Multi-Star Wavefront Control:

What is it and does it help starshade missions?

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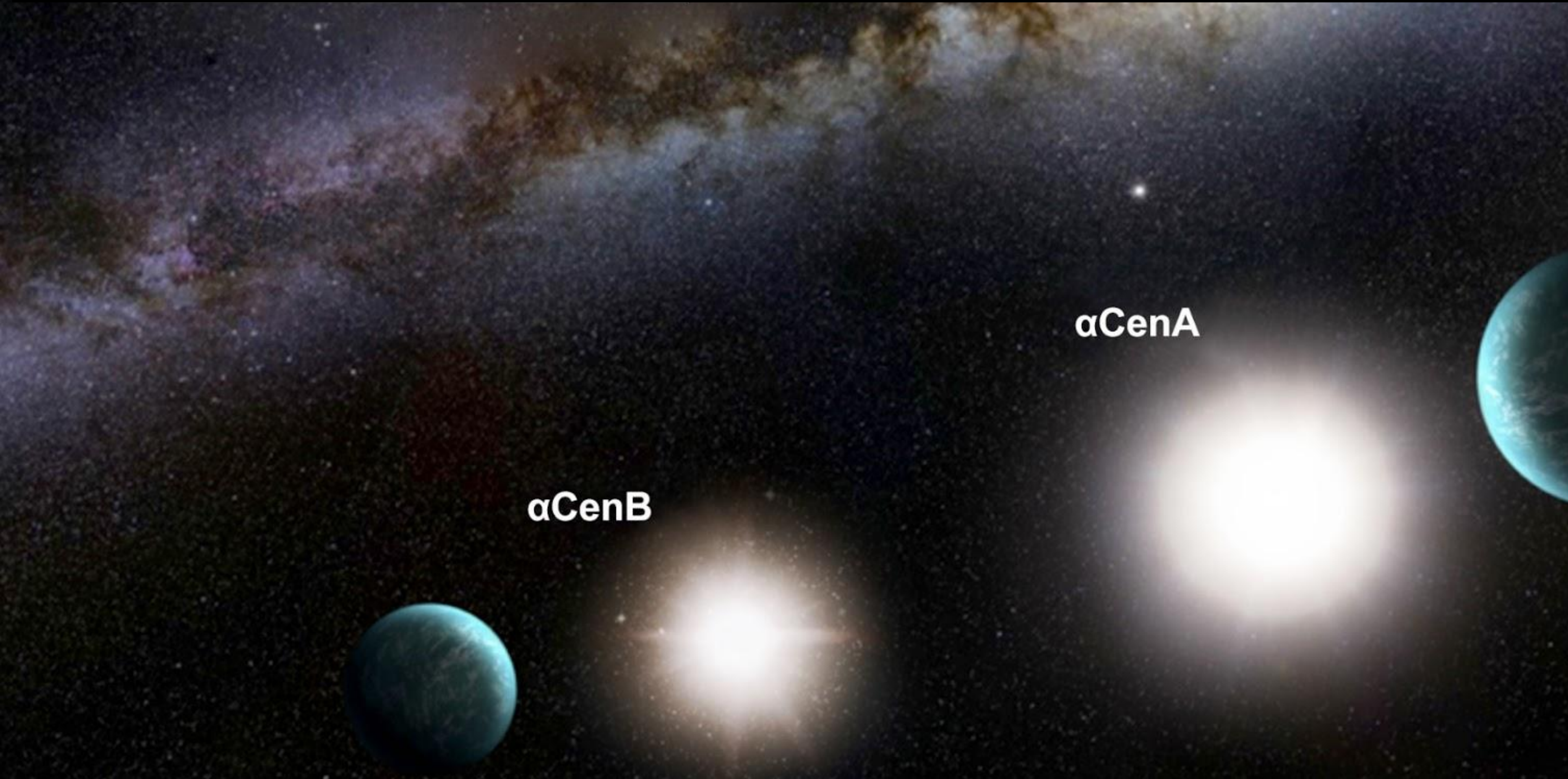

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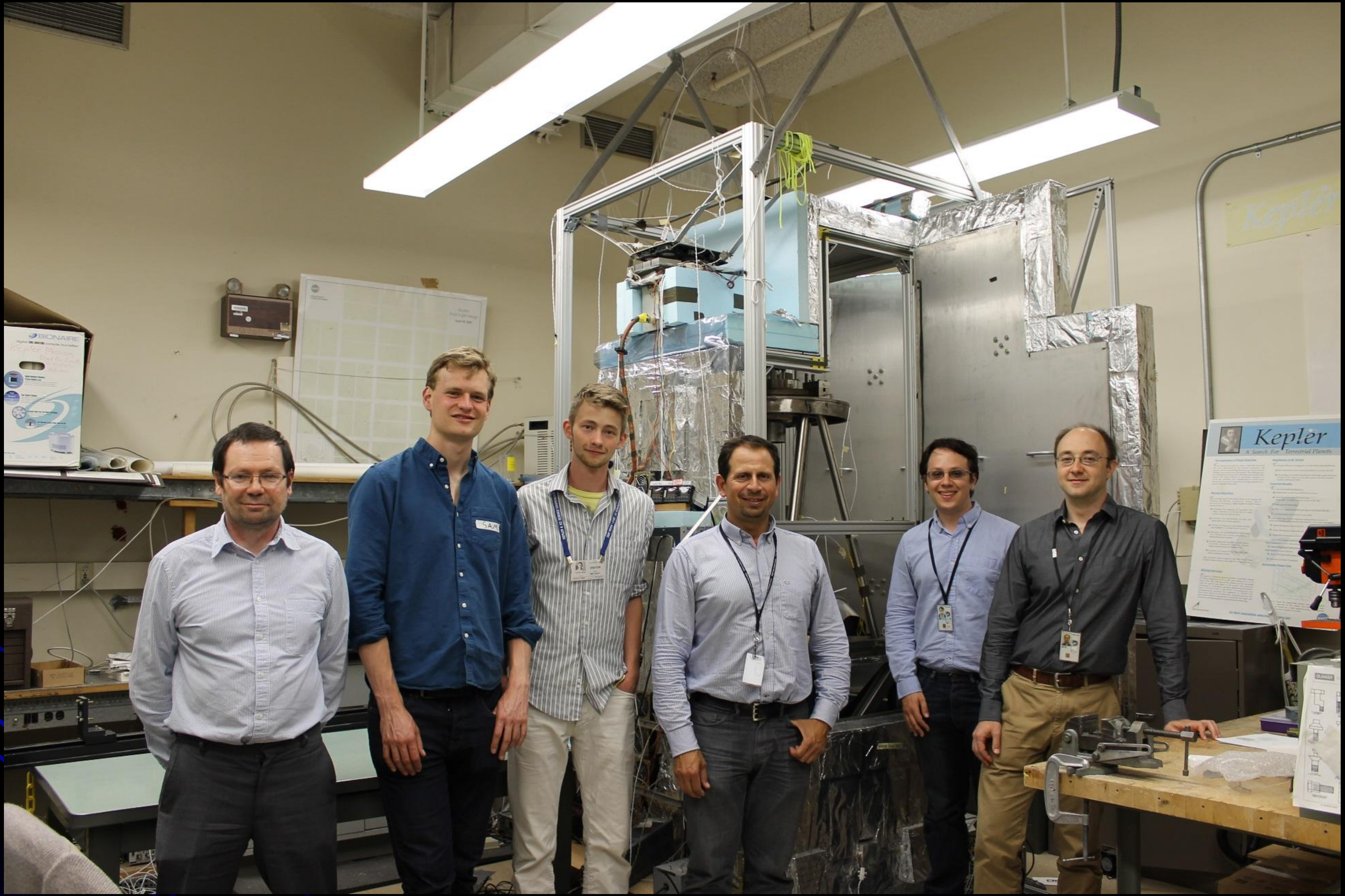
SIP, 11/19/2020

Exoplanets Technologies group at NASA ARC



Eugene Pluzhnik, Sam Harrison, Elias Holte, Eduardo Bendek, Dan Sirbu, Rus Belikov

Part-time members (not pictured): Pete Zell, Jack Lissauer, Steve Bryson, Chris Henze

Outline

- Value of binary stars for exoplanet science
- MSWC theory
- Laboratory demonstrations

Dan Sirbu’s presentation:

- Binary target statistics
- Simulations for missions

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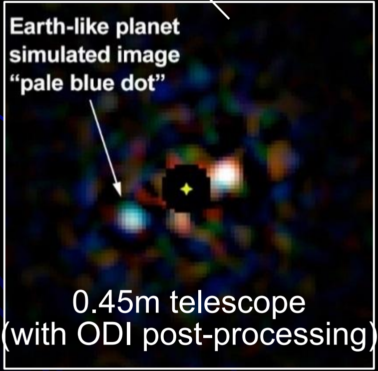
Importance of Multi-Star Systems

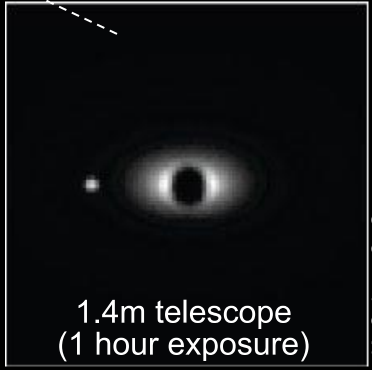
- Most non-Mdwarf stars are in multi-star systems. For example, within 4pc:
  - 5 Multiples: aCen, Sirius, Procyon, 61 Cyg, e Ind
  - 2 Single: e Eri, t Cet
- Alpha Centauri is an unusually favorable outlier

Missions that can benefit from multi-star suppression

Belikov et al. 2015
Bendek et al. 2015



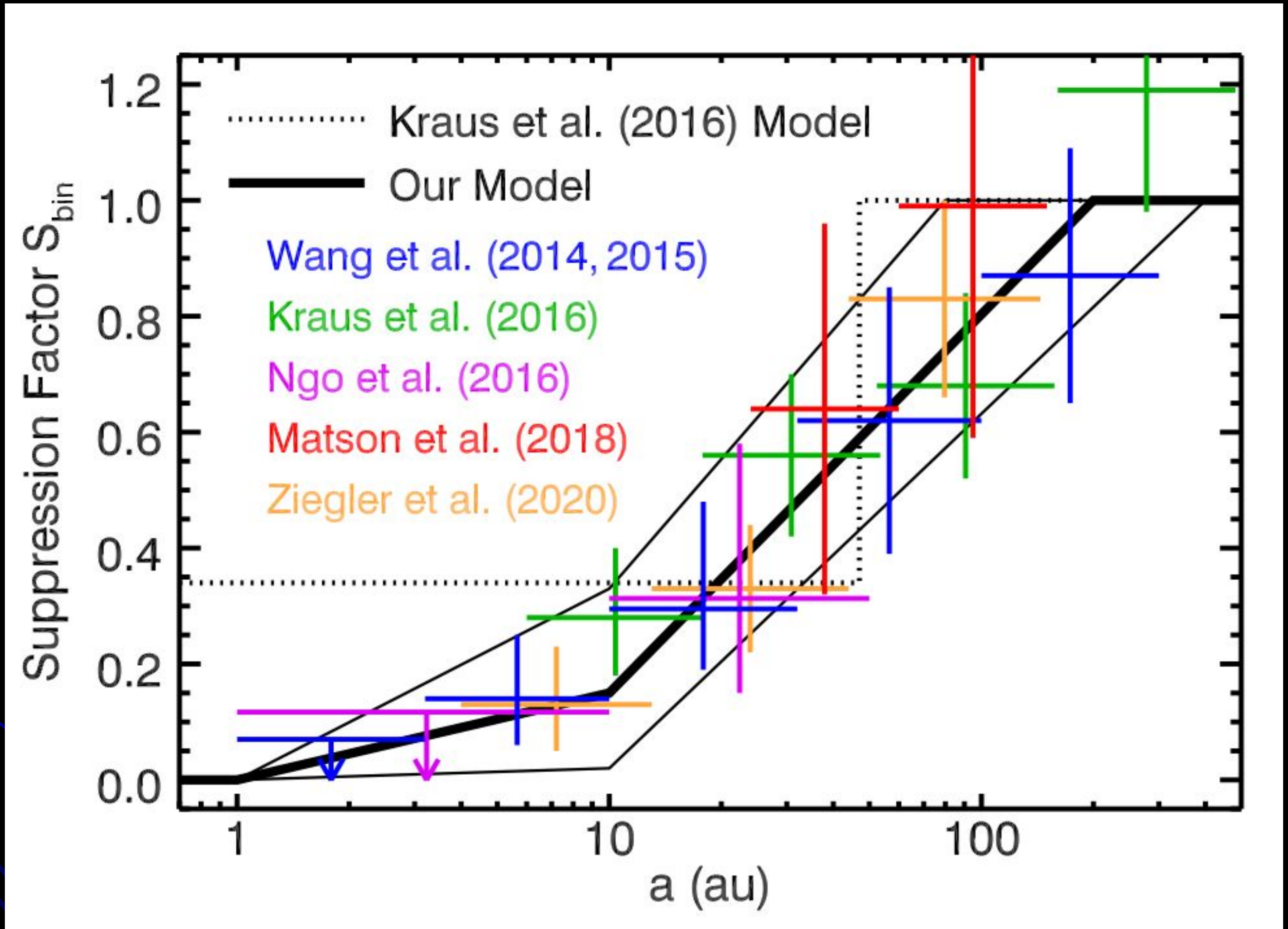
J. Males, R. Belikov



K. Cahoy, O. Guyon

Simulations of exo-Earth detections around Alpha Centauri A
(if the other star could be suppressed)

Can binaries form planets? (as efficiently as single stars?)

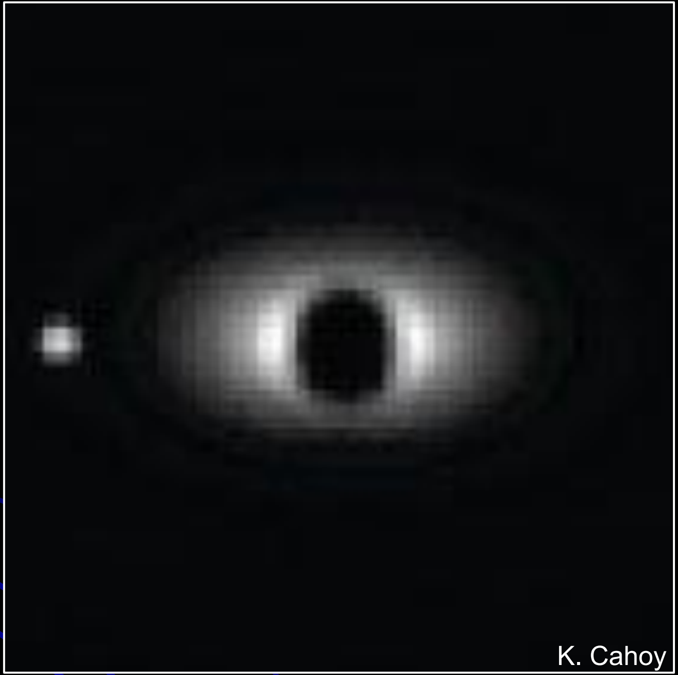


(Moe and Kratter, 2020)

Alpha Centauri: not your typical target

Simulations of an Earth twin detection for a ~1.5 class telescope (similar to Exo-C, Exo-S)

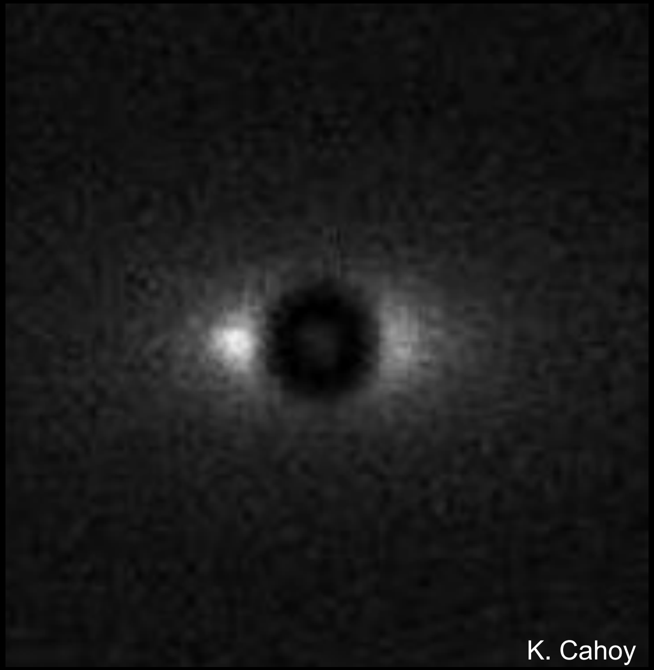
α Cen (A)



1.5m aperture, 1 hour exposure

nothing in-between

τ Cet (~ best of everything else)



1.5m aperture, 1 hour exposure

Alpha Centauri system, if not for the fact that it is a binary, would easily be the best target for direct imaging searches for planets.
– HabEx final report.

Habitable Zones of αCen AB

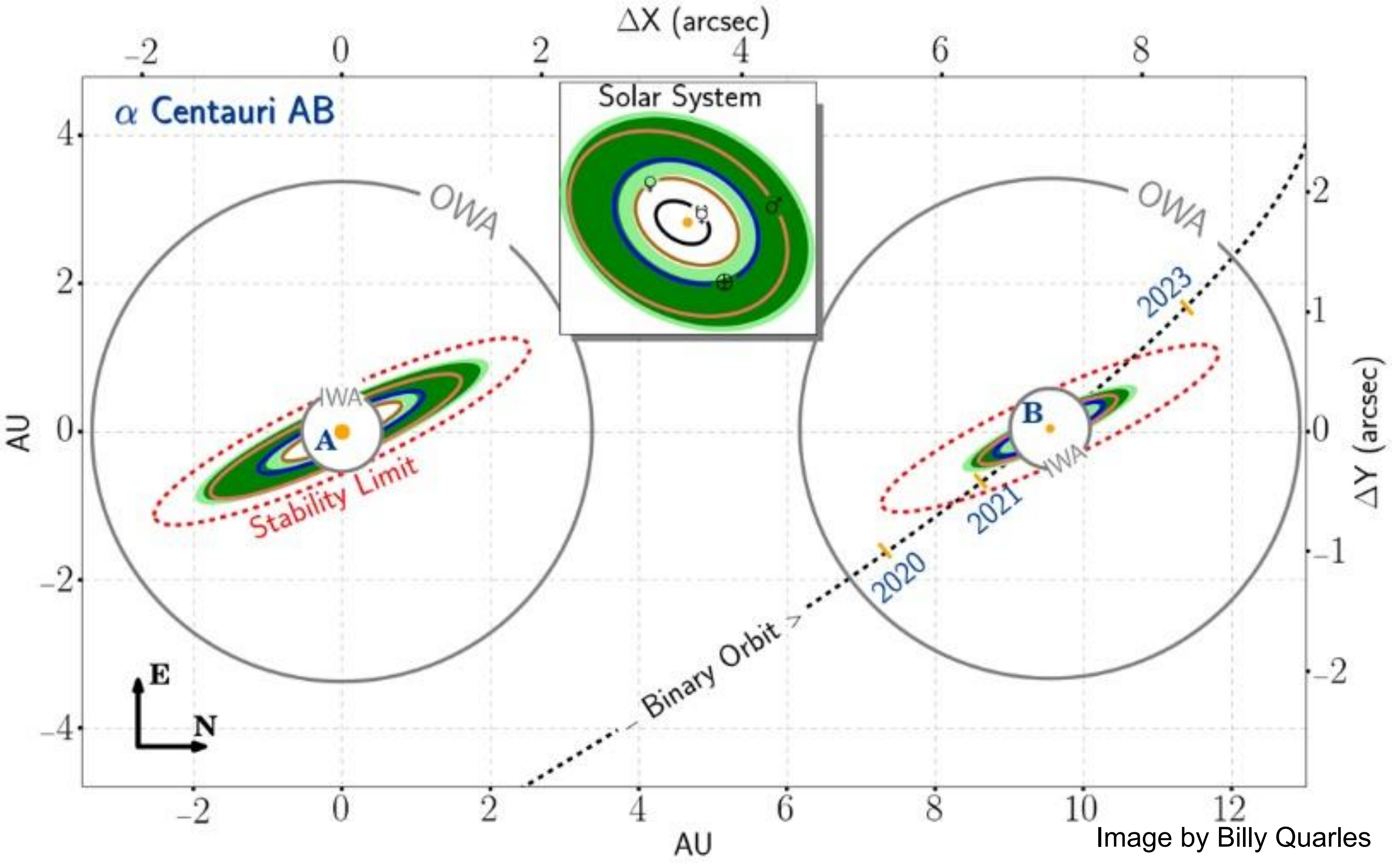


Image by Billy Quarles

see Quarles and Lissauer 2016 for aCen stability
https://arxiv.org/abs/1604.04917

- 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, Quarles and Lissauer 2016)

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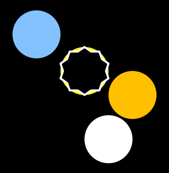
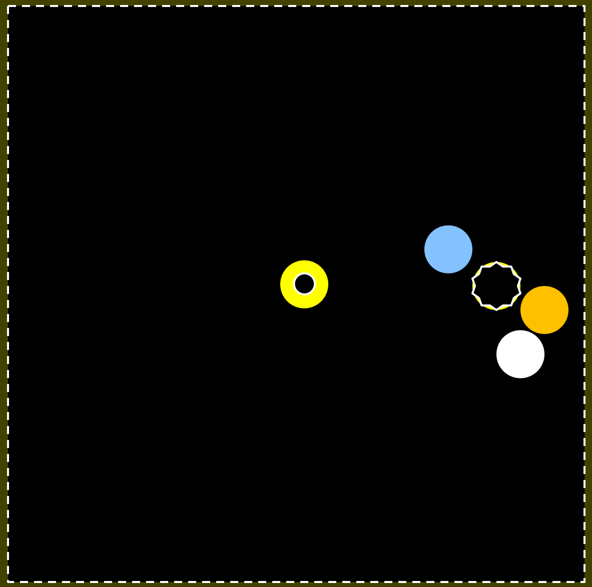
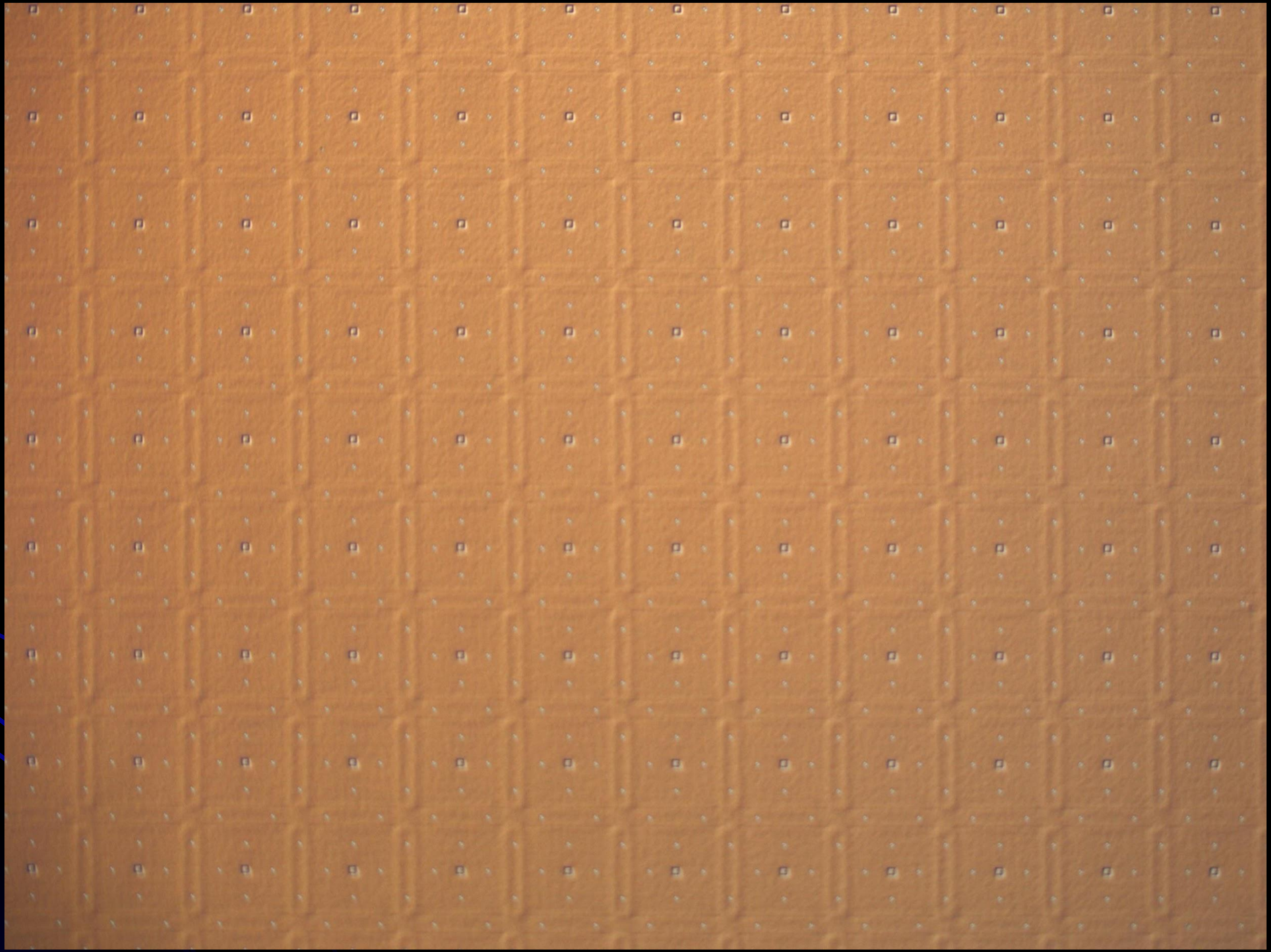
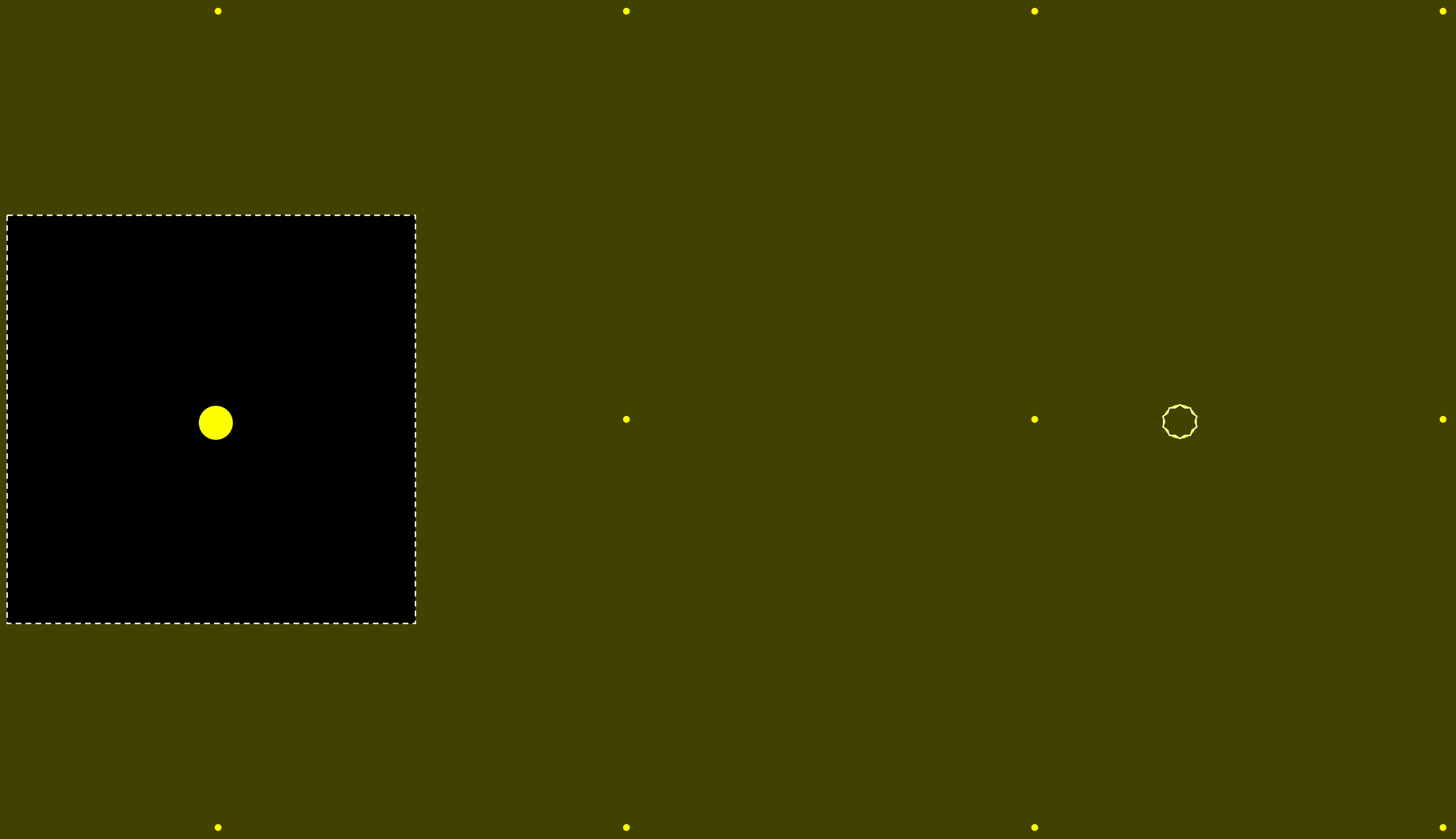


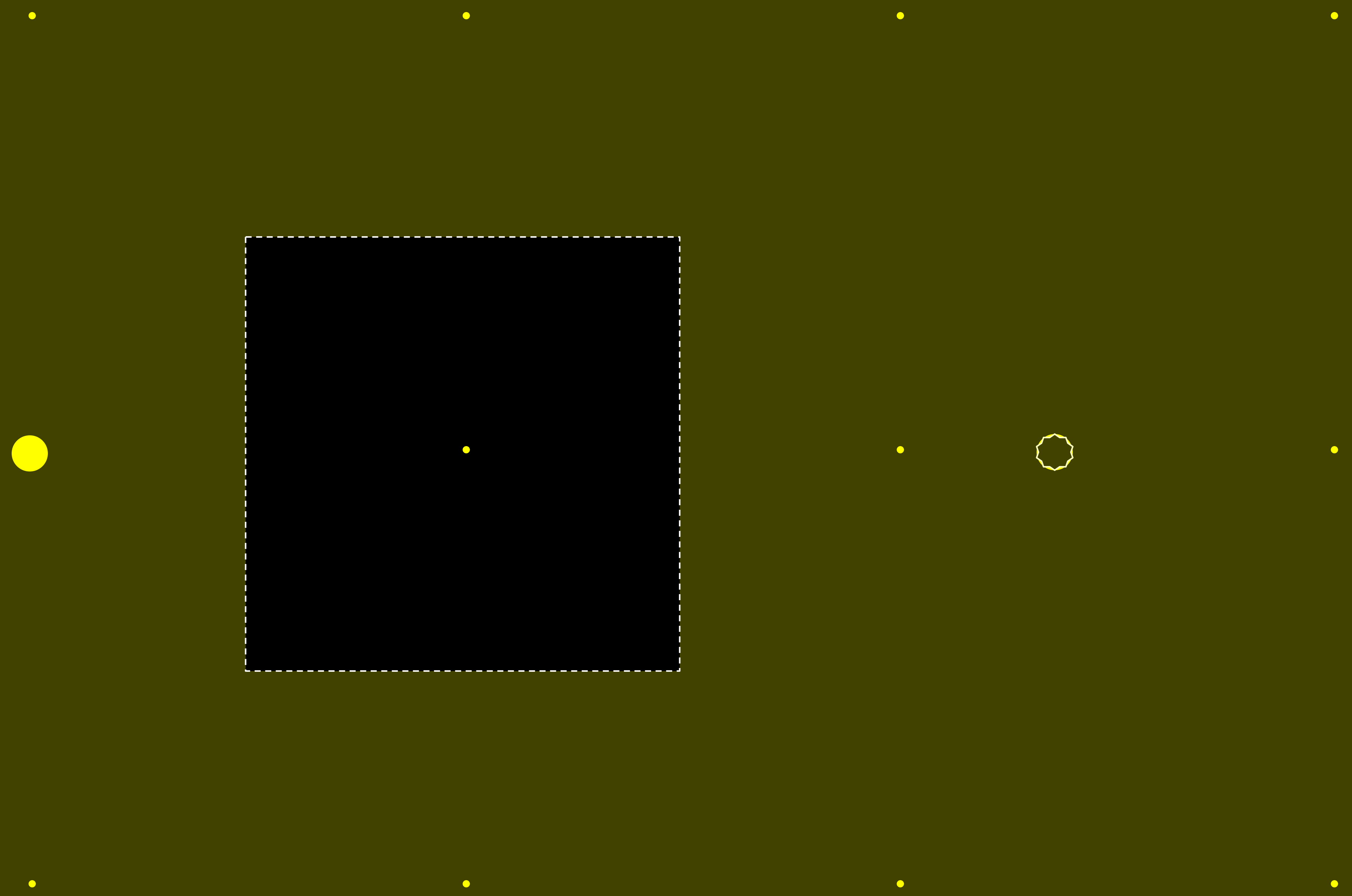


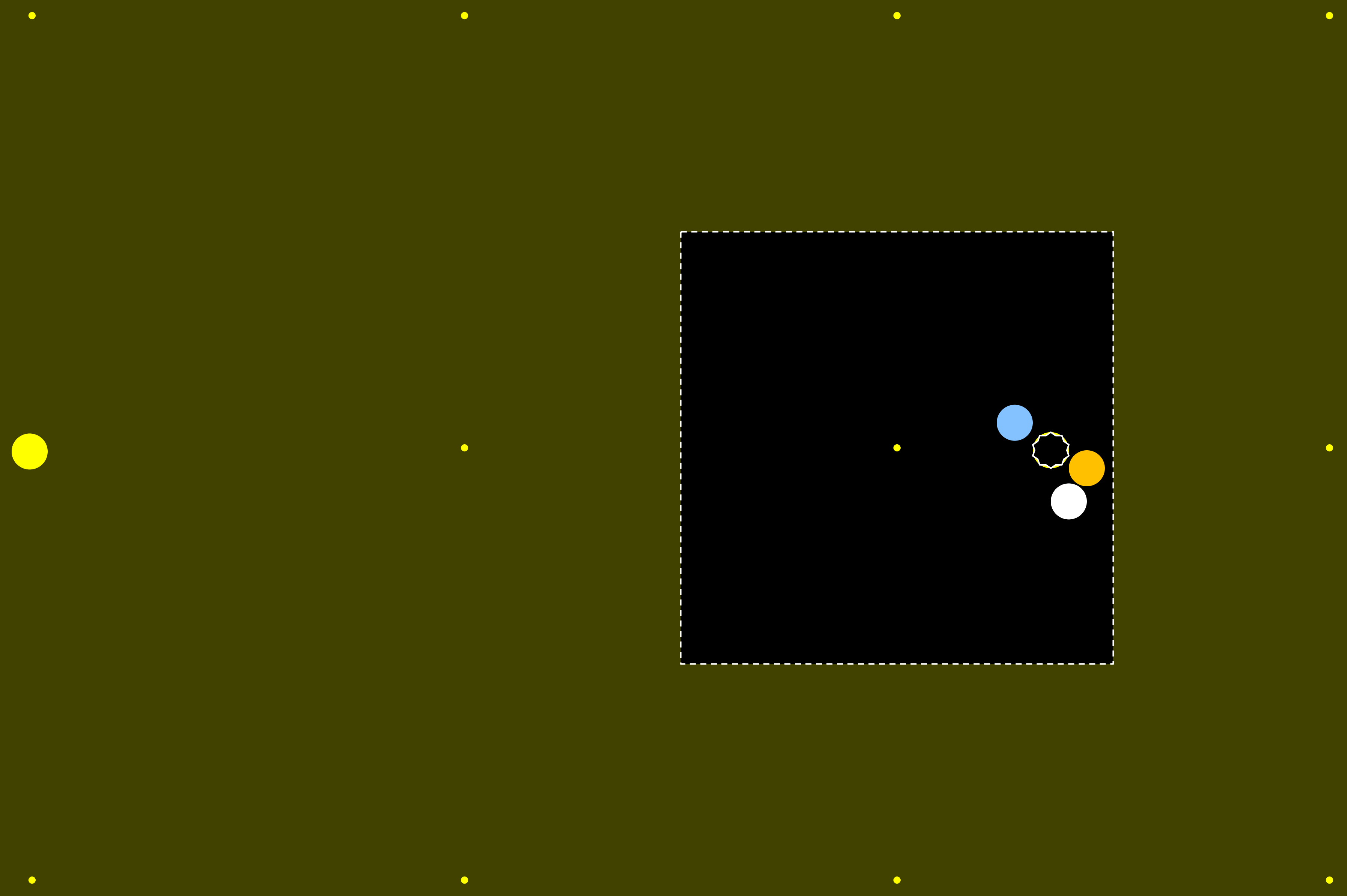
DM “quilting”: a feature, not a bug



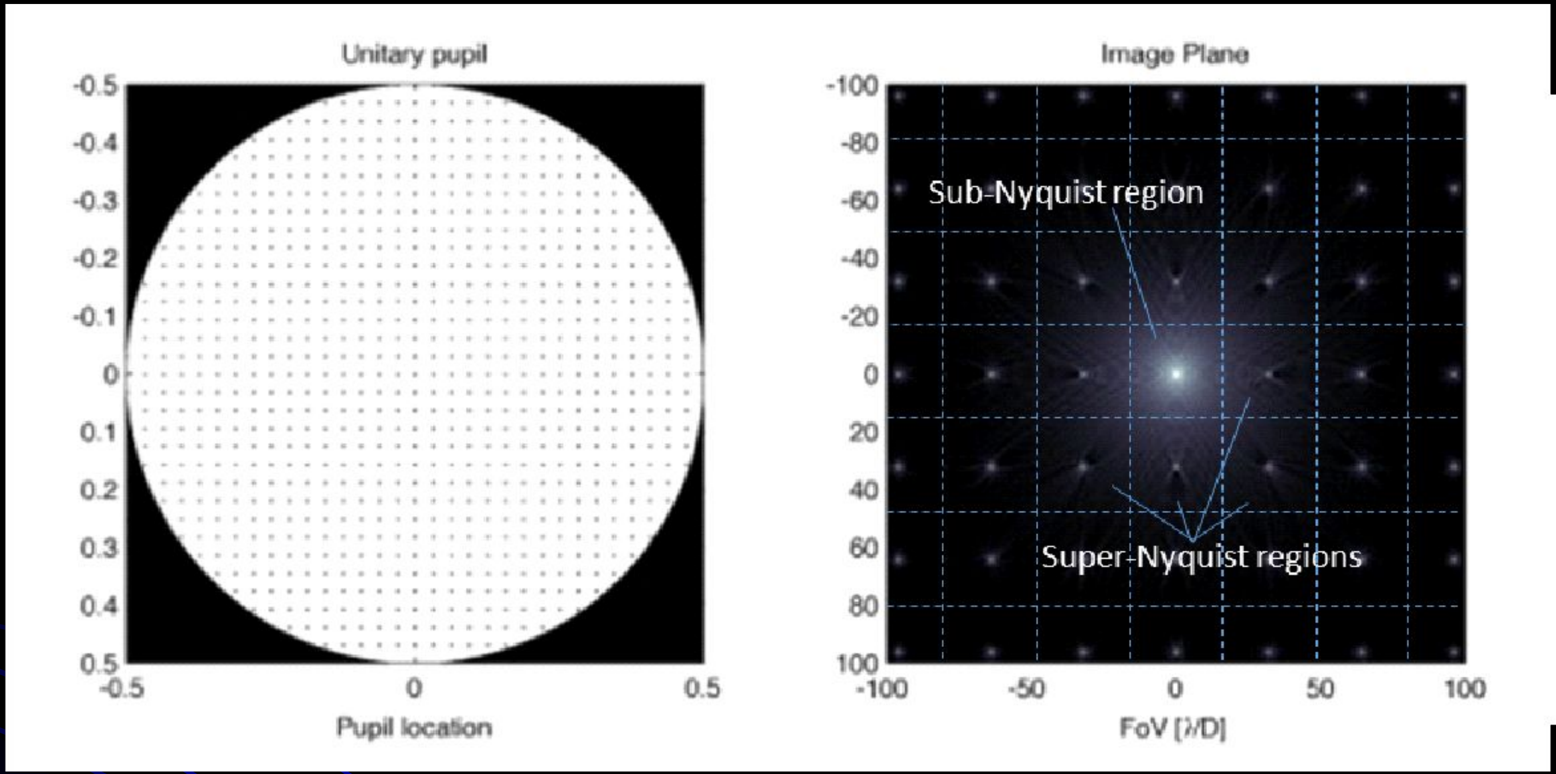
Phase microscope image of a BMC deformable mirror surface

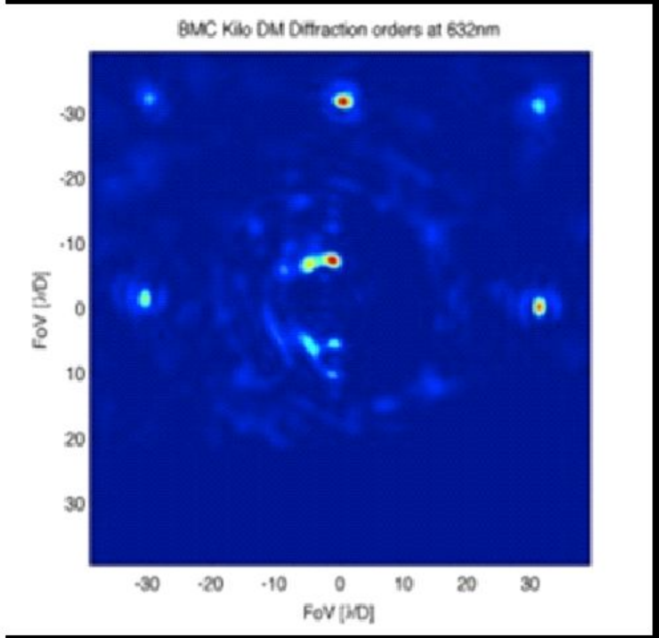






Super-Nyquist WC principle





- Main idea: Diffraction orders or non-smooth influence functions enable the DM to modulate light beyond the Nyquist limit
  - Diffraction order effectively acts as a pseudo star, and almost any WF algorithm can be used to dig a dark hole (at a sub-Nyquist distance) around a diffraction order
  - Can also be understood in terms of aliasing
- If grating periodicity = DM actuator periodicity, then controllable diffraction order regions fully tile the entire focal plane (theoretically to infinity)

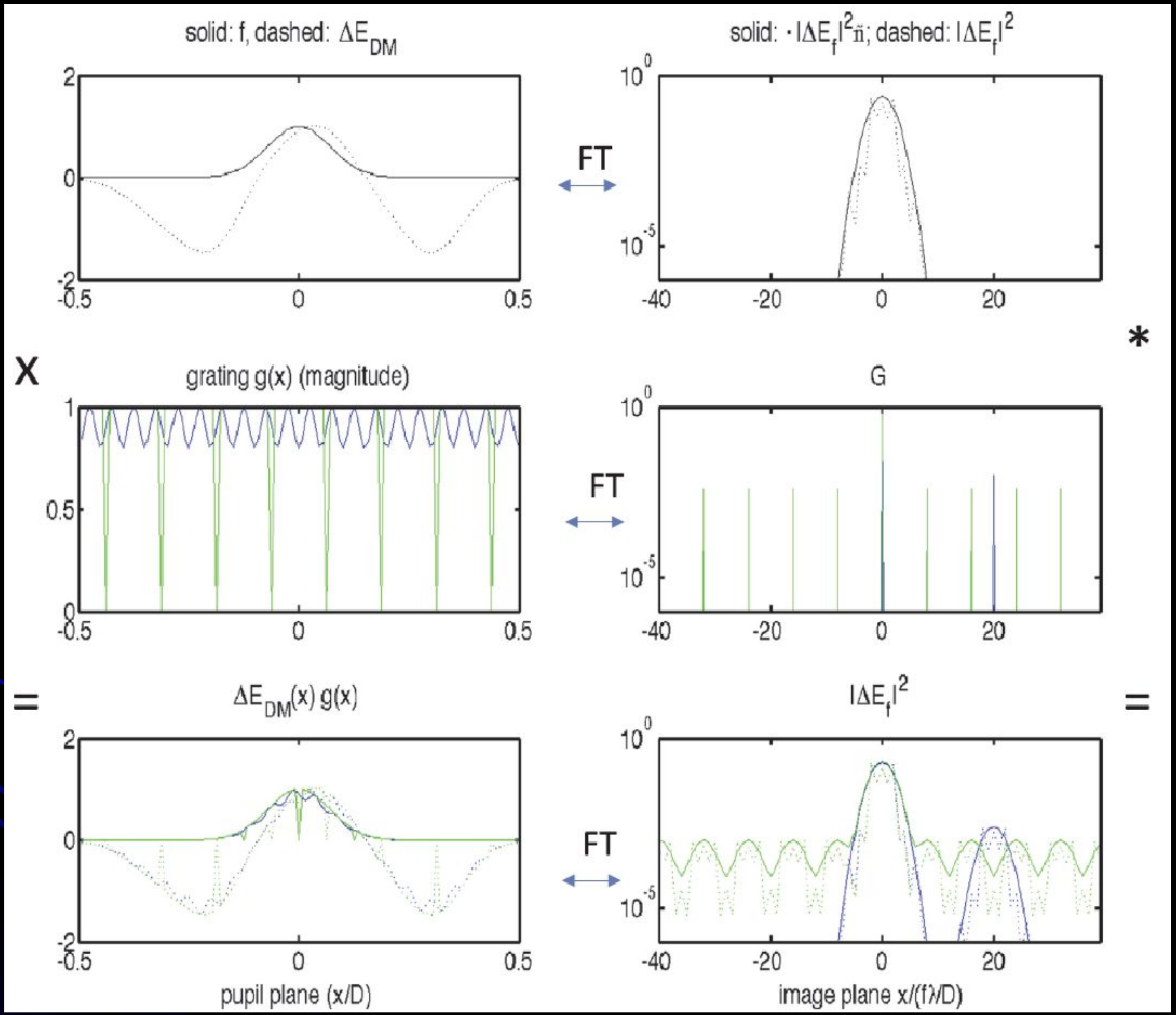
SNWC using quilting or grating

Pupil plane | Focal plane

Solid: influence function
Dashed: DM field perturbation

Grating (green) or
beamsplitter (blue)

DM field perturbation



Sub-Nyquist controllability curve

Super-Nyquist controllability curves (solid)

Thomas et al., ApJ, 2015

SNWC using special influence functions

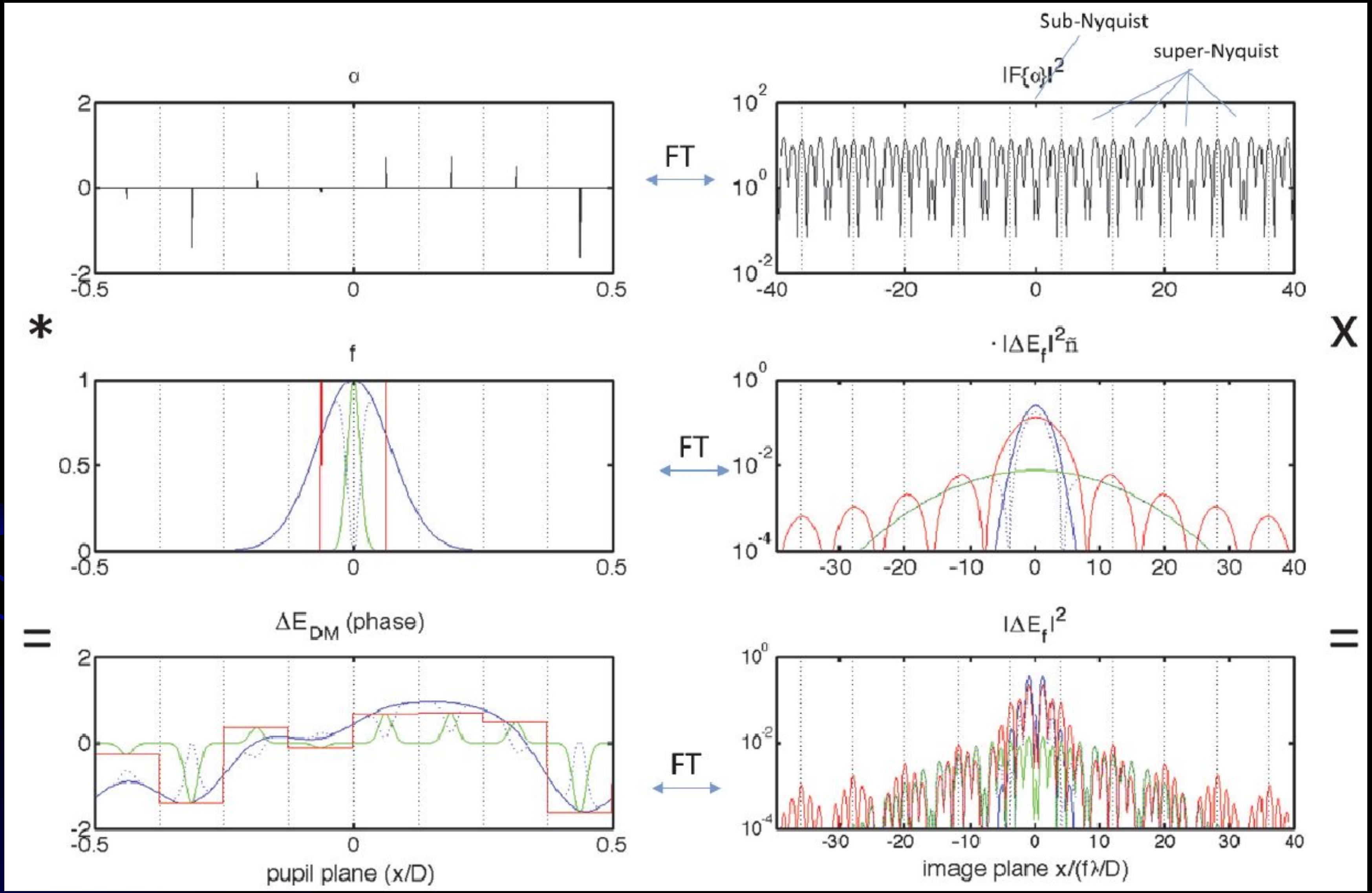
Pupil plane

Focal plane

DM actuator coefficients

Influence functions

DM field perturbation

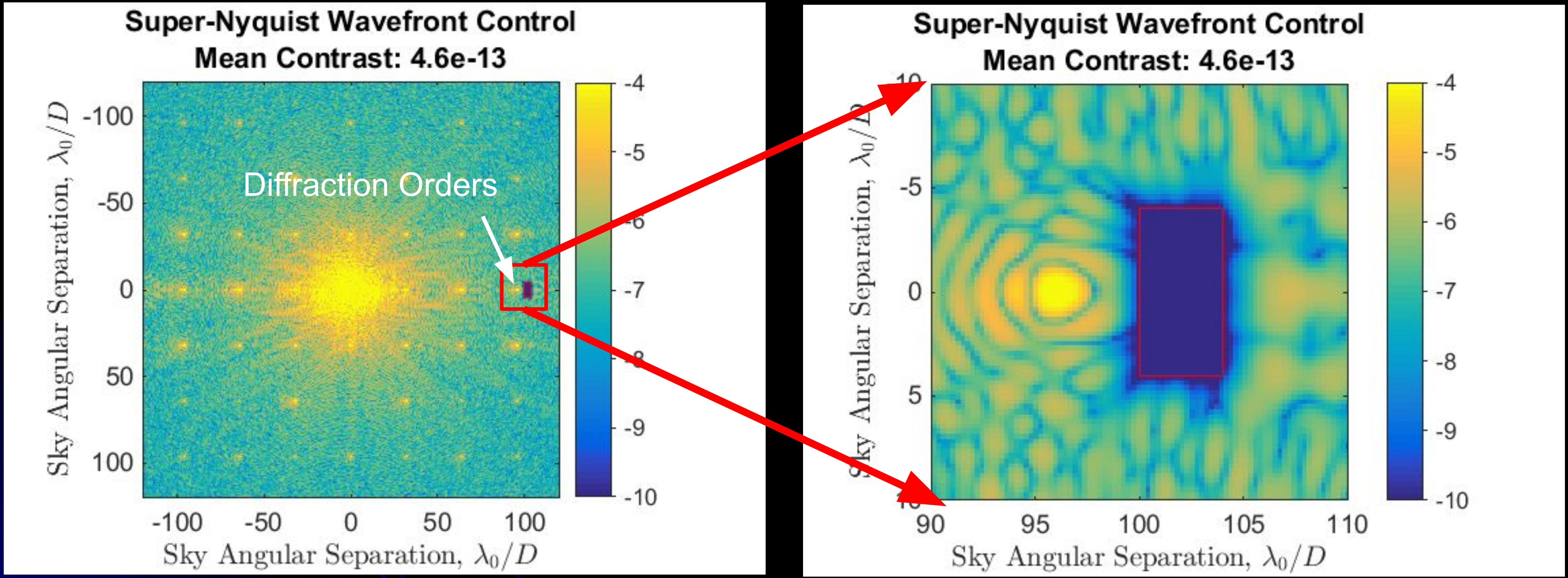


SNWC Controllability

Thomas et al., ApJ, 2015; also see Gerard et al. 2018 for a method that leverages nonlinear terms to control super-Nyquist speckles

Super-Nyquist Wavefront Control

(single star, or multi-star w/starshade)



Simulations by D. Sirbu

Also see Thomas et al. (2015), Belikov et al. (2016)

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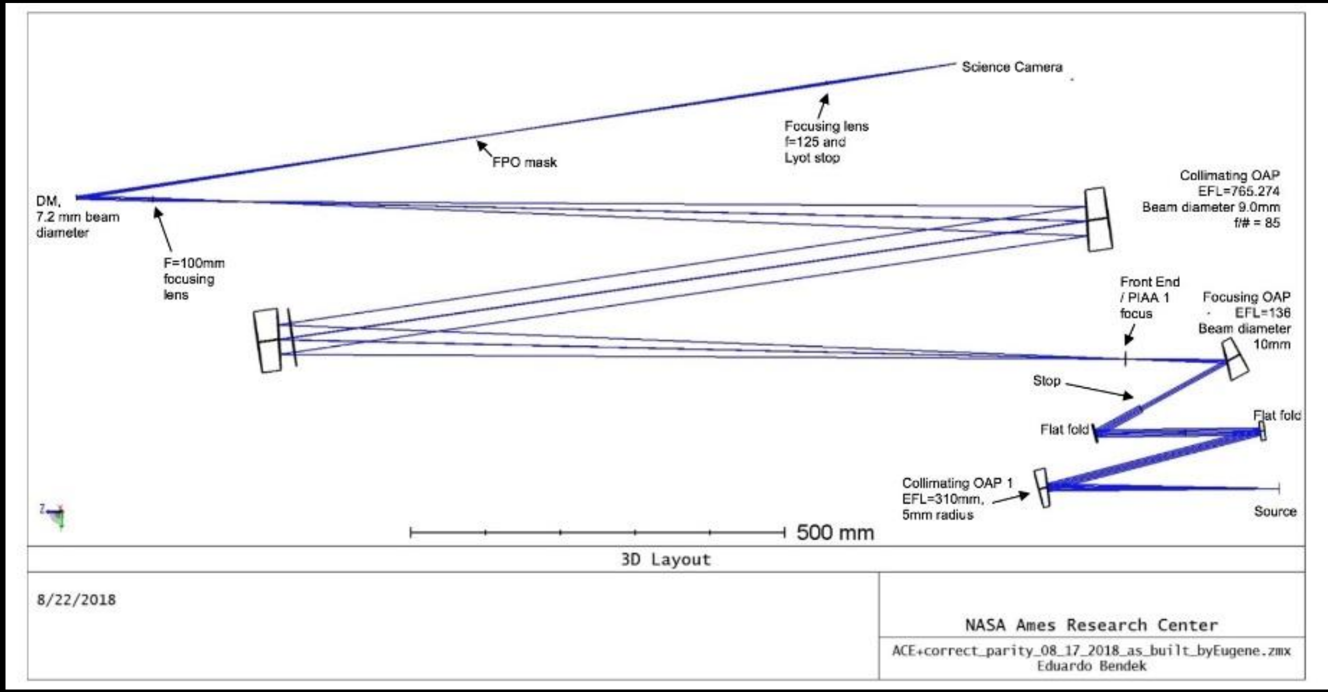
Demonstrations with ACE Testbed

ACE Testbed Enclosure

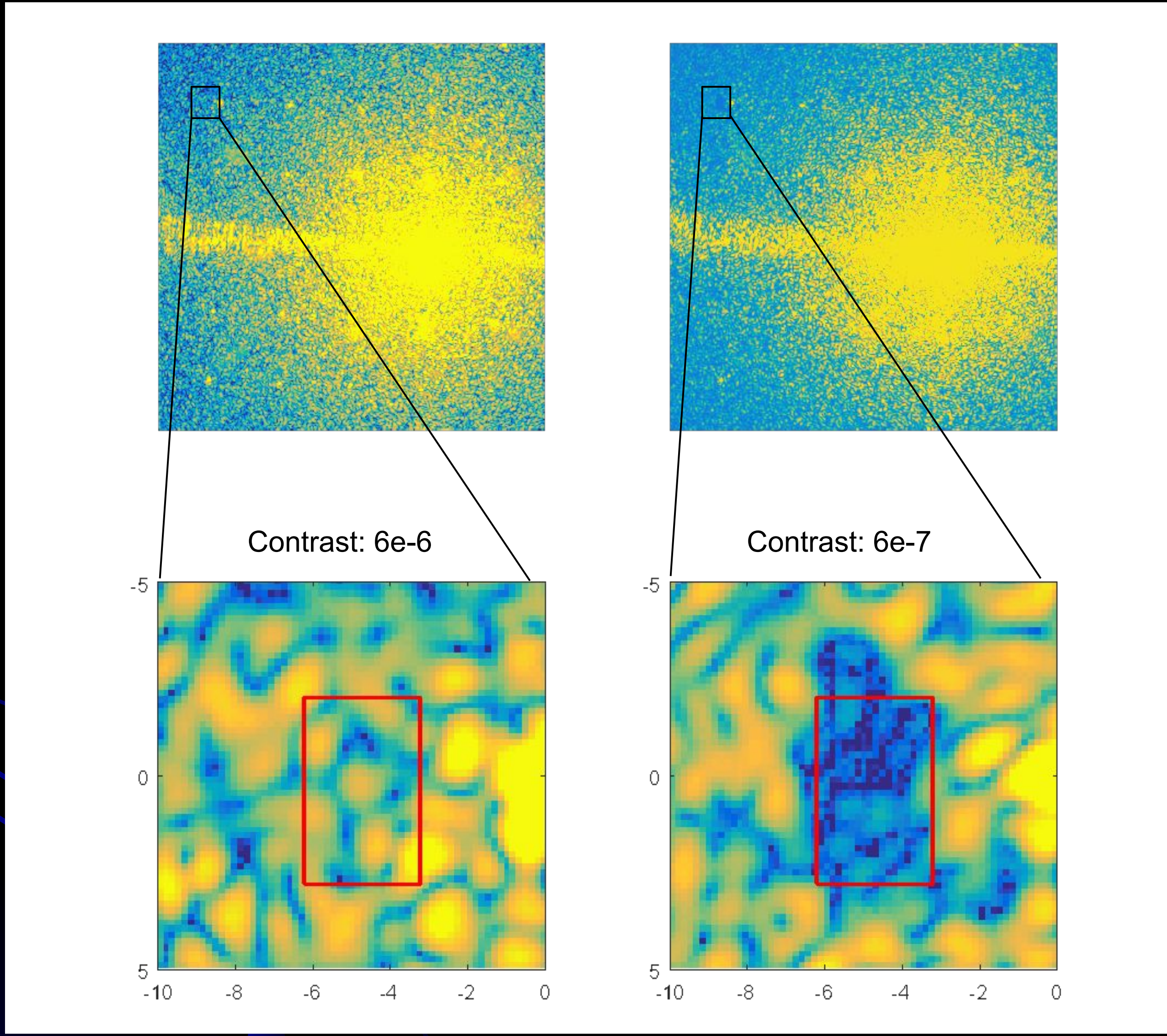


ACE Testbed typical layout

- 655nm light
- No coronagraph (for simplicity)
- Demonstrates basic feasibility of MSWC

Super Nyquist WC Lab demo at 100 λ/D

(representative of aCen w / WFIRST-size telescope and starshade)



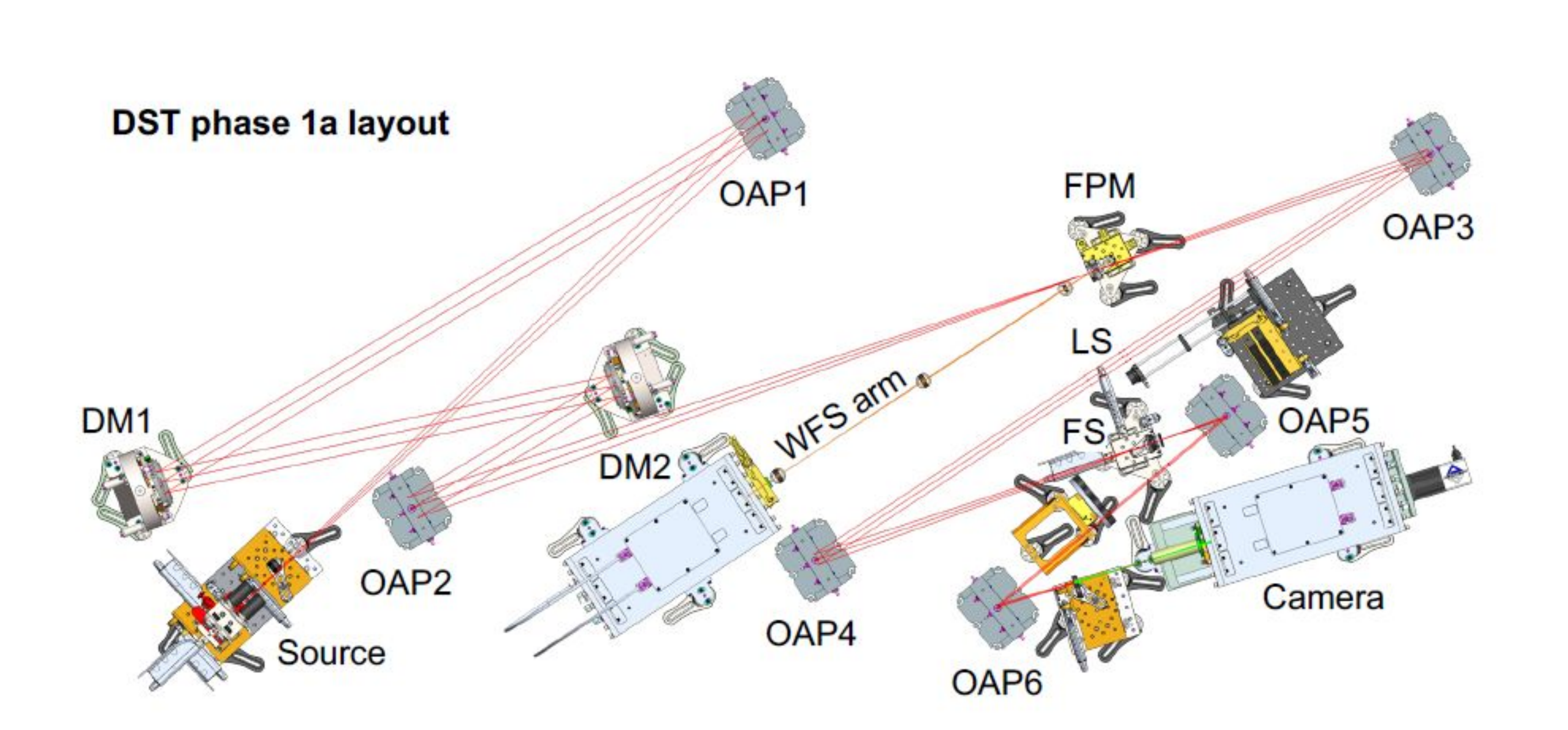
Belikov et al. 2017, SNWC operated by Pluzhnik

Details of this demonstration:

- In order to isolate pure WFC effects, coronagraph was not used
- For this initial demo, monochromatic light was used (655nm) rather than broadband
- DM: Boston Micromachines kilo (32x32)
- Performed at the Ames Coronagraph Experiment laboratory

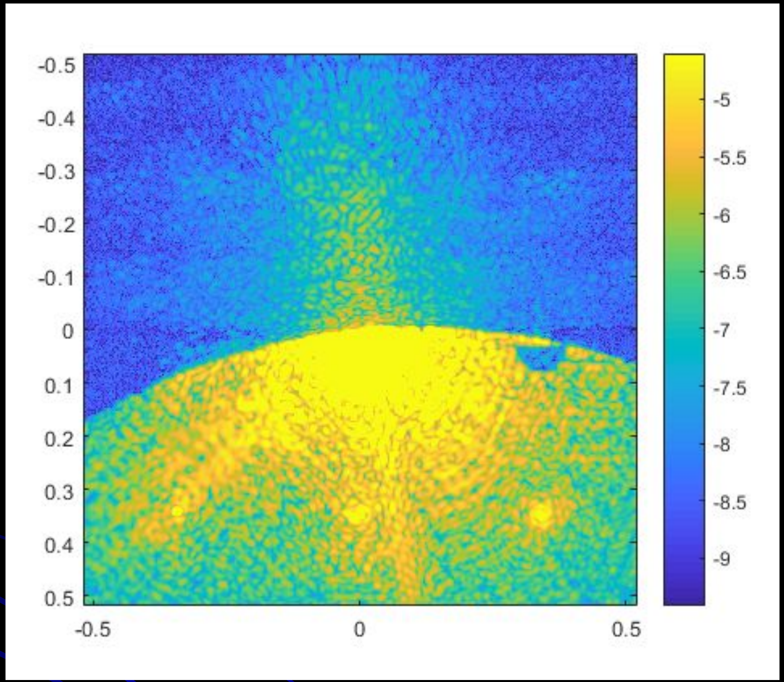
Factor of 10 suppression demonstrated at 100 λ/D

MSWC on Decadal Survey Testbed (DST)

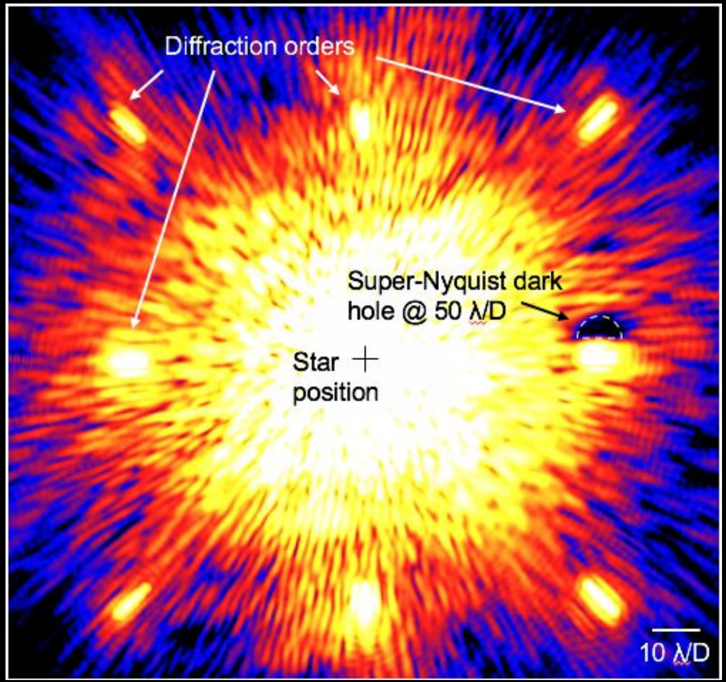


First vacuum demonstrations of super-Nyquist wavefront control

monochromatic light, contrast 4e-8



10% broadband light, 4e-7
(also: 6e-8 demonstrated in a smaller dark zone)



- Source: single star (demonstrating super-Nyquist capability)
- Coronagraph: Vector Vortex
- Testbed operated by Garreth Ruane

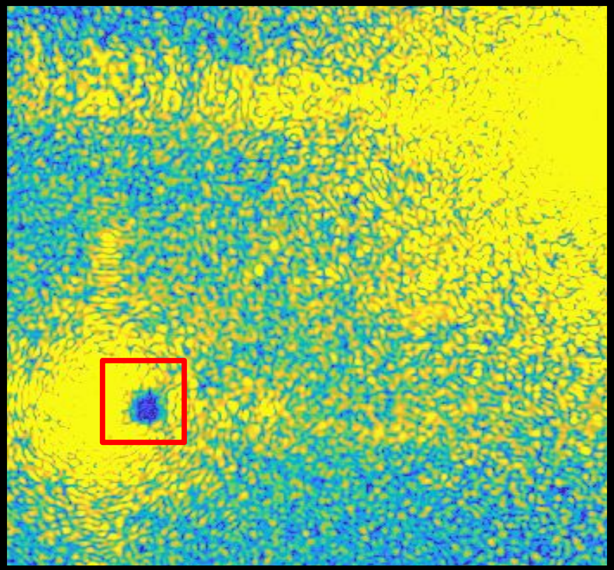
Conclusions

- Binary star targets are important for direct imaging
  - More than half of Sun-like stars belong to multi-star systems
  - Alpha Centauri is an unusually favorable outlier

- Super-Nyquist Wavefront Control (SNWC) enables starshade missions to target most binary star targets
  - Telescope needs a deformable mirror (with quilting or a mild grating), but does not need a coronagraph

- TRL ~4 lab demonstrations at ACE, SCExAO, and DST
  - Super-Nyquist dark zones demonstrated at 16-300 λ/D with a 32x32 DM
  - MSWC for (effectively) 2 light sources demonstrated
    - both sub- and super-Nyquist versions
  - Preliminary contrasts achieved in vacuum (in single-star super-Nyquist mode): 4e-8 in monochromatic light, 4e-7 in 10% band

- We are always looking for talented student interns / postdocs!
  - Contact ruslan.belikov@nasa.gov and/or dan.sirbu@nasa.gov



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