Optical Tricks to Image Habitable Planets Around Nearby Stars

Are we alone ?

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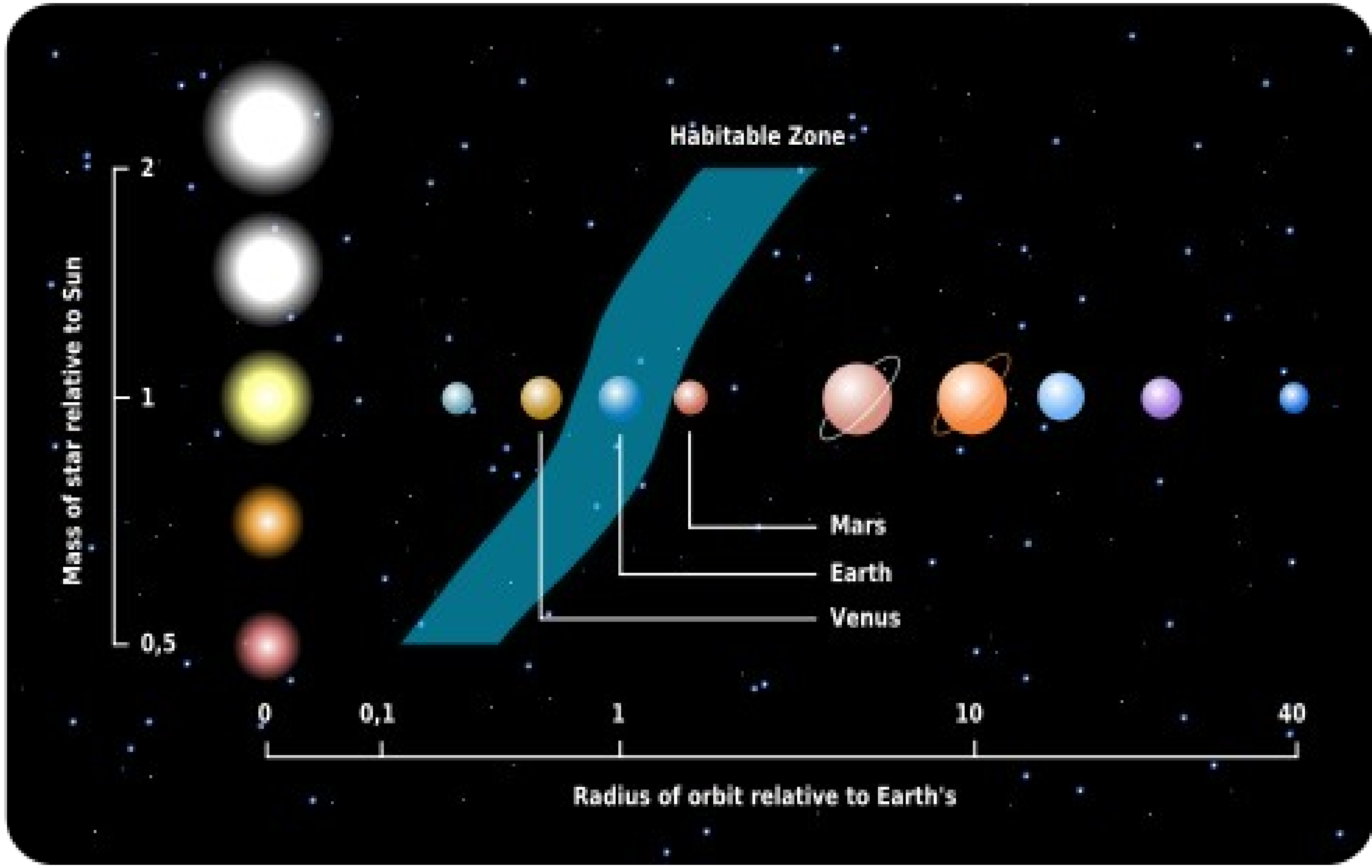
University of Arizona & Subaru Telescope

Frontiers in Optics, Rochester, 2012

Exploplanets

839 exoplanets confirmed belonging to 662 exoplanetary systems

Almost all planets are indirectly detected... we do not know much about them

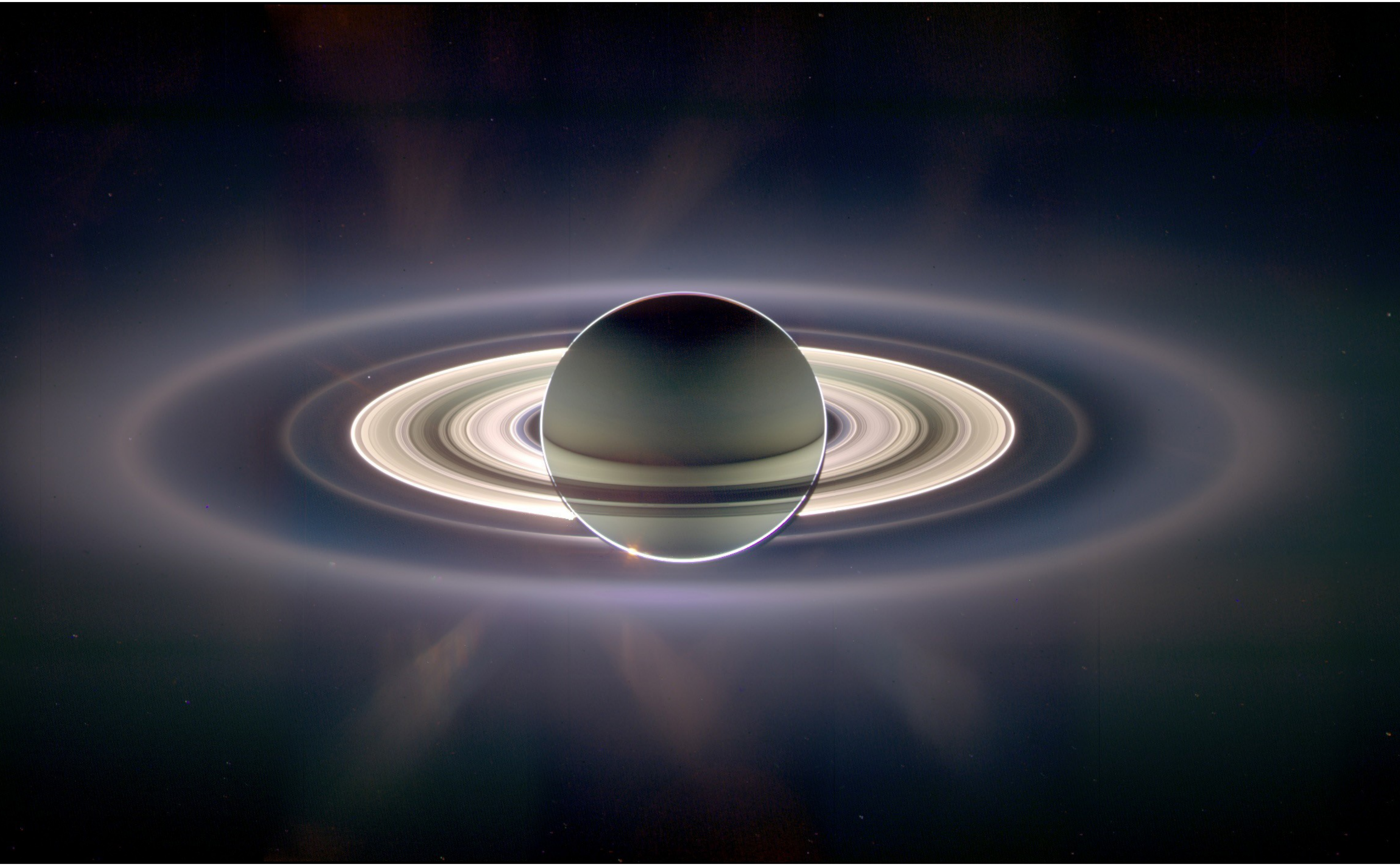


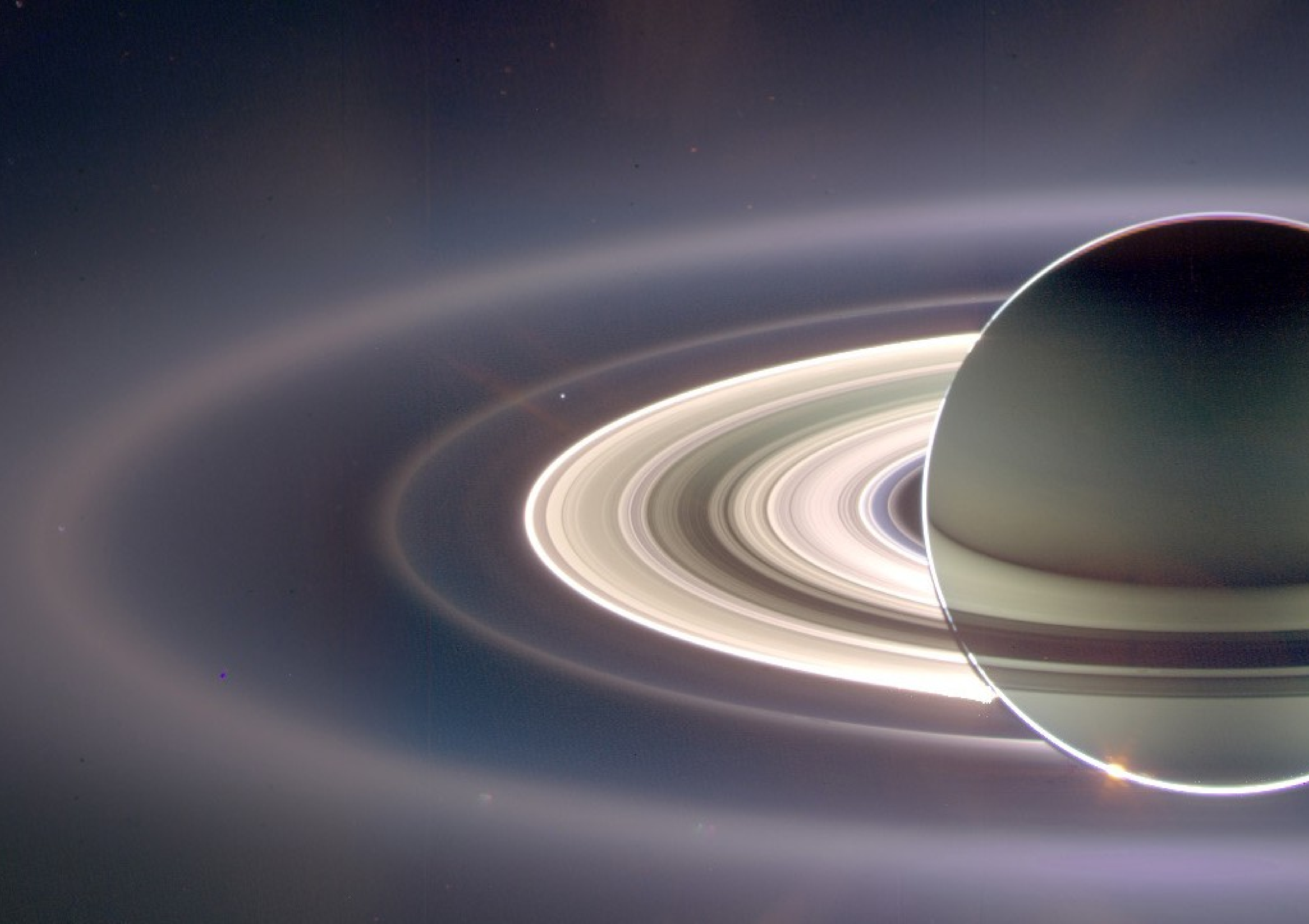
Most planets are ~Jupiter mass. Potentially habitable planets are very difficult to detect with current techniques

→ we need tools to detect and characterize low-mass planets that are **potentially habitable**

This is challenging: planet flux/mass/size is a tiny fraction of star flux/mass/size

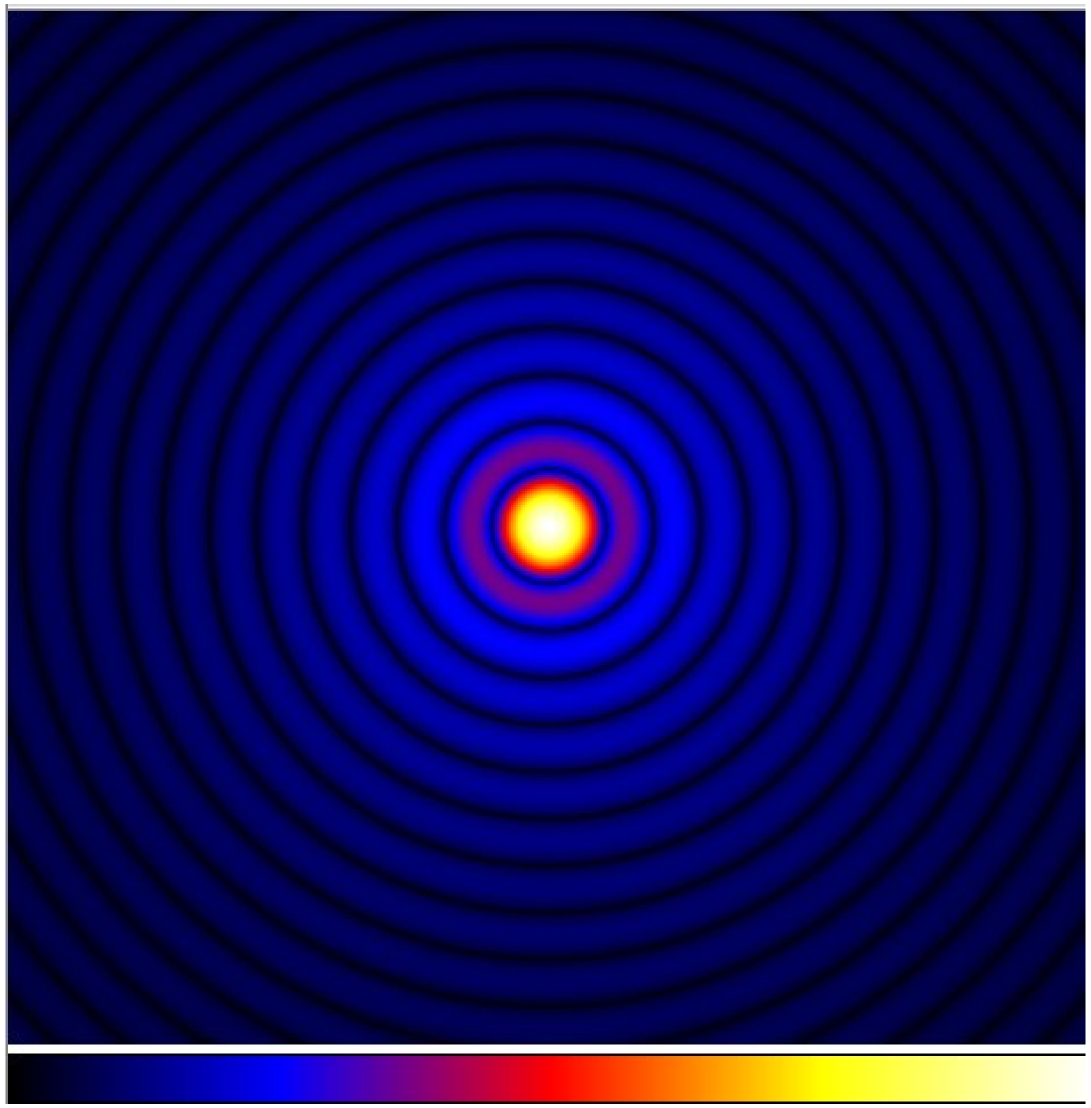
Conventional telescopes won't work !

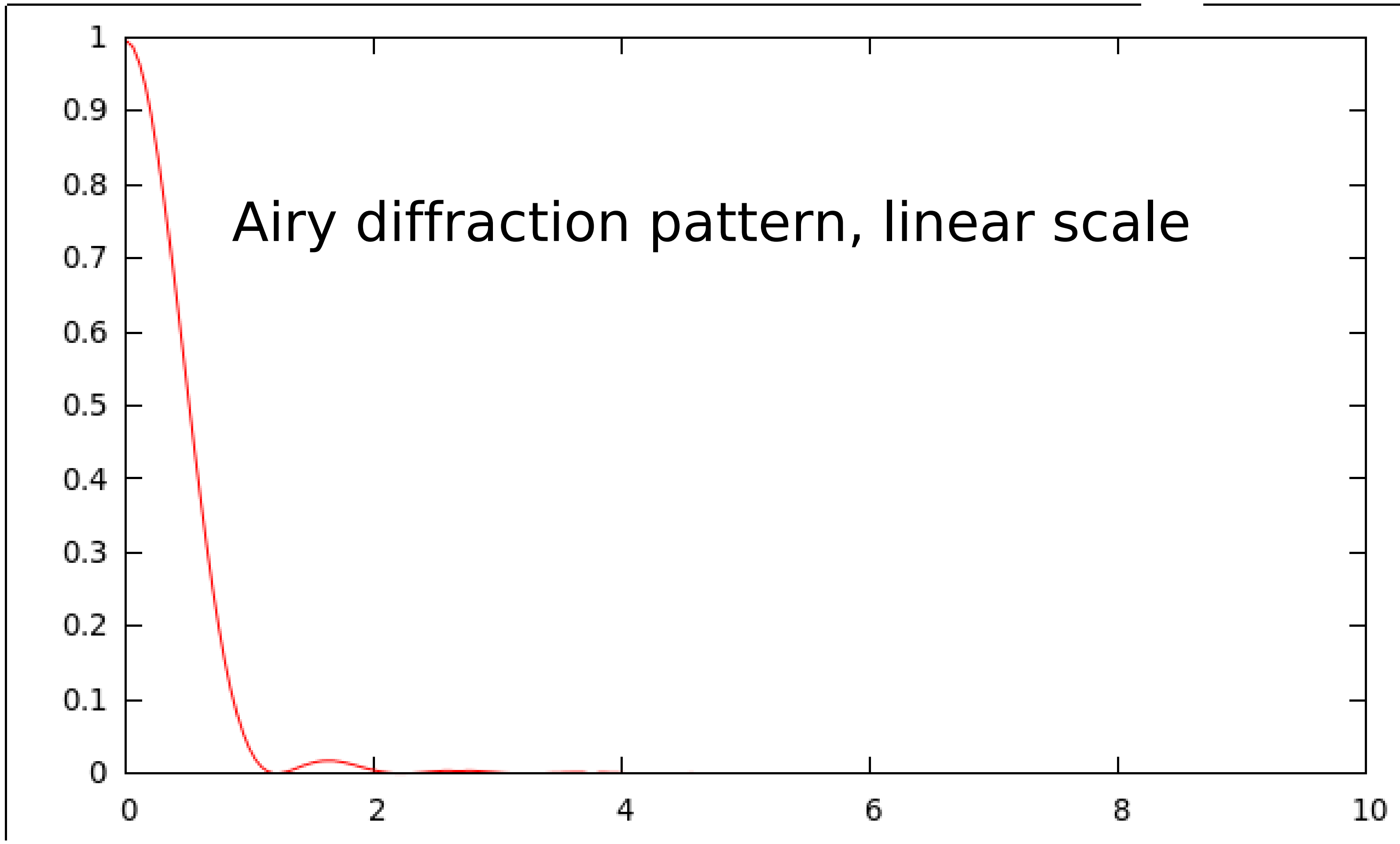


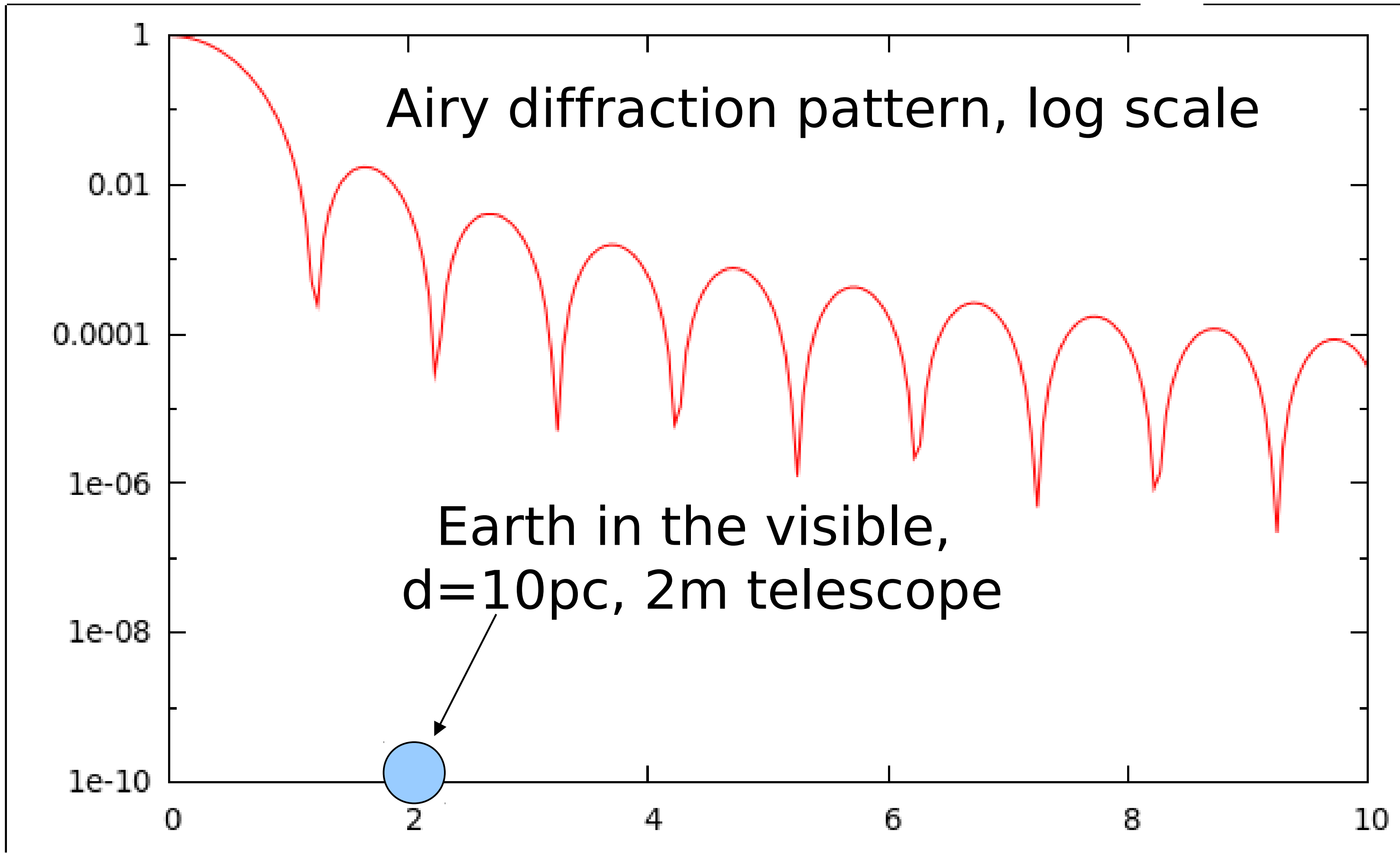


Why coronagraphy ?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction





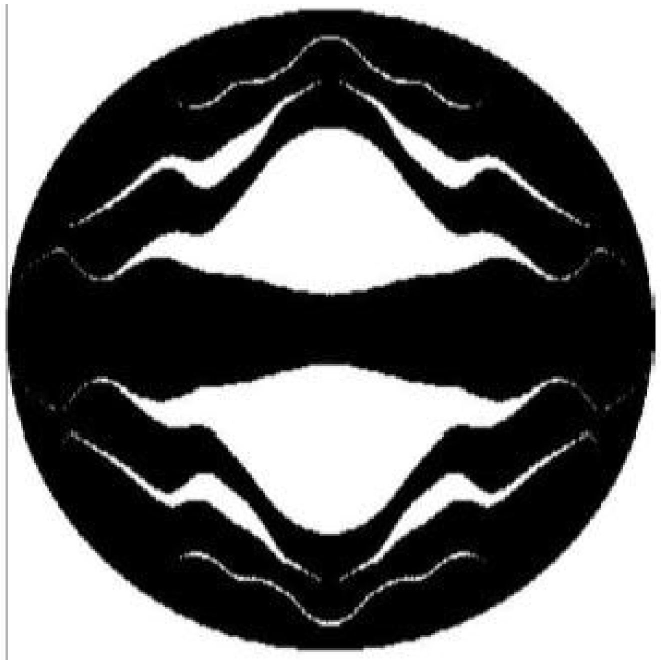


Conventional Pupil Apodization (CPA)

Many pupil apodizations
have been proposed.

Apodization can be
continuous or binary.

\+ Simple, robust, achromatic
\- low efficiency for high contrast



Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

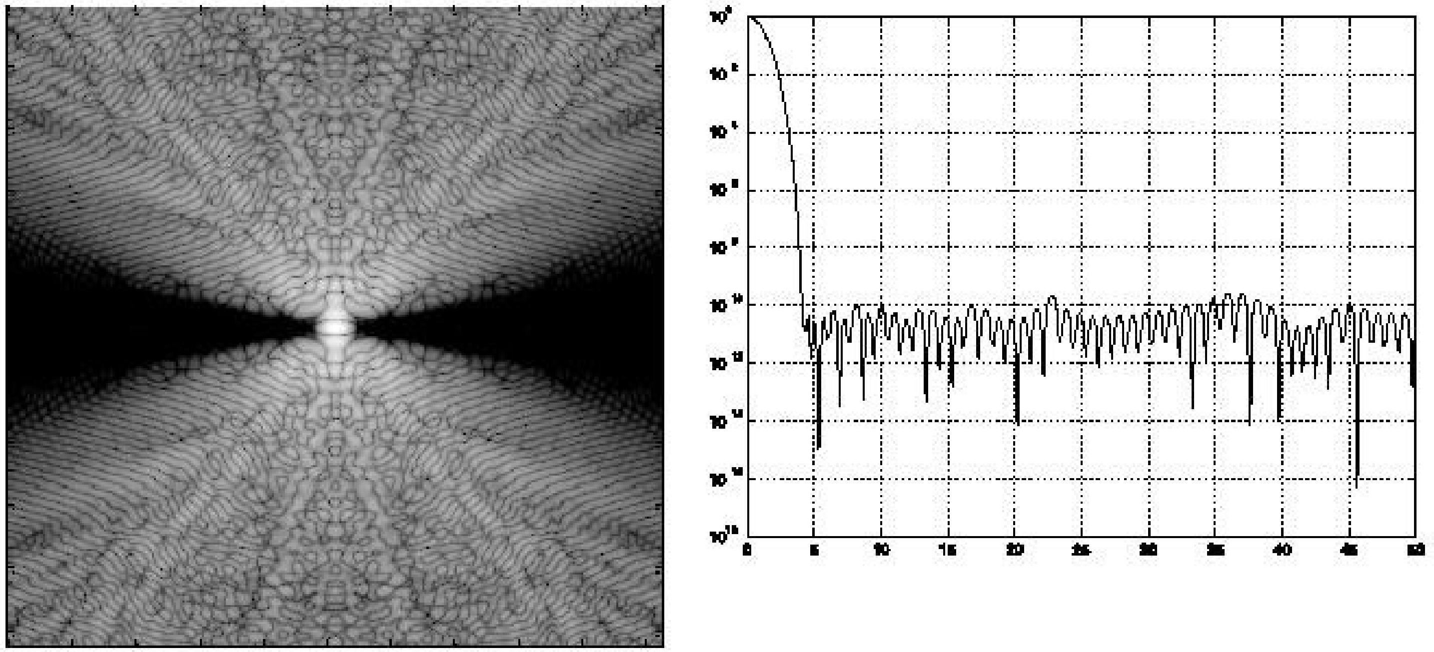
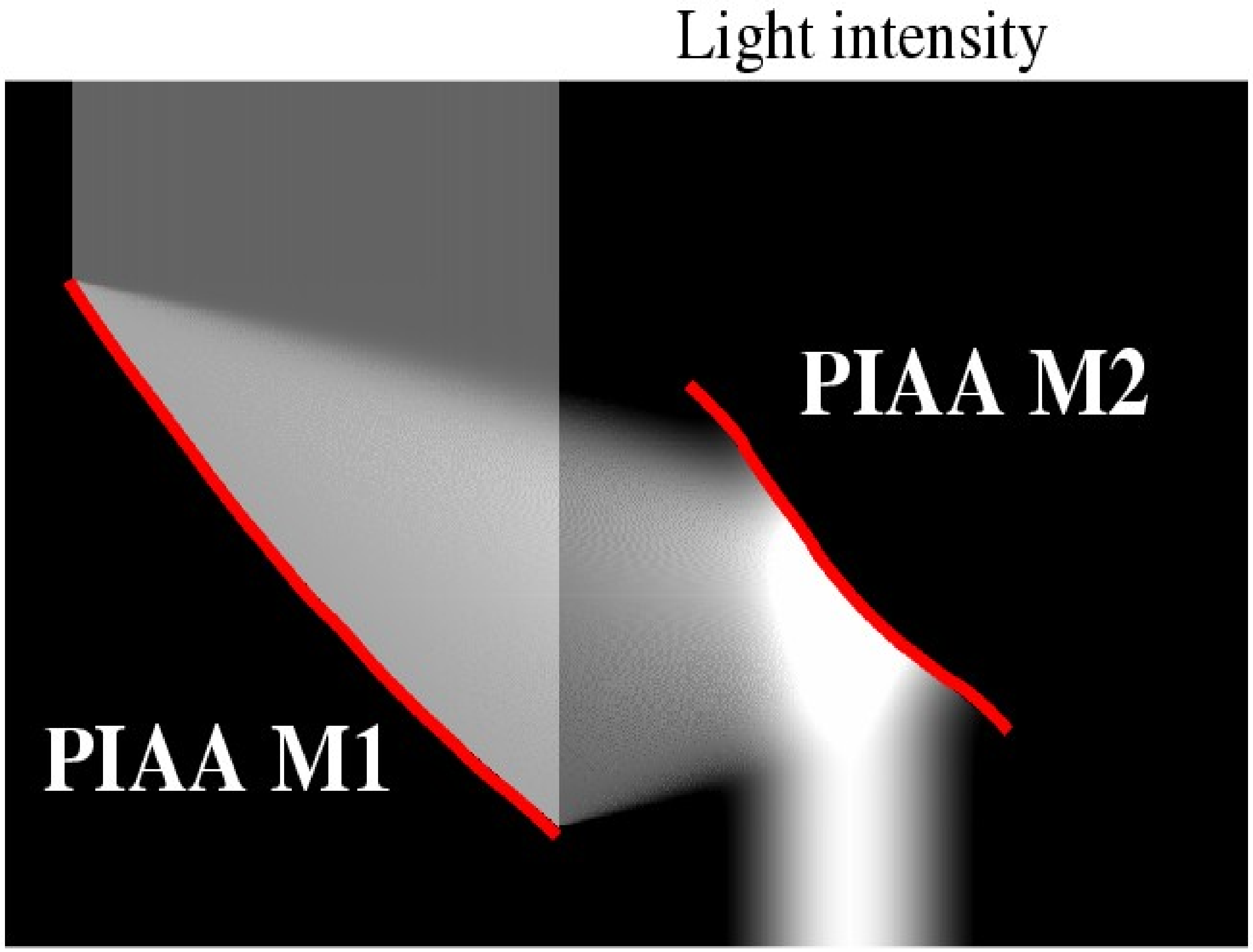


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

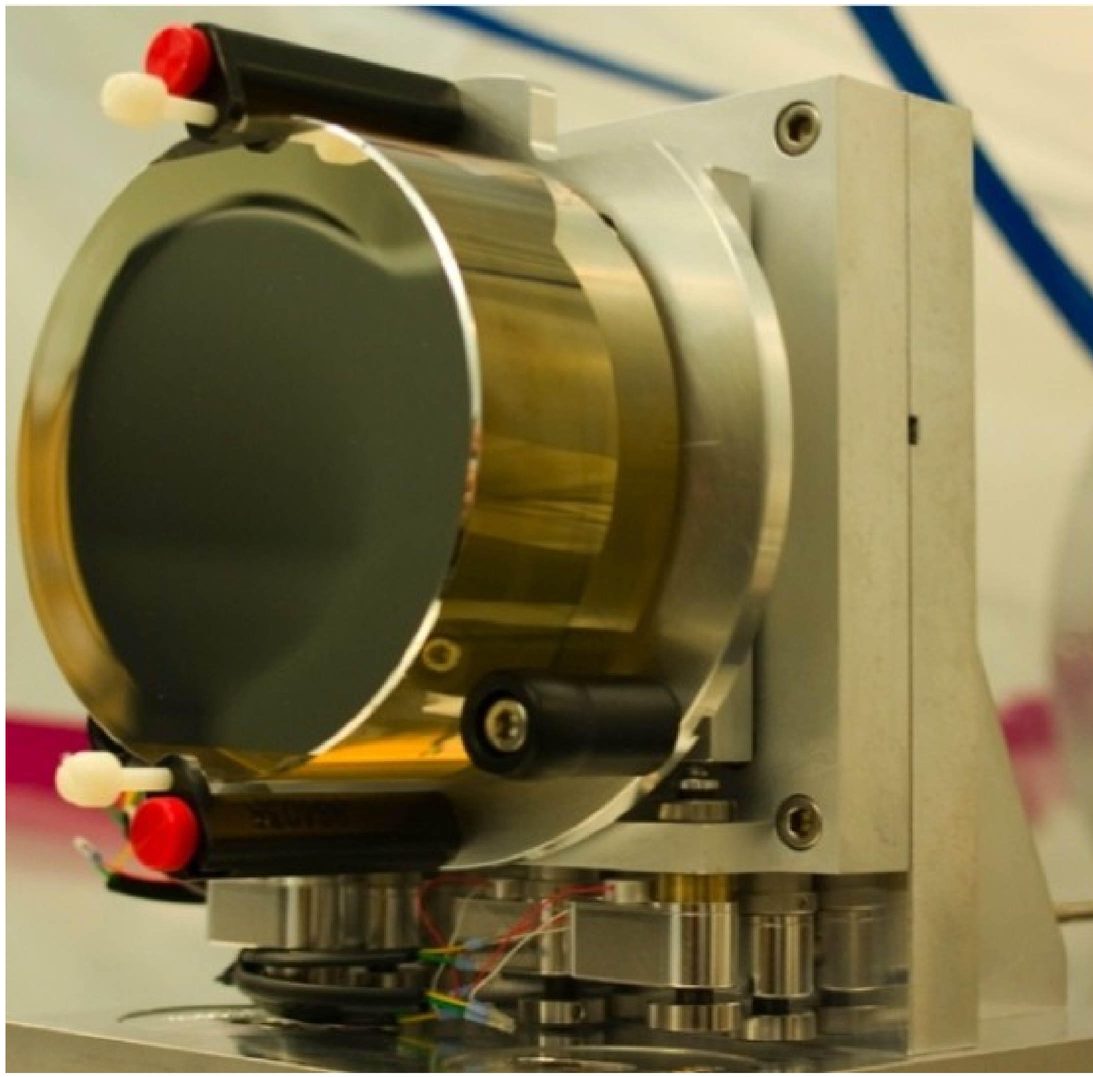


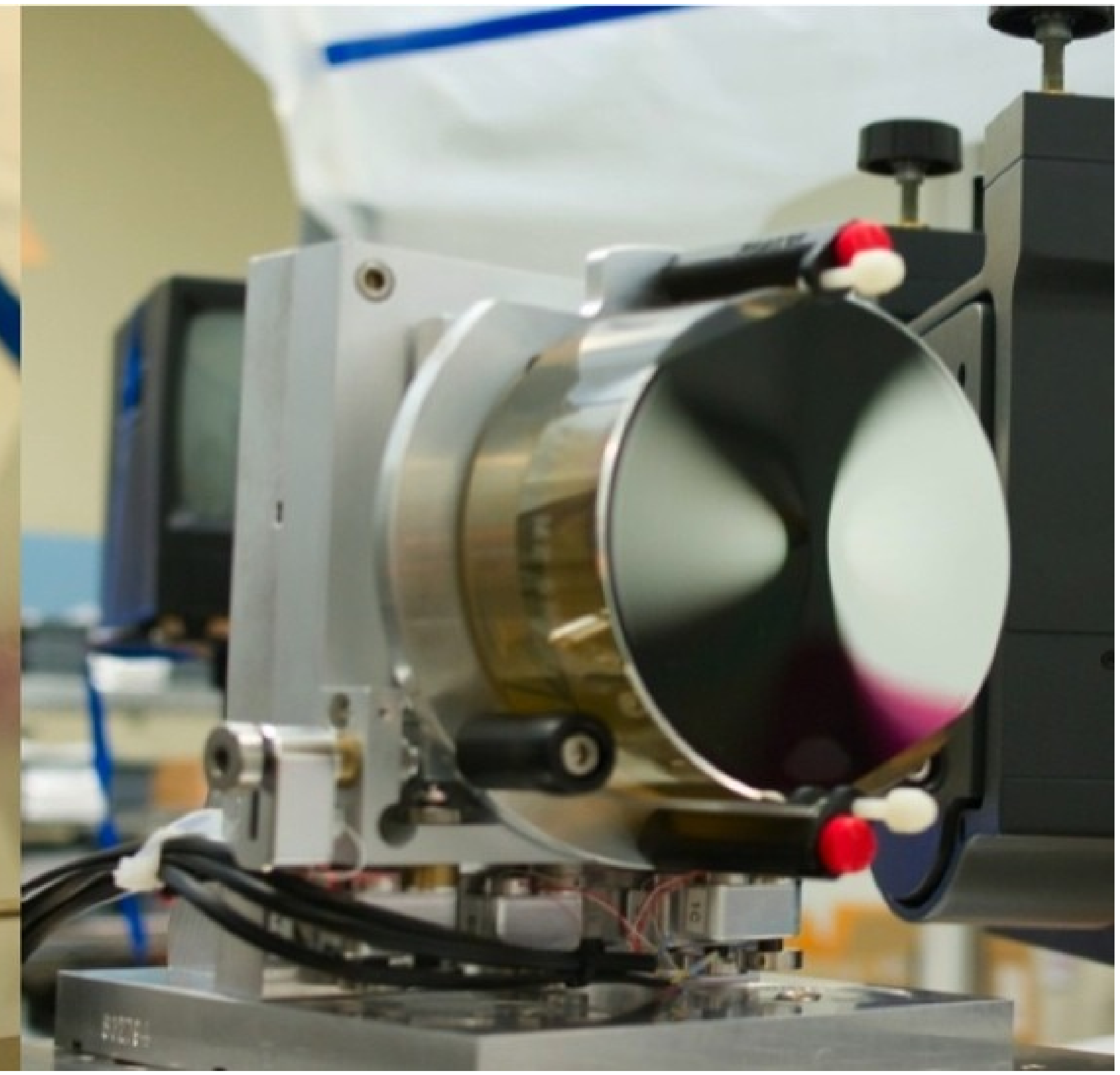
No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

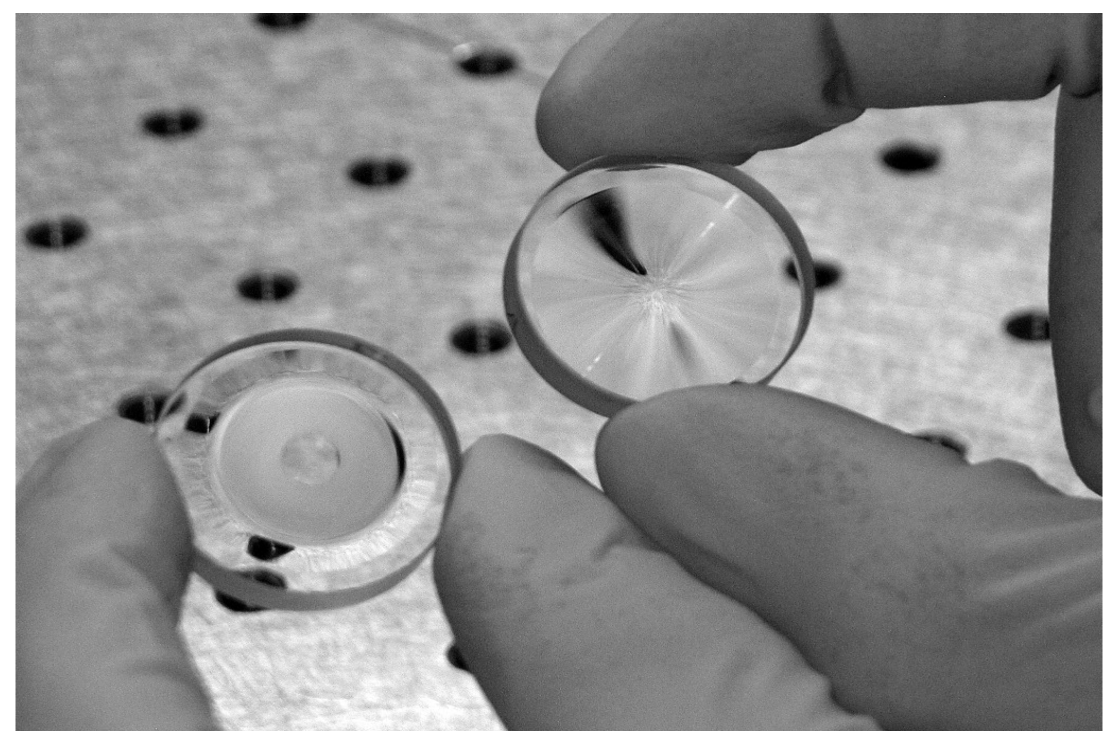
→ Gain ~x2 in telescope diameter over previous concepts

Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

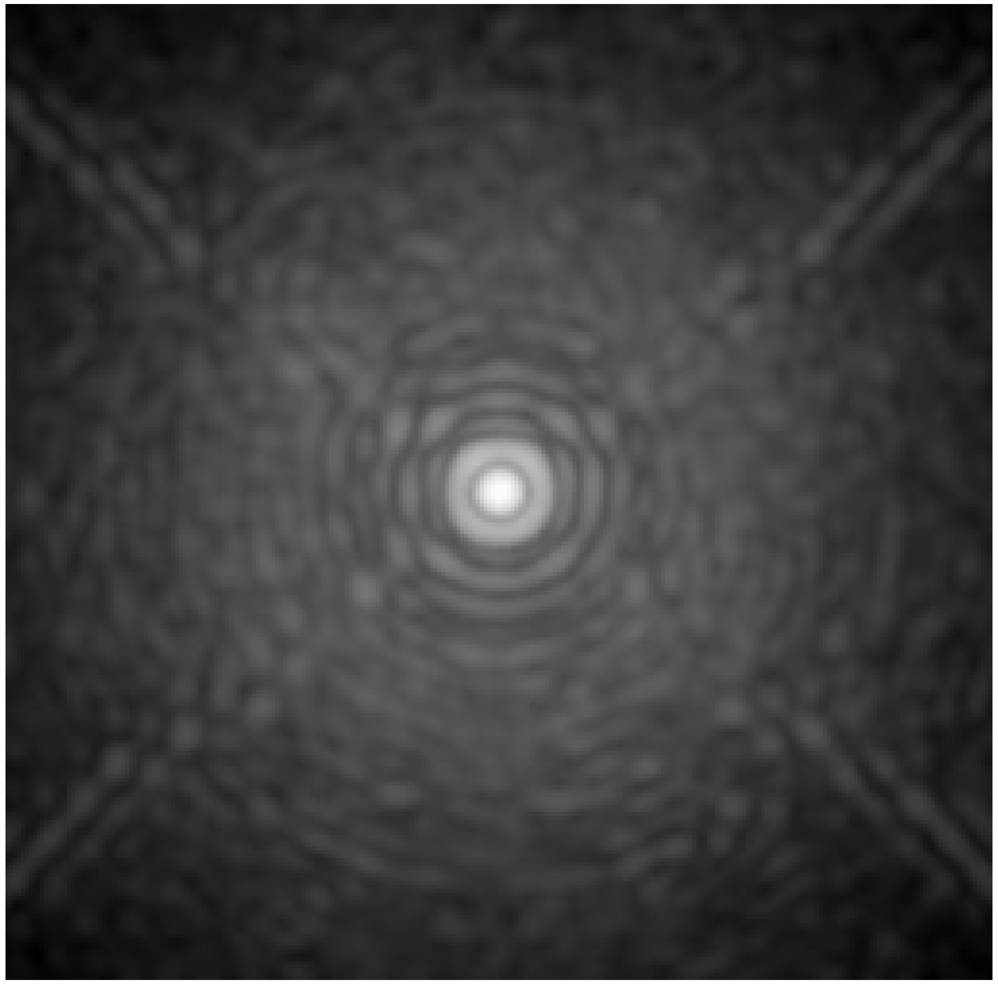
PIAA optics







Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

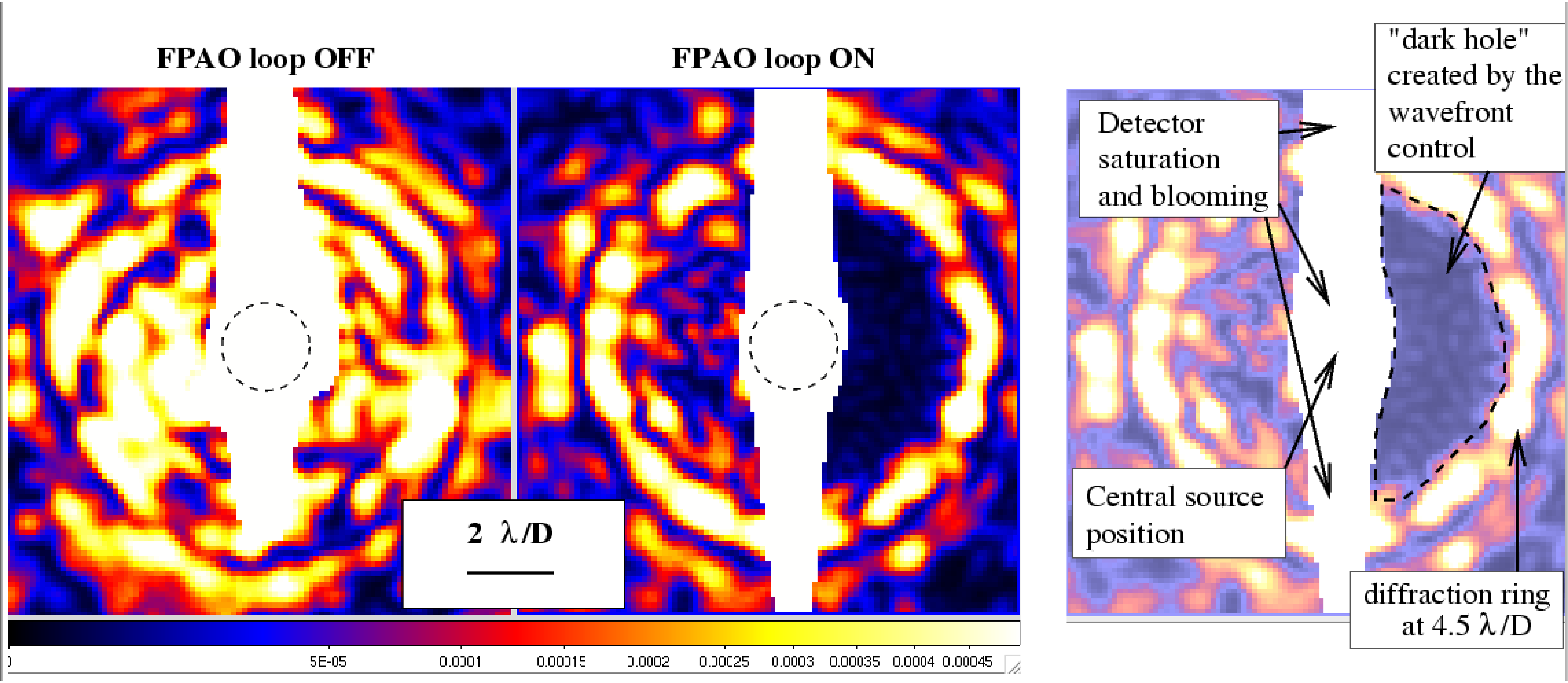
SENSING: Put “test speckles” to measure speckles in the image, watch how they interfere

CORRECTION: Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing:
“What you see is EXACTLY what needs to be removed / calibrated”

Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

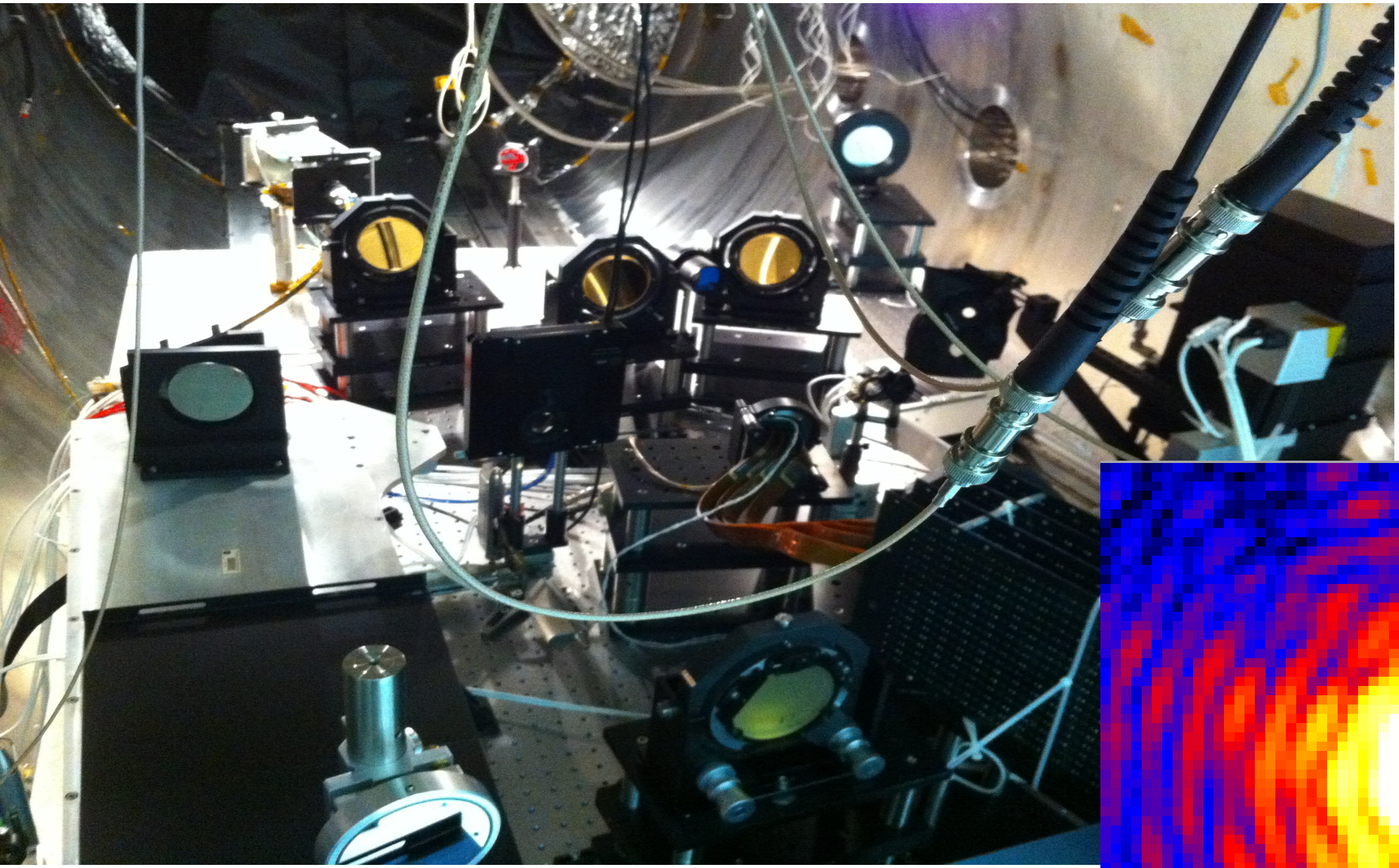


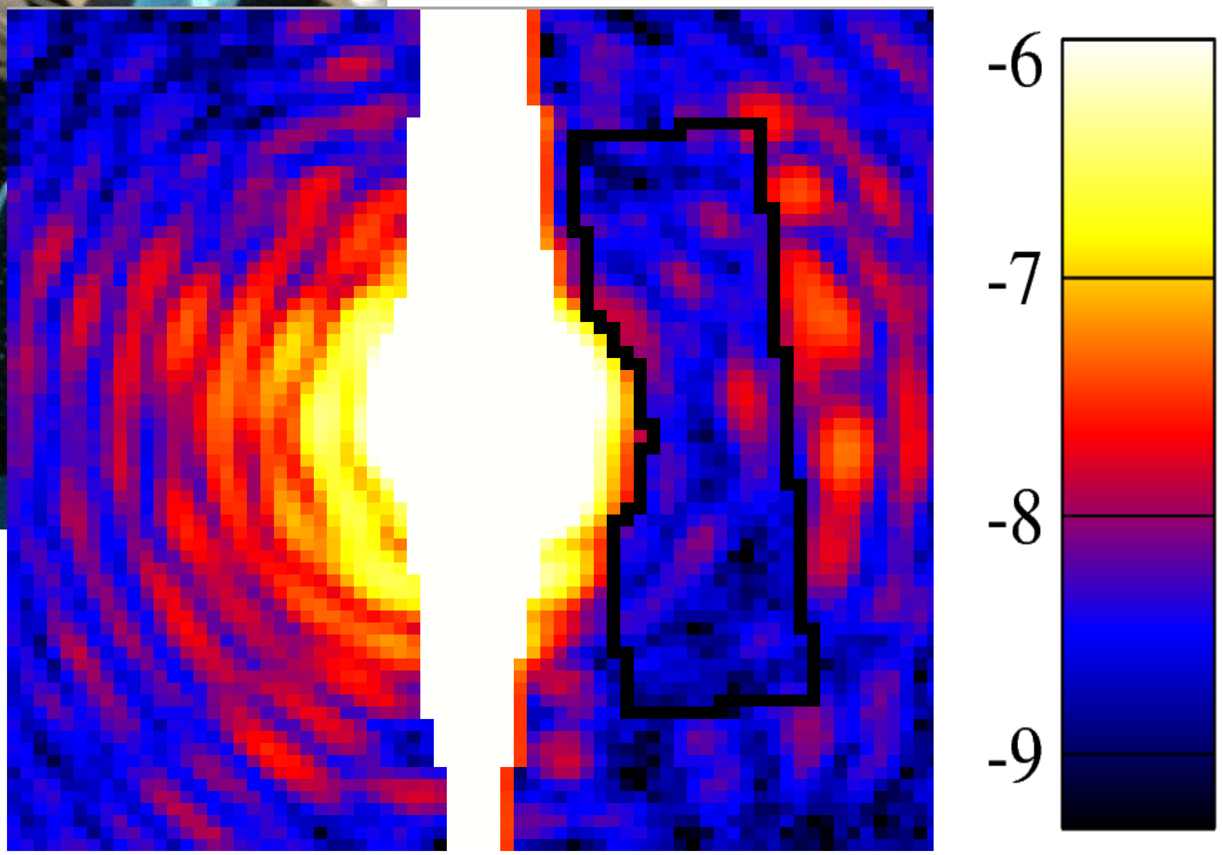
See also results obtained at NASA JPL HCIT, NASA Ames & Princeton lab

All high contrast coronagraphic images acquired in lab use this technique.

- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics

NASA JPL vacuum testbed

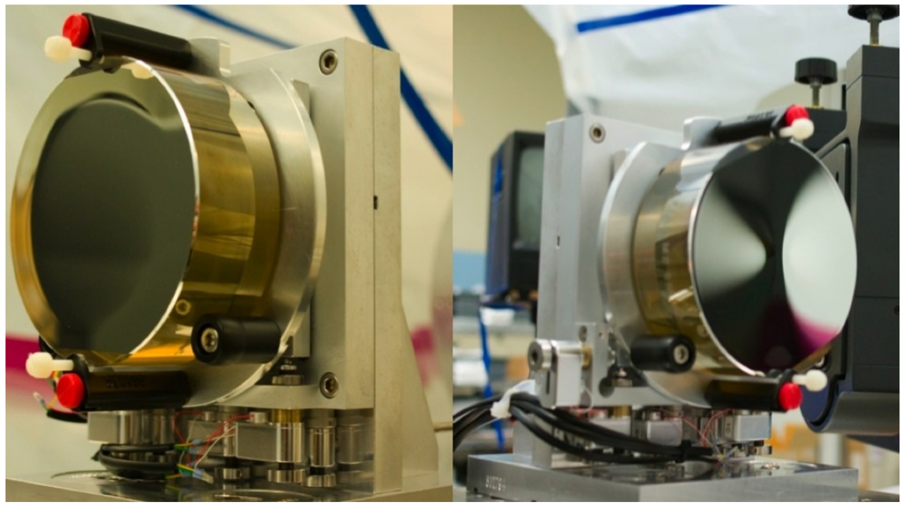


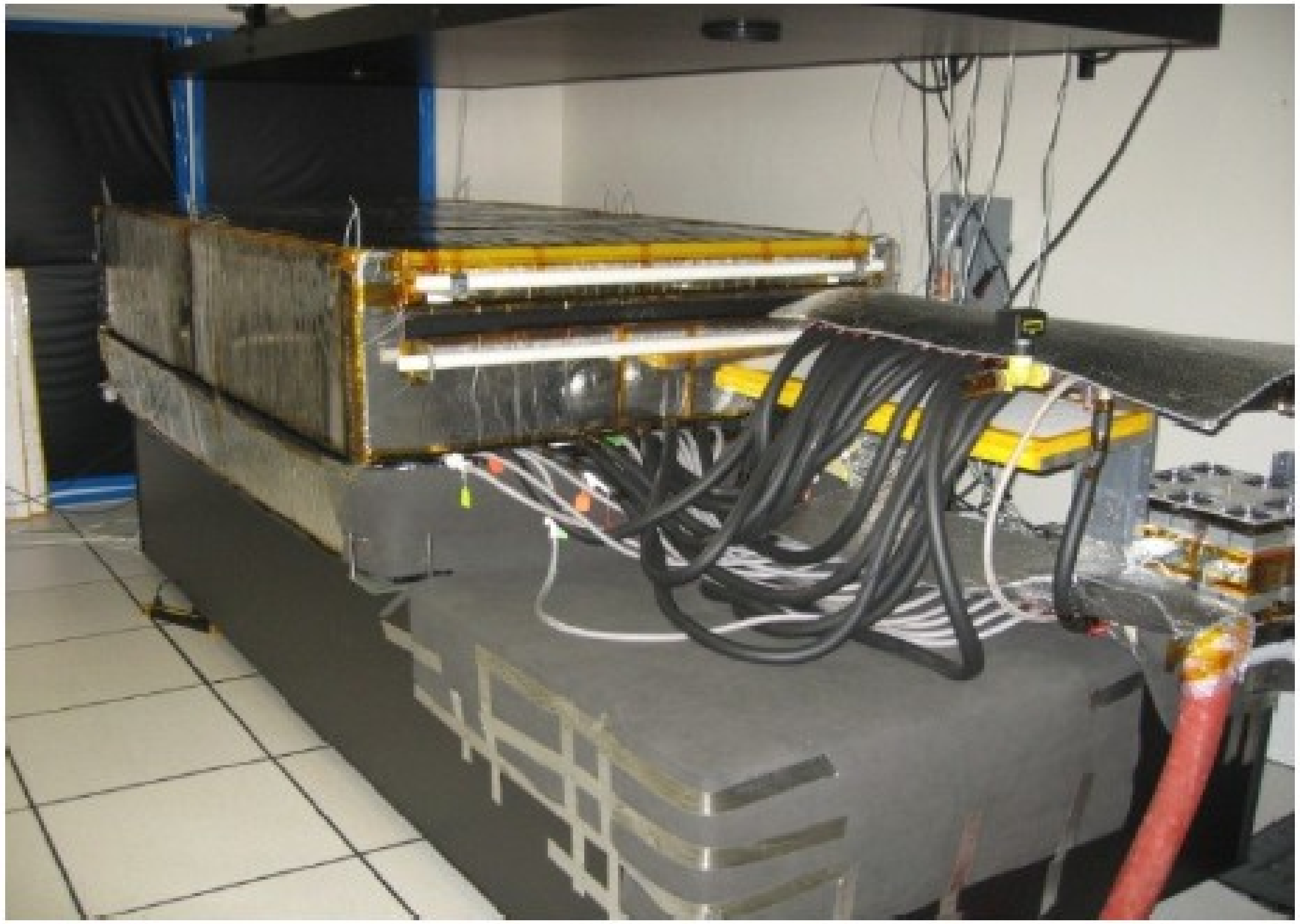


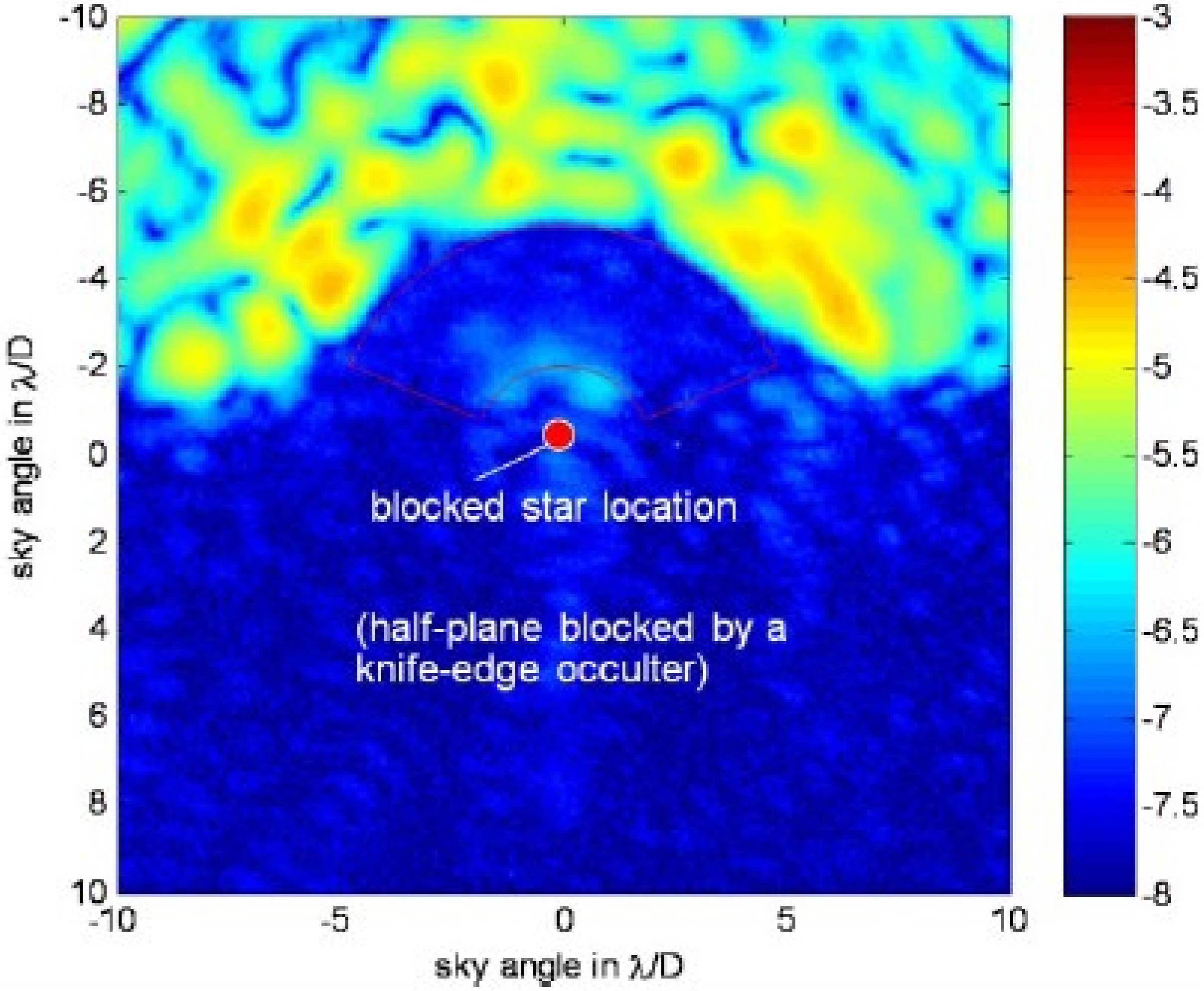
PIAA is reaching few x1e-9 contrast at 2 lambda/D separation

NASA Ames testbed

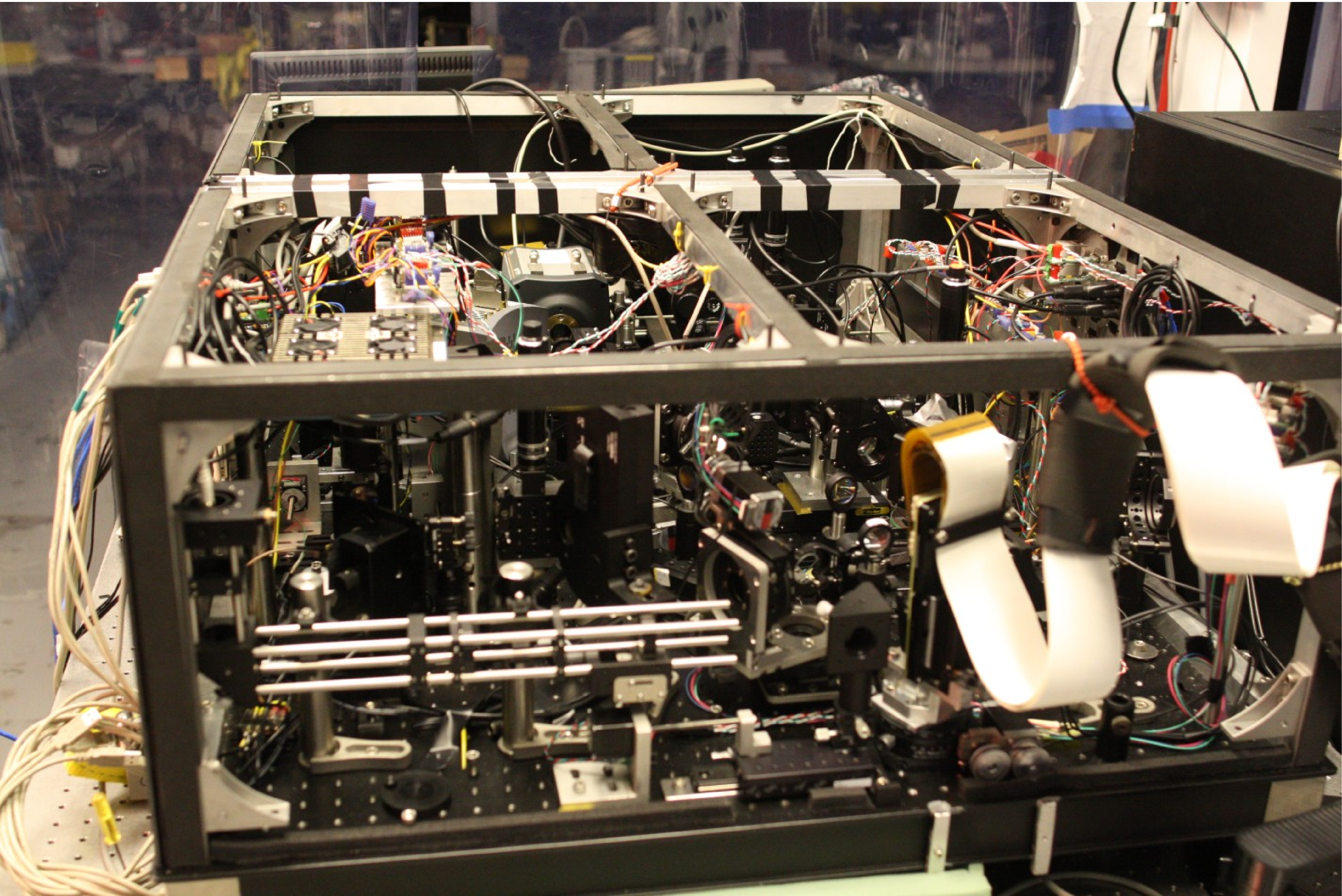
Contrast ratio with PIAA already reaching ~1e-6 at 1.2 l/D in visible



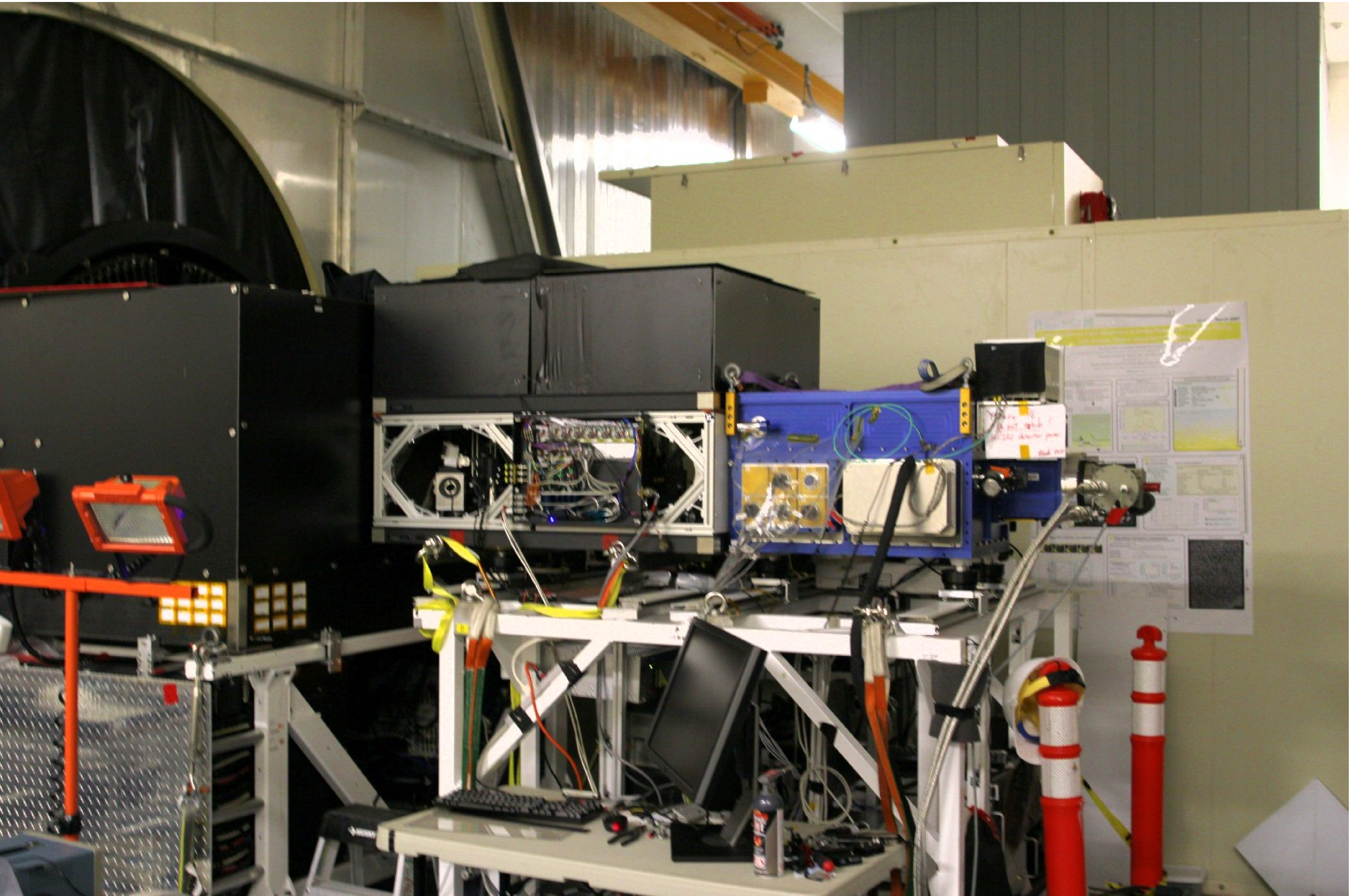




The Subaru Coronagraphic Extreme-AO (SCExAO) system



Current AO188 → SCExAO → HiCIAO architecture
SCExAO at the summit (Sept 2012)



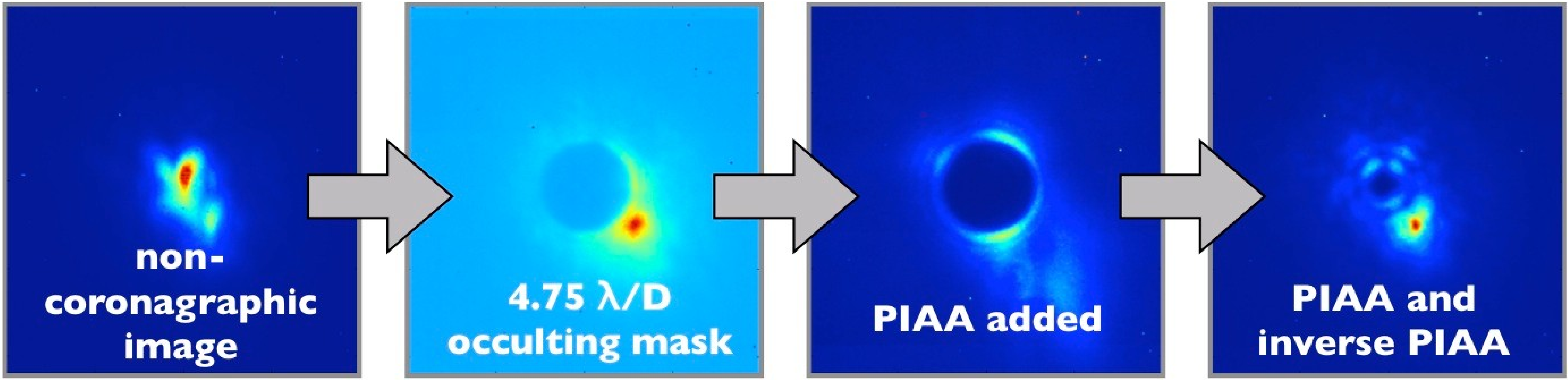
SCExAO coronagraph Results

LOWFS validated on sky

- robust performance at low gain (~0.1) in difficult conditions
- calibration can be time consuming

PIAA coronagraphy at 1.2 lambda/D validated

- Inverse PIAA image sharpening validated



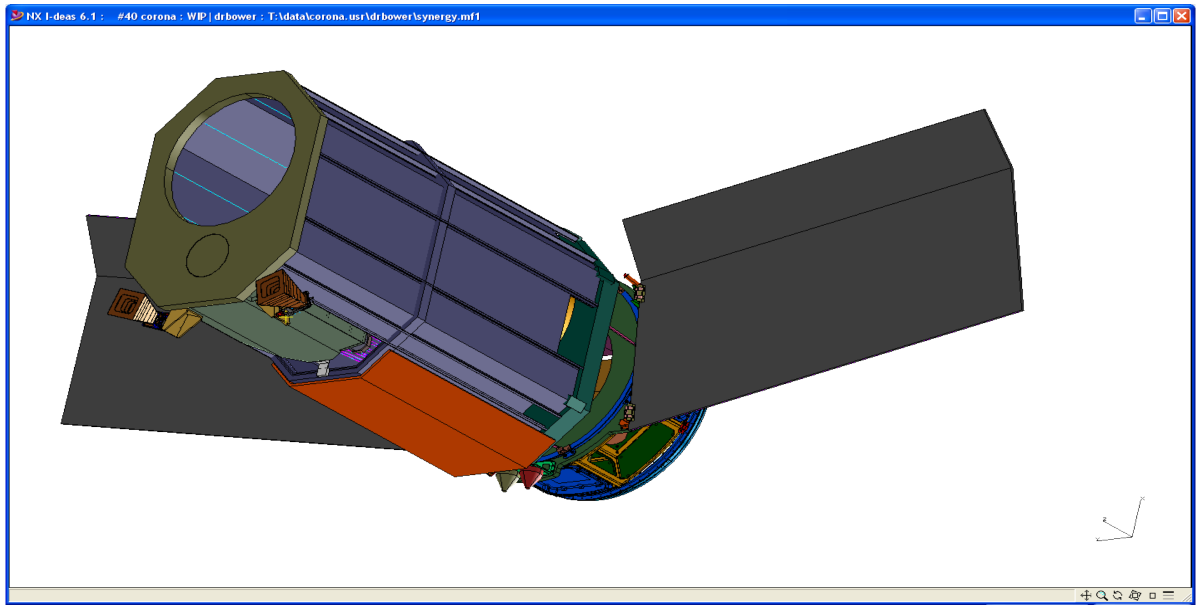
EXCEDE

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Mission Overview

Dr. Glenn Schneider (PI)
Dr. Olivier Guyon (IS)
Steward Observatory, The University of Arizona
NASA Ames, Lockheed Martin

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.



- 0.7 meter off-axis visible-light telescope

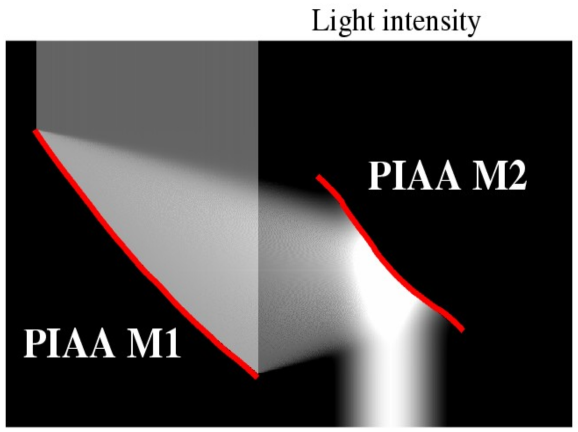
- Active Starlight Suppression System:
  - PIAA Coronagraph (~1 l/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor

- Two-band Imaging Polarimeter

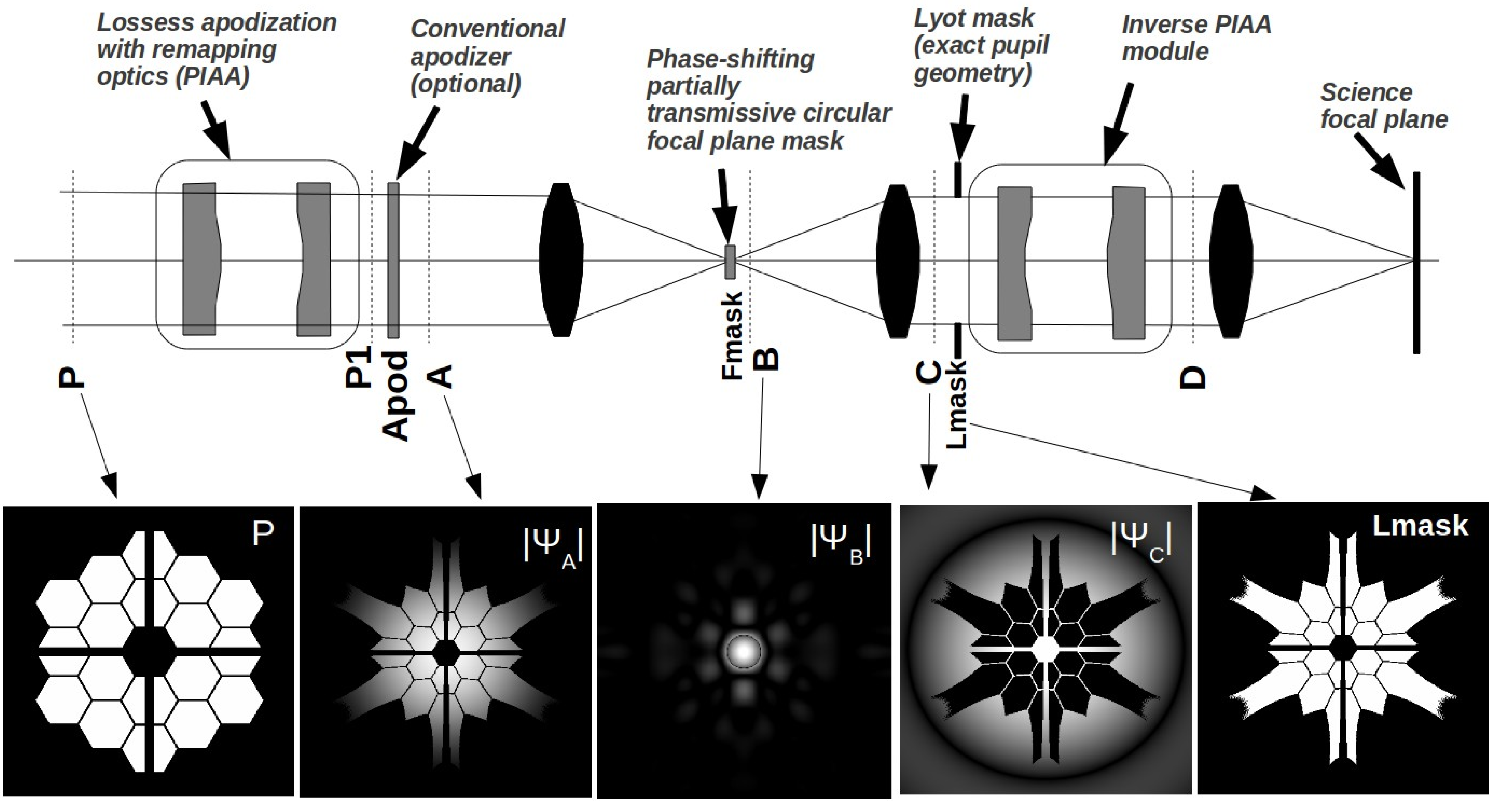
- Three-year mission (2000-km LEO Sun-synchronous orbit)
  - Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs

- Newly NASA-funded 2-year Tech. Dev program
  - Partnership contributions from UofA, Lockheed-Martin, NASA/AMES

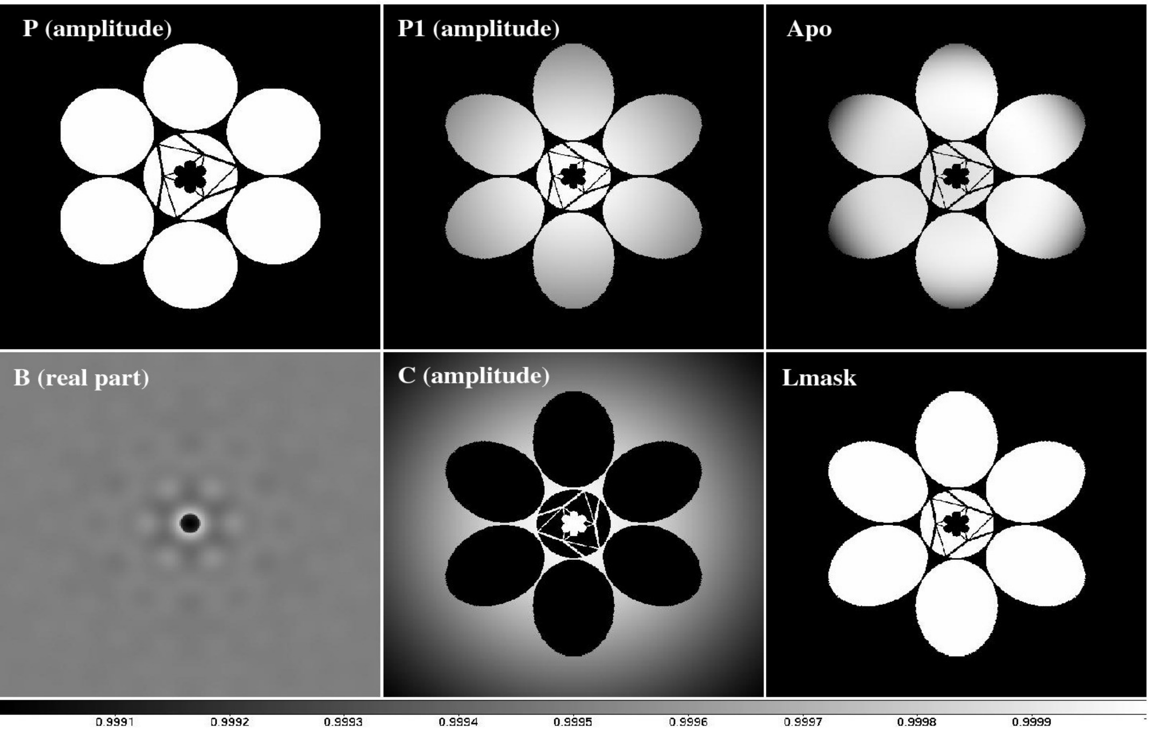
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



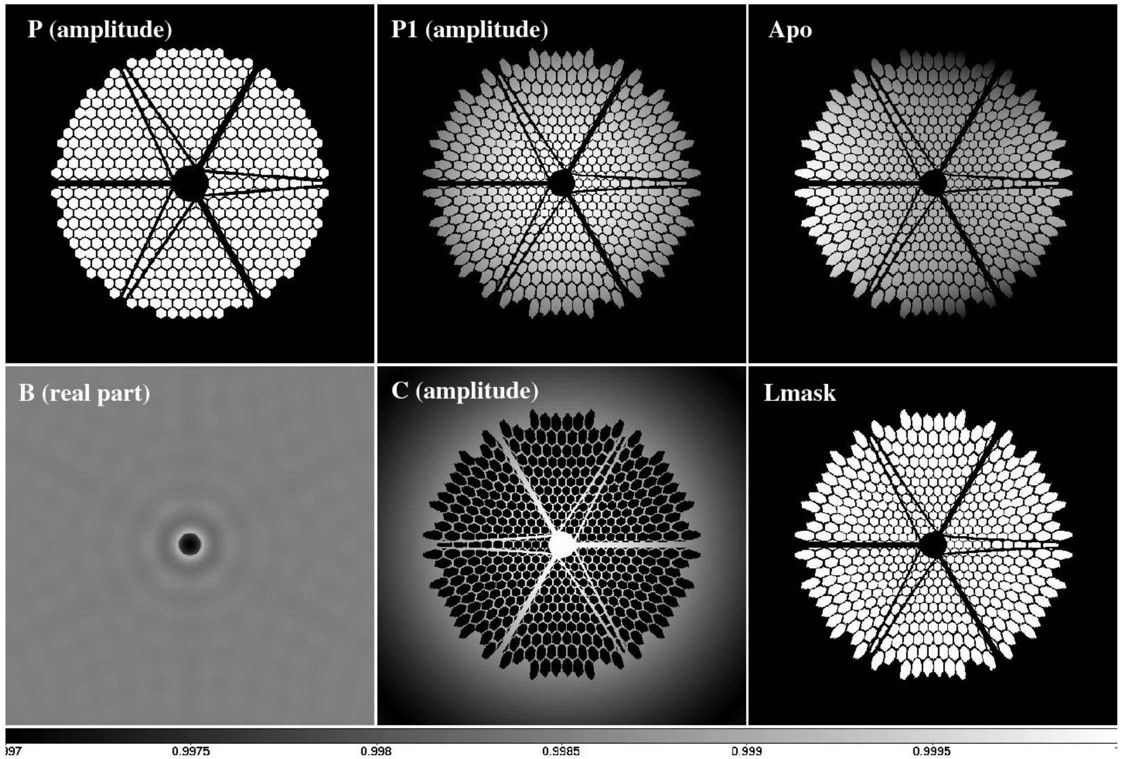
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

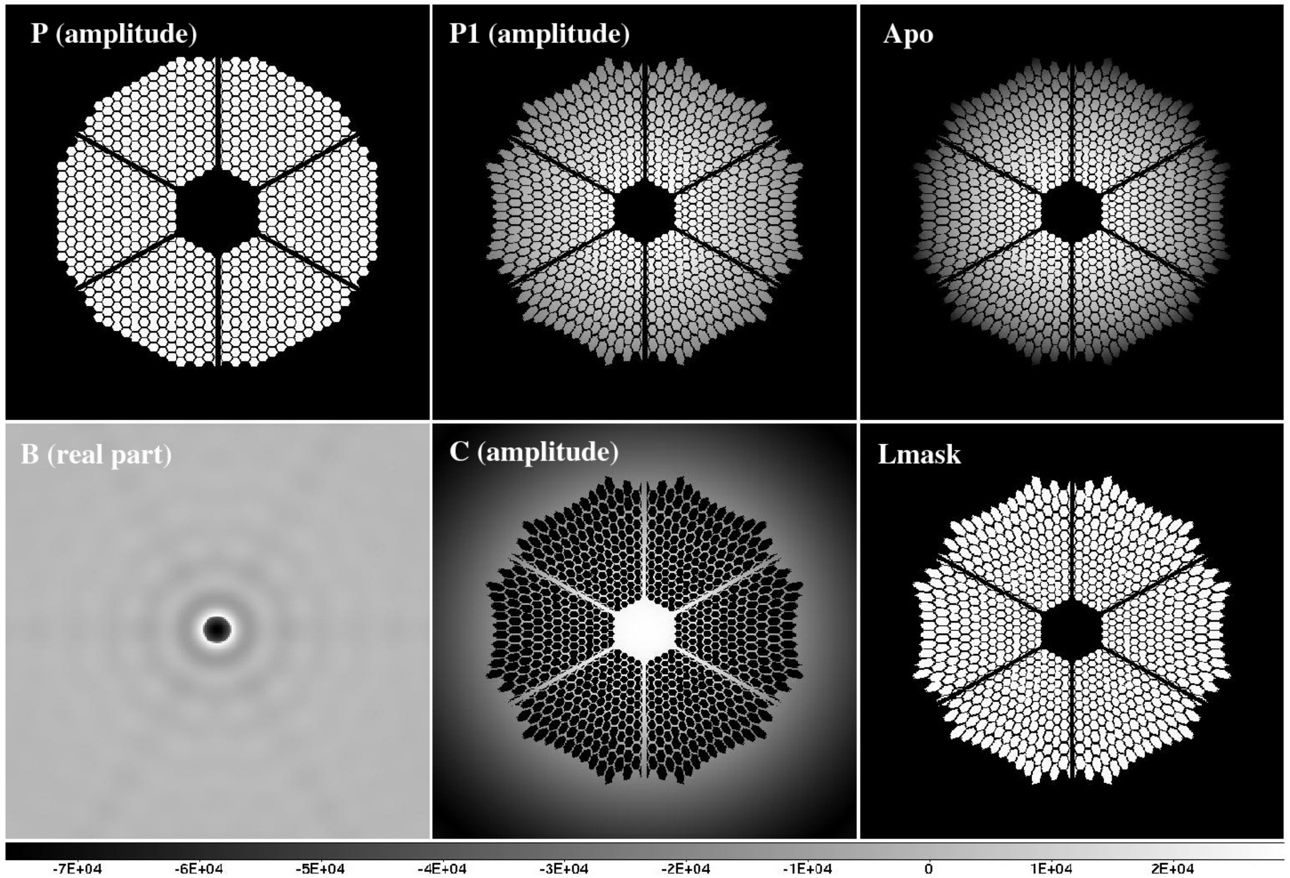


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



<u>Pupil shape does not matter !!!</u>

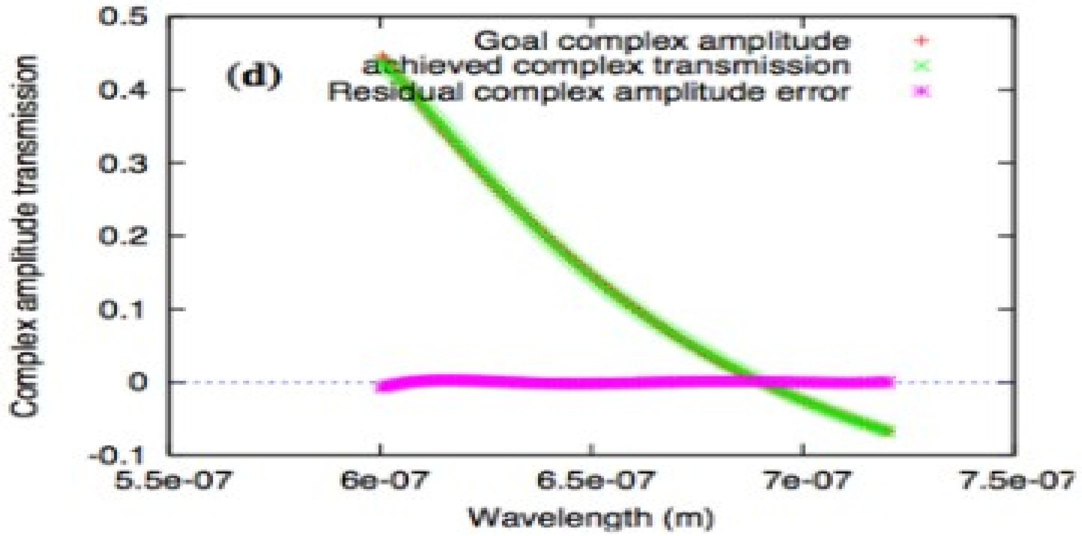


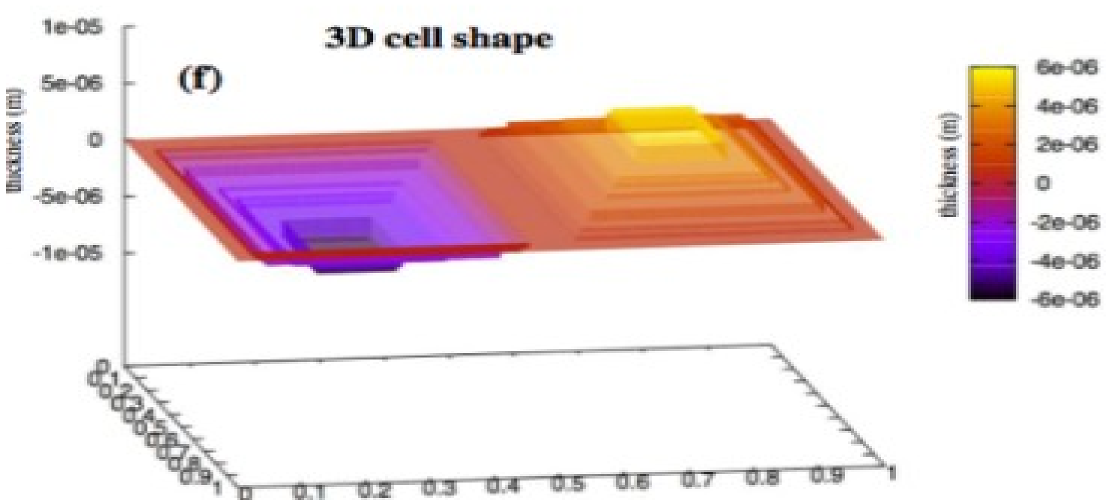


Coronagraphy: chromaticity

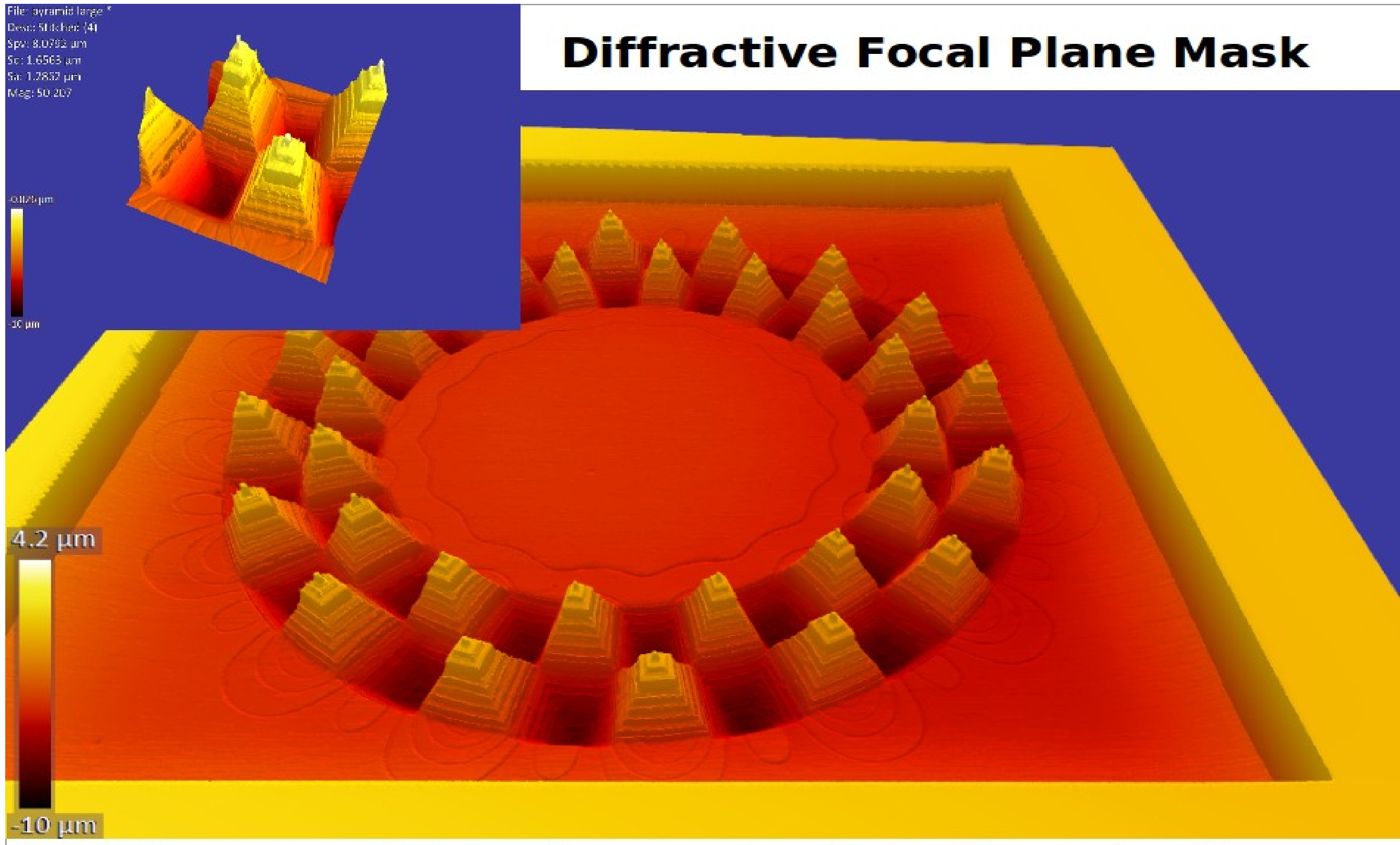
Diffractive focal plane mask for
high performance coronagraphy in broad band
(developped for ~1e-9 contrast, directly applicable to ELTs)
Work funded by NASA, PI: R. Belikov, NASA Ames

Design of a single diffractive cell



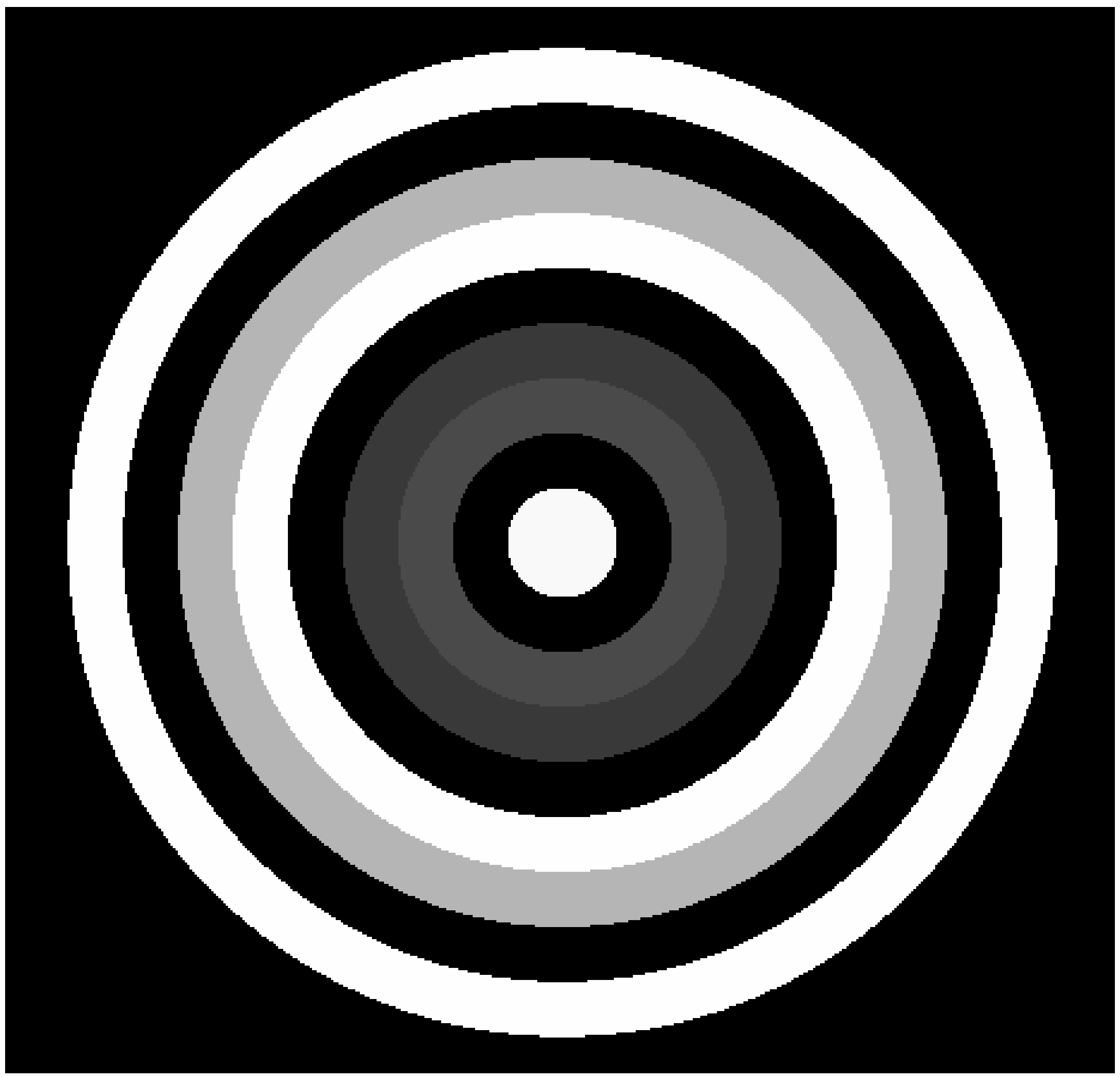


Prototype mask
(Manufactured by JPL MDL)

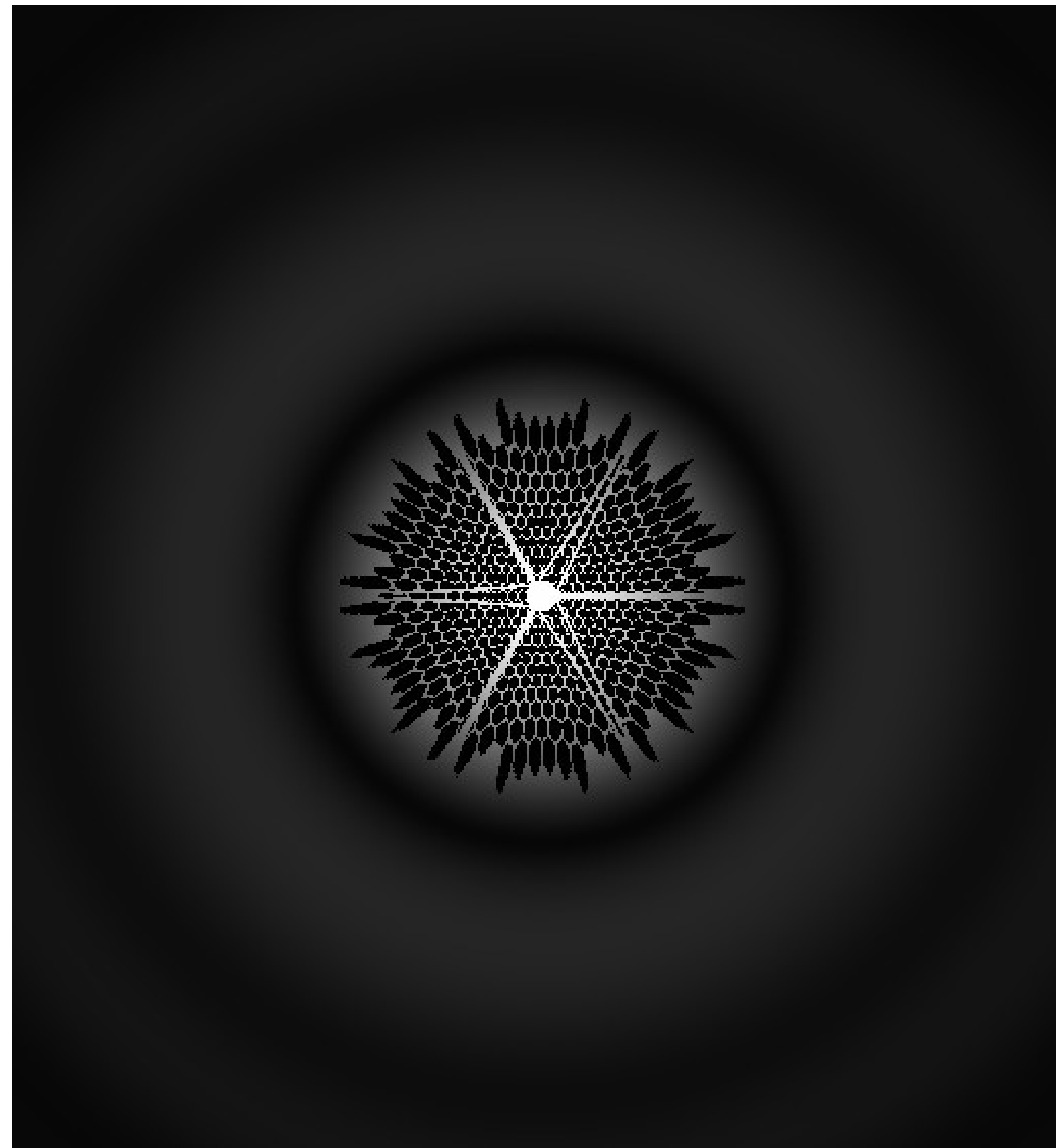


Coronagraphy: chromaticity

Multi-ring mask is much simpler and offers sufficient performance
Easy to manufacture (few $1000s), single material

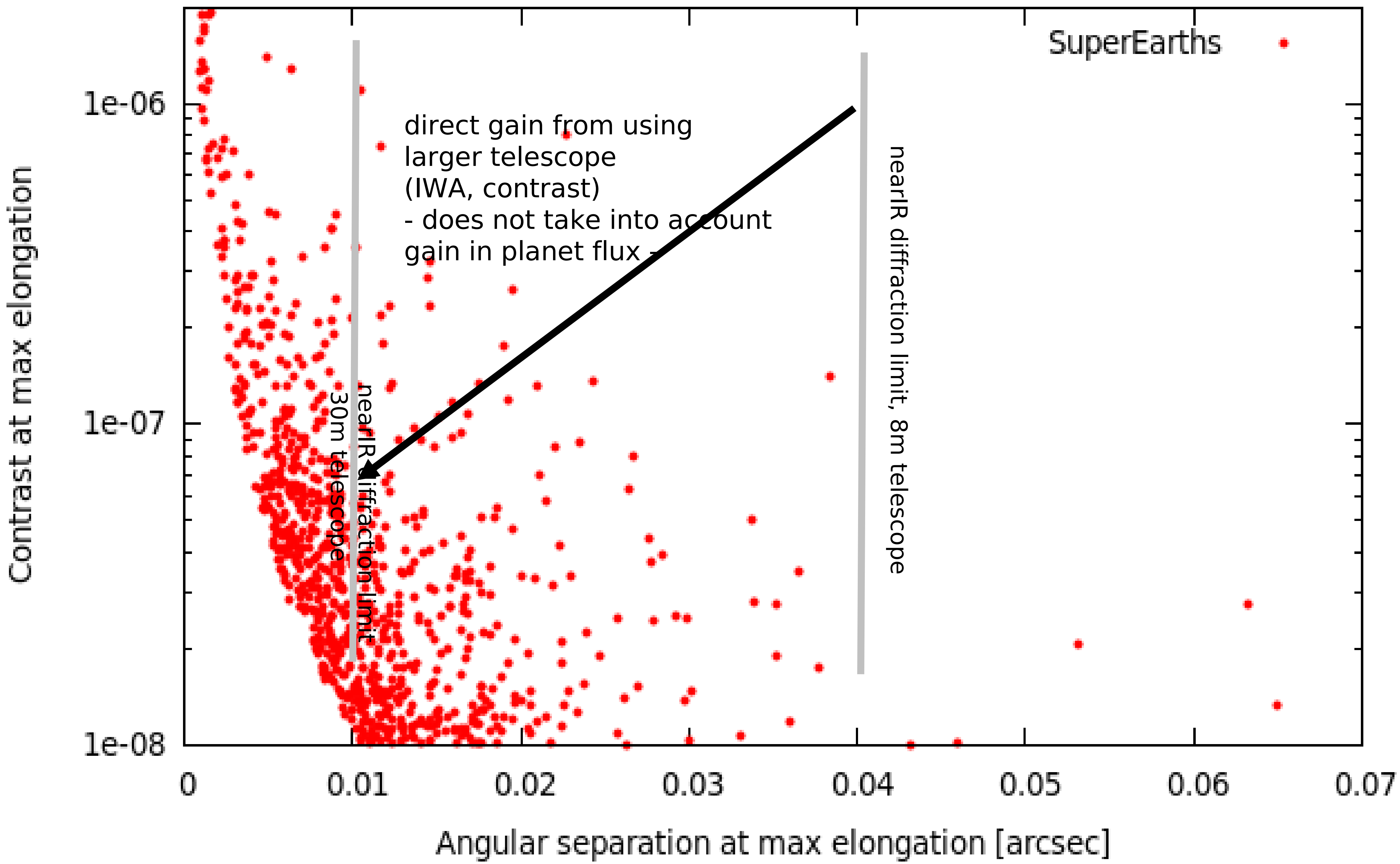


focal plane mask phase (central lambda)
+/- 16 um maximum material thickness
SiO2, designed for H band (20% wide)



Reflected light planets with ELTs

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance
(assumes Earth albedo, contrast and separation for max elongation)

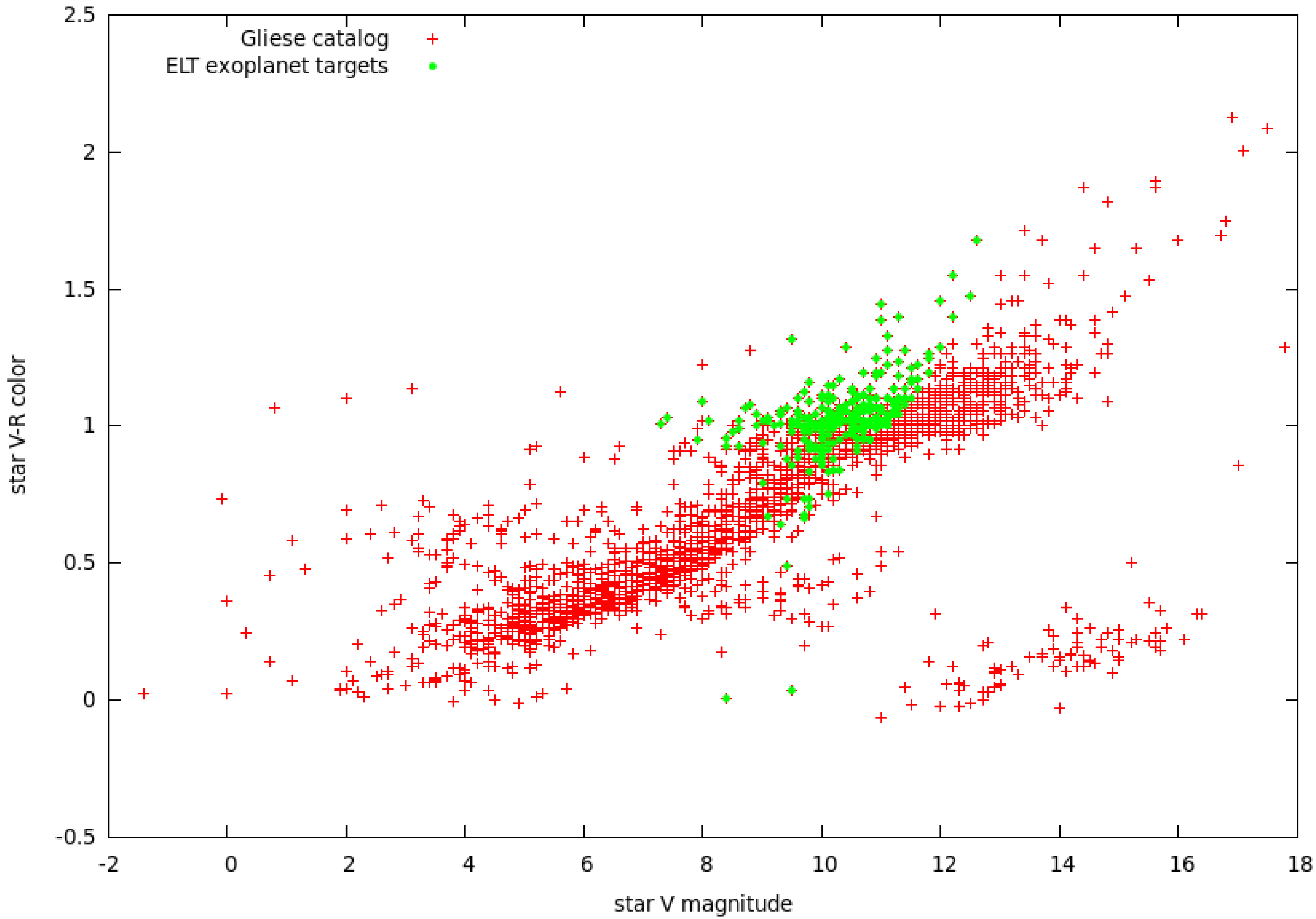


Reflected light planets

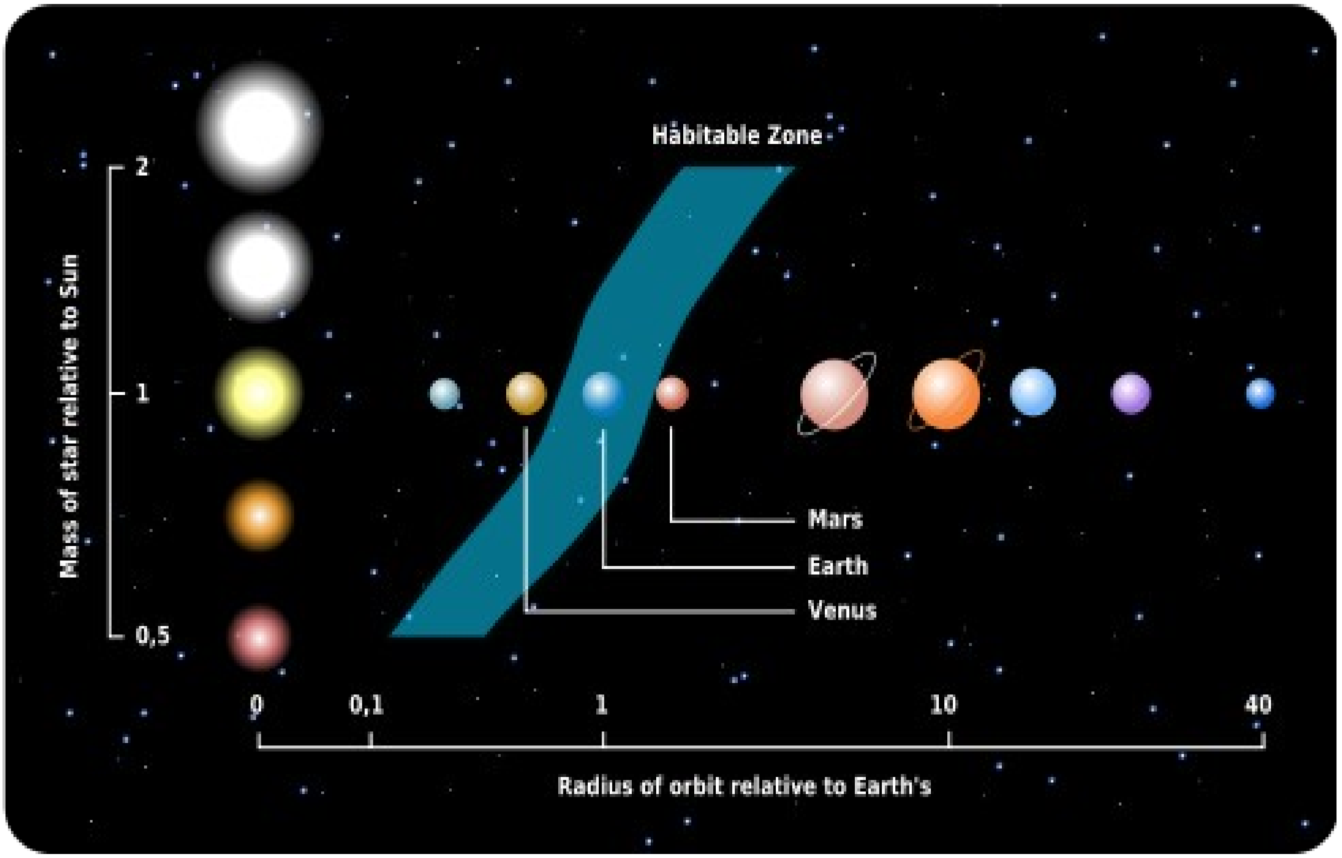
Most targets are red stars (M type), around V ~ 10, R ~ 9

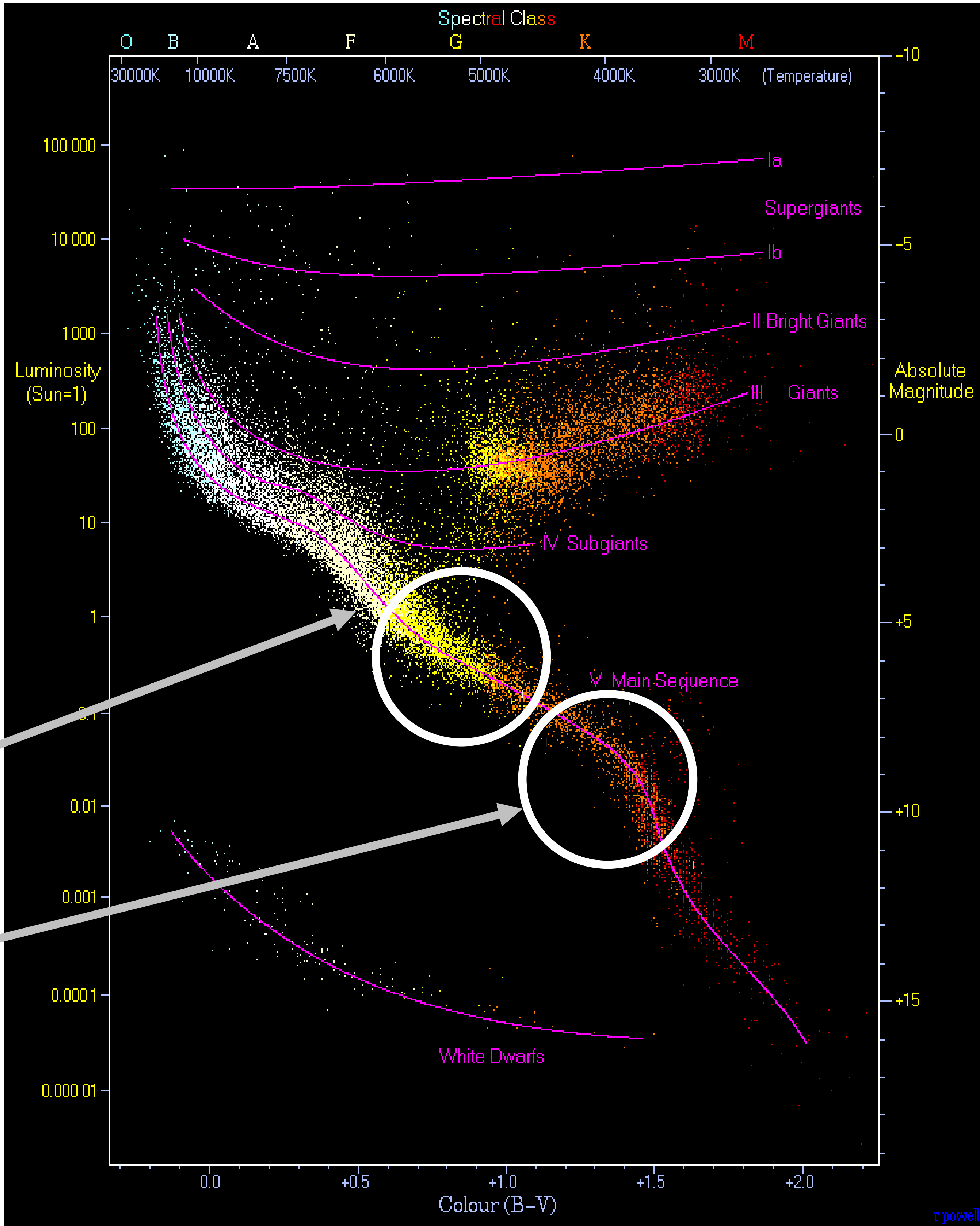
2 white dwarfs : 40 Eri B and Sirius B

Early type stars → contrast too challenging



Habitable planets spectroscopy

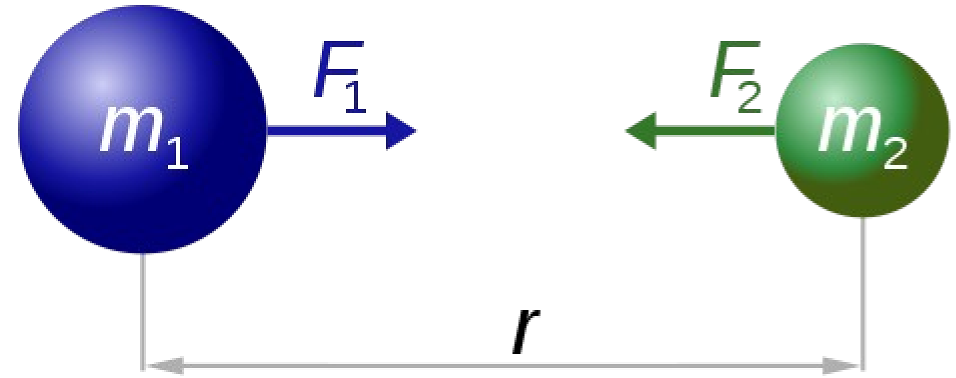




Space (~4m telescope):
F-G-K type stars, visible light
(~203x)

Ground (ELT):
M type stars, nearIR
(~ 202x)

Astrometry → orbit & mass



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Astrometric signature of planets

Star AND planet orbit the center of mass of the system

planet mass

star mass

orbit radius

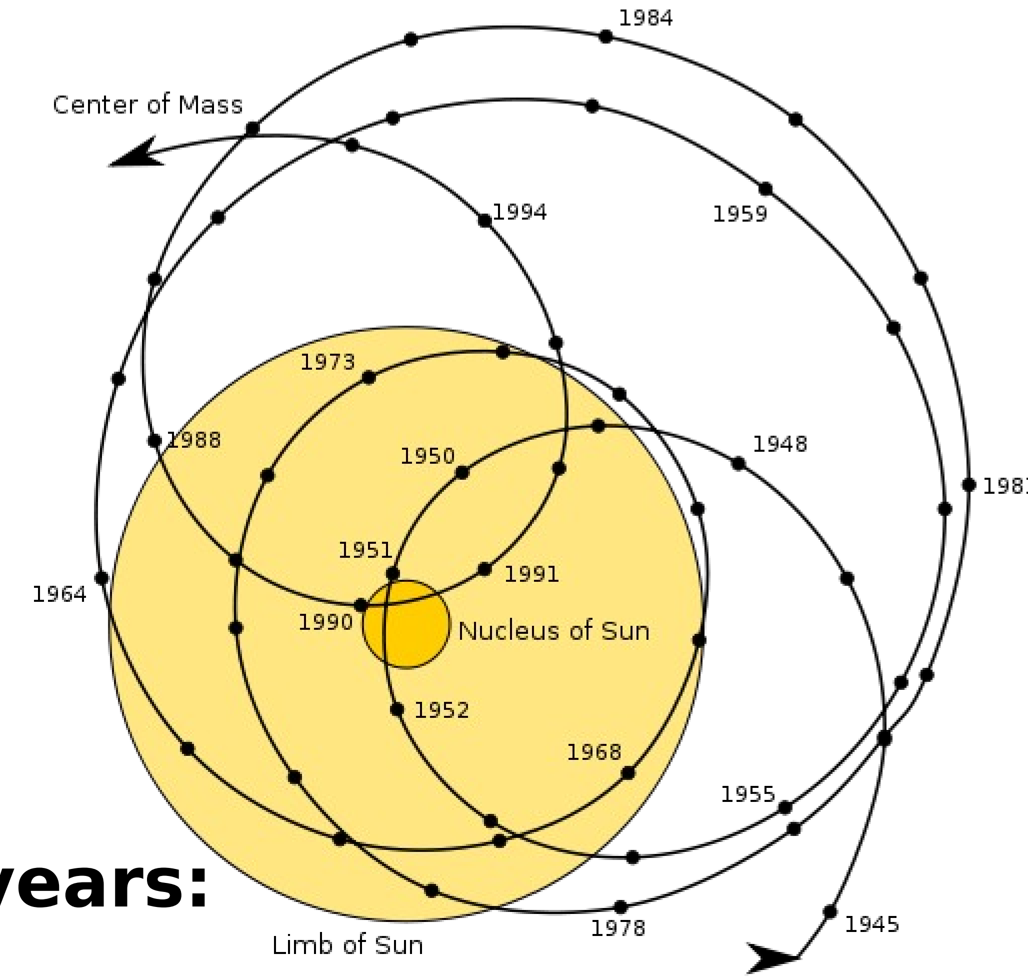
distance to system

$$\textbf{signal} = (m_{planet}/m_{star})\,(a/d)$$

0.3 uas for Earth around Sun at 10 pc
0.5 mas for Jupiter around Sun at 10 pc

signal period = orbital period

For circular orbit, an ellipse is observed
(circle only if viewed face-on)



Astrometric motion of the Sun due to solar system planets

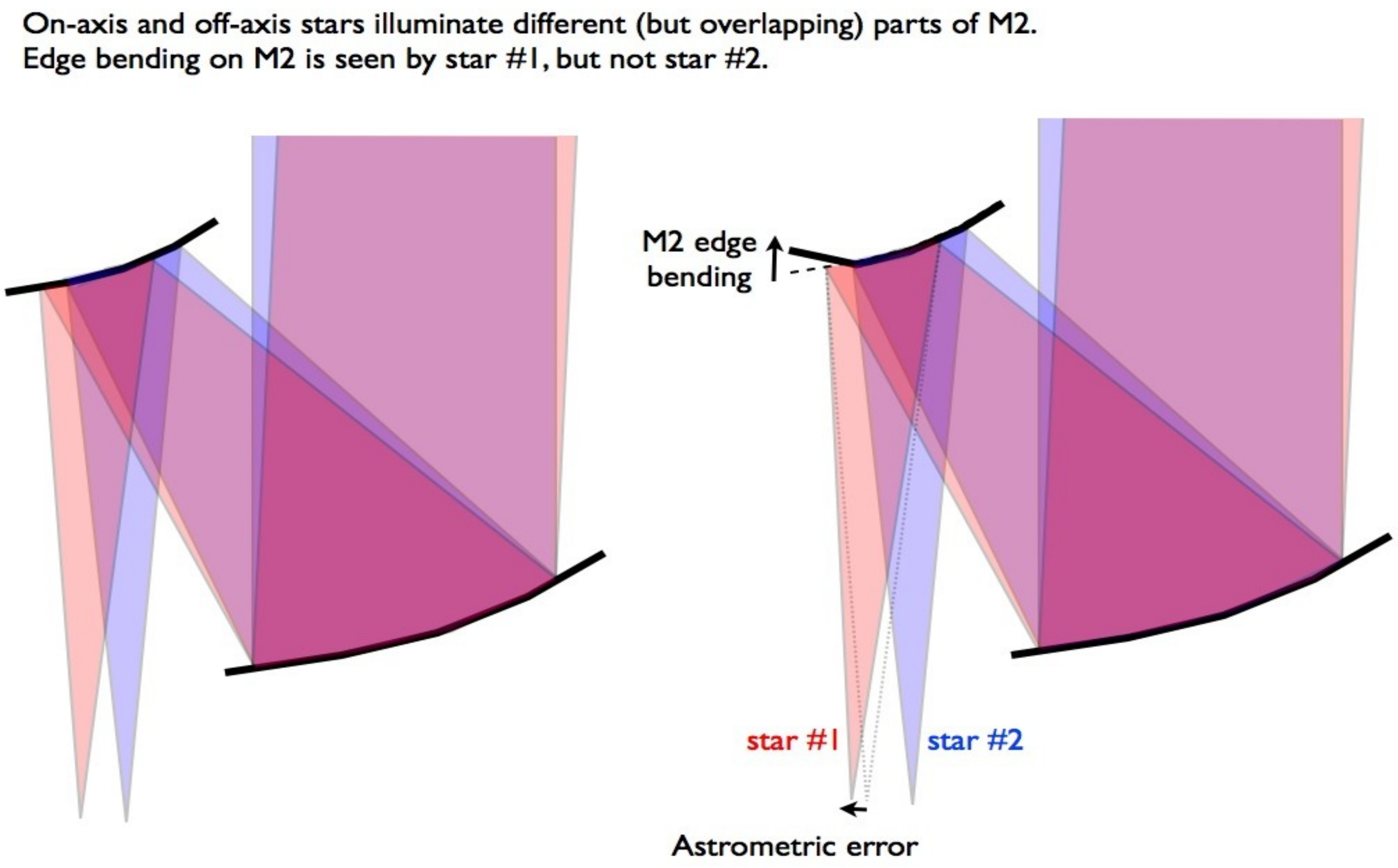
Earth around Sun, as seen from 30 light years:
0.3 uas = 1.5e-12 rad

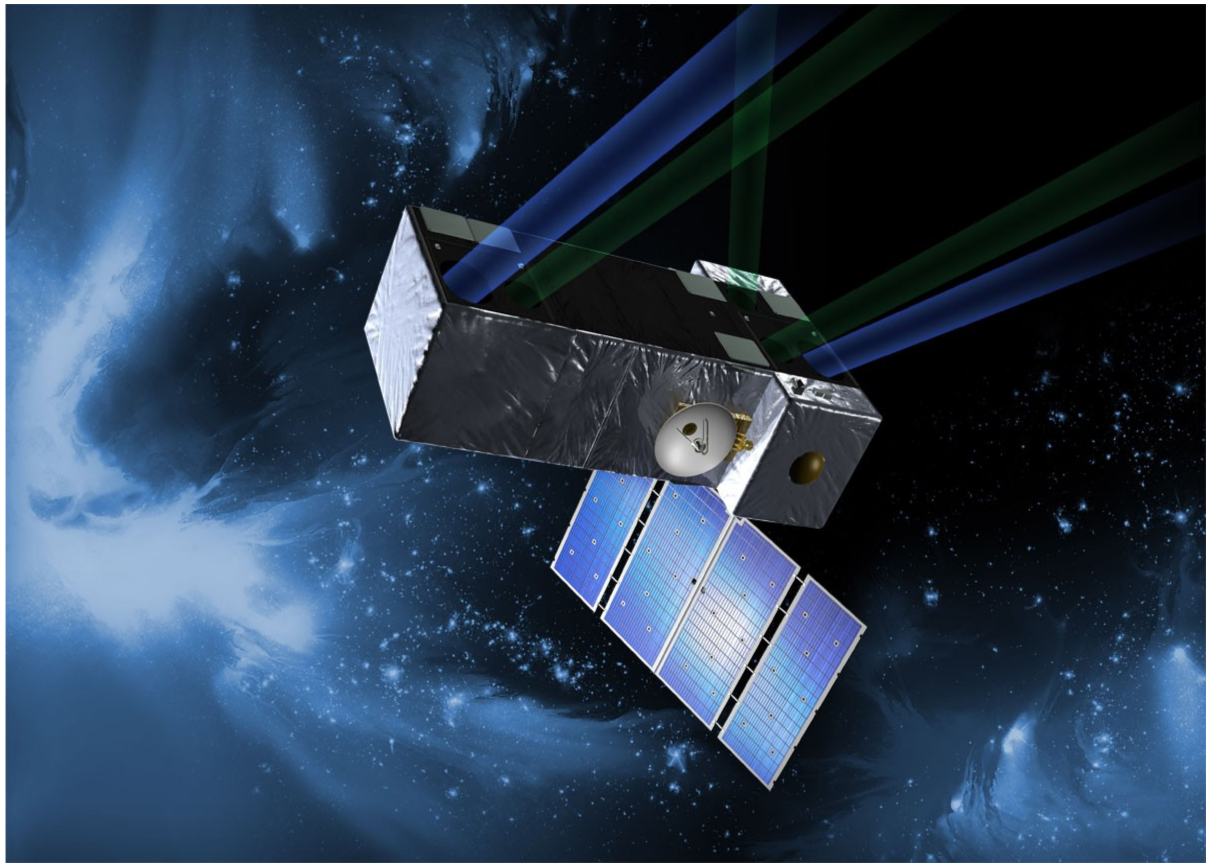
Astrometry

Earth around Sun, as seen from 30 light years:
0.3 uas = 1.5e-12 rad

A conventional telescope cannot measure star positions to this level of accuracy due to optical distortions

1e-12 rad astrometry would require pm-level stability over years





Space Interferometry Mission
2-apertures interferometer + laser metrology
Cancelled due to high cost (~$2B)

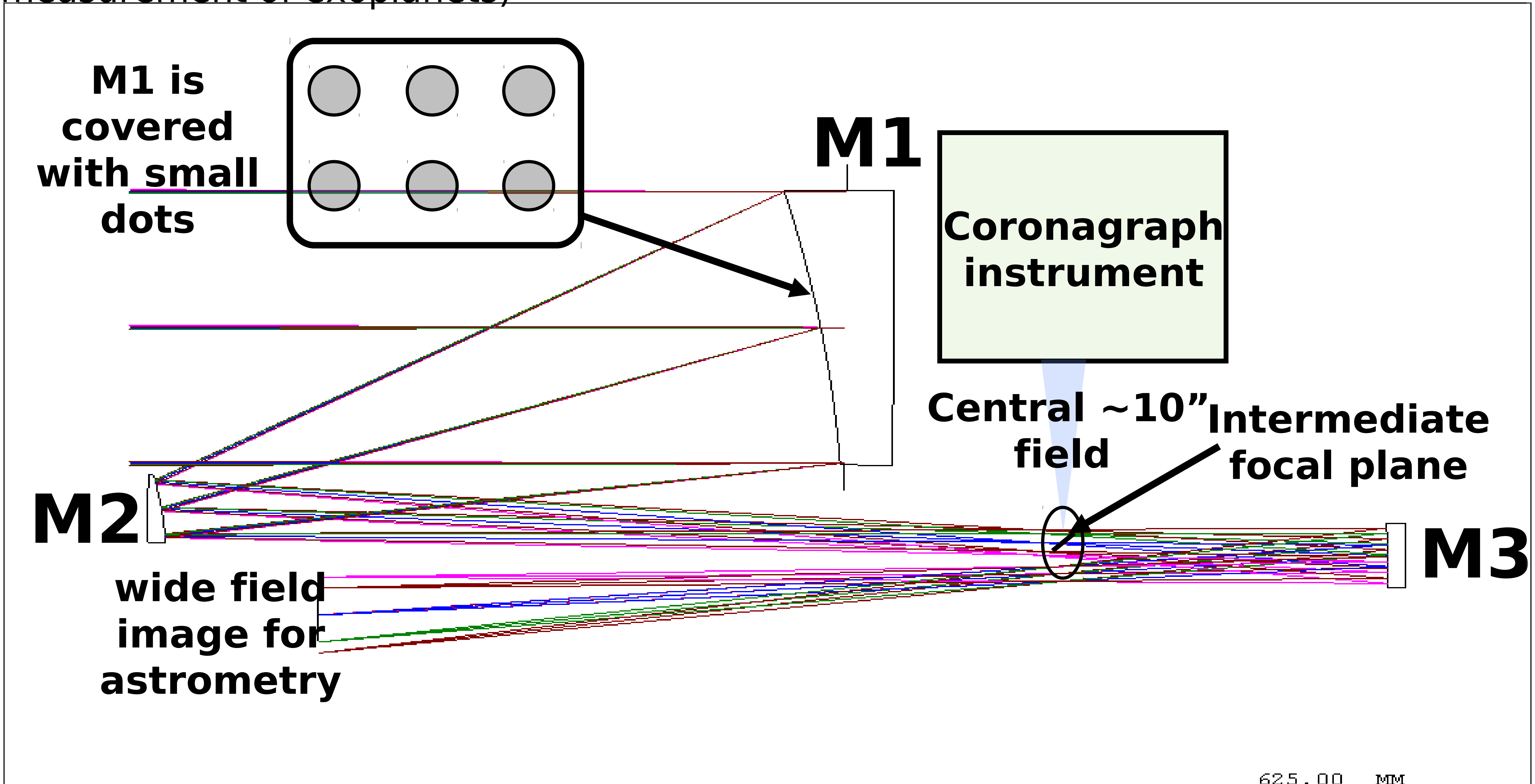
Wide field imaging technologies are now mature (optics, detectors)
Can we use wide field images for astrometry to identify and characterize exoplanets ?

Fundamental problem:
what do you do if you are looking at this field from the bottom of a swimming pool ?

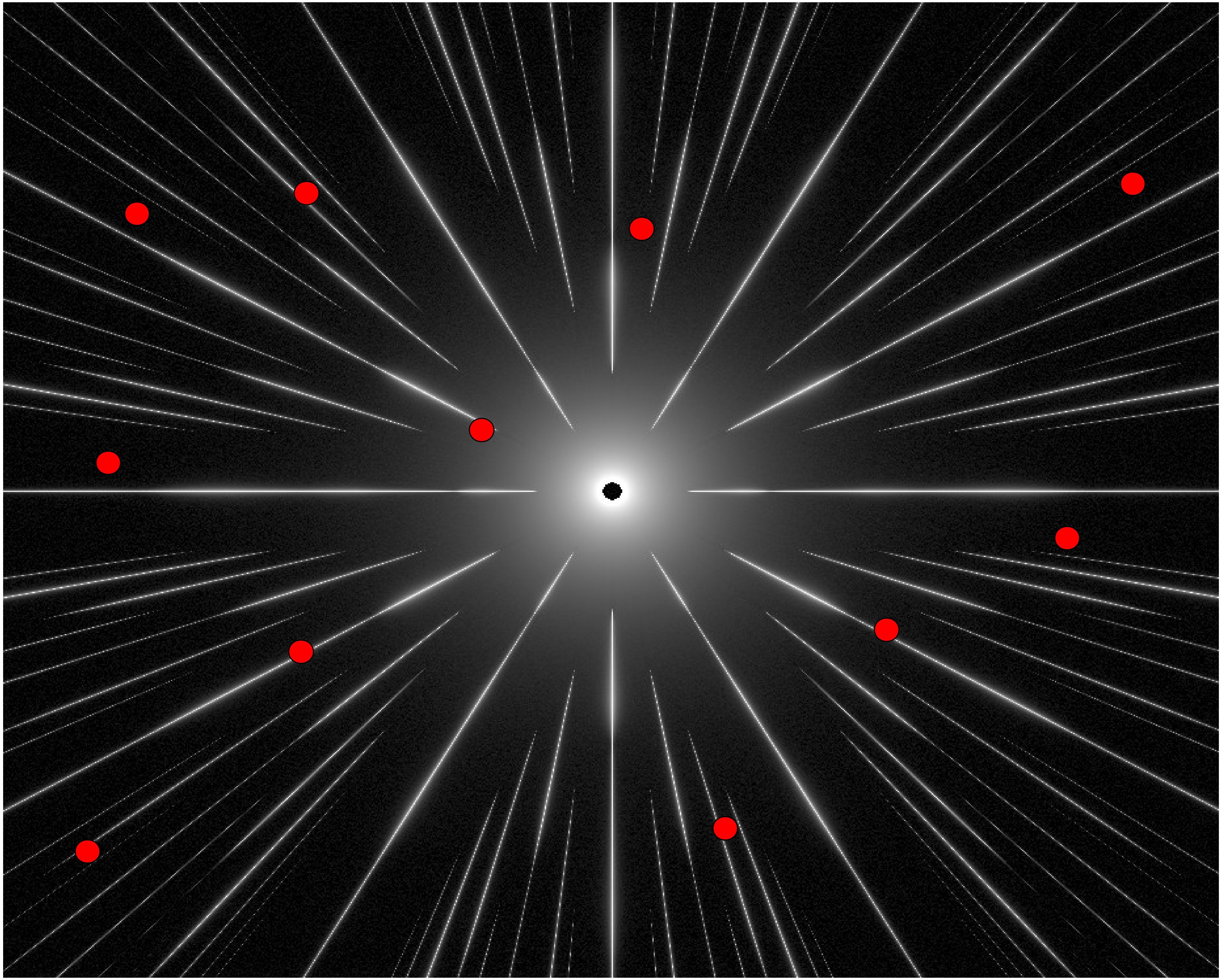
Optical Layout for simultaneous coronagraphy and astrometry

The telescope is a conventional TMA, providing a high quality diffraction-limited PSF over a 0.5 x 0.5 deg field with no refractive corrector. The design shown here was made for a 1.4m telescope (PECO).

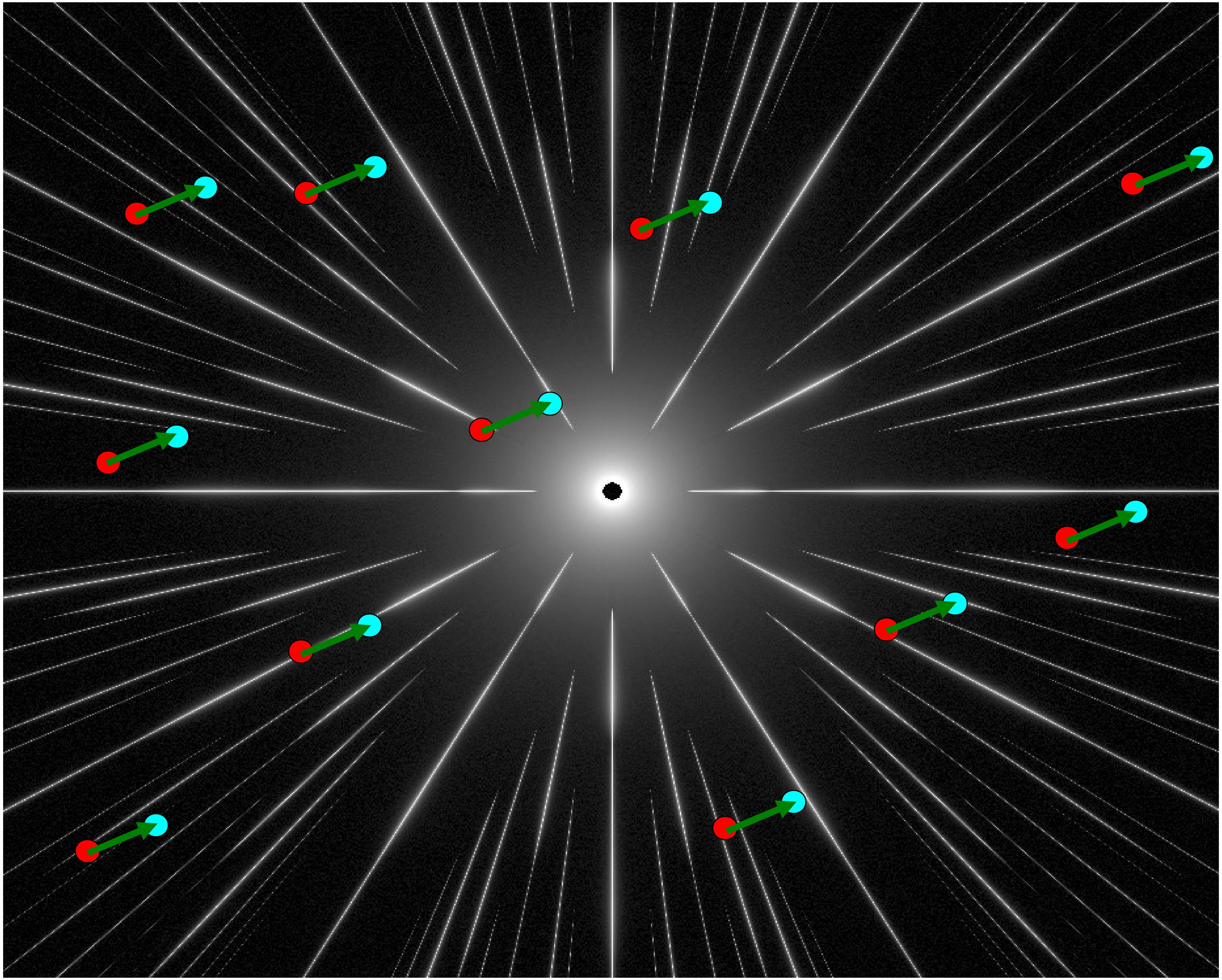
Light is simultaneously collected by the coronagraph instrument (direct imaging and spectroscopy of exoplanet) and the wide field astrometric camera (detection and mass measurement of exoplanets)



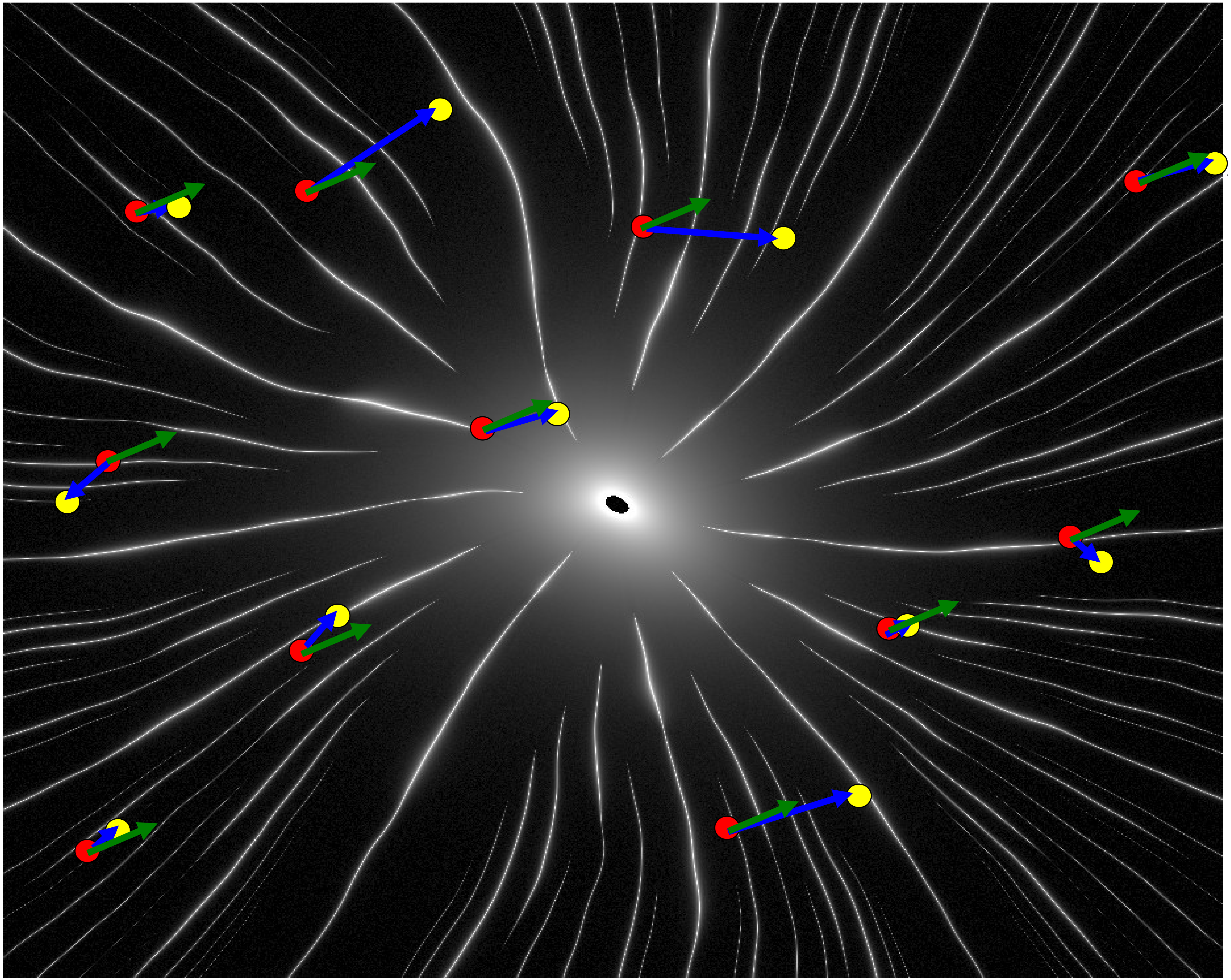
Red points show the position of background stars at epoch #1 (first observation)



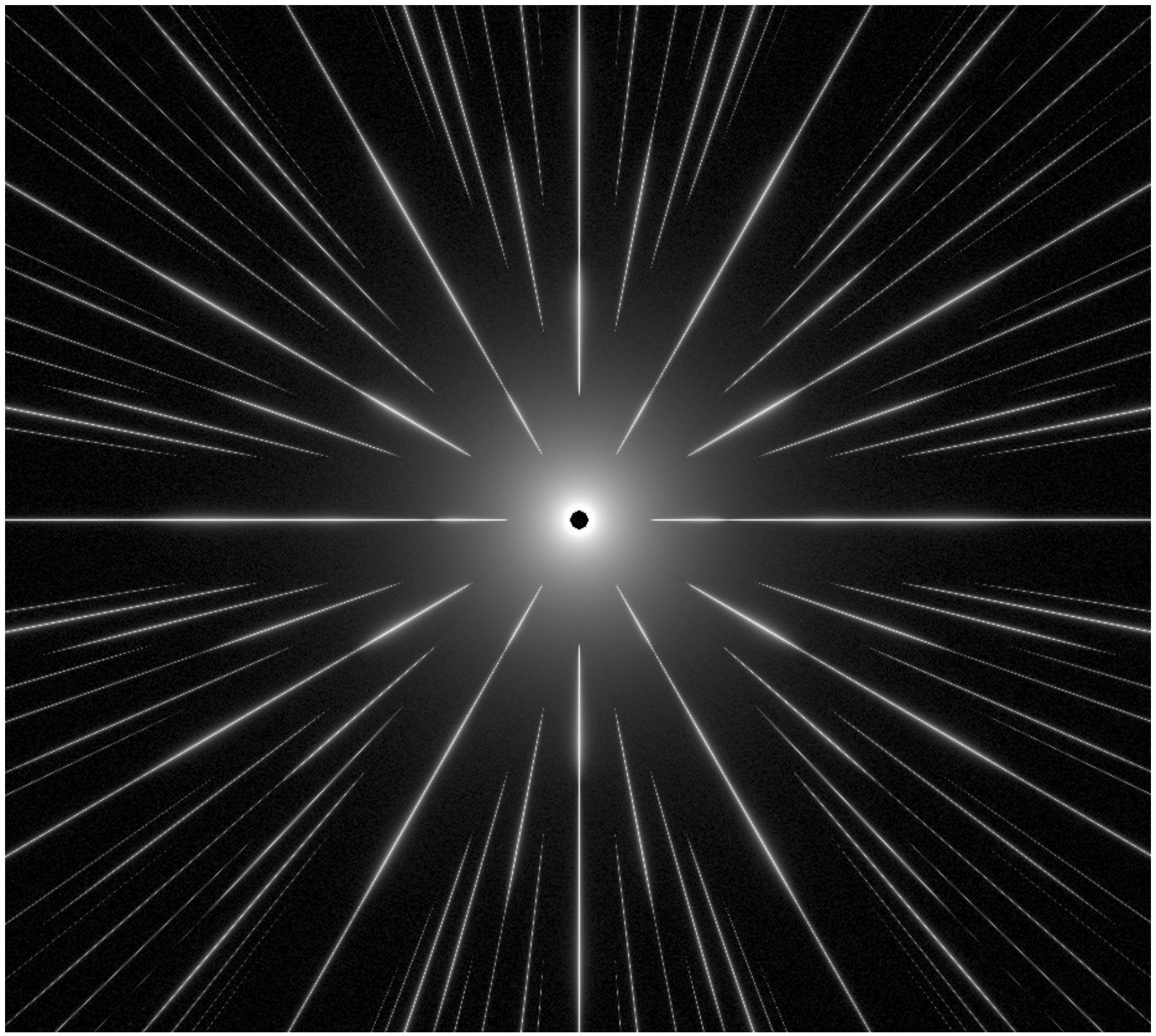
Blue points show the position of background stars at epoch #2 (second observation)
The telescope is pointed on the central star, so the spikes have not moved between the 2 observations, but the position of the background stars has moved due to the astrometric motion of the central star (green vectors).

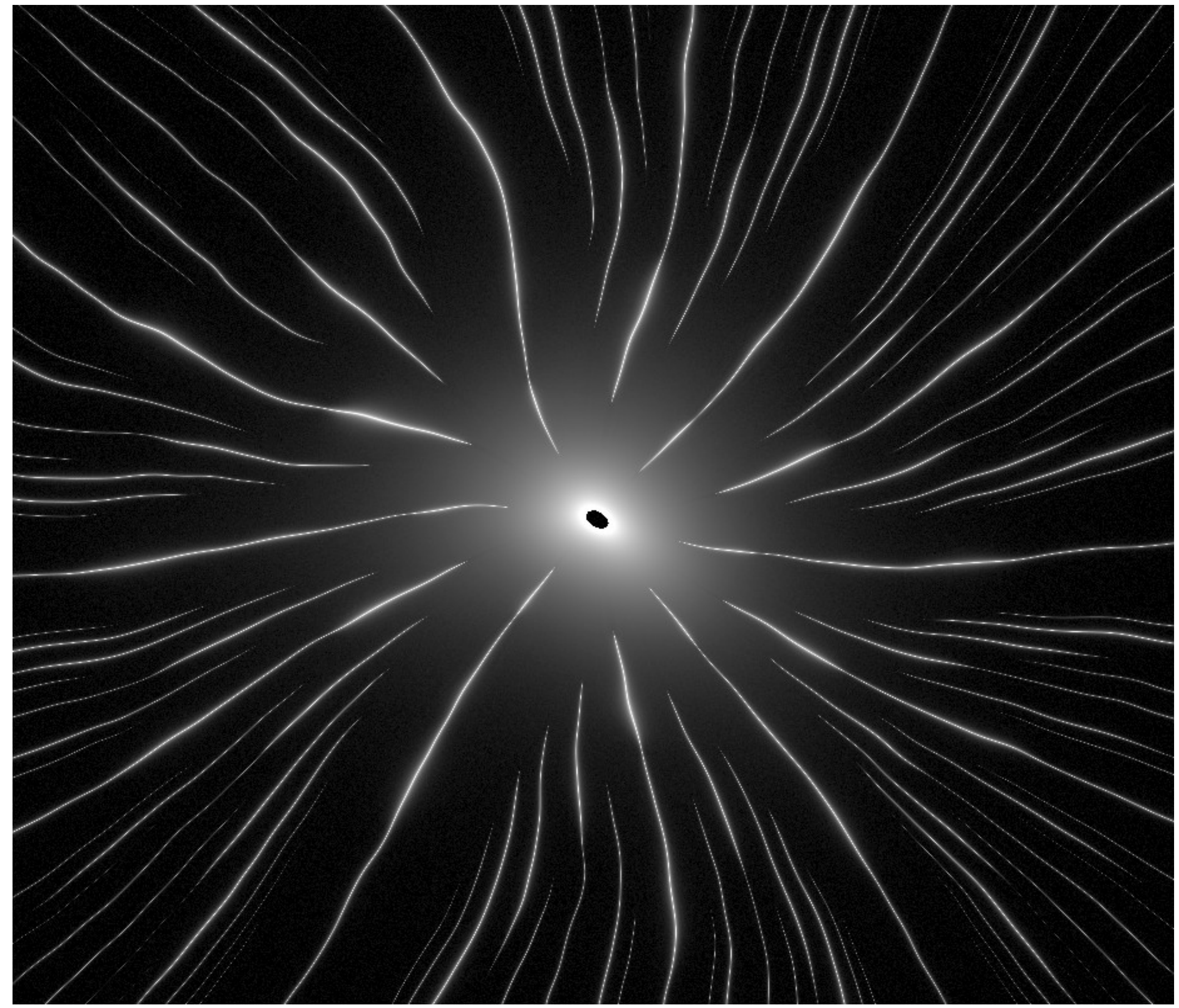


Due to astrometic distortions between the 2 observations, the actual positions measured (yellow) are different from the blue point. The error is larger than the signal induced by a planet, which makes the astrometric measurement impossible without distortion calibration.

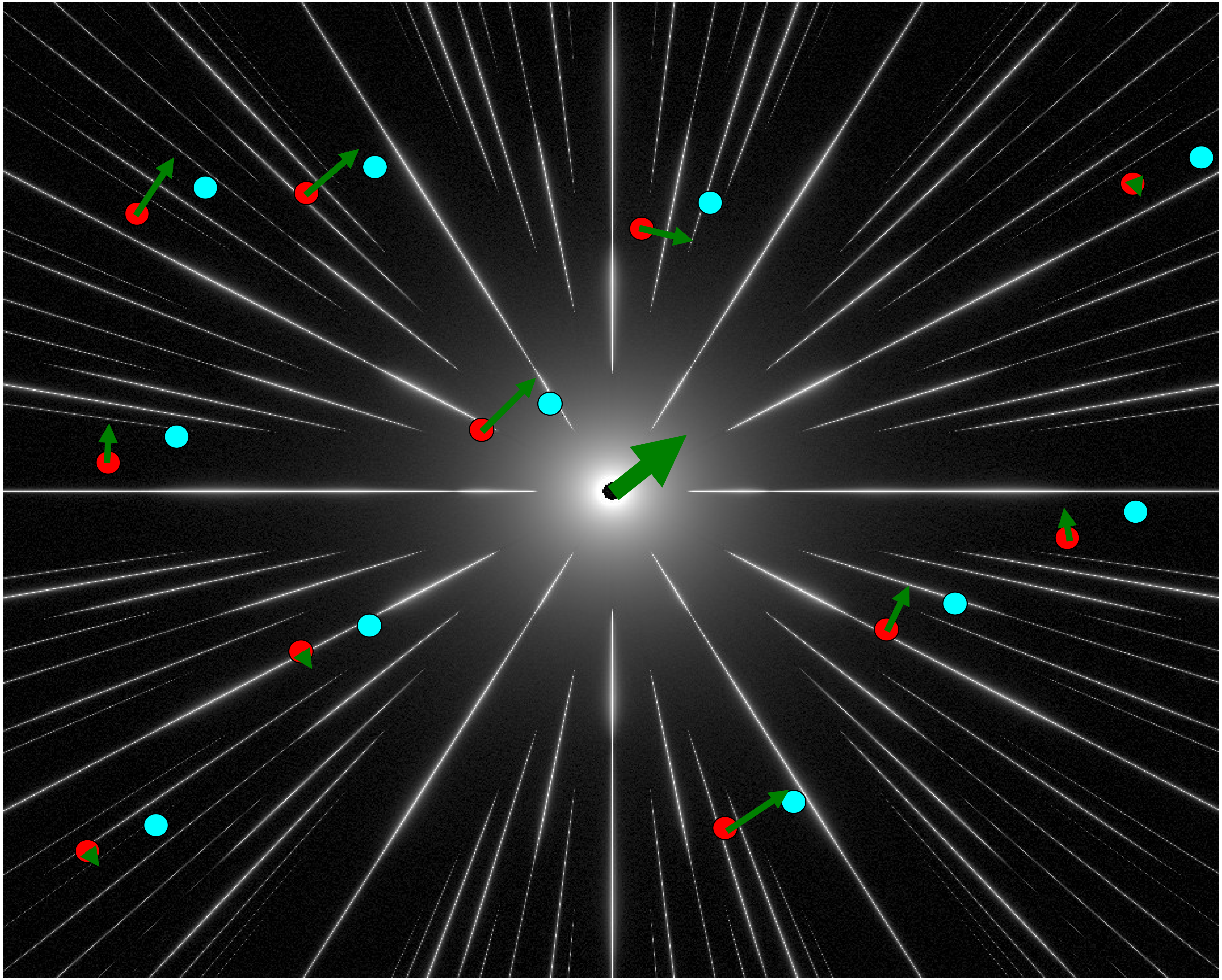


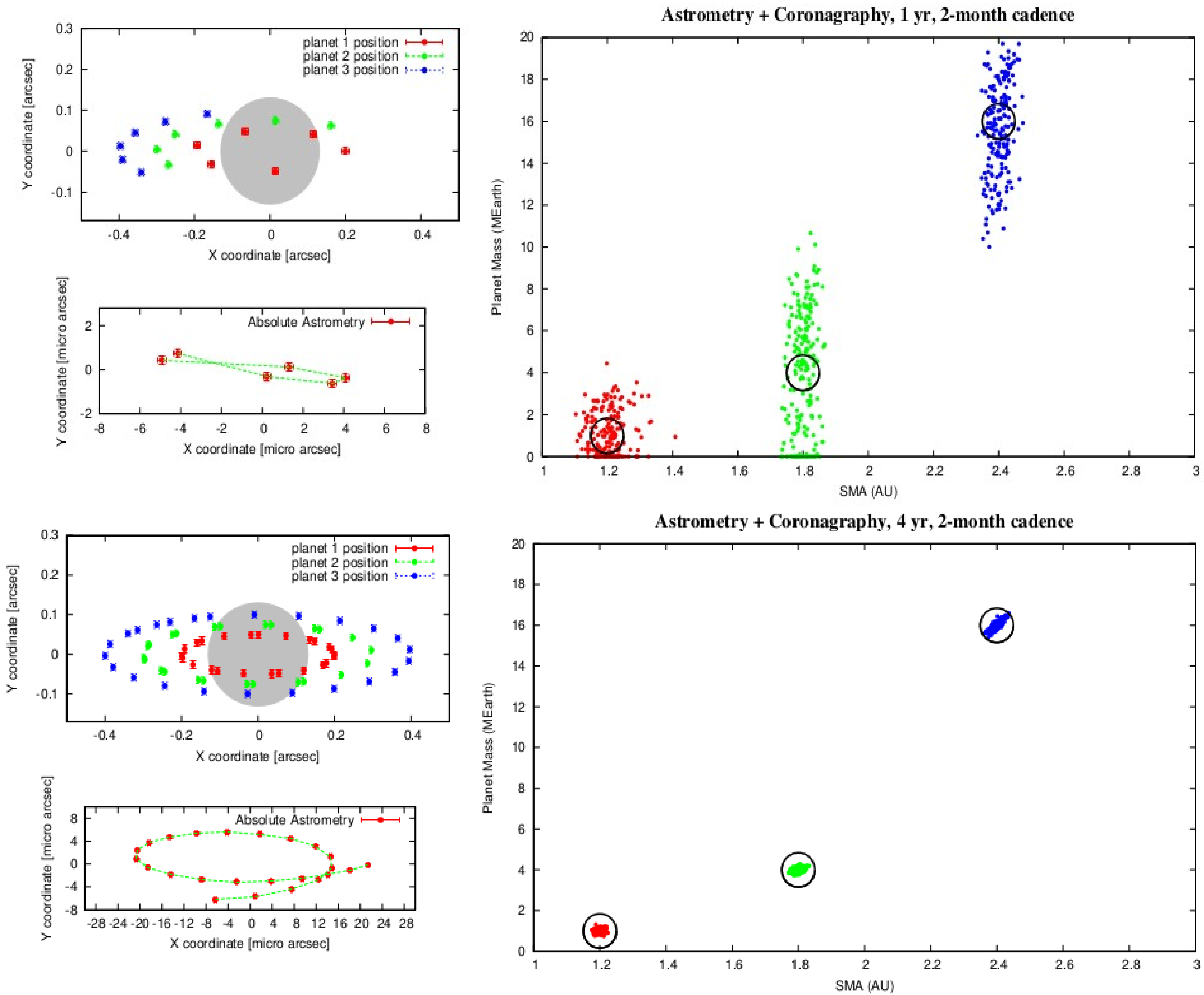
The measured astrometric motion (blue vectors in previous slide) is the sum of the true astrometric signal (green vectors) and the astrometric distortion induced by change in optics and detector between the 2 observations.
Direct comparison of the spike images between the 2 epochs is used to measure this distortion, which is then subtracted from the measurement to produce a calibrated astrometric measurement.





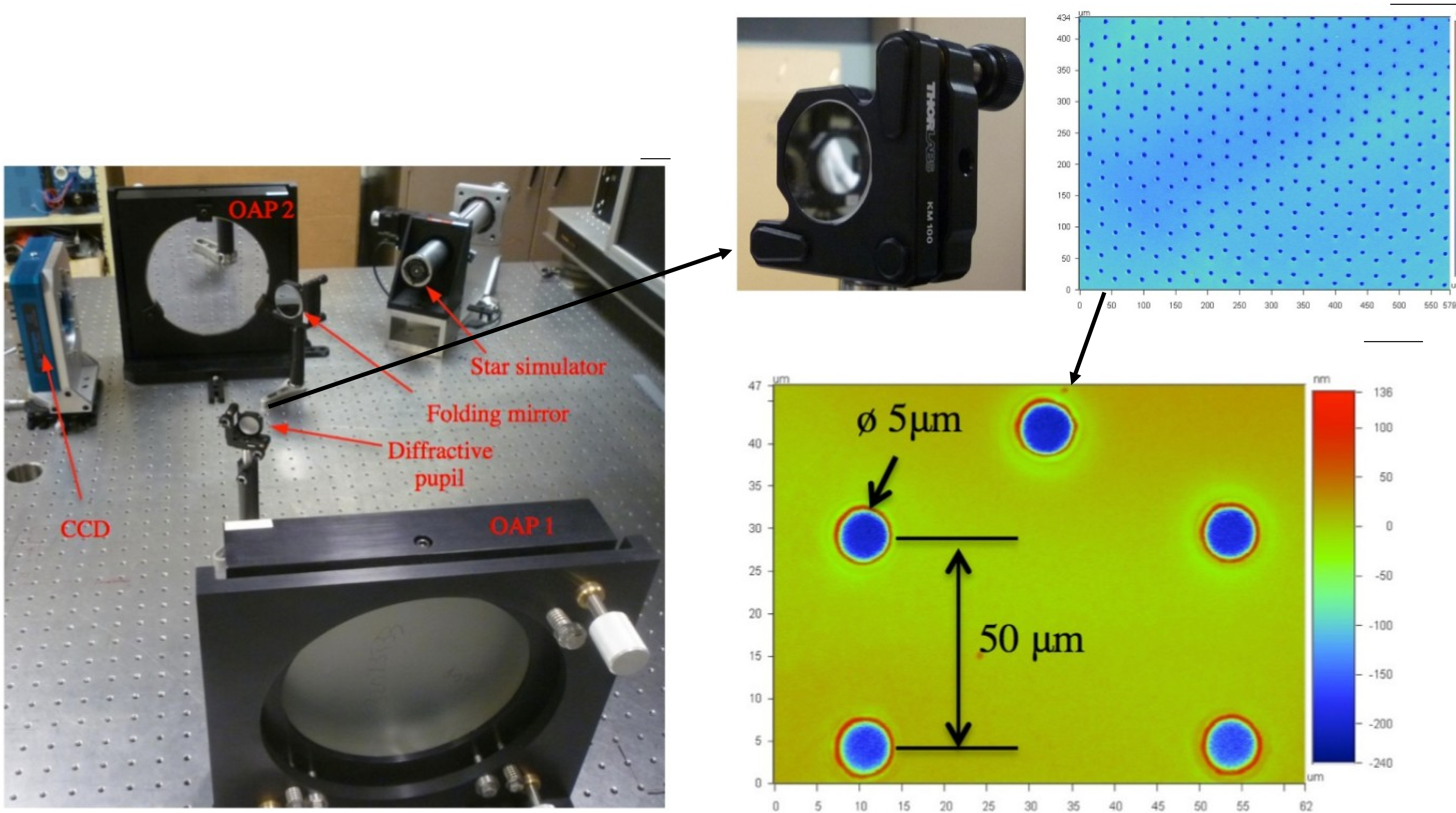
The calibration of astrometric distortions with the spikes is only accurate in the direction perpendicular to the spikes length. For a single background star, the measurement is made along this axis (1-D measurement), as shown by the green vectors. The 2-D measurement is obtained by combining all 1-D measurements (large green vector).

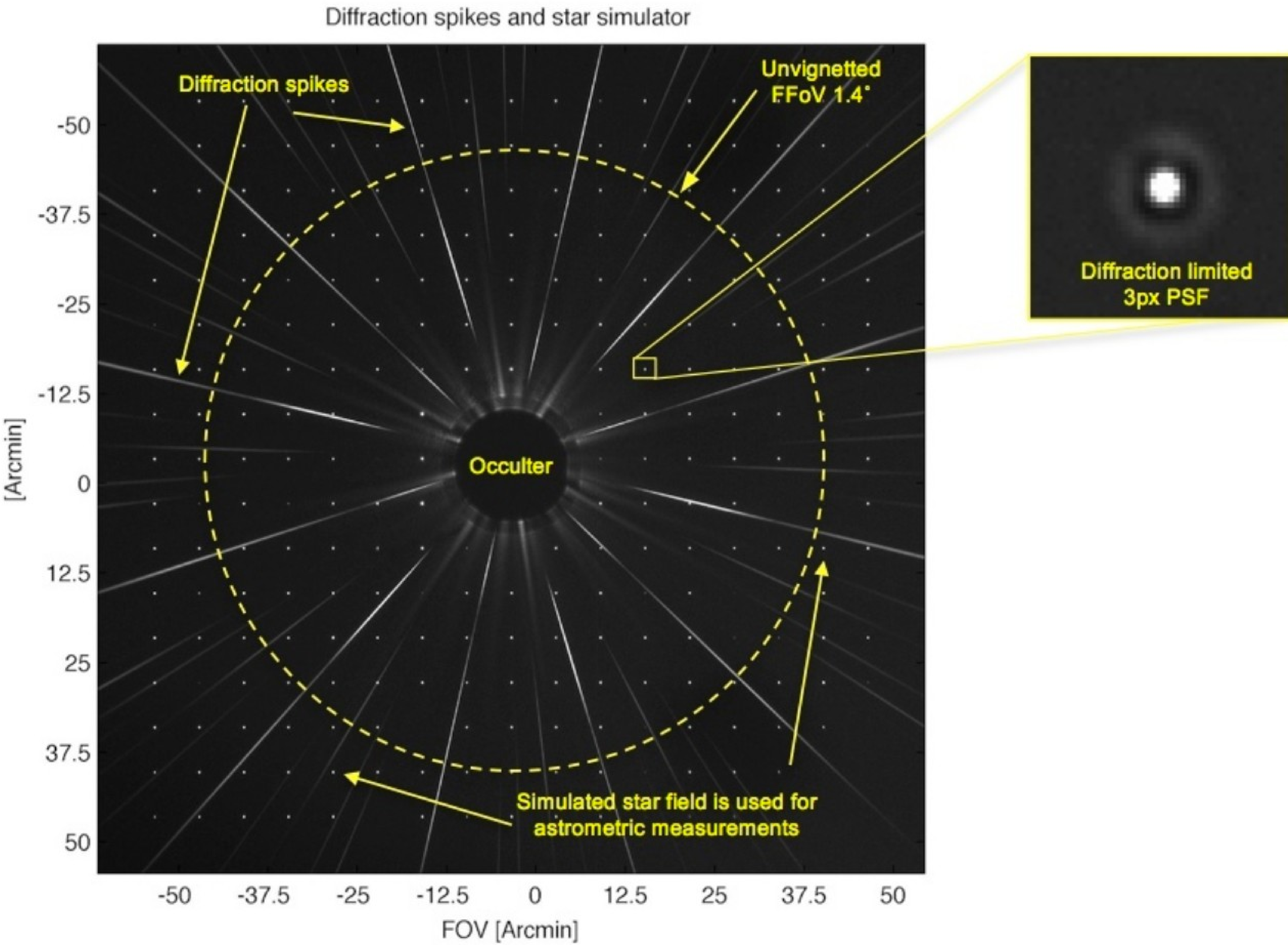




planet 1 position
planet 2 position
planet 3 position
Y coordinate [arcsec]
X coordinate [arcsec]
Absolute Astrometry
Y coordinate [micro arcsec]
X coordinate [micro arcsec]
Astrometry + Coronagraphy, 1 yr, 2-month cadence
Planet Mass (MEarth)
SMA (AU)
planet 1 position
planet 2 position
planet 3 position
Y coordinate [arcsec]
X coordinate [arcsec]
Absolute Astrometry
Y coordinate [micro arcsec]
X coordinate [micro arcsec]
Astrometry + Coronagraphy, 4 yr, 2-month cadence
Planet Mass (MEarth)
SMA (AU)

Astrometry testbed at UofA
E. Bendek et al.
(testbed moving to NASA Ames)

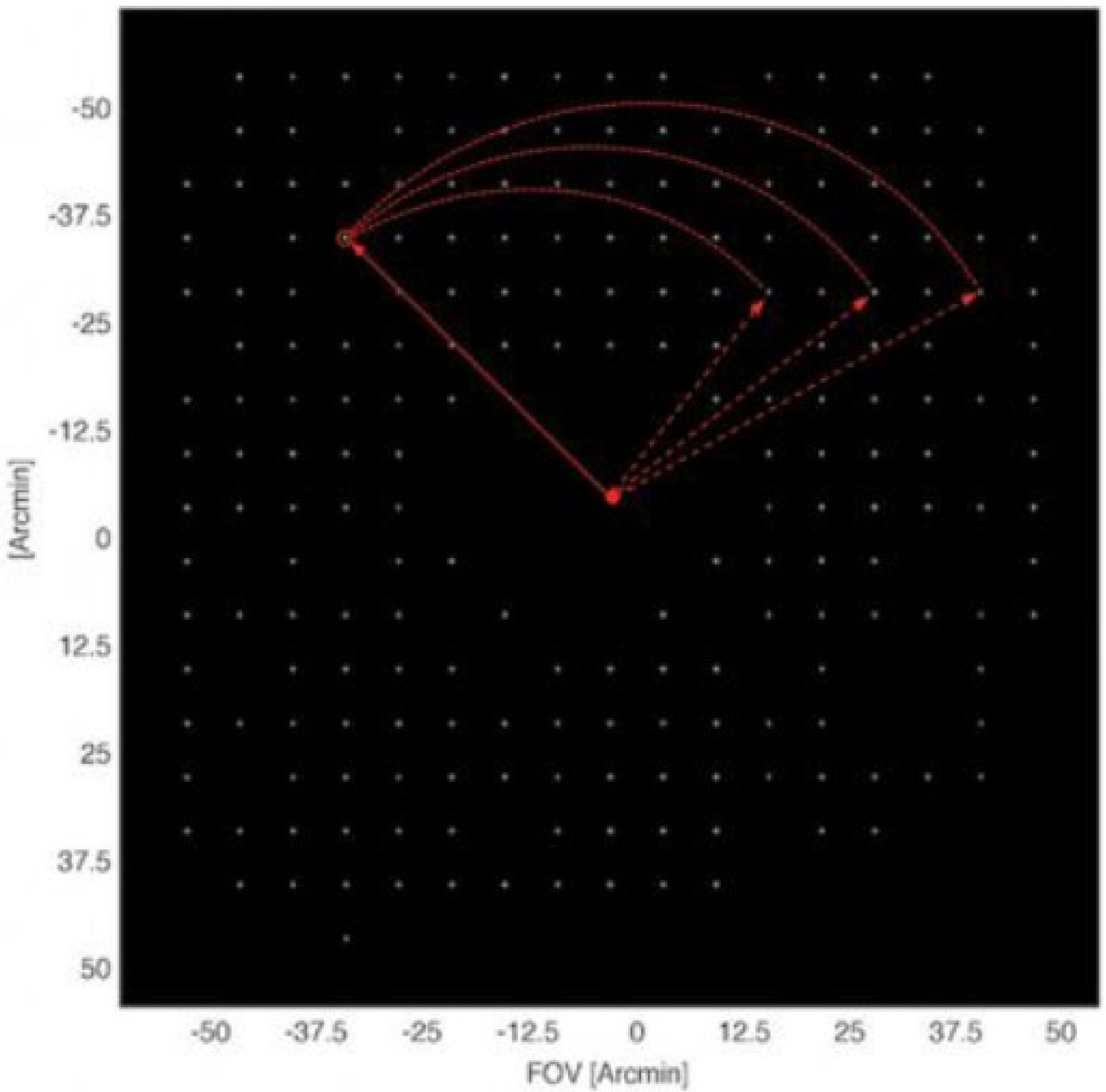


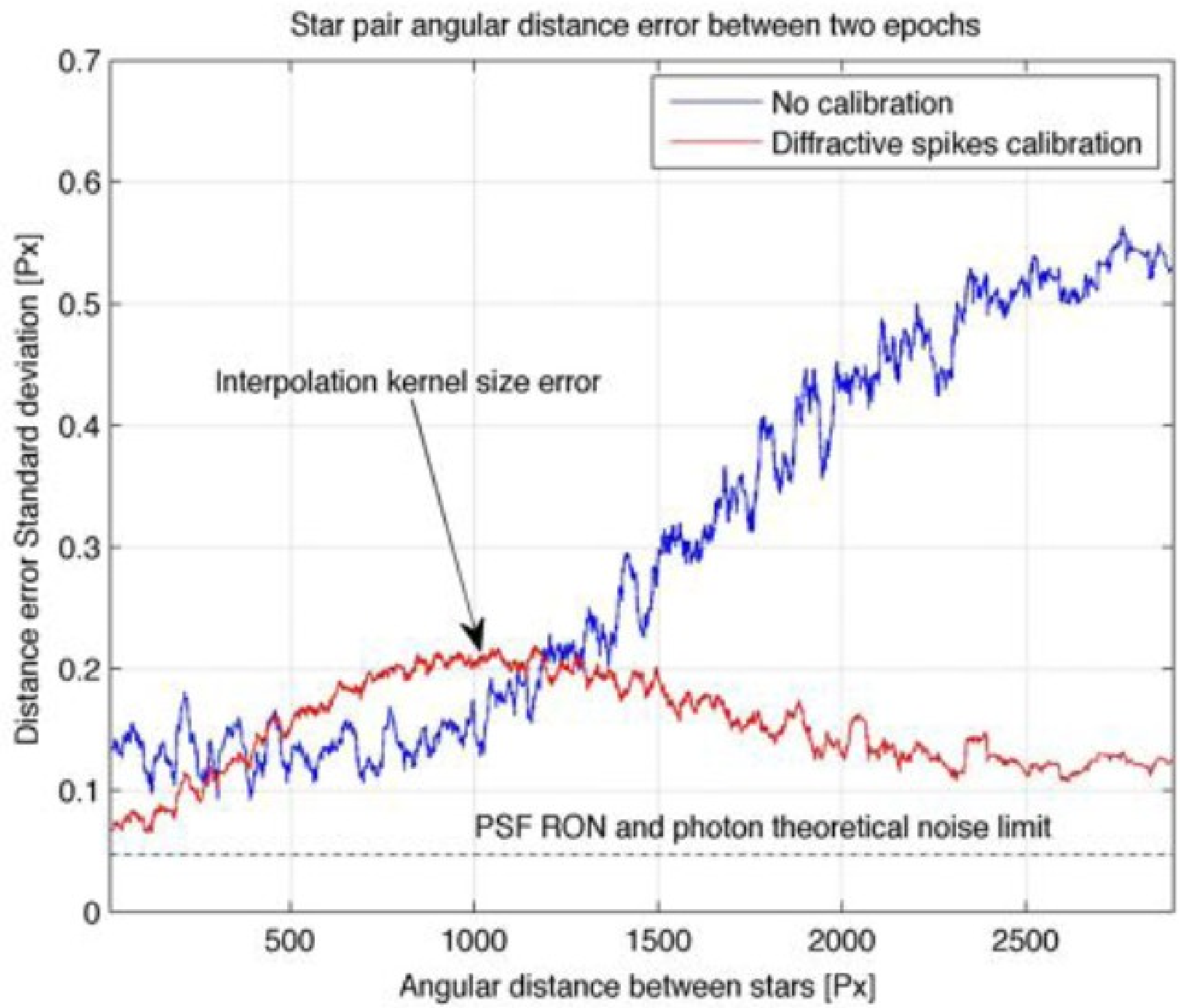


Diffraction spikes and star simulator
Diffraction spikes
Unvignetted FFoV 1.4˚
Occulter
Diffraction limited 3px PSF
Simulated star field is used for astrometric measurements
[Arcmin]
FOV [Arcmin]
-50
-37.5
-25
-12.5
0
12.5
25
37.5
50

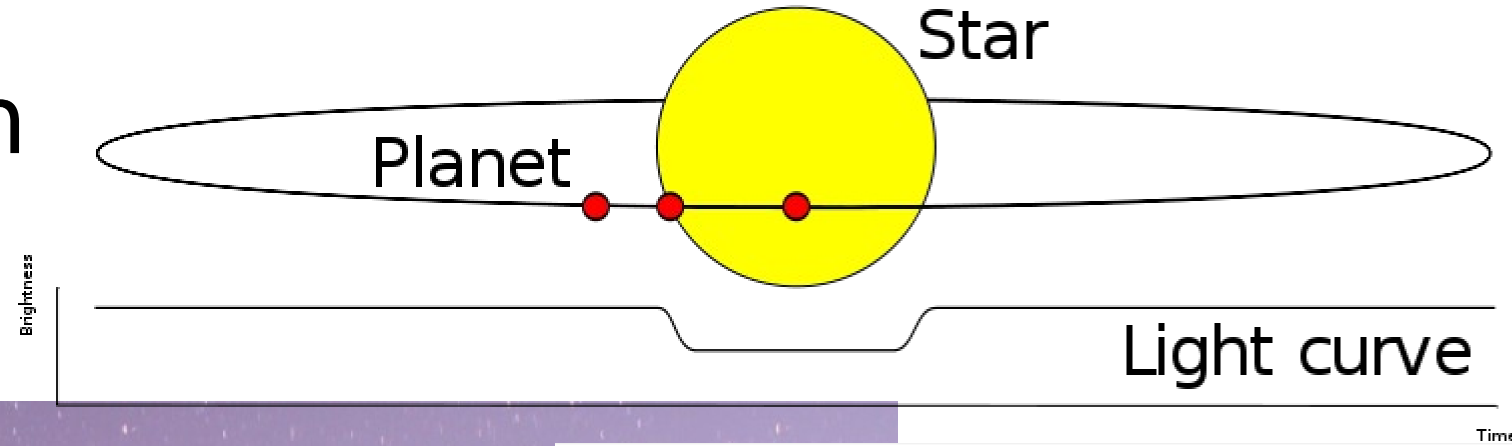
Laboratory validation (E. Bendek)

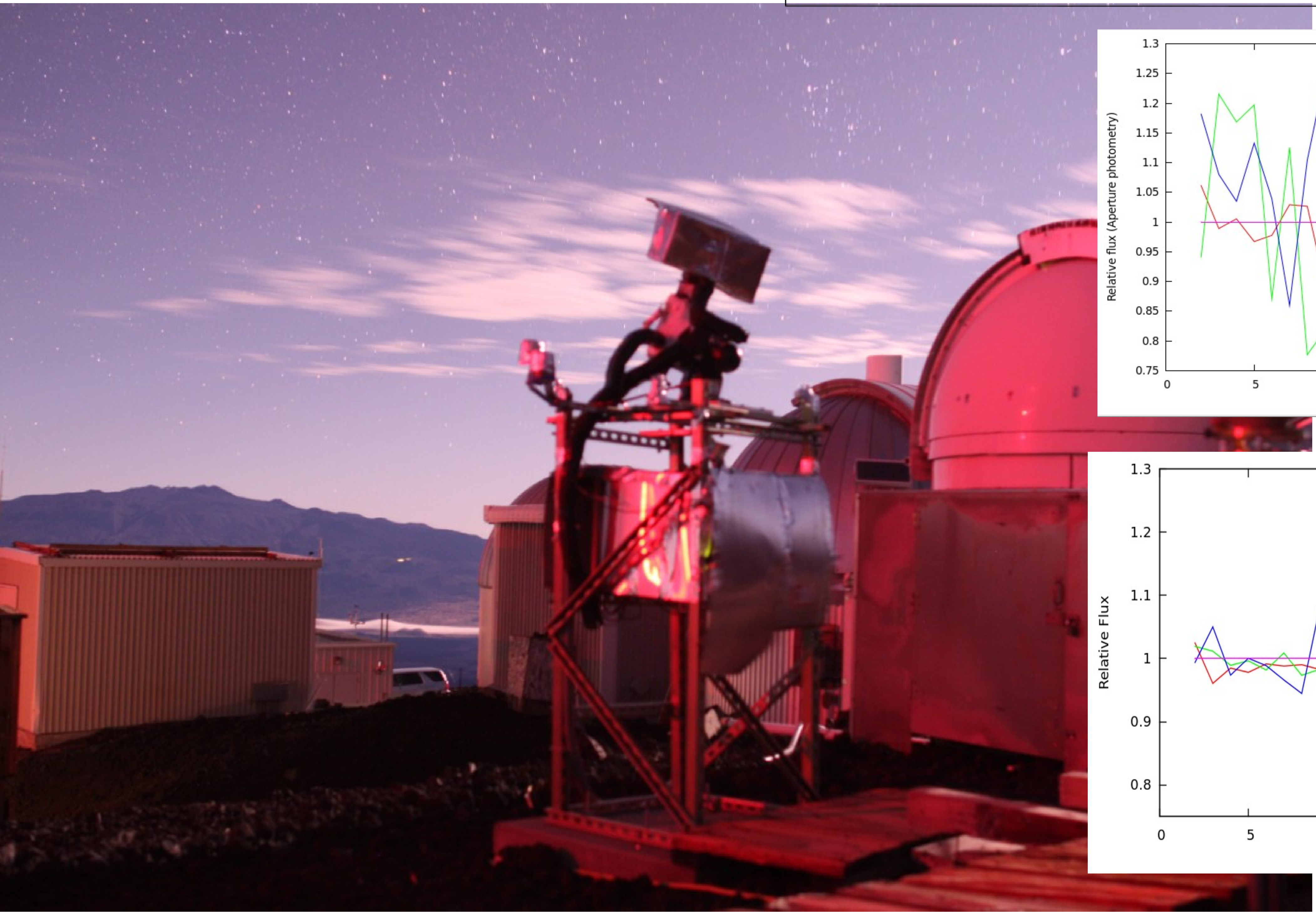
With astrometric calibration using spikes, astrometric error does not increase with angular separation or time

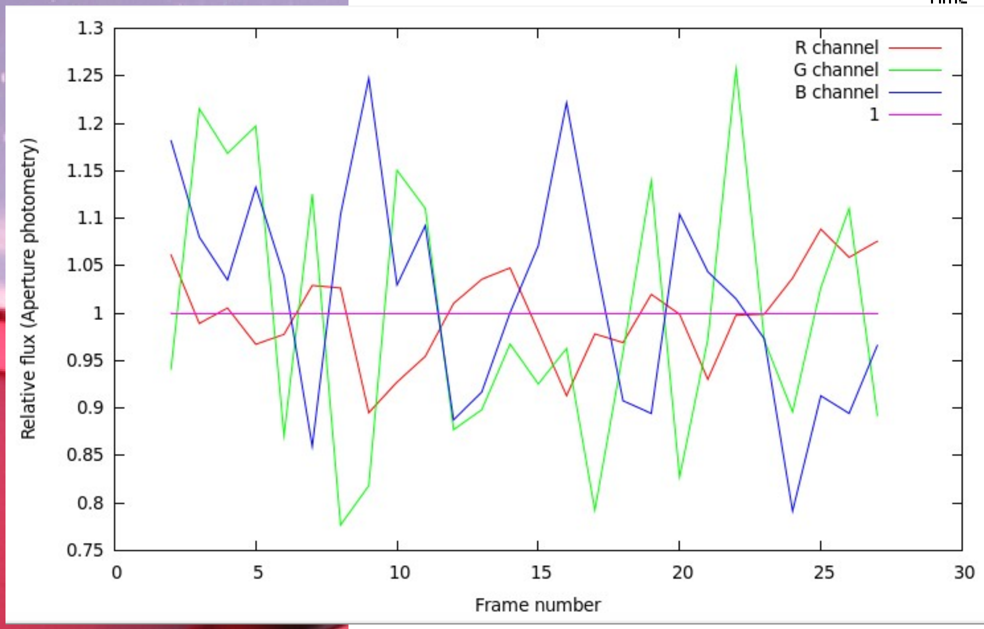


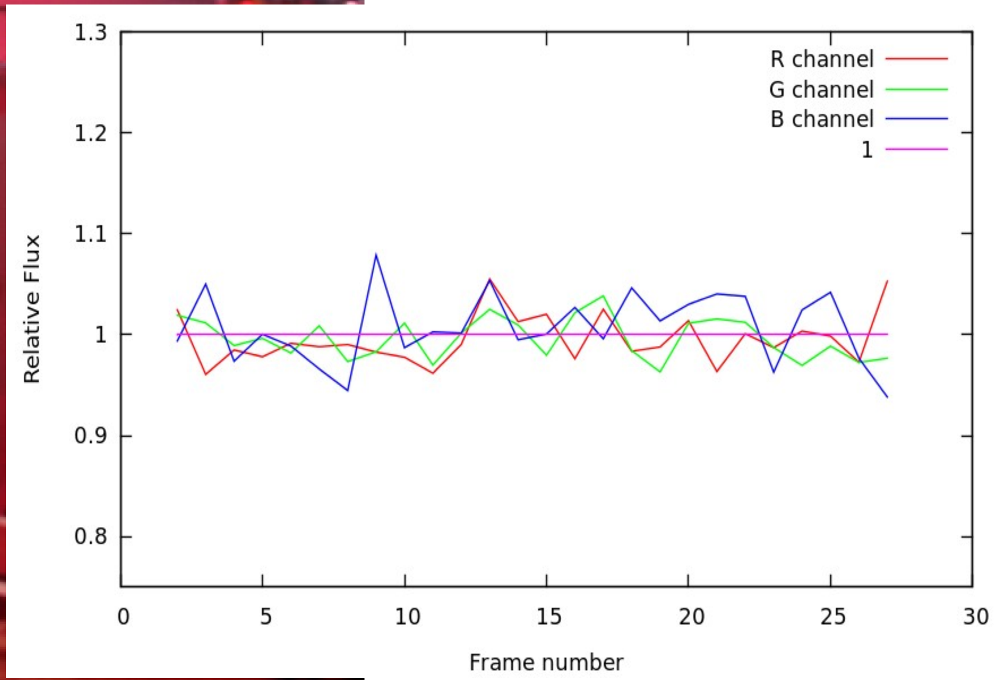


Exoplanet transit with commercial DSLRs









Transit Field #1 (in Cygnus), camera 2 (Sept 11, 2012 UT)

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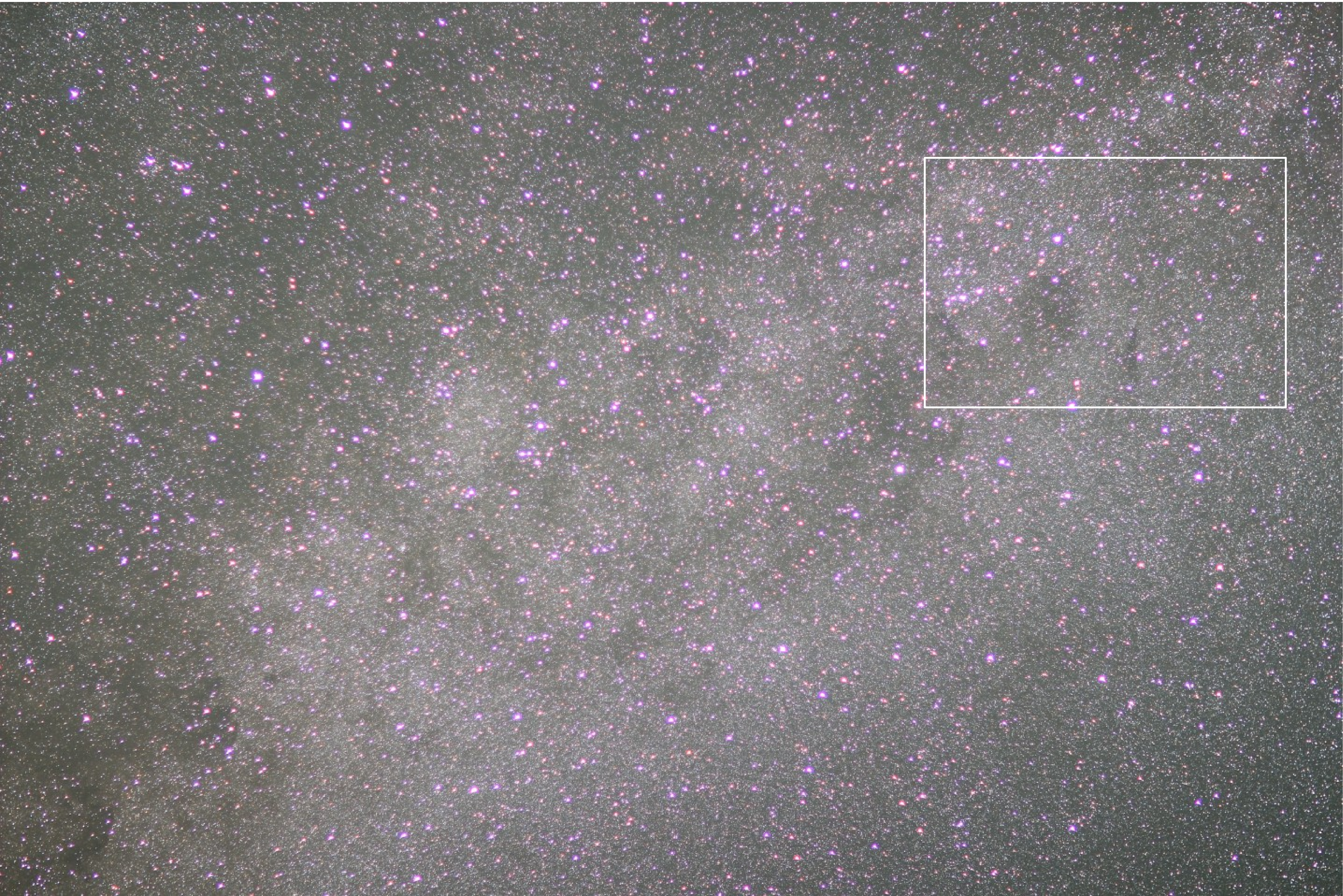
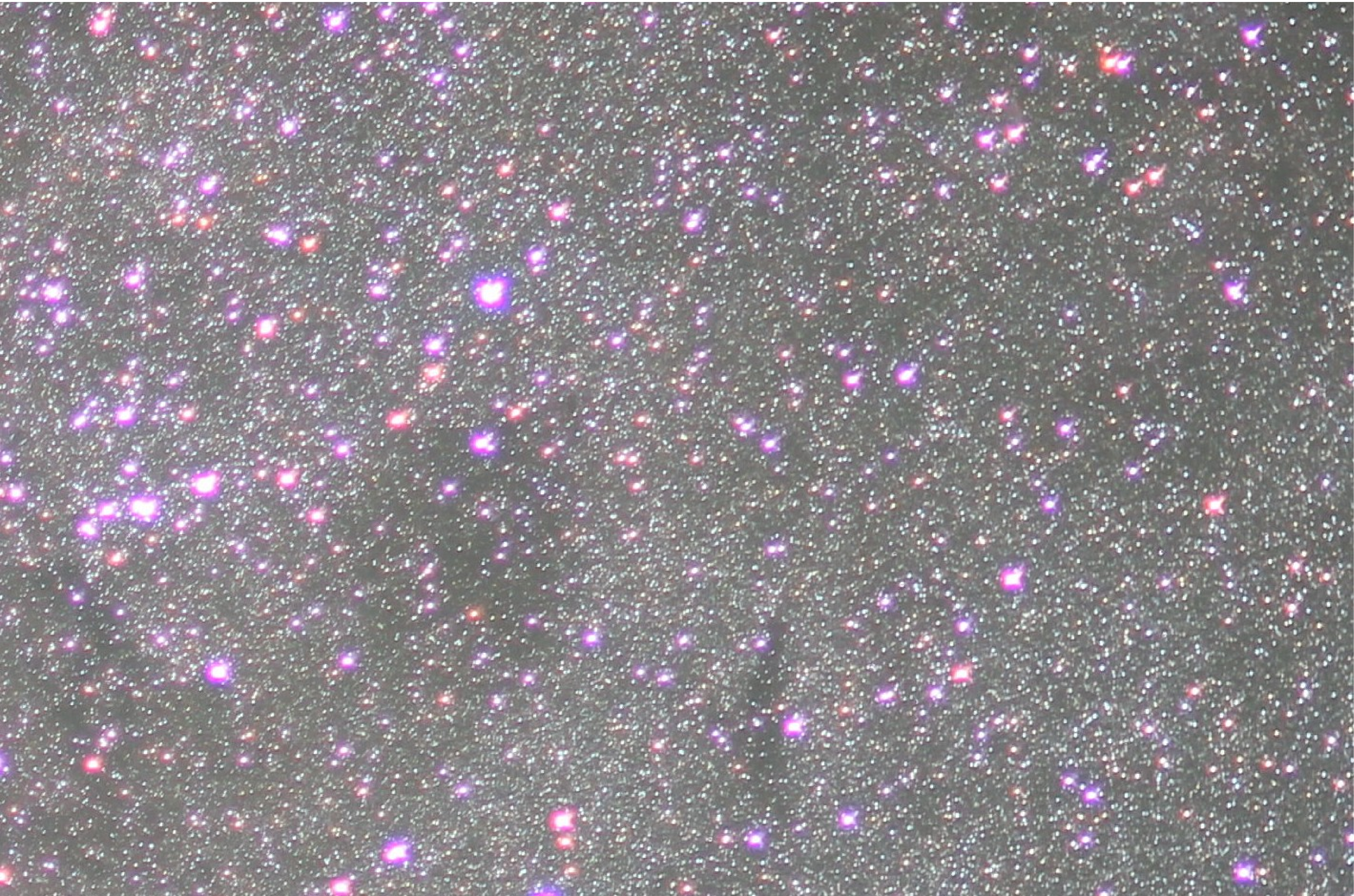
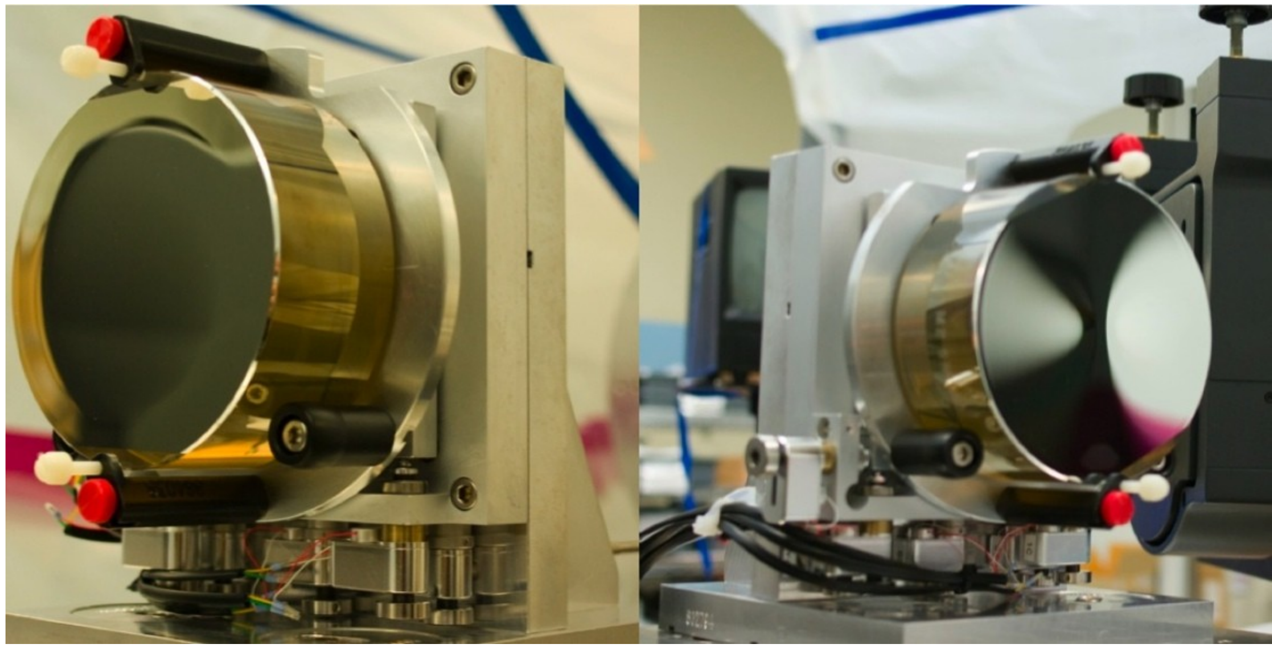


Transit Field #1 (in Cygnus), camera 2 (Sept 11, 2012 UT)



Conclusions



Observation of exoplanets requires high precision
AND unusual optical systems

- built-in calibration (astrometry)
- high wavefront quality
- high stability

Direct imaging is especially challenging
BUT also very scientifically rewarding

Unique opportunities in near future, using new optical tricks:
Extremely Large Telescopes (ELTs)
Space telescopes