Phase-Induced Amplitude Apodization Complex Mask Coronagraphy (PIAACMC) for Large Segmented Apertures

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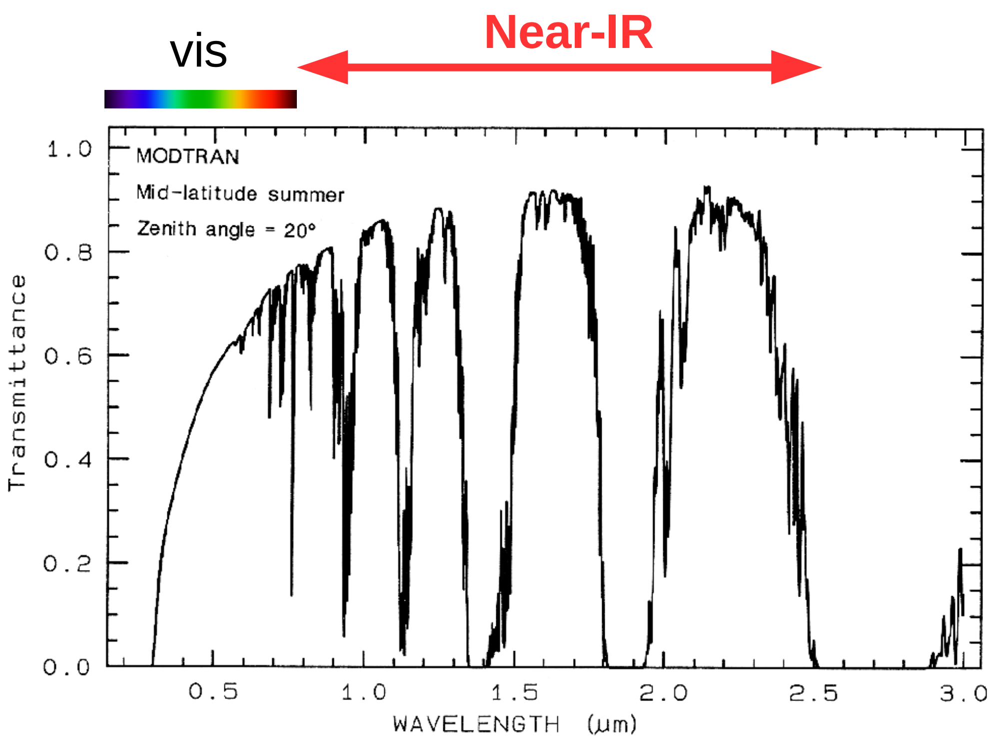
Scientific Motivation for small IWA

Spectroscopic characterization
Near-IR (~ 0.7 - 2.5 um) is the most valuable spectral range for atmospheric characterization of habitable planets

Planet diversity
Small IWA enables access to HZs of cooler stars (smaller HZ)

Yield
Small IWA = large number of targets



Earth atmosphere transmittance illustrates value of near-IR

Our Approach: PIAACMC … without PIAA

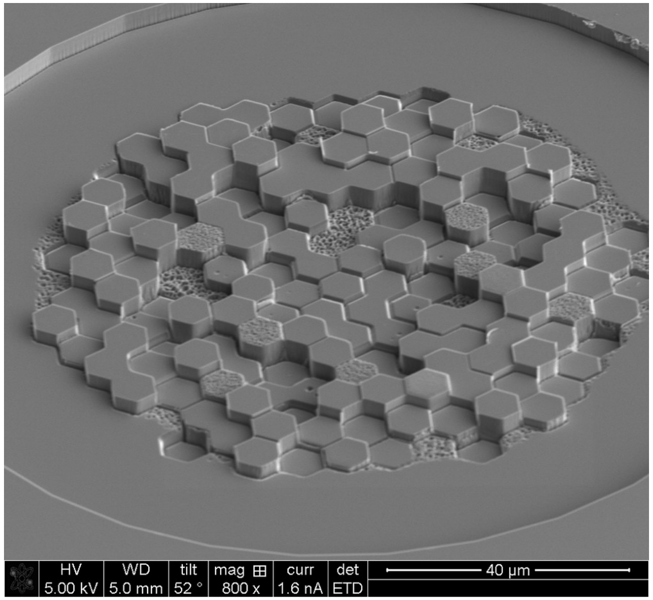
We adopted APLCMC (= PIAACMC without PIAA) for convenience
Pupil amplitude apodizer → Focal plane mask → Lyot stop

Apodization loss→ Low throughput (~30%), **Some loss in IWA**, **Larger PSF core**
(FUTURE designs will use PIAA → ~2-3x gain in efficiency expected)

Easier to design, faster numerical simulation → rapid exploration of design optimization & trades (<u>THIS presentation</u>)

Design process:
(1) Design ideal monochromatic APLCMC: complete supression of on-axis light in monochromatic light, small IWA
(2) Replace ideal focal plane mask with multi-zone mask. Optimize zones for broadband light and stellar angular size.

<u>**For both APLCMC and PIAACMC, the multi-zone focal plane mask is the most critical element (Can it be manufactured ?)**</u>

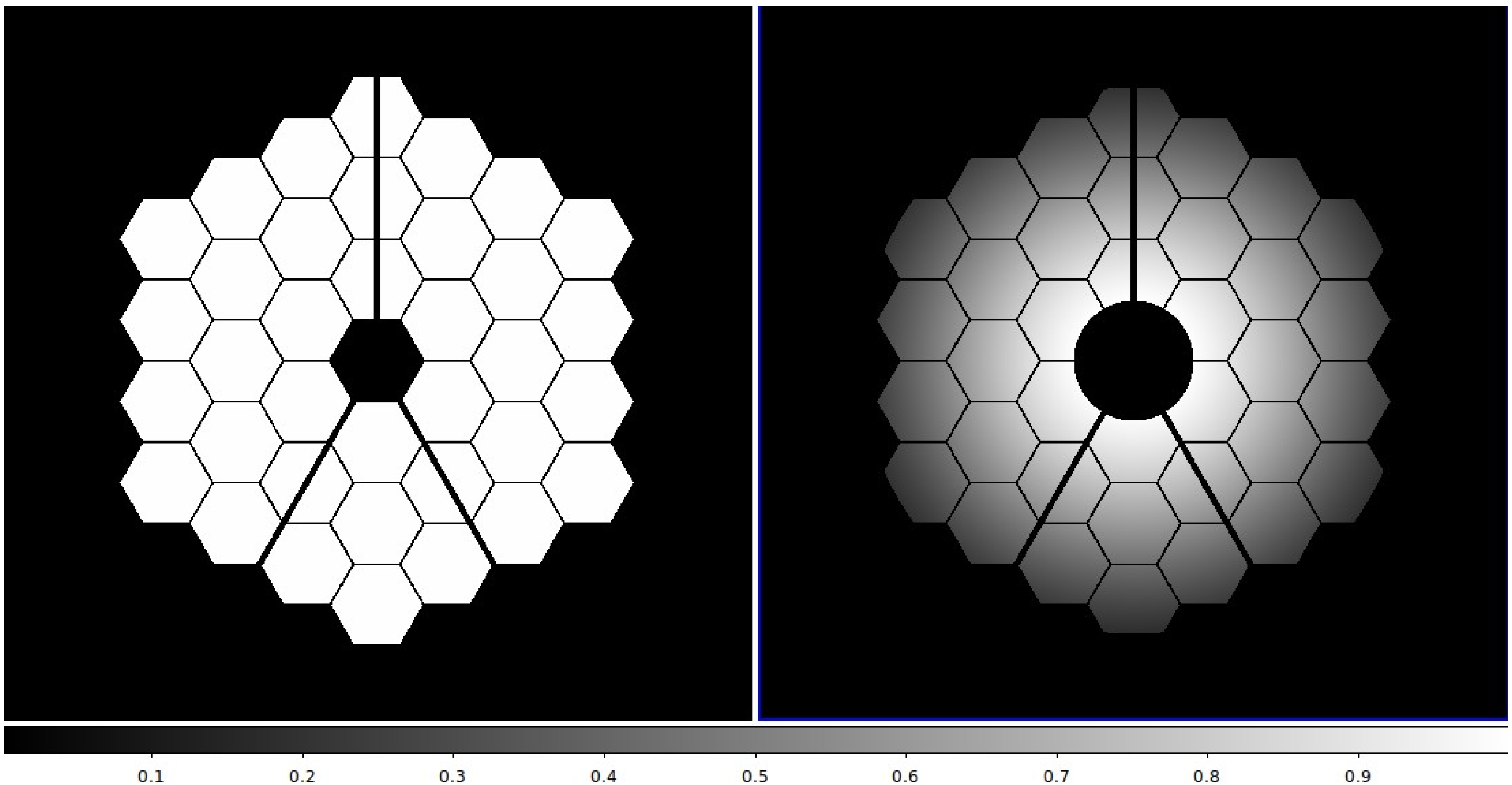


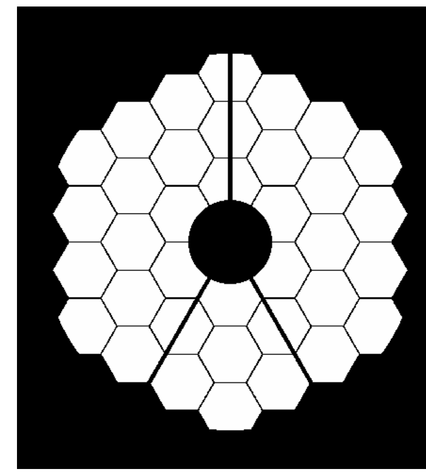
Multi-zone focal plane mask. Each zone imprints an optical pathlength delay. Mutual interference between zones creates deep achromatic null. (credit: NAOJ/CNF)

Baseline APLCMC design

Apodization throughput = 34.13%
(Note: few % could be regained by removing circular constraint on inner and outer edges)

Outer edge intensity transmission = 4%



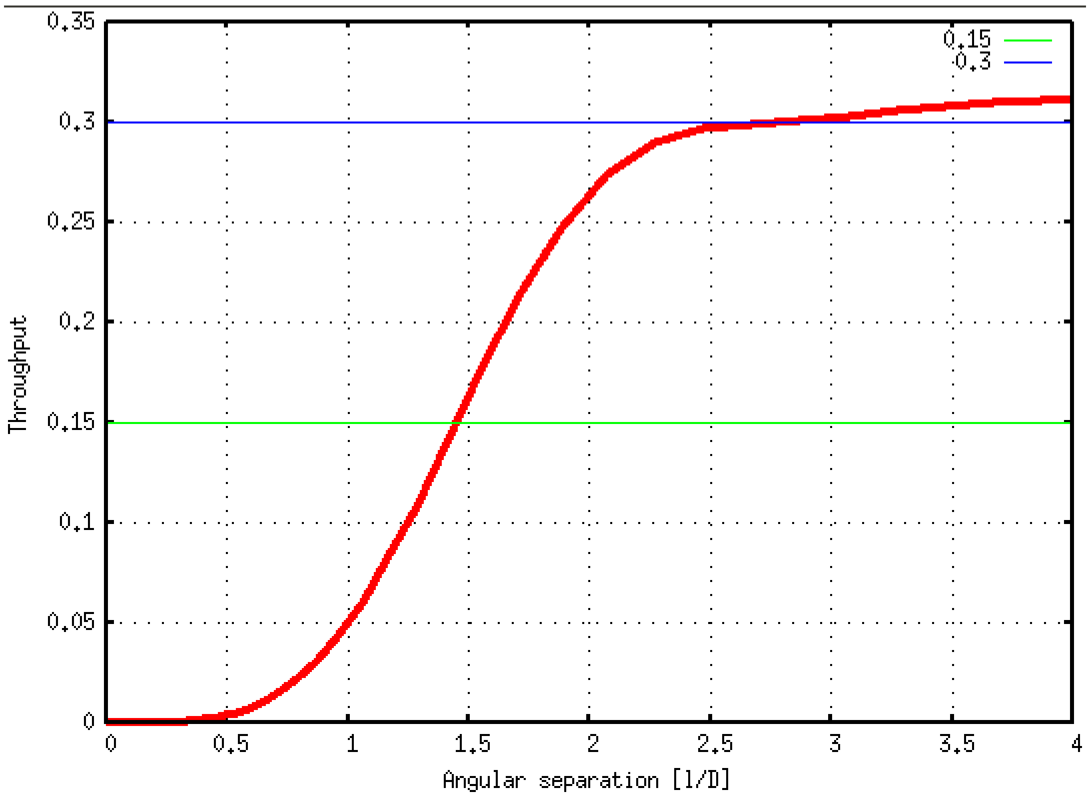


Lyot stop directs nearly ALL starlight to LOWFS

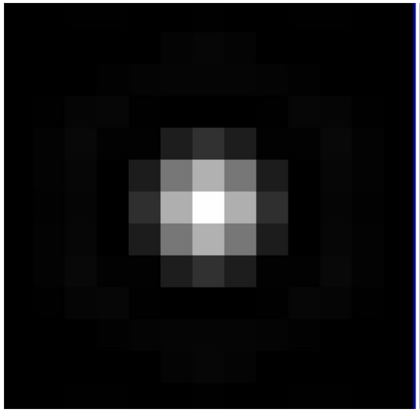
Focal plane mask has 1237 zones over a 3 l/D radius at central wavelength

Throughput & PSF quality

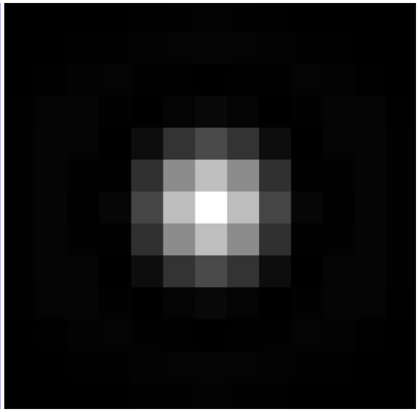
30% throughput at 2.5 l/D
15% throughput at **1.45 l/D = IWA**



Clean PSF outside ~2 l/D, but ~11% wider than unapodized PSF



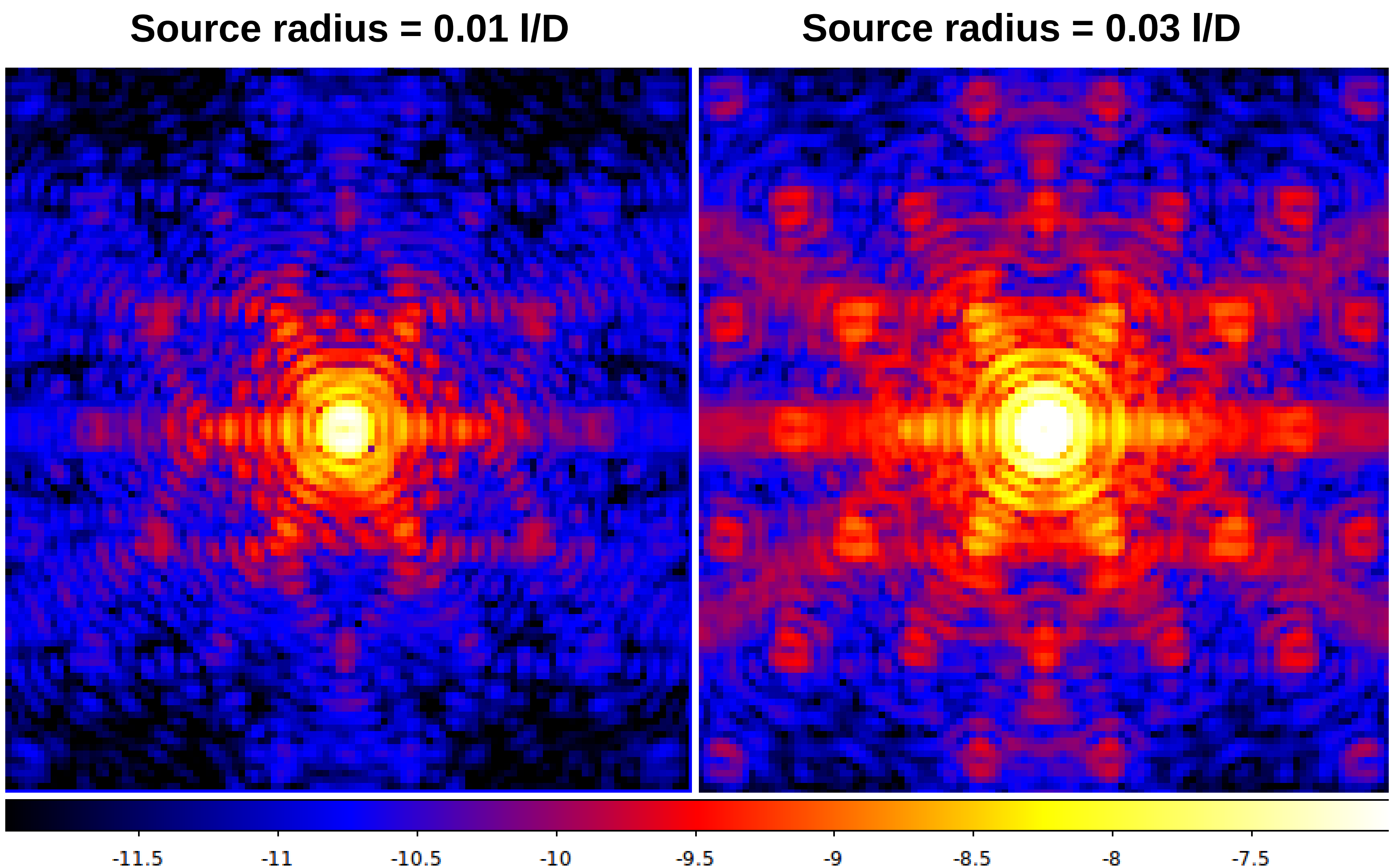
PSF for unapodized pupil (linear scale)



PSF for apodized pupil (linear scale)

PSF is dominated by stellar angular size

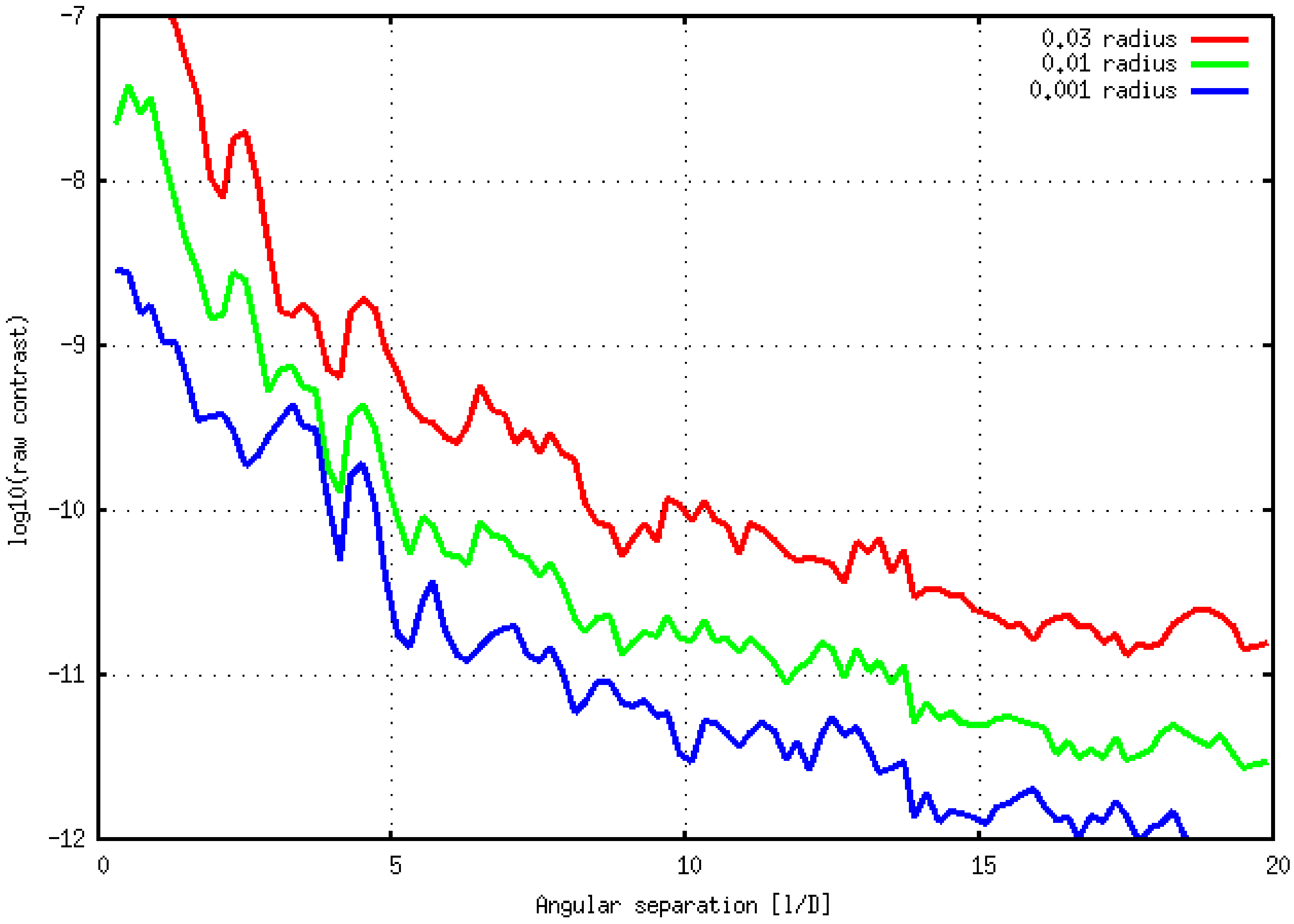
PSF dominated by incoherent spots due to stellar angular size →contributes to photon noise, but does not interfere coherently with wavefront errors → can be removed in post-processing
Instead of radial average contrast, we use 50-percentile (search) and 20-percentile (spectroscopy) radial contrasts for performance evaluation: we avoid the bright spots



568 nm shown
10% bandwidth optimized

APLCMC design – Raw Contrast

(20 percentile along each radius)



How does pupil geometry affect performance ?

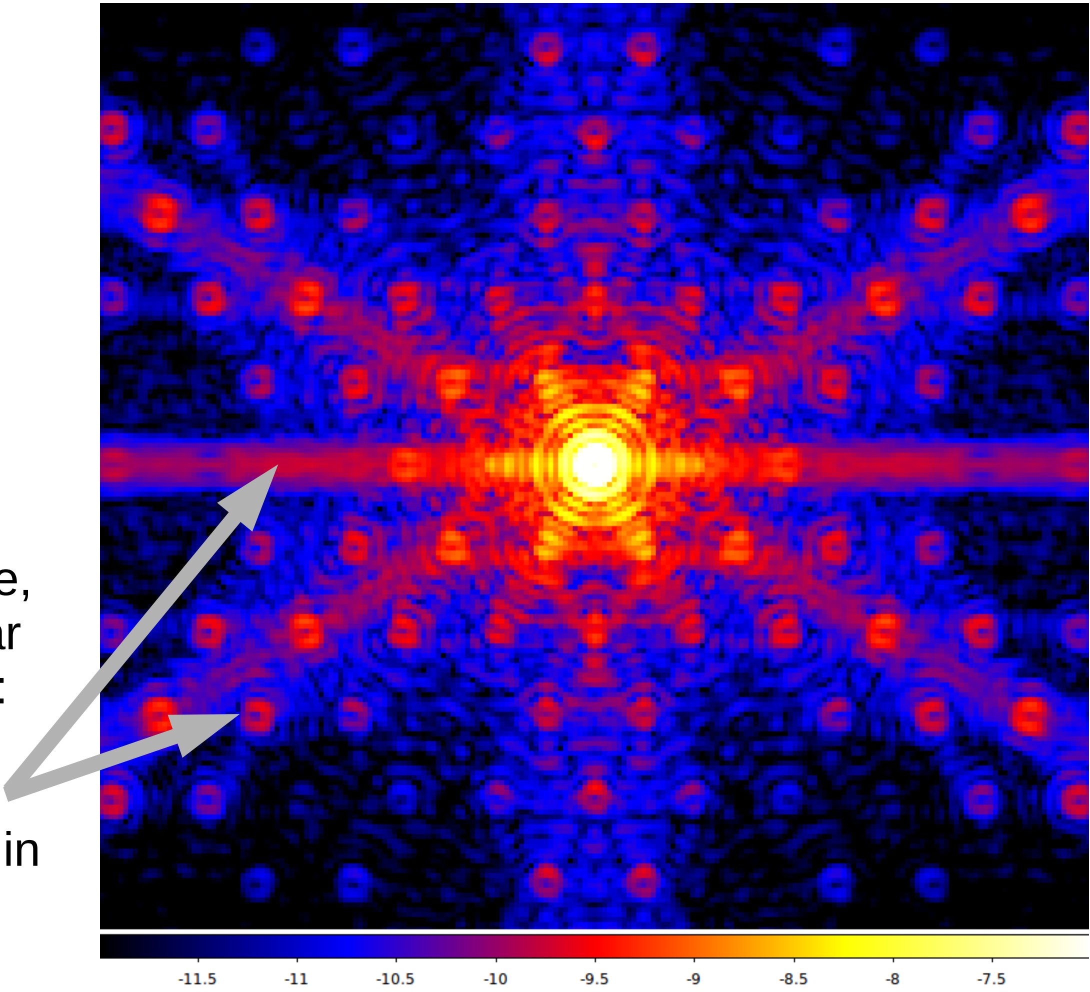
In theory…

APLCMC and PIAACMC do not care about pupil geometry. Performance should be the same for segmented and non-segmented apertures.

We find that …

This holds true when considering point source, but there is a coupling between stellar angular size and segment/spiders diffraction features:

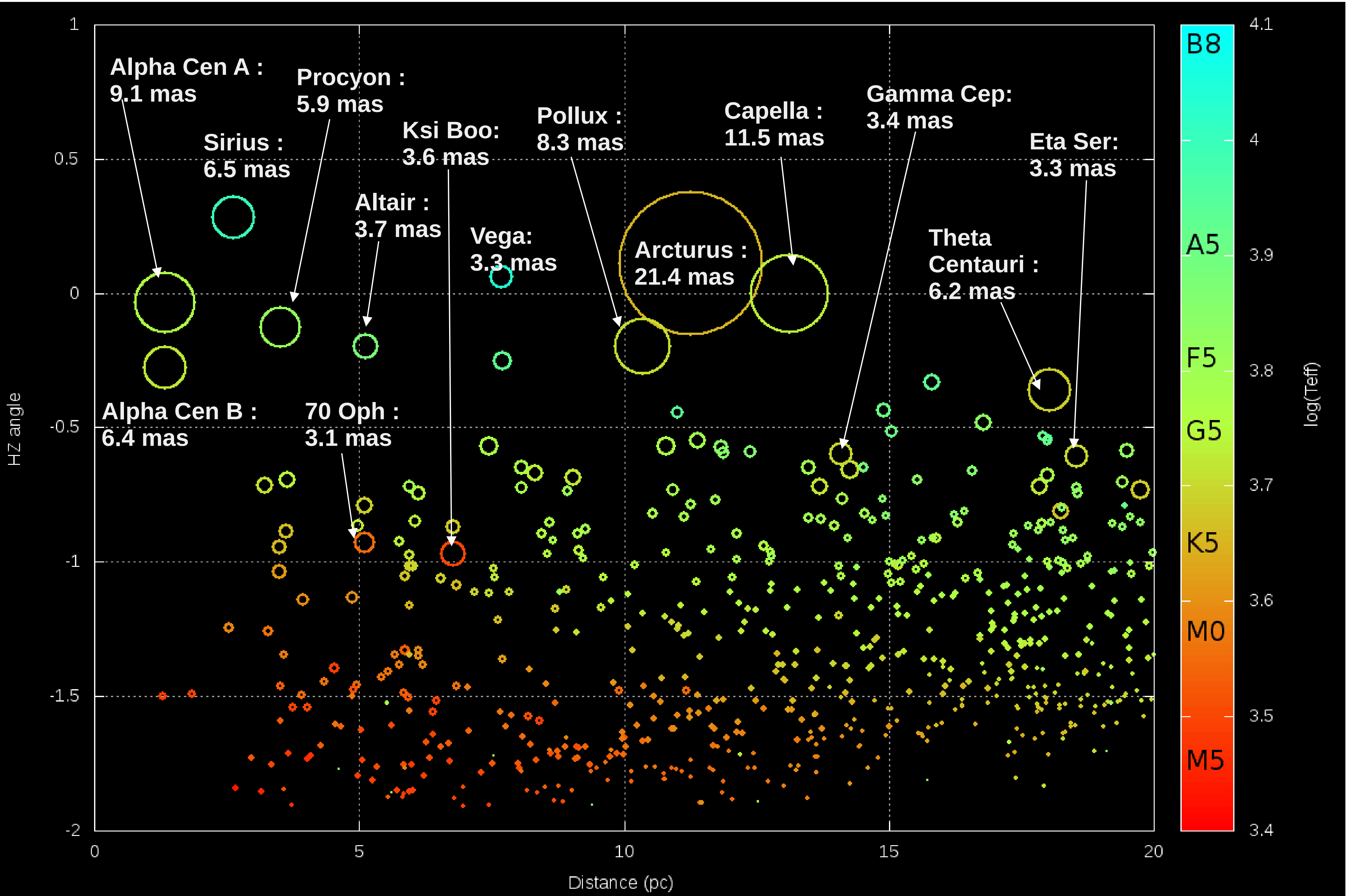
Partially resolved star + segmented aperture → incoherent bright “spots” and lines appear in PSF



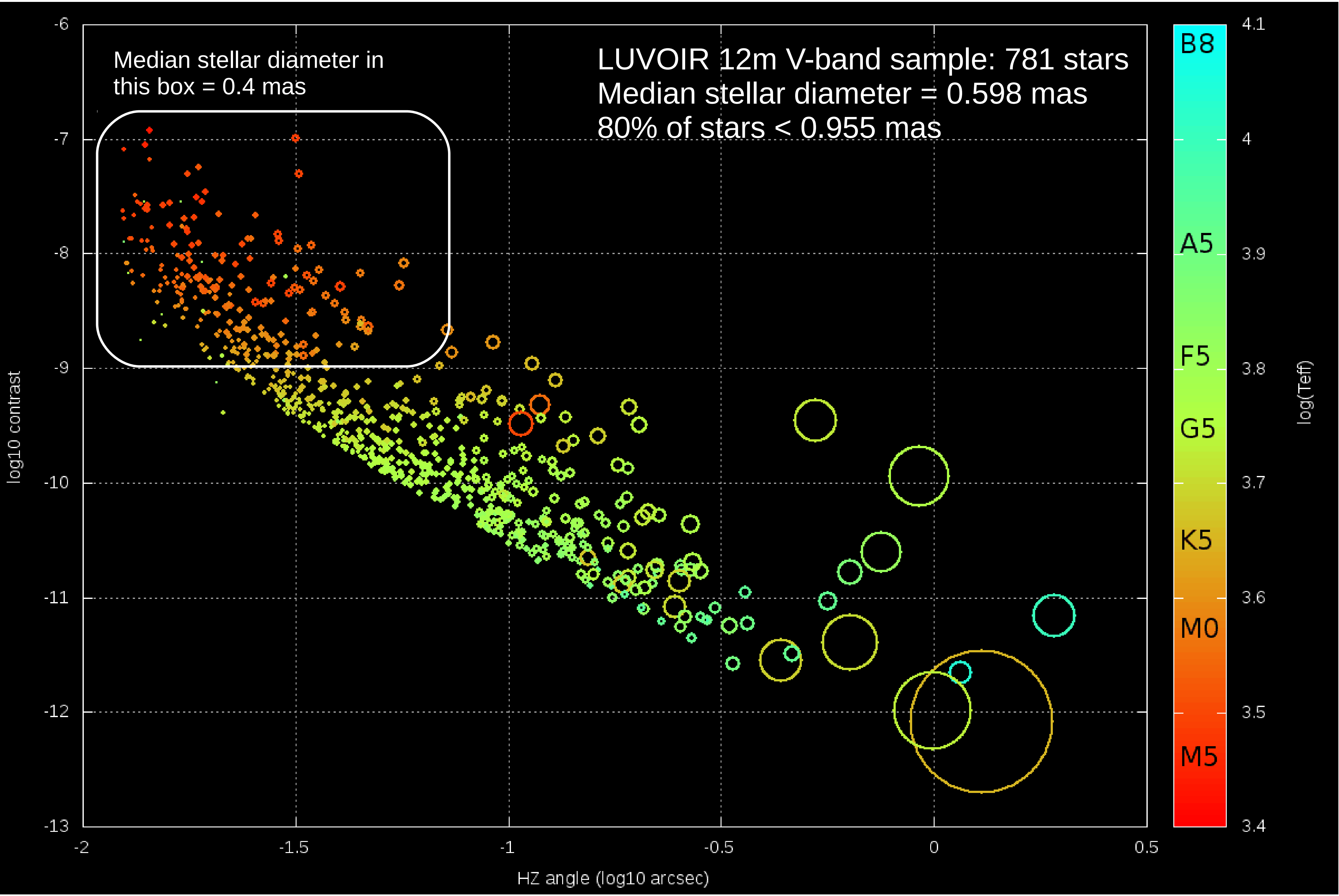
Stellar Angular Size Study

What is the impact of stellar angular size on planet characterization ?

Stellar angular sizes strongly correlate with HZ angle



… and contrast



Spectroscopic Characterization

Assumptions (see APLCMC design details):

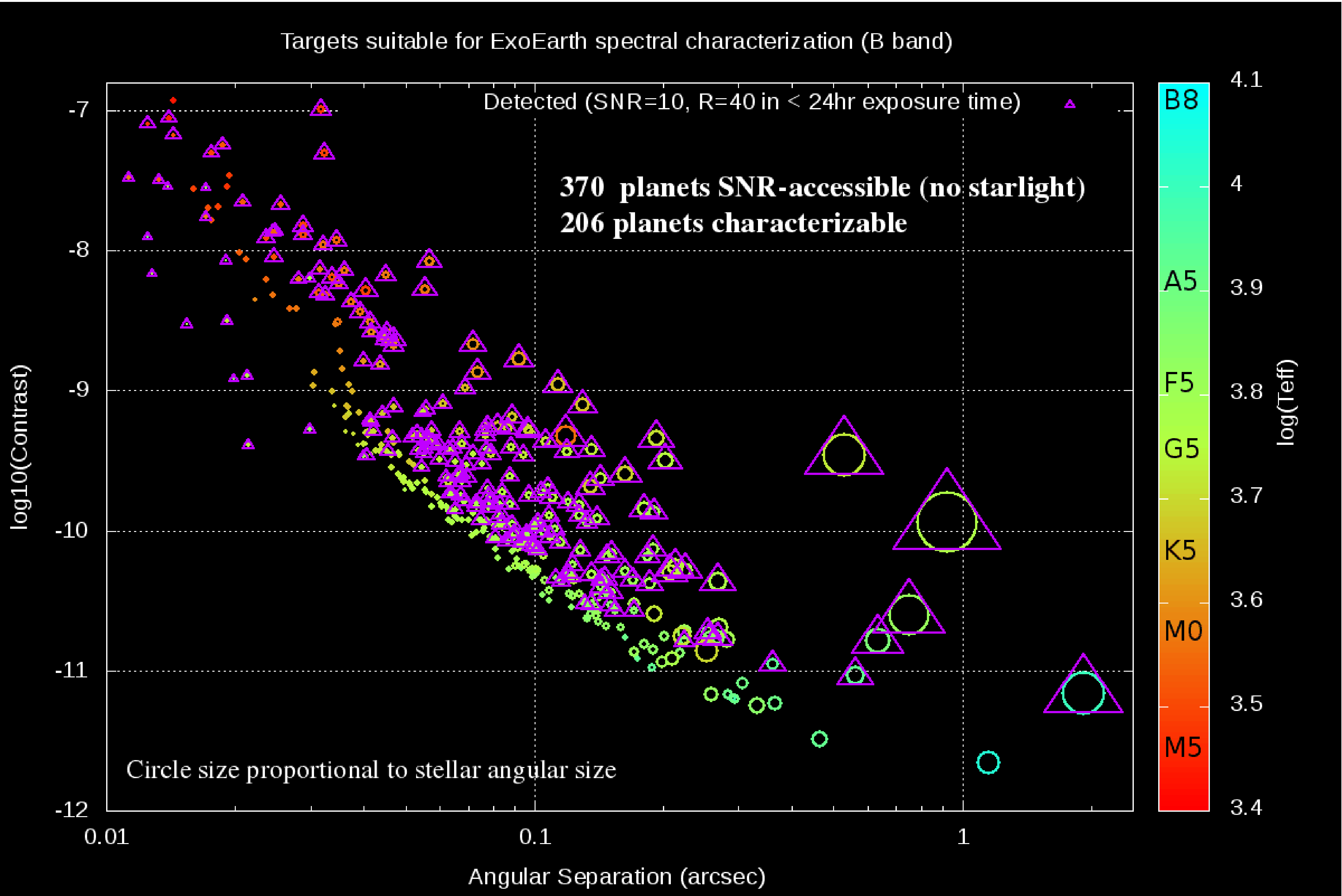
- 12m aperture, 50% efficiency, 30% Airy througput, FWHM=1.11 l/D, IWA=1.45 l/D
- Exozodi has same dust density as local zodi. 3x brighter (incl + double pass). Color effects are taken into account.

Following slides quantify planet yield for spectroscopic characterization.

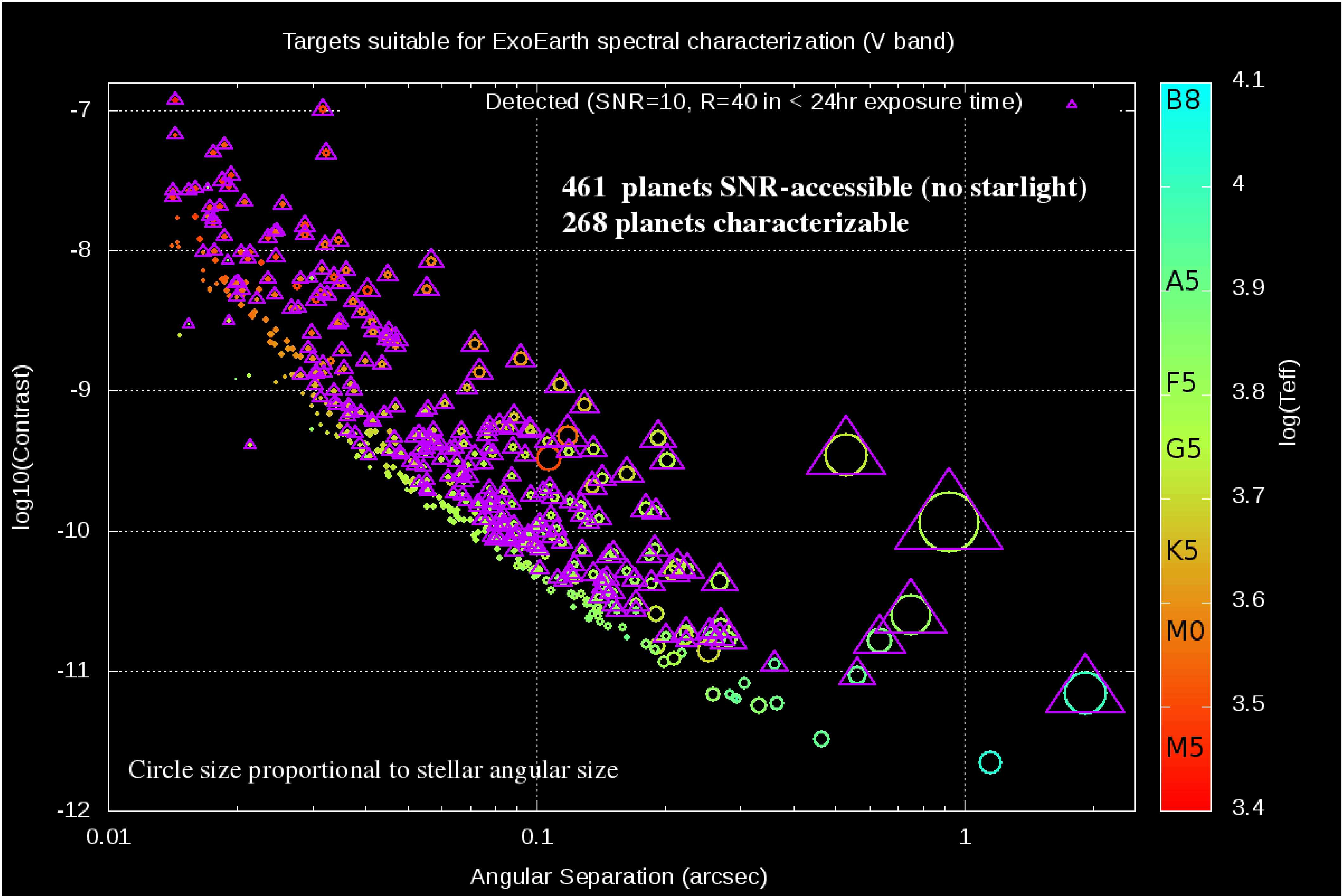
We assume 1 Earth-like planet around each star, and count:
- **# of SNR-accessible targets**: stars around which an Earth analog is bright enough to be characterized assuming ALL starlight is removed (perfect coronagraph)
- **# of characterizable targets**: Takes into account coronagraph contrast, due to combination of stellar angular size and chromatic effects

Difference between the 2 numbers = targets lost due to coronagraph leak

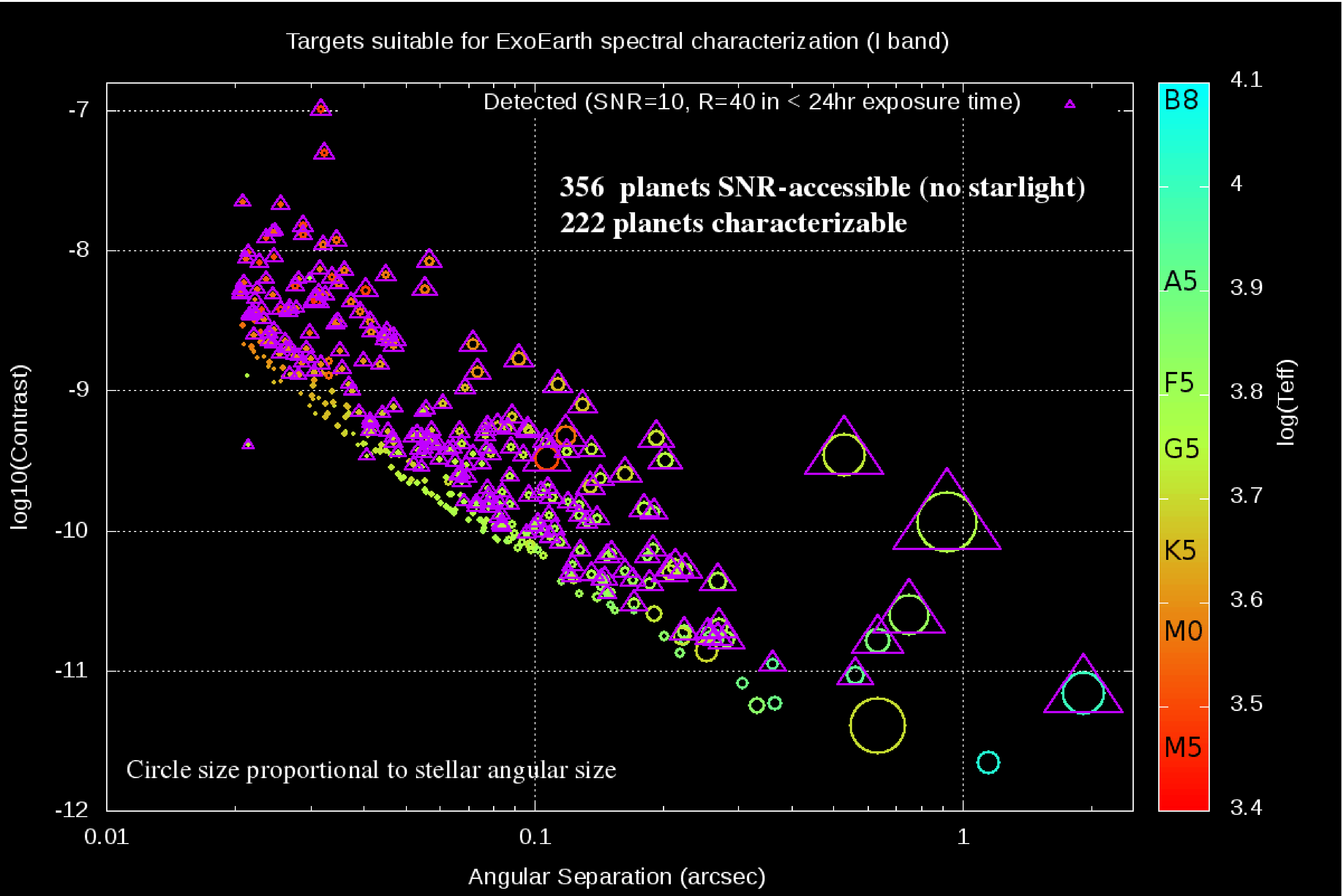
B band ExoEarth spectral characterization (436nm)



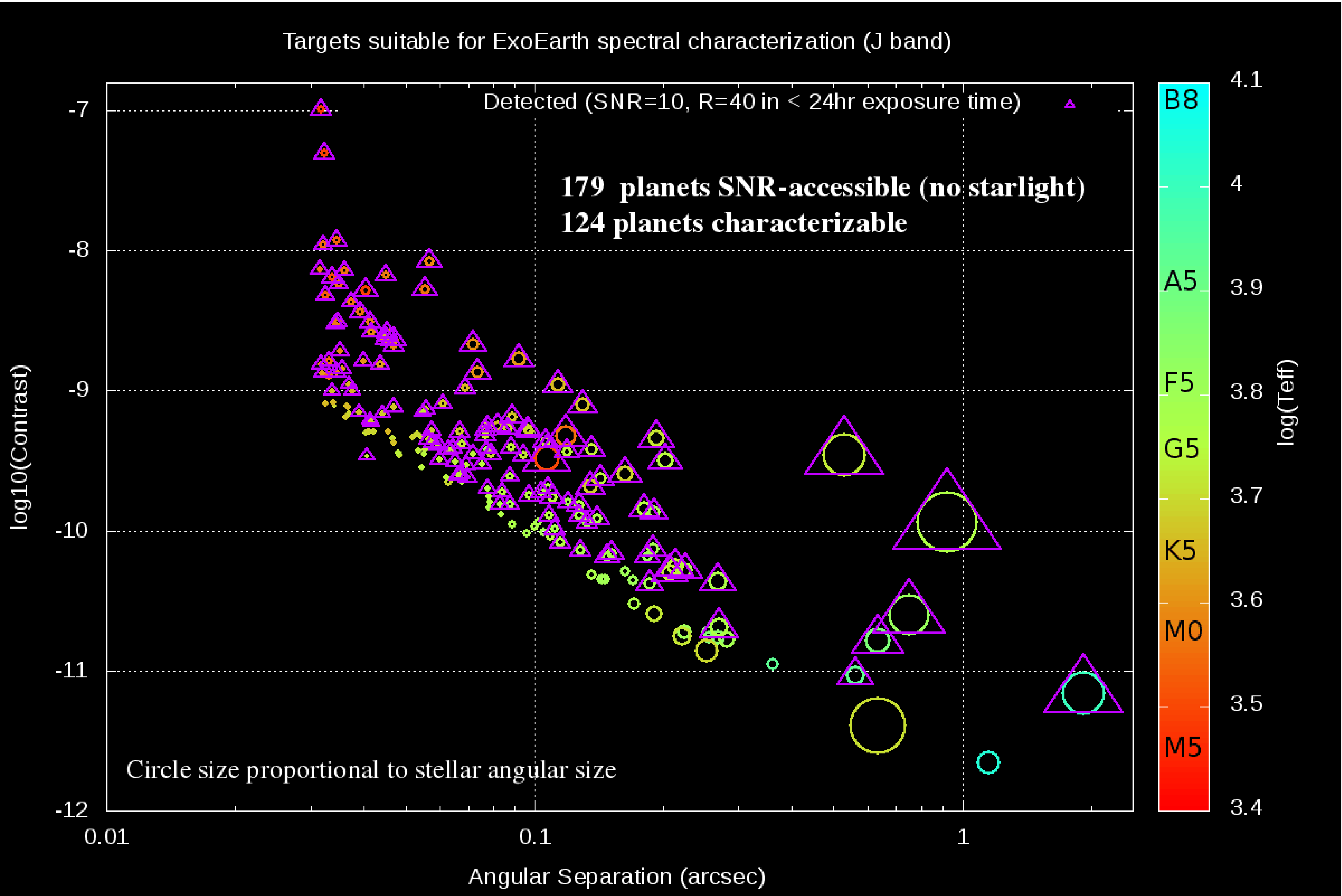
V band ExoEarth spectral characterization (545nm)



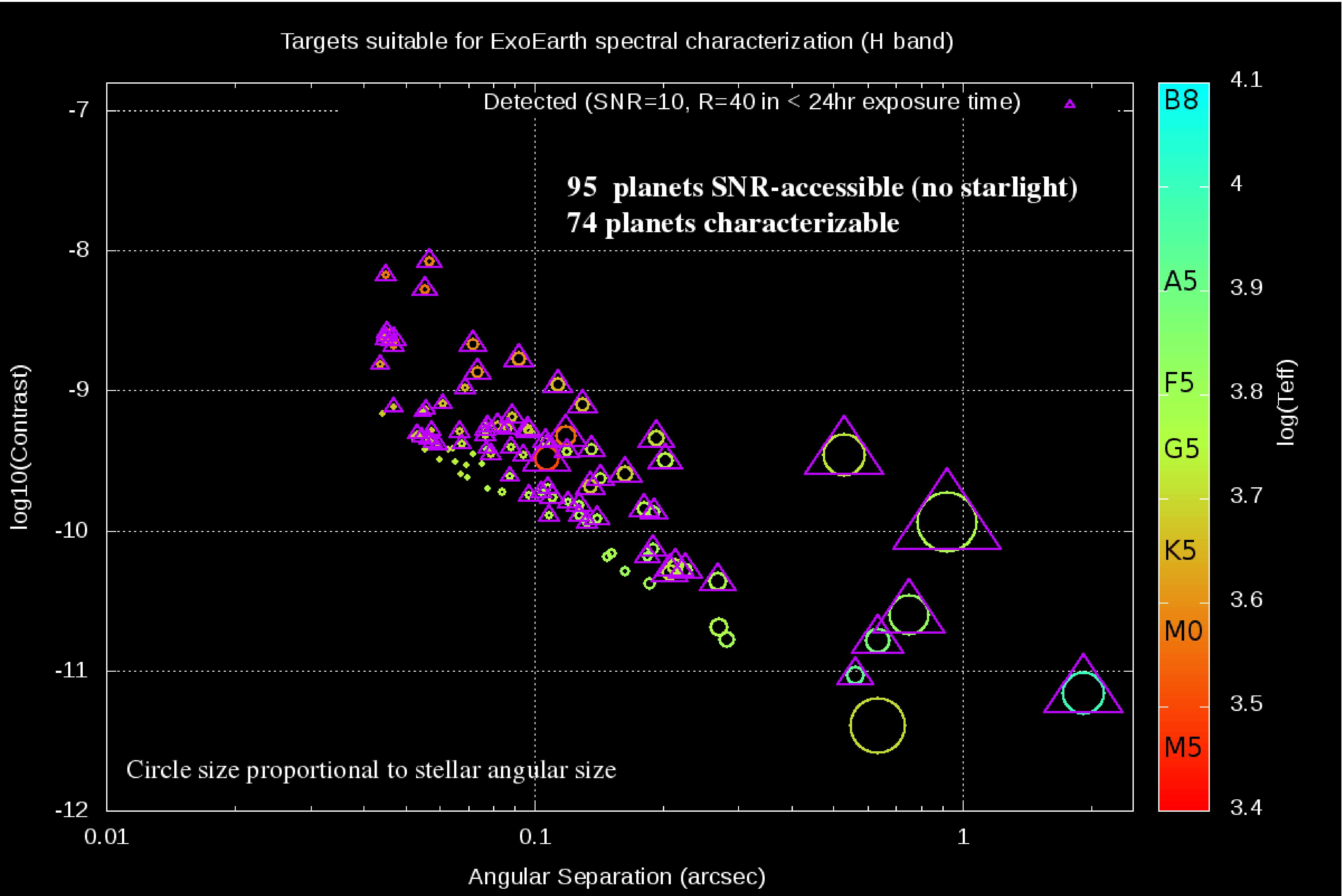
I band ExoEarth spectral characterization (797nm)



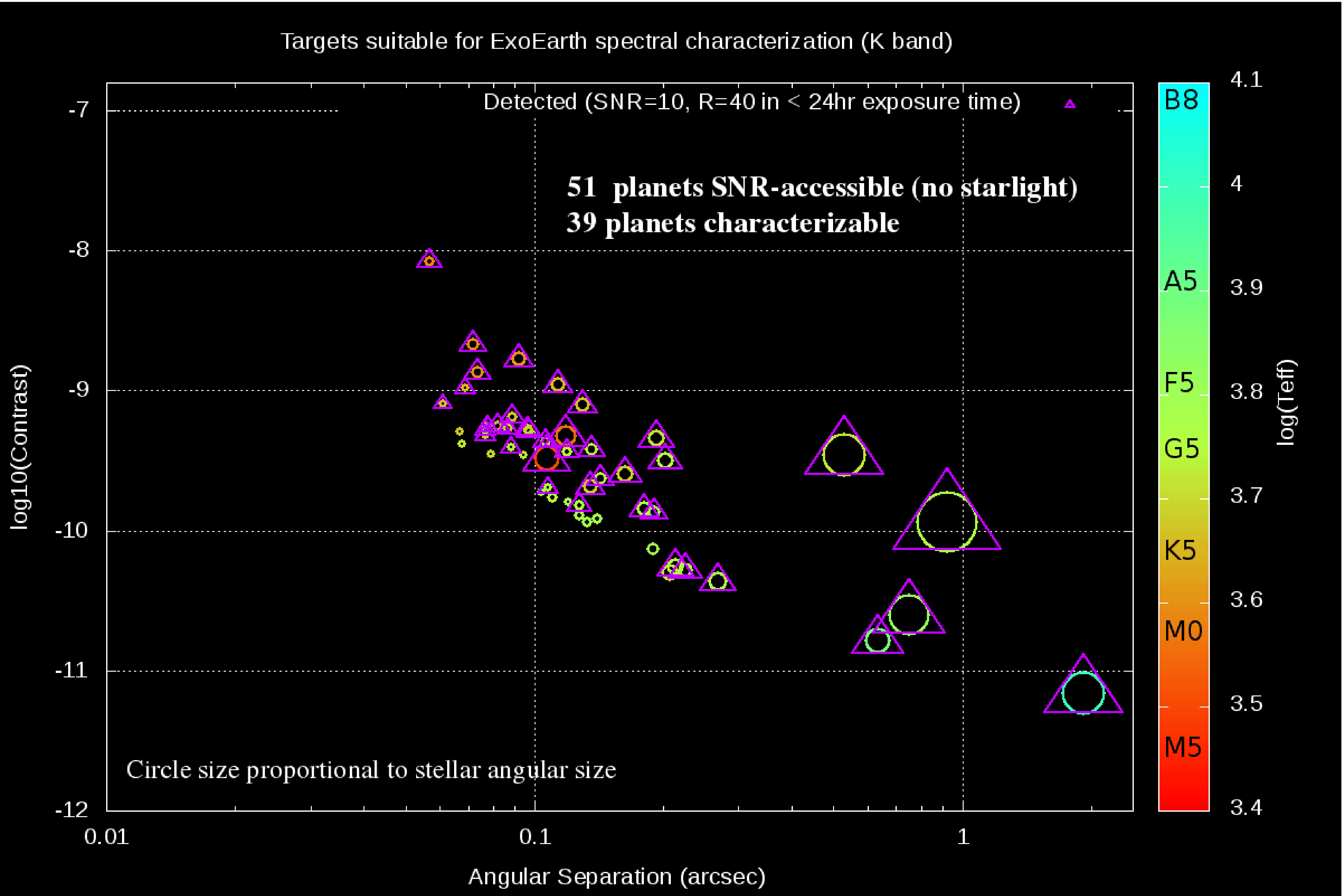
J band ExoEarth spectral characterization (1.22um)



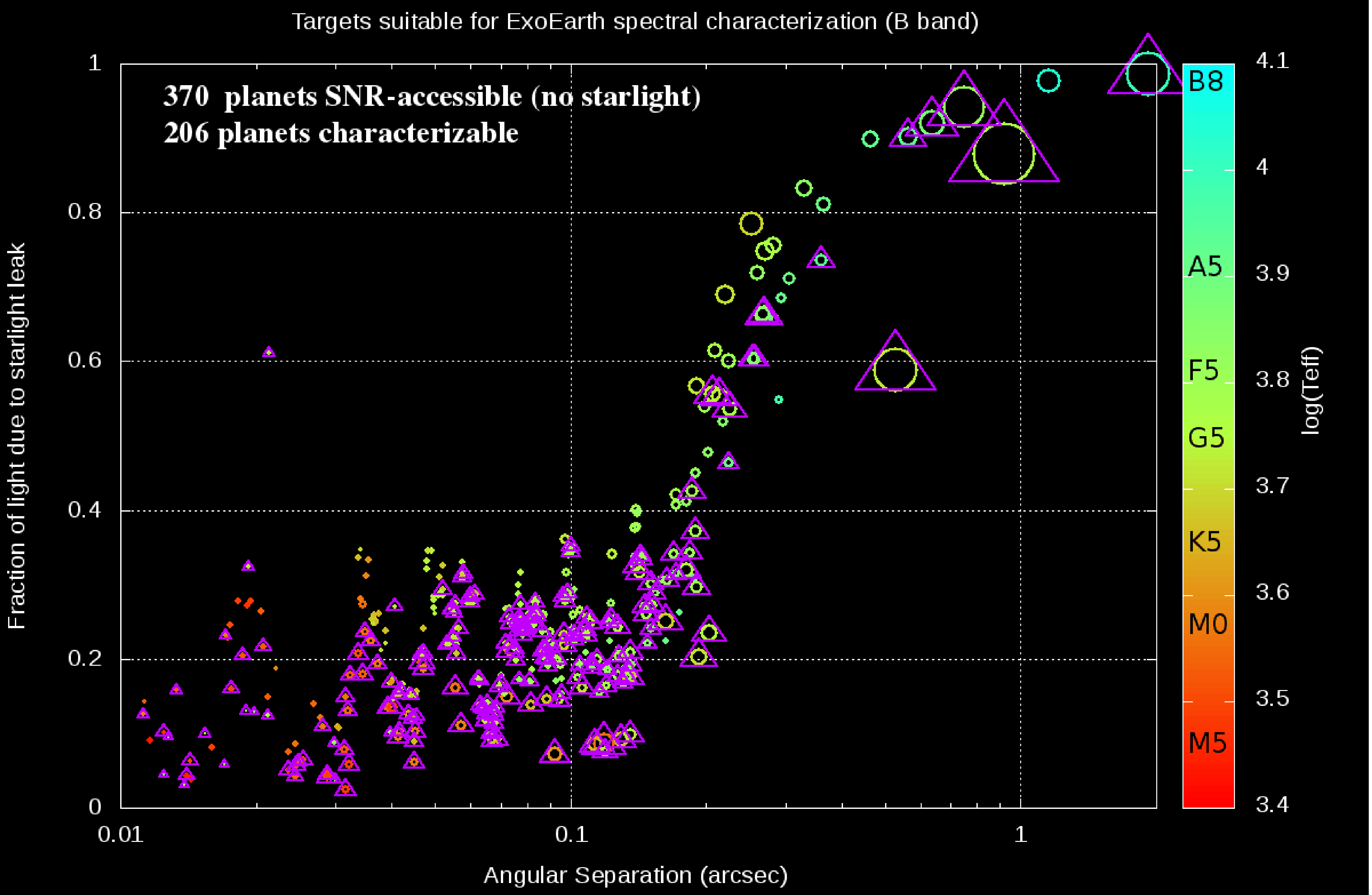
H band ExoEarth spectral characterization (1.63um)



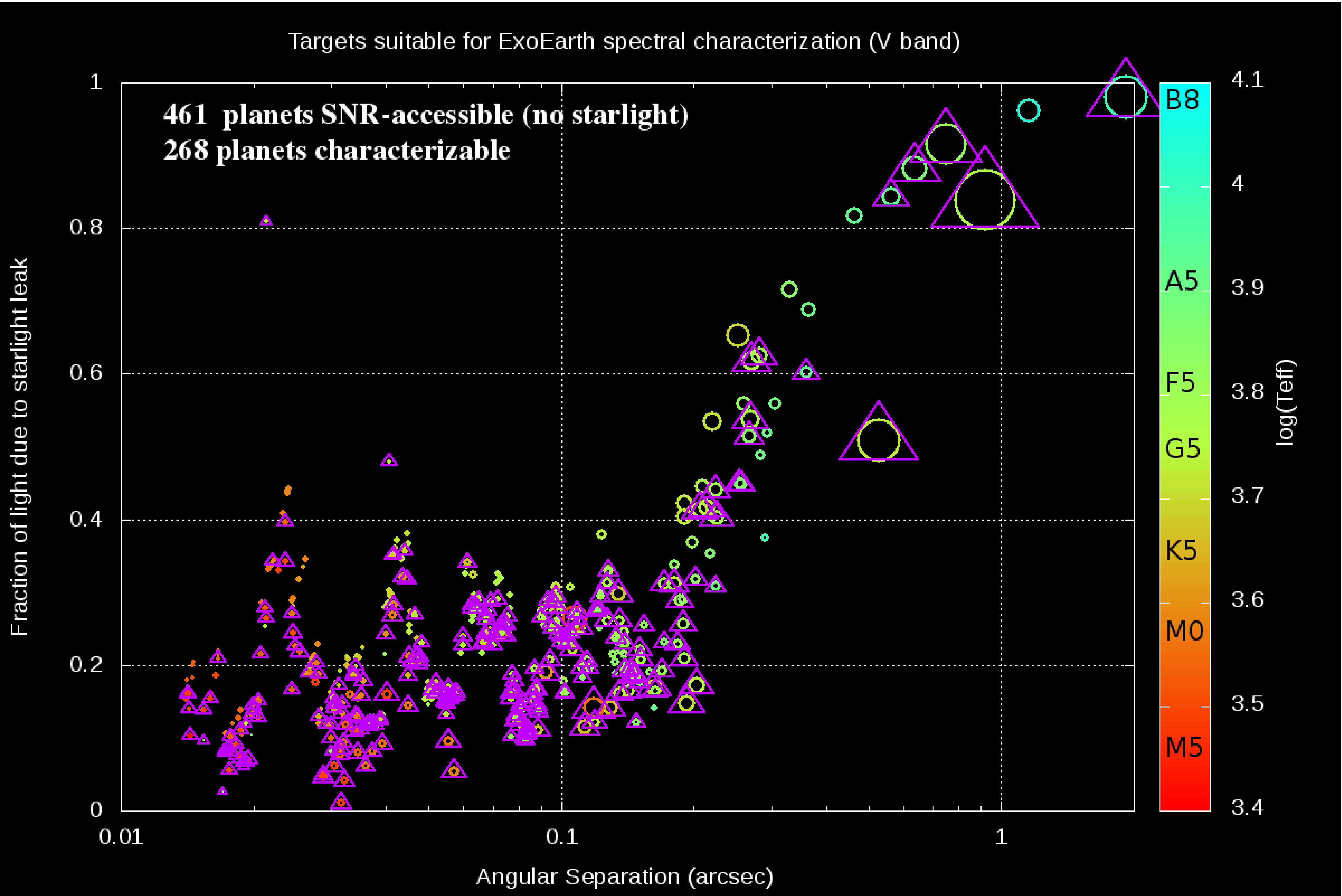
K band ExoEarth spectral characterization (2.19um)



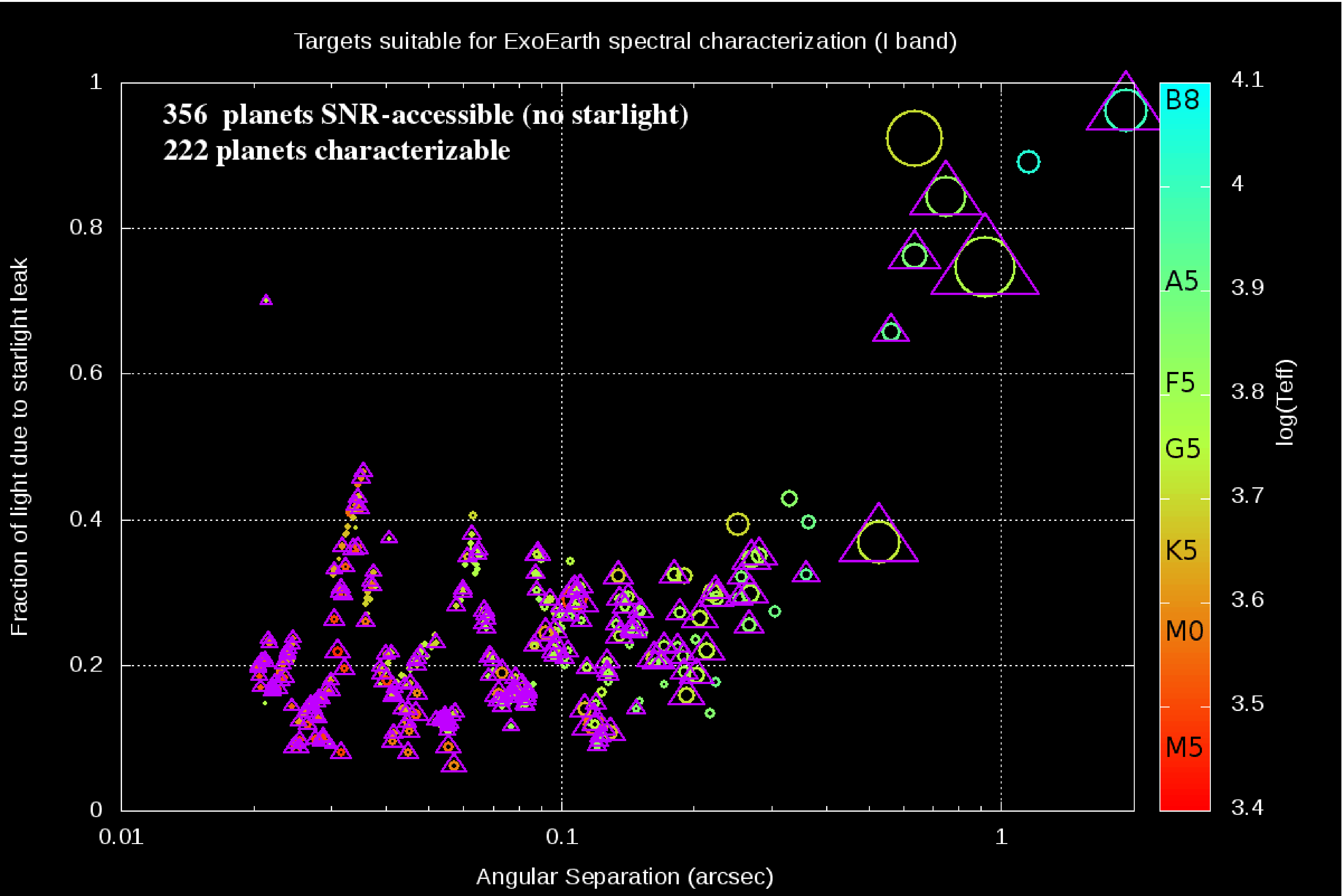
Fraction of light due to coronagraph leak (B band)



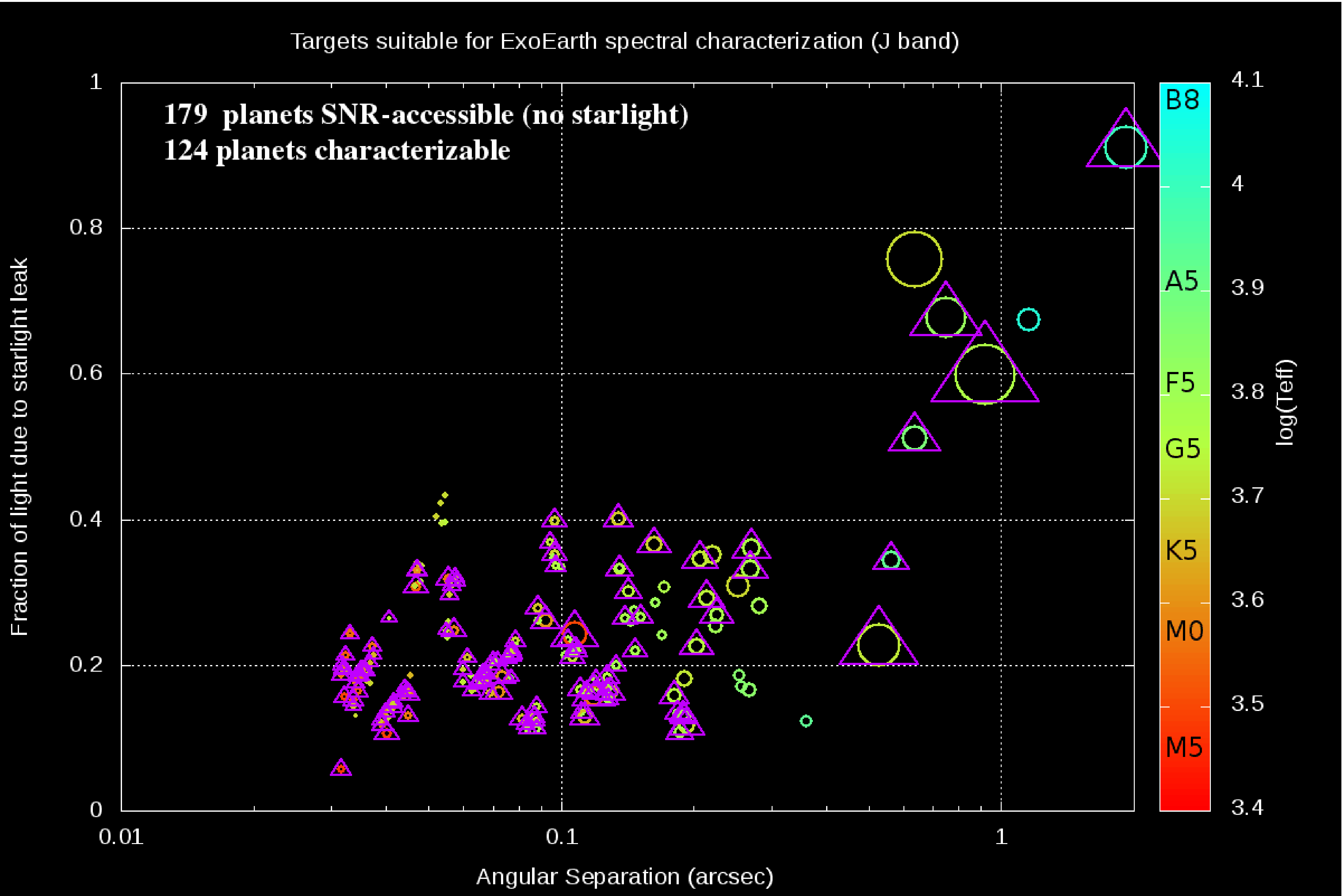
Fraction of light due to coronagraph leak (V band)



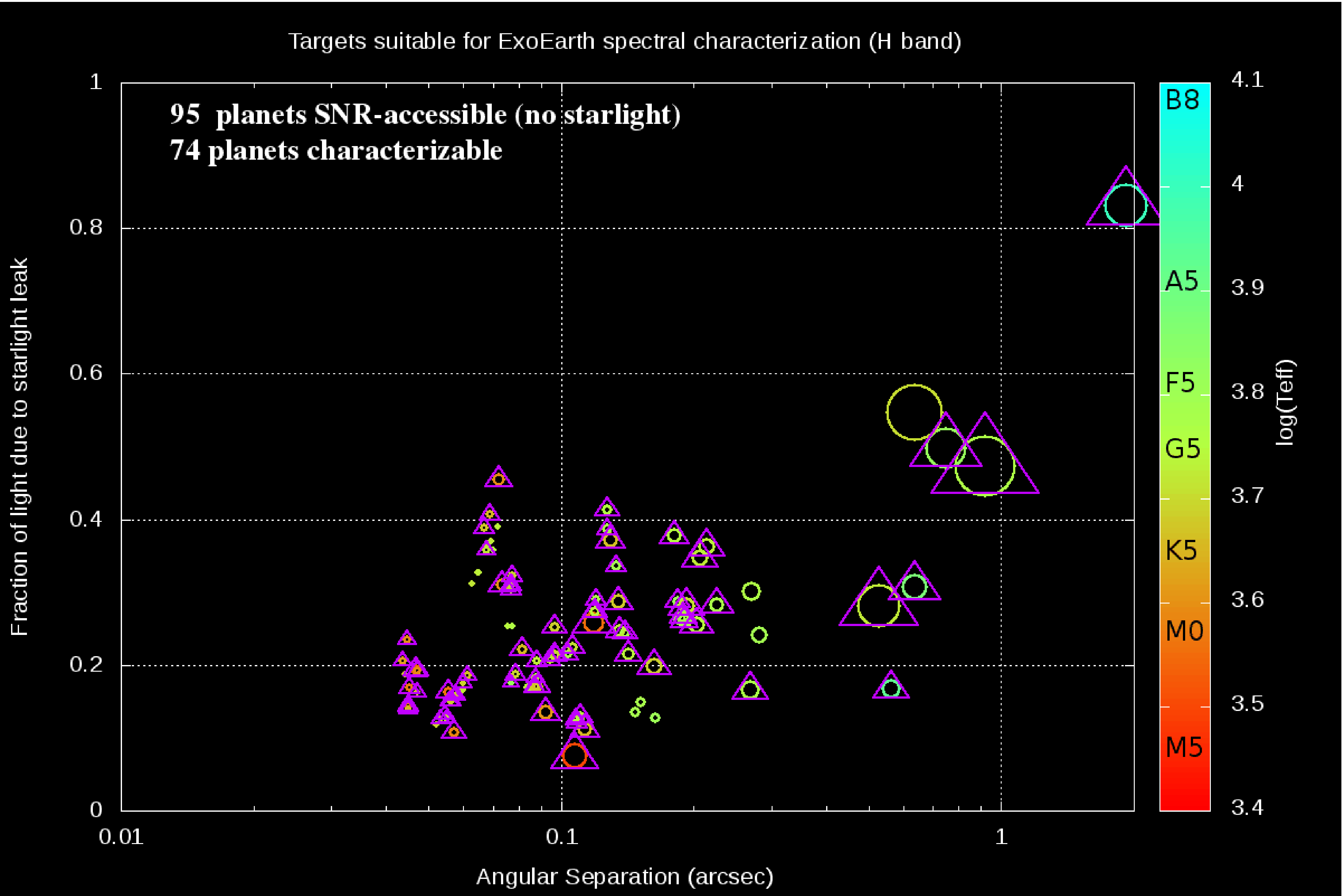
Fraction of light due to coronagraph leak (I band)



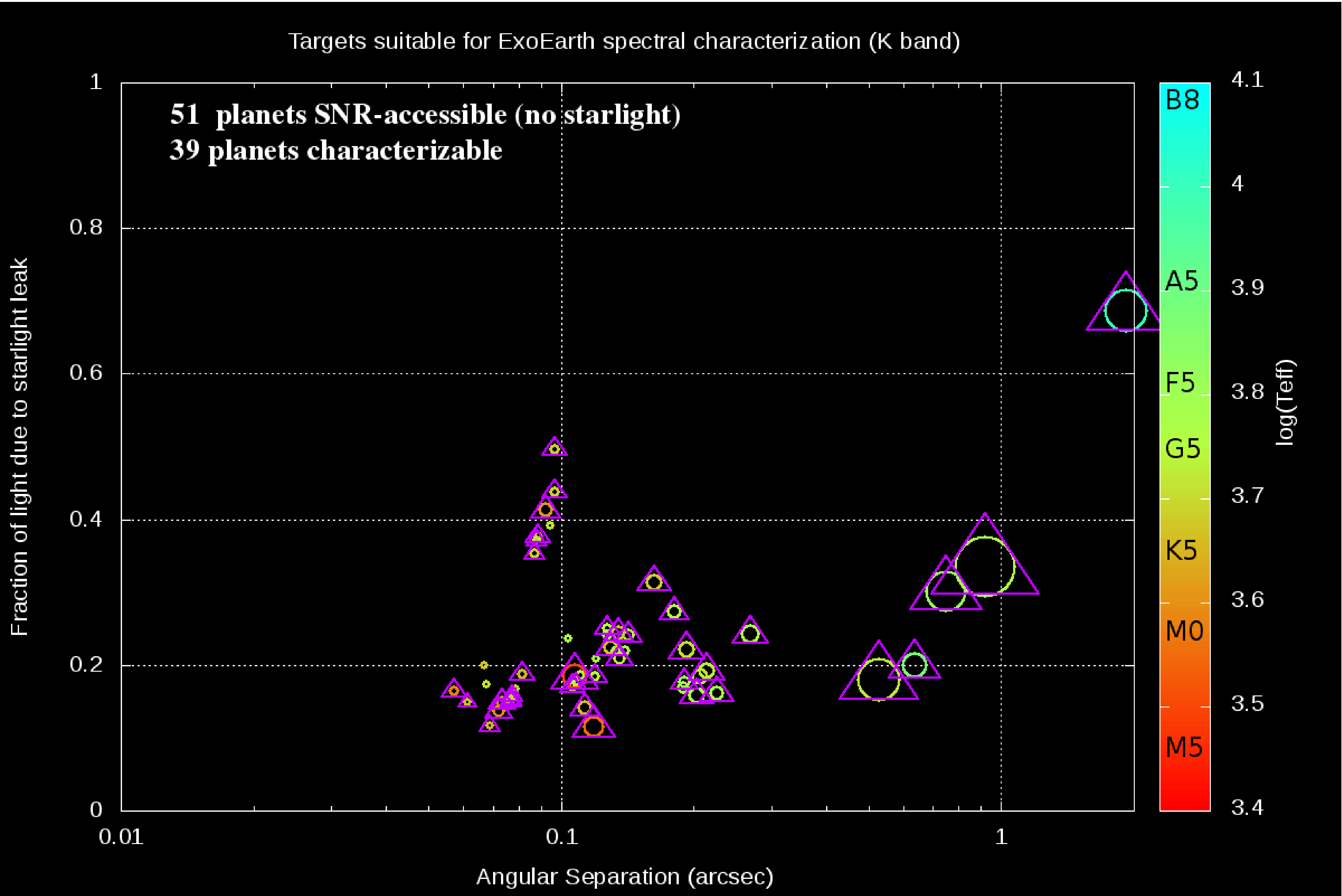
Fraction of light due to coronagraph leak (J band)



Fraction of light due to coronagraph leak (H band)



Fraction of light due to coronagraph leak (K band)



CONCLUSIONS

APLCMC provides coronagraph solution compatible with any segmented aperture. Throughput is low (~30%), but IWA is good (< 1.5 l/D).
Note: PIAACMC should recover throughput … future work

For most targets, coronagraphic leak due to stellar angular size has small effect on SNR
For most targets, about 20% contribution to total light in the planet PSF (other contributions: planet, zodi, exozodi) → SNR is comparable to ideal SNR (no starlight) that a perfect coronagraph or starshade would obtain.

Stellar angular size is a concern for planets at large angular separation observed at short wavelength. APLCMC / PIAACMC is not the ideal coronagraph for these observations, but other solutions exist in this regime.

For 12m aperture, spectroscopy can be obtained on Earth-like planets around a sample of 74 stars to H-band (1.65um)

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