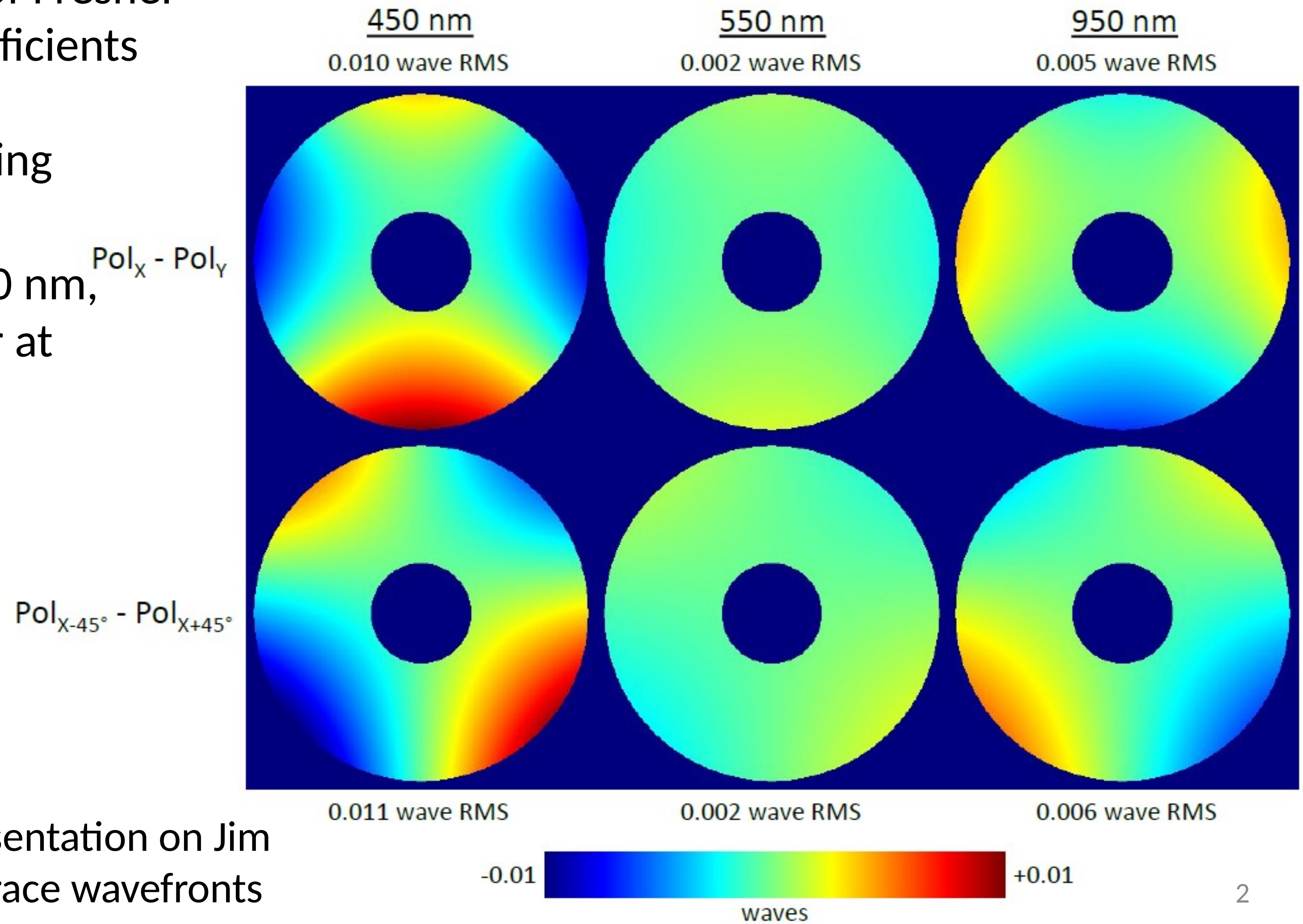
PIAACMC polarization

WFIRST polarization

- WFIRST fast primary (F/1.3) creates variable linear retardance
  - Combination of Fresnel reflection coefficients and multilayer dielectric coating
  - Effects are weakest at 550 nm, much stronger at 450 nm



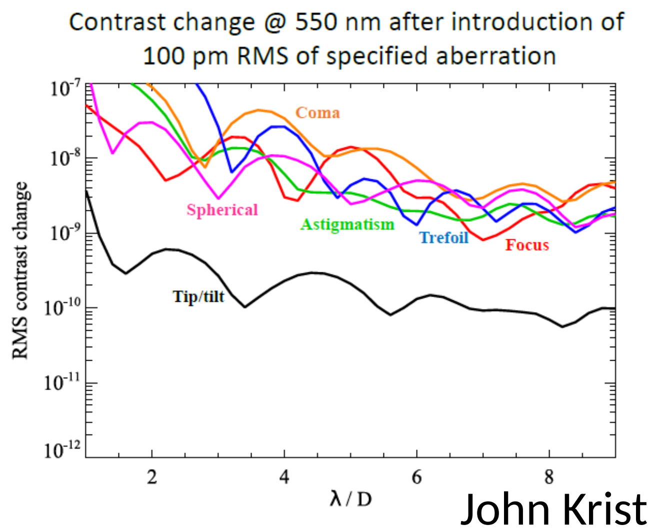
John Krist's presentation on Jim McGuire's ray-trace wavefronts

WFIRST polarization generalized

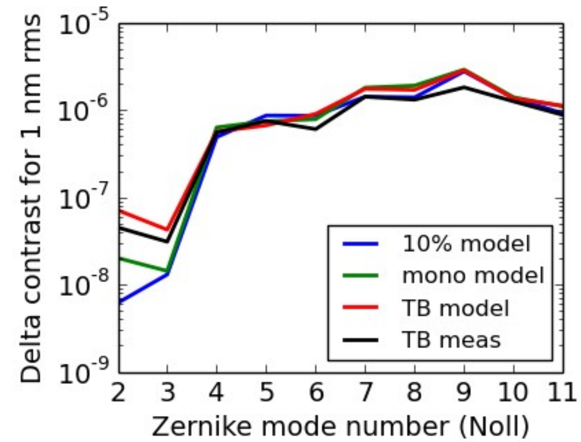
- Two problems:
  - Variation of wavefront error with input polarization state
    - Unpolarized light is incoherent sum of two orthogonal polarization states
    - Each input state receives different WFE
  - Variation of output polarization state with pupil position
    - Wavefront control can't interfere different polarization states to cancel one another
- These two categories each produce a dominant astigmatic phase term
  - Variation between cases is +/- sign
  - Astigmatisms of each are in orthogonal spatial modes
    - Variation of WFE can't cancel variation of output polarization state
    - Magnitudes of the effects (WFE variation, pol variation) are same
  - Some contribution of tilt due to off-axis nature and folds

PIAA Gen 3 sensitivity

- Sensitivity of WFIRST PIAACMC Gen 3 to astigmatism is high
  - 2 mλ rms @ 550 nm ~ 1 nm rms
  - 1 nm rms astig ~ 10^{-6} contrast @ 3 λ/D
- We can put analyzer in system to eliminate second problem
  - Variation of output pol across pupil
- We cannot put polarizer in front of telescope primary
  - Variation of WFE with input polarization remains

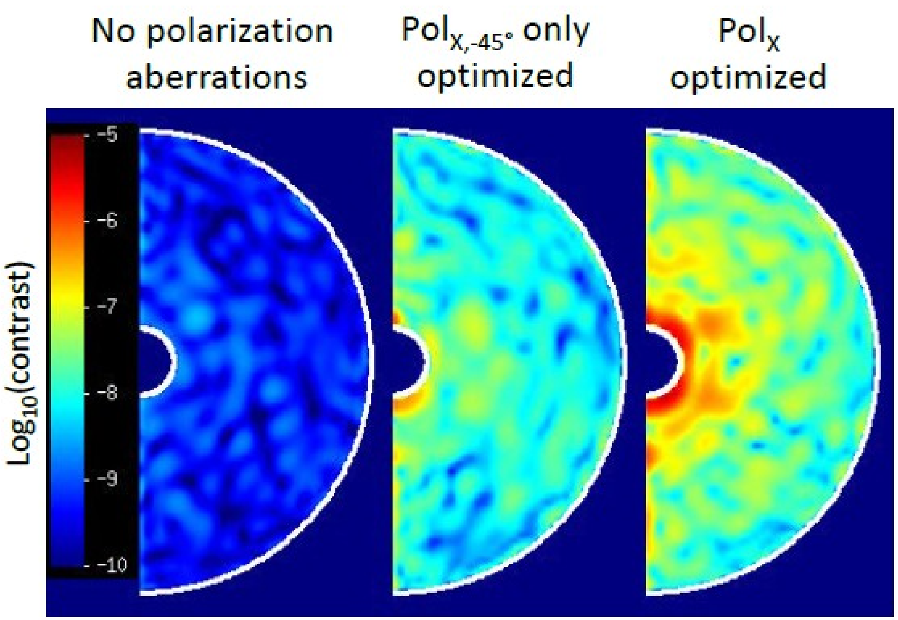


John Krist's analysis

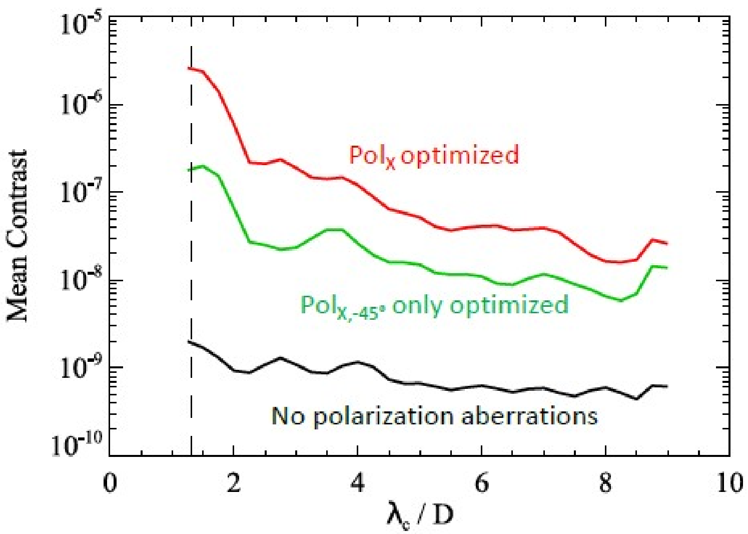


Polarization impact on contrast

- Resulting contrast with analyzer in place is > 10^{-7}
- Even with polarizer in front of primary, variation of WFE with wavelength is strong effect
  - Astigmatic term varies from 2 mλ to 10 mλ from 550 nm to 450 nm



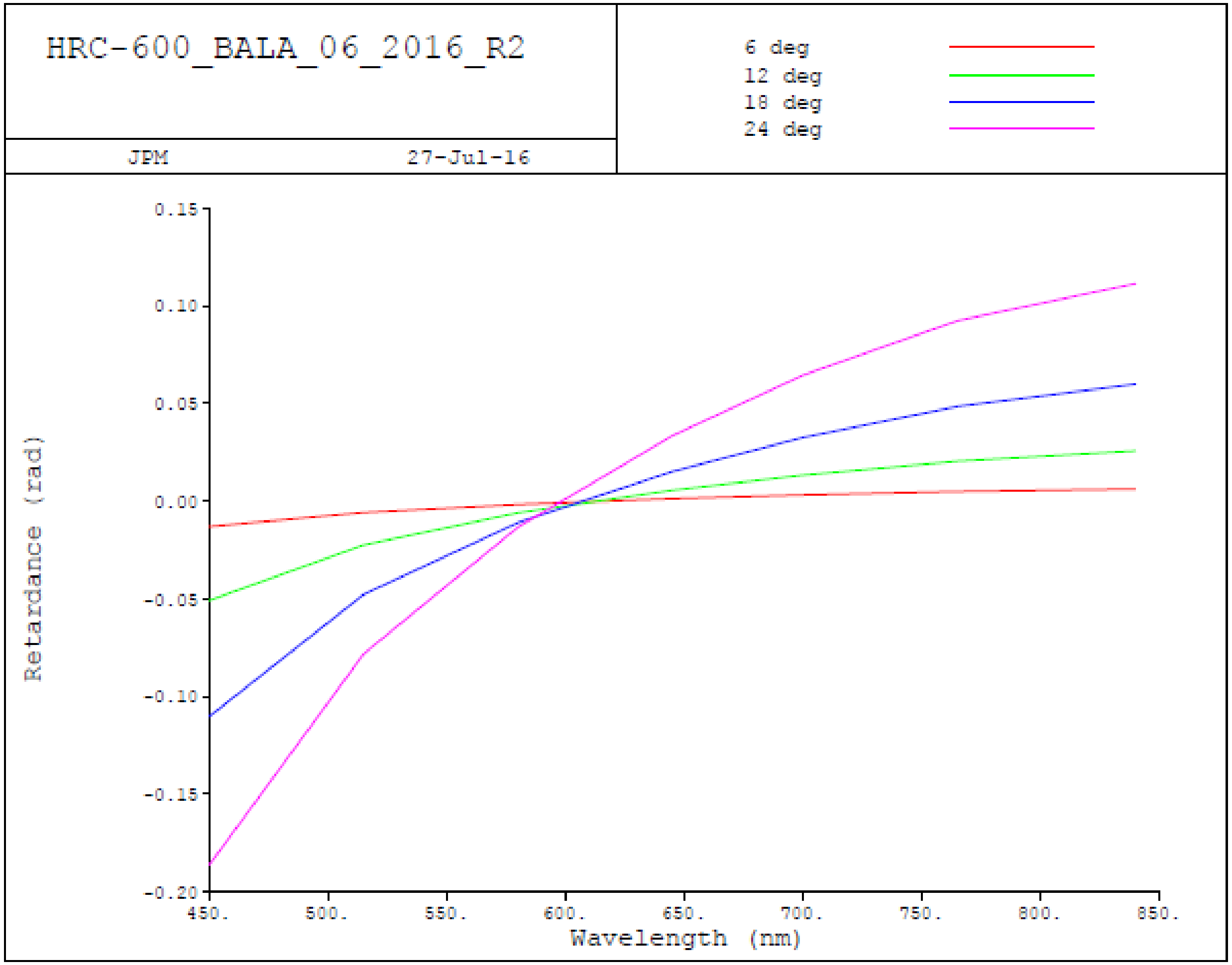
Circles are r = 1.3 & 9 λ_c/D



John Krist's analysis

Backup info on Fresnel reflection coefficients

- At OD of F/1.3 primary, angle of incidence is ~ 11 deg
- At 550 nm, retardance is ~ 0.02 rad ~ 3 mλ
- Difference between orthogonal inputs is 2x P-V, ~ 6 mλ
  - rms ~ P-V / 5 for astig



Jim McGuire's presentation of Bala's calculations

(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

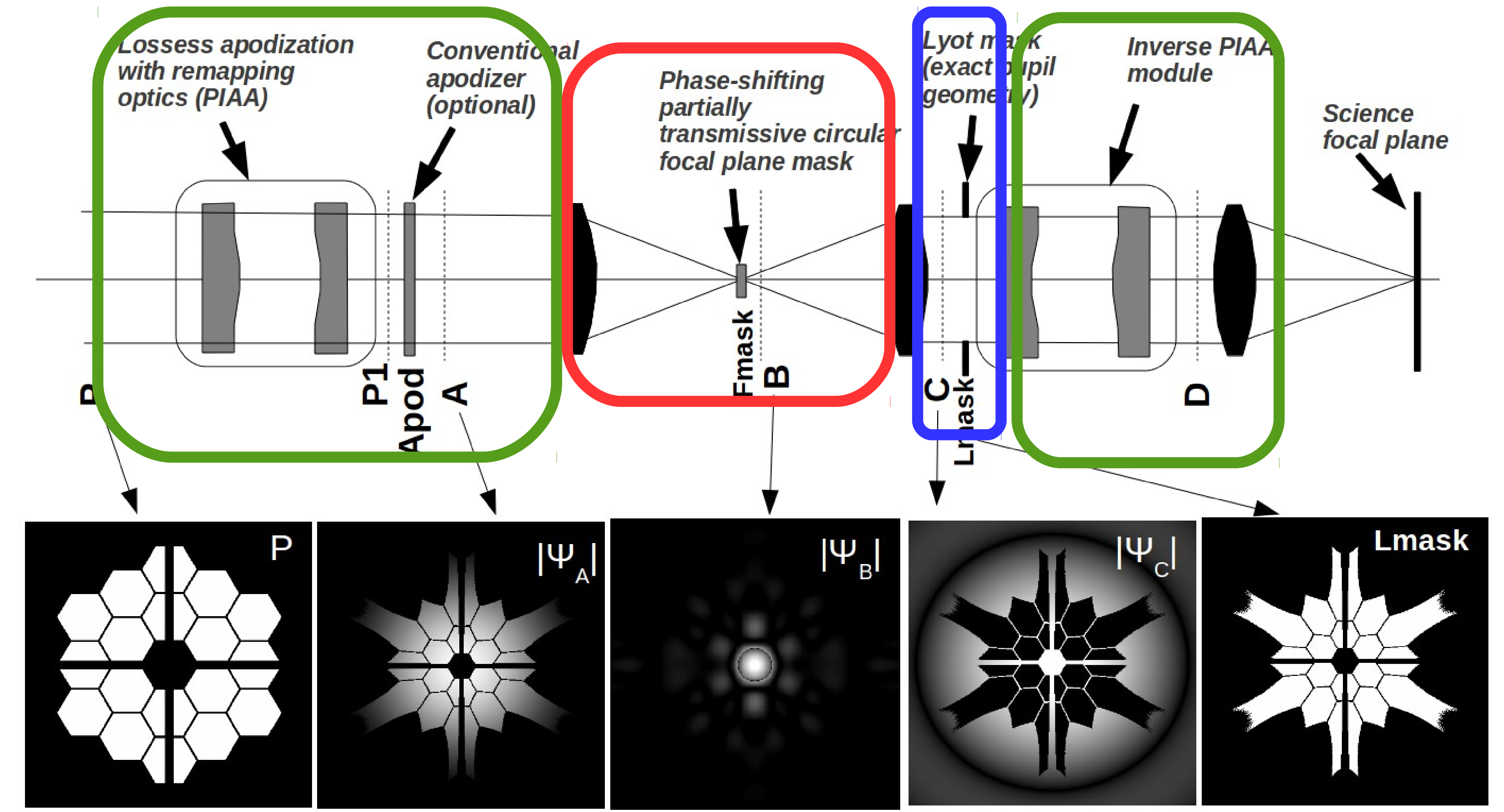
Lyot stop

Blocks starlight

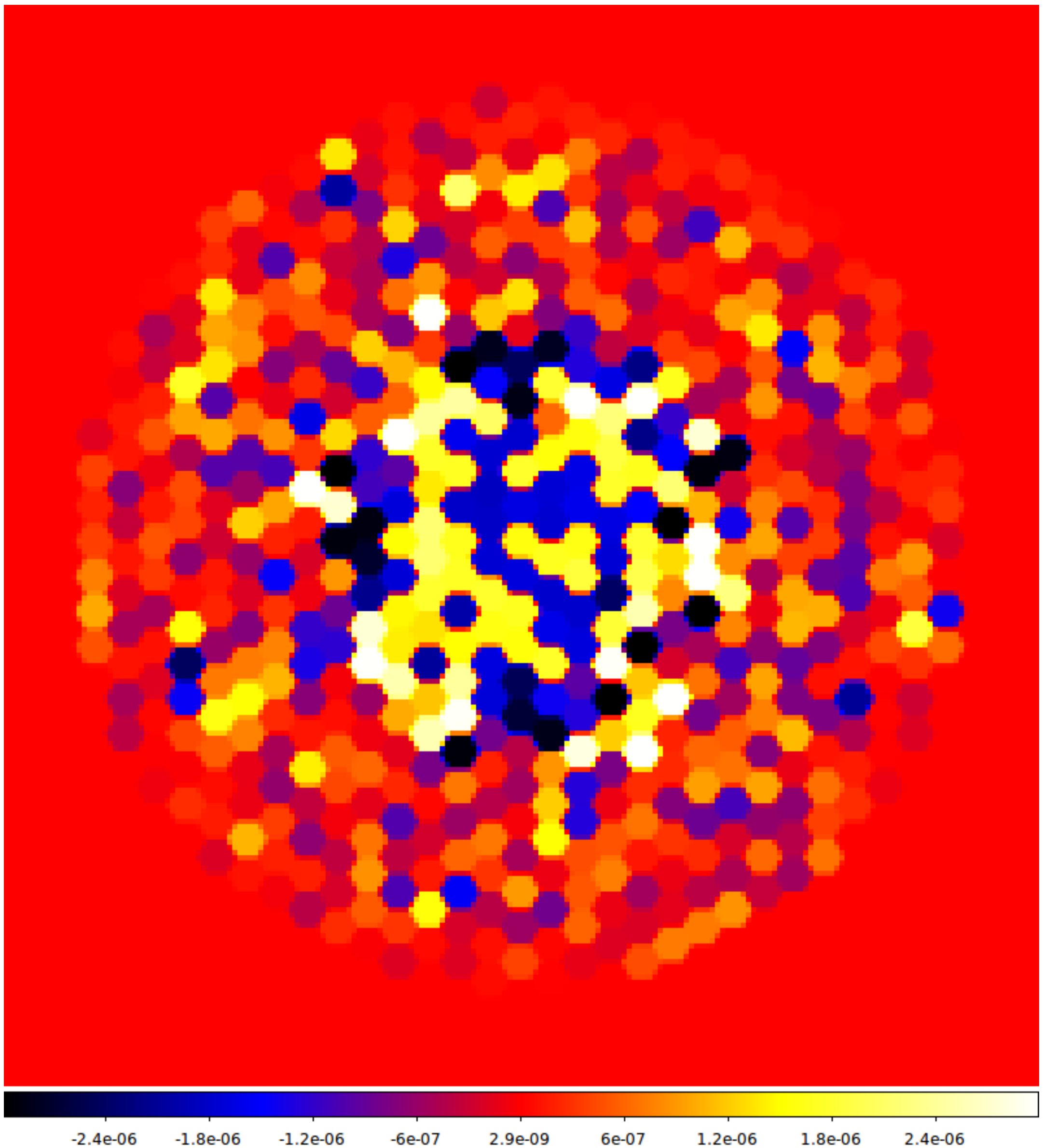
Inverse PIAA (optional)

Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Focal plane mask



Multiple zones (sectors for Gen3, now hexagons) phase-shift light

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

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

PIAACMC
Polarization issue

Our approach:
Mitigate polarization sensitivity by optimizing mask design
(motivated by previous success using same approach for Tip-Tilt)

Focal mask zones are optimized to maximize contrast across a 10% spectral band for 5 wavefront maps:
- 3 flat tilted wavefronts
- positive and negative astigmatism, 0.01 wave RMS

~ WFIRST polarization error at 450nm

~ 5x larger than WFIRST polarization error at 550nm (25x contrast factor)

PIAACMC
Polarization issue: software

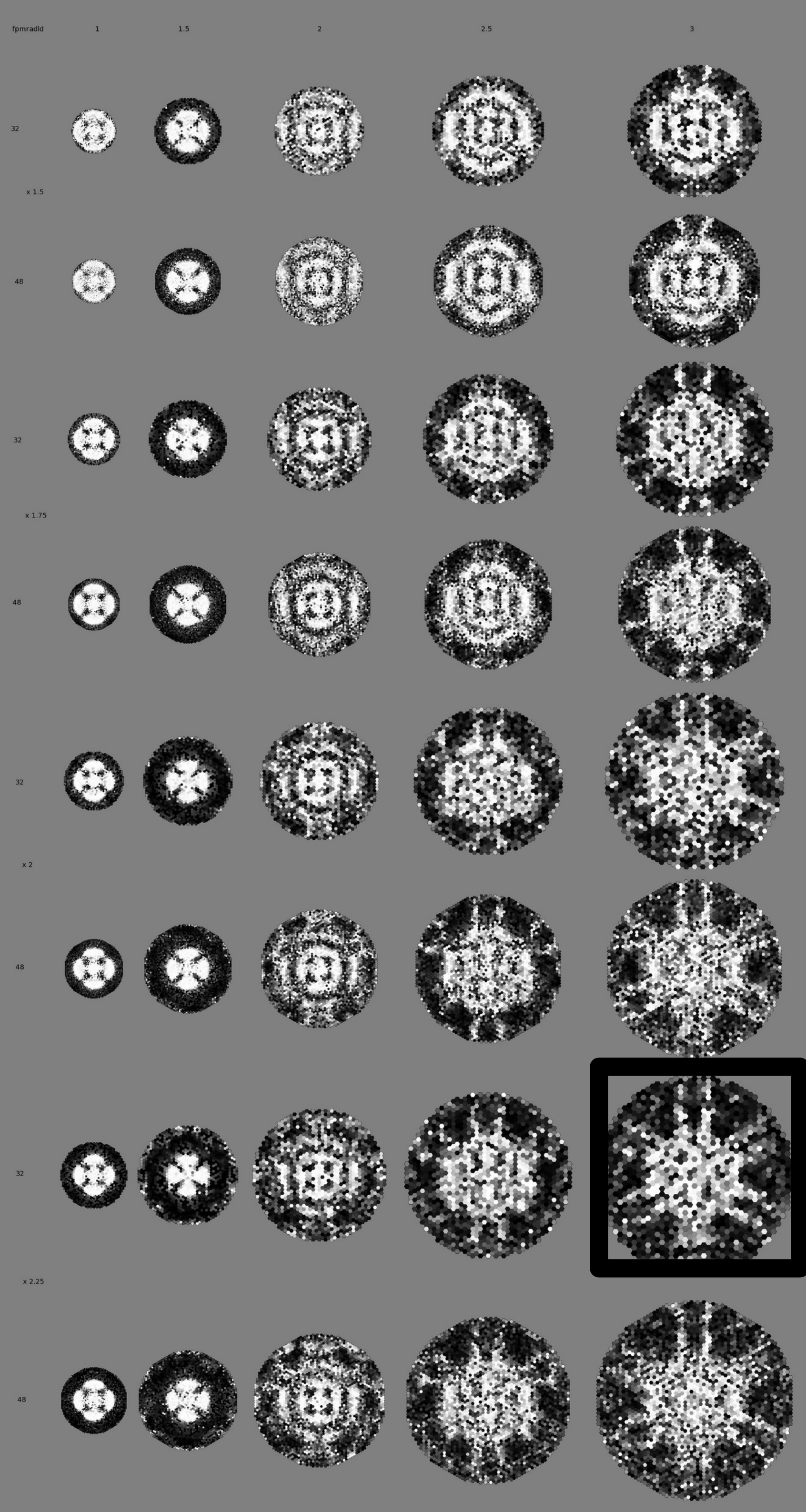
PIAACMC design software :
www.github.com/oguyon/PIAACMCdesign

Added new capabilities since Gen3 design:
- better regularization of focal plane mask → less IWA-damaging, easier to manufacture
- better search → higher performance, ability to design larger focal plane masks
- added arbitrary WF error input (astig)

Code review, cleanup and usage (Ames team):
→ now runs on Linux & OS-X systems with GPU acceleration
→ runs on Ames hyperwall cluster for rapid parameter exploration
128-node cluster, each: 20 cores, 64GB mem, 646 Tflop/s GPU

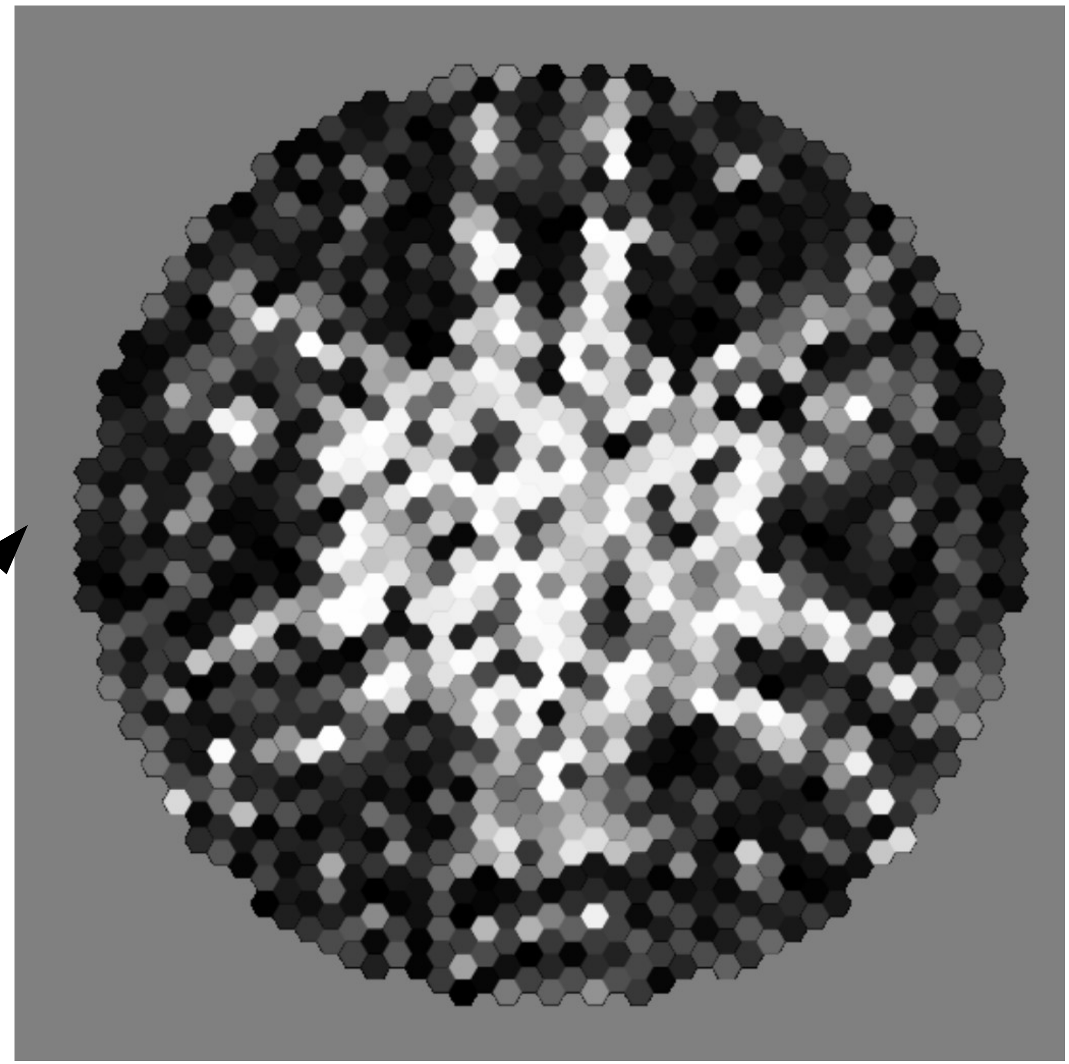
Independent verification of results at Ames (Dan Sirbu)

PIAACMC
Focal plane mask examples

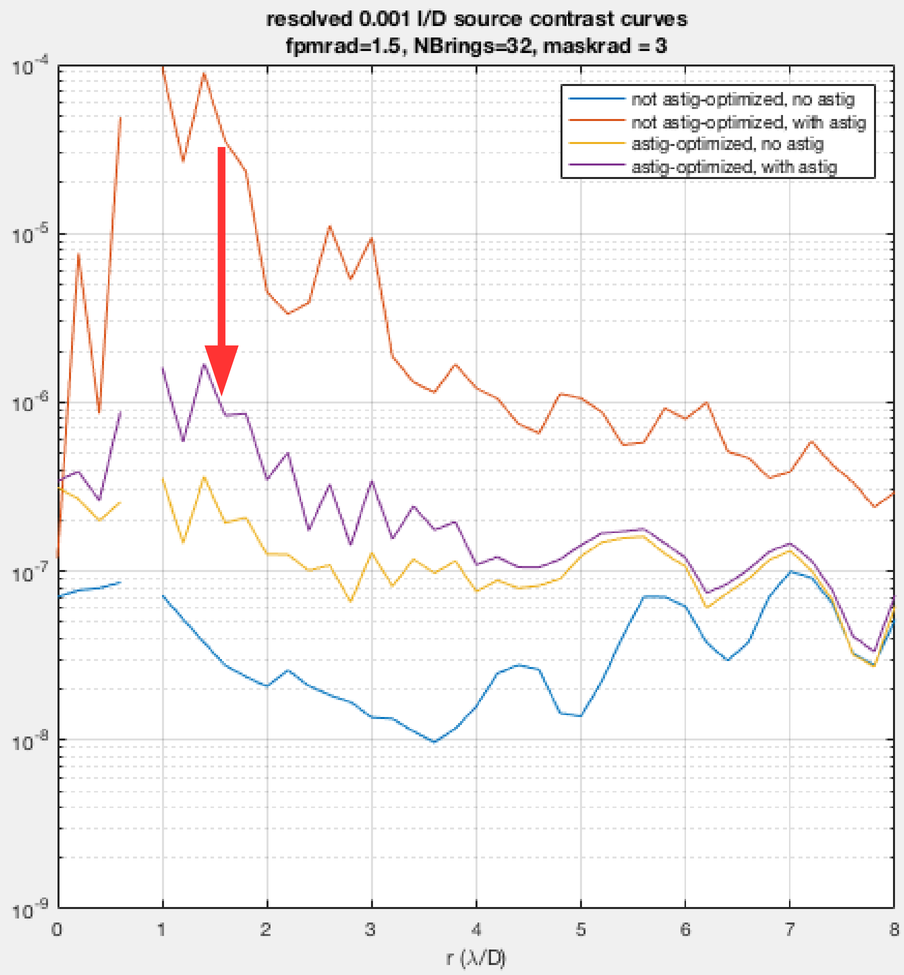


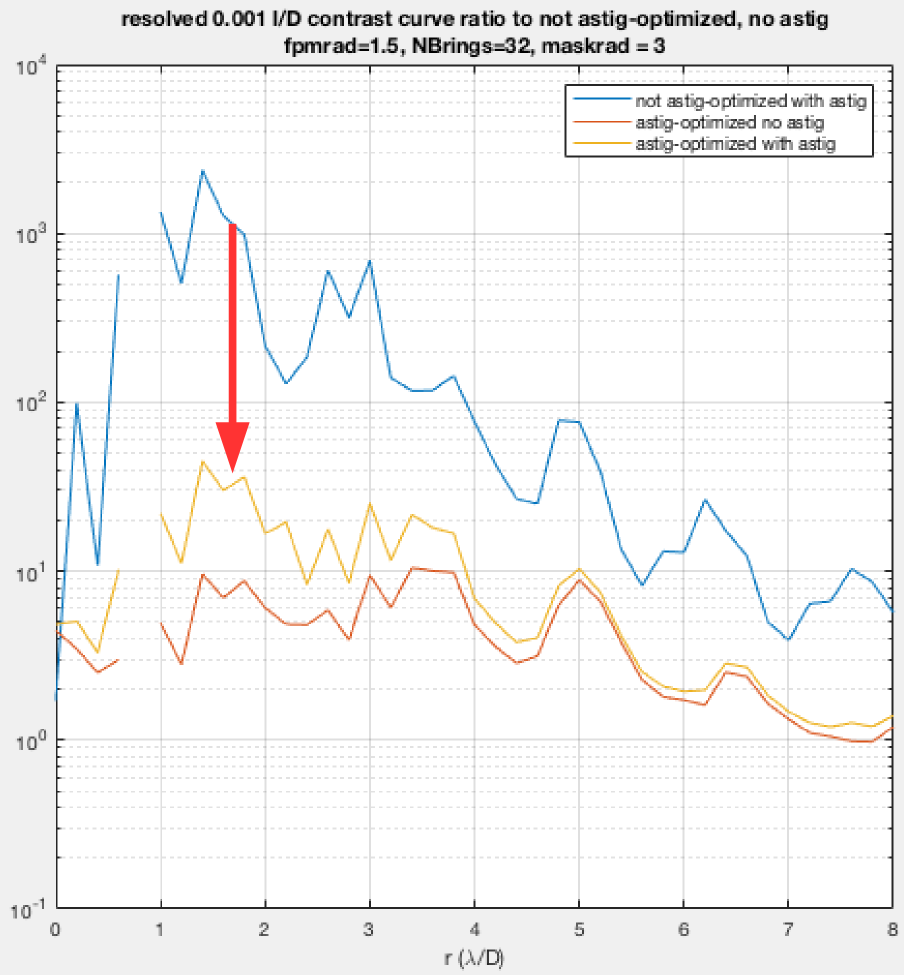
Shown here: amplitude of (1 – FPMcomplexamplitude)

0 (black) ↔ high throughput

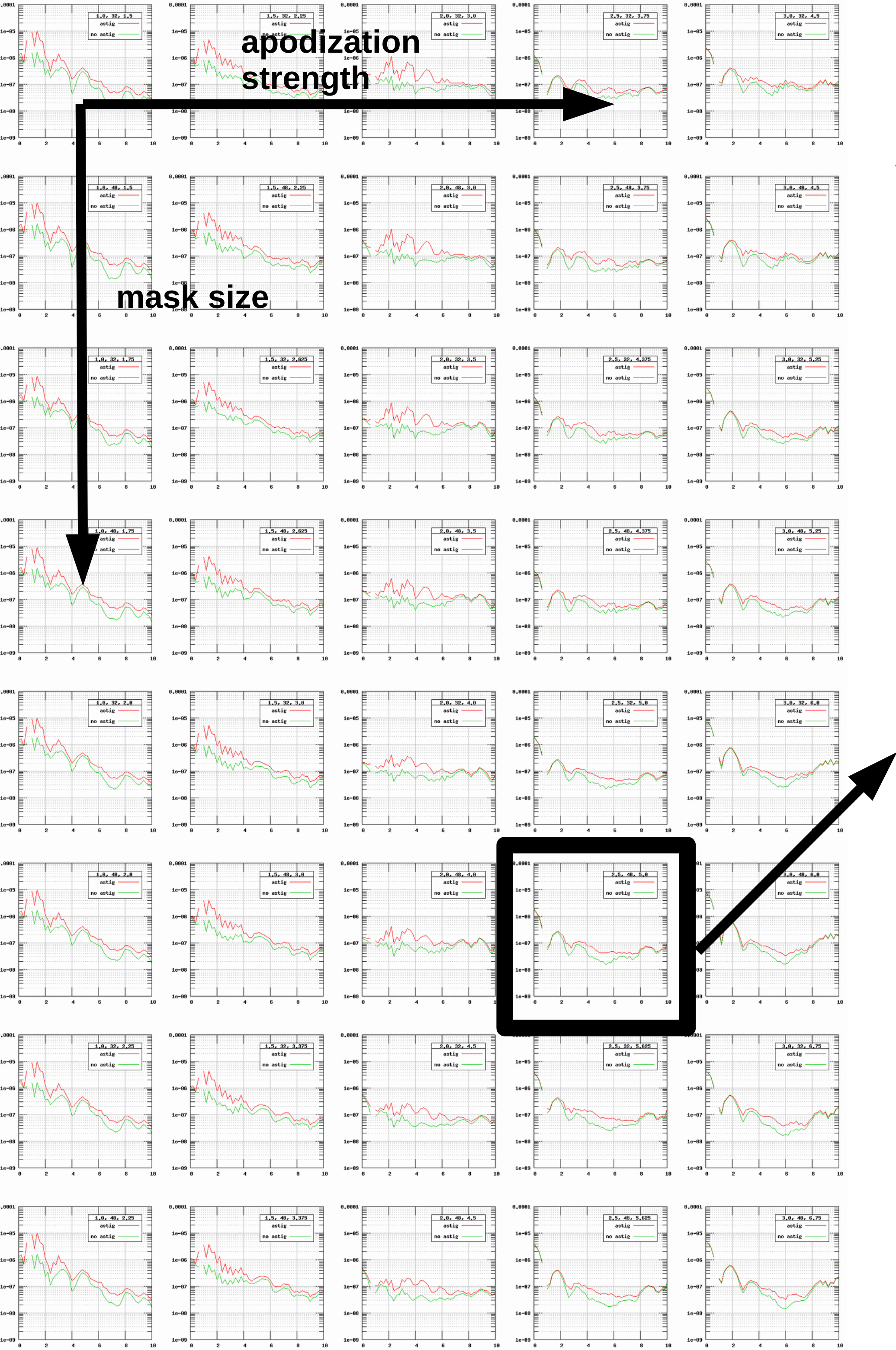


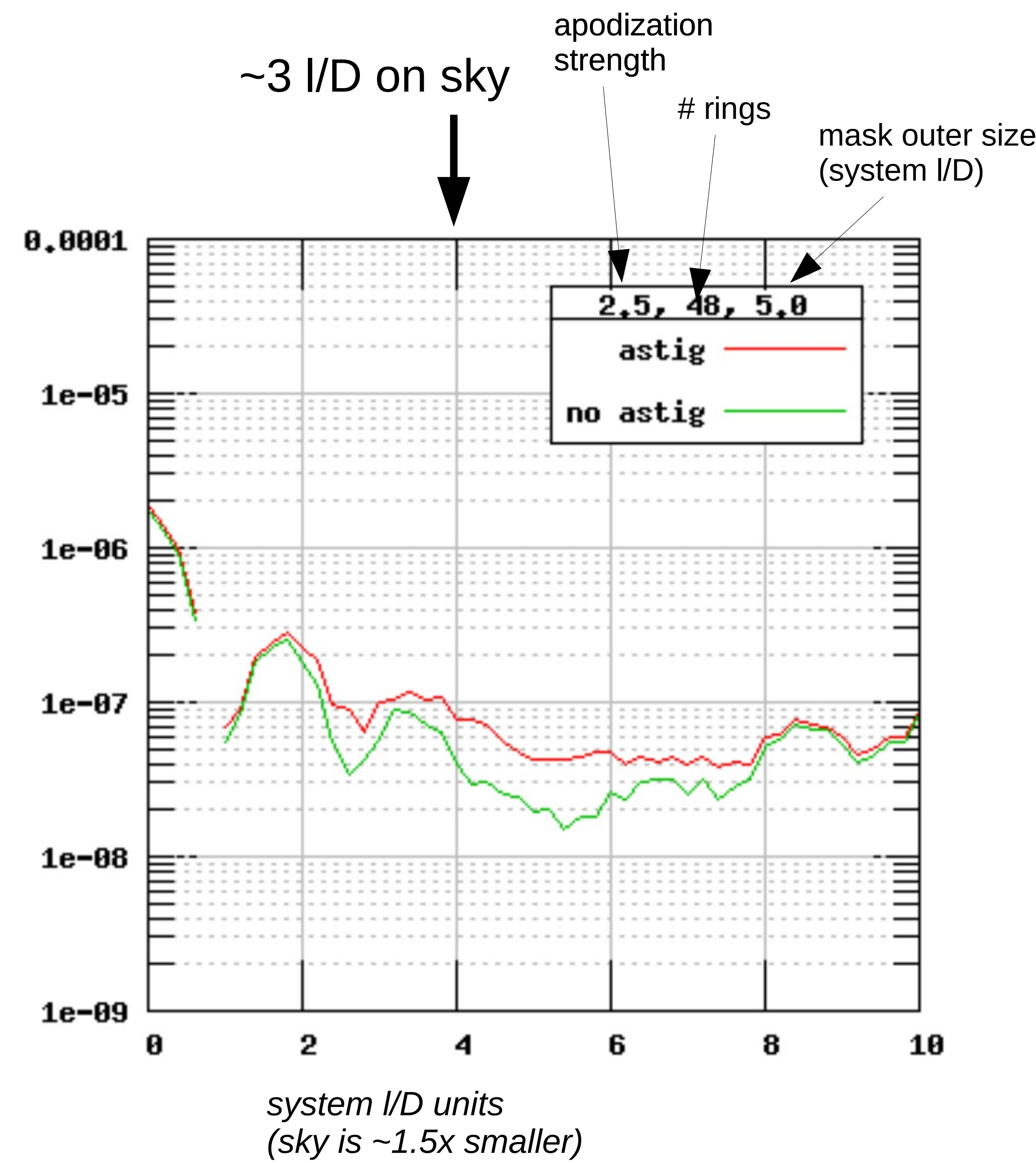
FPM design mitigates polarization 10-25x gain in contrast observed





Extensive parameter scan @ Ames hyperwall





PIAACMC
Polarization issue: preliminary conclusions

Focal plane mask design does mitigate polarization sensitivity by rejection of specific WF modes (astigmatism)

We have **reduced polarization sensitivity by 25x** for the “worst case” WFIRST band (450nm, 0.01 wave astig). In this case, polarization dominates contrast, but unclear if 25x gain carries to other cases

Larger focal plane mask size, stronger apodization seems to help → there is a small cost in IWA (to be quantified accurately, probably around 1.5-1.7 l/D instead of Gen3's 1.3 l/D)

Results are preliminary:
- does not include simultaneous optimization with strong TT jitter
- does not include details of wavelength dependency of polarization astig (should improve performance)

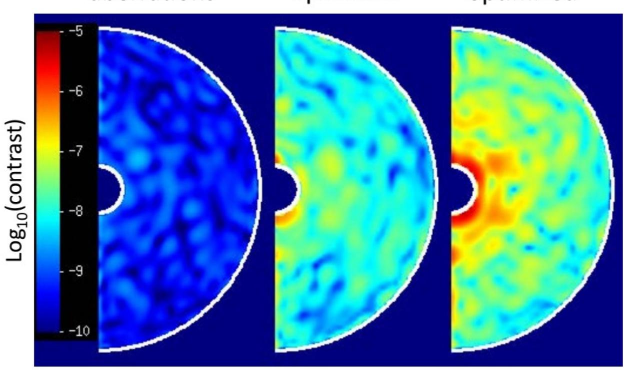
Polarization-limited contrast

PIAACMC polarization analysis @ 550nm, where polarization effect is 5x less than 450nm band simulated by PIAA team, shows ~1e-6 contrast @ 2 l/D, and ~1e-7 contrast at 4 l/D (see J. Krist slide below)

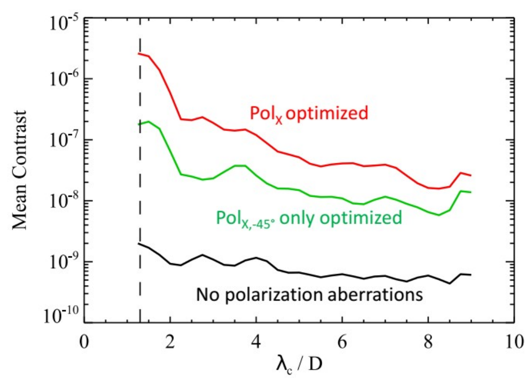
After astig optimization, we reached 1-5x better contrast with 5x more polarization error → >25x gain in contrast in this polarization-dominated regime

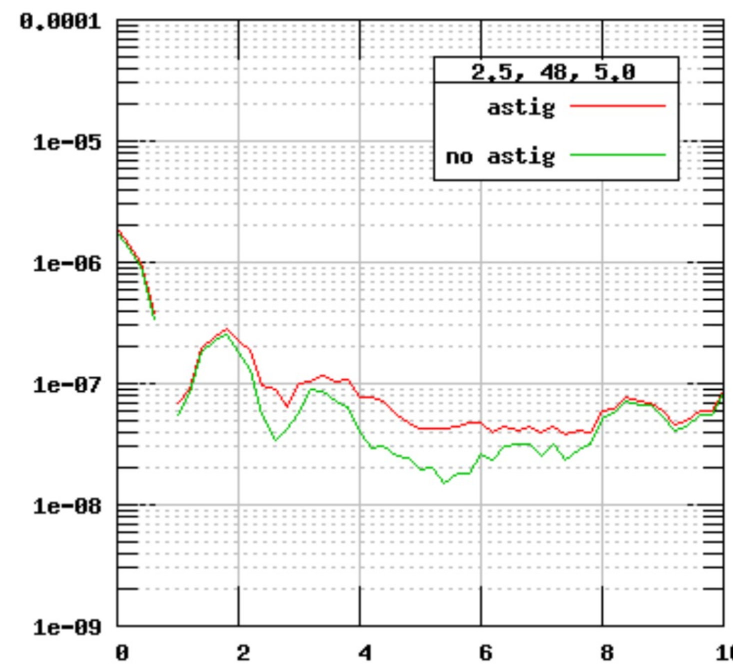
PIAACMC 20150322: 523 – 578 nm, λ_c=550 nm

The PIAACMC design uses a single DM, so full control is only over a half dark hole.
The X polarization channel result was bad enough that another run was done for a single cross term ($Pol_{x,-45°}$) to explore the sensitivities.



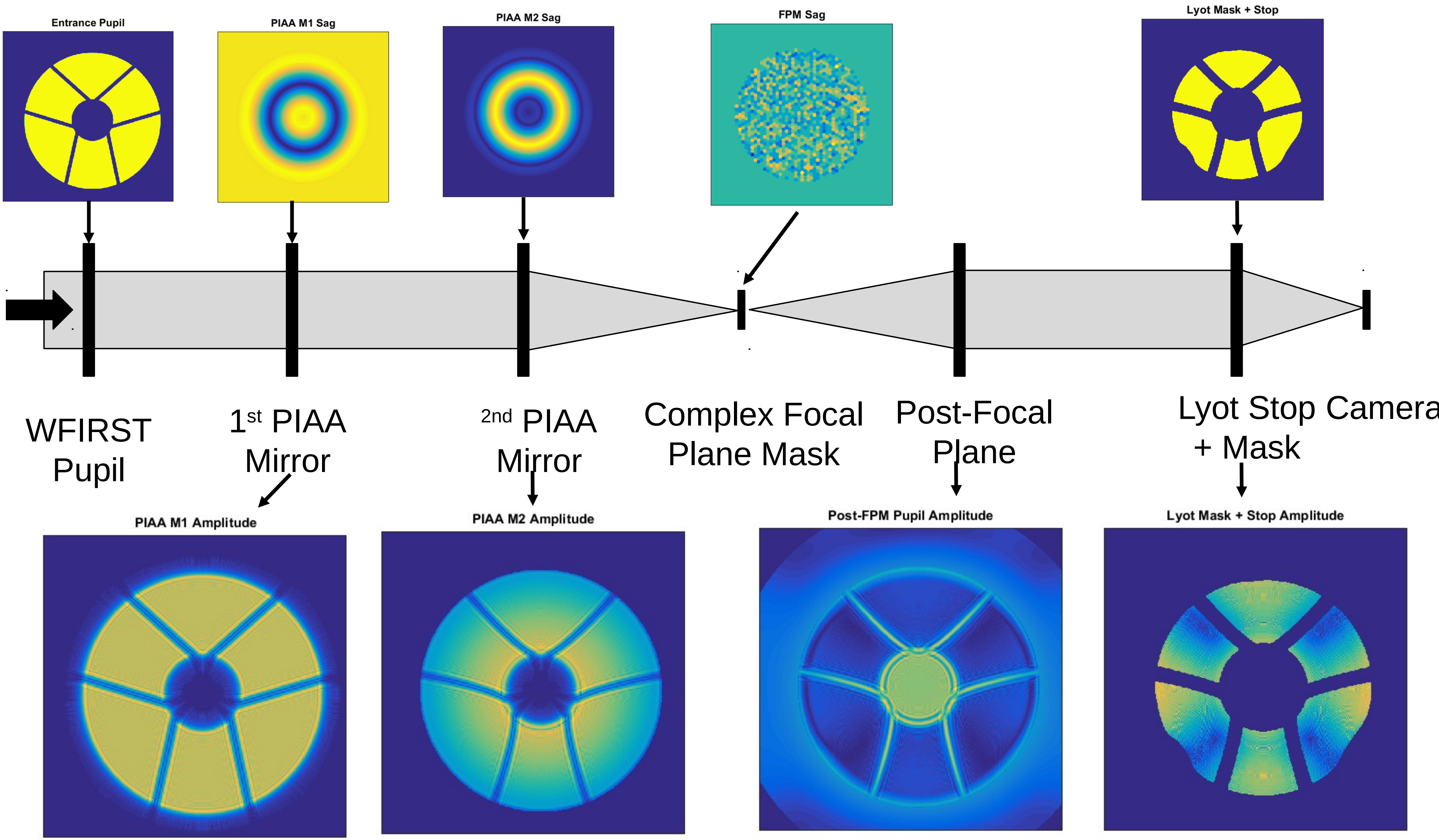
Circles are r = 1.3 & 9 λ_c/D



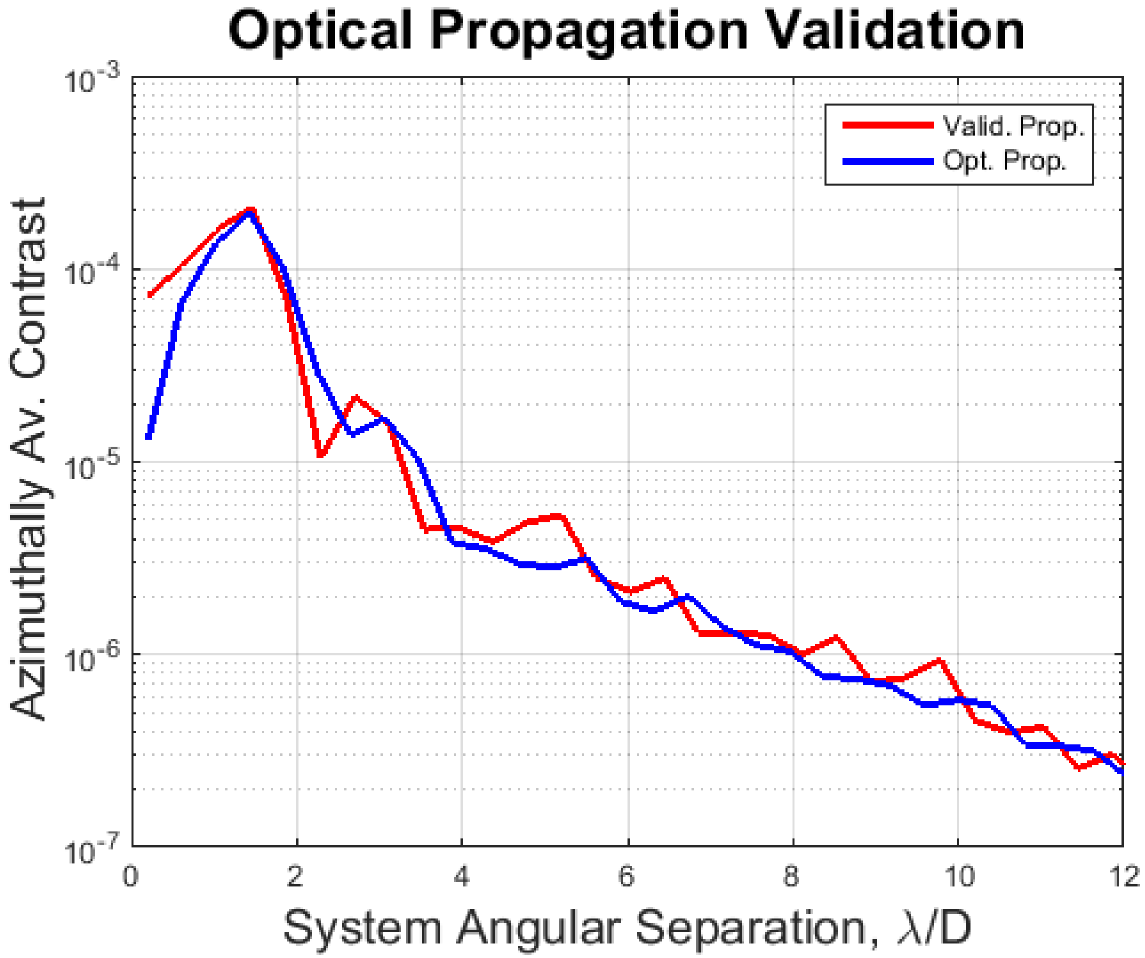


$Pol_X = Pol_{X,-45°} + Pol_{X,+45°}$

PIAACMC Optical Propagation



PIAACMC Optical Propagation

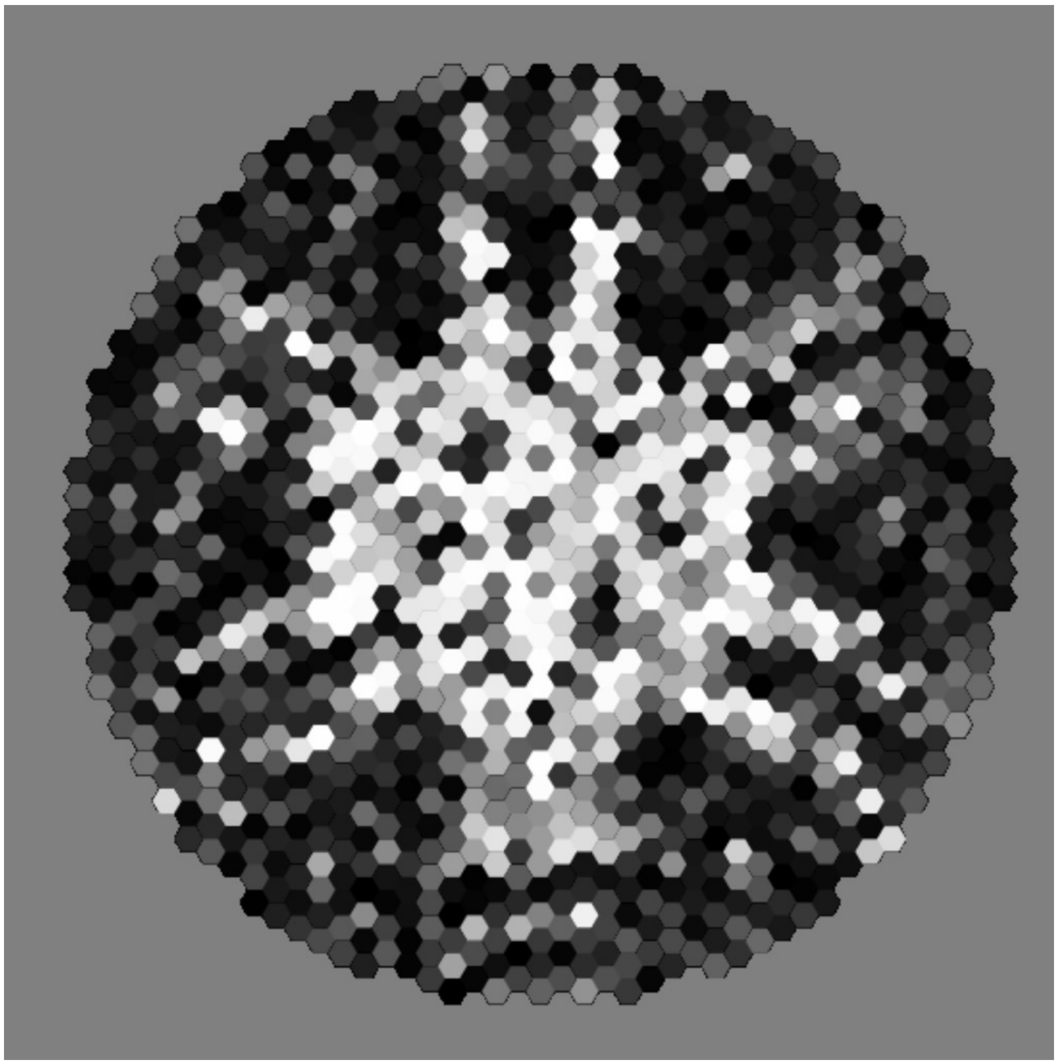


PIAACMC
Polarization issue: Next steps

- Broader exploration of optimization parameters using Ames HyperWall cluster
- Include tip-tilt jitter sensitivity optimization
- Include more accurate representation of polarization errors
- Software improvements: better optimization, making code easier to use and more reliable
- Validate solution in simulation including wavefront errors and wavefront control

Future Plans & other PIAACMC activities

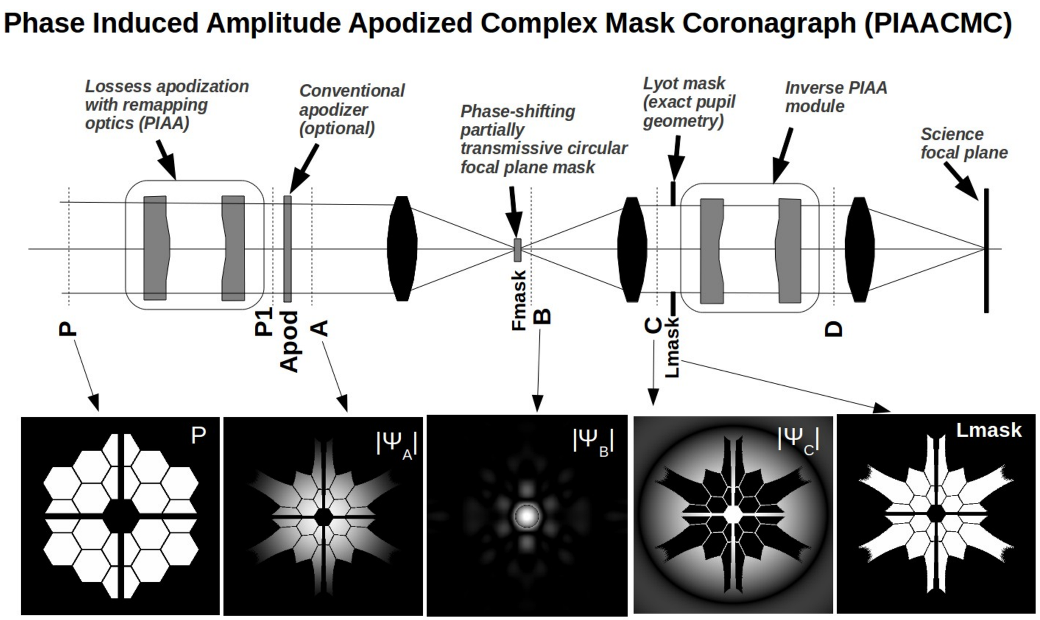
Focal plane masks for non-PIAACMC coronagraphs



Our multi-zone focal plane mask design approach and software can be applied to other coronagraphs: APLC, Vortex and HLC
→ strong potential for performance improvement
Current code includes APLC and APLC/PIAACMC hybrid designs
Vortex, HLC would be relatively easy to support

WFIRST PIAACMC mask manufacturing milestone demonstrates that the multi-zone focal plane mask approach is sensible.

Segmented apertures (SCDA activity)



PIAACMC and APLC/PIAACMC hybrids are well-suited to segmented apertures

Performance is largely independent of aperture geometry

Early work promising. Little recent activity (team was focused on WFIRST), but this activity is now becoming higher priority.

All recent code improvements are telescope-agnostic and should benefit seg apertures

Focal plane mask manufacturing (J. Knight, UofA)

UA Link Award → Provides funding for a small team (1 Graduate: Knight, 2 UG students) to generate pilot data for coronagraph mask fabrication, characterization, and testing during the 2016-2017 academic year; survey national nanofabrication facilities capabilities, limitations, and interest in coronagraph component development

Current activities → Developing competencies with design process using PIAACMCdesign code, fabrication equipment, and testing equipment

Fabrication processes (funded by Award) at UA:
Reactive ion-beam etching
Bosch process (deep RIE)
E-beam lithography

Testing equipment at UA:
Atomic force microscope
SEM
VEECO optical interferometer

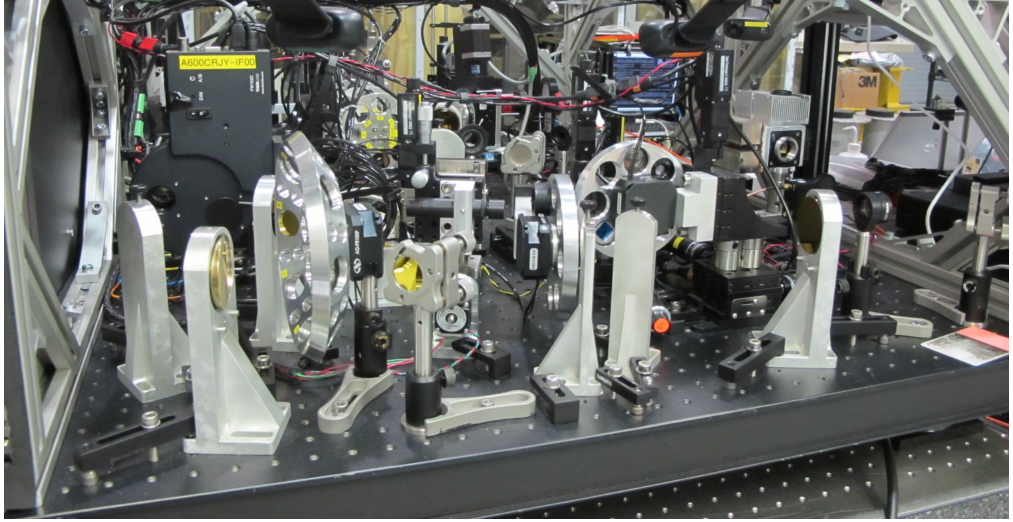
Plan → 1. Create an FPM suitable for testing on UAWFC testbed using multiple processes: APLCMC style coronagraph
2. Extend mask fabrication to PIAACMC suitable for testing at collaborating facilities, e.g. Subaru, AMES
3. Report results locally in March, target funding agency such as NASA, NSF for continued work

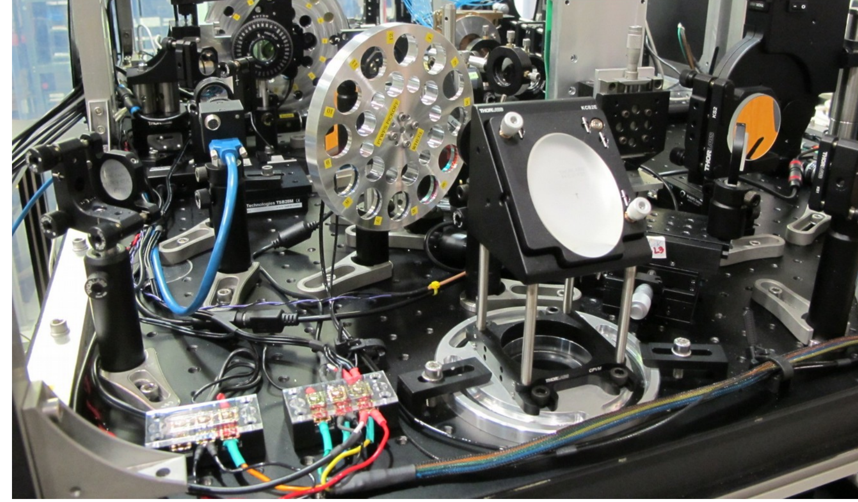
Subaru Coronagraphic Extreme Adaptive Optics

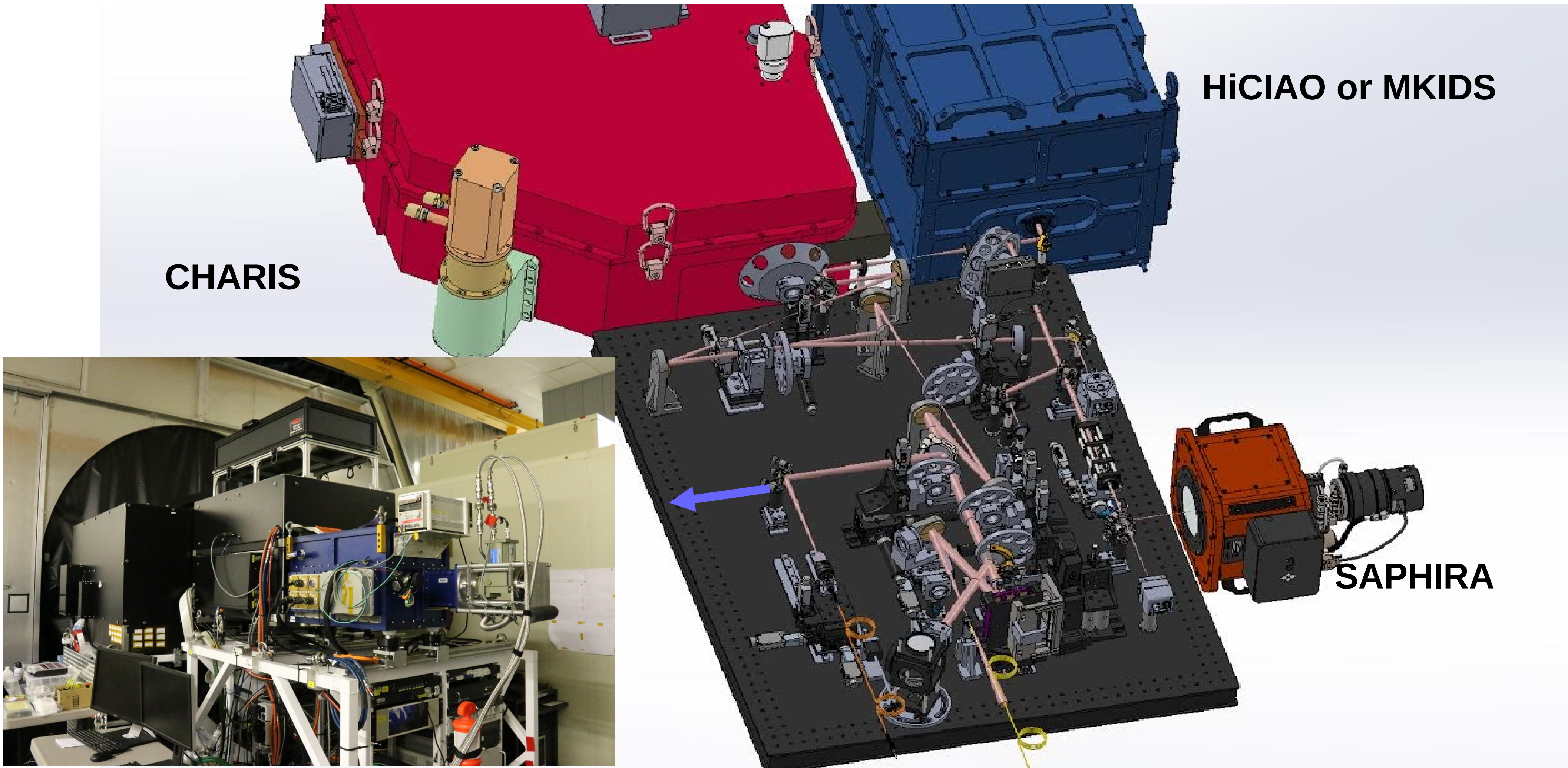
High contrast imaging system for ground-based Subaru Telescope
Operates at moderate contrast levels (limited by atmosphere), fast speed
Can run at high moderate/contrast with internal filtered supercontinuum source (no turbulence)

Technology demonstrator for system-level operation:
- LOWFS was first developed on SCExAO, now integral part of instrument (science operation)
- Includes Vortex, 8-octant, shaped pupil, PIAA (ongoing upgrade to PIAACMC)
- Includes IFS (built by Princeton Univ.), EMCCD-based WFS/C
- Active research in speckle control

Several research area with strong overlap with WFIRST and future space missions:
- efficient speckle control (need to run at kHz speed on SCExAO, with a few photon per iteration)
- integrated WFS/WFC, combining multiple sensors: speckle (fast camera + IFS), LOWFS, Pyramid
- New speckle control approaches (LDFC etc…)
- Postprocessing using WFS telemetry
- Fiber-fed high resolution spectroscopy, visible and near-IR
- New detectors (MKIDs, SAPHIRA, deep depletion EMCCD, EI)



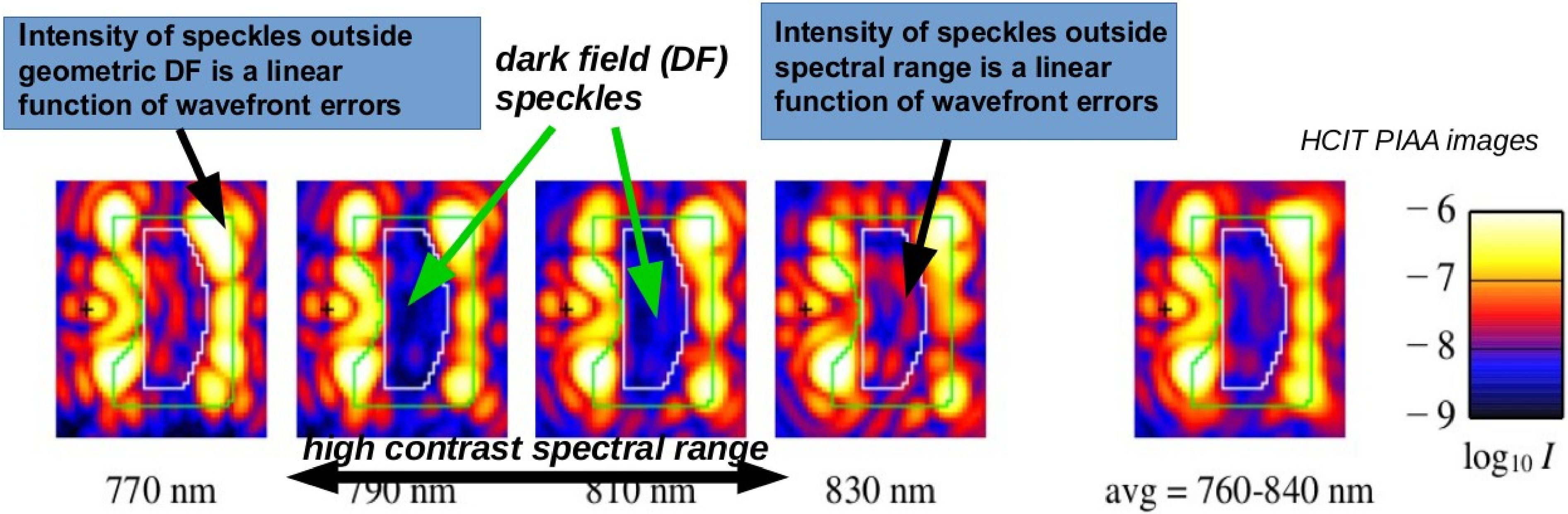



HiCIAO or MKIDS
CHARIS
SAPHIRA

Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



Quantifying Planet Detectability at Small Inner Working Angle

Steve Bryson, Rus Belikov

NASA Ames Research Center

PIAA team future work

- **Continue HCIT testing on WFIRST pupil → understanding PIAACMC limits**
  HCIT test could be “easily” adapted to other pupil shapes (HabEx, LUVOIR ?)
- **Coronagraph design for segmented apertures ***
  New design capabilities (incl. polarization mitigation)
  Exploring PIAACMC and hybrids
- **PIAACMC components manufacturing**
  Exploring focal plane mask manufacturing approaches
- **Understanding/mapping fundamental design trade space**
  IWA, contrast, throughtput, bandwidth, sensitivity to stellar angular size
- **Wavefront control development**
  Optimizing speed under realistic (low) light levels
  Including realistic disturbances / system level validation
  Multi-star WFC *
- **Astrometry ***
- **Post-processing**
  Using WFS/WFC telemetry for PSF calibration (LOWFS, speckle control loop)
  Coherence differential imaging (CDI) and Linear Dark Field Control (LDFC)
  Optical differential imaging (ODI)

Resources
Testbeds: HCIT, Ames lab, SCExAO, UofA lab
Computing: Ames hyperwall cluster

** Separely funded*