Robustly Searching for Earth-like bio-signatures

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Motivation

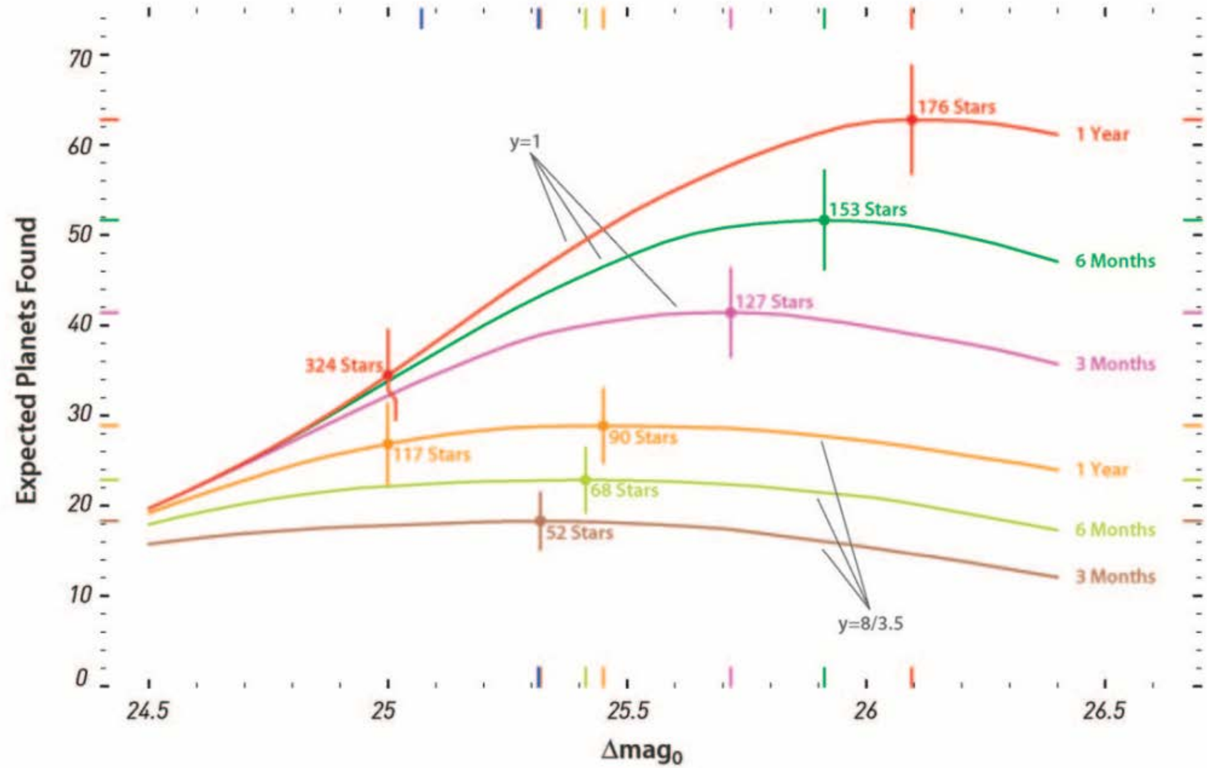
General Question:
How common is life in the Universe?

Specific Questions:
How common are Earth-like exoplanets in the habitable zone (HZ) that show the O_2 A-band bio-signature in their spectra?
What's the biggest telescope that can be squeezed in to an Ariane-V (or similar) and does it do the job?

Design the Experiment:
From the local star population make an exoplanet yield calculator quantified in terms of contrast, angular separation and apparent magnitude. Then calculate the yield for the specific design of a dedicated telescope operating for a 5 year observing program.

Conclusion:
It might be possible to launch a suitable telescope, with a yield of between 50-100, on an Ariane V (or a Delta IV heavy or a Space-X Falcon Heavy).

Previous work on yield



Brown, R. A. 2005, ApJ, 624, 1010

Many people have tackled the question of exoplanet yield already.

We've repeated the work because we want to look at specific experiment designs and yield depends on many parameters.

Postman et al 2009 →

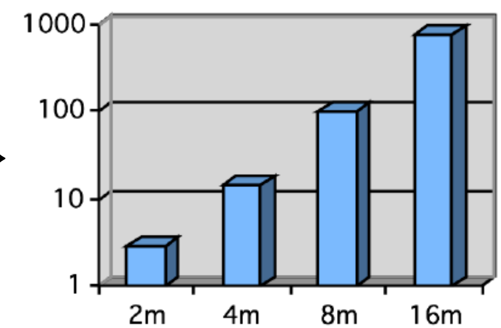


Figure. 1: The average number of F,G,K stars where SNR=10 R=70 spectrum of an Earth-twin ***could*** be obtained in < 500 ksec as a function of telescope aperture, D. The growth in the sample size scales as D^3.

Also,

Brown, R. A., & Soummer, R. 2010, ApJ, 715, 122

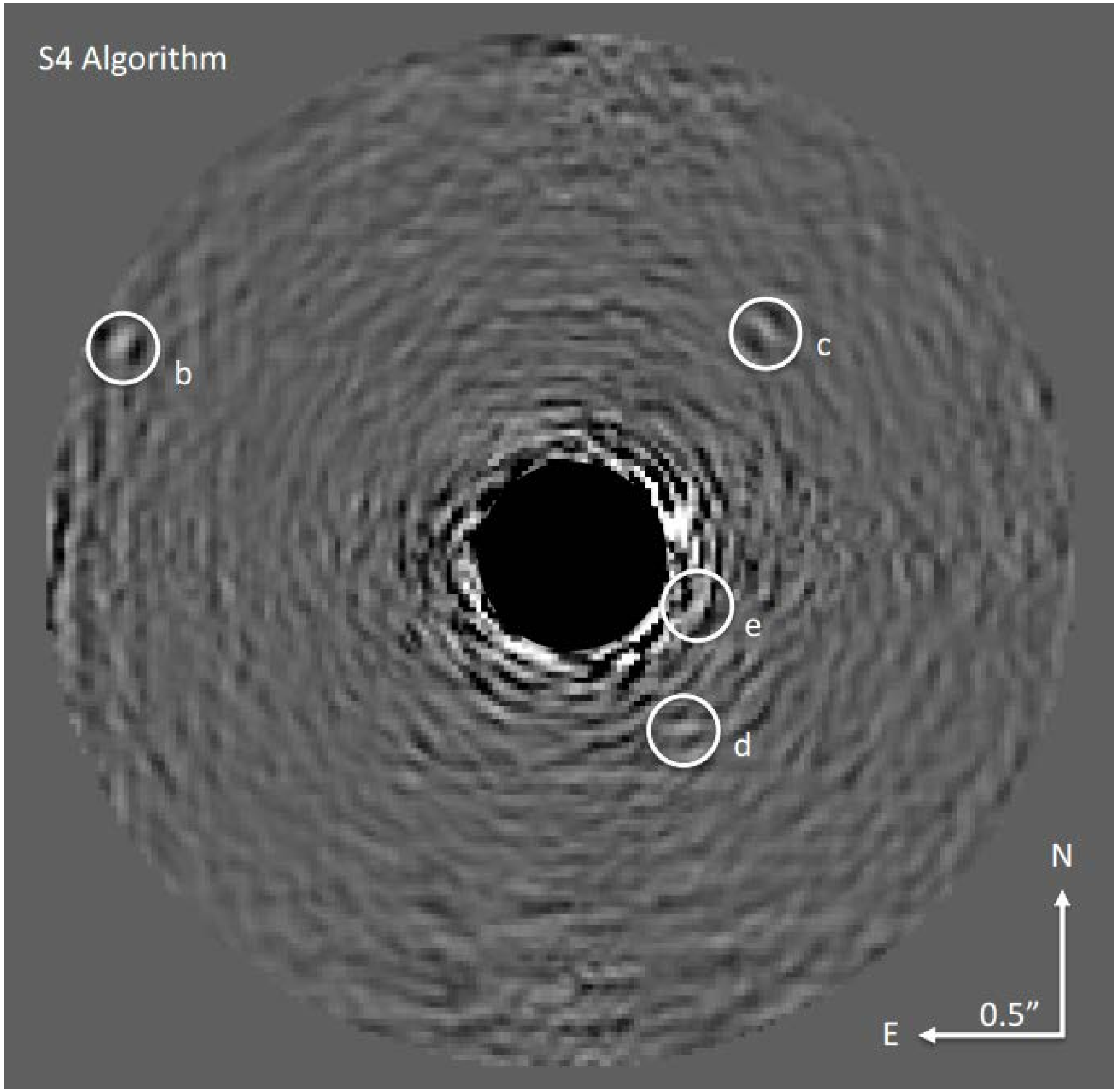
Turnbull, M. C. et al. 2012, PASP, 124, 418

Stark et al, 2014 and 2015

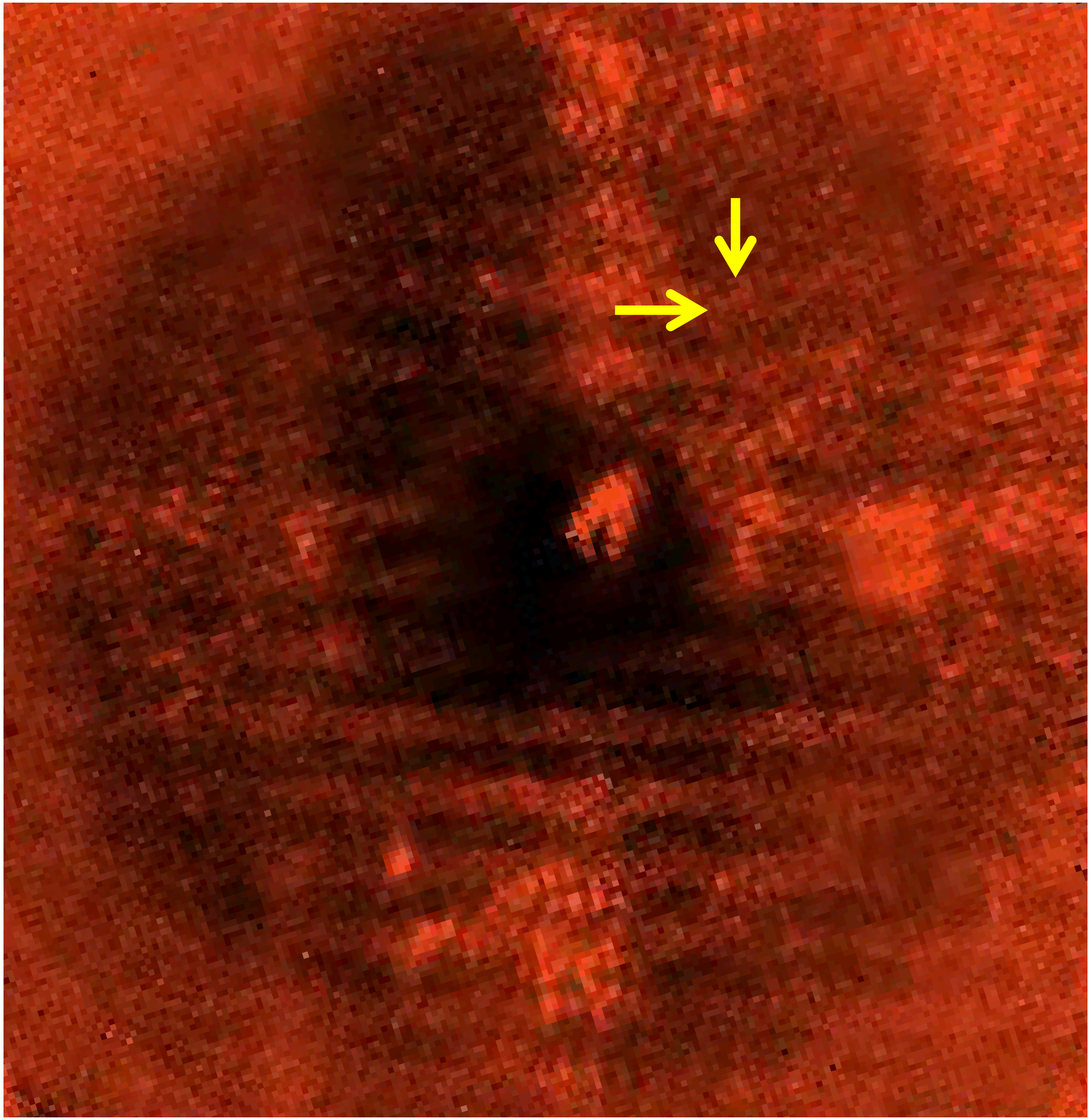
and more....

P1640 image of the HR8799 system

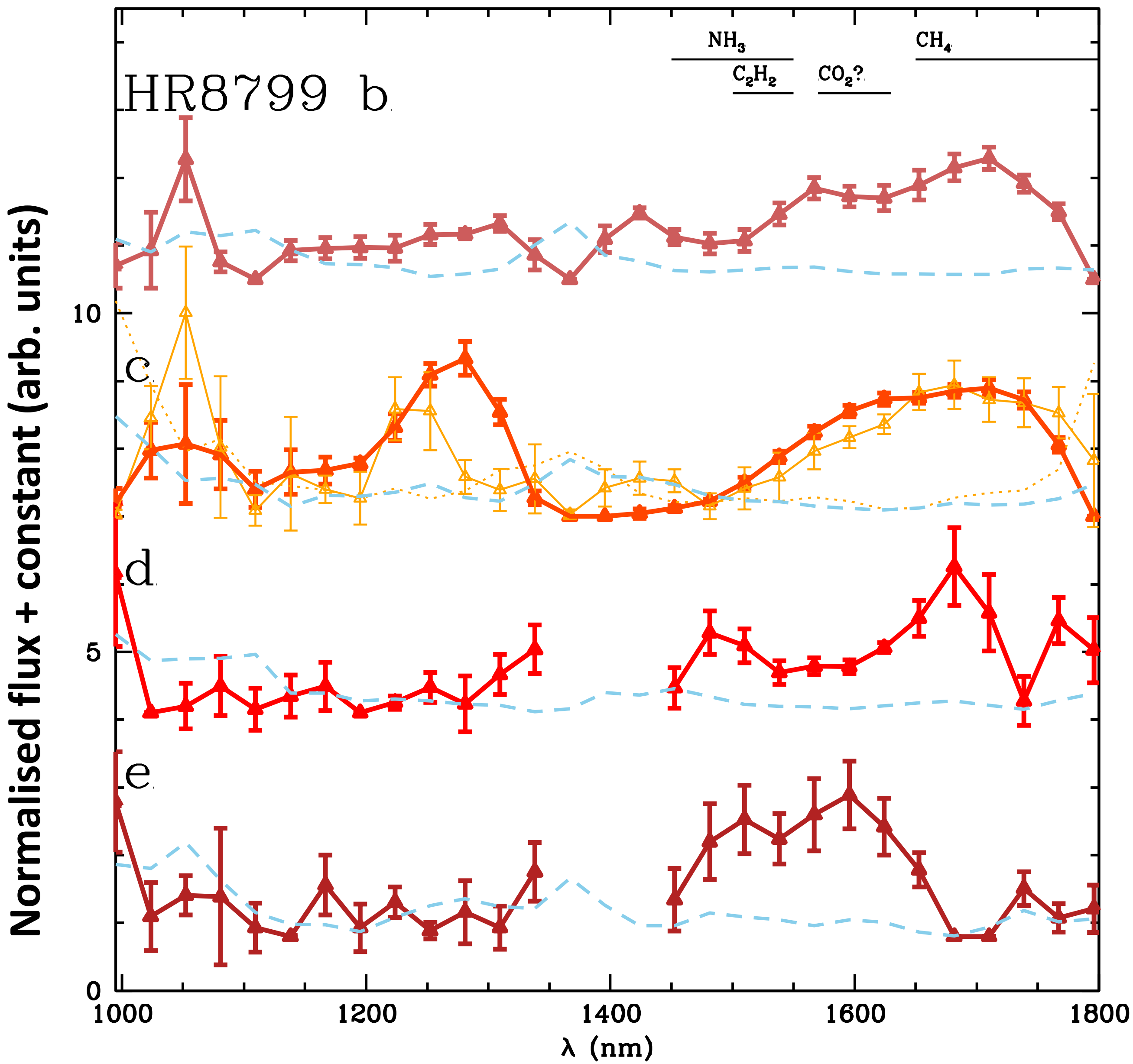
P1640 is a NIR coronagraphic integral field spectrograph on the Palomar 5m telescope. We are part of the P1640 team.



HR8799c is just visible without S4 processing with a contrast = 2.2x10^{-5}.

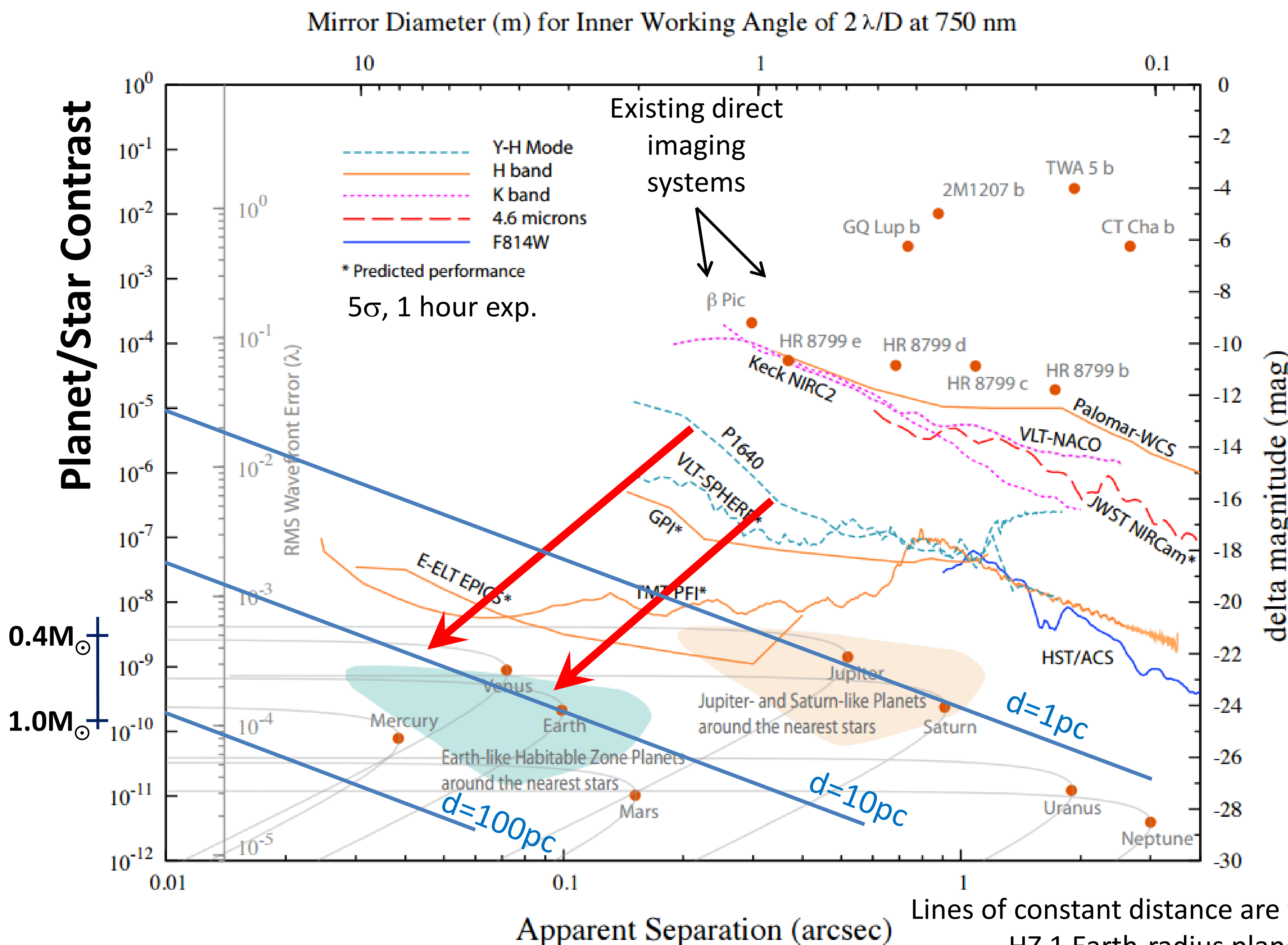


P1640 spectra of the HR8799 exoplanets



Oppenheimer et al 2013

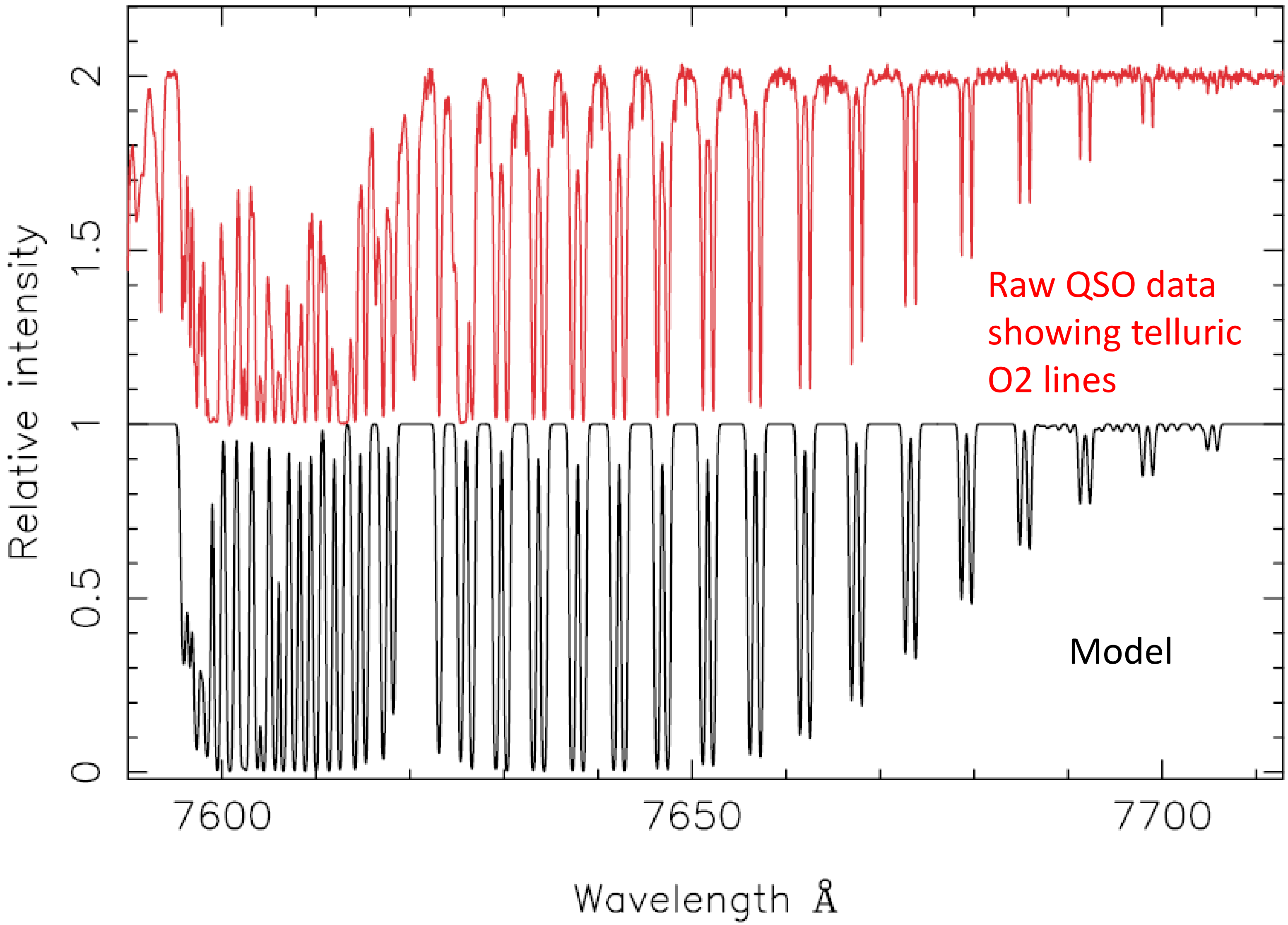
Spectra obtained using S4



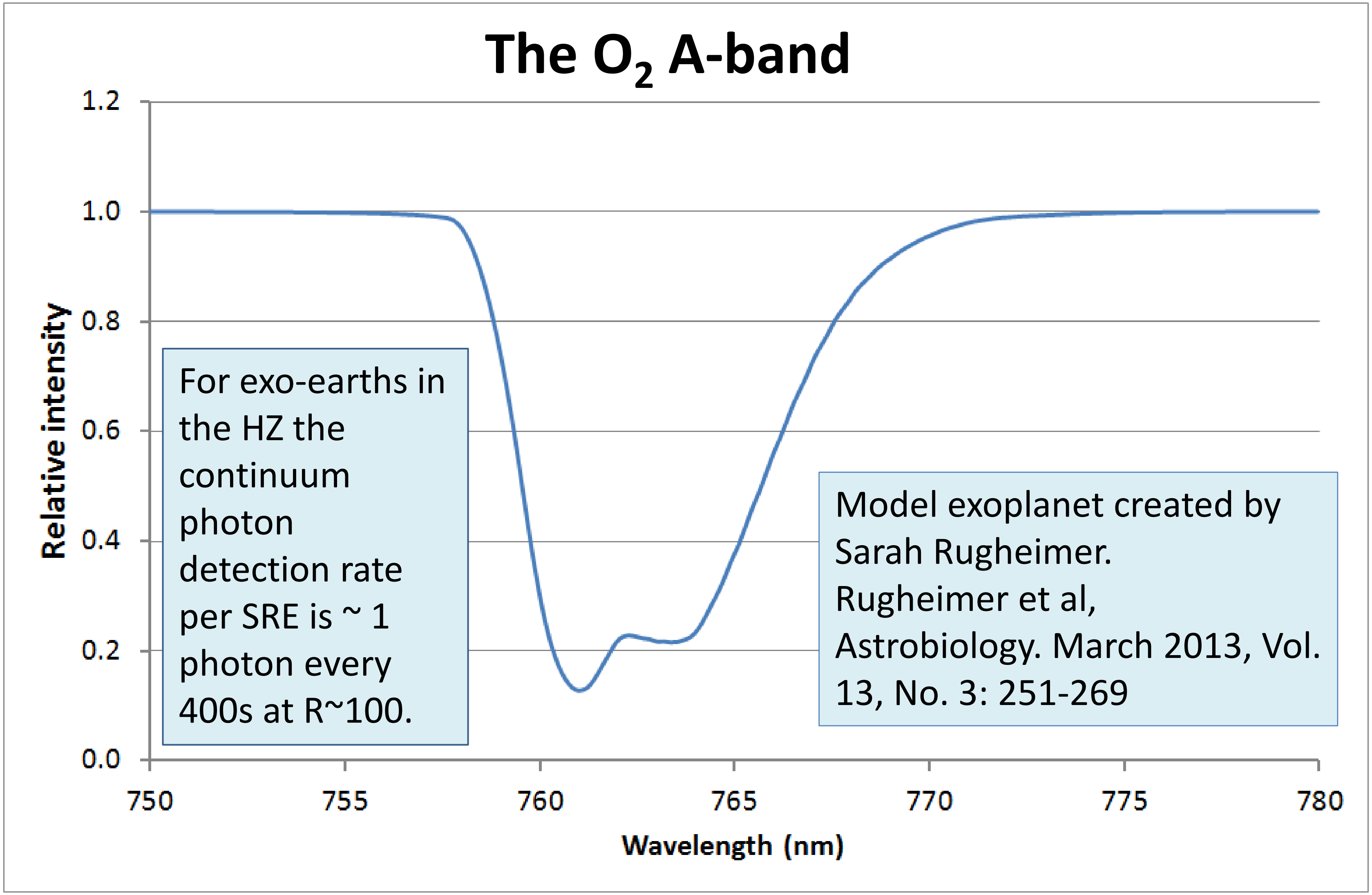
Lines of constant distance are for HZ 1 Earth-radius planets

Figure from Lawson 2012 (JPL Document D-77698)

The O_2 A-band biosignature



From Webb and Wormleaton, 2002



The O2 A-band
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Relative intensity
750
755
760
765
770
775
780
Wavelength (nm)
For exo-earths in the HZ the continuum photon detection rate per SRE is ~ 1 photon every 400s at R~100.
Model exoplanet created by Sarah Rugheimer. Rugheimer et al, Astrobiology. March 2013, Vol. 13, No. 3: 251-269

Yield calculation method

Start with a list of 20,000 stars within 85kpc (parallax, photometry). Also make assumptions about the telescope+instrument (max baseline, collecting area, throughput, instrumental contrast, spectral resolution, required S/N ratio, total amount of observing time available, etc.).

For each star in the list:

1) Assign it a mass and a distance.
2) Define the inner and outer HZ sizes (Kopparapu et al 2013).
3) Throw a 10 sided dice to decide if the star actually has an Earth-sized planet in the HZ (assumes only 10% of stars have such a planet)
4) Randomly assign a position for the planet in the HZ (evenly distributed between the inner and outer edges).
5) Randomly assign a size for the planet between 1 and 2 Earth-radii.
6) Assume an albedo of 0.3 for the planet.
7) Calculate the planet's contrast at max separation.
8) Calculate required exposure time to detect the O_2 feature.

Method (continued)

Make a shortlist of planets that could be observed to look for the O_2 feature. Include stars if:

1) The star is on the main sequence and later than F0 (i.e. mass < 1.58 solar masses).
2) The max observed separation is greater than the inner working angle (IWA) at 762nm.
3) The dice roll says the star has a planet in the HZ.
4) The contrast is observable ($> 1.0 \times 10^{-10}$).

Then sort the list by exposure time with the shortest ones at the top. Work down the list until the total accumulated exposure time is approximately equal to the total exposure time available for the mission. This defines the number of targets that can be observed on the basis of the instrumental assumptions made.

The actual mission

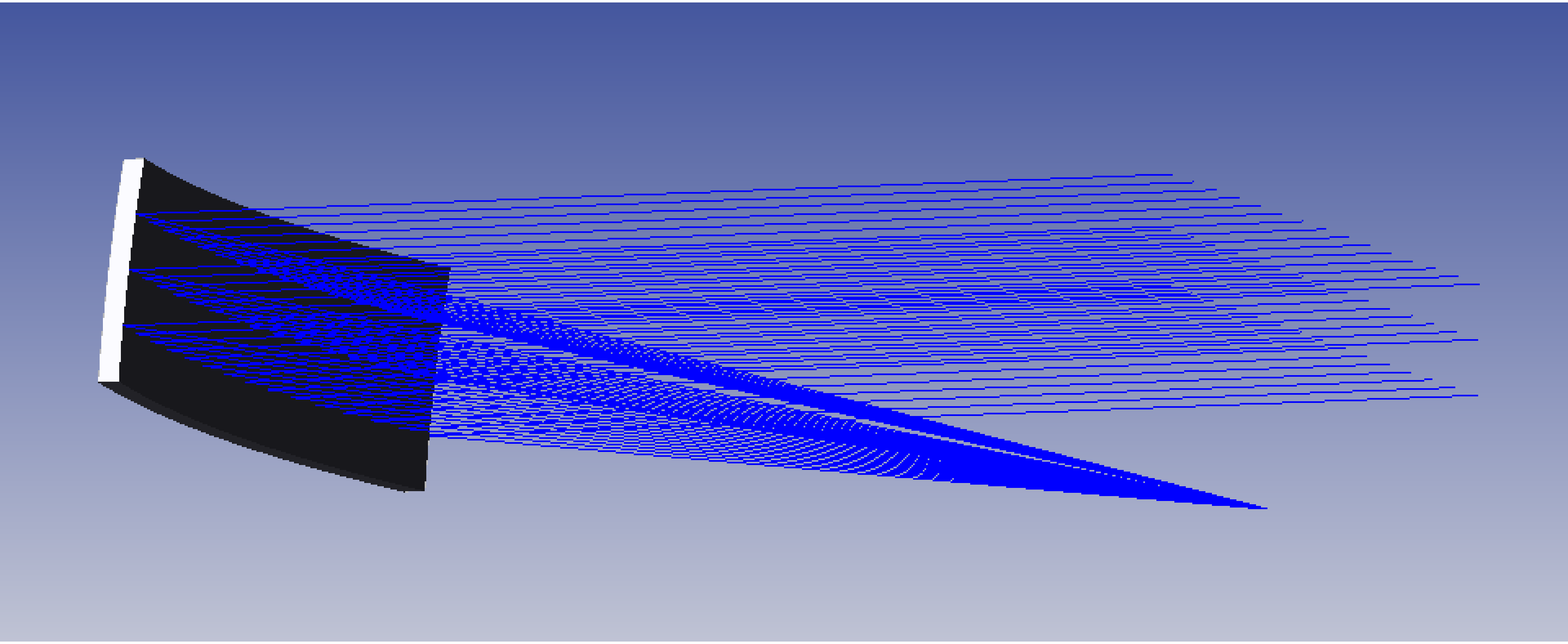
- The telescope will be capable of doing coronagraphic integral field spectroscopy at R~100 over a FOV of 2000×2000mas for the wavelength range 250nm-3000nm.
- The first part of the mission (6-12 months) is a reconnaissance survey, observing the full long list of stars which could have an observable Earth-like planet (500-1000 targets).
- The UV data, rebinned to low resolution can be used to work out which stars actually have Earth-like planets in the HZ. The UV data has a very small IWA (~15mas) so the initially unknown orbital phase for near edge-on systems is less of a problem.
- The second part of the mission (~5 years) is the deep survey of the stars with Earth-like planets in the HZ (50-100 stars) which includes the R~100 O_2 762nm observations modelled by the yield calculator.
- Both the deep survey and the reconnaissance survey will do much more than the bio-signature search because the integral field spectrographs will give spectroscopy of disks, super-Earths, Neptunes, and Jupiters at all star-planet separations (not just in HZ).

Telescope mirror aspect ratio

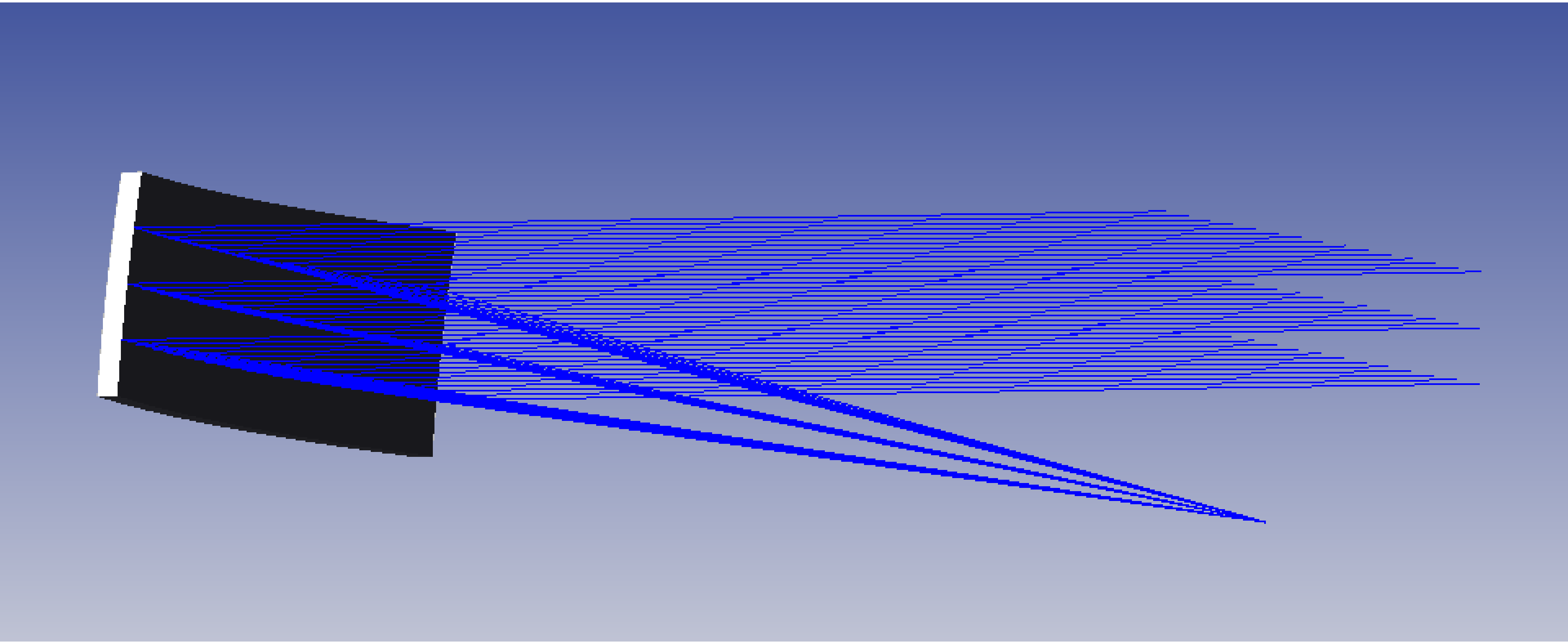
- The IWA is driven by the maximum baseline of the telescope and the exposure times are driven by the collecting area. There's no particular reason (for an internal coronagraph) why the telescope mirror aspect ratio should be unity.
- The IWA directly drives the number of potential targets. The size of the mirror in the orthogonal direction drives the survey duration.
- A long-thin aspect ratio is easier to fit into a rocket fairing than something that has an aspect ratio ~1.
- A mirror with a long-thin aspect ratio can be an off-axis parabola giving a very clean aperture (no spider support structure) thus reducing diffraction effects and improving contrast.
- An interferometer can be thought of as telescope with a large maximum baseline and a relatively low collecting area.

What's the biggest telescope we can squeeze in to an Ariane-V?

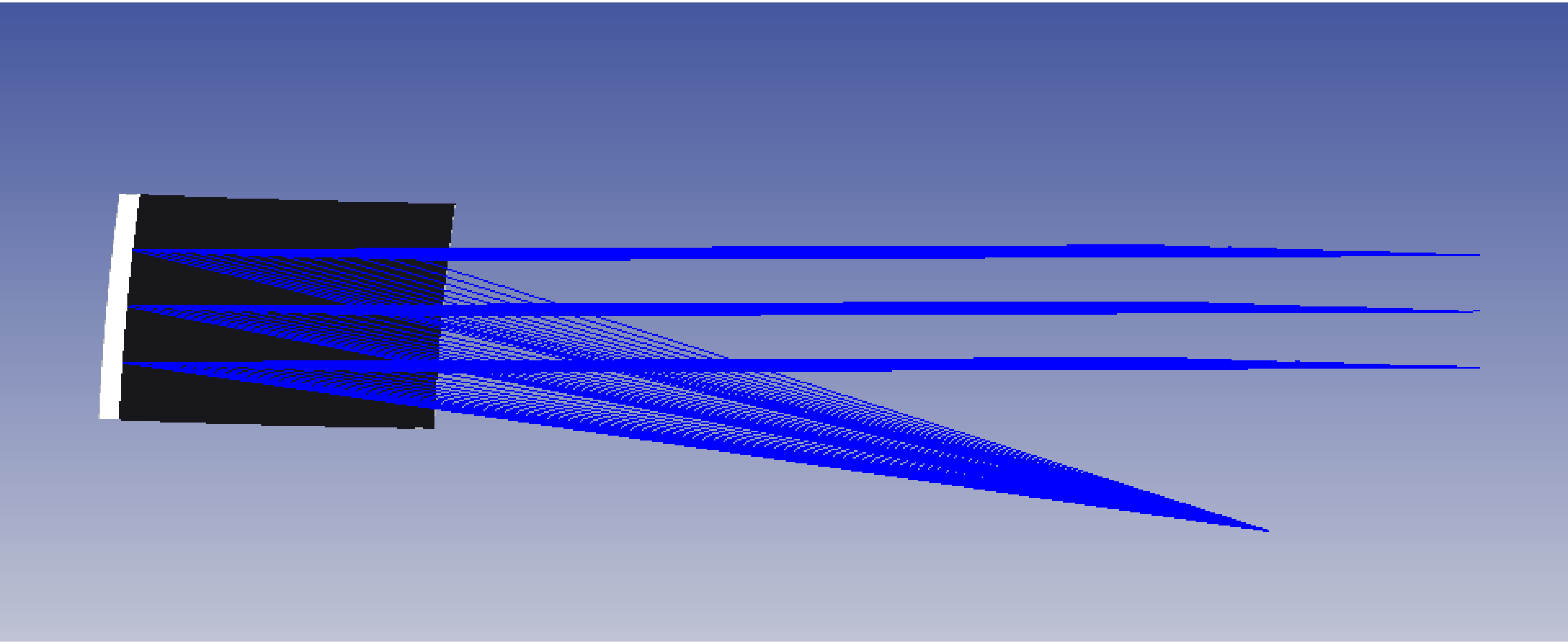
Telescope is a 14m×4m off-axis parabola



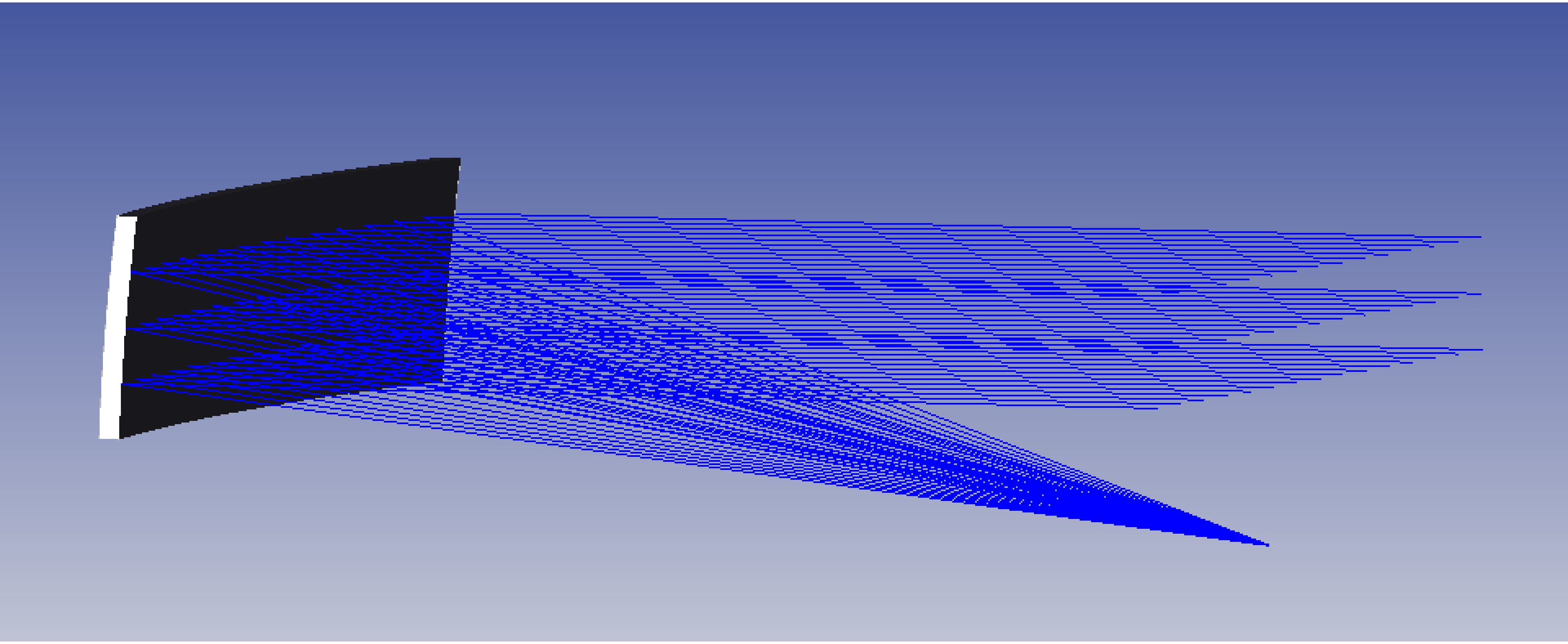
Telescope is a 14m×4m off-axis parabola



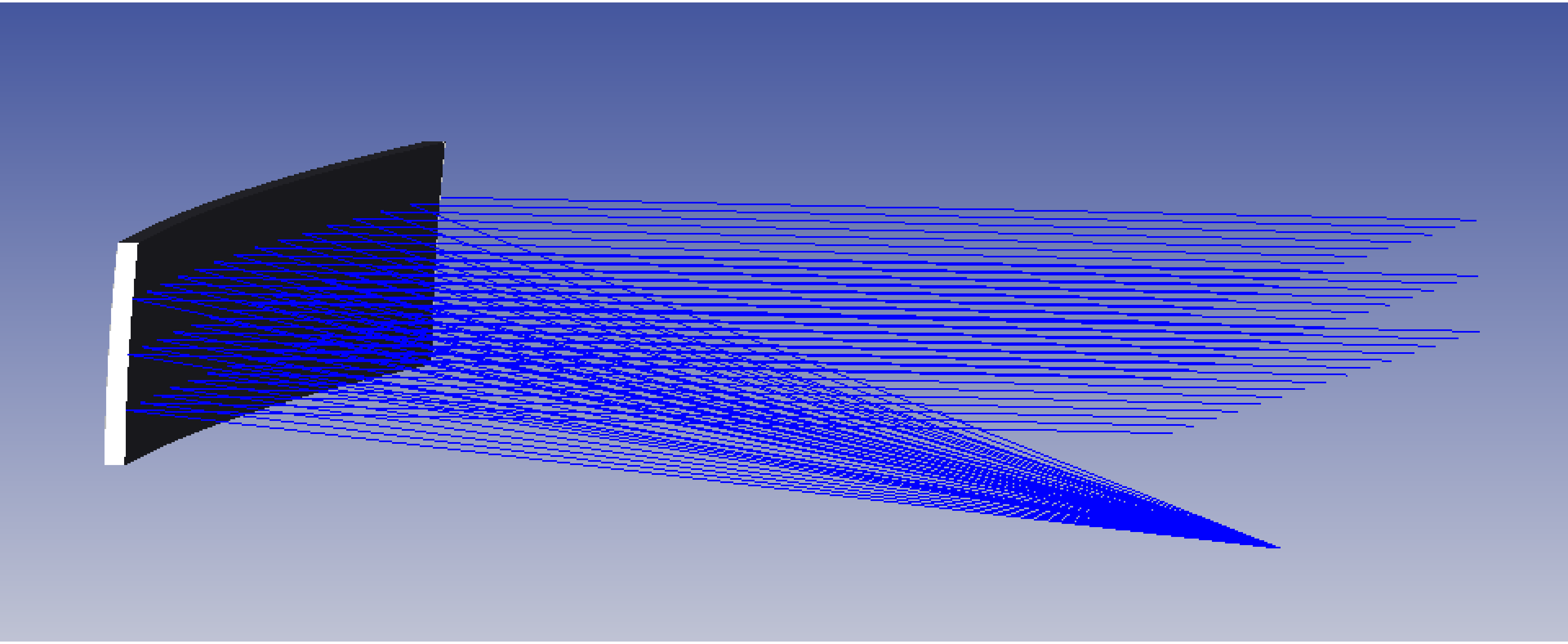
Telescope is a 14m×4m off-axis parabola

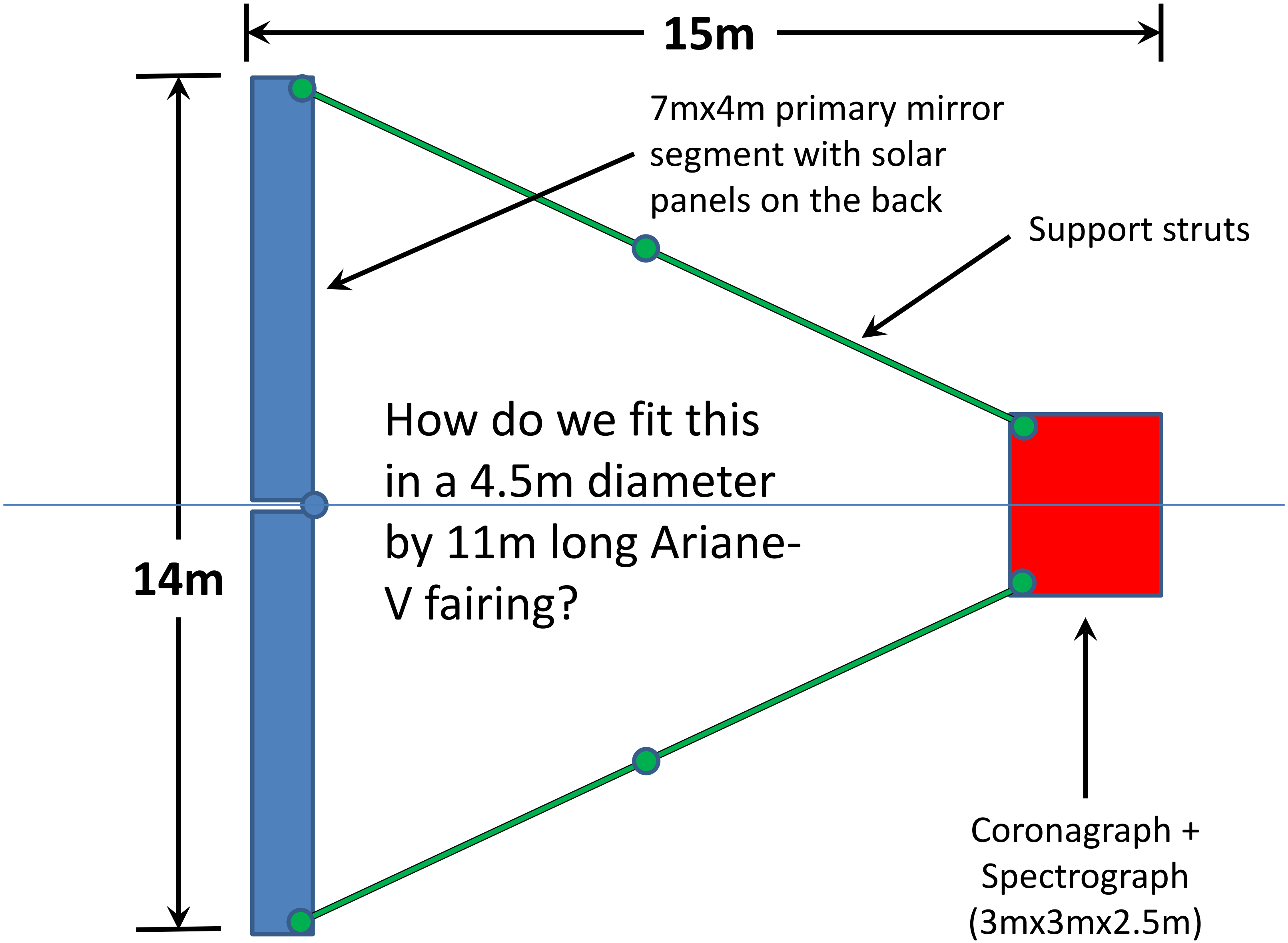


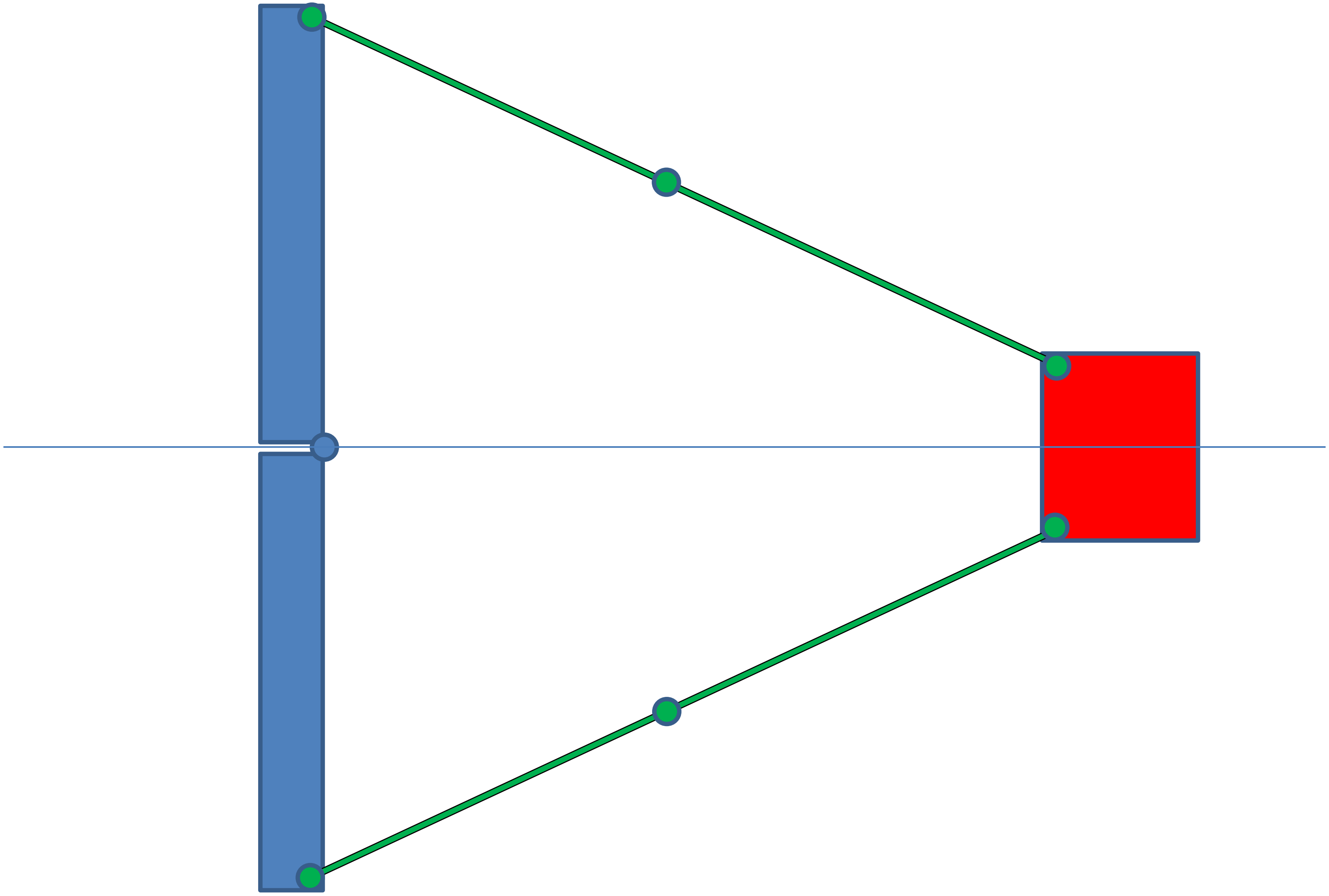
Telescope is a 14m×4m off-axis parabola

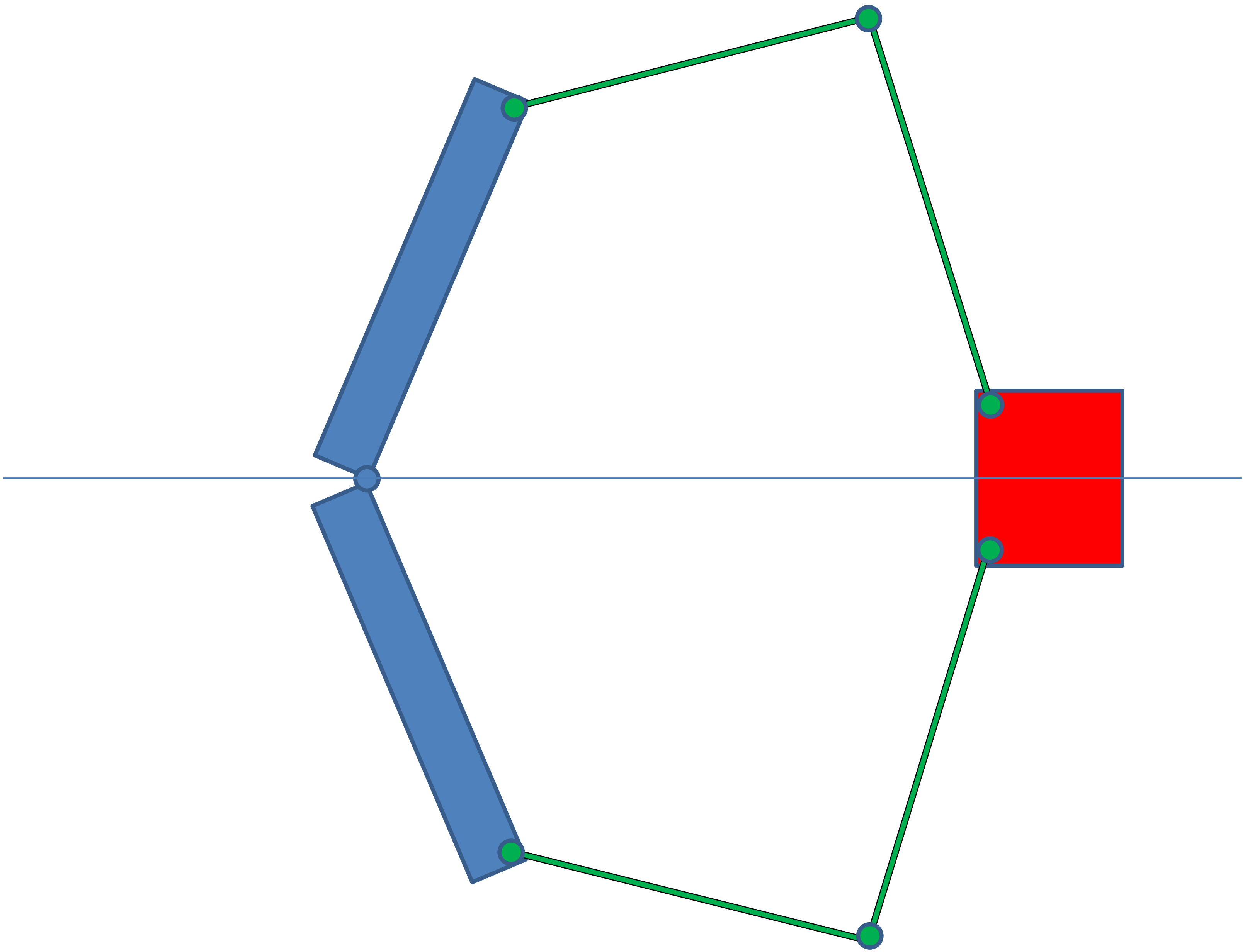


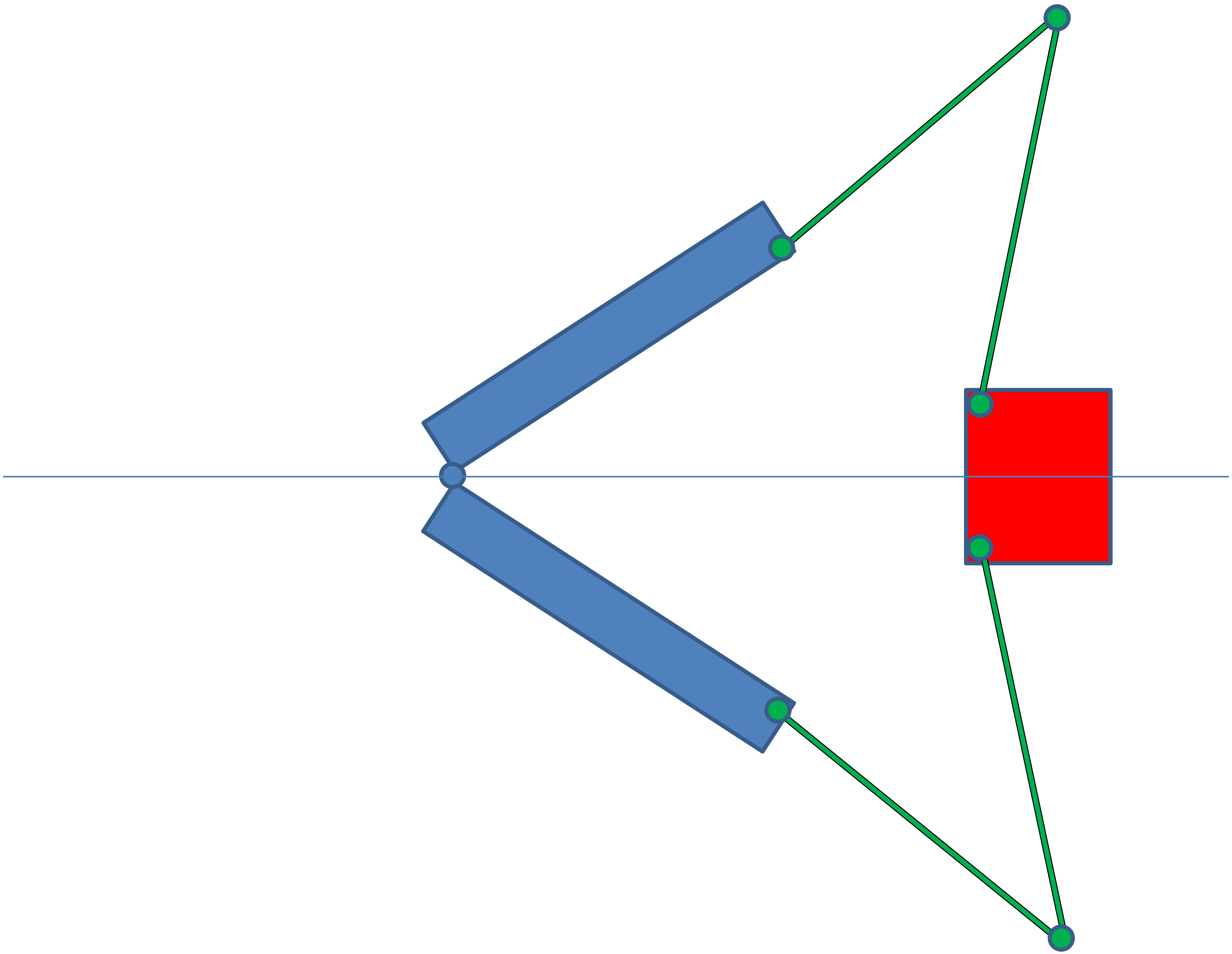
Telescope is a 14m×4m off-axis parabola

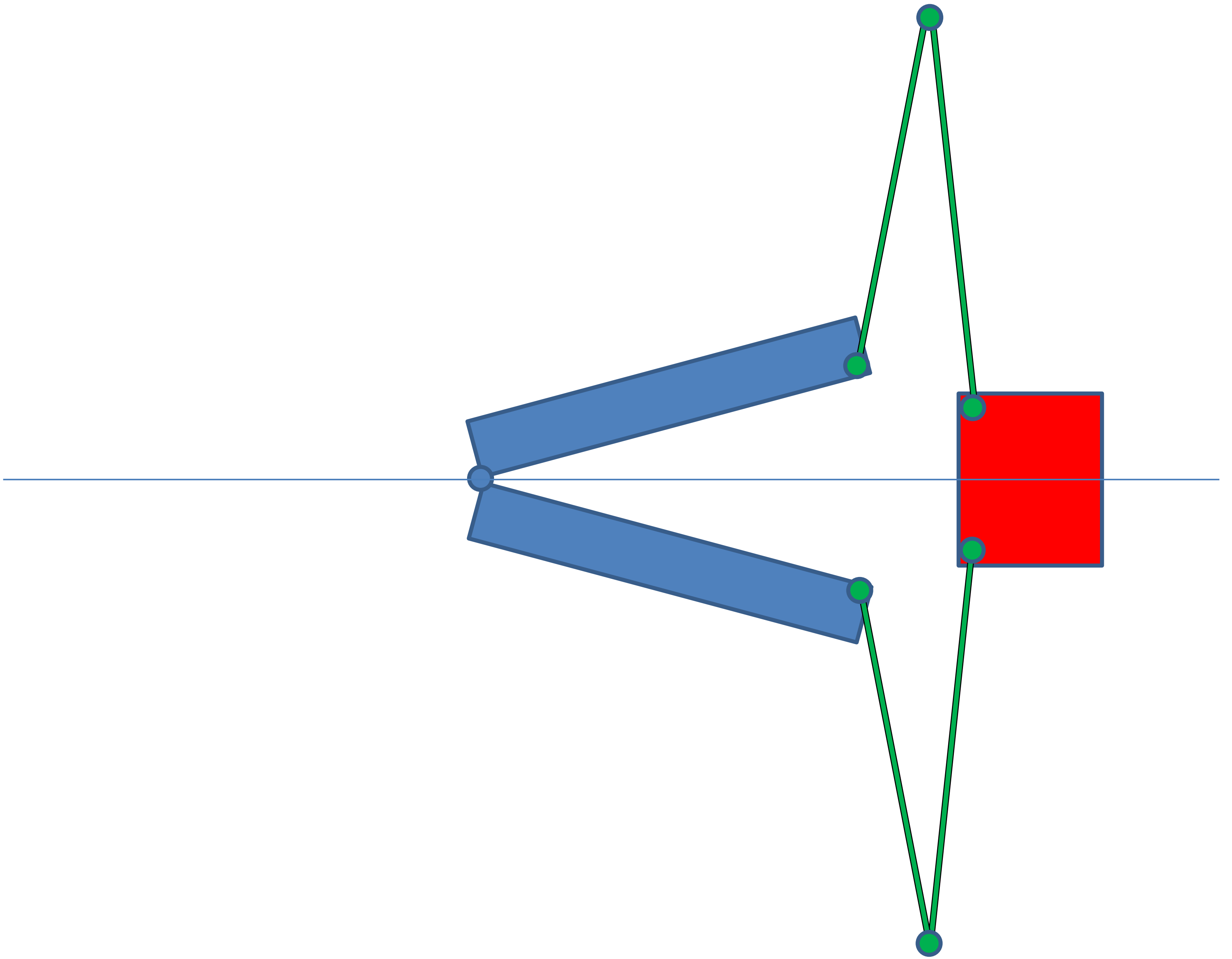


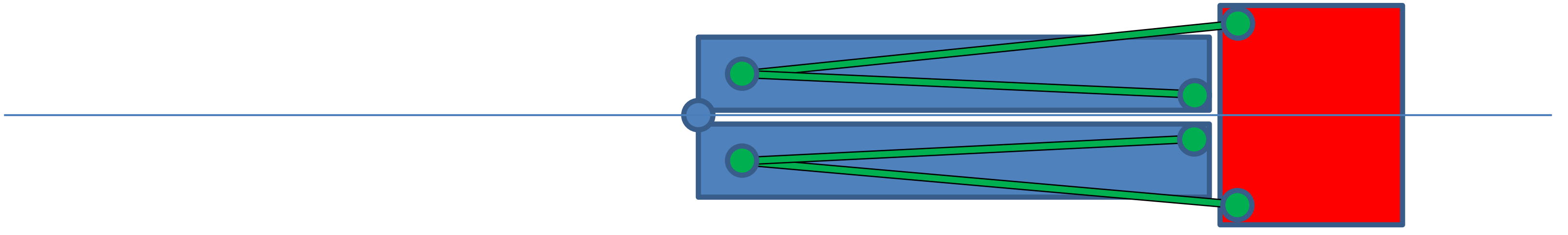

15m
14m
7mx4m primary mirror segment with solar panels on the back
Support struts
How do we fit this in a 4.5m diameter by 11m long Ariane-V fairing?
Coronagraph + Spectrograph (3mx3mx2.5m)

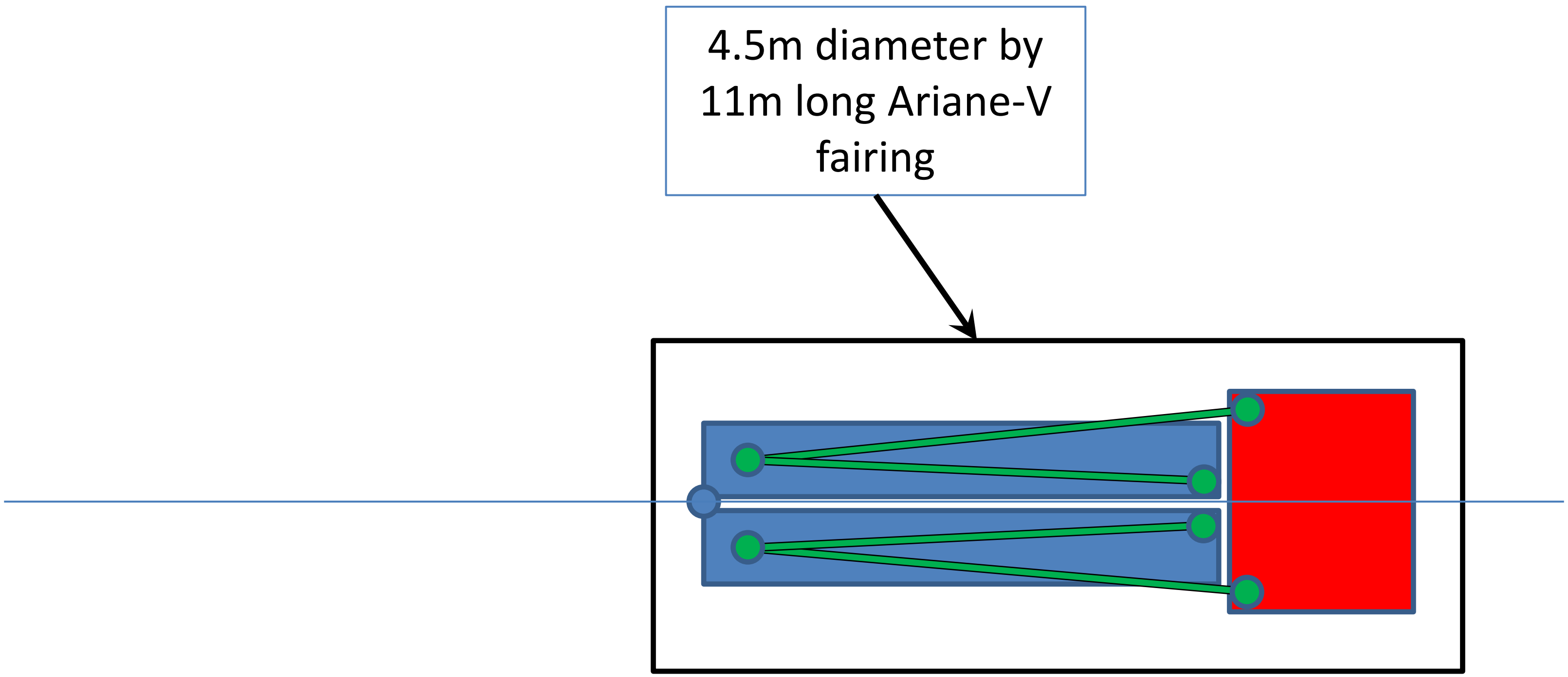




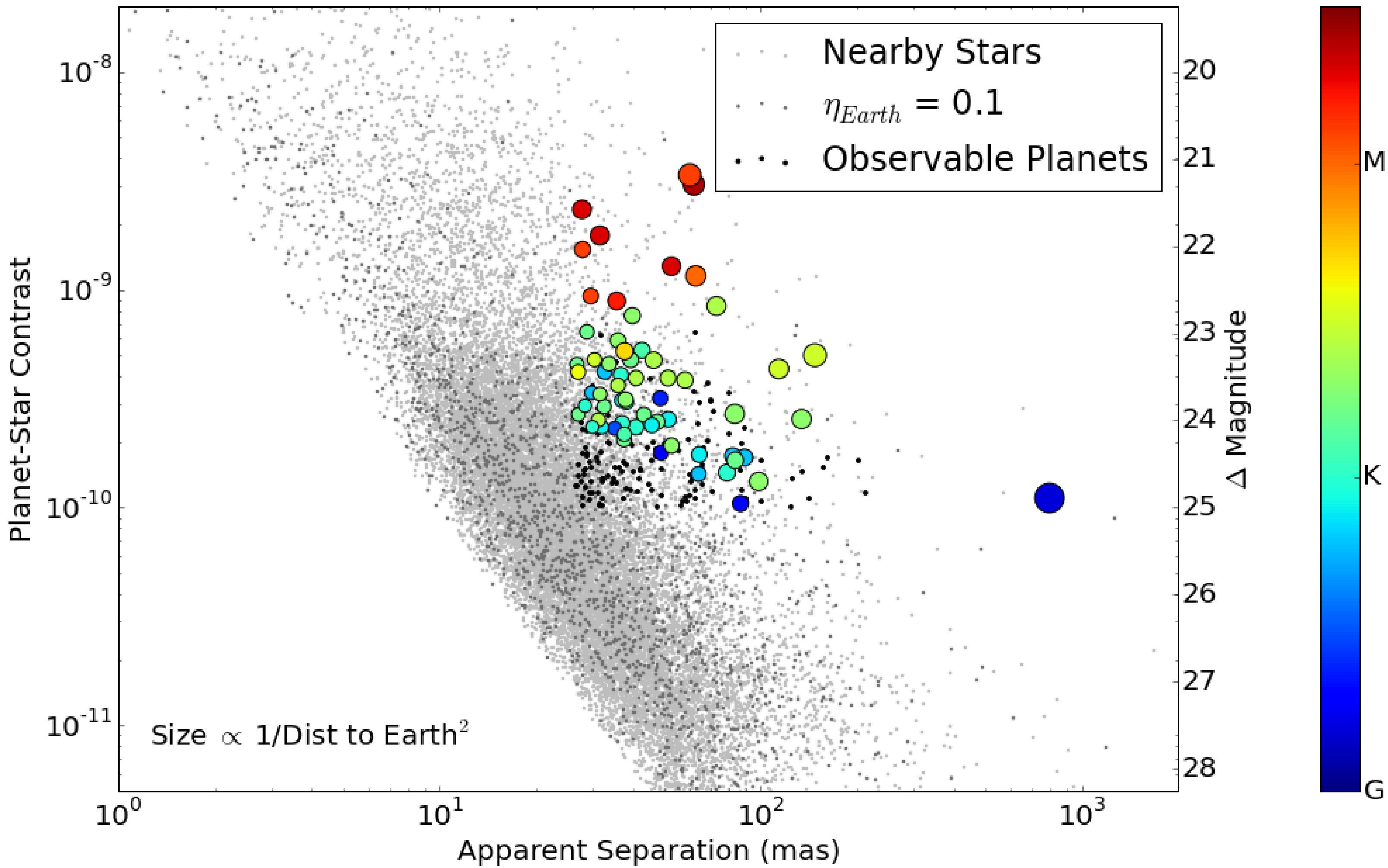







4.5m diameter by
11m long Ariane-V
fairing

Sample selection method produces a list of 65 targets



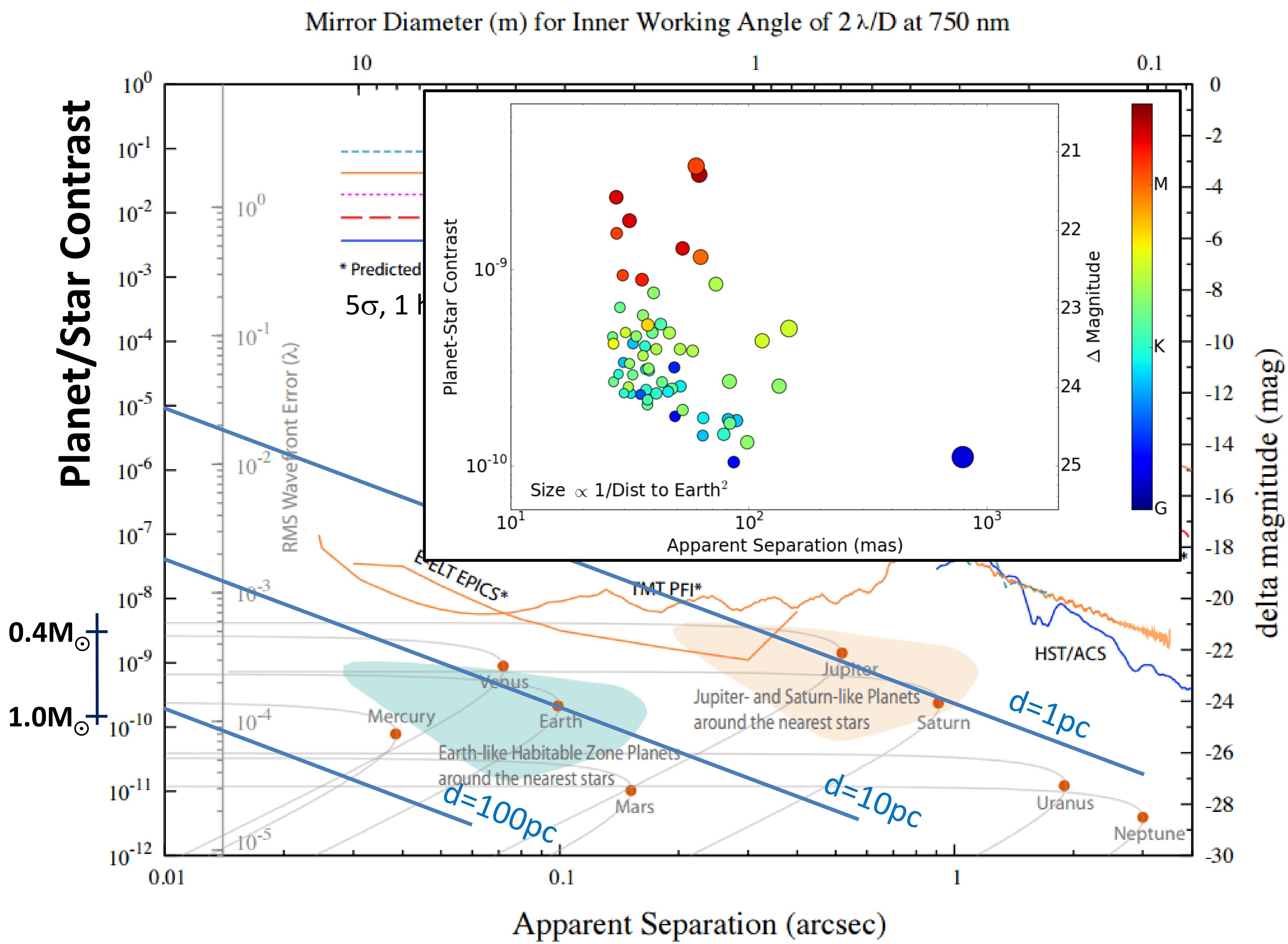


Figure from Lawson 2012 (JPL Document D-77698)

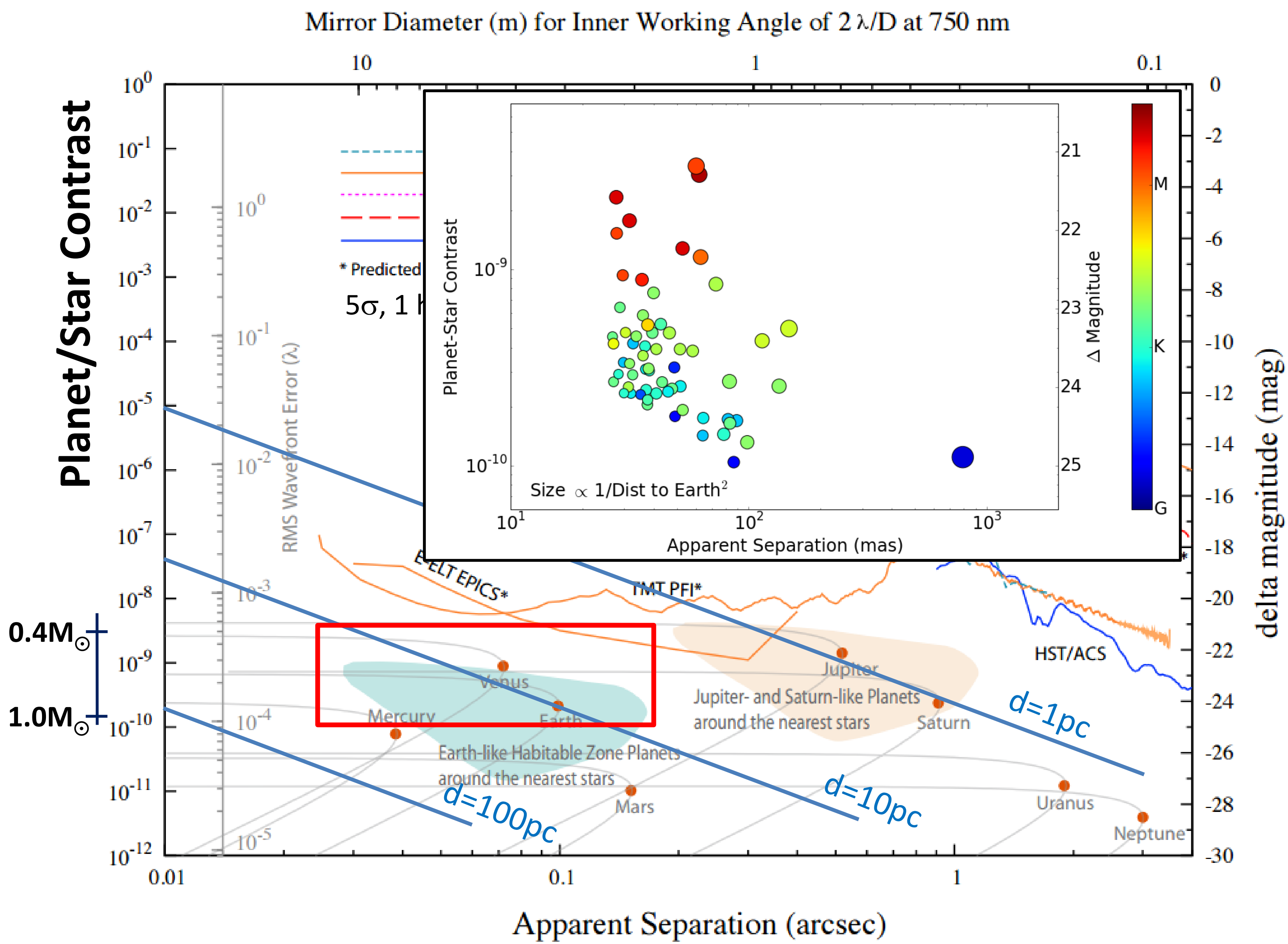


Figure from Lawson 2012 (JPL Document D-77698)

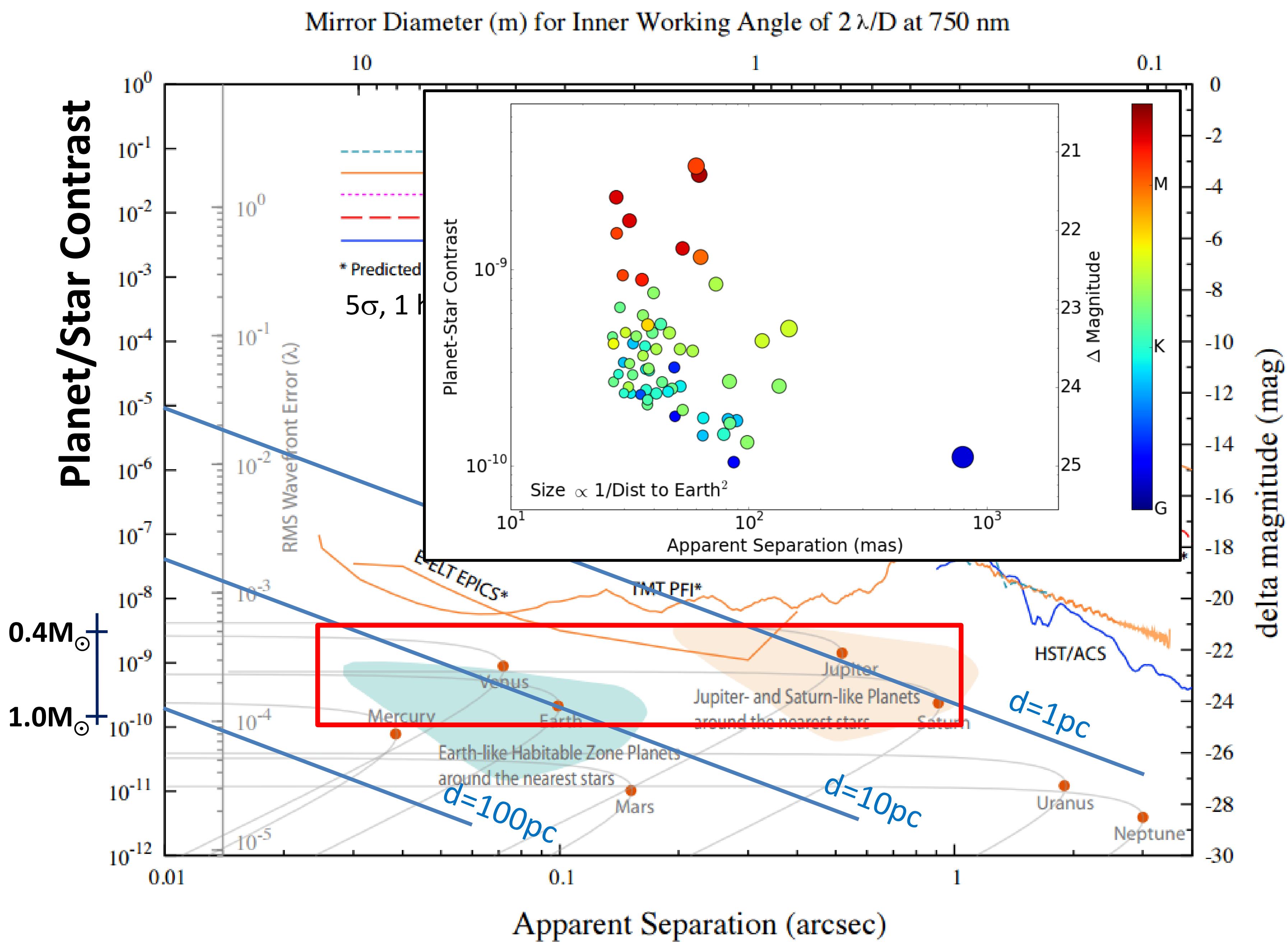
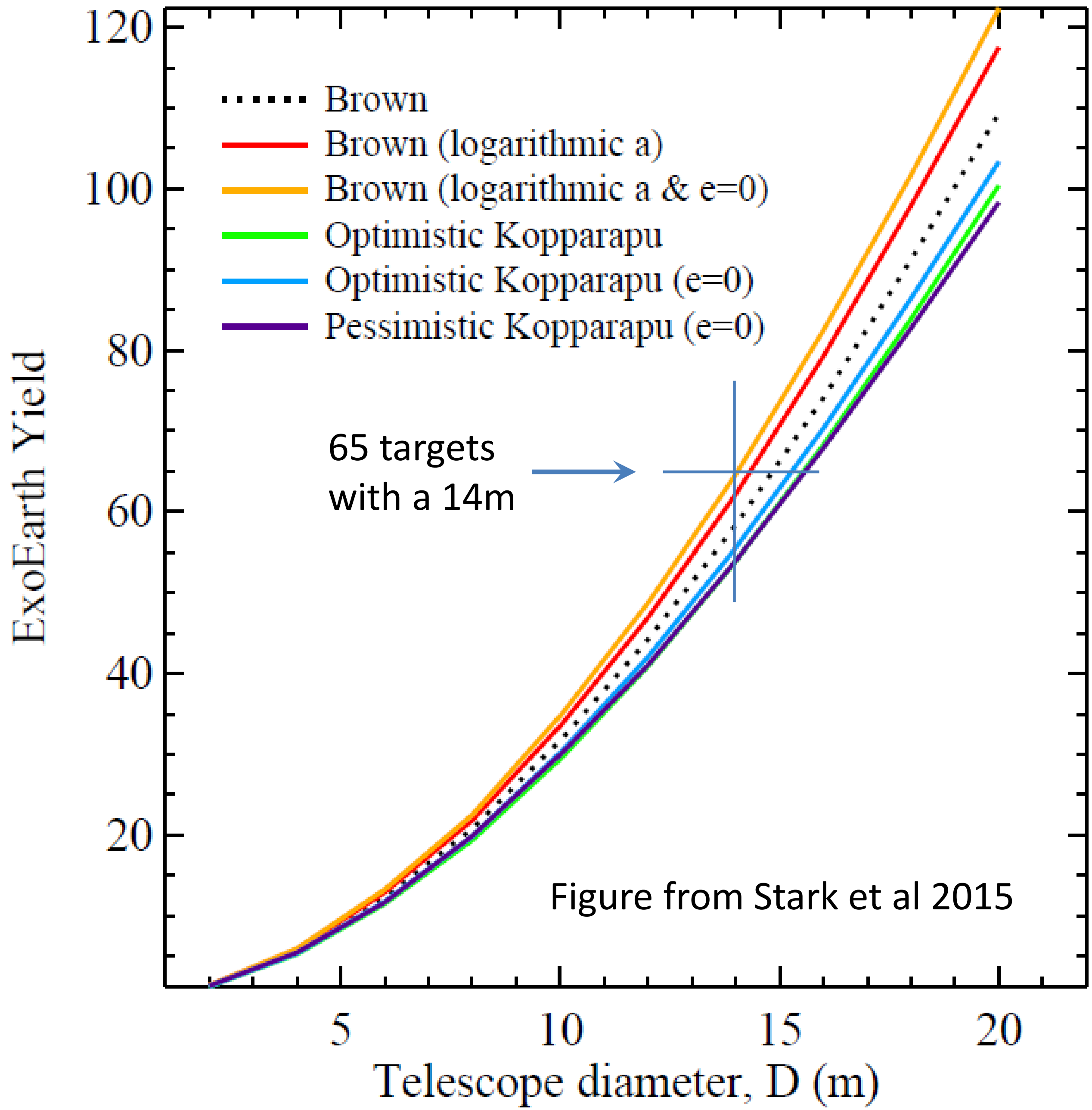
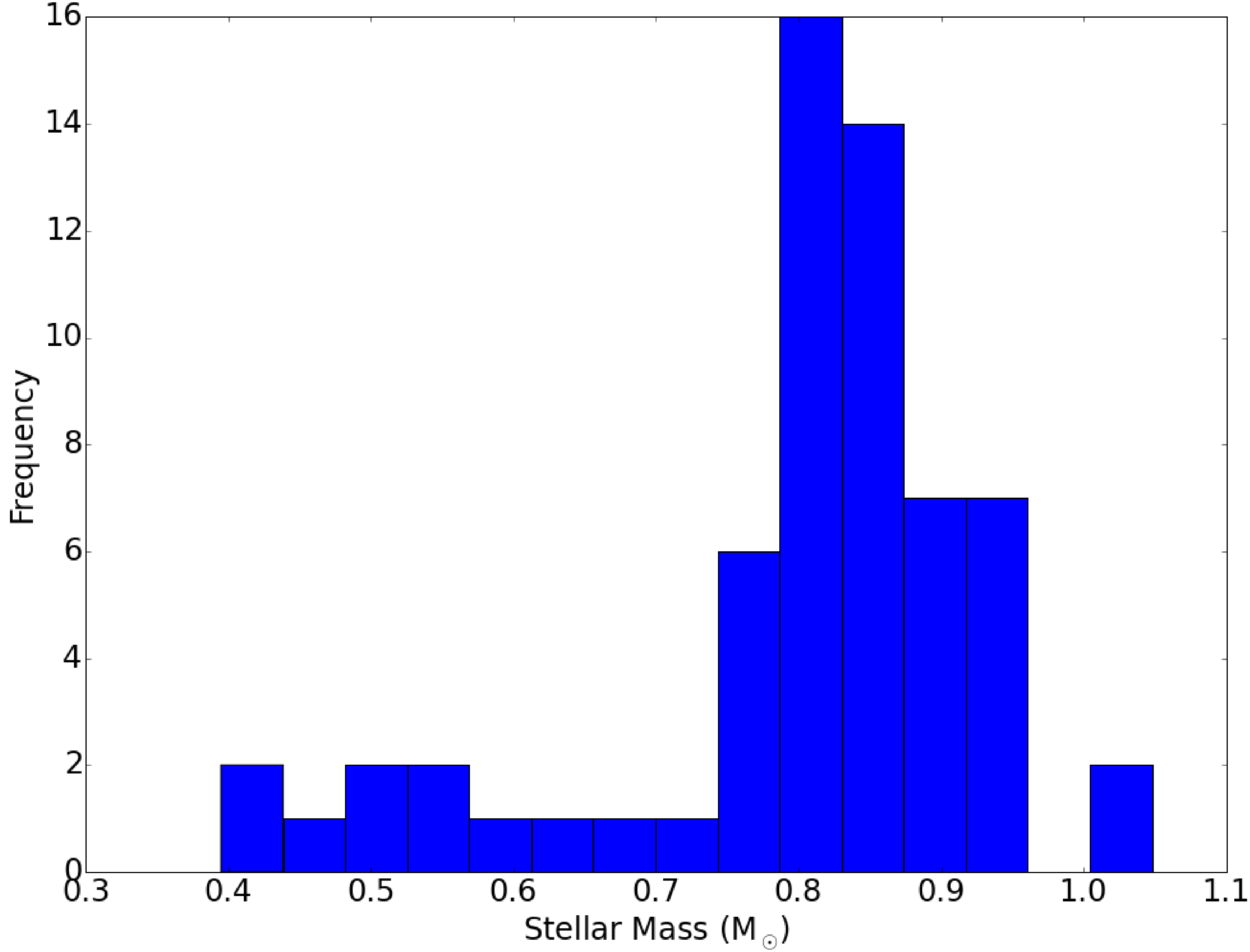


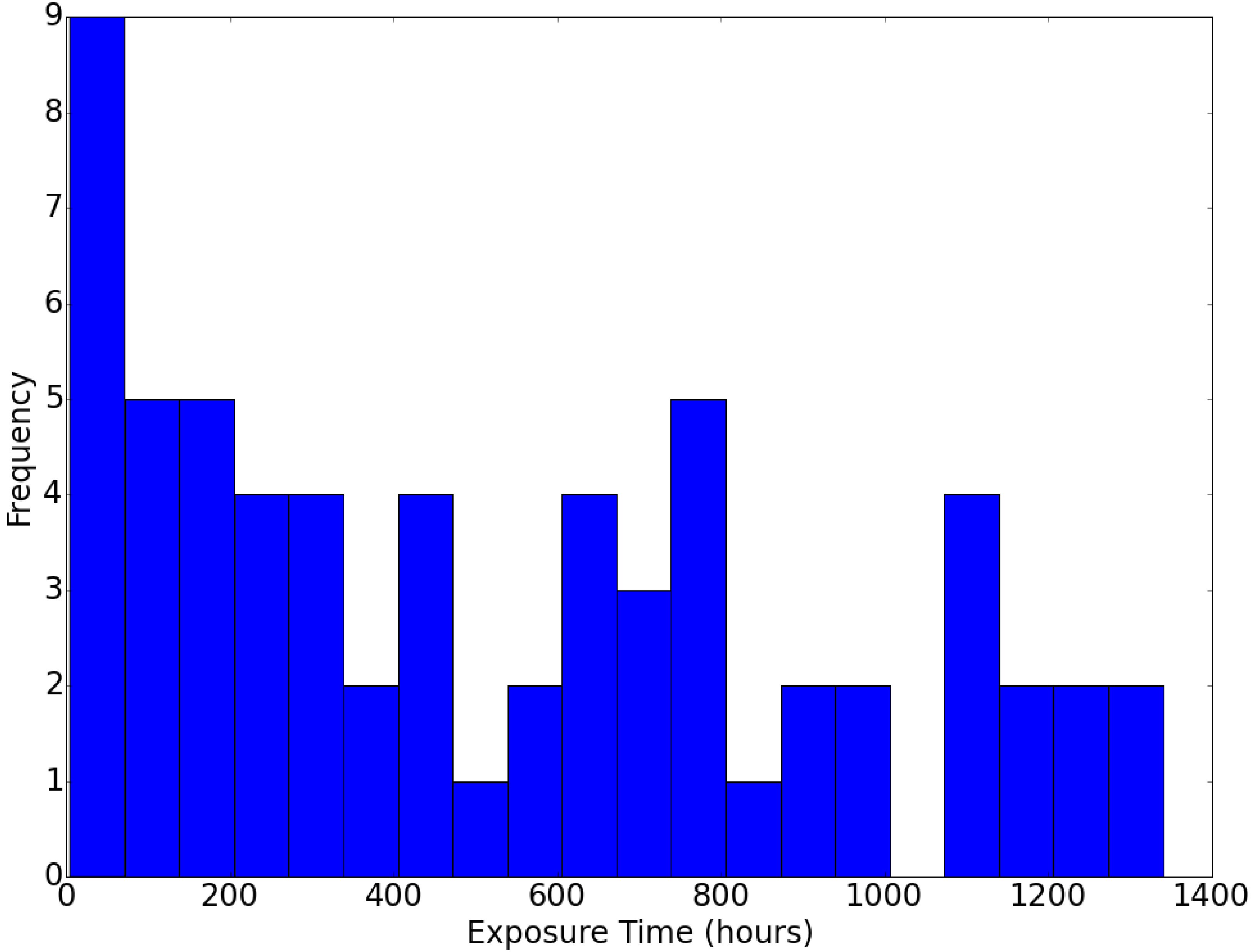
Figure from Lawson 2012 (JPL Document D-77698)

Comparison with other yield estimators.

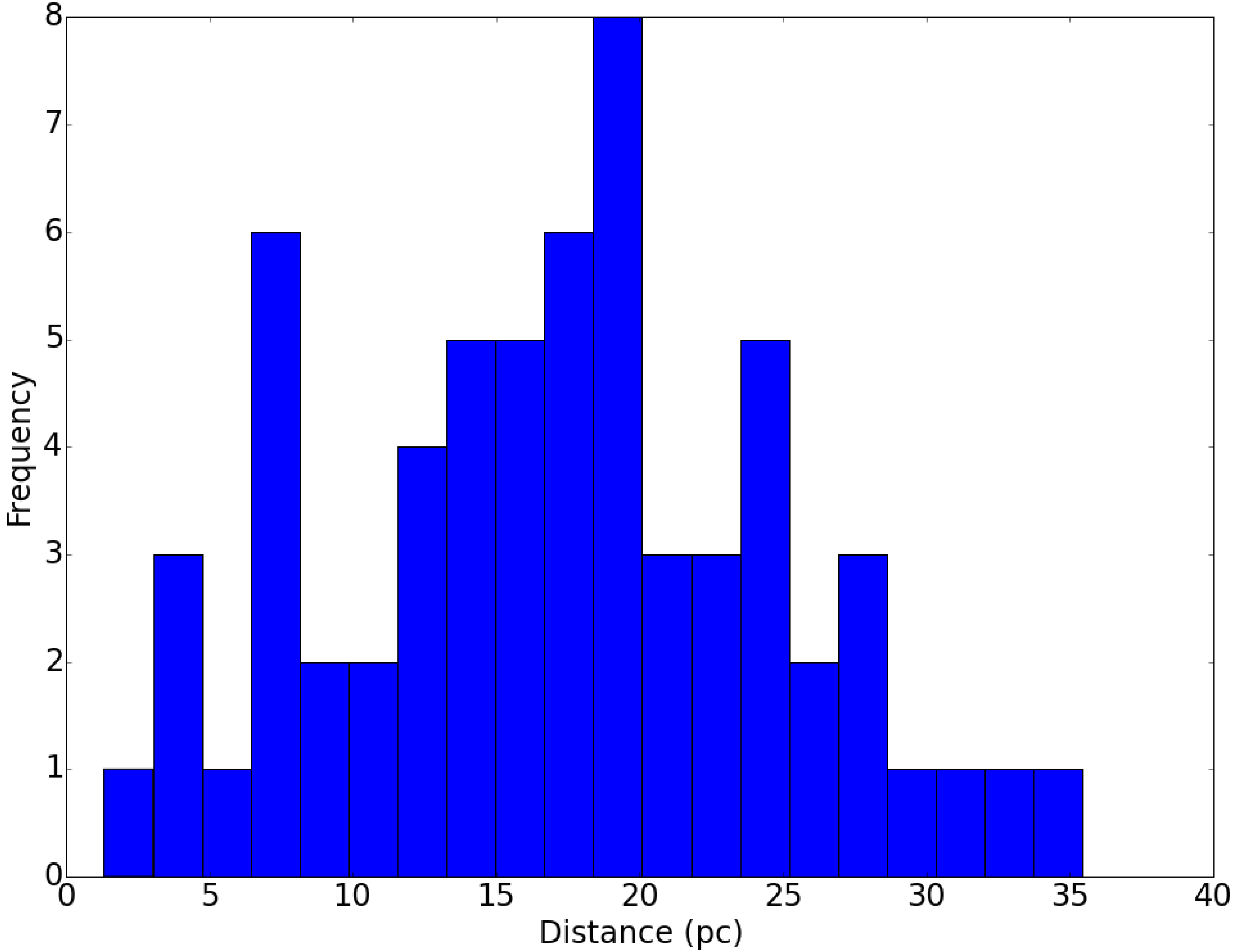




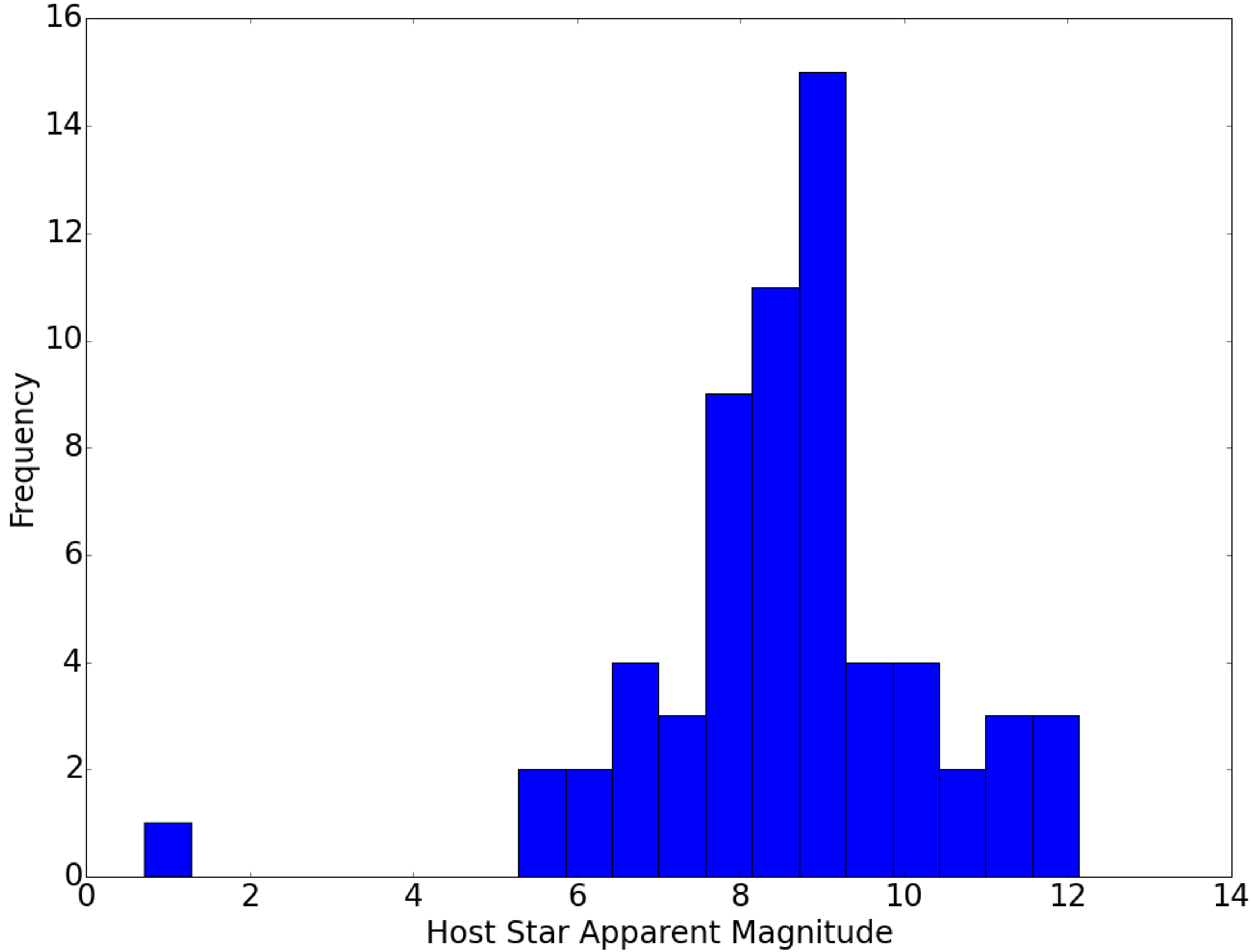
16
14
12
10
8
6
4
2
0
Frequency
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
Stellar Mass ($M_\odot$)



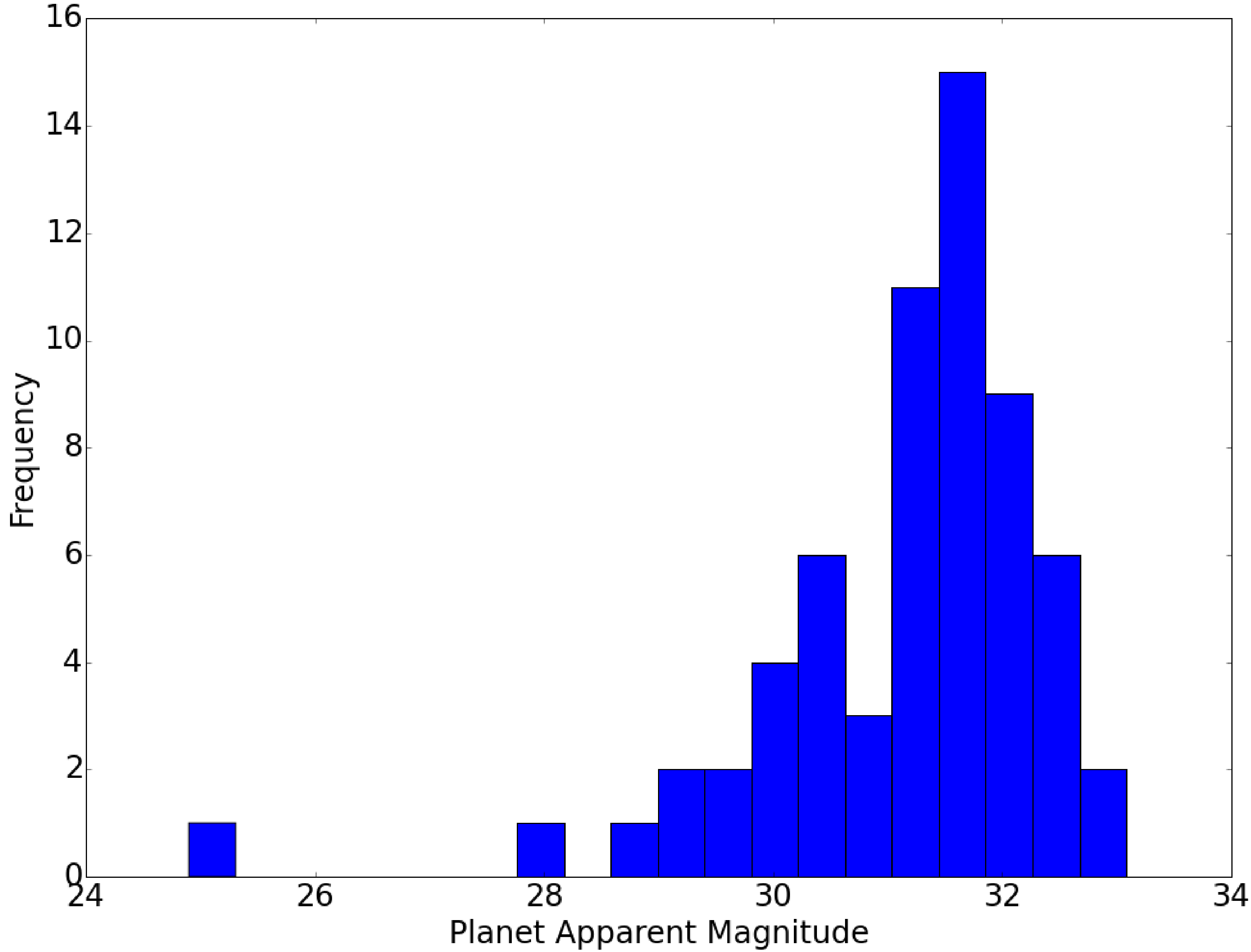
Frequency
Exposure Time (hours)
0
1
2
3
4
5
6
7
8
9
0
200
400
600
800
1000
1200
1400



Frequency
Distance (pc)
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
40



16
14
12
10
8
6
4
2
0
Frequency
0
2
4
6
8
10
12
14
Host Star Apparent Magnitude



16
14
12
10
8
6
4
2
0
Frequency
24
26
28
30
32
34
Planet Apparent Magnitude

Conclusions

- Telescope mirror aspect ratio doesn't have to be unity.
- The O_2 A-band spectrum for ~65 Earth-sized HZ exoplanets could be observed with S/N=5 in ~5 years with a 14m×4m telescope.
- Such a telescope could possibly be launched on an Ariane V (or similar).
- The successor to JWST will be a flag-ship observatory serving the whole astronomical community and not a survey instrument. We should therefore seriously consider a separate dedicated mission to survey exo-Earths for bio-signatures.
- Maybe we don't have to wait until 2040 to robustly search for life?!