# Starshade Stray Light Status Report
# to
# Science and Industry Partnership Group

**Doug Lisman**
*Jet Propulsion Laboratory, California Institute of Technology*

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# Overview



- **Primary stray light updates reported here are to account for the:**
  - Systematic component of noise (post-calibration residual uncertainty)
  - Latest edge scatter measurements with "Zecoated" coupons
  - Reflected light from center of the Milky Way
  - Levels at 1AU solar equivalent angle rather than IWA
  - Attenuated solar leakage with a labyrinth seal at deployable disk optical shield interface to truss

- **Secondary solar reflections are under study via ray trace analysis of system CAD model**
  - Telescope facing surfaces with view factors to sun facing surfaces, with or without deformed shape

- **Noise budgets compile stray light & astrophysical background noises to yield planet sensitivity**
  - Total stray light brightness is less than the local zodiacal light

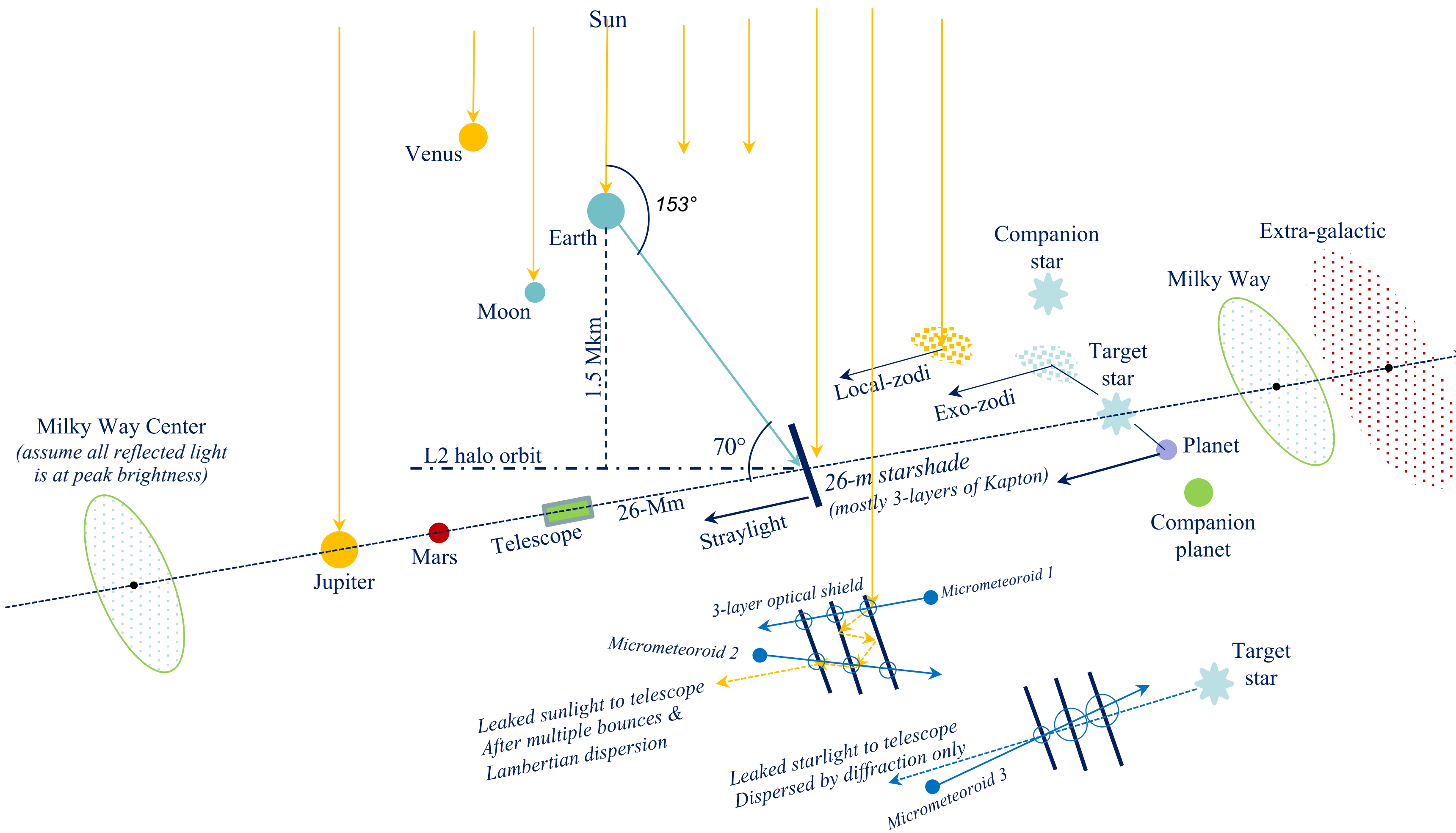
- **Planet sensitivity is translated to HZ search completeness and cumulative HZ search space**
  - Sun-like FGK stars with completeness cutoff at $\geq$ 20%
  - Consider variable band, exozodi level and exozodi calibration accuracy

- **First, stray light sources and their geometry are reviewed**

# Stray Light and Backgrouns Sources and Geometries

**Starshade stray light**
Starlight leakage, Solar glint (edge scatter)
Solar leakage: opacity, mm holes, OS closeout
Reflected bright-bodies: Earth, Venus, Jupiter, Milky Way
Secondary solar reflections, fluorescence,
Thruster exhaust solar scatter, micrometeoroid flashes

**Astrophysical Background**
Milky Way stars
Other galaxies
Exozodi & local zodi light
Companion stars & exoplanets



# Systematic Noise



- **Systematic noise stems from the imperfect calibration of any noise source with spatial structure to present photon *source* uncertainty**
  - Adds in quadrature with the photon *count* uncertainty from photometric noise
  - Formulation below is consistent with CGI error budgets (B. Nemati, 2016)

- **SNR is the ratio of planet counts ($KC_p$) to the RSS of photometric counts ($\sqrt{(KC_n)}$) and systematic noise counts ($KC_n\delta$), or:**
  - $SNR = KC_p / (KC_n + \delta^2K^2C_n{}^2)^{1/2}$
  - where: K is star counts, $C_p$ is planet contrast, $C_n$ is noise contras and $\delta$ is calibration accuracy

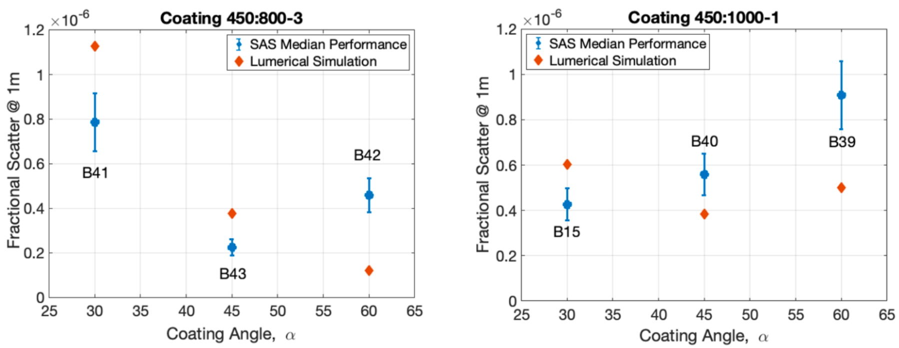
- **Solving for planet contrast ($C_p$) gives:**
  - $C_p = SNR\ (C_n/K + \delta^2C_n{}^2)^{1/2}$
  - Note the systematic term is independent of integration time

- **Exozodi calibration accuracy ($\delta_Z$) is critical and highly uncertain**
  - Planet extraction simulations to inform exozodi calibration capability are critically needed
  - A $\delta_Z$ goal of 5% is evaluated here, but also show results for 3.33% and 0%

# Optical Edge Coating



- **Solar glint is greatly reduced by "ZeCoated" edges**
- **A JPL optical model is validated and used to choose coating application angle, LoS vs. uniform, etc.**
- **JATIS paper submitted for review by Dylan McKeithen, Stuart Shaklan, David Sheikh, et al**
- **Future optimizations include finer coating thickness resolution & weighted sun angles**
- **Prototype plans include performance verification after thermal cycles and stow cycles**




(a) (b)

Fig 6: Comparison between the SAS experimental data and Lumerical results for coatings (a) *450:800-3*, and (b) *450:1000-1* showing good agreement for coatings applied at three different angles.

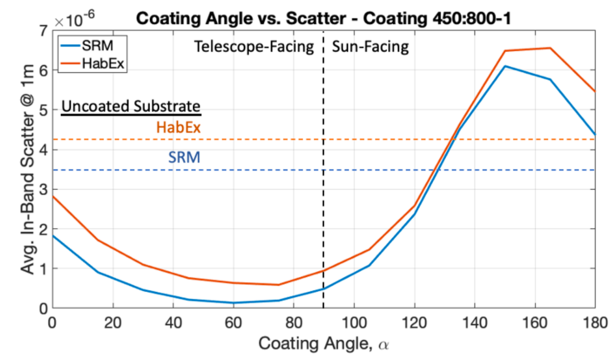



Fig 7: Plot of the average in-band scatter as a function of coating angle. Note the minimum around $\alpha = 60°$, and a maximum near $\alpha = 150°$.

Table 7: Estimated Glint Lobe Magnitude for the SRM 425-552 nm Band

| $\phi$ | IWA Phot. 95% conf. | Improvement Ratio | $\Delta$Mag | Final Mag |
|---|---|---|---|---|
| 53 | 27.3 | 9.2 | 2.4 | 29.7 |
| 63 | 27.5 | 16.7 | 3.1 | 30.6 |
| 73 | 27.3 | 26.8 | 3.6 | 30.9 |
| 83 | 26.7 | 20.5 | 3.3 | 30.0 |

Table 8: Estimated Glint Lobe Magnitude for the SRM 615-800 nm Band

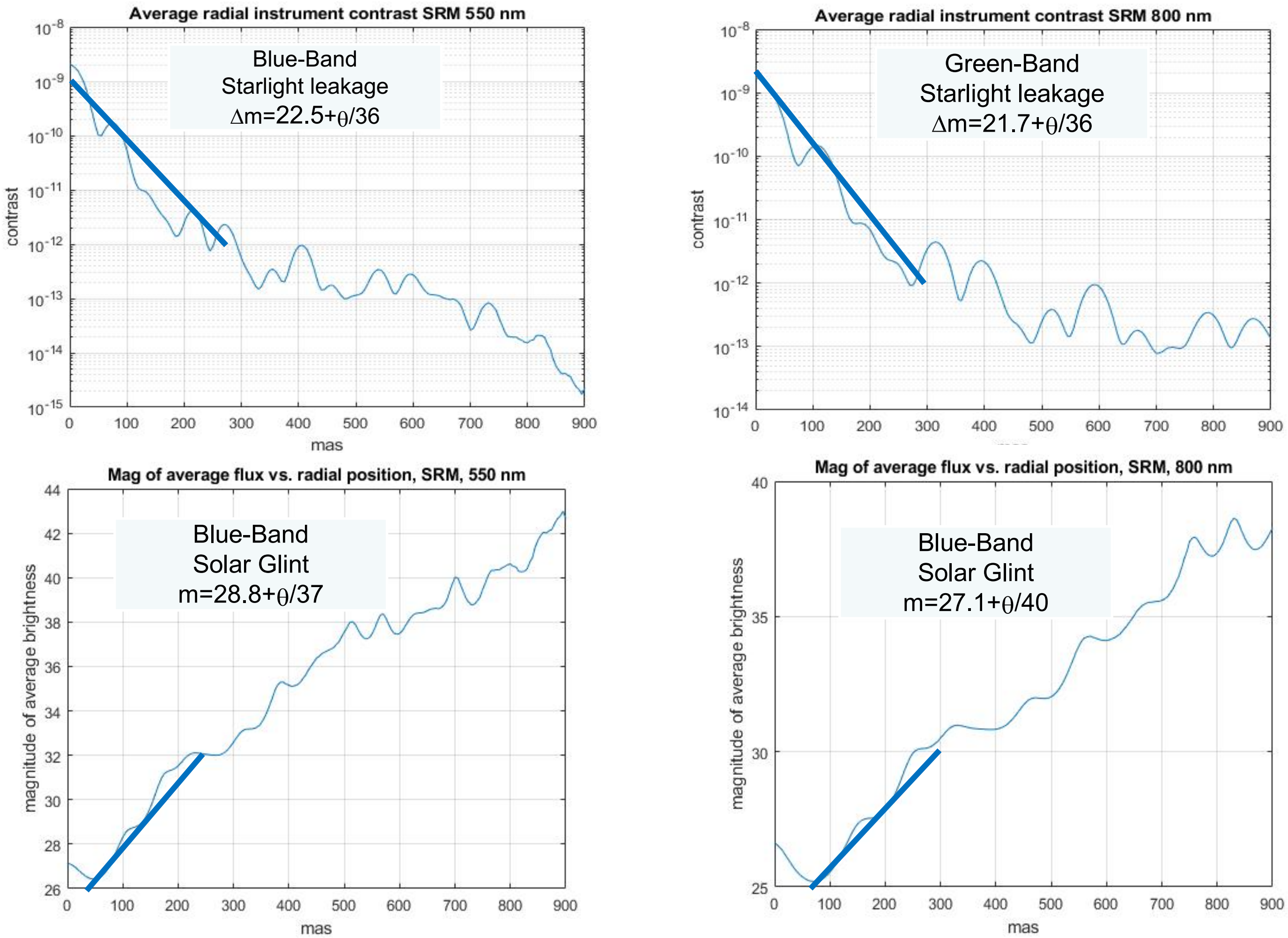
| $\phi$ | IWA Phot. 95% conf. | Improvement Ratio | $\Delta$Mag | Final Mag |
|---|---|---|---|---|
| 53 | 25.2 | 14.3 | 2.9 | 28.1 |
| 63 | 25.4 | 33.3 | 3.8 | 29.2 |
| 73 | 25.2 | 61.0 | 4.5 | 29.7 |
| 83 | 24.6 | 85.3 | 4.8 | 29.4 |

# Reflected Milky Way Light

- **Center of Milky Way is the brightest body for reflected light, when seasonally behind the telescope**
  - Peak brightness is 20.57 mags/arc-sec$^2$
  - ~5% starshade hemispherical reflectance (+3.25 mags)
  - +1 mag fill factor – petals instead of disk
  - Conservatively assume that all reflected light comes from the brightest part of the Milky Way
  - Yields 31.3 mags per resolution element at IWA
- **Combine with Earth at grazing angles for total of 28.2 + $\theta_{mas}$/40 mags (Green-Band)**
  - 30.8 mags per resolution element at IWA
- **Additional light reflected by Jupiter and Venus is possible, but rare and operationally avoidable**
- **All other bodies are much dimmer**

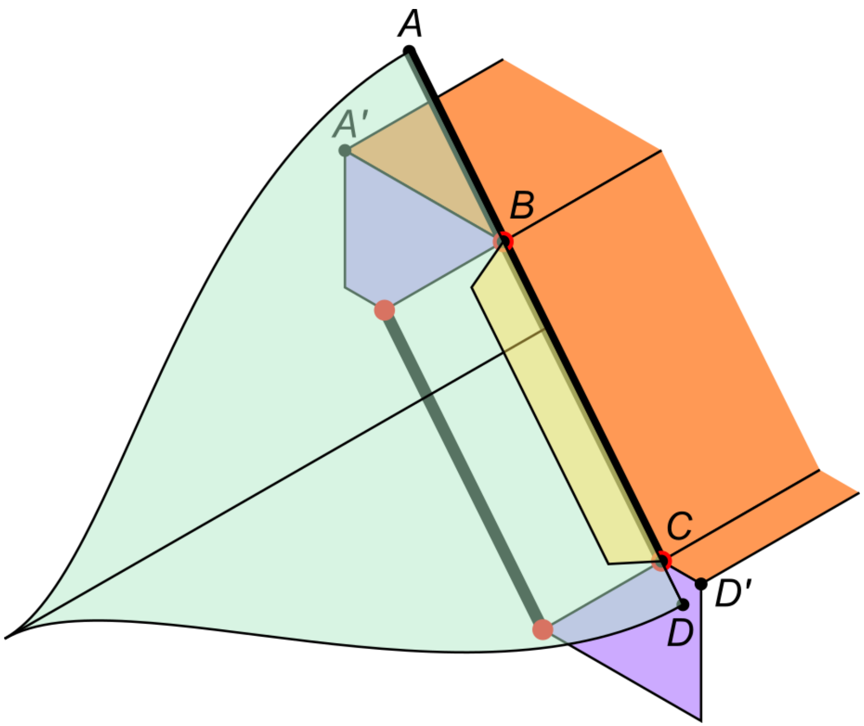
# Translation to 1AU solar equivalent angle

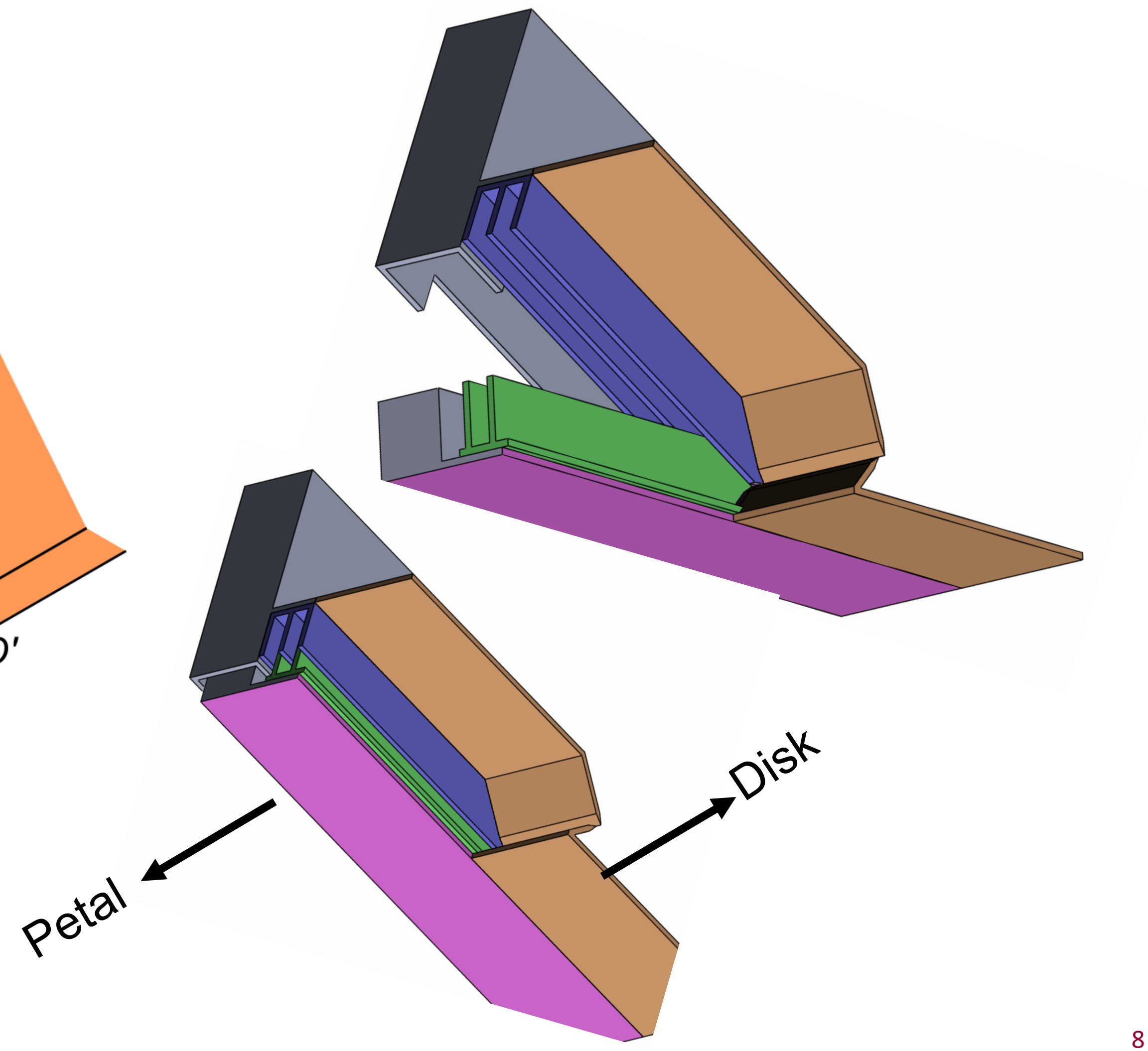
- **Off-axis fall-off for star leakage & solar glint is simulated and curve fit over angles of interest**



# Optical Shield Closeout- 1 of 2

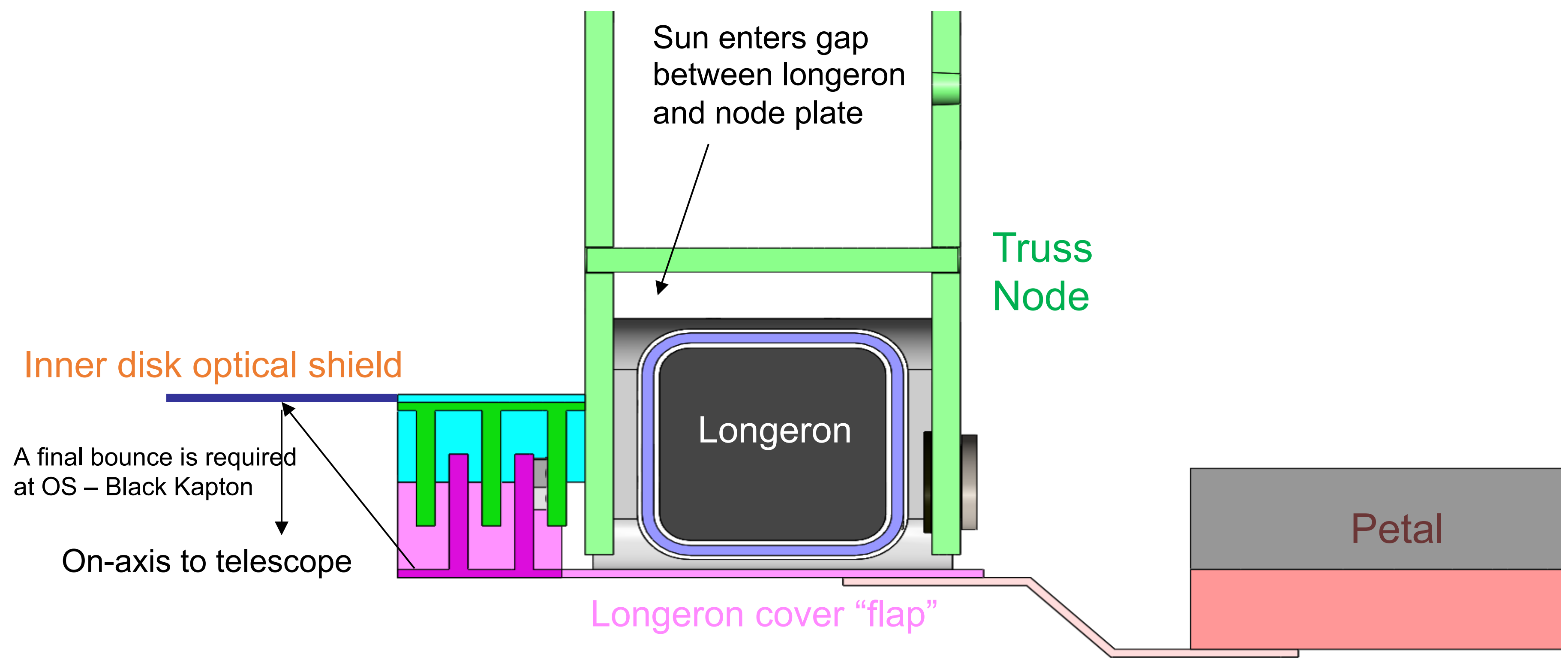
- Deployable disk optical shield (OS) requires a hinged interface at each truss node, with a mechanical clearance (gap) that can leak Sunlight
- A labyrinth seal design (by Manan Aria) expected to transmit $\lesssim 10^{-13}$ (vs. $10^{-12}$ predict for mm holes) is to be verified with straylight tool



# Optical Shield Closeout- 2 of 2

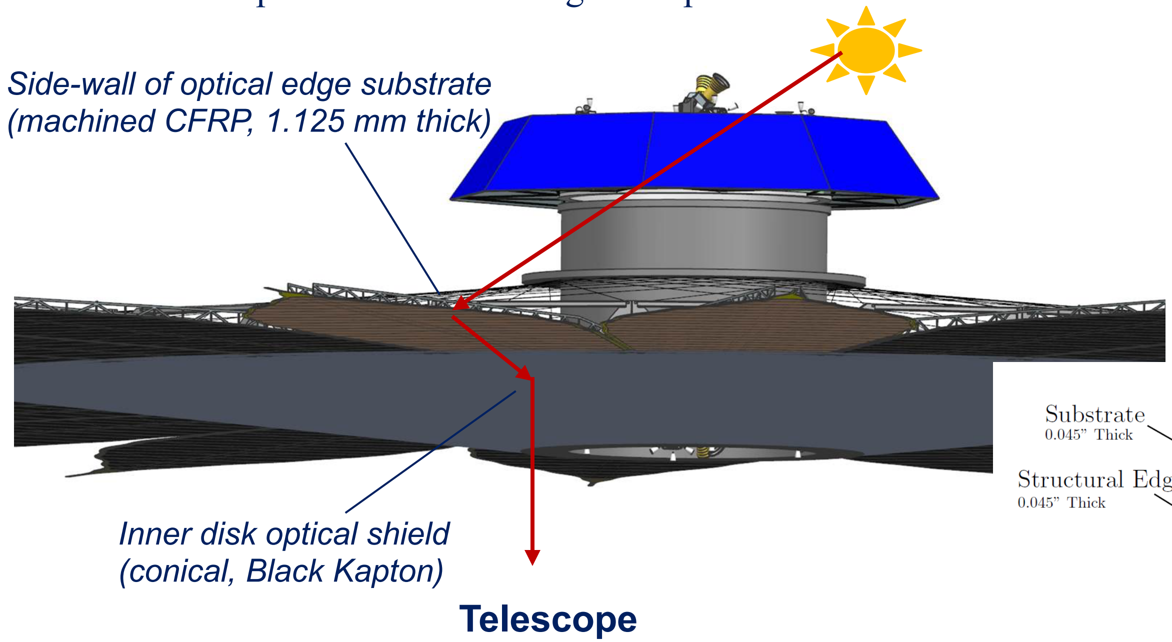


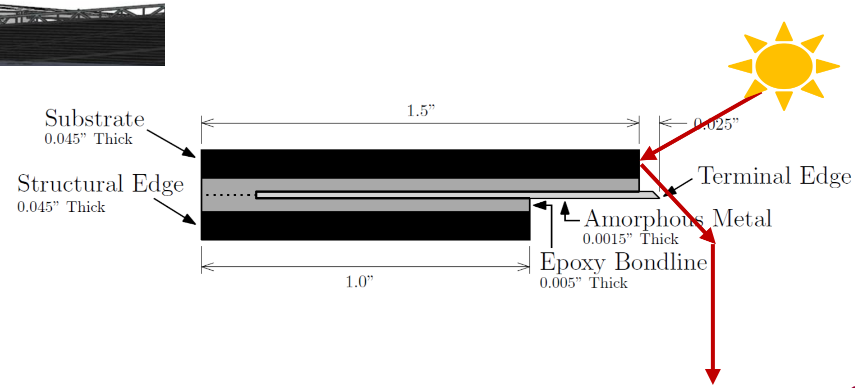


# Secondary Solar Reflections



- **Photon Engineering (Scott Ellis) is conducting a rigorous analysis of starshade stray light**
  - Ray tracing tools applied to starshade system CAD model
  - Computationally challenged by extremely low light level sensitivity
  - Further challenged by limited fidelity CAD model with non-flight like features (iterative CAD fixes)
- **Emphasis is on secondary solar reflections for both nominal shape and twisted/out-of-plane petals**
  - Telescope facing surfaces with a view factor to Sun facing surfaces
  - Machined CFRP side-wall of optical edge substrate to disk optical shield is an example
  - BRDF measurement of this atypical material is underway
- **Expect all secondary reflections will be much dimmer than solar glint, after mitigations**
  - ZeCoat provided dark coating on Kapton is now under test as one mitigation



# Noise Budget Approach & Assumptions



- Focus on top 3 stray light terms, plus a conservative allocation for other sources
- Focus on top 3 astrophysical background sources

- Include systematic noise
- All noise terms combine in quadrature (same as CGI methodology)

- Detector QE is per WFIRST ipac website and includes a variable factor for QE degradation (0.5X does not change planet sensitivity)
- SNR is set to 4 for broadband detections

- Consider both Green and Blue Bands

- Exozodi CBE is 3X Local zodi density (6X brightness) and we also explore 2X density
- Exozodi calibration accuracy best guess is 3-5% and we also consider 0% residuals for the case with smooth symmetric exozodi

# Rendezvous Green-Band Noise Budget



| | | | | | Reference star counts (days=1, L=1, d=1pc) | | | |
|---|---|---|---|---|---|---|---|---|
| **Mission** | **SNR (broadband detection)** | **Exo-zodi density** | **Band** | **Banbdpass** | **Point sources** | **Extended sources** | **QE degrade factor** | **IWA (mas)** |
| Rendezvous | 4 | 3 | Green | 615-800 | 4.20E+14 | 1.40E+15 | 1 | 103 |

1=BOL, 0.5 ~EOL

| | | | | | Star counts (K) after 1 day | | |
|---|---|---|---|---|---|---|---|
| **Star** | **L** | **d (parsecs)** | **1AU Angle (θ, mas)** | **Vmag** | **Point sources** | **Extended sources** | **Planck Function** |
| **Tau Ceti** | 0.52 | 3.65 | 198 | 3.49 | 1.66E+13 | 5.52E+13 | 0.202 |

| Noise Source | Angle dependcence | mags at 1AU | Noise Contrast | Background Counts (BC = $C_n$ K ) | Photometric counts = √BC | Cal Accuracy (δ) | Systematic counts = δ BC | RSS Total noise counts |
|---|---|---|---|---|---|---|---|---|
| Starlight leakage (1E-10 at IWA) | $\Delta m=21.7+\theta/36$ | 30.7 | 1.33E-11 | 220.7 | 14.9 | 10% | 22.1 | 26.6 |
| Solar Glint (coated edges, 73° Sun) | $m=27.1+\theta/40$ | 32.0 | 3.81E-12 | 63.0 | 7.9 | 10% | 6.3 | 10.1 |
| Reflected Milky Way & Earth | $m=28.2+\theta/40$ | 33.1 | 1.38E-12 | 76.2 | 8.7 | 25% | 19.1 | 21.0 |
| Other stray light counts (1 per hour) | | | | | | | | 24.0 |
| **Total straylight (RSS)** | | | | | **19** | | **30** | **43** |
| Local Zodi (22.7 mags/arc-sec2) | | 28.81 | 7.45E-11 | 4110 | 64 | 1% | 41 | 76 |
| Exo/Local Zodi brightness ratio | 6 | 26.86 | 4.47E-10 | 24661 | 157 | 5% | 1233 | 1243 |
| Planet shot noise (iterative solver) | | | | | 71 | | | 71 |
| **Astrophysical background (RSS)** | | | | | **184** | | **1234** | **1247** |
| **Stray light & background (RSS)** | | | | | **185** | | | **1248** |
| Min detectable planet counts | | | | | | | | 4992 |
| Planet contrast sensitivity | | | | | | | | 3.0E-10 |
| **Dimmest detectable planet (mags)*** | | | | | | | | **27.3** |

* A constant for all target stars, dominated by exo-zodi

** micrometeoroid flashes, solar leakage thru micrometeoroid holes, fluorescence, thrust plume solar scatter, etc.

# Rendezvous Blue-Band Noise Budget



| Mission | SNR (broadband detection) | Exo-zodi density | Band | Banbdpass | Reference star counts (days=1, L=1, d=1pc) Point sources | Reference star counts (days=1, L=1, d=1pc) Extended sources | QE degrade factor | IWA (mas) |
|---|---|---|---|---|---|---|---|---|
| Rendezvous | 4 | 3 | Blue | 460-600 | 5.50E+14 | 1.80E+15 | 1 | 77 |

QE degrade factor: 1=BOL, 0.5 ~EOL

| Star | L | d (parsecs) | 1AU Angle (θ, mas) | Vmag | Star counts (K) after 1 day Point sources | Star counts (K) after 1 day Extended sources | Average Planck Function | |
|---|---|---|---|---|---|---|---|---|
| **Tau Ceti** | 0.52 | 3.65 | 198 | 3.49 | 1.86E+13 | 6.08E+13 | 0.173 | std. dev is 0.02 |

| Noise Source | Angle dependcence | mags at 1AU | Noise Contrast | Background Counts (BC = $C_n$ K ) | Photometric counts = √BC | Cal Accuracy (δ) | Systematic counts = δ BC | RSS Total noise counts |
|---|---|---|---|---|---|---|---|---|
| Starlight leakage (1E-10 at IWA) | Δm=22.5+θ/36 | 31.5 | 6.38E-12 | 118.5 | 10.9 | 10% | 11.8 | 16.1 |
| Solar Glint (coated edges, 73° Sun) | m=28.8+θ/37 | 34.1 | 5.50E-13 | 10.2 | 3.2 | 10% | 1.0 | 3.4 |
| Reflected Milky Way & Earth | m=28.0+θ/37 | 33.3 | 1.15E-12 | 69.8 | 8.4 | 25% | 17.5 | 19.3 |
| Other stray light counts (1 per hour) | | | | | | | | 24.0 |
| **Total stray light (RSS)** | | | | | **14** | | **21** | **35** |
| Local Zodi (22.7 mags/arc-sec2) | | 29.41 | 4.29E-11 | 2604 | 51 | 1% | 26 | 57 |
| Exo/Local Zodi brightness ratio | 6 | 27.46 | 2.57E-10 | 15626 | 125 | 5% | 781 | 791 |
| Planet shot noise (iterative solver) | | | | | 56 | | | 56 |
| **Astrophysical background (RSS)** | | | | | **146** | | **782** | **795** |
| **Total noise (stray light & astrophysical (RSS)** | | | | | **147** | | | **796** |
| Min detectable planet counts = Total noise * SNR | | | | | | | | 3184 |
| Planet contrast sensitivity = min planet / star point source counts | | | | | | | | 1.7E-10 |
| **Dimmest detectable planet (mags)*** | | | | | | | | **27.9** |

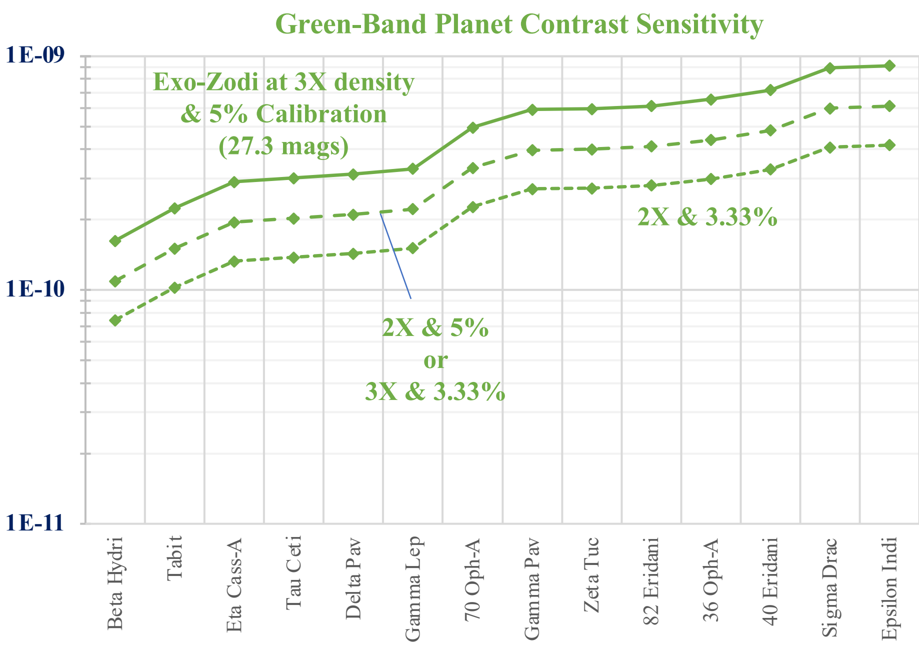
* A constant for all target stars, dominated by exo-zodi

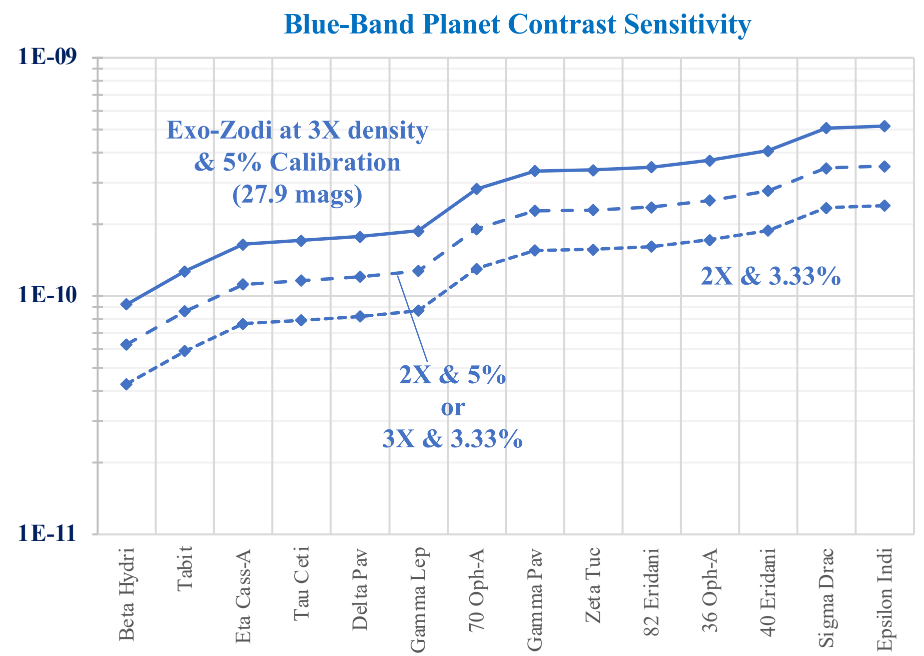
** micrometeoroid flashes, fluorescence, thrust plume solar scatter, etc.

*vs. 27.3*
*for Green-Band*
*(Blue-Band can detect 1.7X dimmer planets)*

# Exozodi dominated planet sensitivity

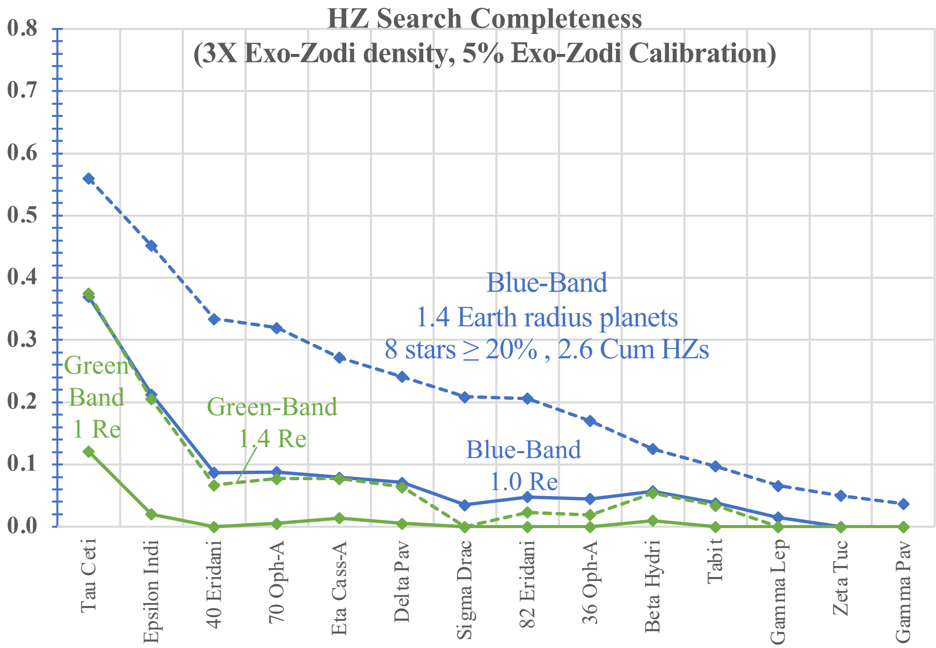


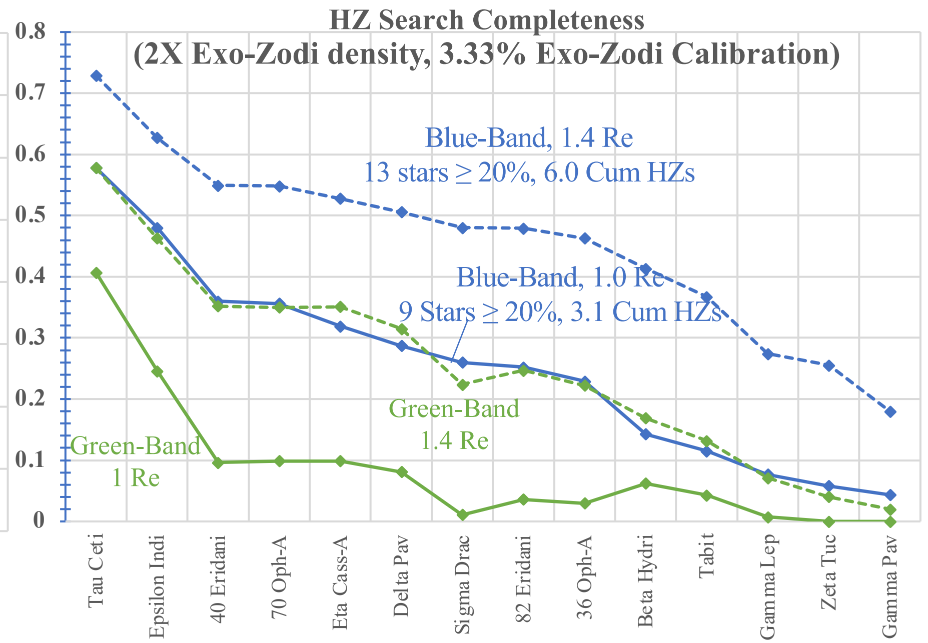



***Planet sensitivity scales with residual Exo-Zodi uncertainty & also $\lambda^2$ and the Planck Function***

# HZ Search Space
## (vs. Band, Exozodi level & Exozodi Cal accuracy)

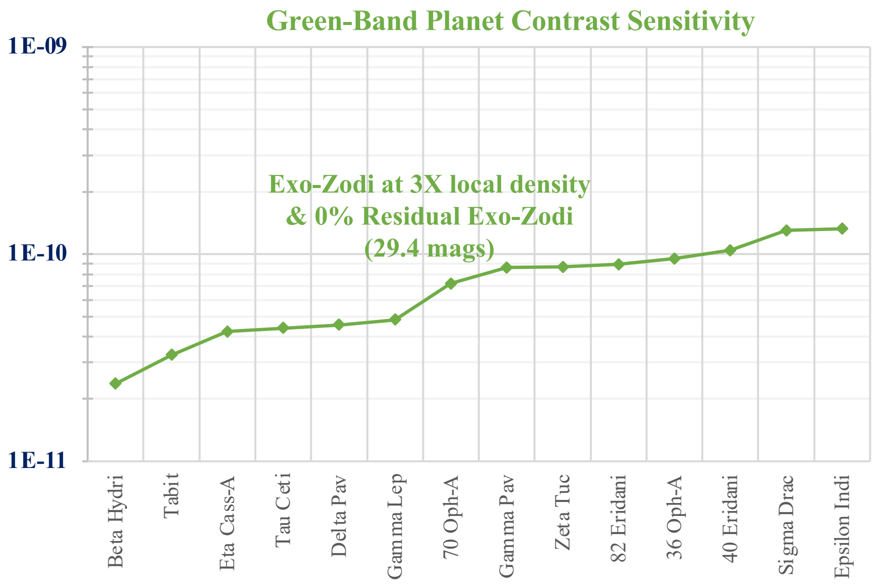


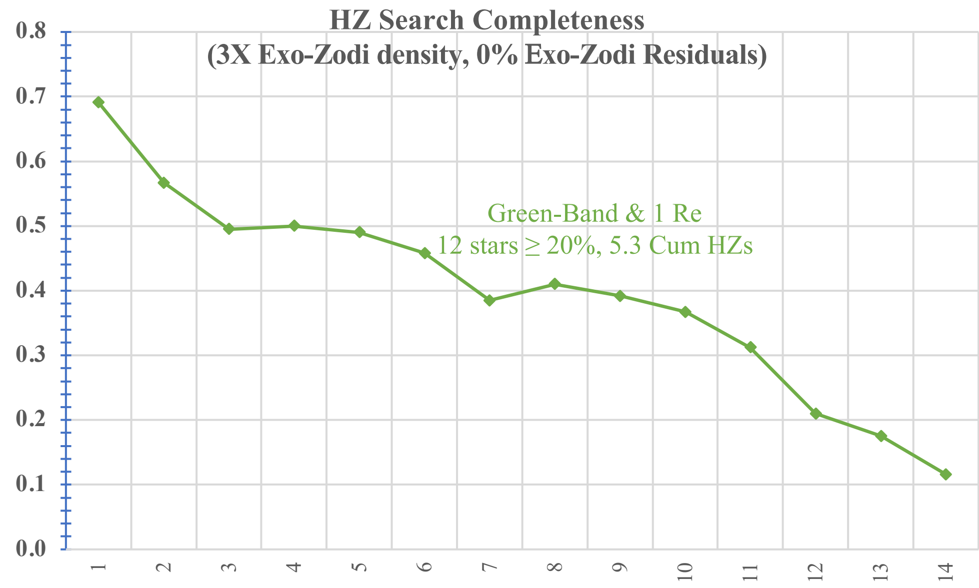




***Residual Exozodi uncertainty (systematic noise) decimates Rendezvous performance***

***Combinations of bandpass, planet size & residual exozodi level restore some performance***

# Perfect Exozodi Calibration ?




***Evolved systems are expected to have highly uniform (not lumpy) exozodis.***
***This would allow subtraction of exozodi based on image symmetry.***
***Here we assume perfect exozodi calibration.***

# Conclusions

- **The good news is that starshade stray light is well under control**
  - Barely detectable at 1AU solar equivalent distances for nearby stars
  - Verification efforts are ongoing and not all sources are quantified
- **The bad news is that planet sensitivity is not so good for CBE of 3X mean exozodi density**
  - And for reasonable calibration accuracy (3-5%)
  - We critically need to inform the actual calibration capability, via planet extraction simulations
- **Evolved systems may have very uniform exozodi that can be very well calibrated**
  - Resolution is sufficient to subtract symmetric exozodi
- **Performance improves with the Blue-Band and larger rocky planets (1.4X Earth mean)**