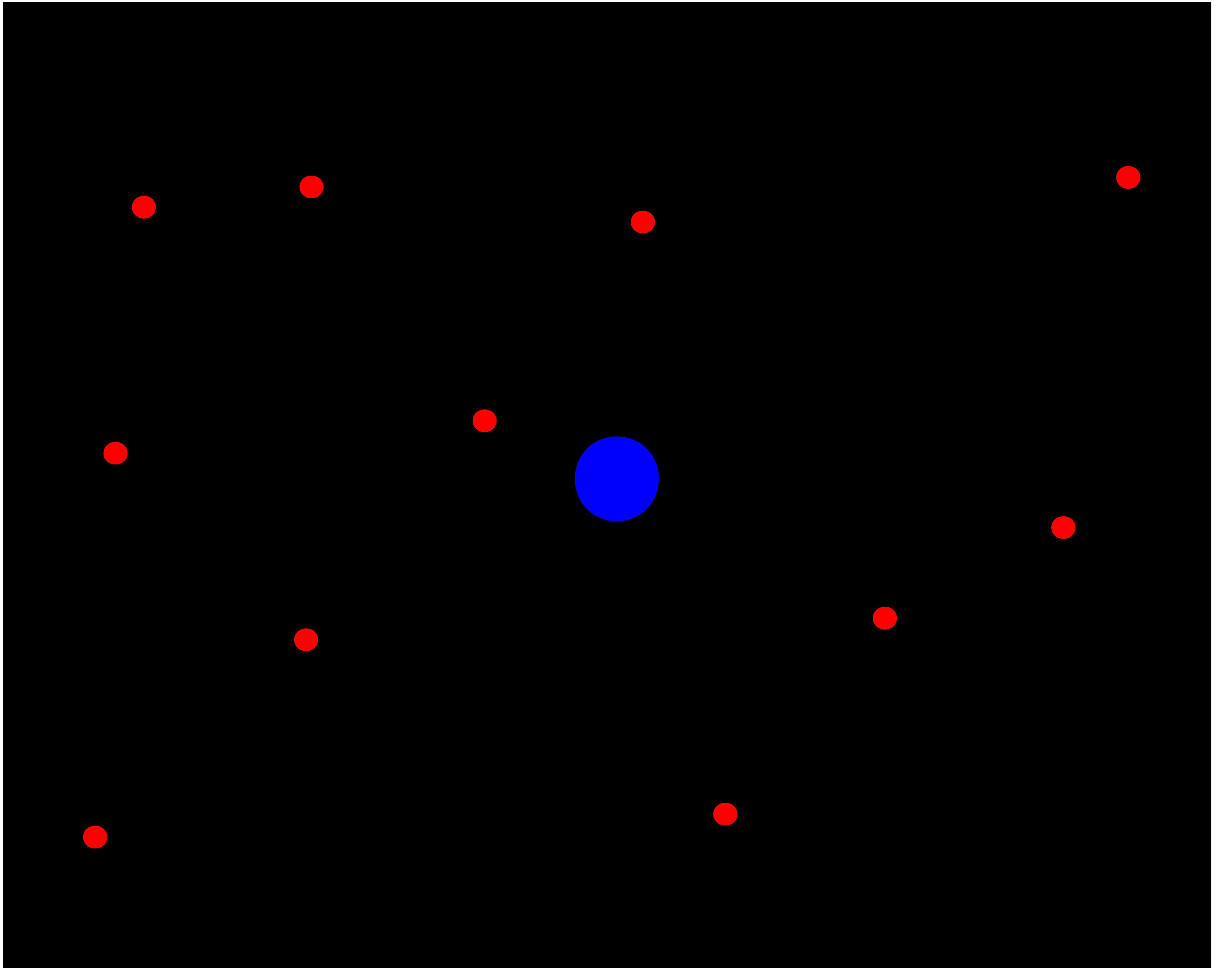
Combined astrometric imaging and coronagraphy

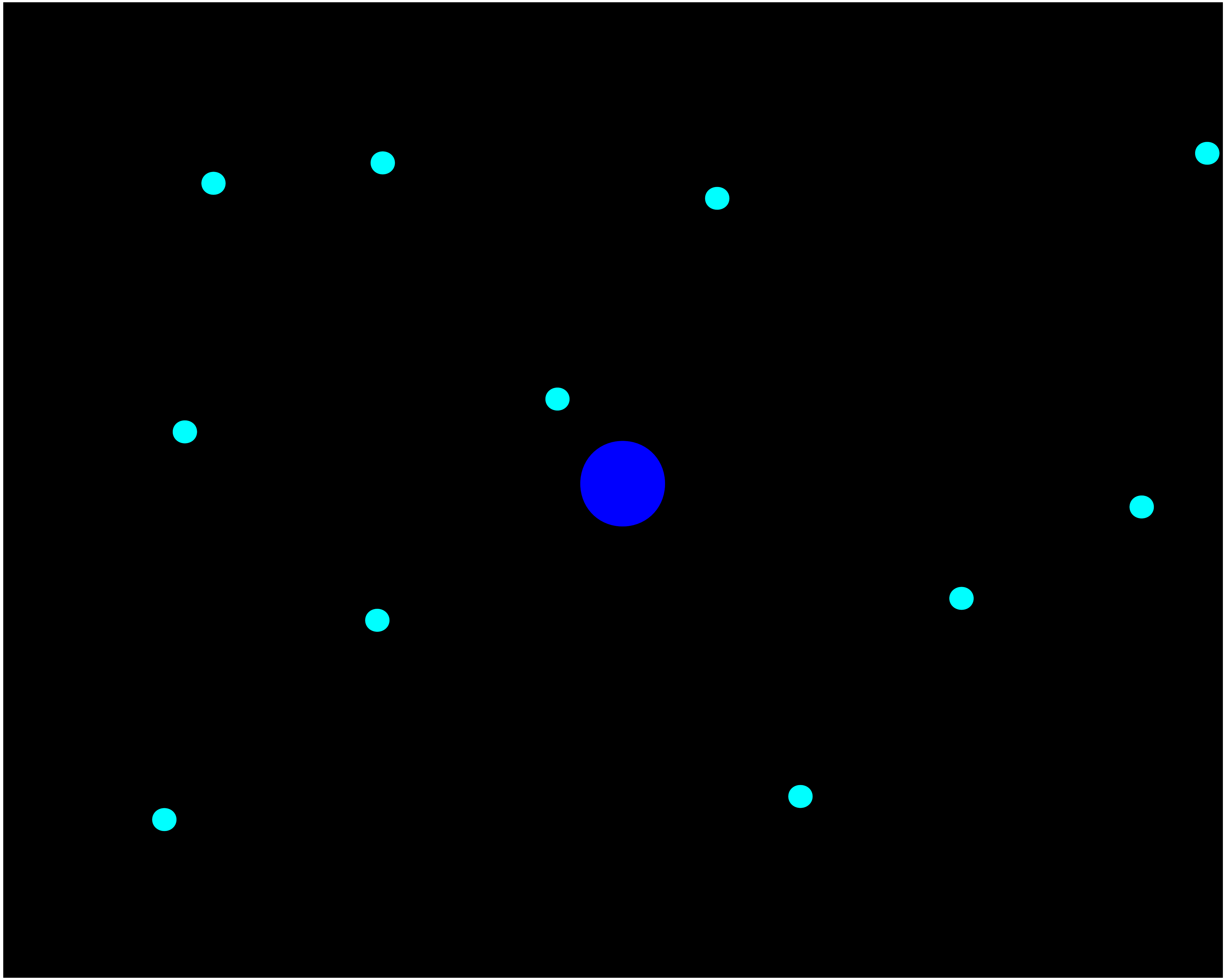
Olivier Guyon (UofA, Subaru Telescope)	
Michael Shao (NASA JPL)	Improvements to original concept, error budget, exoplanet science
Stuart Shaklan (NASA JPL)	Error budget, mission architecture
Robert Woodruff (LMC)	Optical design for wide field telescope compatible with coronagraphy
Bijan Nemati (NASA JPL)	Numerical simulations, modeling approach
Mark Ammons (UofA)	Lab demo design & operation
Eduardo Bendek (UofA)	Lab demo optical design & operation
Marie Levine (NASA JPL)	System engineering, mission architecture
Joe Pitman (Expl. Sci.)	System engineering

Tom Milster (UofA)	Mask manufacturing, scaling of mask manufacturing to full scale PM
Jim Burge (UofA)	Mask manufacturing, scaling of mask manufacturing to full scale PM
Neville Woolf (UofA)	Exoplanet science, concept definition
Roger Angel (UofA)	Exoplanet science, concept definition
Josh Eisner (UofA)	Exoplanet and star formation/evolution science
Ruslan Belikov (NASA Ames)	Compatibility with coronagraphy
Daniel Eisenstein (UofA)	Extragalactic science enabled with wide field camera
Ann Zabludoff (UofA)	Extragalactic science with wide field camera
Dennis Zaritsky (UofA)	Extragalactic & galactic science with wide field camera
Jay Daniel (L3/Tinsley)	Optics manufacturing

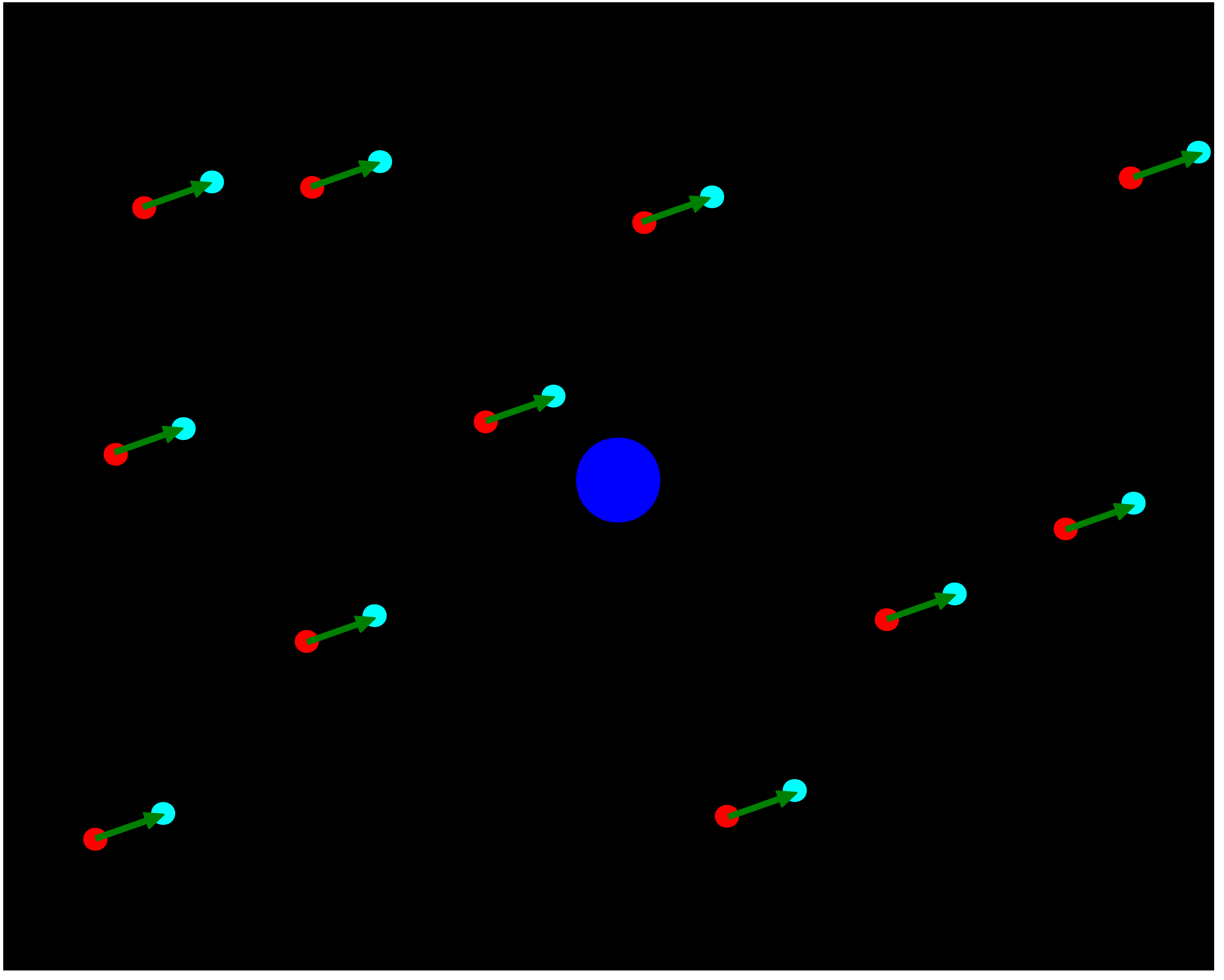
epoch #1 (first observation)



epoch #2 (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).

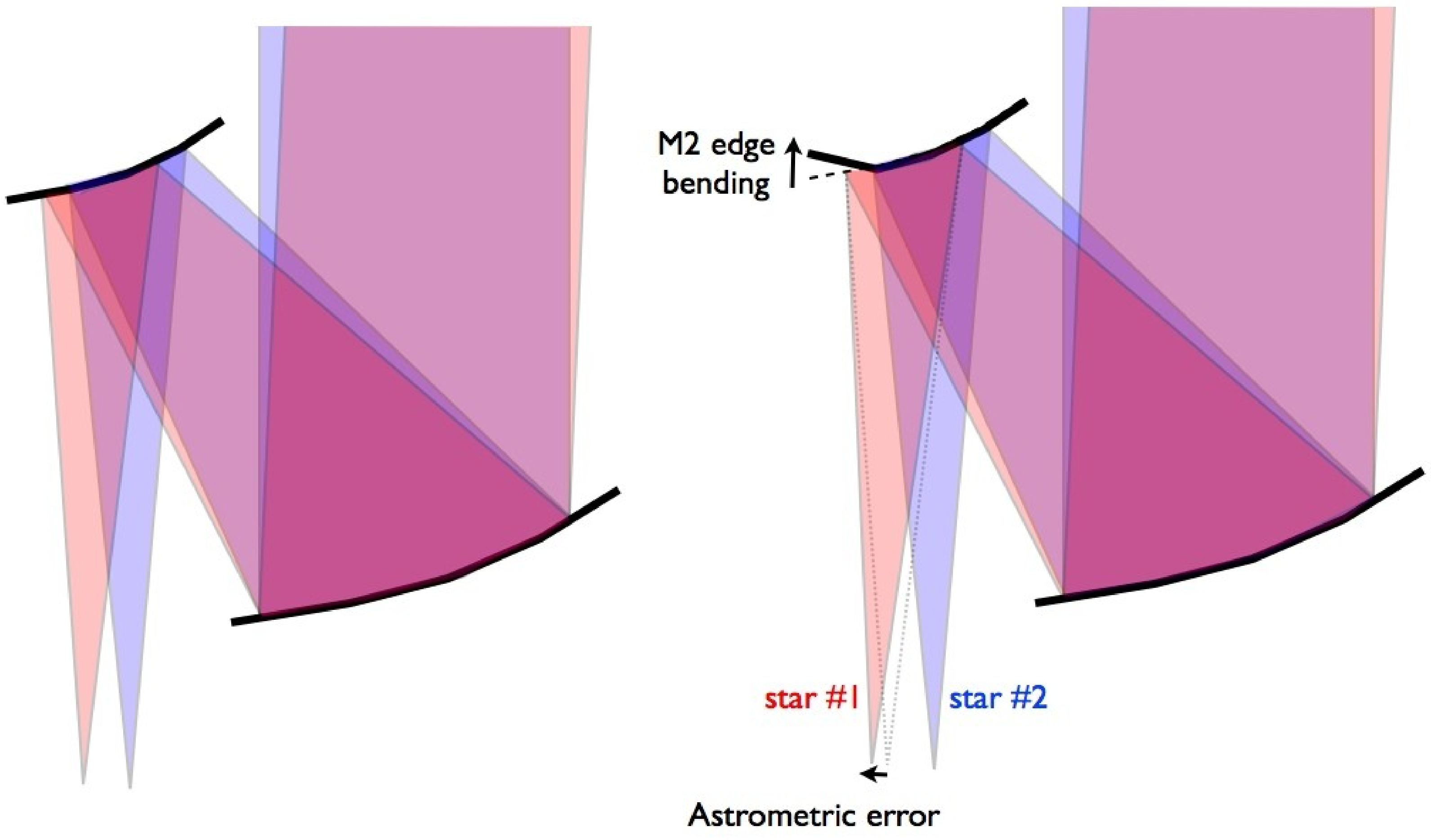


Principle: use background stars around coronagraph target as an astrometric reference

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.

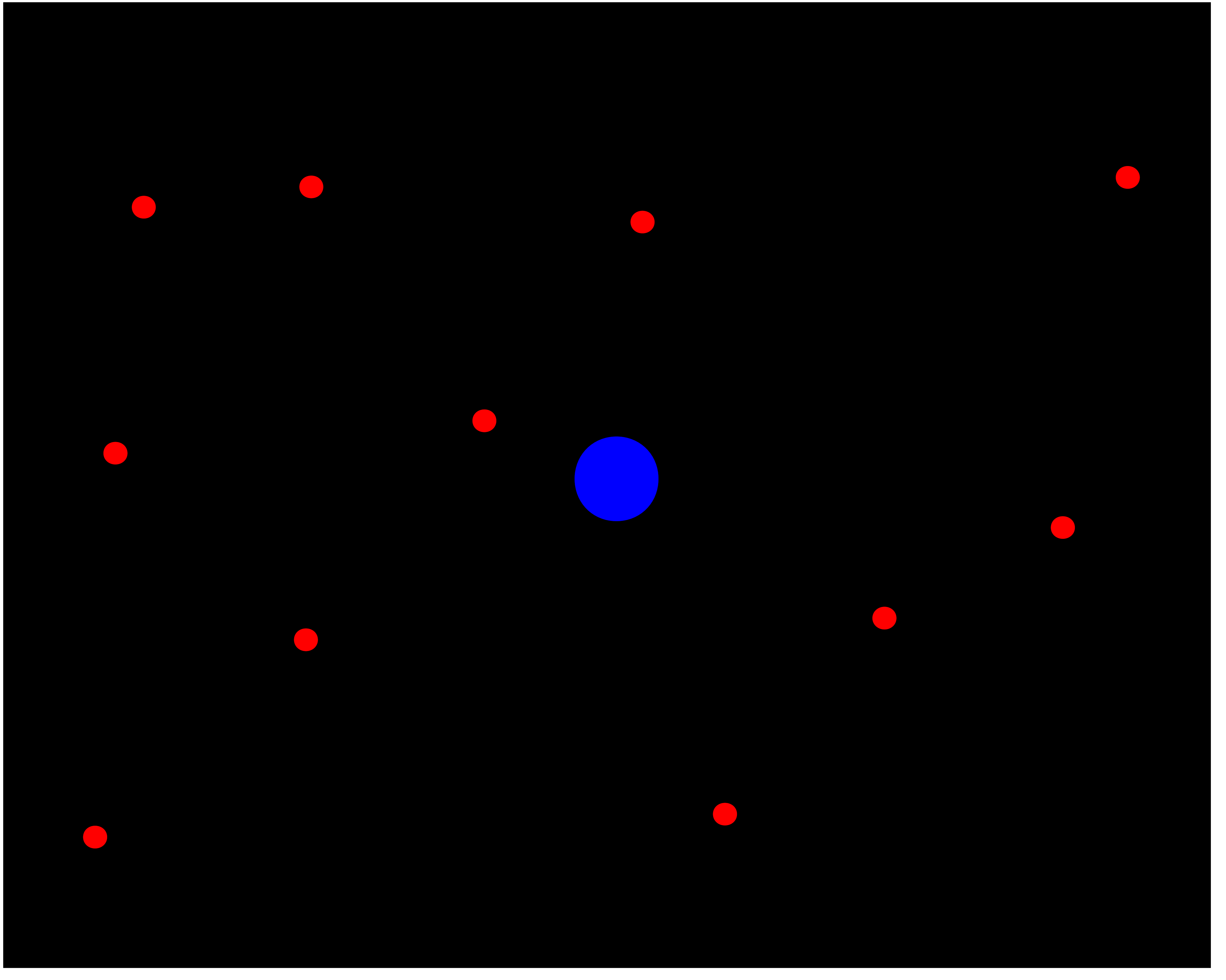


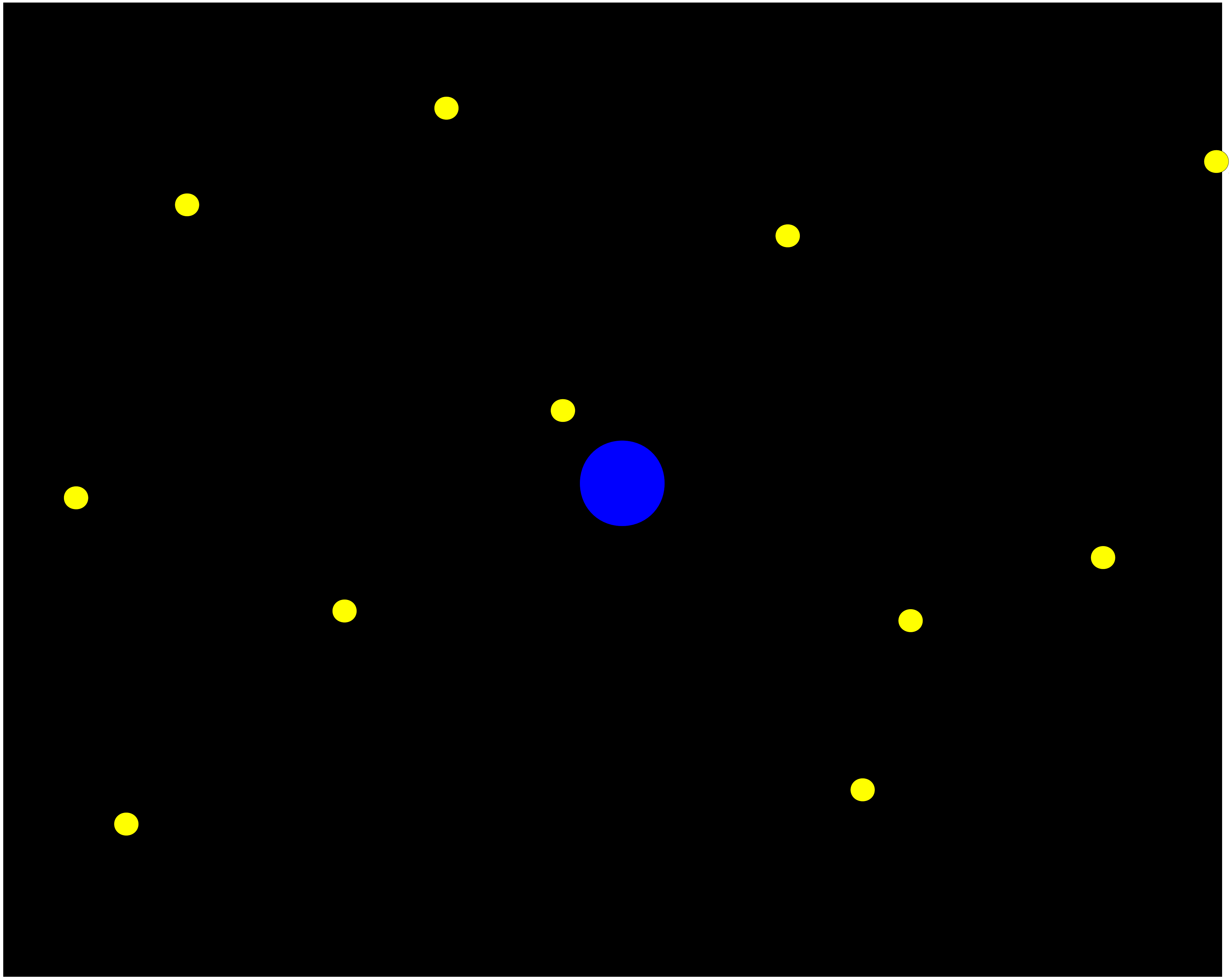
(1) Light from different stars on the sky travels different paths → small bending of optics produces field distortions

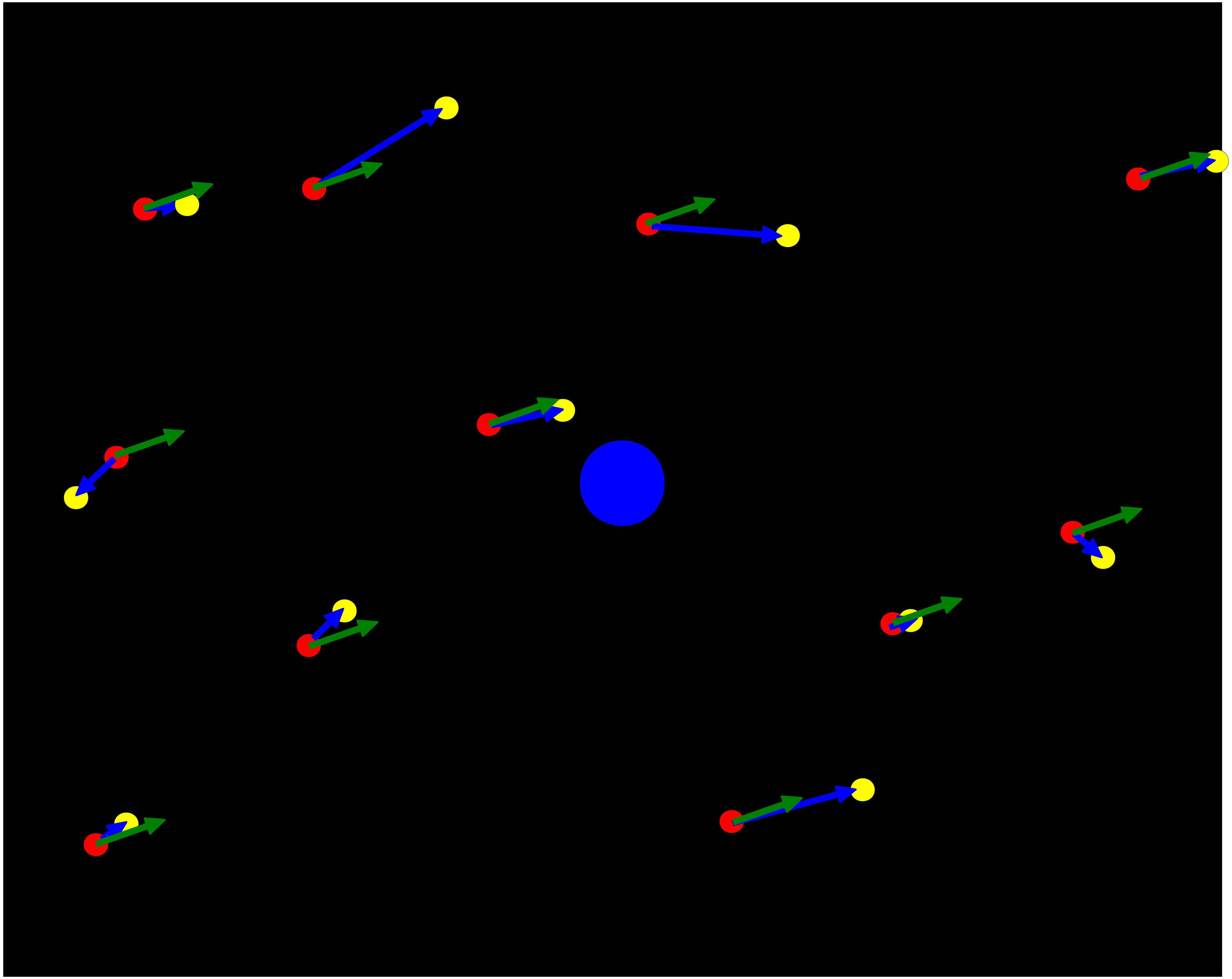
(2) The detector can move between observations (especially when using large mosaics)

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

+ (4) Central star is much brighter than background stars epoch #1 (first observation)



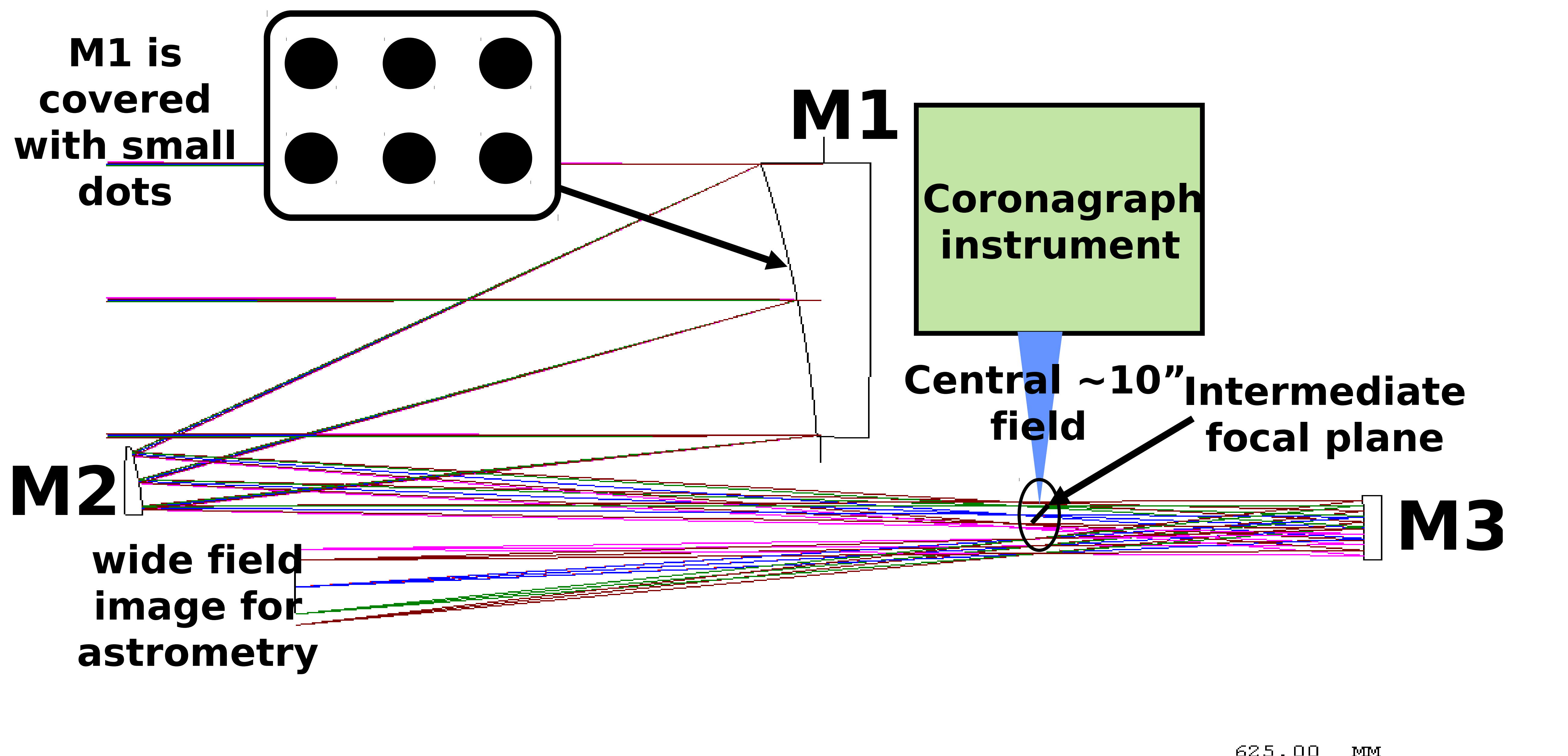




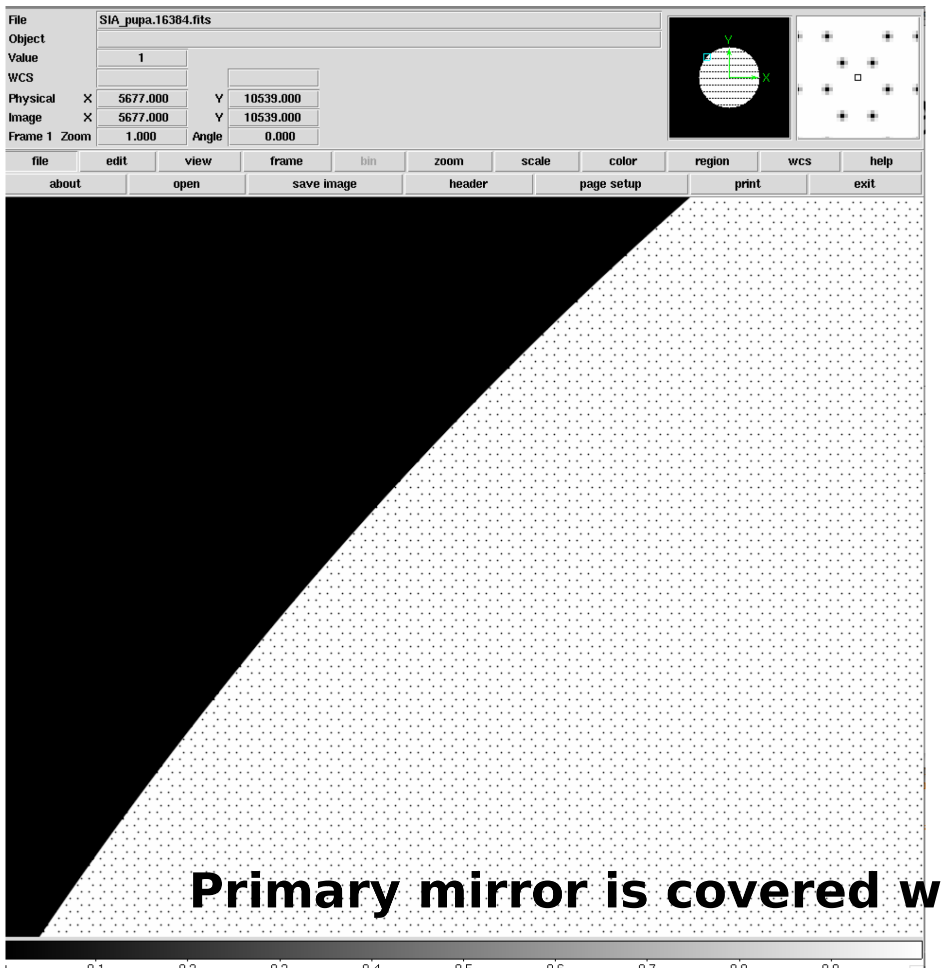
Optical Layout for simultaneous coronagraphy and astrometry

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).

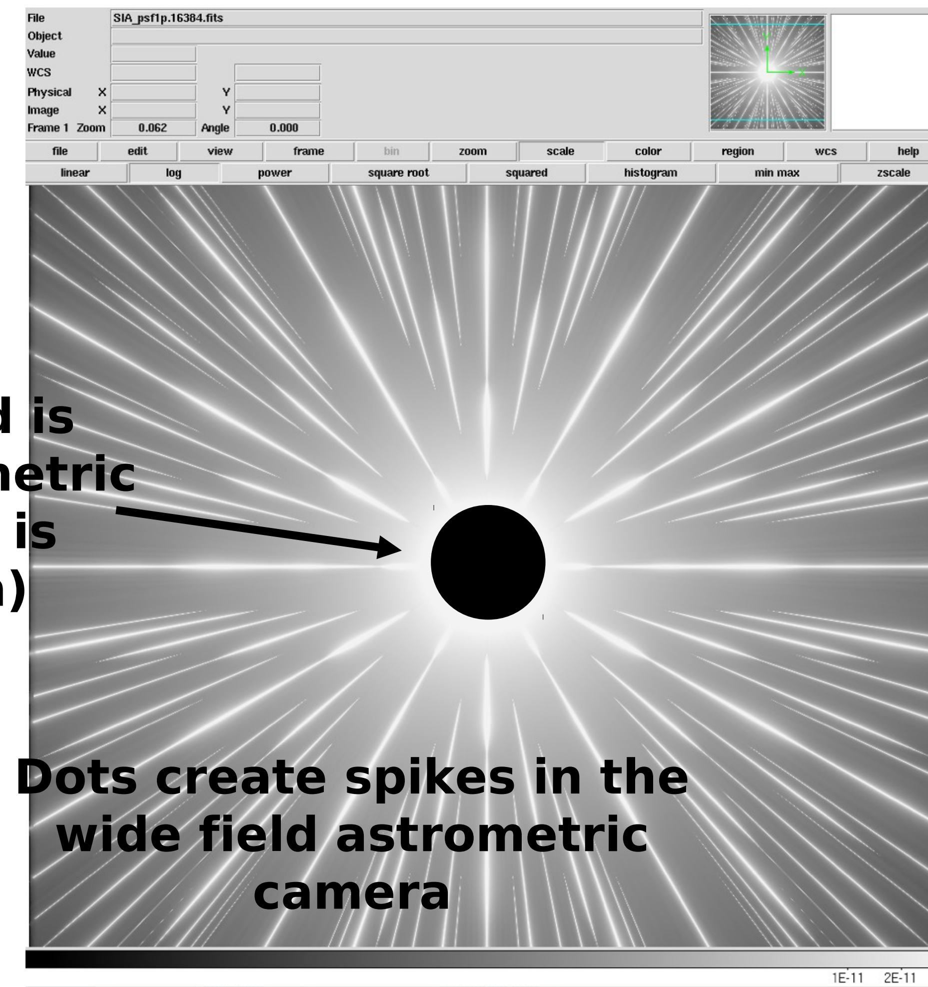
Light is simultaneously collected by the coronagraph instrument (direct imaging and spectroscopy of exoplanet) and the wide field astrometric camera (detection and mass measurement of exoplanets)



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

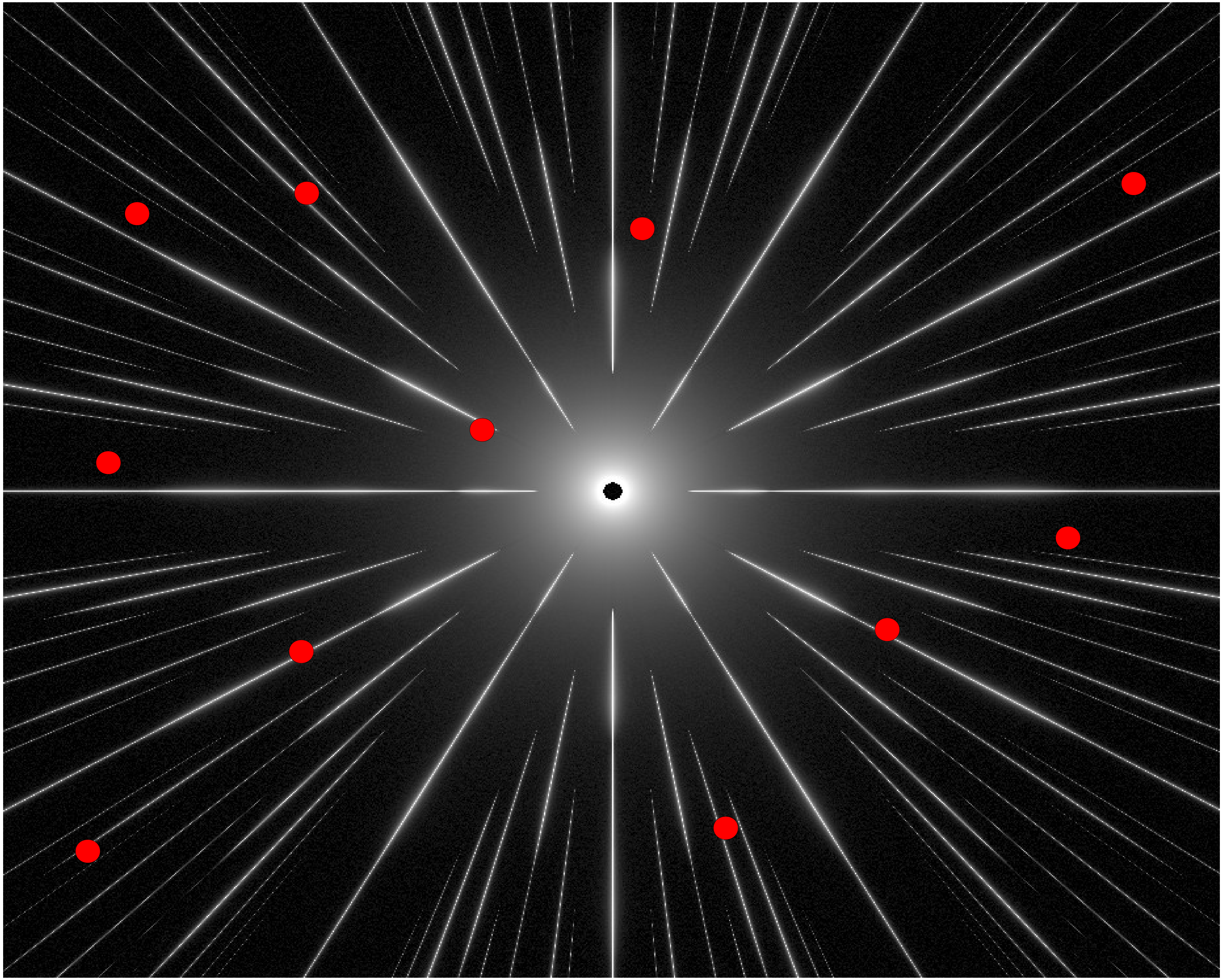


The center of the field is missing from the astrometric camera (central light is sent to coronagraph)

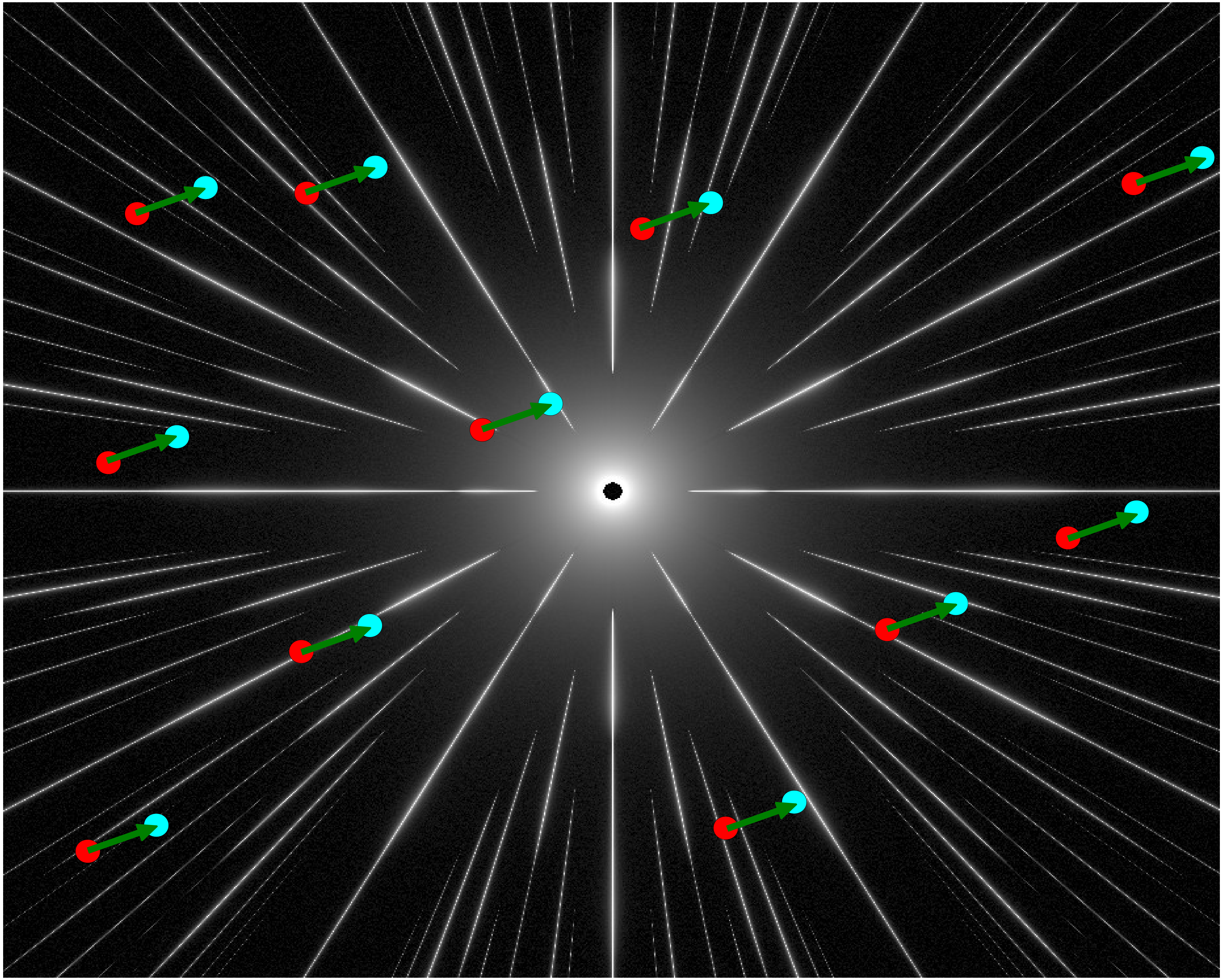


All astrometric distortions (due to change in optics shapes of M2, M3, and deformations of the focal plane array) **are common to the spikes and the background stars**. By referencing the background star positions to the spikes, the astrometric measurement is largely immune to large scale astrometric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

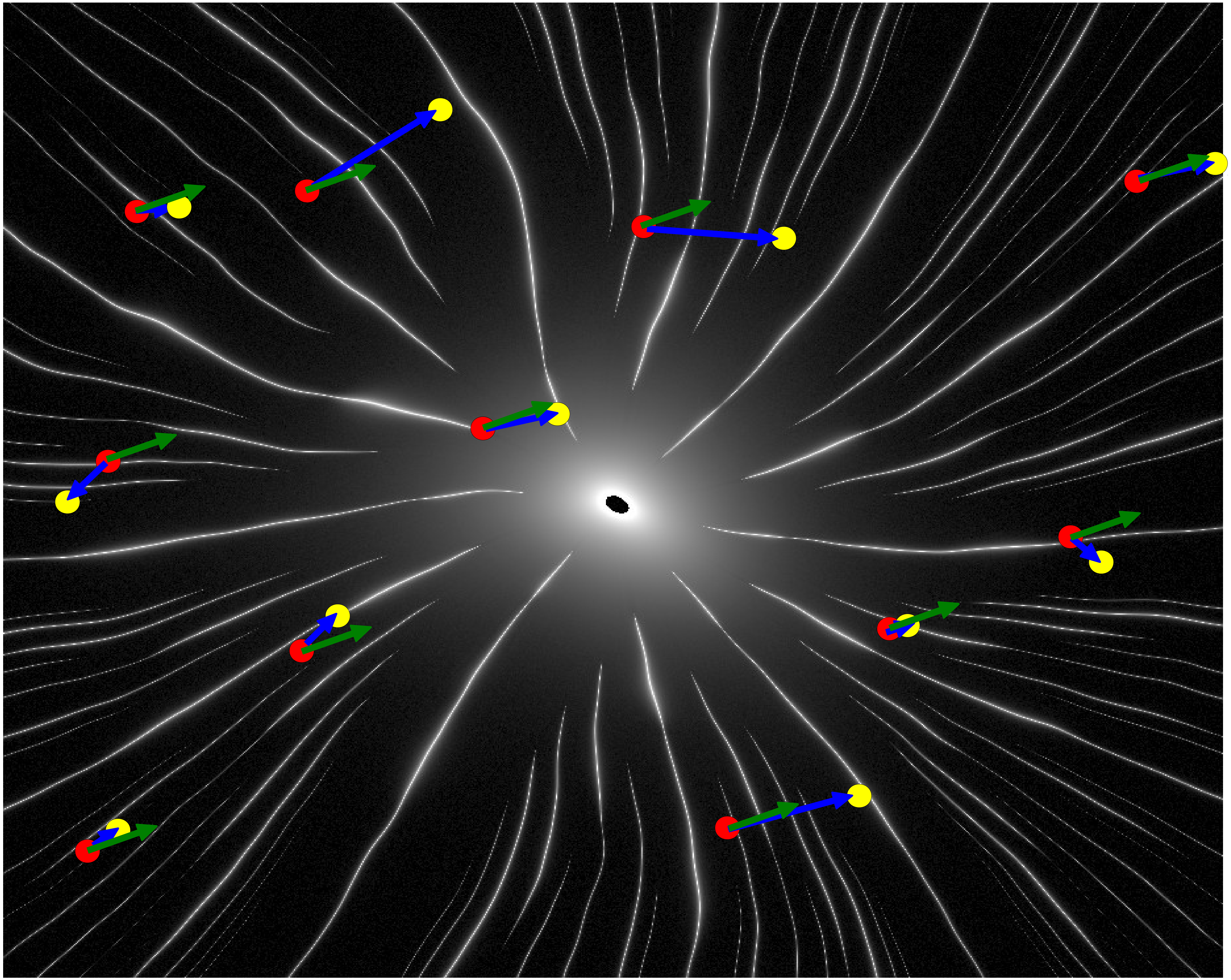
Red points show the position of background stars at epoch #1 (first observation)



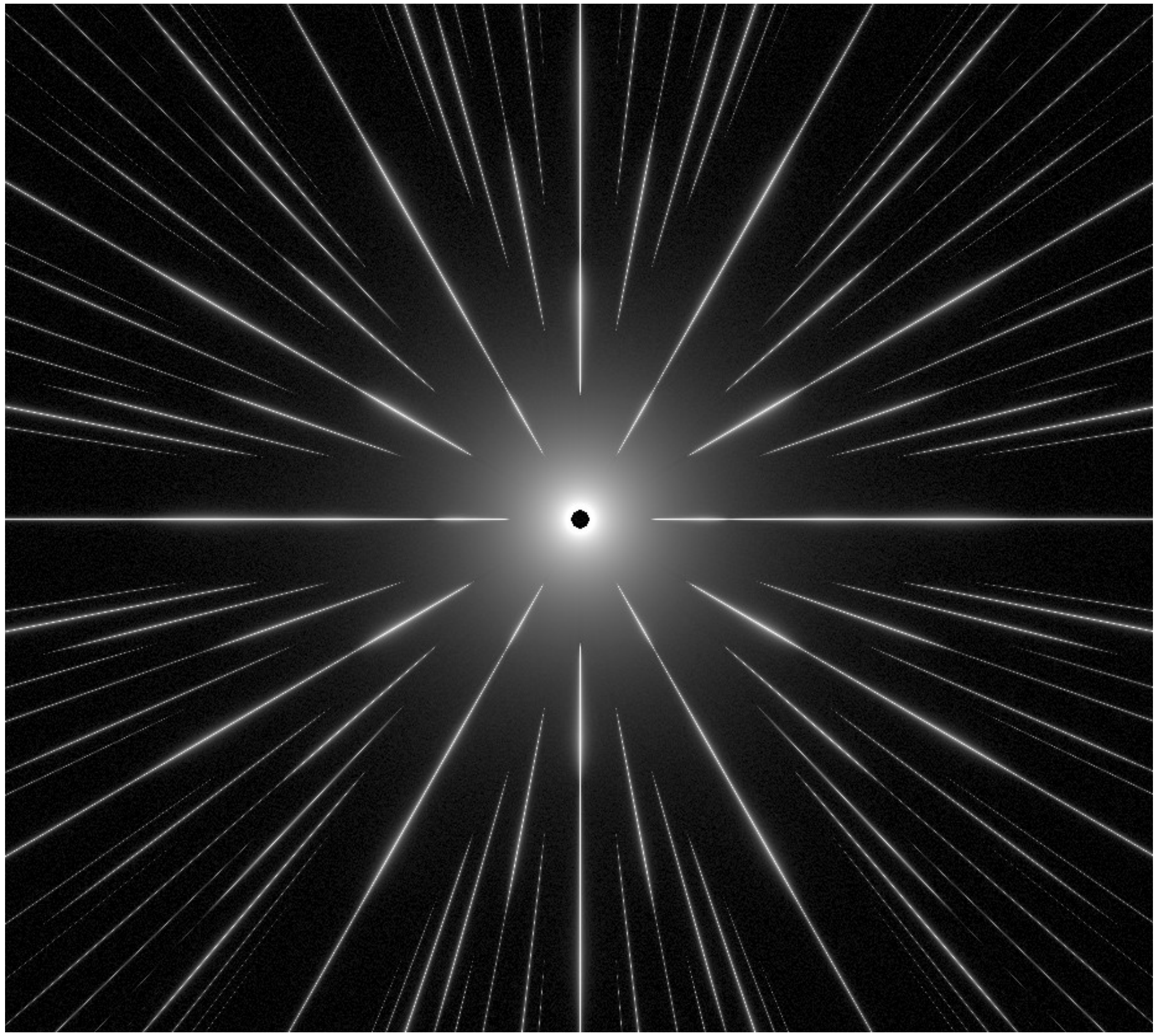
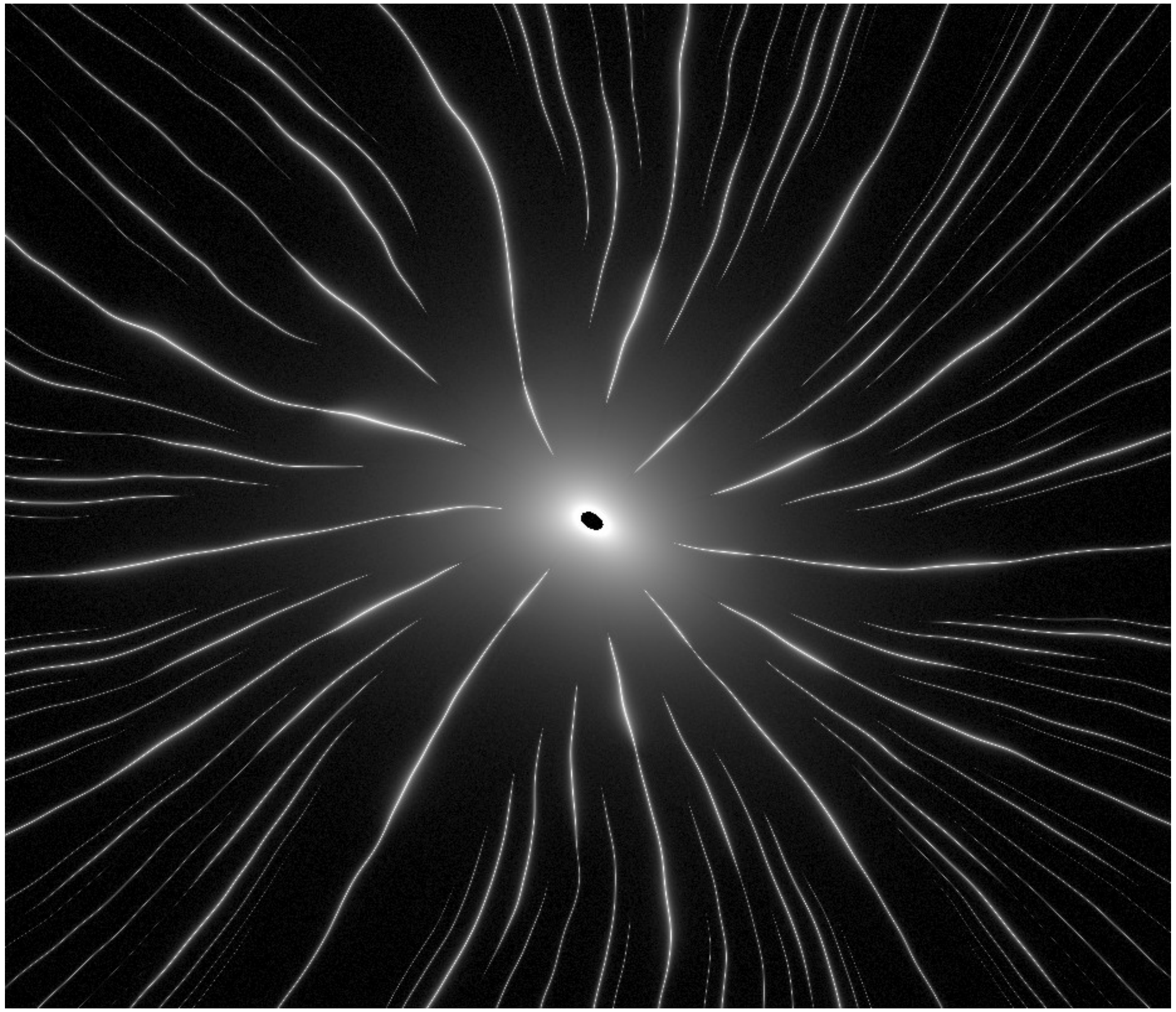
Blue points show the position of background stars at epoch #2 (second observation)
The telescope is pointed on the central star, so the spikes have not moved between the 2 observations, but the position of the background stars has moved due to the astrometric motion of the central star (green vectors).



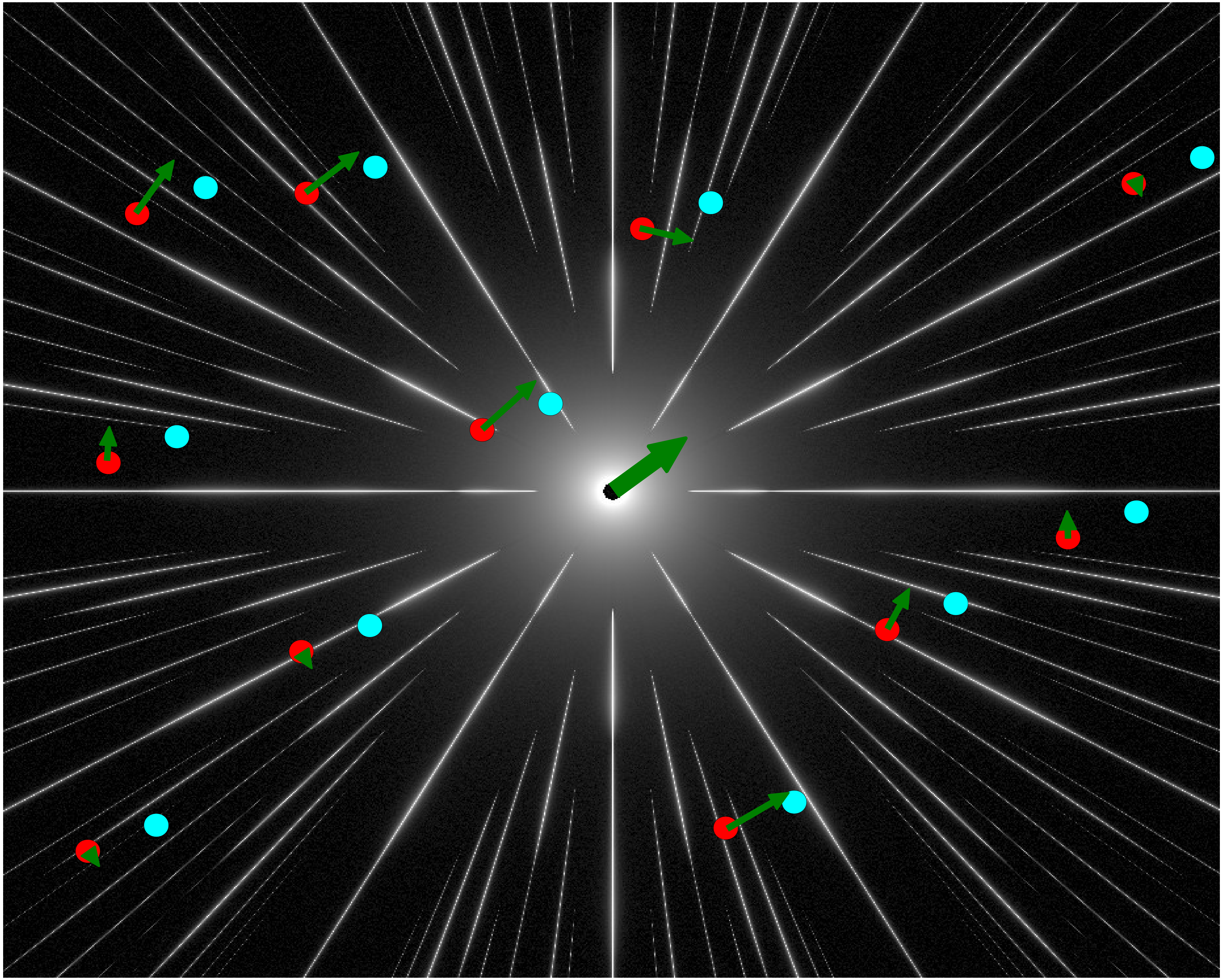
Due to astrometic distortions between the 2 observations, the actual positions measured (yellow) are different from the blue point. The error is larger than the signal induced by a planet, which makes the astrometric measurement impossible without distortion calibration.



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.

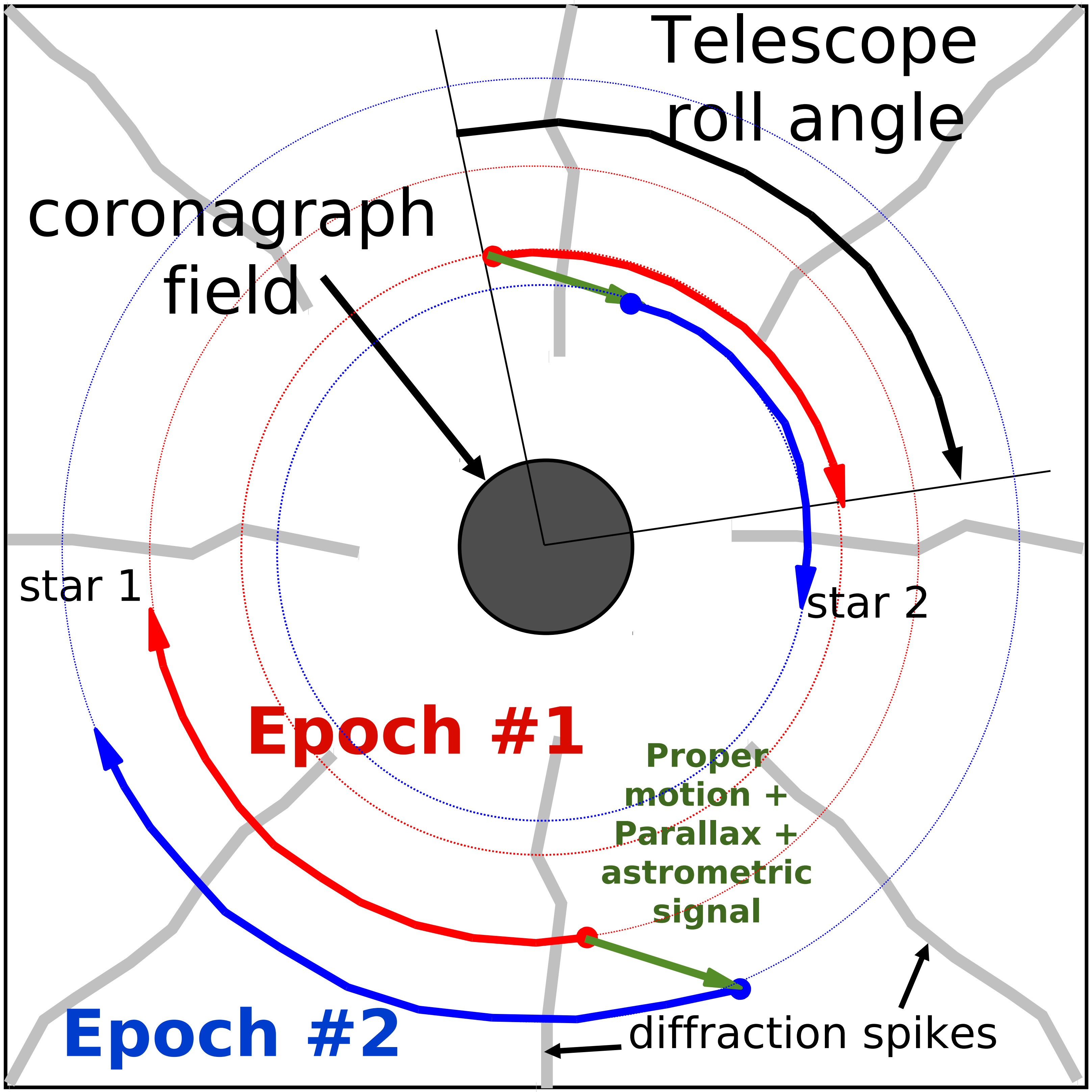
The calibration of astrometric distortions with the spikes is only accurate in the direction perpendicular to the spikes length. For a single background star, the measurement is made along this axis (1-D measurement), as shown by the green vectors. The 2-D measurement is obtained by combining all 1-D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



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-σ) 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)

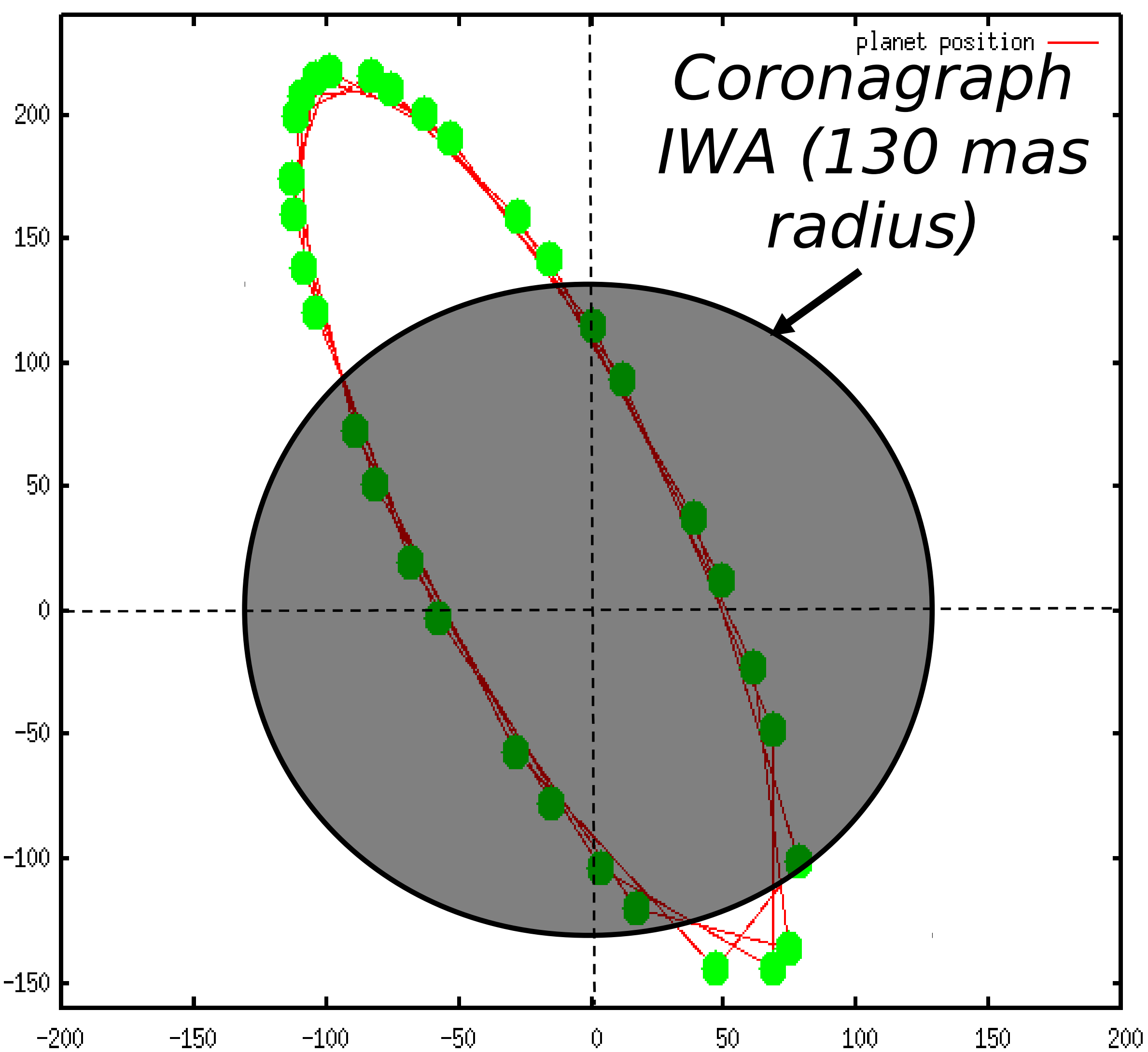
Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO

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

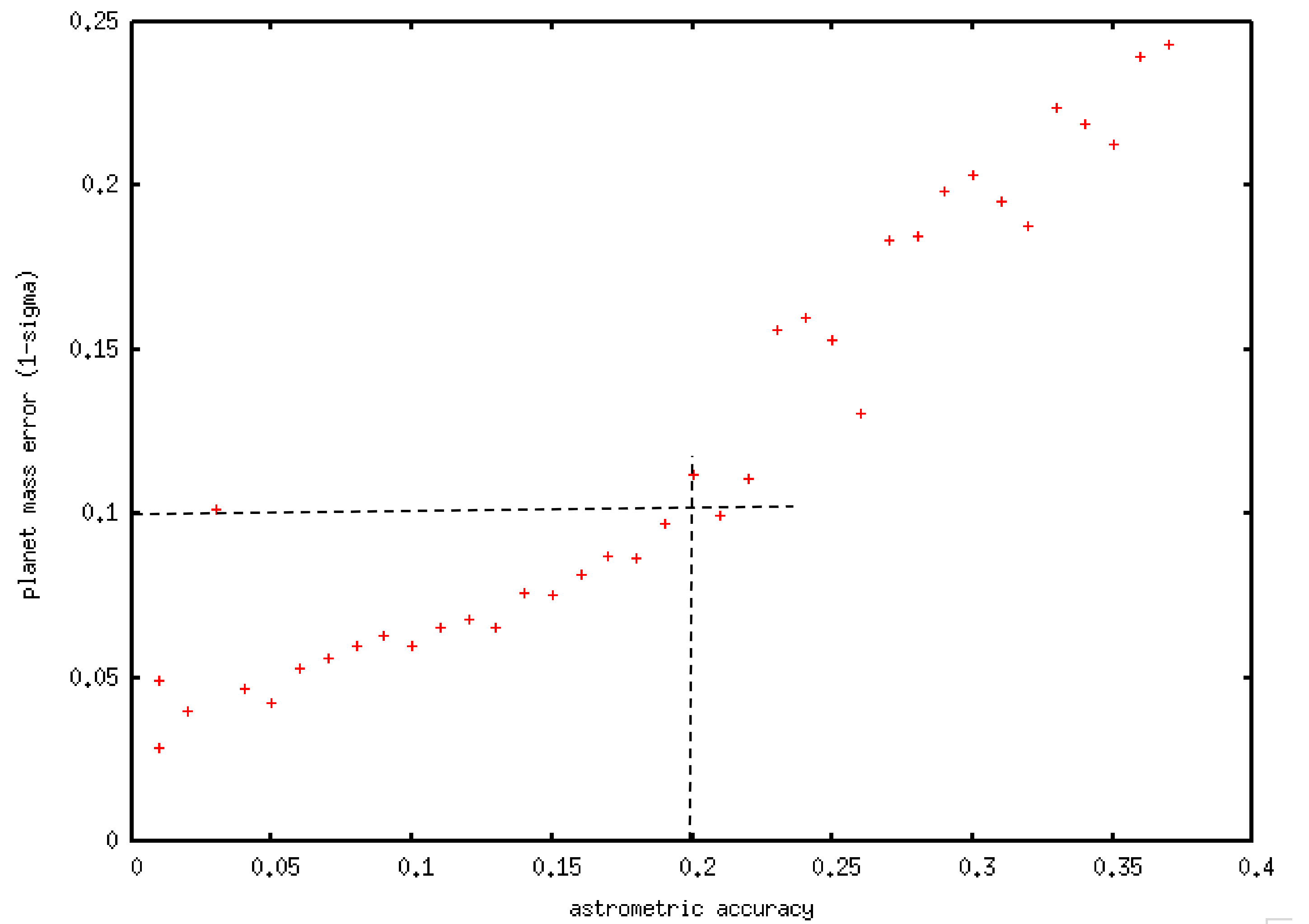
Table extracted from PECO SRD (http://caao.as.arizona.edu/PECO/PECO_SRD.pdf)

Combined solution for simultaneous coronagraphy + astrometry

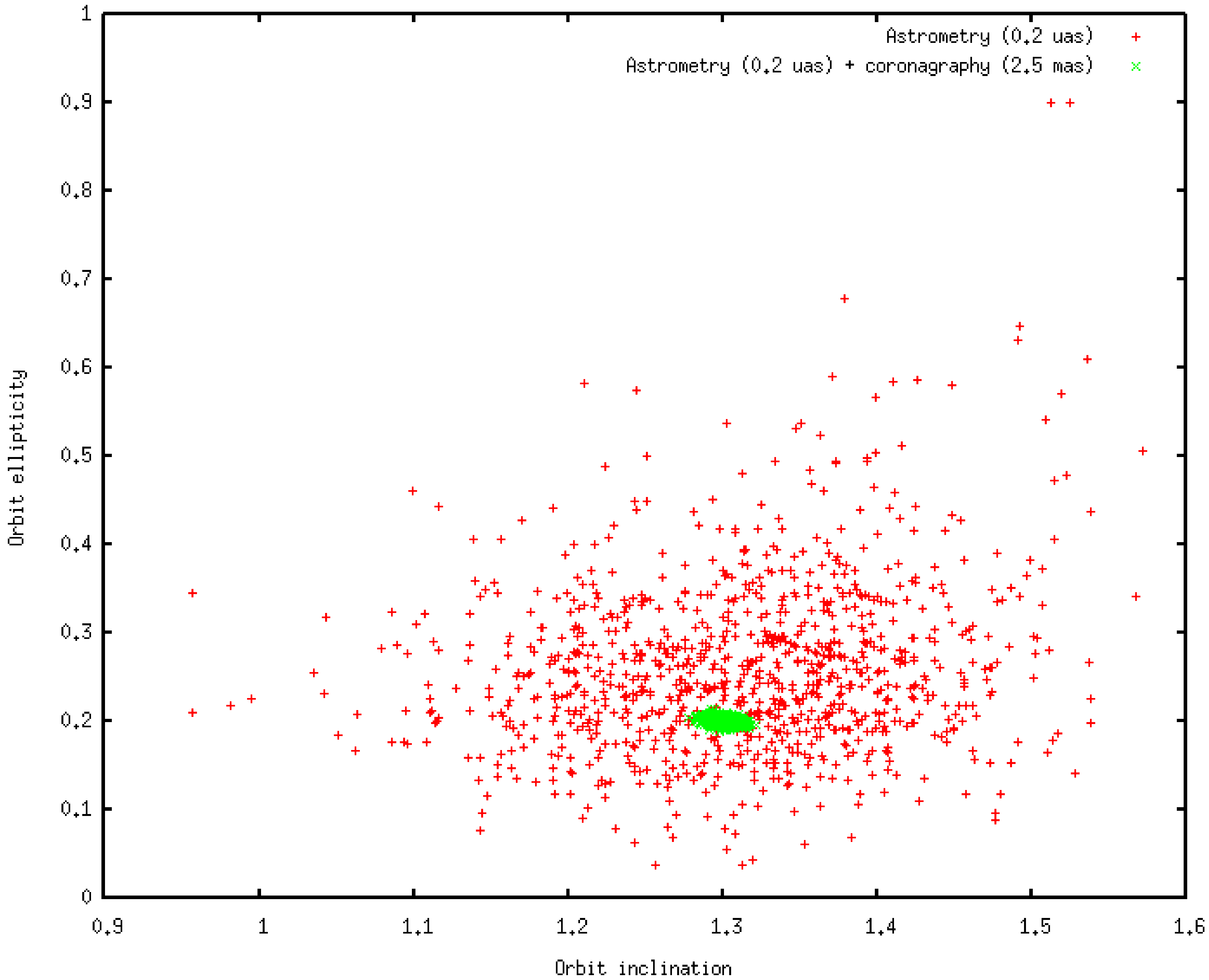
Planet on a 1.2 AU orbit (1.3 yr period), e=0.2
orbit orientation on sky: planet outside the coronagraph IWA for 17 out of the 32 observations.



Required single measurement astrometric accuracy = 0.2 µas (1-sigma, 1D)



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



Combined solution for simultaneous coronagraphy + astrometry

	Standard deviation	
	Astrometry only	**Astrometry + coronagraphy**
parallax	0.037 µas	0.035 µas
x proper motion	0.017 µas/yr	0.012 µas/yr
y proper motion	0.020 µas/yr	0.013 µas/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

- **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

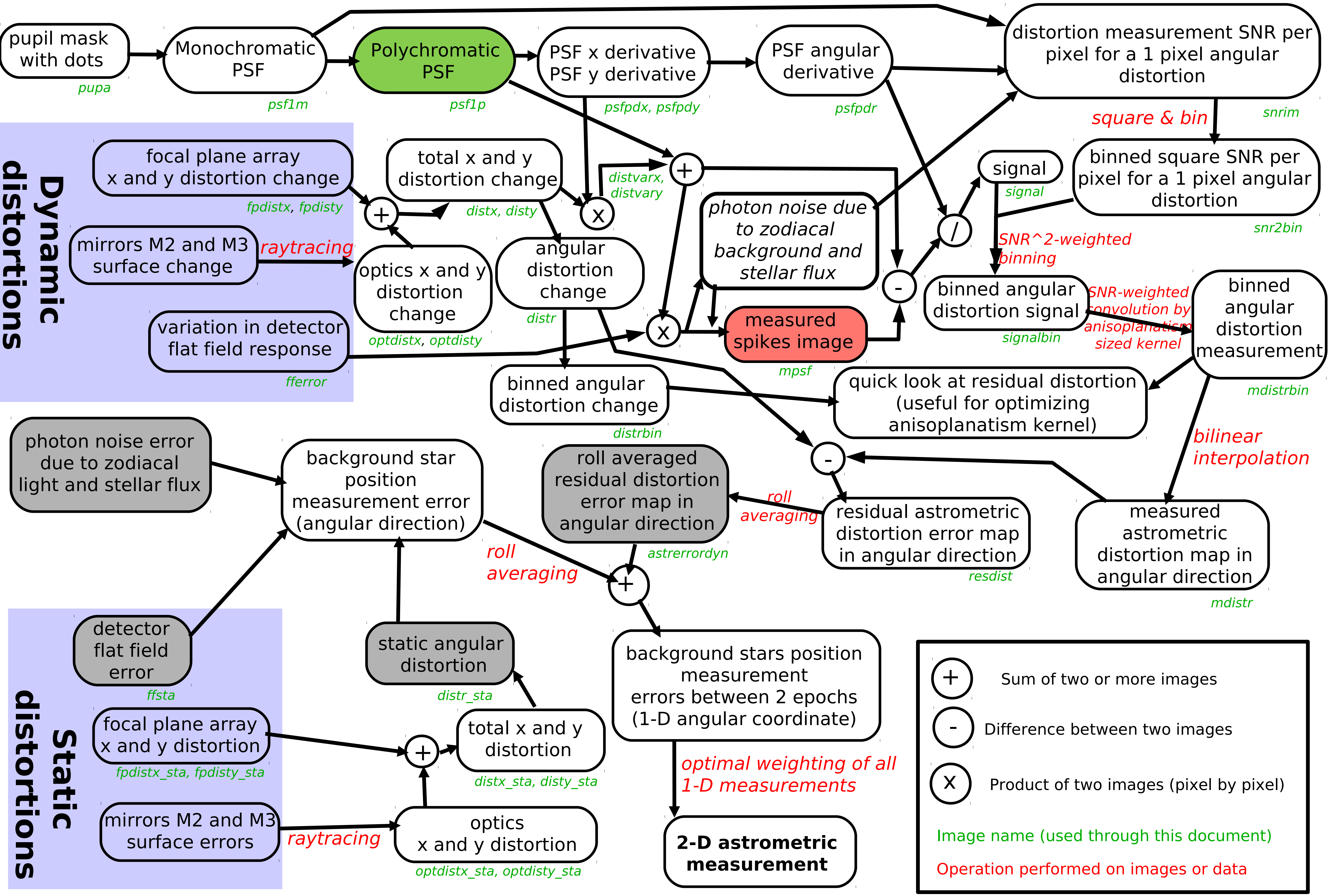
Approach & Assumptions

<u>Baseline: 1.4-m telescope, with 0.29 sq deg FOV (0.31 deg radius)</u>

The FOV is chosen to reach performance goal (0.2 μas/ measurement) in a sufficiently stable system (Photon noise limited performance for this FOV is 0.044 μas single measurement at galactic pole, but actual performance is significantly lower due to distortions and detector limits)
When detailed simulations are required, a smaller FOV system is used (0.1 deg radius = 0.03 sq deg FOV) to ease computations.

Baseline assumes no special requirements on detector or optics, other than a design to support wide field imaging and dots on M1:
<u>ASTROMETRY DOES NOT DRIVE TELESCOPE OR INSTRUMENT DESIGN</u>
- no special detector requirements (standard errors on flat field, geometry), assumes no calibration beyond what is "standard"
- no component requirement exceeds what has already been demonstrated and manufactured
- assumes no data calibration is done between observations of different stars (pessimistic)
- fraction of primary mirror covered by dots kept small (1%) to avoid loss in sensitivity for general astrophysics and coronagraphy

Numerical simulation approach



Performance as function of telescope size and FOV (baseline system)

1 % 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) → spike calibration accuracy goes as D^{-2}
- more light in background stars (D^2), and smaller PSF (1/D) → position measurement goes as D^{-2}

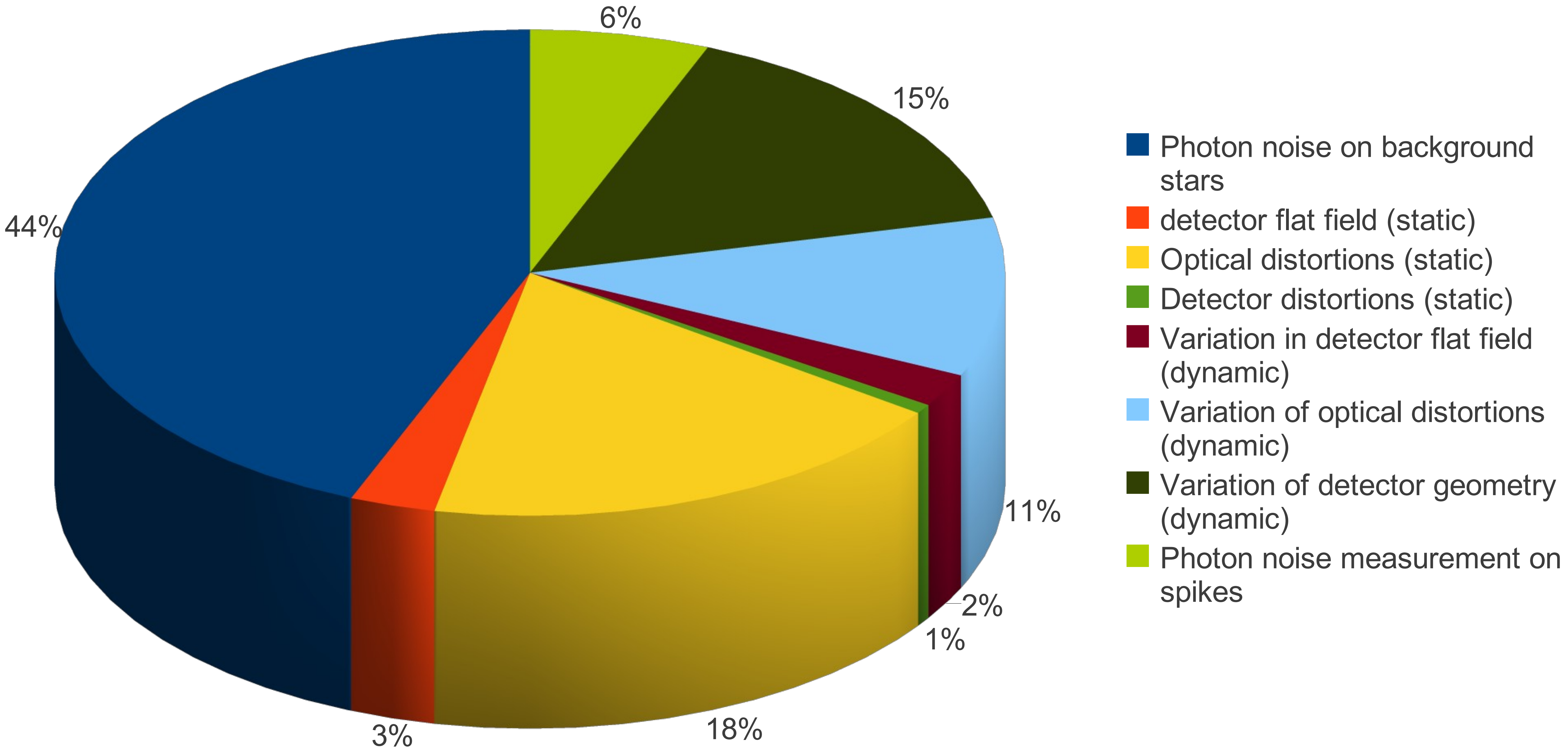
Astrometric accuracy goes as D^{-2} $FOV^{-0.5}$
Number of pixels goes as D^{-2} FOV
At fixed number of pixels, larger D is better (FOV can be reduced as D^{-4})

	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	0.62 *μas*	0.34 *μas*	0.22 *μas*	0.15 *μas*	0.11 *μas*
D = 2.0 m	0.30 *μas*	0.17 *μas*	0.11 *μas*	0.07 *μas*	0.053 *μas*
D = 3.0 m	0.14 *μas*	0.074 *μas*	0.047 *μas*	0.033 *μas*	0.023 *μas*
D = 4.0 m	0.076 *μas*	0.042 *μas*	0.026 *μas*	0.019 *μas*	0.013 *μas*

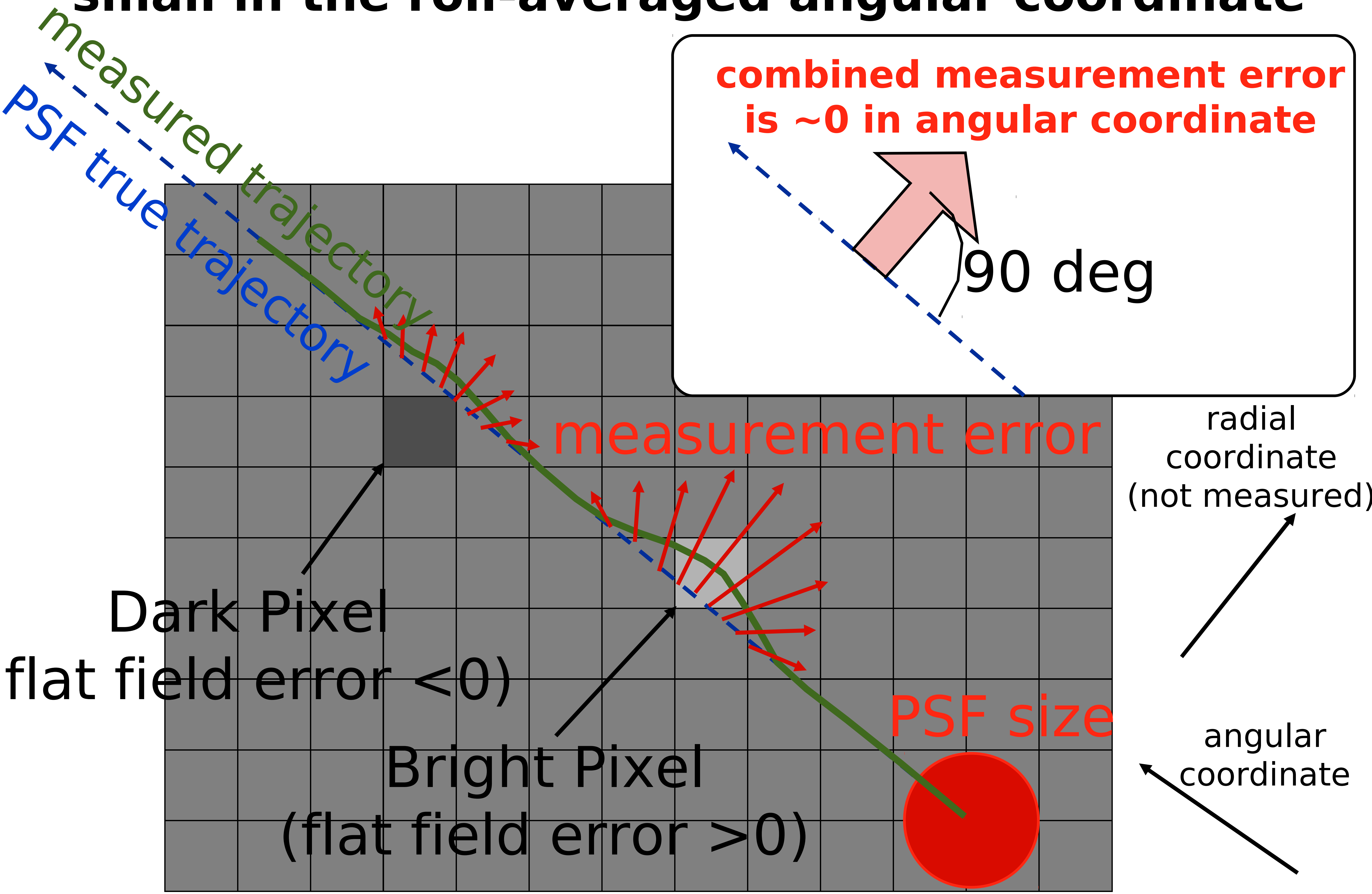
Error budget (baseline)

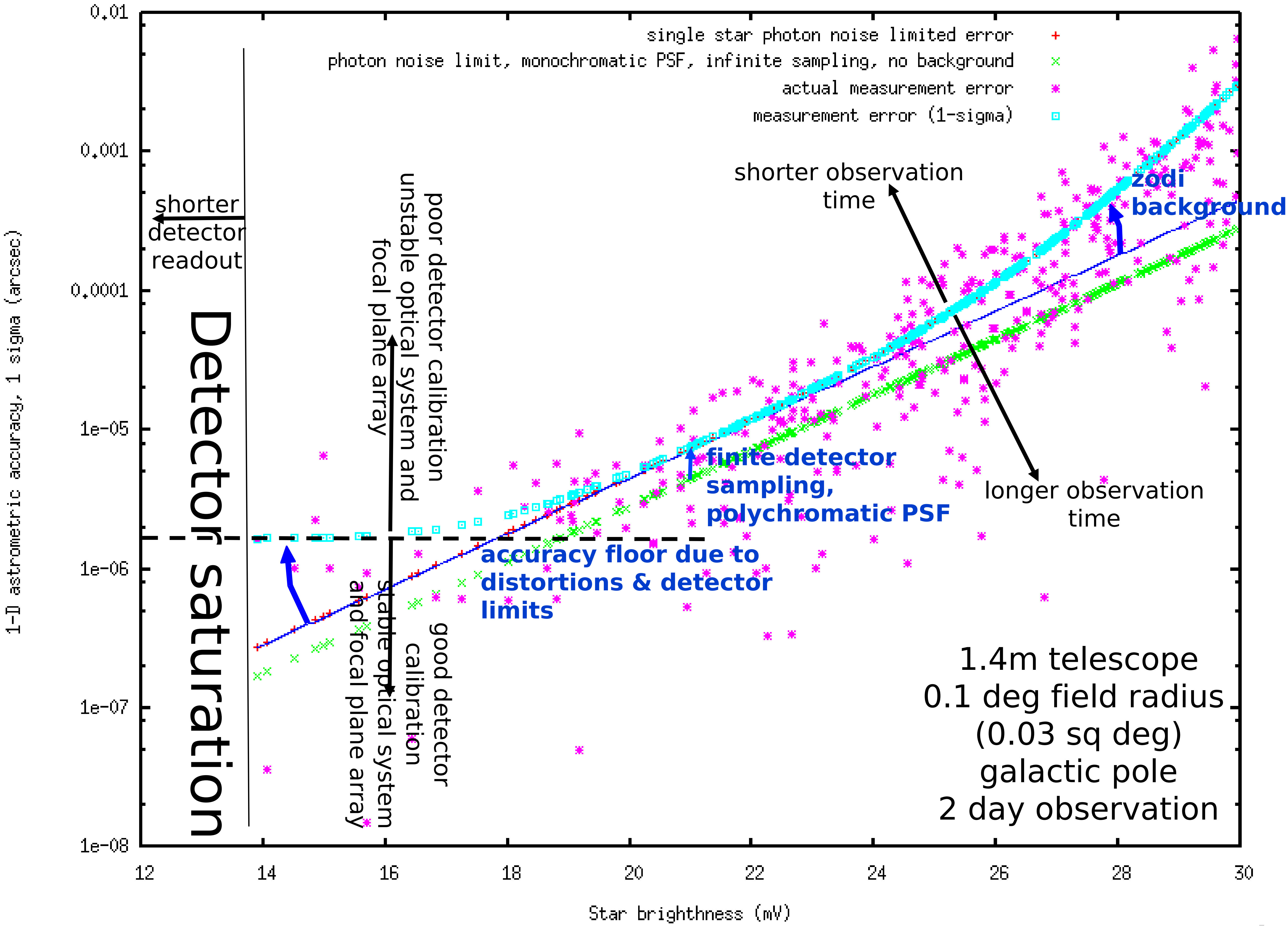
	Value	Assumption(s)	Mitigation(s)
Error on background stars position (photon noise, zodi, sampling)	0.128 ***µas***	Galactic pole pointing	Reduce other terms → brighter stars can be used with smaller photon noise
Detector flat field error (static)	0.033 ***µas***	1% RMS, 6% Peak	Better calibration of detector flat field
Optical distortions (static)	0.083 ***µas***	1.5 nm optics for M2 & M3	Better optics
Detector distortions (static)	0.0153 ***µas***	0.2% of pixel size	Project interference fringes on detector
Variation in detector flat field (dynamic)	0.0289 ***µas***	0.1 % RMS	Calibrate flat field regularly
Variation of optical distortions (dynamic)	0.0629 ***µas***	40 pm on surfaces	More stable system More light into spikes Correlate distortions to temperature
Variation of detector geometry (dynamic)	0.0755 ***µas***	~20 mK uncalibrated variations across FPA	More stable temperature control Correlate temperature to distortions Project fringes on detector
Photon noise on spikes	0.0478 ***µas***	Includes zodi photon noise mV = 3.7 star	More light on spikes
TOTAL	***0.20 µas***	***Obtained with 0.29 sq deg FOV***	

Error budget: overview (baseline system)



Detector static errors are expected to be very small in the roll-averaged angular coordinate





single star photon noise limited error
photon noise limit, monochromatic PSF, infinite sampling, no background
actual measurement error
measurement error (1-sigma)
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
12
14
16
18
20
22
24
26
28
30
1-D astrometric accuracy, 1 sigma (arcsec)
Star brightness (mV)
shorter detector readout
Detector saturation
poor detector calibration unstable optical system and focal plane array
good detector calibration stable optical system and focal plane array
shorter observation time
longer observation time
zodi background
finite detector sampling, polychromatic PSF
accuracy floor due to distortions & detector limits
1.4m telescope
0.1 deg field radius
(0.03 sq deg)
galactic pole
2 day observation

Enhancements

Main sources of error:
(1) **optical distortions** (static and dynamic)
Why ? → because of high spatial frequencies in distortions which are not sampled by the spikes (they fall between the spikes)
(2) **variations in detector geometry**

Apodizing the edges of M1 (mitigates issue #1)
→ beam walk effect on M2 and M3 becomes unable to produce distortions that change rapidly with sky position
→ astrometric calibration by spikes becomes much better

Issues:
- Small loss in throughput (few % ?)
- manufacturing of apodized edge on M1
- many issues to check (chromaticity, compatibility with coatings, etc..)

Projecting interference fringes on the detector (mitigates issue #2)
→ allows measurement of detector geometry any time

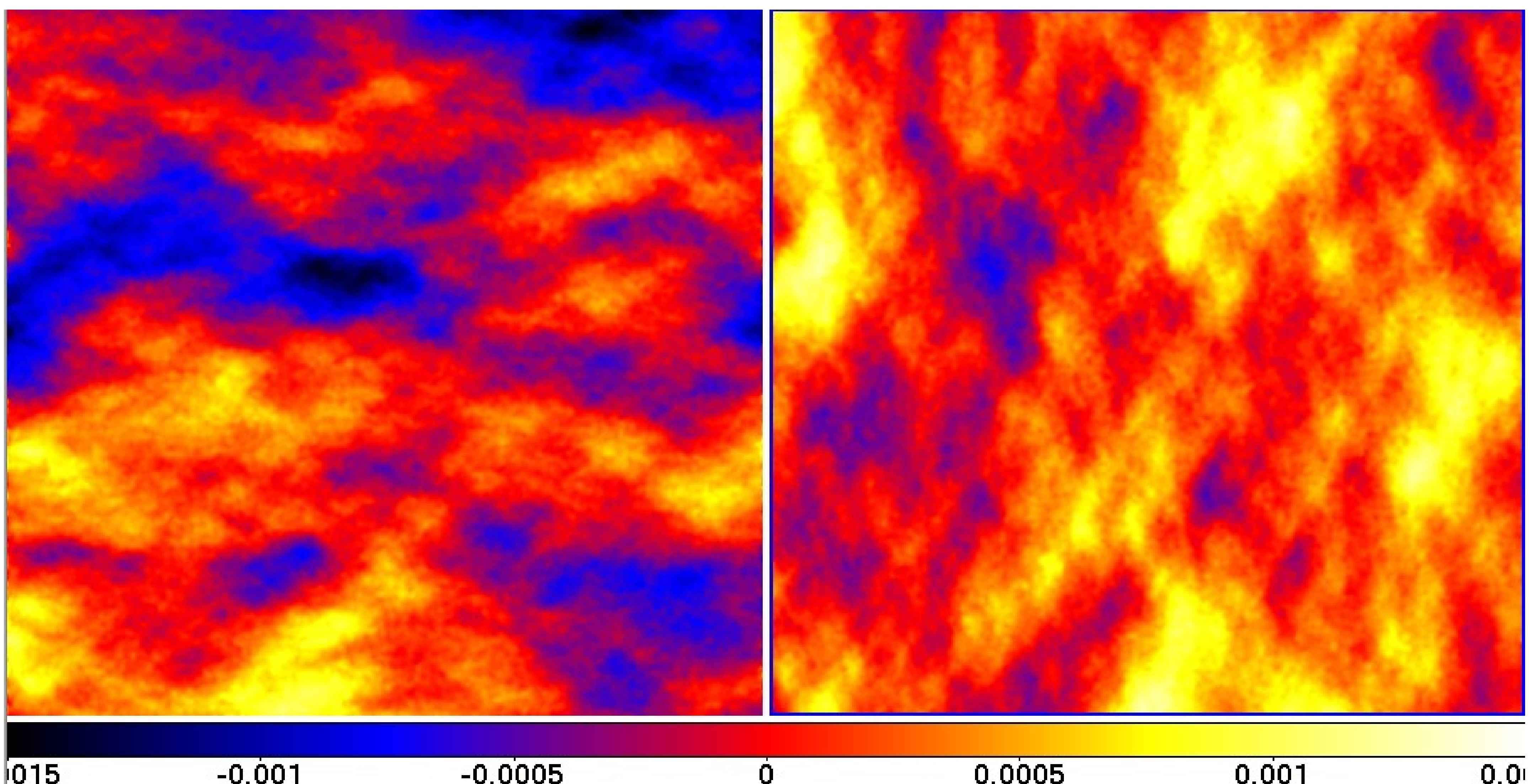
Issues:
- Takes time away from observation
- Complexity (add laser, fibers)

Warning: as instrumental errors become smaller, risk and impact of possible companions on field stars increase

Static distortion map due to M2 & M3 optical surfaces

Distortion maps shown below is for 0.46x0.46 deg field. Unit is arcsec; left map is x, right map is y. Distortion map is computed at 220000 positions on the sky with raytracing software written in C (cross-checked with code-V), then interpolation is used to compute the full map. Total number of rays used = 7e11 (122 day CPU of execution time on 2 GHz CPUs)

Distortion amplitude is ~1 mas, dominated by low order modes. The differential distortion over ~1” is much smaller.



Exoplanet science with coronagraphy + astrometry + wide field imaging

Provides a complete picture of a planetary system:

<u>CORONAGRAPH:</u>

•Planets orbits

•Planet atmospheres (spectra, polarization from coronagraph)

•Rotation periods (time photometry from coronagraph)

•Zodiacal cloud: morphology, spectra, polarization (coronagraph)

<u>ASTROMETRY:</u>

•Planet masses

<u>CORONAGRAPHY + CORONAGRAPHY:</u>

•Good sensus of planets in a system (astrometry + coronagraphy)

<u>WIDE FIELD IMAGING:</u>

•Very distant planets, possibly ejected

•Debris disks at large separation

•Occultations of field stars by Kuiper belt objects

Also: high precision photometry of field stars

- Microlensing program possible (with pointing to galactic bulge)
  stable sharp PSF with good astrometry valuable
- Transit observations

Deep wide field imaging science

Wide field + stable diffraction limited PSF is scientifically valuable for many scientific programs, and will be unique in visible:

- Cosmology: weak lensing, type Ia supernovae
- Galactic astronomy
- Planetary astronomy: search for small & distant objects (asteroids, comets, KBOs)

The dots on PM do not significantly impact sensitivity

Loss in sensitivity is due to 3 effects:

- Light absobed by the dots → 1% loss in throughput
- Light diffracted out of the PSF core by the dots → 1% loss in flux
- Additional background due to diffraction spikes of central star
  - spikes occupy a tiny fraction of the FOV, and are sufficiently stable to be efficiently removed from images by postprocessing
  - for a mV=3.7 central source, over 95% of the field, additional diffracted light is less than 1% of zodi background
  - mean value for additional diffracted background over the field = 6 ph/pix/day (unfiltered), vs 20000 ph/pix/day for zodi

Conclusion

Coronagraphy, astrometry and wide field imaging can be combined for Simultaneous observation without compromizing performance.
→ rich science for both exoplanet science and general astrophysics
→ could be key to gain support and funding for large (>1m) space mission for spectroscopy of habitable exoplanets

Future work ...

- Lab testbed at UofA: demonstrate performance and algorithms, validate error budget
- Test with coronagraph at NASA Ames and NASA JPL
- We are investigating ground-based system and doing science with it

(Funding from University of Arizona and NASA)

More info ...

- See Eduardo Bendek's poster today (lab testbed at UofA)
- J. Catanzarite's talk today "The synergy of Direct Imaging and Astrometry for Detection of Exo-Earths"
- Website (includes detailed error budget, algorithms, C source code): http://www.naoj.org/staff/guyon/
  → research → coronagraphic astrometry