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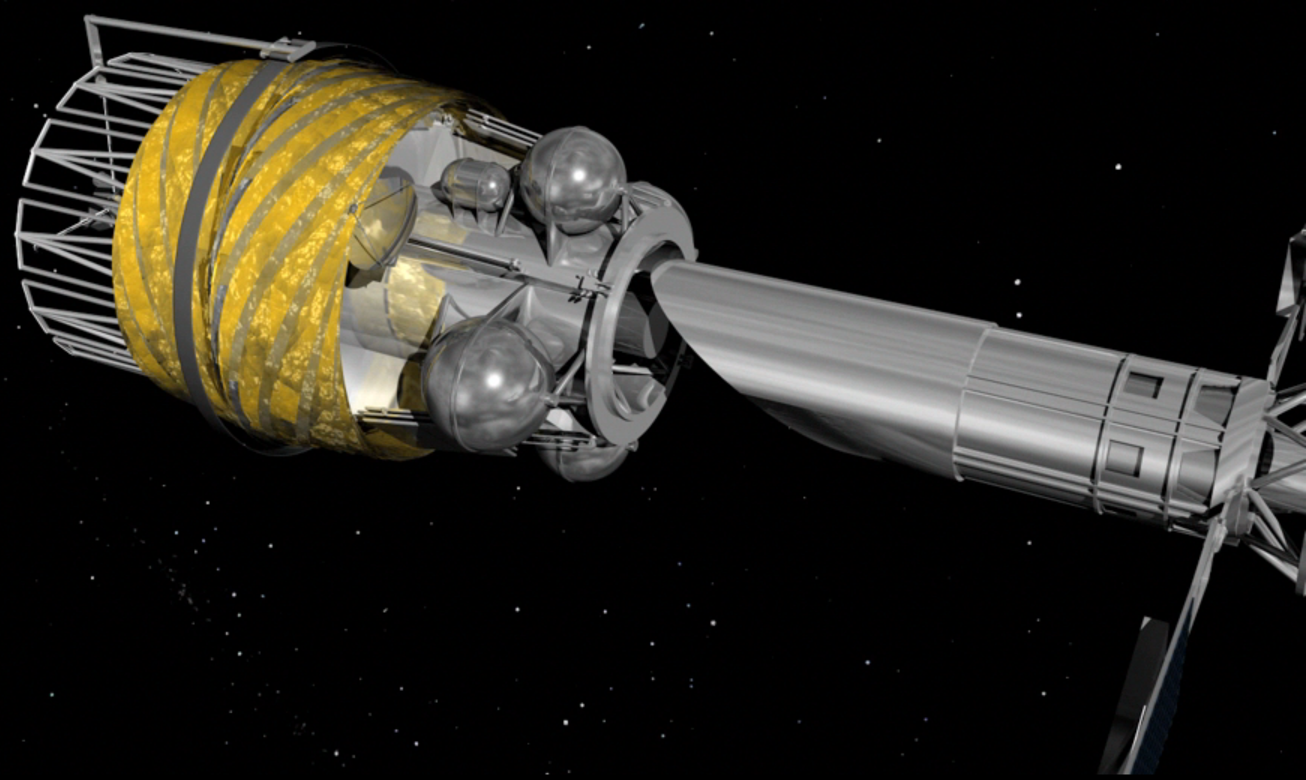
THE THEORY AND DEVELOPMENT OF STARSHADES



Starshade strengths

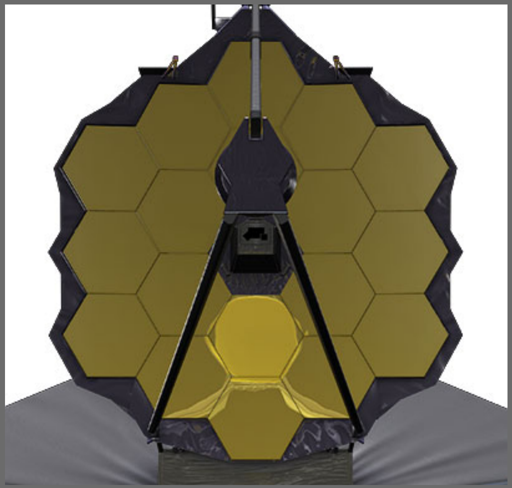
- Contrast and inner working angle decoupled from telescope aperture size
  - IWA not proportional to λ / D anymore
- Broad bandpass, high total throughput
- No constraints on other astronomical instruments

NASA / Swift

Starshade strengths

- No outer working angle
- 360 degree suppressed field of view
- High quality telescope not required
  - Segments & obstructions not a problem
  - Wavefront correction unnecessary

W. Cash (Colorado)



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Starshade drawbacks

- Full-scale end-to-end system test on the ground not possible
  - Sub-scale lab and field tests possible (more later)

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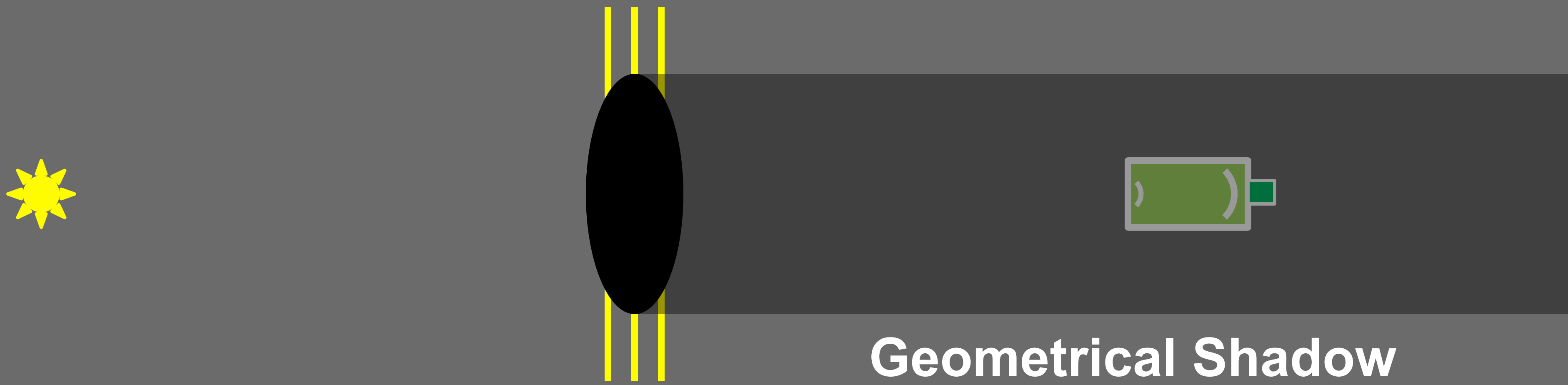
- Long times between observations
  - Need to slew the starshade between targets
- Limited number of starshade movements

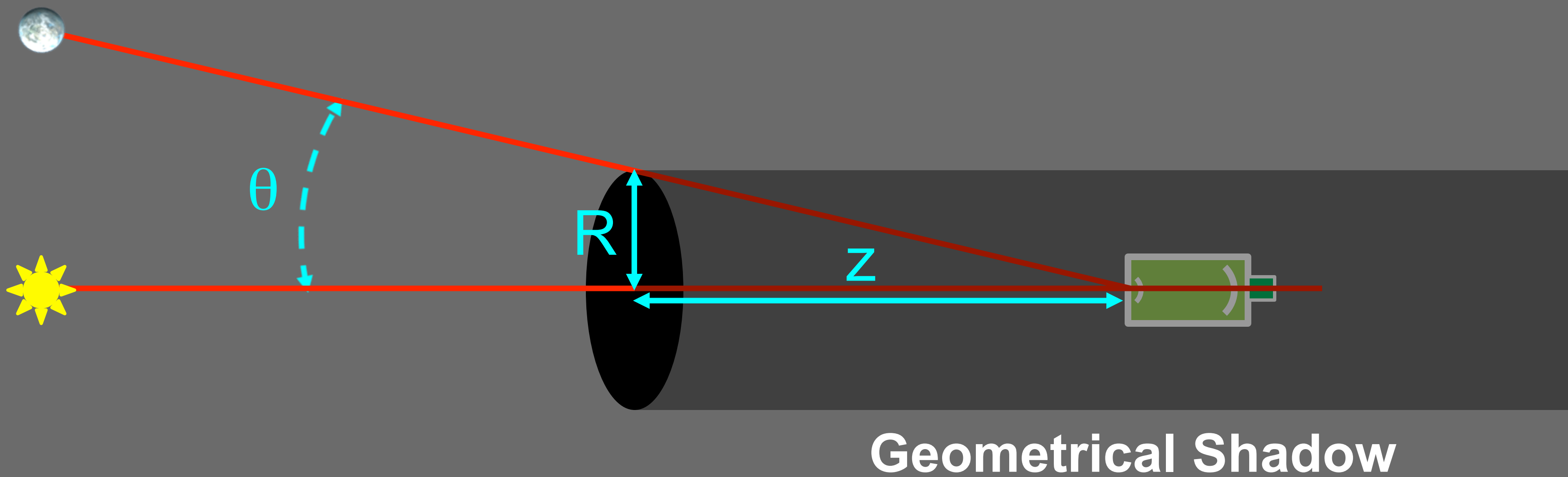
Basics: shadow the telescope



- Starshade positioned to block the starlight
- Must be larger than the telescope to keep the starlight out

Credit: S. Shaklan

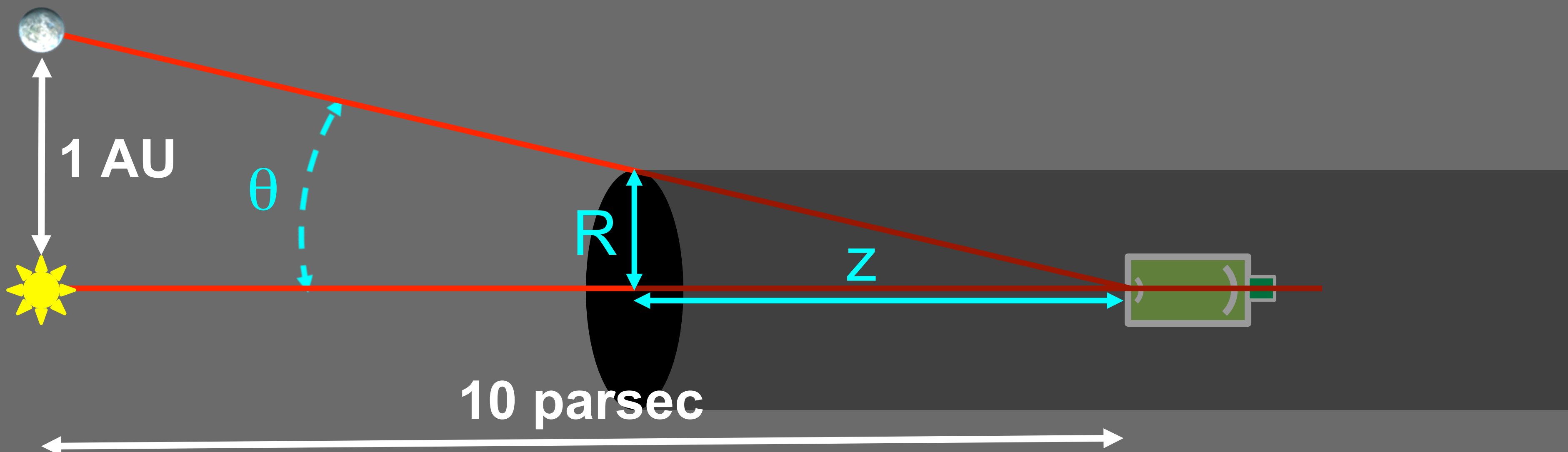
Inner working angle



IWA ~ angle to edge of starshade

$$\theta \sim R / z$$

Inner working angle

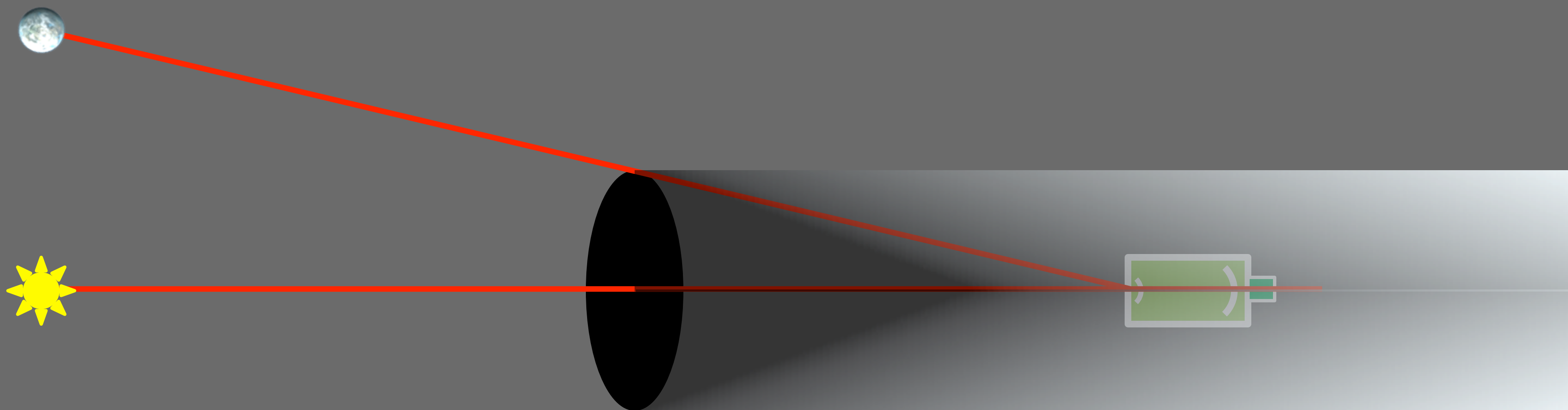


Earth at 10 pc: IWA = 100 mas

For D = 4 m, 2 × R = 6 m

z ~ 6200 km

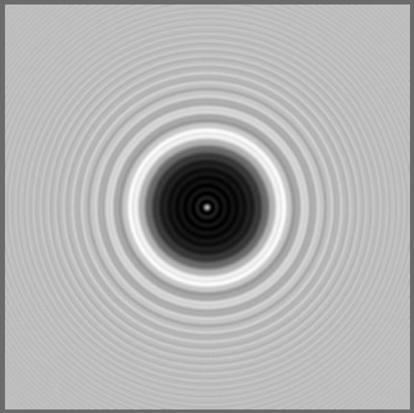
Not so simple: diffraction



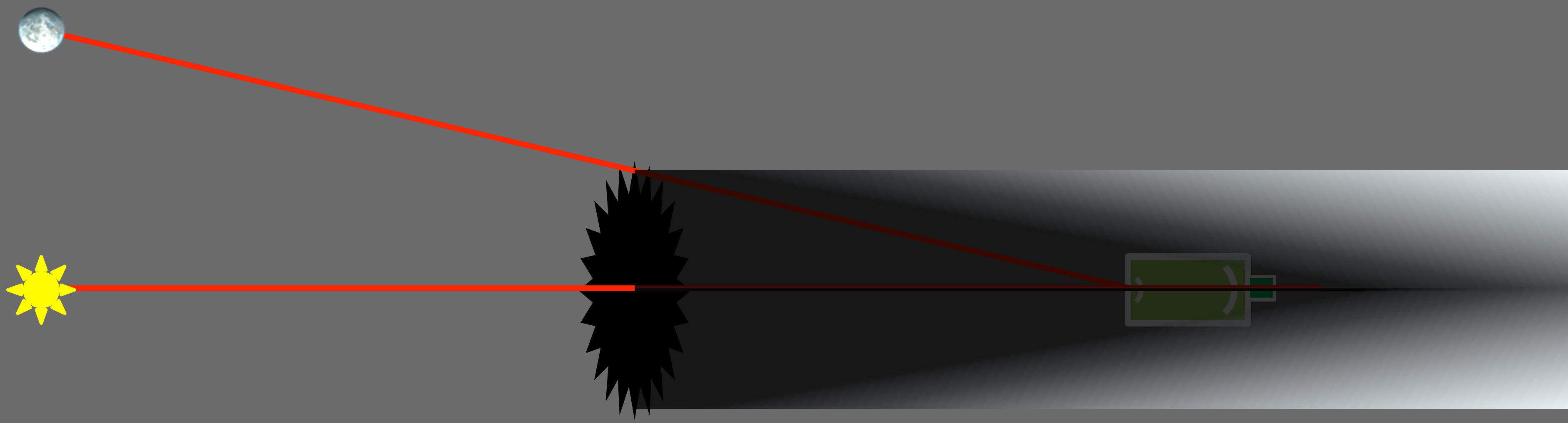
Diffraction Shadow

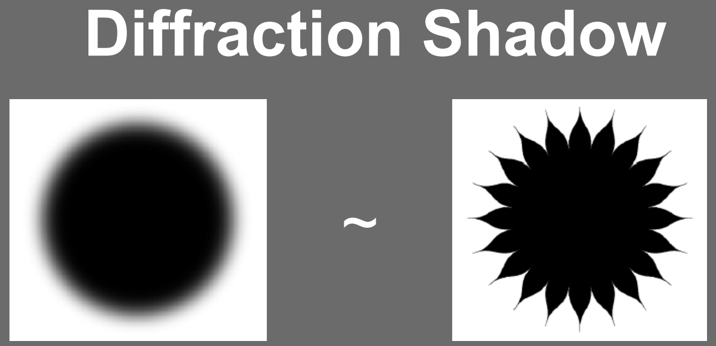
Circular disk makes diffraction pattern with Arago spot.

Shadow isn't dark enough.



Petals for high contrast





Approximate smooth radial apodization using petals.

Now can get better than 10^{-10} contrast with reasonably sized starshade.

Calculating a starshade shape

Fresnel (near-field) diffraction with apodization function A(r)

$$E(\rho) = E_0 e^{\frac{2\pi i z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda z} e^{\frac{i\pi}{\lambda z}\rho^2} \int_0^R A(r) e^{\frac{i\pi}{\lambda z} r^2} J_0\left(\frac{2\pi r \rho}{\lambda z}\right) r dr \right)$$

z = separation between starshade and telescope

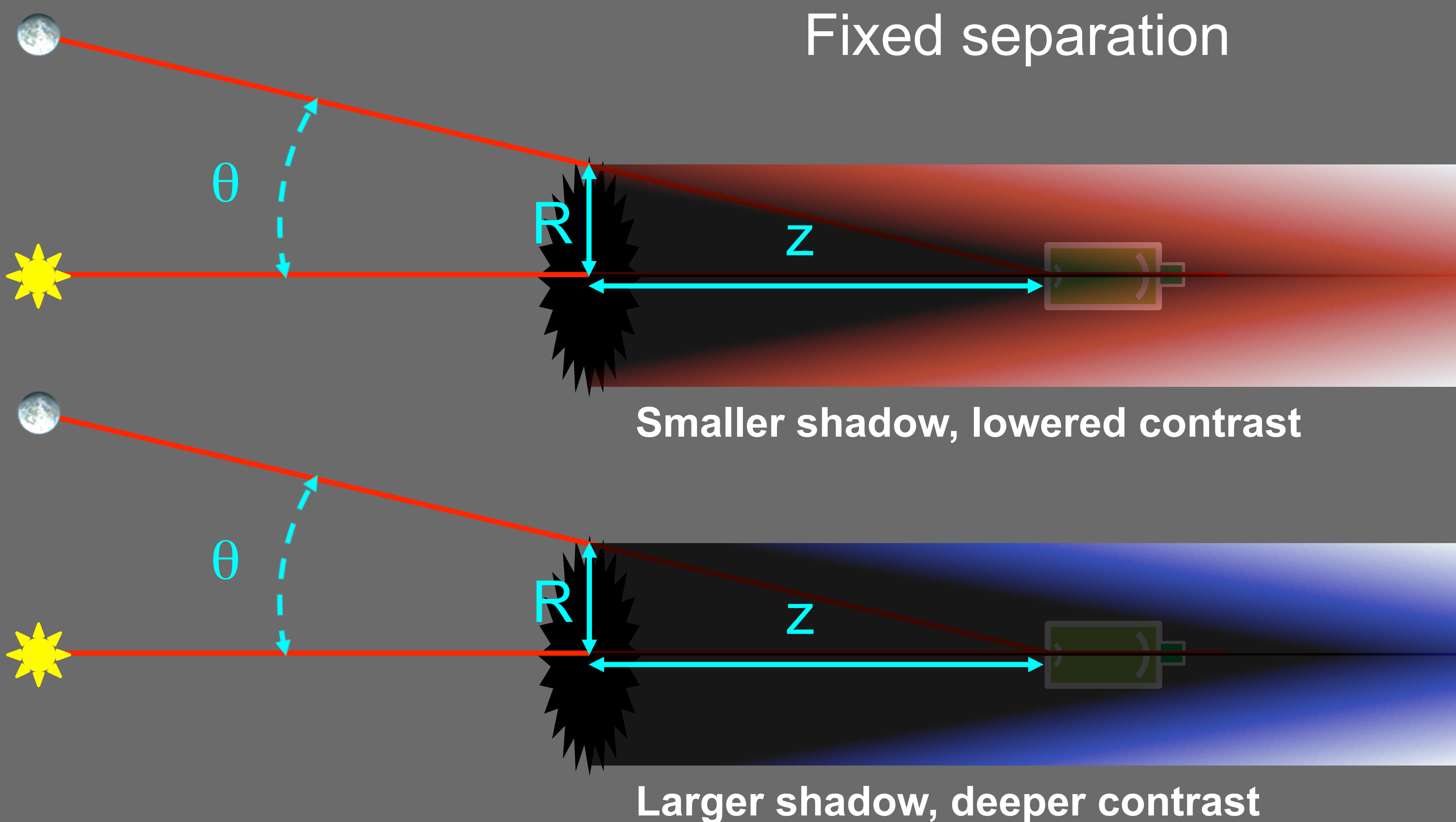
R = radius of starshade

ρ = radial position measured from center of shadow at telescope entrance

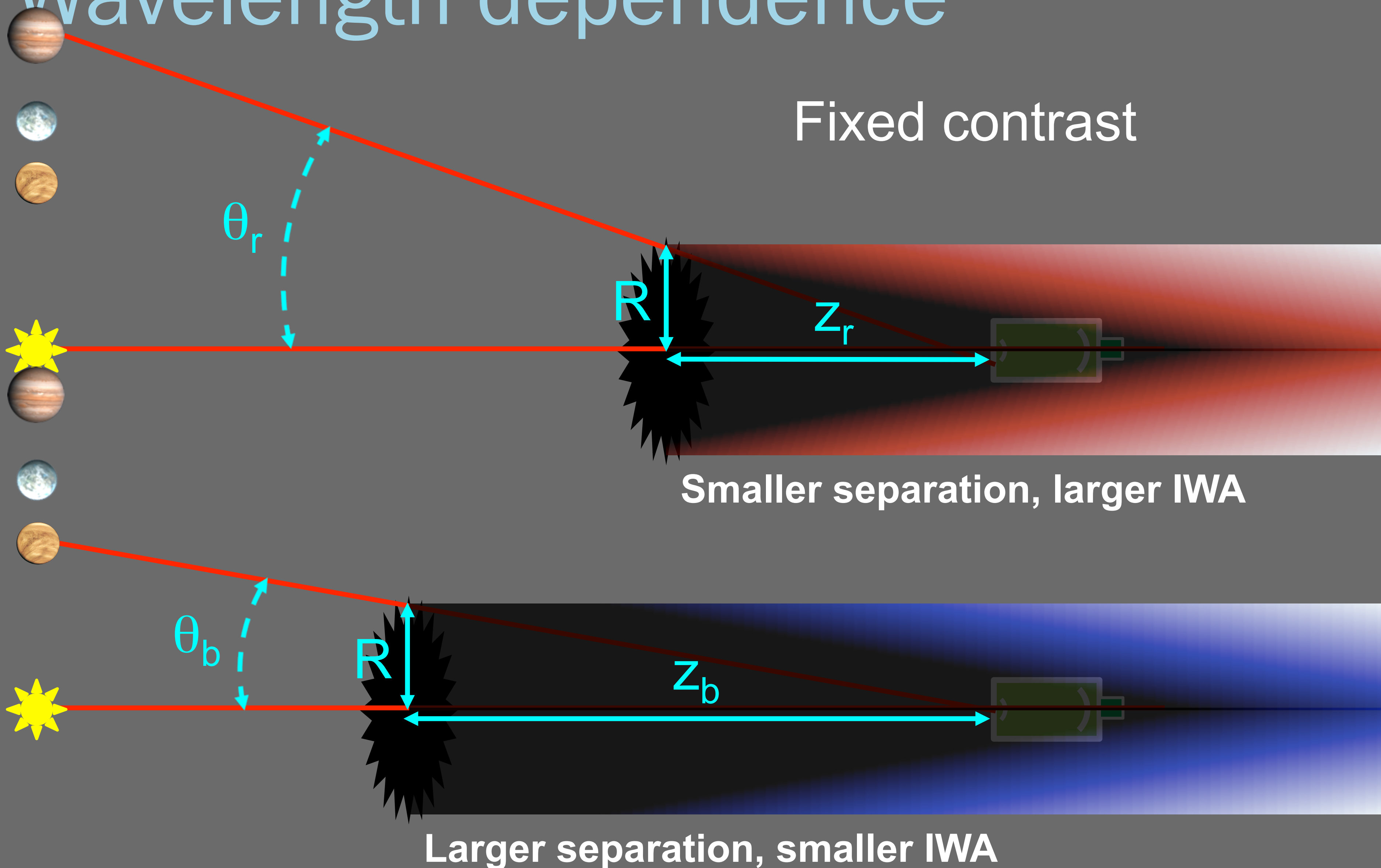
r = radial position measured from center of shadow at the starshade

1. Exact solution for A(r) with ρ = 0 : Hypergaussian
   (Cash 2006)
2. Numerically calculate optimal A(r)
   (Vanderbei, Cady, & Kasdin 2007)

Wavelength dependence

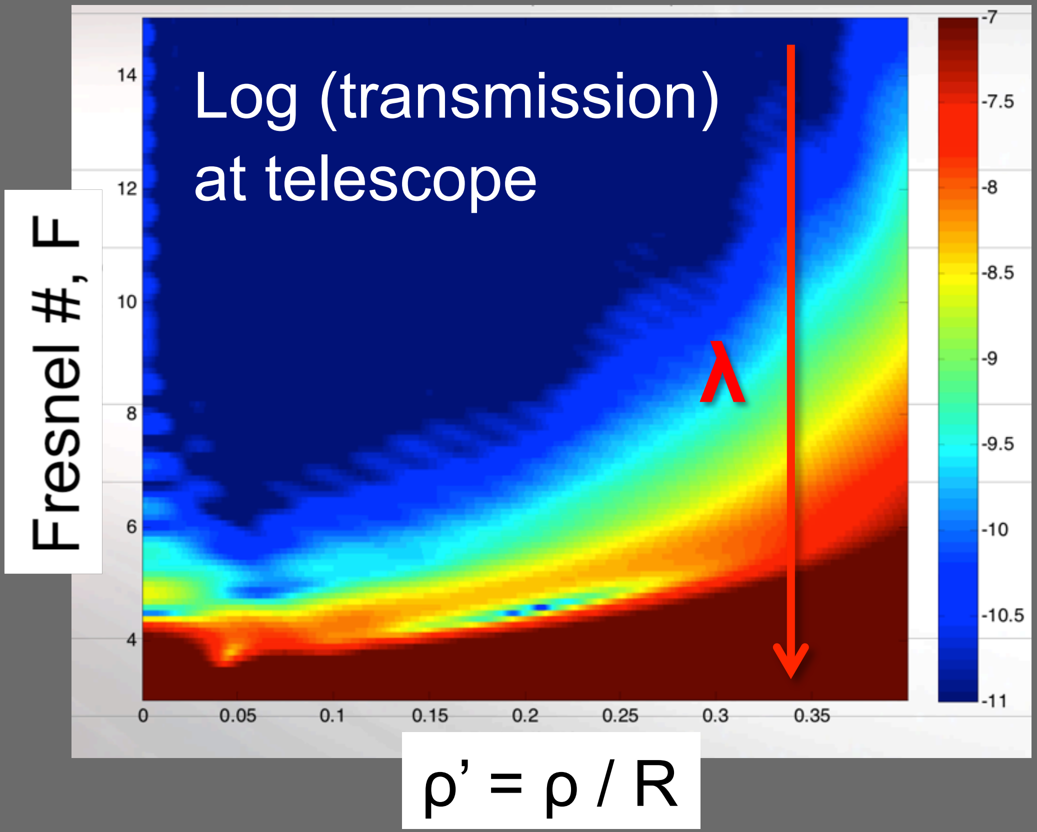


Wavelength dependence



Scaling a hypergaussian starshade

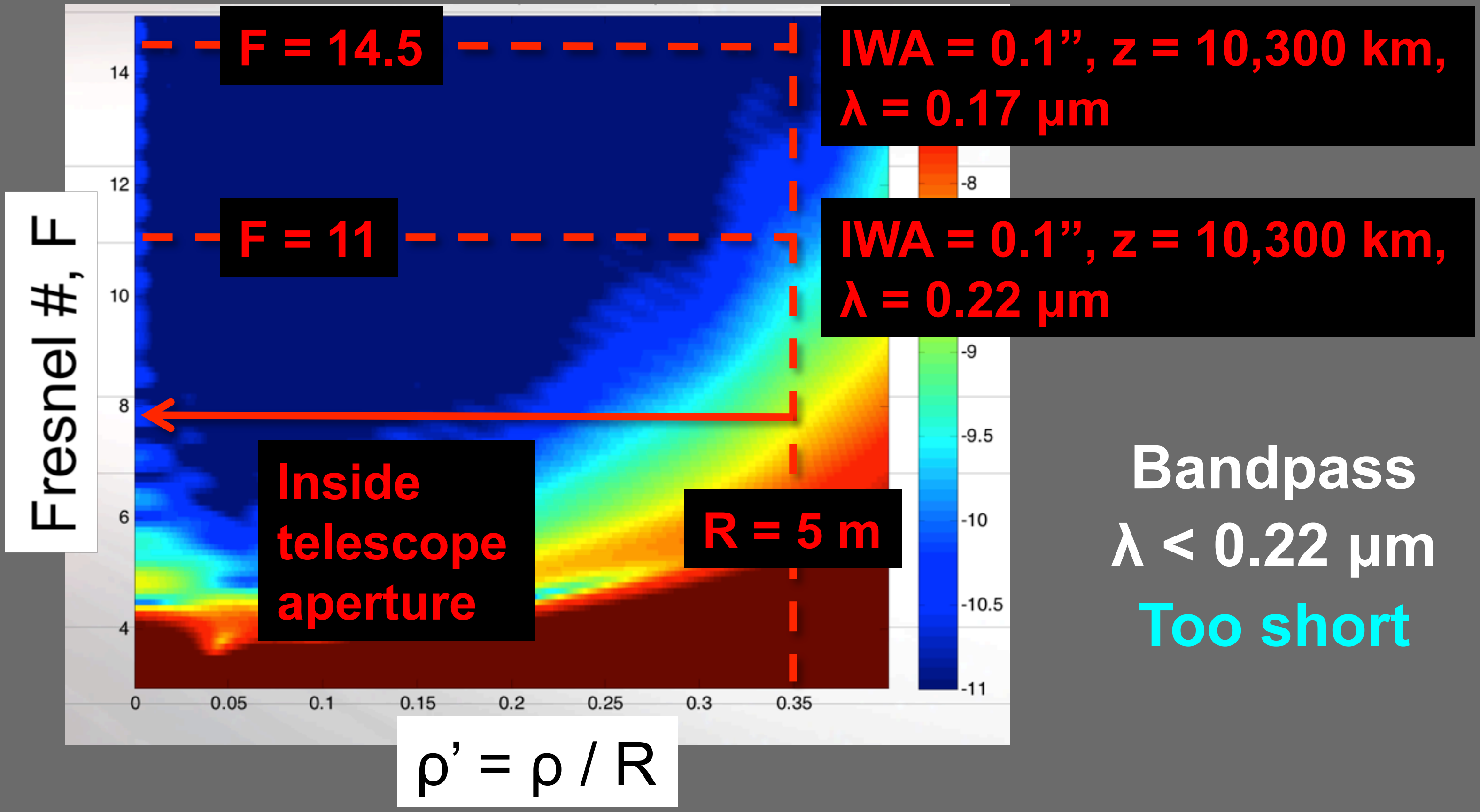
- Fresnel #:
  $F = R^2 / (\lambda z)$
- For a given λ, IWA:
  $R = F \times \lambda / IWA$
  $z = F \times \lambda / IWA^2$
- For a given R, IWA:
  $F = R \times IWA / \lambda$



Credit: C. Noecker

Small starshade

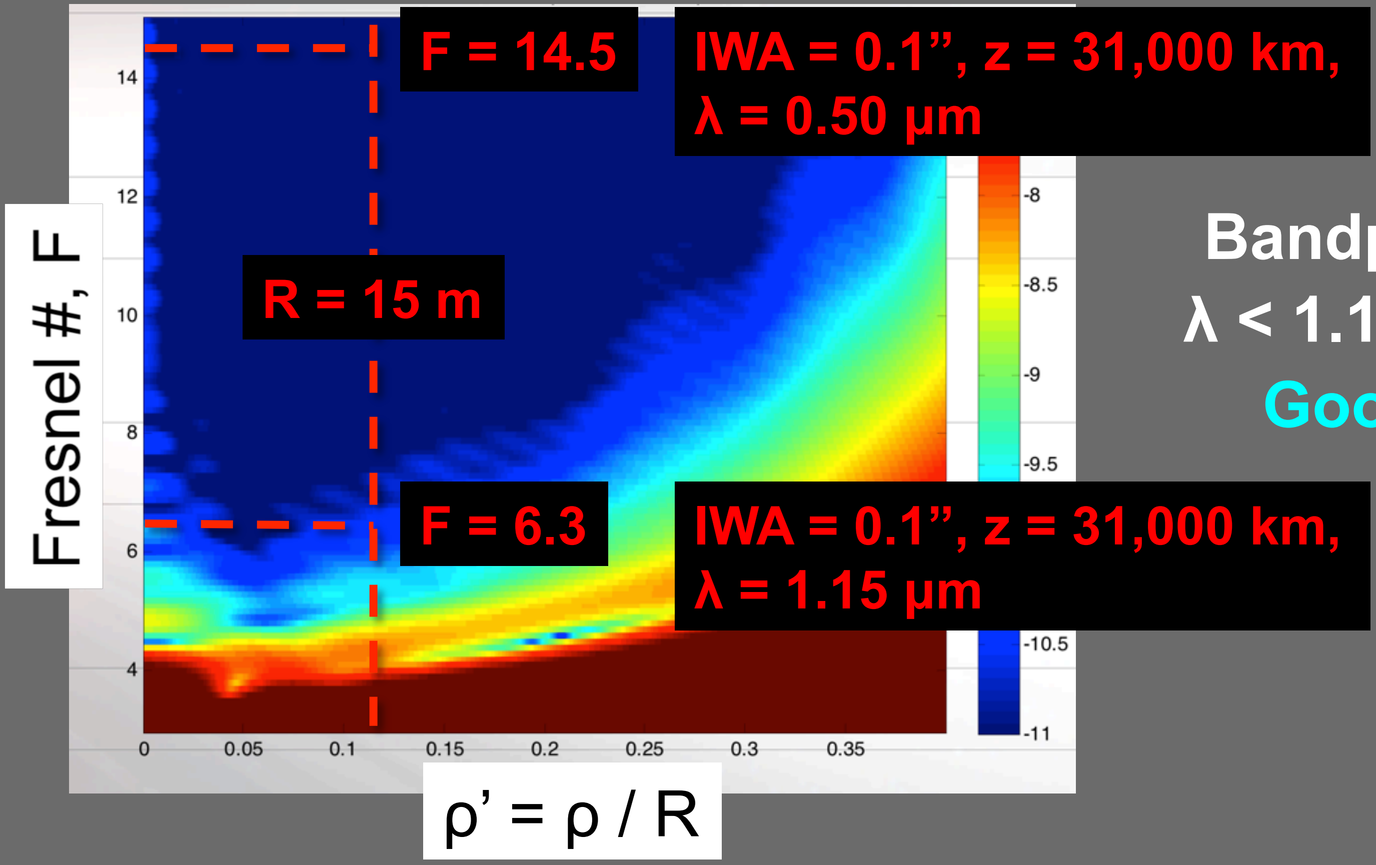
- D = 1.5 m, R = 5 m, ρ_{max} = 1.75 m, ρ'_{max} = 0.35
- Want contrast = 10^{-10} or better : blue region



Bandpass
λ < 0.22 μm
Too short

Larger starshade

- D = 1.5 m, R = 15 m, ρ_{max} = 1.75 m, ρ'_{max} = 0.12
- Want contrast = 10^{-10} or better : blue region

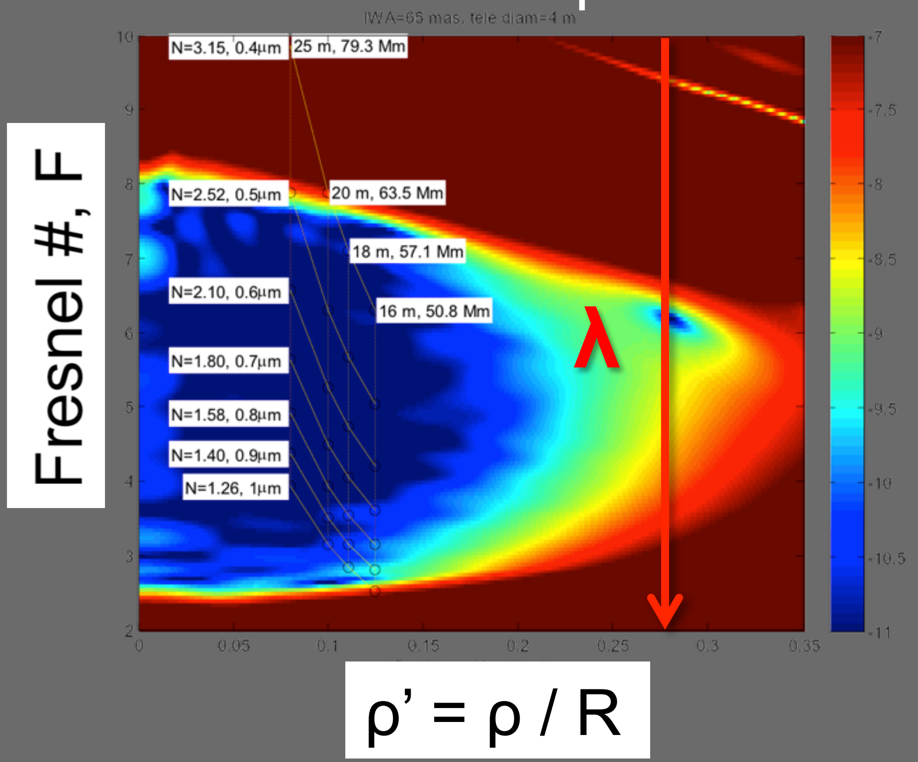


Bandpass
λ < 1.15 μm
Good!

Optimal starshade differences

- Numerically calculated optimal starshade is smaller for same contrast
- But it has a short-wavelength cutoff

Log (transmission) at telescope



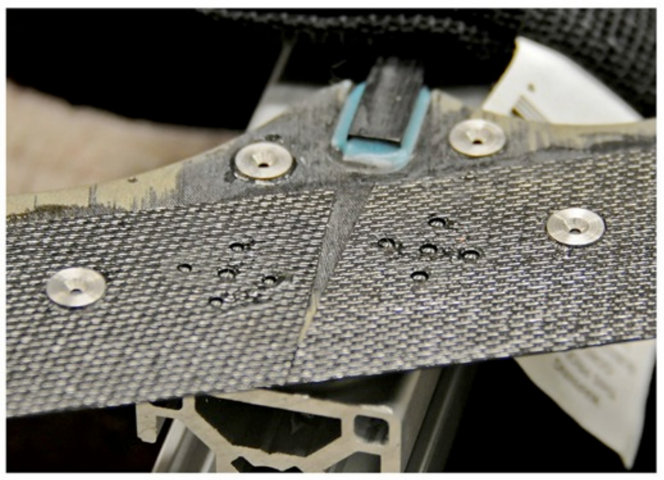
Credit: C. Noecker

Starshade behavior summary

- Redder bandpass needs larger starshade
- Larger starshade has to be further away to get same IWA
- If starshade is further away, longer slew times for retargeting
- Hypergaussian starshade size set to achieve desired contrast at longest wavelength of interest
- Numerically calculated optimal starshade is smaller for same contrast but has a short wavelength cutoff

Technical challenges

- Precise edge profile (~ 50 μm tolerance) required over large structure
- Knife-edge to prevent sunlight scattering into telescope
- On-orbit deployment of large structure
- Precise alignment between starshade and telescope needed (± 1 meter tolerance). Soft requirement



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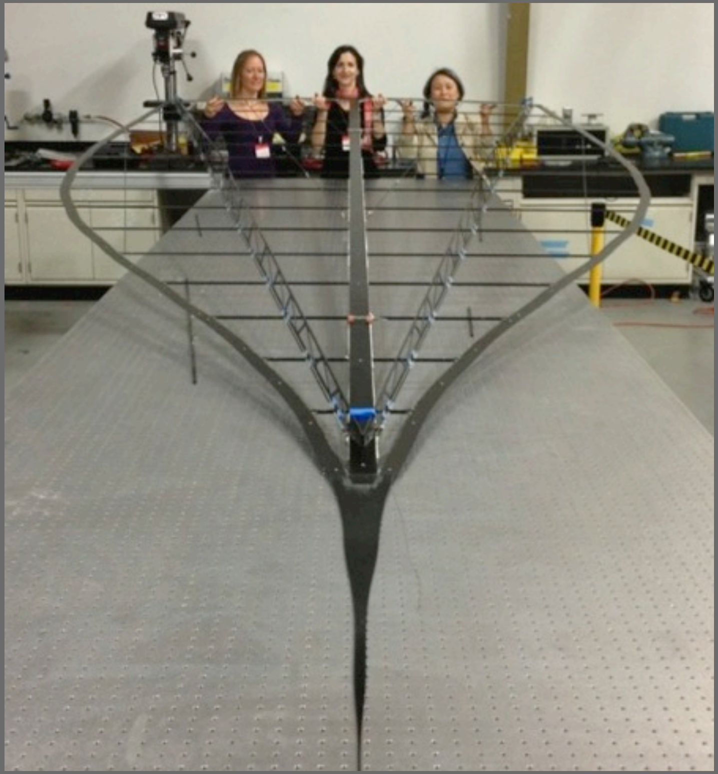
Precision petal manufacturing

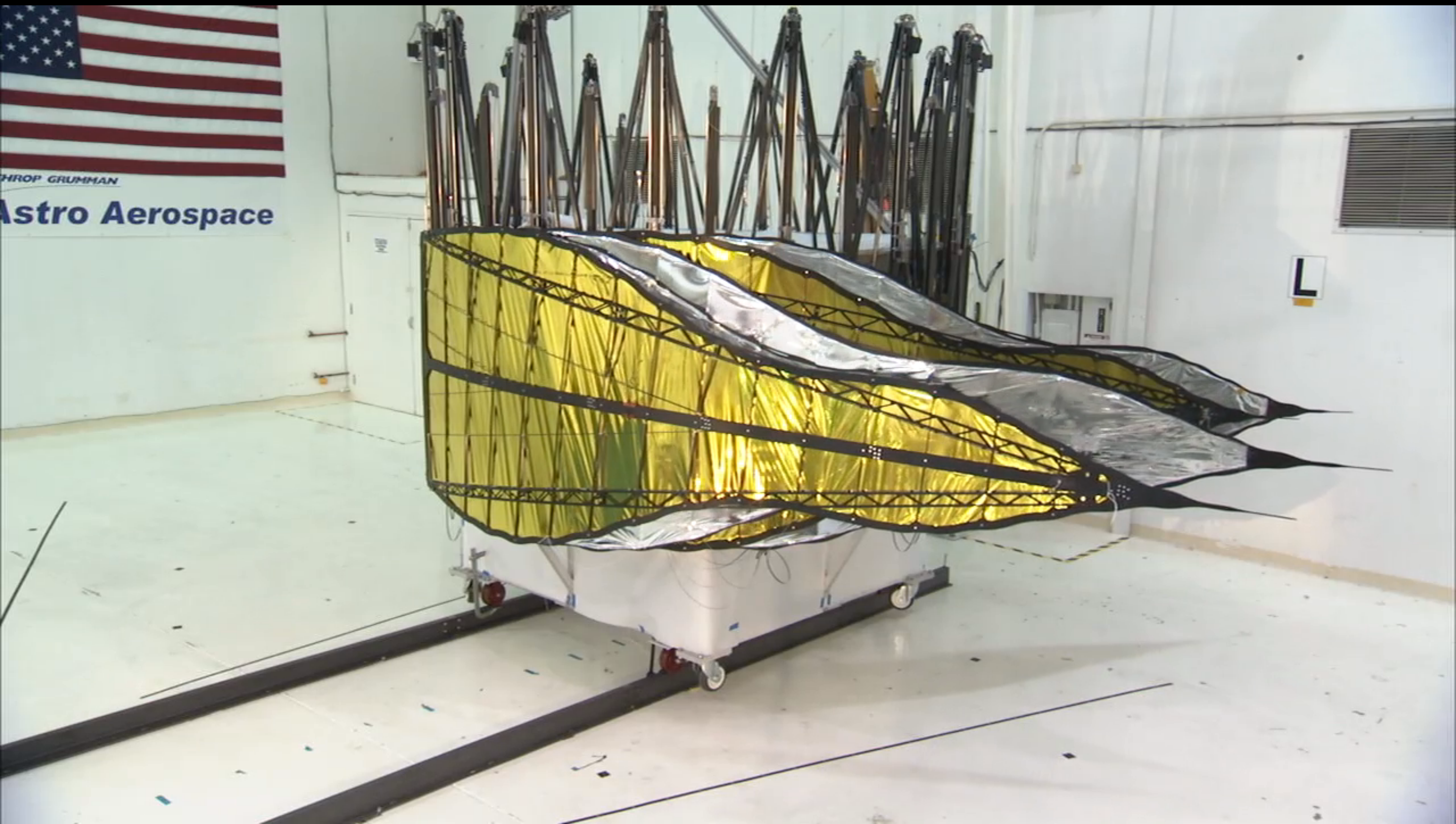
Full-scale petal with edge profile for contrast < 10^{-10}



Credit: D. Lisman

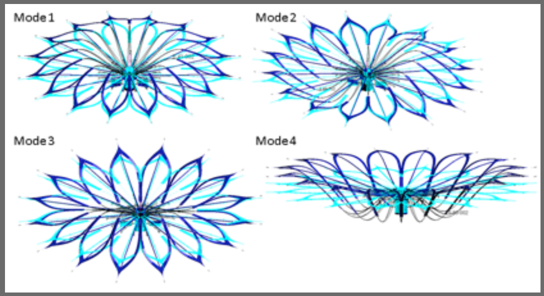
Development of knife-edge to control edge scatter underway

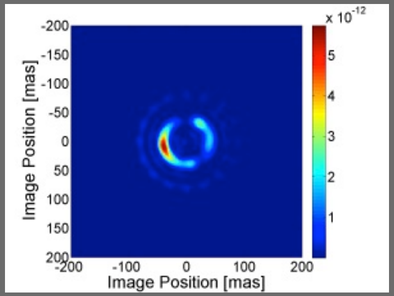
Deployment demonstration



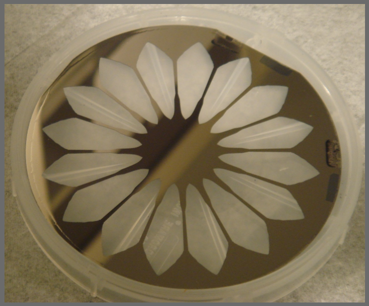
Contrast demonstrations

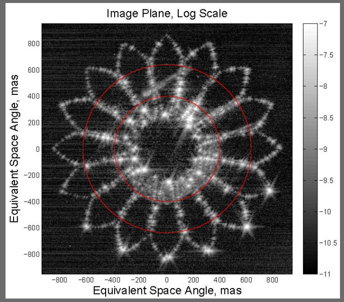
Optical models with distortions
monochromatic: 10^{-12}





0.1% scale lab testing
monochromatic: 10^{-10}





~ 1% scale field testing
50% bandpass: 10^{-8}

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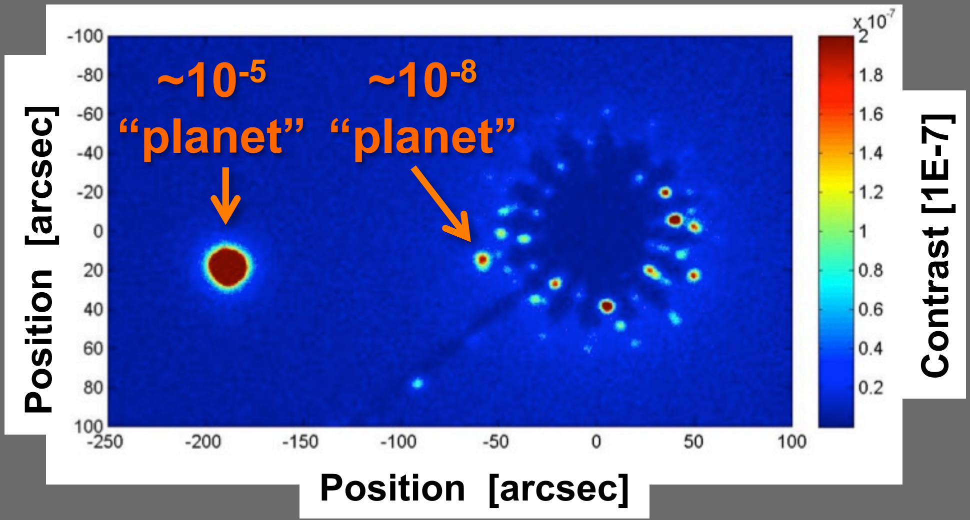

More info

Cash, W. (2006). “Detection of Earth-like planets around nearby stars using a petal-shaped occulter.” Nature, 442, 51

Vanderbei, R., Cady, E., & Kasdin, N. J. (2007). “Optimal Occulter Design for Finding Extrasolar Planets.” ApJ, 665, 794

Shaklan, S., et al. (2010). “Error budgeting and tolerancing of starshades for exoplanet detection”, SPIE, 77312G http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=749972

Kasdin, N. J., et al. (2013). “Recent progress on external occulter technology for imaging exosolar planets.” http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6497155