Progress in Shaped Pupil Design for AFTA

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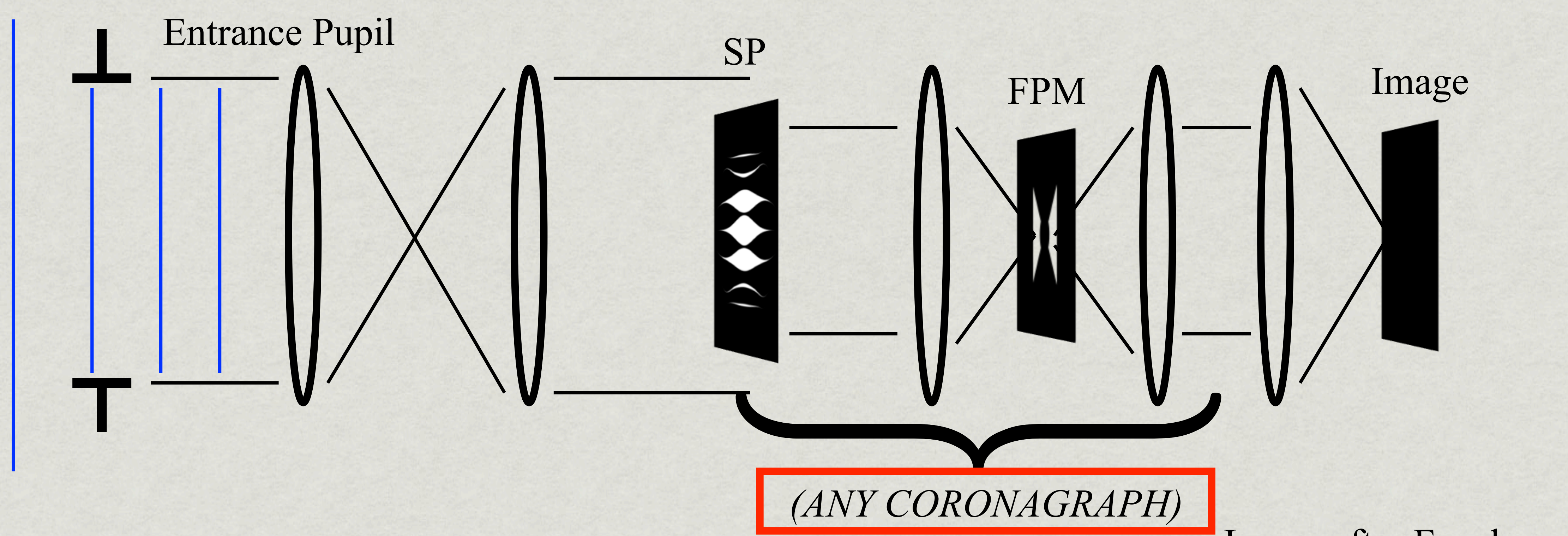
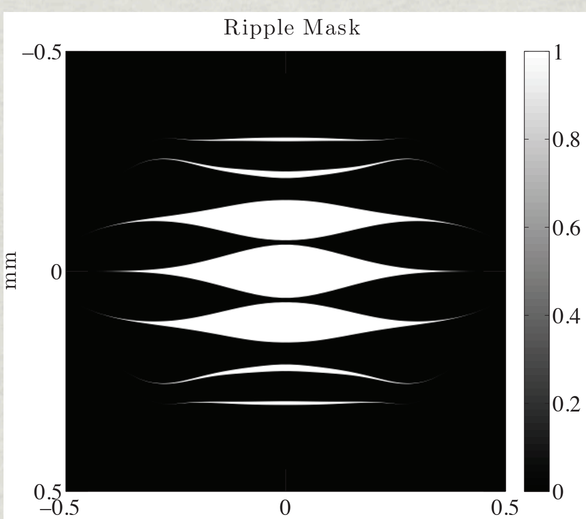
ACWG 2
September 25-27, 2013

Reminder - Shaped Pupils for High-Contrast

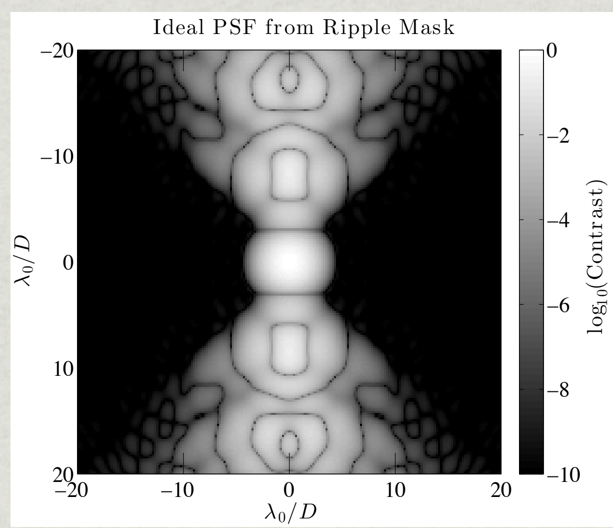


Shaped Pupil Coronagraph



Transmission: 15%

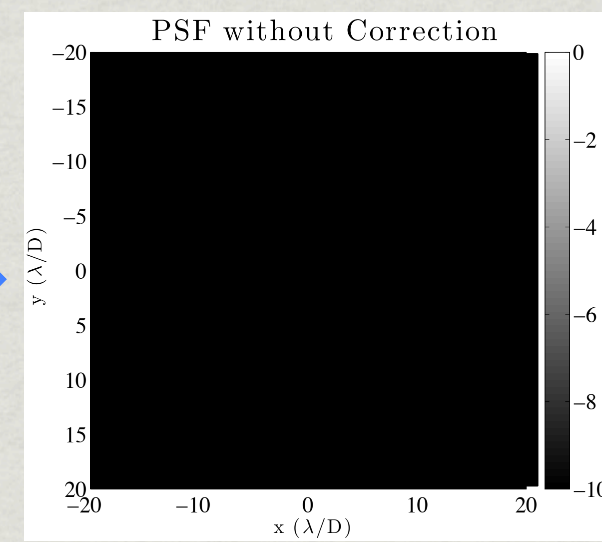
Ideal Image (Log Scale)



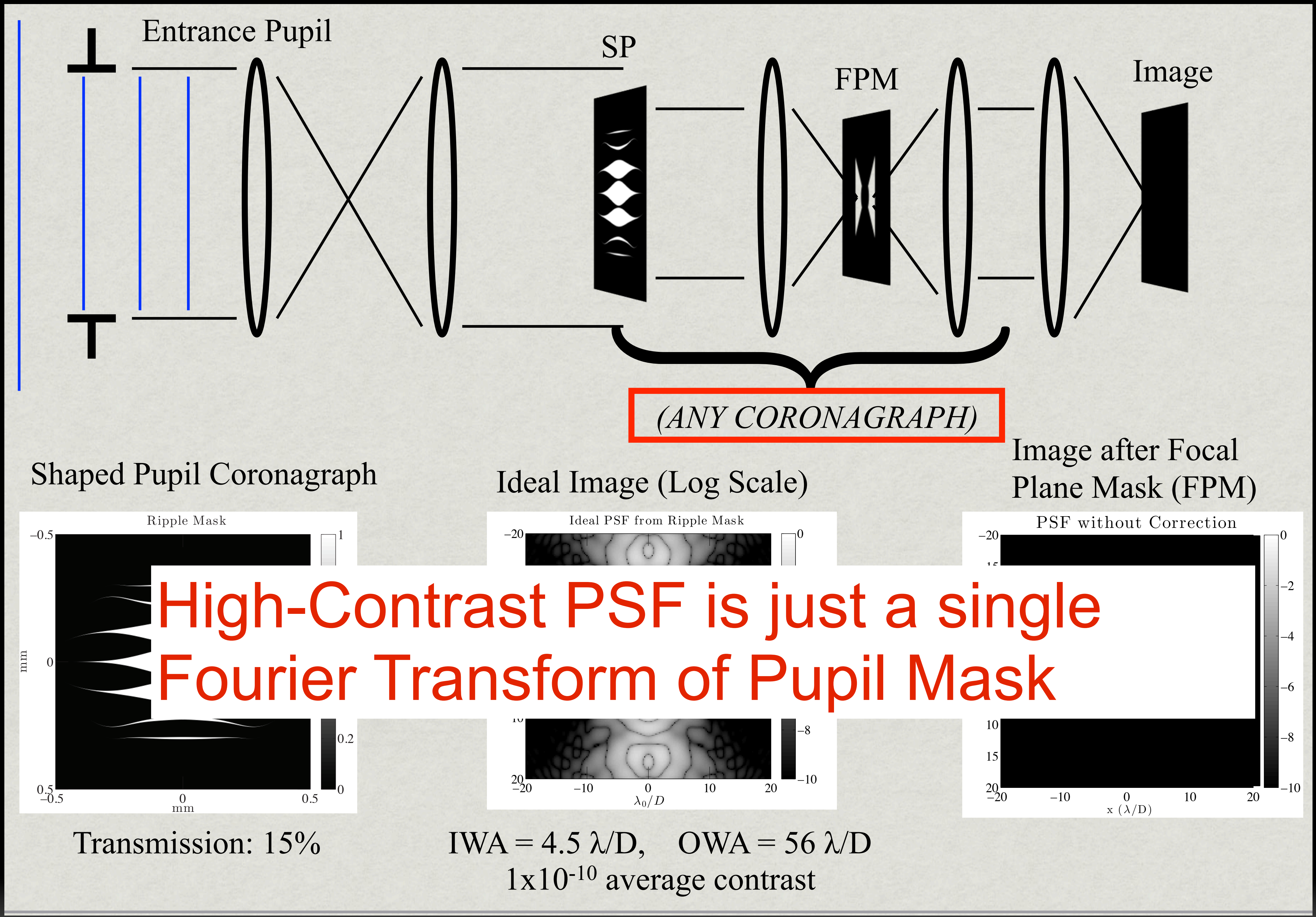
IWA = 4.5 λ/D, OWA = 56 λ/D

1×10^{-10} average contrast

Image after Focal Plane Mask (FPM)



Reminder - Shaped Pupils for High-Contrast

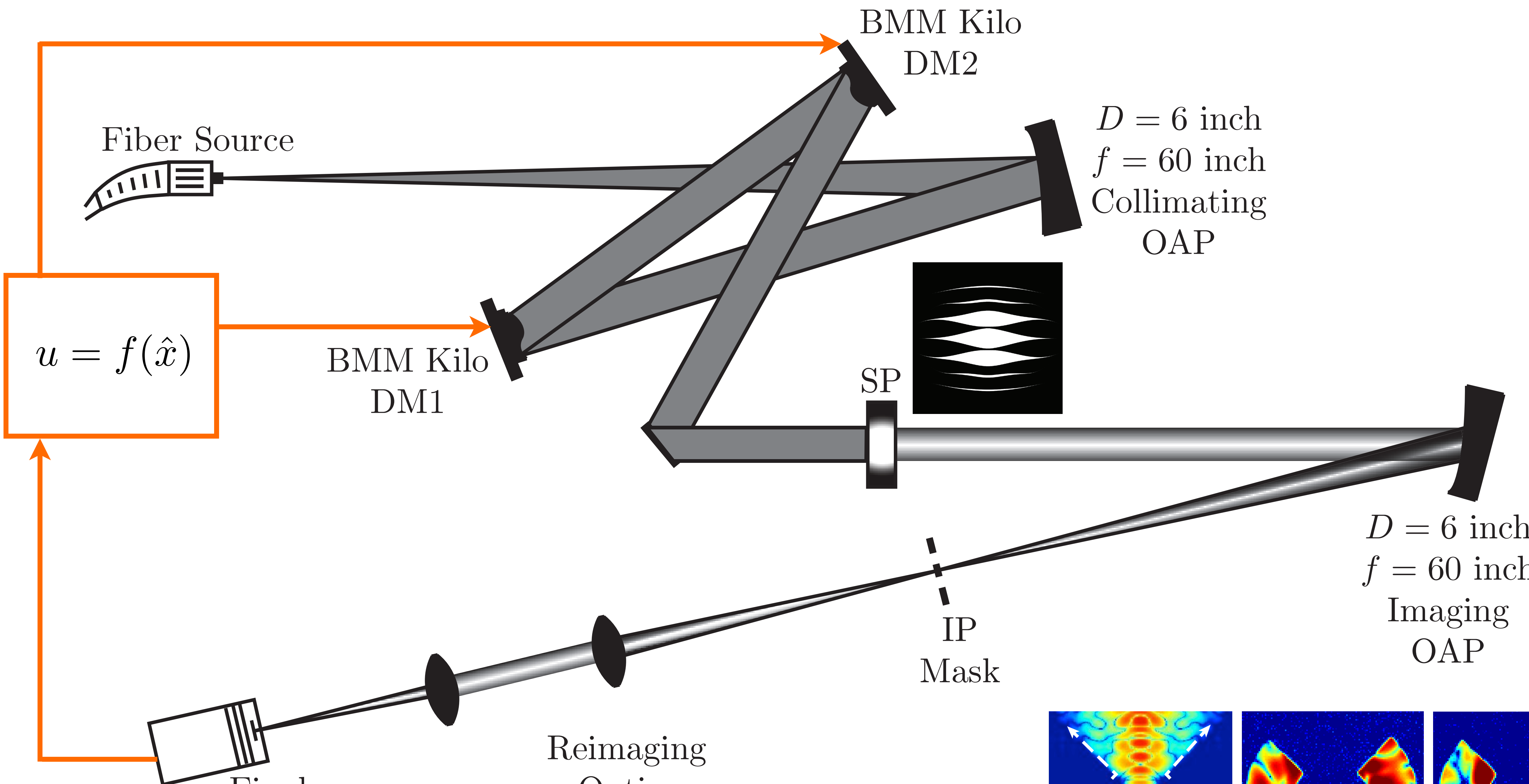


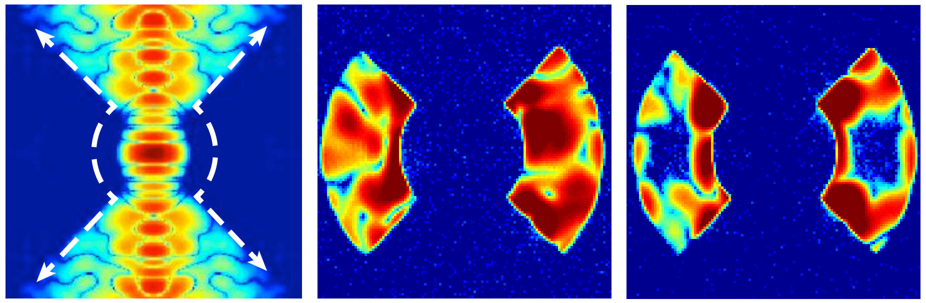
Wednesday, September 25, 13

Some initial thoughts

- High-contrast achieved by entire instrument, not just mask
- Instrument includes deformable mirrors, other stops, filters, mechanisms, IFS, camera, LOWFS, etc.
- Except for VNC, current configuration is common to all coronagraphs
- Ability to detect planets is a function of instrument and operational scenarios. Total package should be considered the “coronagraph”.
- I encourage a holistic view and that we consider multiple approaches!

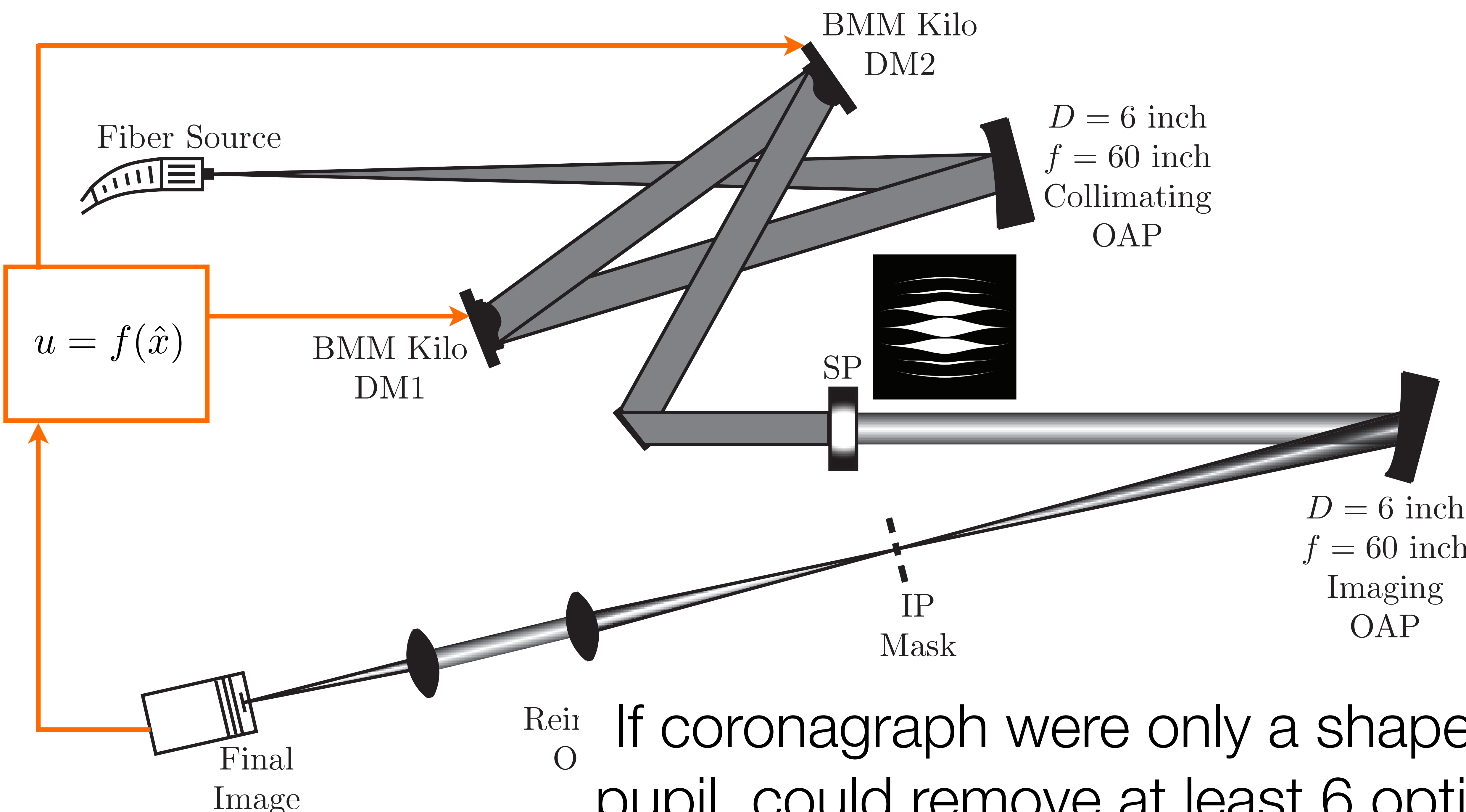
Minimal Optical Design





Two DMs gives symmetric dark holes
(Amplitude Correction)

Minimal Optical Design



If coronagraph were only a shaped pupil, could remove at least 6 optics and improve throughput by 20% or more.

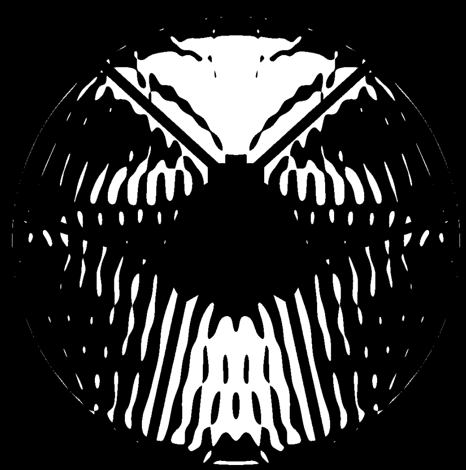
Current design approach

- Focus first on shaped pupil alone for high contrast.
  - Most robust and simple design
  - Achromatic (bandwidth defined by control and amplitude errors)
  - Design procedure mature and efficient
  - Minimum performance baseline
- Confirm performance in broadband
- Design multiple masks consistent with observing scenario
- Next step is high performance hybrids combined with DMs

Note: Results still preliminary as we discovered an inconsistency in the pupil we were using and the one used by John Krist. Results likely to get worse (lower throughput).

2D optimal apodization

Shaped pupils for any aperture, achromatic.

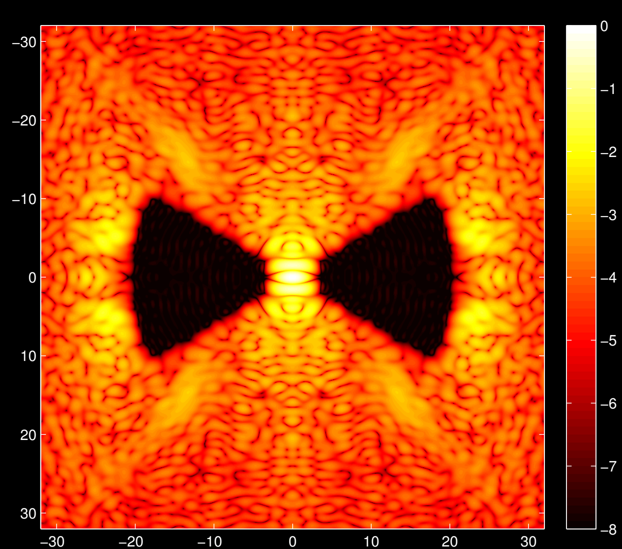


Transmission is maximized in linear optimization problem:

$$T = \sum_{i}^{N} \sum_{j}^{N} A_{i,j} dx dy$$

while PSF is constrained in dark holes:

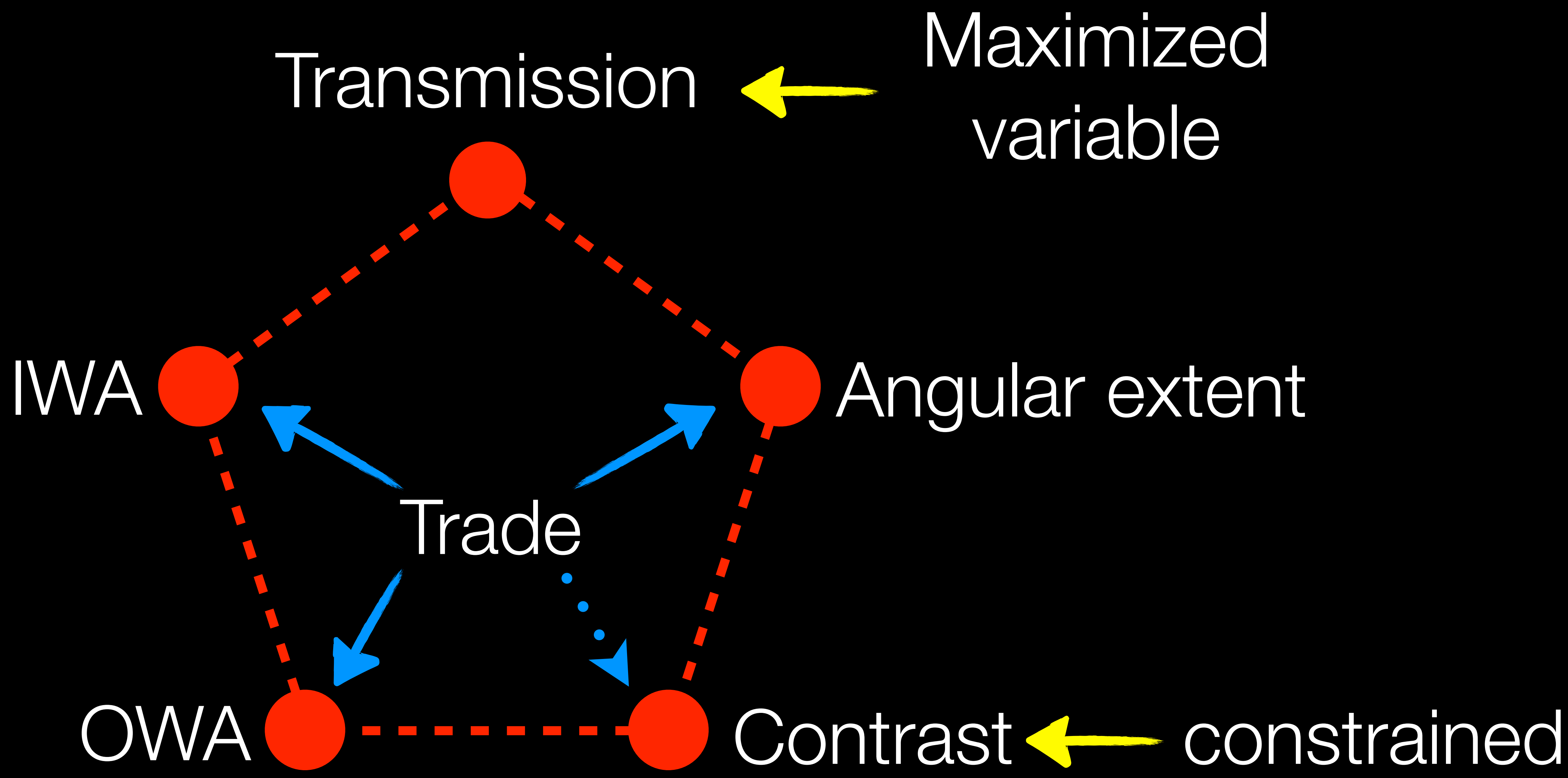
$$\begin{array}{ccccc} -10^{-c/2}\widehat{F}\{A\}(0,0) & \leq & \mathrm{Re}(\widehat{F}\{A\}(u,v)) & \leq & 10^{-c/2}\widehat{F}\{A\}(0,0) \\ -10^{-c/2}\widehat{F}\{A\}(0,0) & \leq & \mathrm{Im}(\widehat{F}\{A\}(u,v)) & \leq & 10^{-c/2}\widehat{F}\{A\}(0,0) \end{array}$$



Example for AFTA: 10^{-8} from 3.6 λ/D to 20 λ/D.

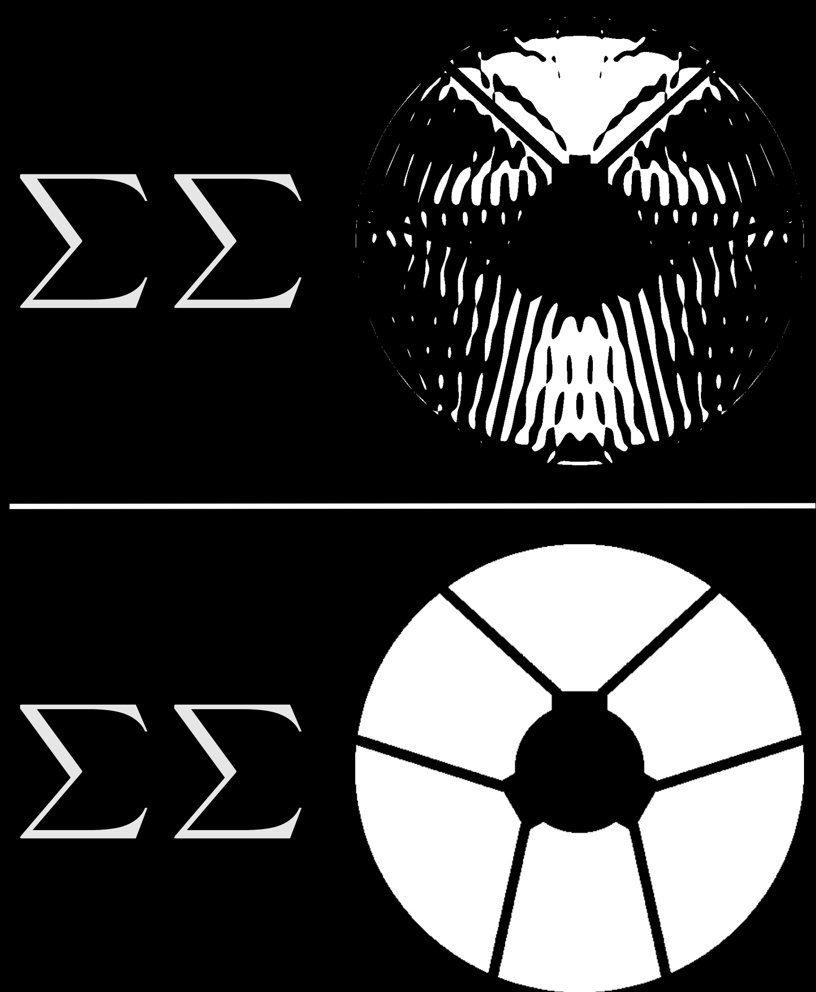
Carlotti et al. (2011); Vanderbei (2012)

Trade-offs

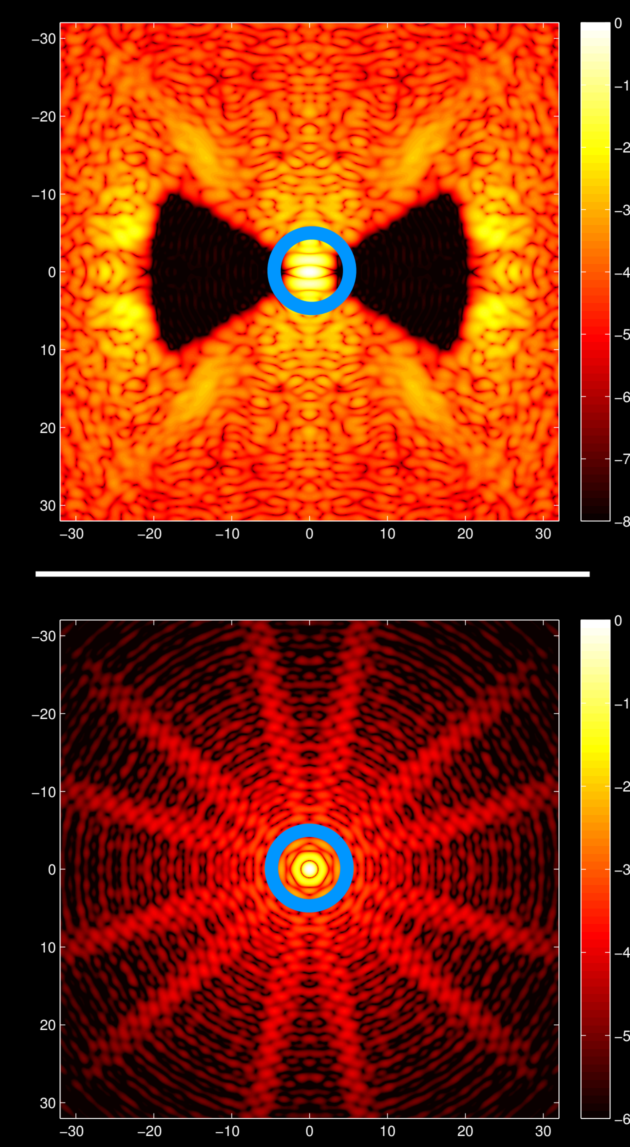


Effective throughput depends on 5 parameters

Transmission & Throughput

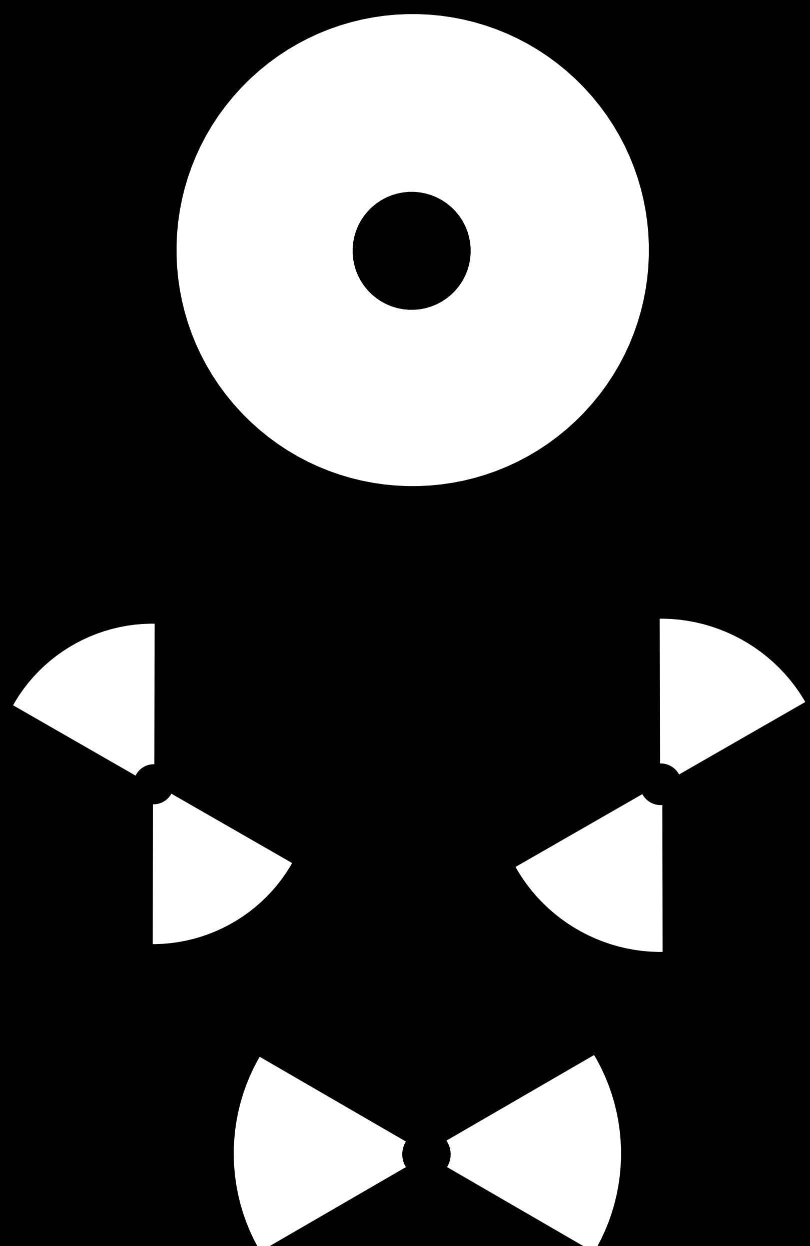


Ratio of light going through apodizer



Ratio of light inside IWA

Operational Scenario



60 deg holes exploit 120 deg pupil symmetry, but others are possible.
diagrams not to scale

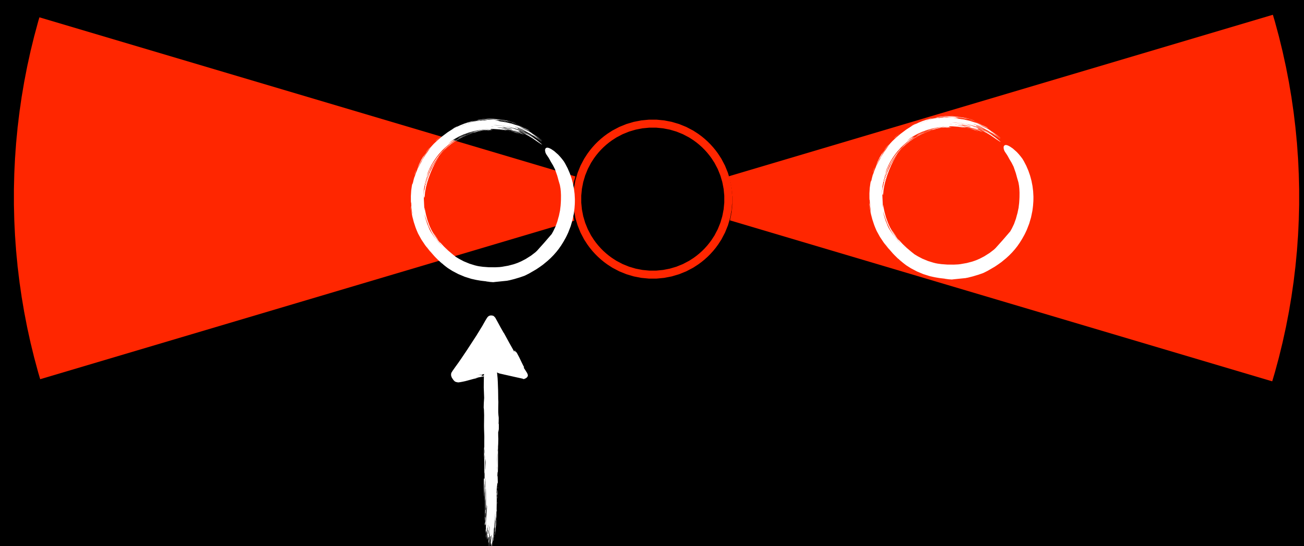
2 masks: outer & inner regions

Discovery mask with larger iwa to observe outer region over 360° at shorter wavelength.

Characterization mask(s) with smaller iwa to take spectra over broadband. Can be split into **subregions** for smaller IWA.

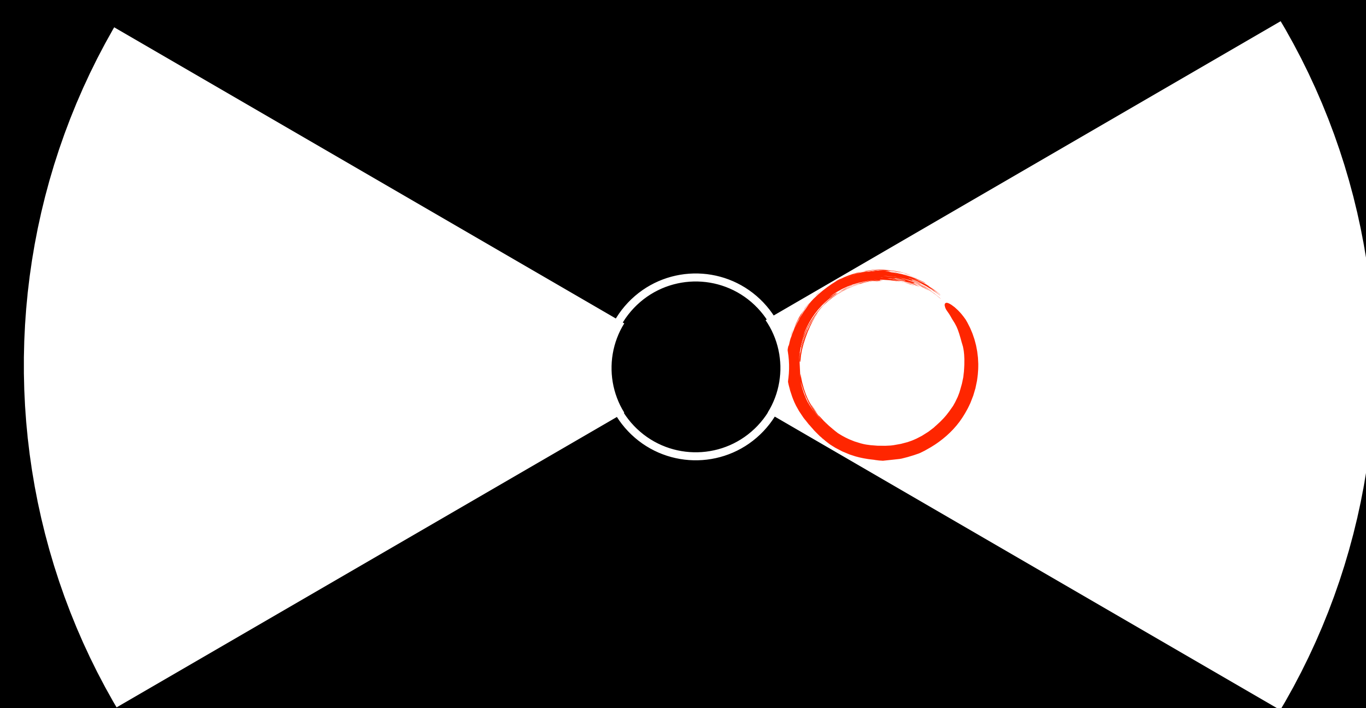
Note: some amount of telescope rotation may be required if planet falls on boundary, depending on final mask design.

60° > 30°

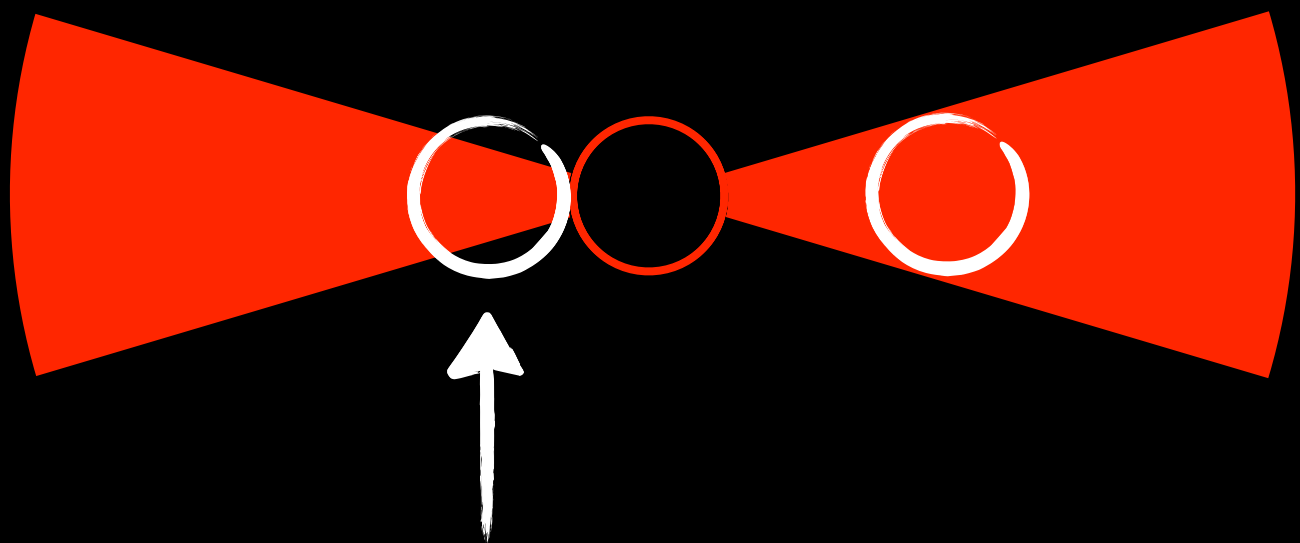


30° too small angular extent.
effective IWA > design IWA

60° good IWA / ang.
extent combination

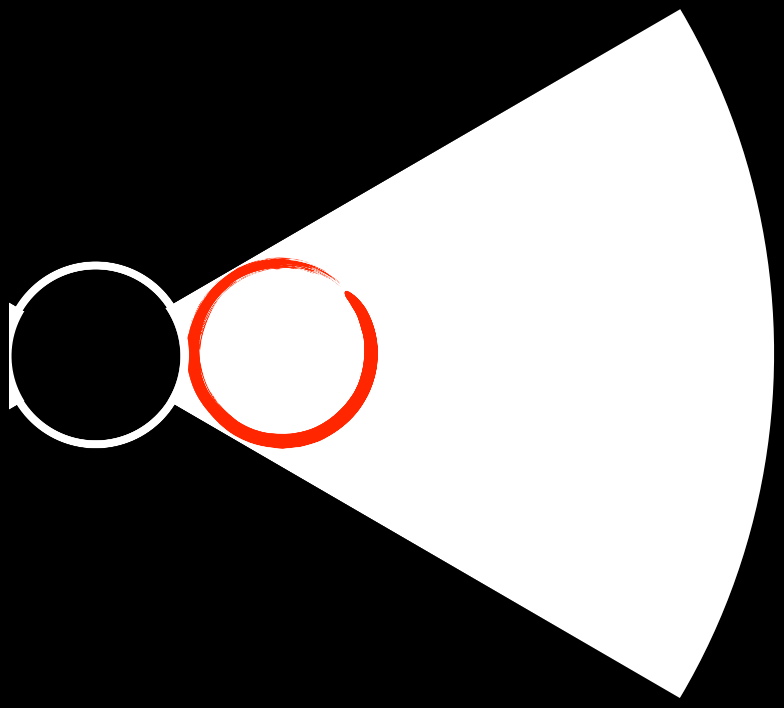


60º > 30º

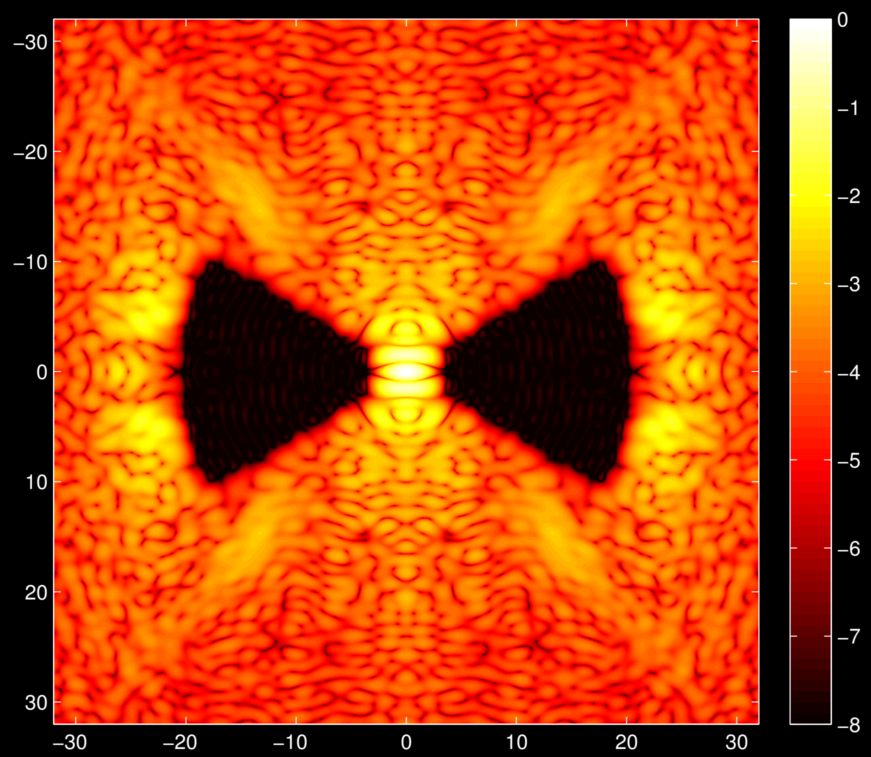


30º too small angular extent.
effective IWA > design IWA

In fact, single sided dark hole is sufficient for characterization. Can gain bandwidth.

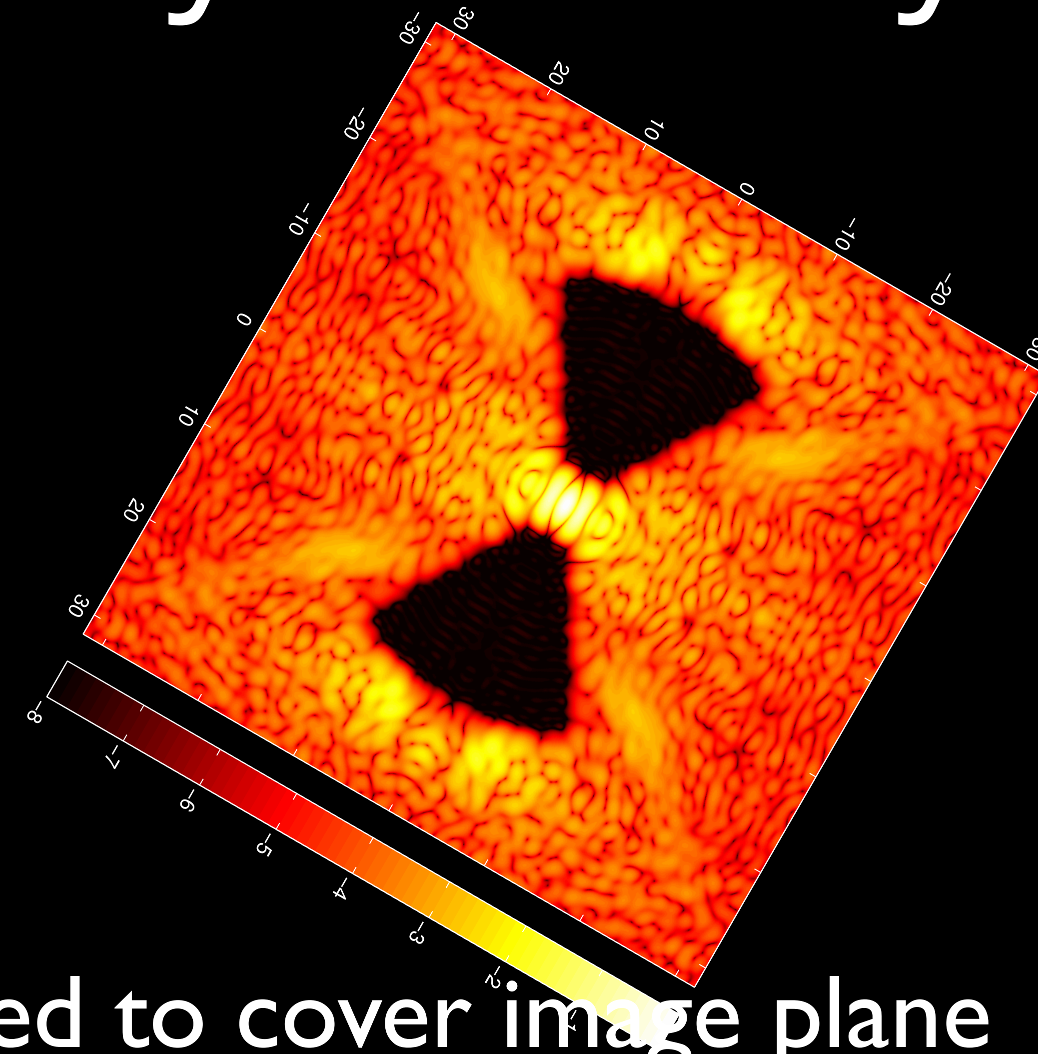


Using 3-fold symmetry



Symmetry is typically required to cover image plane without telescope rotation (using 3 masks) and speed up optimization.

Using 3-fold symmetry



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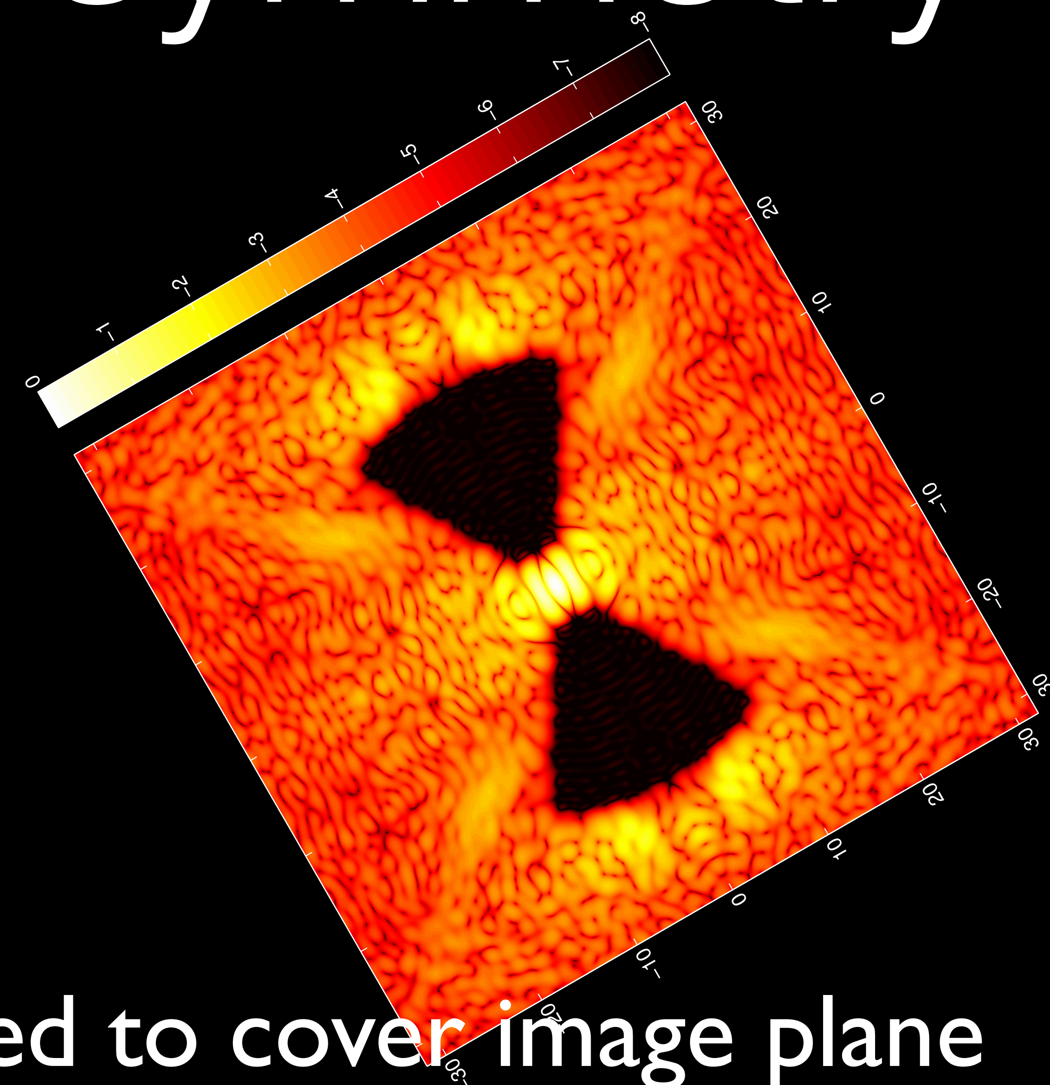

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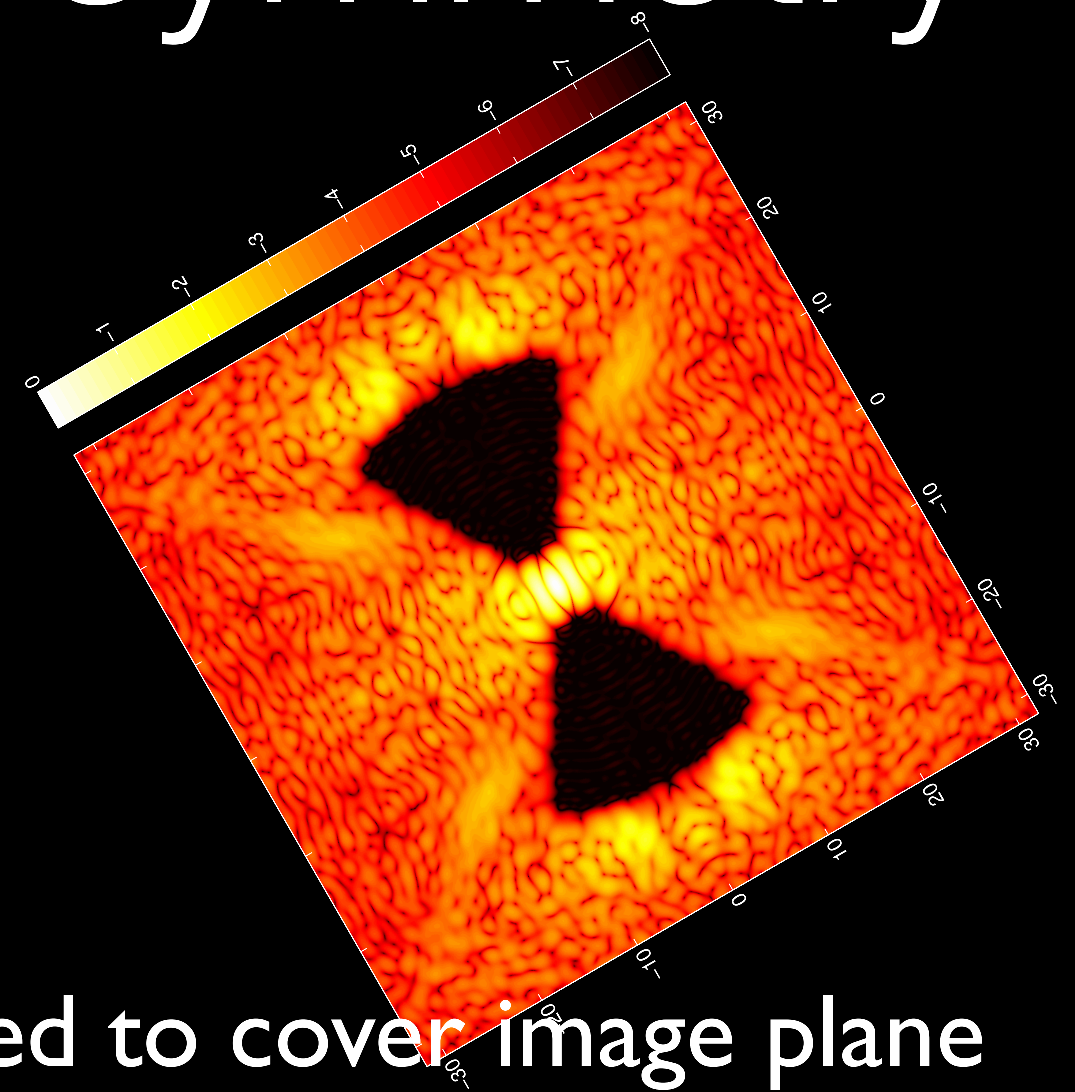
Using 3-fold symmetry

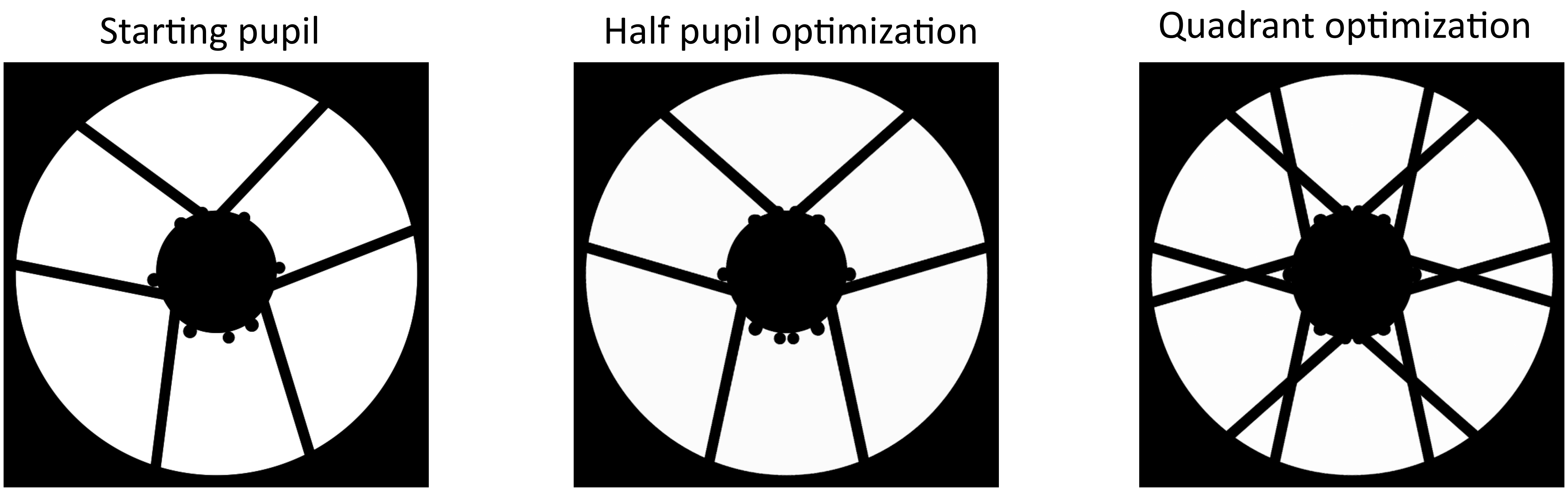


Symmetry is typically required to cover image plane without telescope rotation (using 3 masks) and speed up optimization.

We typically force symmetry through reflection or rotation. The result is a loss in throughput and iwa (spider thickness increases)

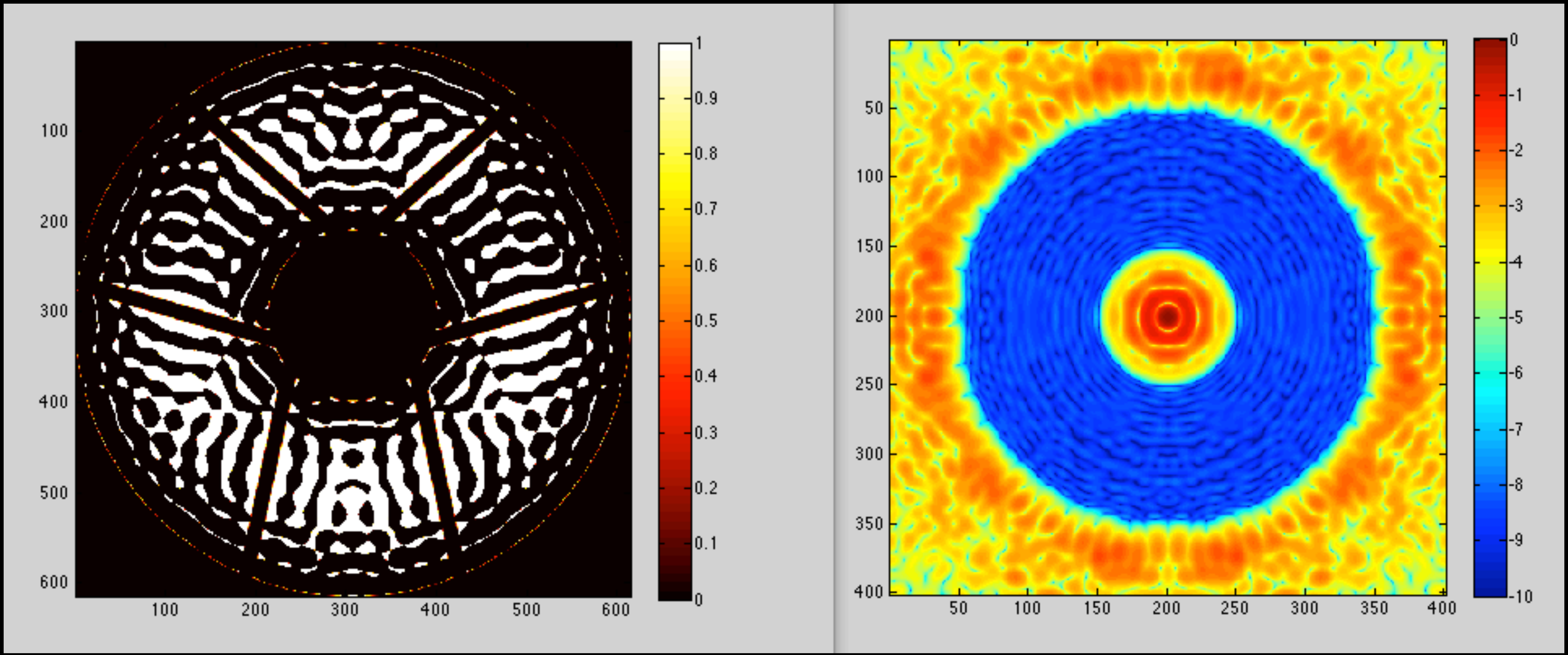
Symmetrization

- Each line of symmetry makes the optimization easier:
  - Exponential in FT reduces to: $e^{i2\pi x\xi} = \cos(2\pi x\xi)$
  - Half number of pixels in pupil and image plane
- Design for now using ¼ or ½ pupil. For final design use full or ½ pupil.



Using single quadrant of pupil and image allows > 500x speed improvement.

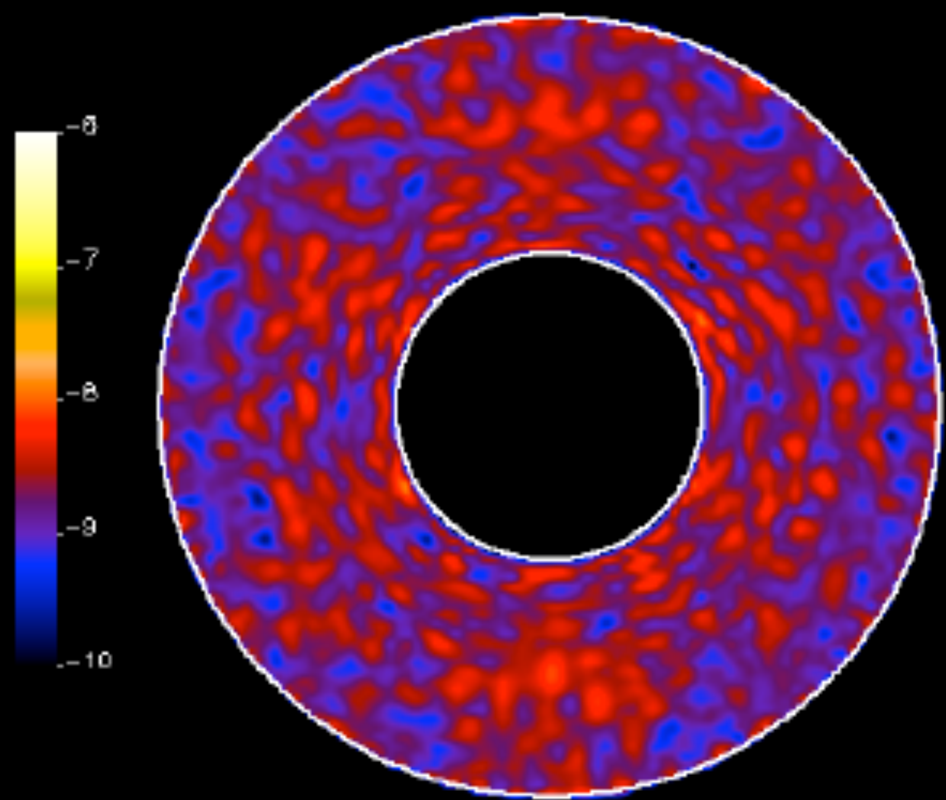
First Discovery Mask Design

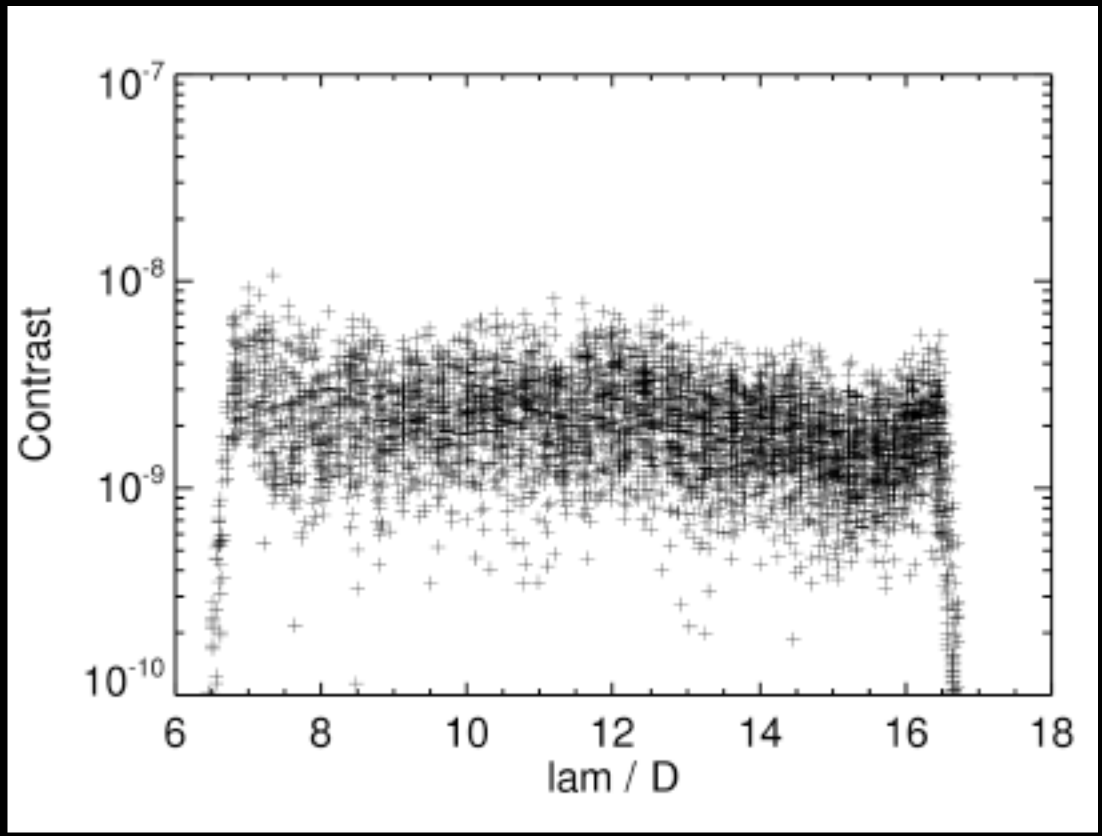


iwa: 6 lambda/D
owa: 17.5 lambda/D

Transmission: 27%
Mean Contrast: 3e-9

Preliminary Result from John after Control



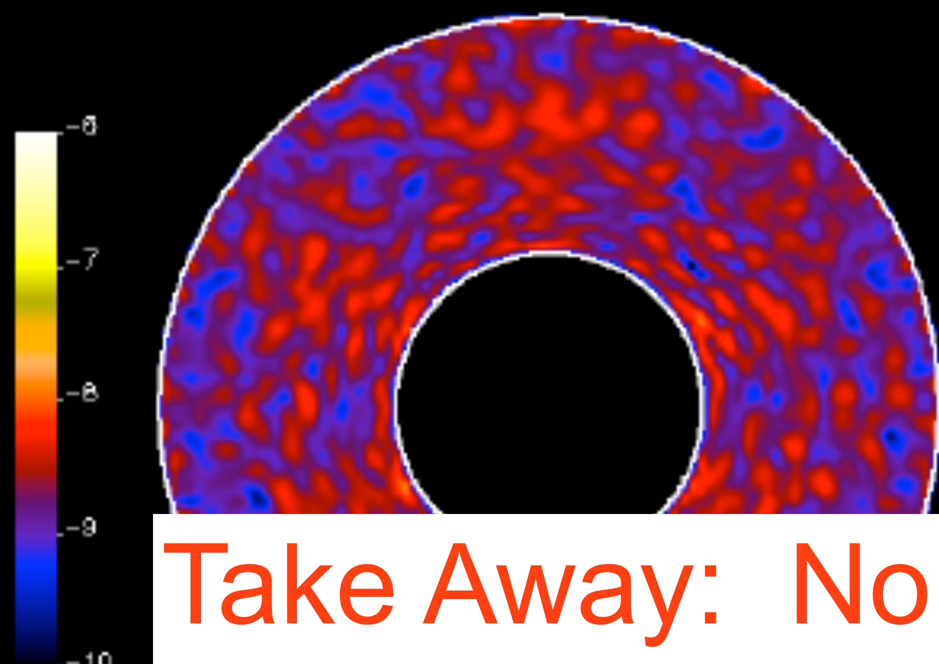


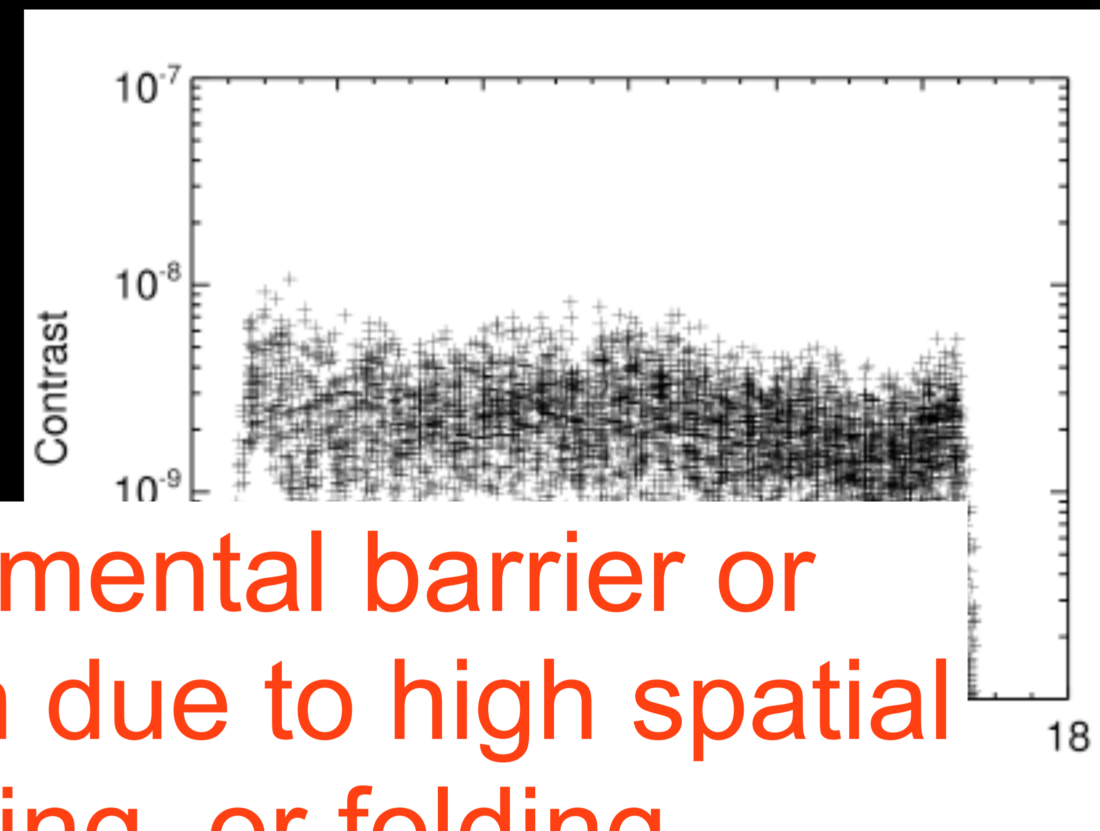
mean contrast = 2.2×10^{-9}
from 6.5 to 16.5 lambda/D

Bandpass = 522-578 nm

Caveat: The pupil had to be modified to match our sampling; “certified” pupil will likely reduce transmission and/or iwa. John will explain further in his talk.

Preliminary Result from John after Control





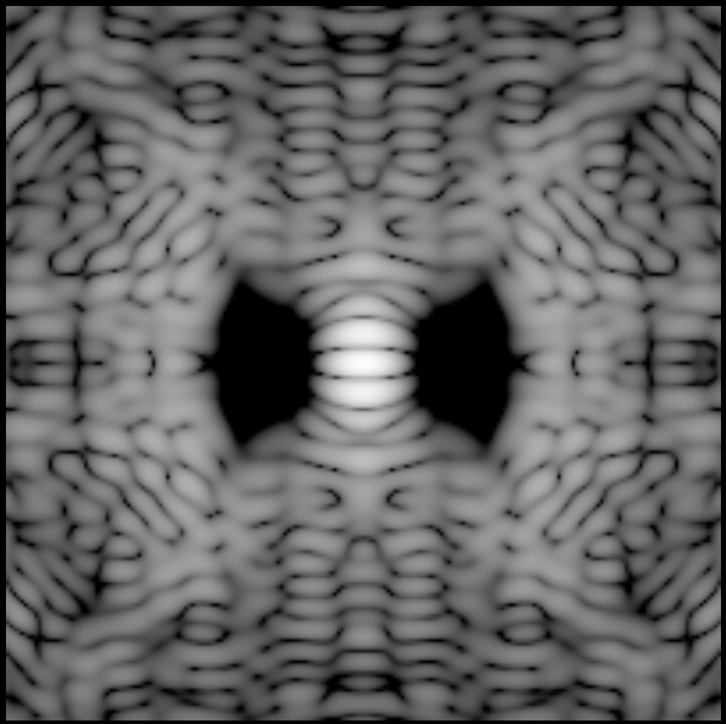
Take Away: No fundamental barrier or problems in correction due to high spatial frequency errors, quilting, or folding.

mean contrast = 2.2 x 10
from 6.5 to 16.5 lambda/D

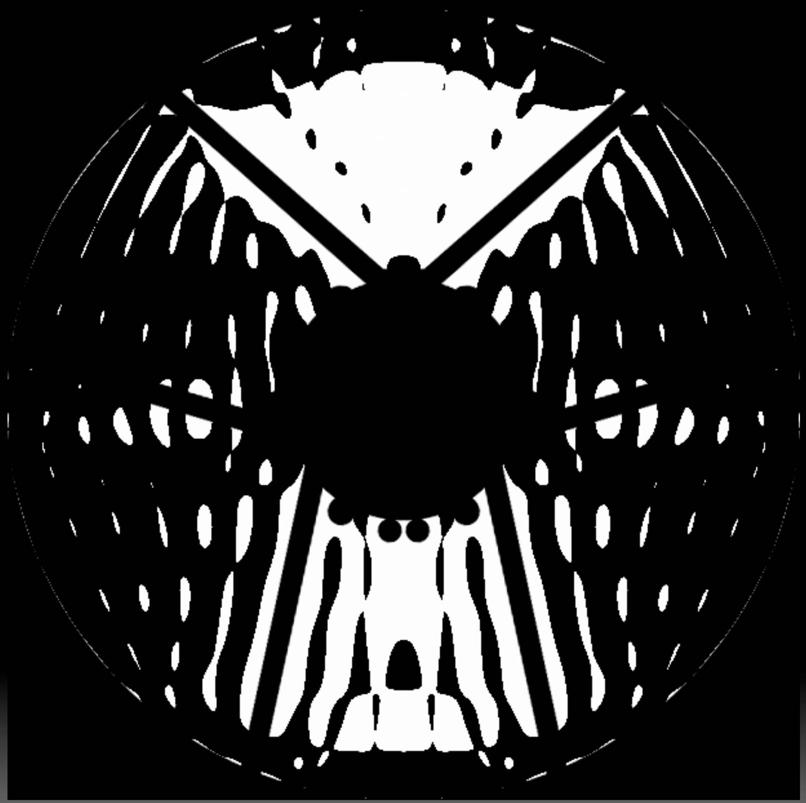
Bandpass = 522-578 nm

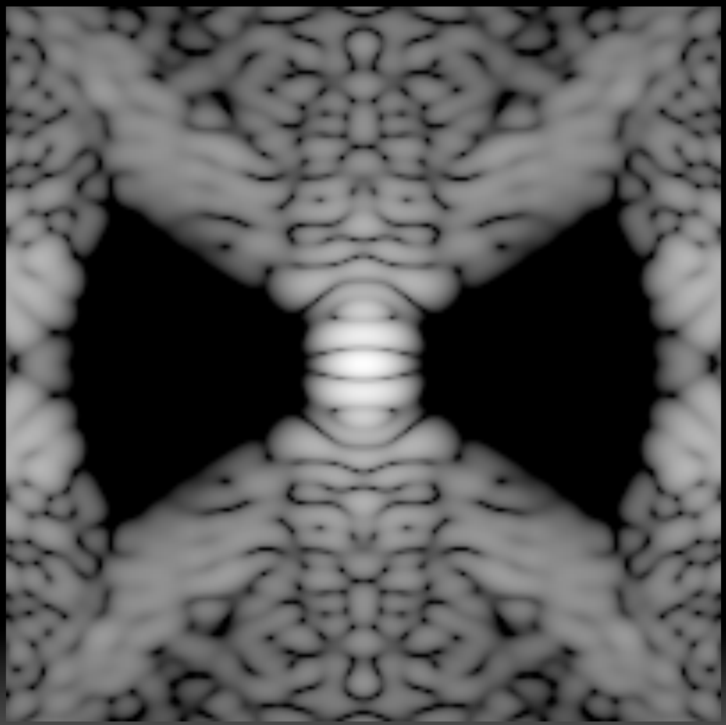
Caveat: The pupil had to be modified to match our sampling; “certified” pupil will likely reduce transmission and/or iwa. John will explain further in his talk.

Initial Characterization Mask Designs



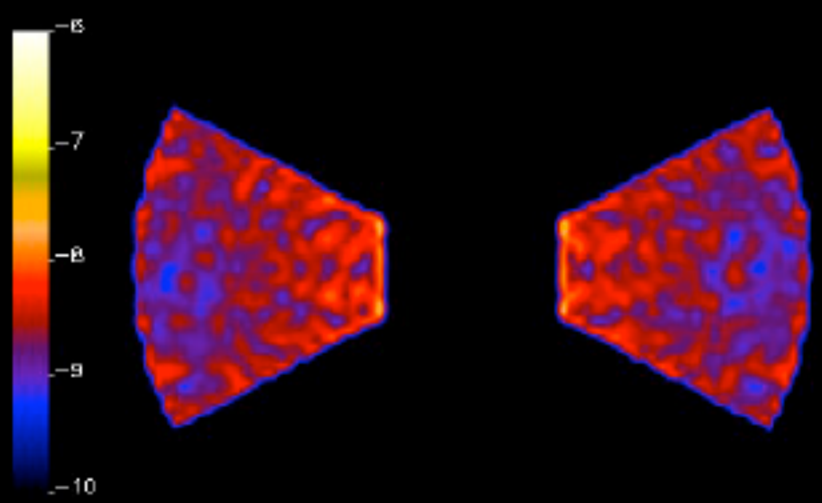
iwa: 3.5
owa: 8
contrast: 5e-9
Transmission: 32%

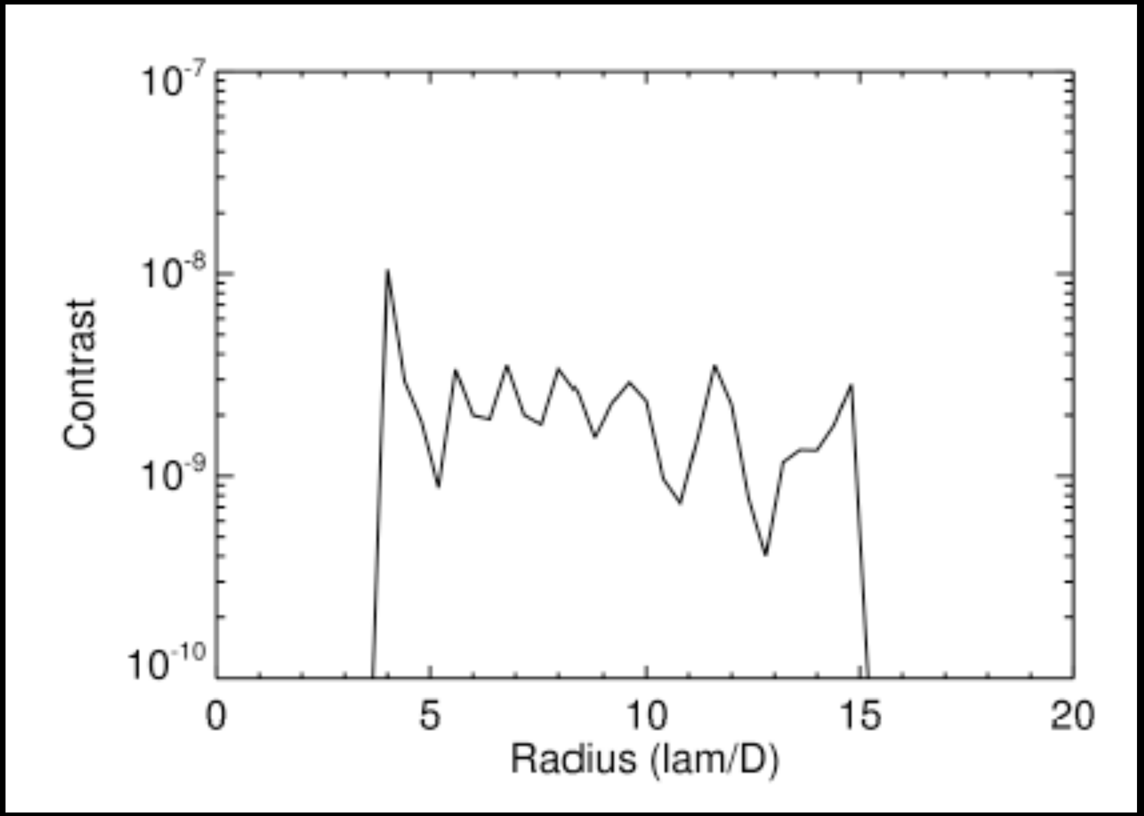




iwa: 3.9
owa: 16
contrast: 5e-9
Transmission: 29%

Preliminary Result from John after Control



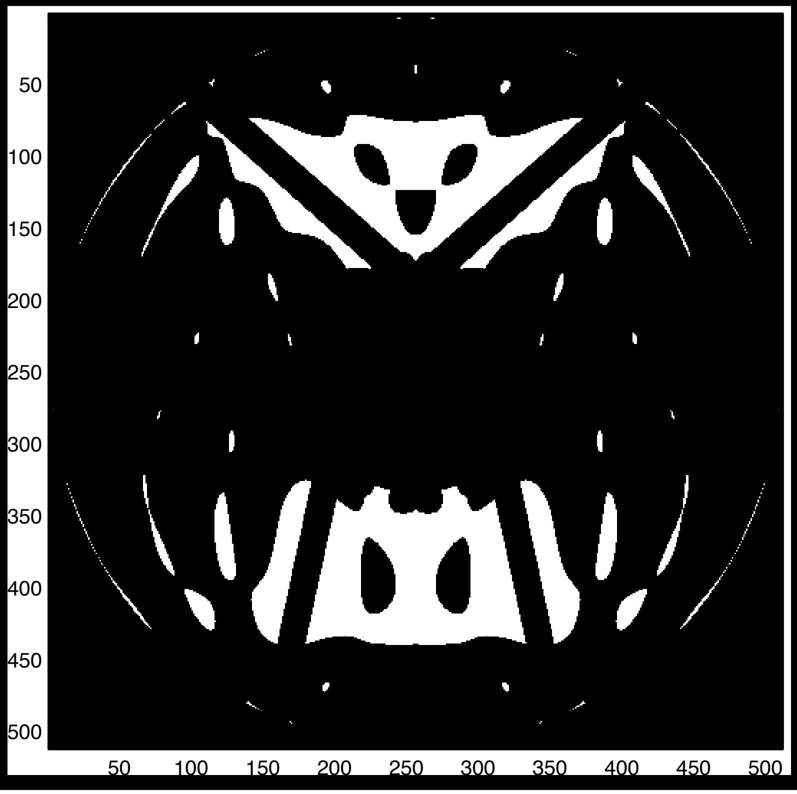


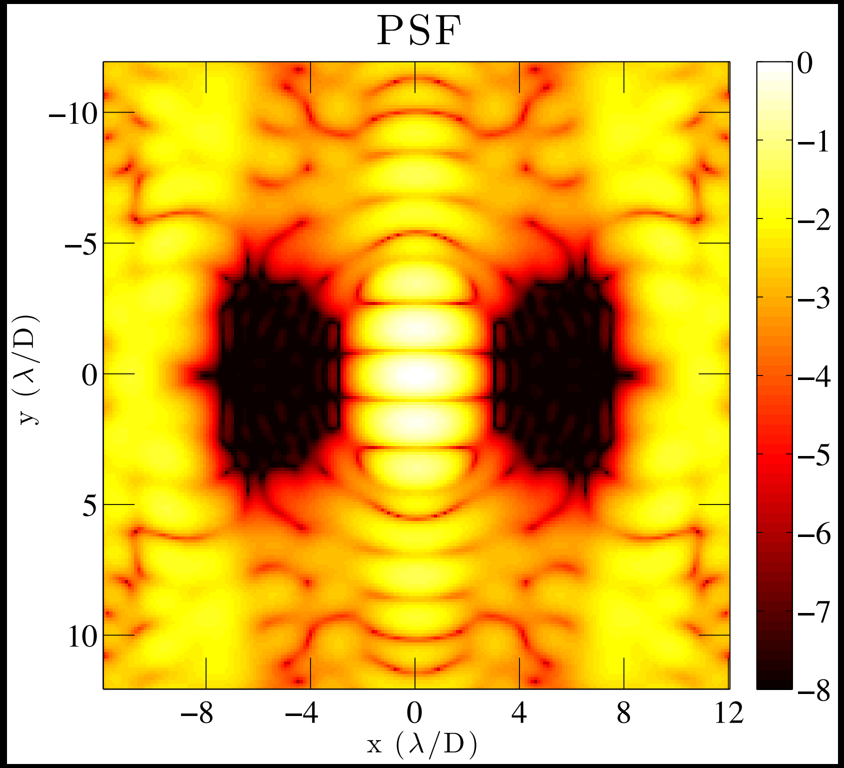
mean contrast = 2.7 x 10^{-9}
from 4 to 15 lambda/D

Bandpass = 522-578 nm

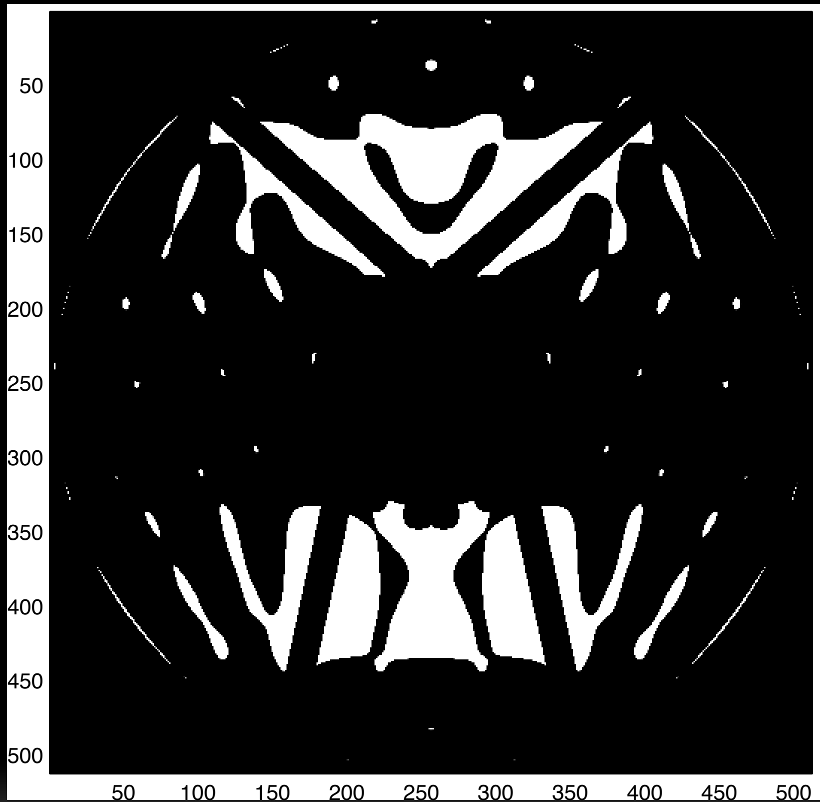
Same caveat.

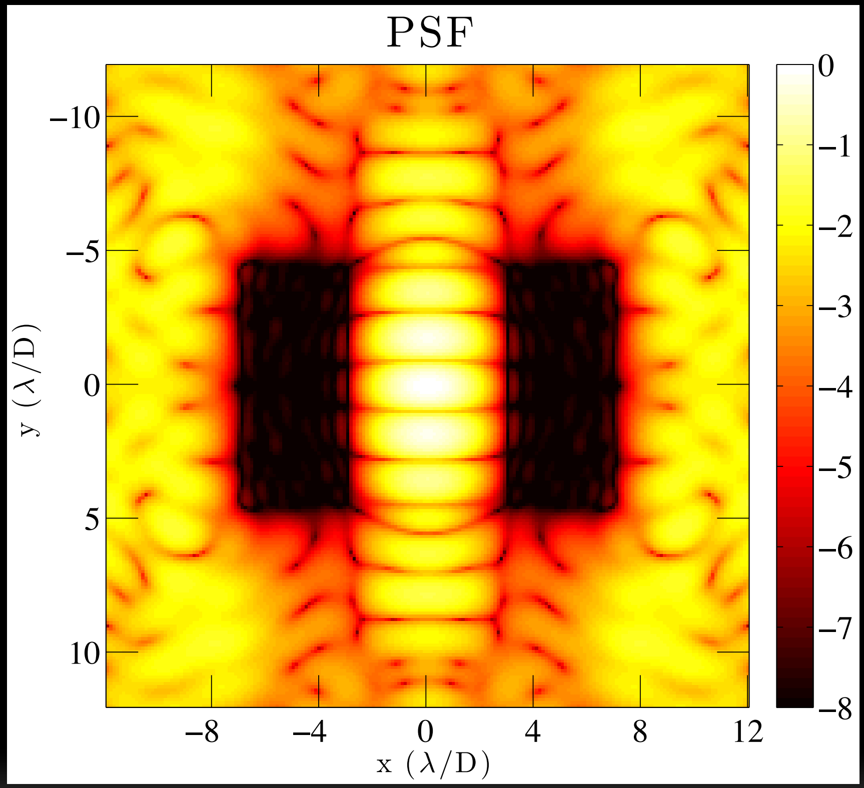
Another recent design (using certified pupil):





iwa: 3 lambda/D
owa: 8 lambda/D
Trans.: 20%
Contrast: 1e-8





iwa: 2.5 lambda/D
owa: 7.5 lambda/D
Trans.: 20%
Contrast: 1e-8

What's next?

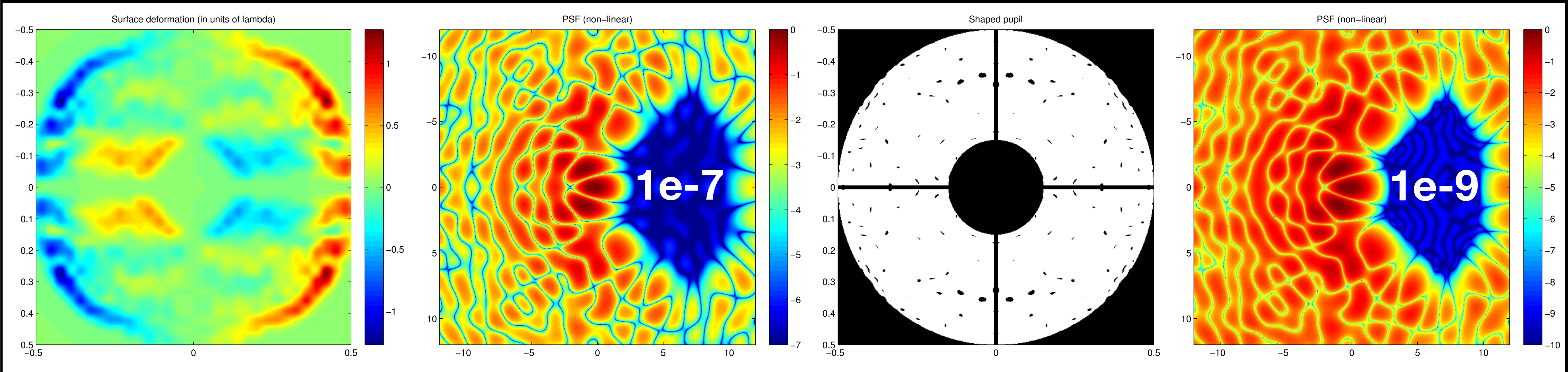
- Redesign to provided sampled pupil
  - Aside: The 0.6 deg off-axis makes a BIG difference!
- Refine designs exploring characterization zones
- Attempt higher performance designs by hybridizing with DMs

DM + SP Hybrids, proof of concept

- Control is limited with some shaped pupils
- Same IWA, more throughput

How?

- Optimize DM settings to induce phase.
- Optimize SP when contrast stalls.

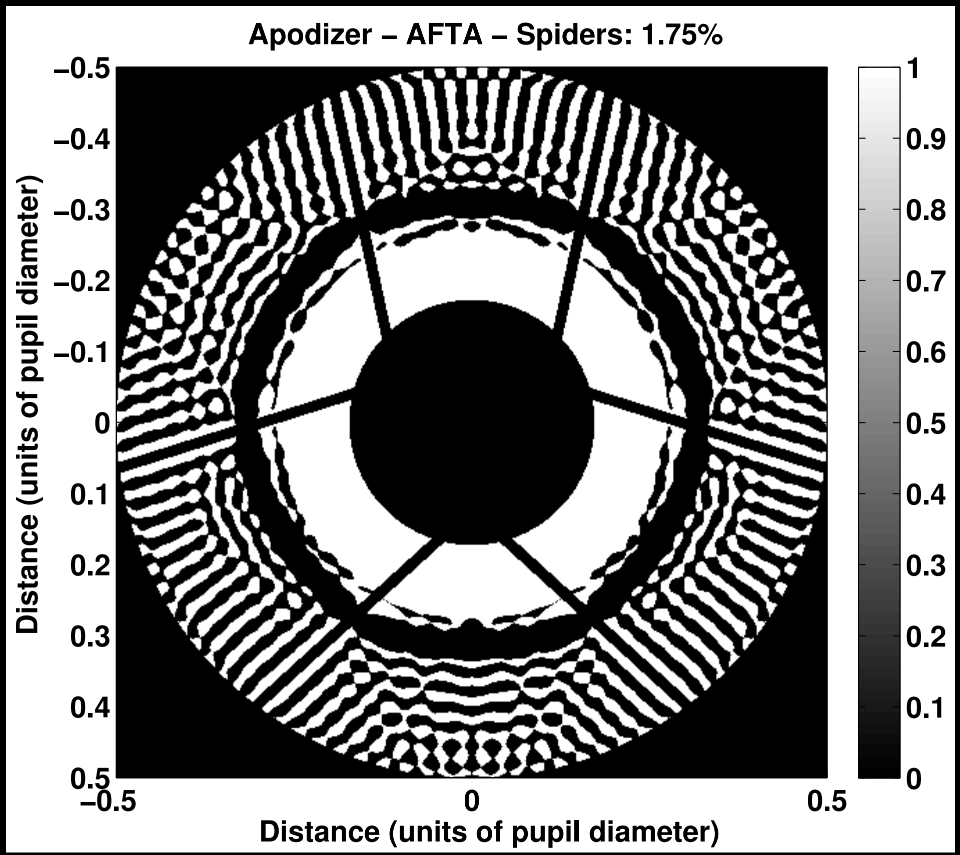


Carlotti et al. [8864-60]

SP + FPM combinations

Choice of Lyot, Vortex, 4QPM...

--> 360° coverage around star
--> 2-3 λ/D IWA ; 10^{-8}-10^{-9} contrast



1.75% spiders

- 12% throughput
- 5×10^{-8} @ 3 λ/D
- 3×10^{-9} @ 10 λ/D

0.5% spiders

- 29% throughput
- 4×10^{-9} @ 2.9 λ/D
- 1×10^{-9} @ 10 λ/D

Carlotti et al. [8864-61]

See also Mawet et al. 2013, in prep.
& Mawet et al. [8864-35]

Extra Slides on Recent HCIT Tests

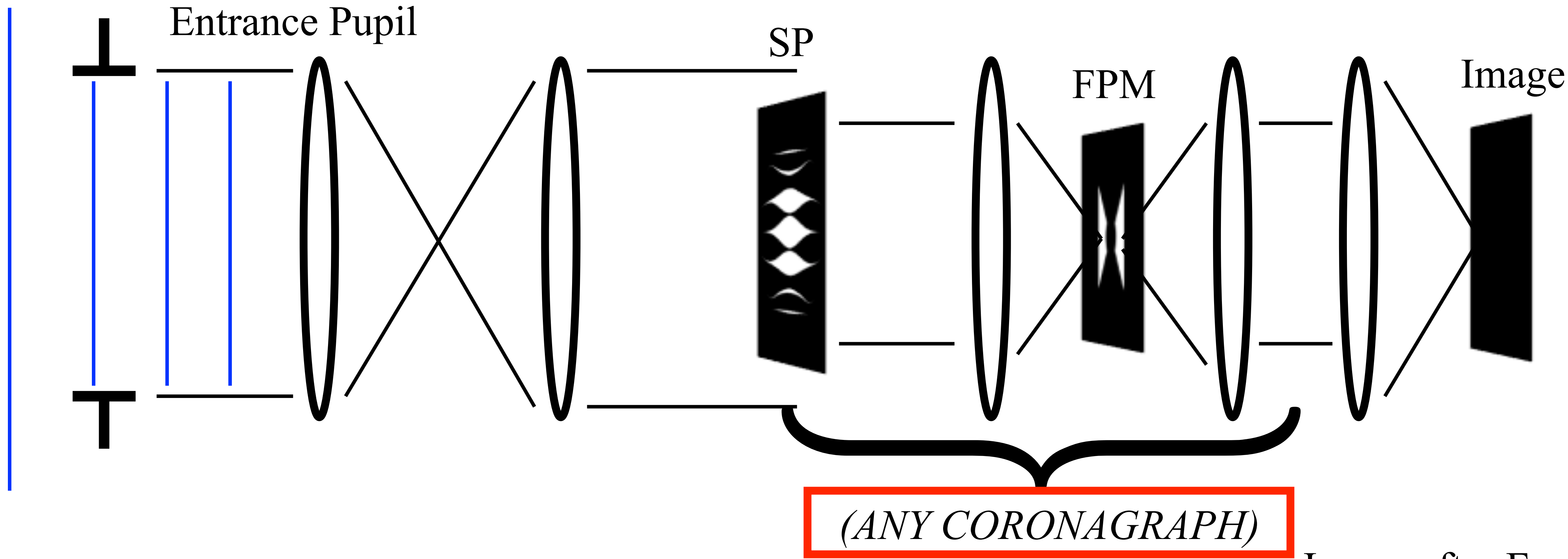
2012 TDEM on Control with 2 DMs

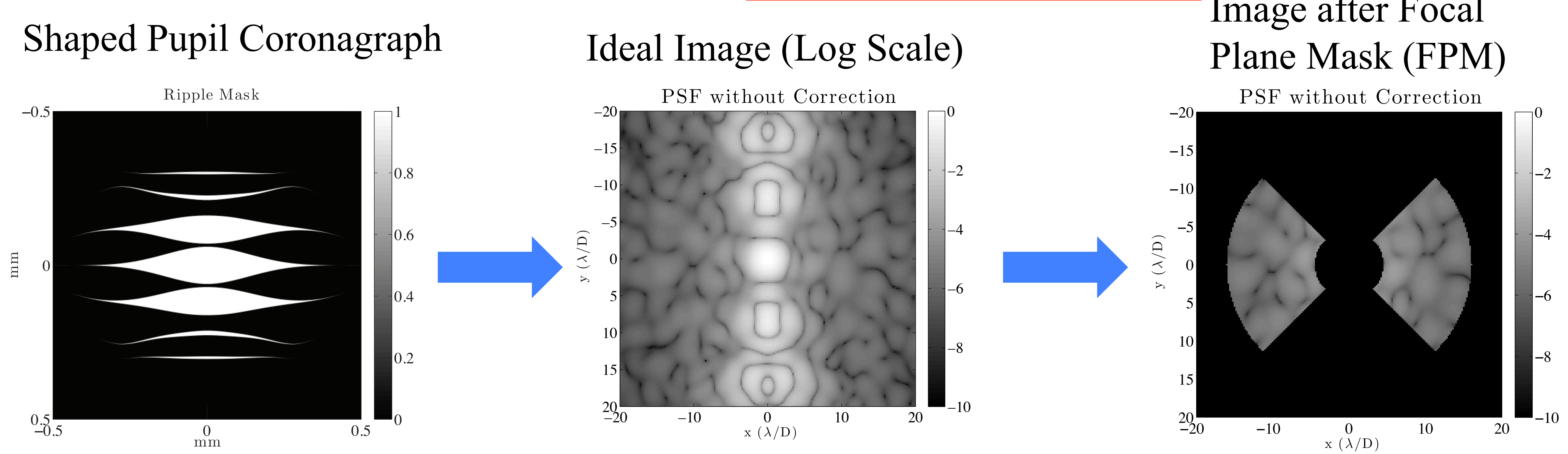
- Demonstrate double sided dark holes using 2 DMs at Princeton and at HCIT
- Milestone to achieve 10^{-9} contrast monochromatic
- Goal to achieve 10^{-9} contrast in broadband
- Secondary goals to demonstrate Kalman Filter for estimation and Stroke Minimization for control

Because of schedule and other limitations (no changes to HCIT layout), used same transmissive shaped pupil as in 2007 and second DM in a converging beam.

Experiments run from June to August, 2013.

Coronagraphy: Actual Optics

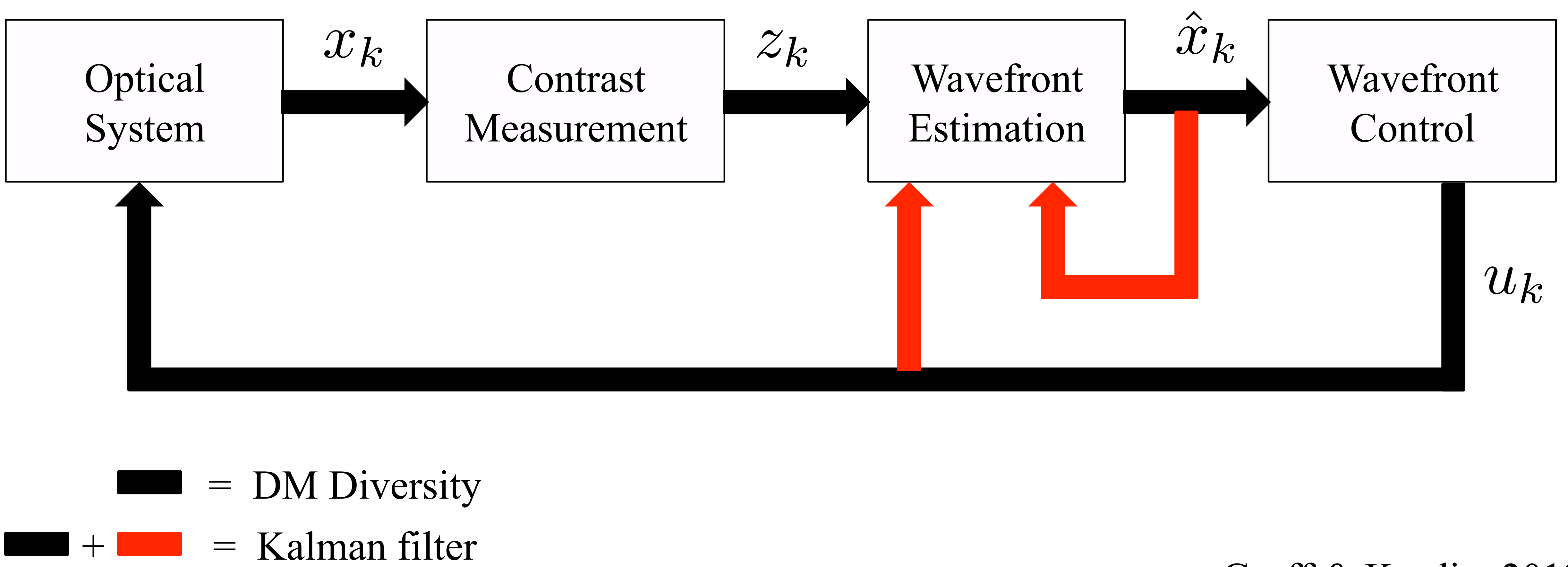




Aberrations degrade contrast: $10^{-10} \rightarrow \sim 10^{-5}$

Wavefront Estimation with a Kalman Filter

- Recursive least-squares estimator (closed loop)
- Initialize with batch process DM Diversity
  - 1+ image pairs per estimate update
  - More robust at high contrast because of stored data



Groff & Kasdin, 2012

Control with Stroke Minimization

- Cost function:

$$\text{minimize} \sum_{k=1}^{N_{act}} a_k^2$$

$$\text{subject to } C_{DH} \leq C_{target}$$

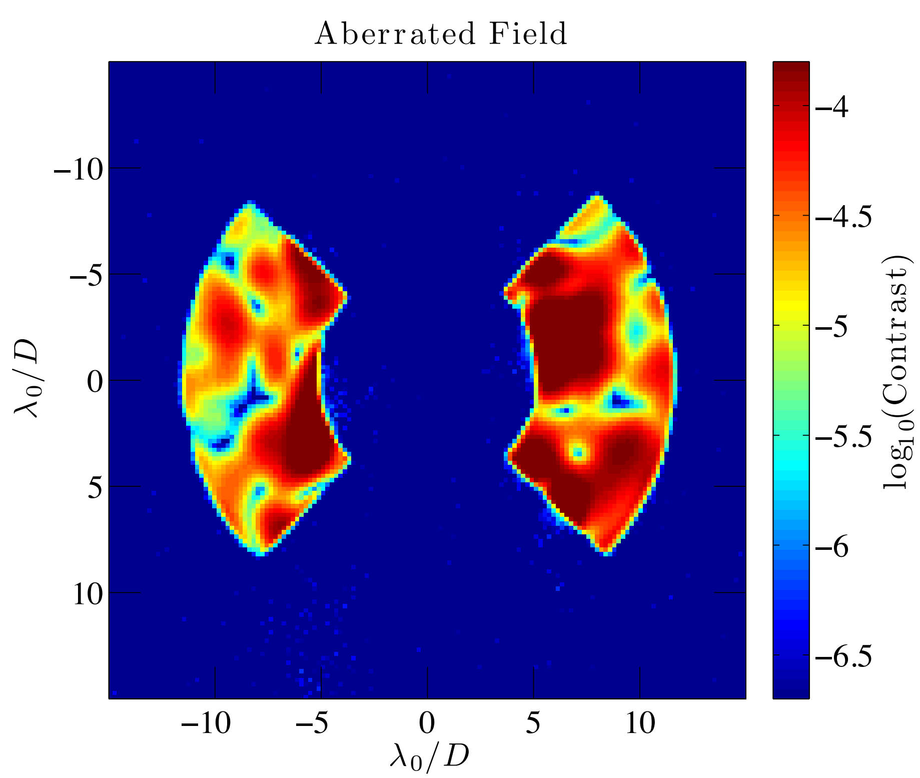
a_k = stroke commanded to k^{th} actuator
N_{act} = number of actuators
C_{DH} = target contrast level in dark hole

Pueyo et al. 2009

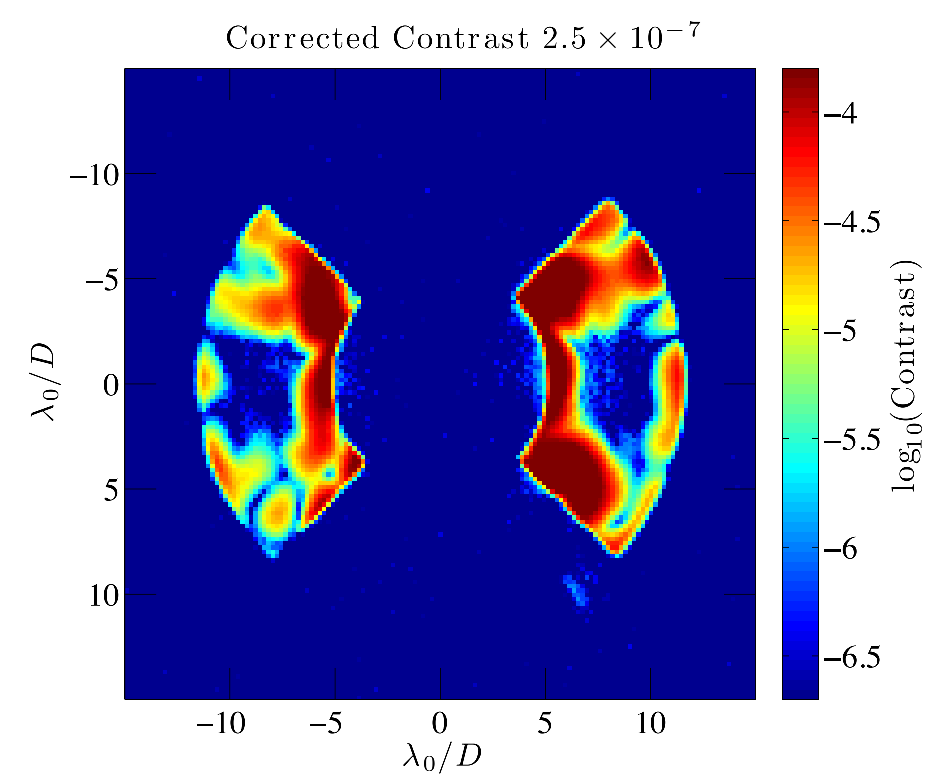
- Minimizes stroke on each DM
  - Keeps linear model valid
  - Consumes less power

Two-DM Control at Princeton

- Symmetric dark holes with 2 DMs in series first demonstrated at Princeton's HCIL [Pueyo, Kay, et al. 2009]
- Used Kalman filter for 1-pair estimate updates
  - Monochromatic: **2.3x10^{-7}** [Groff & Kasdin 2012]
  - Broadband (10%): **4.9x10^{-6}** [Groff & Kasdin 2012]
- Limited by air, rough DM surfaces, and model accuracy



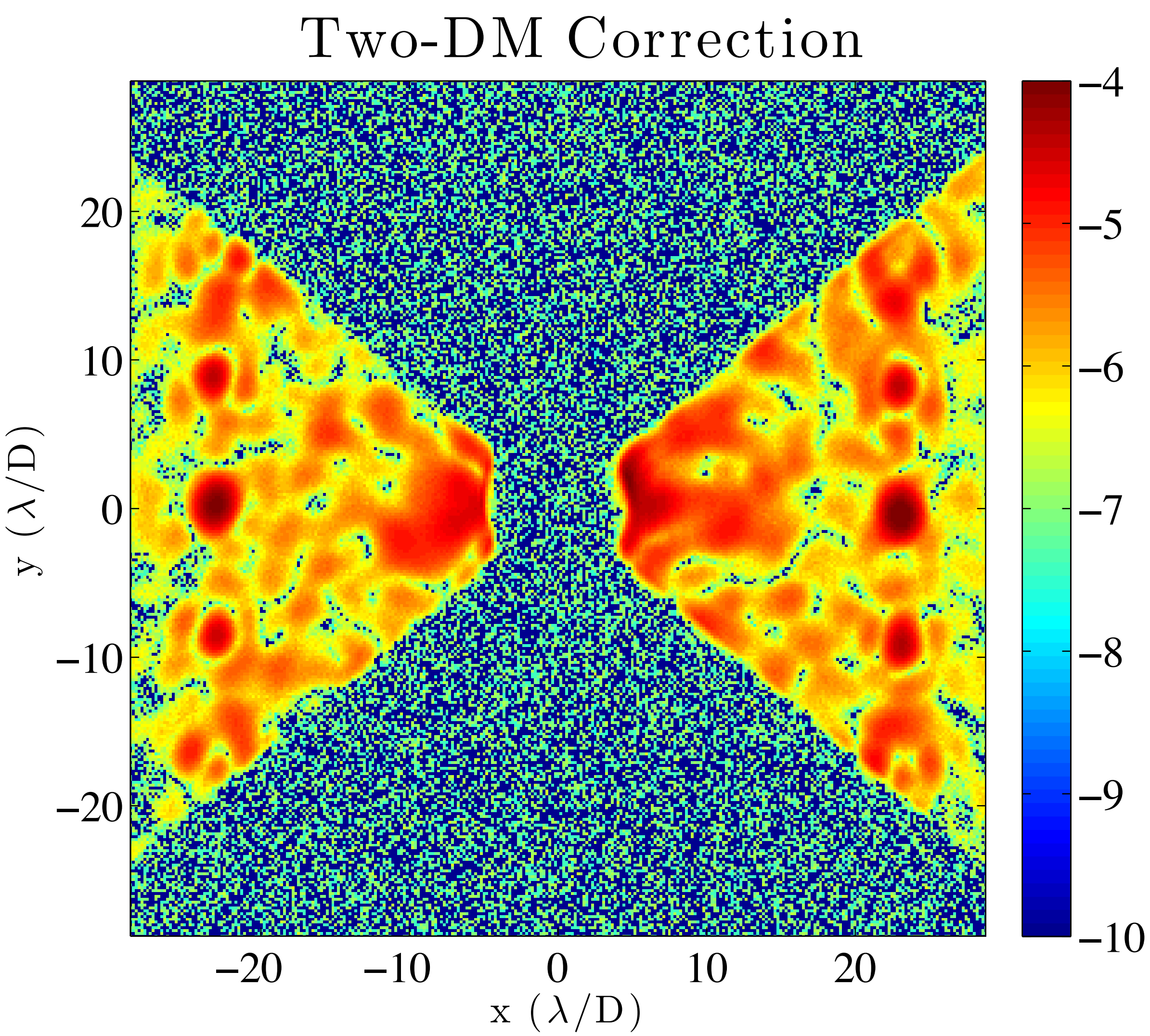
Groff & Kasdin, 2012



Two-DM Control at the HCIT

- Monochromatic correction at 790 nm

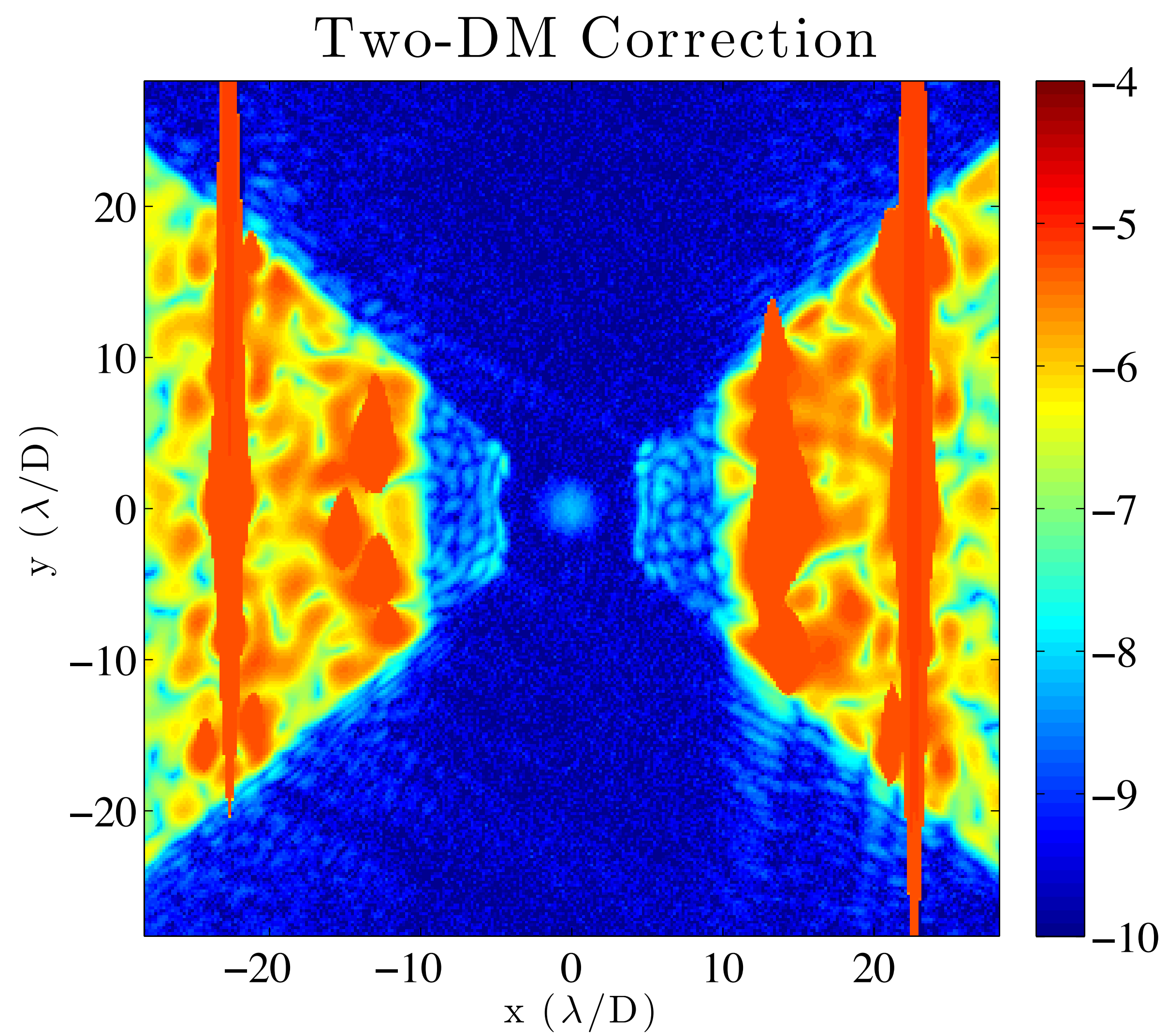
Before Correction:



7.8 x 10^{-6} contrast

5 to 9.5 λ/D

After Correction:

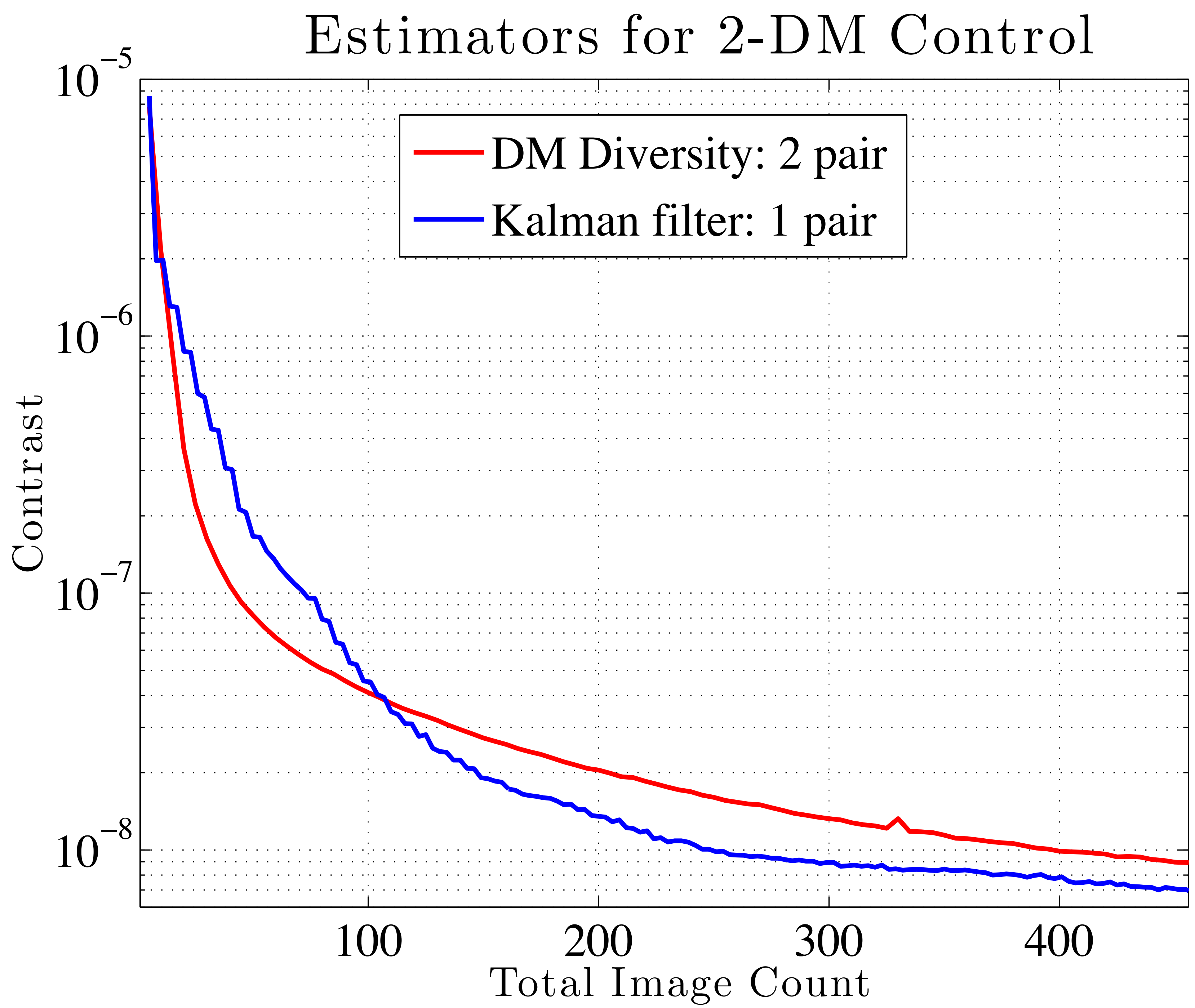


3.6 x 10^{-9} contrast

5 to 9.5 λ/D

HCIT Results with the Kalman Filter

- Single-pair update with Kalman filter needed fewer images
- ~2x faster than DM Diversity

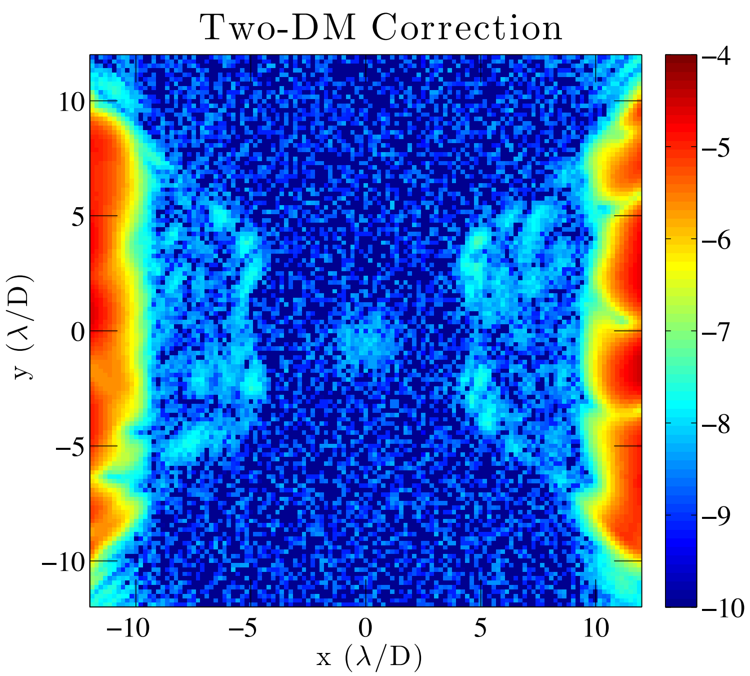


Comparison of EFC and Stroke Minimization

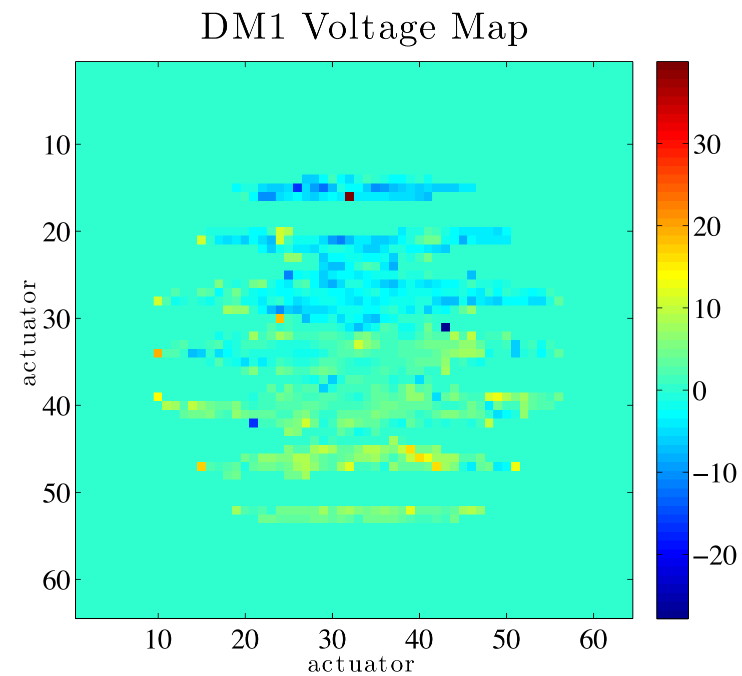
EFC (Energy Minimization)

Aug. 14, 2013

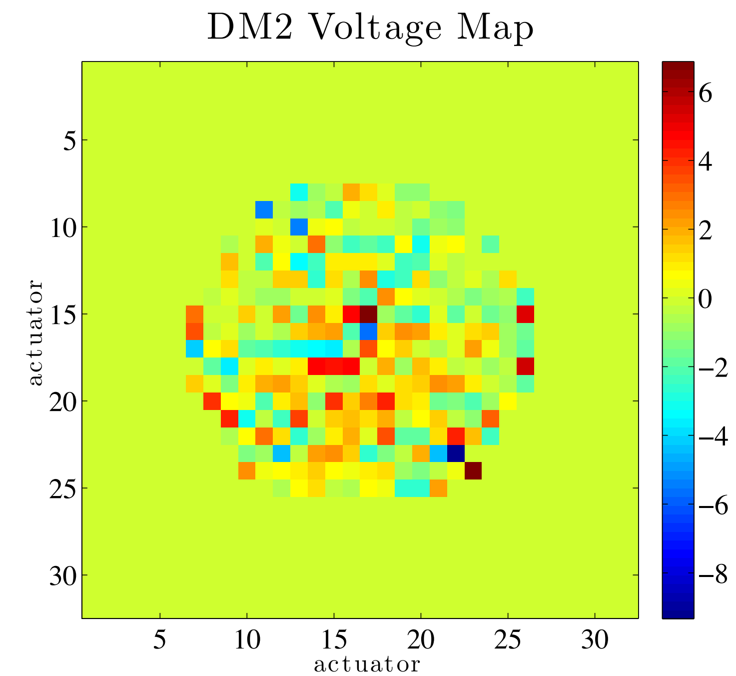
5 to 9 λ/D



4.1 x 10^{-9} contrast



68-volt spread

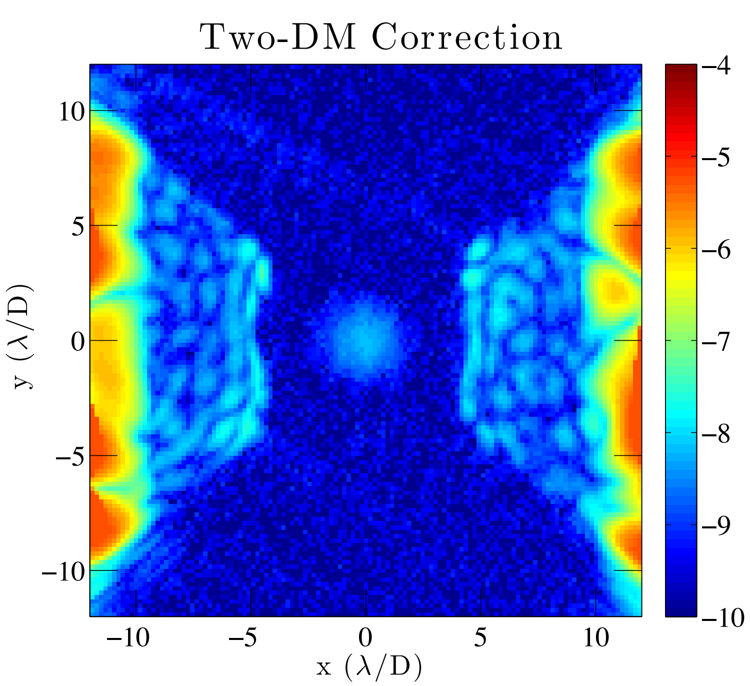


16-volt spread

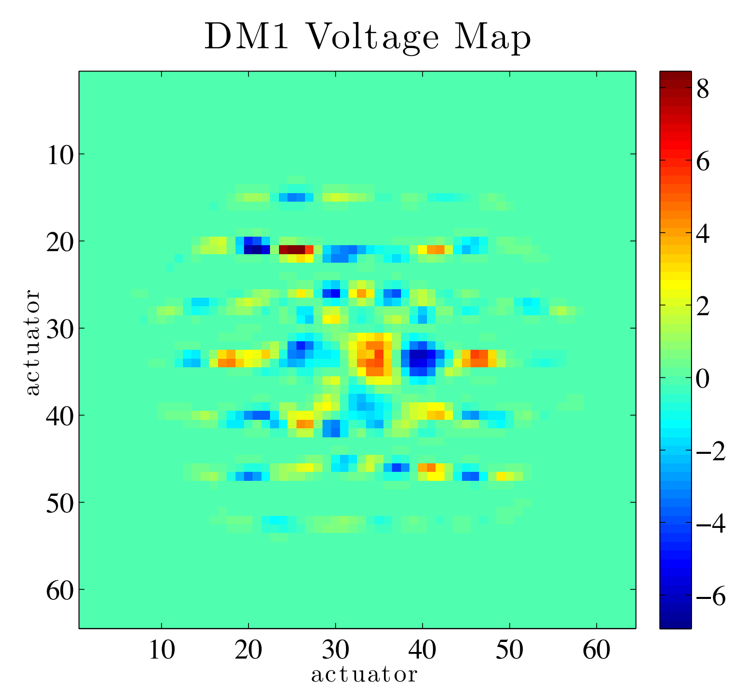
Stroke Minimization

Aug. 23, 2013

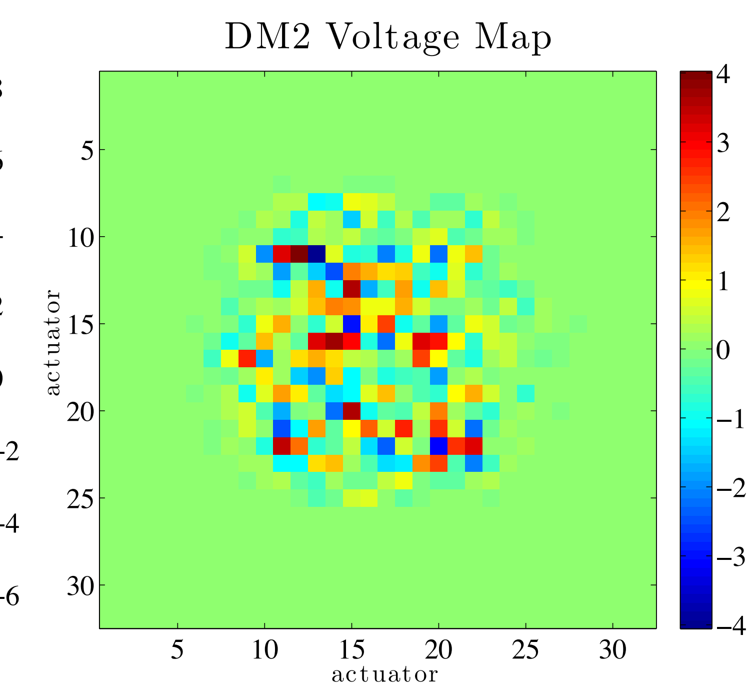
5 to 9.5 λ/D



3.6 x 10^{-9} contrast



15-volt spread



8-volt spread