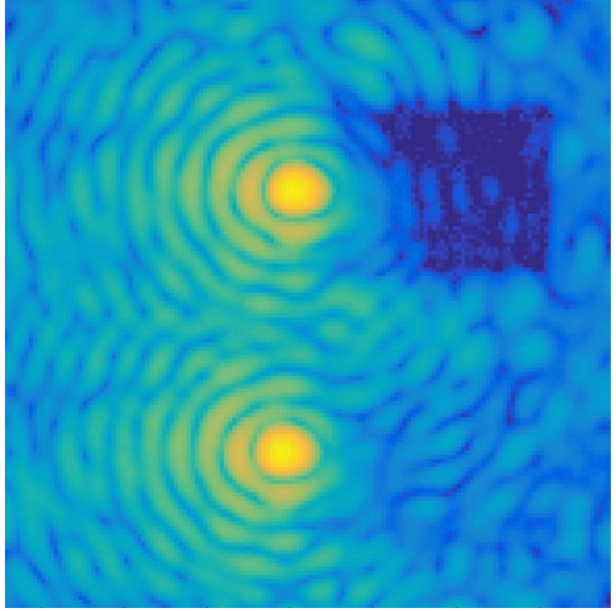
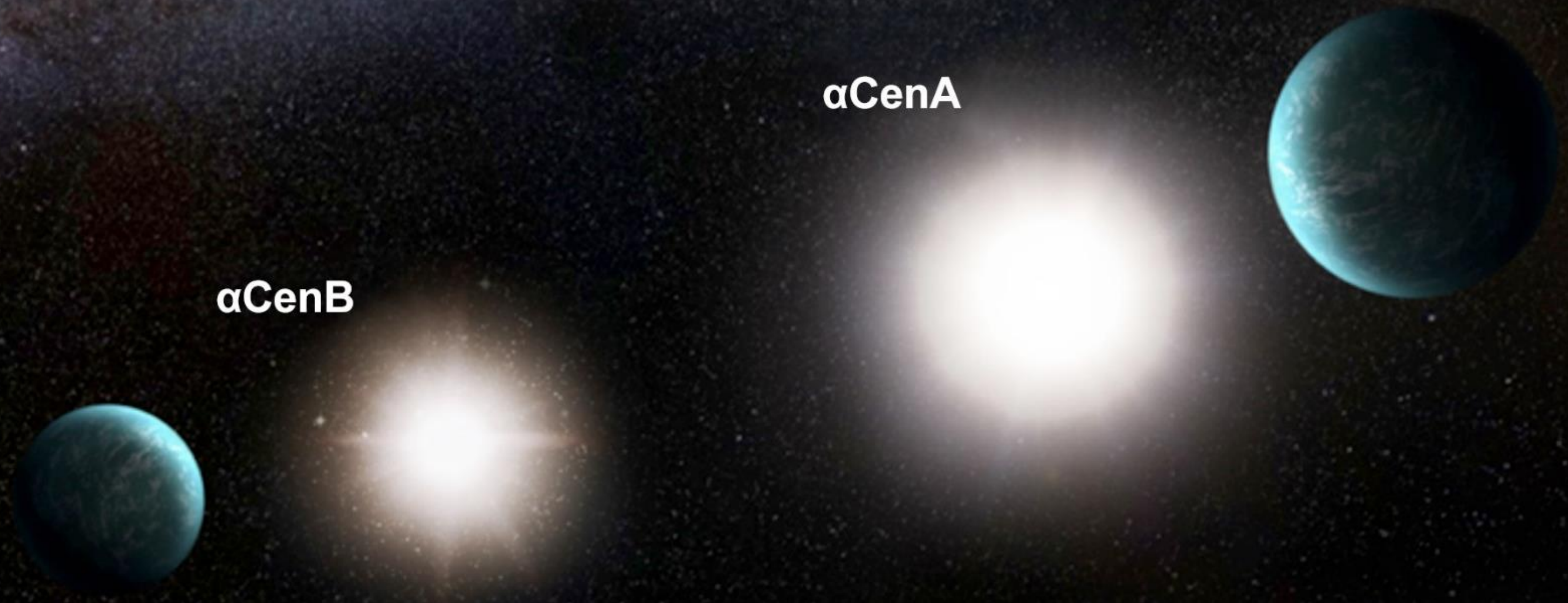


Imaging the Closest Exoplanets to the Sun

Ruslan Belikov, Eduardo Bendek, Dan Sirbu, Eugene Pluzhnik

NASA Ames Research Center



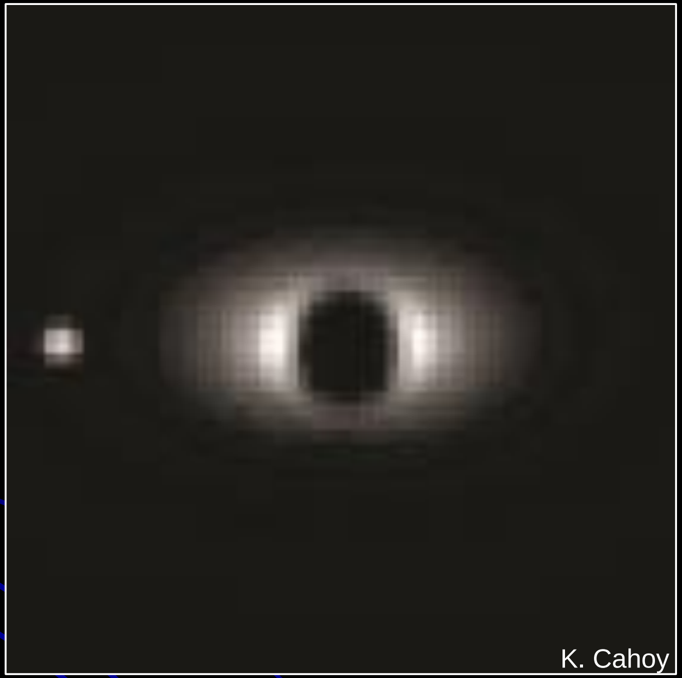
KISS workshop, Caltech, 4/12/2018

Alpha Centauri: not your typical target

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

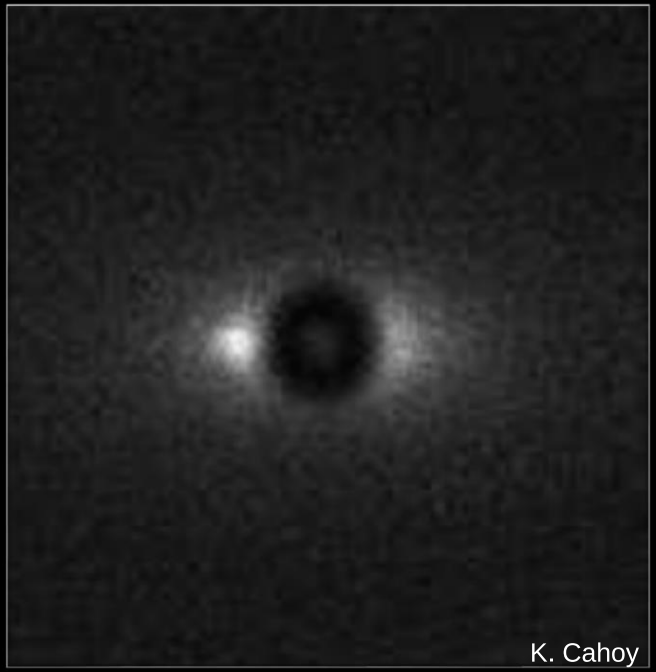
α Cen (A)

τ Cet (~ best of everything else)



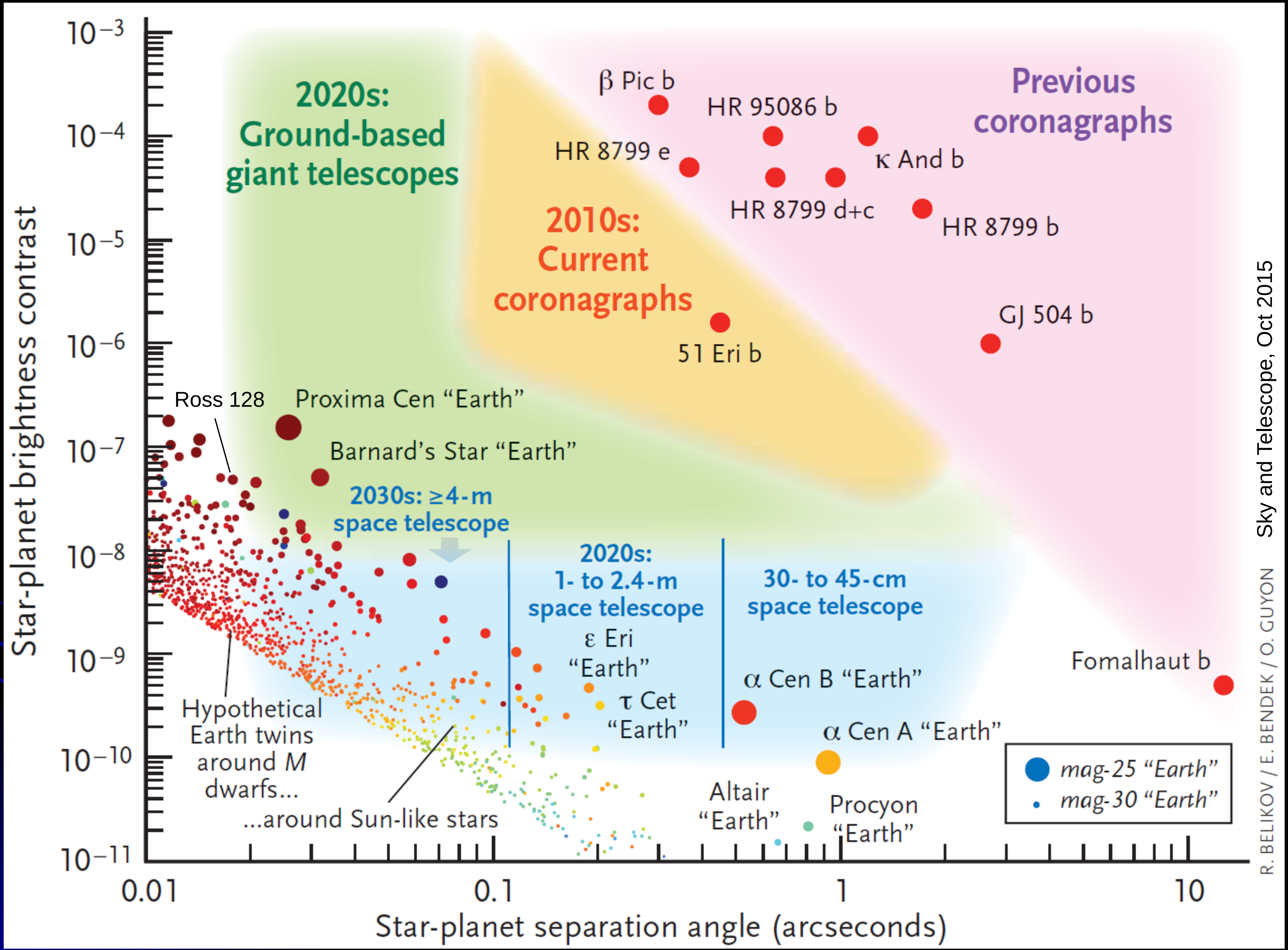
1.5m aperture, 1 hour exposure

nothing
in-between



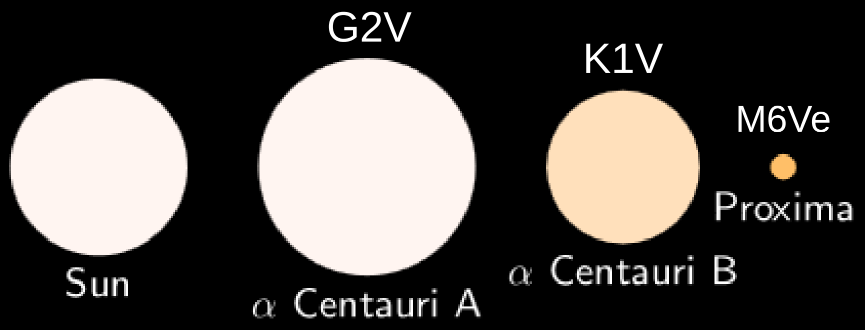
1.5m aperture, 1 hour exposure

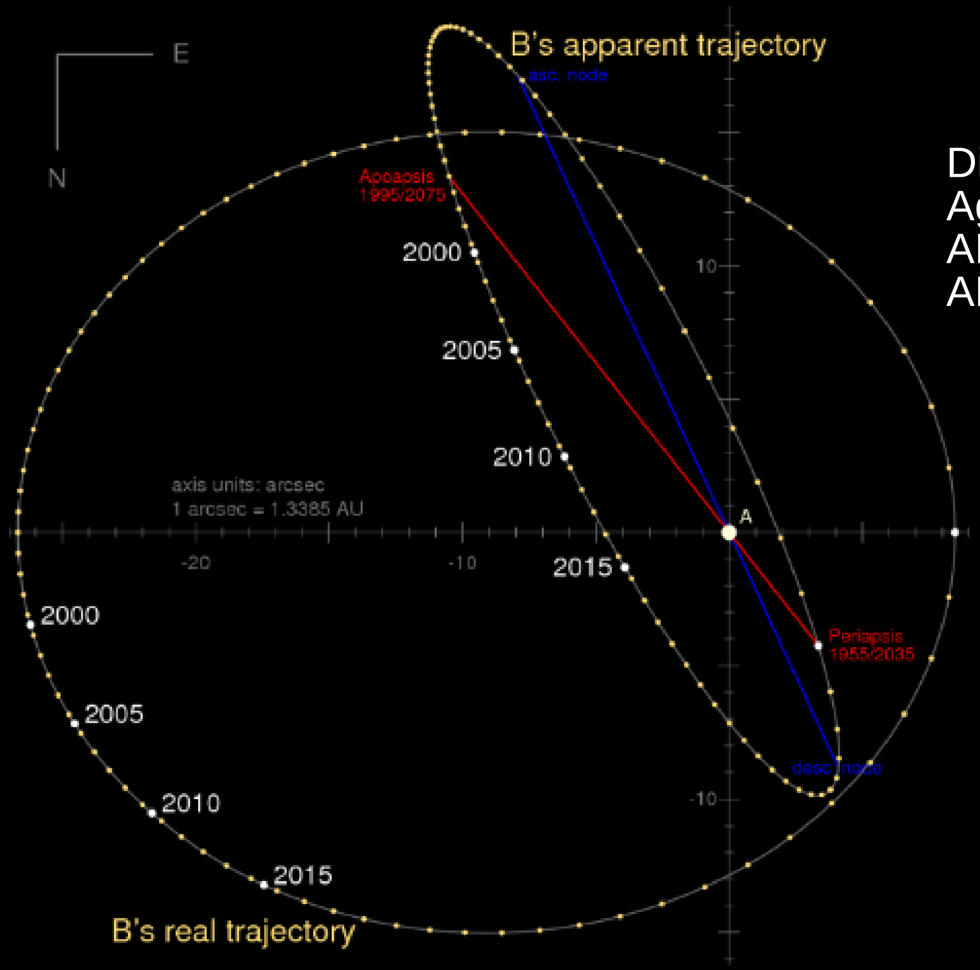
If Alpha Centauri was not a binary, it would probably be the best target for any direct imaging mission, by a large margin



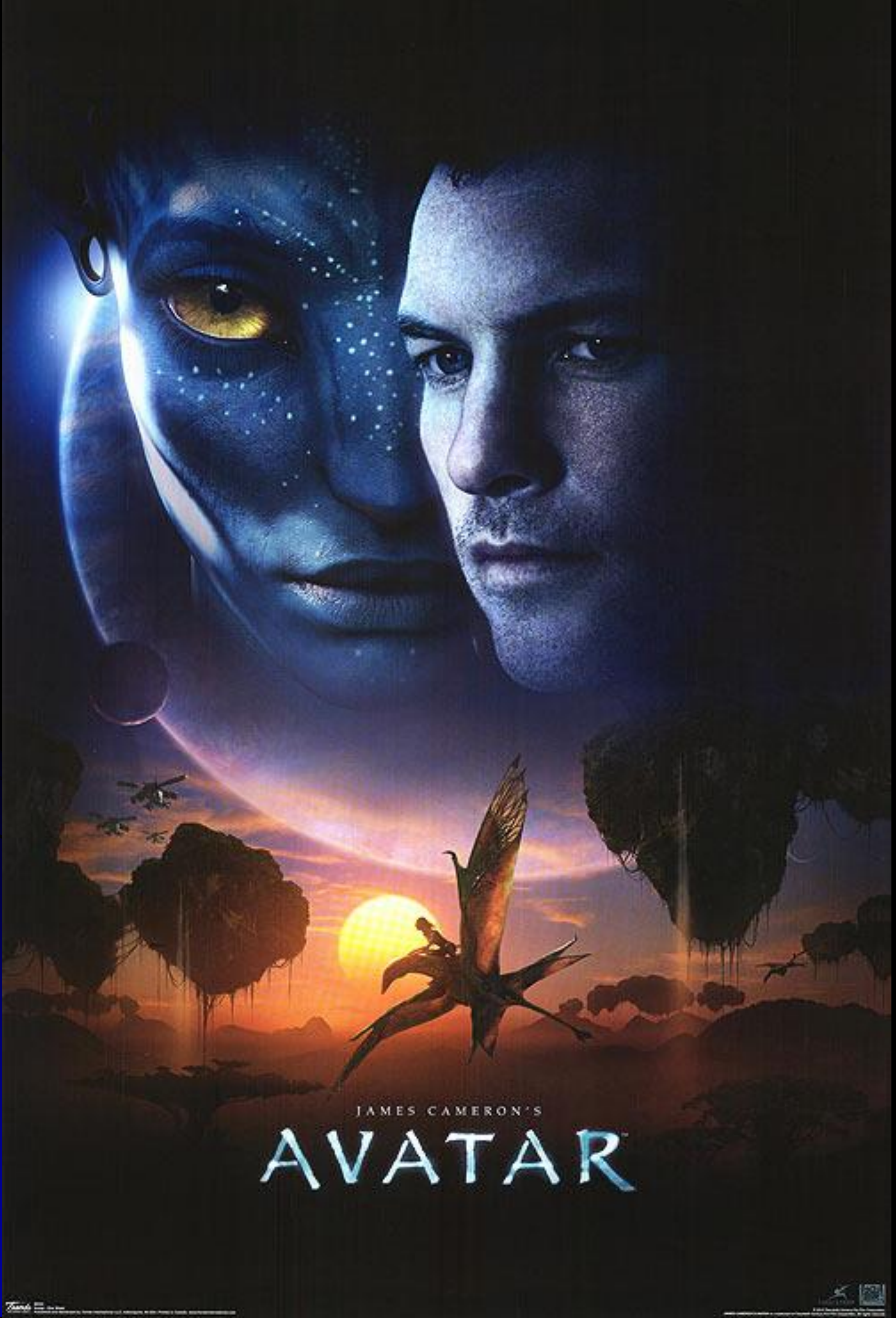
Sky and Telescope, Oct 2015

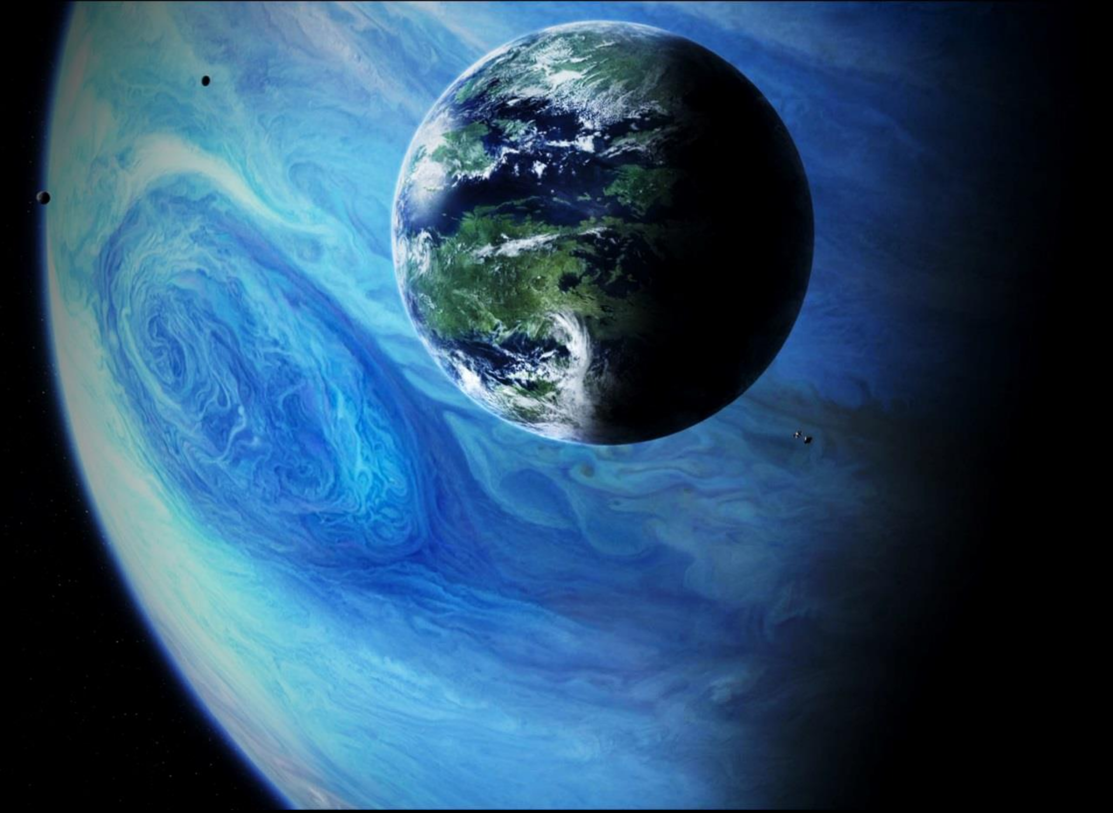
α Cen System Overview





Distance: 1.3pc
Age: ~4.5 – 7 Gy
AB Period: 79.91y
AB SMA: 17.57 AU





Alpha Centauri A

- 2 inner rocky planets
- 3 gas giants
  - Oceanus
  - Polyphemus
    - Pandora (5th/14 moons)
  - Crius

Alpha Centauri B

5 inner rocky planets

3 gas giants

"Discovered by space telescopes at some point between 2050 and 2077, Pandora has been the single most interesting thing to happen to the human race in hundreds of years"

Discovery telescope: co-orbiting synchronized telescopic interferometer network (COSTIN)

Source: http://james-camerons-avatar.wikia.com/wiki/Alpha_Centauri_System

Habitable Zones of αCen AB

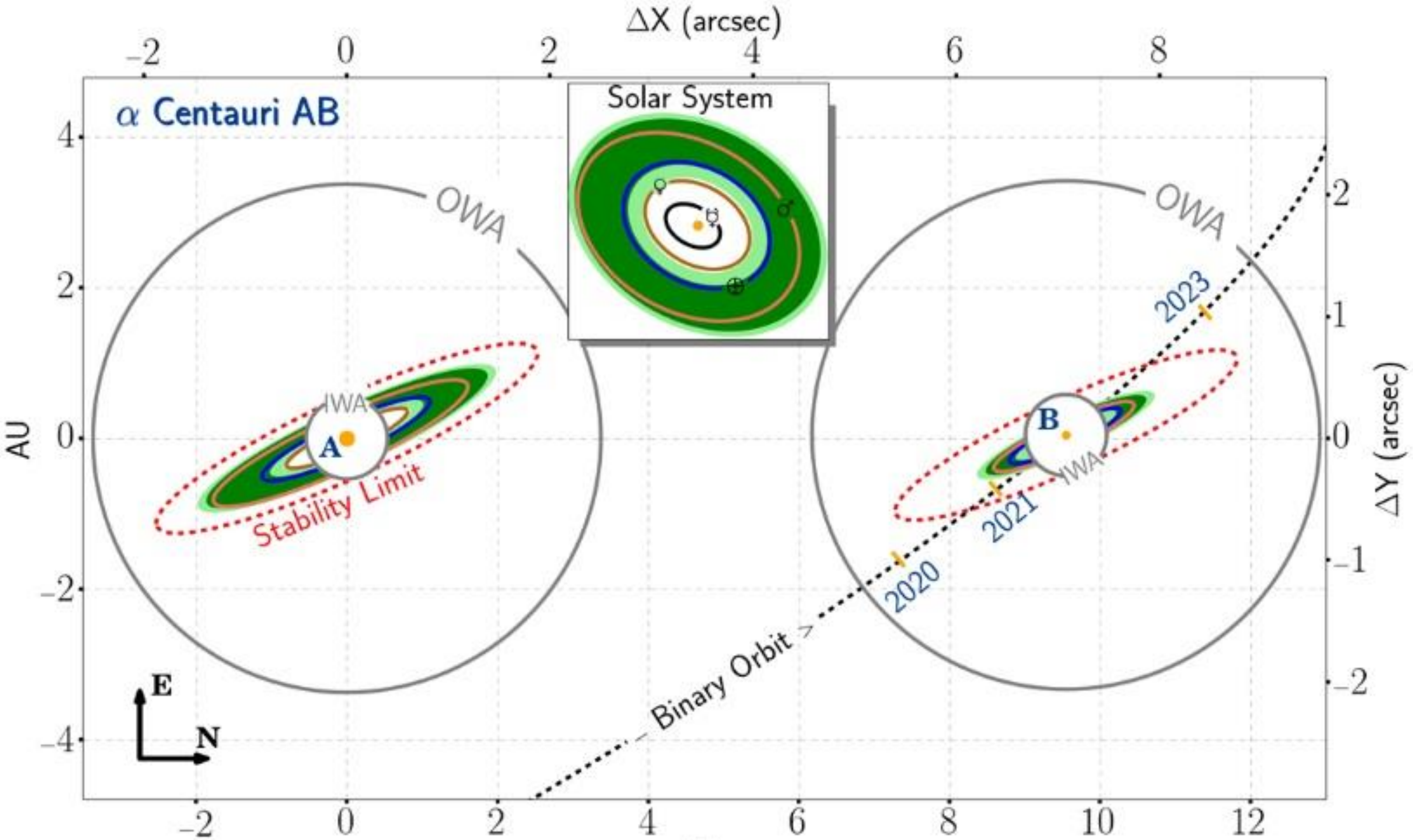


Image by Billy Quarles

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)

Posterior distributions accounting for dynamical stability

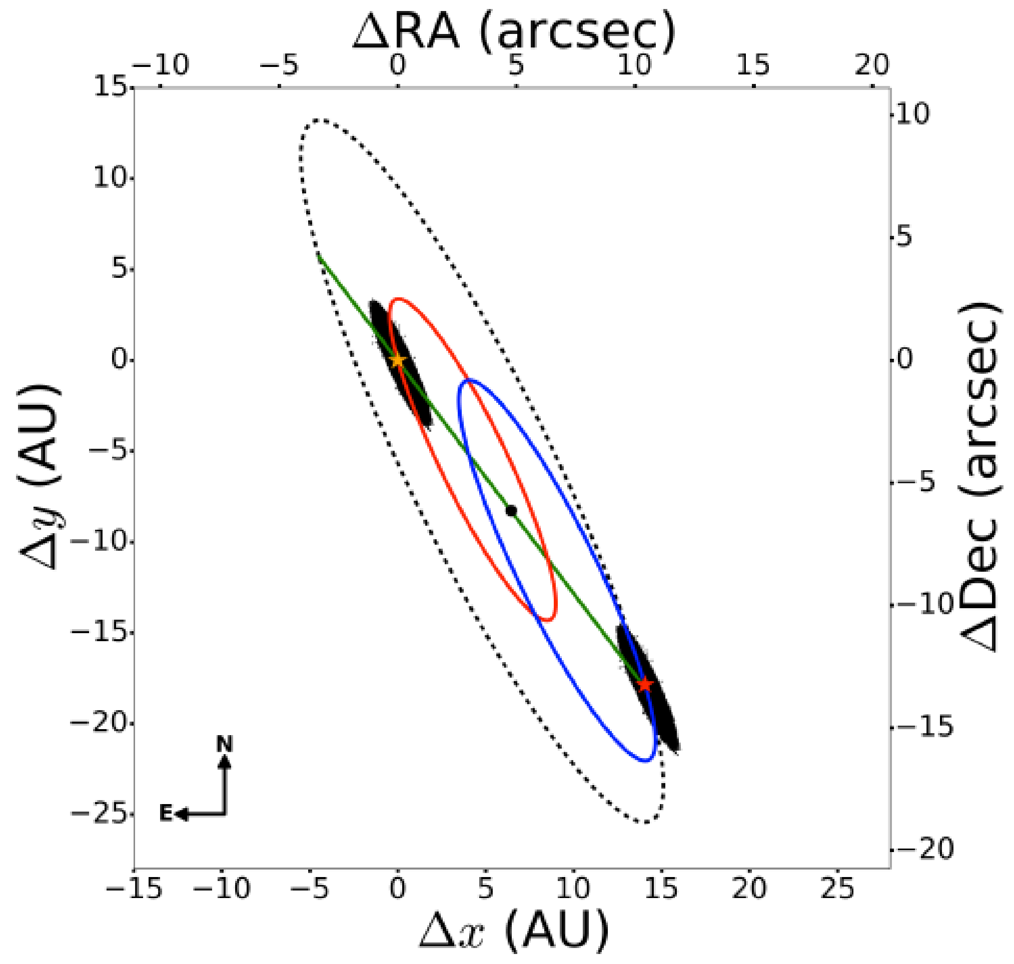
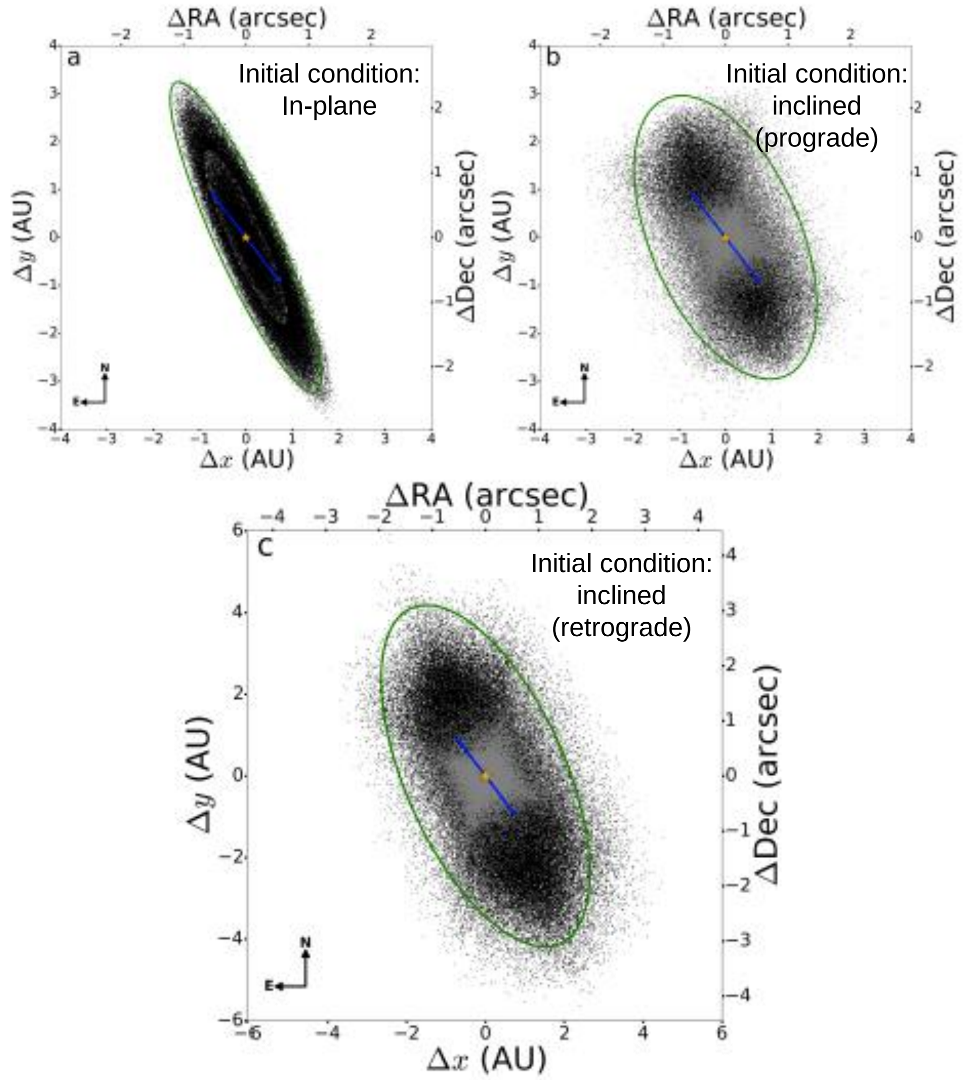


Figure 9. Projection of the stellar orbit of α Cen AB at apastron onto the sky. The astrocentric orbit α Cen B about α Cen A is shown by the dashed curve, with the stars shown at apastron. The center of mass (dot near the center of the image) is shown along with the barycentric ellipses for both α Cen A (red) and α Cen B (blue). Disks have been placed around each star to illustrate the areal coverage of stable test particles orbiting with the plane of the binary. The scale for potential observers in Right Ascension and Declination is given on the top and right axis, respectively.



Quarles and Lissauer, 2016

Calculations of single-star habitable occurrence rates (example for G-dwarfs)

Integrating SAG13 parametric fit
web app: http://www.princeton.edu/~rvdb/SAG13/SAG13.html

		Habitable Zone*	
		Conservative	Optimistic
Planet radius range	1.0-1.5	$\mathbf{0.14^{+0.12}_{-0.04}}$	$\mathbf{0.2^{+0.18}_{-0.06}}$
	0.5-1.5	$\mathbf{0.40^{+0.48}_{-0.14}}$	$\mathbf{0.58^{+0.7}_{-0.2}}$

(uncertainties correspond to 1-sigma equivalent deviations across submissions)

$\eta_{\mathrm{habSol,SAG13}}$

Using Burke et al. 2015 posterior tool
https://github.com/christopherburke/KeplerPORTs

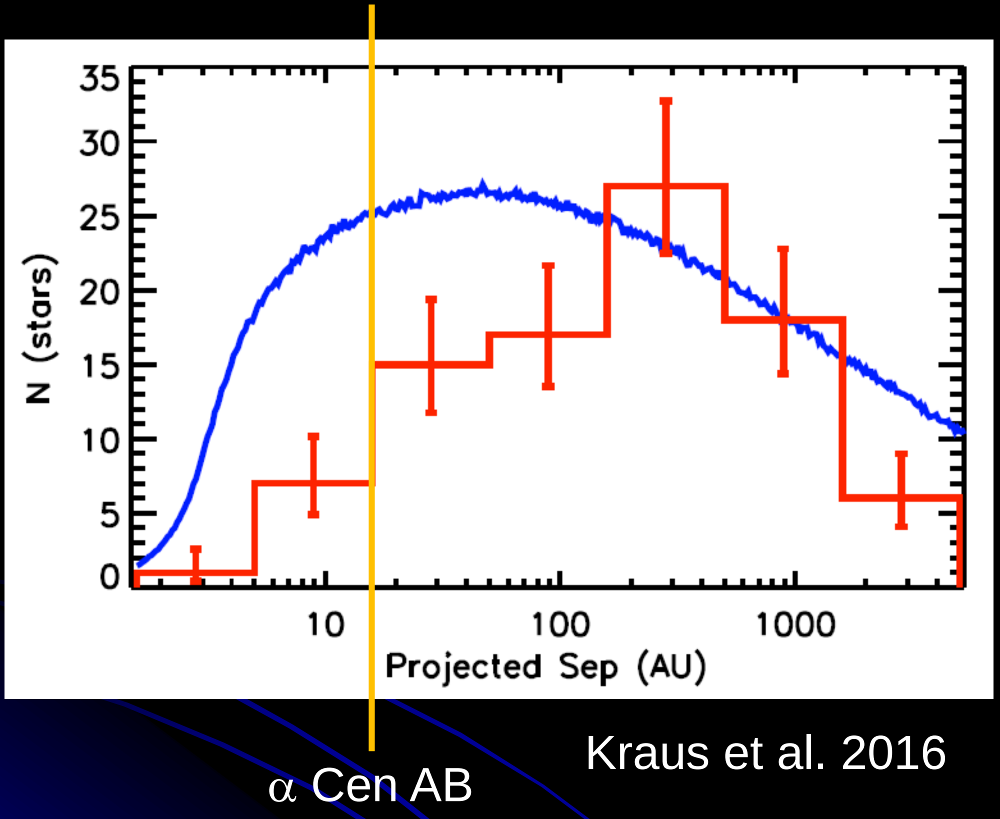
		Habitable Zone*	
		Conservative	Optimistic
Planet radius range	1.0-1.5	$\mathbf{0.21^{+0.08}_{-0.08}}$	$\mathbf{0.31^{+0.1}_{-0.1}}$
	0.5-1.5	$\mathbf{0.5^{+0.4}_{-0.2}}$	$\mathbf{0.73^{+0.6}_{-0.3}}$

Caution: Some preliminary analyses of new Kepler data release (DR25) are resulting in values up to 2-3x lower! It is not yet clear whether this reduction is real.

*Habitable zone definitions are from Kopparapu 2013 for Solar twin
Conservative: 338-792 days; Optimistic: 237-864 days

SAG13 References:
https://exoplanets.nasa.gov/system/internal_resources/details/original/680_SAG13_closeout_8.3.17.pdf
Kopparapu et al. 2018

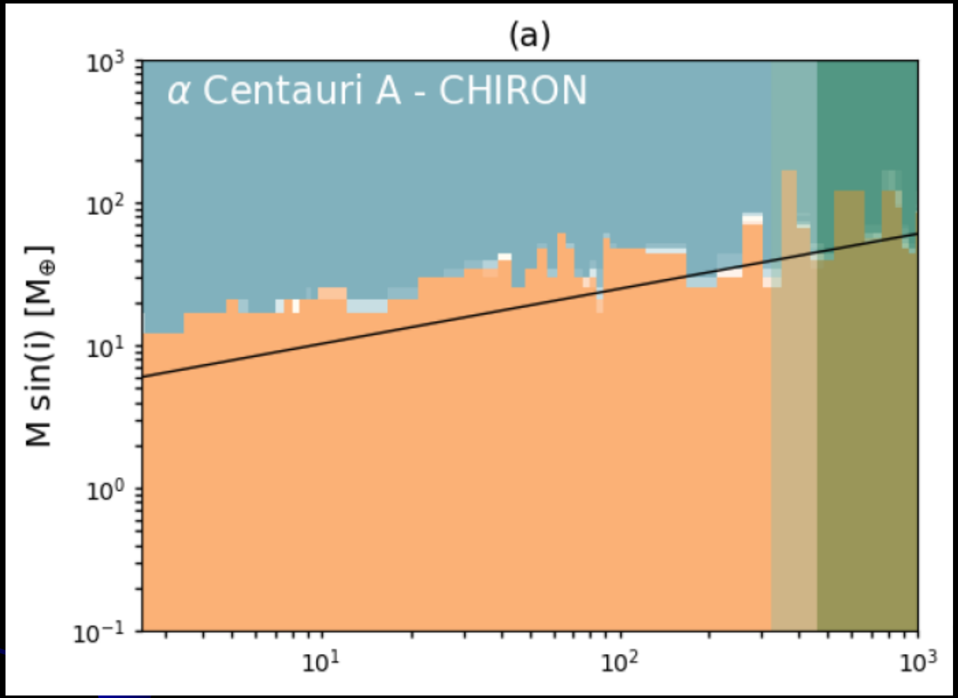
Possible "ruinous influence" of binaries on planet formation

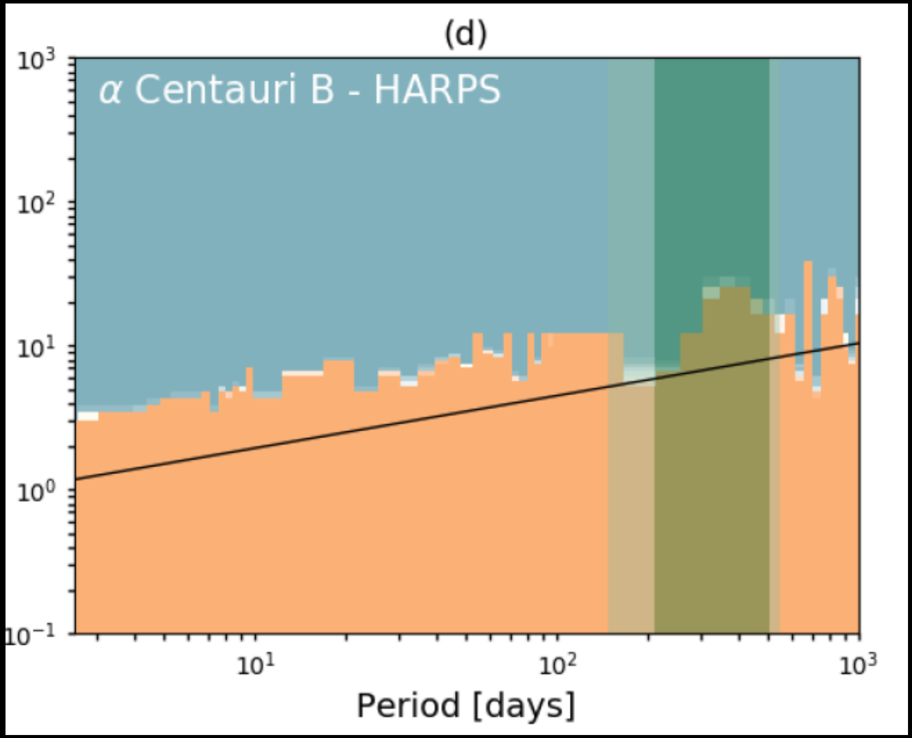


Kraus et al. 2016

- Kraus et al. 2016 suggests planet formation around binaries with SMA < 47^{+59}_{-23} is suppressed by a factor of $0.34^{+0.14}_{-0.15}$
- The specific case of αCen AB may not be as bleak:
  - Expected suppression for SMA of 17.6 is ~0.5 rather than 0.34.
  - SMA of 17.6 AU is within ~1 sigma of Kraus SMA threshold
    - If threshold is < 17.6, then aCen AB are nominally safe from "ruinous influence"
  - Ruinous influence is all-or-nothing
    - If any planet is found around aCen AB, the ruinous effect does not apply and probability of additional planets becomes similar to single stars
    - If Proxima Cen can be shown to have dynamically interacted with aCen AB during planet formation, "ruinous effect" may be ruled out (?)
- An optimist would say that Kraus et al. shows that planets around binaries are still plentiful even with the ruinous influence!

m sin(i) limits from RV non-detections

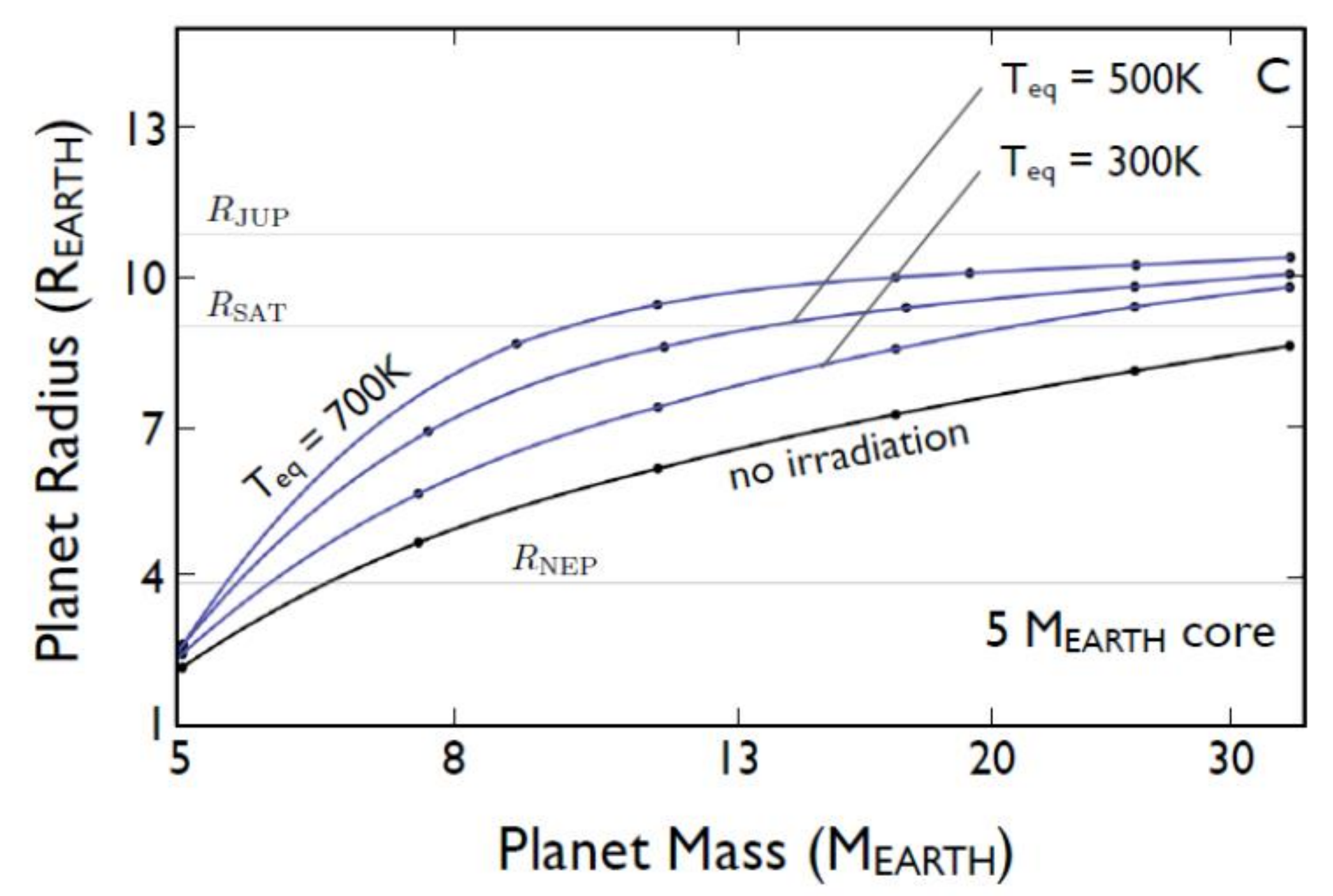




Zhao et al. 2018, submitted

- Habitable zone limits:
  - 53 M_Earth for aCen A
    - Ruled out ~ 7% of all possible planets down to 1 Earth mass
  - 8.4 M_Earth for aCen B
    - Ruled out ~ 32% of all possible planets down to 1 Earth mass
  - (Neptune mass: ~17 Earths)

Limits on brightness from RV non-detections?



Batygin & Stevenson (2013). Mass-Radius relationship for a low-mass, gas-dominated planetary model (for a 5 MEarth core). Planets with Neptune mass (17 Mearth or 0.05 MJupiter) can still have a radius comparable to Jupiter.

What do we know about aCen exozodi?

How dusty is α Centauri? ⋆ ⋆⋆

Excess or non-excess over the infrared photospheres of main-sequence stars

J. Wiegert[1], R. Liseau[1], P. Thébault[2], G. Olofsson[3], A. Mora[4], G. Bryden[5], J. P. Marshall[6], C. Eiroa[6], B. Montesinos[7], D. Ardila[8,9], J. C. Augereau[10], A. Bayo Aran[11,12], W. C. Danchi[13], C. del Burgo[14], S. Ertel[10], M. C. W. Fridlund[15,16], M. Hajigholi[1], A. V. Krivov[17], G. L. Pilbratt[18], A. Roberge[19], G. J. White[20,21], and S. Wolf[22]

(Affiliations can be found after the references)

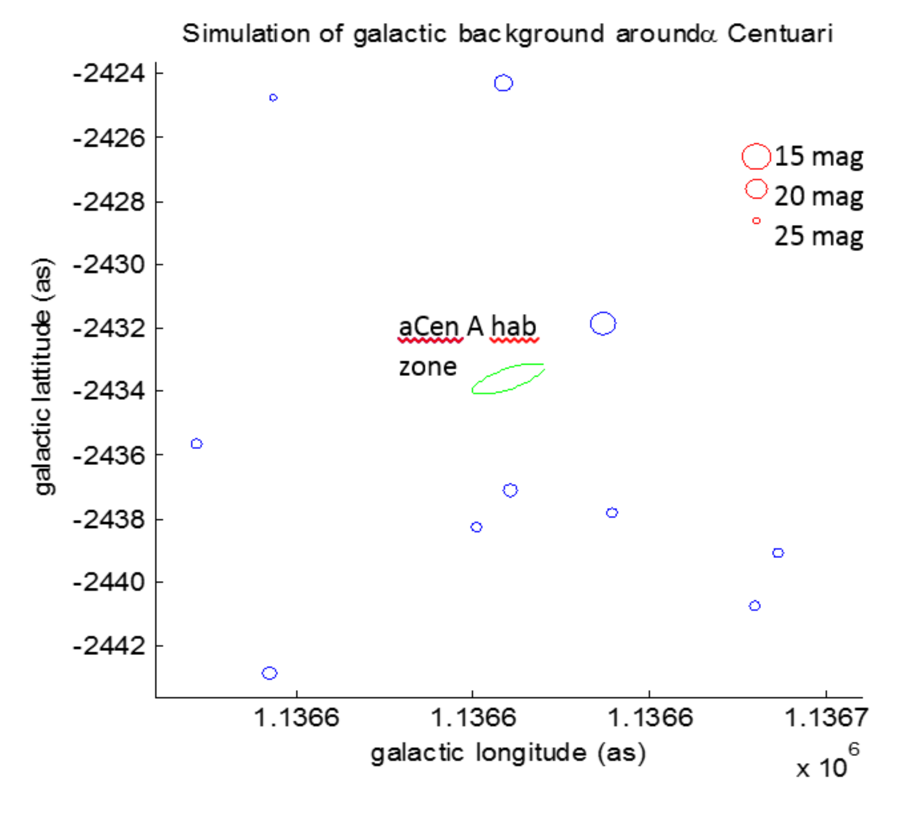
Recieved ... / Accepted ...

ABSTRACT

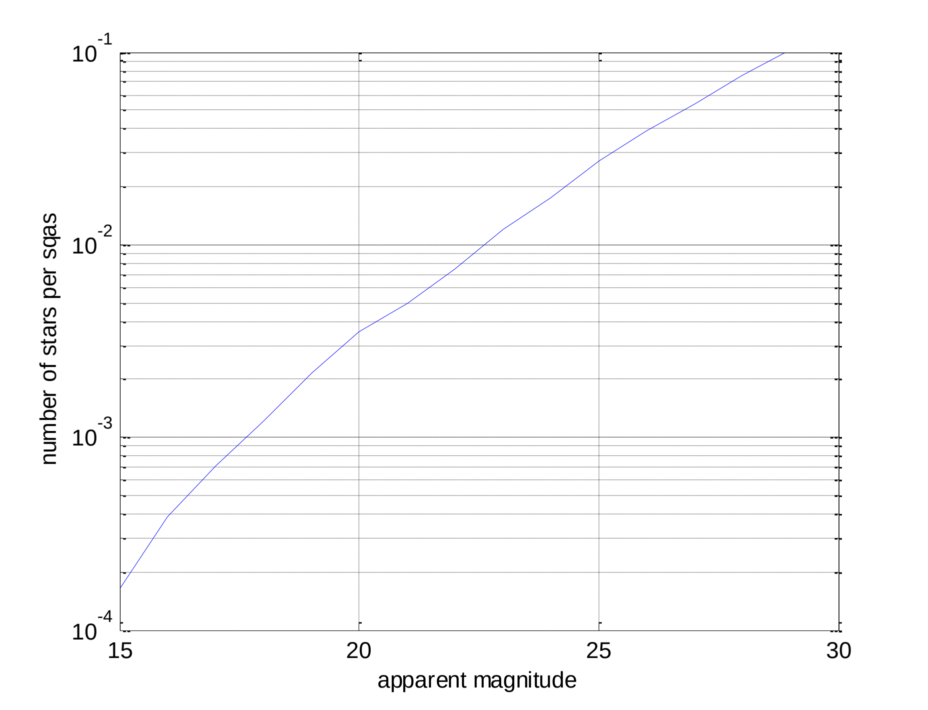
Context. Debris discs around main-sequence stars indicate the presence of larger rocky bodies. The components of the nearby, solar-type binary α Centauri have higher than solar metallicities, which is thought to promote giant planet formation.
Aims. We aim to determine the level of emission from debris around the stars in the α Cen system. This requires knowledge of their photospheres. Having already detected the temperature minimum, $T_{\rm min}$, of α Cen A at far-infrared wavelengths, we here attempt to do so also for the more active companion α Cen B. Using the α Cen stars as templates, we study possible effects $T_{\rm min}$ may have on the detectability of unresolved dust discs around other stars.
Methods. We use *Herschel*-PACS, *Herschel*-SPIRE, and APEX-LABOCA photometry to determine the stellar spectral energy distributions in the far infrared and submillimetre. In addition, we use APEX-SHeFI observations for spectral line mapping to study the complex background around α Cen seen in the photometric images. Models of stellar atmospheres and of particulate discs, based on particle simulations and in conjunction with radiative transfer calculations, are used to estimate the amount of debris around these stars.
Results. For solar-type stars more distant than α Cen, a fractional dust luminosity $f_{\rm d} \equiv L_{\rm dust}/L_{\rm star} \sim 2 \times 10^{-7}$ could account for SEDs that do not exhibit the $T_{\rm min}$-effect. This is comparable to estimates of $f_{\rm d}$ for the Edgeworth-Kuiper belt of the solar system. In contrast to the far infrared, slight excesses at the $2.5\,\sigma$ level are observed at $24\,\mu$m for both α Cen A and B, which, if interpreted to be due to zodiacal-type dust emission, would correspond to $f_{\rm d} \sim (1-3) \times 10^{-5}$, i.e. some 10^2 times that of the local zodiacal cloud. Assuming simple power law size distributions of the dust grains, dynamical disc modelling leads to rough mass estimates of the putative Zodi belts around the α Cen stars, viz. $\lesssim 4 \times 10^{-6}\,M_☾$ of 4 to $1000\,\mu$m size grains, distributed according to $n(a) \propto a^{-3.5}$. Similarly, for filled-in $T_{\rm min}$ emission, corresponding Edgeworth-Kuiper belts could account for $\sim 10^{-3}\,M_☾$ of dust.
Conclusions. Our far-infrared observations lead to estimates of upper limits to the amount of circumstellar dust around the stars α Cen A and B. Light scattered and/or thermally emitted by exo-Zodi discs will have profound implications for future spectroscopic missions designed to search for biomarkers in the atmospheres of Earth-like planets. The far-infrared spectral energy distribution of α Cen B is marginally consistent with the presence of a minimum temperature region in the upper atmosphere of the star. We also show that an α Cen A-like temperature minimum may result in an erroneous apprehension about the presence of dust around other, more distant stars.

Confusion with background sources: does not appear to be an issue (if models can be trusted…)

Simulation of background stars
in the vicinity of alpha Centauri line of sight



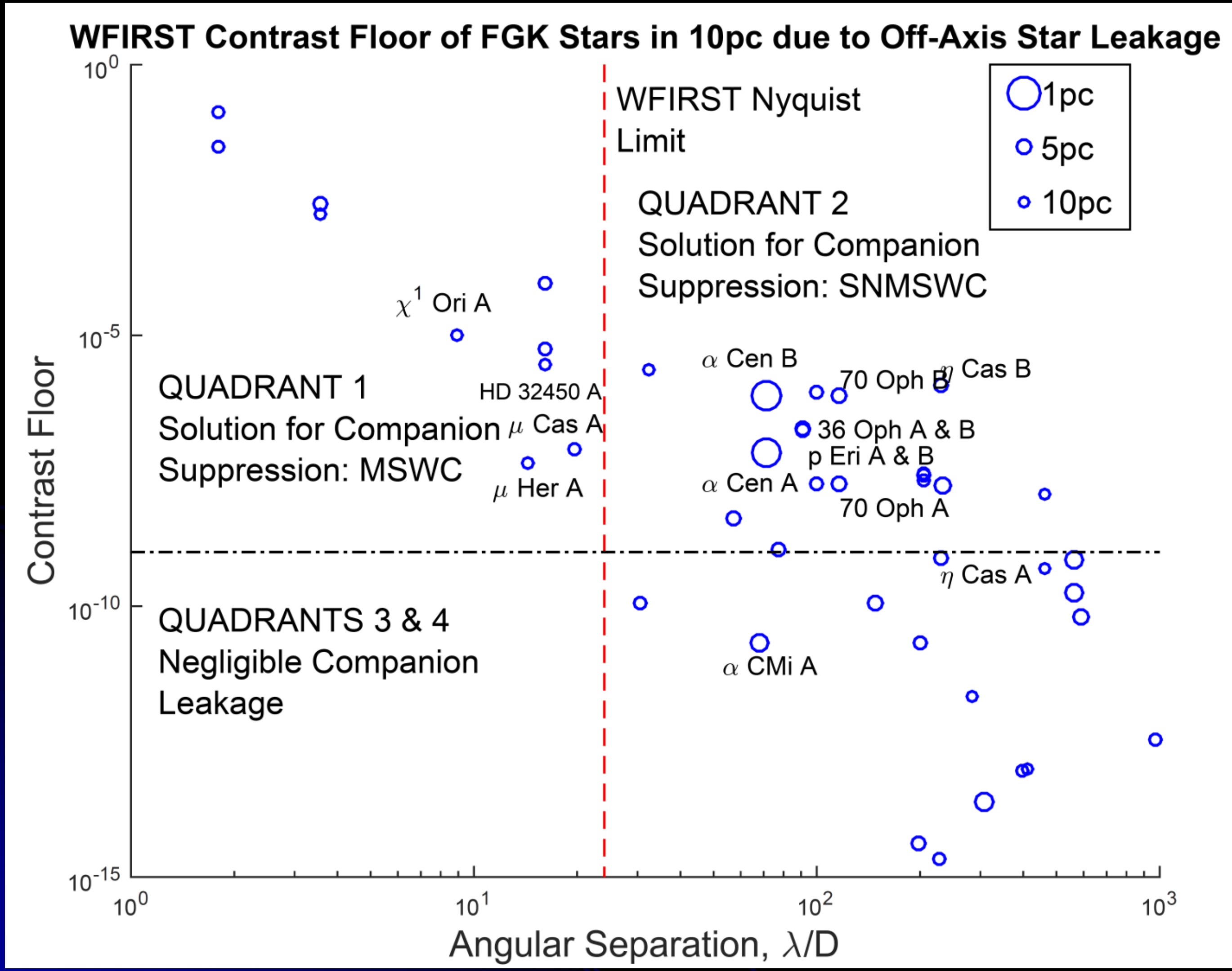
Cumulative number of stars per sqas as a function of minimum brightness. For example, there are 0.03 stars per sqas 25th magnitude or brighter.



Belikov et al. 2015; data from Daniel Huber using Galaxia code, which implements the Besancon model

- Probability of confusion in any one image: 0.03
- The high proper motion of aCen (4"/yr) will remove (already unlikely) confusion with background objects

Multi-Star Direct Imaging Science with WFIRST



Sirbu et al. 2017

Multi-Star Science Statistics:
- 70 FGK stars within 10pc
- 43 multi-stars (dynamical)
- 28 stars limited at > 1e-9
  - 8 stars with sep. < N/2 λ/D

WFIRST assumptions:
- D = 2.4m
- λ = 650nm
- λ/20 RMS with f^{-3} power spectrum
- 48x48 DM

Note: Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star

SCENARIO WC SOLUTIONS *Assuming DM = NxN actuators

On-axis blocker	Off-axis blocker	Star Separation at < N/2 λ/D*	Star Separation at > N/2 λ/D*	Notes
Coronagraph	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane
Coronagraph	2nd Coronagraph	**MSWC-0**	**MSWC-s**	**The second (off-axis) coronagraph is theoretically not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Coronagraph	Starshade	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade	Coronagraph	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade	2nd Starshade	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

How to Block 2^{nd} Star?

Source: AJ Riggs

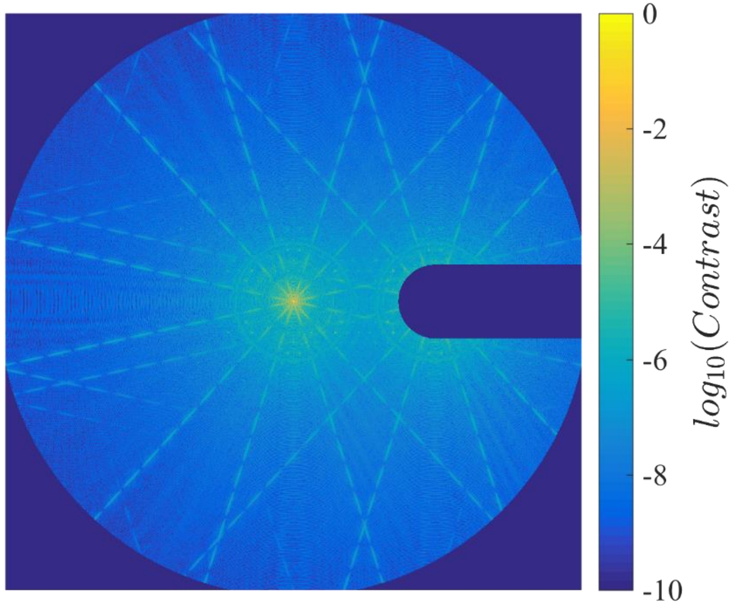
Option 1: Simple Starshade

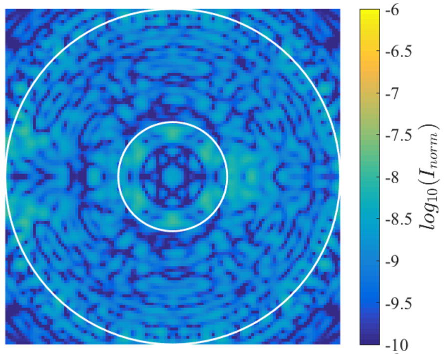
- Low contrast: Only ~10^{-4} needed
- Small: 5m-10m diameter fine.
- ➢ Inexpensive

~2.5 hours for SNR=5 at 10^{-10} contrast for α Cen A & B

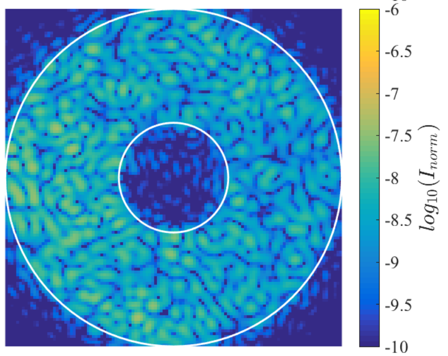
Option 2: Extra Mask inside WFIRST CGI

Occult off-axis star upstream of SPC





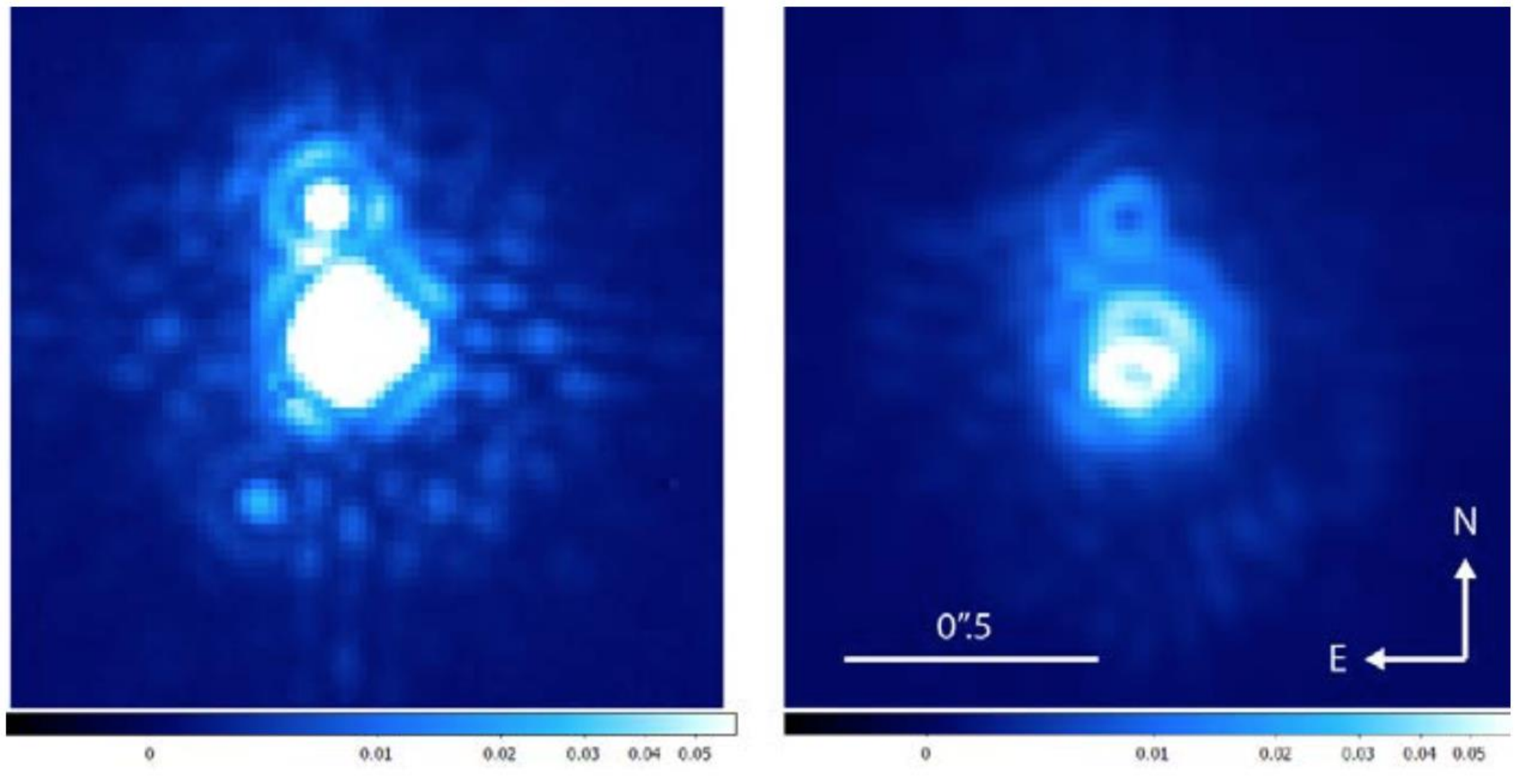
<=1 x 10-9
from
on-axis star



5-10 x 10-9
from
off-axis star

<=1 day to get SNR=5 at 10^{-10} contrast for α Cen A

Stellar Double Coronagraph on Palomar



Credit: Jonas Kuhn, Farisa Morales, Ji Wang, Michael Bottom

SCENARIO

WC SOLUTIONS

*Assuming DM = NxN actuators

On-axis blocker	Off-axis blocker	Star Separation at < N/2 λ/D*	Star Separation at > N/2 λ/D*	Notes
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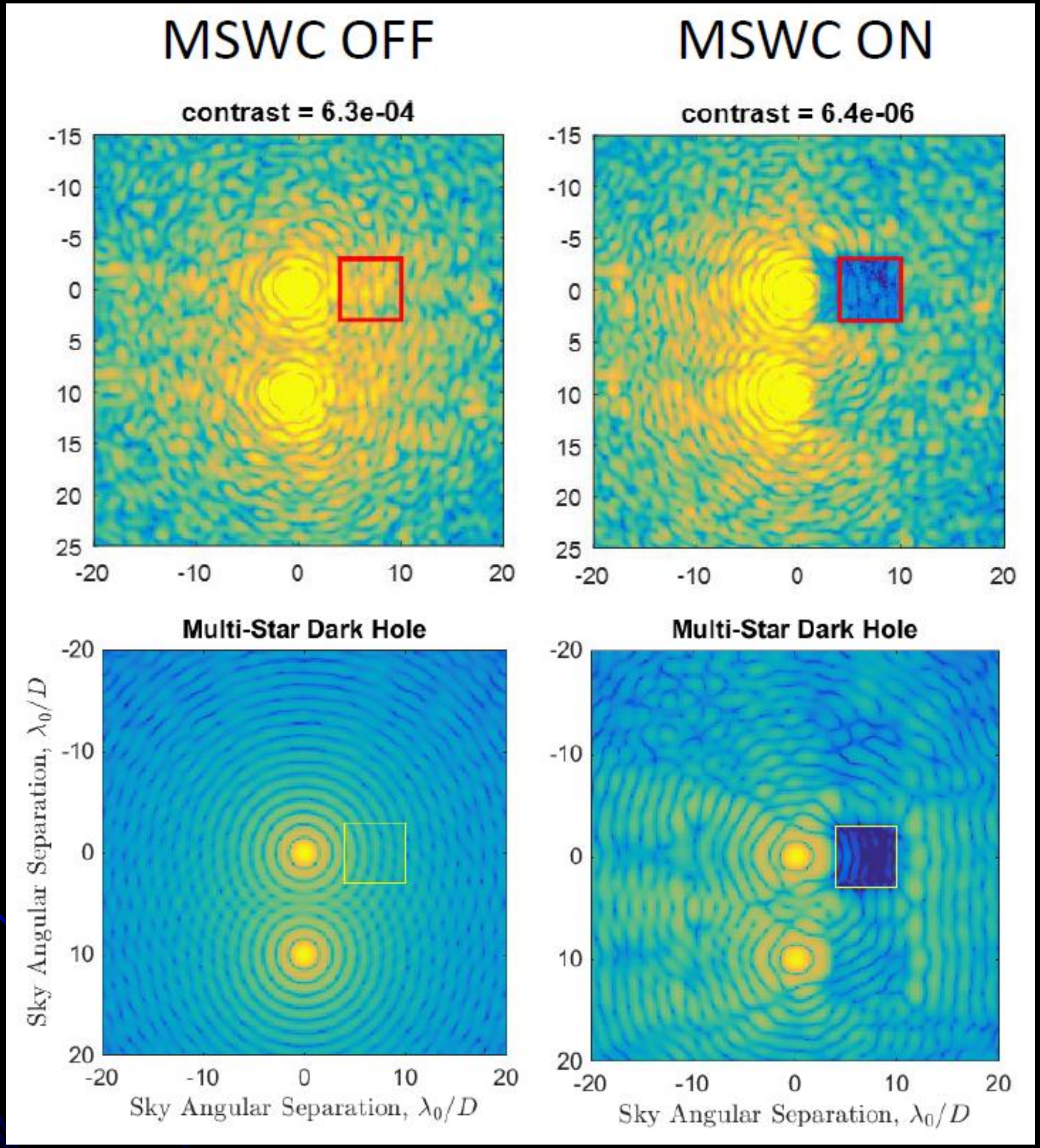
Lab tests of MSWC-0

(for now, without coronagraph)

Lab images
(Pluzhnik)

Simulation
(Sirbu)



655nm light

No coronagraph (for simplicity)

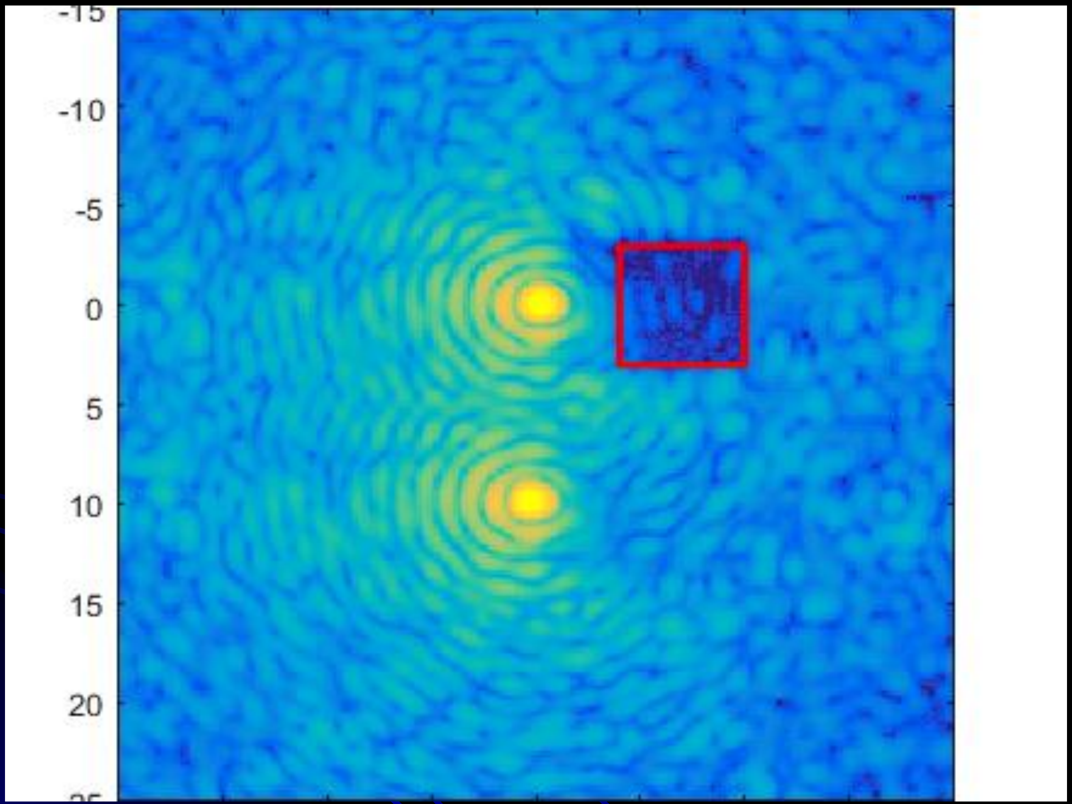
10 λ/D star separation

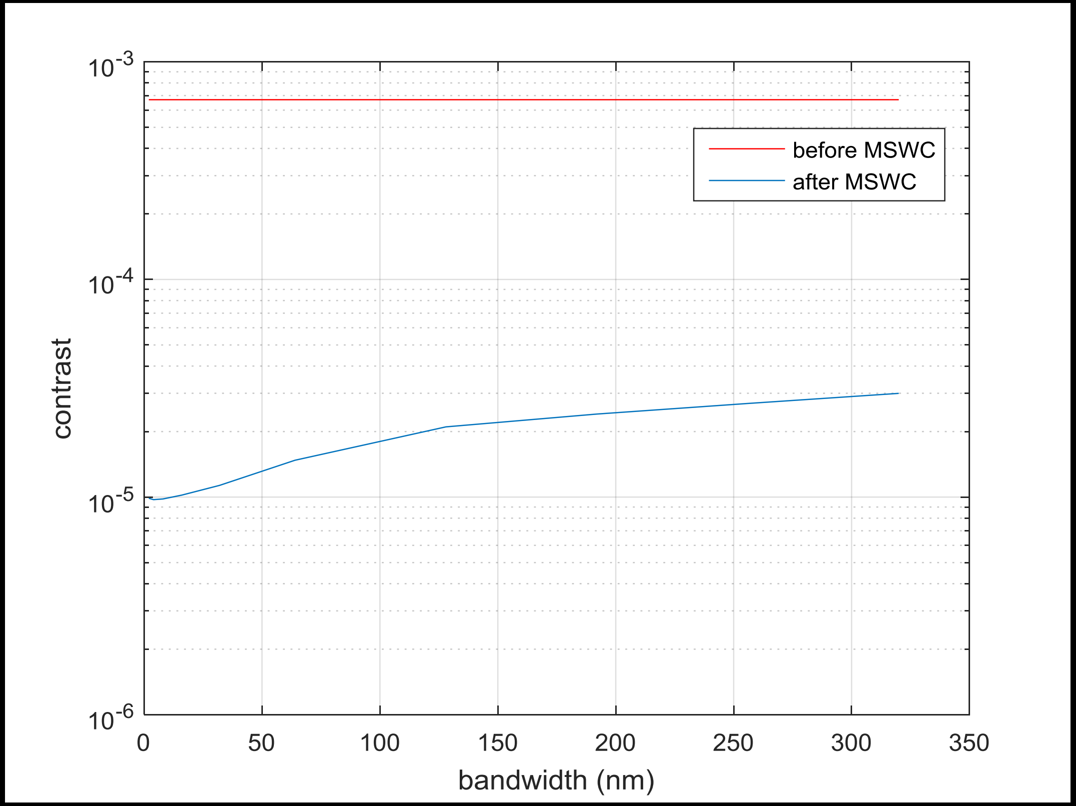
Equal brightness

Belikov et al. 2016

Preliminary broadband test (MSWC-0)

Scanning from 0 to 50% band





SCENARIO

WC SOLUTIONS

*Assuming DM = NxN actuators

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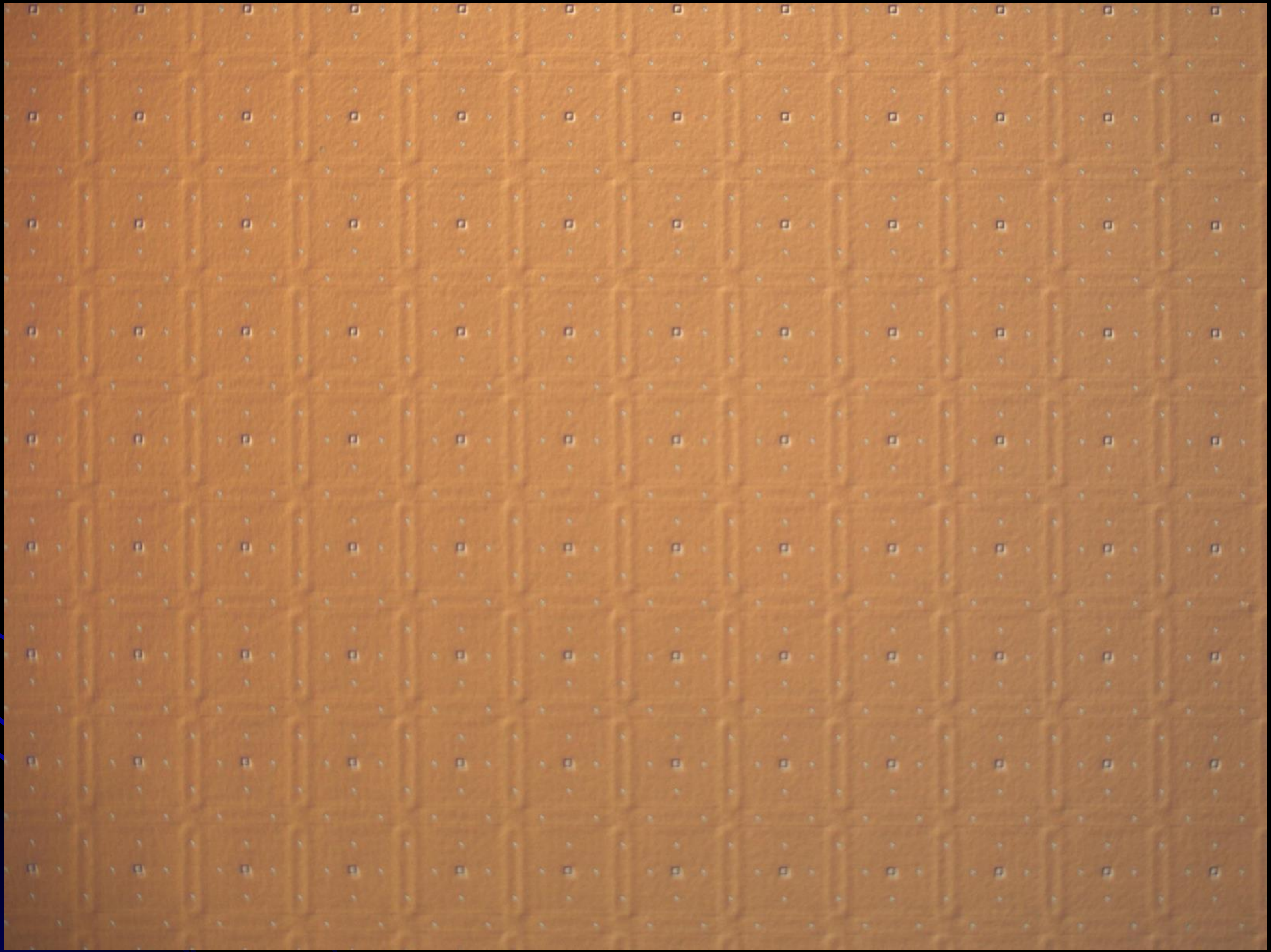
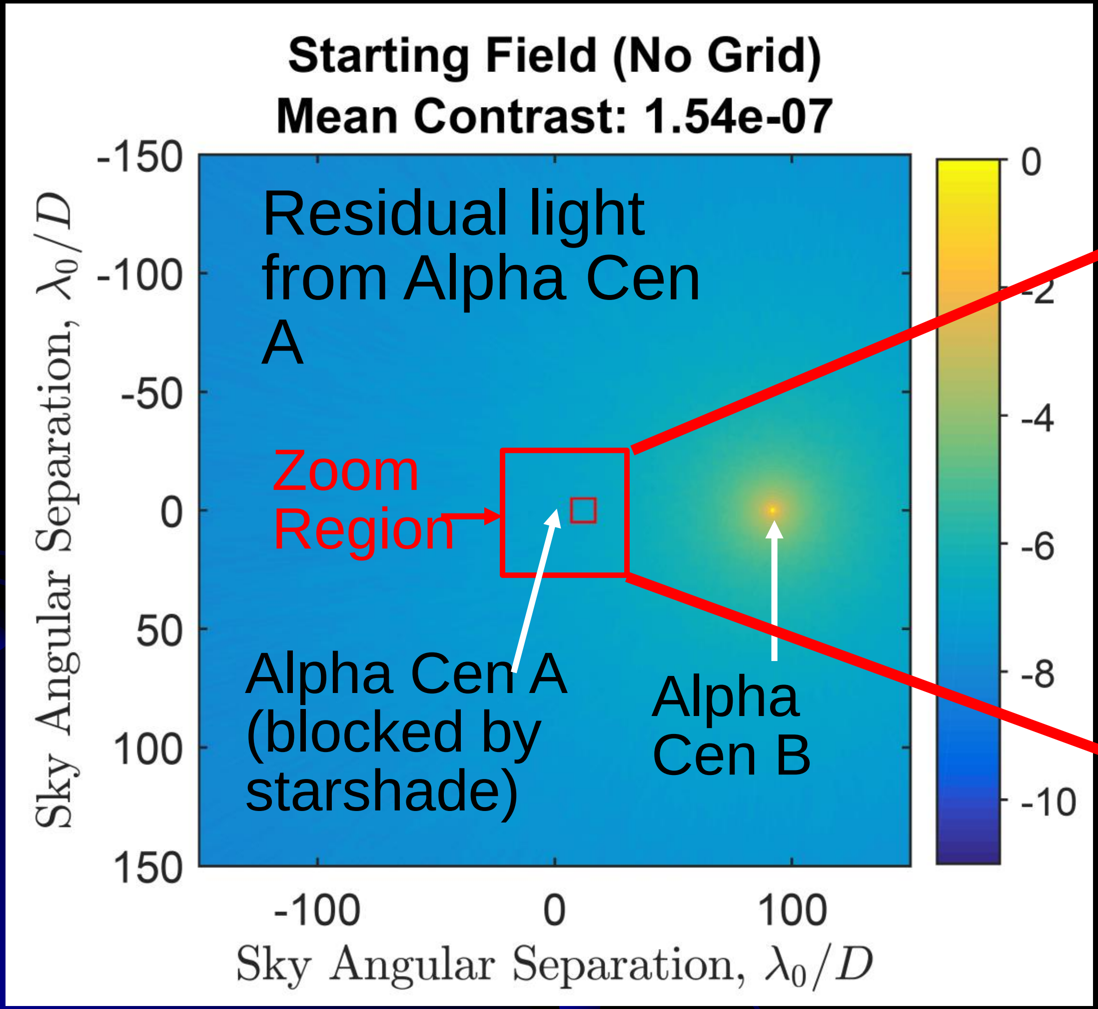
DM “quilting”: a feature, not a bug

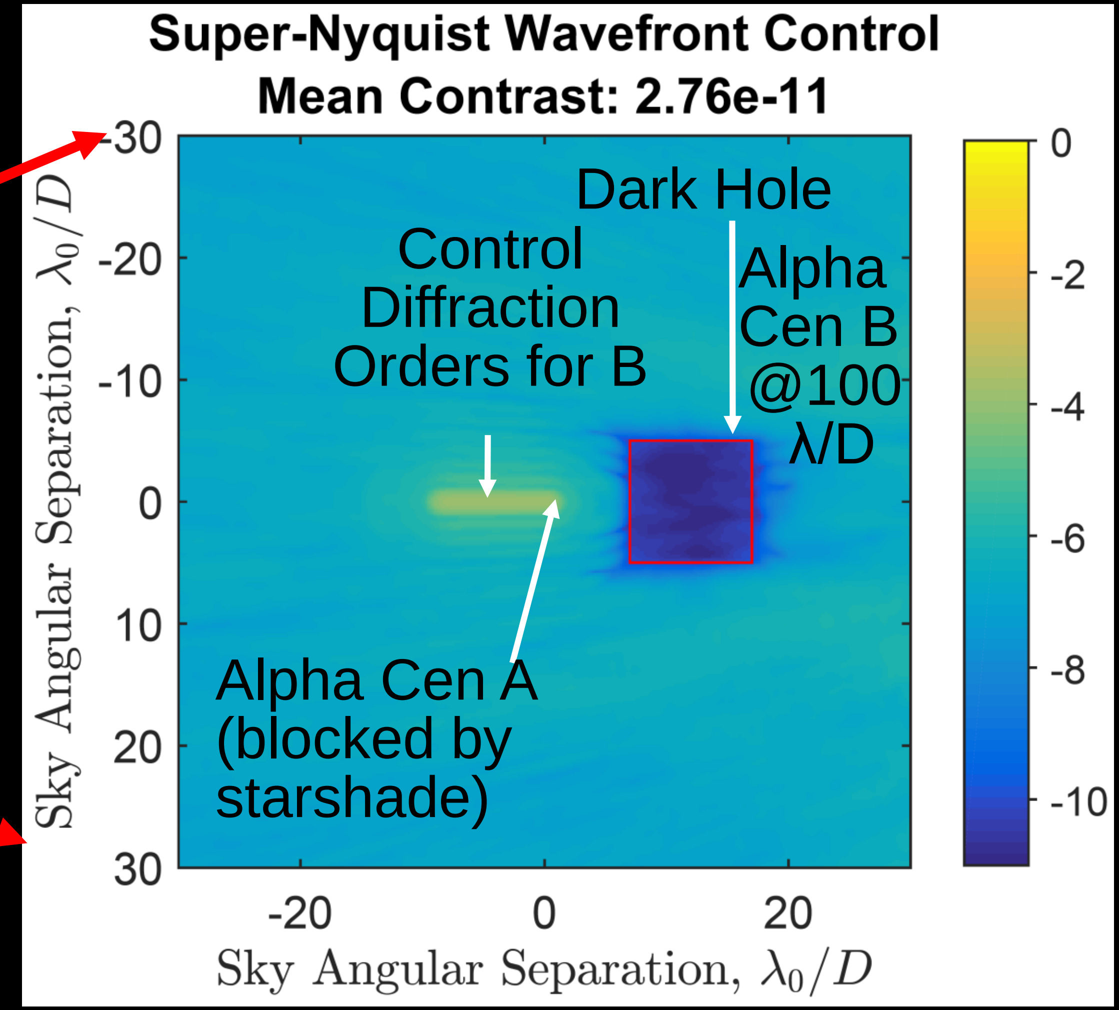


Phase microscope image of a BMC deformable mirror surface

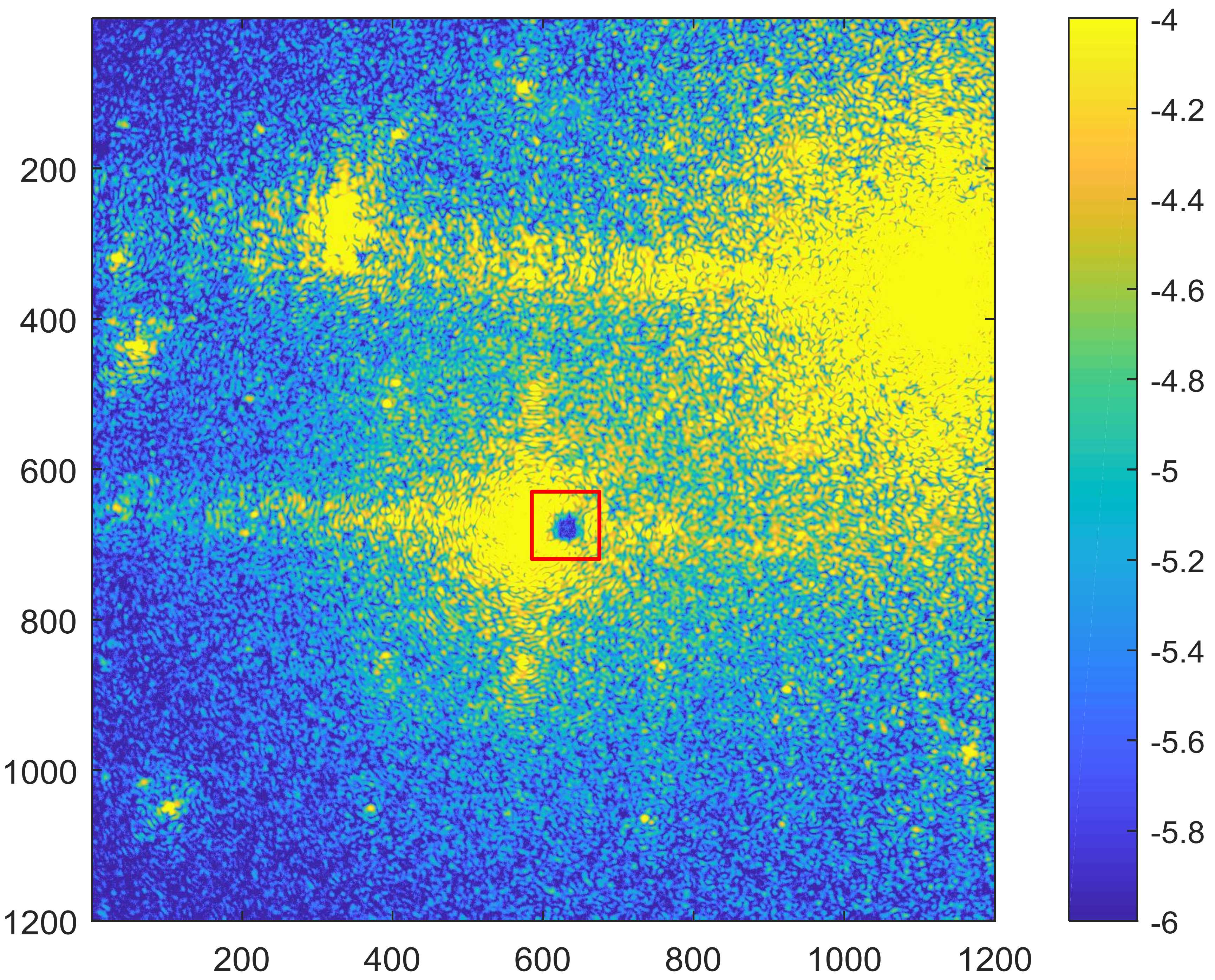
10% Broadband SNWC simulation @ 100 λ/D

(similar to of aCen w/WFIRST)





Simulation by D. Sirbu

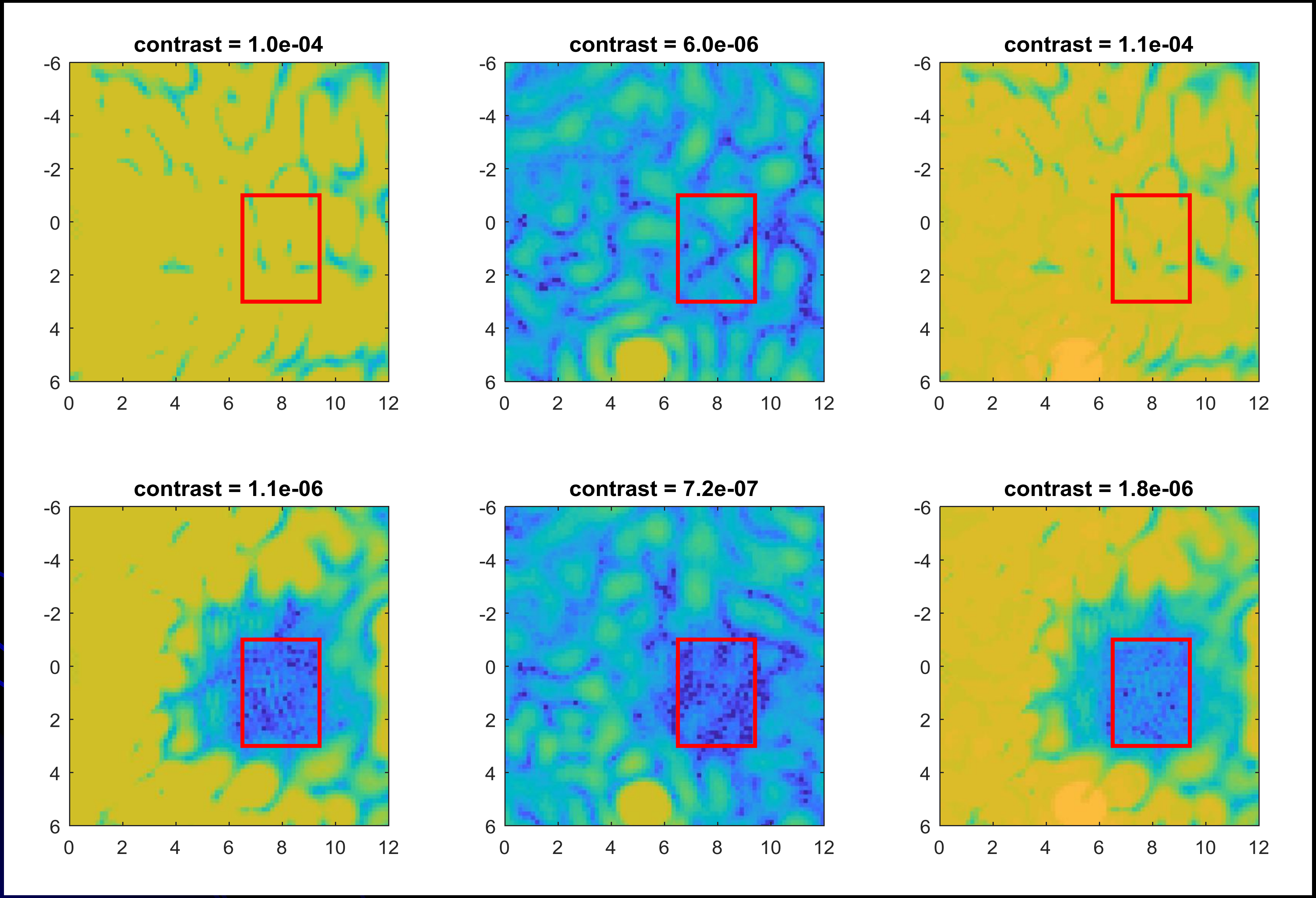

200
400
600
800
1000
1200
200
400
600
800
1000
1200
-4
-4.2
-4.4
-4.6
-4.8
-5
-5.2
-5.4
-5.6
-5.8
-6

MSWC-s lab demonstration @ ~100 λ/D

Target star only | off-axis star only | both stars

before MSWC-s →

after MSWC-s →



Star separation representative of aCen w/WFIRST

MSWC-s operation by Pluzhnik

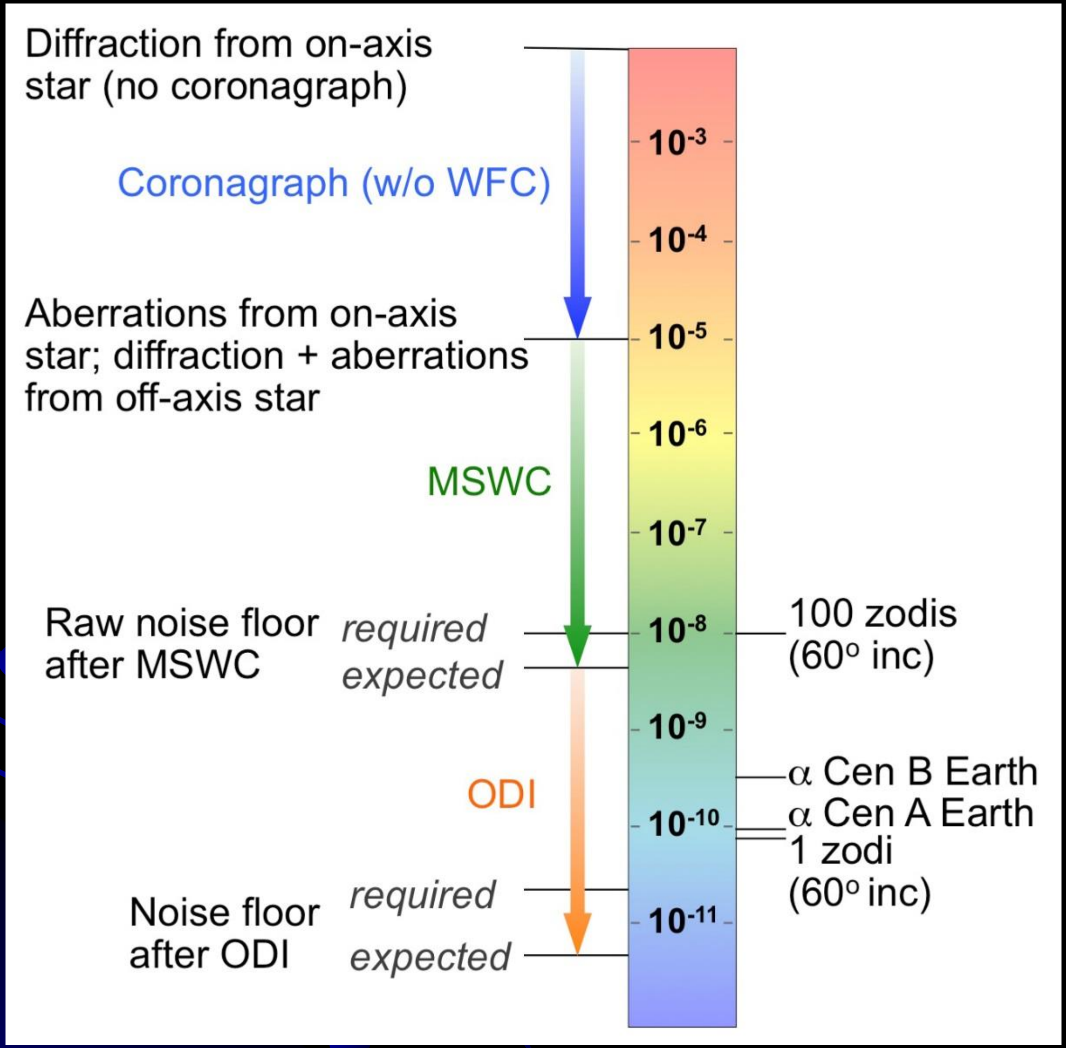
ACESat: Alpha Centauri Exoplanet Satellite

Mission Time Life and Orbit	SMEX-Class, launch 2020, 2-Years, Earth trailing
Instrument/ Telescope	Unobstructed 45cm, Full Silicon Carbide
Coronagraph architecture	Baseline: PIAA Embedded on Secondary and tertiary telescope mirror.
Coronagraph performance	1×10^{-8} raw 6×10^{-11} @ 0.4" (with ODI) 2×10^{-11} @ 0.7" (with ODI)
Wavelength	400 to 700 nm, 5 bands @ 10% each.

Belikov, R. (PI),
Bendek, E. (DPI)
Batalha, N.
Kuchner, M.
Lissauer, J.
Males, J.
Marley, M.
Quarles, B.
Quintana, E.
Robinson, T.
Schneider, G.
Traub, W.
Turnbull, M.
Chakrabarti, S.
Guyon, O.
Kasdin, J.
Lozi, J.
McElwain, M.
Pluzhnik, E.
Thomas, S.
Vanderbei, B.
et al.

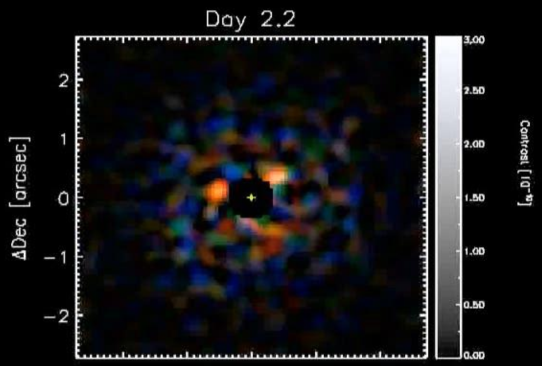
NASA · Ames Research Center · SPACE SYSTEMS LORAL · NORTHROP GRUMMAN · LOCKHEED MARTIN

Getting to high contrast on αCen with a small telescope
Two enabling technologies



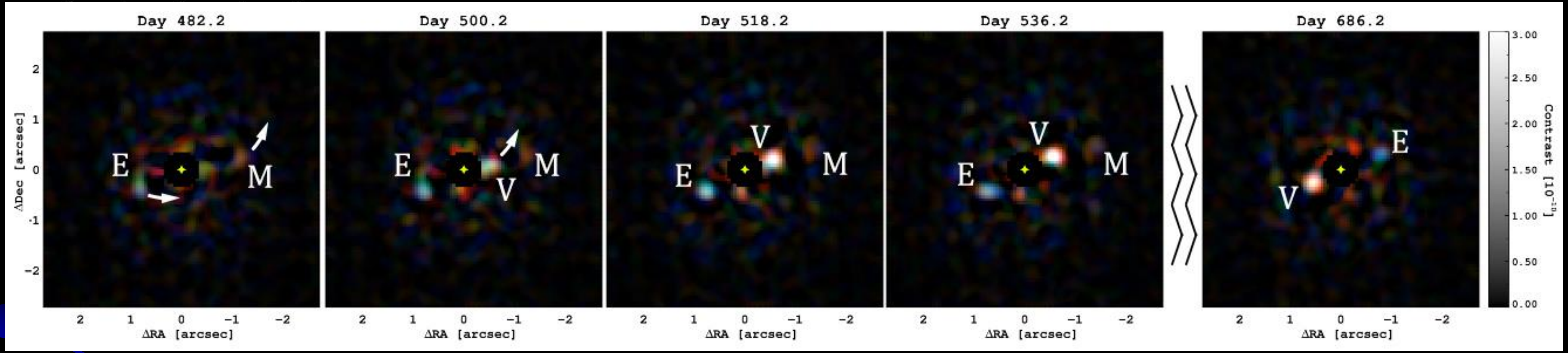
- MSWC: multi-star wavefront control
  - Suppresses light from both stars
  - Thomas, Belikov, Bendek, accepted by ApJ, 2015 (http://arxiv.org/abs/1501.01583)
  - No new hardware required
- ODI: Orbital Differential Imaging
  - Continuous imaging of the system enables 20K images and large post-processing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

ACESat Data 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)

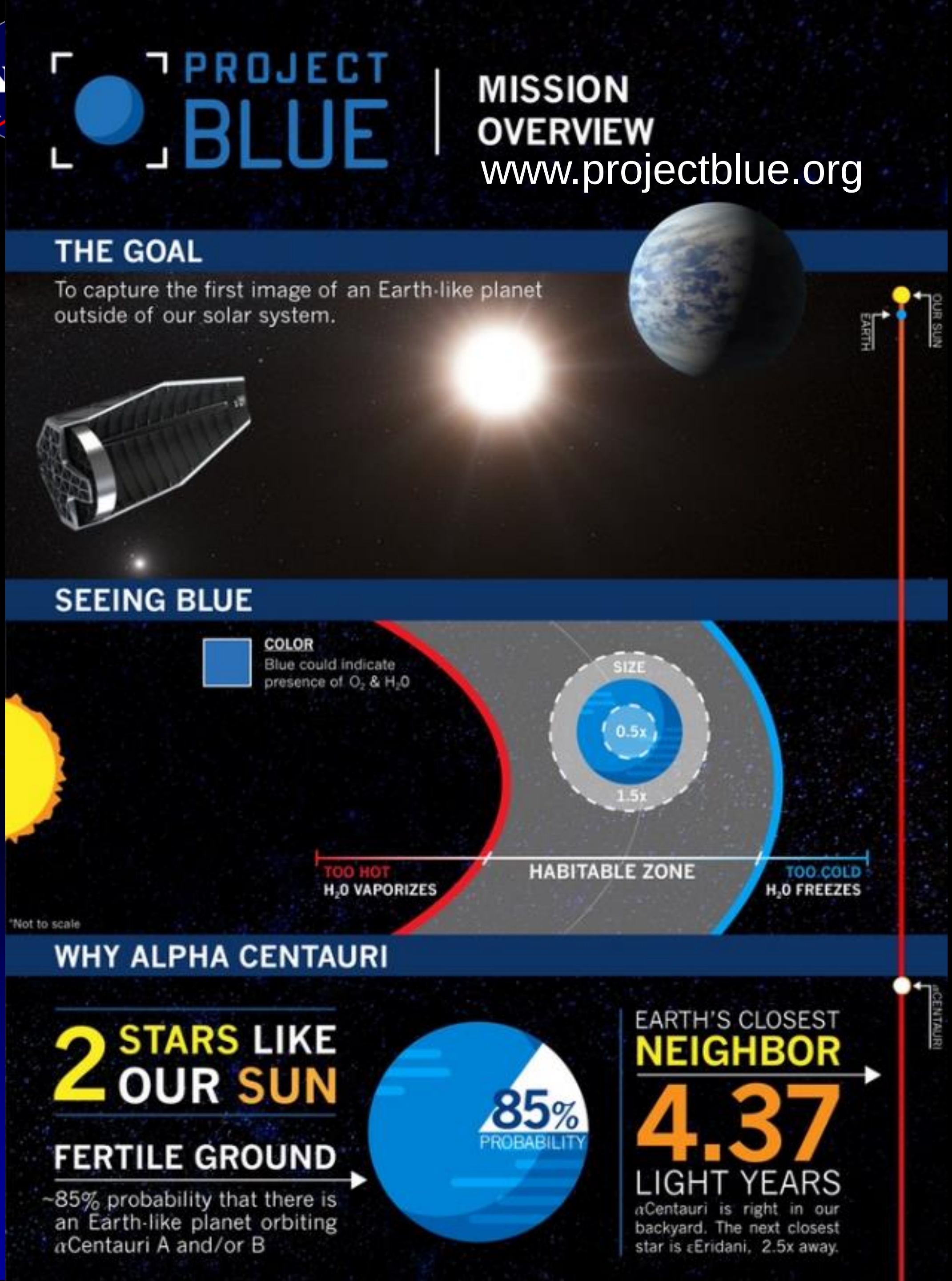
After filtering:

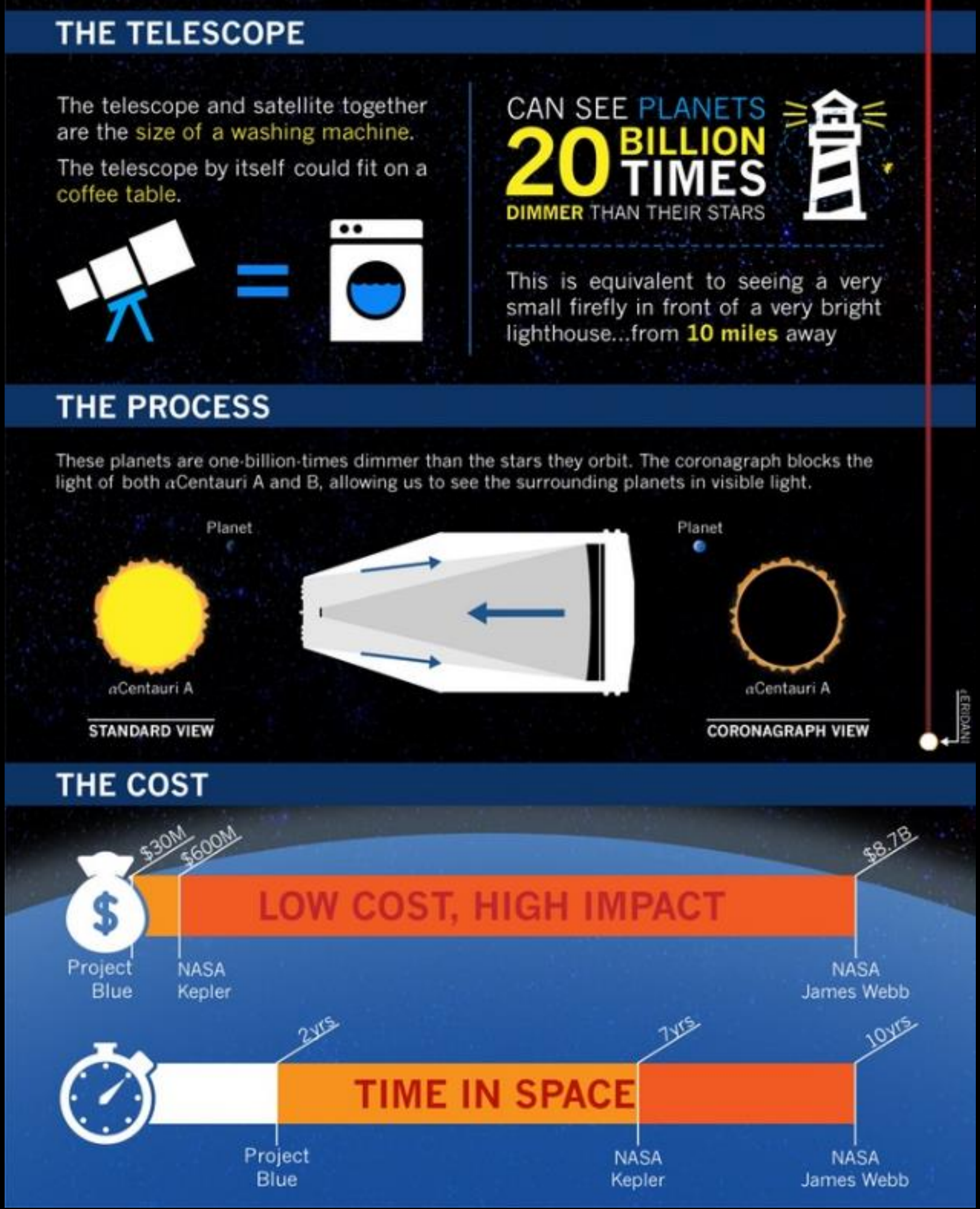


After shift-and-add

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

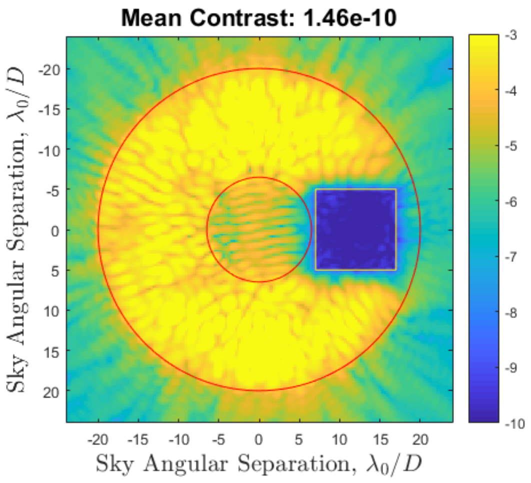
Males et al. 2015


PROJECT BLUE
MISSION OVERVIEW
www.projectblue.org
THE GOAL
To capture the first image of an Earth-like planet outside of our solar system.
EARTH
OUR SUN
SEEING BLUE
COLOR
Blue could indicate presence of O₂ & H₂O
SIZE
0.5x
1.5x
TOO HOT
H₂O VAPORIZES
HABITABLE ZONE
TOO COLD
H₂O FREEZES
*Not to scale
WHY ALPHA CENTAURI
αCENTAURI
2 STARS LIKE OUR SUN
FERTILE GROUND
~85% probability that there is an Earth-like planet orbiting αCentauri A and/or B
85% PROBABILITY
EARTH'S CLOSEST NEIGHBOR
4.37 LIGHT YEARS
αCentauri is right in our backyard. The next closest star is εEridani, 2.5x away.

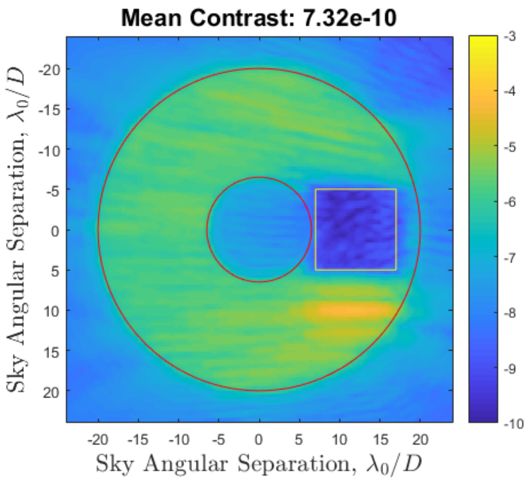

THE TELESCOPE
The telescope and satellite together are the size of a washing machine.
The telescope by itself could fit on a coffee table.
CAN SEE PLANETS 20 BILLION TIMES DIMMER THAN THEIR STARS
This is equivalent to seeing a very small firefly in front of a very bright lighthouse...from 10 miles away
THE PROCESS
These planets are one-billion-times dimmer than the stars they orbit. The coronagraph blocks the light of both αCentauri A and B, allowing us to see the surrounding planets in visible light.
Planet
αCentauri A
STANDARD VIEW
Planet
αCentauri A
CORONAGRAPH VIEW
εERIDANI
THE COST
$30M
$600M
$8.7B
LOW COST, HIGH IMPACT
Project Blue
NASA Kepler
NASA James Webb
2yrs
7yrs
10yrs
TIME IN SPACE
Project Blue
NASA Kepler
NASA James Webb

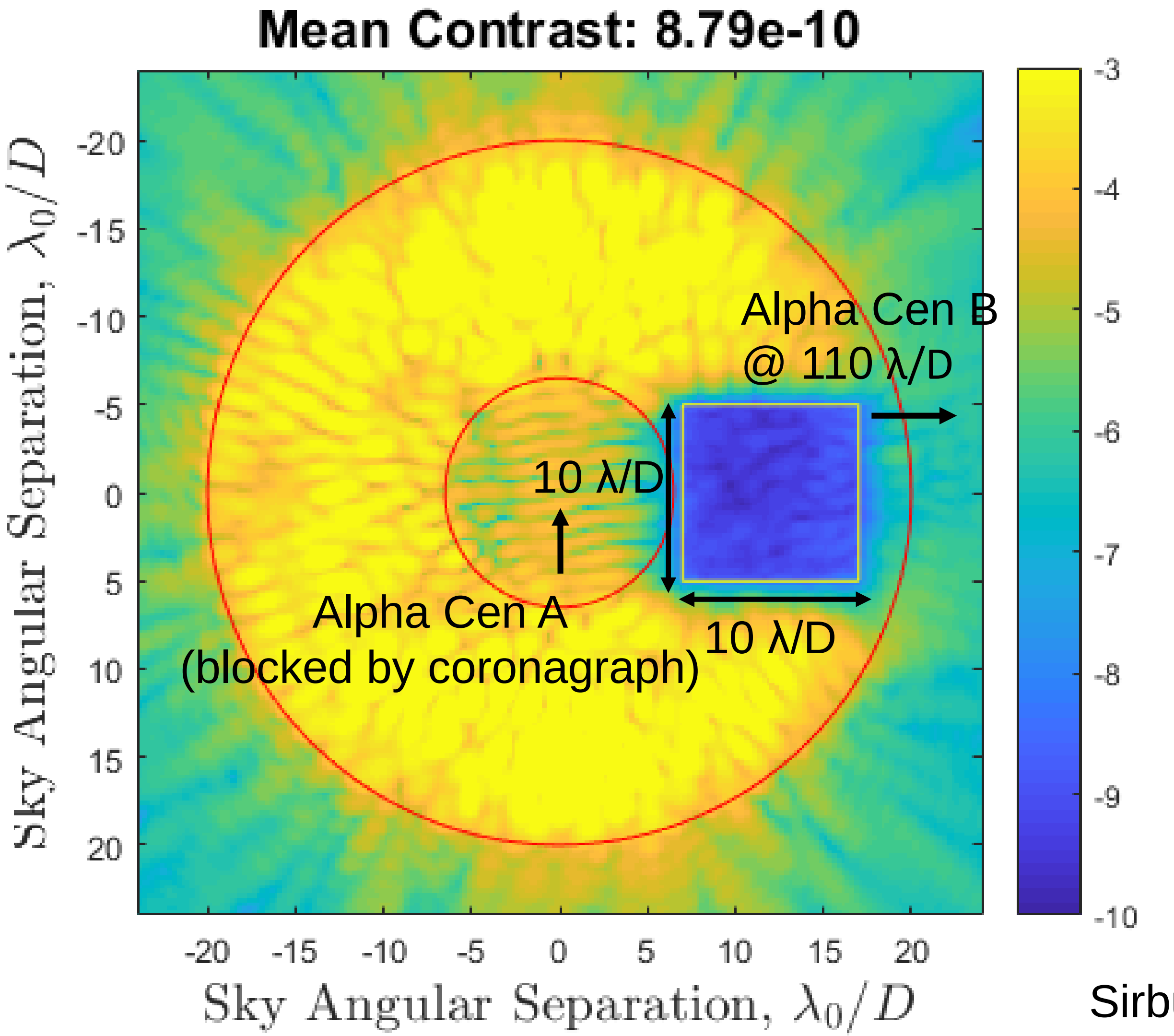
Multi-Star Wavefront Control for Alpha Cen with WFIRST SPC-Disk Mask

On-axis contribution



Off-axis contribution



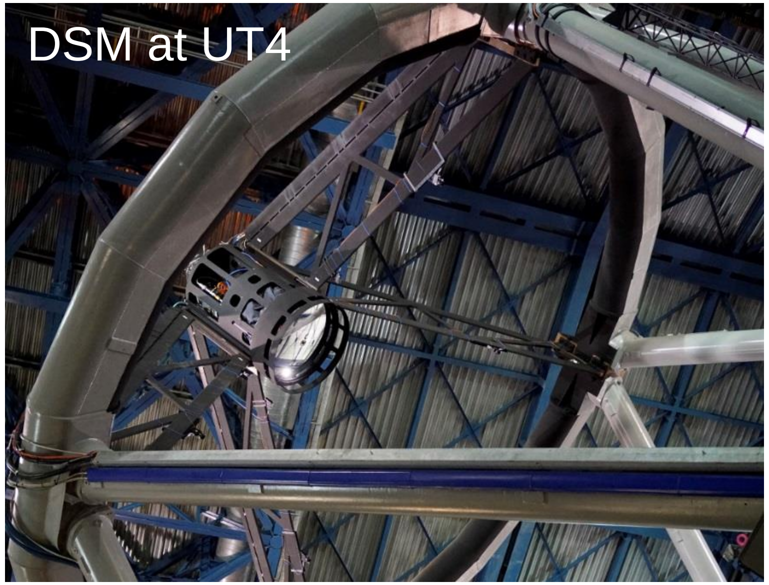


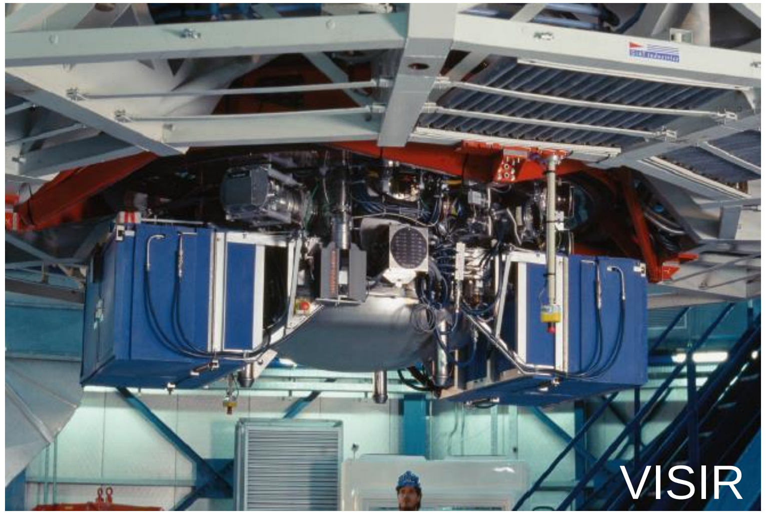
- On-axis star behind focal plane mask
- Off-axis star located 110 λ/D

- 10% bandwidth about 575 nm
- 2-DM control (48x48 actuators)
- Dark hole geometry:
  [7,17]x[-5,5] λ/D

Sirbu et al. 2018 (AAS presentation)

VLT NEAR – VISIR with AO to search for low-mass planets in αCen A and B

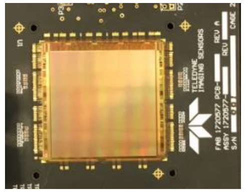




- ESO / Breakthrough Initiatives experiment
  - Kasper, Arsenault, Käufl et al., The Messenger 169, 2017
- Move VISIR to UT4 (Deformable Secondary)
- Flange in front of cryostat equipped with
  - AO WFS (SHS, 40x40)
  - Internal chopper
- VISIR cryostat equipped with
  - AGPM coronagraph
  - ZELDA NCPA calibrator
- Performance
  - Sensitivity: 80μJy / 100 hr in N-band (10-12.5 μm)
  - Contrast $< 10^{-6}$ at $\sim 3\ \lambda/D$ (0.85'')
  - Sensitive to 1.5 - 2 R_E planet in HZ ($T_{N\text{-band}}$ ~320-275 K)
- Schedule
  - 1st light March 2019
  - Campaign (100 hrs over ~15-20 nights) mid 2019

Breakthrough Watch: Setting Sail with Magellan, MIRAC5, and Geosnap

- Heritage from Magellan, MagAO, and MIRAC.
- Complementary to JWST (superior in extreme contrast limit).
- New GeoSnap long-wave MCT detectors: x2 QE + lower noise.
- Test device to be delivered from TIS in late summer 2018.
- If successful, new devices ordered (delivery in mid-2020).
- Magellan/Gemini Breakthrough Watch (BTW) final decisions pending.
- ESO NEAR BTW already funded.
- All BTW experiments cooperating (Templeton proposal submitted).
- Magellan BTW plans to be on-sky in April/May 2021.
- BTW enables pathfinder experiments for all three ELTs.



TELEDYNE IMAGING SENSORS
Everywhereyoulook

For more information on imaging small planets around nearby stars in emission see white paper submitted to NAS Exoplanet Strategy Review "Thermal IR ELT Opportunity" (https://arxiv.org/abs/1804.03218).

Michael R. Meyer (PI), John Monnier,
Katie Morzinski (DPI), Bill Hoffmann, Jared Males, Phil Hinz
Alycia Weinberger, John Mulchaey
Avi Loeb, David Charbonneau, Volker Tolls
Sara Seager, Ian Crossfield

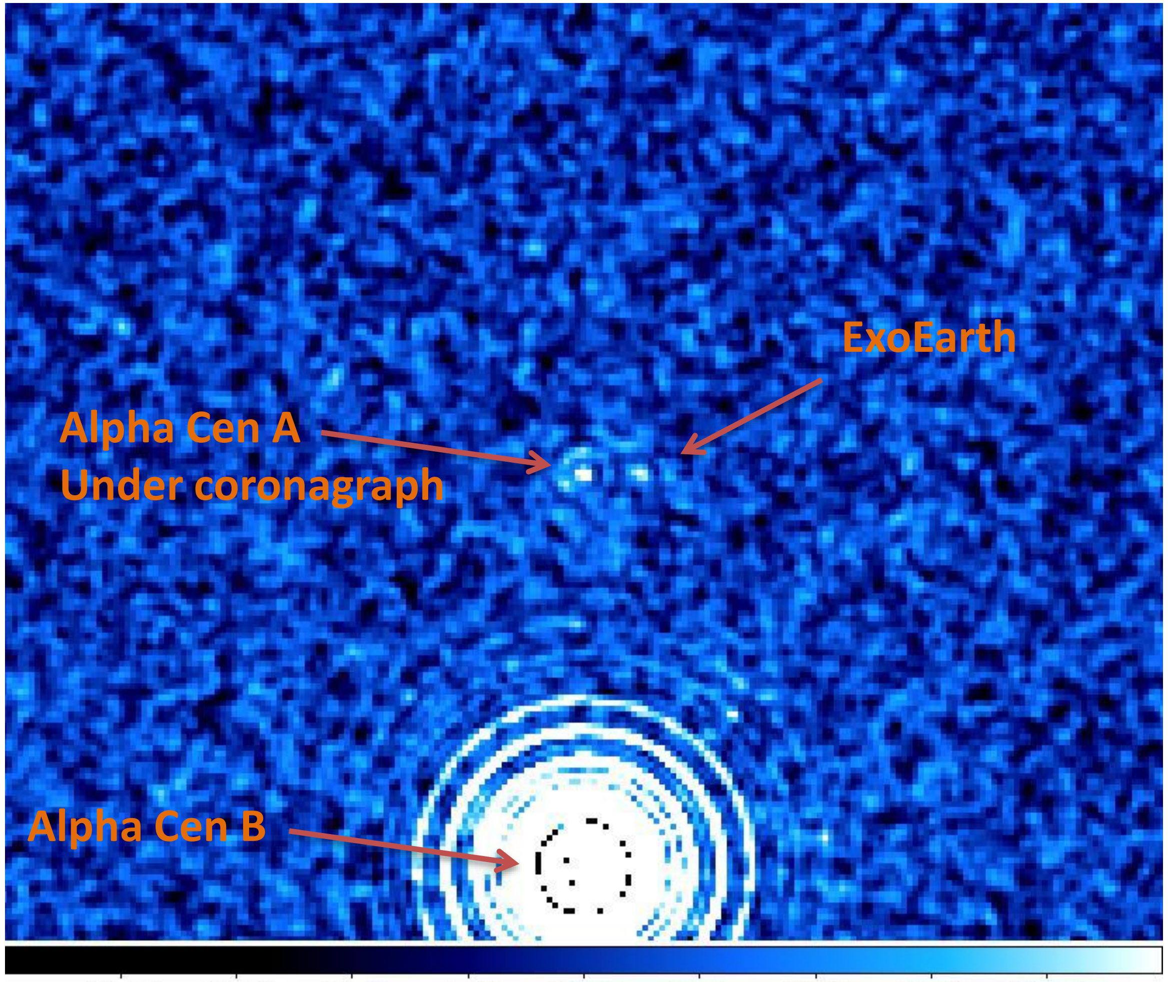
UNIVERSITY OF MICHIGAN
CARNEGIE INSTITUTION FOR SCIENCE
DTM
CfA

Tiki: A ground-based ExoEarth Imager

Team: Christian Marois (NRC-Canada) & Franck Marchis (SETI Institute)

Simulation:

- Based on GPI error budget and its data analysis methods
- Instrument cooled down (based on Michelle Instrument)



Simulation:

- Alpha Centauri System

(A V=0 K1) , B V=1.3 (K1)

- Band N= 10 um
- N=17 mag of contrast
- N(Exoplanet)=15 mag
- (300 K, $M=M_{Earth}$)
- Observation at 10 um
- 40-h exposure time
- 5-sigma detection

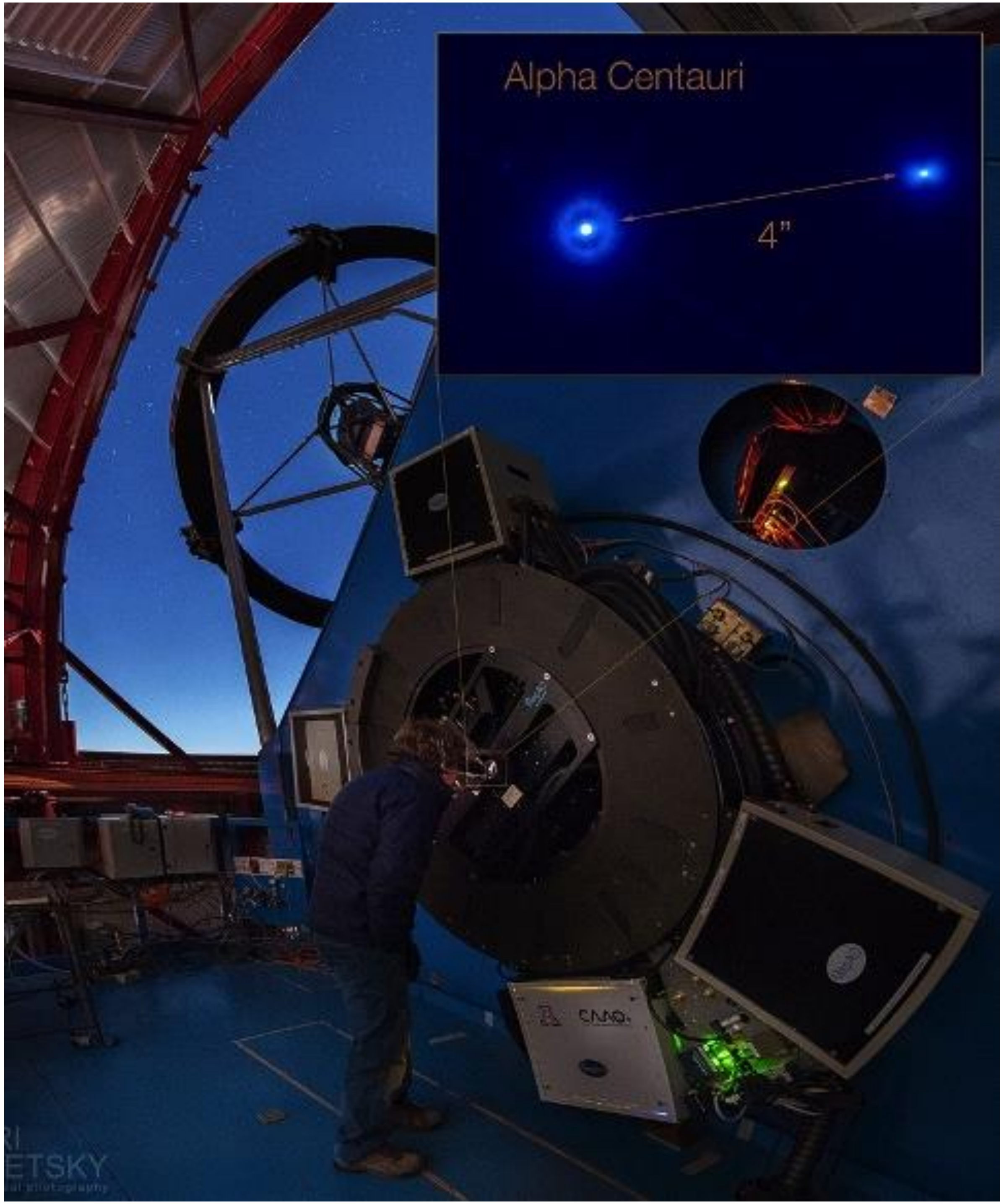
Assessment & Budget

- $5-10M
- 2-3 years of development
- From the ground (easy access)
- Versatile: at Gemini South, TMT?

Technological challenges:

- Mid-IR detector
- Cryogenics AO

6.5-m visible-light diffraction-limited imaging: an eyepiece is mounted in Clio’s place



Conclusions

- Alpha Centauri is a particularly attractive target for direct imaging, by a large margin (if the binary can be suppressed)
  - If aCen has a rocky planet in HZ, it may be possible to directly image it within 5-10 years
- Efforts
  - aCen AB
    - Vis/NIR imaging with current telescopes: MagAO, SPHERE, GPI (large planets)
    - 10-micron imaging with current ground-based telescopes (VLT, Gemini, Magellan)
    - Vis / NIR small space telescope mission (ACESat, Project Blue)
    - Development of Techniques for WFIRST, LUVOIR, HabEx
      - Multi-Star Wavefront Control is at TRL3
  - Proxima b
    - HDC-assisted imaging with current ground-based telescopes
    - ELT imaging in vis / NIR