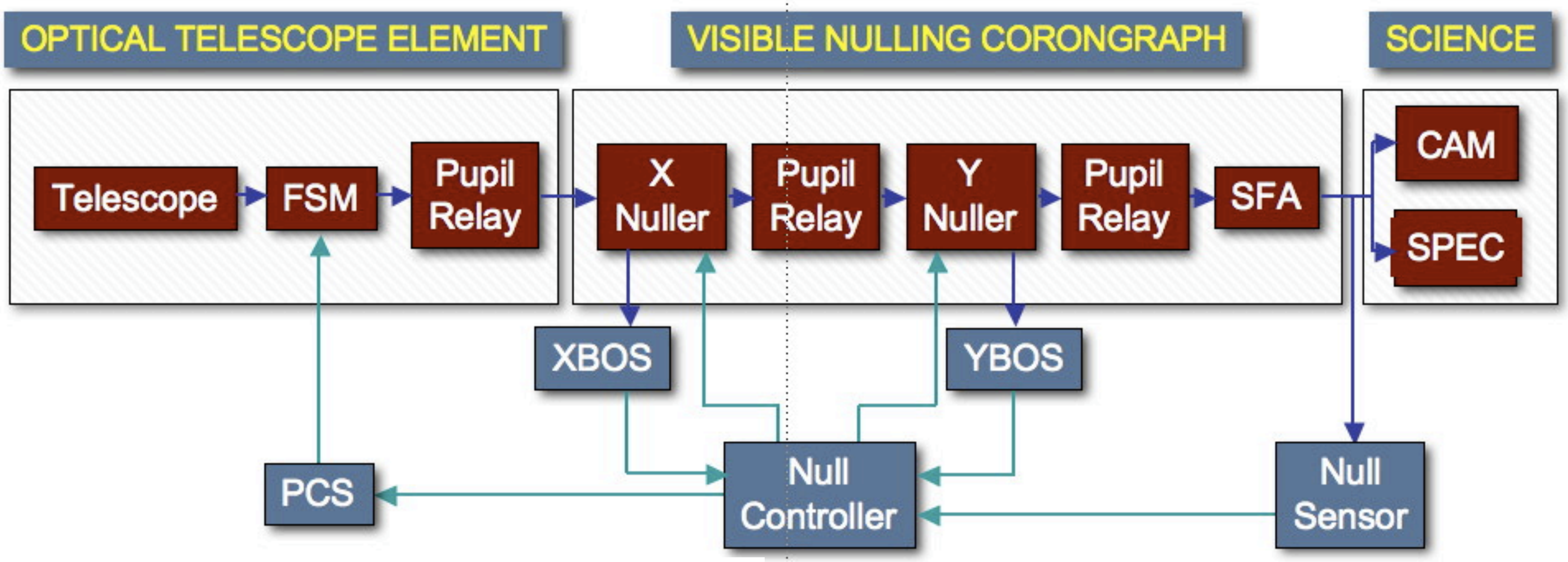
$$T^{\{4\}} \sim \theta^4$$

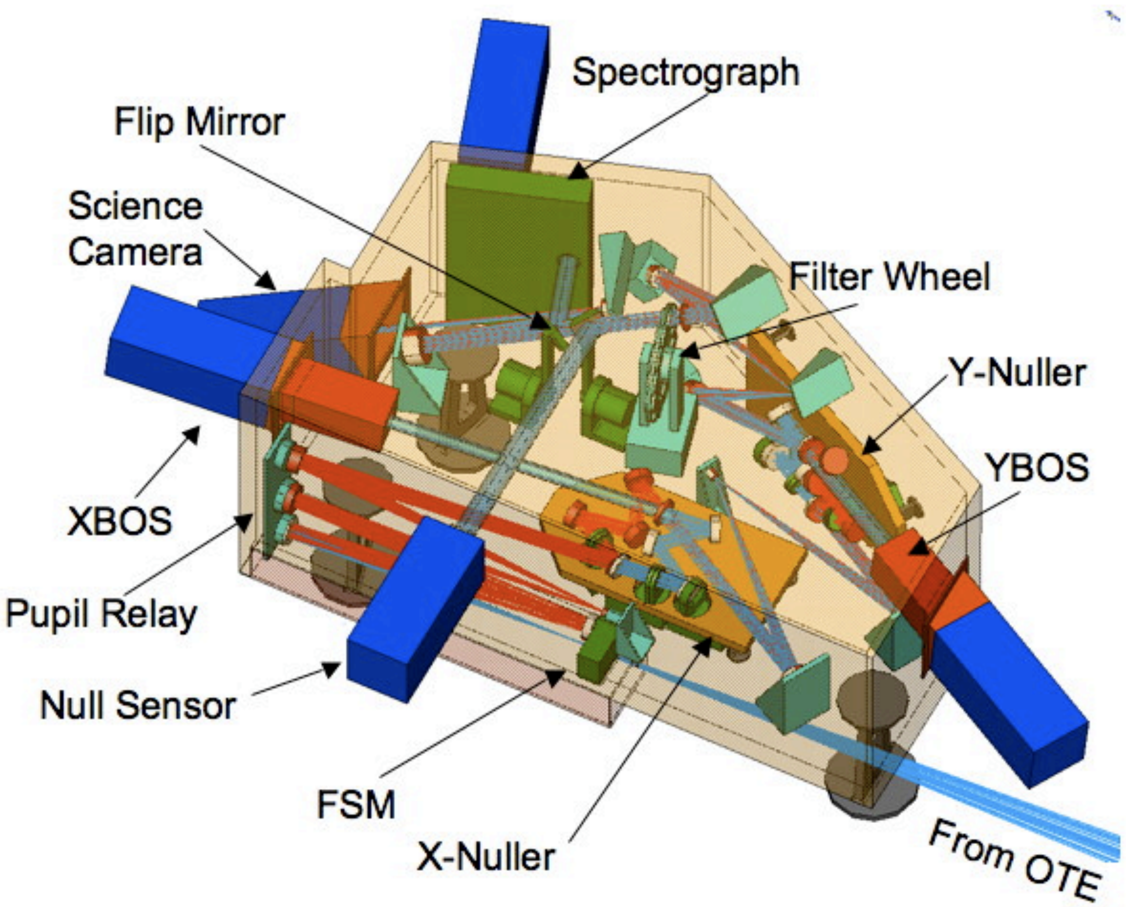
$$IWA = \frac{1}{s}$$

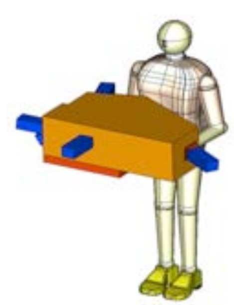
$$s = 0.25 \Rightarrow IWA = 2\frac{\lambda}{D}$$

Lyon/Clampin
09/06/12

Architecture Overview





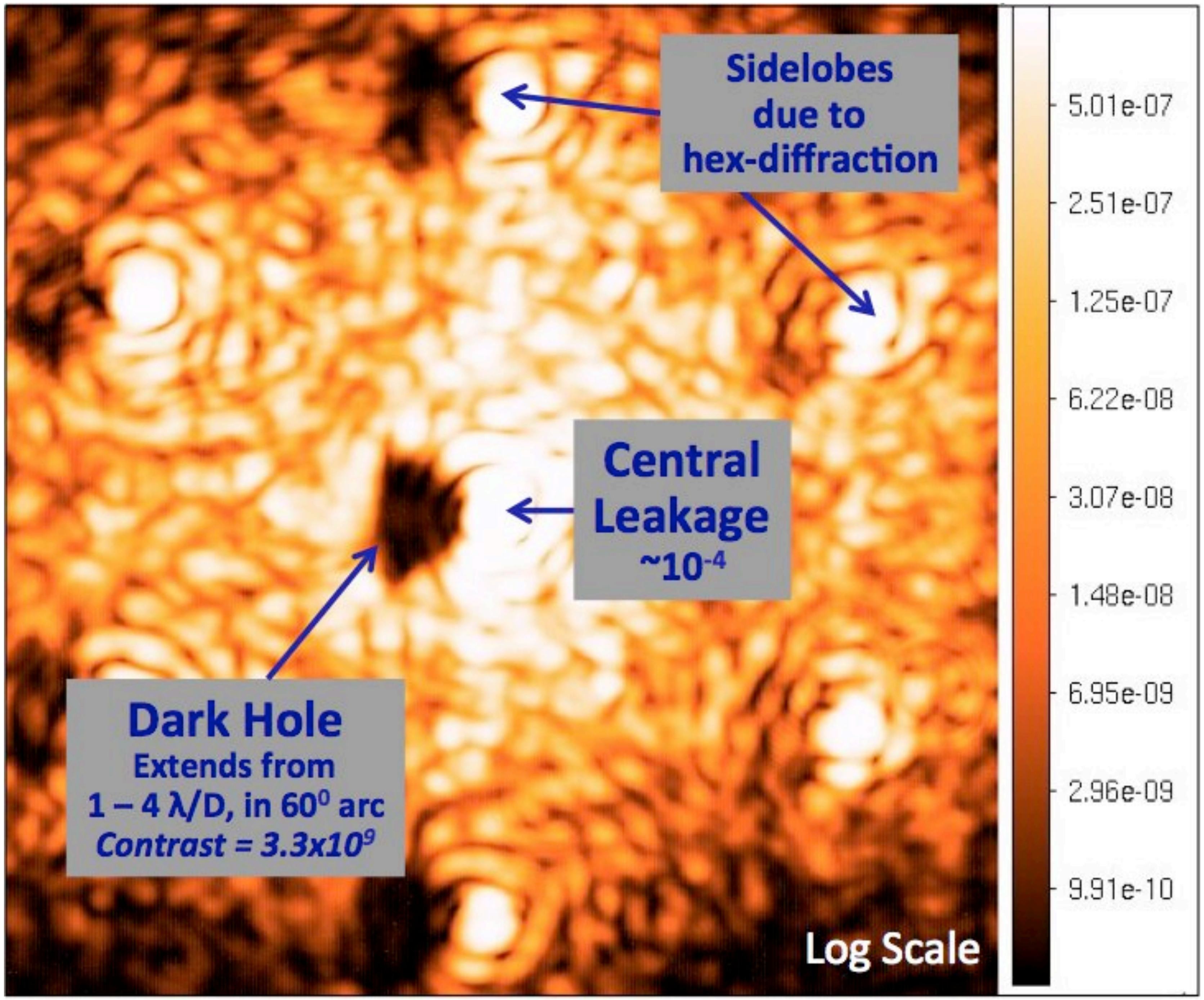


- XBOS used for fine pointing
- XBOS, YBOS, Null Sensor used for coarse & fine null control
- YBOS & Science Cam used for in-situ null control monitoring

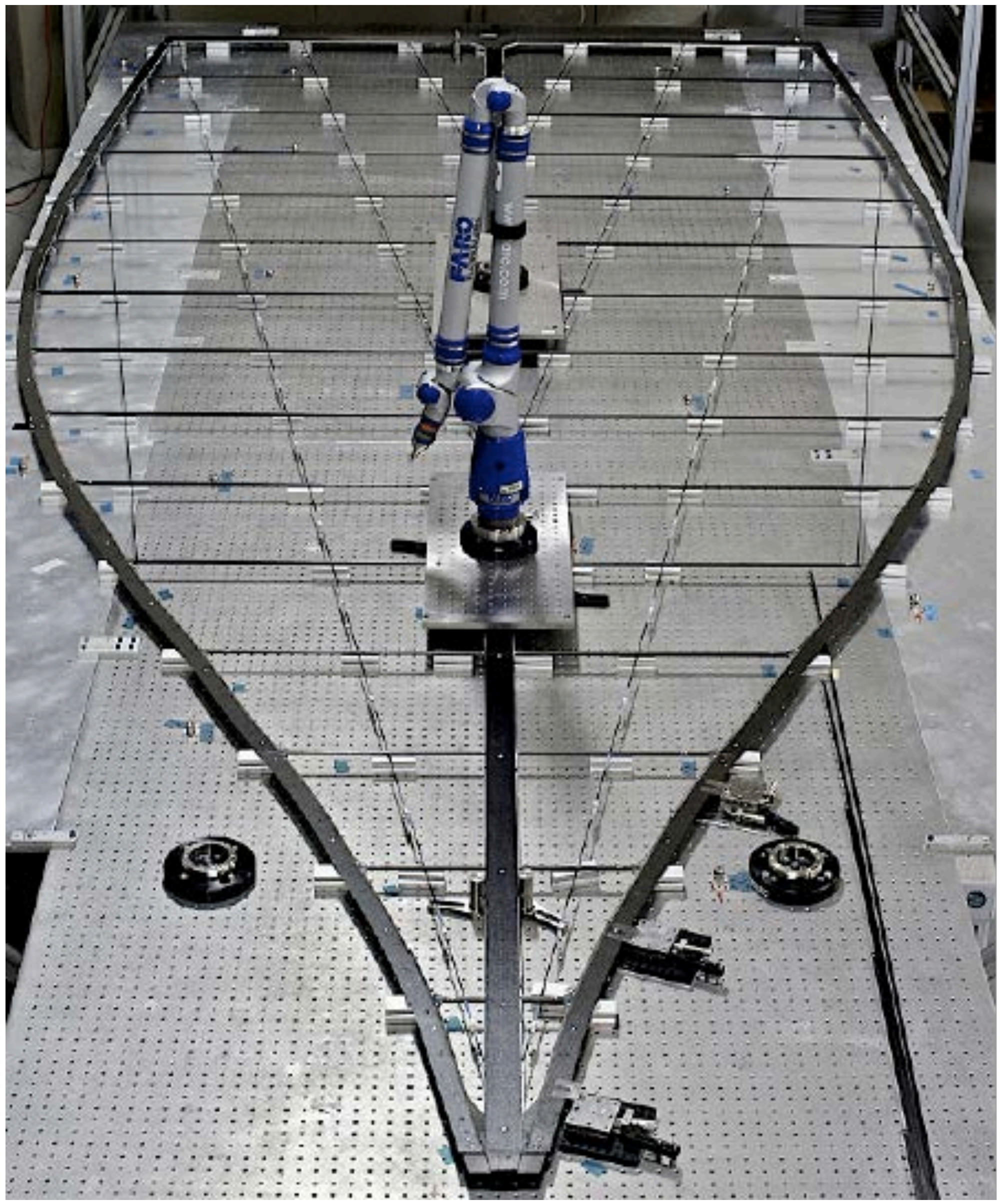
Most optics within VNC are Flats
<2 cm diameter
Size limited by DM technology

10^9 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
  - (λ,Δλ) = (633, 1.2) nm
- **~10^9 Contrast averaged over 1-4 λ/D, 60^0 arc region**
- 1st Demo using segm DM
  - hex-packed segment MEMs DM
- FY12/13 TDEM broaderband
  - increase spectral bandpass from Δλ= 1.2 nm to Δλ= 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.

Or perhaps with the second telescope . . .

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.

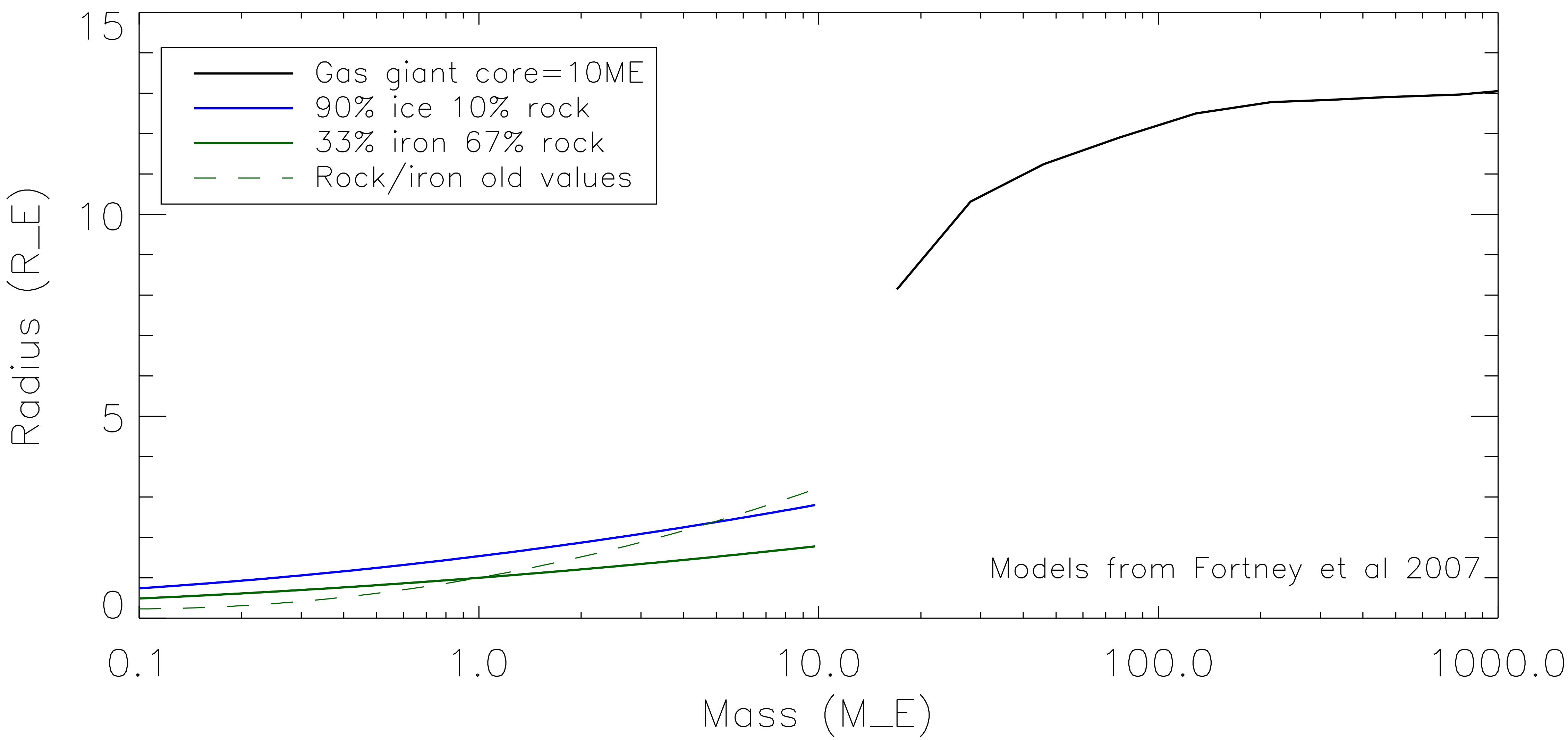
- What is WFE and thermal and dynamic stability of telescope?
- How will low-order aberrations affect contrast for different coronagraphs?
- Is there room for a spectrograph or just filter photometry?
- What is available mission time for observations?
- What is observing band and how many channels?

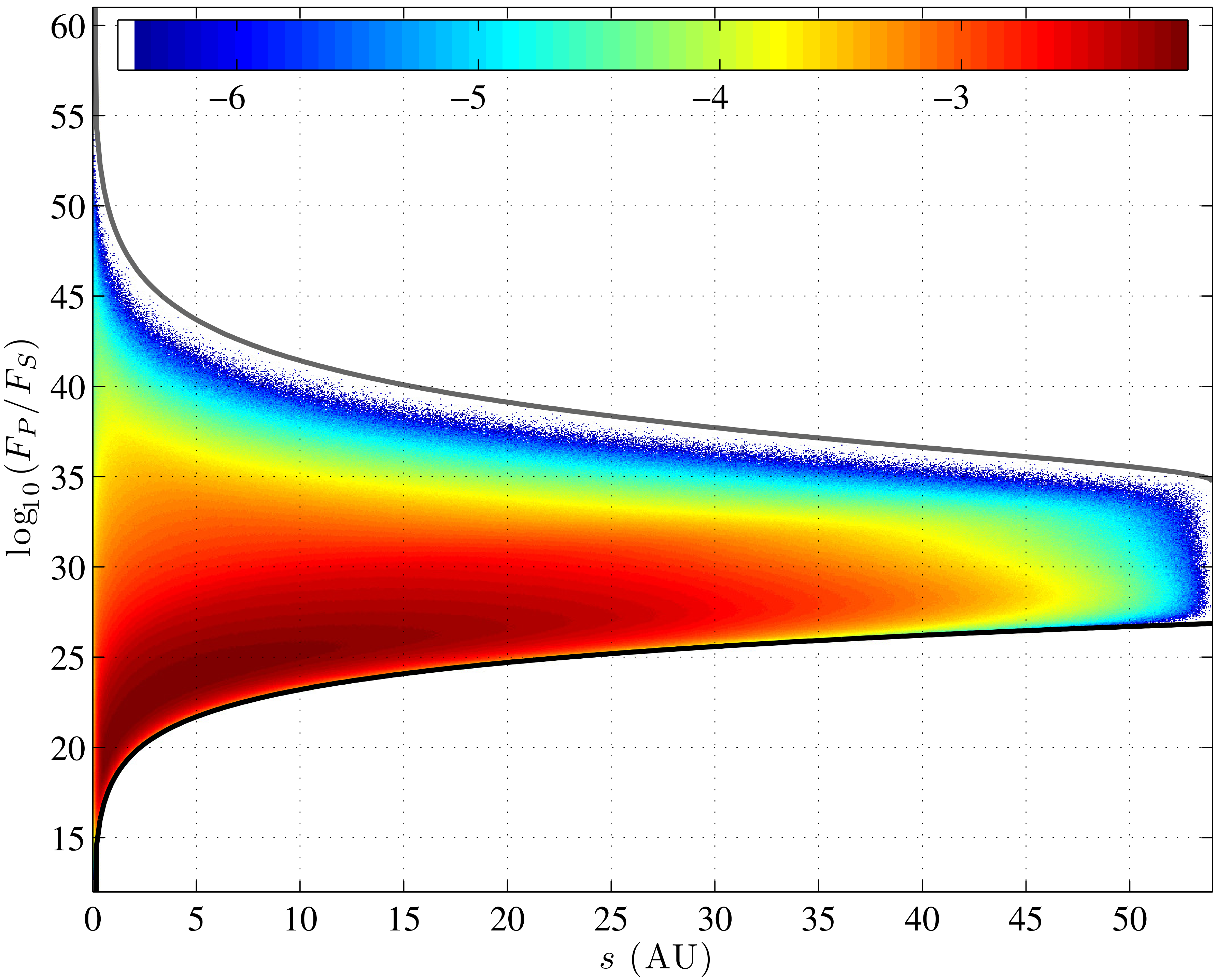
Opportunity to perform science and advance the state of the art!

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

Backup Slides

Mass Radius Relationship





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s (AU)