

Diffraction Pupil Telescope for high-precision space astrometry (*and coronagraphy!*)

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Improvements to original concept, error budget, exoplanet science

Error budget, mission architecture

Optical design for wide field telescope compatible with coronagraphy

Numerical simulations, modeling approach

Lab demo design & operation

Lab demo optical design & operation

System engineering, mission architecture

System engineering

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Mask manufacturing, scaling of mask manufacturing to full scale PM

Mask manufacturing, scaling of mask manufacturing to full scale PM

Exoplanet science, concept definition

Exoplanet science, concept definition

Exoplanet and star formation/evolution science

Compatibility with coronagraphy

Extragalactic science enabled with wide field camera

Extragalactic science with wide field camera

Extragalactic & galactic science with wide field camera

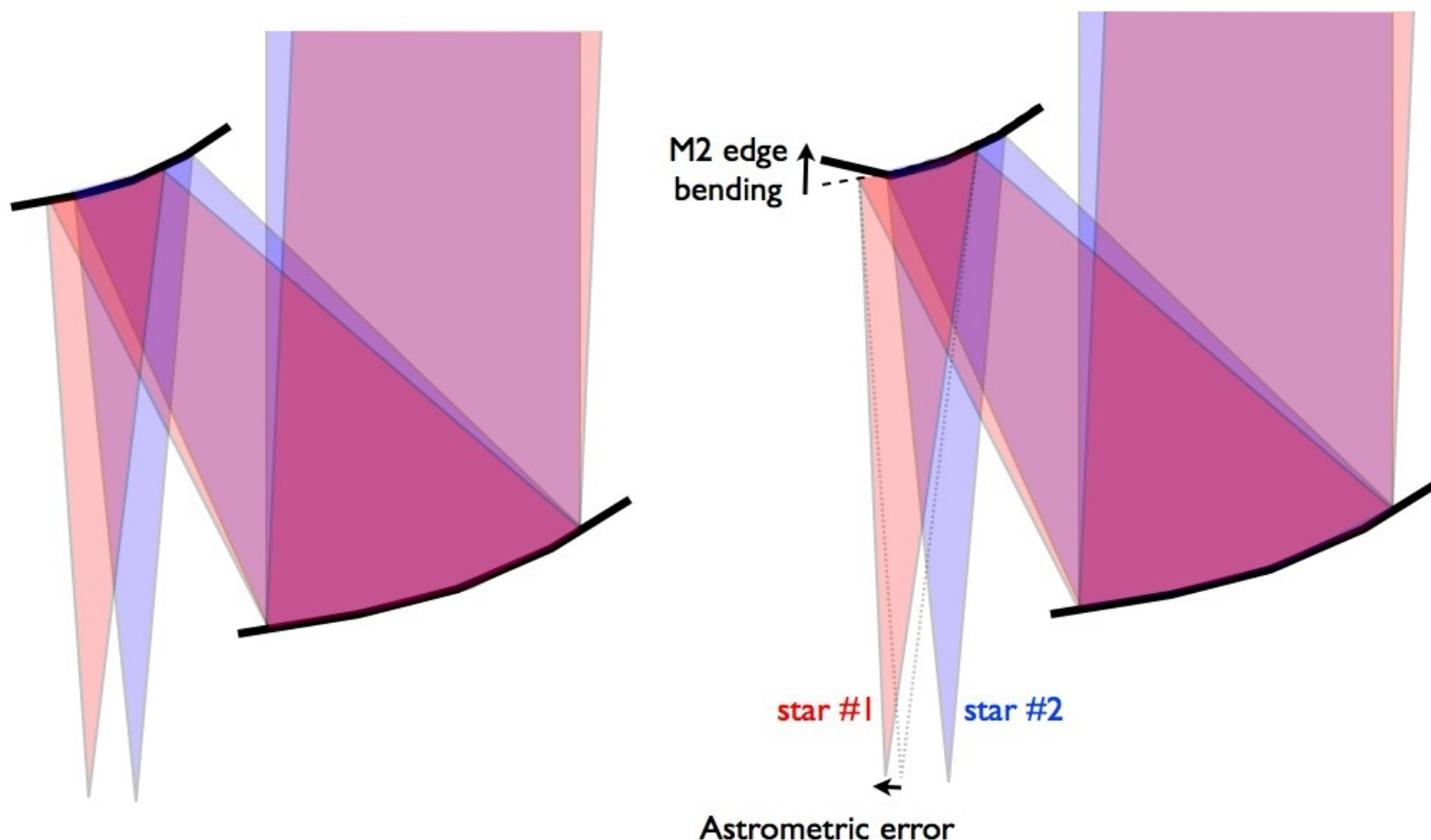
Optics manufacturing

Principle: use background stars around coronagraph target as an astrometric reference

With a 1.4-m telescope in the visible, 0.25 sq deg offers sufficient photons from stars at the galactic pole to provide an astrometric reference at the <50 nano-arcsec after taking into account realistic efficiency, zodi light and pixel sampling.

Why is imaging astrometry difficult ?

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.



(1) Light from different stars on the sky travels different paths $\rightarrow$ small bending of optics produces field distortions

(2) The detector can move between observations (especially when using large mosaics)

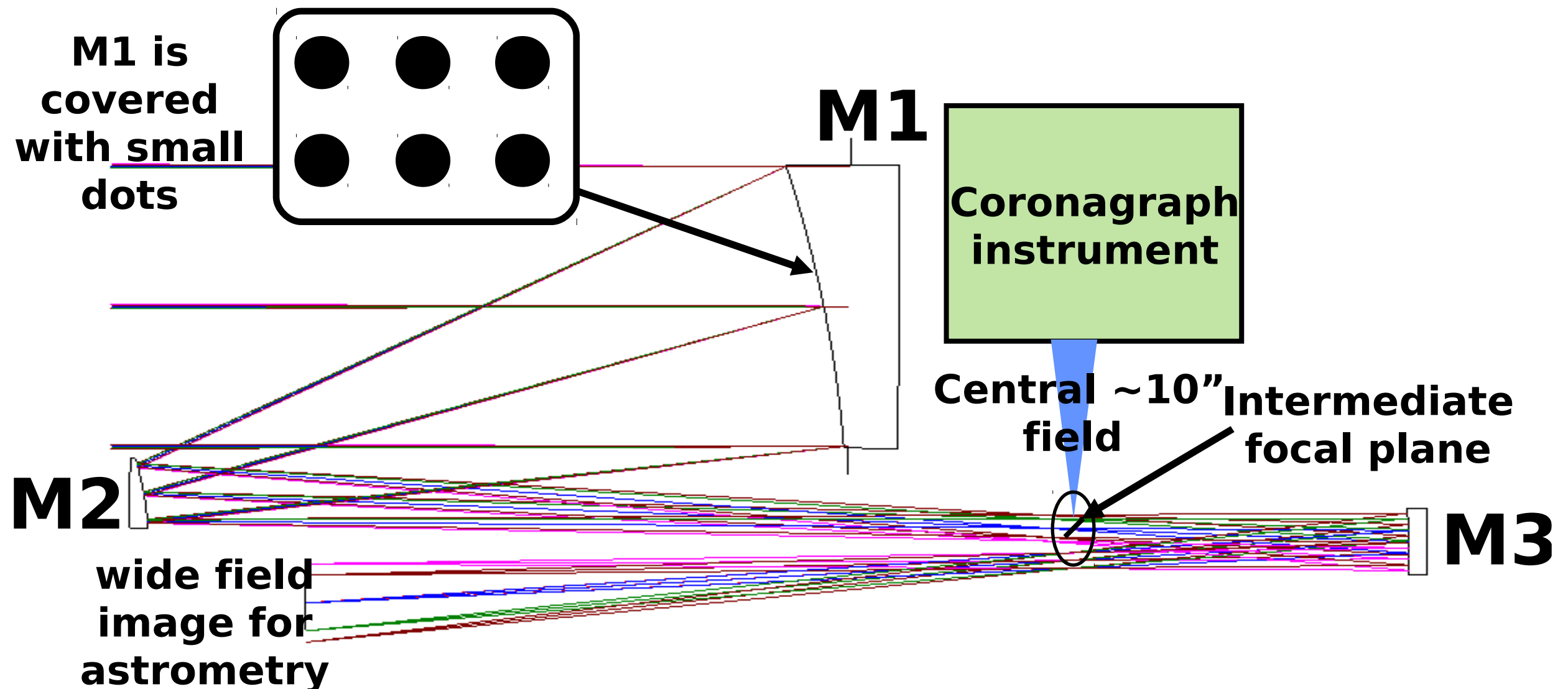
(3) Pixels are not perfect and their response changes with time

+ (4) Central star is much brighter than background stars

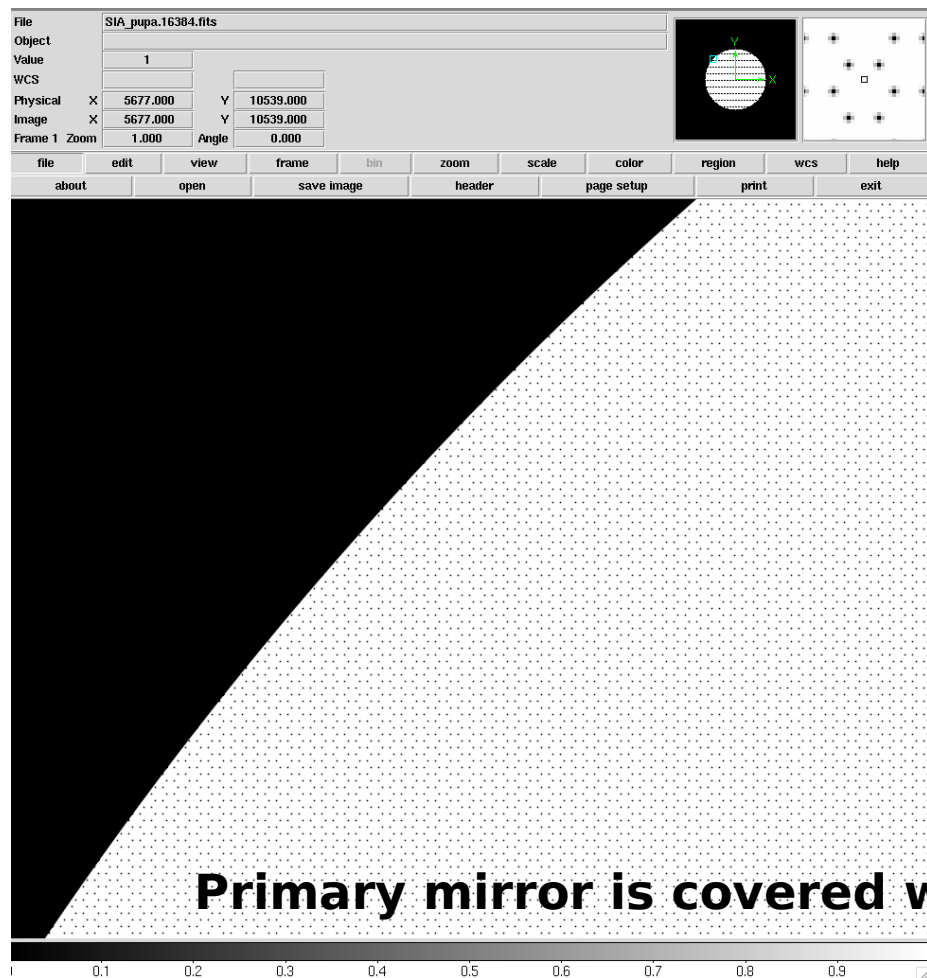
Optical Layout for simultaneous coronagraphy and astrometry

The telescope is a conventional TMA, providing a high quality diffraction-limited PSF over a 0.5×0.5 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)

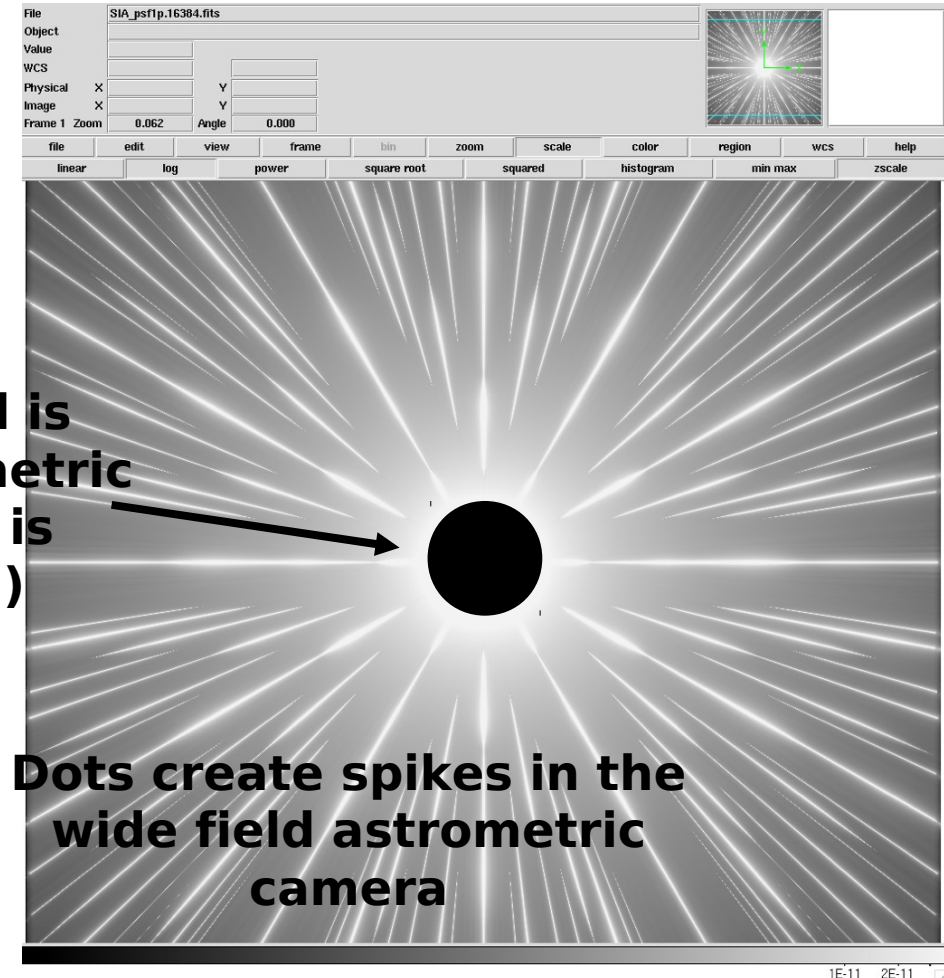


Dots on primary mirror create a series of diffraction spikes used to calibrate astrometric distortions



Primary mirror is covered with small dots

The center of the field is missing from the astrometric camera (central light is sent to coronagraph)

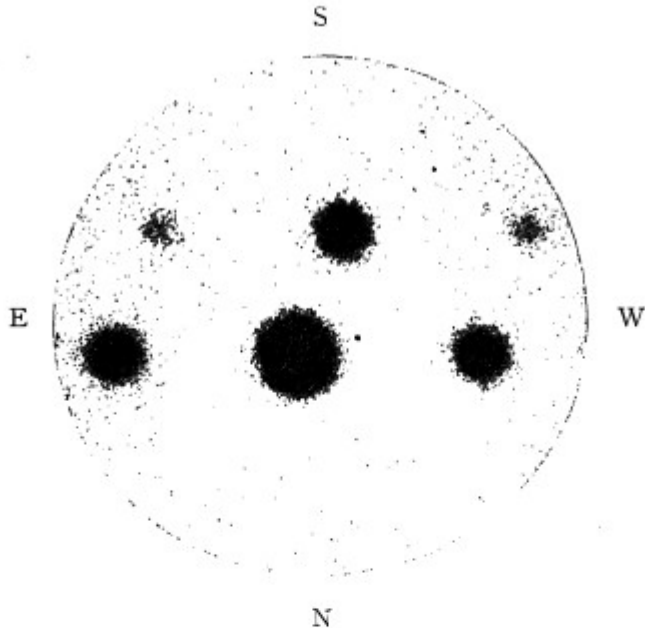


Dots create spikes in the wide field astrometric camera

All astrometric distortions (due to change in optics shapes of M2, M3, and deformations of the focal plane array) **are common to the spikes and the background stars**. By referencing the background star positions to the spikes, the astrometric measurement is largely immune to large scale astrometric distortions.

Instead of requiring ~pm level stability on the optics over yrs, the stability requirement on M2, M3 is now at the nm-level over approximately a day on the optics surfaces, which is within expected stability of a coronagraphic space telescope. (Note: the concept does not require stability of the primary mirror).

Precursors...



A 5-seconds exposure of Castor, enlarged 75 times. The separation of the components is 3".74 or 0.198 mm on the plate. The first order spectra are one magnitude fainter than the central image. Taken December 1, 1939, by K. Aa. Strand, with the Sproul 24-inch refractor, aperture reduced to 13 inches, Eastman IV G emulsion, Wratten No. 12 (minus-blue) filter.

age of the fainter component, a compensation for possible magnitude error is provided by using the mean of the measured positions of the two spectral images instead of the central image. As long as the difference in intensity between the images does not exceed half a magnitude, the magnitude error is usually negligible; it is therefore sufficient to have a limited number of gratings, producing first-order spectra which are a whole number of magnitudes fainter than the central image. For example, in his work with the Sproul refractor, Strand^a used four gratings, made of duraluminum, giving differences of one, two, three, and four magnitudes, respectively, between the central image and the first-order spectra. The bars are mounted on 10 cm-wide annular frames, cut from sheets of duraluminum, 3 mm thick. The constants of the four gratings are given below.

CONSTANTS OF SPROUL OBJECTIVE GRATINGS

Grating	—width of— bar	opening	extinction for central image	first order minus central image mag. difference	distance
1	11.25 mm	11.21 mm	1.51 mag	.98 mag	.270 mm = 5".10
2	7.12 mm	15.06 mm	.84 mag	2.05 mag	.273 mm = 5.15
3	3.98 mm	14.80 mm	.52 mag	3.01 mag	.322 mm = 6.08
4	3.20 mm	19.06 mm	.34 mag	3.95 mag	.272 mm = 5.13

"Long-focus photographic astrometry", van de Kamp, 1951

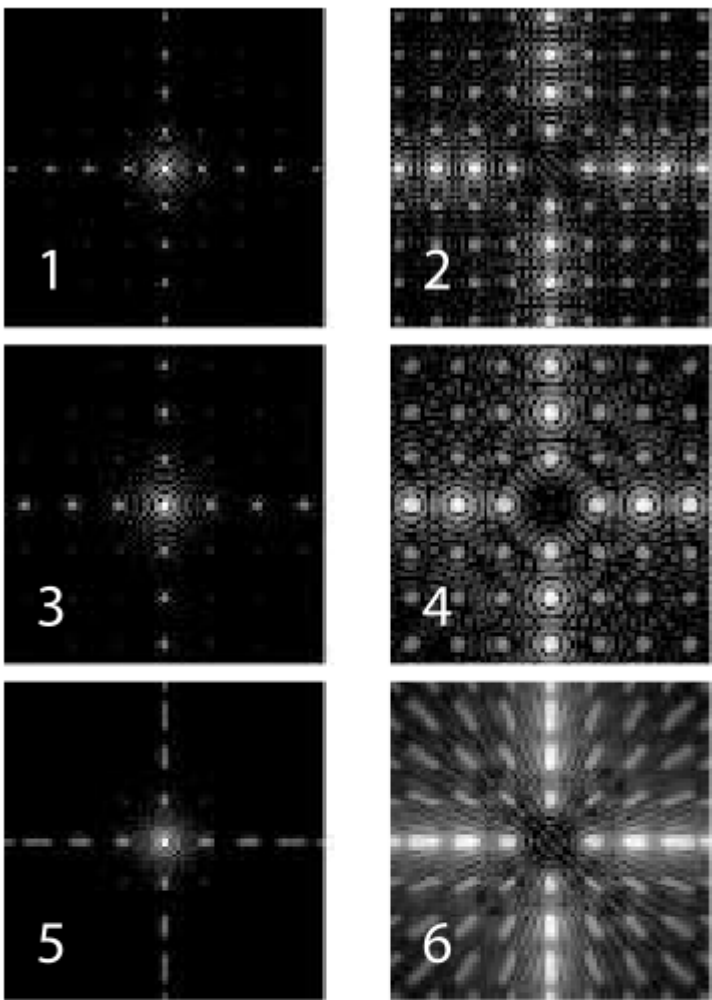
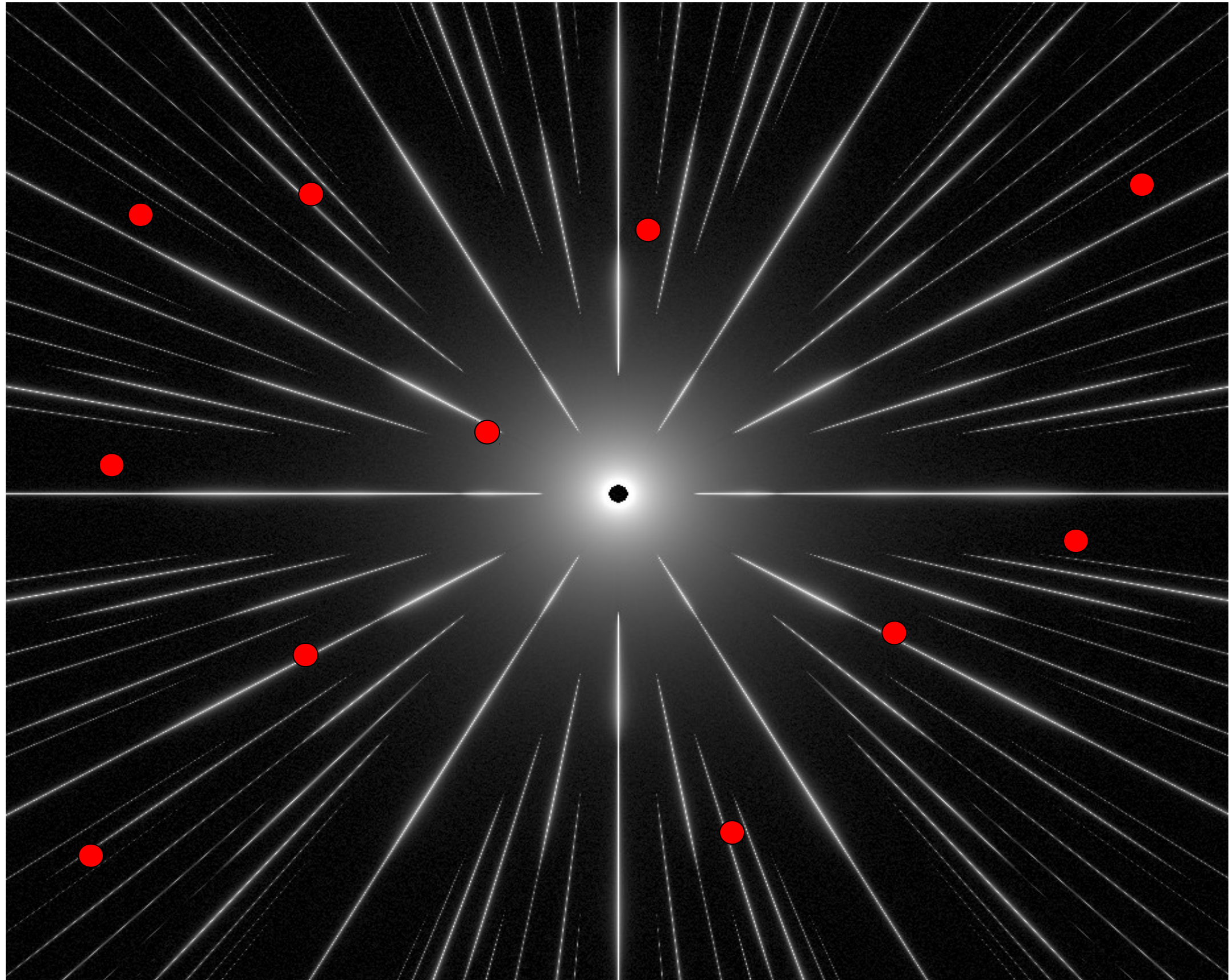


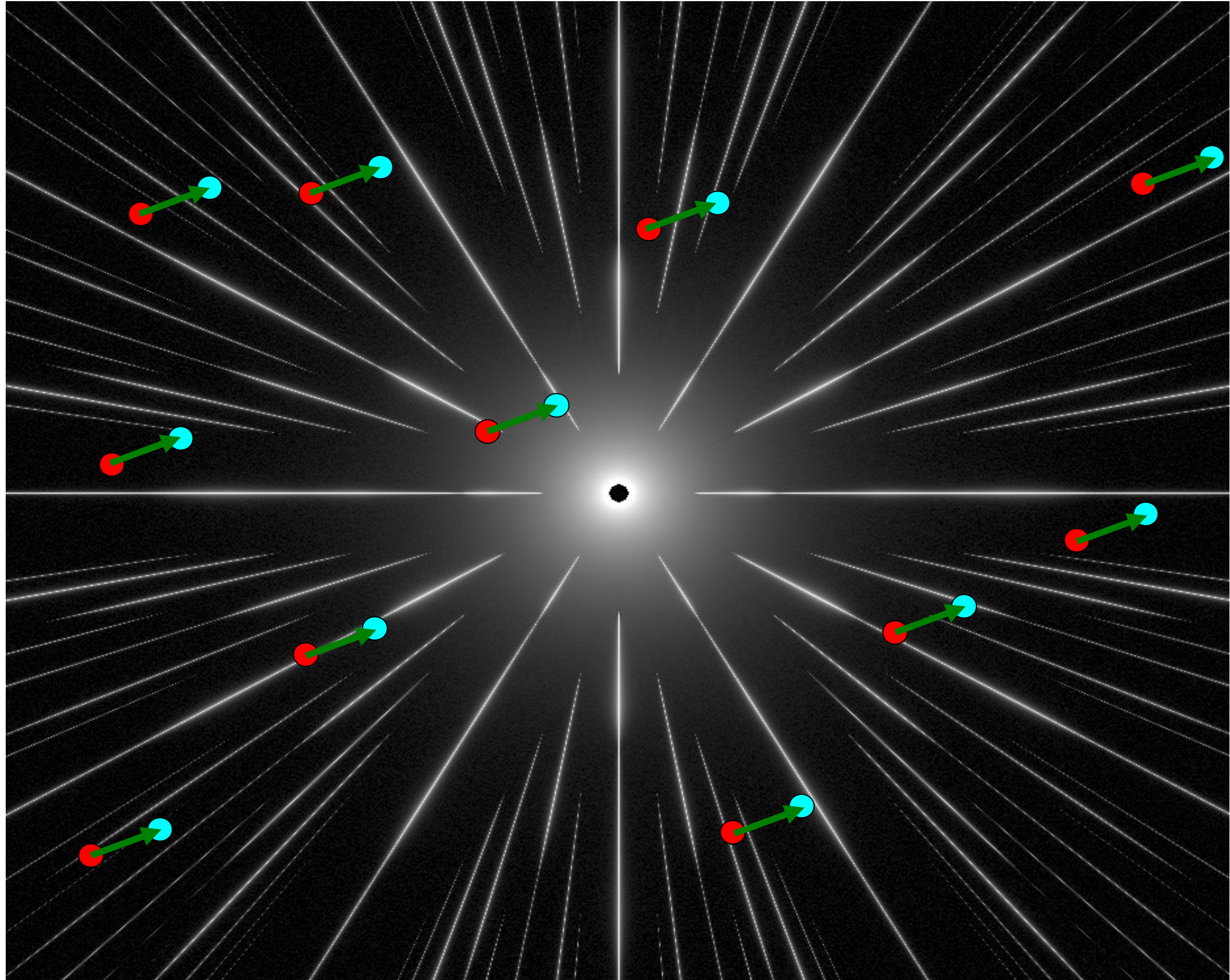
FIG. 1.—Monochromatic and broadband direct and coronagraphic PSFs with a square-geometry reticulate pupil mask. All images are on a logarithmic gray scale stretching 10 mag fainter than their peaks. The pupil is 128 pixels across, and the grid has a wire spacing of 16 pixels, with 2-pixel-wide wires. (1): Direct PSF for the shortest wavelength of a 20% bandwidth filter with uniform transmission within the bandpass, in the absence of phase errors. The satellite PSFs off the origin but along the horizontal and vertical axes are fainter than the central core of the PSF by a factor $\epsilon^2 = (g/d)^2$, where g is the wire thickness and d is the wire spacing. The satellite spots off the axes are ϵ^4 fainter than the corresponding central peak. (2): Coronagraphic PSF at the shortest wavelength of the filter. The off-axis sea of satellite spots are more visible in the coronagraphic image because the core has been suppressed. (3) and (4): Direct and coronagraphic PSFs for the longest wavelength of the filter. (5) and (6): Direct and coronagraphic PSF for the full bandpass. The length of any particular radial streak in this last pair of images (in resolution elements at the central wavelength of the bandpass) is approximately the fractional filter bandwidth multiplied by the radial distance of the spot at band center. The streaks all point toward the origin, so the smearing has no effect on astrometric precision according to Fraunhofer regime image formation theory. We suggest using the four satellite peaks closest to the core as fiducials for the position of the central occulted star in coronagraphic images.

"Astrometry and Photometry with Coronagraphs", Sivaramakrishnan, Anand; Oppenheimer, Ben R., 2006

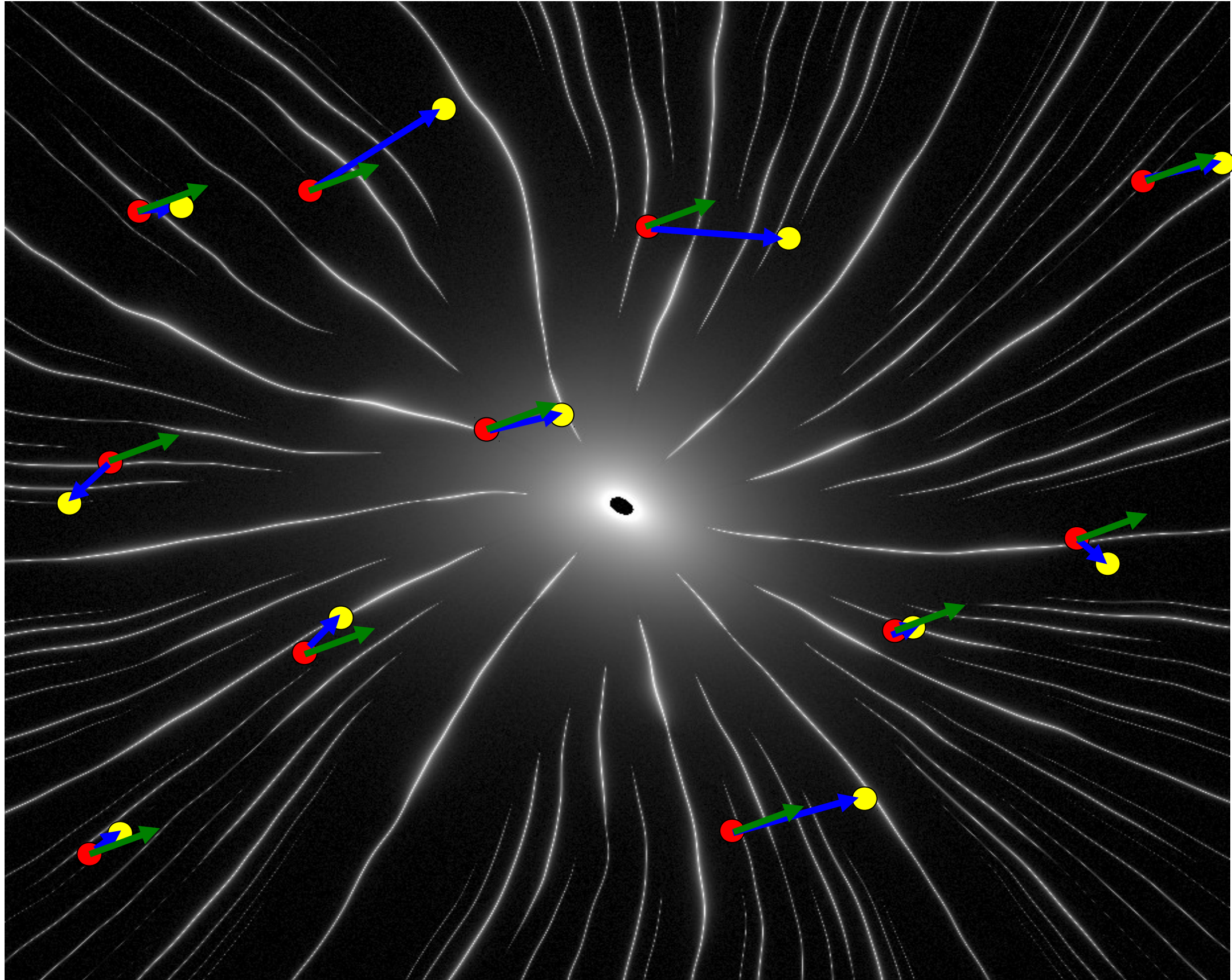
Red points show the position of background stars at epoch #1 (first observation)



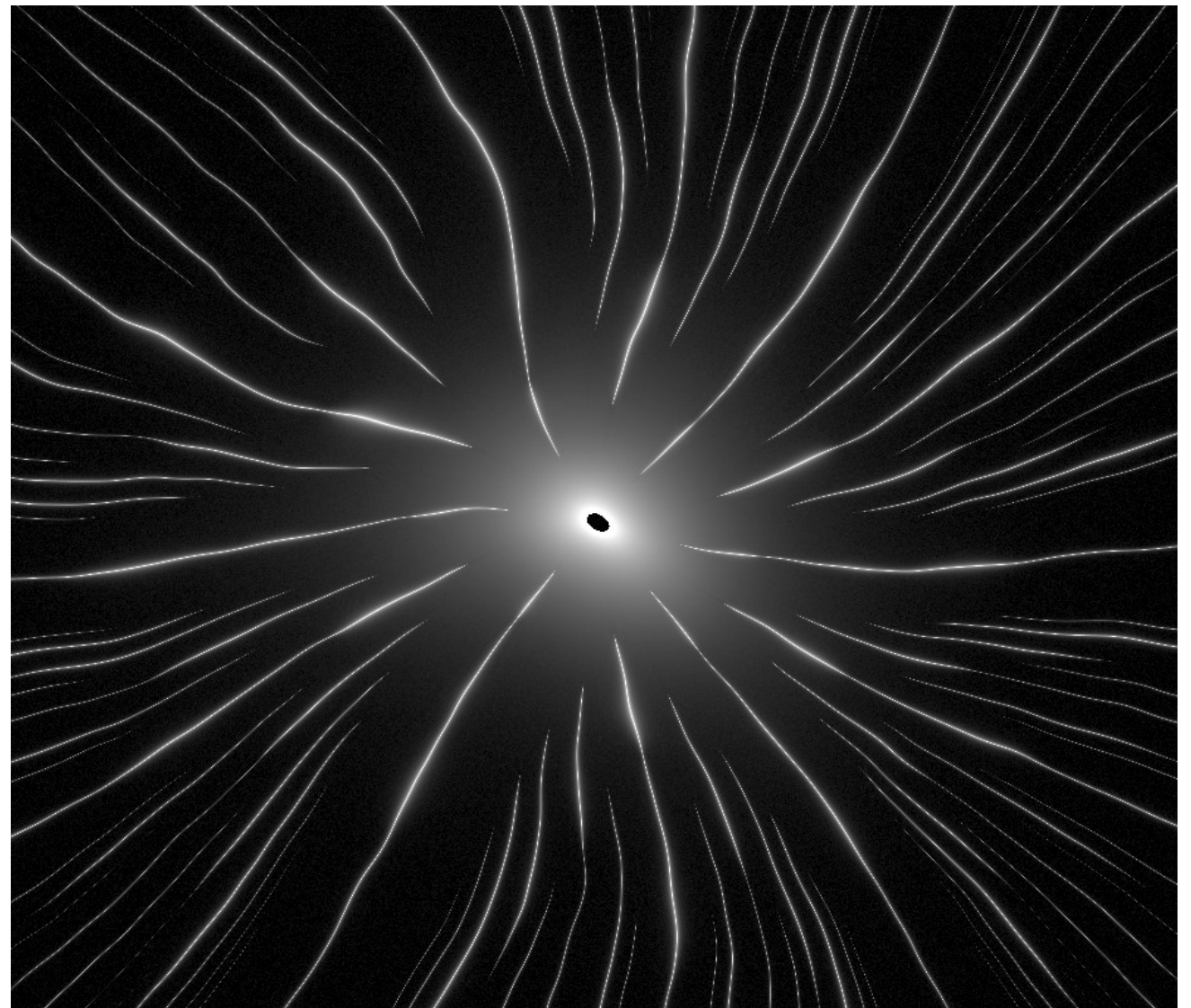
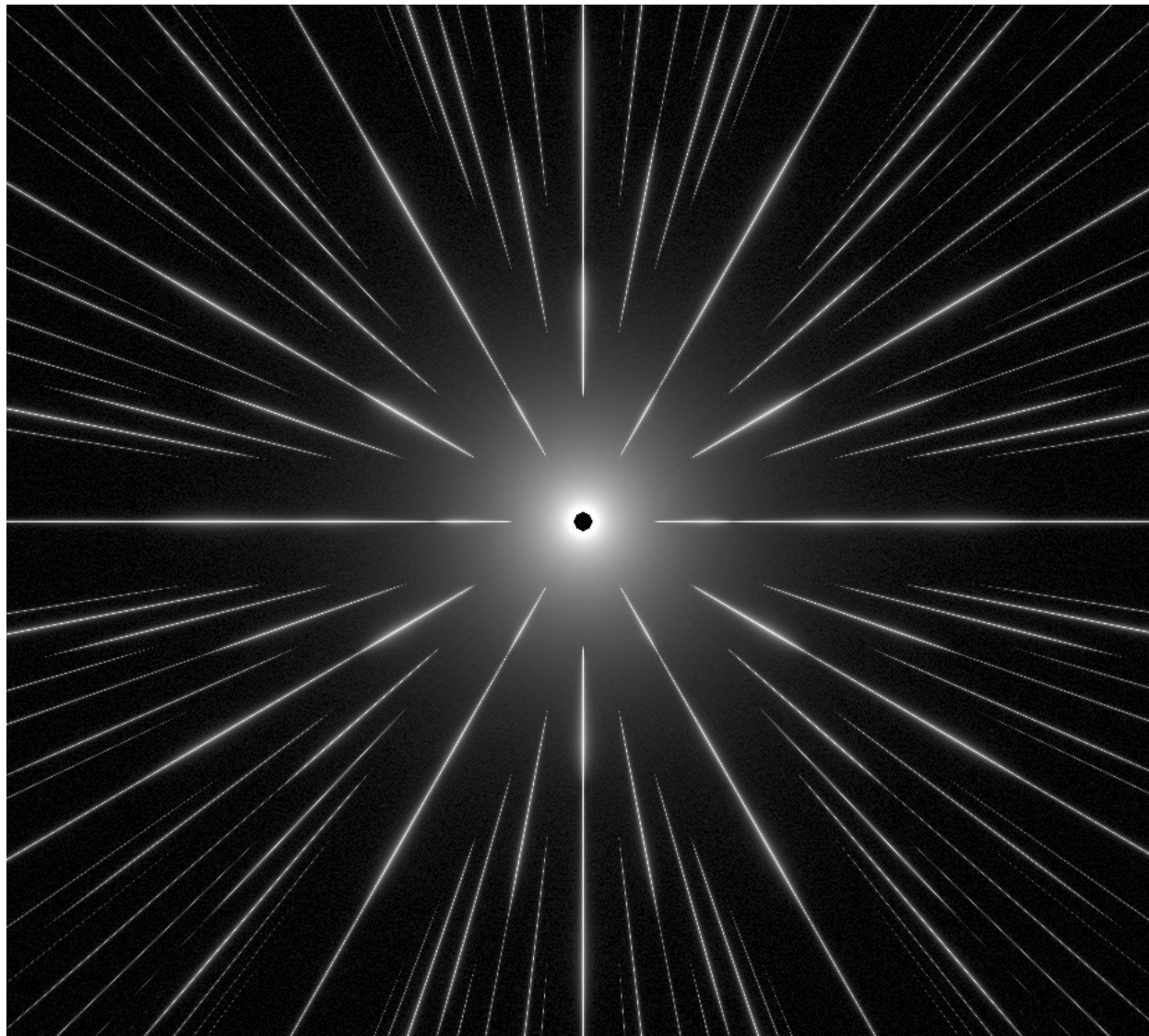
**Blue points show the position of background stars at epoch #2 (second observation)
The telescope is pointed on the central star, so the spikes have not moved between
the 2 observations, but the position of the background stars has moved due to the
astrometric motion of the central star (green vectors).**



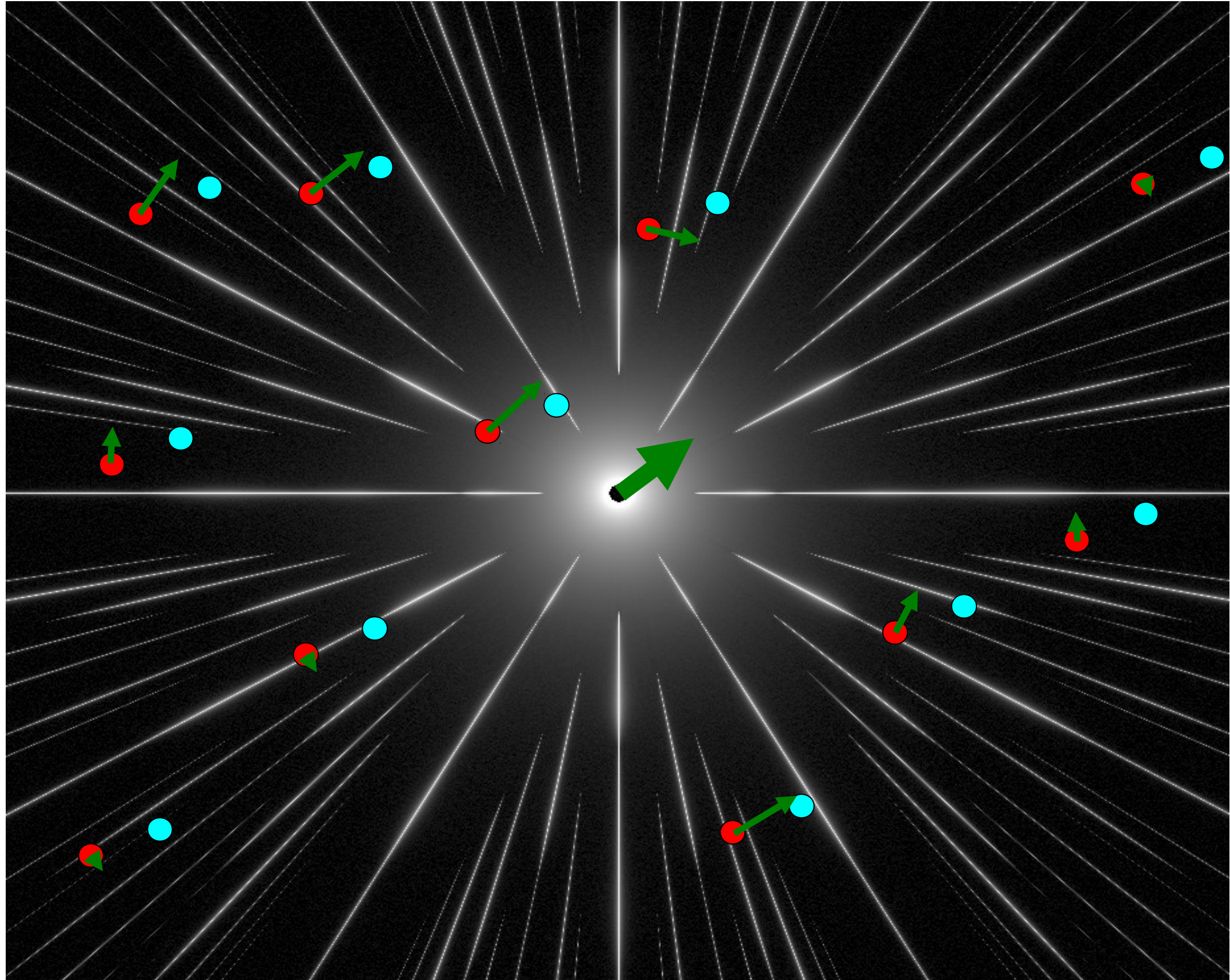
Due to astrometric distortions between the 2 observations, the actual positions measured (yellow) are different from the blue point. The error is larger than the signal induced by a planet, which makes the astrometric measurement impossible without distortion calibration.



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.



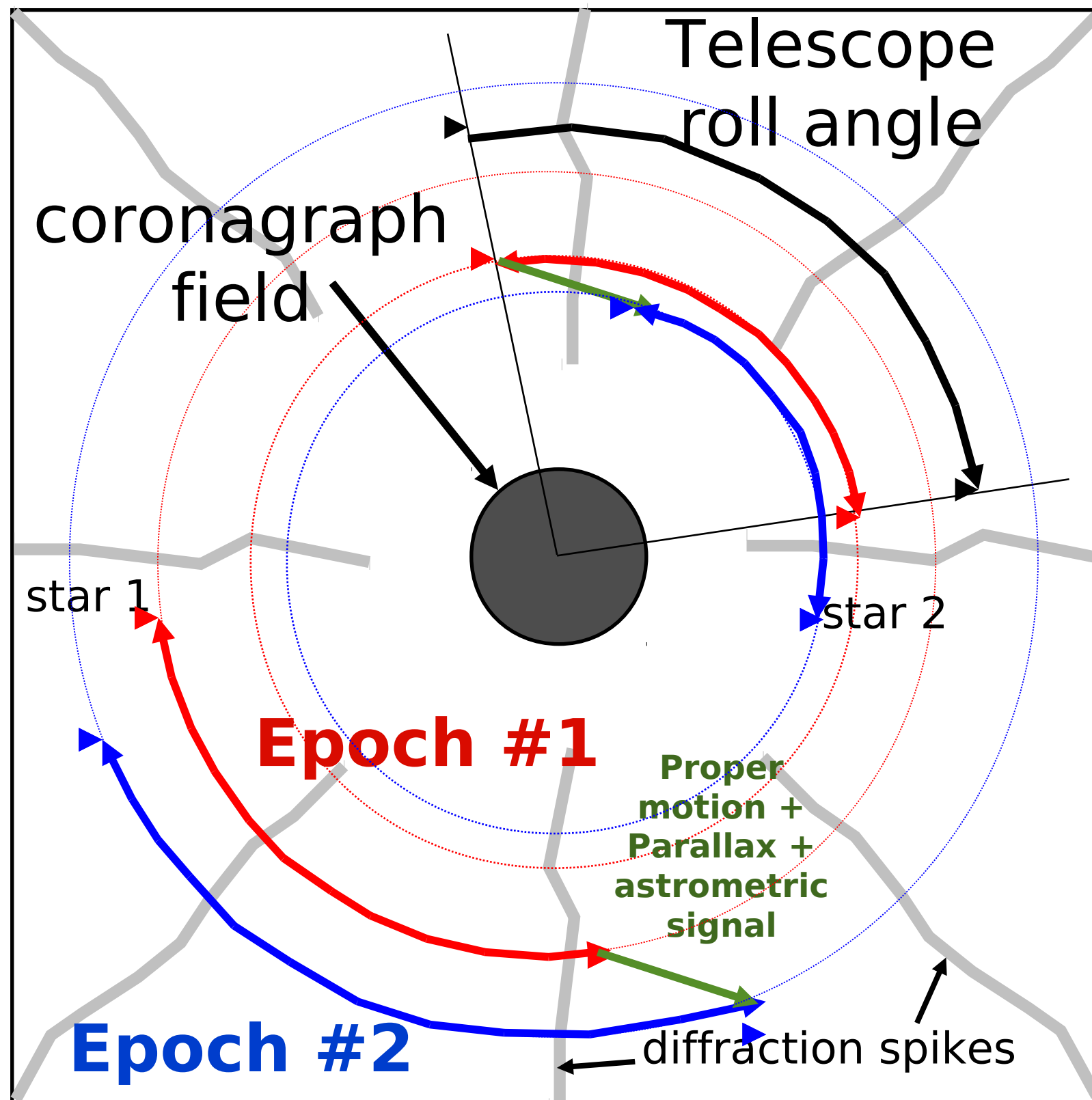
The calibration of astrometric distortions with the spikes is only accurate in the direction perpendicular to the spikes length. For a single background star, the measurement is made along this axis (1-D measurement), as shown by the green vectors. The 2-D measurement is obtained by combining all 1-D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



Observation scheme

A slow telescope roll is used to average out small scale distortions, which are due to non-uniformity in the pixel size, (spectral) response, and geometry

The green vector is what should be measured



Science goals

Primary science goal:

Measure planet mass with 10% accuracy ($1-\sigma$) for an Sun/Earth analog at 6pc.

This allows mass measurement of all potentially habitable planets (Earth-like & SuperEarths) imaged by PECO.

SNR>5 detection at $R=5$ in less than 6 hrs along 20% of the planet orbit, assuming 45% system efficiency, and 1 zodi (no WF errors)

Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO

HIP#	dist (pc)	max el (λ/D)	*rad (λ/D)	SNR (1s, tp)	t20% (s, tp)	Comment
71683	1.3	11.5	0.06	0.49	35	Alf Cen A G2 V, V=0
71681	1.3	6.6	0.04	0.45	44	Alf Cen B K2 IV, V=1.3
8102	3.6	2.3	0.01	0.08	2750	Tau Cet G8.5 V, V=3.5 **
16537	3.2	2.2	0.01	0.09	2968	Eps Eri K2 V, V=3.7 **
3821	6.0	2.3	0.01	0.04	14329	Eta Cas G0 V V=3.5 ***
2021	7.5	3.1	0.01	0.03	14878	Bet Hyi G0 V, V=2.8
99240	6.1	2.2	0.01	0.03	19636	Del Pav G8 IV, V=3.6

Table extracted from PECO SRD (http://caao.as.arizona.edu/PECO/PECO_SRD.pdf)

Simulated observations

Planetary system characteristics

Star	Sun analog
Distance	6 pc
Location	Ecliptic pole
Orbit semi-major axis	1.2 AU
Planet mass	1 Earth mass
Orbit excentricity	0.2
Astrometric signal amplitude	0.5 μ as
Orbit apparent semi-major axis	200 mas

Observations

Number of observations	32 (regularly spaced every 57 days)
Coronagraph: planet position measurement accuracy in coronagraphic image	2.5 mas per axis (= 3.6 mas in 2D): corresponds to diffraction-limited measurement with 100 photon at 550 nm on PECO
Coronagraph: Inner Working Angle	130 mas (coronagraph cannot see planet inside IWA)
Astrometry: accuracy	Variable (to be matched to science requirements)

Combined solution derived from simultaneous coronagraphy and astrometry measurements

Known variables:

- **Star location** on the sky (effect of parallax is known except for star distance, aberration of light perfectly known)
- **observing epochs**
- **Stellar mass** (assumed to be known at the 5% accuracy level)
- **measurement noise levels** for astrometry ($\sim \mu\text{as}$), coronagraphy planet position (few mas) and star mass ($\sim 5\%$)

Measurements

Astrometry:

star position
(nb of variables =
 $2 \times \text{\#observations}$)

Coronagraphy:

planet position
(nb of variables =
 $2 \times \text{\#observations}$)

Solution

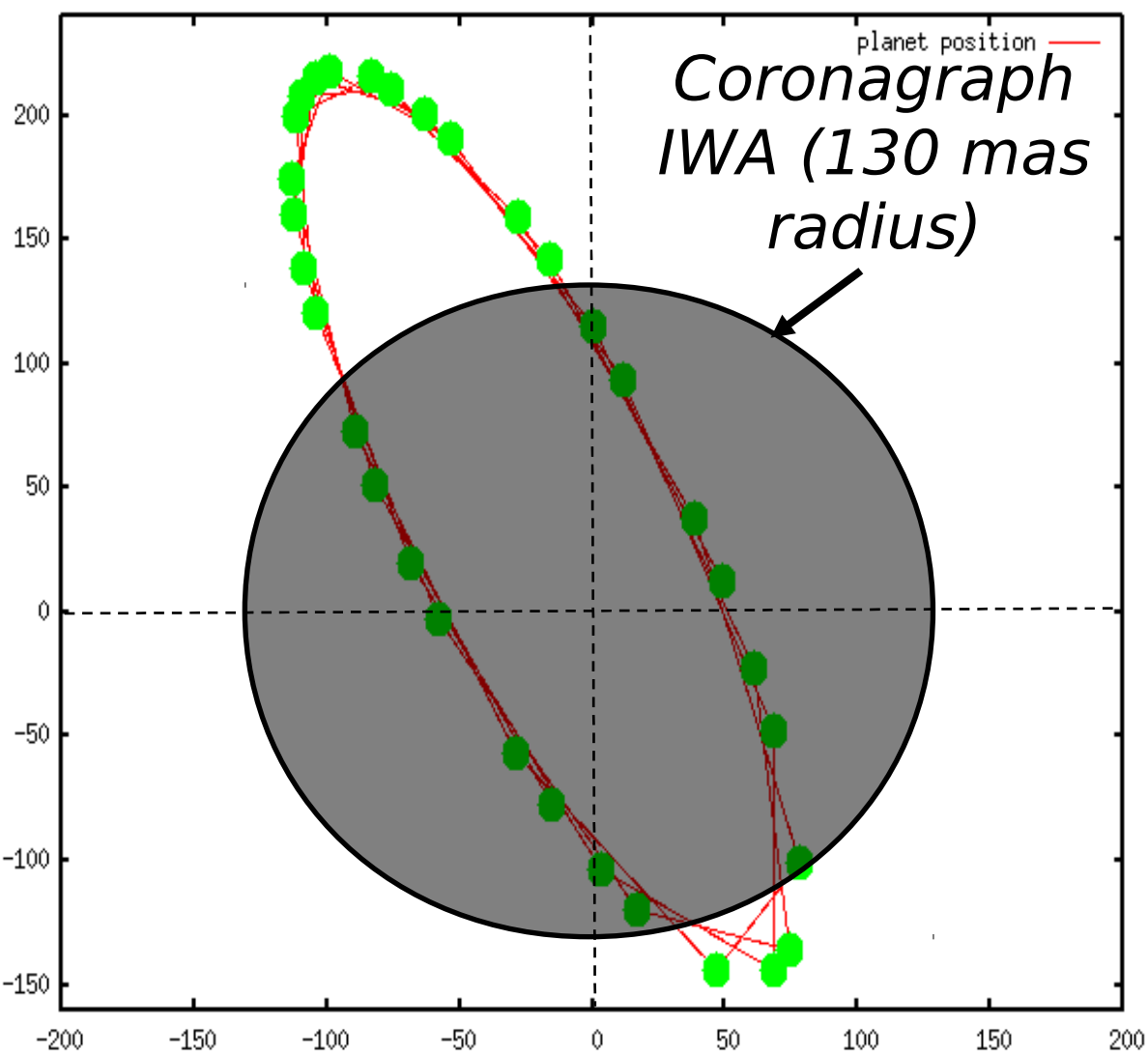
Maximum likelihood solution for
11 free parameters to be solved for:

- star parallax (1 variable)
- proper motion (2 variables)
- star mass (1 variable)
- planet mass (1 variable)
- orbital parameters (6 variables)

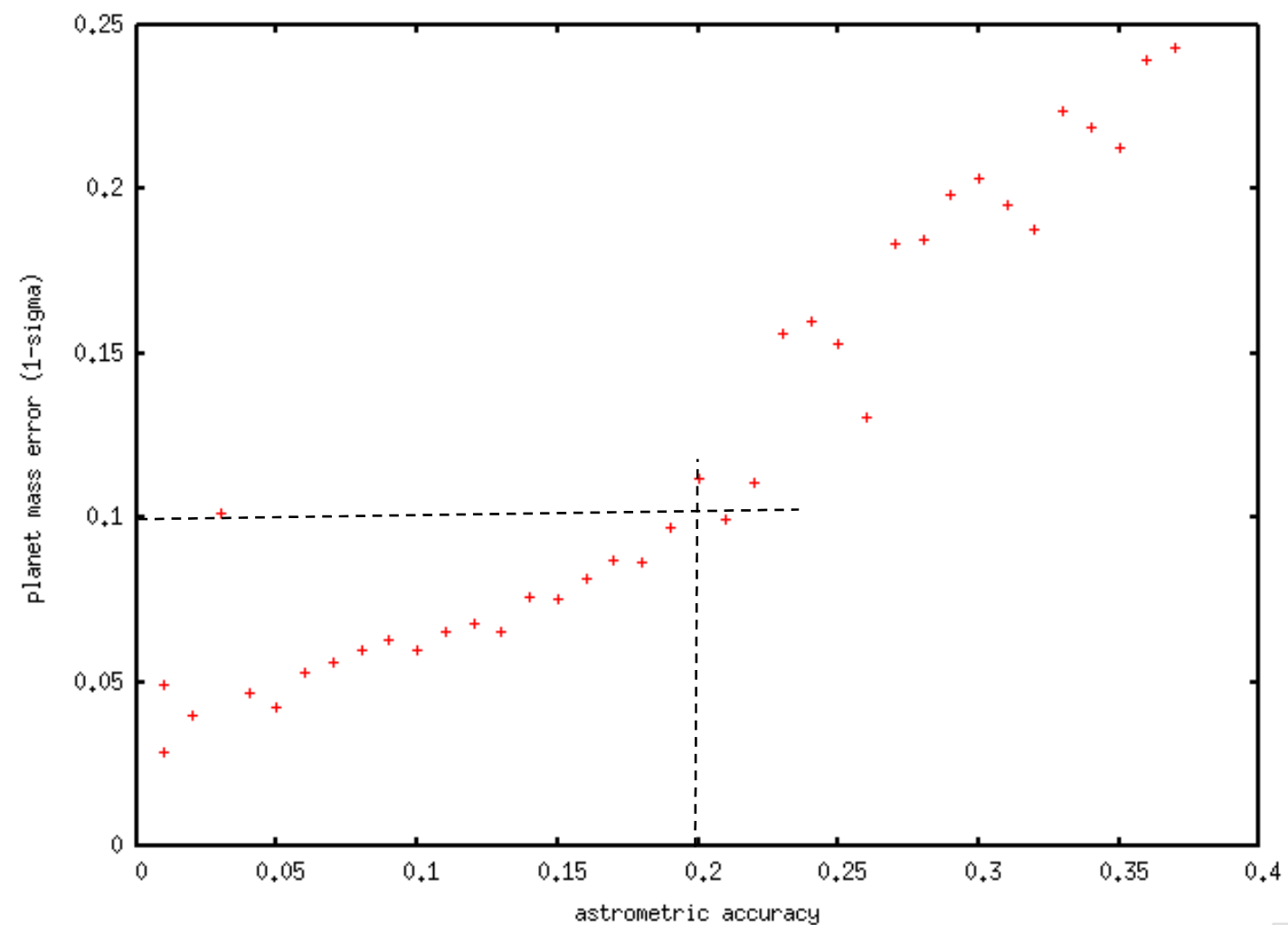
Combined solution for simultaneous coronagraphy + astrometry

Planet on a 1.2 AU orbit (1.3 yr period), $e=0.2$

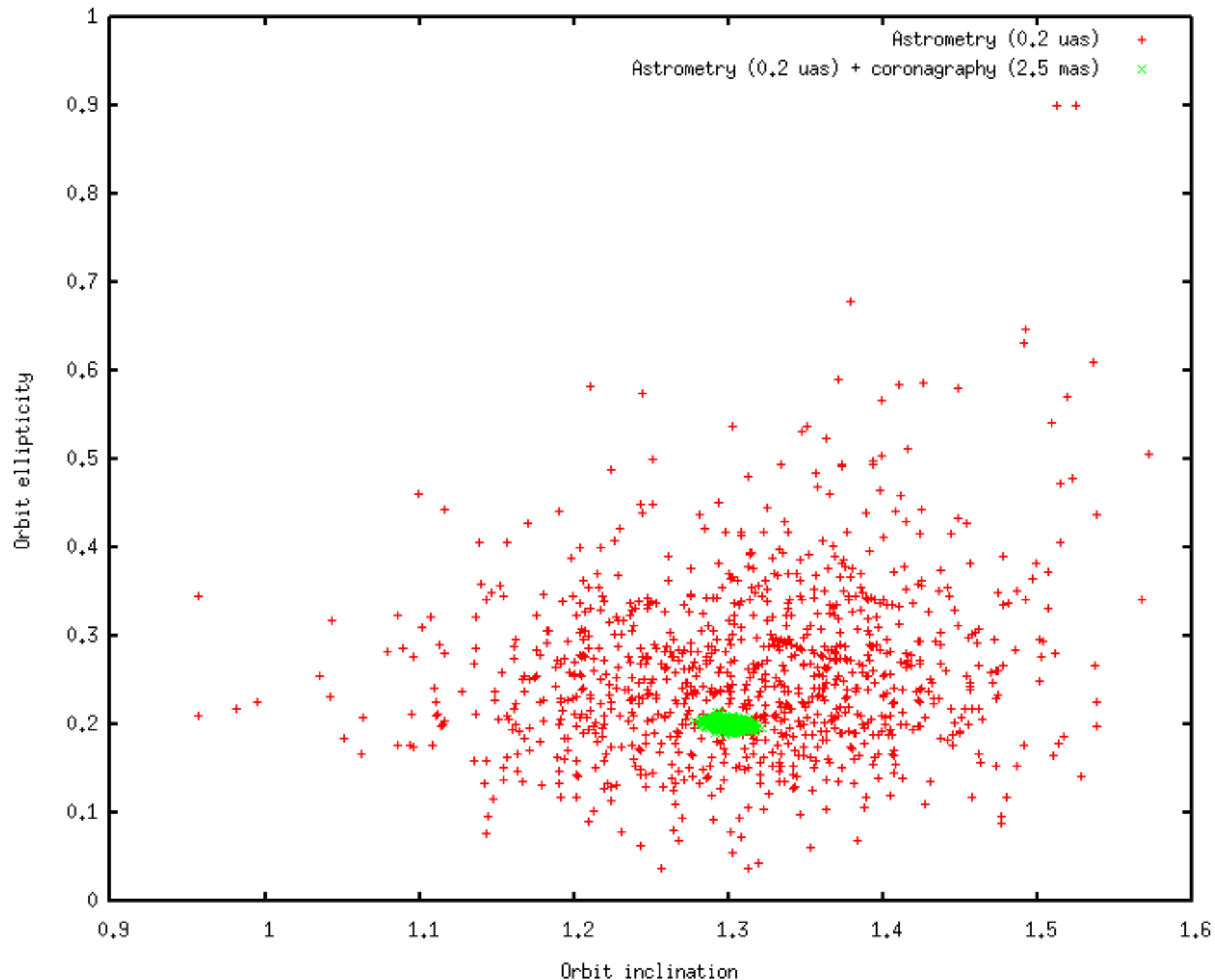
orbit orientation on sky: planet outside the coronagraph IWA for 17 out of the 32 observations.



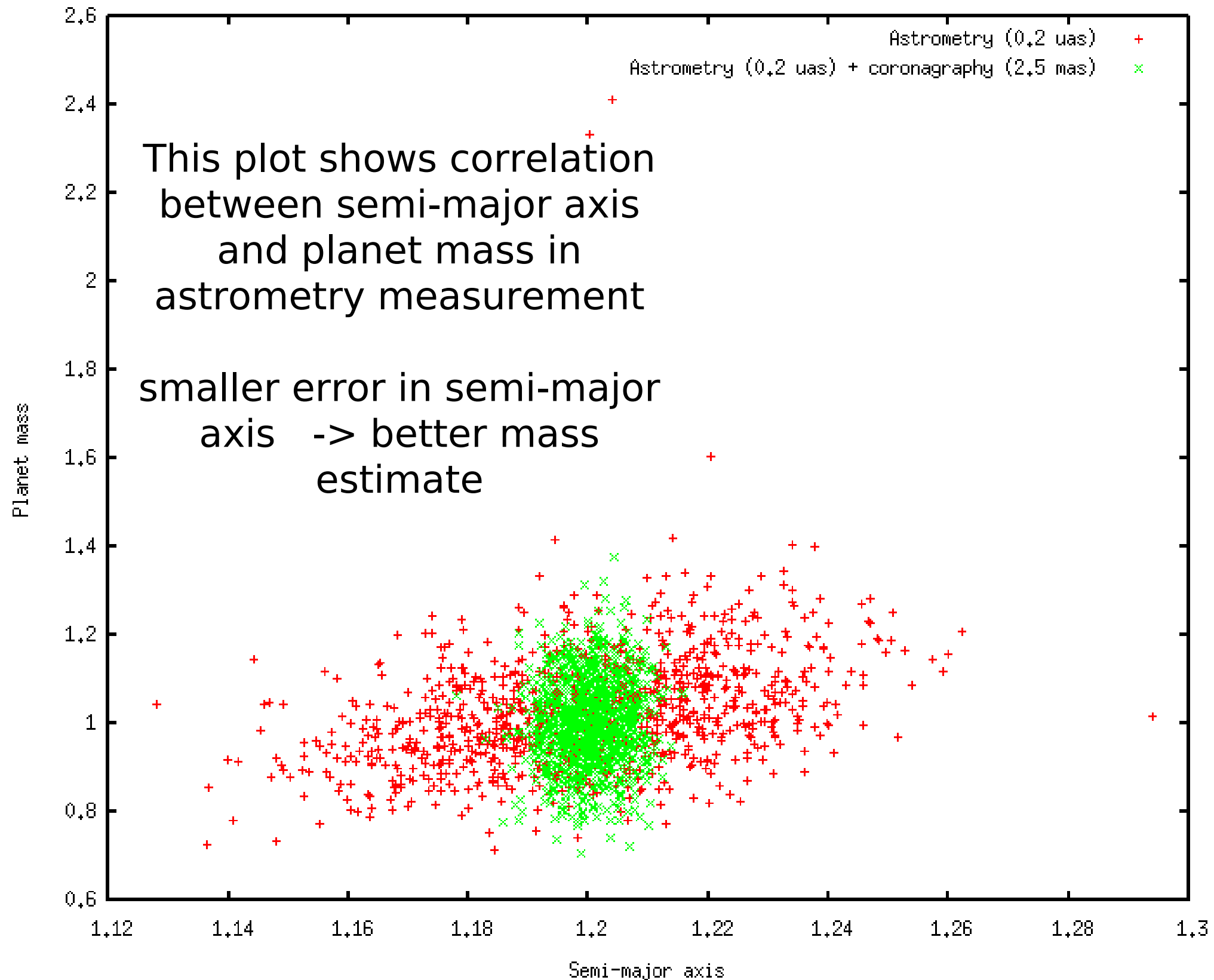
Required single measurement
astrometric accuracy = $0.2 \mu\text{as}$ (1-sigma, 1D)



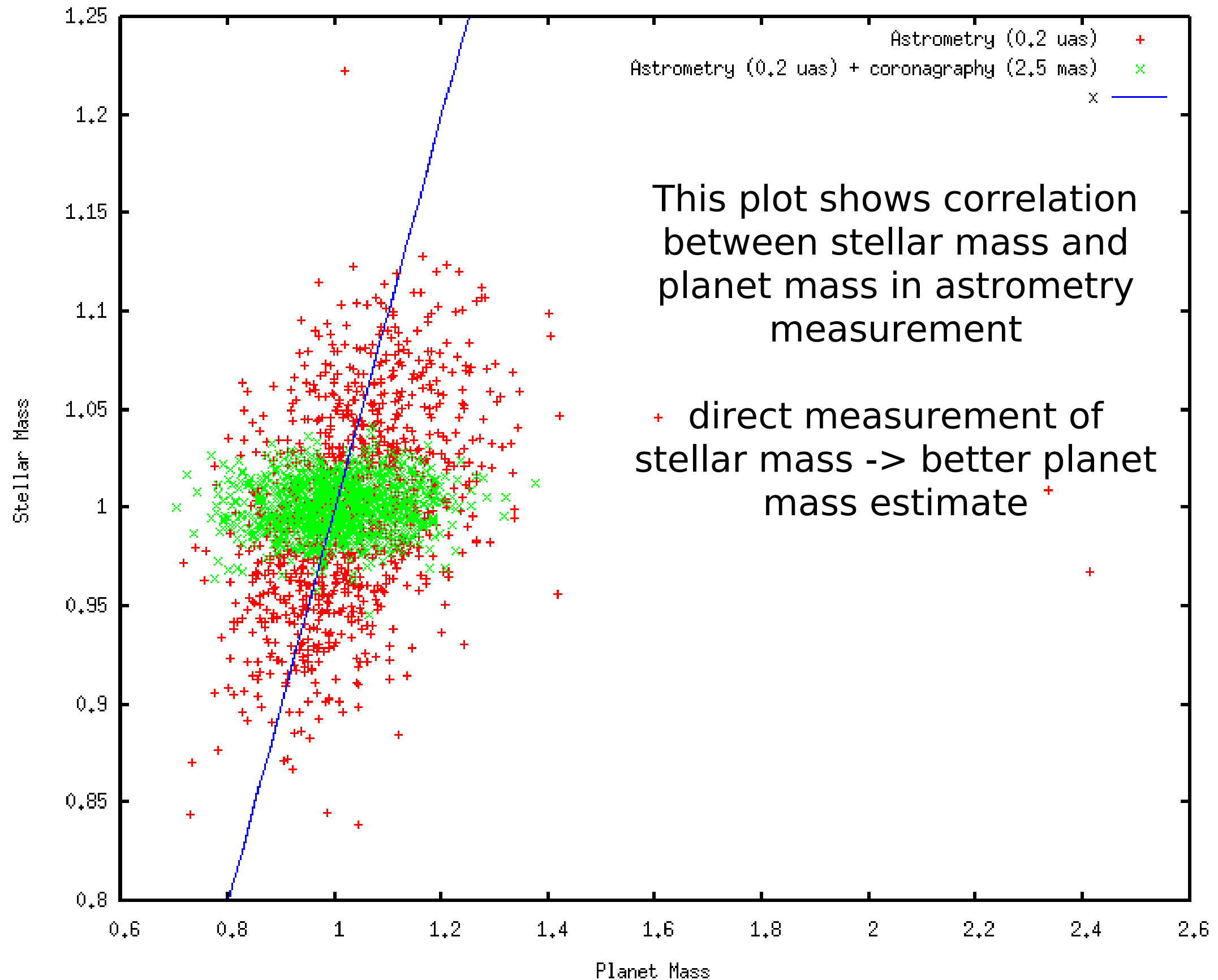
Combined solution for simultaneous coronagraphy + astrometry is very accurate for orbital parameters measurement



Better estimate of orbital parameters -> better planet mass estimate



Better estimate of stellar mass -> better planet mass estimate



Combined solution for simultaneous coronagraphy + astrometry

	Standard deviation	
	Astrometry only	Astrometry + coronagraphy
parallax	0.037 μas	0.035 μas
x proper motion	0.017 $\mu\text{as/yr}$	0.012 $\mu\text{as/yr}$
y proper motion	0.020 $\mu\text{as/yr}$	0.013 $\mu\text{as/yr}$
Planet mass	0.132 ME	0.098 ME
Semi-major axis	0.0228 AU	0.0052 AU
orbital phase	0.653 rad	0.039 rad
orbit inclination	0.0968 rad	0.0065 rad
sma projected PA on sky	0.1110 rad	0.0040 rad
orbit ellipticity	0.098	0.0035
PA of perihelion on orbit plane (w)	0.648 rad	0.0034 rad
stellar mass	0.050 M_{Sun}	0.013 M_{Sun}

~10x better estimate on orbital parameters

Direct stellar mass measurement

Benefits of simultaneous coronagraphy + astrometry

Solving for planet orbit and mass using the combined astrometry + coronagraphy measurements is scientifically very powerful:

- **Reduces confusion with multiple planets.** Outer massive planets (curve in the astrometric measurement) will be seen by the coronagraph.
- Astrometry will **separate planets from exozodi clumps.**
- Astrometric knowledge allows to **extract fainter planets from the images, especially close to IWA**, where the coronagraph detections are marginal.
- Mitigates the **1yr period problem** for astrometry

	Value in simulations	Value for mission	Rationale for flight instrument value	Impact on astrometric accuracy
Telescope diameter (D)		1.4 m	PECO sized, cost constrained	Astrometric accuracy goes as D^{-2} , thanks to larger collecting area and smaller PSF size (assuming constant FOV)
Detector pixel size		44 mas	Nyquist at 600 nm	Little impact as long as sampling is close to or finer than Nyquist
Field of view (FOV)	0.03 sq deg (0.1 deg radius)	0.25 sq deg (0.5 deg X 0.5 deg)	low WF error across field, 1.6 Gpix detector	Astrometric accuracy goes as $FOV^{-0.5}$
Single measurement time		48 hr	Typical single observation duration for coronagraph	Astrometric accuracy goes as $t^{-0.5}$
Dot coverage on PM (area)	1%	8%	Keeps throughput loss moderate in coronagraph	Larger dot coverage allows observation of fainter sources.
Flat field error after calibration, static (high spatial frequency)		1.02% RMS, 6% peak	Conservative estimate for modern detector after calibration	Negligible effect on background PSF measurement (well averaged with roll)
Flat field error, dynamic		1e-4 RMS per pixel, uncorrelated spatially and temporally between observations	1e-4 loss in sensitivity for each pixel over 48 hrs = 2% per year = 10% over 5 yrs	Negligible effect on background PSF measurement, but significant effect on measurement of spikes locations
Telescope roll		1.0 rad (+/- 0.5 rad)	Manageable sunshielding	Larger telescope roll leads to better averaging of detector errors
Uncalibrated change in optics surface between observations for M2 & M3		40 pm	Wavefront measurement repeatability (optical element removed / reinserted) obtained when testing similar sized optics on ground	Larger change in optics surface reduces astrometric accuracy
Static optics surface error (M3 mirror)		1.5 nm	WF error and PSD taken from similar existing optical element	Small impact on performance, as background PSFs are almost fixed between observations
<i>Astrometric accuracy, single measurement, single axis, $m_v=3.7$, galactic pole</i>	<i>0.58 μas</i>	<i>0.20 μas</i>	<i>0.2 μas is required to achieve science goals</i>	

Simulation description

Simulation details available on: www.naoj.org/staff/guyon/
(60 slides describing next chart)

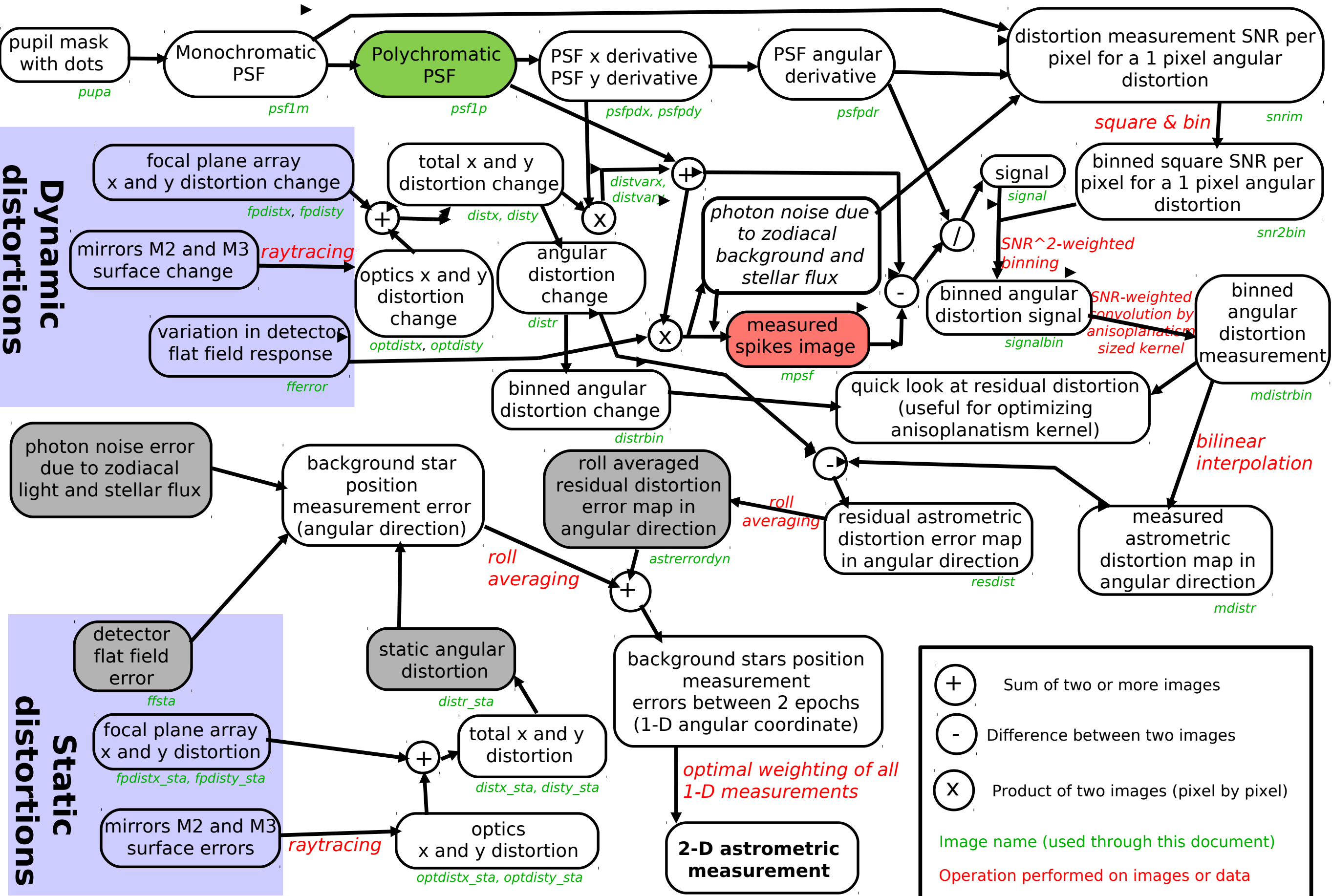
Simulation assumes:

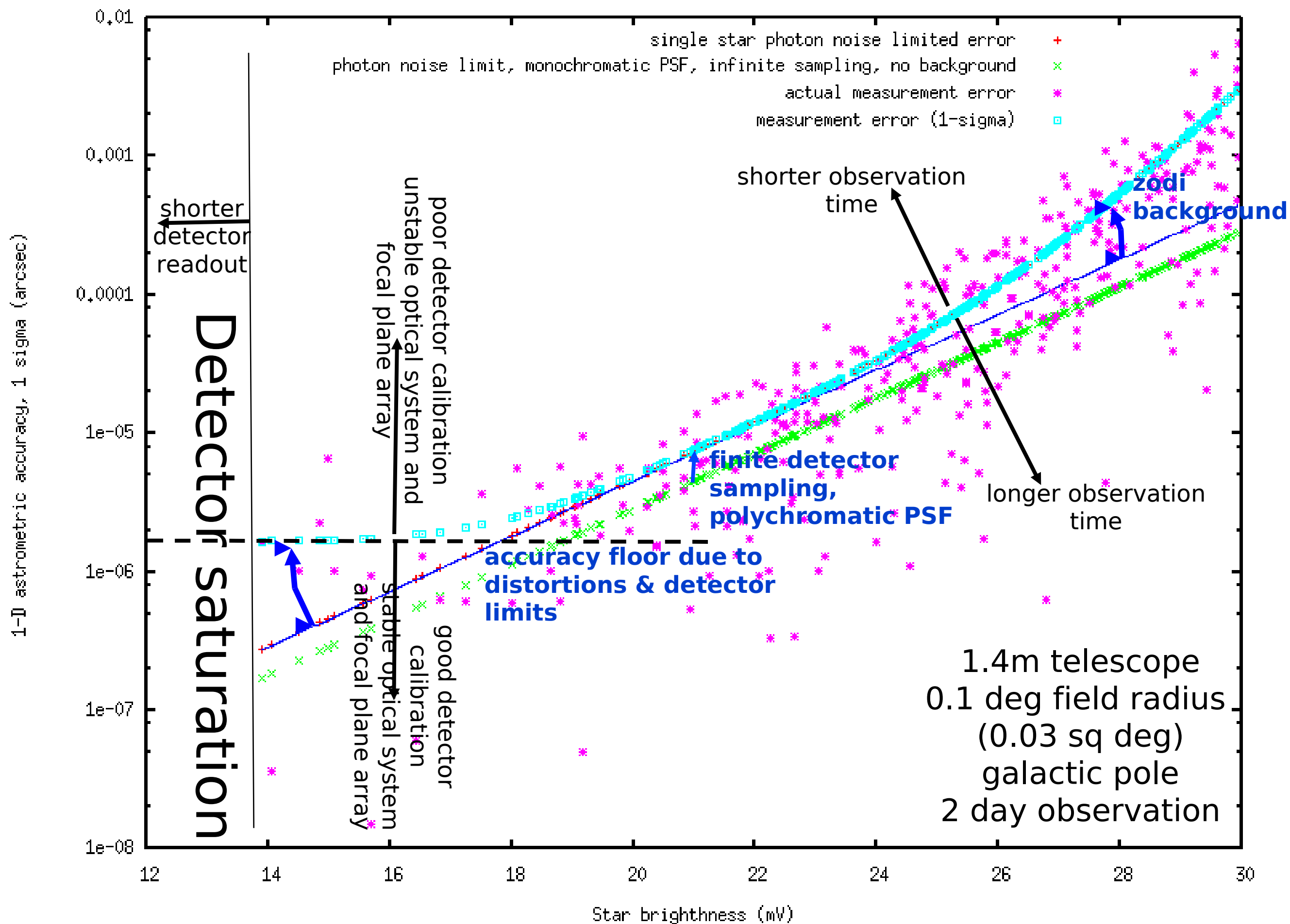
- 1.4m telescope TMA (Woodruff design)
- 1.5nm surface (3nm WF) optics for M2 and M3, PSD provided by Tinsley
- Circular field of view, 0.2 deg diam (0.03 sq deg)
- Galactic pole observation (worst case scenario)
- central star is $m_v=3.7$ (faintest of the 7 PECO targets for which an Earth can be imaged in <6hr, 14th brightest target in the 20 high priority targets list)
- 90% detector peak QE, 80% optical throughput (0.96^3 for optics reflectivity x 0.92 due to dots on PM)
- Nyquist sampled detector at 0.6 micron = 44 mas pixels
- Telescope roll = 1 rad (larger angle = better averaging, but more difficult to maintain stability)
- Single epoch observation = 2 day

Distortions in the system are computed with 3D raytracing (code written in C, agreement with Code V results from Woodruff has been checked)

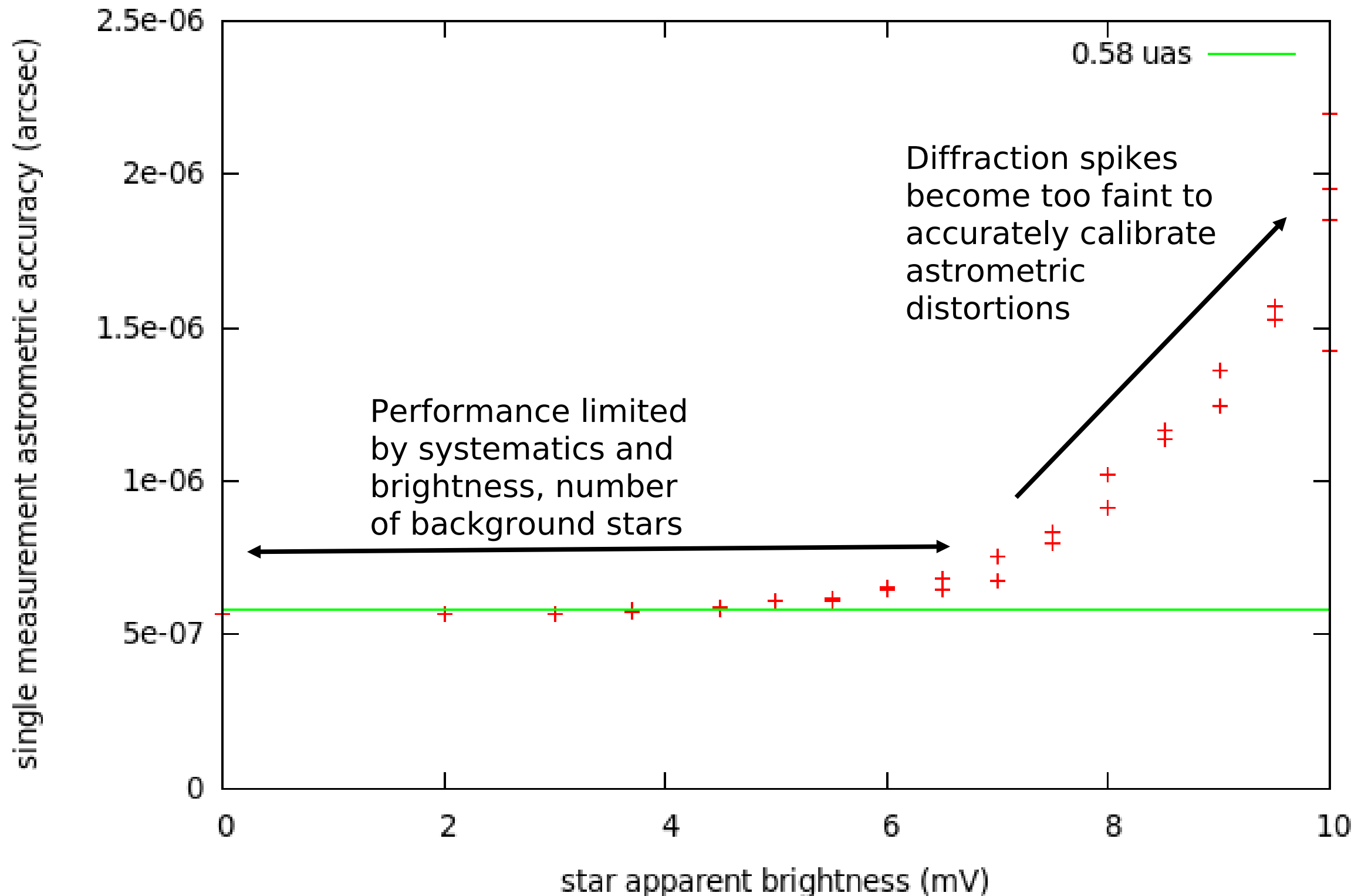
Images produced by Fourier transform, and then distorted according to geometrical optics. Image sizes are 16k x 16k.

Numerical simulation approach

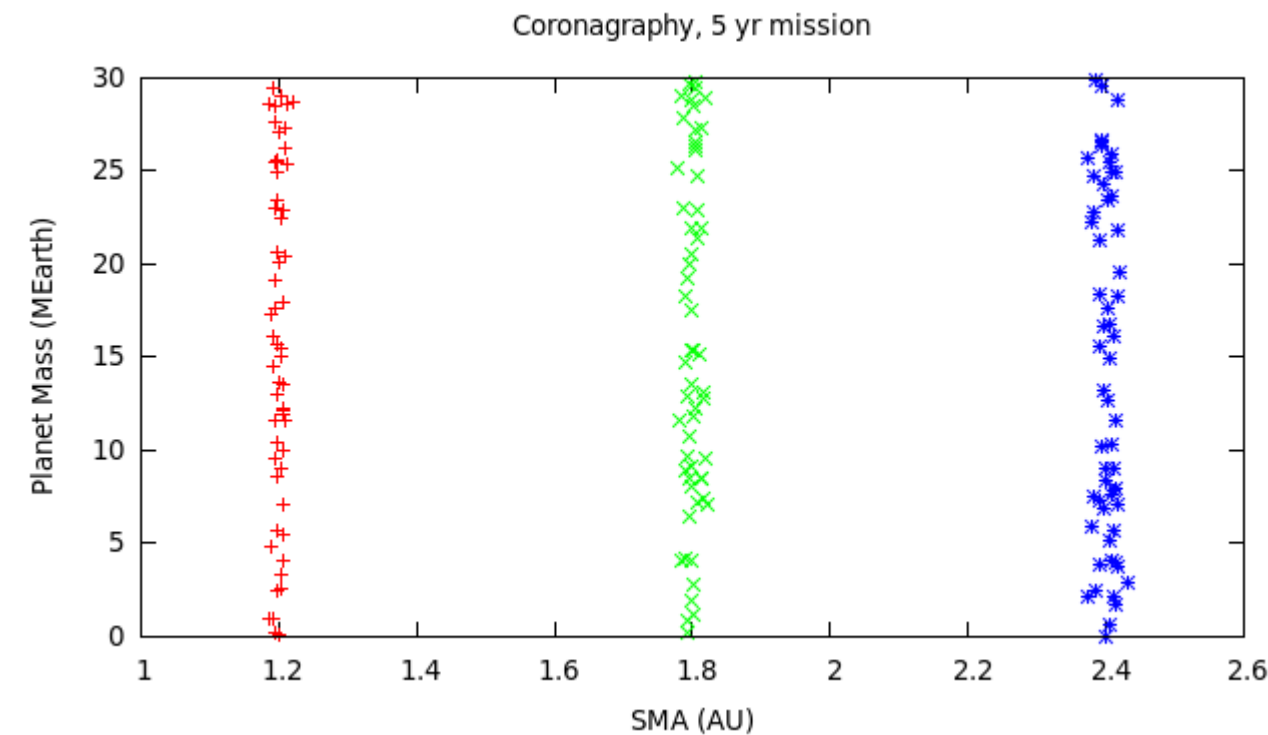
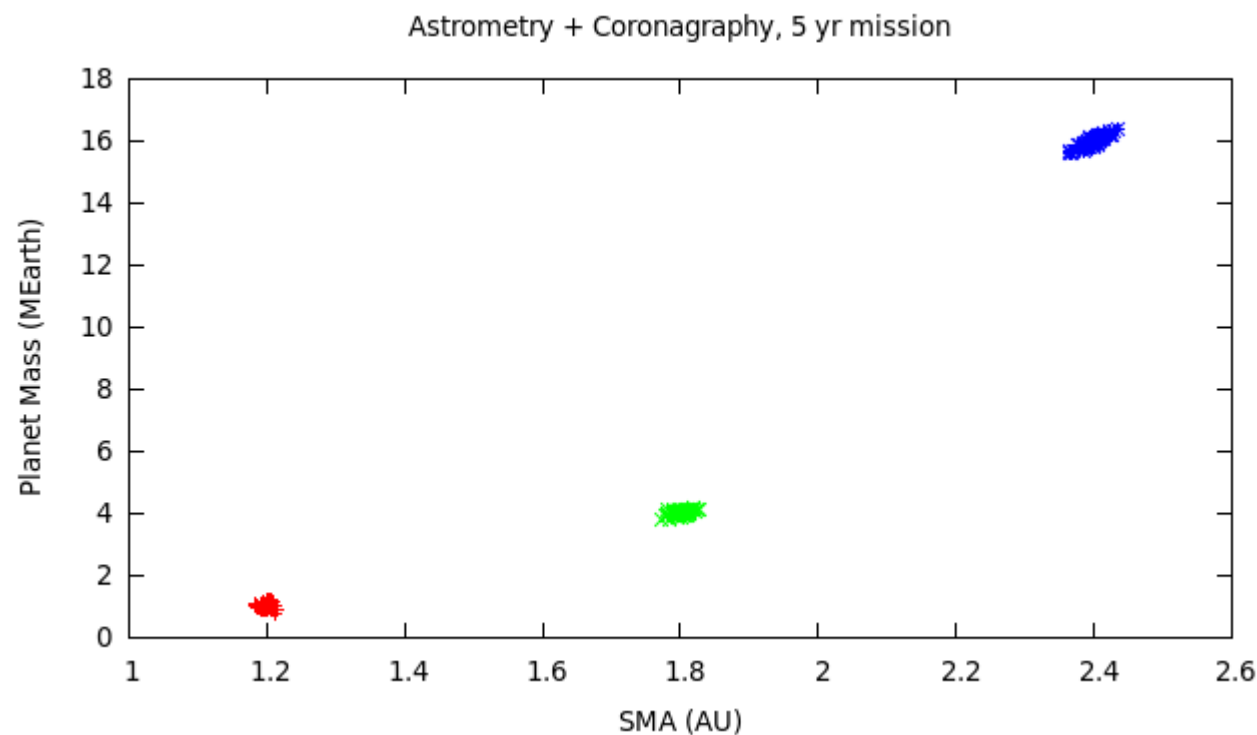




Performance as a function of star brightness (FOV = 0.03 sq deg)

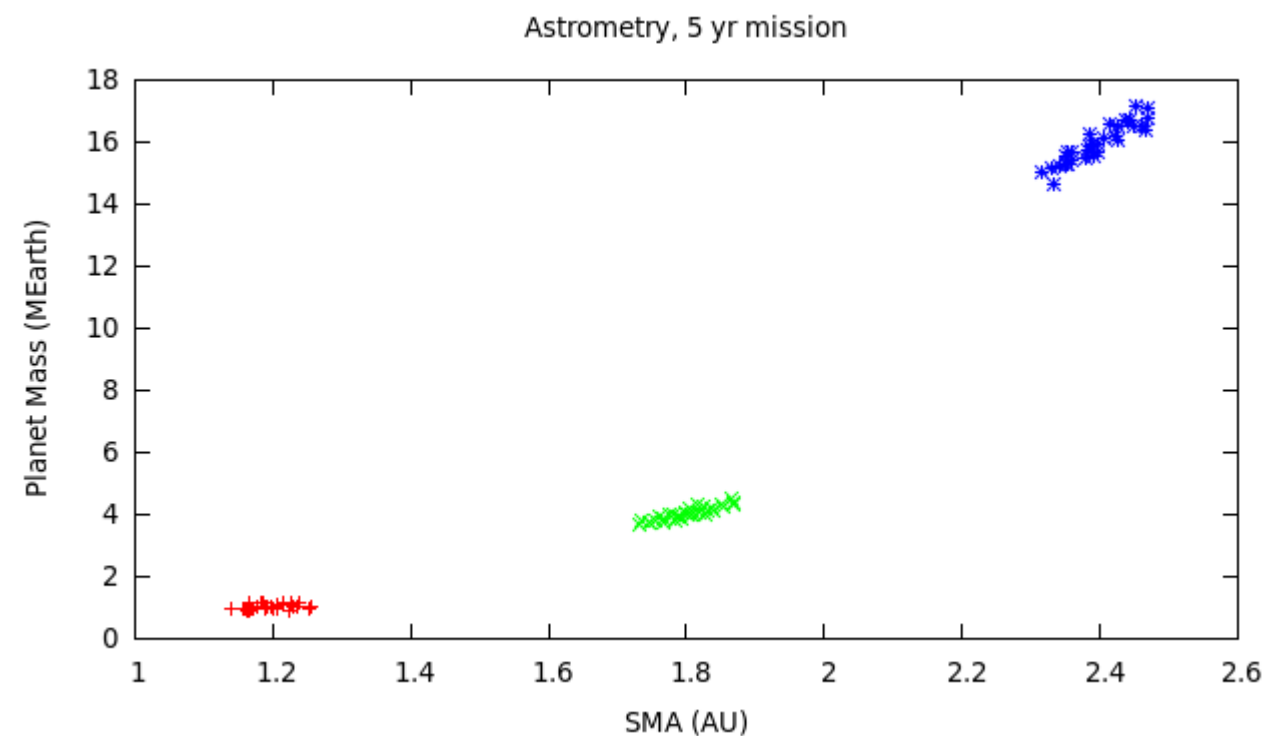


Astrometry + coronagraphy can precisely measure mass and orbital parameters of multiple planets systems



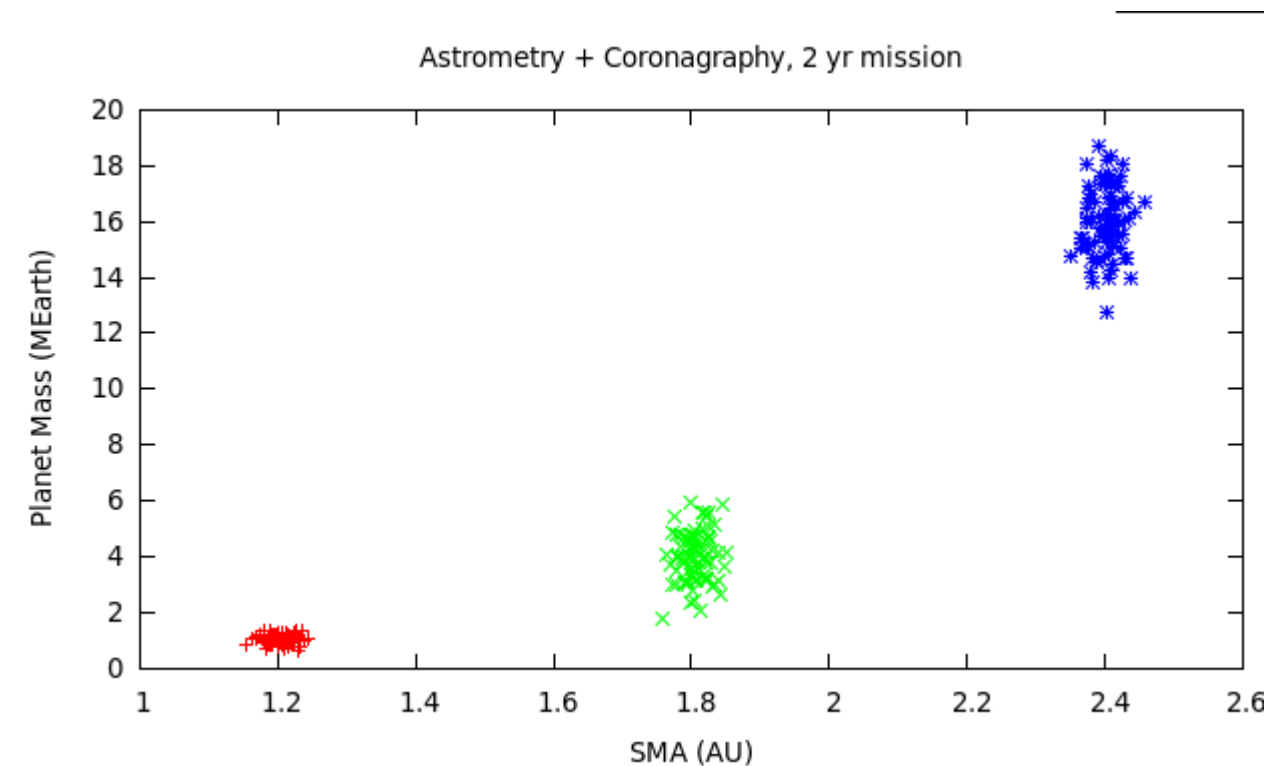
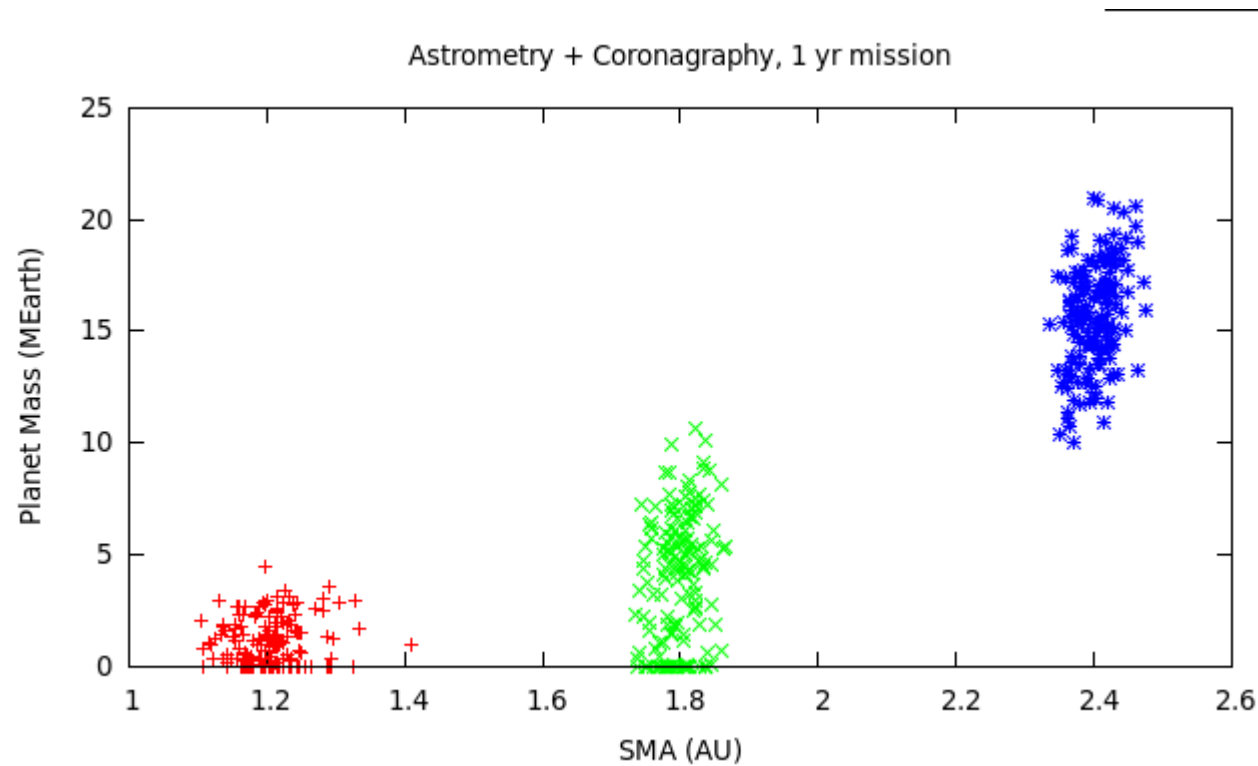
Astrometry+Coronagraphy,
Coronagraphy only :
1 observation every 2 month

Astrometry only:
1 observation per month

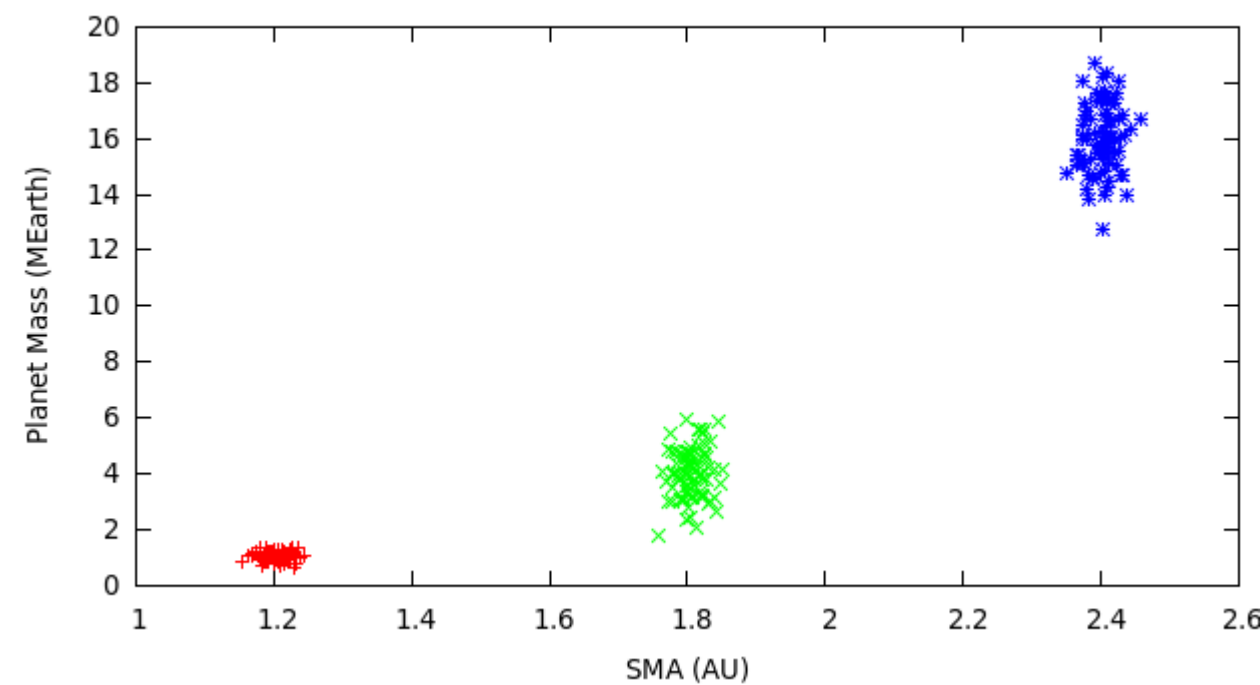


Mass can be constrained quickly

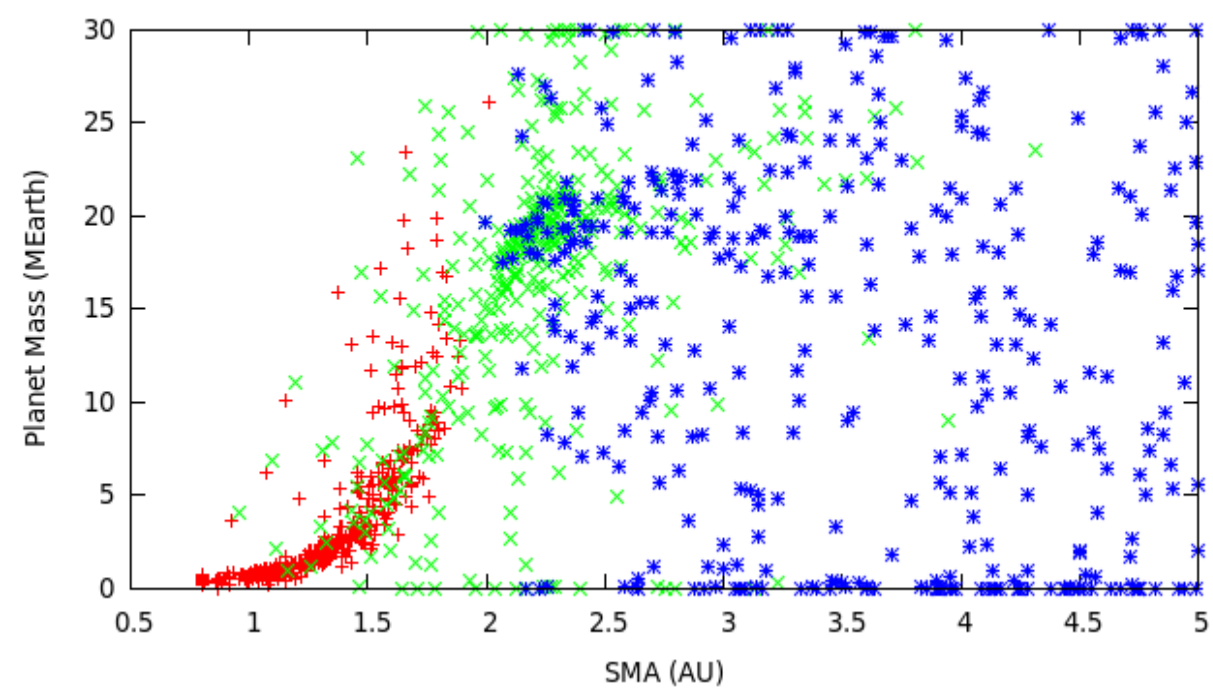
→ **firm identification of Earth-like planets within 1 to 2 yrs**



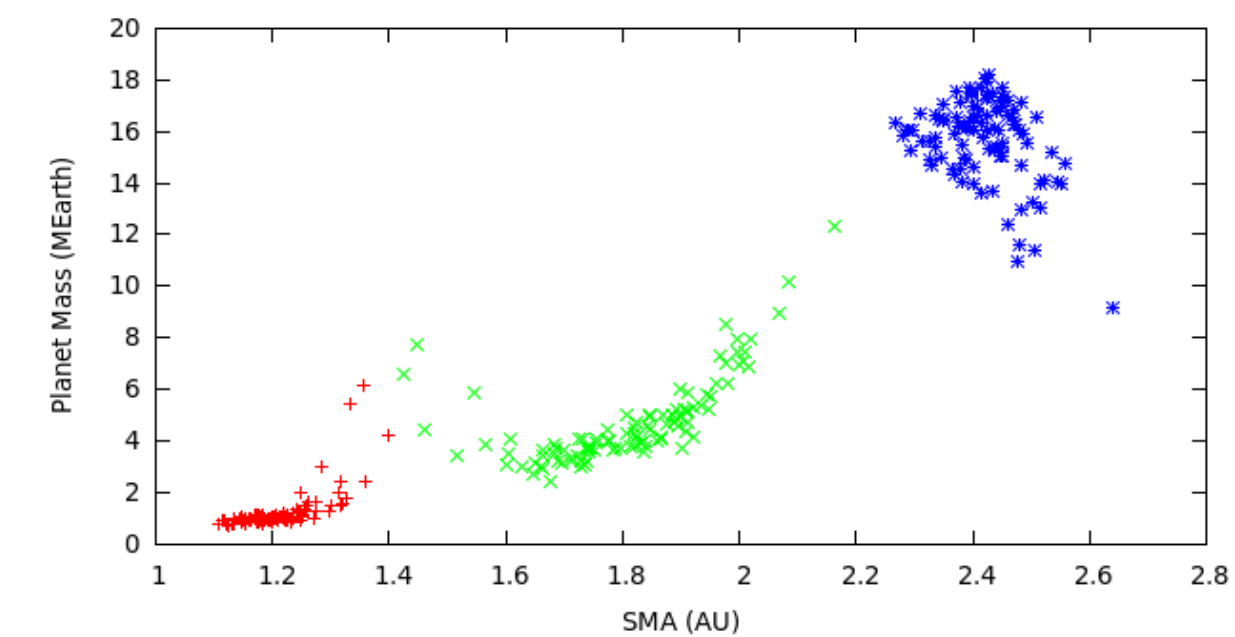
Astrometry + Coronagraphy, 2 yr mission



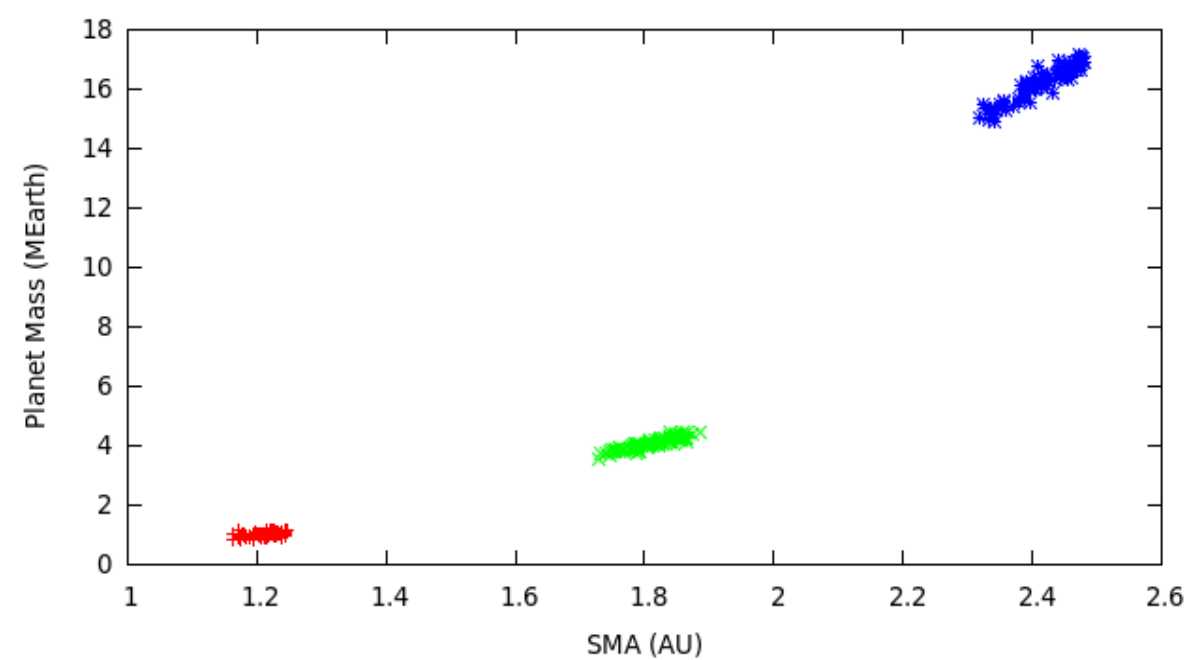
Astrometry only, 2 yr mission



Astrometry only, 4 yr mission



Astrometry only, 5 yr mission



8 % area coverage on PM
 $m_v = 3.7$ target
Galactic pole observation
2 day per observation

Larger telescope diameter :
- more light in spikes (D^2), finer spikes ($1/D$) $\rightarrow$ spike calibration accuracy goes as D^{-2}
- more light in background stars (D^2), and smaller PSF ($1/D$) $\rightarrow$ position measurement goes as D^{-2}

Astrometric accuracy goes as $D^{-2} \text{FOV}^{-0.5}$
Number of pixels goes as $D^{-2} \text{FOV}$
At fixed number of pixels, larger D is better

But: mean surface brightness of spikes gets fainter as FOV increases

	FOV = 0.03 sq deg	FOV = 0.1 sq deg	FOV = 0.25 sq deg	FOV = 0.5 sq deg	FOV = 1.0 sq deg
D = 1.4 m	0.58 μas	0.31 μas	0.20 μas	0.14 μas	0.11 μas
D = 2.0 m	0.28 μas	0.15 μas	0.10 μas	0.07 μas	0.05 μas
D = 3.0 m	0.13 μas	0.067 μas	0.044 μas	0.030 μas	0.024 μas
D = 4.0 m	0.071 μas	0.038 μas	0.025 μas	0.017 μas	0.013 μas

D = 4.0m, FOV = 0.1 sq deg $\rightarrow$ 0.2 uas in <2hr

Conclusions

For more info:

<http://www.naoj.org/staff/guyon/04research.web/30astrometry.web/content.html>

Wide field imaging, coronagraphy and astrometry could be done on the same Telescope, simultaneously

Simultaneous astrometry + coronagraphy is extremely powerful

- Improved detection
- Mass measurement

On-sky demonstration and science considered

Lab demo has started at U of Arizona

will be used to validate error budget and data reduction