Evaluating Coronagraph Performance with End-to-End Numerical Modeling: WFIRST and Beyond

John Krist
Jet Propulsion Lab/Calif. Inst. of Technology
5 May 2016

Stages of Coronagraph Design

Concept
Mathematical, perfect modulations of the wavefront, perhaps only monochromatic

↓

Realize
How to modify wavefront with real materials and devices?

↓

Build
Fabricate & measure components

↓

Testbed
Test system on ground

↓

Fly
Use system for science

Coronagraph Optimization: The Past

- Contrast
- Inner working angle
- Transmission

Coronagraph Optimization: Now

- Contrast
  - aberrations, jitter, finite star diameter, bandwidth, DM stroke
- Inner working angle
  - jitter, finite star diameter, aberrations, bandwidth
- Effective Throughput
  - planet PSF morphology, mask transmission
- Wavefront control
  - ACAD, DM control spatial frequencies, stroke limits, polarization, bandwidth

End-to-End Modeling

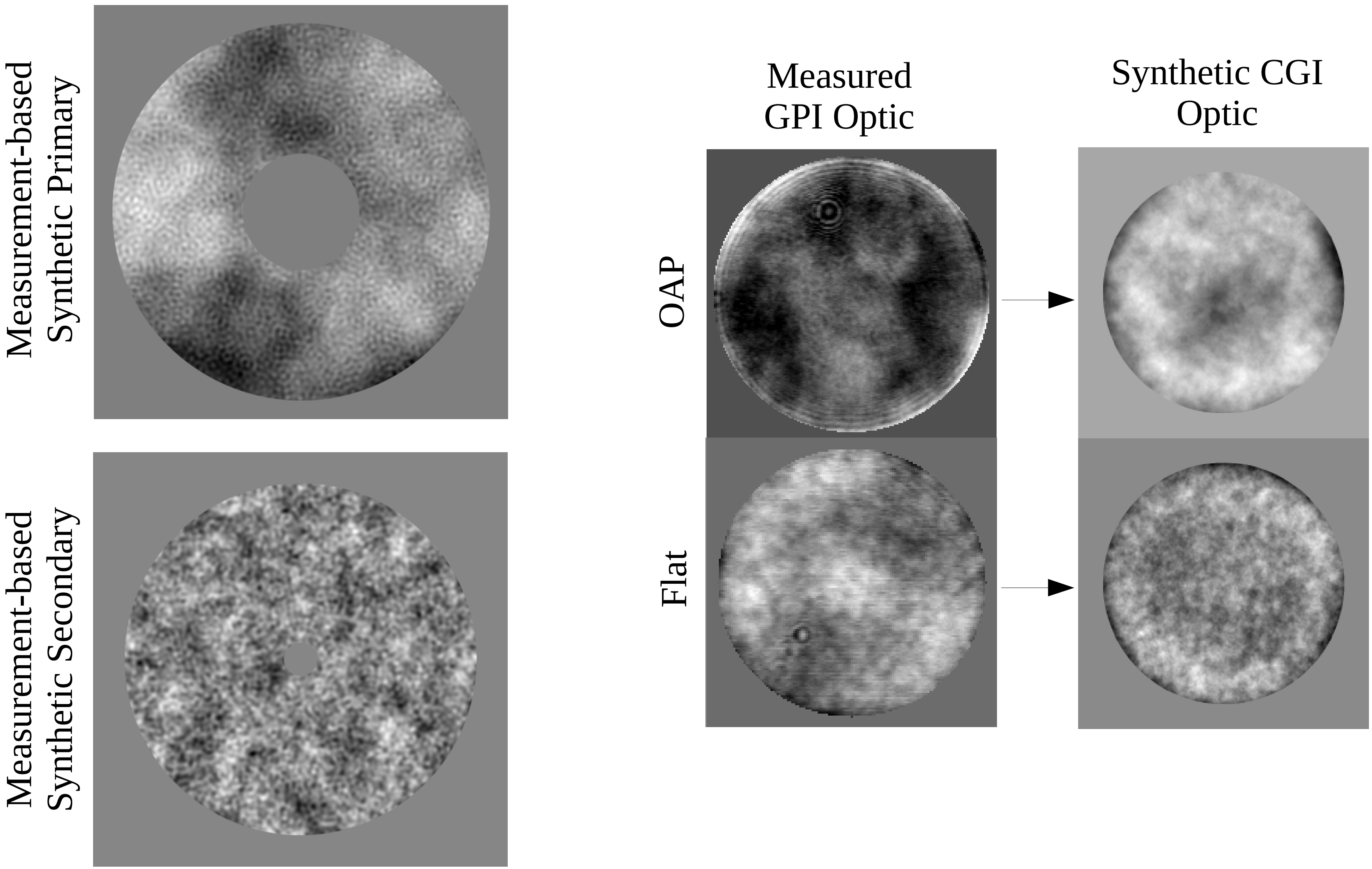
- Propagation through all significant optical components, with realistic defects
  - PROPER[*] used for WFIRST & Exo-C modeling
- Wavefront control using deformable mirrors and wavefront optimization algorithms (EFC, stroke minimization)
- Jitter, finite stellar diameter
- Potential misalignments (pupil)
- Evaluation of field (planet) PSFs

[*]Available from proper-library.sourceforge.net

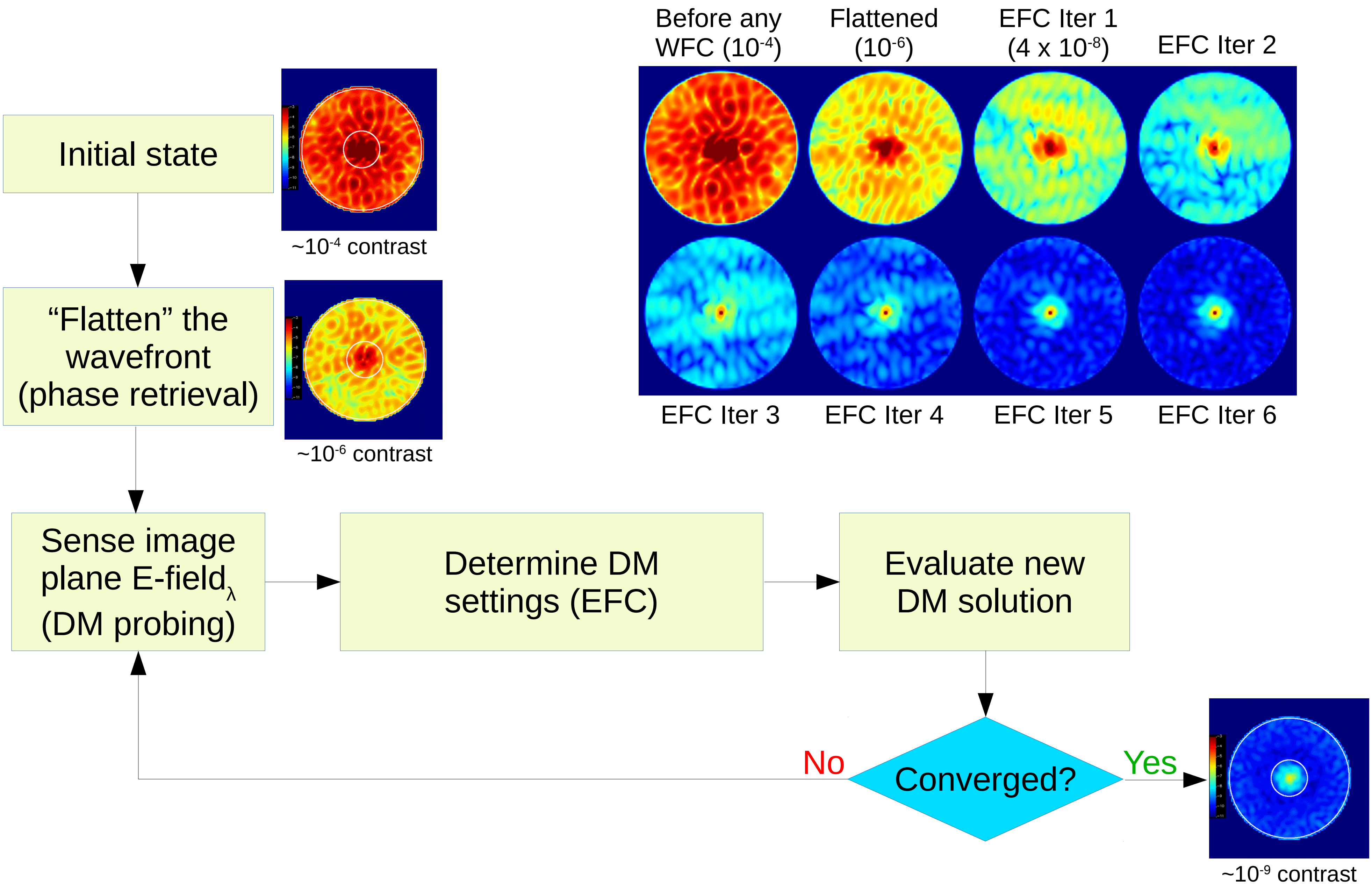
WFIRST Coronagraph Downselect

- **Coronagraph advocates submitted their designs in 2013**
  - Hybrid Lyot (HLC)
  - Shaped Pupil (SPC)
  - PIAACMC
  - Shaped pupil + ACAD + vortex
  - Visible nuller (two types; modeling incomplete)
- **Evaluated via end-to-end modeling**
  - Dig a dark hole around the star in a realistically aberrated system with DMs and EFC wavefront control
  - Determine contrast degradation due to pointing jitter
  - Determine field (planet) PSF properties
- **Used model-derived properties to predict planet yields for different jitter levels and post-processing factors**
- **Downselected to HLC, SPC, & PIAACMC (backup)**
  - revised designs with improved efficiencies and jitter tolerances have been provided
- **A similar process was done for the Exo-C Probe study (unobscured telescope with HLC, classical PIAA, vector vortex)**
- **WFIRST modeling described in Krist et al., JATIS, v.2, 011003 (2016)**

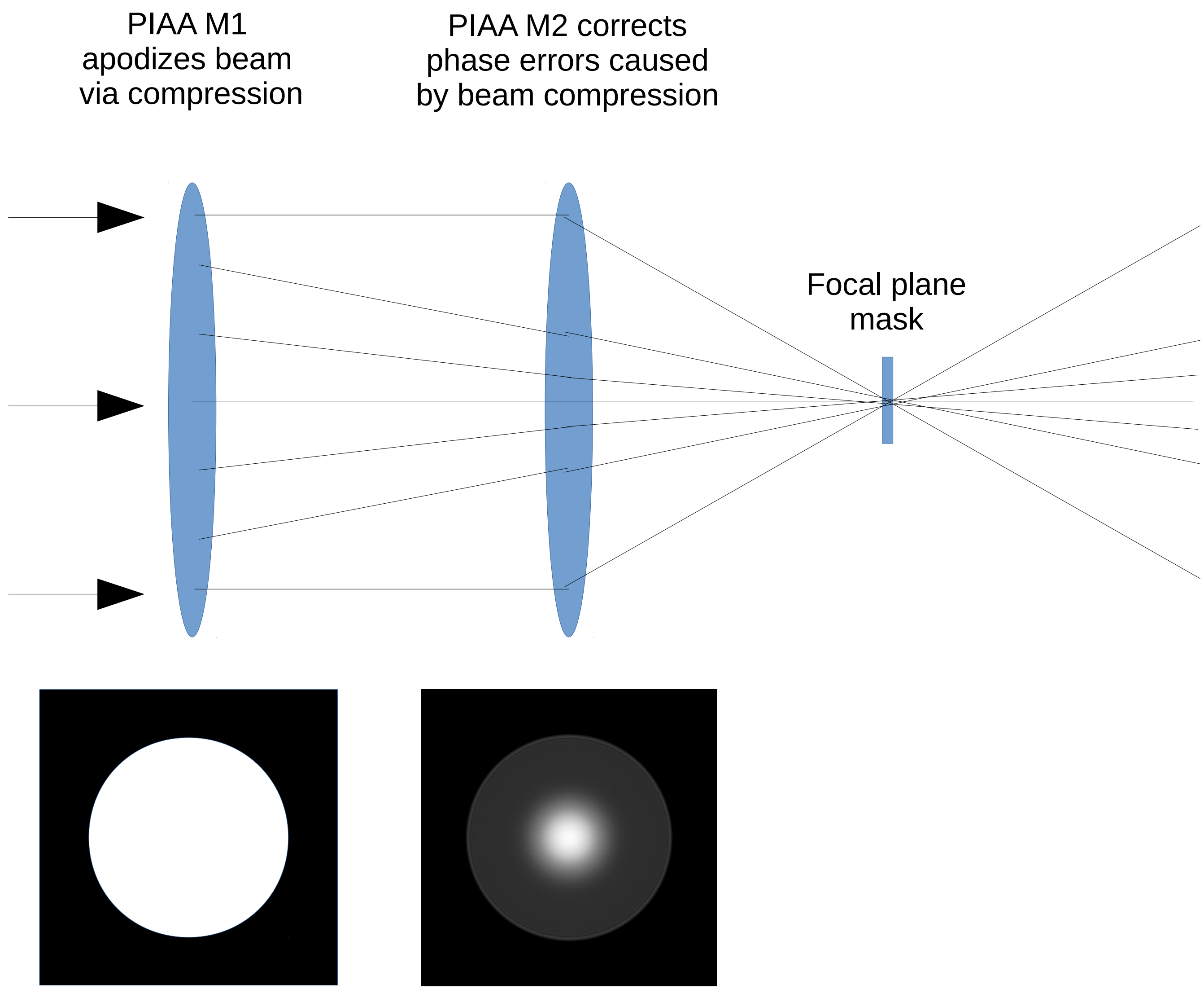
Optical Surface Error Maps



Dark Hole Generation Process



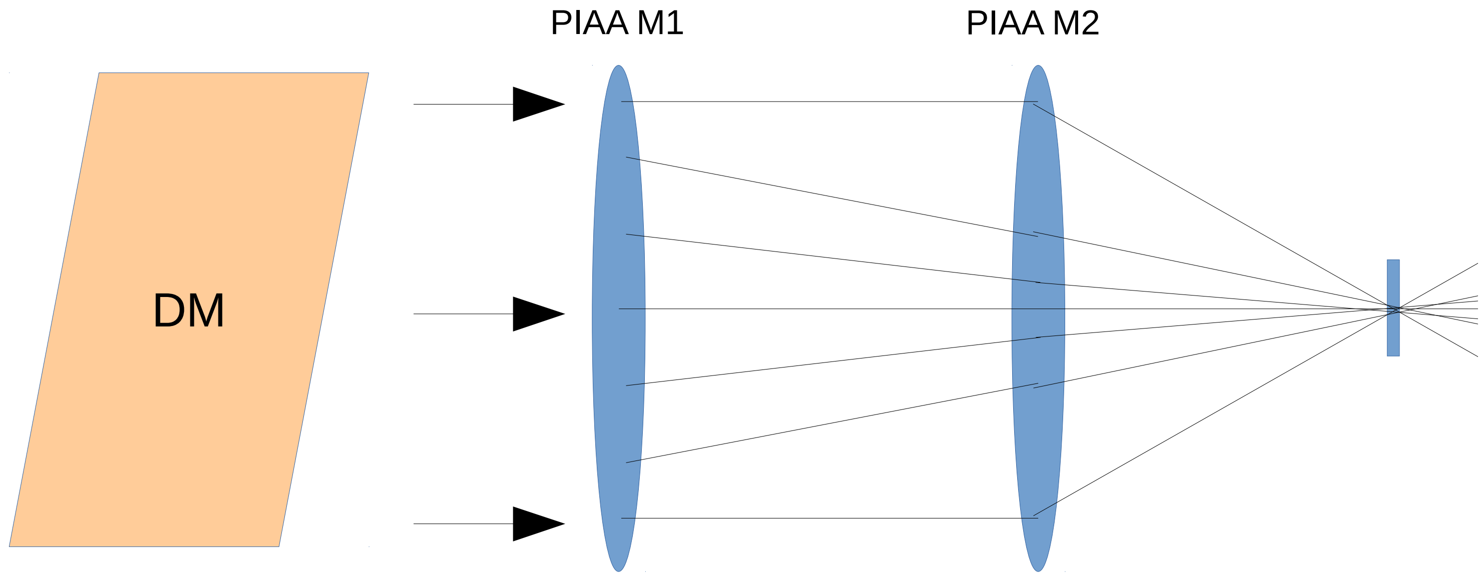
PIAA Schematic



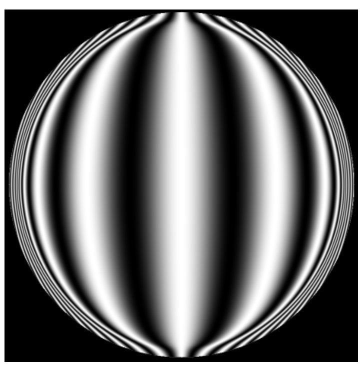
Beam @ M1

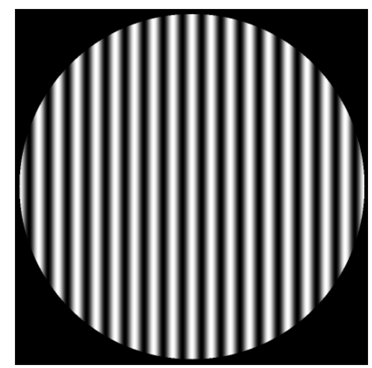
Beam @ M2

PIAA with Wavefront Control



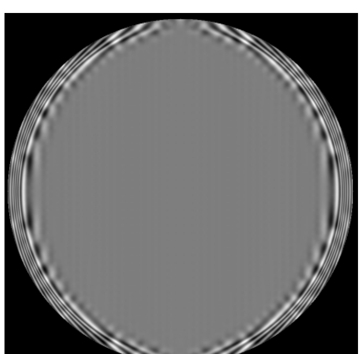
M2 error as seen by DM

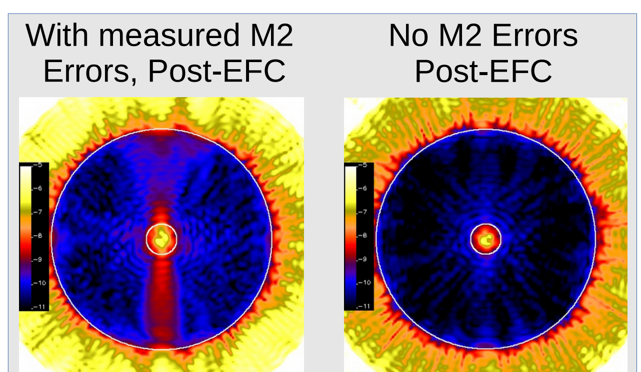




Error on M2

After DM correction

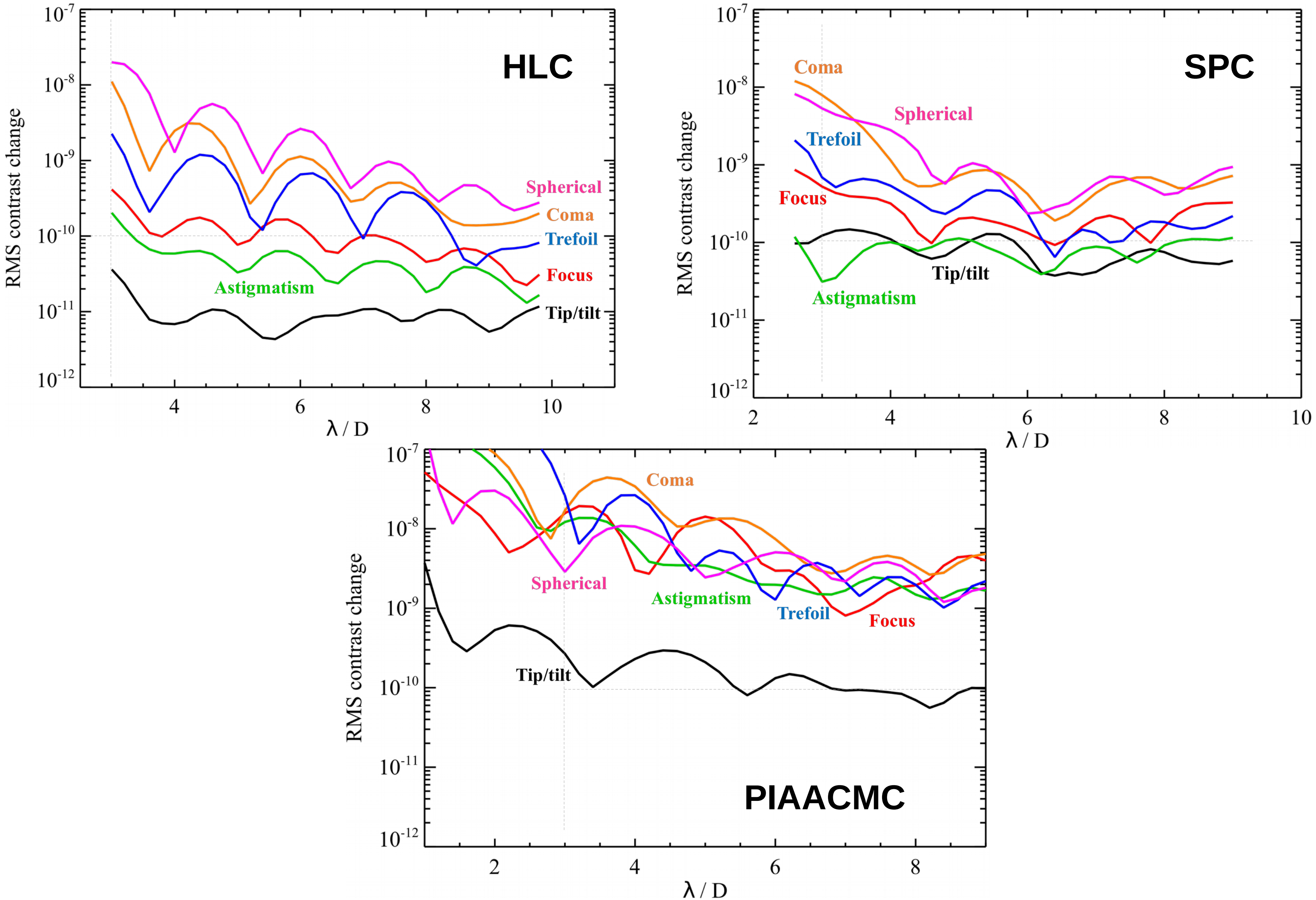




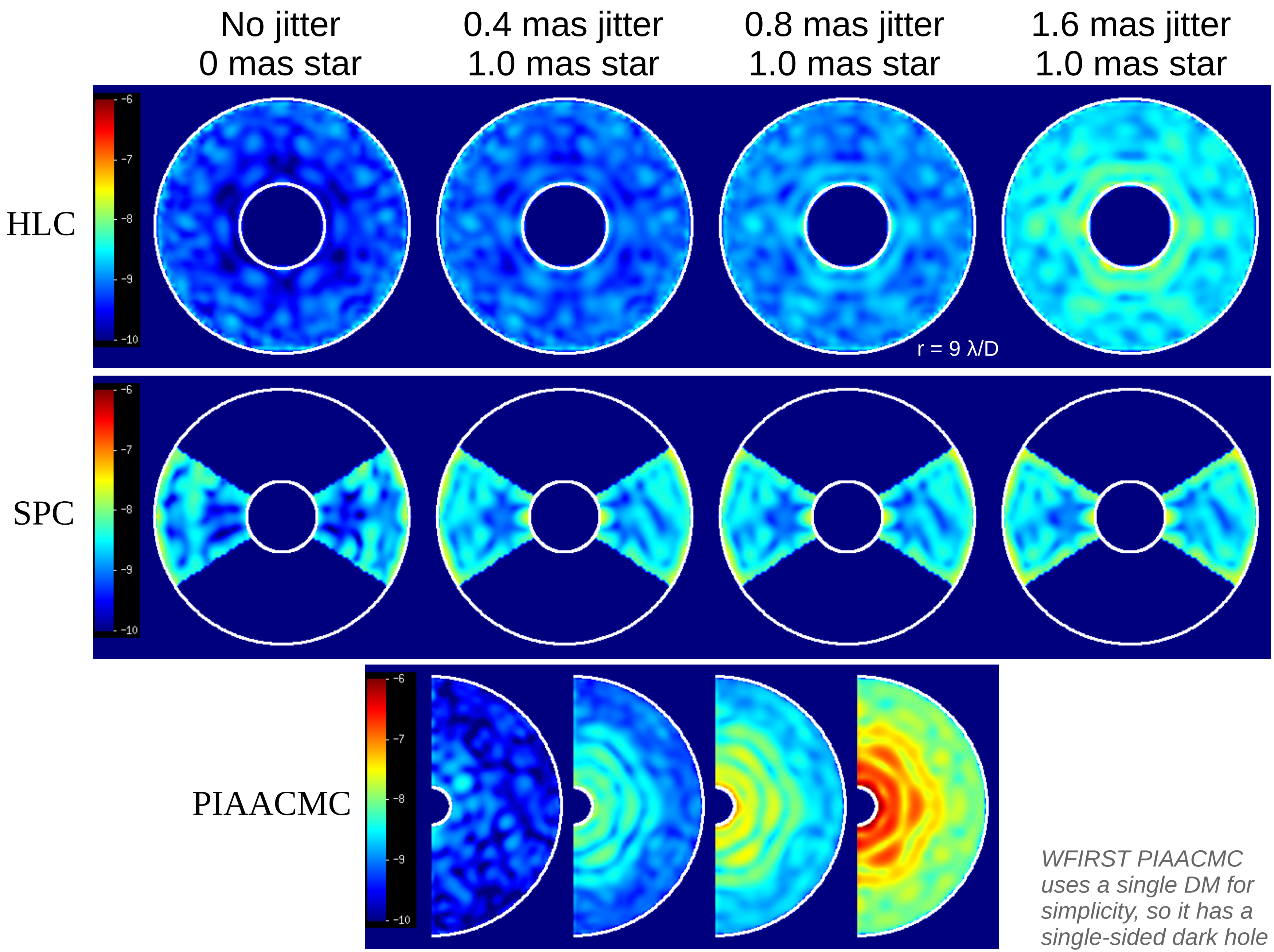
From Internal Coronagraph Modeling Milestone #2 Results Report by Krist et al.: exep.jpl.nasa.gov/technology

WFIRST Coronagraph Aberration Sensitivities

100 picometers RMS of aberration



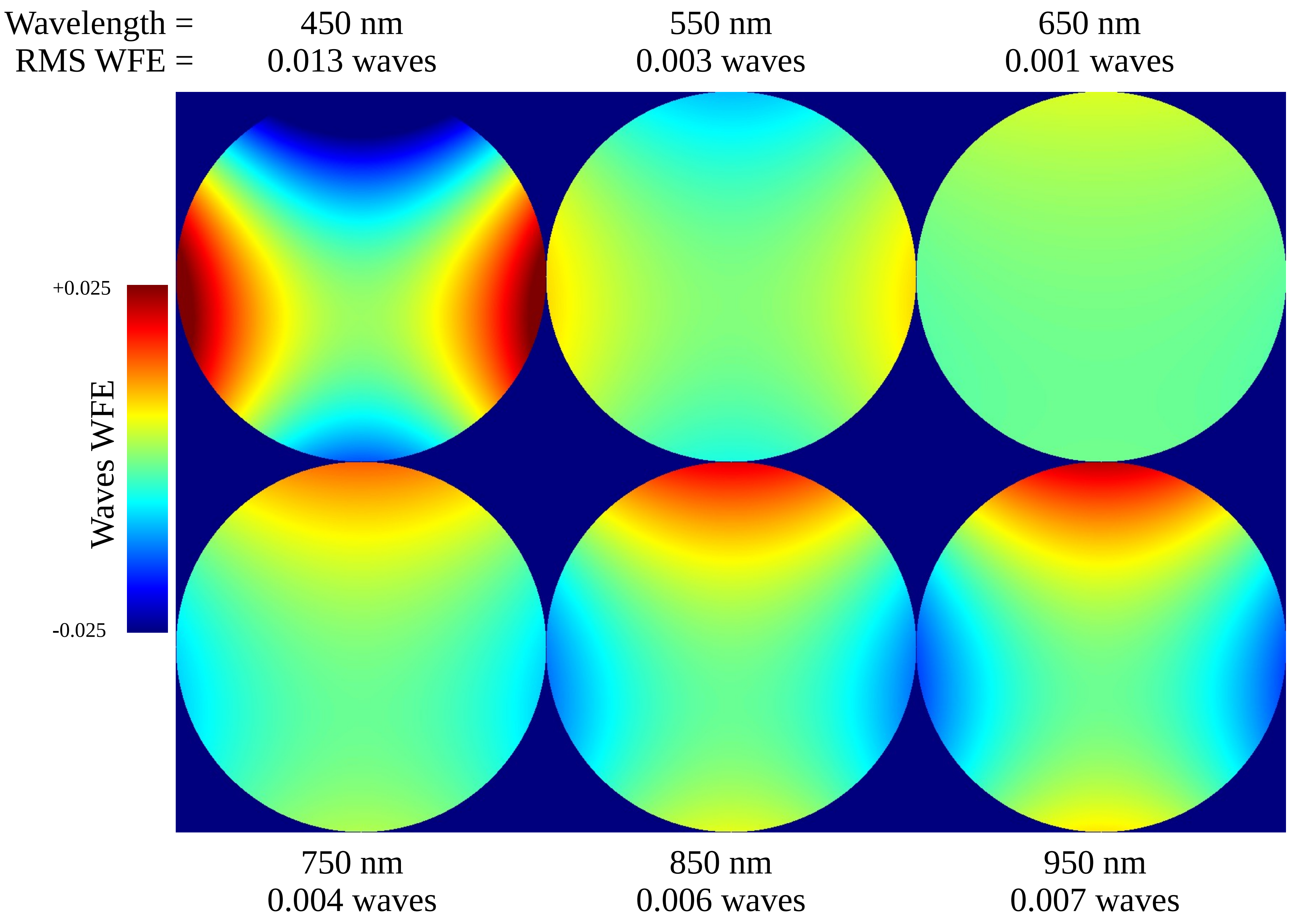
WFIRST Dark Holes with Pointing Jitter & Finite Star



WFIRST PIAACMC uses a single DM for simplicity, so it has a single-sided dark hole

WFIRST Polarization: WFE_Y-WFE_X

See tomorrow's talk by Shaklan

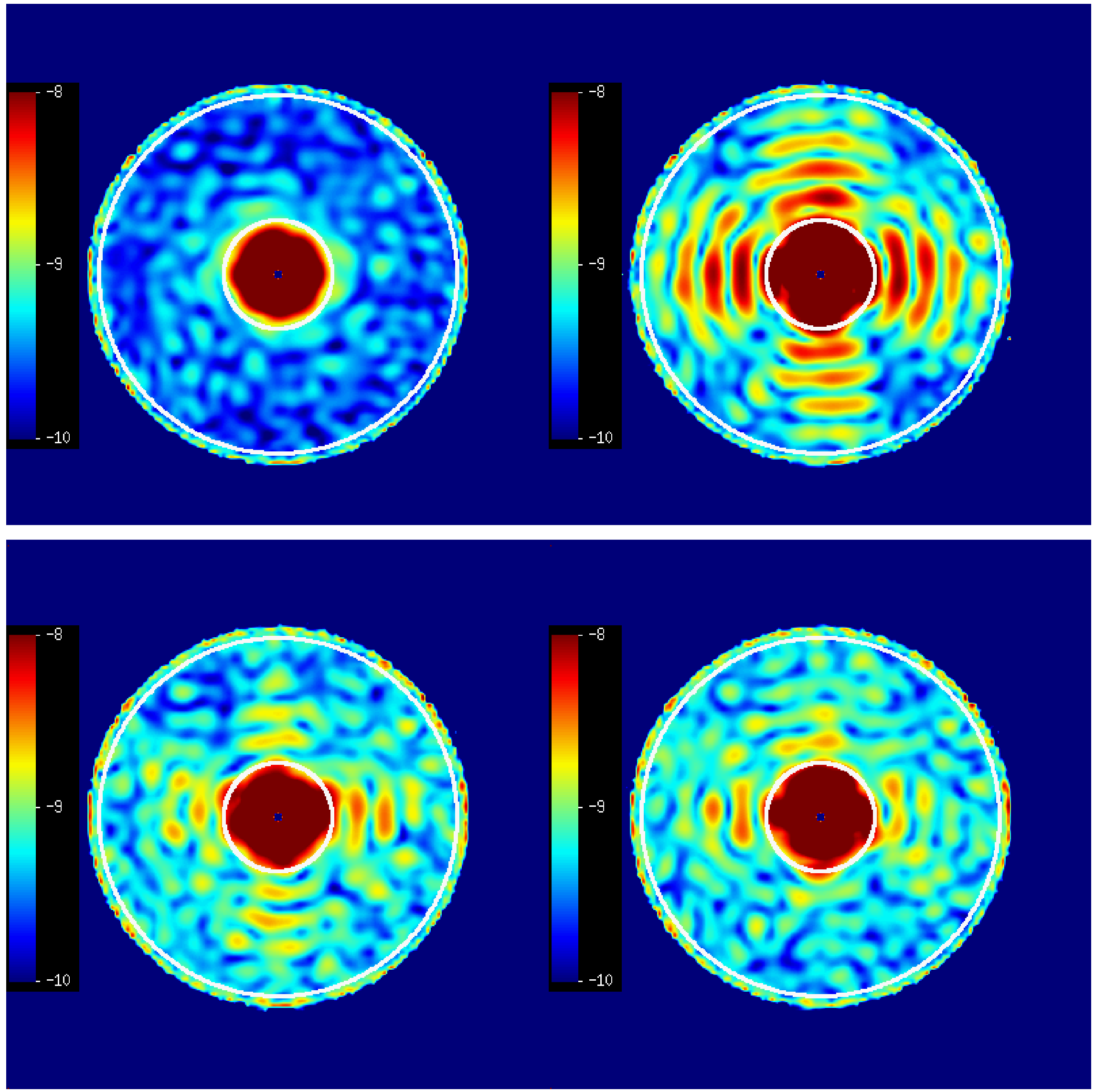


HLC Post-EFC with Polarization (523-578 nm)

X polarization | Y polarization

Optimized for X polarization only

Optimized for both polarizations simultaneously



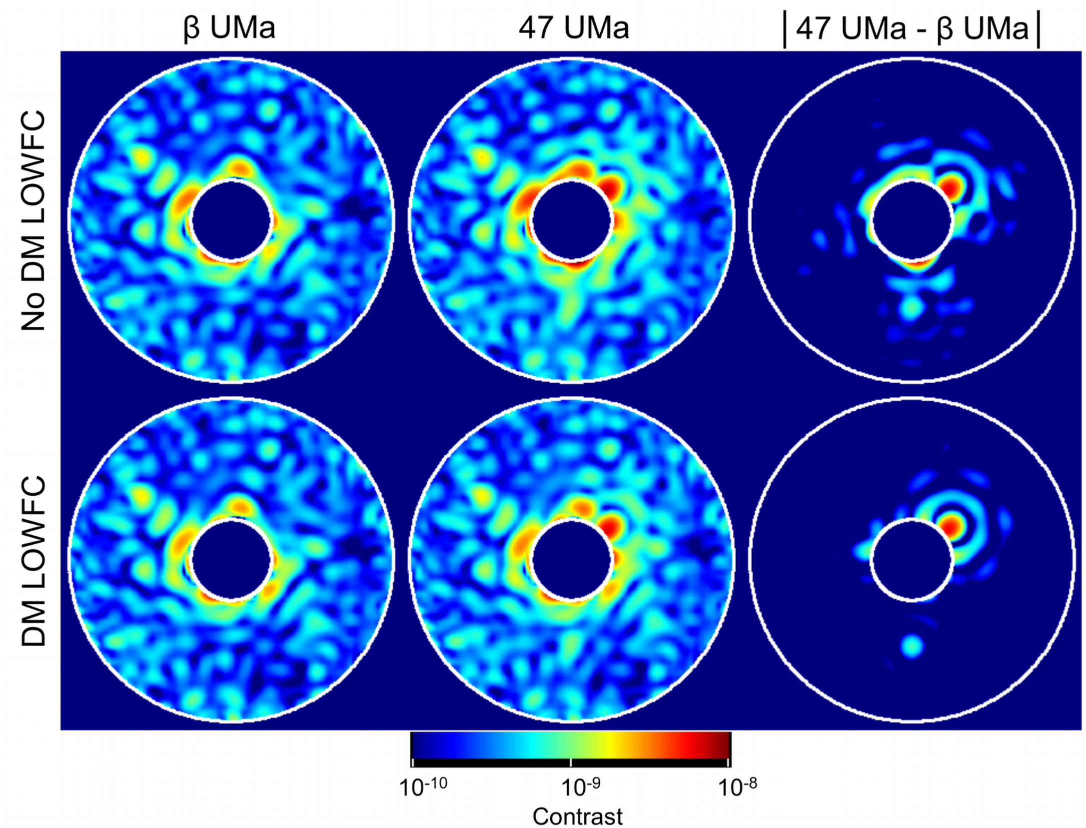
Circles are
r = 3 & 9.9 λ/D

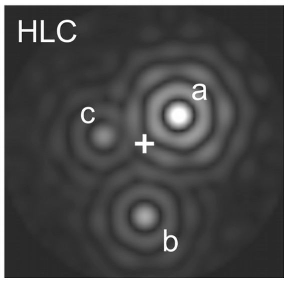
Polarization-induced aberration is mainly astigmatism due to the f/1.2 primary.

Time-Dependent Speckle Variations

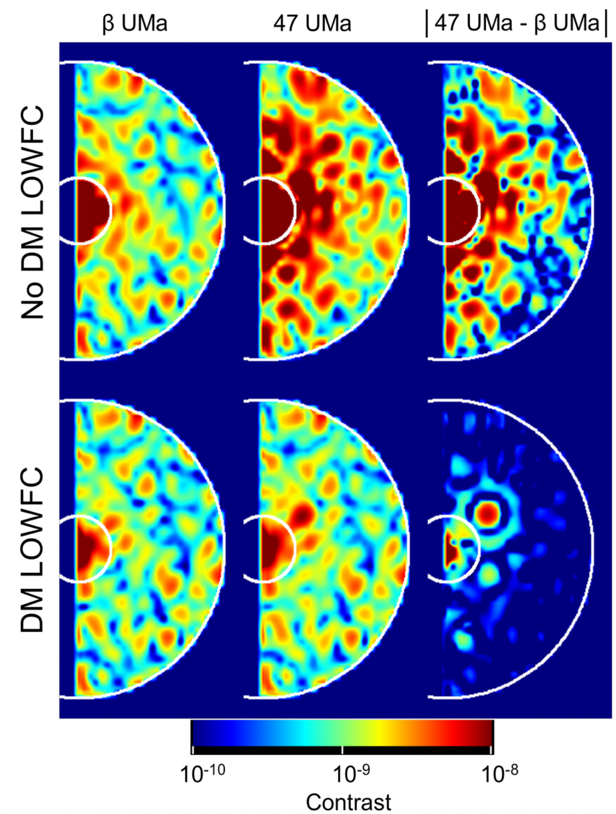
Wavefront changes from thermal & structural modeling

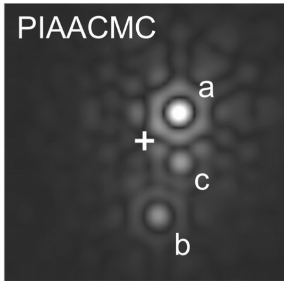
HLC





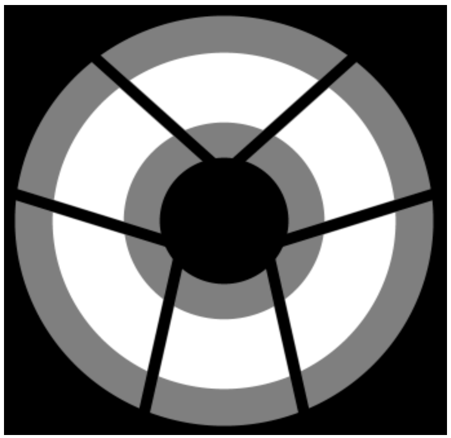
PIAACMC





Hybrid Lyot Coronagraph Planet PSF

λ = 509 – 591 nm, r = 3 – 9 λ/D,
7×10^{-10} IWA contrast (10^{-4} without DM patterns)

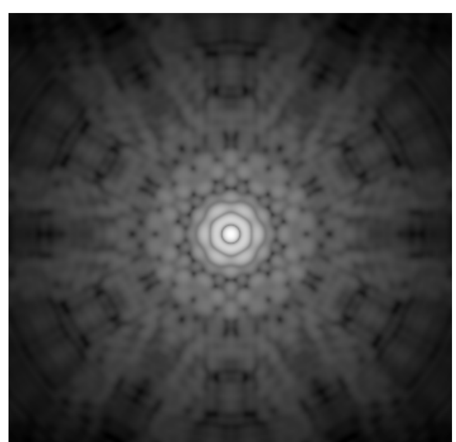


Lyot stop
(grey)

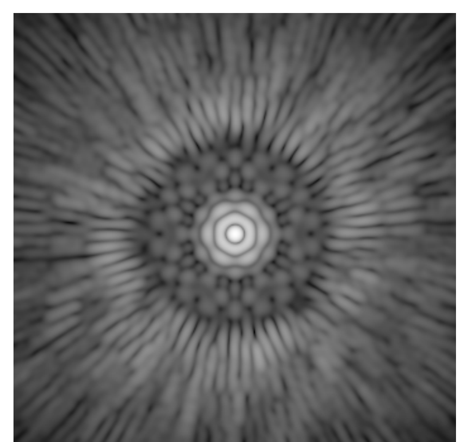
DM 1 DM 2

Obscuration-compensating DM patterns
(200 nm P-V stroke)

Planet PSFs

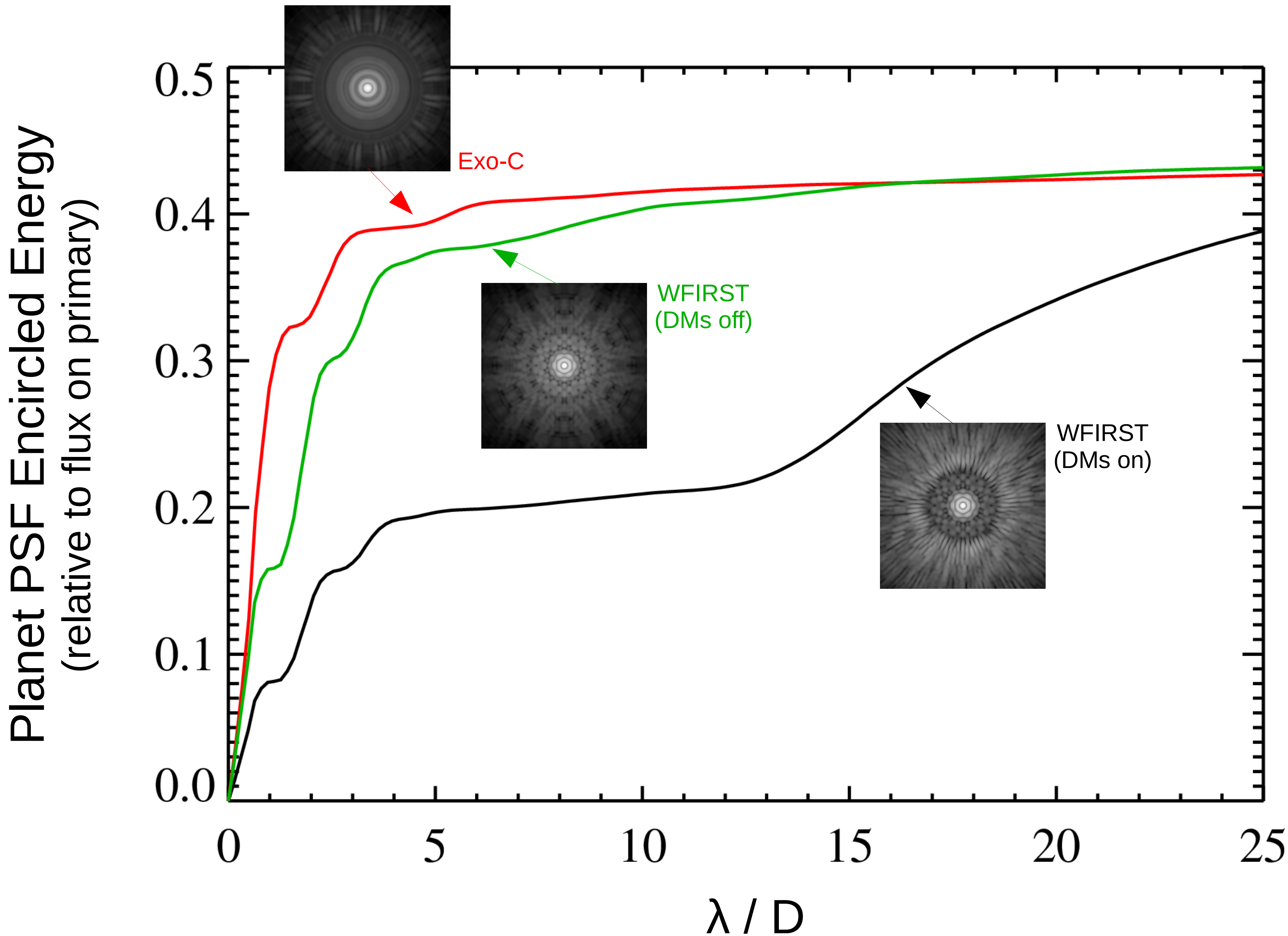


DMs off

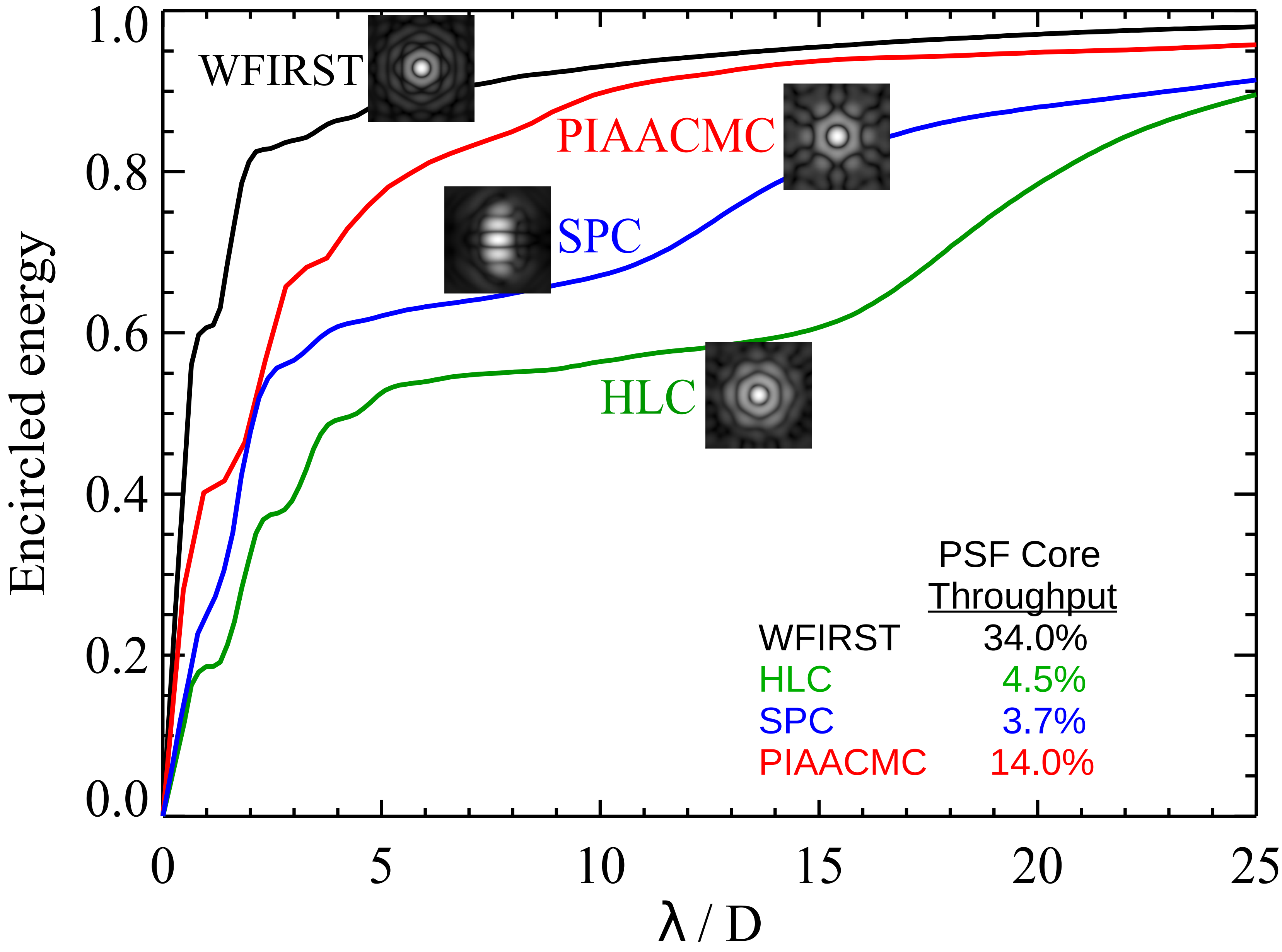


DMs on

Hybrid Lyot Coronagraph: Exo-C & WFIRST

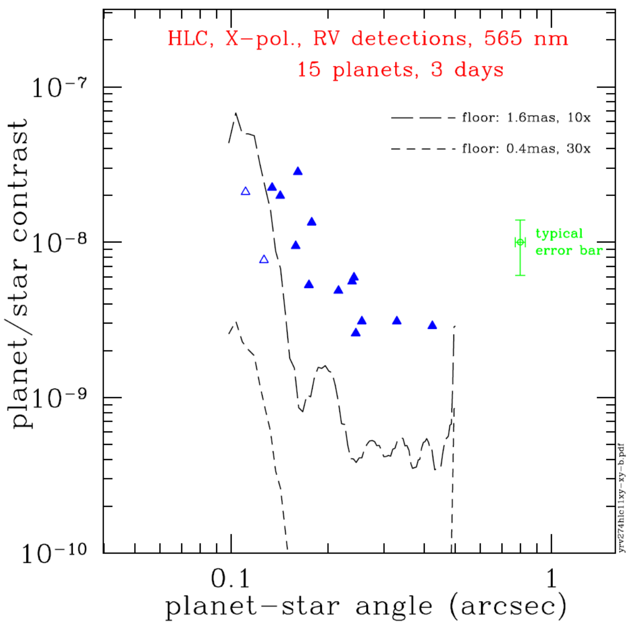


WFIRST Coronagraph Field PSF EE

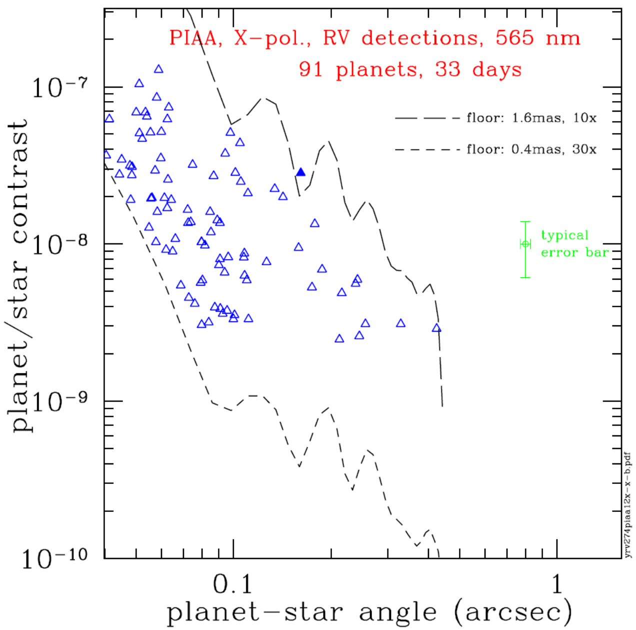


WFIRST RV Planet Yield Estimates

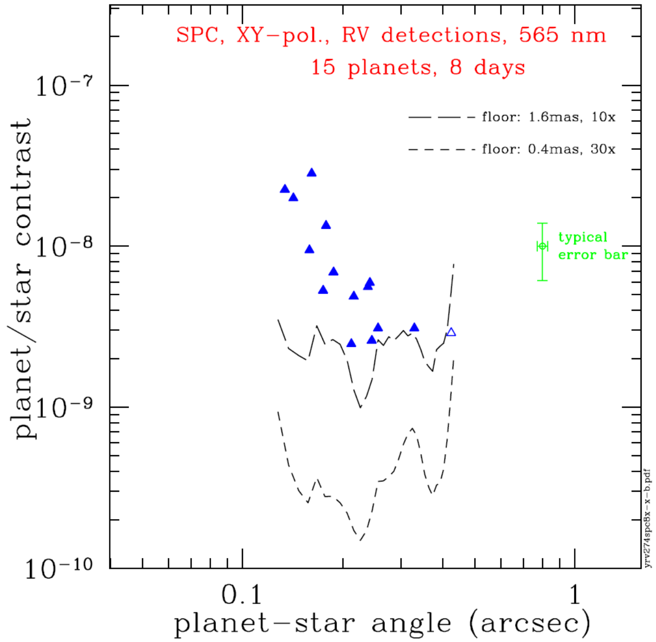
HLC



PIAACMC



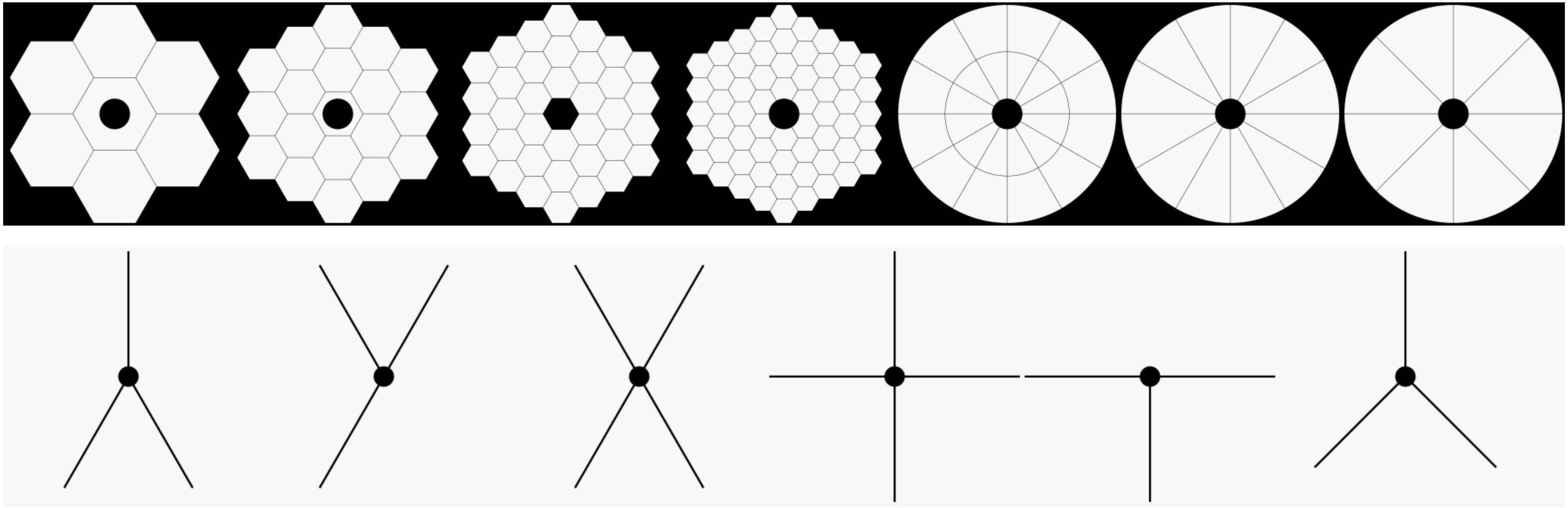
SPC



From Traub et al., JATIS, v.2, 011020 (2016)

See talks by Stark, Morgan in this workshop.

Segmented Telescope Coronagraph Considerations



Effective throughput

Planet PSF morphology

Aberration sensitivity

Segment-to-segment piston, global low-order, wavefront jitter

Jitter & finite stellar diameter

DM patterns (ACAD)

Affect on PSF morphology, increased aberration & jitter sensitivities, stroke limitations

Alignment tolerances

Mask-to-pupil registration, pupil distortion

Stages of Coronagraph Design