# SCDA / PIAACMC status

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# PIAACMC principle, theoretical performance

**Lossless apodization**
***Creates a PSF with weak Airy rings***

**Inverse PIAA (optional)**
***Recovers Airy PSF over wide field***

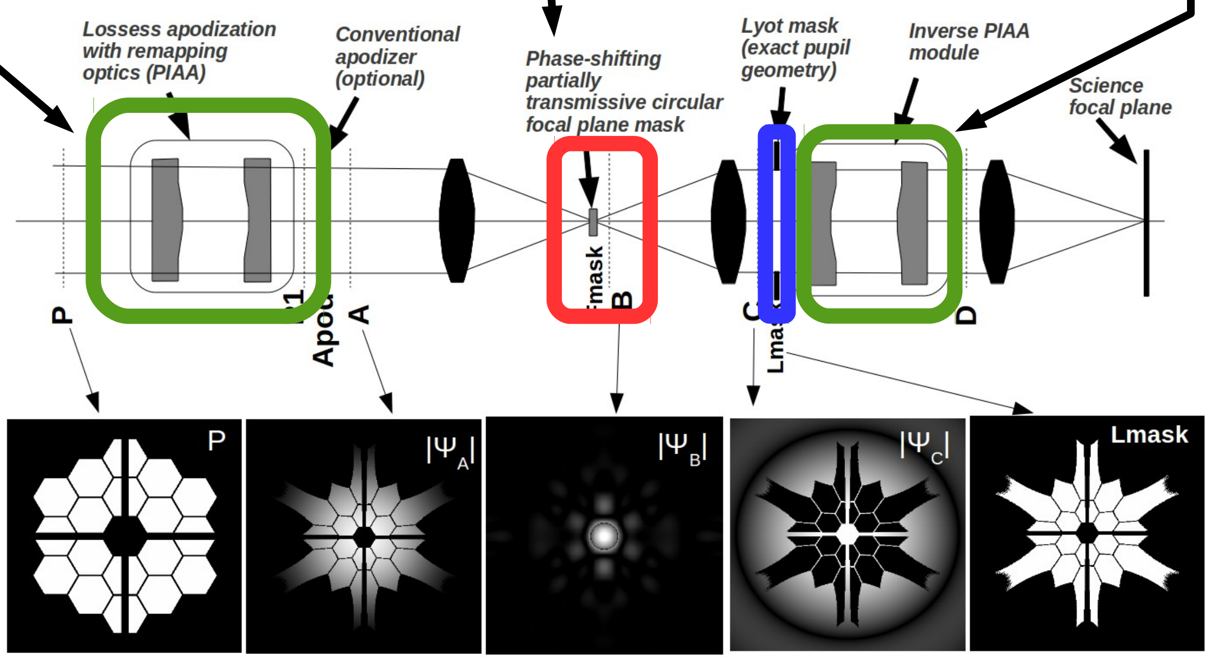
**Focal plane mask: -1<t<0**
***Induces destructive interference inside downstream pupil***

**Lyot stop**
***Blocks starlight → LOWFS***

**PIAACMC provides, for any aperture shape, full rejection (infinite contrast), 1.0 l/D IWA and 100% throughput under the following assumptions**:

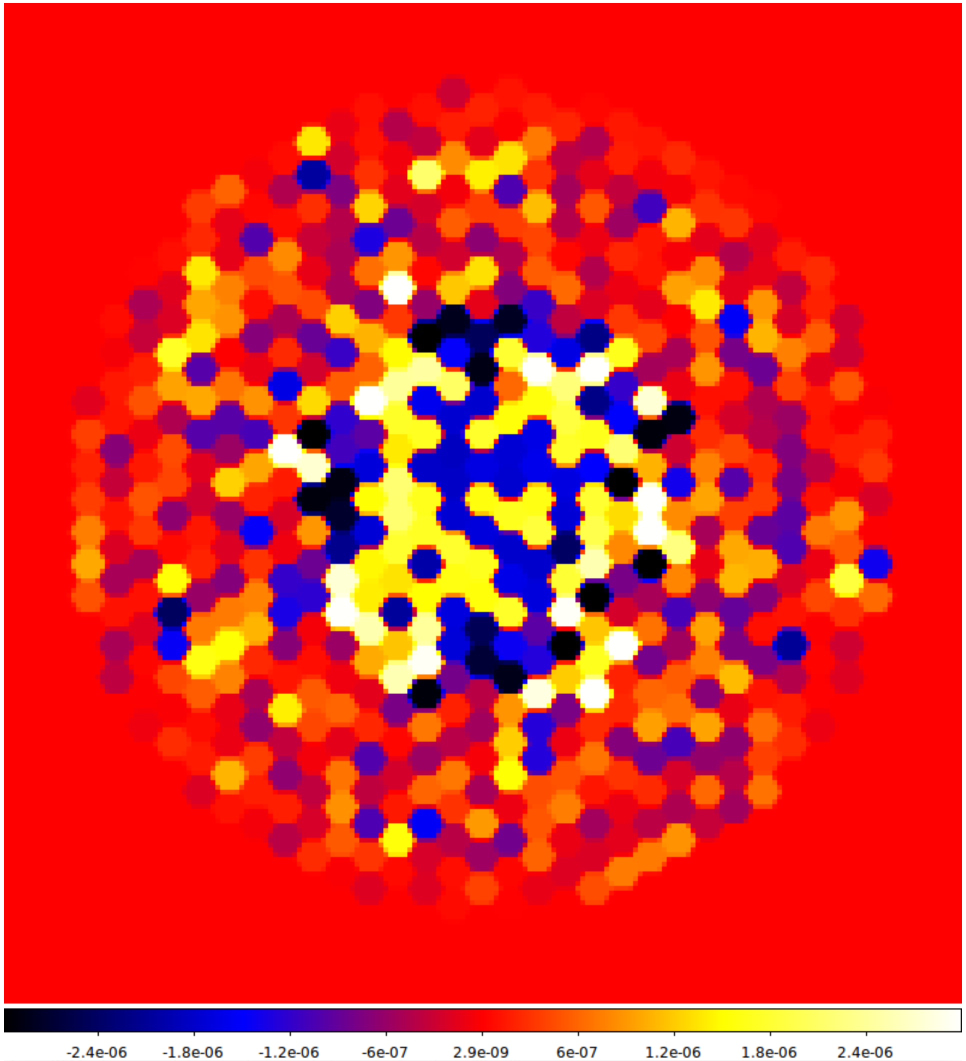
- No wavefront error
- On-axis point source
- Ideal focal plane mask
- Fourier Optics (no propagation of edge diffraction through finitely sized optical elements)

**Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)**




***Our SCDA effort goes from ideal concept to realistic implementation by taking into account these 3 effects***

# Focal plane mask




***Ideal PIAACMC calls for a phase-shifting disk with a fixed l/D radius***
***There is no demonstrable way to make such a mask in broadband light***
***→ we approximate it by a multi-zone physical device (mirror), which can be manufactured***

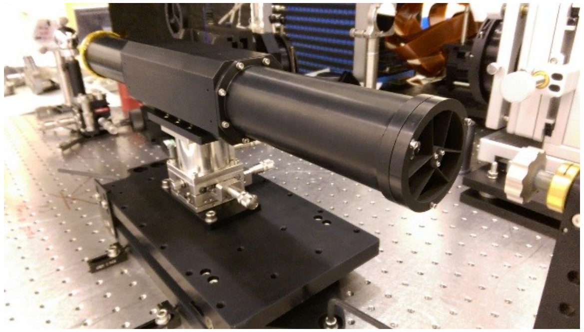
Multiple zones (sectors or hexagons) phase-shift light

Multiple zones interfere destructively inside the pupil across the science spectral bandwidth

No light is absorbed → ALL starlight sent to the LOWFS for efficient sensing of low-order aberrations

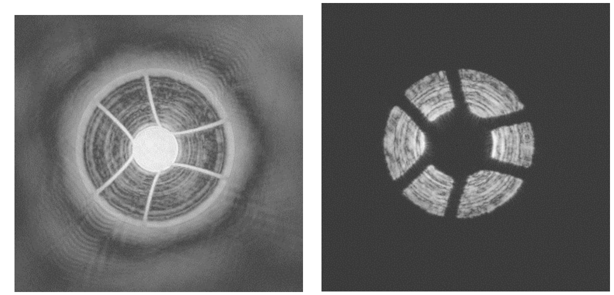
***Much of our SCDA activity has been to design manufacturable FPMs for PIAACMC FPM co-optimized for broadband performance, stellar angular size (+ optional resilence to known aberrations)***

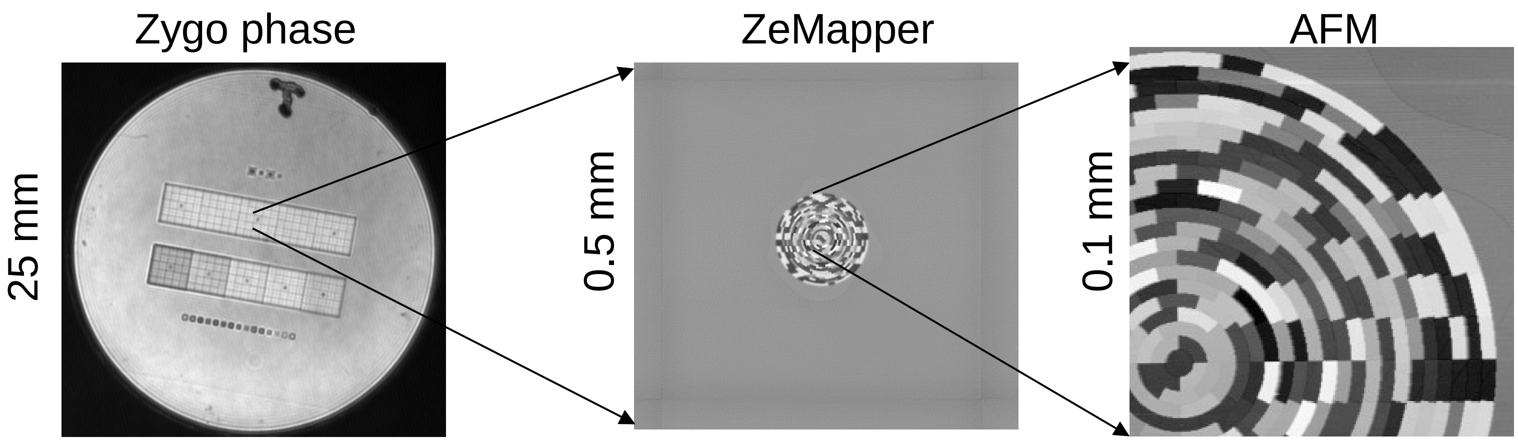
# PIAACMC SCDA design uses same approach as WFIRST PIAACMC (some hardware, technology heritage)

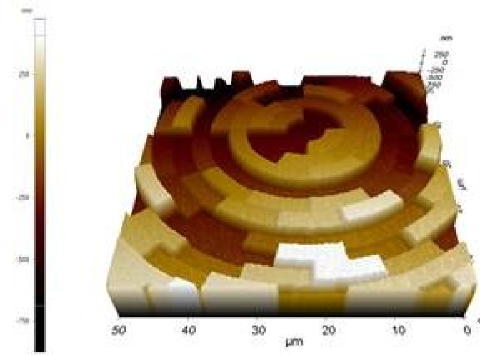


On-axis PIAACMC system (Gregorian telescope)

Single Lyot Stop → easy feed to LOWFS



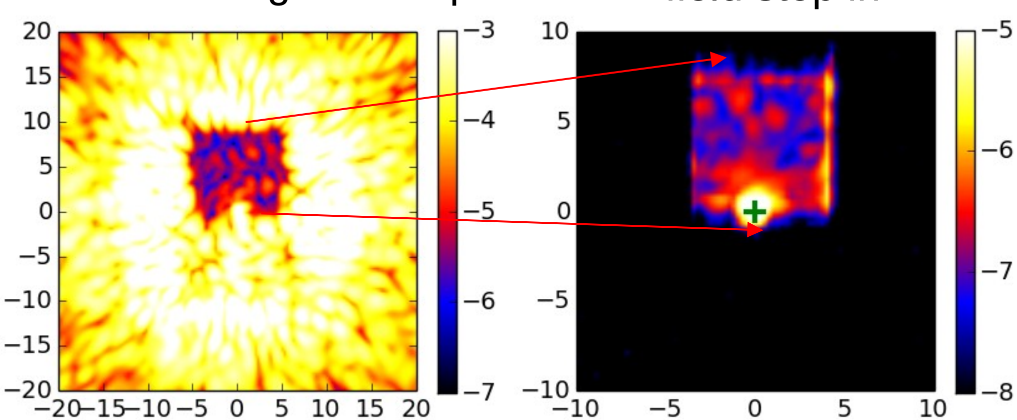


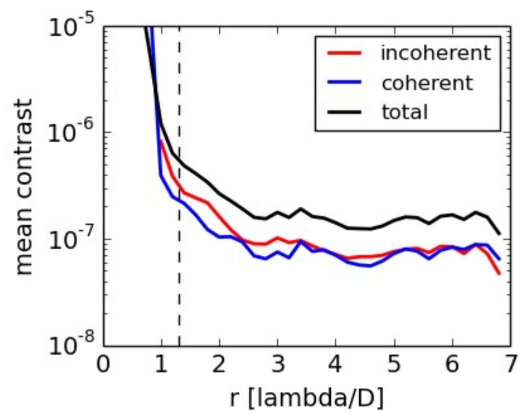



Reflective multi-zone focal plane mask

1 DM, 1-sided, ±6 $\lambda/D$ before inserting field stop

field stop in





# PIAACMC science trade space

**<u>Key advantages</u>**

- **High throughput, "undisturbed" PSF**
- **Access to small IWA (~1.0-1.5 l/D)** … but comes with high sensitivity to stellar angular size
- **Maintains high performance on segmented aperture**

**<u>→ Brings additional potential science capabilities not accessible to "classical" coronagraph approaches working at larger IWA:</u>**

- **Longer wavelength science (near-IR)**: star is smaller, planet is closer in (in l/D units), planet may have thermal emission (kicks in @ ~3+ um)
- **Provides access to later-type stars**. Proxima Cen b -like targets: moderate contrast (~1e-7) but small angular separation
- **Provides access to distant targets**. Small angular separation, small stellar size

**<u>→ PIAACMC/SCDA effort key goals:</u>**

(1) Demonstrate viable architecture for segmented aperture: managing edge diffraction with realistic optical design and manufacturable components

(2) Demonstrate/quantify additional science capabilities enabled by small IWA access

(3) Can PIAACMC @ segmented aperture <u>ALSO</u> operate in the more conventional performance regime (contrast ~1e-9 / 1e-10 at 4 l/D) ?

# Key findings

**(1) Demonstrate viable architecture for segmented aperture → Completed to 1e-8 level, now pushing deeper**

We have produced designs that deliver PIAACMC key IWA & throughput advantages: ~1 l/D IWA, 70% throughput in broadband light

Designs are matched to realistic optical design and components manufacturing capabilities, as demonstrated on HCIT with PIAACMC testbed

**(2) Demonstrate/quantify additional science capabilities → Ongoing, promising… but needs further improvement (stellar angular size)**

Performance limited by stellar angular size

With stellar size = 2% l/D, raw contrast ~1e-7. Smaller stellar size → deeper contrast

→ does bring in unique near-IR science, planets around M-type stars

… but needs further improvement

**(3) Can PIAACMC @ segmented aperture ALSO (simultaneously) operate in the more conventional performance regime (contrast ~1e-9 / 1e-10 at 4 l/D) ? → Optimization of high perf solution at 4 l/D not been seriously started yet. Likely requires changes in architecture/hybrid (some progress with APLC / PIAACMC hybrid).**

Stellar angular size is a significant issue even at >3 l/D → we have not yet demonstrated deep contrast with small-IWA PIAACMC

**Does an architecture offering simultaneously access to small IWA and deep contrast at > 3l/D exist ?**

Promising avenues currently under investigation, but with reduced throughput:

APLCMC architecture does offer improved sensitivity to stellar angular size

APLC + PIAACMC : apodize pupil to deliver deep contrast @ > 3 l/D, use PIAACMC for < 3 l/D

# PIAACMC design process

## Design is a 2-step process

(1) Design PIAACMC (or APLCMC) in monochromatic light, point source, and ideal focal plane mask

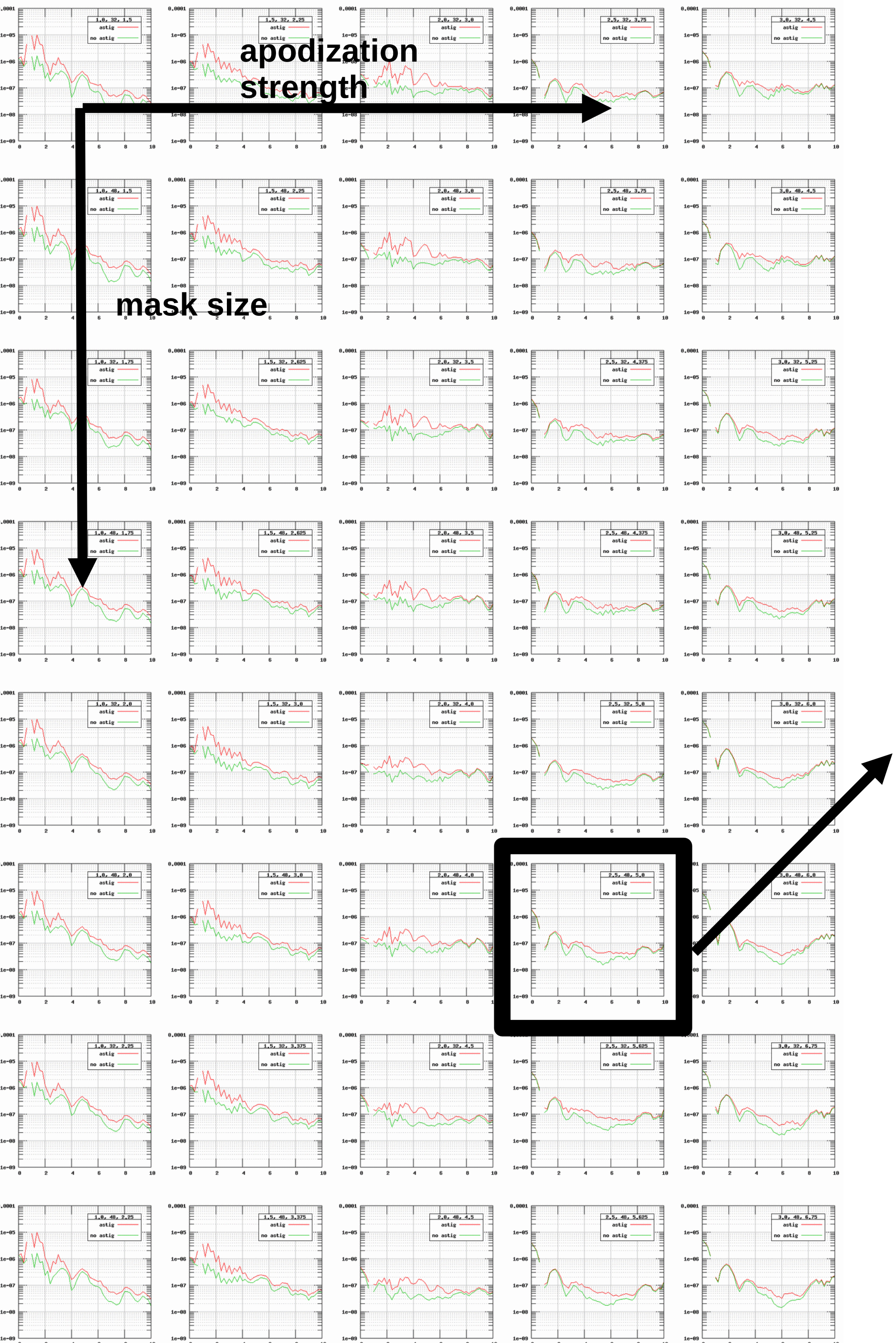
(2) Add chromaticity, stellar angular size and physical mask → optimize mask zone thicknesses

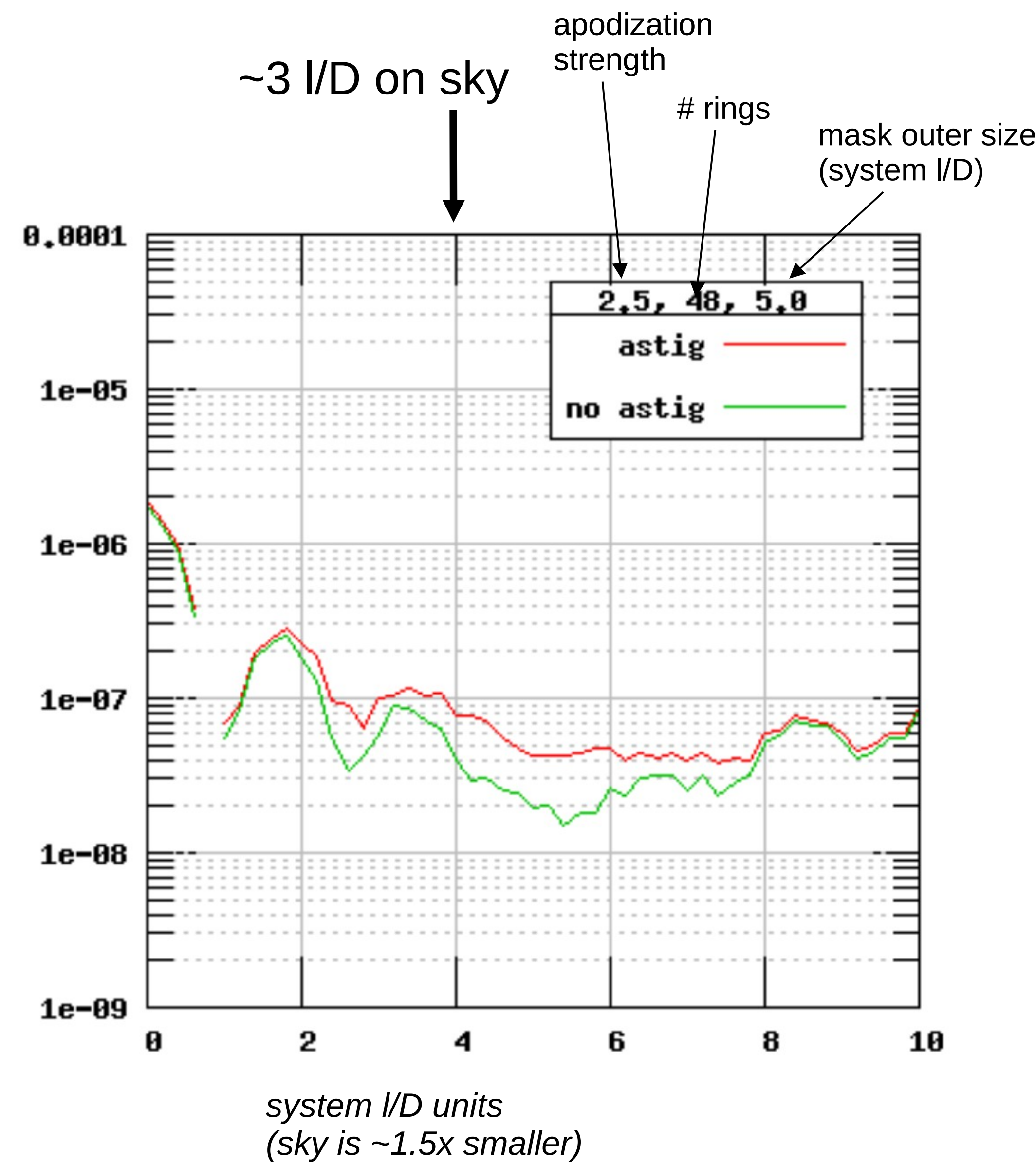
## PIAACMC design software

Source code: www.github.com/oguyon/PIAACMCdesign

- C code, runs on Linux & OS-X systems, uses GPU acceleration
- Development & single/few design(s) evaluation on computers at UofA, Hawaii & Ames
- Preparing for use of NASA Ames hyperwall cluster for rapid parameter exploration (128-node cluster, each: 20 cores + GPU, 64GB mem, 646 Tflop/s)
- Independent verification process of results @ Ames under development

# Extensive parameter scan @ Ames hyperwall (example shown here for WFIRST/polarization study)



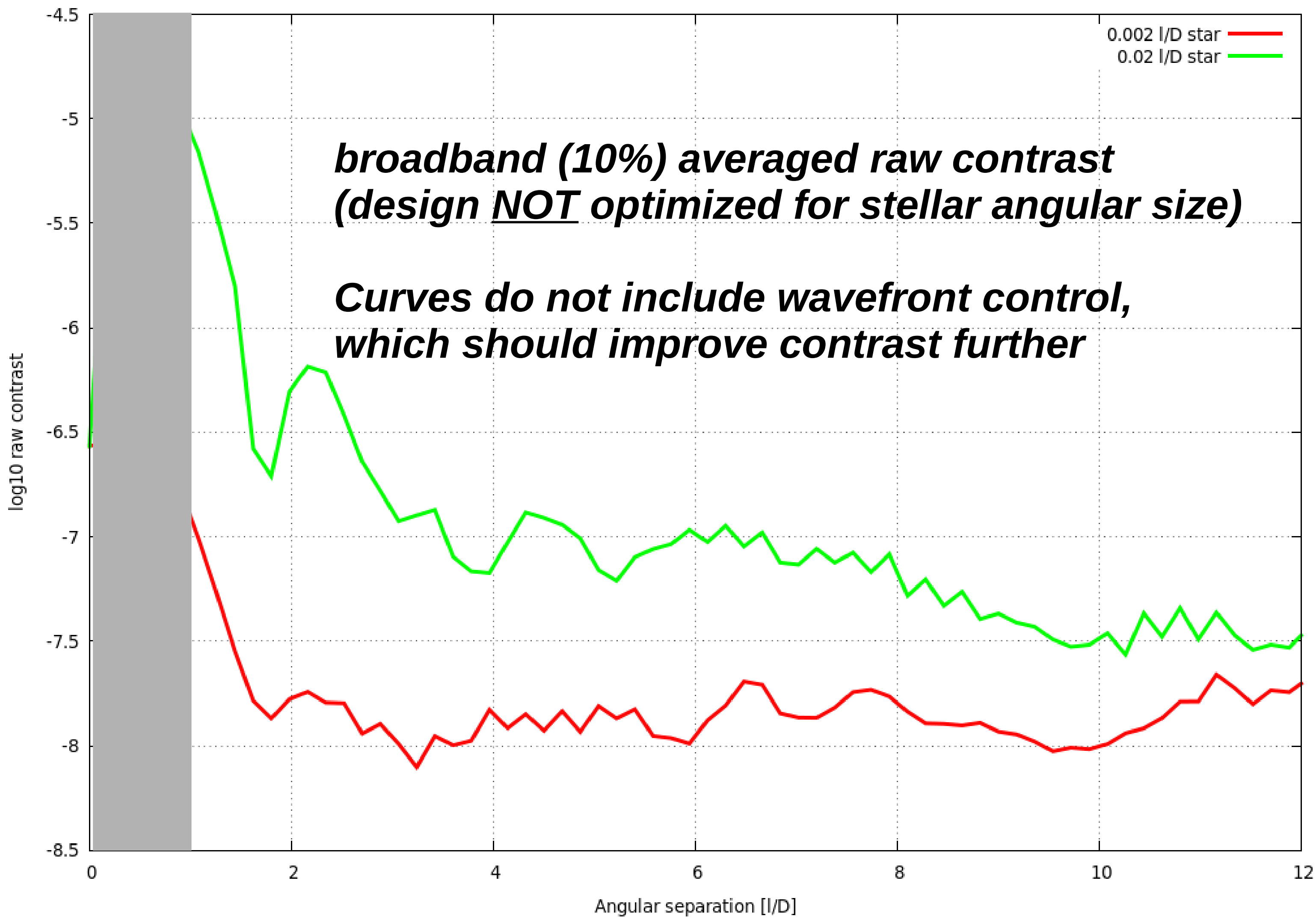
# Design #1: “Aggressive” PIAACMC, 3-ring SCDA aperture

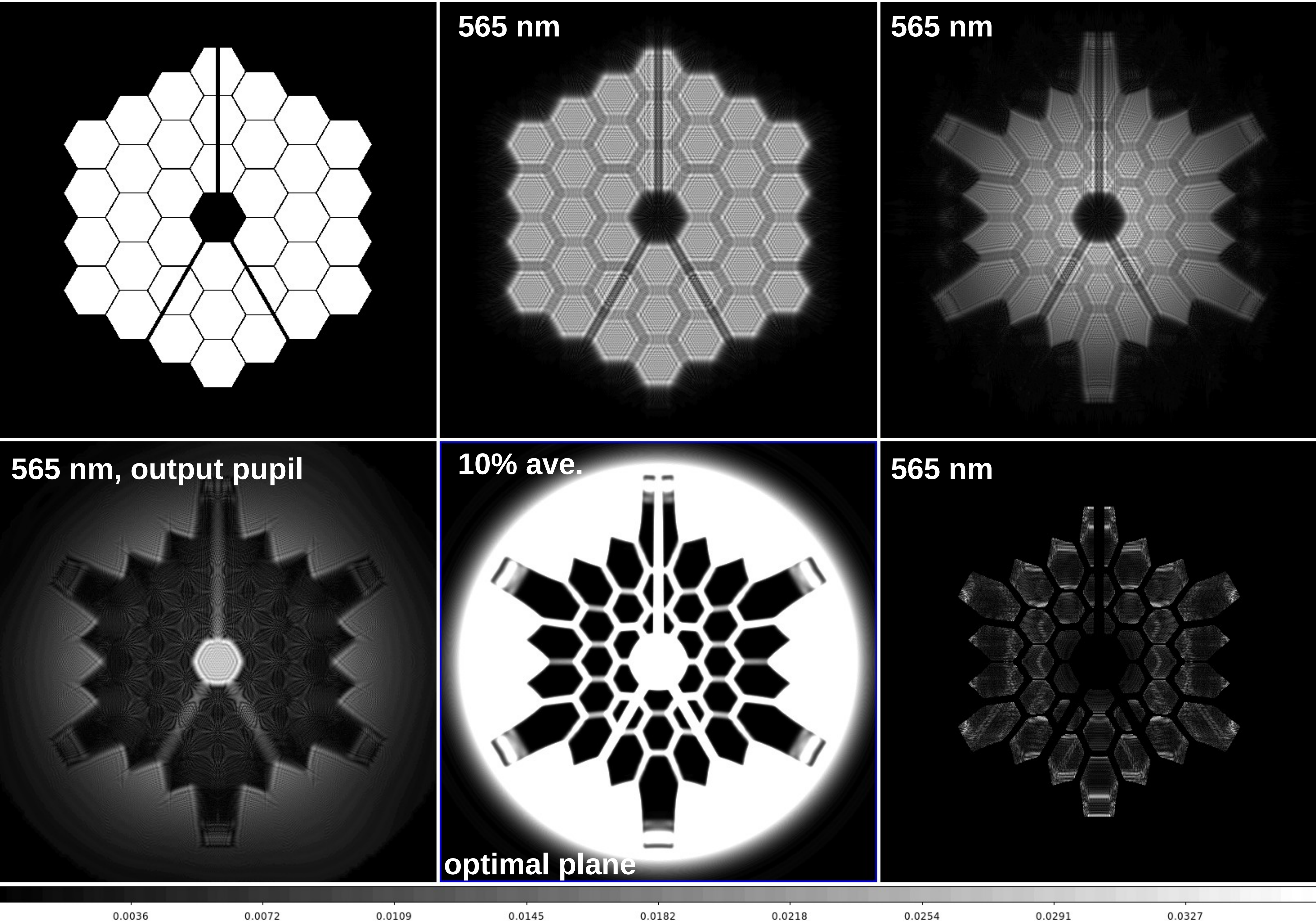
High perf. near IWA for point source, but very sensitive to stellar angular size

- 1.0 l/D IWA
- 70% throughput
- Single Lyot stop (Performance improves with >1 Lyot stop)
- No invPIAA (simpler)

Optimized for:
- 10% band centered at 565nm
- point source
- Optics diam = 2x beam size

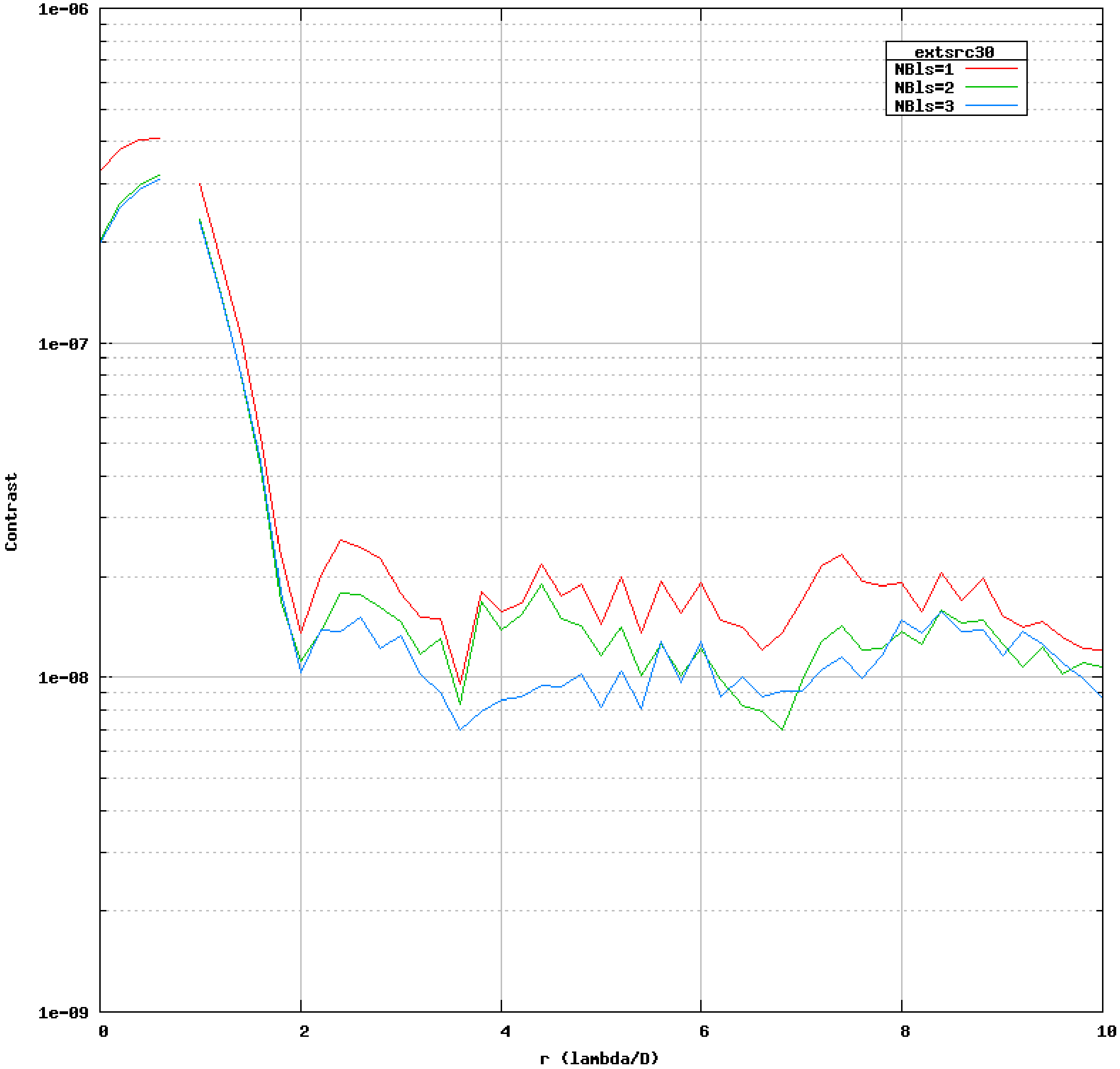
Focal plane mask:
- 0.9 l/D nominal size
- 32 rings, 3.6 l/D outer zone






*Brightness scale is different between images*

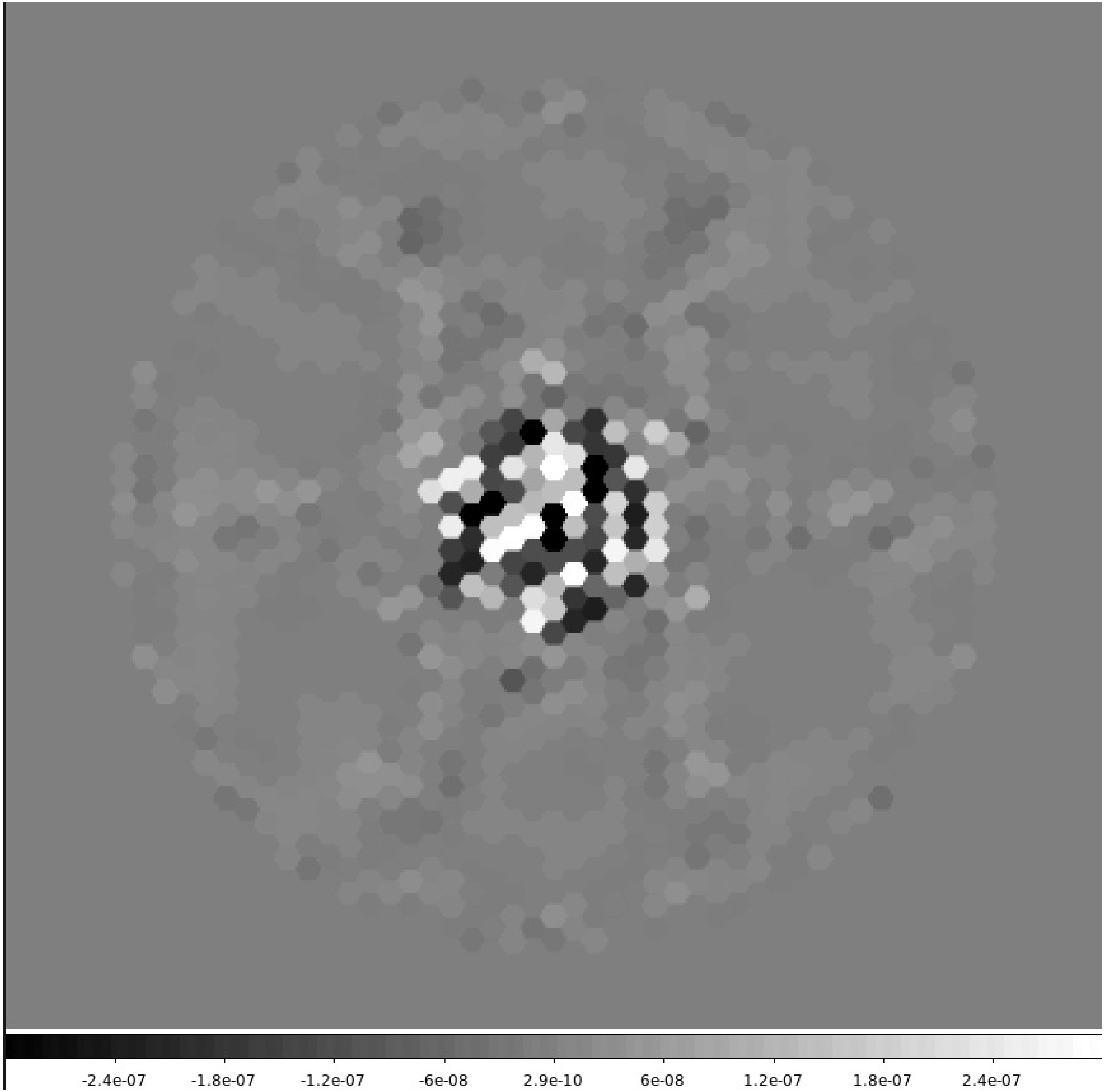
# Multiple Lyot Stops help



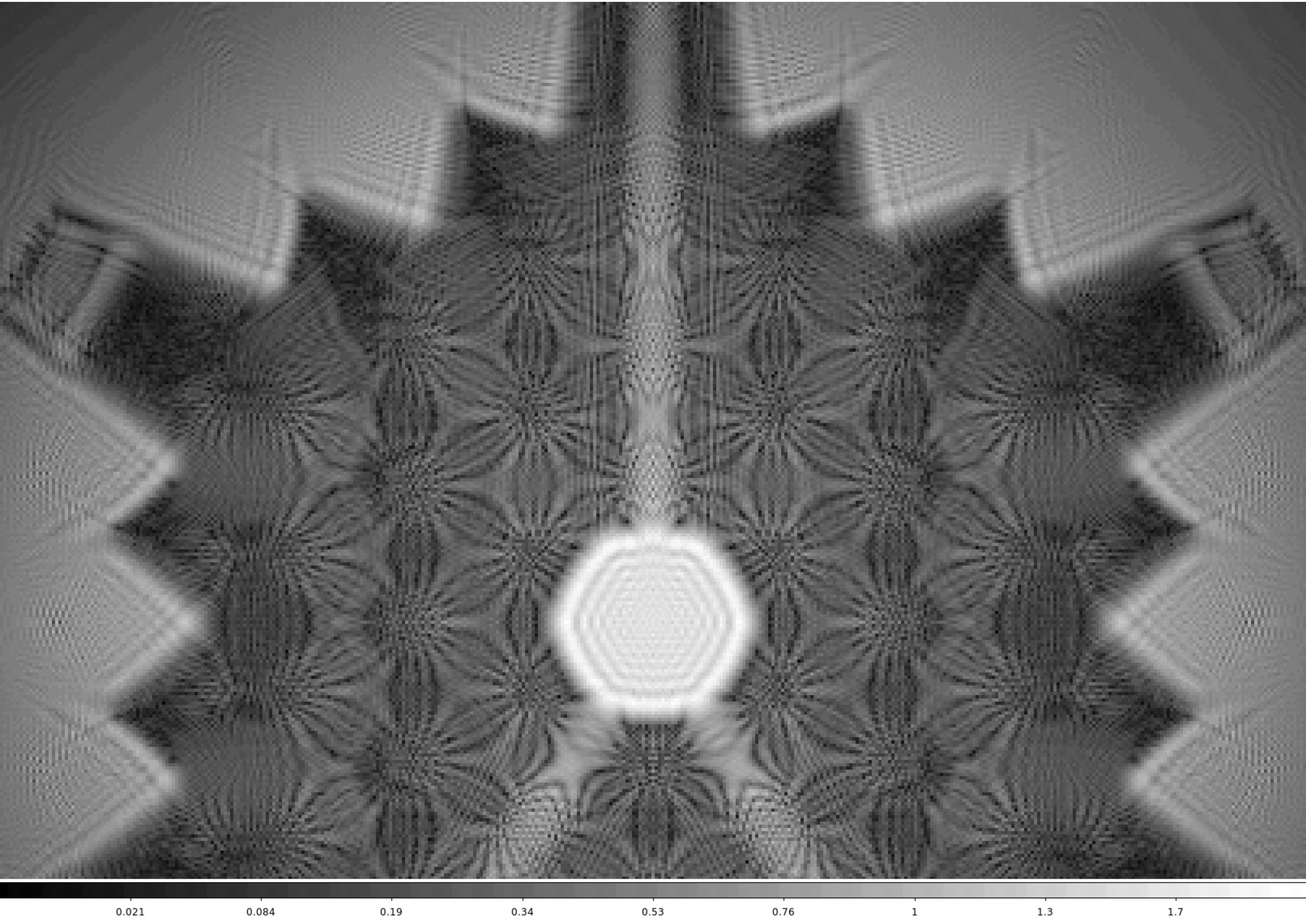
# Focal plane mask design (mirror)

Sag +/- 600nm

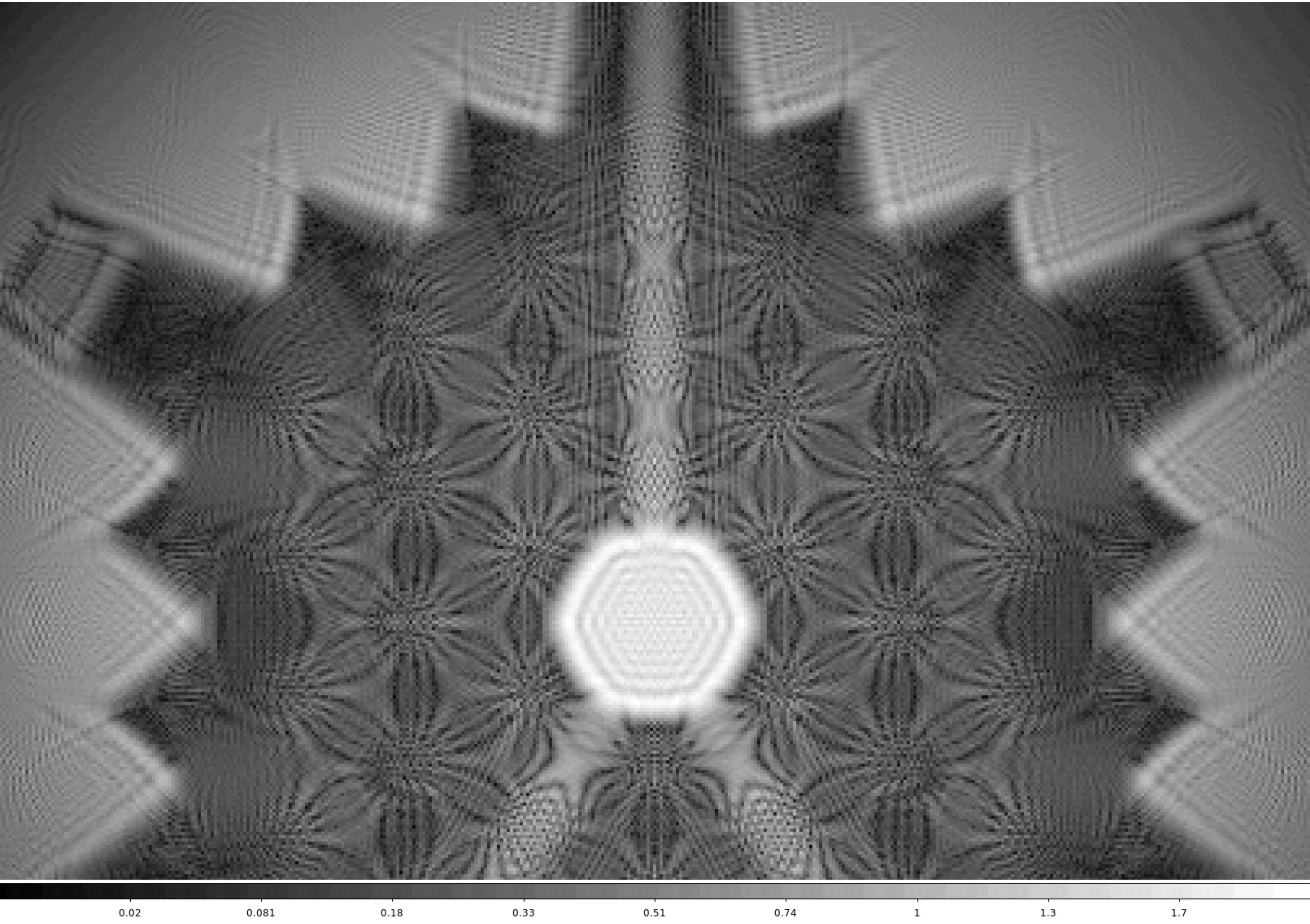
Little sag outside 1 l/D



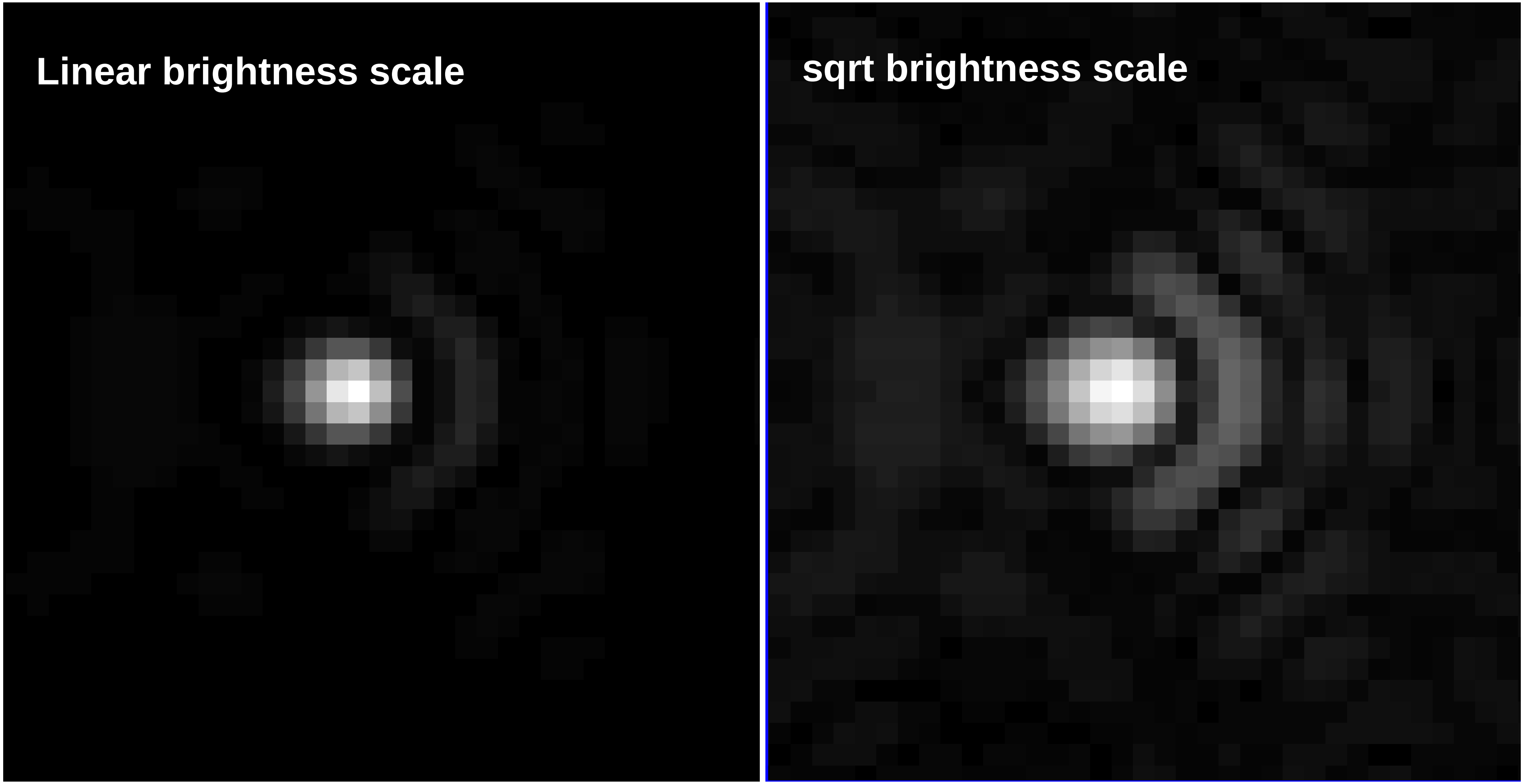
# 540 nm – diffraction effects due to segments, beam truncation, PIAA



# 590 nm – diffraction effects due to segments, beam truncation, PIAA



# Off-axis image quality @ 5 l/D (contrast reference)



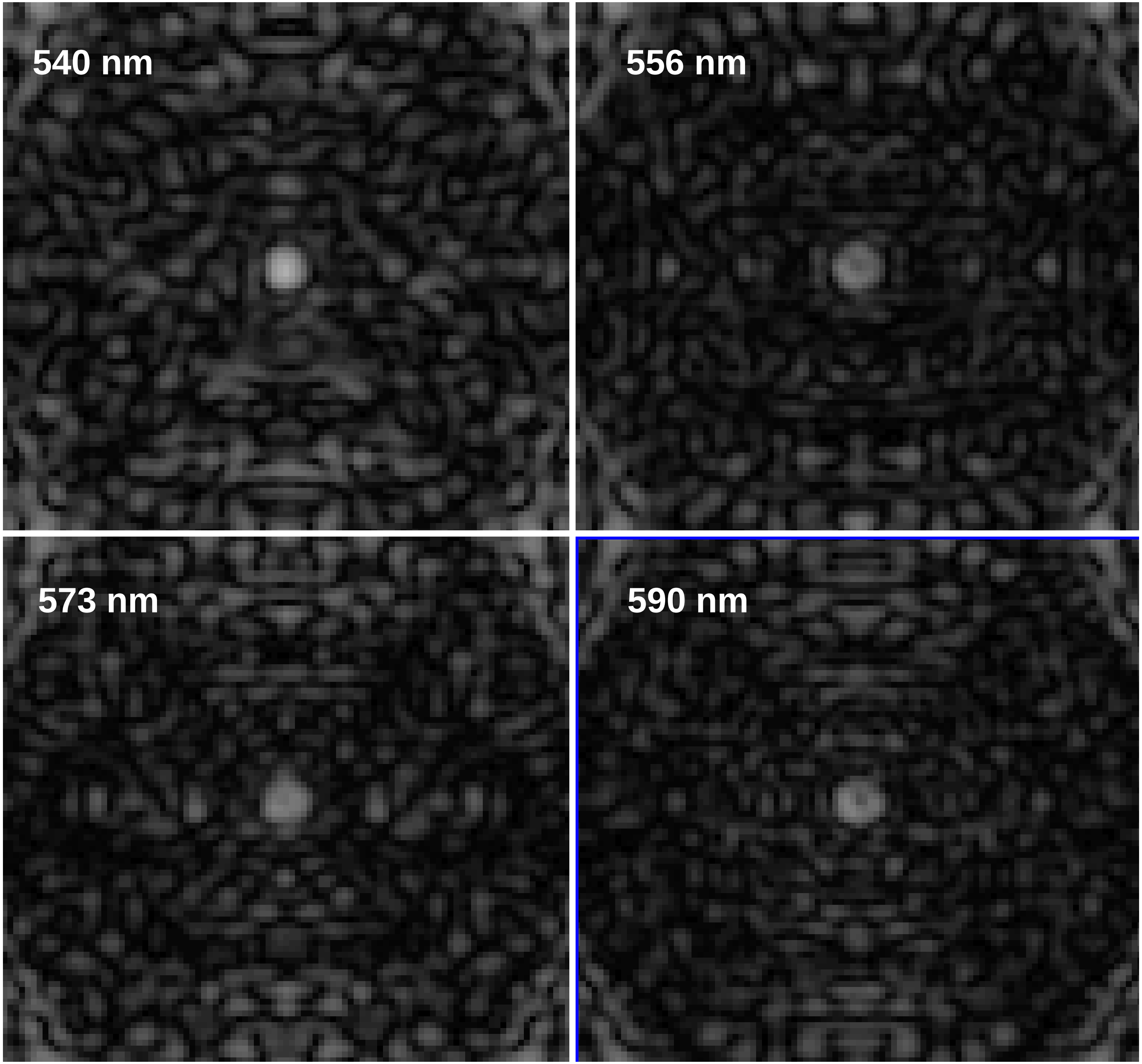

Off-axis PSF has similar core throughput to full aperture nominal PSF
Fainter Airy ring (thanks to apodization), but some off-axis coma

High contrast PSF is strongly chromatic

- Effect of numerical sampling to be evaluated

- Wavefront control is unlikely to have significant leverage on chromatic residual

→ need to adopt finer sampling (more computing time)



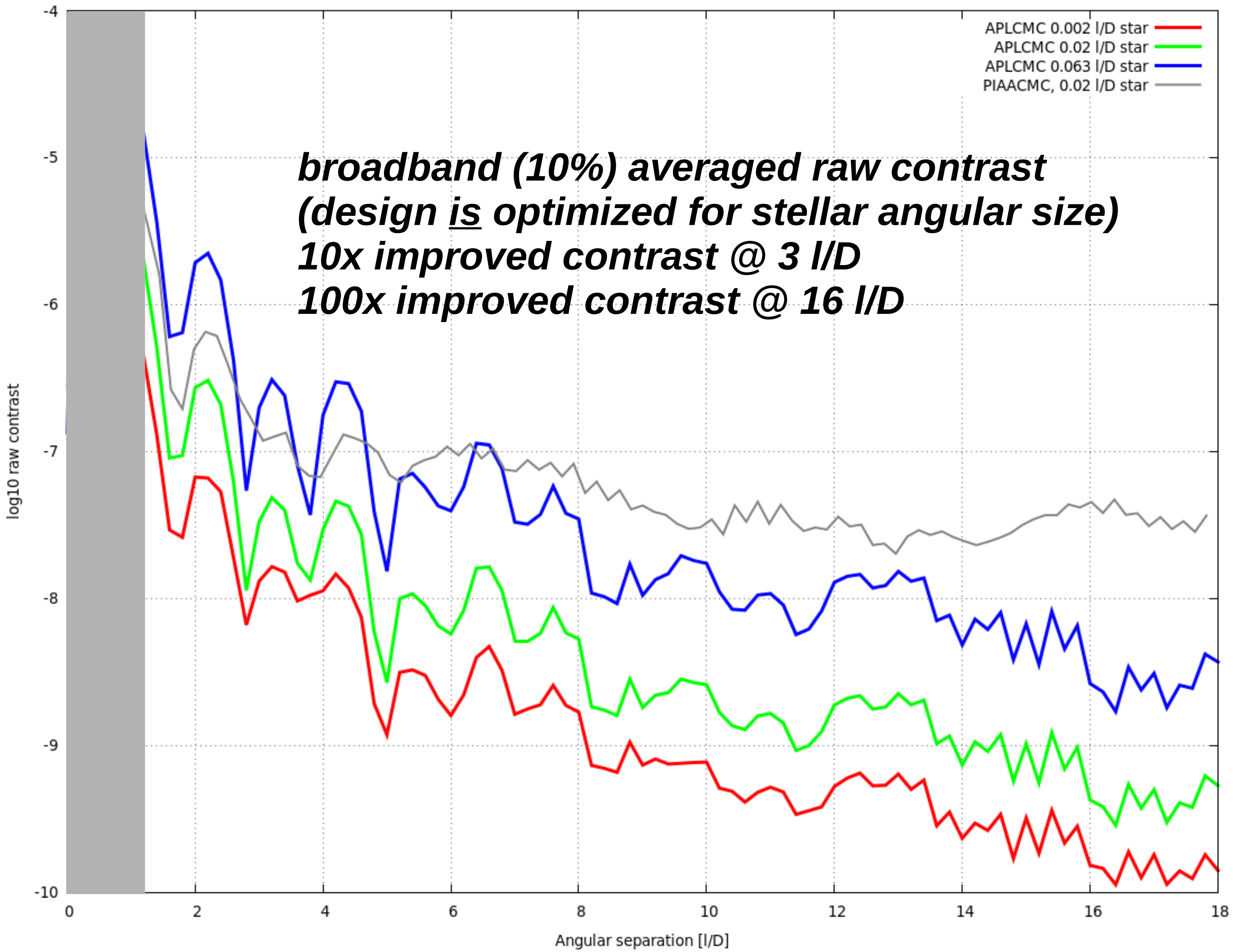
# Design #2: APLCMC, 3-ring SCDA aperture

Lower throughput, improved sensitivity to stellar angular size

- ~1.1 l/D IWA
- 46% throughput (**pupil apodizer**)
- Single Lyot stop

Optimized for:
- 10% band centered at 565nm
- **0.02 l/D source**
- Optics diam = 2x beam size

Focal plane mask:
- 1.0 l/D nominal size
- 32 rings, 4.0 l/D outer zone



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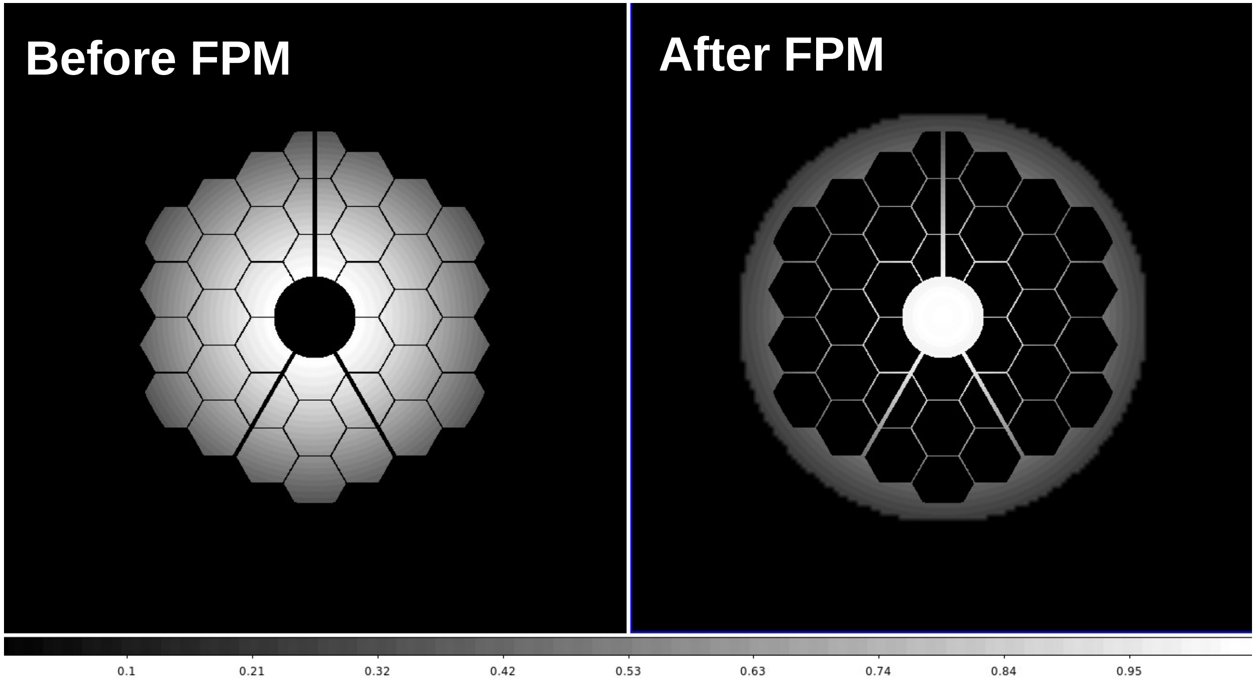


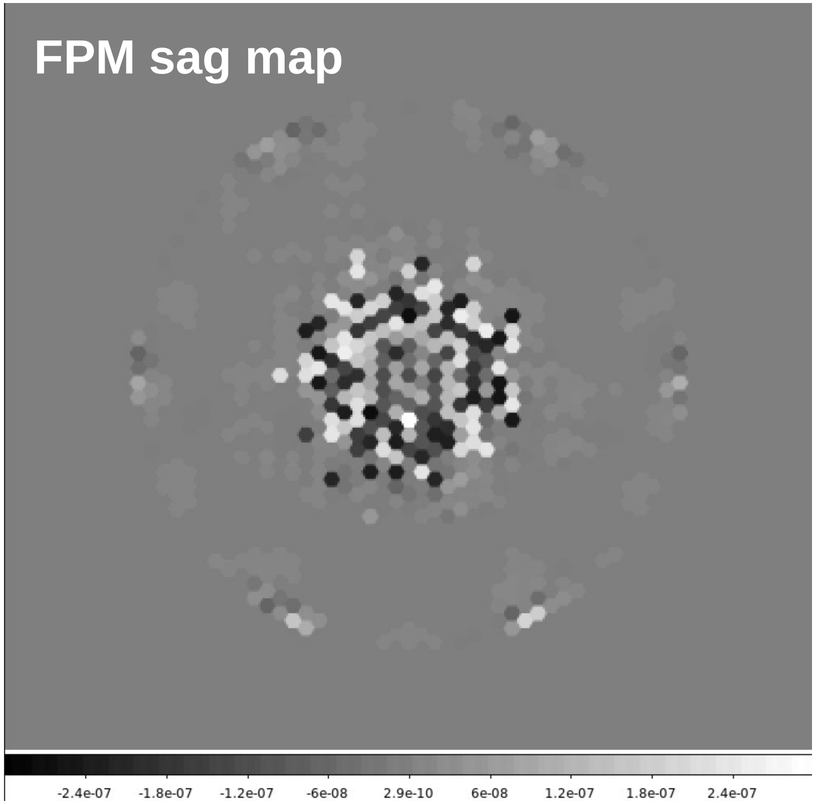


**Warnings:**

- **This design was not simulated using truncated optics in intermediate planes (uses Fourier transforms, not actual physical propagations)**
  **→ Does not fully capture segment edge diffraction effects in realistic optical design**
- **Ideal apodizer assumed (how to manufacture it ? Binary mask ?)**

# Preparing for lab demo:
# Exploring FPM manufacturing options @ UofA

UA Link Award → A small graduate-led (J. Knight) team will generate pilot data for coronagraph mask manufacturing efforts during the 2016-2017 academic year

Major Tasks:

Manufacture coronagraph focal plane masks
Focus on in-house capabilities:  binary etching e-beam lithography into Si with a mask-aligner (MA6)
Testability: Subaru telescope, etching into Si wafer; master silicone mold-to-UV epoxy → AR coatings are important for multi-wavelength performance!
Draw from previous/current device manufacturing efforts, e.g. JPL MDL Gen 3 PIAACMC, SNF achromatic PIAACMC FPMs (K. Newman), Subaru masks at Cornell

Survey local and national manufacturing capabilities
Create a database of nanofabrication facility processes/tools geared toward FPM creation
Establish collaborative relationships with coronagraph research groups around the world – here's what *we* do, what do *you* do? How can we help?

There are multiple ways to make masks already, yet the space of manufacturing is relatively unexplored such that a "best" process has been developed, esp. for PIAACMC masks. While there is a path forward from design to manufacturing of these devices, we have the flexibility to take different approaches presently.

# Conclusions & Next Steps

Demonstrated PIAACMC design on segmented aperture in realistic optical system, 10% band
Achieves ~1.0 l/D IWA, 70% throughput
Contrast floor at 1e-8 may be due to sampling effects (under investigation)
Contrast limited by stellar angular size
→ **PIAACMC can deliver low IWA + high throughput, but sensitivity to stellar angular size increases as IWA decreases**
**Implementation is compatible with realistic optical design and manufacturing capabilities**

**PIAACMC unlikely to have strong aperture geometry preference (will confirm by running designs on all apertures)**

Demonstrated that hybridization with APLC and focal plane mask optimization can mitigate sensitivity to stellar angular size
→ **Encouraging step toward coronagraph solution offering simultaneously small IWA and maintains deep contrast at larger separations**

**Next steps:**
- Simulate less aggressive PIAACMC (larger IWA)
- Investigate sampling effects
- Include wavefront control
- Explore Hybrids
- Code improvements, validation and verifications → run batch scans on Ames HyperWall
- Compare results with fundamental limits