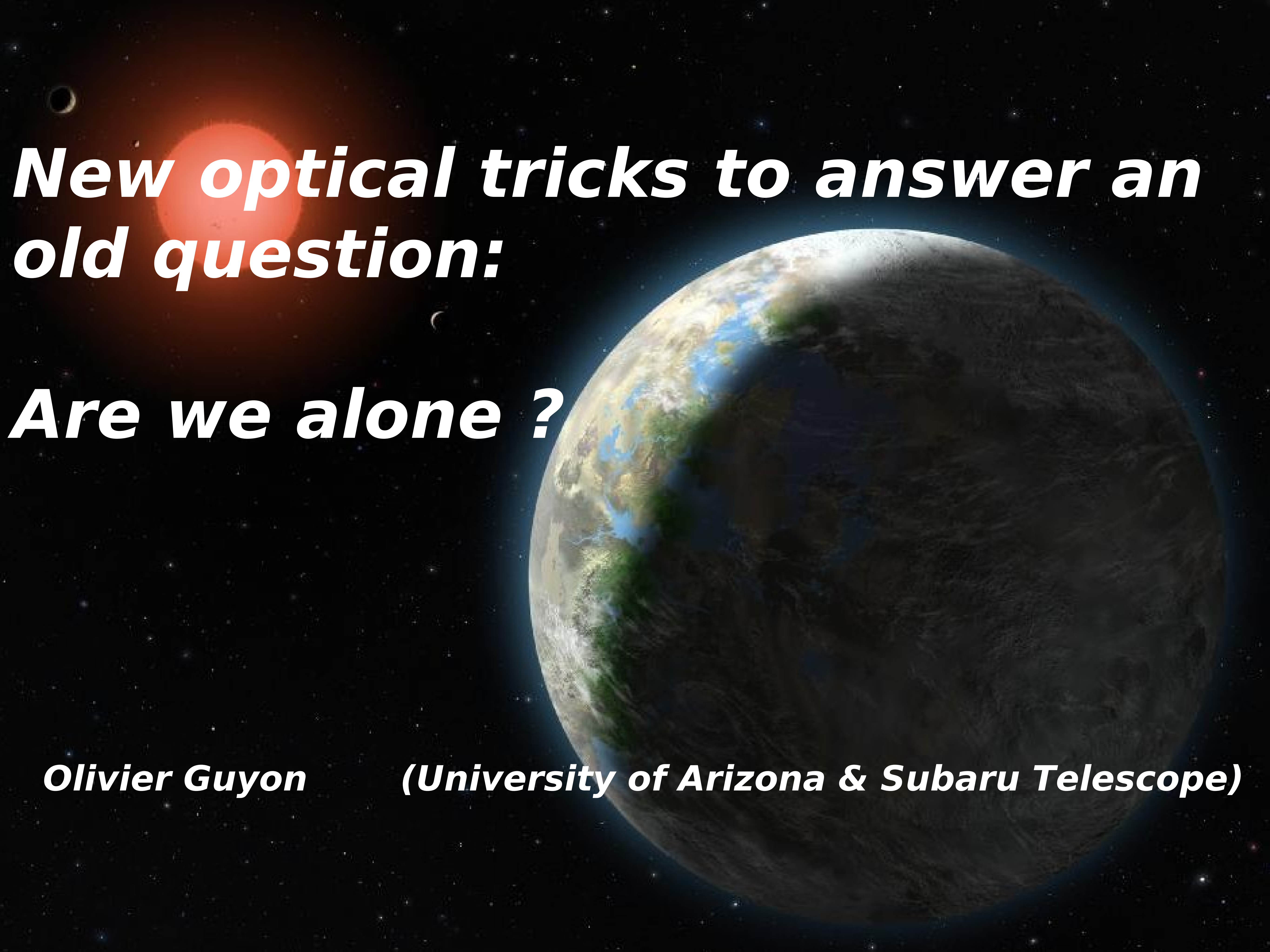


New optical tricks to answer an old question:

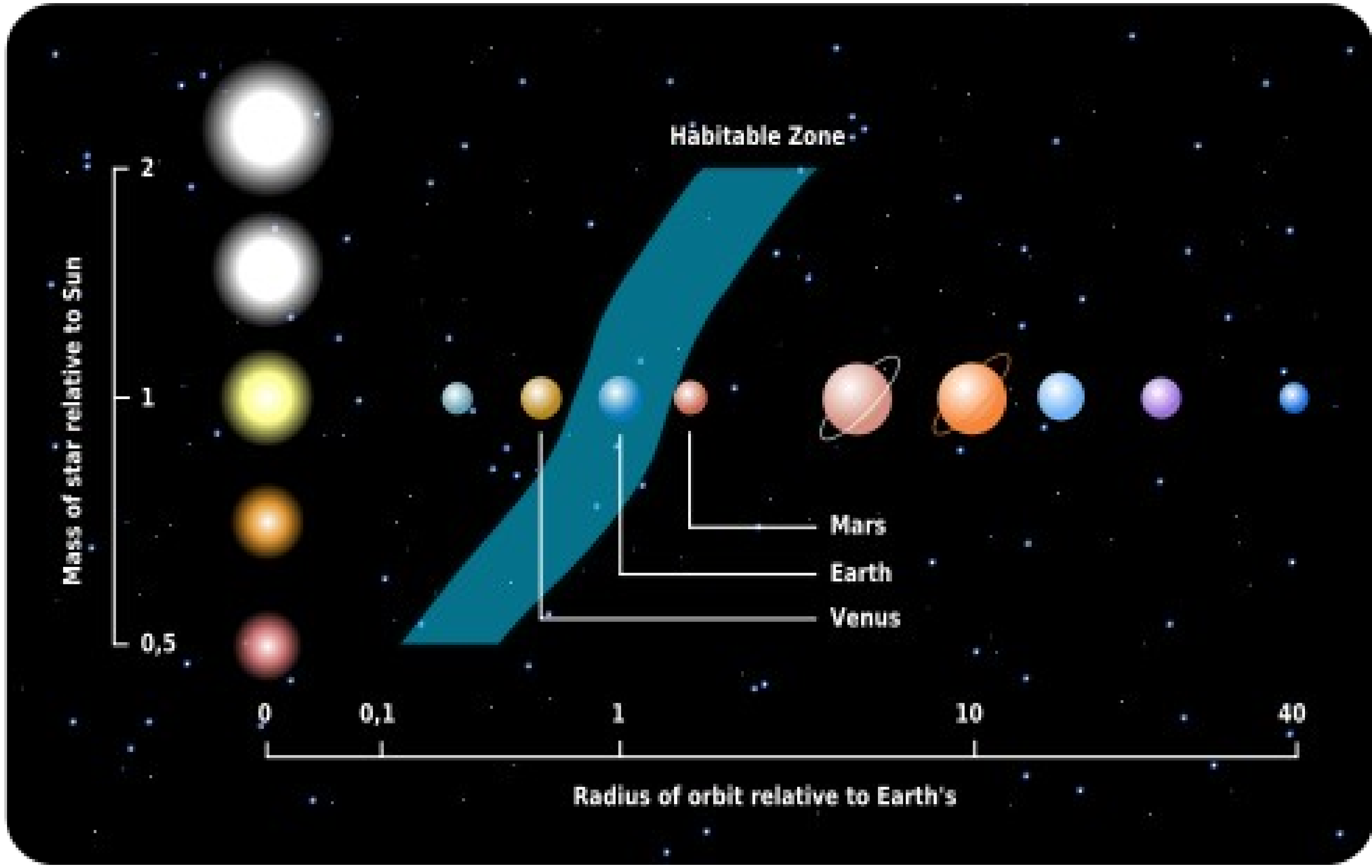
Are we alone ?

Olivier Guyon *(University of Arizona & Subaru Telescope)*

Exoplanets

839 exoplanets confirmed belonging to 662 exoplanetary systems

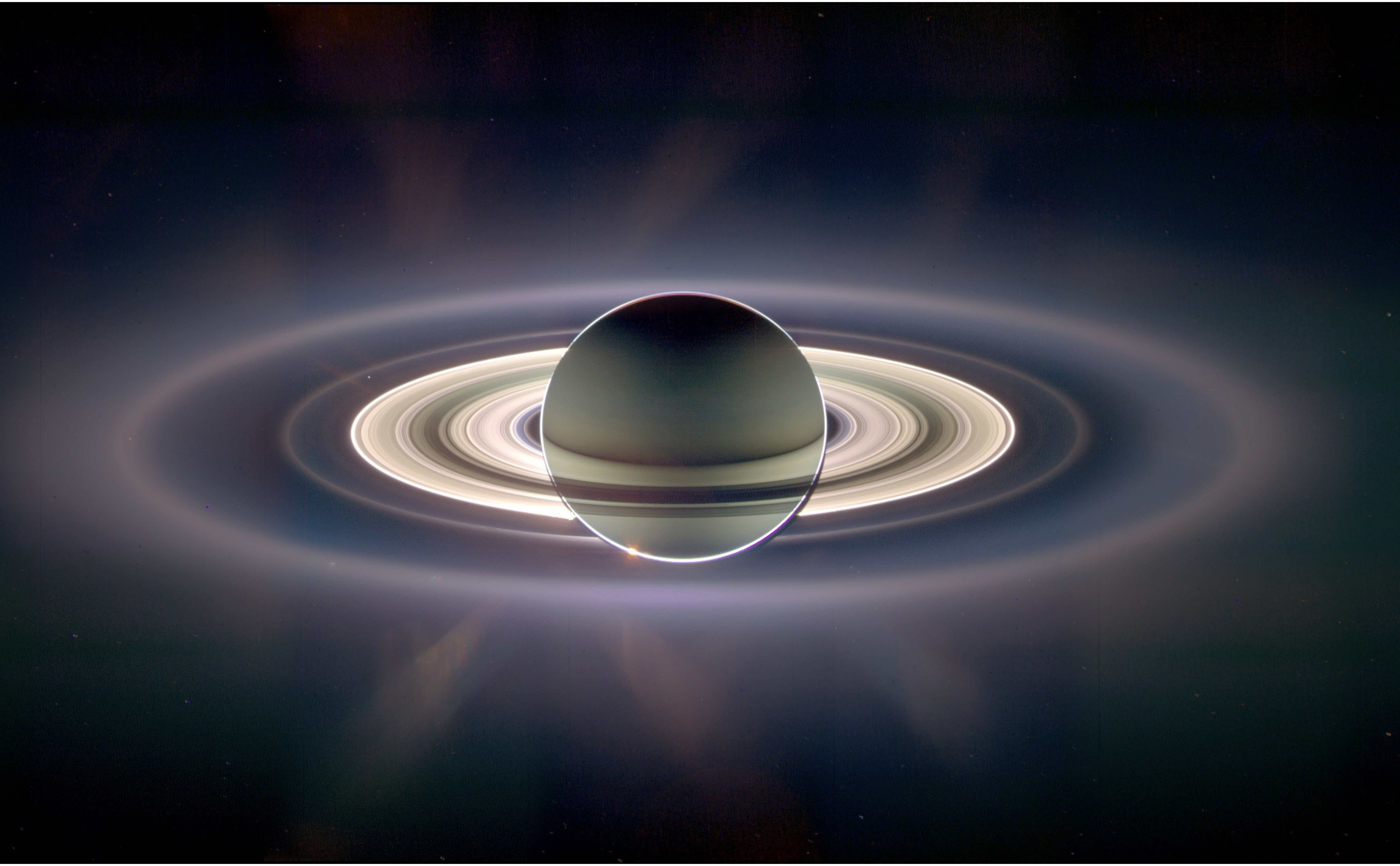
Almost all planets are indirectly detected... we do not know much about them

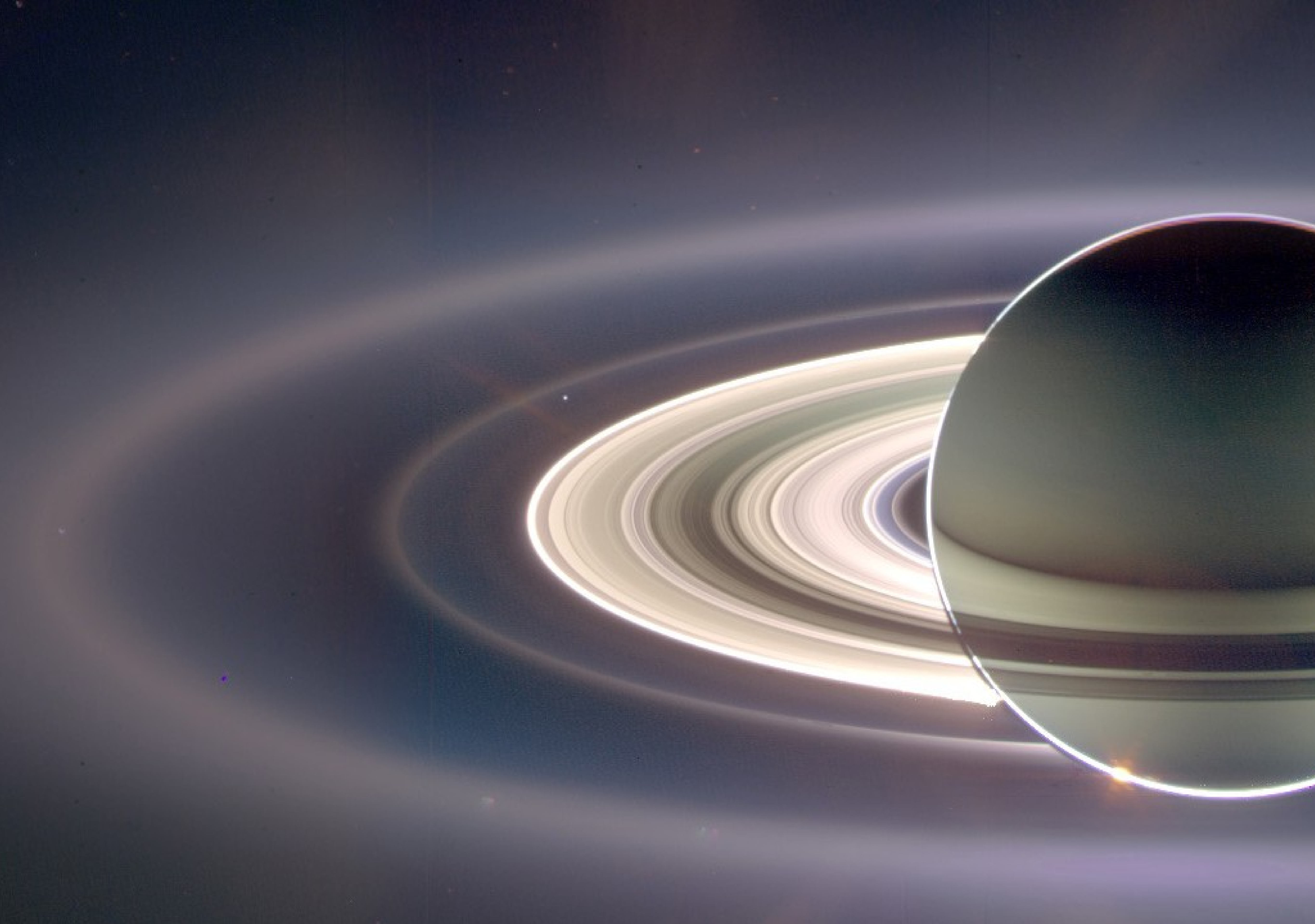


Most planets are ~Jupiter mass. Potentially habitable planets are very difficult to detect with current techniques

→ 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

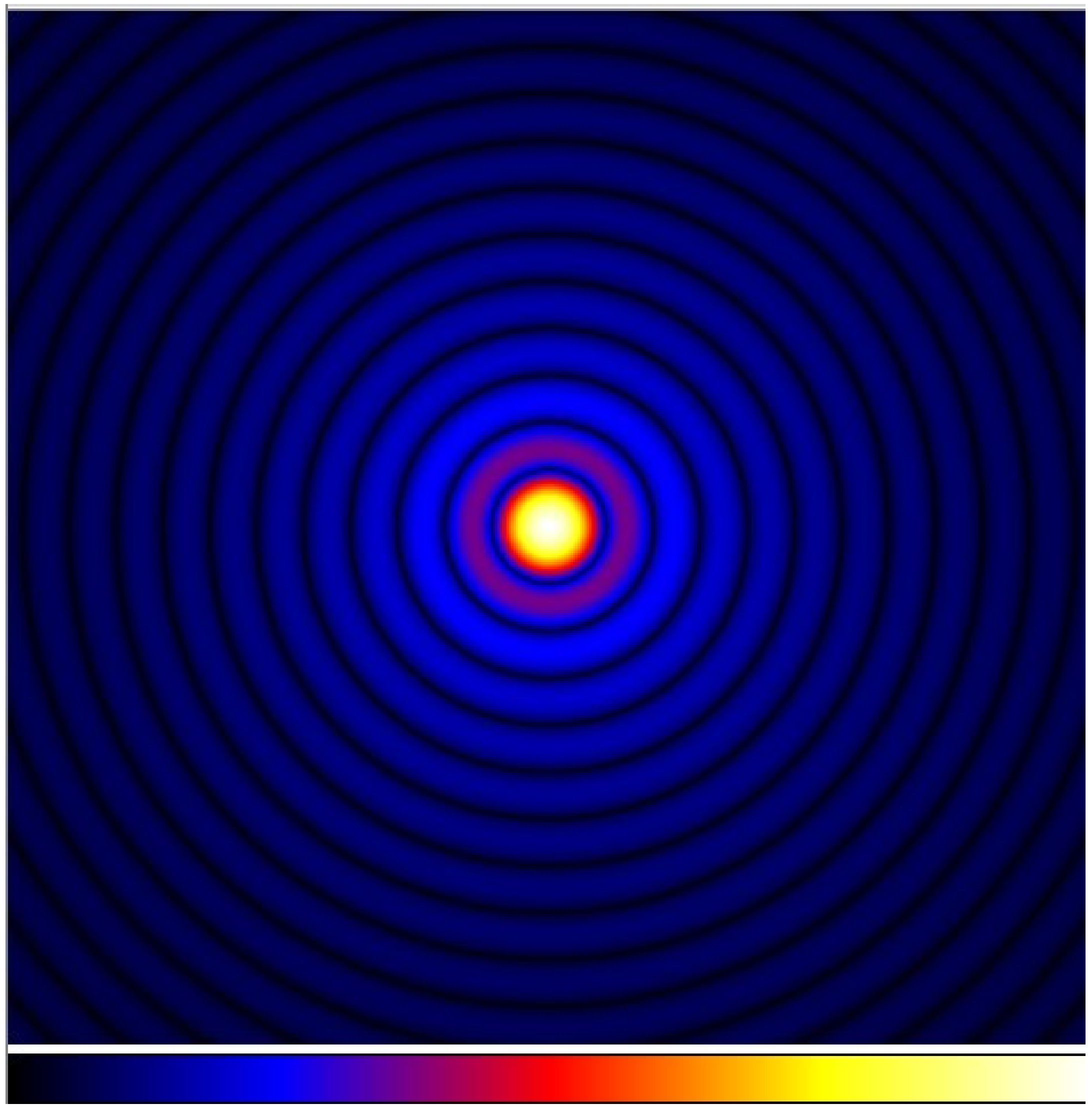
Conventional telescopes won't work !

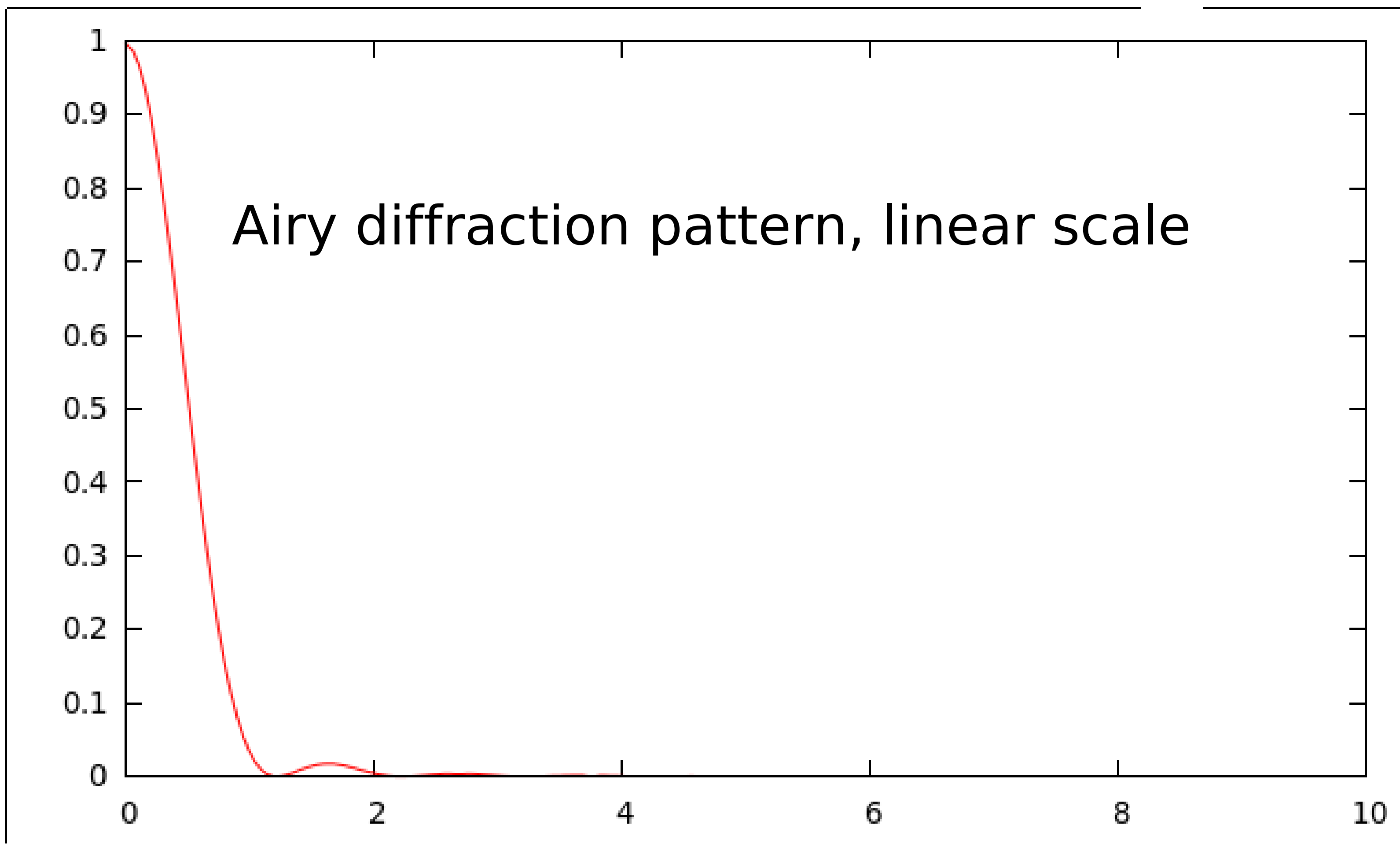


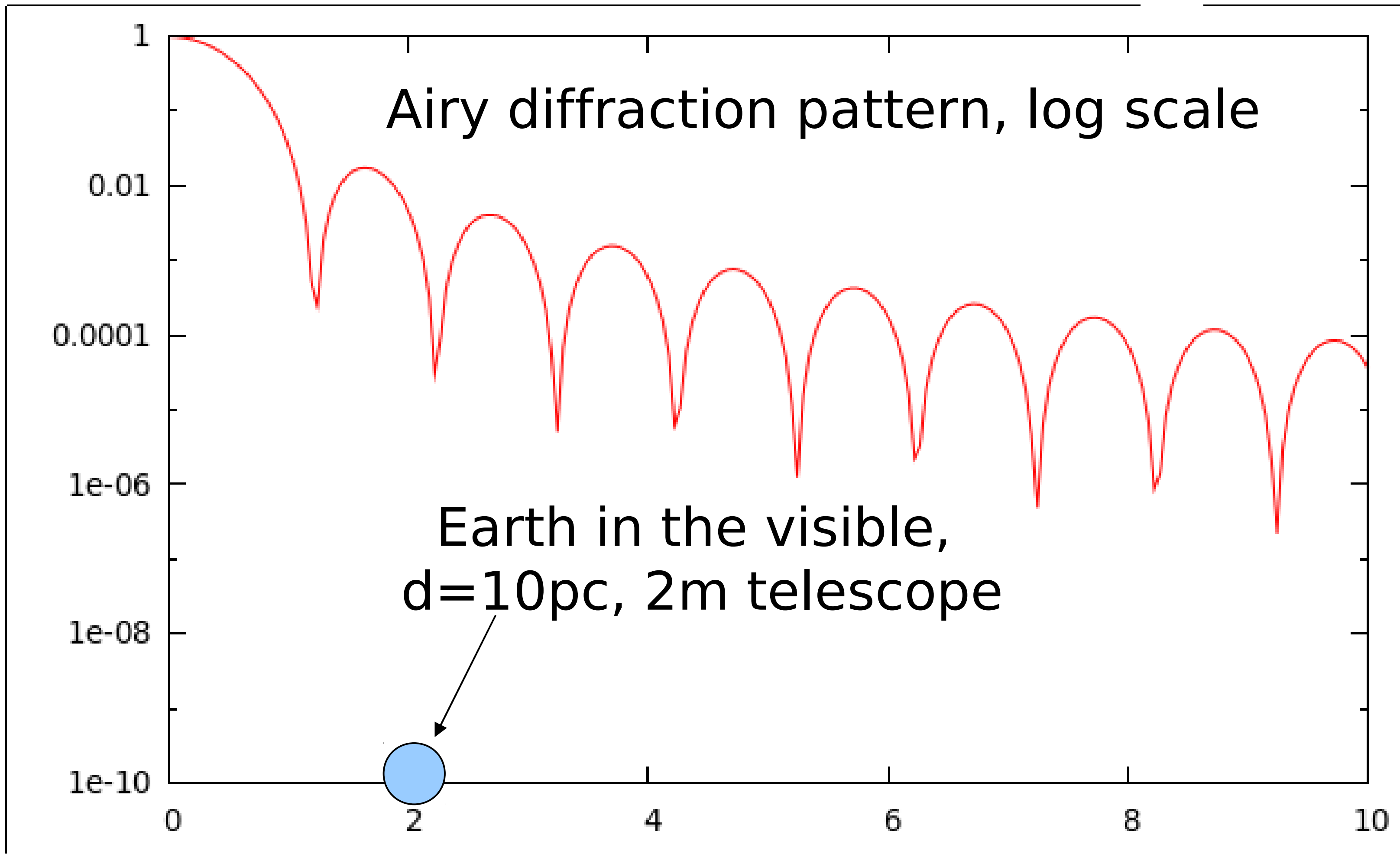


Why coronagraphy ?

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





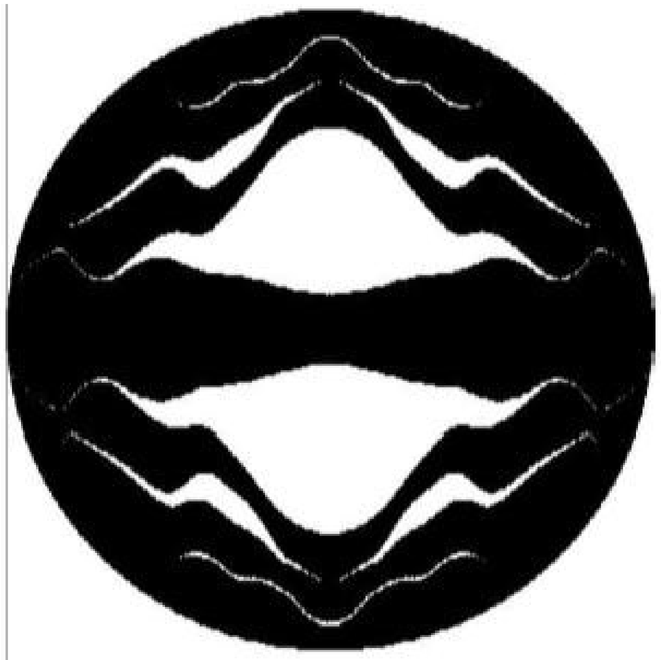


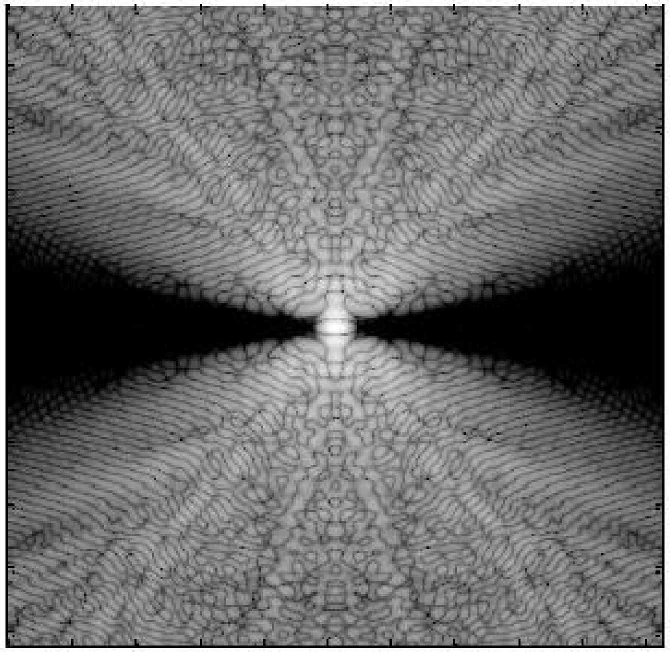
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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





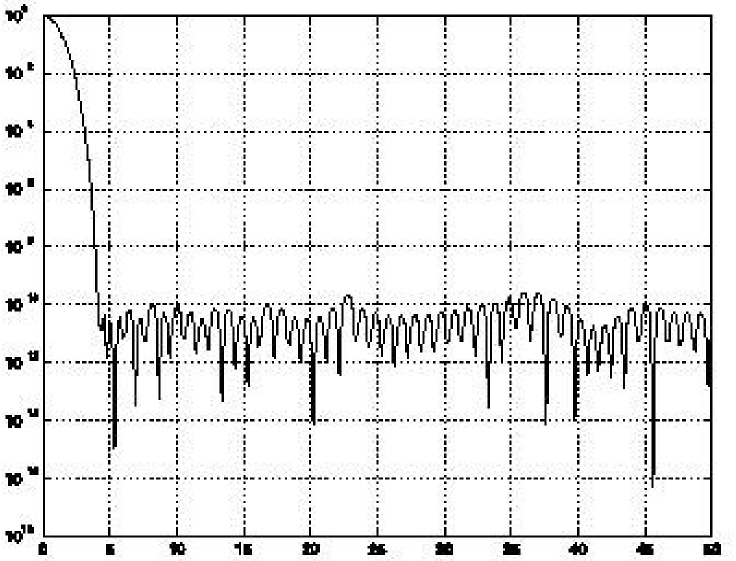
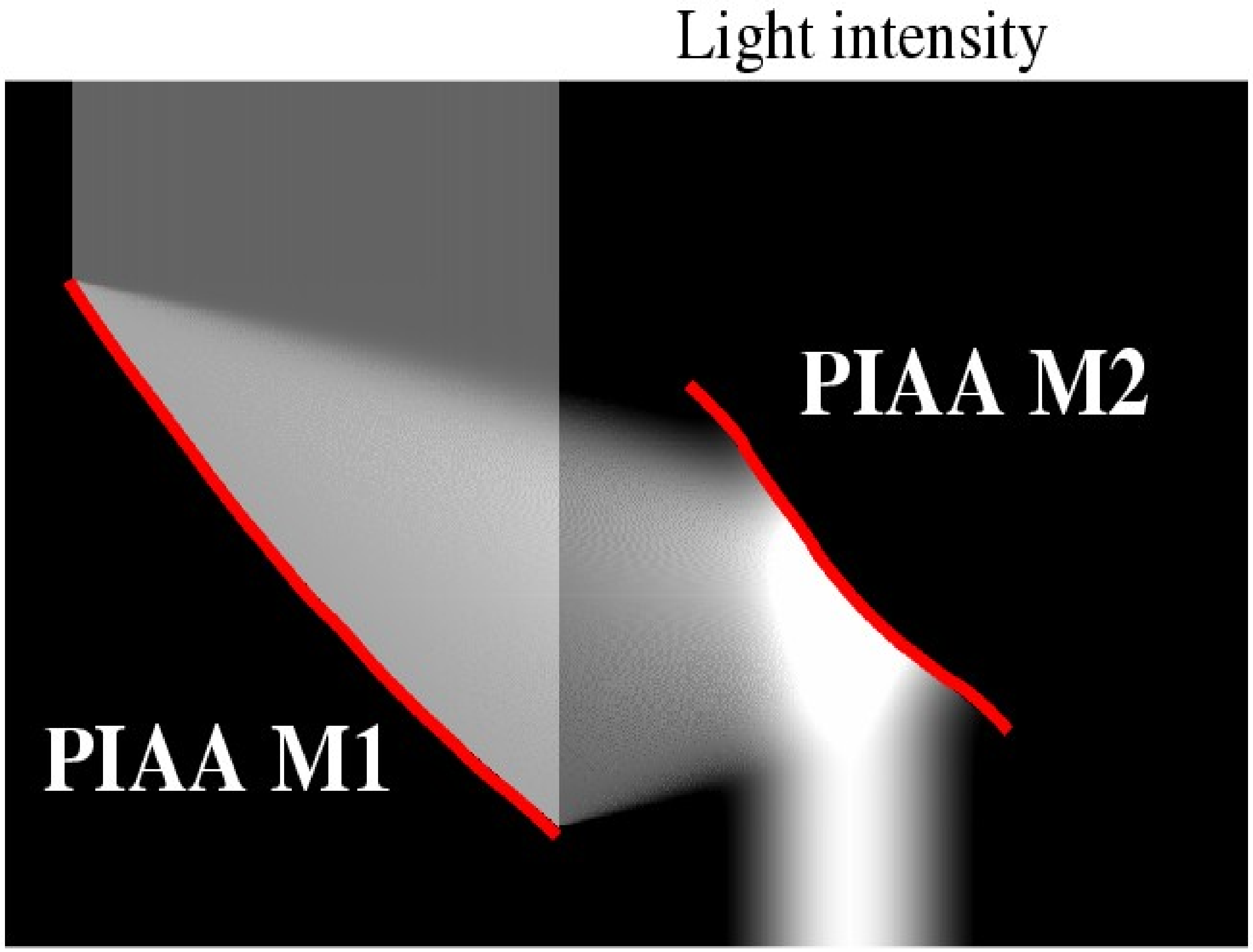


Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

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

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

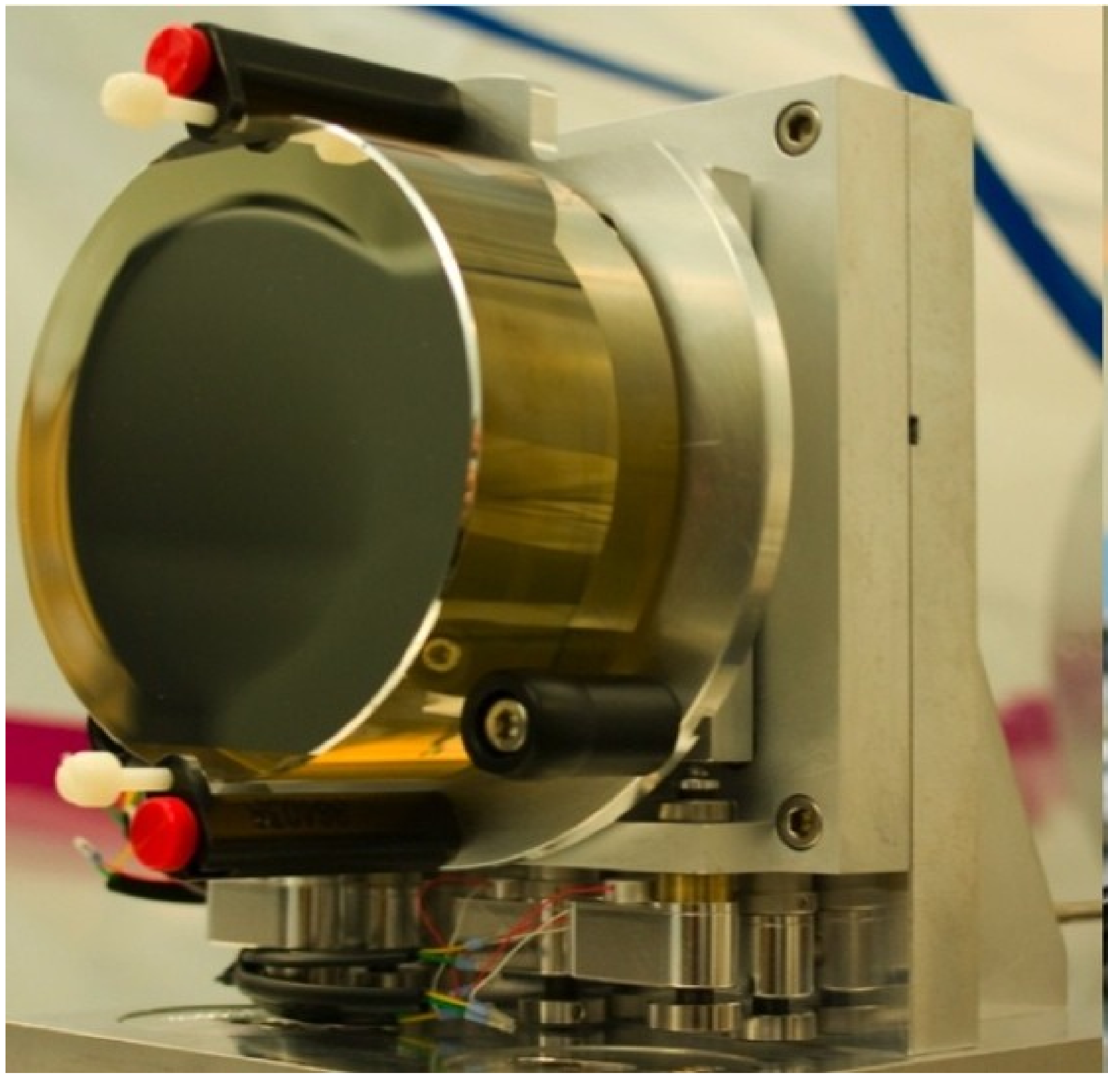


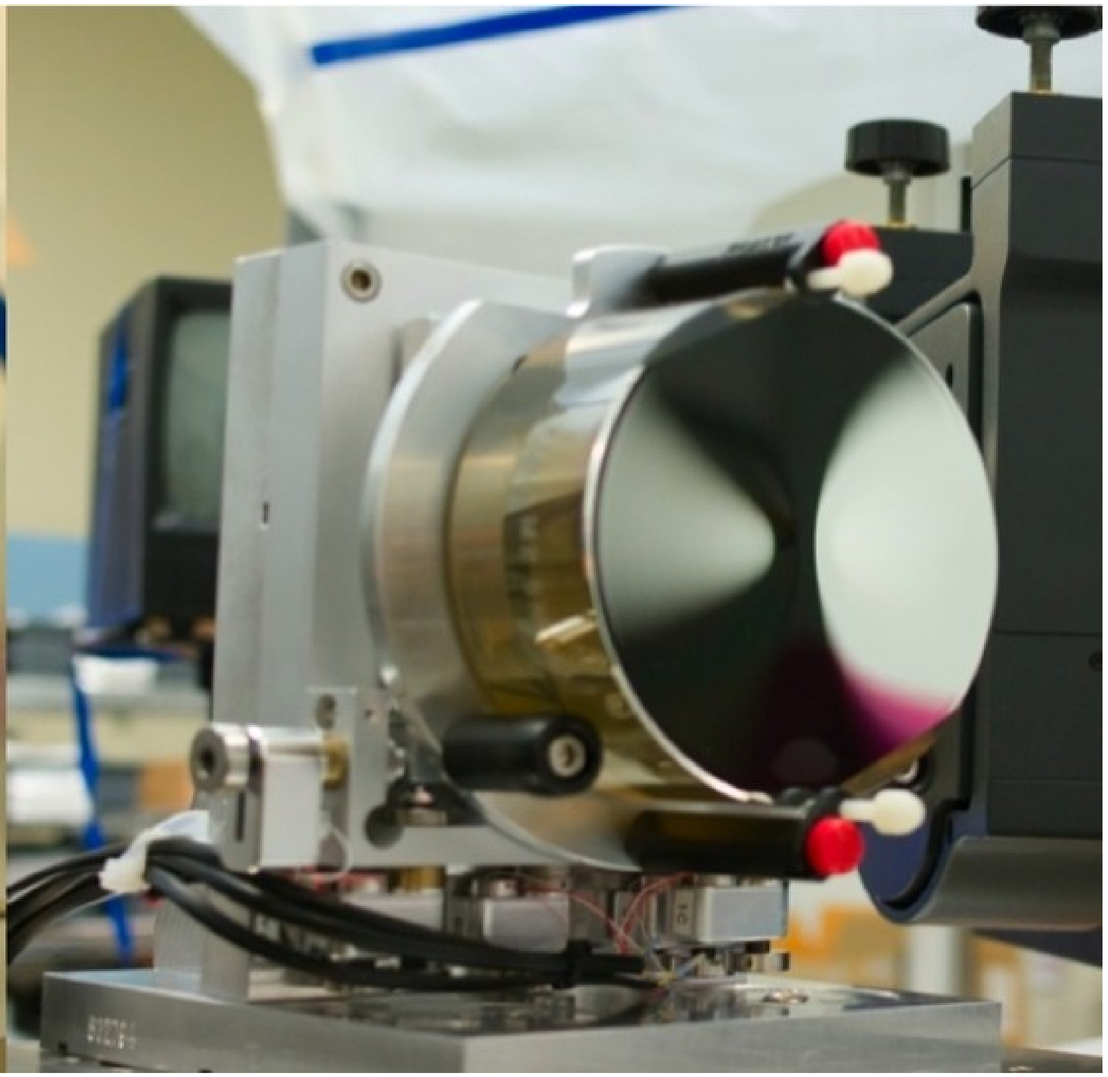
No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

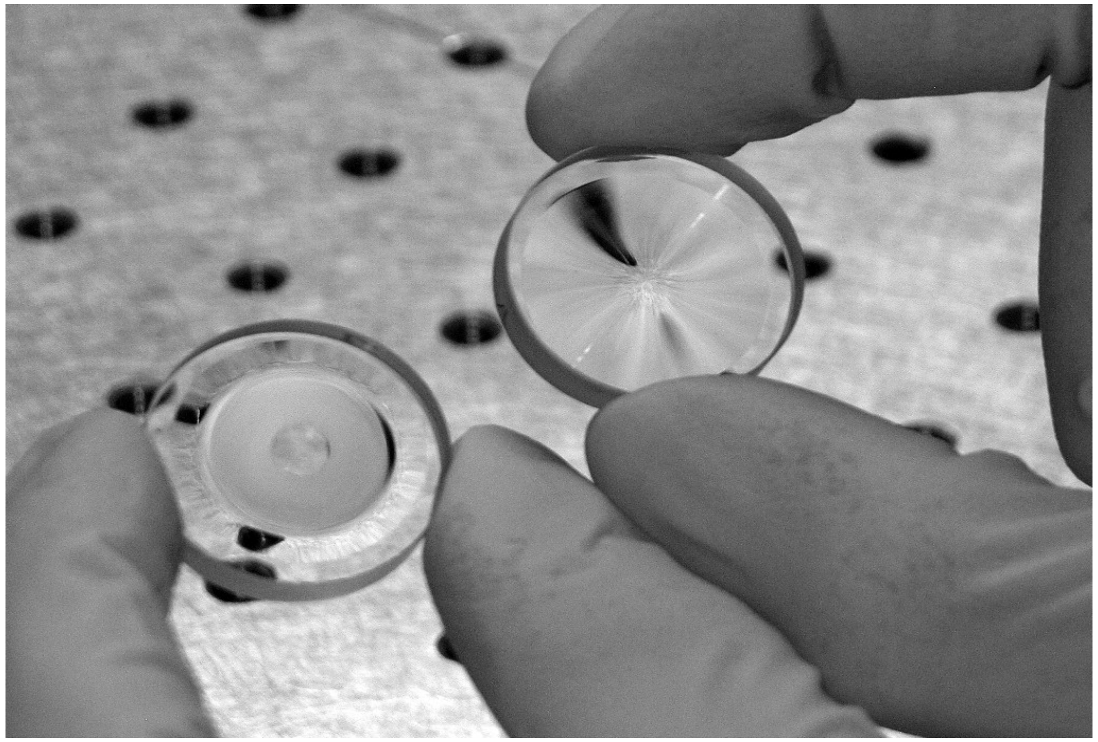
→ Gain ~x2 in telescope diameter over previous concepts

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

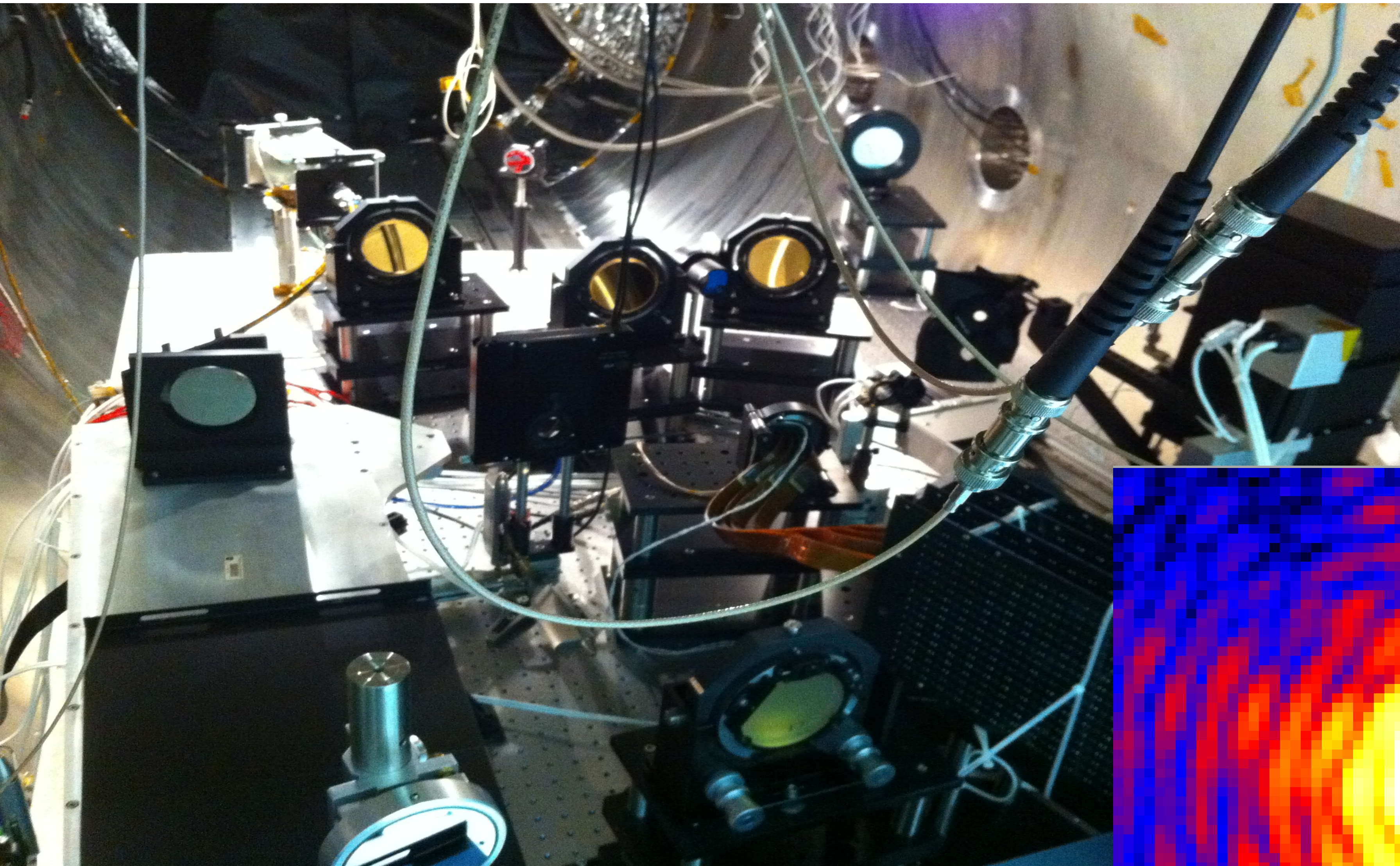
PIAA optics

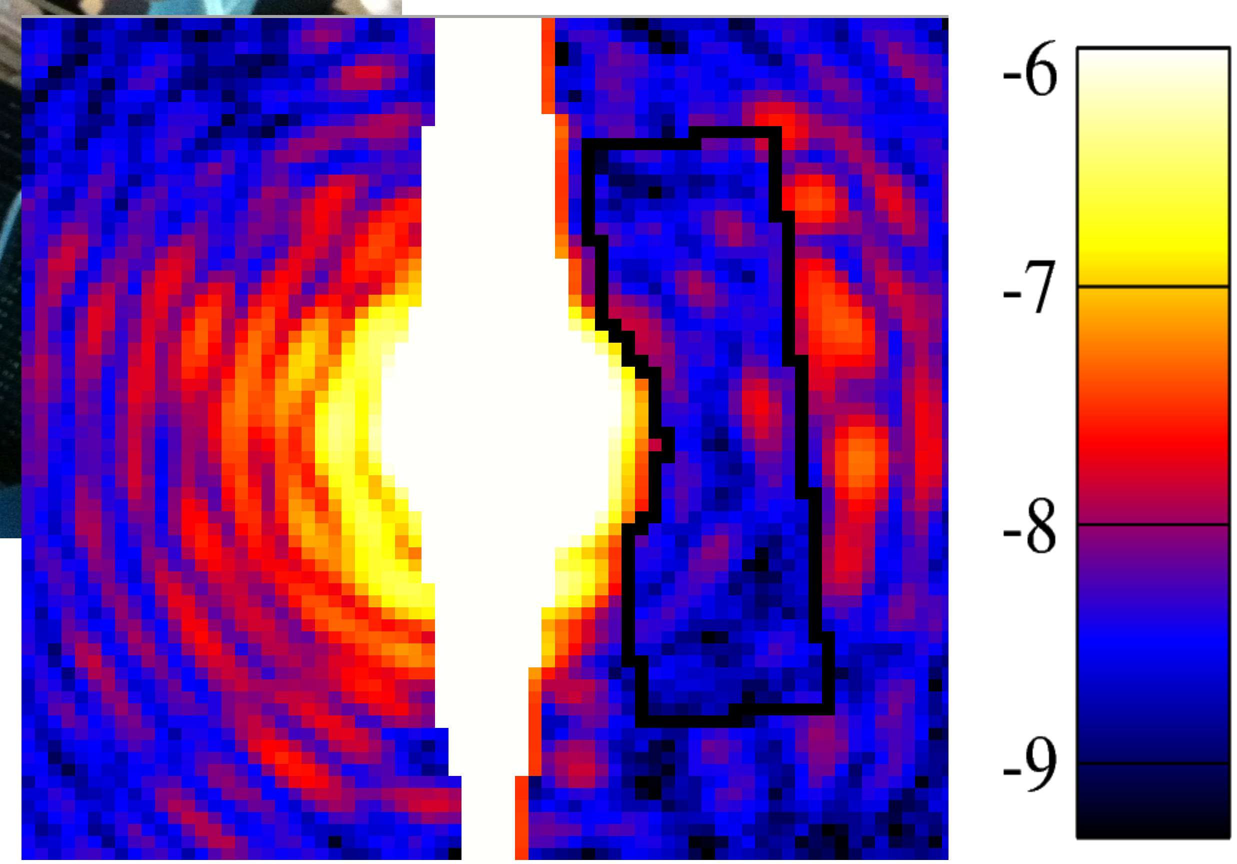






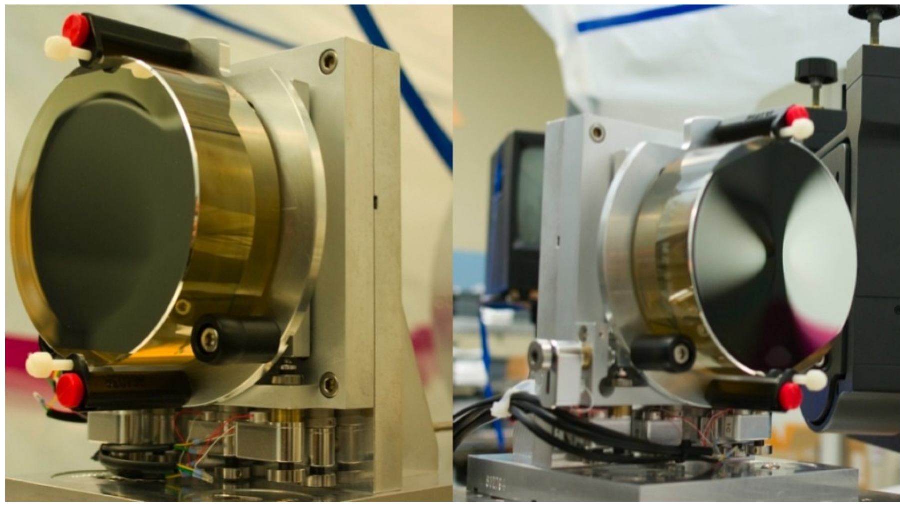
NASA JPL vacuum testbed



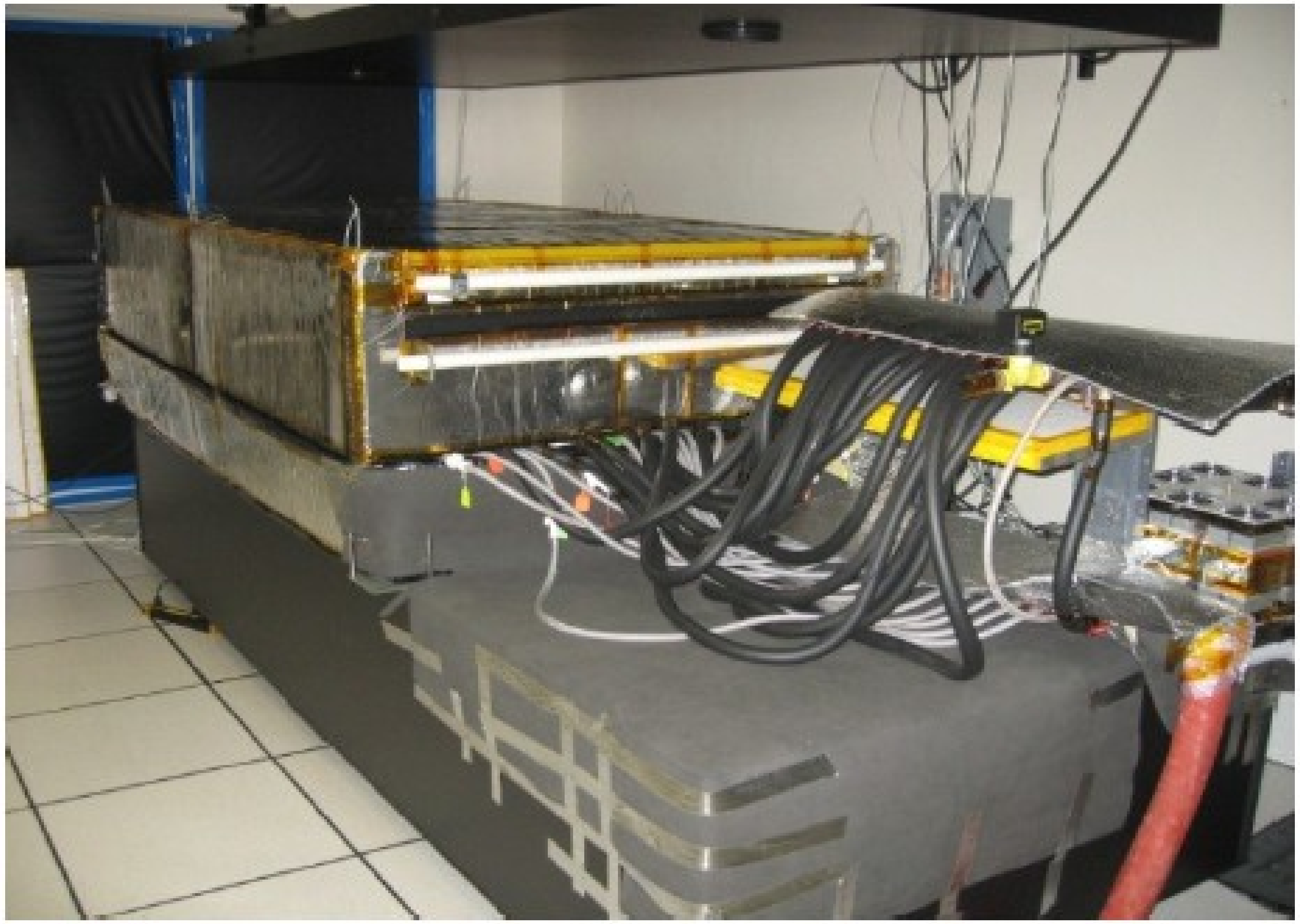


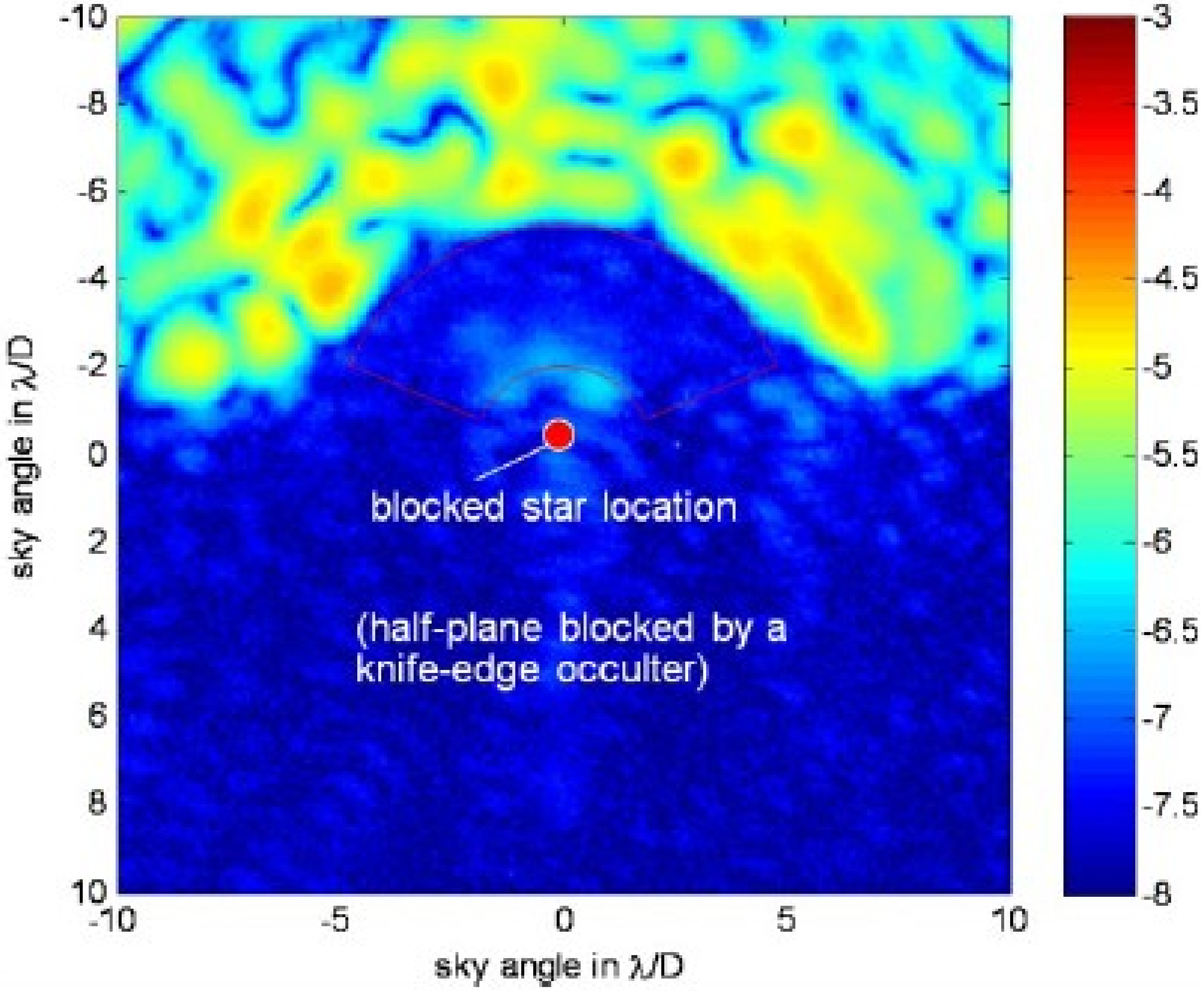
PIAA is reaching few x1e-9 contrast at 2 lambda/D separation

NASA Ames testbed

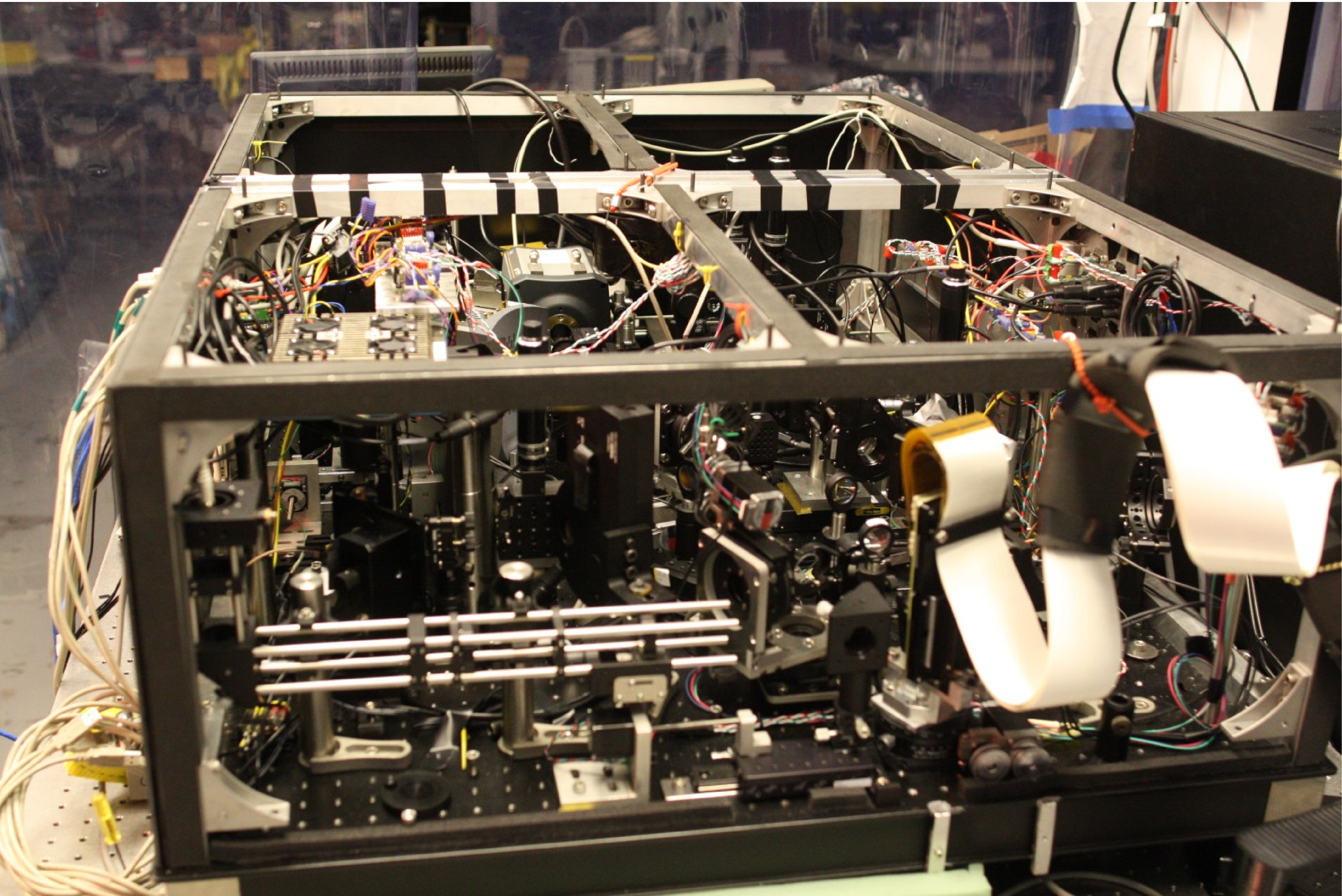


Contrast ratio with PIAA already reaching ~1e-6 at 1.2 l/D in visible





The Subaru Coronagraphic Extreme-AO (SCExAO) system



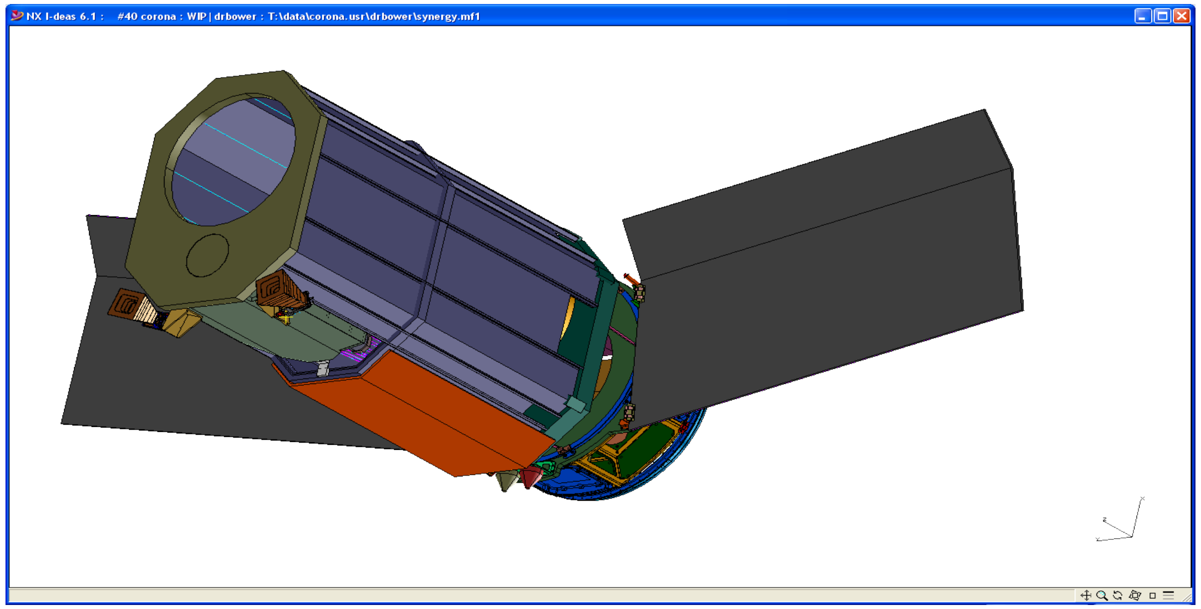
Mission Overview

EXCEDE

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

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

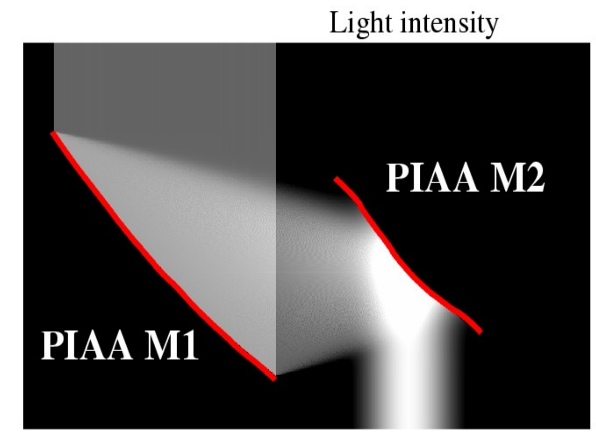
- Active Starlight Suppression System:
  - PIAA Coronagraph (~1 l/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor

- Two-band Imaging Polarimeter

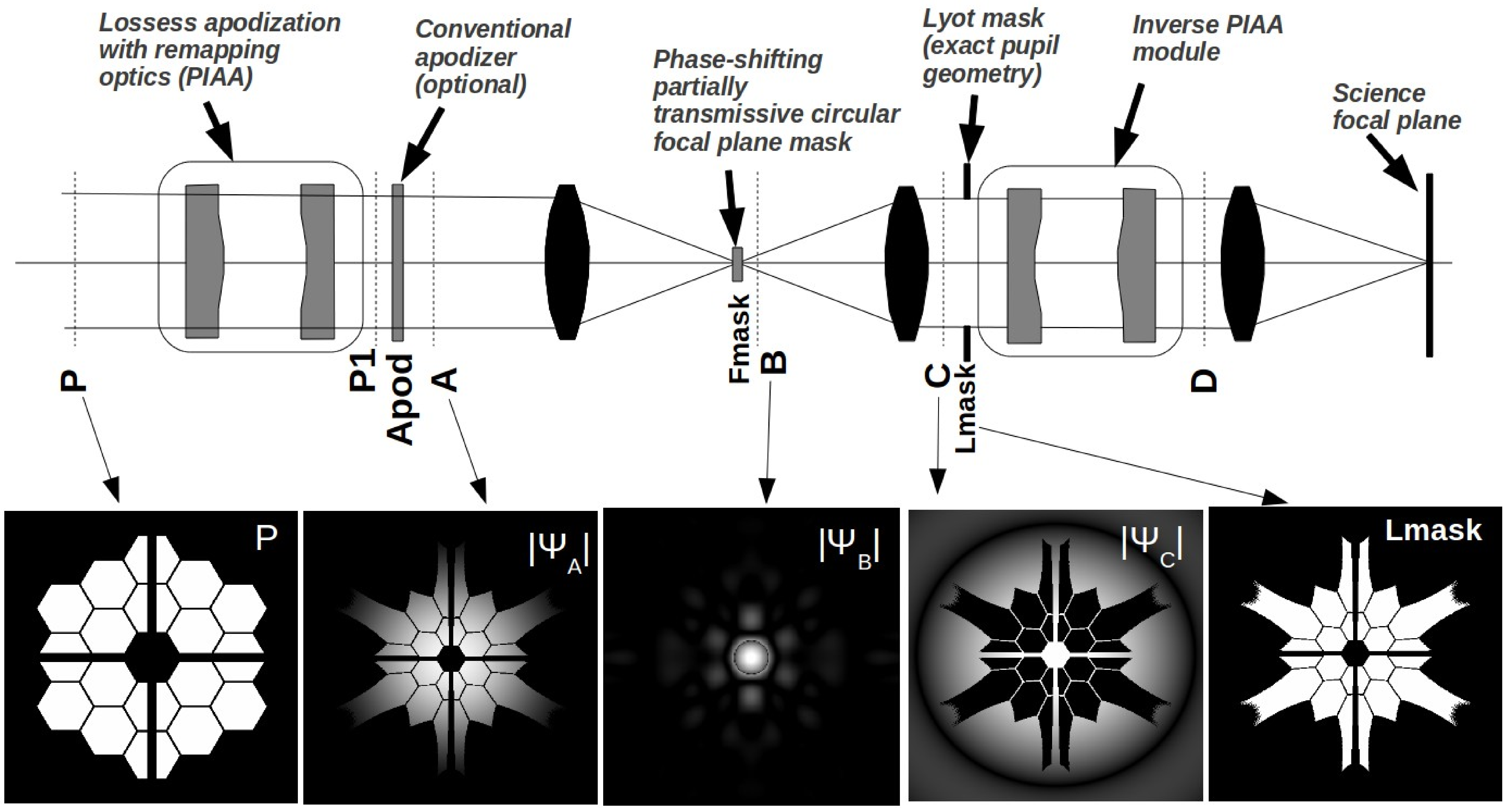
- Three-year mission (2000-km LEO Sun-synchronous orbit)
  - Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs

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

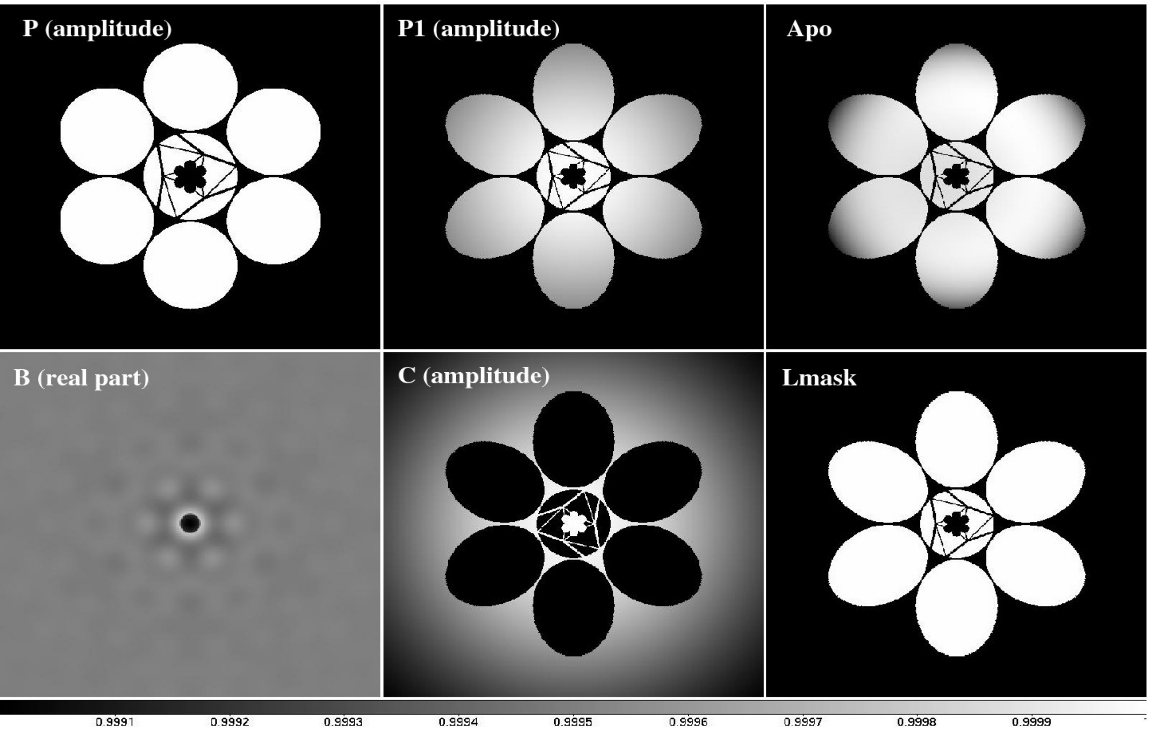
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



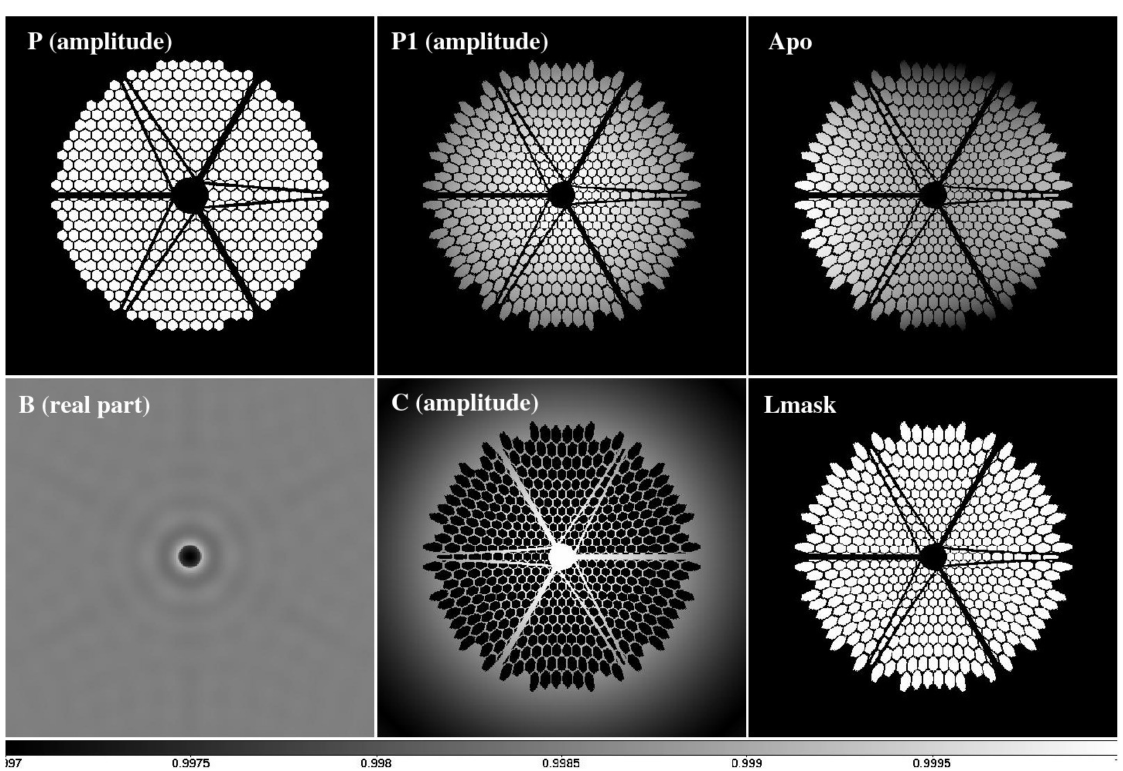
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

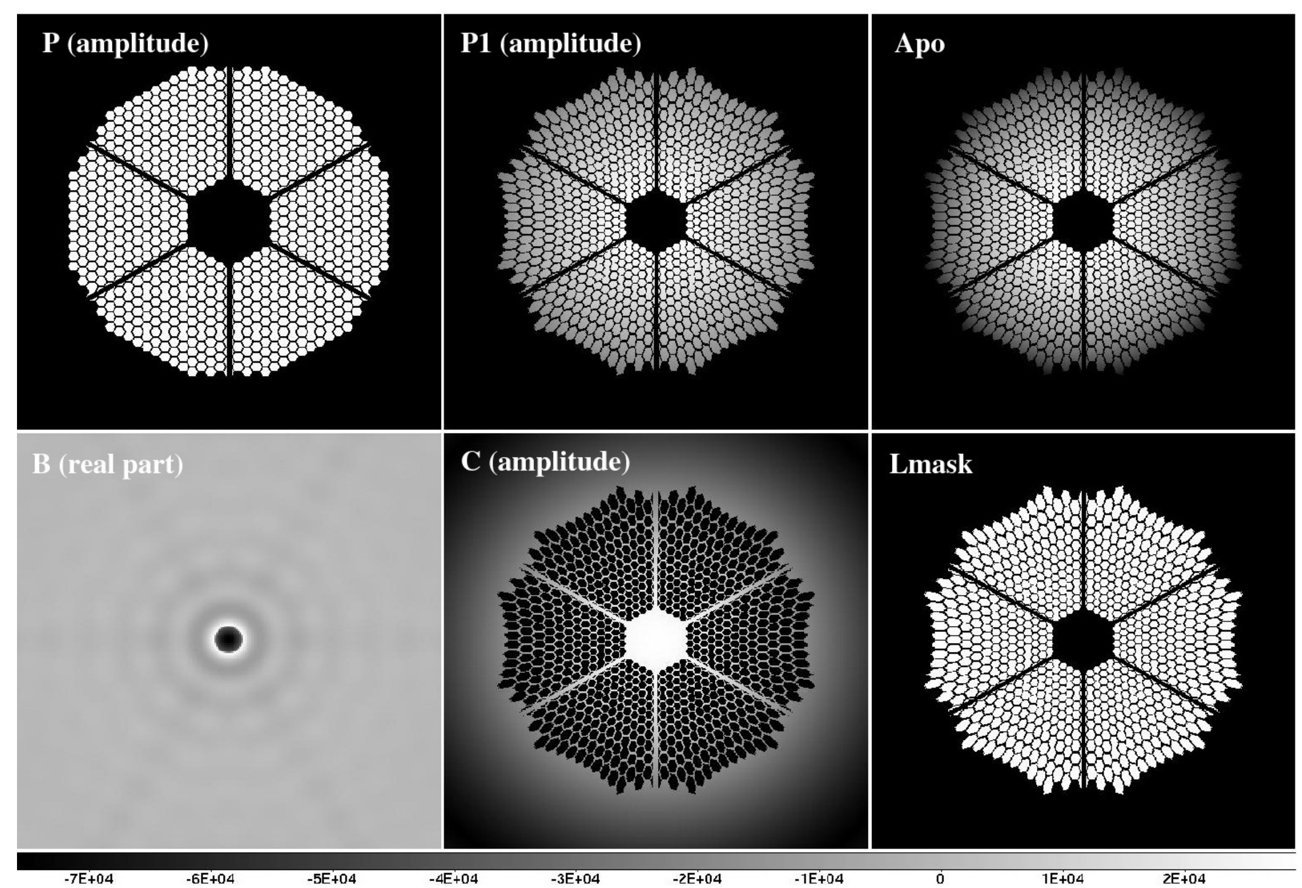


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



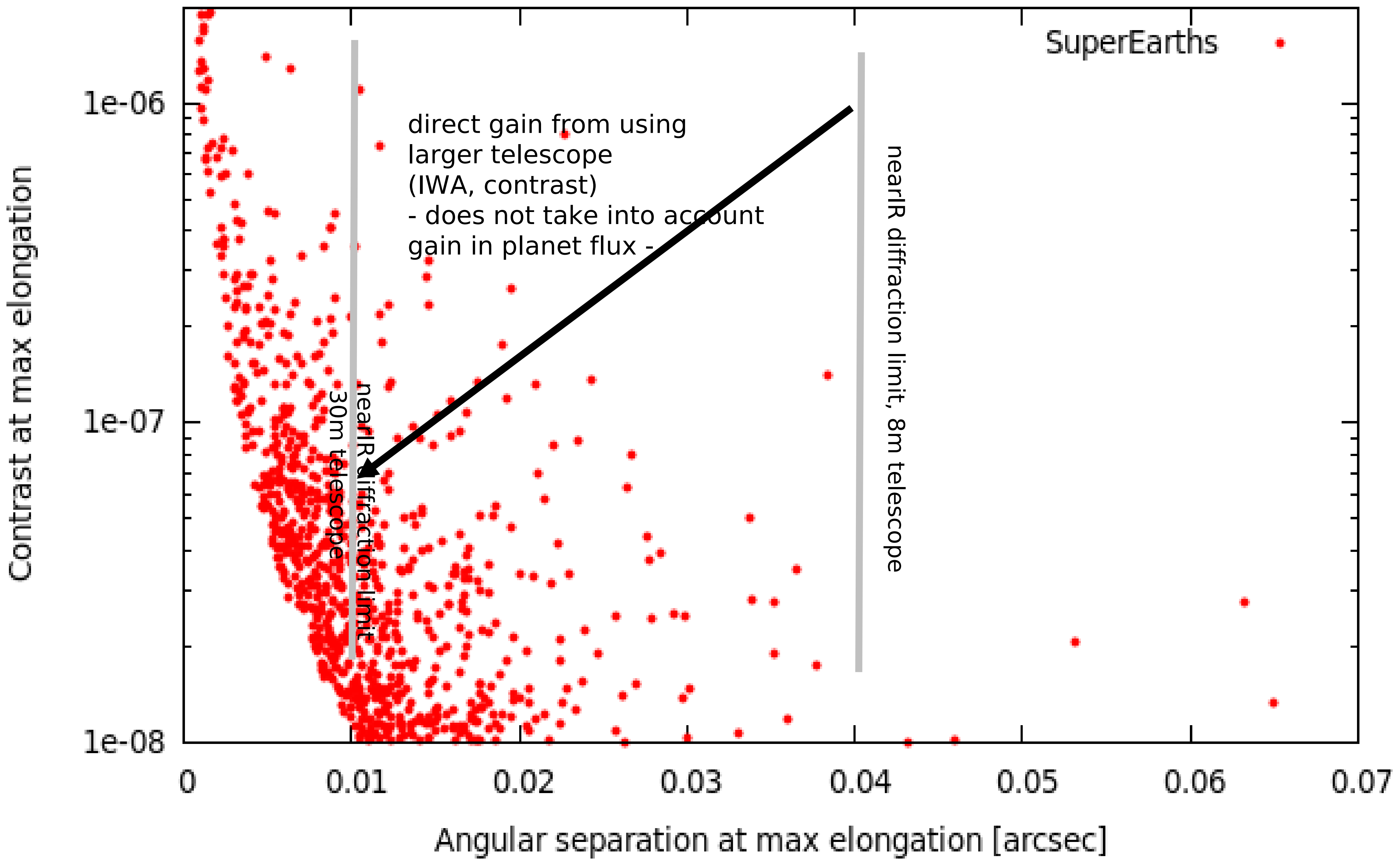
<u>Pupil shape does not matter !!!</u>



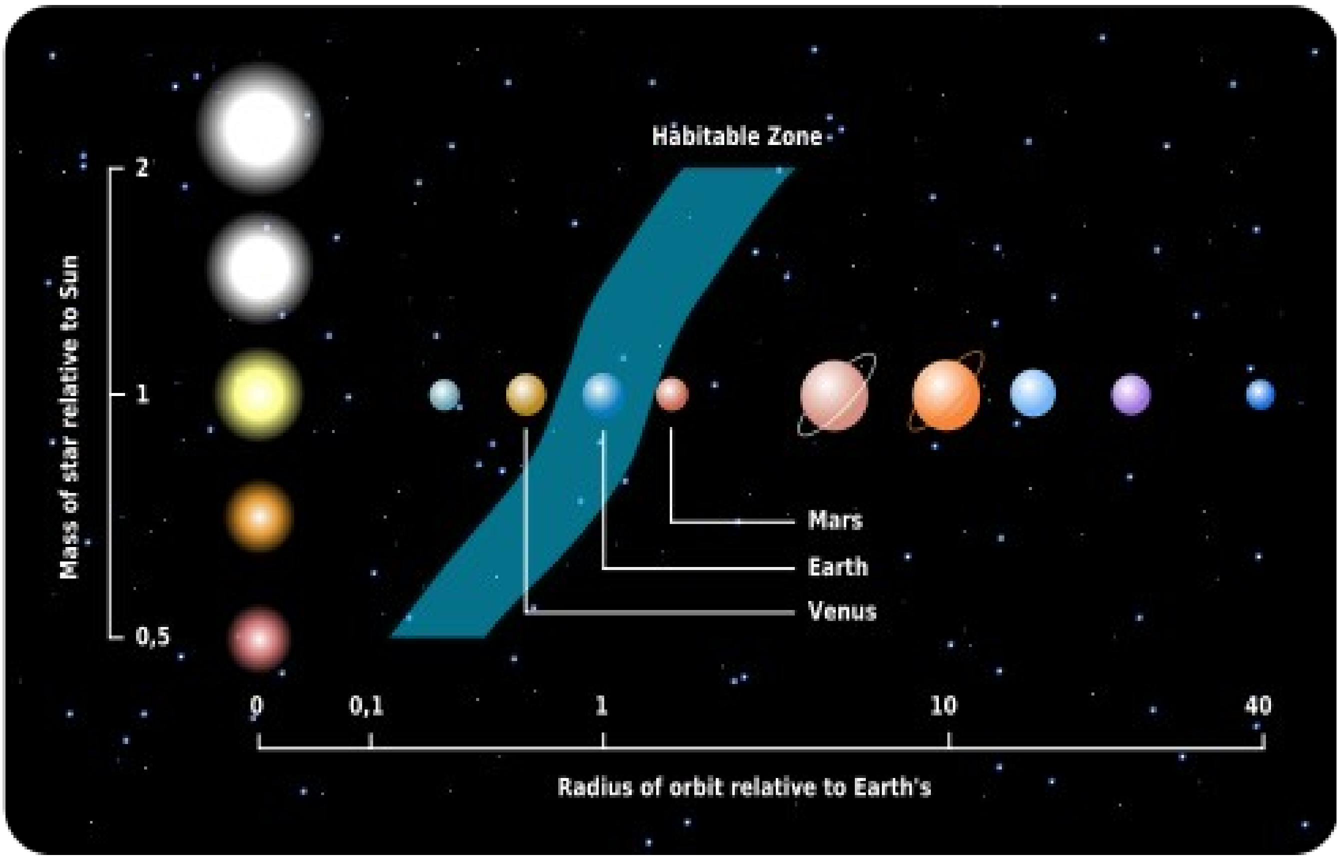


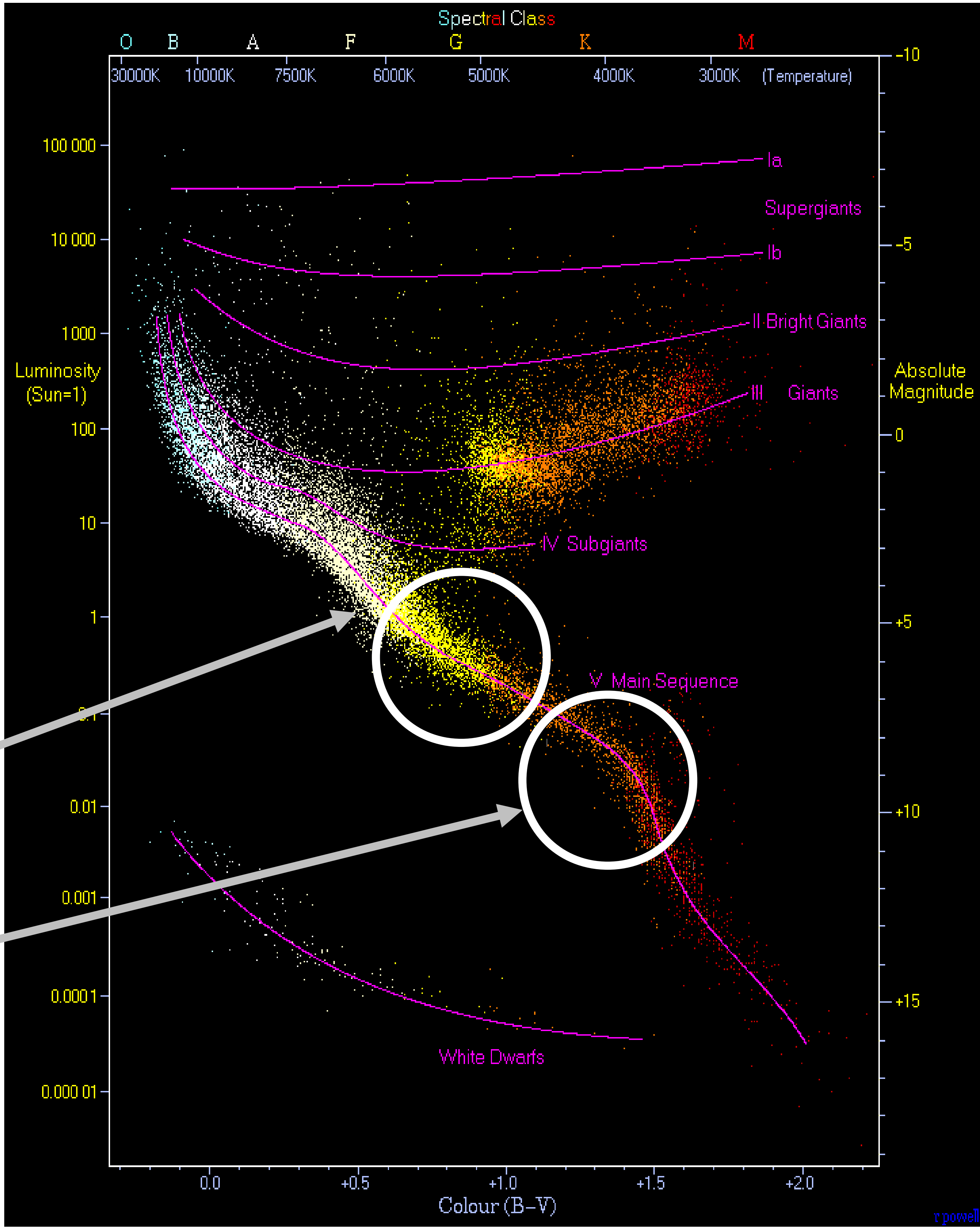
Reflected light planets with ELTs

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)



Habitable planets spectroscopy

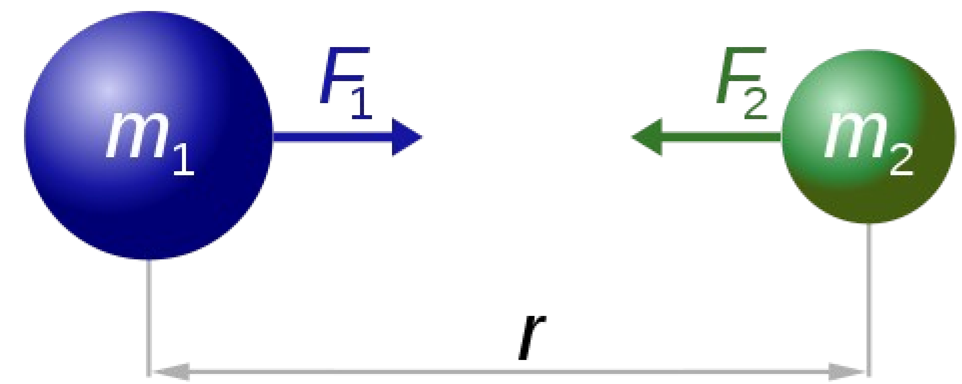




Space (~4m telescope):
F-G-K type stars, visible light
(~203x)

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

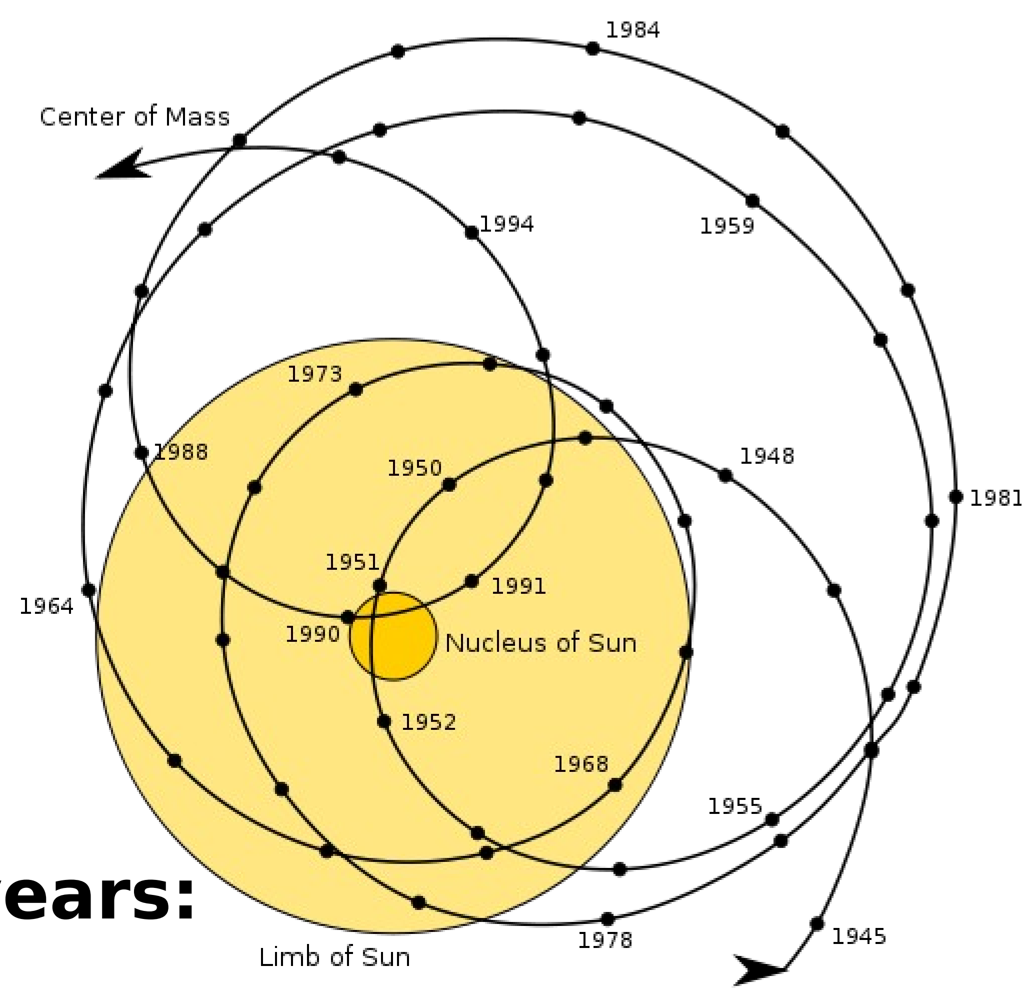
planet mass → star mass → orbit radius → distance to system

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

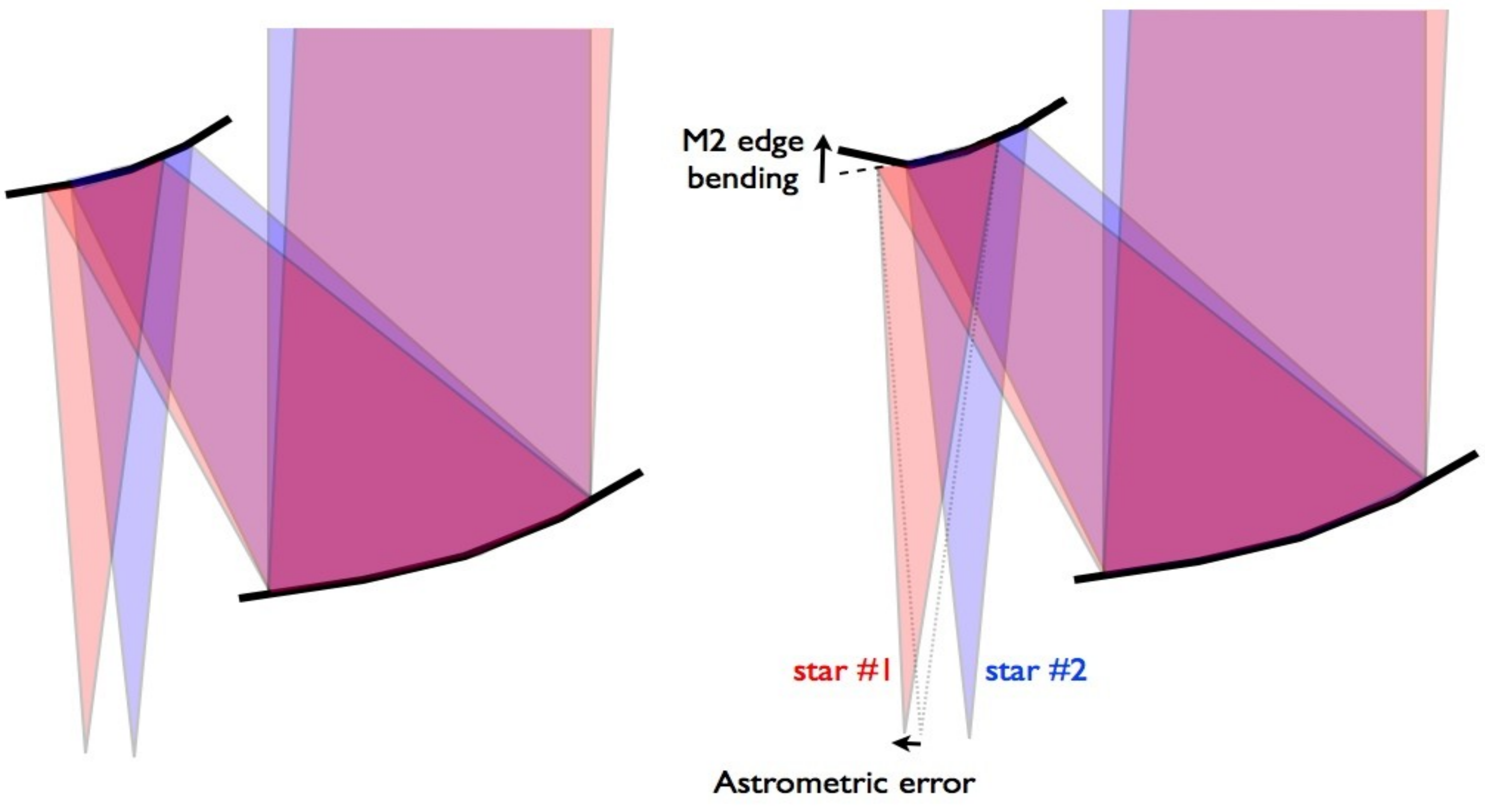
Earth around Sun, as seen from 30 light years:
0.3 uas = 1.5e-12 rad

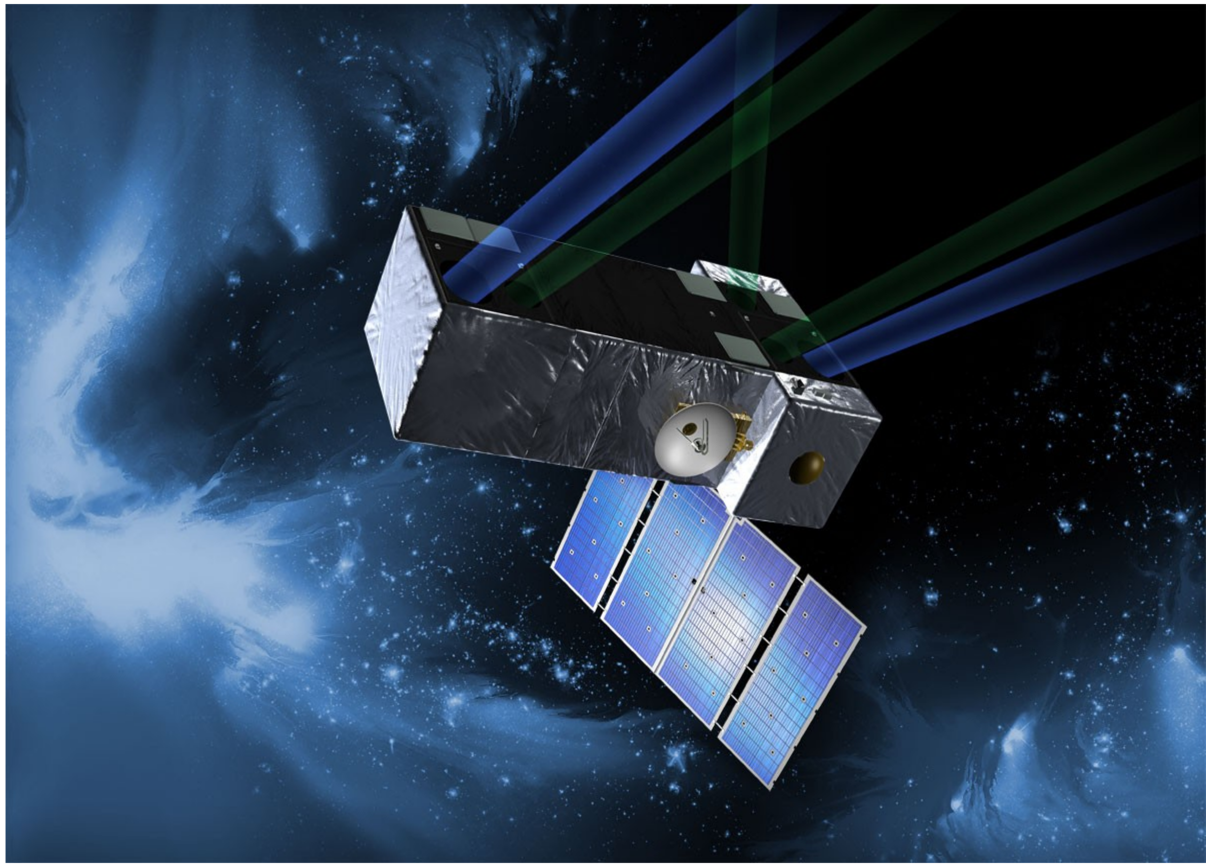
Astrometry

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

On-axis and off-axis stars illuminate different (but overlapping) parts of M2.
Edge bending on M2 is seen by star #1, but not star #2.





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

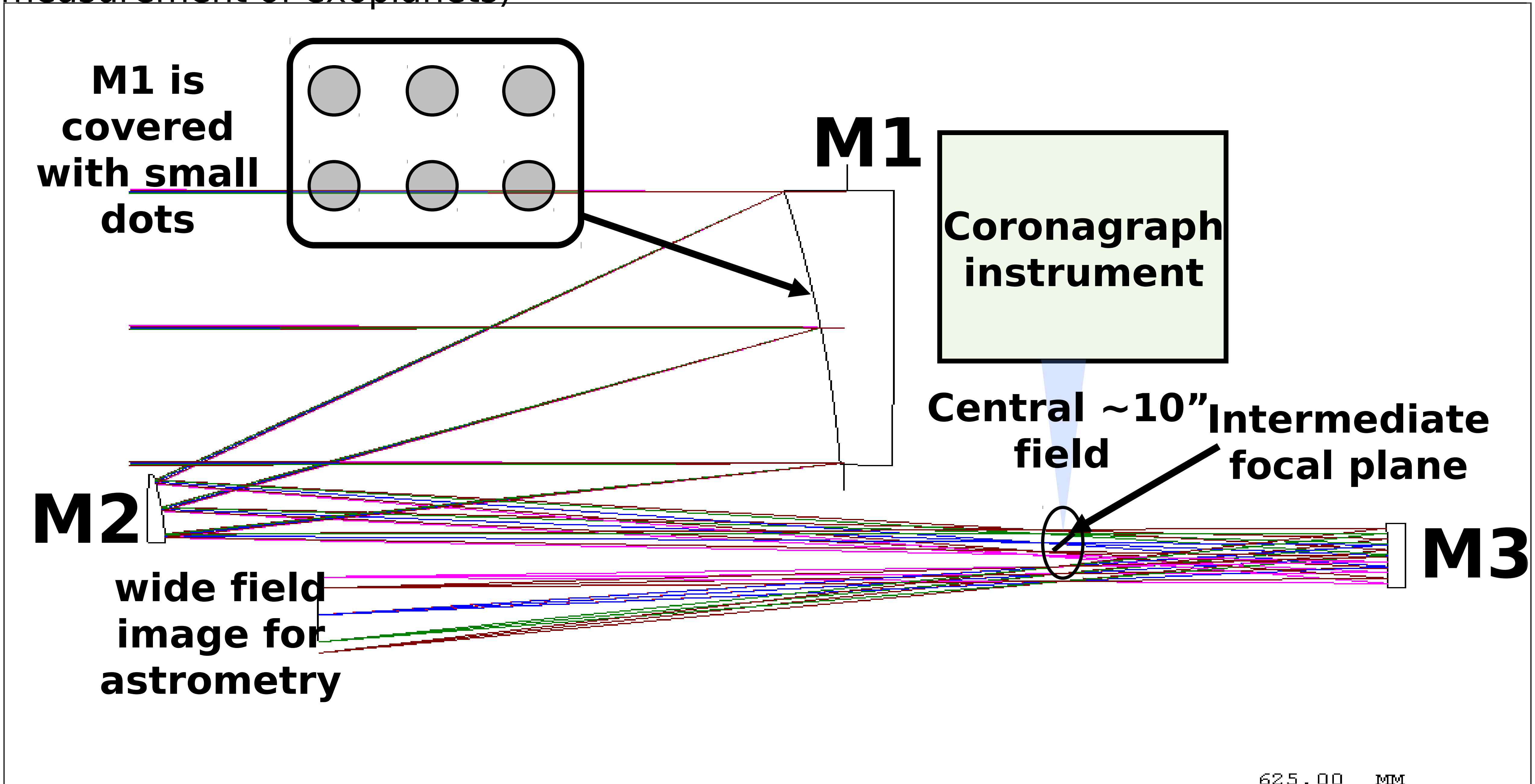
Wide field imaging technologies are now mature (optics, detectors)
Can we use wide field images for astrometry to identify and characterize exoplanets ?

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

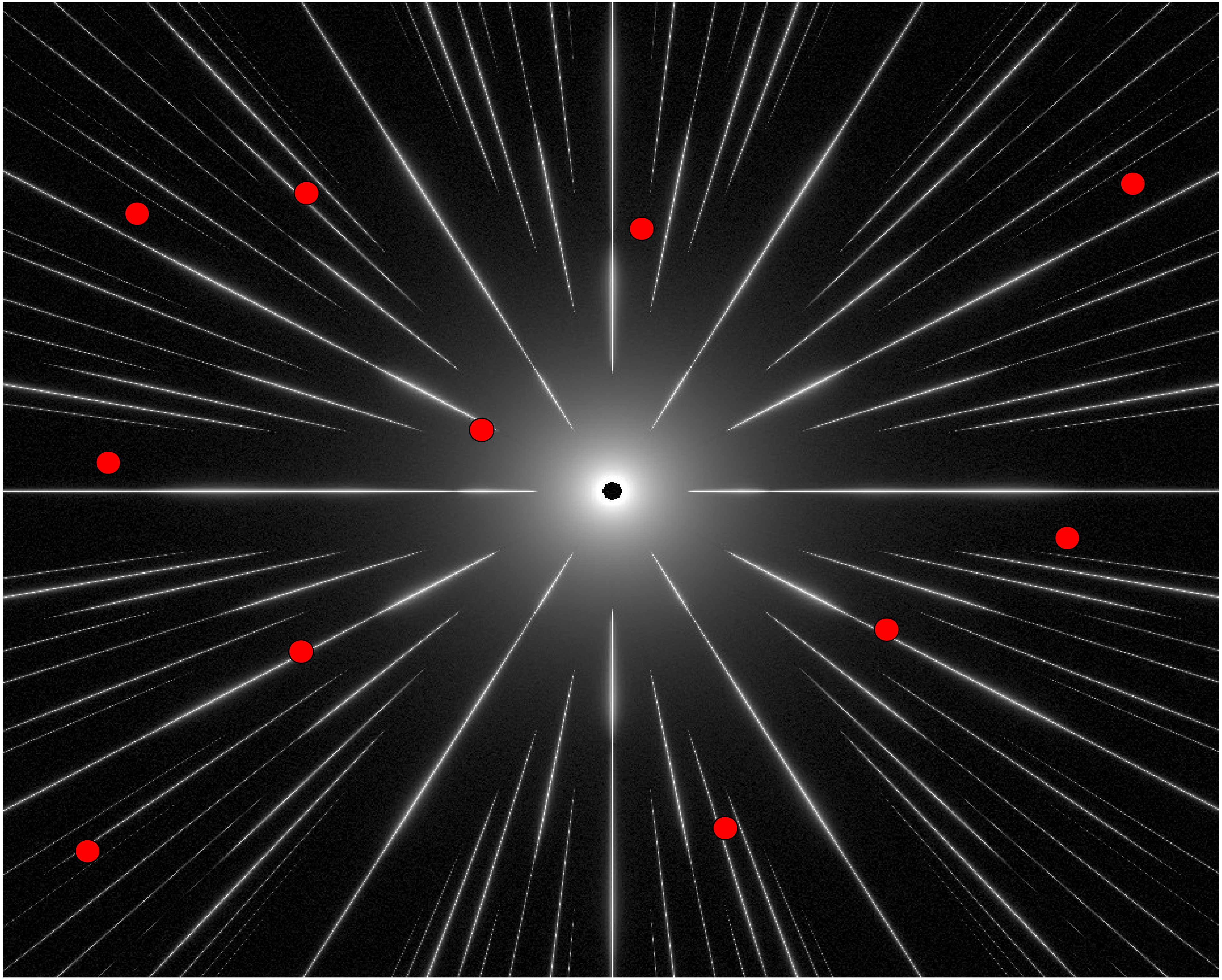
Optical Layout for simultaneous coronagraphy and astrometry

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).

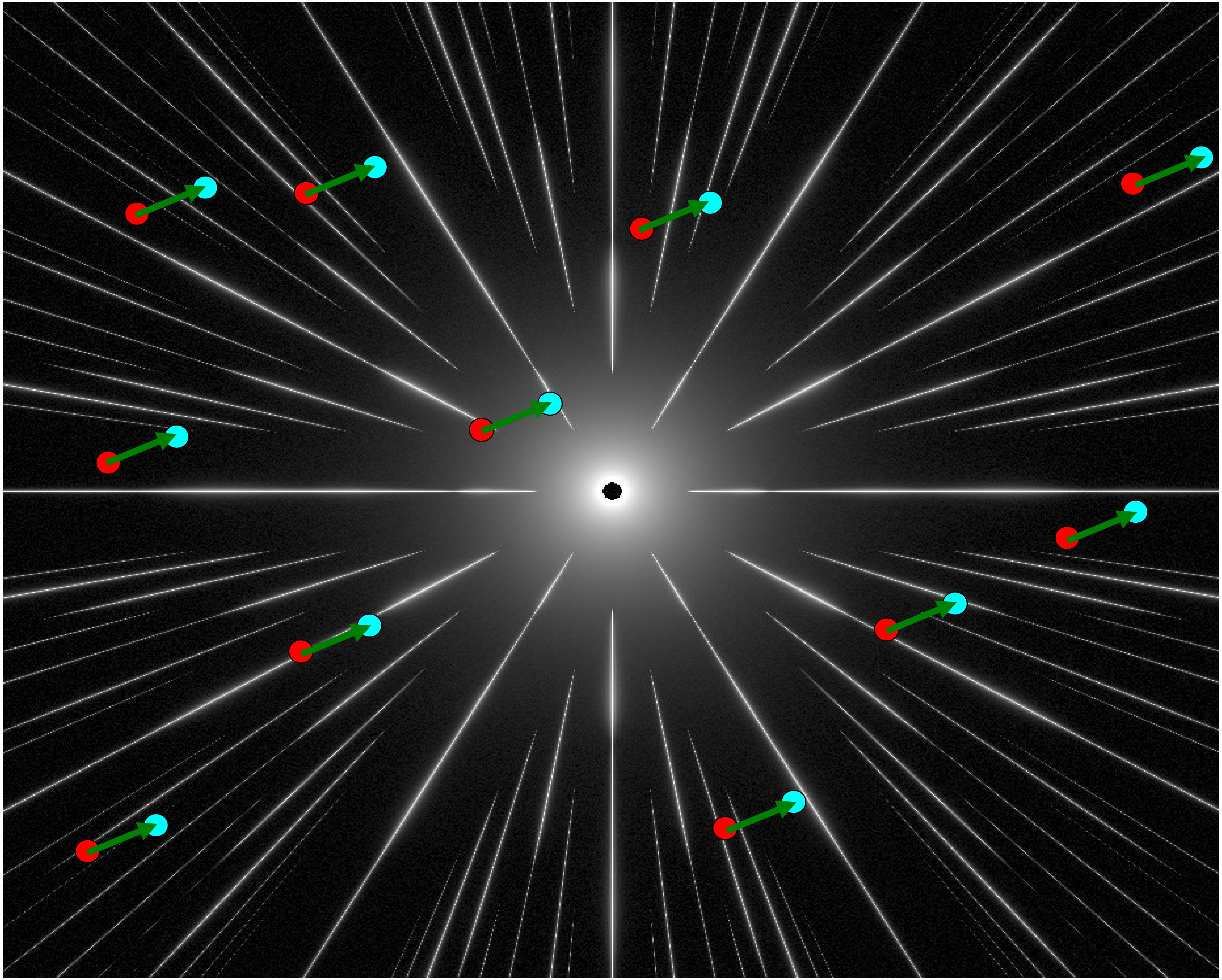
Light is simultaneously collected by the coronagraph instrument (direct imaging and spectroscopy of exoplanet) and the wide field astrometric camera (detection and mass measurement of exoplanets)



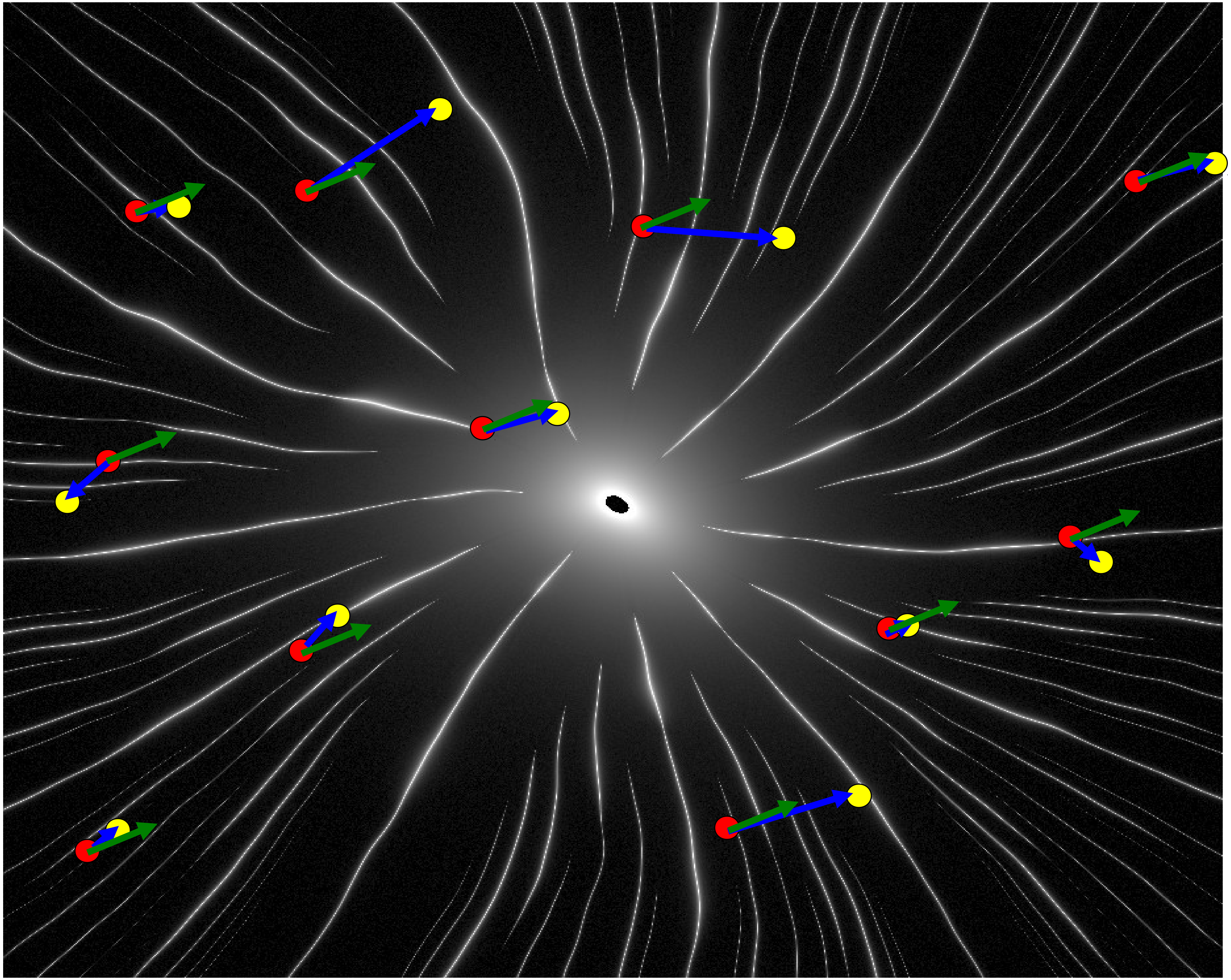
Red points show the position of background stars at epoch #1 (first observation)



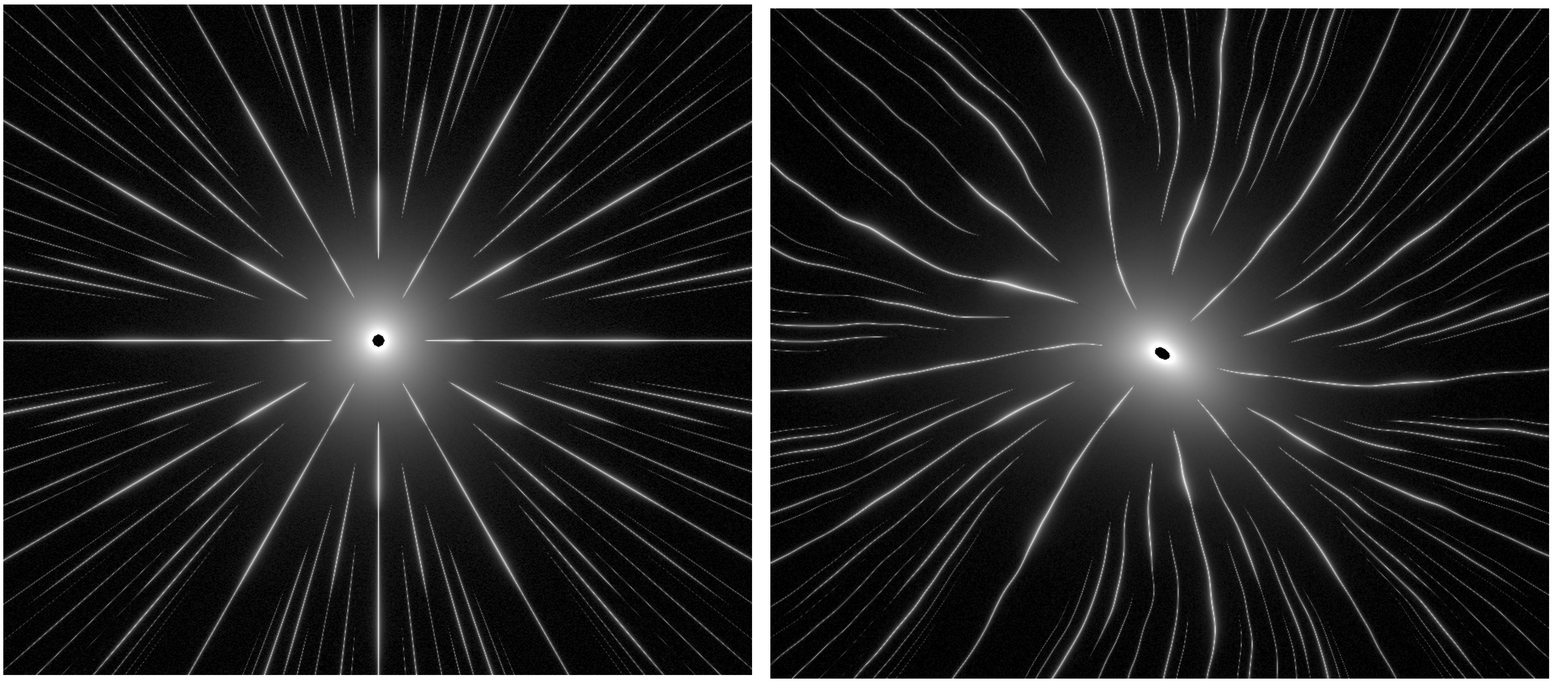
Blue points show the position of background stars at epoch #2 (second observation)
The telescope is pointed on the central star, so the spikes have not moved between the 2 observations, but the position of the background stars has moved due to the astrometric motion of the central star (green vectors).



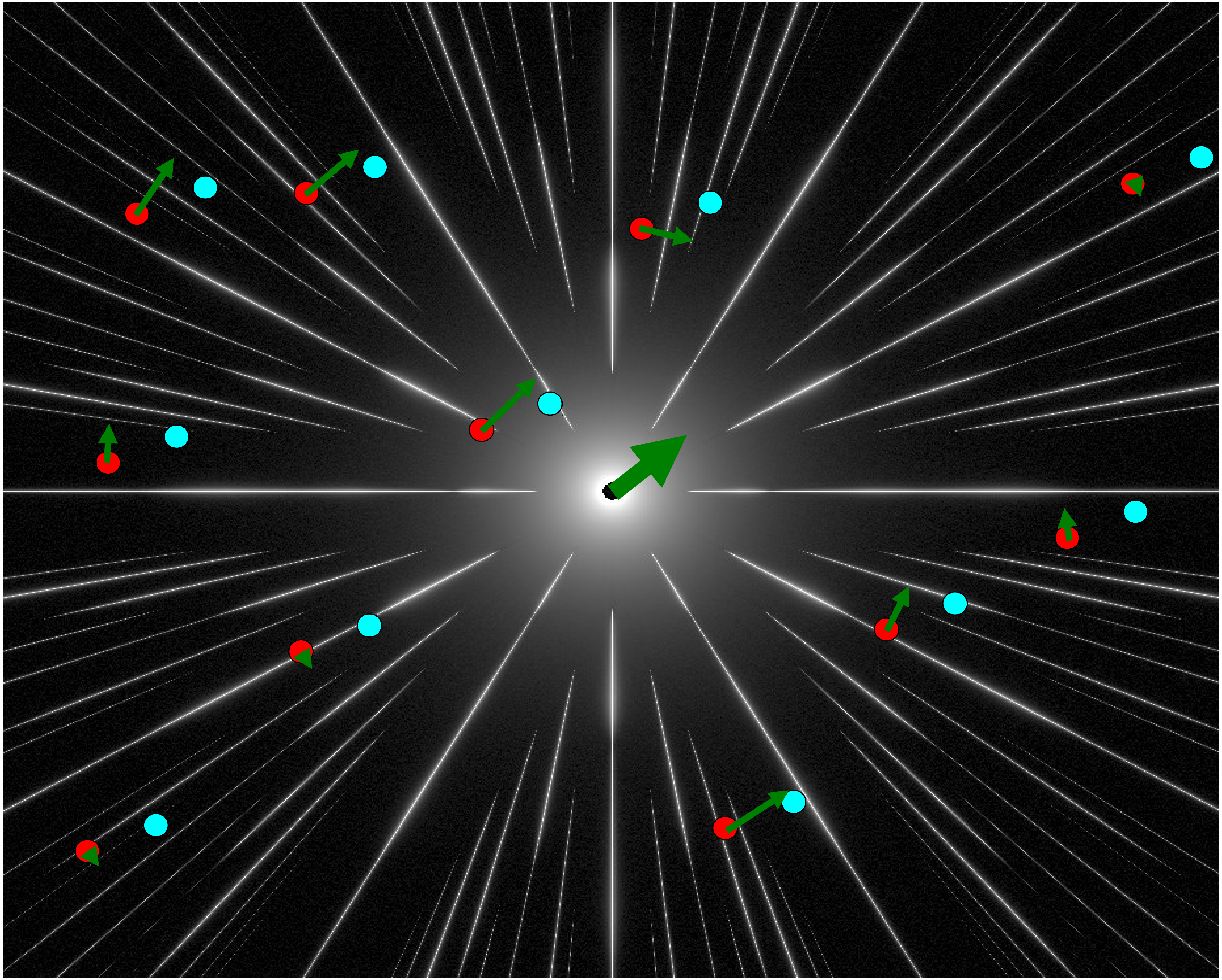
Due to astrometic distortions between the 2 observations, the actual positions measured (yellow) are different from the blue point. The error is larger than the signal induced by a planet, which makes the astrometric measurement impossible without distortion calibration.

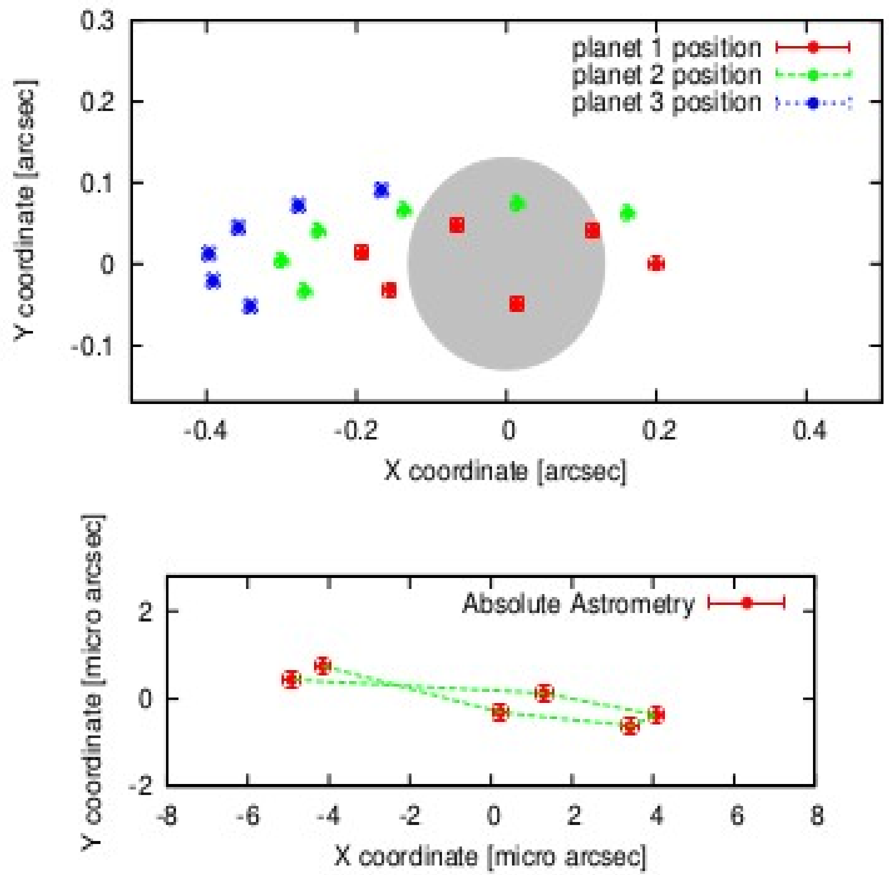


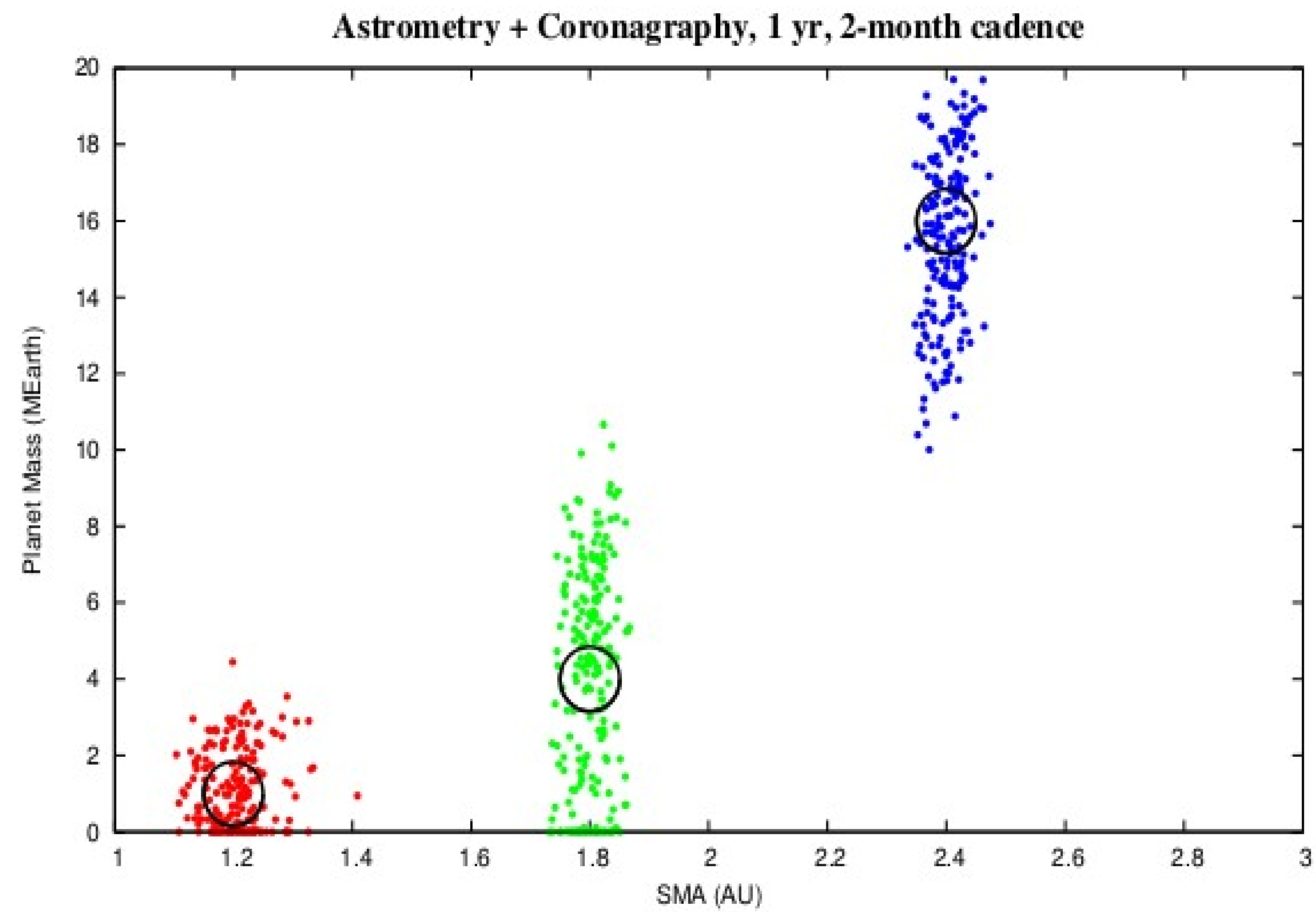
The measured astrometric motion (blue vectors in previous slide) is the sum of the true astrometric signal (green vectors) and the astrometric distortion induced by change in optics and detector between the 2 observations.
Direct comparison of the spike images between the 2 epochs is used to measure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

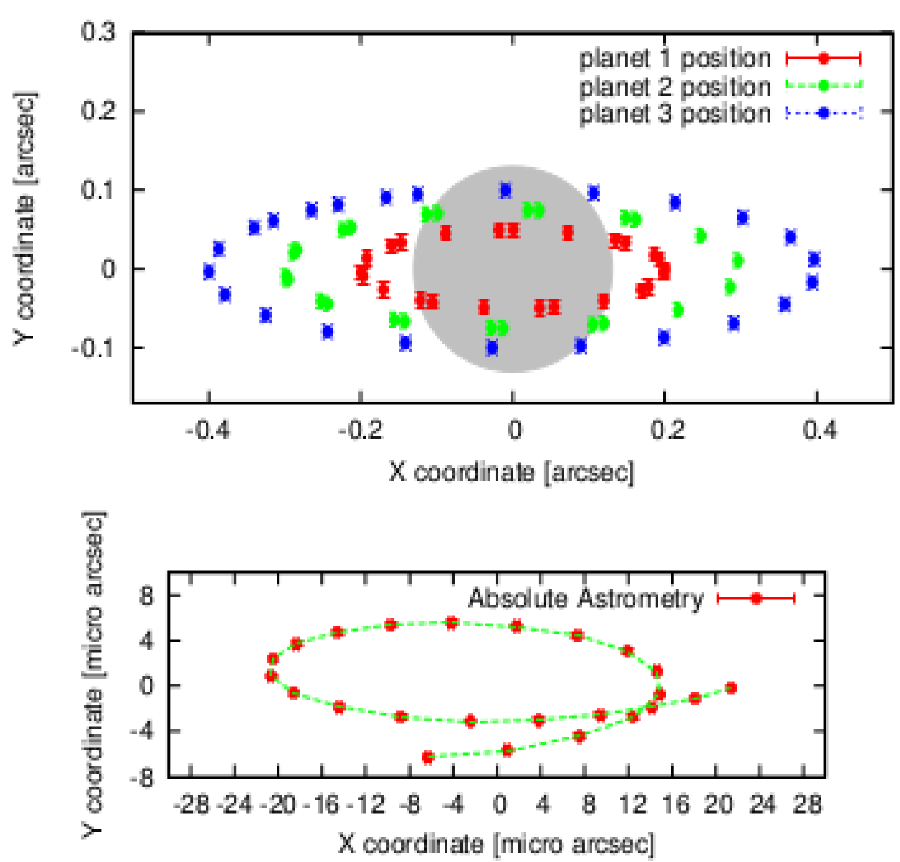


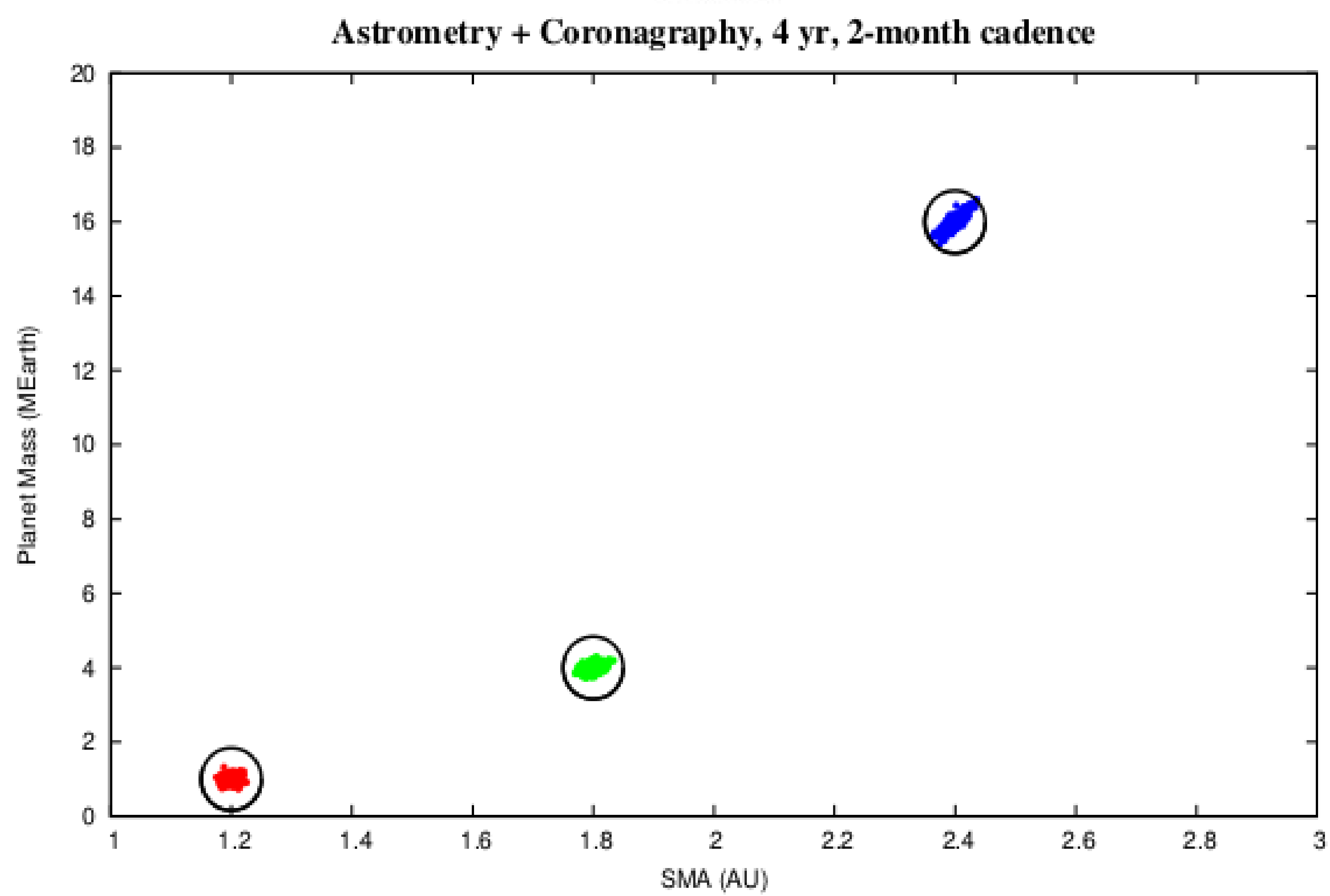
The calibration of astrometric distortions with the spikes is only accurate in the direction perpendicular to the spikes length. For a single background star, the measurement is made along this axis (1-D measurement), as shown by the green vectors. The 2-D measurement is obtained by combining all 1-D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



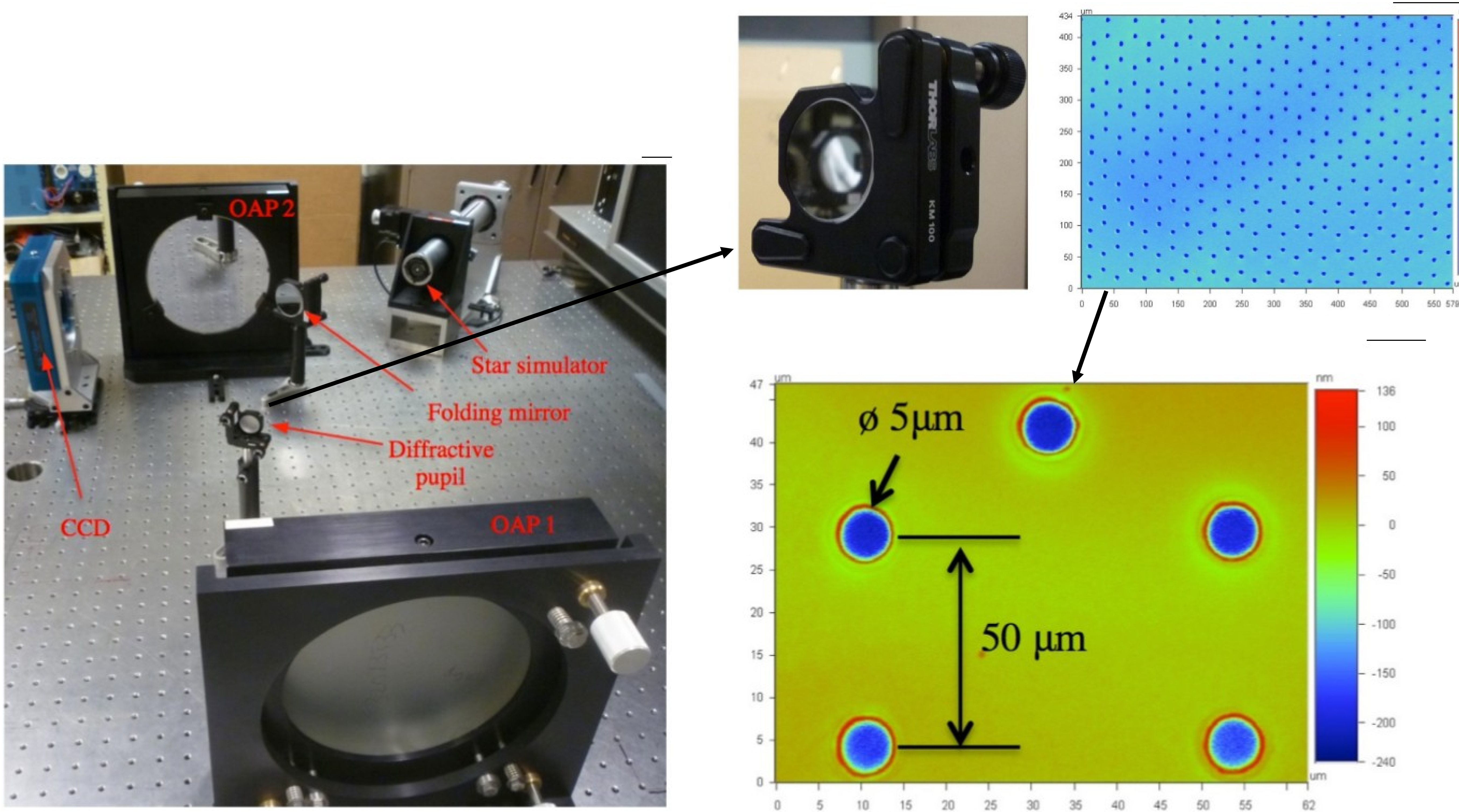

planet 1 position
planet 2 position
planet 3 position
Y coordinate [arcsec]
X coordinate [arcsec]
Absolute Astrometry
Y coordinate [micro arcsec]
X coordinate [micro arcsec]

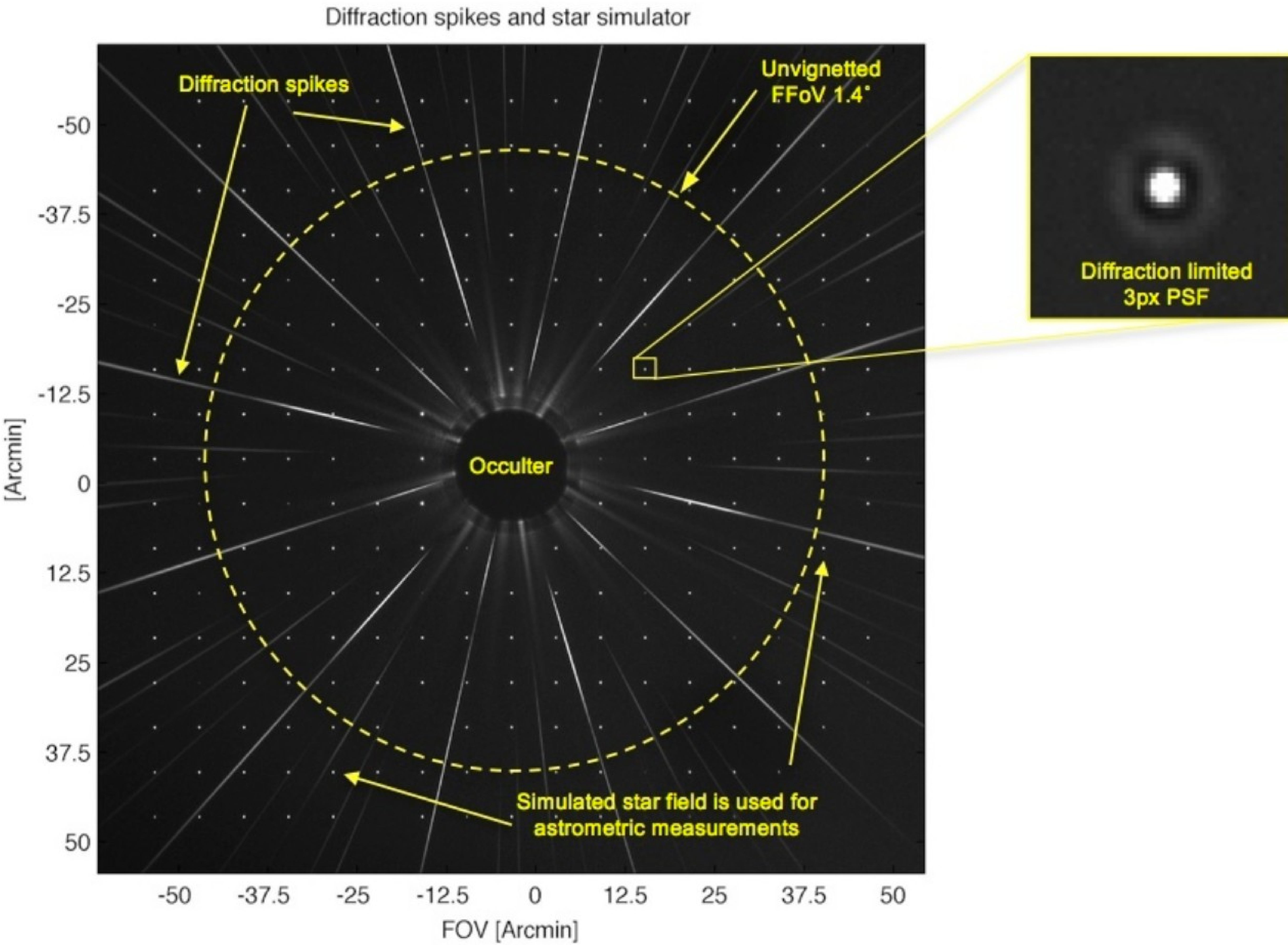

Astrometry + Coronagraphy, 1 yr, 2-month cadence
Planet Mass (MEarth)
SMA (AU)


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)

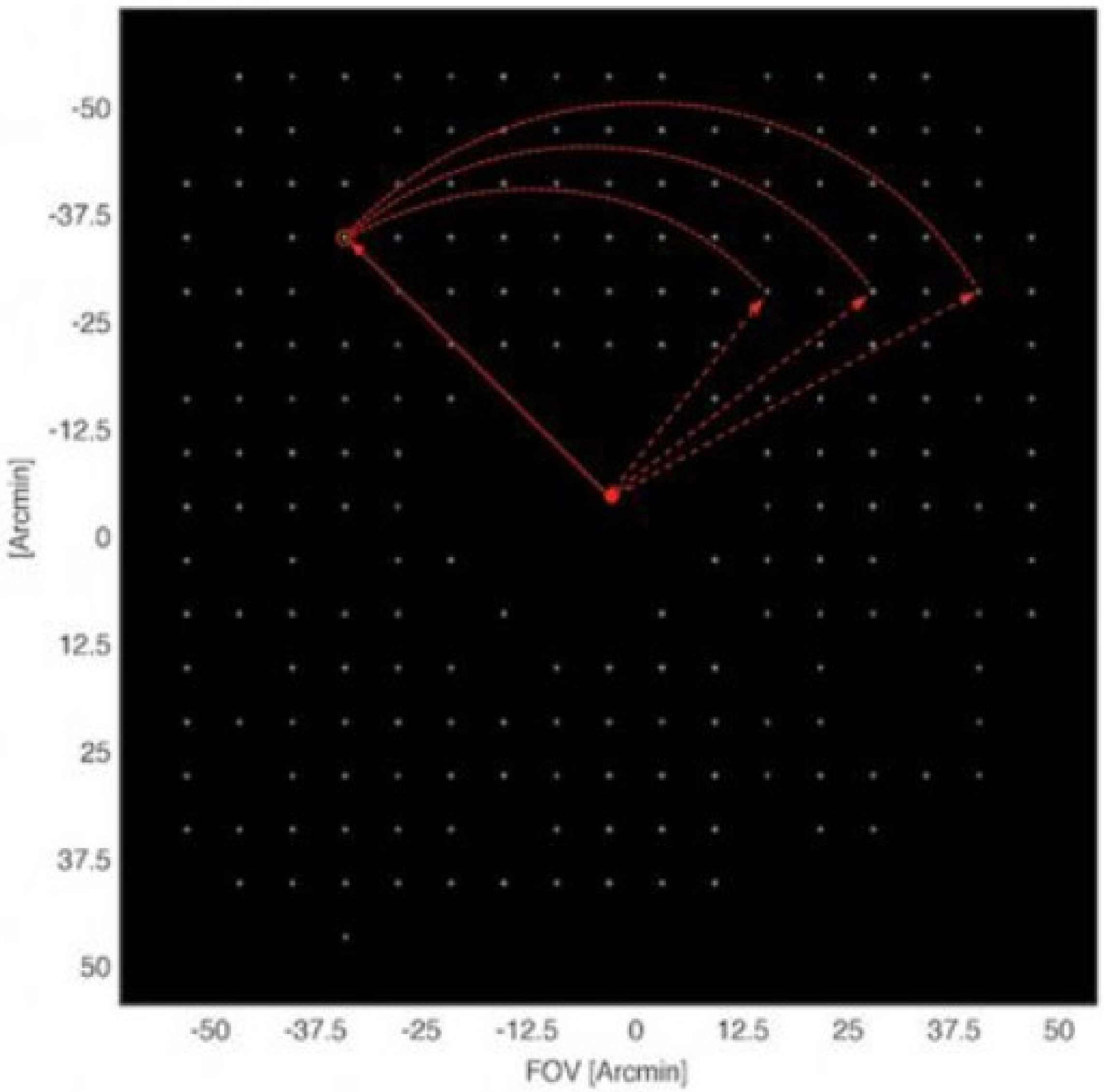


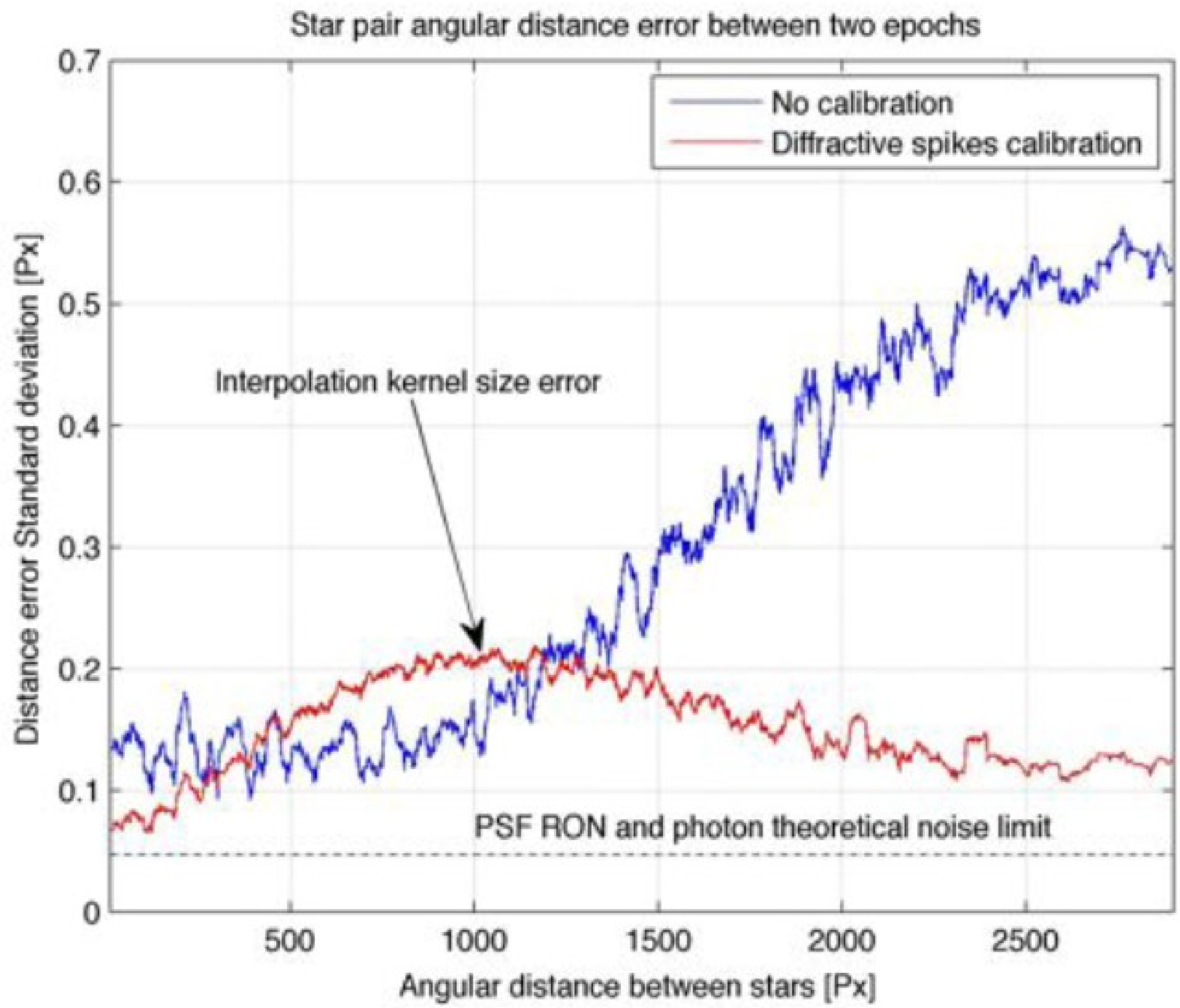


Diffraction spikes and star simulator
Diffraction spikes
Unvignetted FFoV 1.4˚
Occulter
Diffraction limited 3px PSF
Simulated star field is used for astrometric measurements
-50
-37.5
-25
-12.5
0
12.5
25
37.5
50
[Arcmin]
FOV [Arcmin]

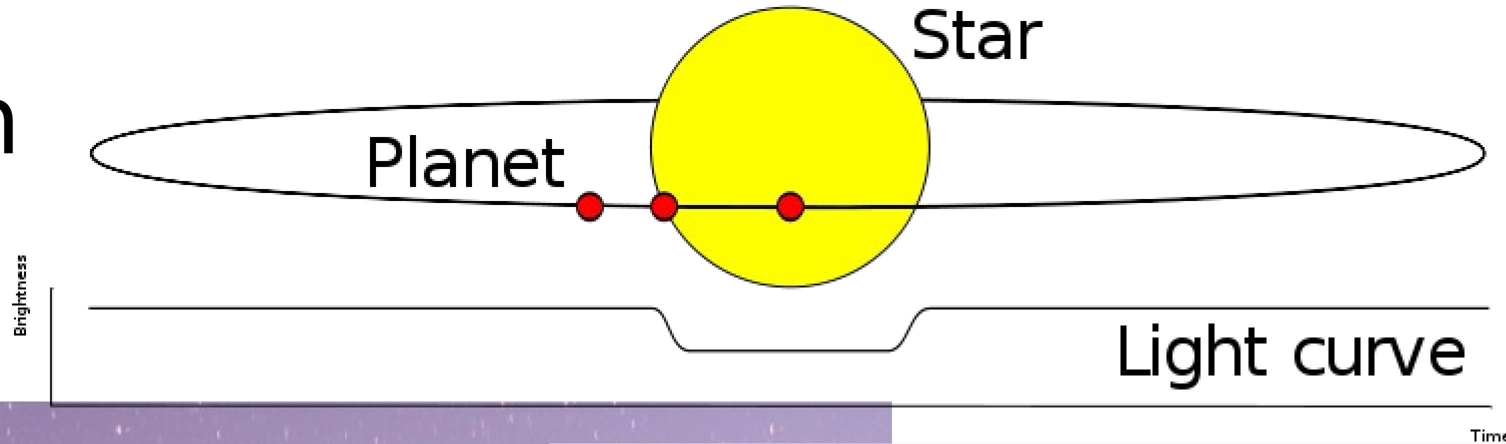
Laboratory validation (E. Bendek)

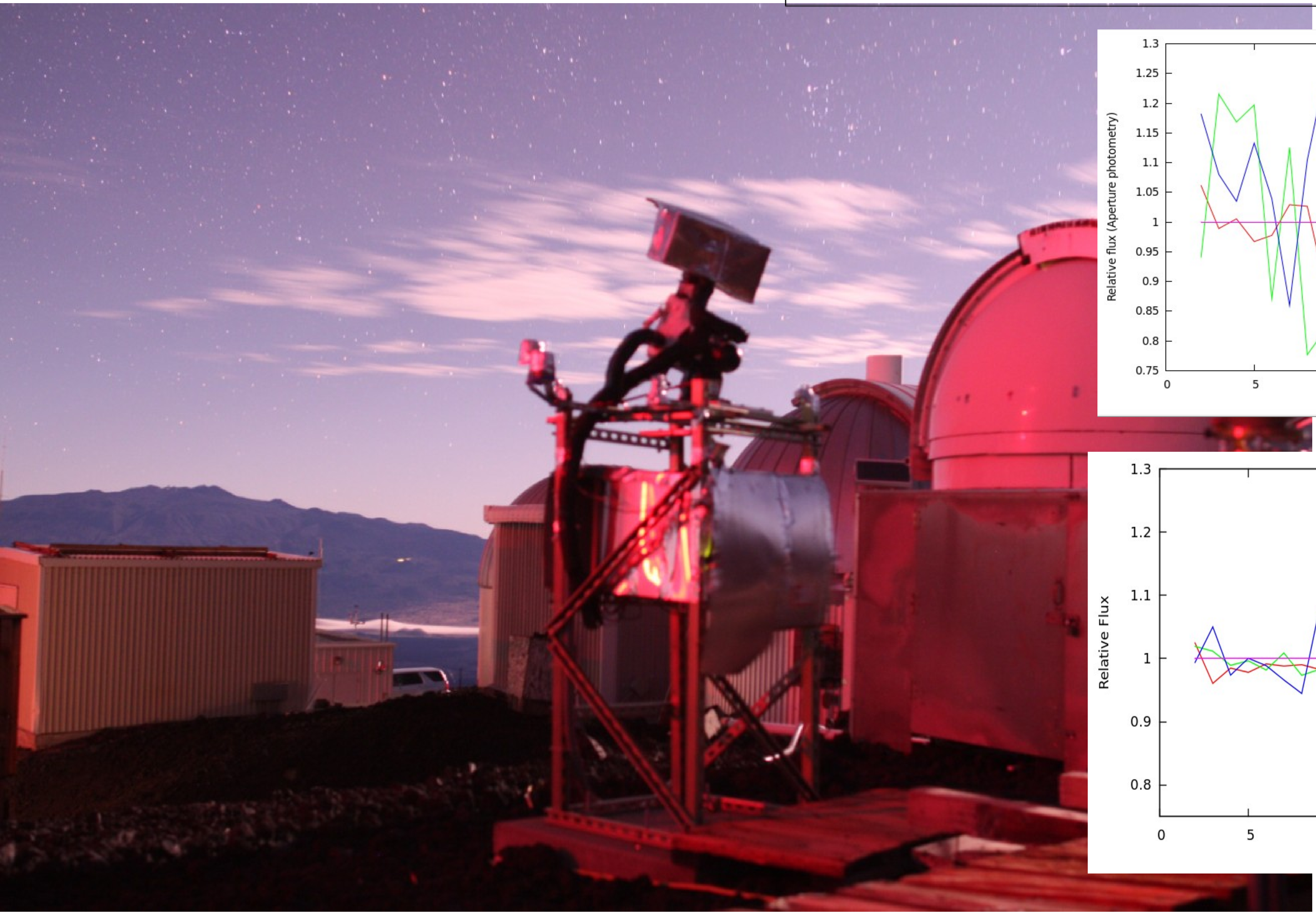
With astrometric calibration using spikes, astrometric error does not increase with angular separation or time

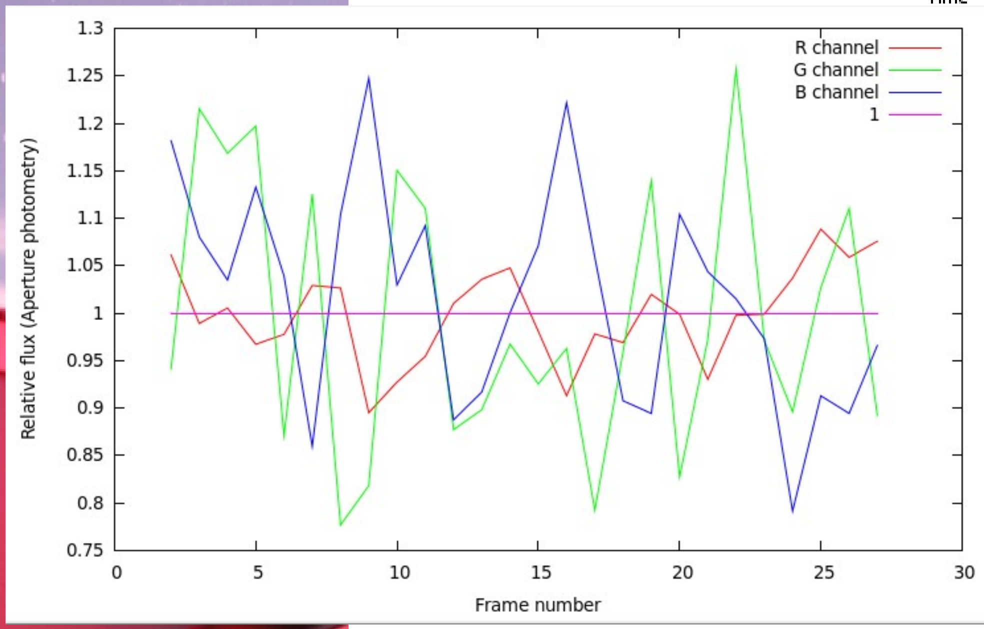


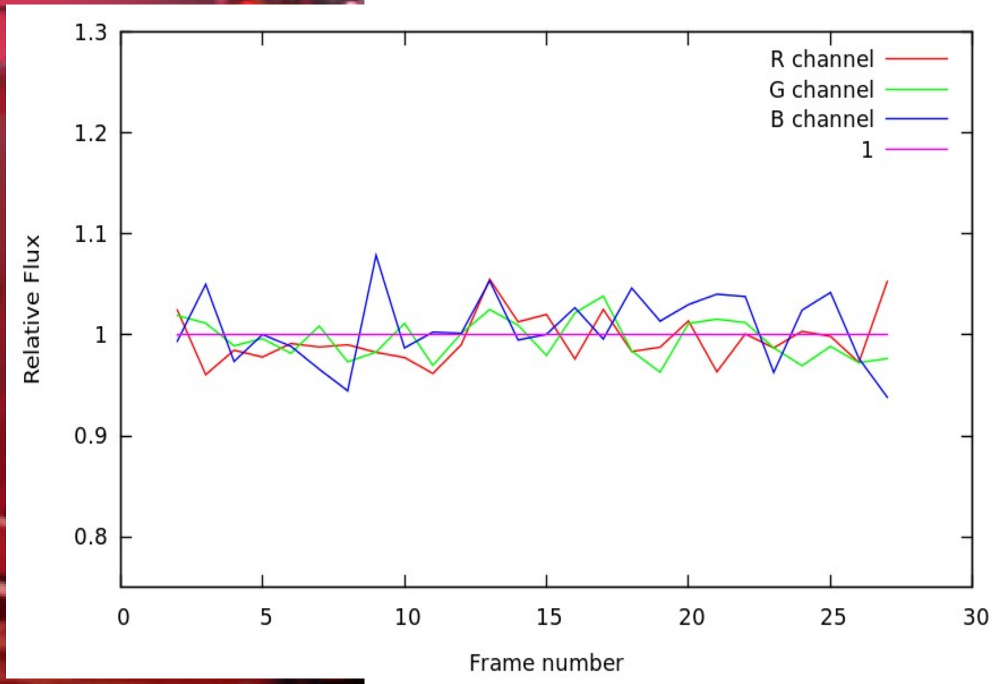


Exoplanet transit with commercial DSLRs



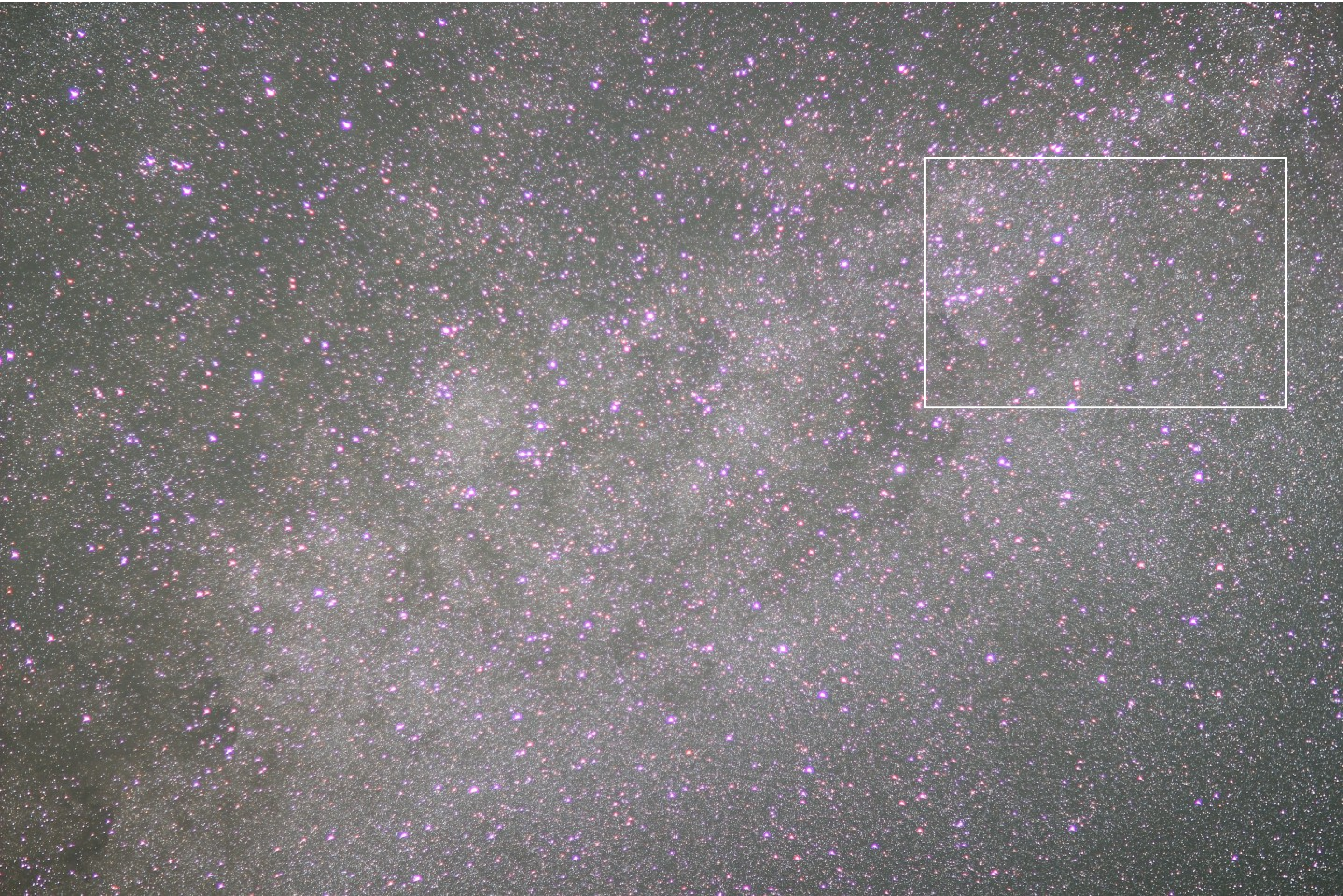






Transit Field #1 (in Cygnus), camera 2 (Sept 11, 2012 UT)

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



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