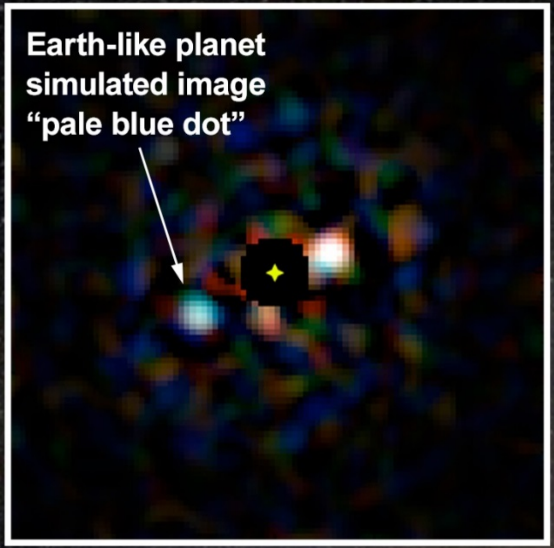
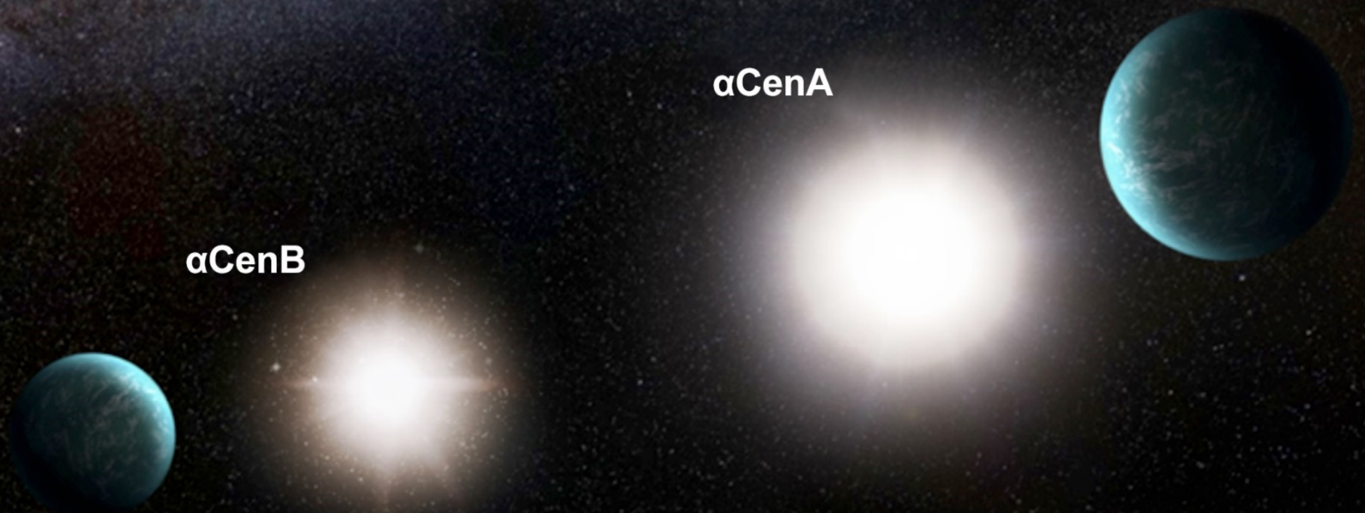


Super-Nyquist and Multi-Star Wavefront Control

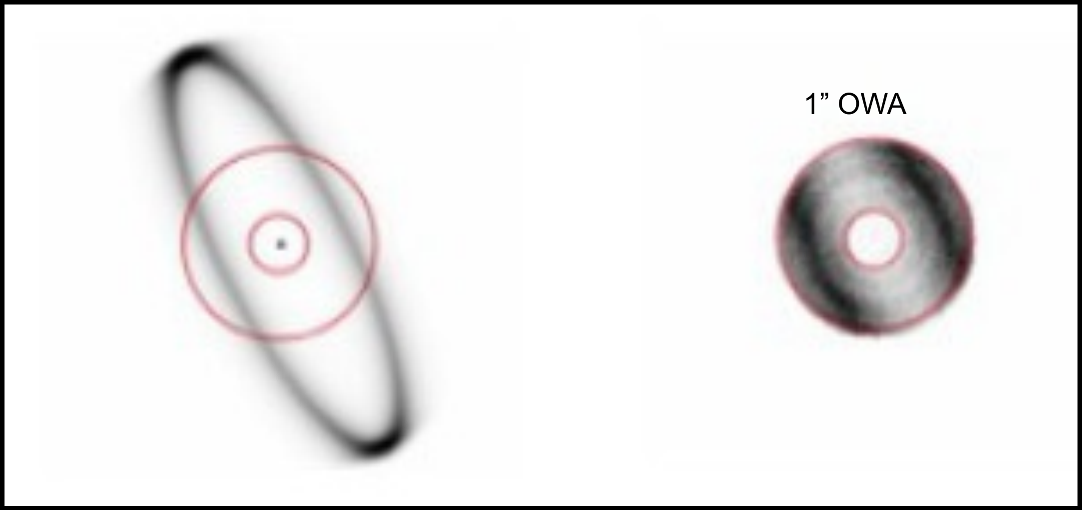
Ruslan Belikov, Sandrine Thomas, Eduardo Bendek
NASA Ames Research Center



LOWFS meeting, NASA JPL, Pasadena, CA 2/12/2015

Motivation 1

Overcoming the OWA limit of the DM

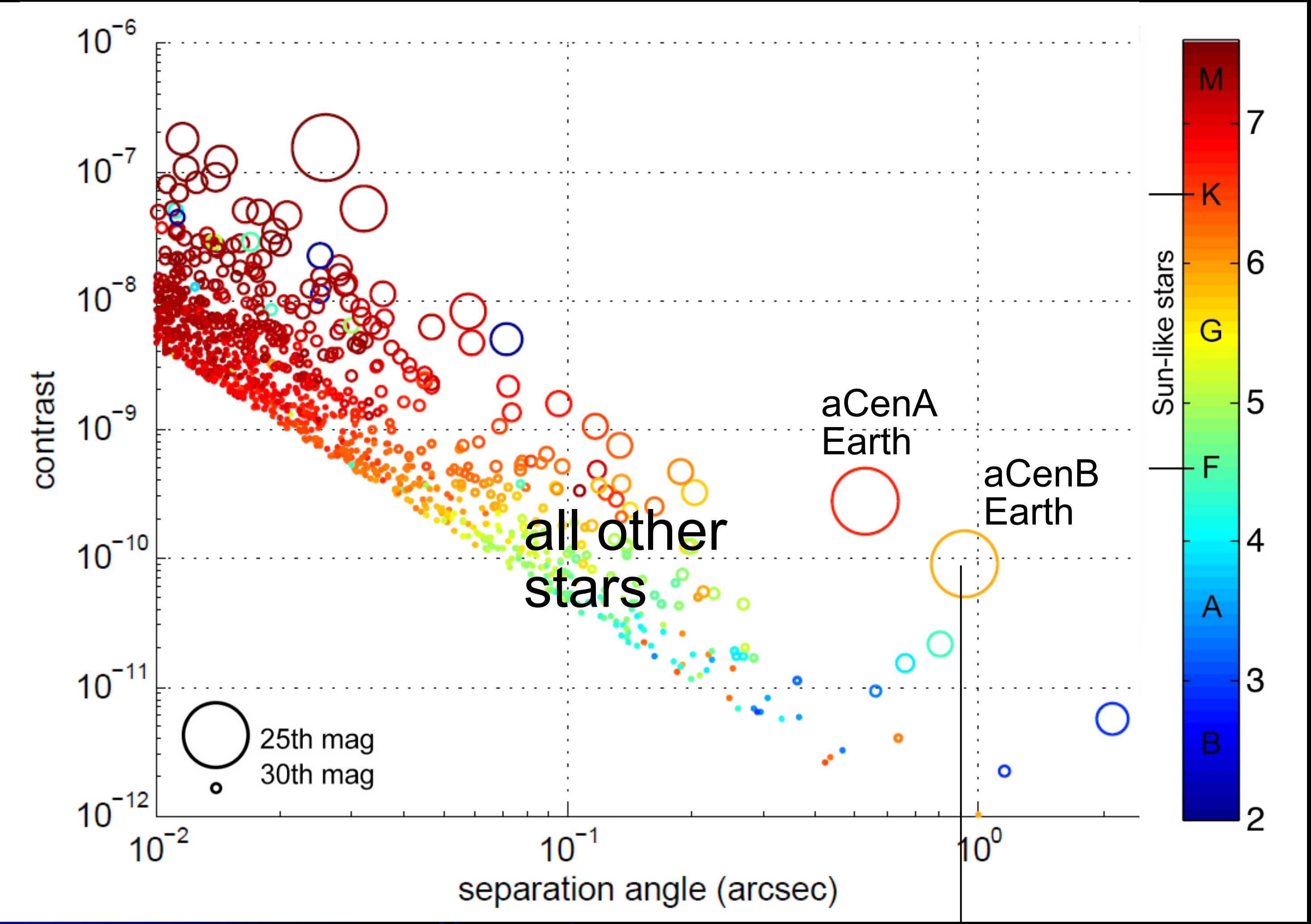


Example: HR4796A disk extends beyond the AFTA OWA
(Courtesy of Tom Greene)

(Solution: Super-Nyquist WFC)

Motivation 2:
Binary stars, especially Alpha Centauri

Simulation of a (hypothetical) Earth twin at quadrature around every nearby star



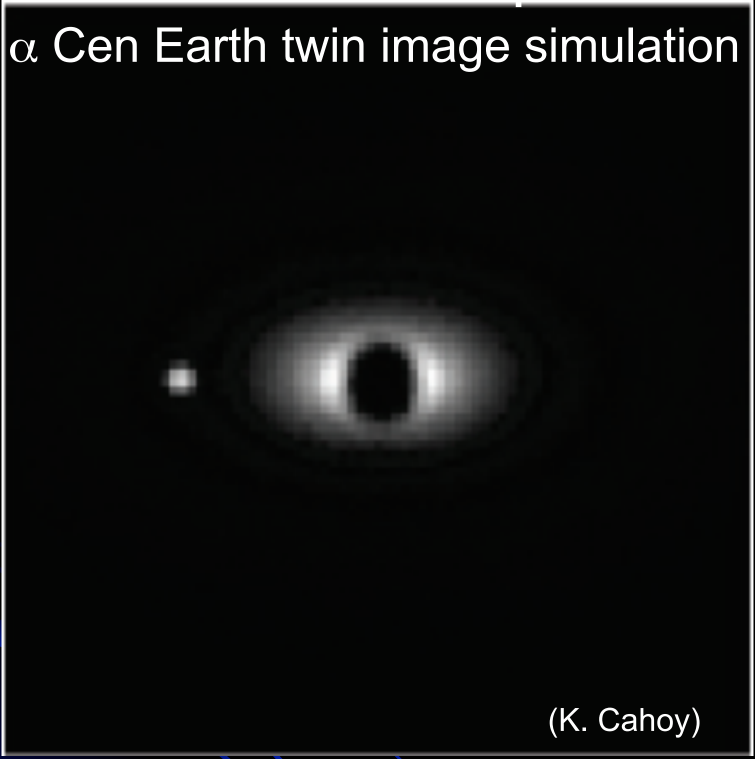
2.7 λ/D for 30cm telescope (for 500nm)

- αCen is in a class of its own: any other star requires a >3x larger (> 10x more expensive) telescope
- 10pc star system with a 17m telescope is equivalent to 1.4pc system with a 2.4m telescope (in terms of resolution and photon flux)

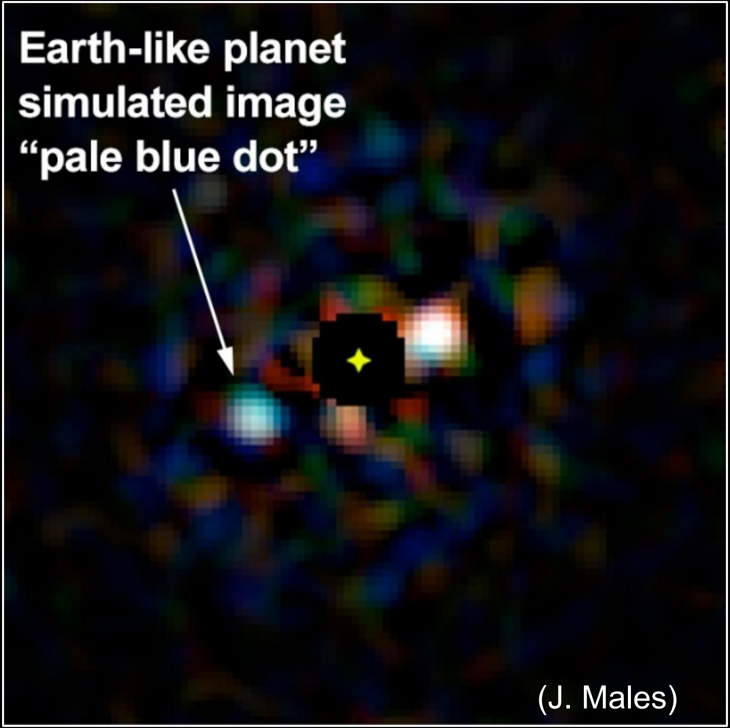
(Solution: Multi-Star WFC)

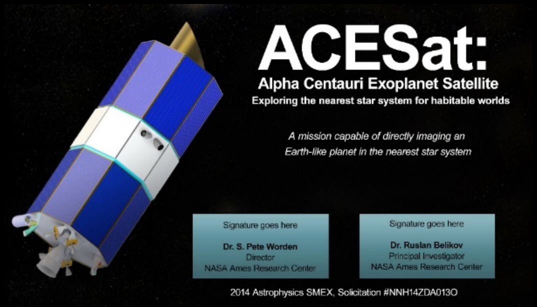
Earth twin simulations around aCen (if it was a single star)

1.4m telescope

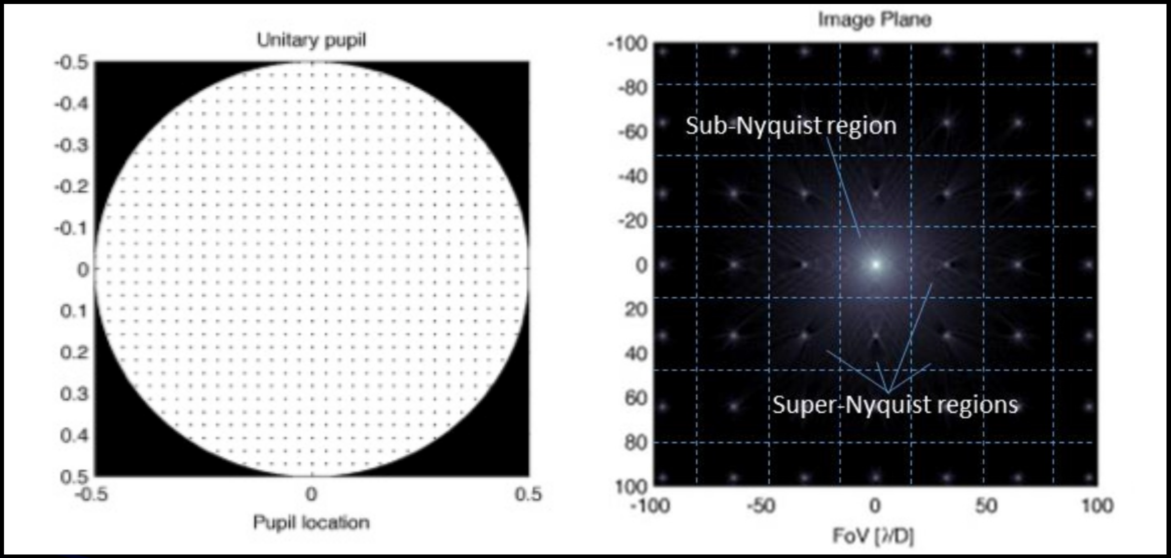


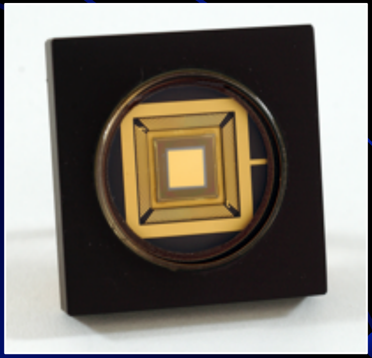
0.45m telescope

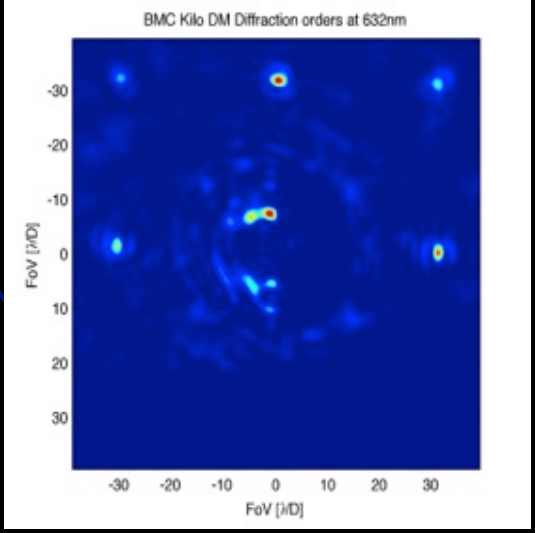




Super-Nyquist Wavefront Control: Concept

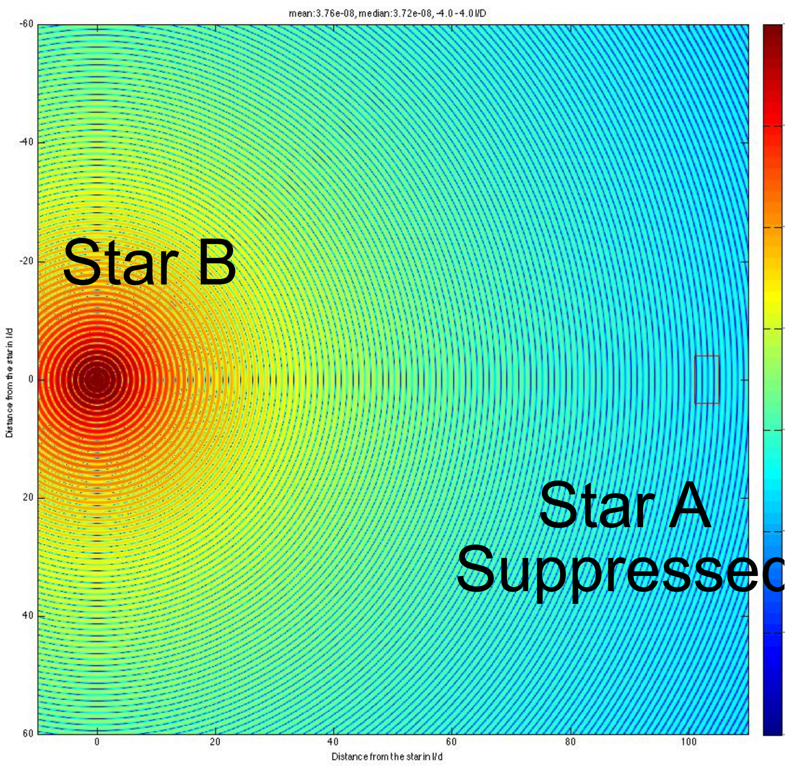


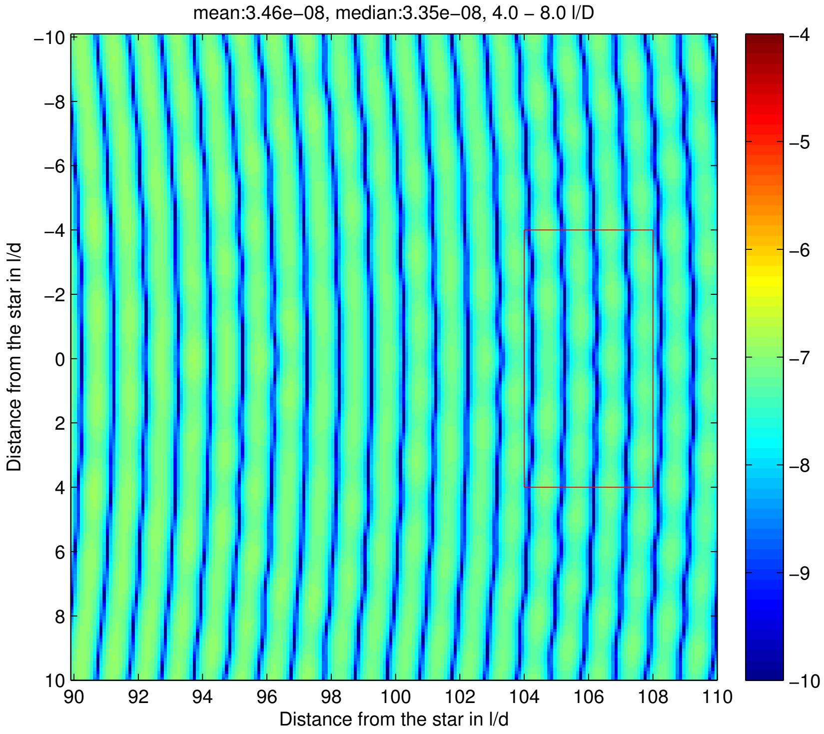




- DMs often have a mild diffraction grating on them:
  - Print-through or “quilting” pattern
  - Segmented DMs
- These generate diffracted faint copies of the star that can be used as a “proxy” star and a dark zone created around them
- Stand-alone mild diffraction gratings can also be used to fine-tune desired performance
- Thomas, Belikov, Bendek 2015 (http://arxiv.org/abs/1501.01583)

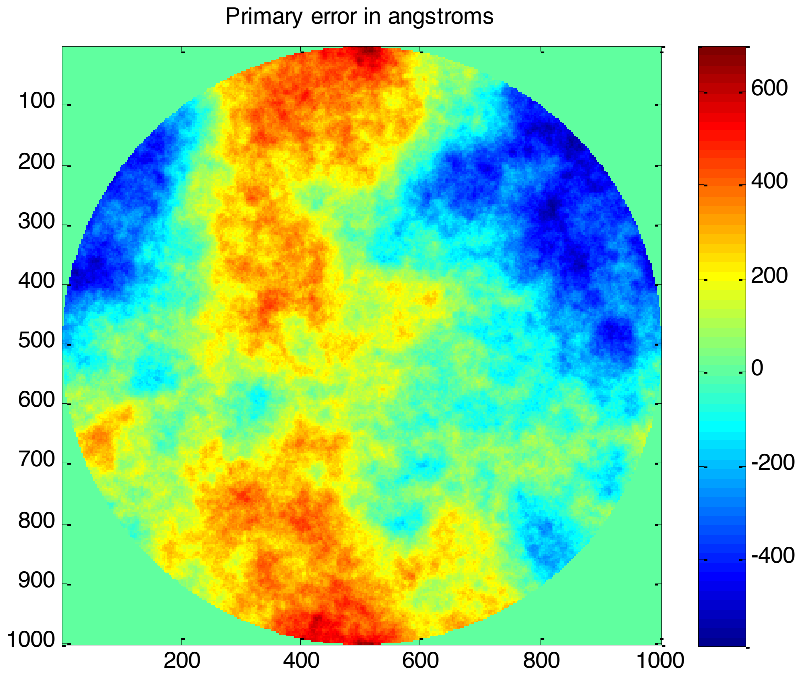
SNWC Simulation: Diffraction at 100 l/D

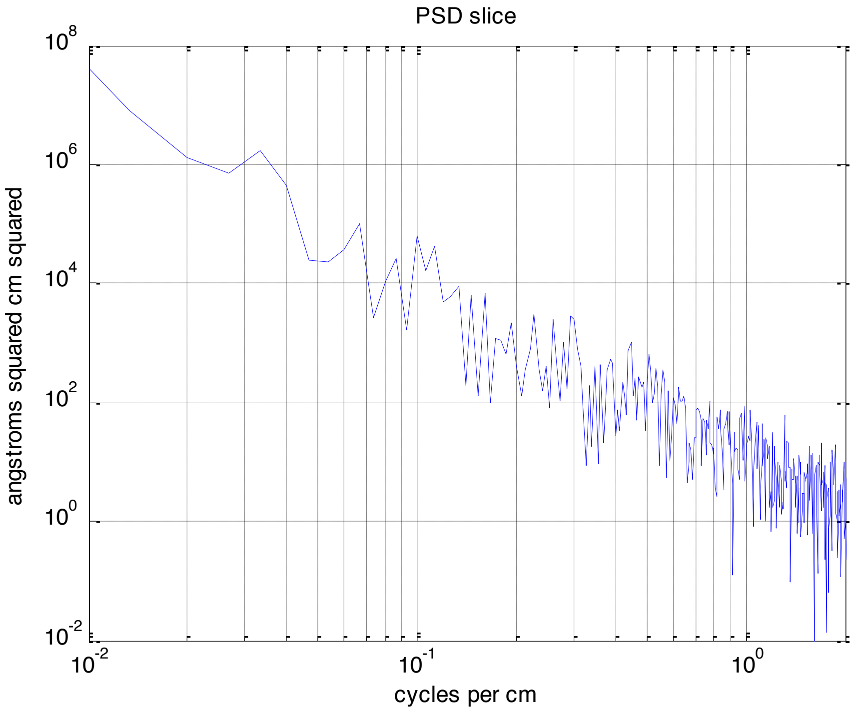




Diffraction from the off axis star: median of 3.4 e-8

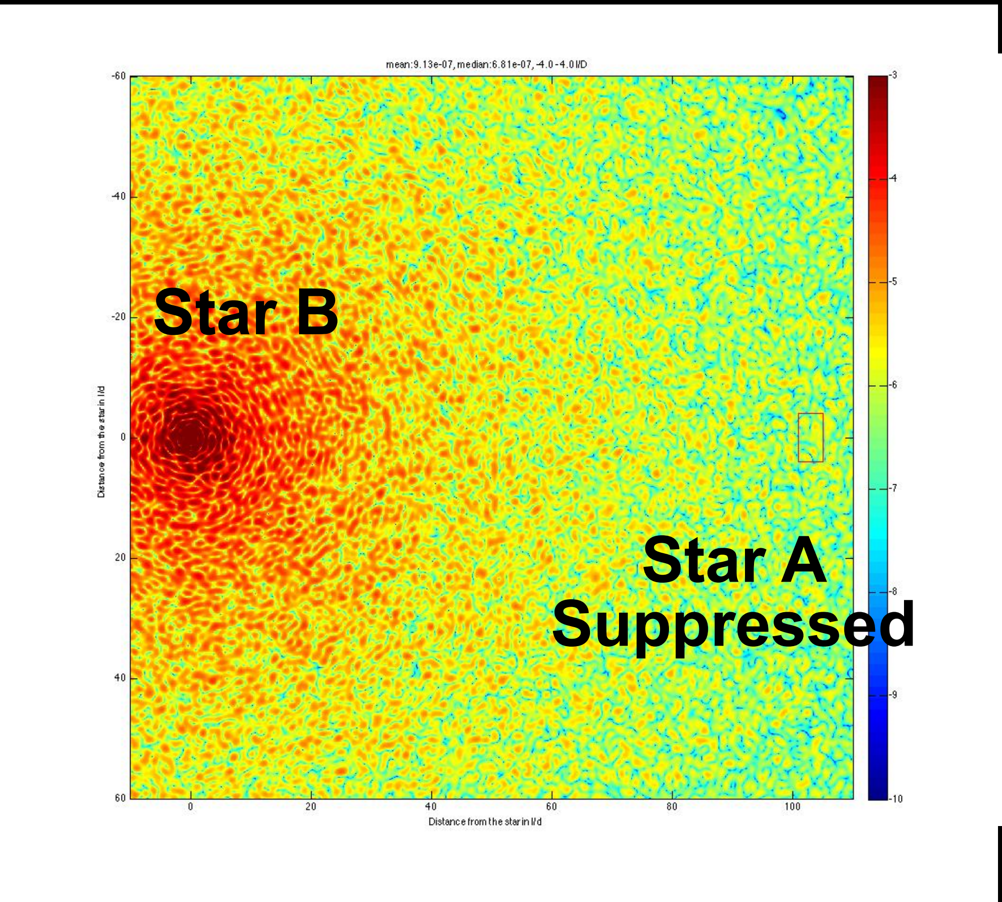
Simulation of typical mirror aberrations

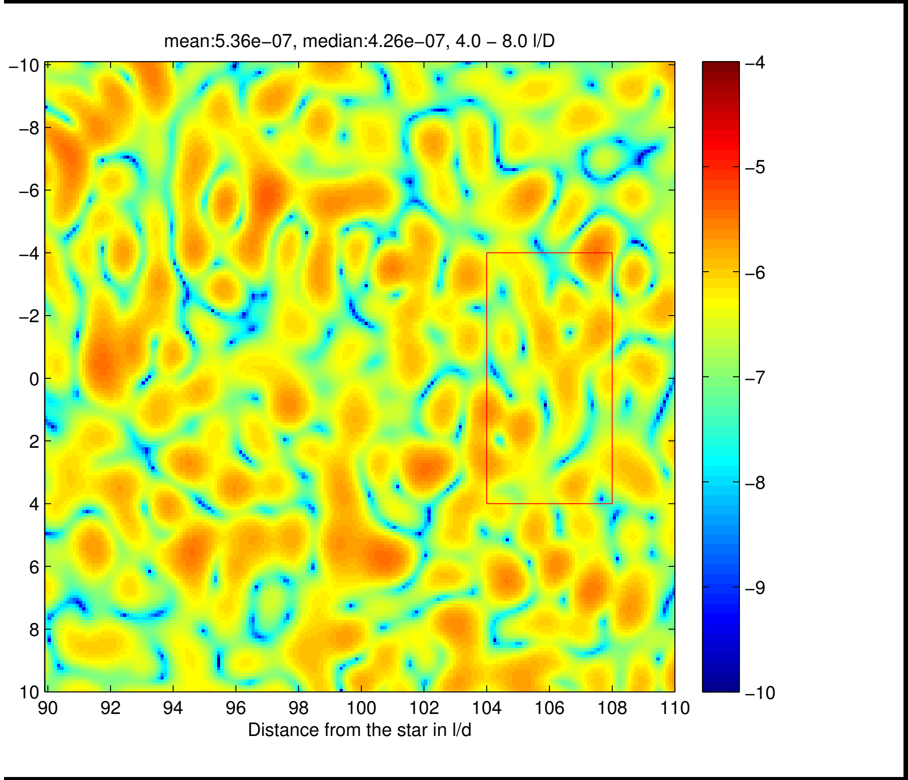




- Surface figure: 250 angstrom rms
- f^{-n} power law
- Equivalent to lambda/24 for 600nm

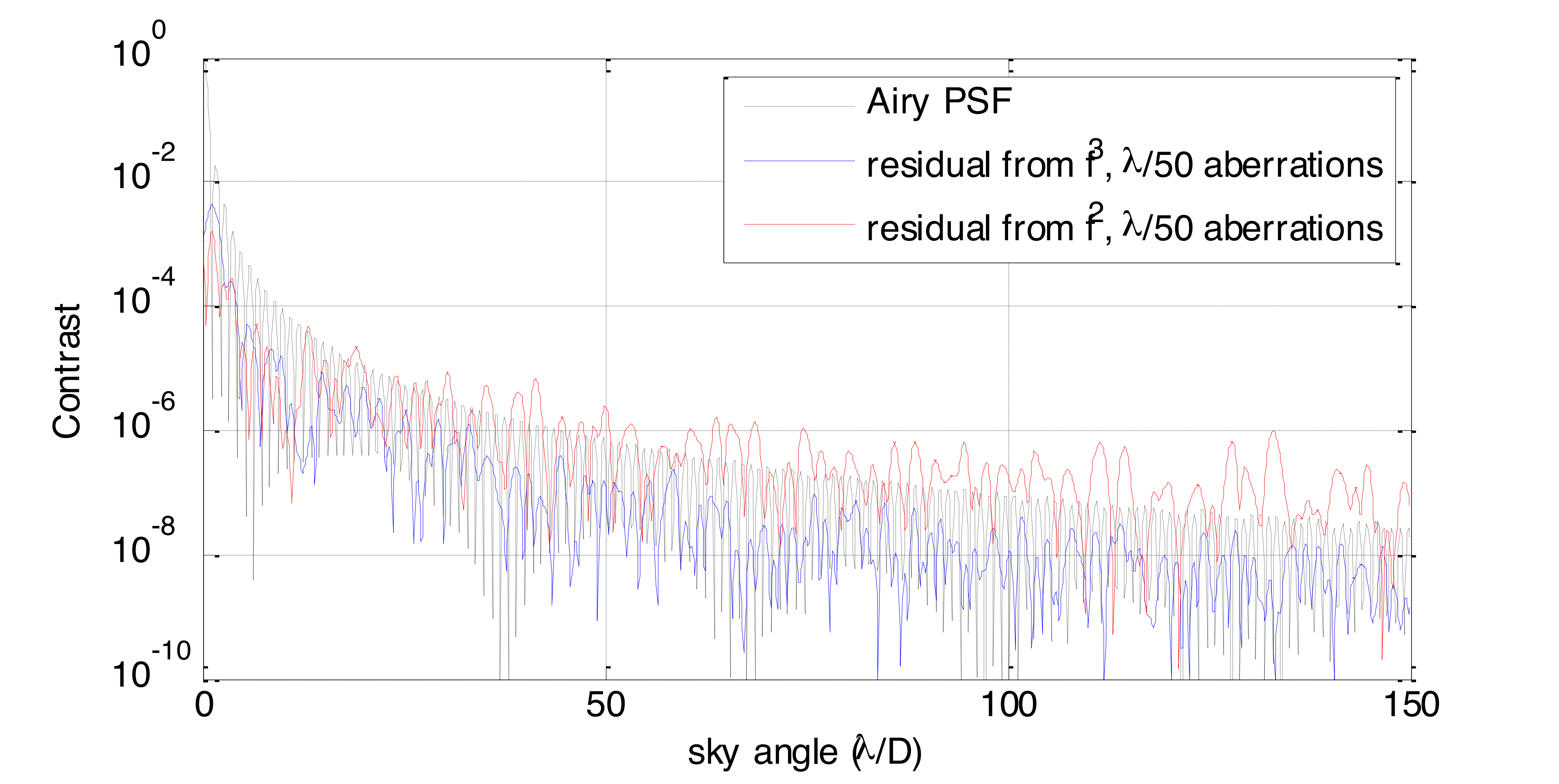
Leakage from the companion star in a Super-Nyquist region





25 nm rms, f^2 Aberrations: leakage from the off axis star: median of 4 e-7

Diffraction vs Aberrations



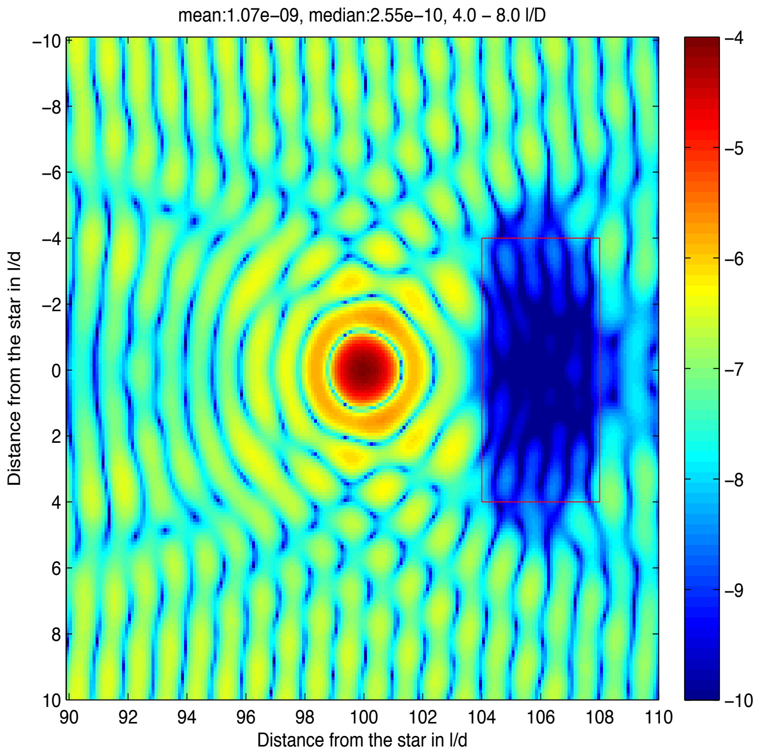
- Multi-star coronagraphs suppress diffraction from both stars but not aberrations
- MSWC will suppress aberrations and diffraction (if diffraction is sufficiently faint, it will not drive requirements)
- Hence, an off-axis coronagraph is neither sufficient nor necessary

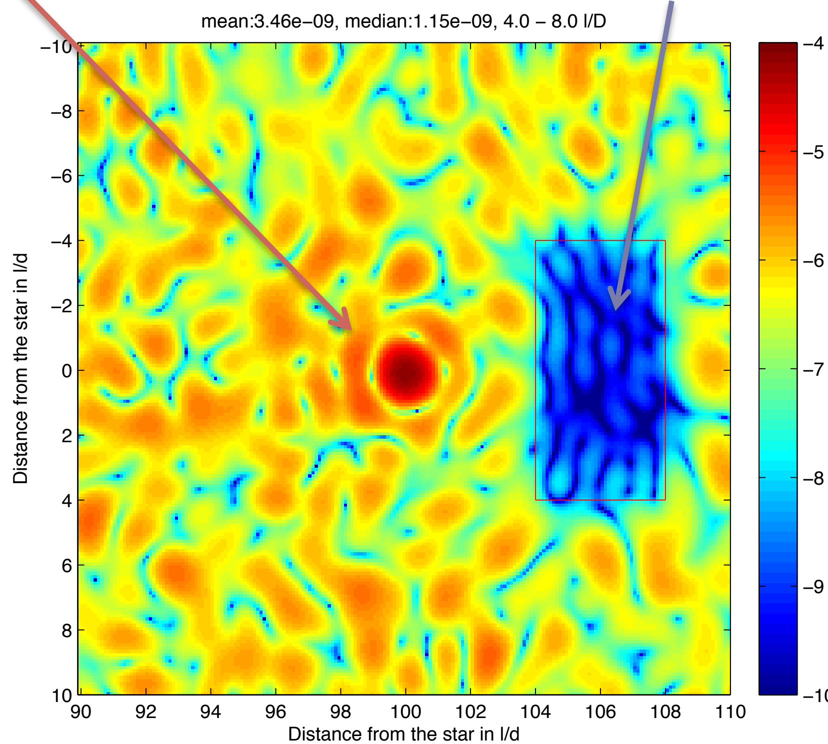
SNWC Simulation:
Dark zones at 100 l/D with a 32x32 DM

With a grid of 50 cycles per aperture, 100 lambda/d, 4x8 lambda/d region, monochromatic, 770 nm

Diffracted star image at 100 λ/D

Super-Nyquist dark zone at 104 λ/D with a 32x32 DM





No aberrations

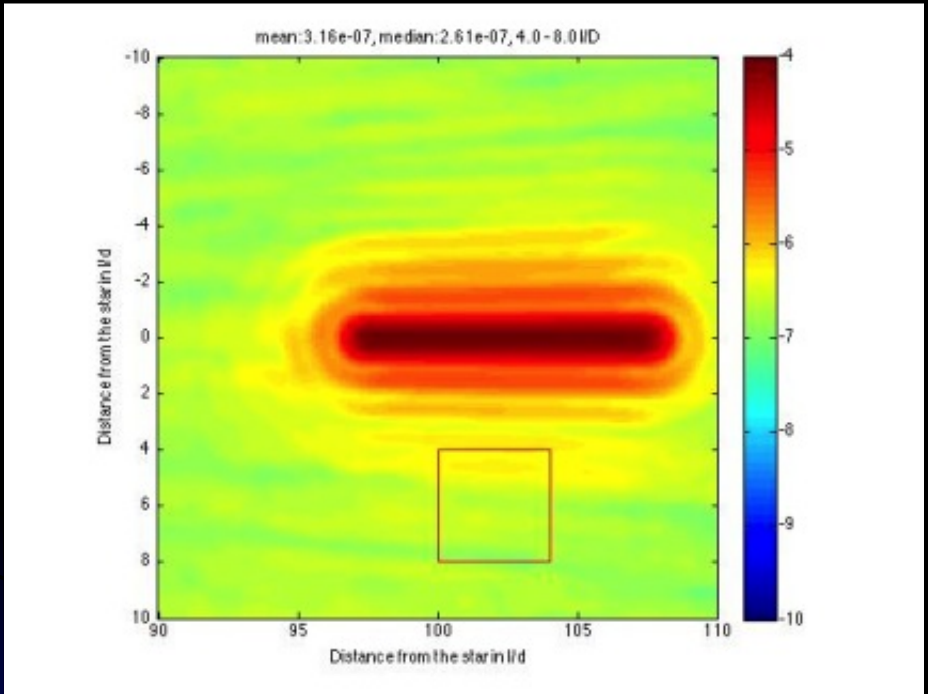
Before correction: 3.35 e-8
After correction: 2.55 e-10
Factor 100 improvement

25nm rms

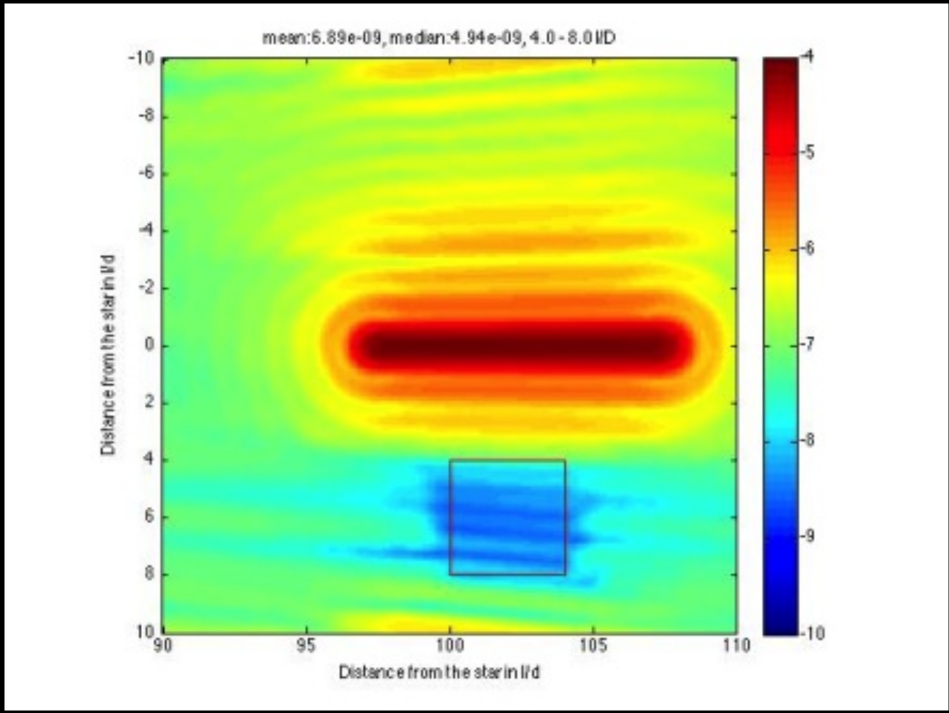
Before correction: 4.26 e-7
After correction: 1.15 e-9
Over a factor 100 improvement

SNWC,10 % broadband light

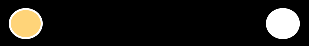
Before: 2.6e-7



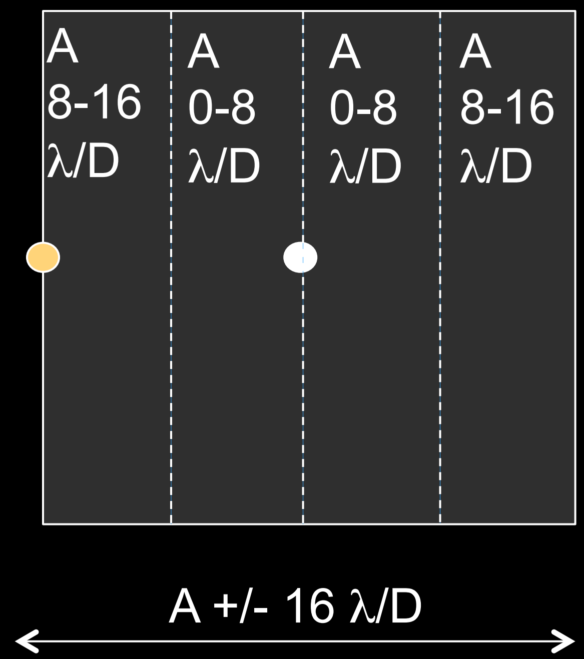
After: 4.9e-9



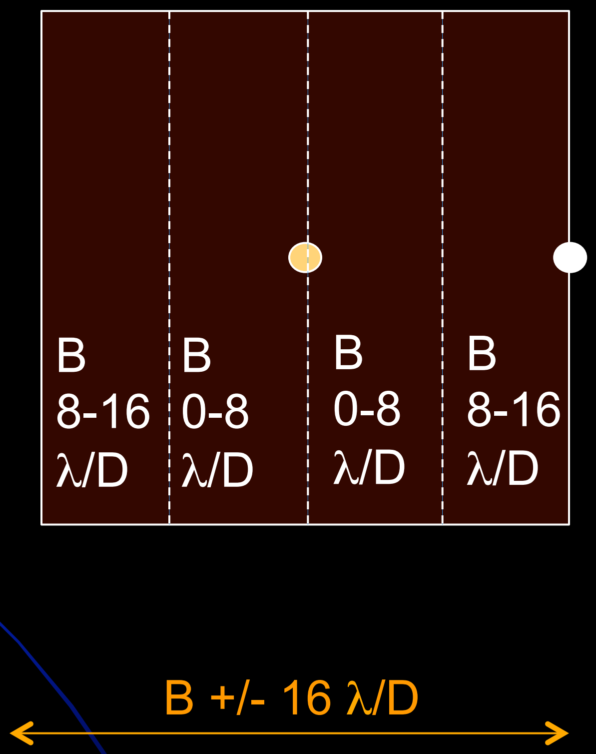
Multi-Star Wavefront Control



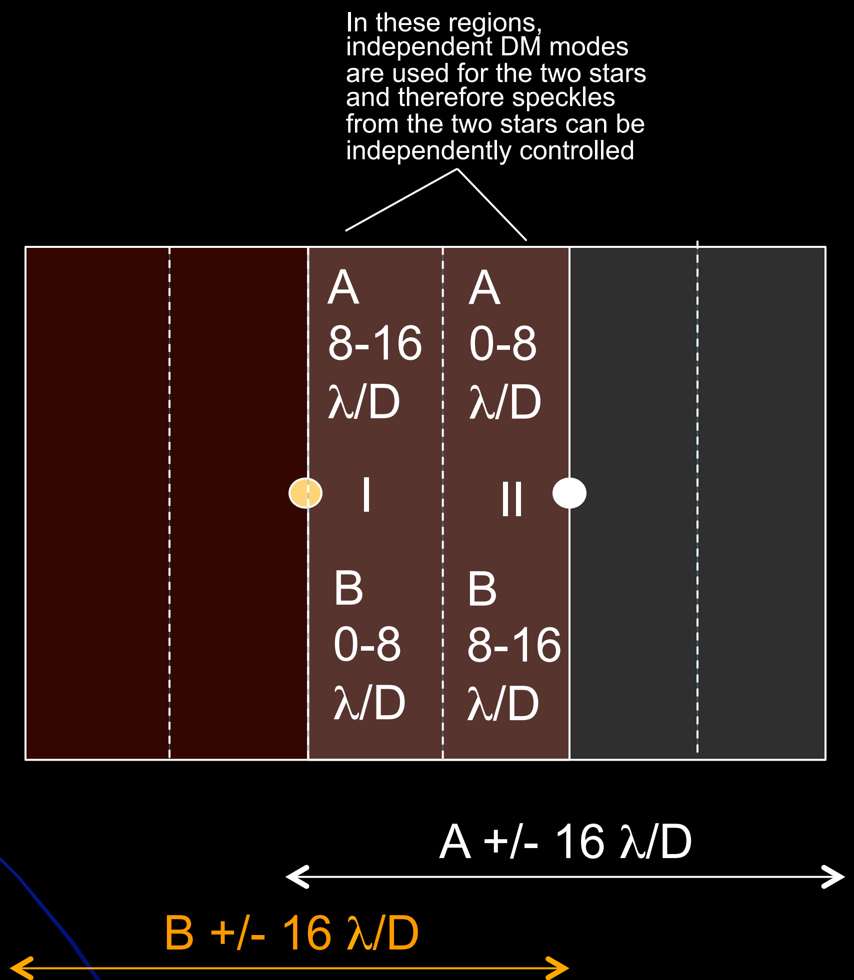
Multi-Star Wavefront Control



Multi-Star Wavefront Control



Multi-Star Wavefront Control



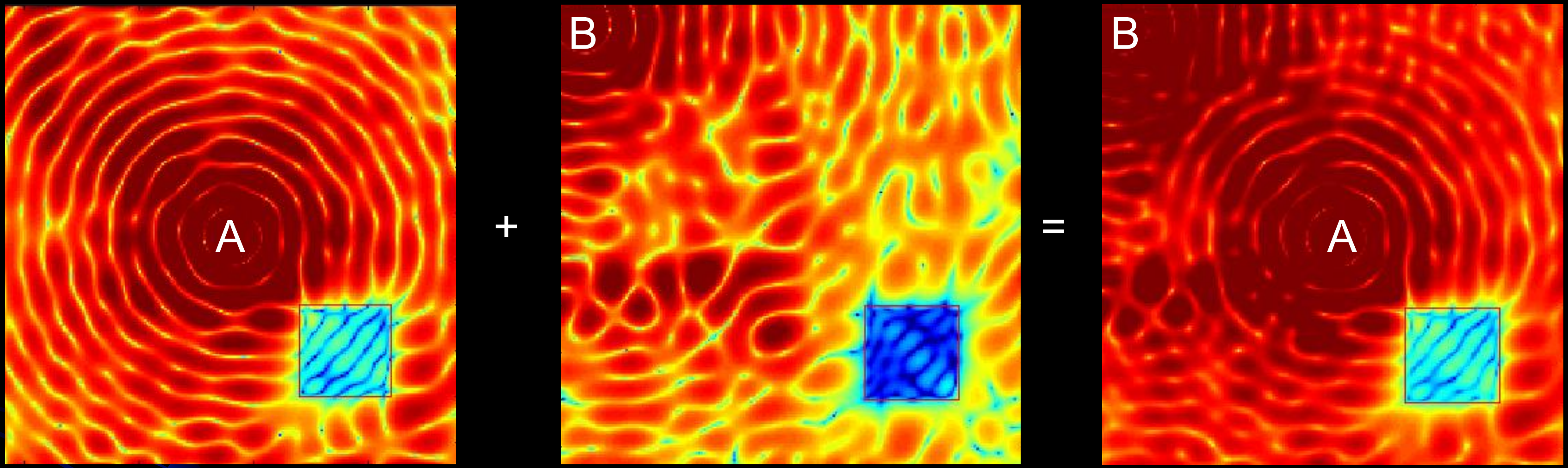
Multi-Star Wavefront Control

(preliminary proof of principle simulation)

On-axis star:
Use lower order
DM modes

Off-axis star:
Use higher order
DM modes

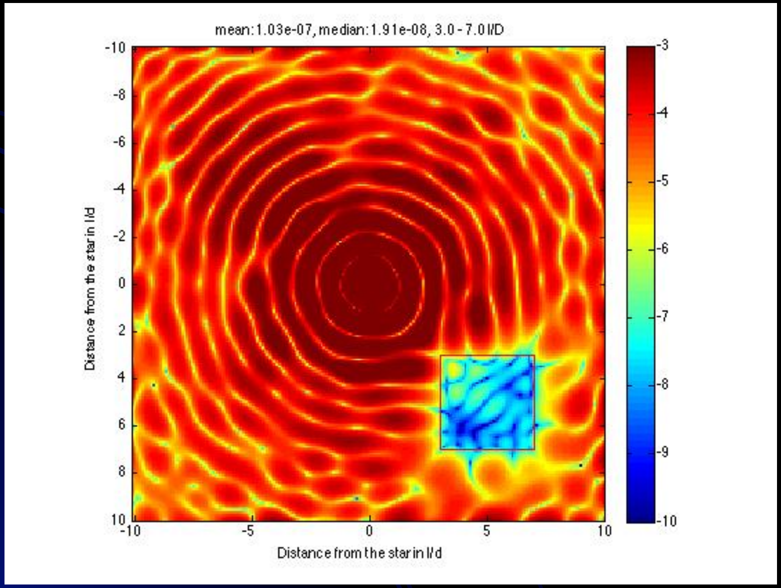
Result:
Independent control
of both stars' speckles

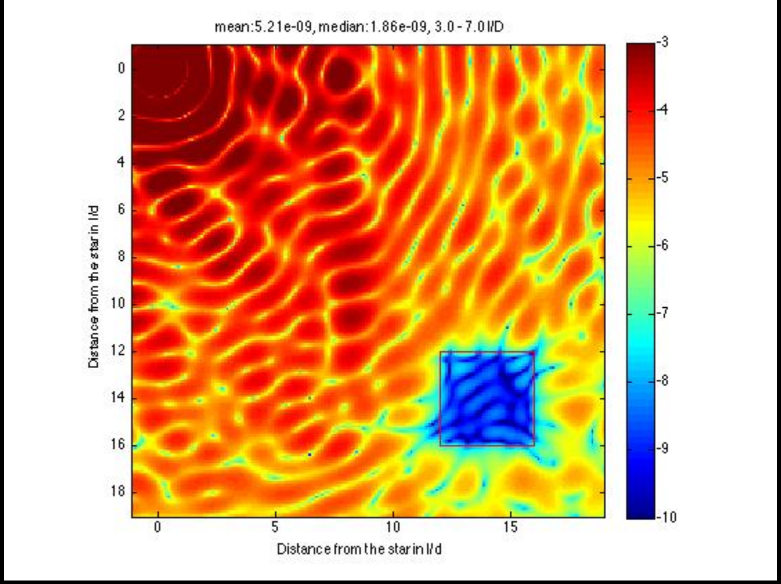


- Blocking off-axis star with a coronagraph is not sufficient (nor necessary)
- Multi-Star Wavefront Control is necessary (and sufficient in theory)
- Main idea: use independent DM modes for each star (halving the dark zone)
- Preliminary simulation demonstrates independent control of two stars' speckles
- Recently awarded technology development to increase dark zone size (in broadband), and do a lab demo
- **No new hardware development is necessary (only DM control algorithm)**

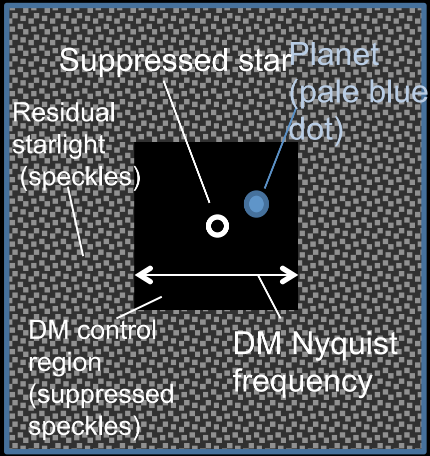
Contrast comparison

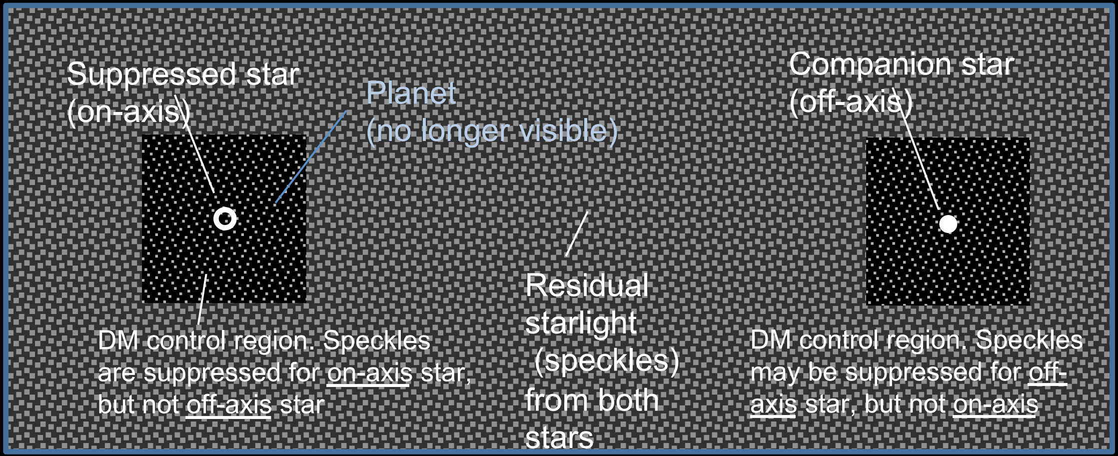
	2 star WC	On axis WC	Off axis WC
Before	1.3e-4	1e-4	7.7e-6
After	5.2e-8	4.5e-8	1.6e-9
1 star	n/a	< 1.9e-8	< 6.2e-10

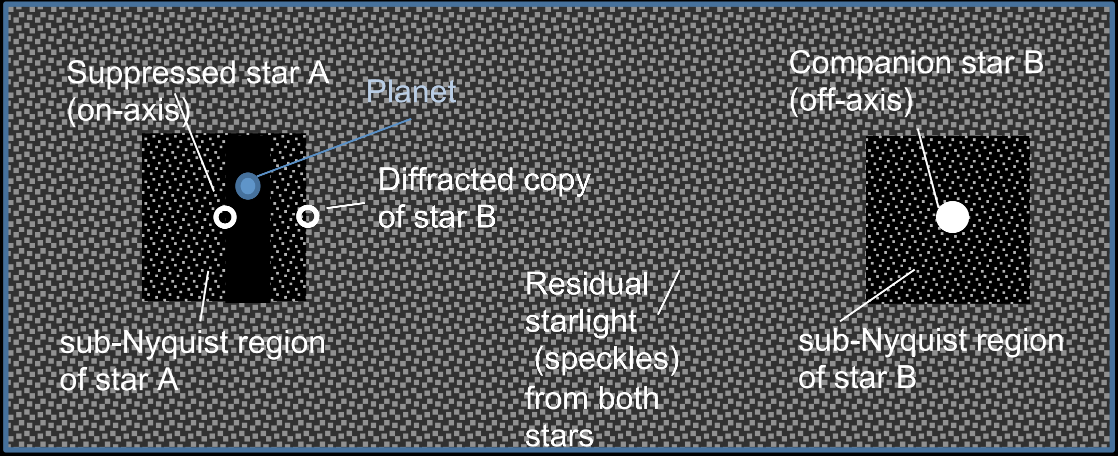




Combination: Super-Nyquist Multi-Star Wavefront Control





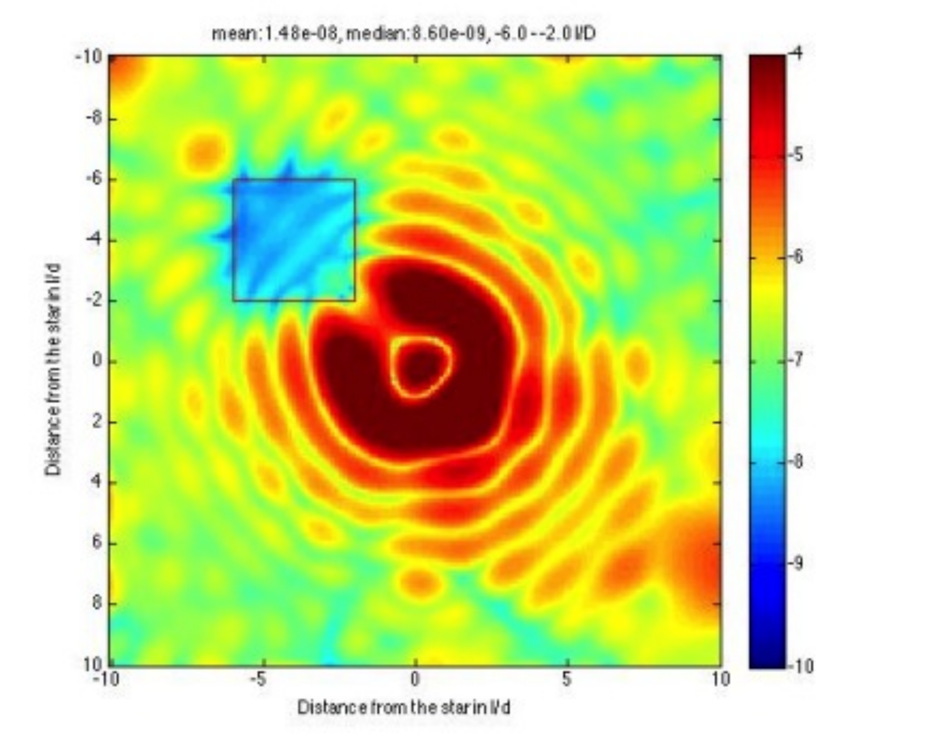


- SNWC creates a copy of off-axis star in Nyquist region
- MSWC independently suppresses both stars in the sub-Nyquist region
- Combination:
  - SNMSWC

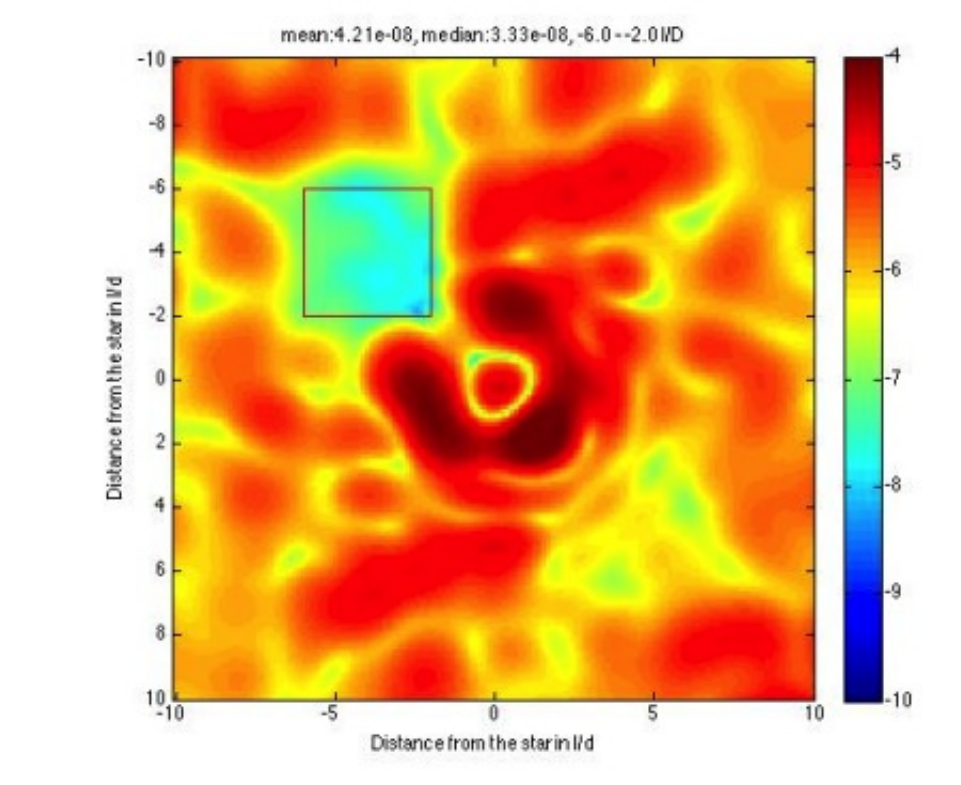
Ruslan Belikov, NASA Ames Coronagraph Laboratory

SNMSWC: Simulations

No aberrations



with 10nm rms aberrations



- 10% band around 550nm,
- binary star system with a separation of 29 λ/d.
- 32x32 DM
- Contrast achieved without aberrations is 8.6×10^{-9} and with aberrations 3.3×10^{-8}

Conclusions

- New wavefront control methods enabling science on almost any direct imaging mission (no new hardware required)
  - Super-Nyquist Wavefront Control
    - Overcomes OWA limit of DM
    - Enables imaging of large disks and binary stars with starshades (if telescope is equipped with a DM)
    - Thomas, Belikov, Bendek, submitted to *ApJ,* 2015 (http://arxiv.org/abs/1501.01583)
  - Multi-Star Wavefront Control
    - Independently controls aberrations from multiple stars (with sub-Nyquist separation)
  - SNMSWC: Combination of the two
    - Independently controls aberrations from multiple stars with any separation
- Preliminary simulations proved basic principles

BACKUP SLIDES

Habitable Zones of αCen AB

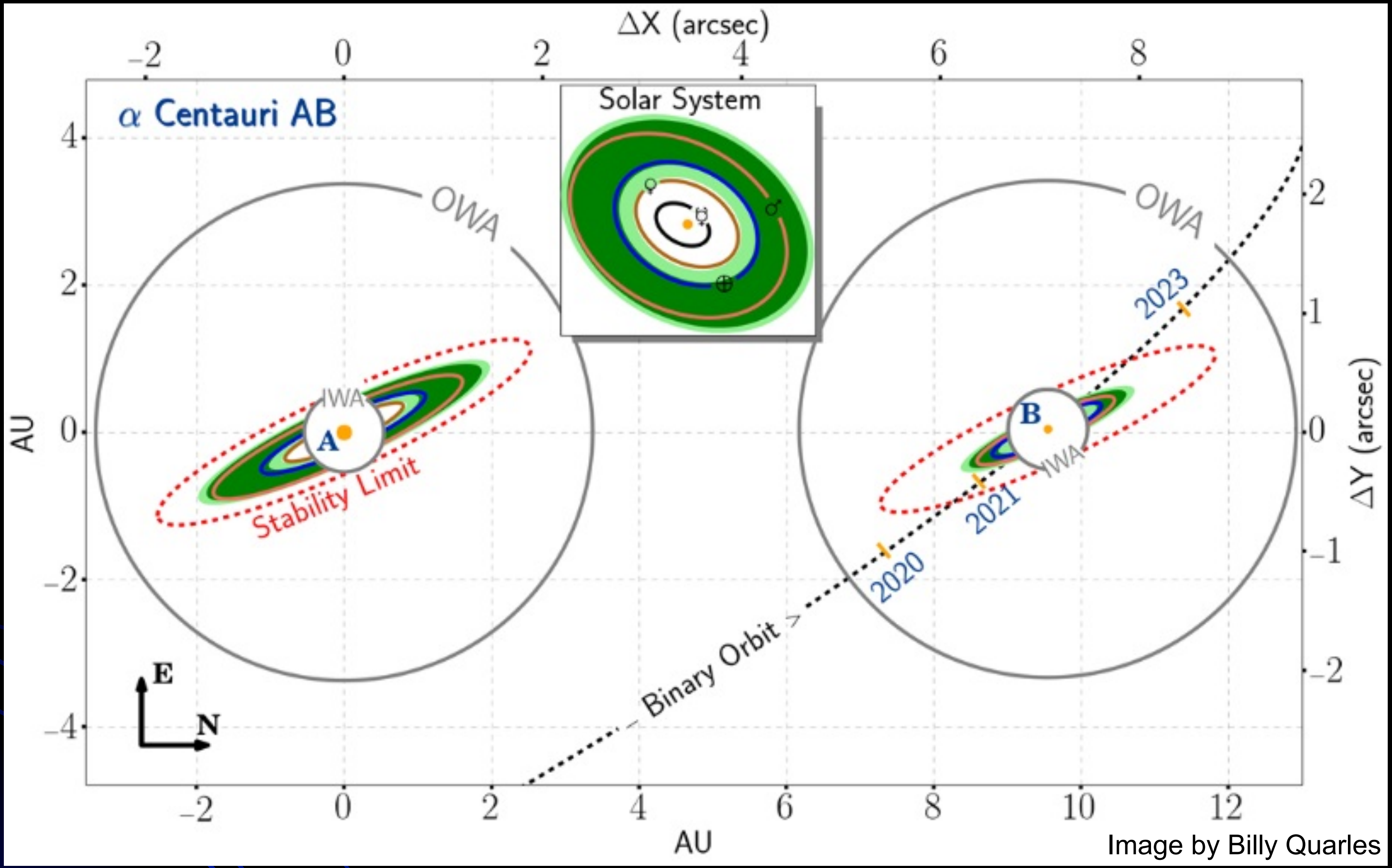
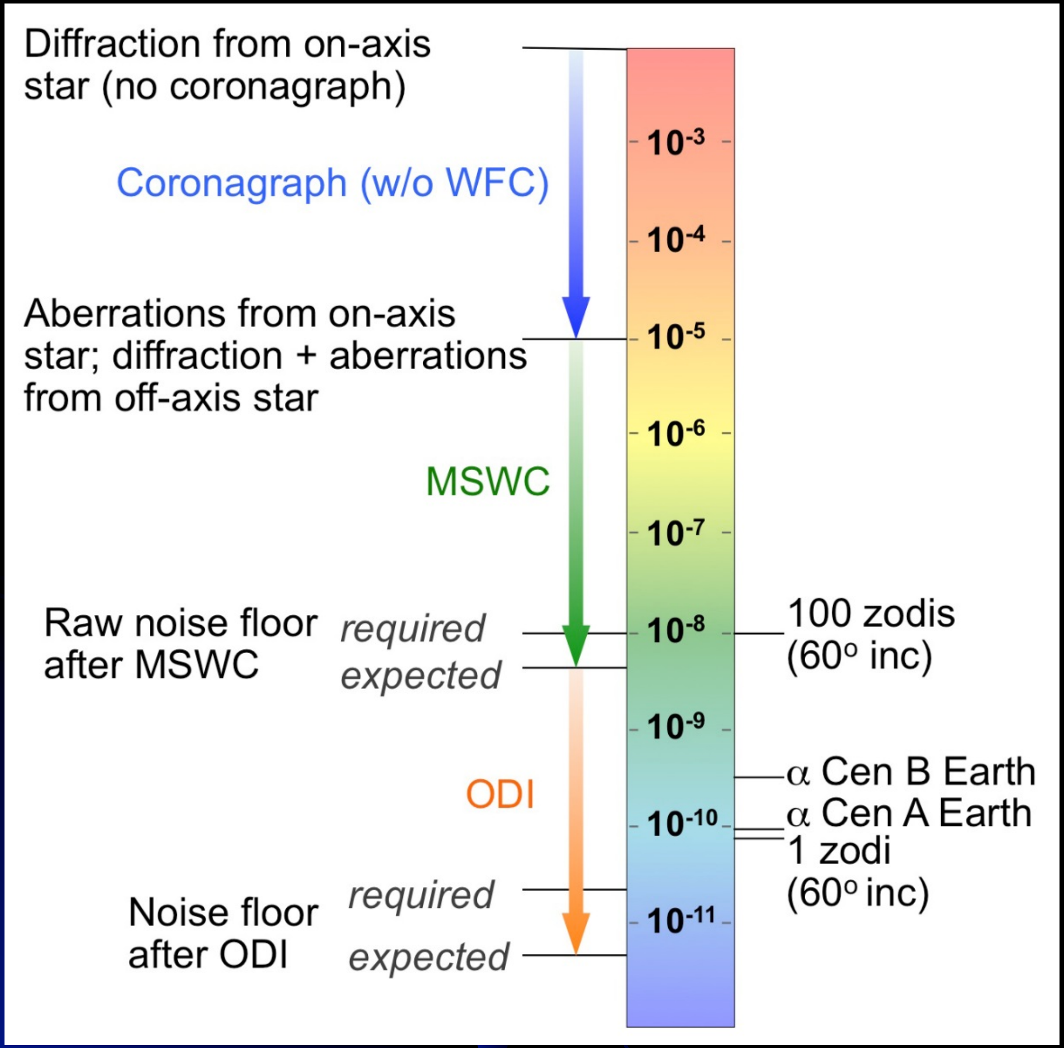


Image by Billy Quarles

- Both HZs are fully accessible with a 0.4” (0.5AU) inner working angle (IWA)
- Orbits are stable out to ~ 2.5 AU (Holman & Wiegert 1999)
- Latest η_{Earth} estimates are ~40-60% -> ~65-85% for the binary system
  - Based on 0.5-2.0 Earth radius, and Kopparapu 2013 optimistic HZ, Traub 2015, Batalha et al. 2015, Burke et al. 2015, Foreman-Mackey et al. 2015

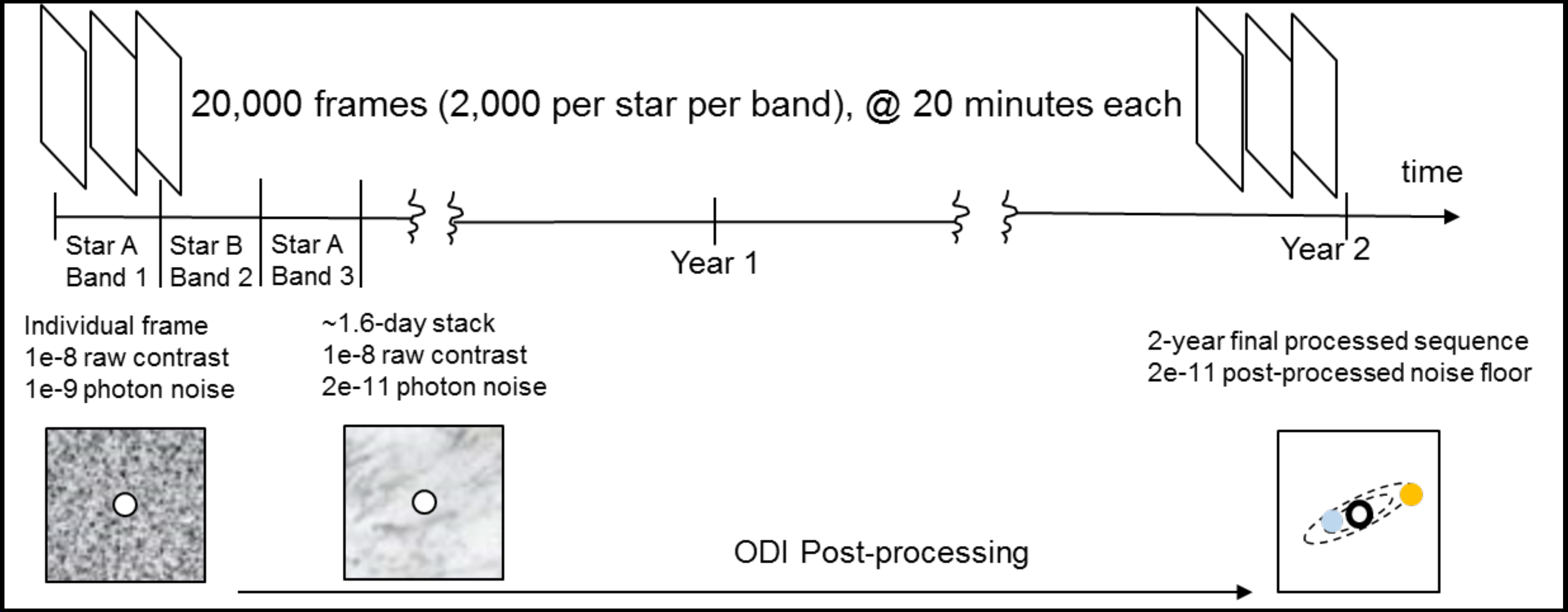
Getting to high contrast on αCen:
Two new enabling technologies



- MSWC: multi-star wavefront control
  - Suppresses light from both stars
  - Thomas, Belikov, Bendek, submitted to ApJ, 2015 (http://arxiv.org/abs/1501.01583)
  - No new hardware required
- ODI: Orbital Differential Imaging
  - Continuous imaging of the system enables 20K images and large post-processing gains
  - Males et al., in prep
  - No new hardware required

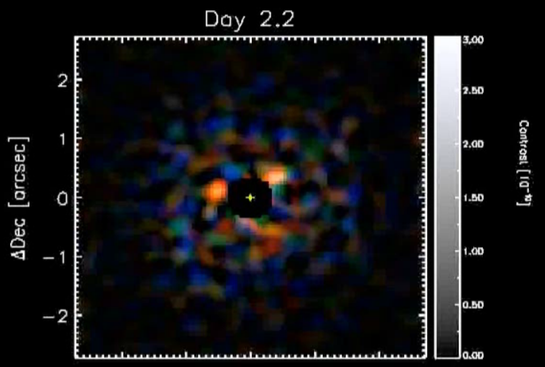
Orbital Differential Imaging:

Powerful post-processing enabled by continuously imaging a planet as it orbits a star



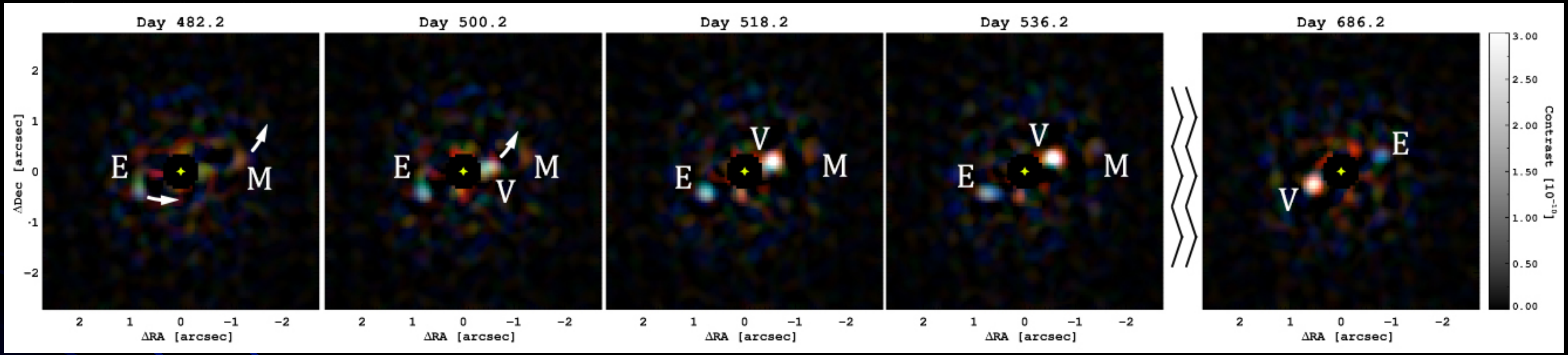
- A very large number of images -> beats down random noise
- Capture continuous Keplerian orbit motion -> differentiates planets from systematic and residual random noise
- ODI pipeline:
  - KLIP PSF subtraction
  - Temporal filter to eliminate everything that does not appear to move on a Keplerian orbit (this includes static part of exozodi)
  - Spatial filter and other standard image processing tools
  - “Shift-and-add” along Kepler orbits to increase candidate planet signal

ODI Pipeline (Simulation)

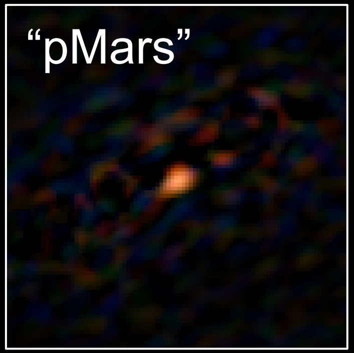


- Simulation parameters (ACESat mission)
  - D = 45cm
  - PIAA coronagraph
  - 1e-8 starting contrast (assumed after MSWC)
  - 0.5mas (1σ rms) random tip/tilt jitter
  - 5 color filters
  - 2-year mission
  - Photon noise included (dominates over read)

After filtering:



After shift-and-add



Note: "pMars" is larger but farther away than Solar Mars

Conclusions

- A ~30-45cm high contrast telescope is sufficient to directly image Earth-like (and larger) planets around αCen AB
- Continuous monitoring of a single star system enables a powerful Orbital Differential Imaging (ODI) post-processing technique that relaxes raw contrast requirements to 10^8.
- Second star is suppressed by Super-Nyquist Multi-Star Wavefront Control (SNMSWC).

Integrating these ideas together: 45cm SMEX concept