The number of sub-bands and spatial sampling required to dig $\Delta\lambda/\lambda$ = 5% and 10% HLC and 18% SPC dark holes in the WFIRST Coronagraph

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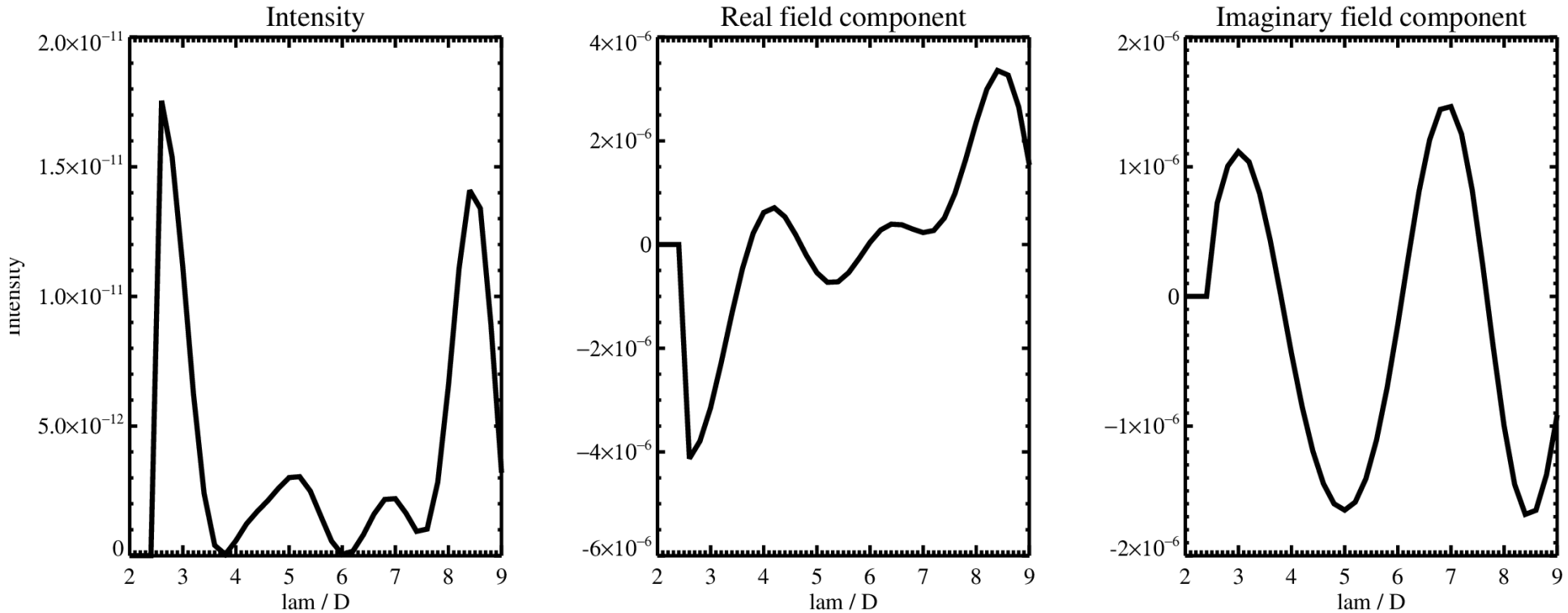
The Dark Hole Field Varies Even within Nyquist-Sampled Pixels



Representing Finite-Sized Pixels

- For HLC the E-field is computed at 0.164 λ/D sampling, SPC at 0.244 λ/D
  - 2K x 2K grids for HLC, 4K x 4K for SPC
- Interpolate E-field at each λ to ~0.05 λ/D sampling
  - choose new sampling that provides an odd-integer subsampling factor of the final pixel size
- If final result is the predicted probe E-field, rebin the subsampled field real & imaginary components separately to final pixel sampling
- If final result is measured intensity (probed & science images), convert subsampled field to intensity and then rebin to final pixel sampling
- Experiments show that results are similar whether or not the EFC Jacobian E-field is averaged over the pixel area or not
- STScI post-processing group stated that sampling should be 0.5 λ/D or better for allow for suitable interpolation (D=telescope, not Lyot stop, clear diameter), so only 0.3, 0.4, and 0.5 λ/D pixel sizes are considered here

Representing Finite-Bandpass Filters

- For HLC used here, 31 wavelengths evenly sample the 10% bandpass (523-578 nm), 45 wavelengths for the 18% SPC bandpass (728-872 nm)
- These wavelengths are divided into sub-band filters for probing
- The intensity images for all of the component wavelengths in each filter are averaged together to represent the image in that filter
- When determining the E-field response to probes or the EFC Jacobian, a single wavelength must be assumed for each filter
  - Experiments show that choosing the central wavelength is best, regardless of filter width or location within the science bandpass
- A “virtual” sub-band filter can be derived using real sub-band filters and the science filter (e.g., the images from two 3.3% sub-band filters can be subtracted from a 10% filter image to create a virtual 3.3% image, since wavelengths add incoherently)

Initial aberrations

- Initial HLC DM pattern defined by fitting DM to Dwight's wavefront maps
  - differences in actuator assumptions between Dwight and me means that my derived wavefront will not exactly match Dwight's
  - assume that this represents the initial state on-orbit where Dwight's patterns are put on the DM and optimized via phase retrieval before running EFC
  - Contrast without DM patterns is ~10^{-4} in unaberrated system
  - Contrast with derived DM patterns is ~10^{-5}
  - Contrast after EFC in unaberrated system is ~2×10^{-10}
- System aberrations computed by propagating at each wavelength through the full aberrated system model up to DM1 and storing the wavefronts
  - These are then used as the initial wavefront at DM1 in the compact model to save execution time, since nothing in the front system changes and the errors on optics after DM1 are not significant here
- Wavelength-dependent polarization aberrations are included where noted
  - Since the HLC used is defined for 523-578 nm, when the shorter bandpass centered at 470 nm is evaluated, the appropriate polarization errors from those wavelengths are used in the default bandpass on the assumption that the coronagraph will respond similarly to low-order aberrations if it were designed for that bandpass

Probing & EFC

- For HLC, 6 probes are used (+/- imaginary full field, up/down real half fields, left/right real half field), with “standard” (sinc-like) probe patterns centered in unobscured region of the pupil; SPC uses 4 (left/right real, +/- imaginary)
- Probe intensities scale as sqrt(contrast * 10^{-5})
  - 10^{-5} contrast probes at 10^{-5} mean field contrast
  - 10^{-7} contrast probes at 10^{-9} mean field contrast
- Probe predicted E-field responses are computed using current DM settings at each iteration
  - Without doing so the contrast is limited to ~10^{-8} due to large DM strokes caused by HLC patterns
- To parallelize the process, each probe pattern is sent to a separate workstation to compute the probed field at each of the 31 or 45 wavelengths
  - On each workstation, the wavelengths are computed in parallel in batches of 10 or 11 at a time
- When polarization is included, the images must be computed for both the $+45^{\circ}_{in}$ and -45°_{in} wavefront errors, with the resulting intensities averaged in the end to represent the field seen through the polarizer, including cross terms; this doubles the processing requirement
  - For SPC, which lacks a polarizer, 4 images are computed ($\pm 45^{\circ}_{in}, X_{out}$ and $\pm 45^{\circ}_{in}, Y_{out}$), quadrupling the time
- EFC is run with a constant regularization, chosen via trial-and-error, for 10-20 iterations with 5x weighting applied at r = 3 – 5 λ/D for HLC and 2.5 – 4.5 λ/D for SPC
- When polarization is included with the HLC it takes 90 minutes to complete a 3-filter run using 6 workstations (would take 9 hours if just one workstation was used)
- SPC takes 15 min per iteration (45λ x 4 probes + 45λ evaluation)
- No jitter
- Perfect model & instrument agreement

HLC 20160129

- 10% bandpass (λ = 522.5 – 577.5 nm)
- Two 48x48 DMs for obscuration compensation
  - 46.3 mm diameter pupil on DMs
  - DM *wavefront maps* (not DM settings) provided by Dwight
- Lyot stop
- Focal plane mask defined at 31 wavelengths

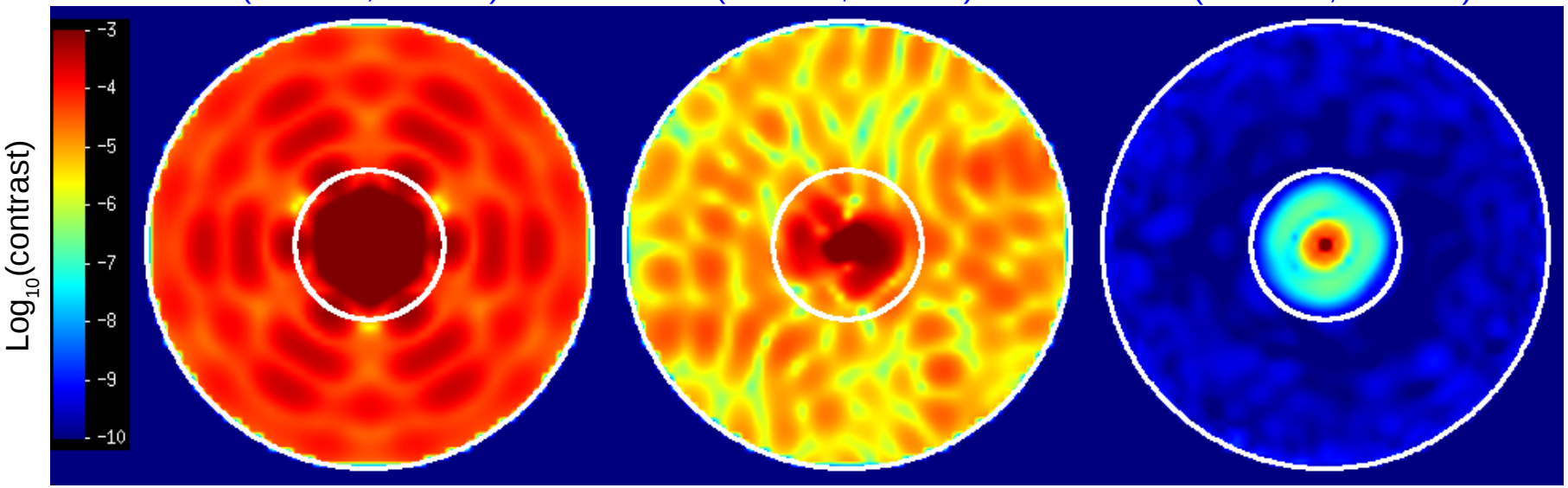
HLC, 10% (λ=523-578 nm), unaberrated
9 λ EFC, no probing

(r = 3-4, 3-9 λ/D mean contrast)

No DM patterns
(1.9×10^{-4},1.0×10^{-4})

Initial HLC DM patterns
(9.9×10^{-6},9.1×10^{-6})

After EFC
(1.8×10^{-10},2.8×10^{-10})



Circles are r = 3 & 9 λ/D

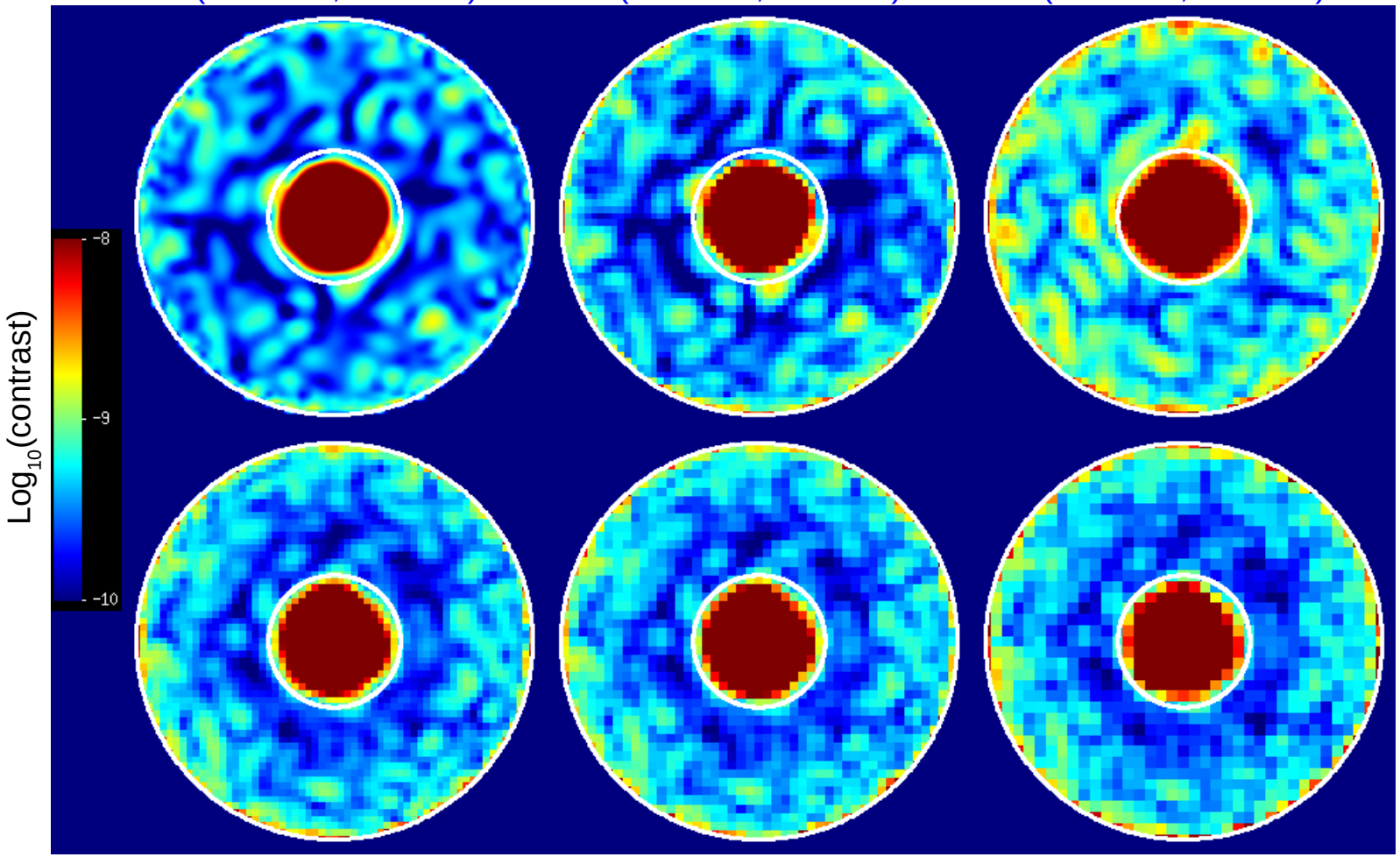
HLC, 10% (λ=523-578 nm), aberrated

(r = 3-4, 3-9 λ/D mean contrast)

9 λ @ 0.3 λ/D point sampling, no probes
(3.8×10^{-10},4.2×10^{-10})

9 x 1.1% filters
0.3 λ/D pixels
(4.2×10^{-10},4.6×10^{-10})

2 x 5% filters
0.3 λ/D pixels
(9.0×10^{-10},7.8×10^{-10})



Circles are
r = 3 & 9 λ/D

3 x 3.3% filters
0.3 λ/D pixels
(3.3×10^{-10},5.0×10^{-10})

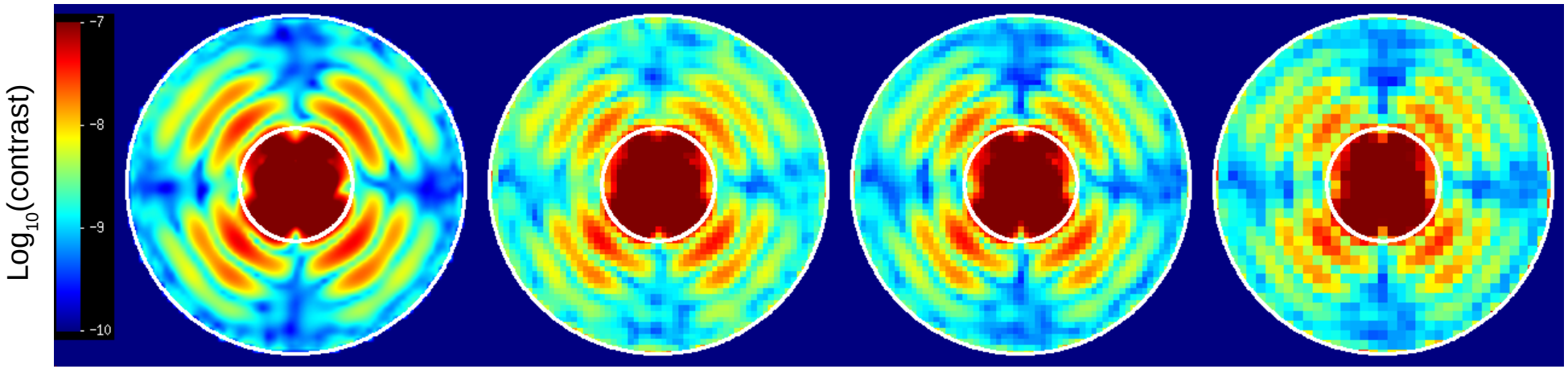
3 x 3.3% filters
0.4 λ/D pixels
(3.2×10^{-10},5.3×10^{-10})

3 x 3.3% filters
0.5 λ/D pixels
(3.3×10^{-10},5.5×10^{-10})

HLC, 10% (λ=447-494 nm)
X polarization (including cross terms) + aberrations

(r = 3-4, 3-9 λ/D mean contrast)

9 λ @ 0.3 λ/D point sampling, no probes	2 x 5% filters 0.3 λ/D pixels	3 x 3.3% filters 0.3 λ/D pixels	3 x 3.3% filters 0.5 λ/D pixels
(1.2×10^{-8},5.1×10^{-9})	(1.2×10^{-8},5.1×10^{-9})	(1.0×10^{-8},4.6×10^{-9})	(1.0×10^{-8},4.5×10^{-9})



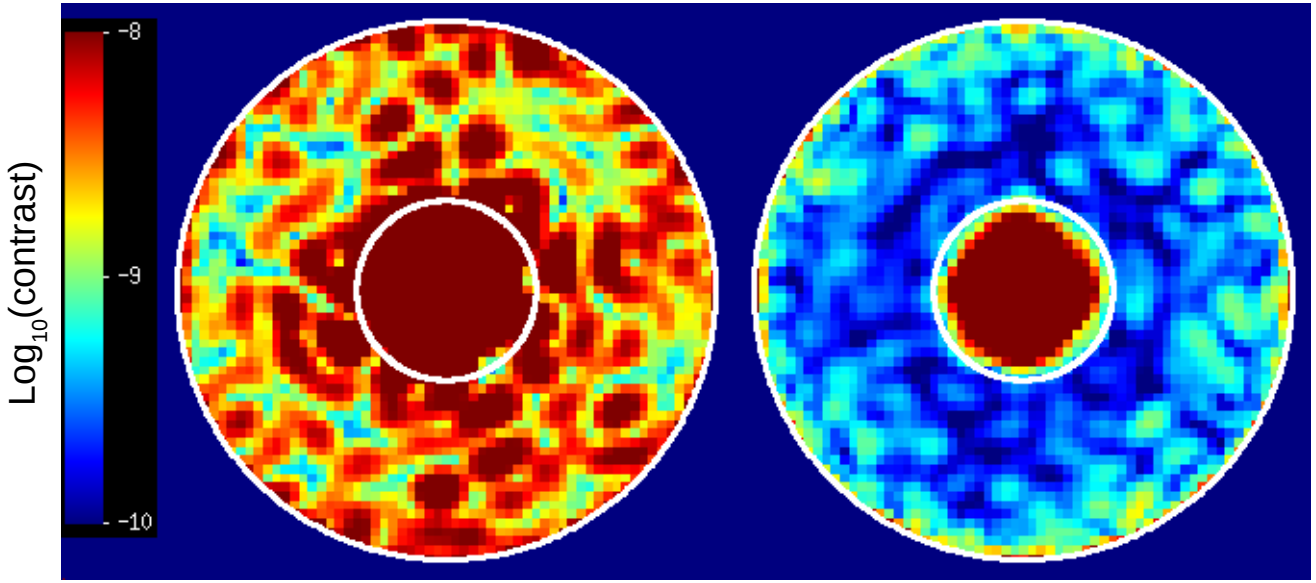
Circles are r = 3 & 9 λ/D

HLC, 5% (λ=523-550 nm), aberrated

(r = 3-4, 3-9 λ/D mean contrast)

1 x 5% filter
0.3 λ/D pixels
(1.9×10^{-8},6.1×10^{-9})

2 x 2.5% filters
0.3 λ/D pixels
(2.8×10^{-10},4.6×10^{-10})



Circles are r = 3 & 9 λ/D

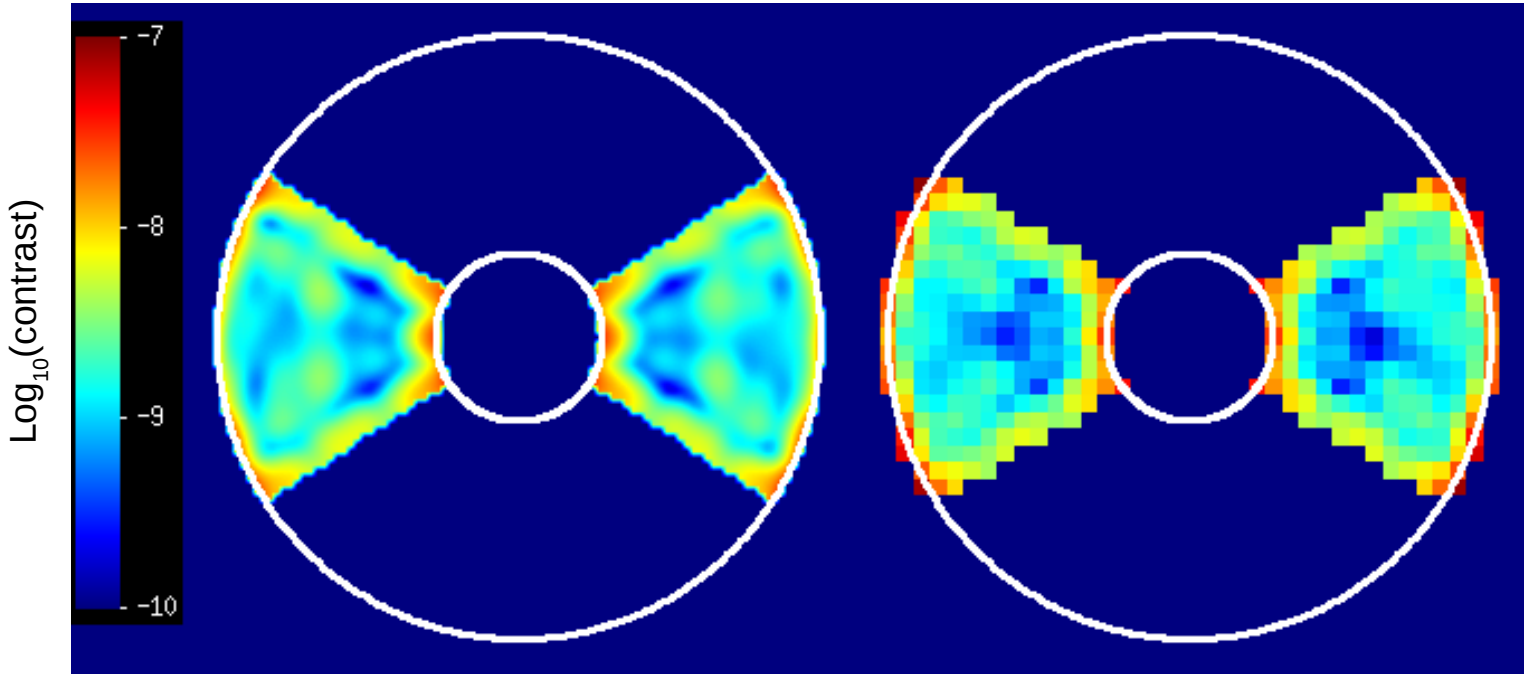
SPC 20140902

- 18% bandpass (λ = 728 – 872 nm)
- Two 48x48 DMs
  - 46.3 mm beam diameter on DMs
- r = 2.5 – 9 λ/D bowtie focal plane mask with 65° opening angle
- Lyot stop

SPC, 18% (728 – 872 nm)

Polarization included

	9 monochromatic wavelengths, perfect knowledge (no probing) 0.2 λ/D point sampling	5 x 3.6% sub-bands, probing, 0.5 λ/D finite pixels
Contrast (IWA, full) =	(1.1×10^{-8}, 3.9×10^{-9})	(1.5×10^{-8}, 3.9×10^{-9})



For perfect knowledge case, mean polarization WFE was used to when running EFC, then the solution was evaluated separately for each of the 4 polarization input wavefronts, and the resulting fields added in intensity

Circles are r = 2.5 & 9 λ/D

Summary

- For the HLC 10% bandpass evaluated, good ($<10^{-9}$) dark holes can be generated using probing with:
  - Pixel sizes of 0.3 – 0.5 λ/D (D=telescope diameter)
  - Three 3.3% sub-bands
    - Two 3.3% sub-band filters + virtual 3.3% sub-band using 10% science filter
  - Two 5% sub-bands are about 2x worse at best-contrast case (no polarization errors at 523-578 nm) but not when polarization errors dominate (short wavelengths)
- In HLC 5% bandpass, need two 2.5% sub-bands
- A 15% HLC would almost certainly require at least 3 sub-bands (yet to evaluate)
- For SPC 18% bandpass, 5 sub-bands provide a good dark hole
  - sub-bands created by adding spectral channels