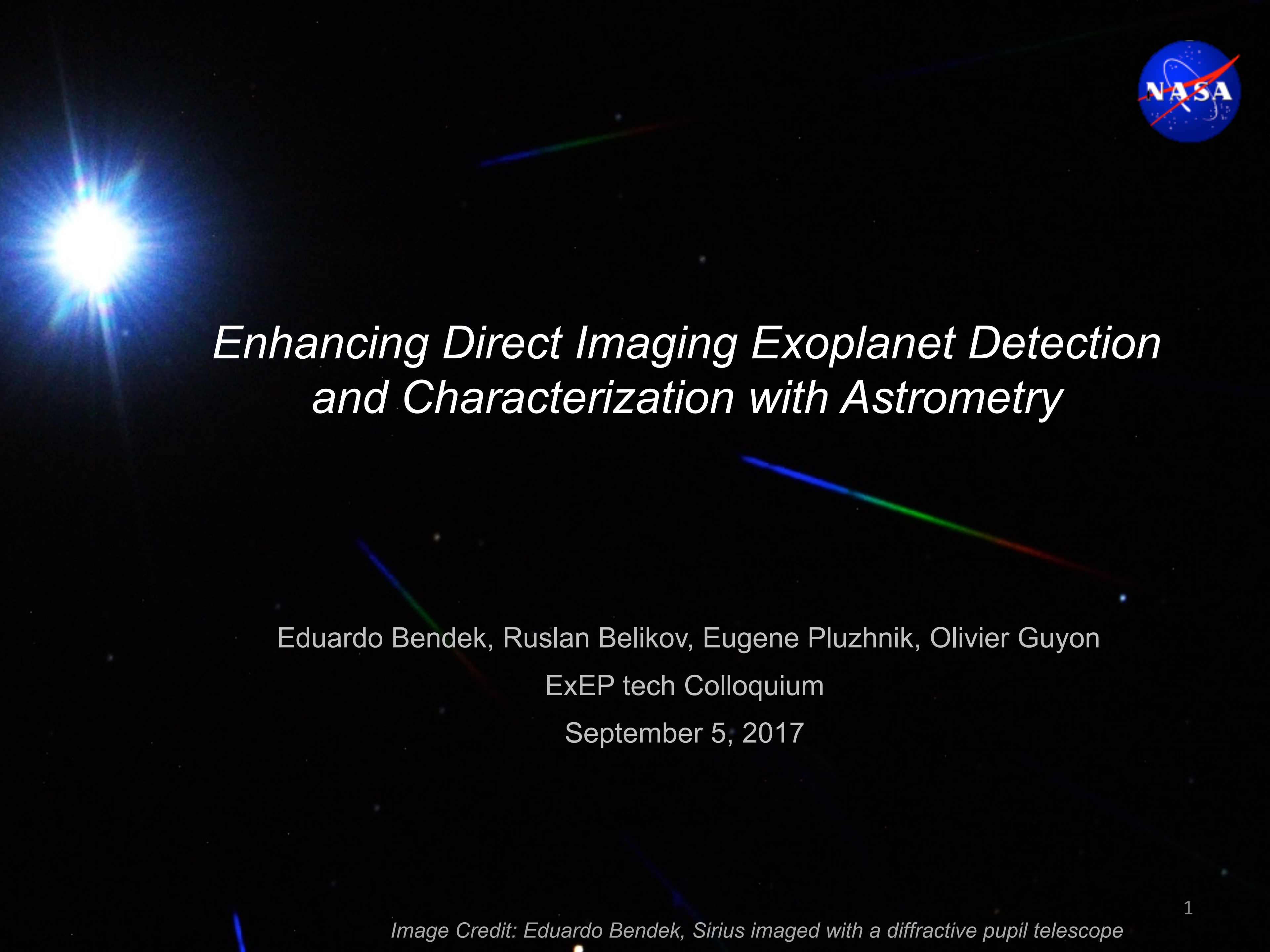

Enhancing Direct Imaging Exoplanet Detection and Characterization with Astrometry

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ExEP tech Colloquium

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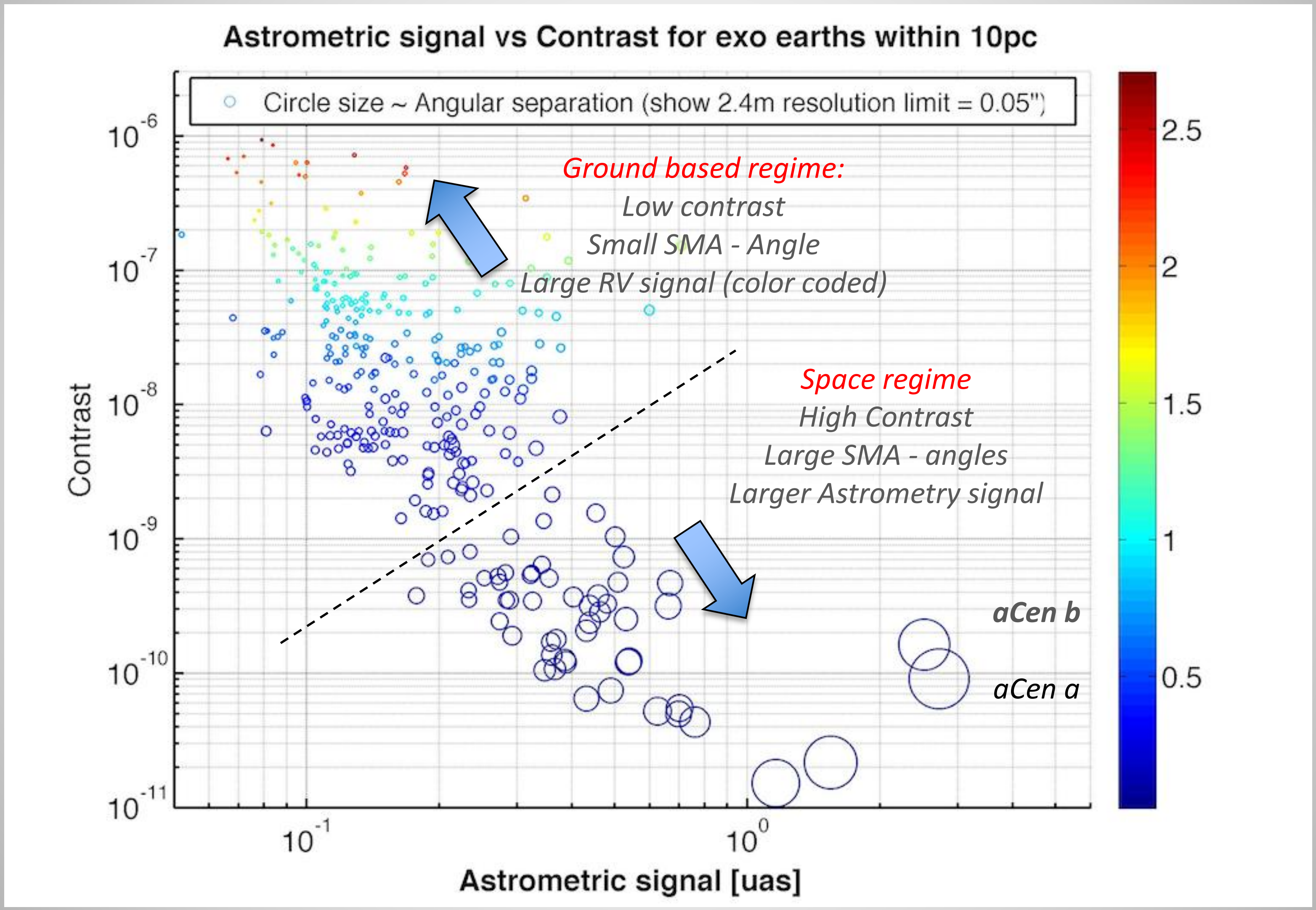
Image Credit: Eduardo Bendek, Sirius imaged with a diffractive pupil telescope

Why Astrometry?

- Exoplanets (with L. Rogers input)
  - **<u>Mass determination</u>**
  - System inclination ambiguity
  - To assess atmospheric loss rates (e.g., Zahnle & Caitling 2013).
  - To distinguish terrestrial planets from water-rich planets and mini-Neptunes (e.g., Grasset et al. 2009).
  - Confirm RV and transit detections
  - Explore outer areas of planetary systems i.e.:
    - Large SMA
    - Long periods
    - Younger, brighter stars ($A_s \sim M_s^{a/2-1}$) for planets in the HZ

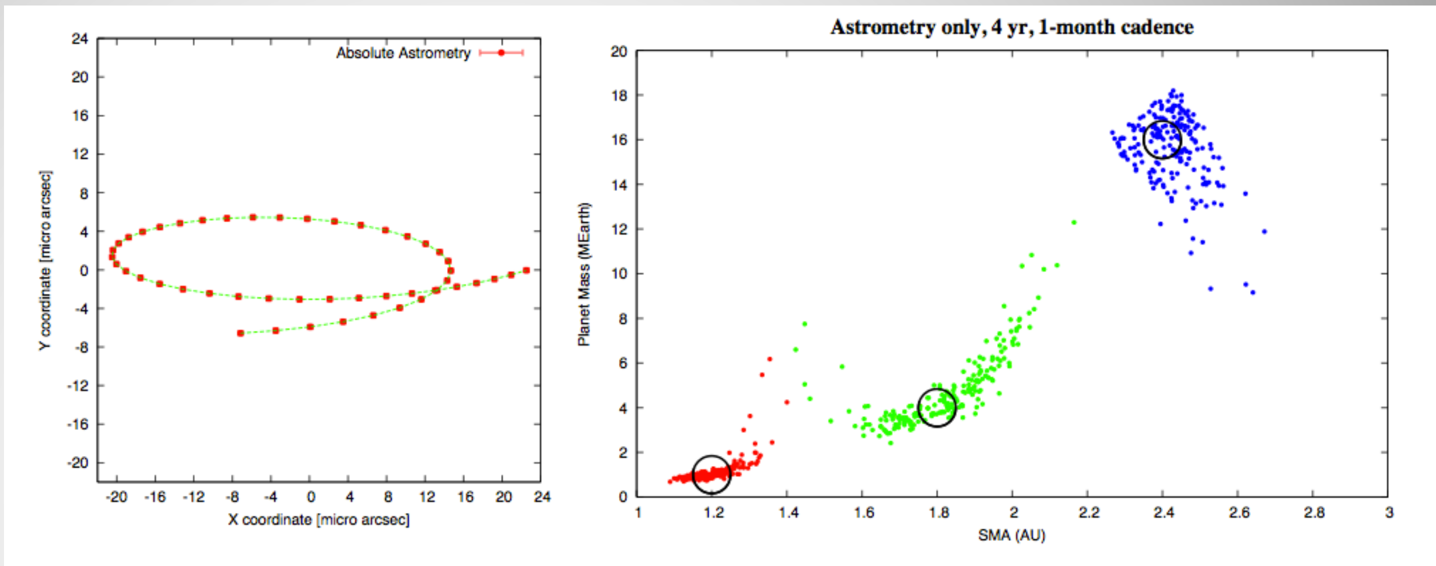
    -> for main sequence stars a=4, => Astrometry grows linearly with Luminosity for main sequence stars ($A_s \sim M_s$)
  - Distinguish zodi / dust from planets

Overview: Astrometry and direct Imaging

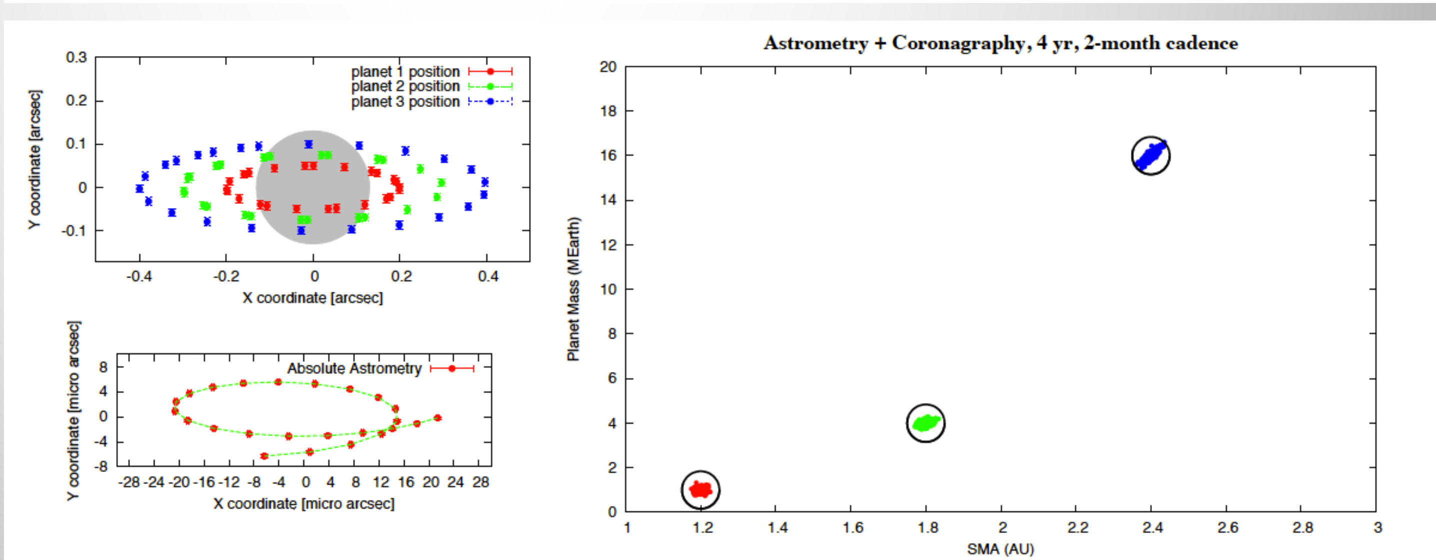


Overview: Astrometry and direct Imaging

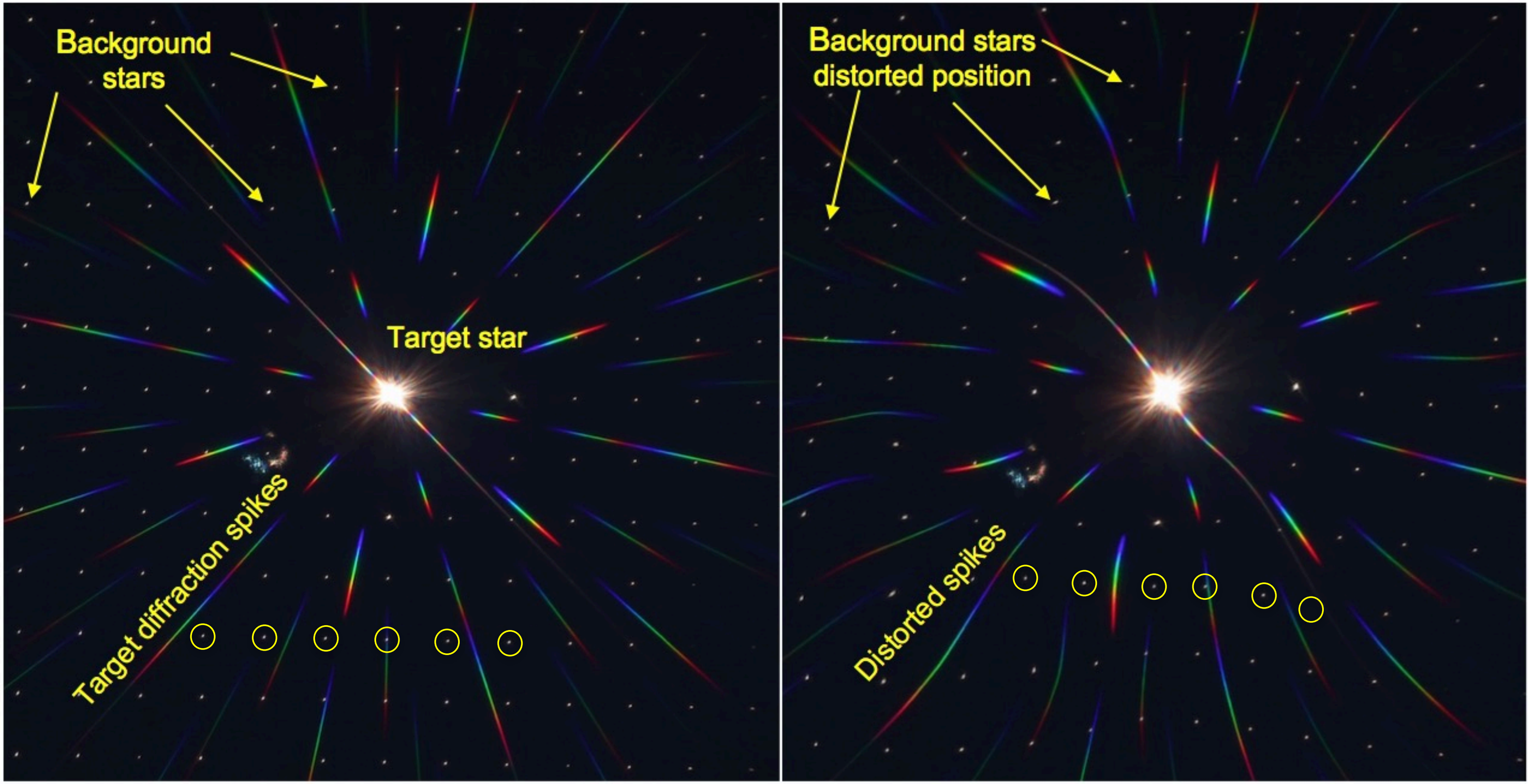
4 Year mission,
1 Month Cadence
Astrometry only
Guyon et al, Apj 2013.



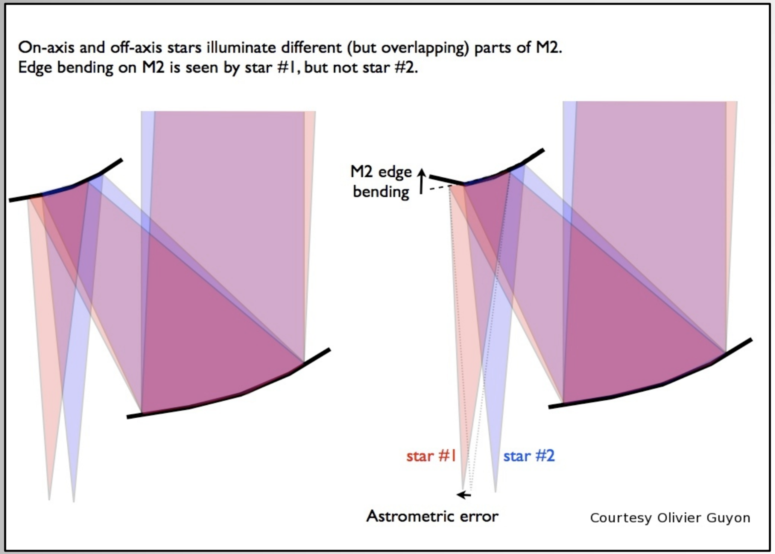
4 Year mission,
2 Month Cadence
Astrometry +
Coronagraphy
Guyon et al, ApJ2013.



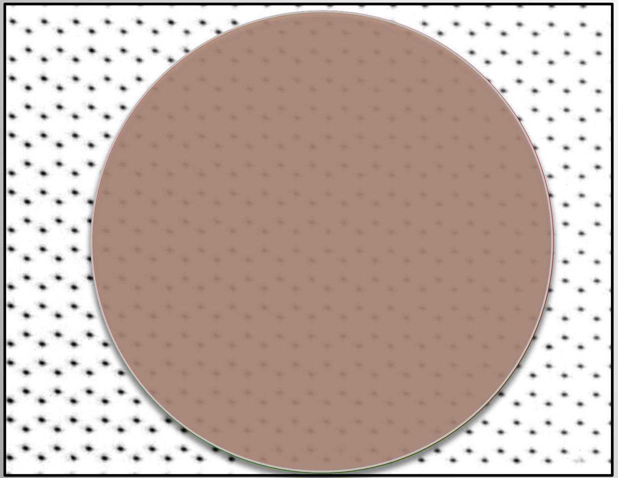
Diffractive Pupil Concept



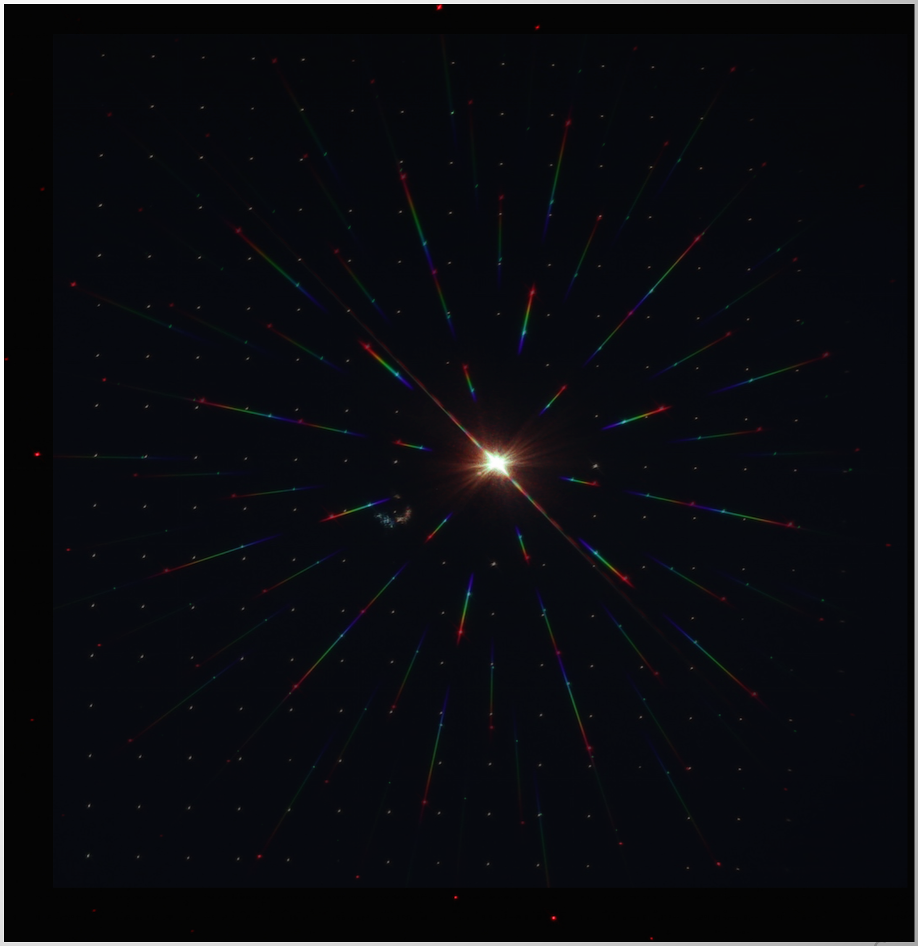
Diffractive Pupil Concept



- Create a diffraction pattern that will map the distortions induced by the optical system:



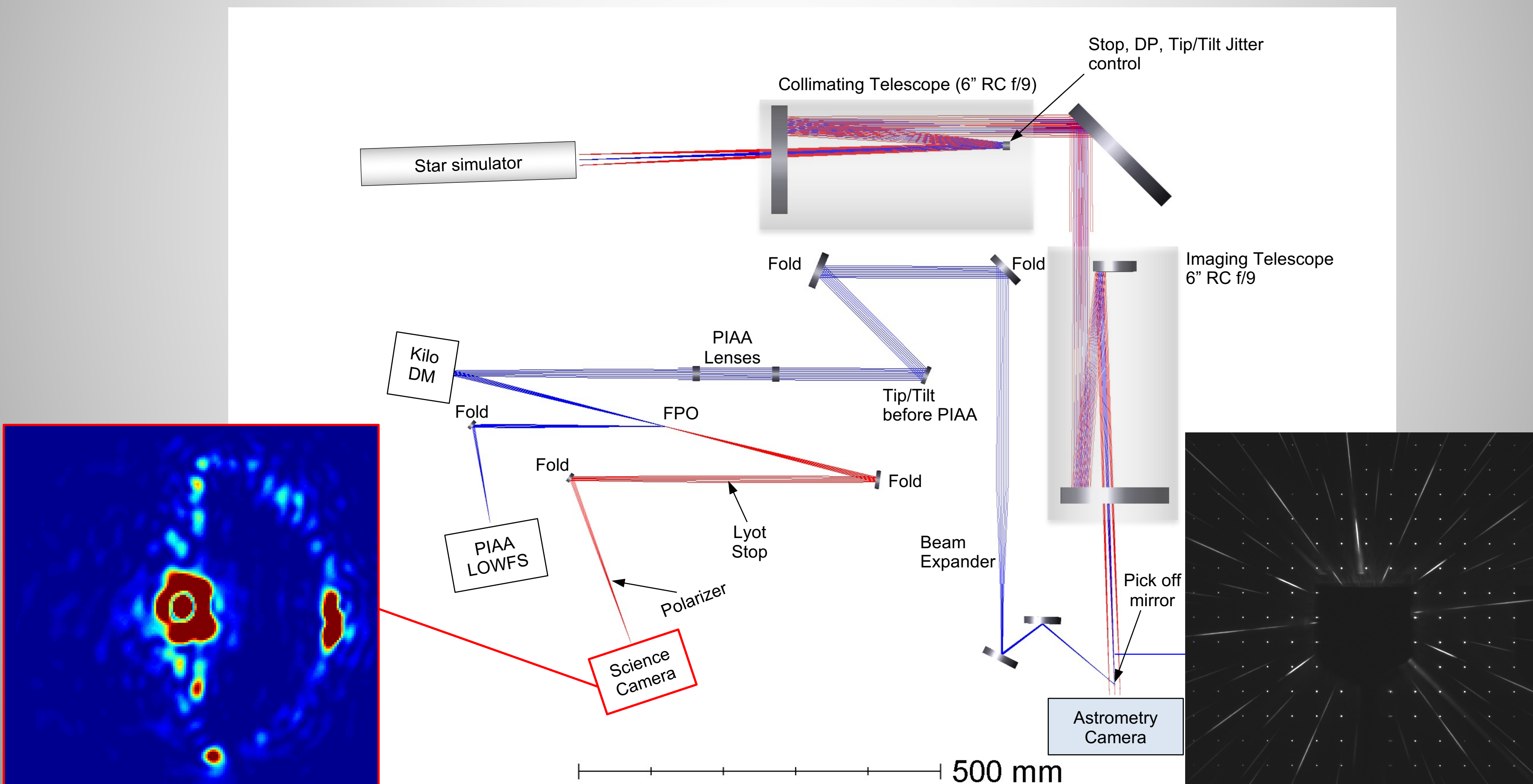
Pupil plane



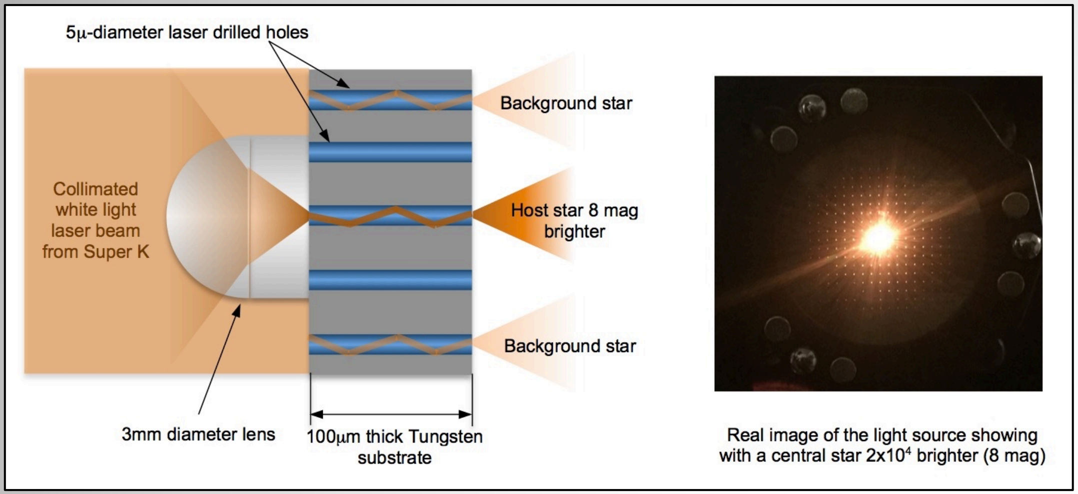
Combined lab at NASA Ames

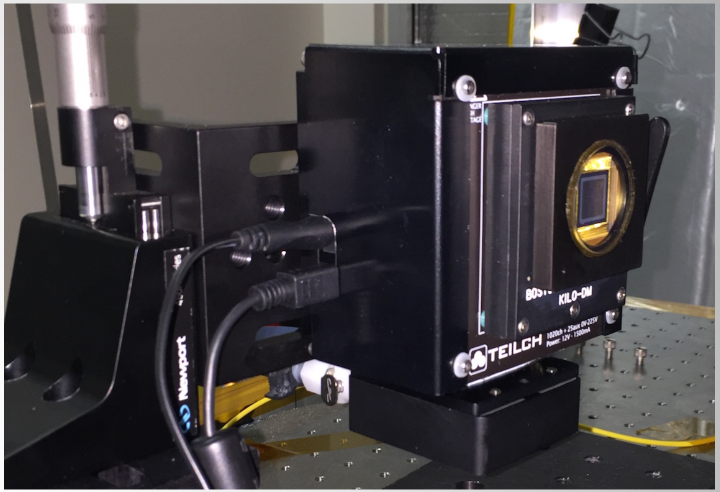
First lab to demonstrate simultaneous astrometry and high contrast imaging.

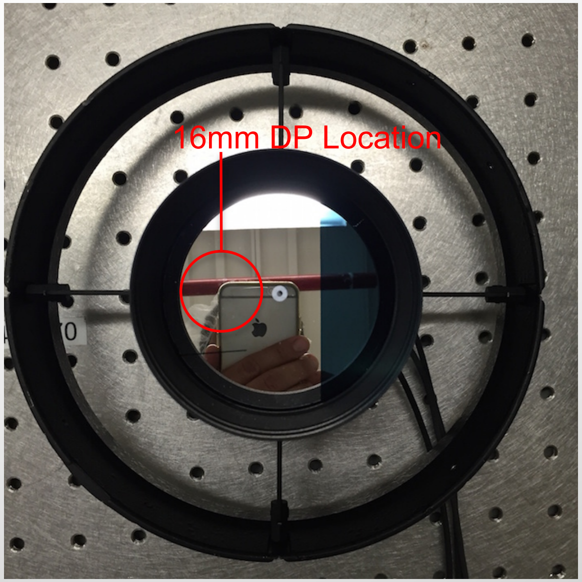
- Demonstrate real mission configuration
- Increase astrometry fidelity
- Coronagraph independent



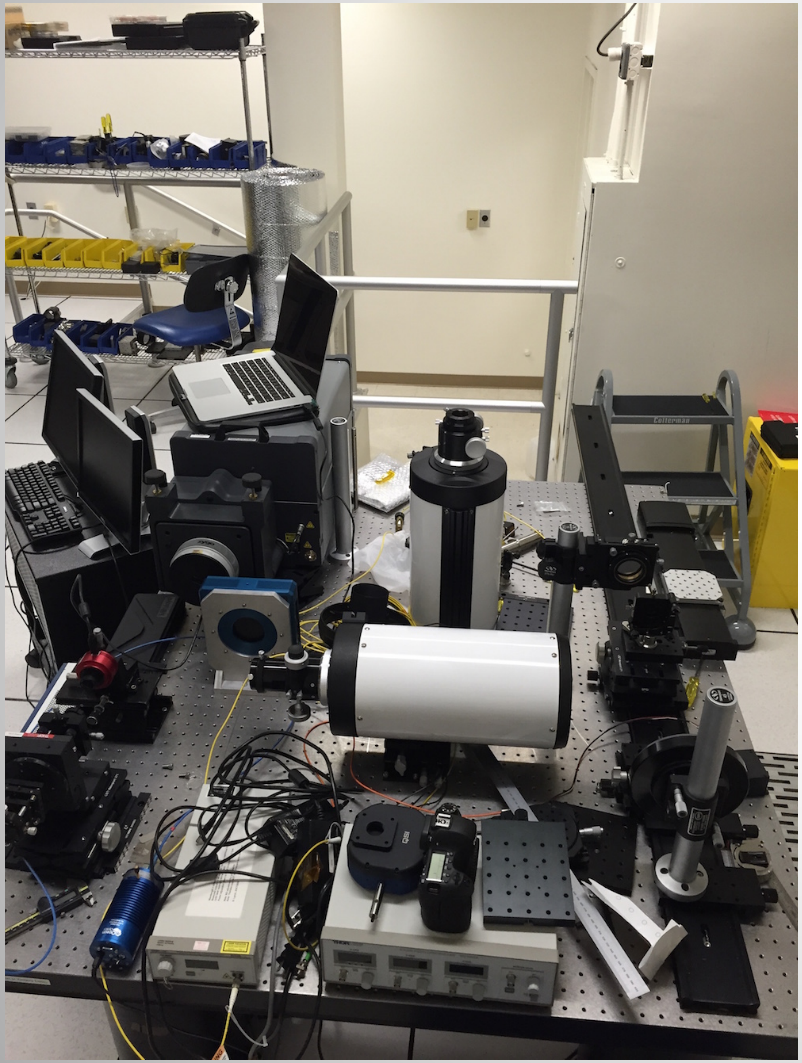
Key Components

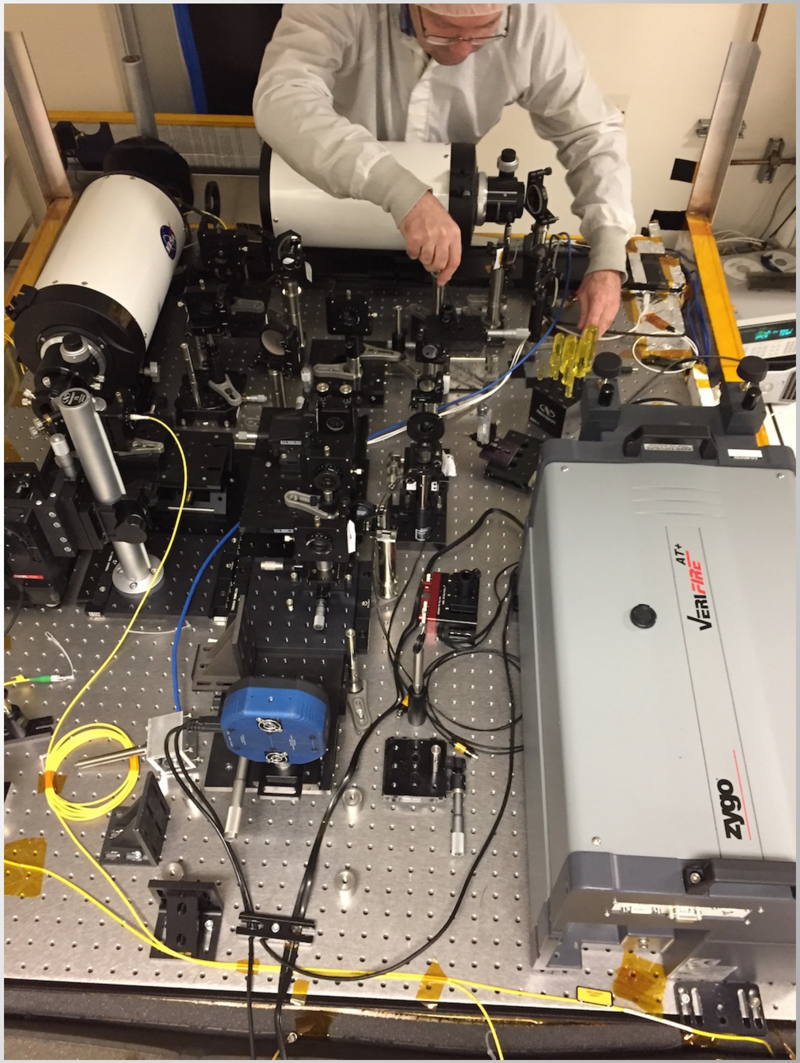






Assembly





Thermal Control

Thermal enclosure

- 15 min A/C thermal cycle ~0.4˚C PV
- Two nested thermal enclosures
- Active air temperature control in the gap between enclosures
- Liquid cooling to remove heat
- 3mK PV over 24
- 1mK RMS over 24

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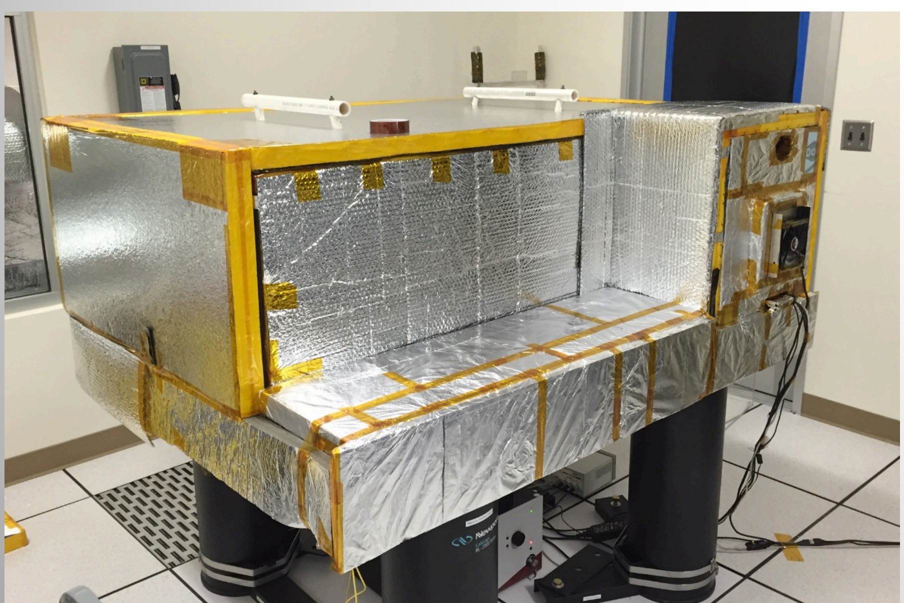
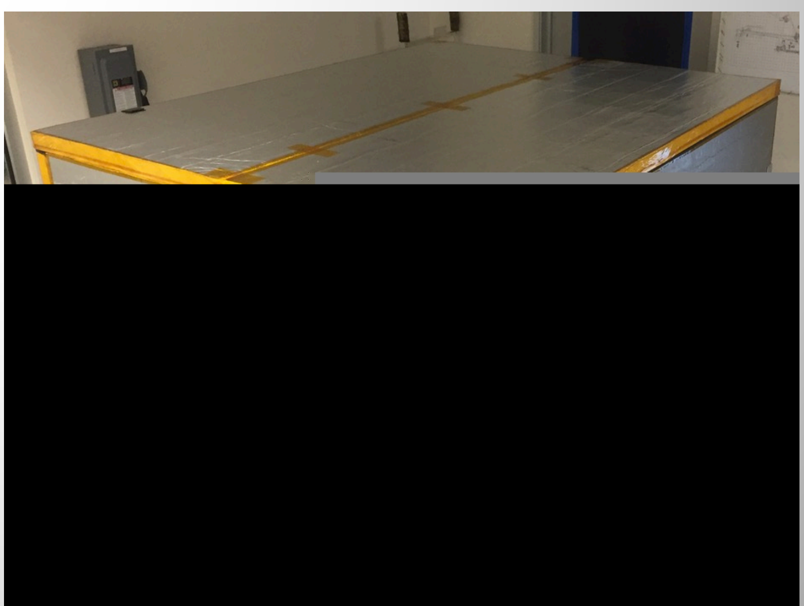




Milestones Definitions

Milestone #1 definition

Broadband medium fidelity imaging astrometry demonstration

Demonstrate 2.4×10^{-4} λ/D astrometric accuracy per axis performing a null result test.

=> Equivalent to 10µas on a 2.4m telescope at 500nm (i.e. Hubble)

Milestone #2 definition

Broadband medium fidelity simultaneous imaging astrometry and high-contrast imaging

Demonstration of milestone #1, and performing high-contrast imaging achieving 5×10^{7} raw contrast between 1.6 and 6λ/D by a single instrument, which shares the optical path

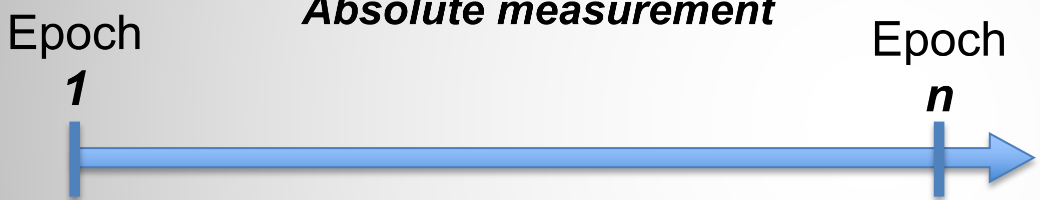
Astrometry

Astrometry Milestone Null Test

Difficult to create well calibrated astrometric signals at ~1uas
=> How well we can measure no motion in presence or real perturbations?

Demonstrate $2.4x10^{-4}$ λ/D astrometric accuracy per axis performing a null result test.
=> Equivalent to 10µas on a 2.4m telescope at 500nm (i.e. Hubble)

Absolute measurement



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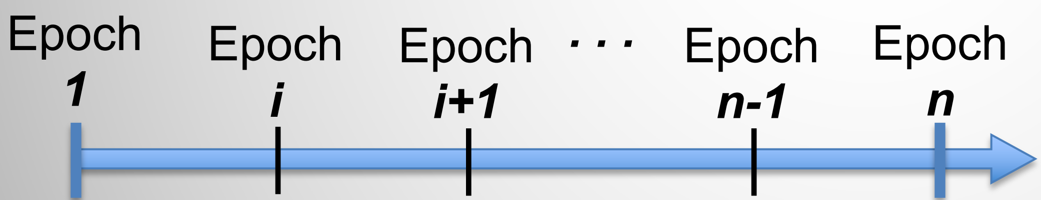
Relative measurement



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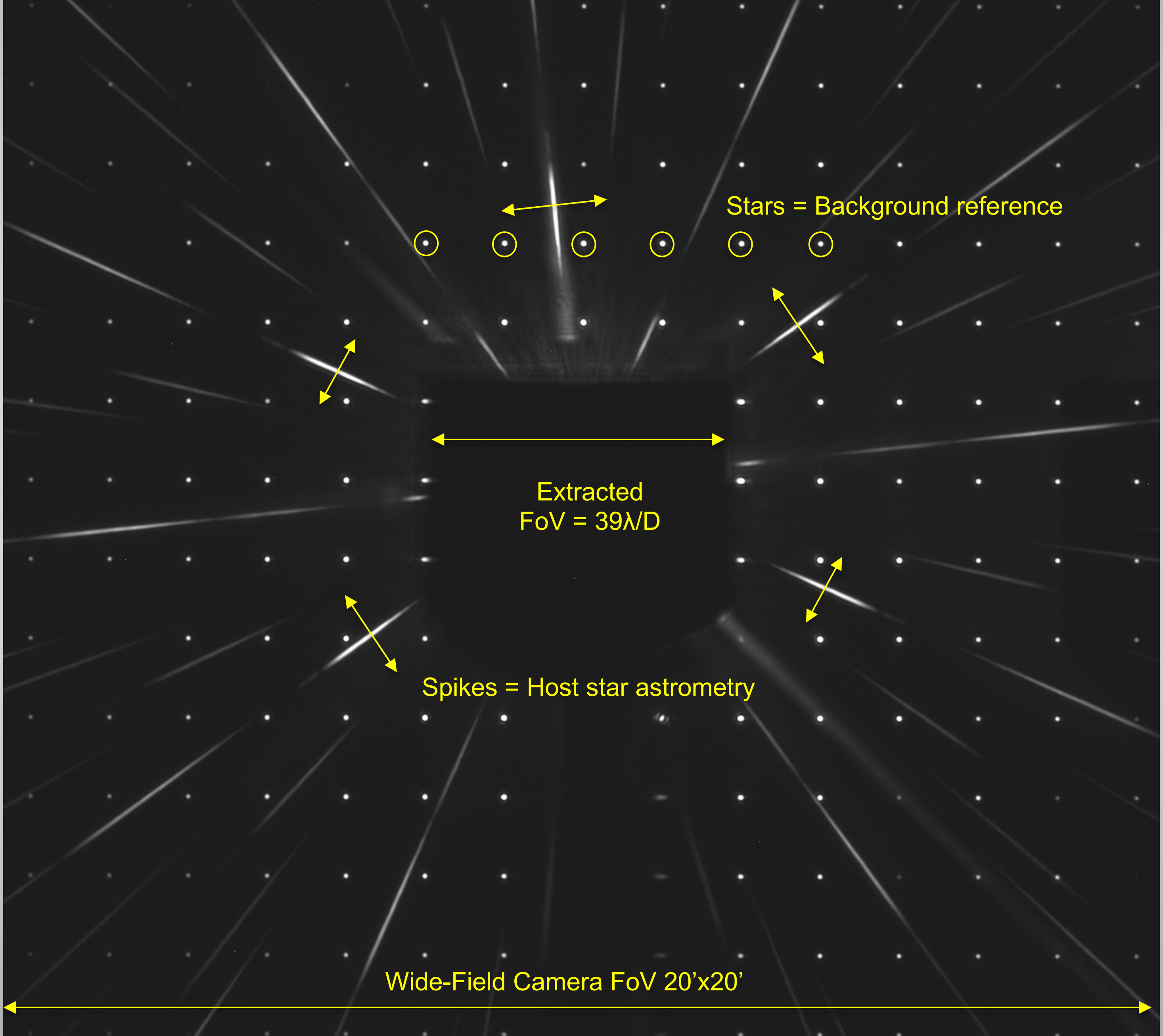
Success if: $A_{abs}(n)-A_{rel}(n) < 2.4x10^{-4}\,\lambda/D$

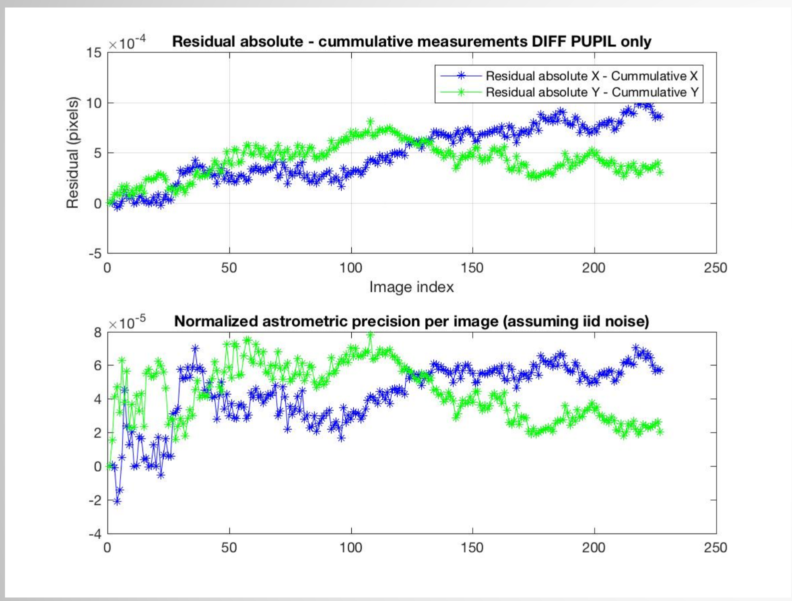
Milestone 1 Results

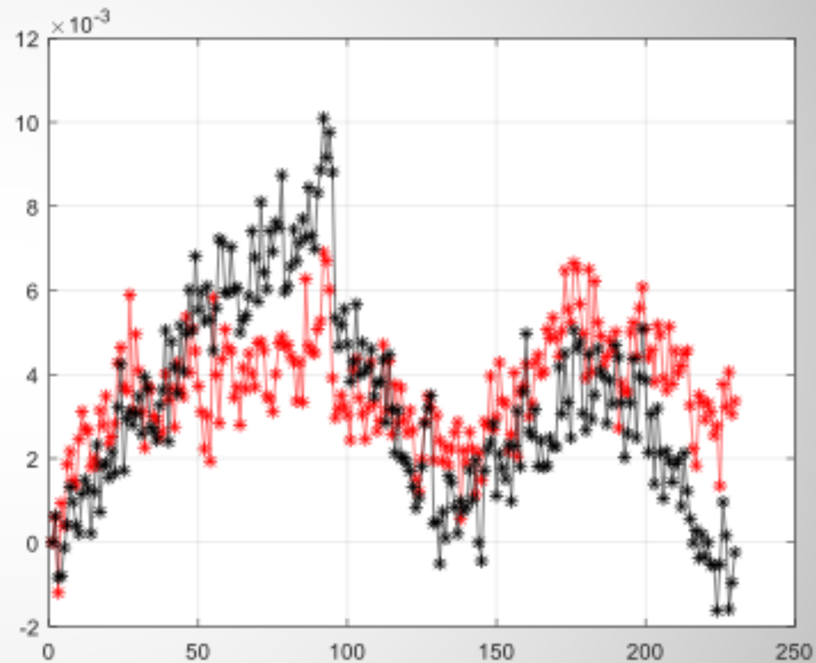


Milestone 1 Results

3 data sets:

- 48 hrs long, 12 Epochs, 5 images per epoch, delay of 4hrs between epochs
- Thermal stabilization to 22.5˚C+/- 20mK over 48hrs
- T/T Jitter stabilization





Set 2	Null test RMS (λ/D)		Milestone #1 (λ/D)	Stars to spikes relative(λ/D)	
	X-axis	Y-axis	1-axis	X-axis	Y-axis
TDEM	2.38×10^{-5}	4.00×10^{-5}	2.0×10^{-4} ✔	4.0×10^{-4}	2.0×10^{-4}
2.4m	1.0µas	1.7µas	10.0µas	17µas	8.5µas
4.0m	0.6µas	1.0µas	6.2µas	10µas	5.0µas

Milestone 1 Results

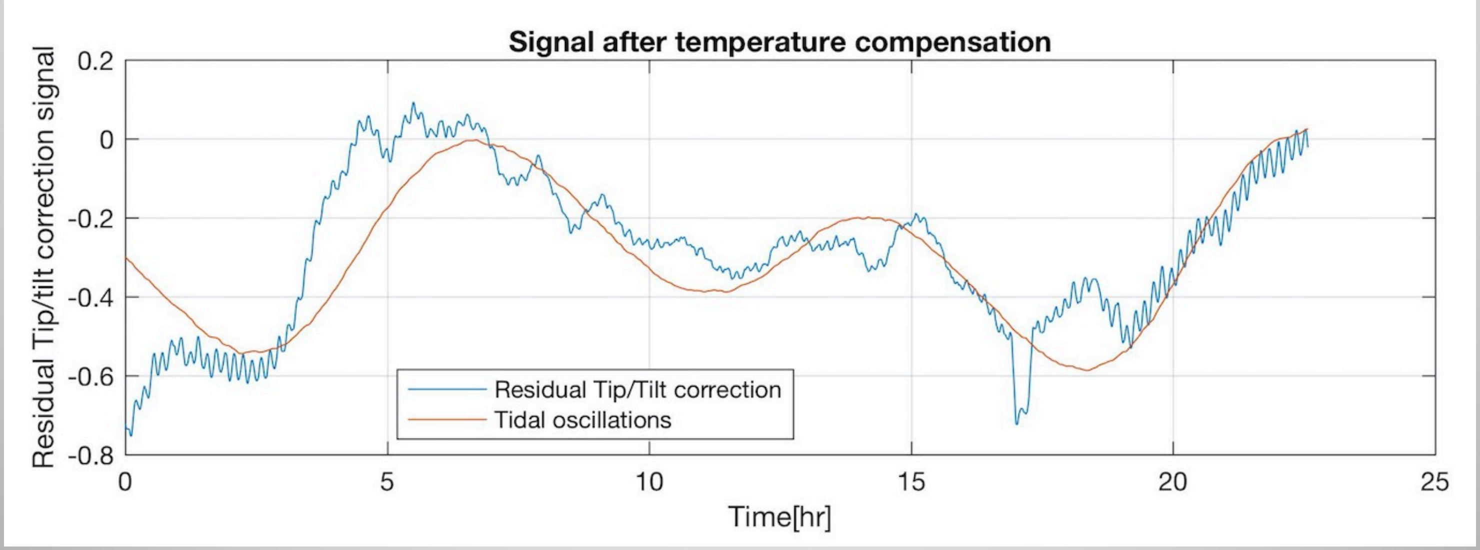
Milestone #1 successfully met

Factor of 10 improvement over milestone requierement
⇒ 1μas for 2.4m aperture achieved => High Fidelity Demo
⇒ Open the grounds for earth-like planet characterization

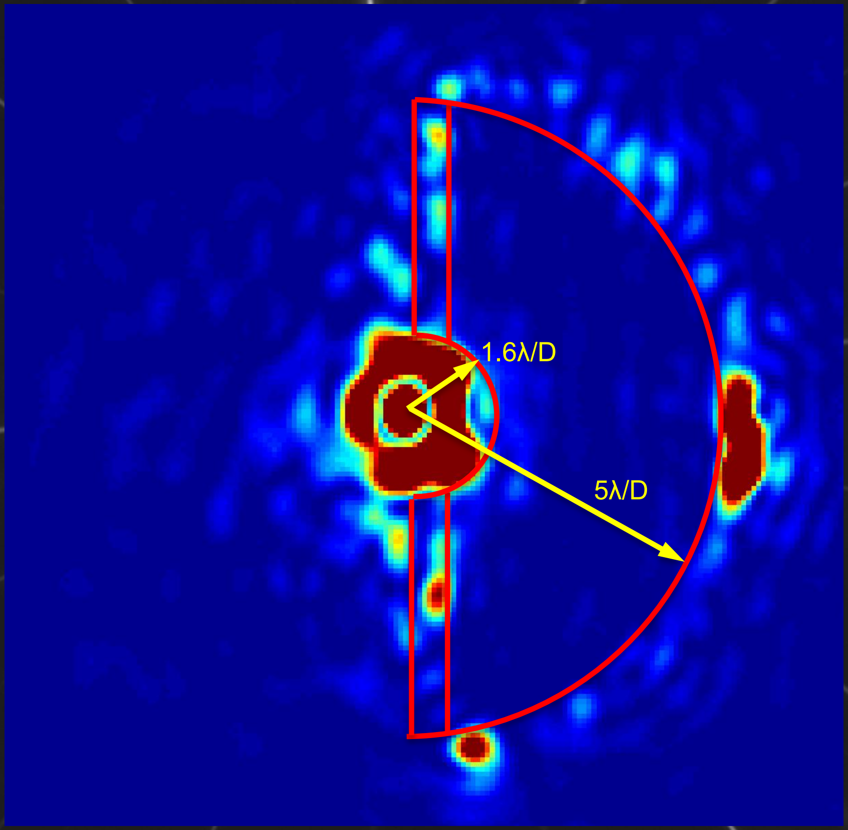
Other important info

NO detector calibration, normal APOGEE Alta U16000 used with TEC cooling

- Result **can be further** improved, far from photon limit
  - ⇒ Software and CCD Calibration
- Thermal stability is remarkable, ***5m˚K PV***, over 12hrs and ***15m˚K over 48hrs***



Milestone 2 Results



Coronagraph:

- Standard PIAA lenses
- 16mm aperture
- λ=655nm
- C-shape Focal plane occulter
- Kilo-DM 1024x1024
- Tip/Tilt Jitter stability loop
- Lyot stop

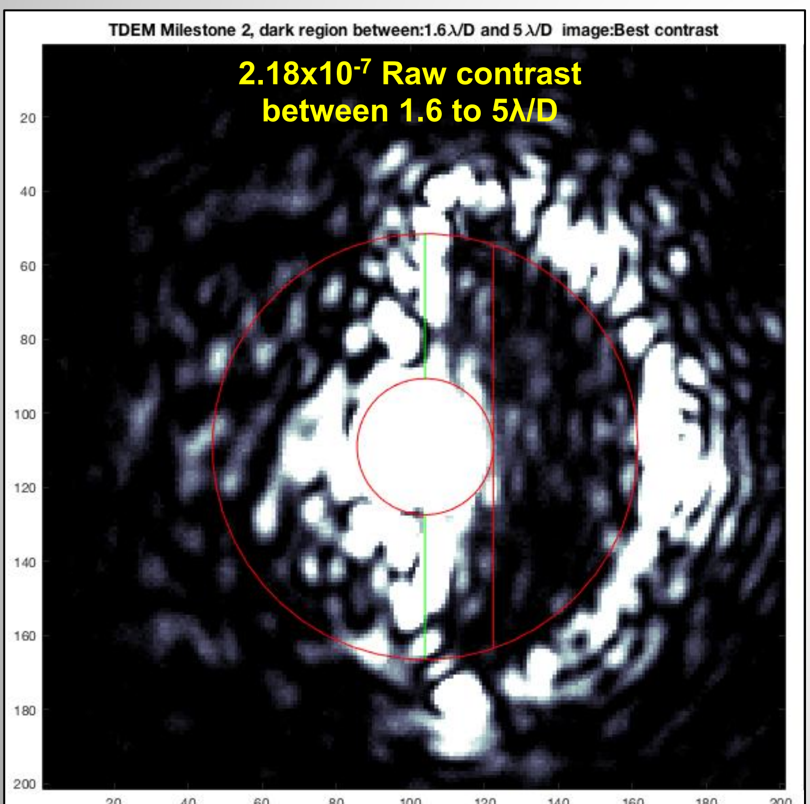
Milestone 2 Results

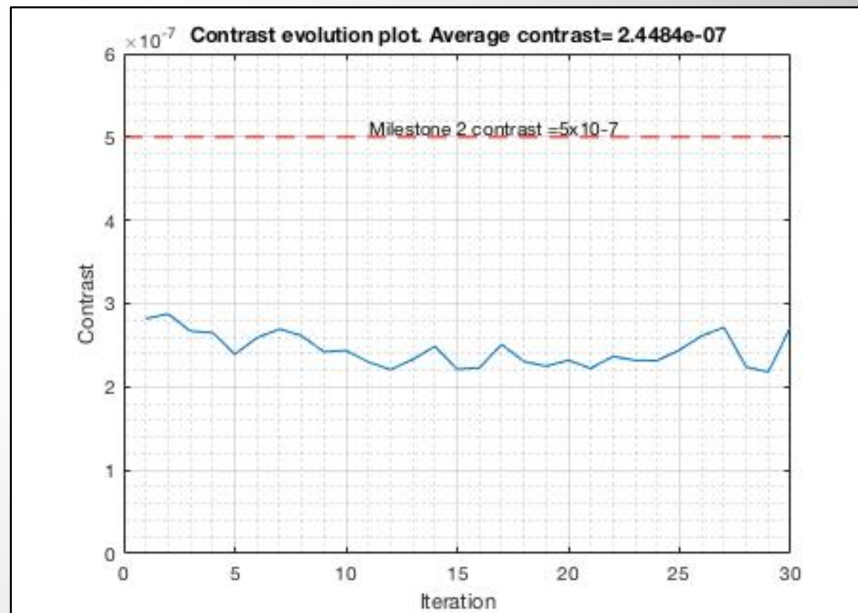
3 data sets:

- Speckle Nulling Algorithm (Starts from Flat DM)
- **2.18x10^{-7} Raw contrast between 1.6 to 5λ/D,** **Factor 2 better than the milestone!**

- Stability test at the end of the run
- Simple average subtraction reached **3.50x10^{-9} contrast between 1.6 to 5λ/D**

=> PROOF of no IWA contamination down to 3.50x10^{-9}





Contrast stability over 30 iterations at low amplitude speckle nulling

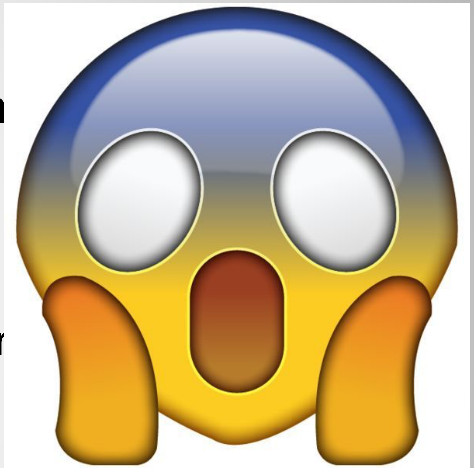
WFC by Eugene Pluzhnik

Impact for the community

=> Astrometry for HABEX (and maybe LUVOIR)

Expected exo-earth yields is between 6 to 17 planets,

- Even if RV instruments achieve <10cm/s to constrain the mass
- It will be still be a function of *sin(i)*
- And no signal in the case of best configuration for in



Why not put dots on the primary mirror?

-Almost imperceptible in comparison with segments or spider

-No co-phasing problem.

-No mid-spatial frequency instabilities

-No Polarization issues

-No IWA contamination, demonstrated to 3.5x10-9

-BONUS!! => Independent tomography to track optics motion/deformation

HABEX has the right configuration, scientific goals and appropriate targets for this technology

General astrophysics and diffractive telescope

- The diffractive pupil is compatible with a general astrophysics mission.
- Spiders diffracted light is 5 times more.
- ***Huge gain: Better than 1uas astrometry!***

For the case presented (Dots cover 1% of the primary)

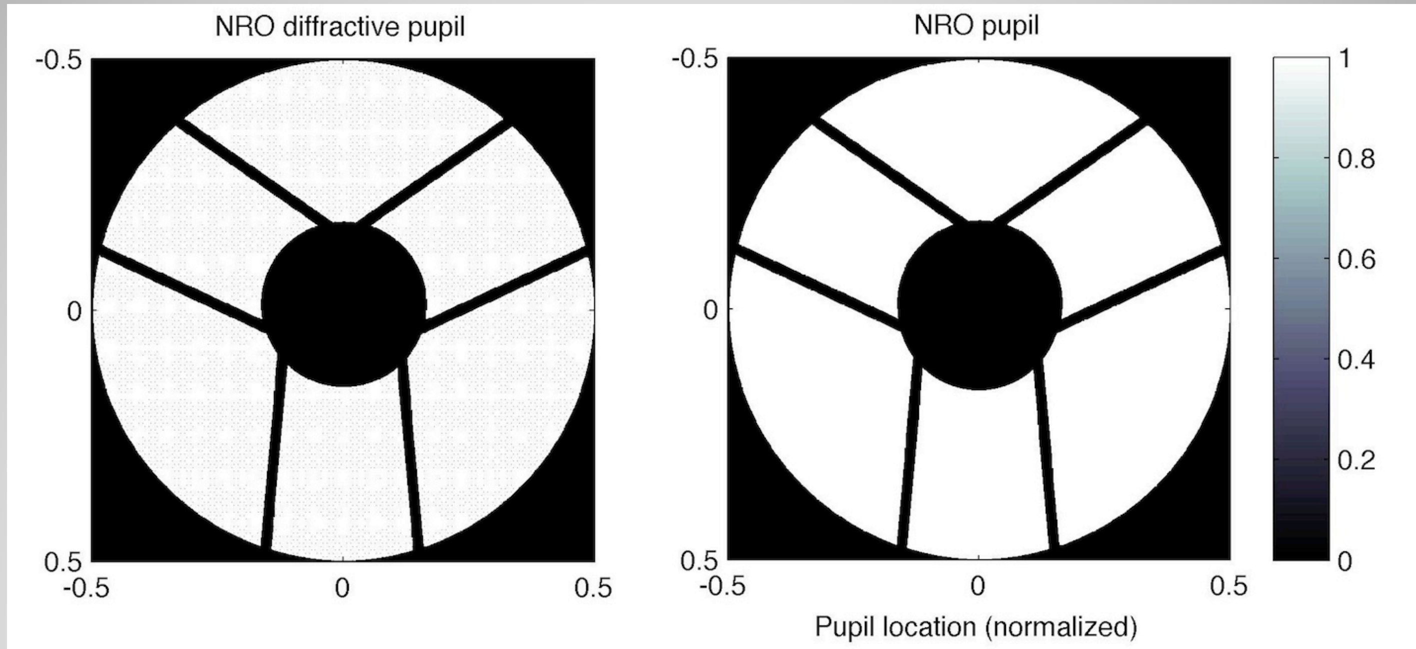
	$Flux_{spike}/Flux_{Zodi}$ ratio for different star magnitudes			
	mV=8	**mV=6**	**mV=3.7**	**mV=-1.46**
99% of FoV	$< 8 \times 10^{-3}$	$< 5 \times 10^{-2}$	$< 4 \times 10^{-1}$	$< 4.5 \times 10^{1}$
95% of FoV	$< 1.7 \times 10^{-4}$	$< 1.1 \times 10^{-3}$	$< 8.8 \times 10^{-3}$	< 1
90% of FoV	$< 5.8 \times 10^{-5}$	$< 3.6 \times 10^{-4}$	$< 3.0 \times 10^{-3}$	$< 3.4 \times 10^{-1}$

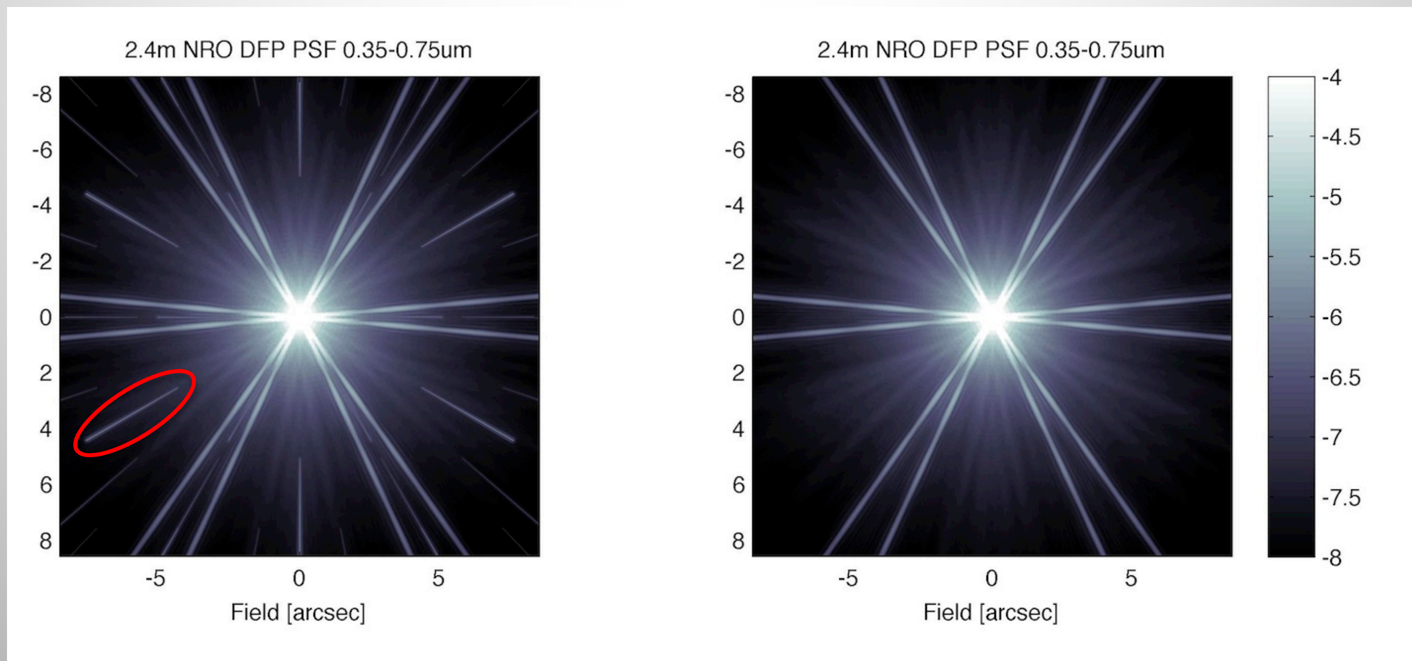
Typical deep imaging bright stars (mV=8, mV=6)

Very unlikely to get a bright star in the field (mV=3.7, mV=-1.46)

Mitigation strategy:

1. Spikes' positions are very accurate and can be subtracted.
2. A trade study is needed to determine the best possible astrometry with minimal interference with other uses of the telescope.


NRO diffractive pupil
NRO pupil
-0.5
0
0.5
-0.5
0
0.5
Pupil location (normalized)
1
0.8
0.6
0.4
0.2
0


2.4m NRO DFP PSF 0.35-0.75um
2.4m NRO DFP PSF 0.35-0.75um
-8
-6
-4
-2
0
2
4
6
8
-5
0
5
Field [arcsec]
Field [arcsec]
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8

Going on sky

- *Modified 14” SC telescope at Ames*
- *Diff Pupil imprinted on the corrector (Pupil for an Schmidt Cassegrian)*
- *Goal: Multi-month observation of a single target to beat down turbulence.*
- *Anybody wants to help with a second telescope somewhere else?*

Sirius imaged with a diffractive pupil telescope

Conclusions

1) Astrometry and direct imaging TDEM completed! Milestone meets by ample margin.
   - $2.4 \times 10^{-5}\ \lambda/D$ astrometry achieved (1μas on Hubble)
   - 2.3x10-7 raw contrast between 1.6 to 5λ/D

3) The Diffractive Pupil technology would enable measuring masses of earth-like planets.

4) There is no significant telescope performance degradation cause by the Diffractive Pupil

5) Next steps: Ground demo, and a microsat.

Thank you