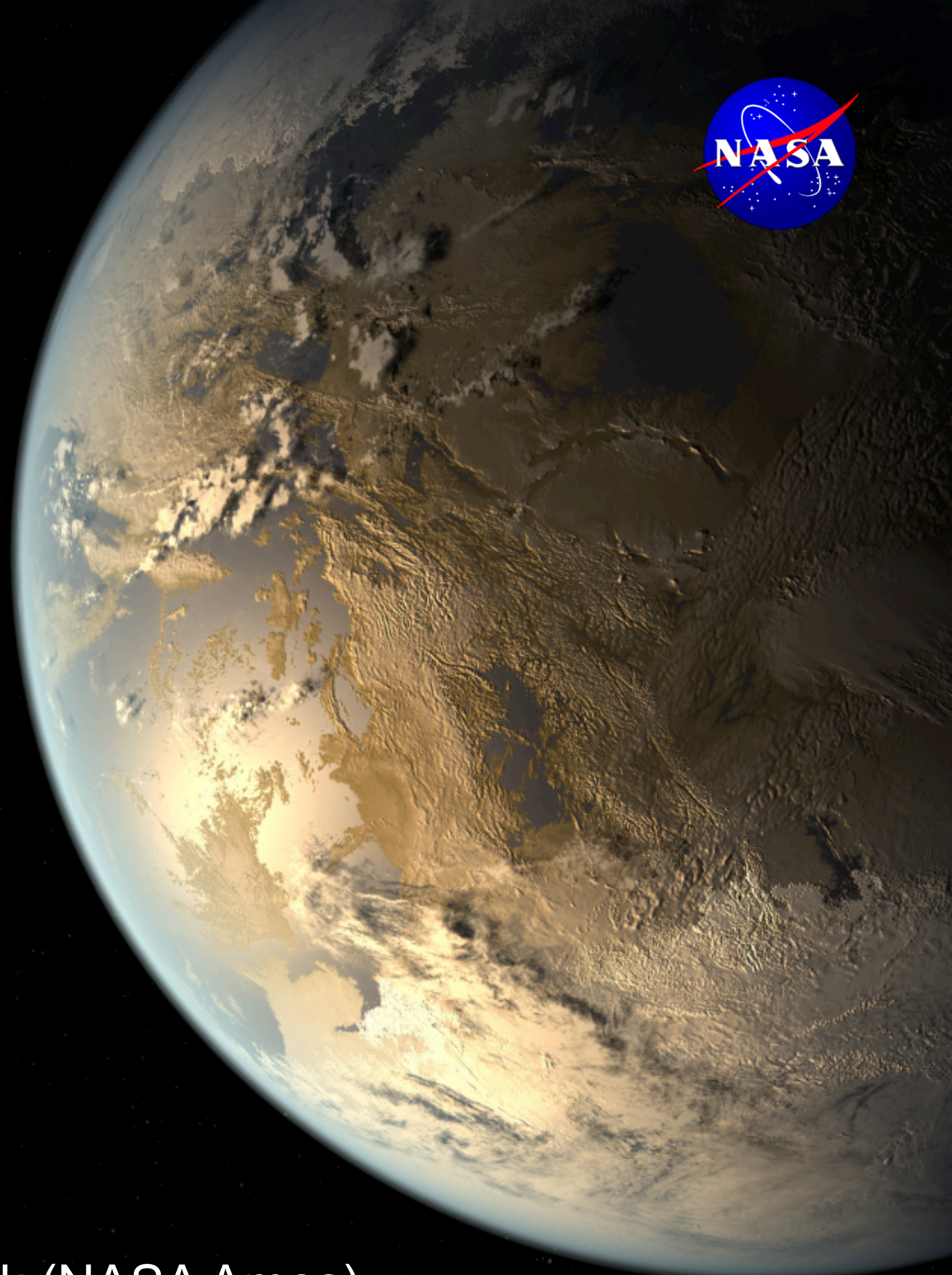
Exopag 10

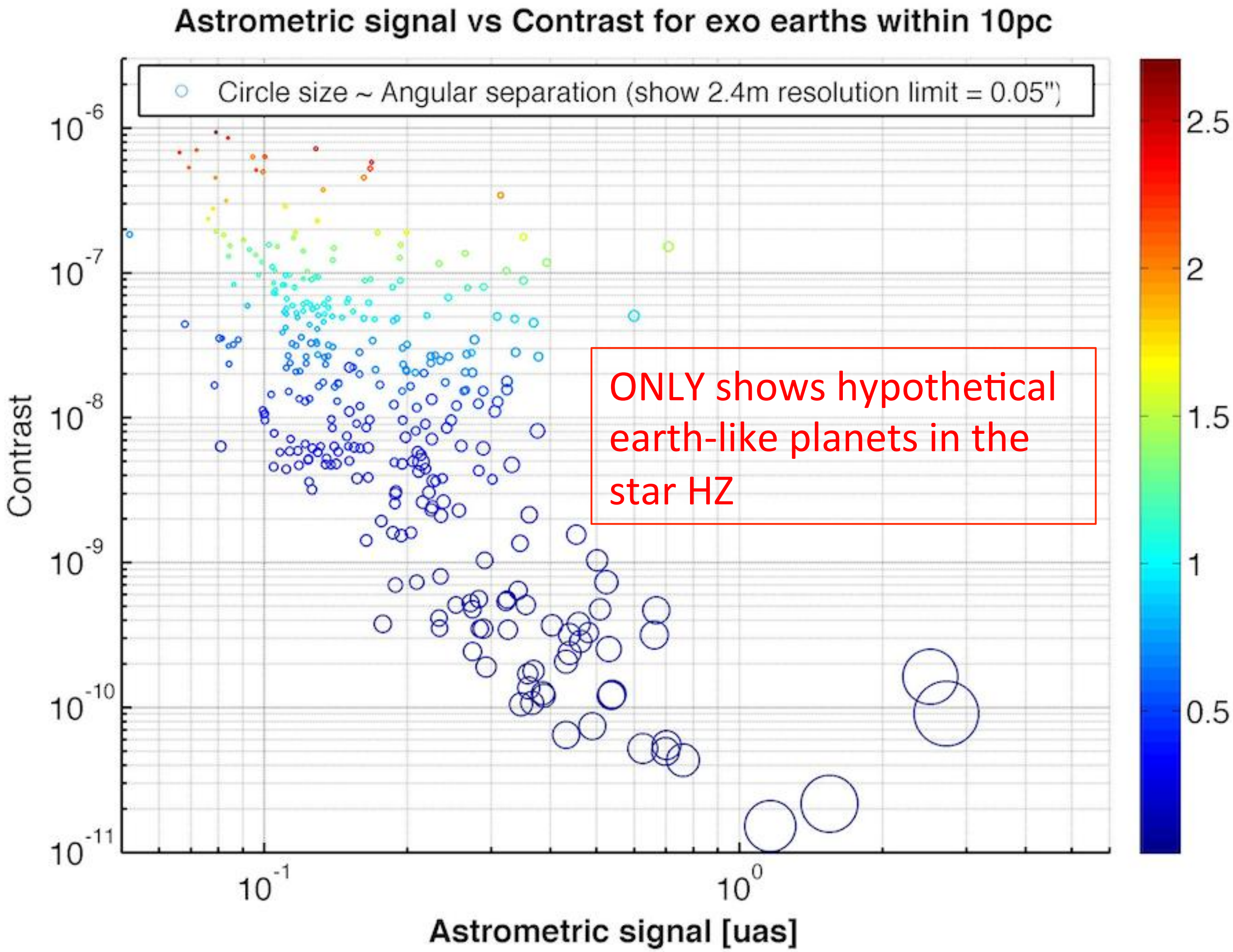
Astrometry for exoplanet detection



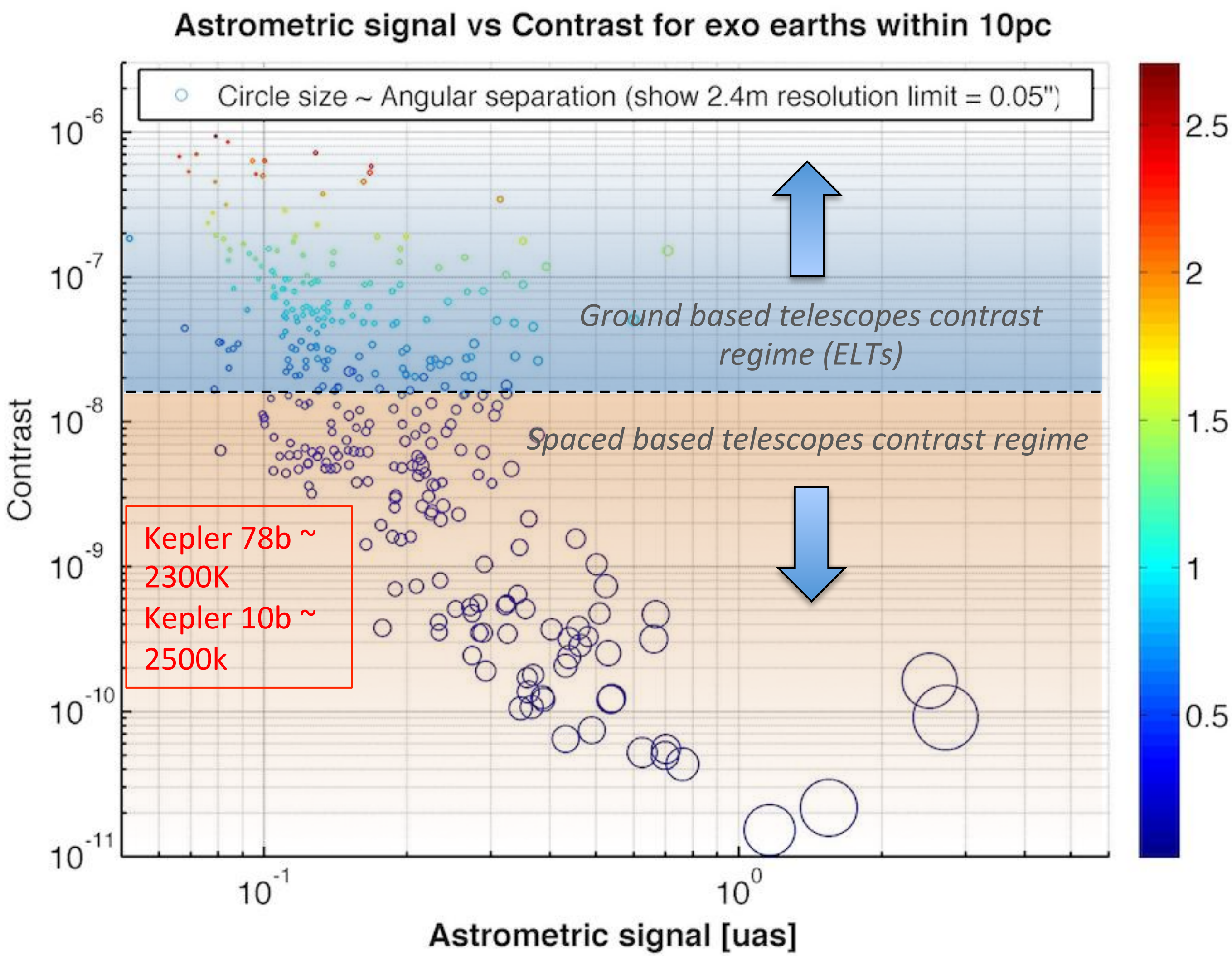
Eduardo Bendek (NASA Ames)

Image Credit: NASA Ames K

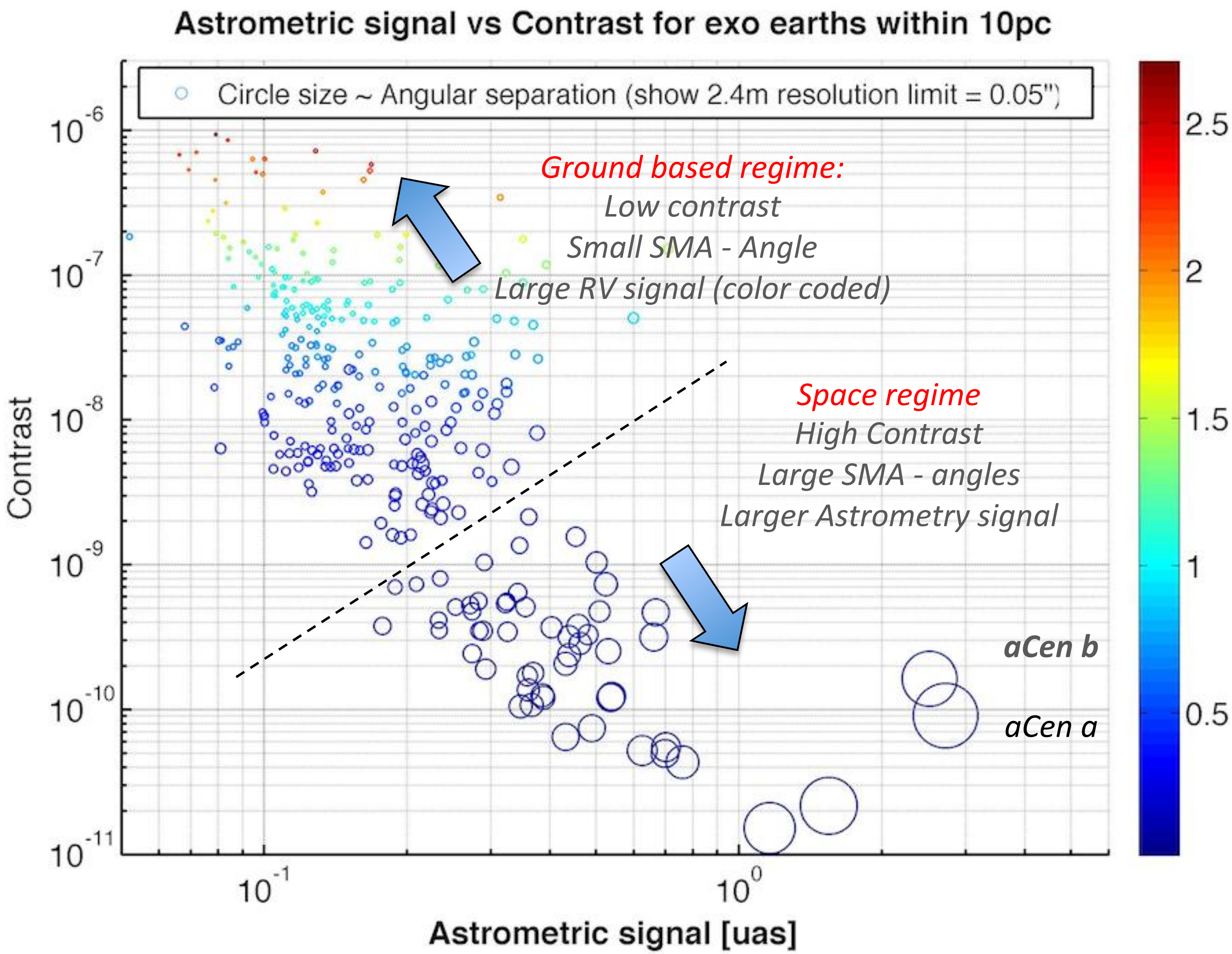
Why astrometry from space?



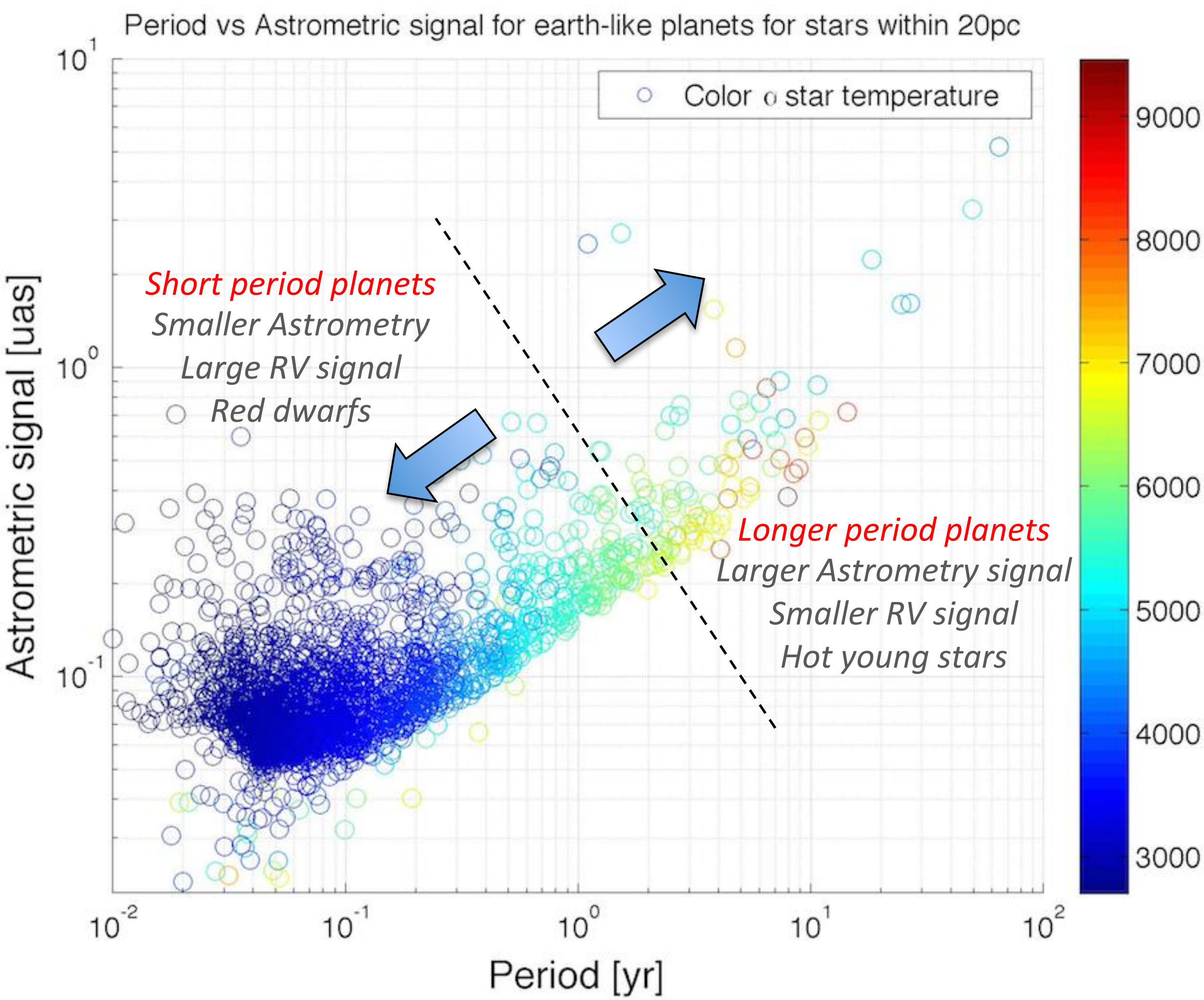
Why astrometry from space?



Astrometry and direct Imaging

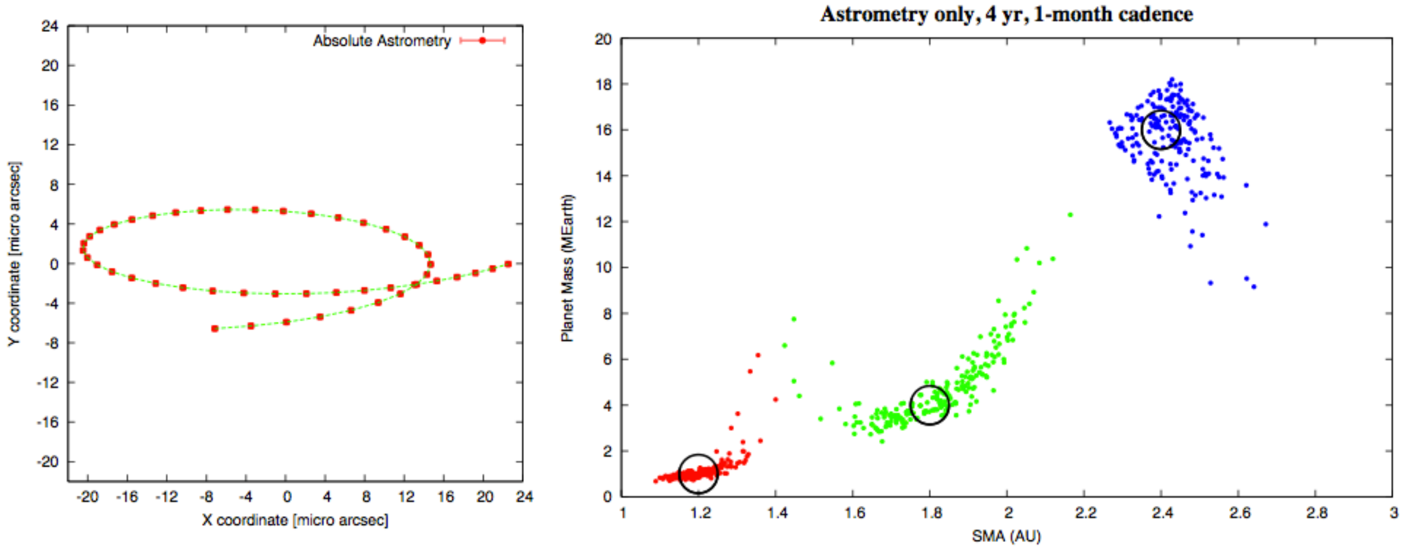


Astrometry and Period

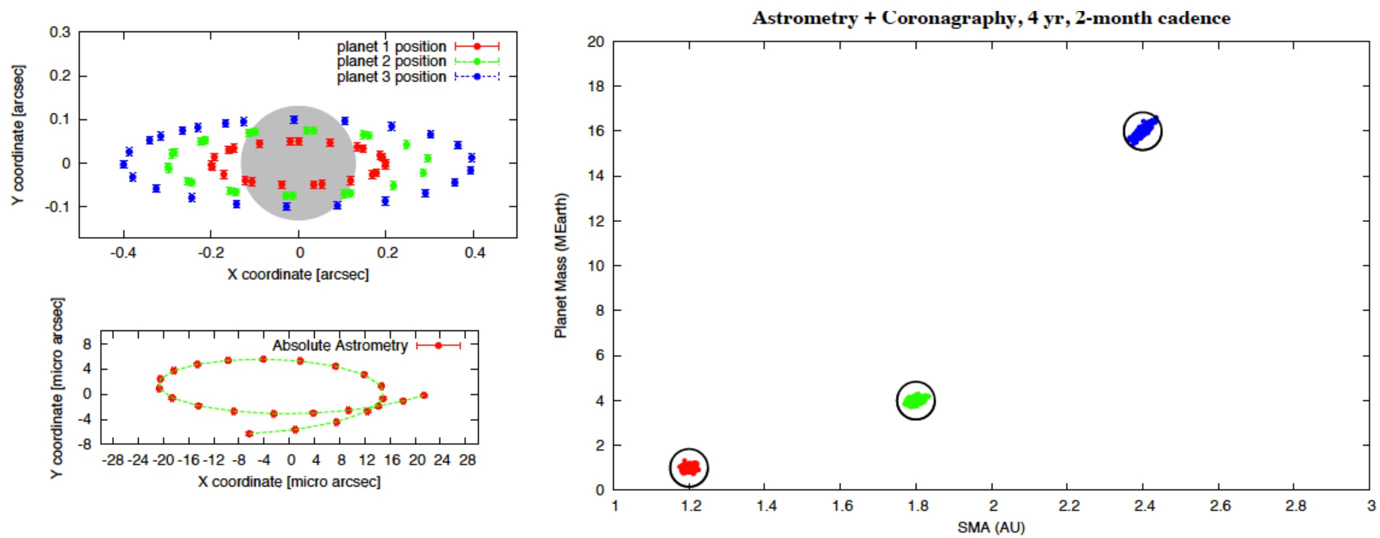


Astrometry + Direct imaging

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

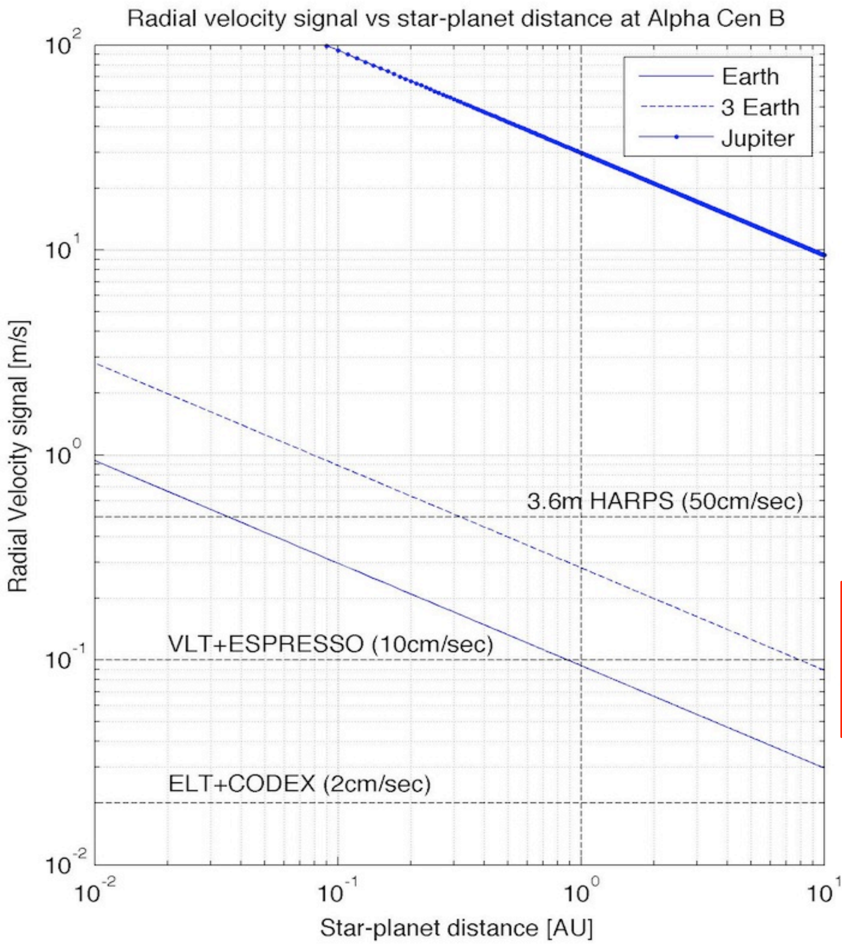


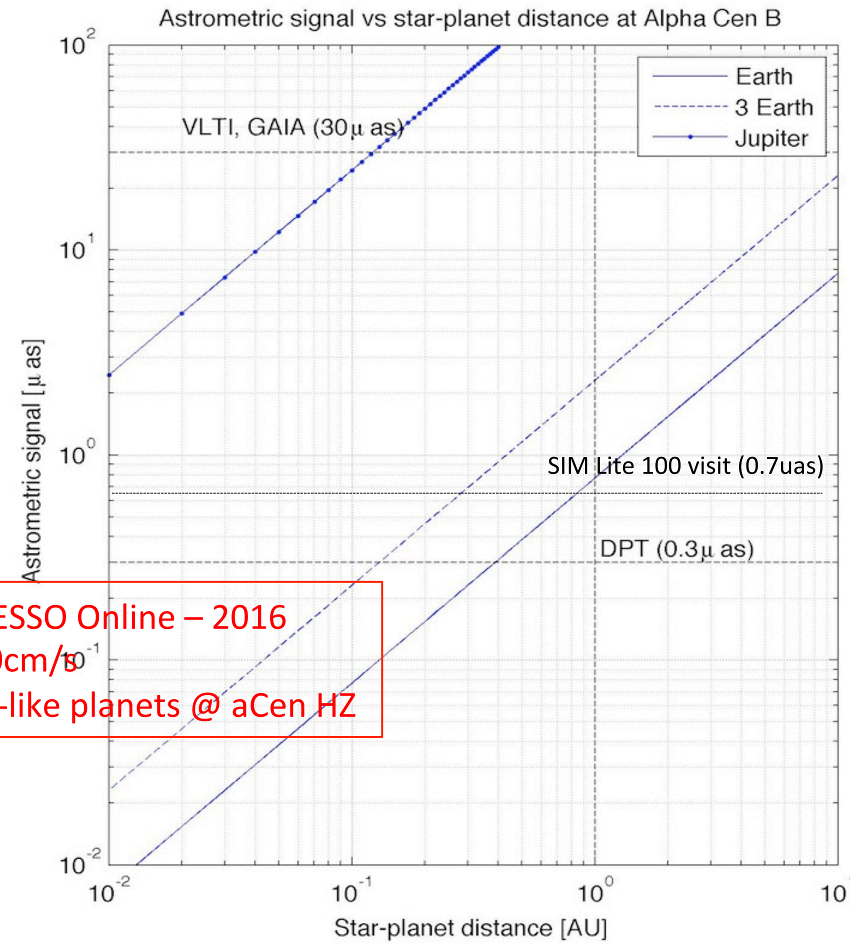
4 Year mission,
2 Month Cadence
Astrometry + Coronography
Guyon et al, ApJ2013.



Astrometry + Radial Velocity

- Expands the exploration envelope, complements RV
- Solves inclination ambiguity



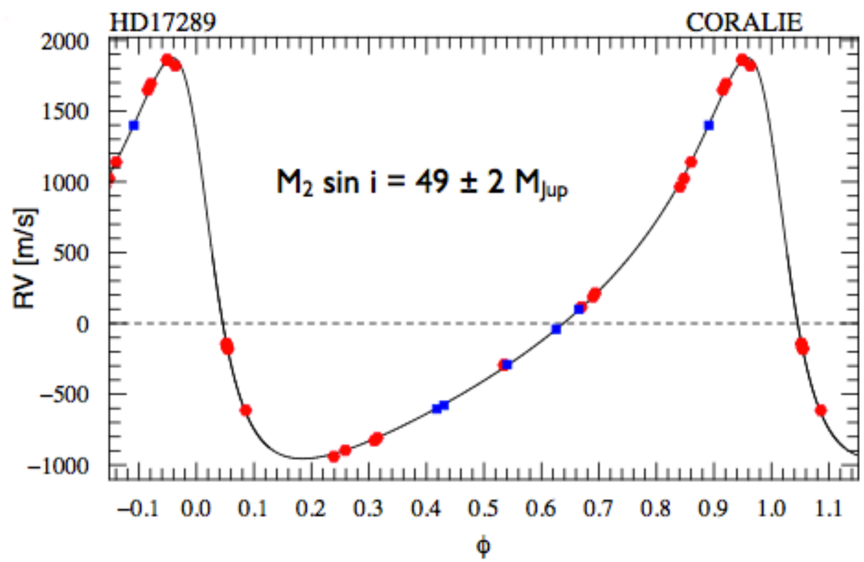


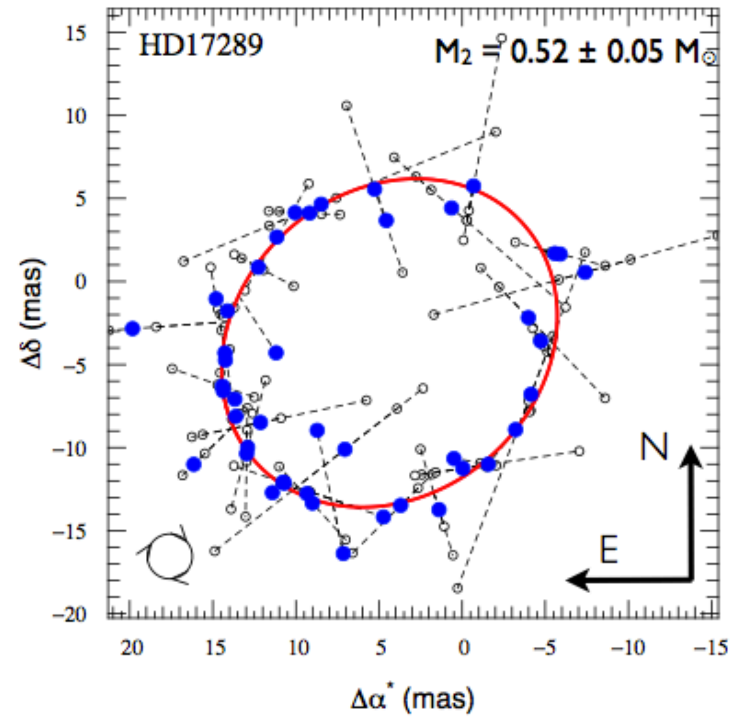
ESPRESSO Online – 2016
RV 10cm/s
Earth-like planets @ aCen HZ

HIPPARCOS ASTROMETRY CONSTRAINS THE TRUE COMPANION MASS OF RADIAL VELOCITY COMPANIONS

From Johannes Sahlmann, ESA

Sahlmann et al., 2011, A&A, 525





Radial velocities:
orbit inclination unconstrained
Brown dwarf ?

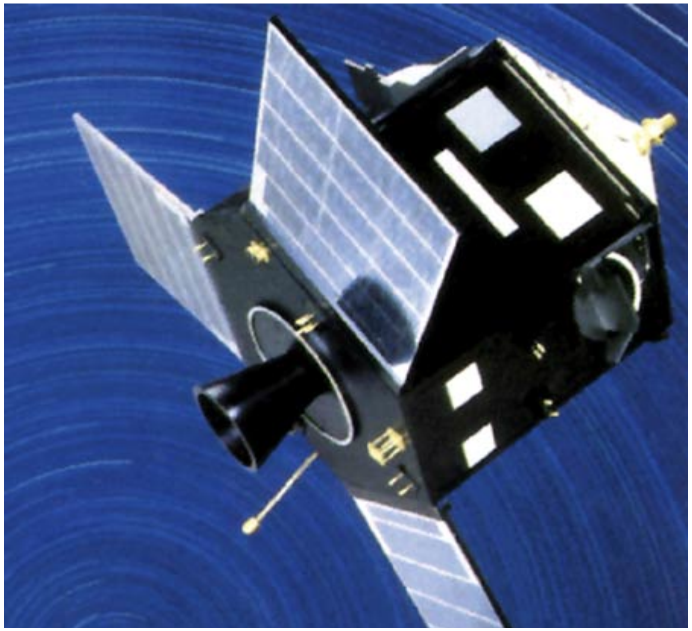
RV + Hipparcos astrometry:
orbit inclination determined
M-dwarf !

Astrometry and exoplanets…

- Great science:
  - Measure planet masses
  - Solve system inclination (AND can see any inclination)
  - Highly efficient when used with Direct Imaging
  - Complementary with RV discovery space
  - Better suited for longer period planets (closer to HZ)
- 1μas < required for earth-like measurements
- 10μas enables super-earths and Neptunes
- Sparse field capability required

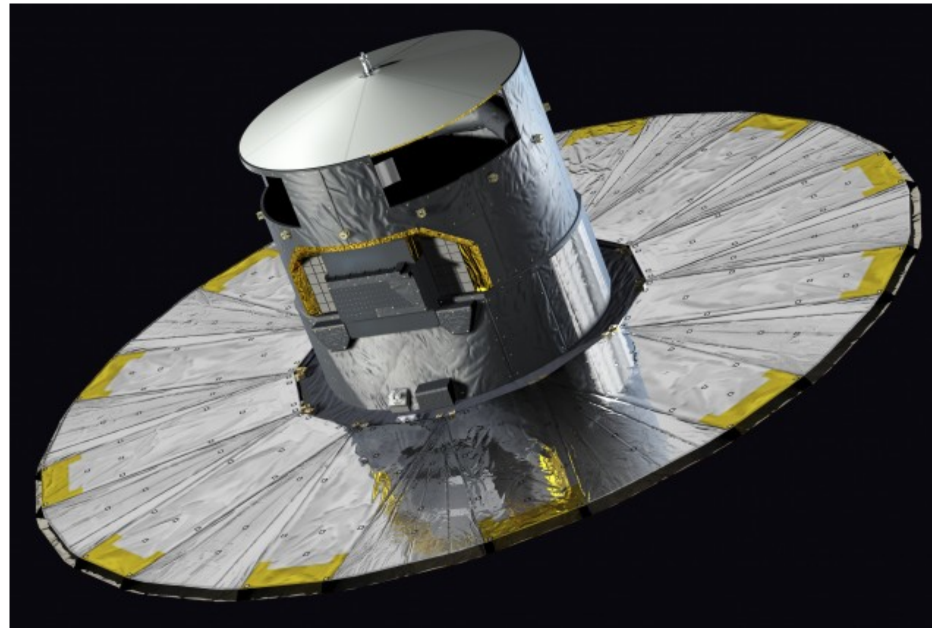
European astrometry missions

Hipparcos – ESA 1989 - 1993



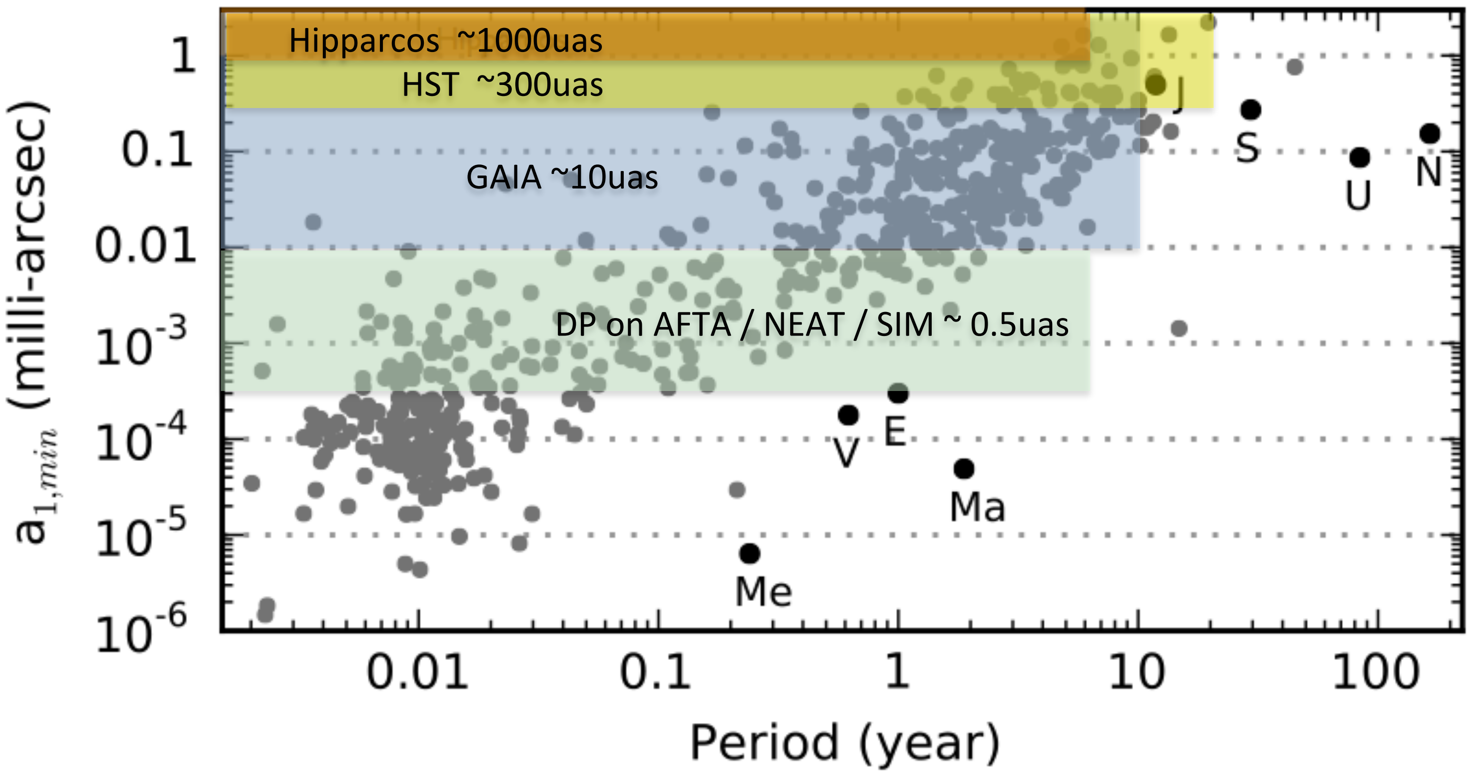
- 0.001 µas for 117,000 stars
- 0.03 as for 2.5 million stars (Tycho2)
- 2.5 million stars
- 300Ly range

GAIA ESA 2013 - 2018



- **8µas per visit for stars 6 < m_v < 12**
- **25µas per visit for stars m_v = 15**
- 70 visits in 5 years.
- 1000 million stars
- 30.000Ly range
- Up to 7 thousand exoplanets to be detected

Astrometry missions



$$a_1 \propto \frac{m_2}{d}\left(\frac{P}{m_1 + m_2}\right)^{2/3}$$

exoplanet.org

Fischer et al. PPVI

10 -100 μas astrometry required to access statistical samples of exoplanets

Earth twin detection requires 0.5-1 μas

HST Astrometry

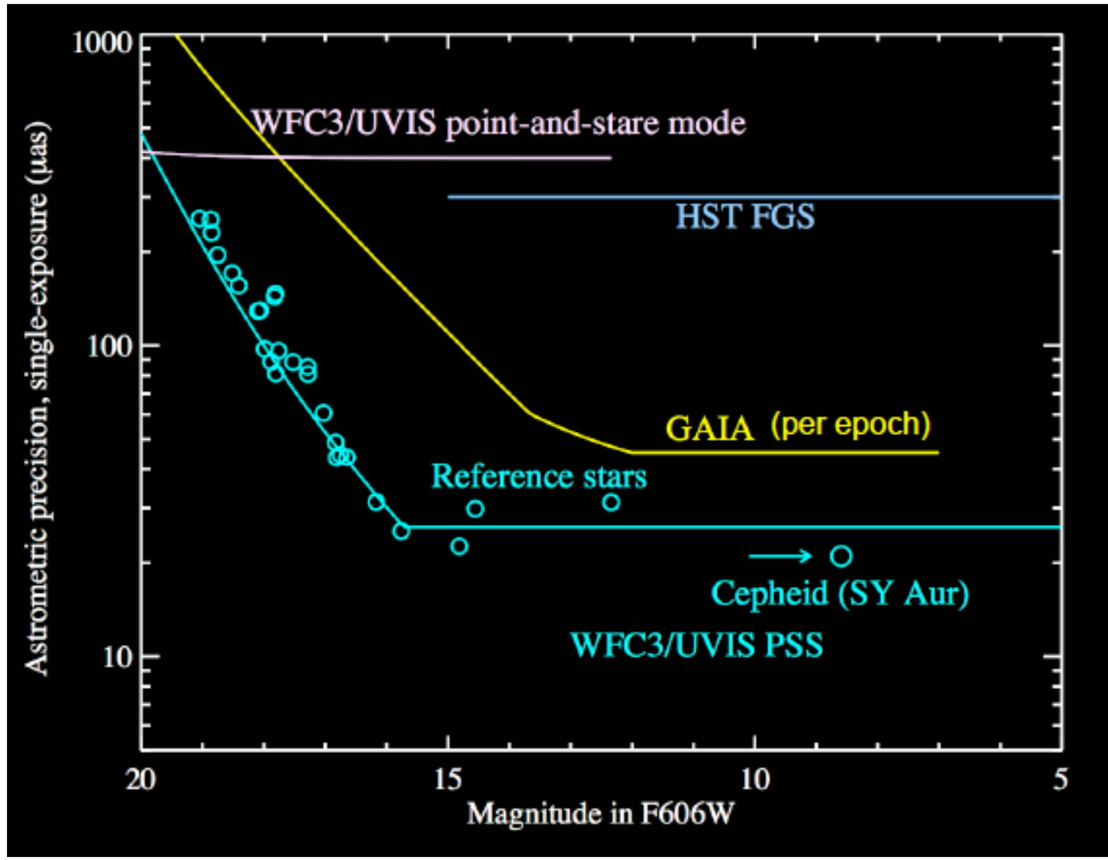
From Adam Reiss

Wide field

- WFC3/UVIS Point and stare mode ~ 400µas
- HST FGS ~ 300µas

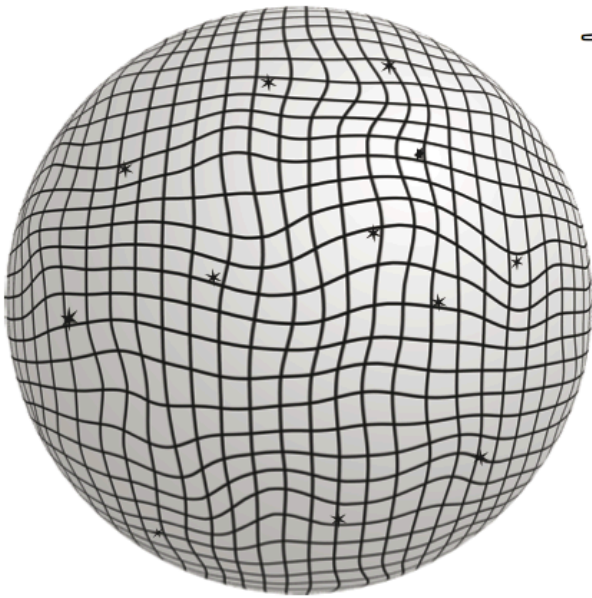
Narrow field

- Precision Astrometry with Spatial Scanning ~25µas



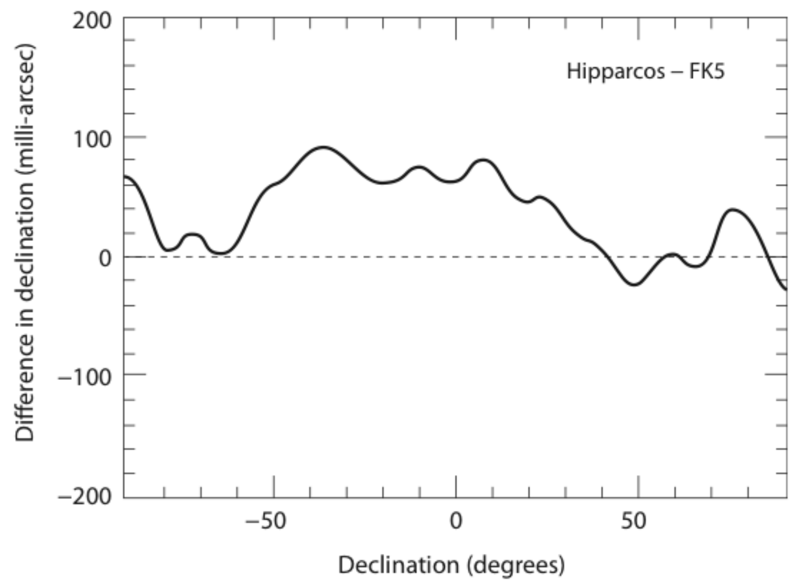
Limiting factor

From Michael Perryman



☞ schematic of a distorted reference frame

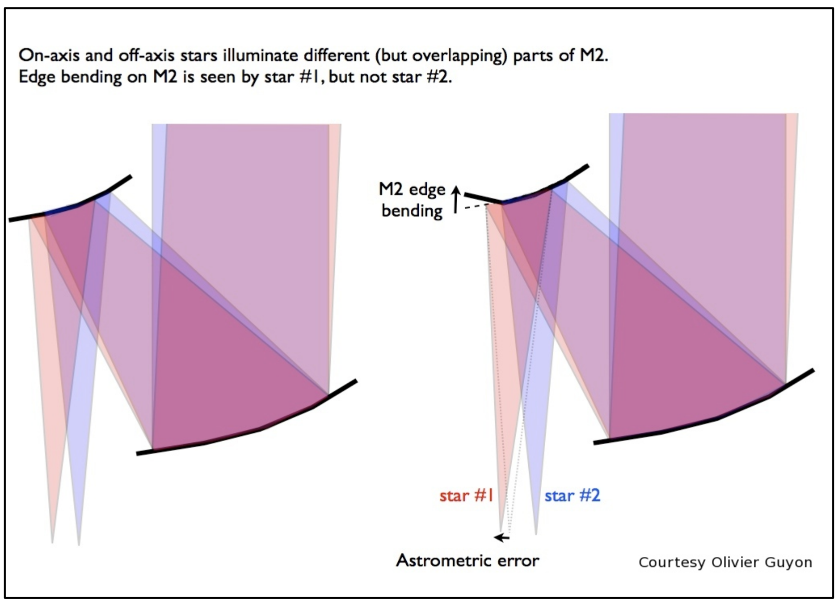
...it has proven impossible to eliminate these local distortions from small field observations (photographic plate or CCD), even using the method of 'block adjustment' (Eichhorn 1988)

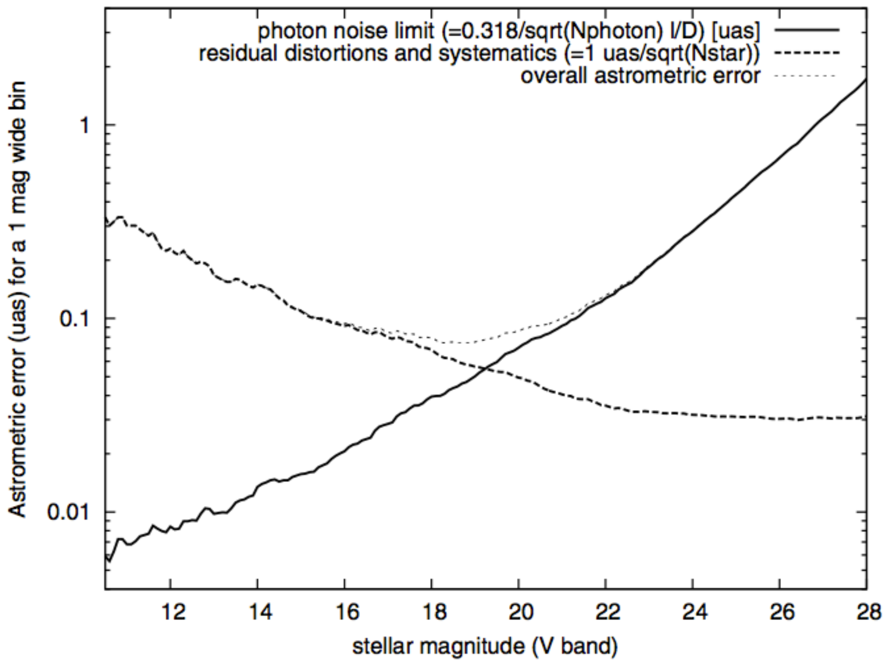


Hipparcos − ground-based (FK5) systematic errors (Schwan 2002)

Distortion and Astrometry

- How distortions affect astrometry
  - Cause local plate scale changes
  - Bias the astrometric measurements
- Diffractive spikes can calibrate the plate scale

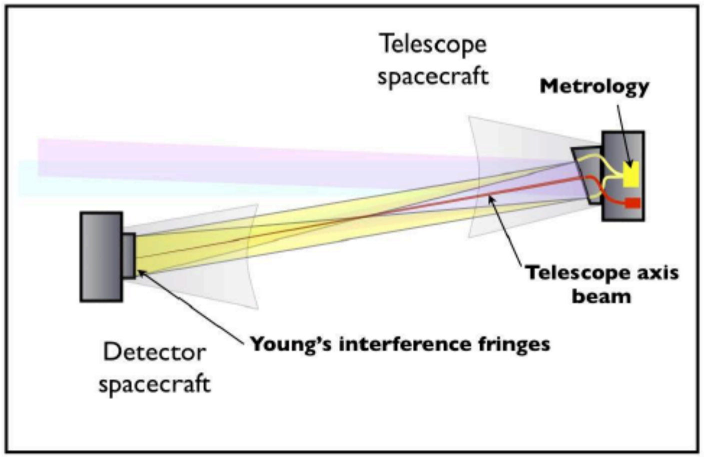


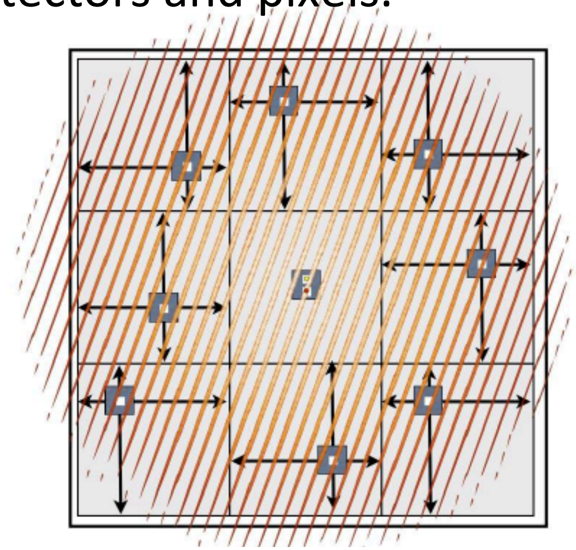


NEAT

From Malbet F., Leger A., Shao M., et al.

- Remove non-pupil optics: 2 spacecrafts, 1m off-axis aperture
- Add interferometric calibration for detectors and pixels.

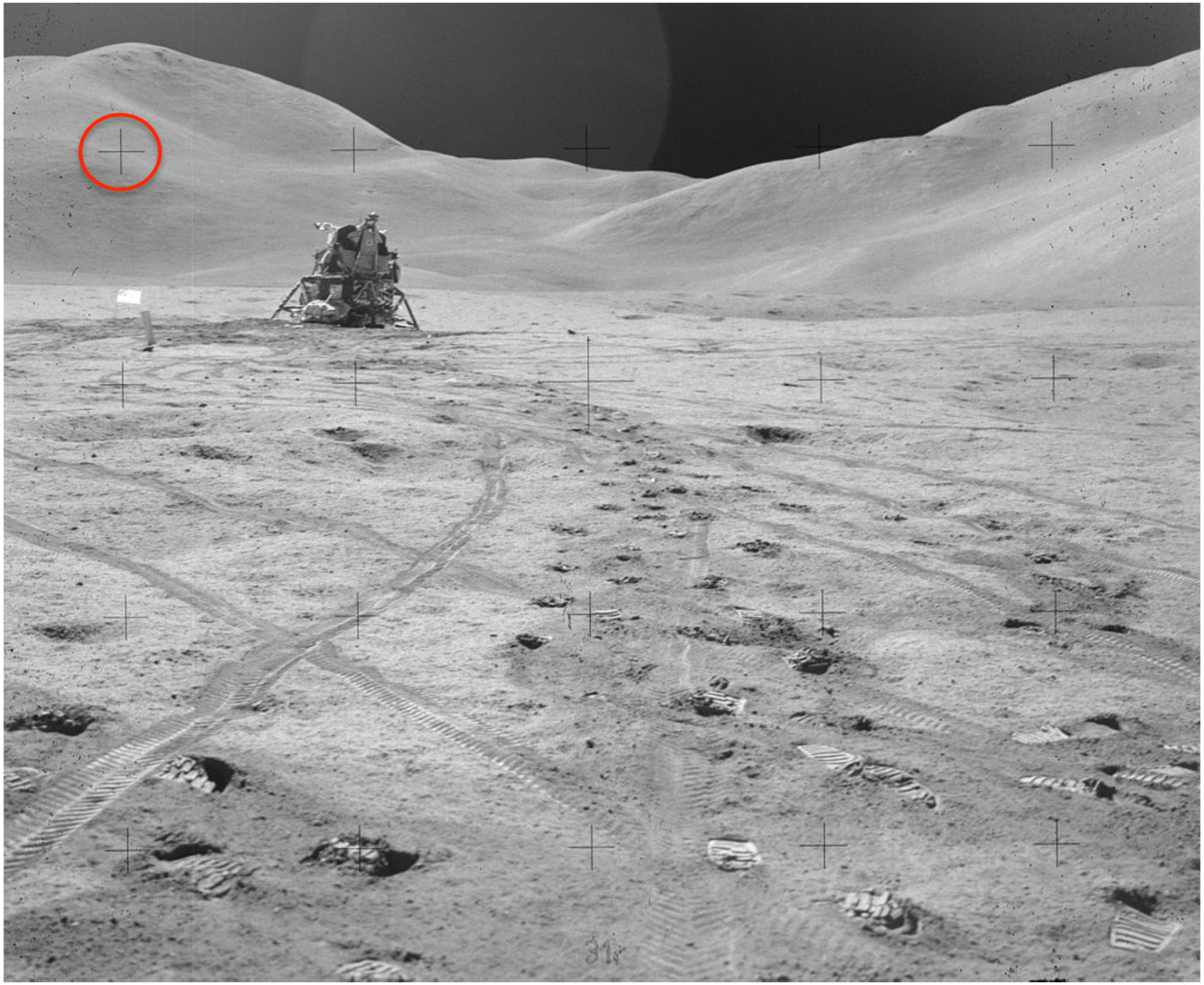




Mission name	Mirror diameter	Focal length	Field of view diameter	Focal Plane size	Ref. star mean magnitude	DMA in 1h	# targets for a given mass limit		
	(m)	(m)	(deg)	(cm)	(R mag)	(μas)	$0.5M_\oplus$	$1\ M_\oplus$	$5\ M_\oplus$
NEAT plus	1.2	50	0.45	40	11.5	0.7	7	100	200
NEAT	1.0	40	0.56	40	11	0.8	5	70	200
NEAT light	0.8	30	0.71	35	10.5	1.0	4	50	200
EXAM	0.6	20	0.85	30	10.1	1.4	2	35	200

DMA = Differential astrometric Measurement Accuracy (rms)

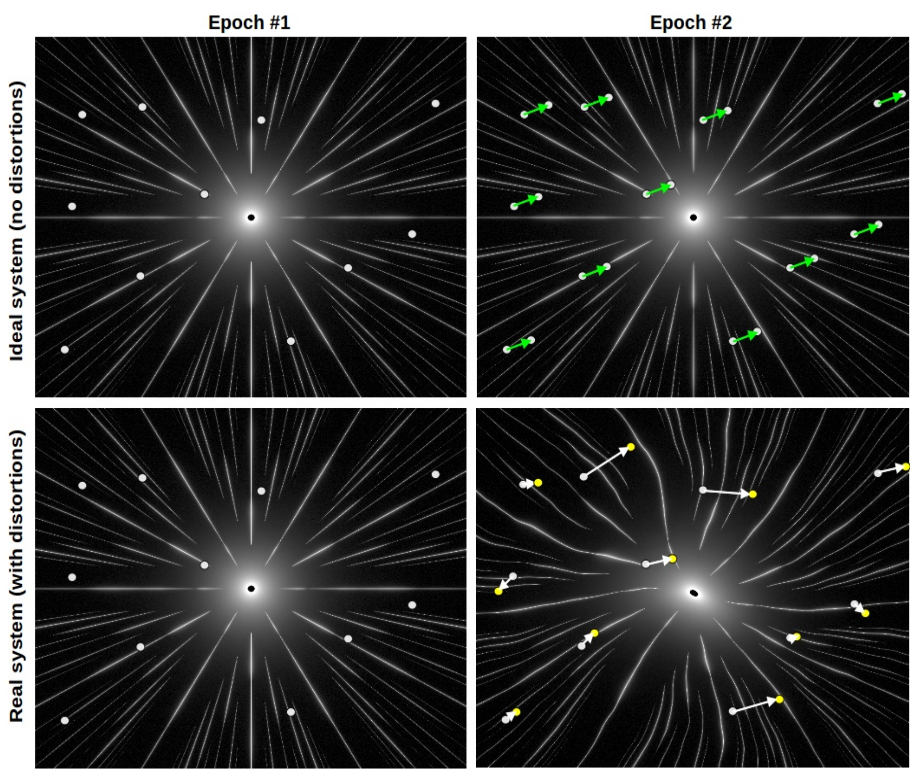
Distortion and Astrometry



Courtesy: NASA

Diffractive Pupil Concept

- Concept and anticipated performance
  - Astrometry accuracy: ~ 0.3μas (quadratic with FoV and Aperture)
    Guyon et al., ApJ 200:11, 2012

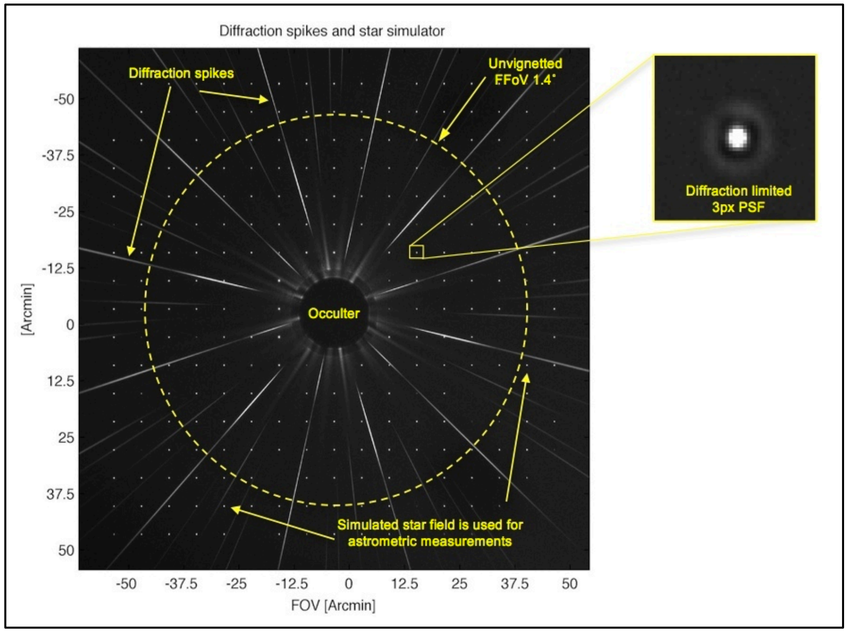


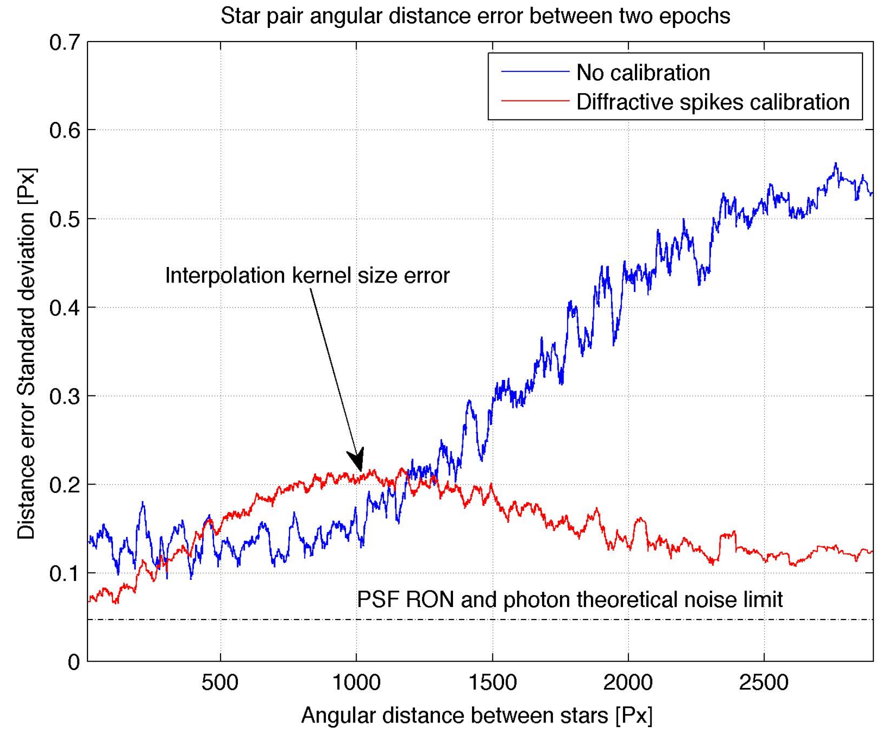
Expected Single Measurement Astrometric Accuracy as a Function of Telescope Diameter and Field of View (Galactic Pole Pointing, 2 Day Integration)

Tel. Diam.	Field of View: 0.03 deg^2 ($\o = 0.2$ deg)	0.1 deg^2 ($\o = 0.36$ deg)	0.3 deg^2 ($\o = 0.6$ deg)	1 deg^2 ($\o = 1.13$ deg)
1.0 m	0.99 μas	0.54 μas	0.31 μas	0.17 μas
1.4 m	0.62 μas	0.34 μas	0.20 μas	0.11 μas
2.0 m	0.38 μas	0.21 μas	0.12 μas	0.066 μas
2.8 m	0.24 μas	0.13 μas	0.076 μas	0.041 μas
4.0 m	0.15 μas	0.081 μas	0.047 μas	0.026 μas
5.7 m	0.092 μas	0.050 μas	0.029 μas	0.016 μas
8.0 m	0.059 μas	0.032 μas	0.019 μas	0.010 μas

- For a D=2.4m and FoV=0.03 deg^2
  0.32μas (Vis)
- Assuming:
  - 2 Day integration
  - Galactic pole pointing
  - Telescope roll
  - Diffraction limited PSF

First Laboratory Test





Relevant work or proposal	Astrometric accuracy		Start TRL	End TRL
	λ/D	Equivalent accuracy for D=2.4m and λ =500nm		
First lab demonstration	3.42×10^{-3}	147μas*	1	3
This TDEM Milestone	2.35×10^{-4}	10μas*	3	4
Mission goal	2.35×10^{-5}	1μas	>7	9

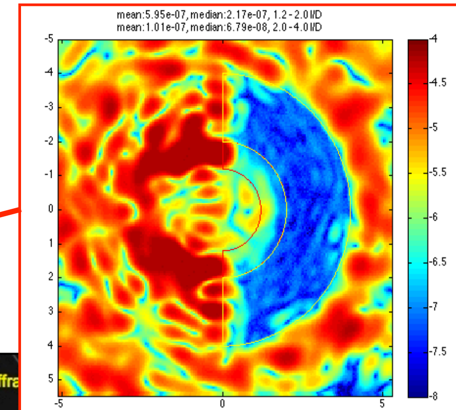
*The lab test for these cases uses D=0.016m.

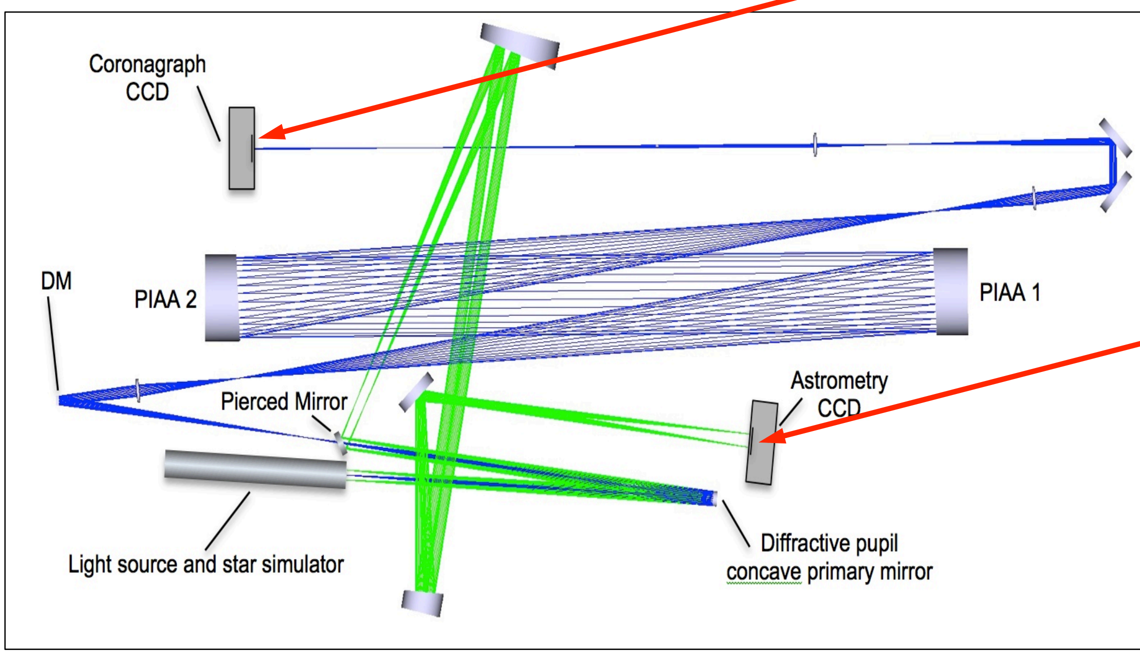
Bendek et al., Accepted PASP Oct 1st, 2013

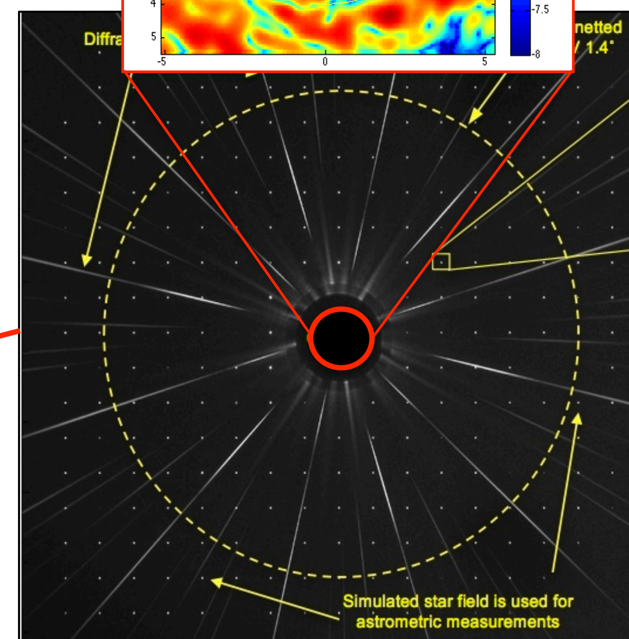
Combined lab at NASA Ames

First laboratory to demonstrate simultaneous astrometry and high-contrast imaging. (2×10^{-8} contrast @ 2.0 to 3.5 λ/D)

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



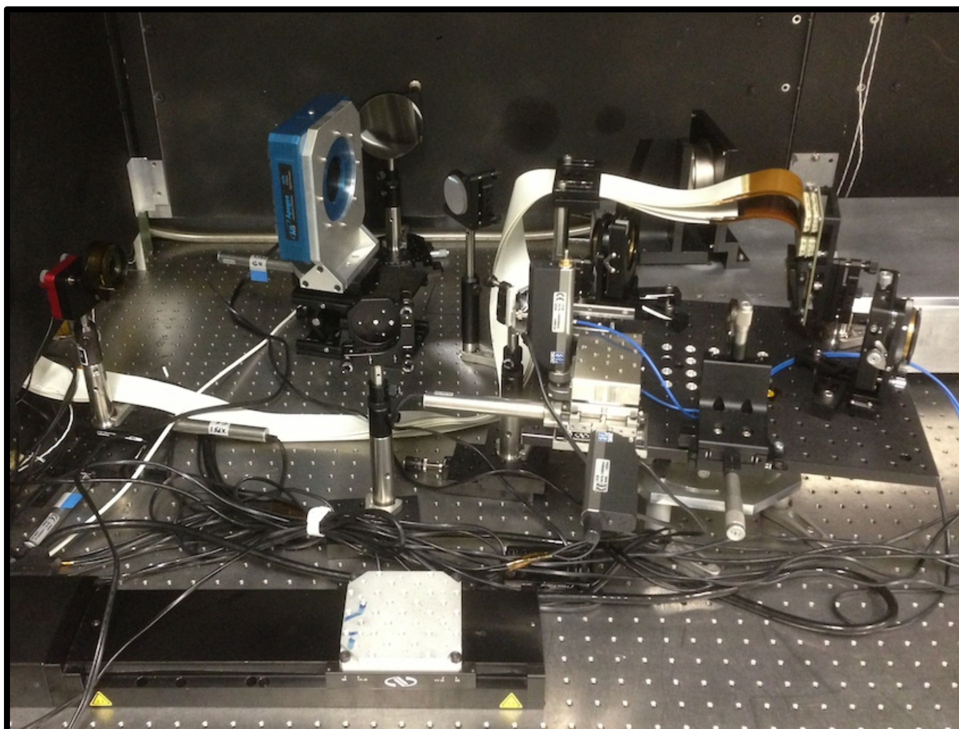


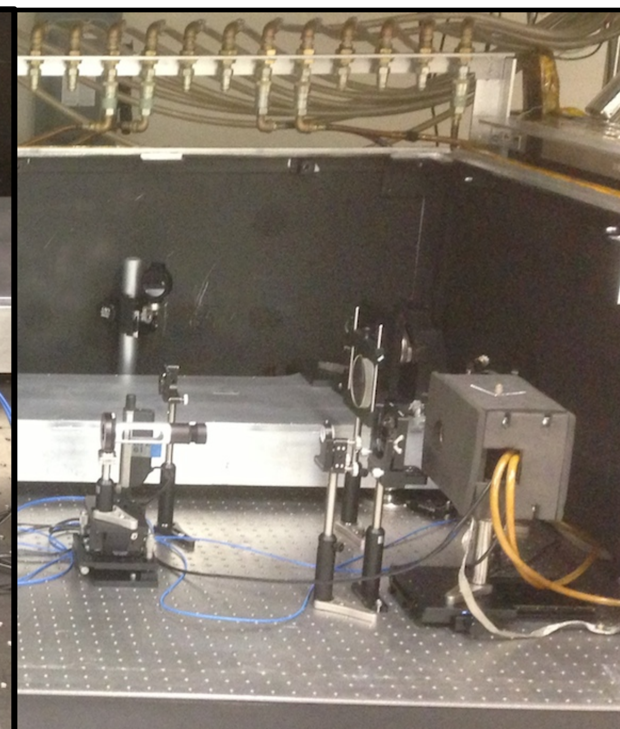


Combined lab at NASA Ames

First laboratory to demonstrate simultaneous astrometry and high-contrast imaging. (TDEM 2013 Submitted)

- Demonstrate real mission configuration
- Increase astrometry fidelity
- Coronagraph independent (SP, HLC, Vortex, PIAA etc)

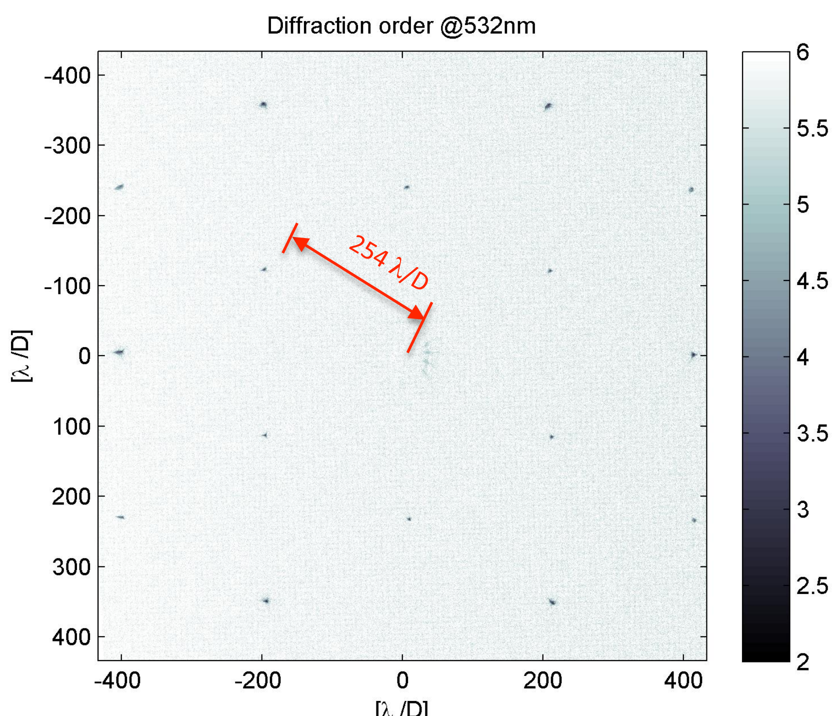


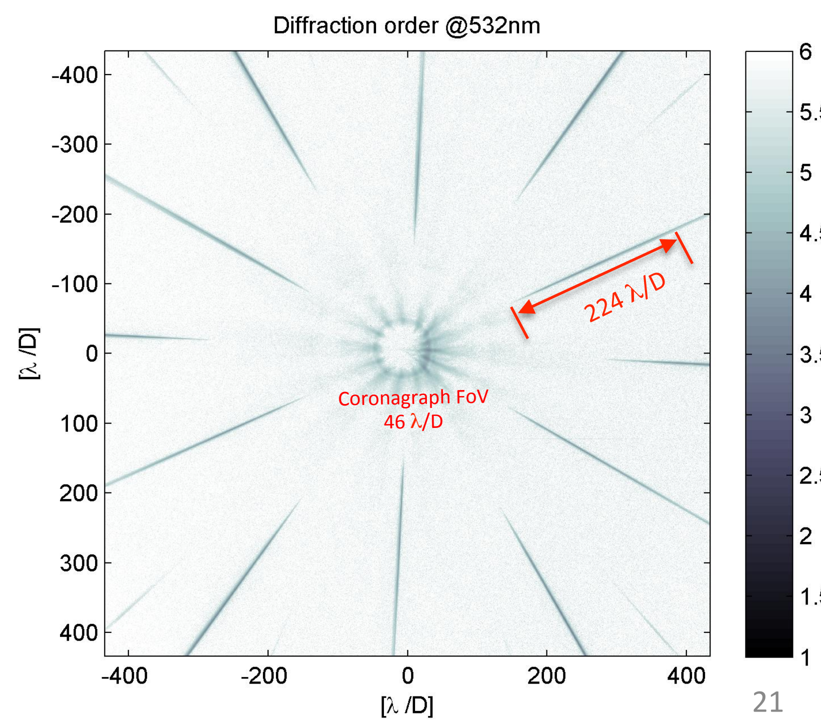


Combined lab at NASA Ames

- Preliminary results shows agreement with model

	Coronagraph field [arcsec]	Hexagon size *a* [µm]	Dot Size [µm]	1st order location @ 632 nm	Spike width (350-900nm)
Angular location	46 λ/D	42µm	7µm	254 λ/D	142 - 366 λ/D
Focal plane	1 mm			5.1mm	3.1 - 7.94mm

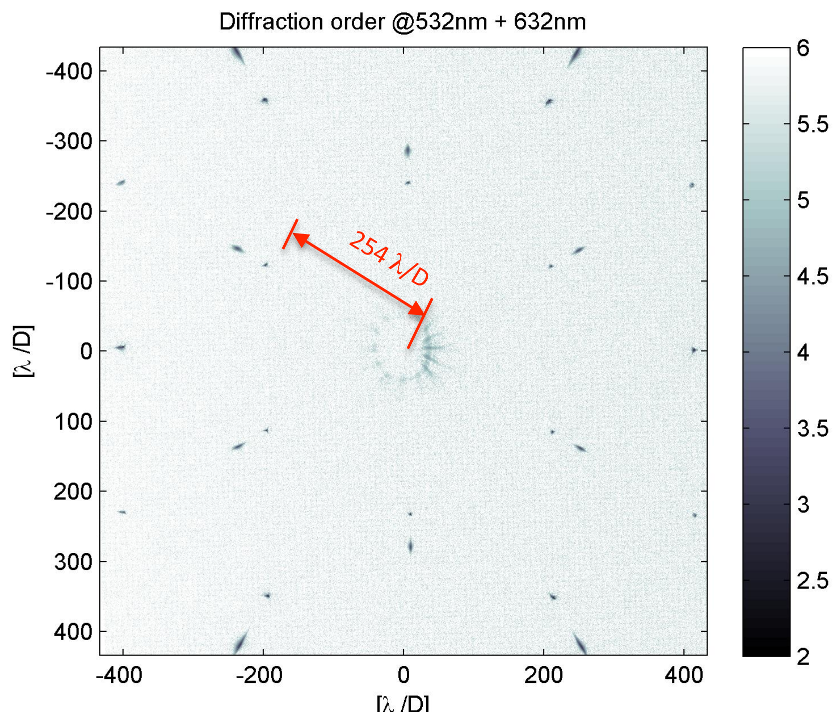


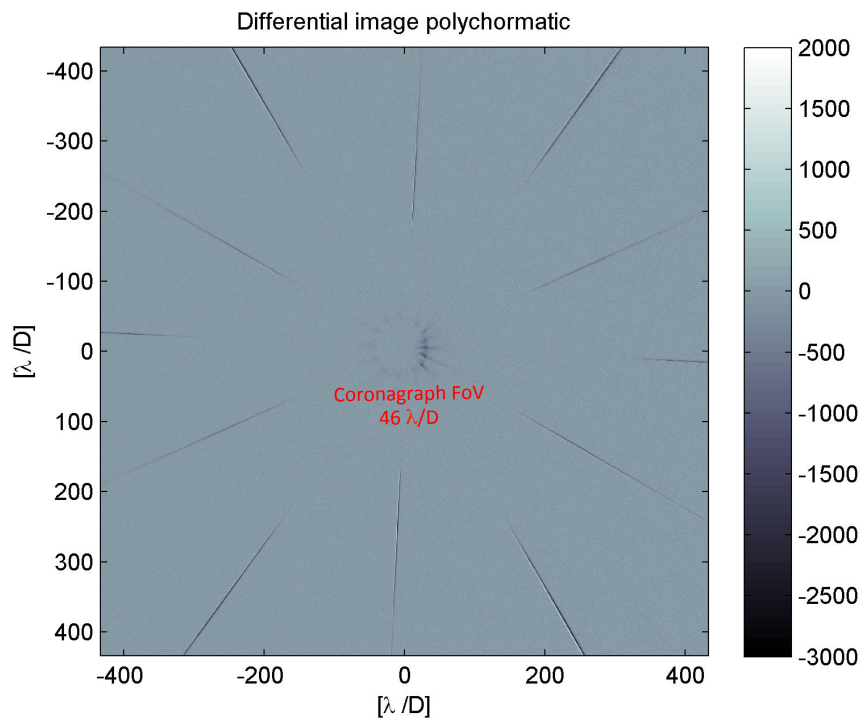


Combined lab at NASA Ames

- Preliminary results shows agreement with model

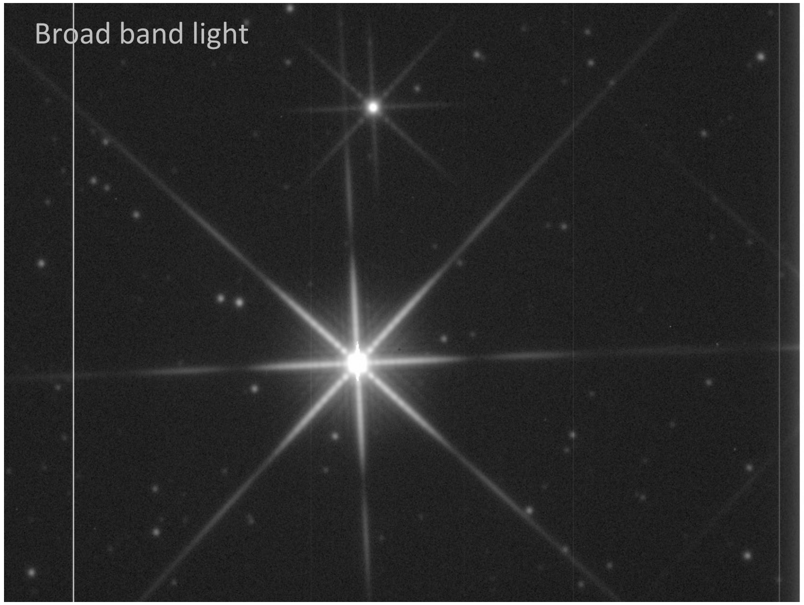
	Coronagraph field [arcsec]	Hexagon size *a* [µm]	Dot Size [µm]	1st order location @ 632 nm	Spike width (350-900nm)
Angular location	46 λ/D	42µm	7µm	254 λ/D	142 - 366 λ/D
Focal plane	1 mm			5.1mm	3.1 - 7.94mm

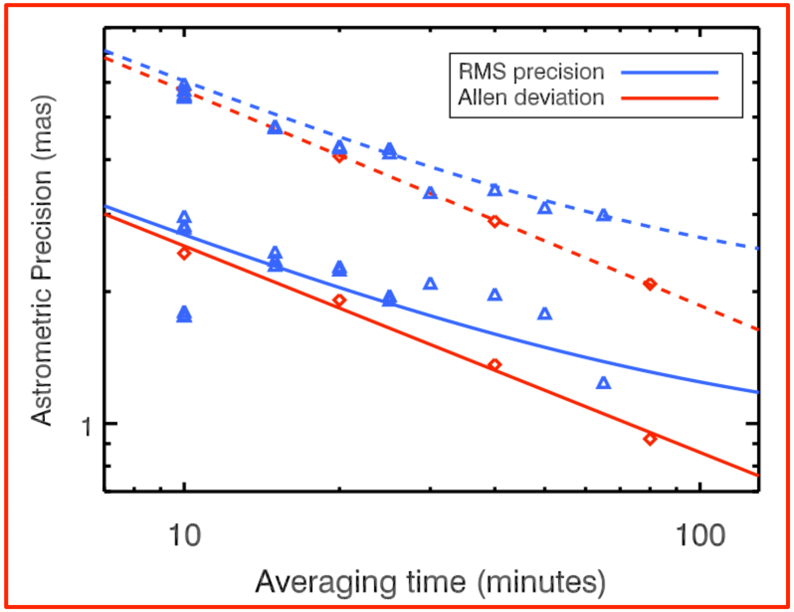




On sky results

- Carbon fiber pupil mask to test concept on sky.
- 1mas accuracy in a 1m telescope (No AO)
- Use of closest diffraction spike (reducing astrometric baseline) lowers systematic component by 2x

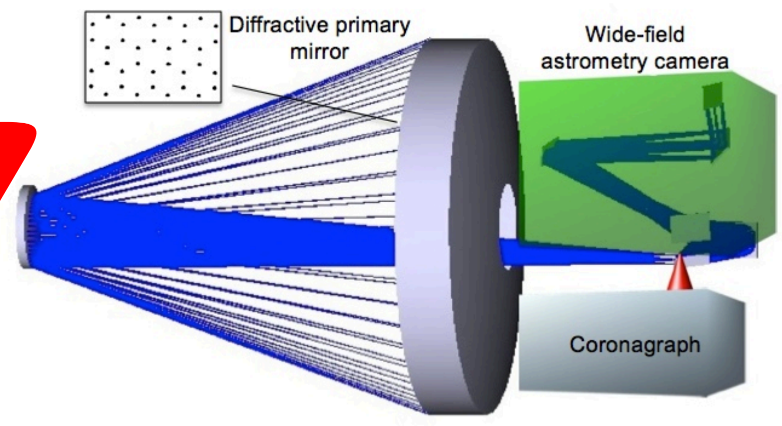




WFIRST

- **0.1µas imaging Astrometry**
- Simultaneous direct imaging
- Wide field telescope 0.3d
- Large aperture 2.4m
- No additional instrument is required, only a coating modification.

EXACT Concept



Astrometry accuracy: ~ 0.1µas
Guyon et al., 2012

For a D=2.4m and FoV=0.3 deg^2
0.098µas (Vis)
0.064µas (H)

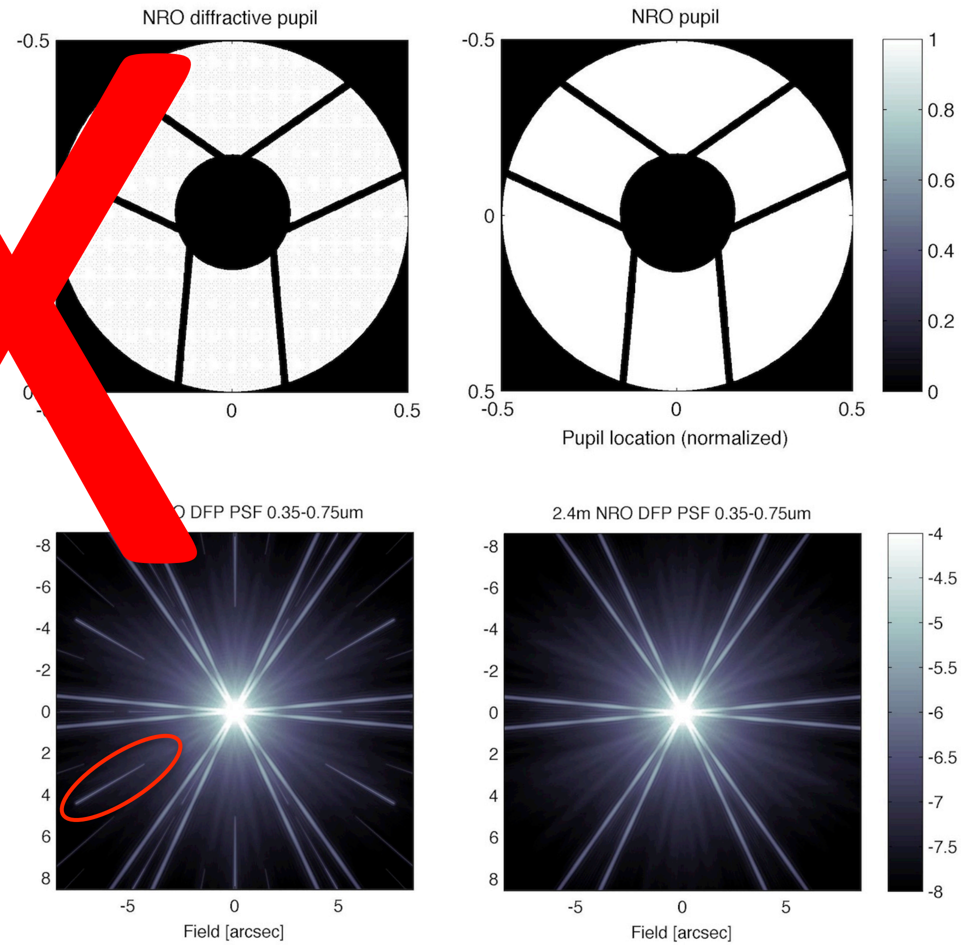
Assuming:
2 Day integration
Galactic pole pointing
Telescope roll
Diffraction limited PSF

AFTA Telescope: Courtesy NASA

Outer Barrel Assembly | Optical Telescope Assembly | Support Structure

WFIRST

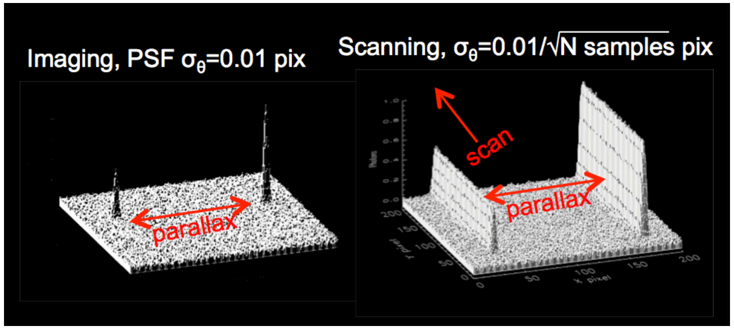
- The diffractive pupil is compatible with a general astrophysics mission.
- A 1% Diffractive pupil covers ~ 1/5th of the area of the spiders.
- Distortion calibration still be used **without** a bright star!

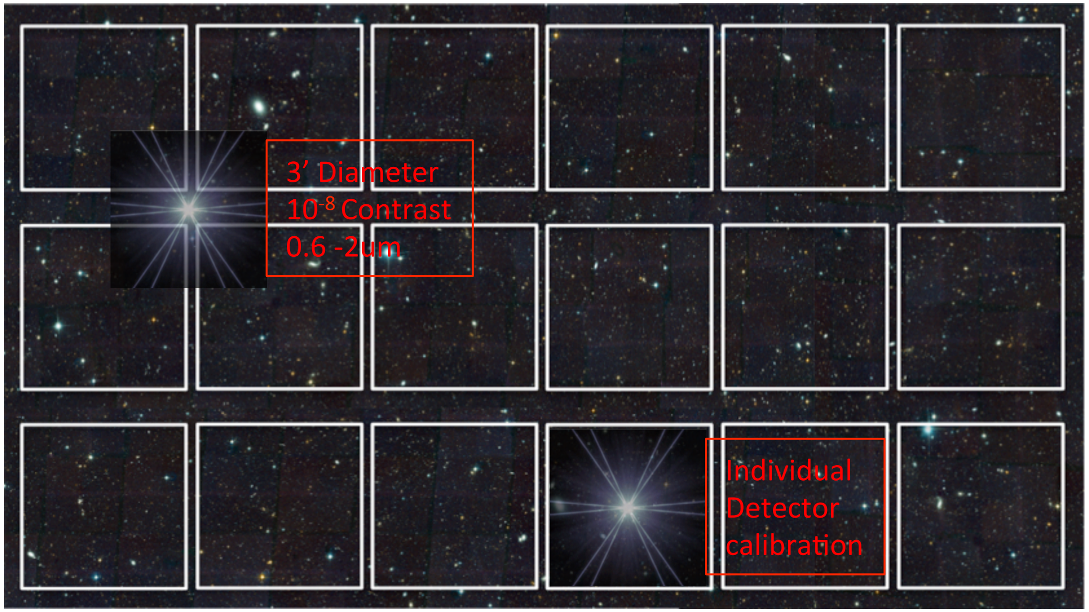


FoV %	$Flux_{spike}/Flux_{Zodi}$ ratio vs star magnitudes		
	mV=6	mV=3.7	mV=-1.46
99%	< 5 x10^{-2}	< 4x10^{-1}	< 4.5x10^{1}
95%	< 1.1x10^{-3}	< 8.8x10^{-3}	< 1
90%	< 3.6x10^{-4}	< 3.0x10^{-3}	< 3.4x10^{-1}

WFIRST

- Combination of PASS and GAIA can deliver <10μas astrometry. *(From D. Spergel - A. Reiss).*





<u>Still need to fit detector orientation positions and orientations:</u>

-6 Parameters x 18 Detectors.

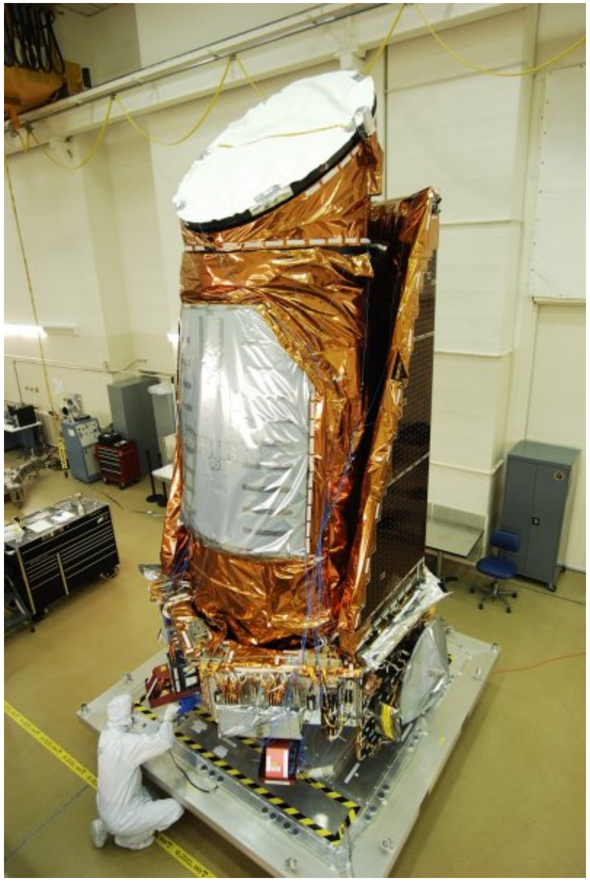
-Diffraction from spiders can help.

-Spiders+Secondary telemetry needed.

-WFIRST Preparatory Science (WPS)

Explorer Class (EXO-S, EXO-C?)

- 1-m Class wide-field explorer mission would allow exo-earth astrometric measurements.



- SSS Independent, works with

-Internal coronagraphs (i.e. EXO-C)

-and Star shade (i.e. EXO-S)

- Kepler-sized D=1m and FoV=1 deg^2

  0.17μas (Vis)

Expected Single Measurement Astrometric Accuracy as a Function of Telescope Diameter and Field of View (Galactic Pole Pointing, 2 Day Integration)

Tel.	Field of View			
Diam.	0.03 deg^2 ($\o = 0.2$ deg)	0.1 deg^2 ($\o = 0.36$ deg)	0.3 deg^2 ($\o = 0.6$ deg)	1 deg^2 ($\o = 1.13$ deg)
1.0 m	0.99 μas	0.54 μas	0.31 μas	0.17 μas
1.4 m	0.62 μas	0.34 μas	0.20 μas	0.11 μas
2.0 m	0.38 μas	0.21 μas	0.12 μas	0.066 μas
2.8 m	0.24 μas	0.13 μas	0.076 μas	0.041 μas
4.0 m	0.15 μas	0.081 μas	0.047 μas	0.026 μas
5.7 m	0.092 μas	0.050 μas	0.029 μas	0.016 μas
8.0 m	0.059 μas	0.032 μas	0.019 μas	0.010 μas

Proposed Astrometry SAG

- Goals:
  - SCIENCE: Identify astrometry niches.
  - COMMUNITY: Gather, individual or institutions that are currently engaged in astrometry research in the U.S.
  - TECHNOLOGY: Identify the most promising astrometry technology.
  - MISSION OPORTUNITIES: Assess cost-benefit of adding astrometry to planned missions.
  - ROAD MAP: Propose long-term roadmap for astrometry to maximize science return.