NIAC Annual Meeting
New Worlds Imager

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University of Colorado
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New Worlds Contributors

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and growing…

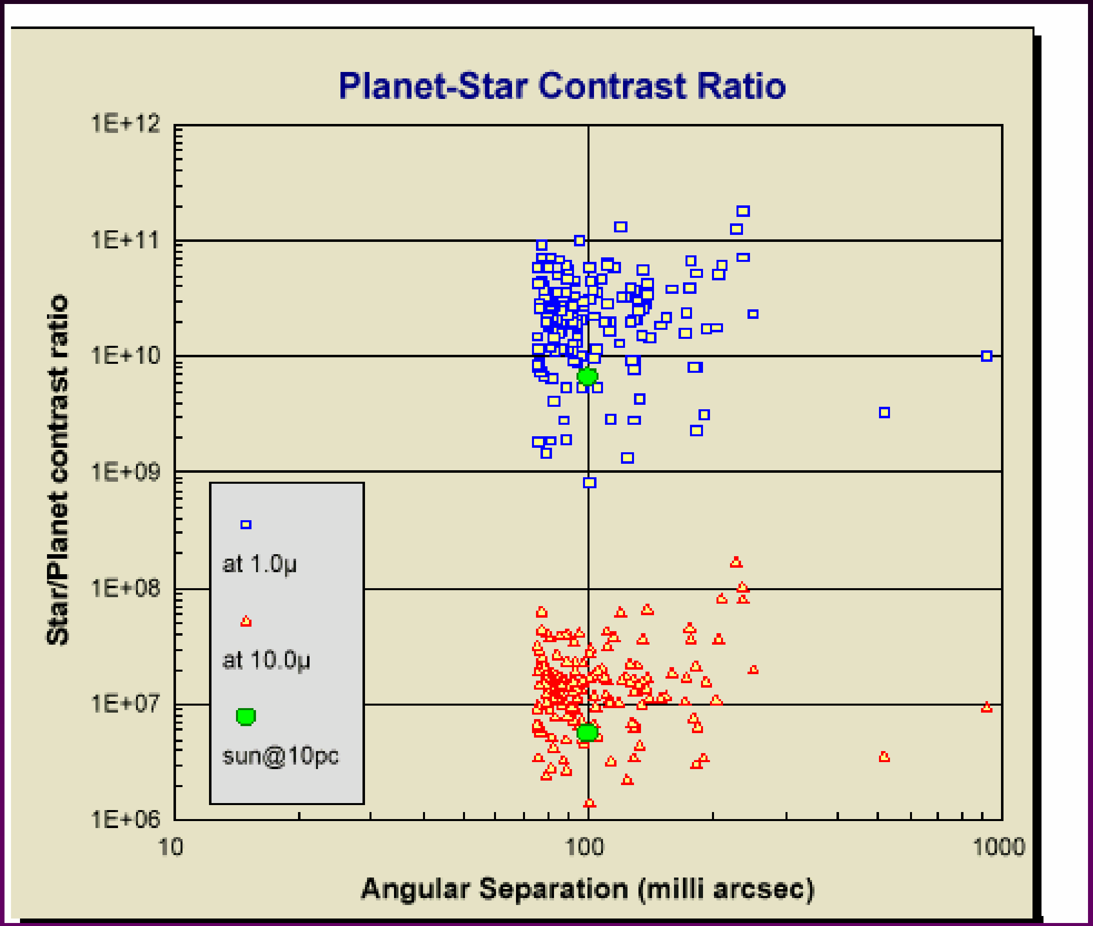
Exo-Planets

- ☞Exo-planets are the planets that circle stars other than our Sun.
- ☞There are probably 10,000 exo-planets within 10pc (30 light years) of the Earth. Indirect means have now found over 200.
- ☞ If we can observe them directly, we will have a new field of astronomy every bit as rich as extragalactic.

Planet Finding: Extinguish the Star

Contrast ratios better than 10 billion to one needed across a tenth of an arcsecond.

Wow. That's tough!

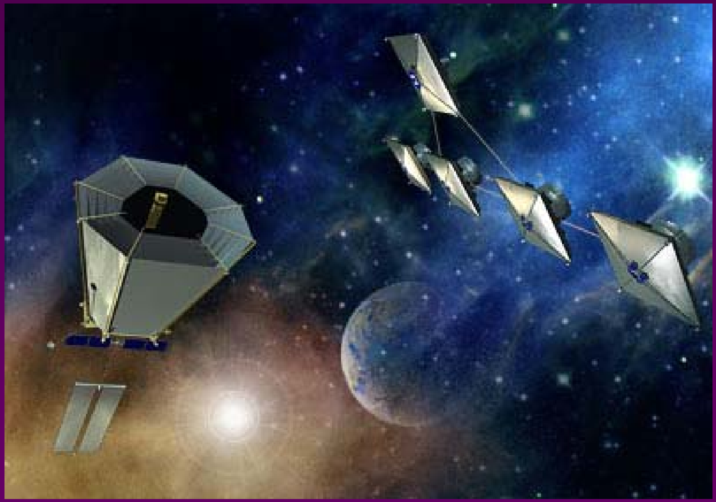


Cartesy of NG

Terrestrial Planet Finder

- ☞ Telescopes must be corrected to *PERFECTION*
  - – to suppress scatter: $\lambda/5000$ surface, 99.999% reflection uniformity

- ☞ TPF is *very* difficult
- ☞ NASA has not been good to TPF lately.
  - ➢ They are on indefinite hold.
- ☞ Is there any easier way?

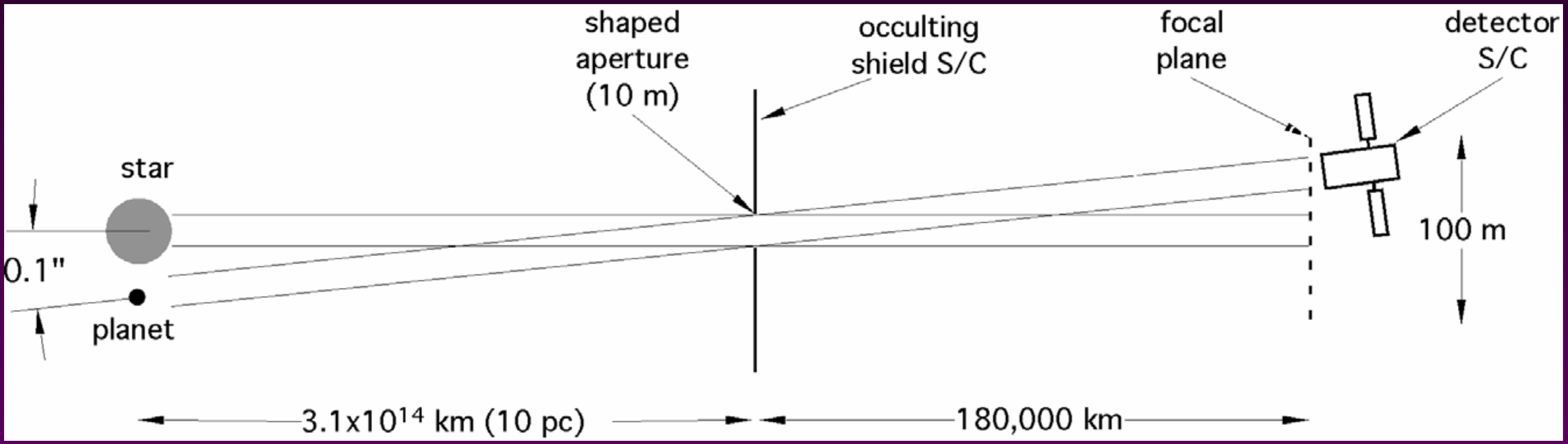


History of New Worlds

- ☞ 2003 – Started looking at TPF alternatives
  - ➢ Pinhole Camera Idea Came First
- ☞ 2003 – Proposed for Vision Mission – rejected
- ☞ 2004 – Proposed to NIAC – accepted
- ☞ 2005 – Solved Occulter Problem
  - ➢ Phase II Proposal Written and Accepted
- ☞ 2006 – New Worlds Discoverer -- ???

A Pinhole Camera Meets The Requirements:

Perfect Transmission
No Phase Errors
Scatter only from edges – can be very low

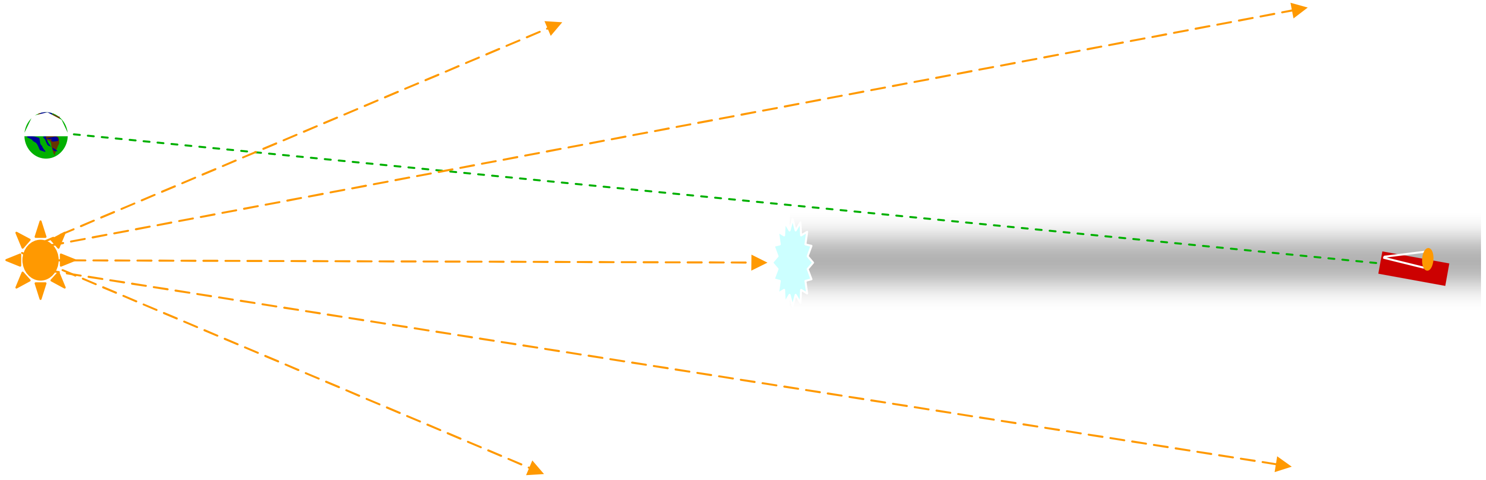


Large Distance Set by 0.01 arcsec requirement

diffraction: $\lambda/D = .01'' \rightarrow D = 10\text{m}$ @500nm

geometric: $F = D/\tan(.01'') = 180{,}000\text{km}$

Occulter Diagram



Telescope big enough to collect enough light from planet

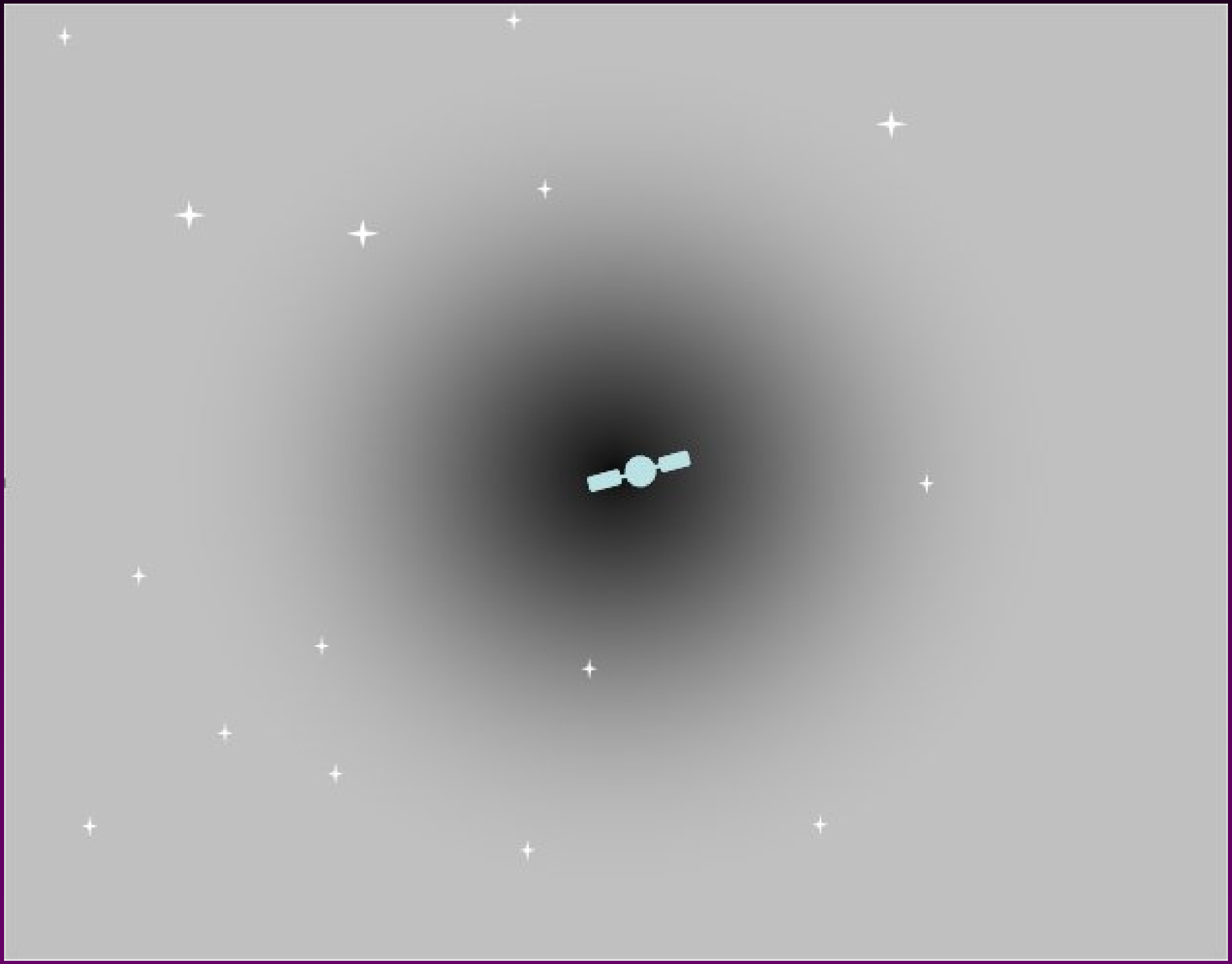
Occulter big enough to block star

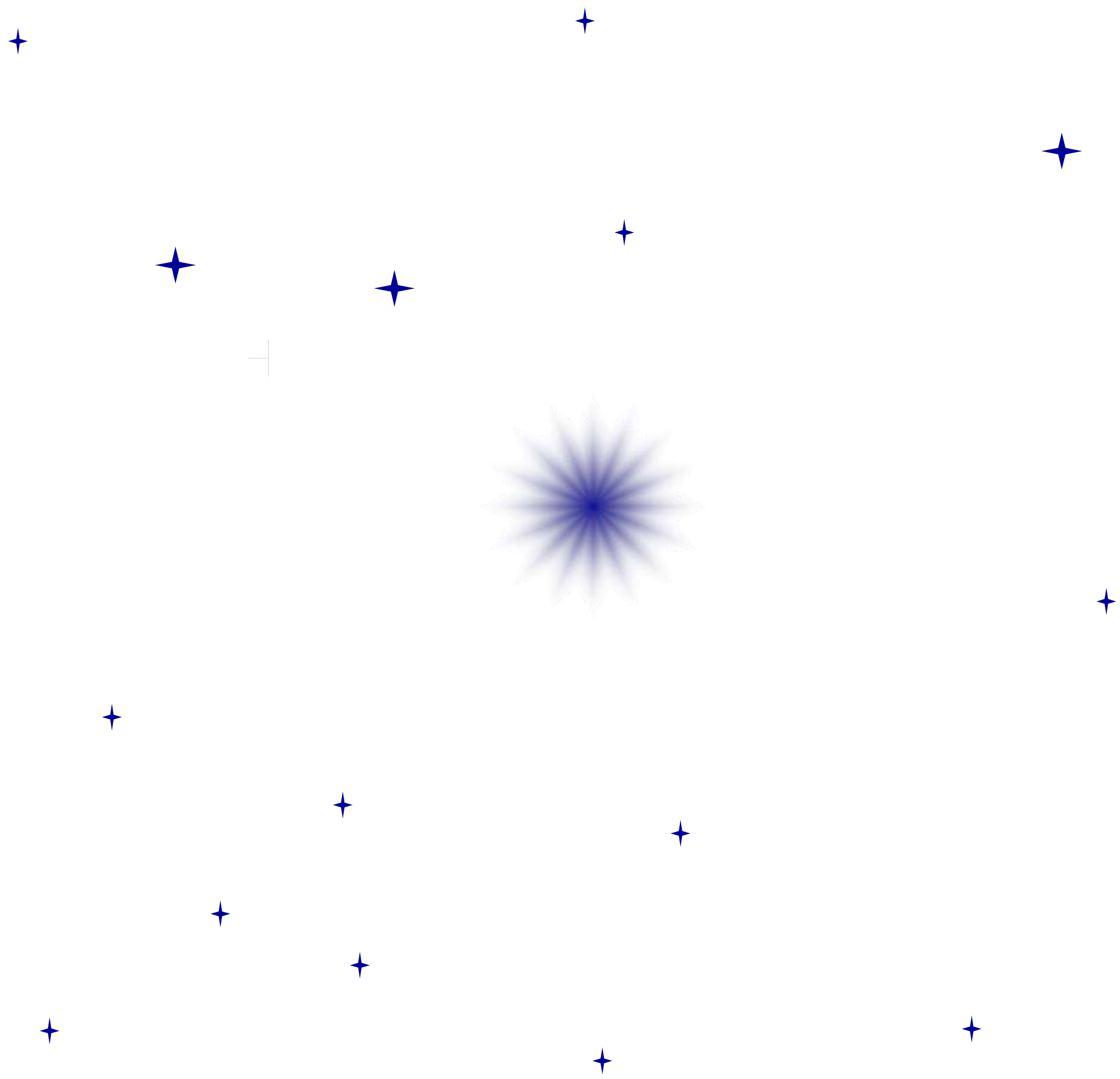
Want low transmission on axis and high transmission off axis

Telescope far enough back to have a properly small IWA

No outer working angle: View entire system at once

Fly the Telescope into the Shadow





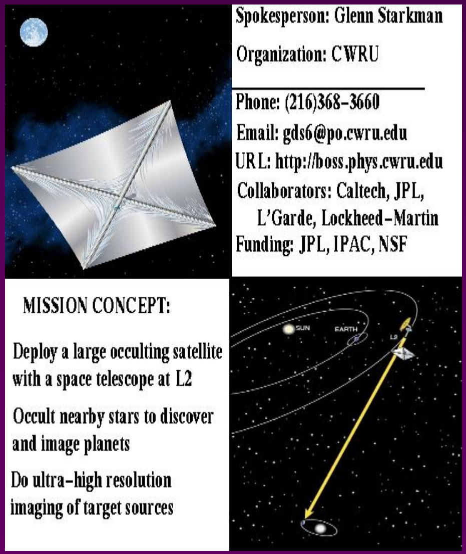
Why Pinhole Camera?
Why Not Occulter?

- ☞Because →
- ☞Everybody knows that diffraction around an occulter is too severe

Occulters

- ☞ Several previous programs have looked at occulters
  - – First look by Spitzer (1962)
- ☞ Used simple geometric shapes
  - – Achieved only 10^{-2} suppression across a broad spectral band
- ☞ With transmissive shades
  - – Achieved only 10^{-4} suppression despite scatter problem

http://umbras.org/



BOSS

Starkman (TRW ca 2000)

Extinguishing Poisson's Spot

- ☞ Occulters Have Very Poor Diffraction Performance
  - The 1818 Prediction of Fresnel led to the famous episode of:
  - Poisson's Spot (variously Arago's Spot)
  - Occulters Often Concentrate Light!

- ☞ Must satisfy Fresnel Equation, Not Just the Fraunhoffer Equation

- ☞ Must Create a Zone That Is:
  - Deep   Below 10^{-10} diffraction
  - Wide   A couple meters minimum
  - Broad   Suppress across at least one octave of spectrum

- ☞ Must Be Practical
  - Binary   Non-transmitting to avoid scatter
  - Size   Below 150m Diameter
  - Tolerance   Insensitive to microscopic errors

The Apodization Function

Found this in April. Extended in June.

This Function Extinguishes Poisson's Spot to High Precision

$$A(\rho) = 0$$

for $\rho < a$

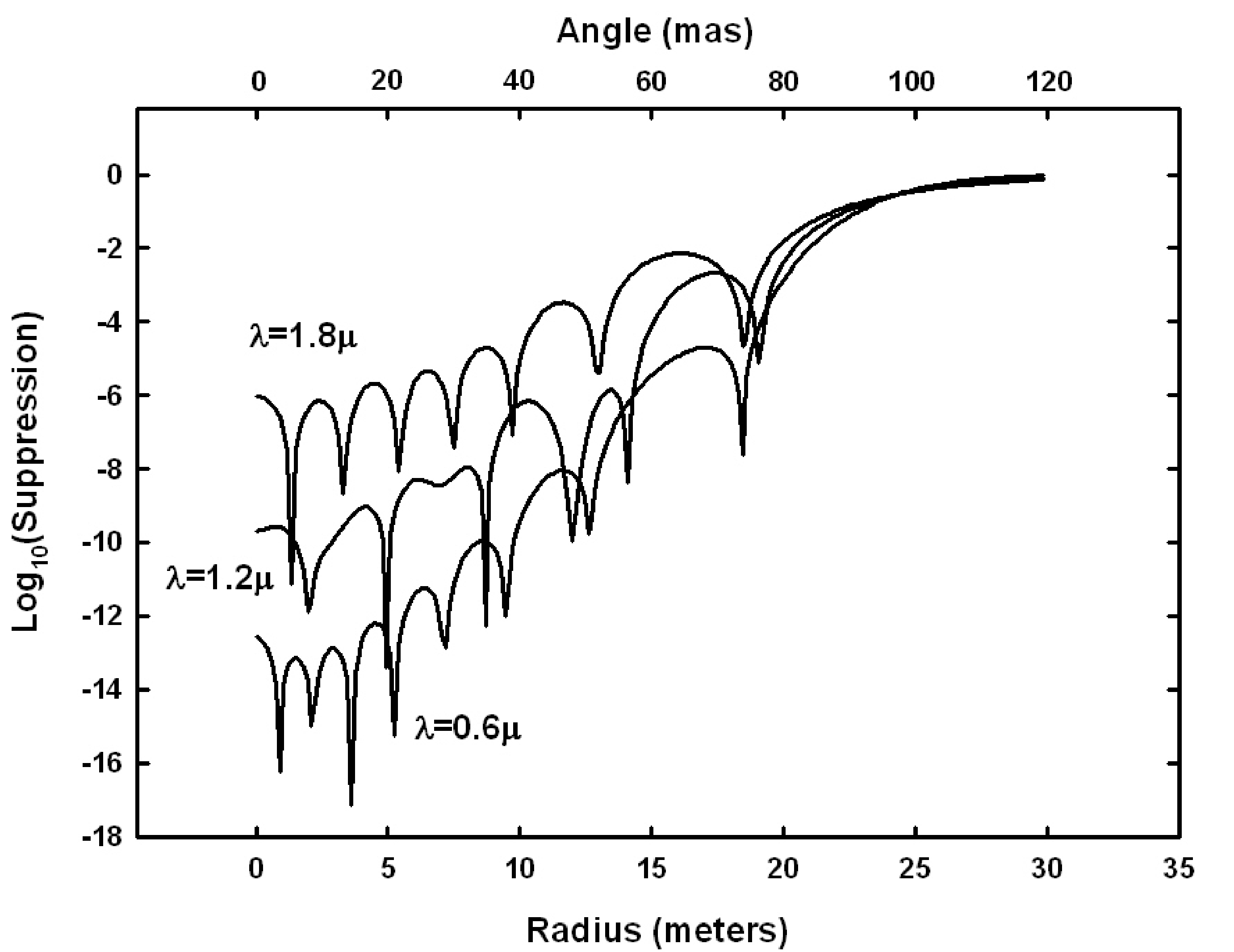
and

$$A(\rho) = 1 - e^{-\left(\frac{\rho - a}{b}\right)^{n}}$$

for $\rho > a$

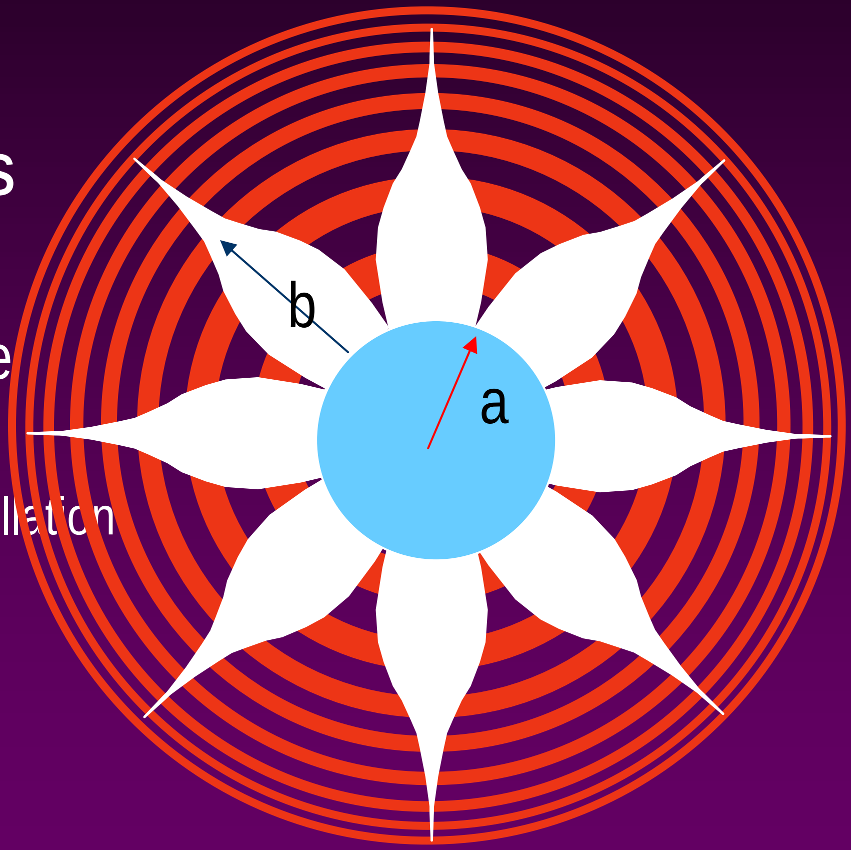
Off Axis Performance

☞The off axis performance shows a rapid rise to unit transmission for the radii greater than the inner edge of the habitable zone



Suppression of Edge Diffraction Can Be Understood Using Fresnel Zones and Geometry

- ☞The occulter is a true binary optic
  - Transmission is unity or nil
- ☞Edge diffraction from solid disk is suppressed by cancellation
  - The power in the even zones cancels the power in the odd zones
    - ➢Need enough zones to give good deep cancellation
      - Sets the length of the petals
  - Petal shape is exponential
    - ➢b is scale of petal shape
    - ➢n is an index of petal shape
    - ➢a is the diameter of the central circle



Doing the Math (Cash, Nature 2006)

- The Residual Intensity in the Shadow is $$I_s = E_s^2$$
- By Babinet's Principle $$E_s = 1 - E_A$$ where E_A is field over Aperture
- So We Must Show

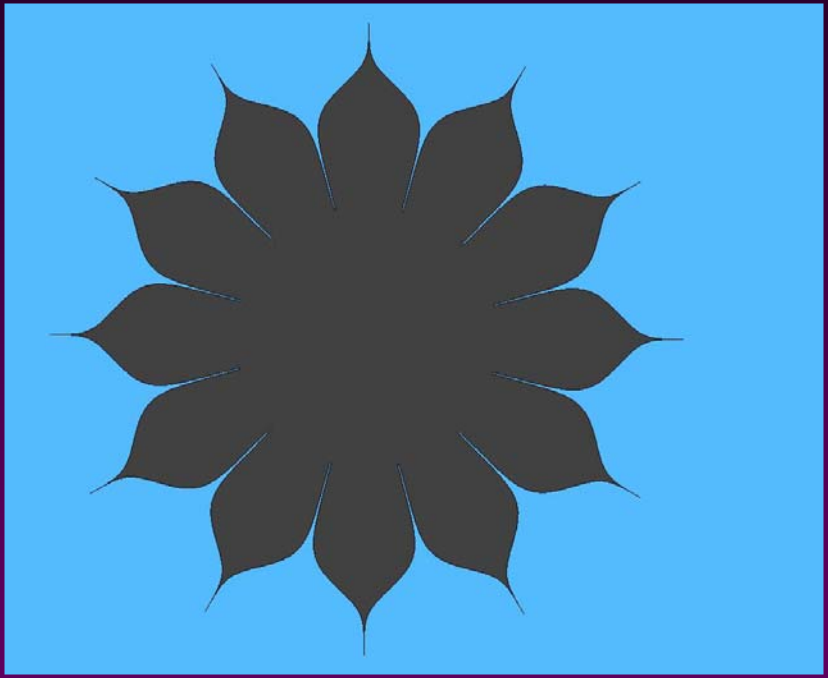
$$\frac{k}{2\pi F}\left[\int_0^{2\pi}\int_0^{a} e^{\frac{ik\rho^2}{2F}} e^{-\frac{ik\rho s\cos\theta}{F}} \rho\, d\rho\, d\theta + \int_0^{2\pi}\int_a^{\infty} e^{\frac{ik\rho^2}{2F}} e^{-\frac{ik\rho s\cos\theta}{F}} e^{-\left(\frac{\rho-a}{b}\right)^n} \rho\, d\rho\, d\theta\right] = i$$

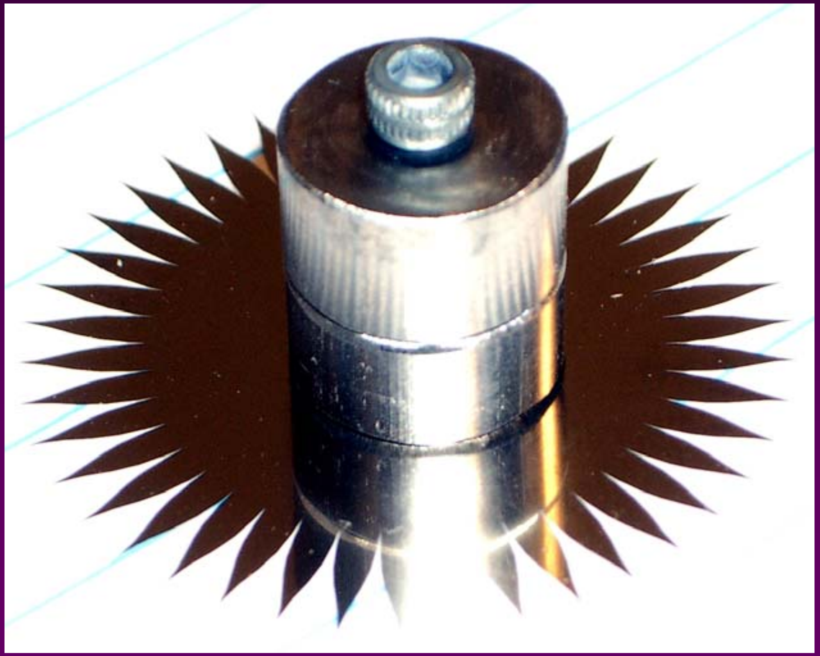
- *F* is distance to starshade, *s* is radius of hole, *k* is $2\pi/\lambda$
- To one part in $$\sqrt{C} \approx 10^{-5}$$

Contrast Ratio

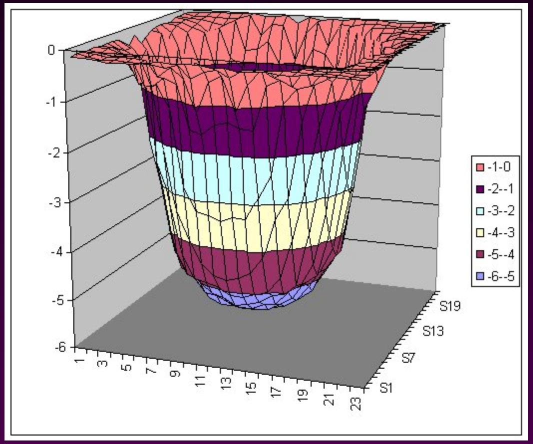
- ☞Preceding integral shows the contrast ratio is
  – $$R = \left[\frac{n!}{a^n b^n} \left(\frac{F\lambda}{2\pi} \right)^n \right]^2$$
  – n is an integer parameter, typically n=6
- ☞To keep R small a~b
  – this is the reason the occulter has that symmetric look

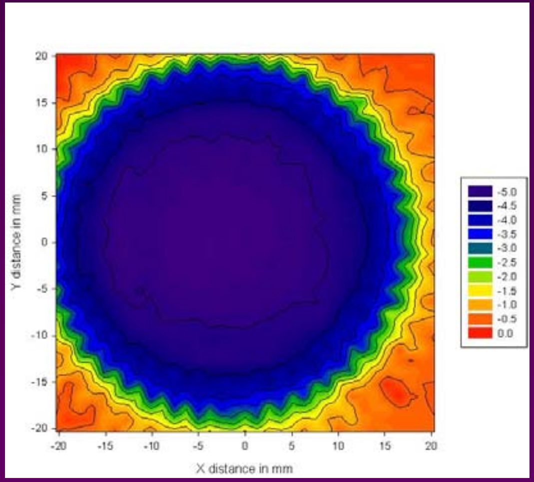
Scale Model Lab Demo





Data from Heliostat by Doug Leviton





Shadow Map
Bottom at $1\text{x}10^{-7}$

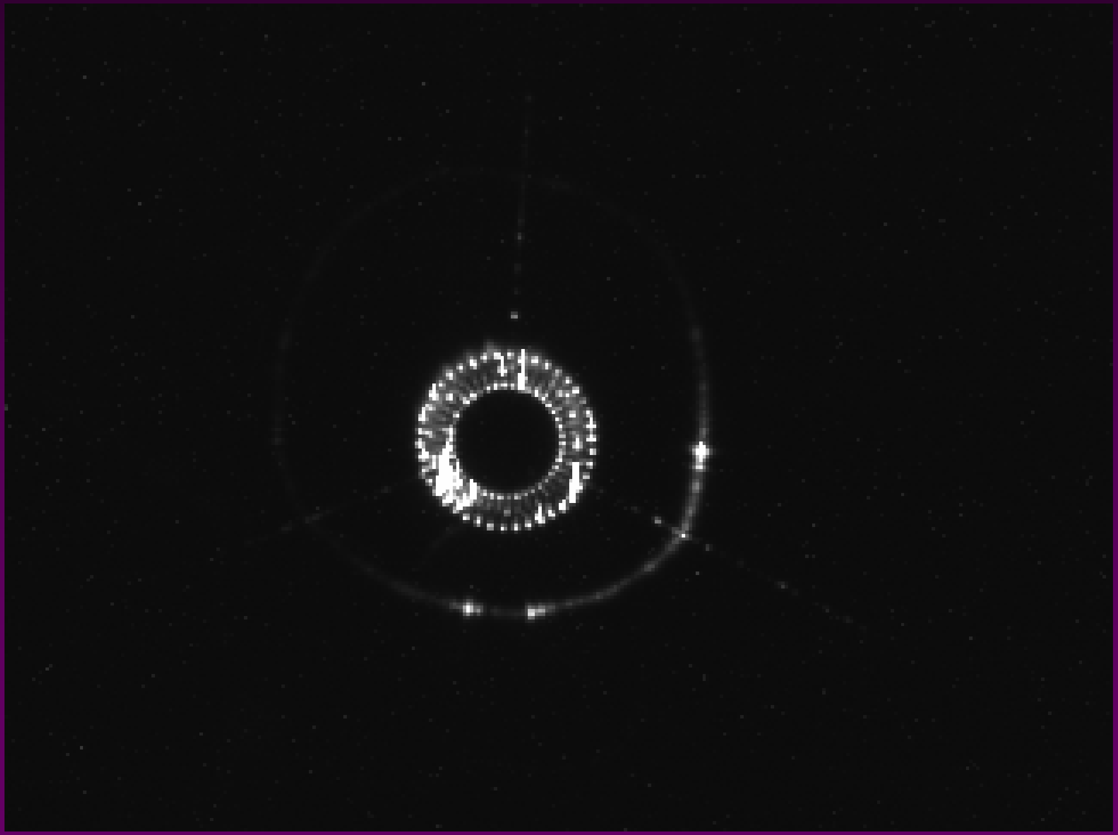


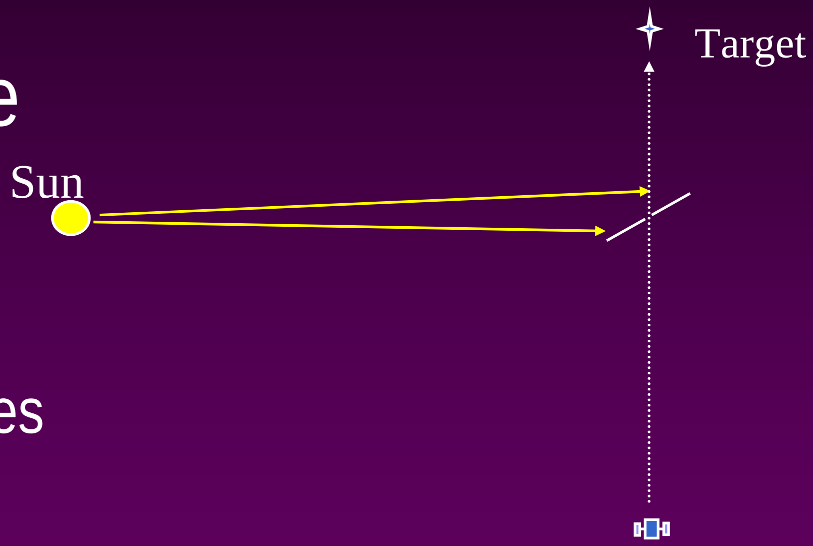
Image of Backlit Starshade

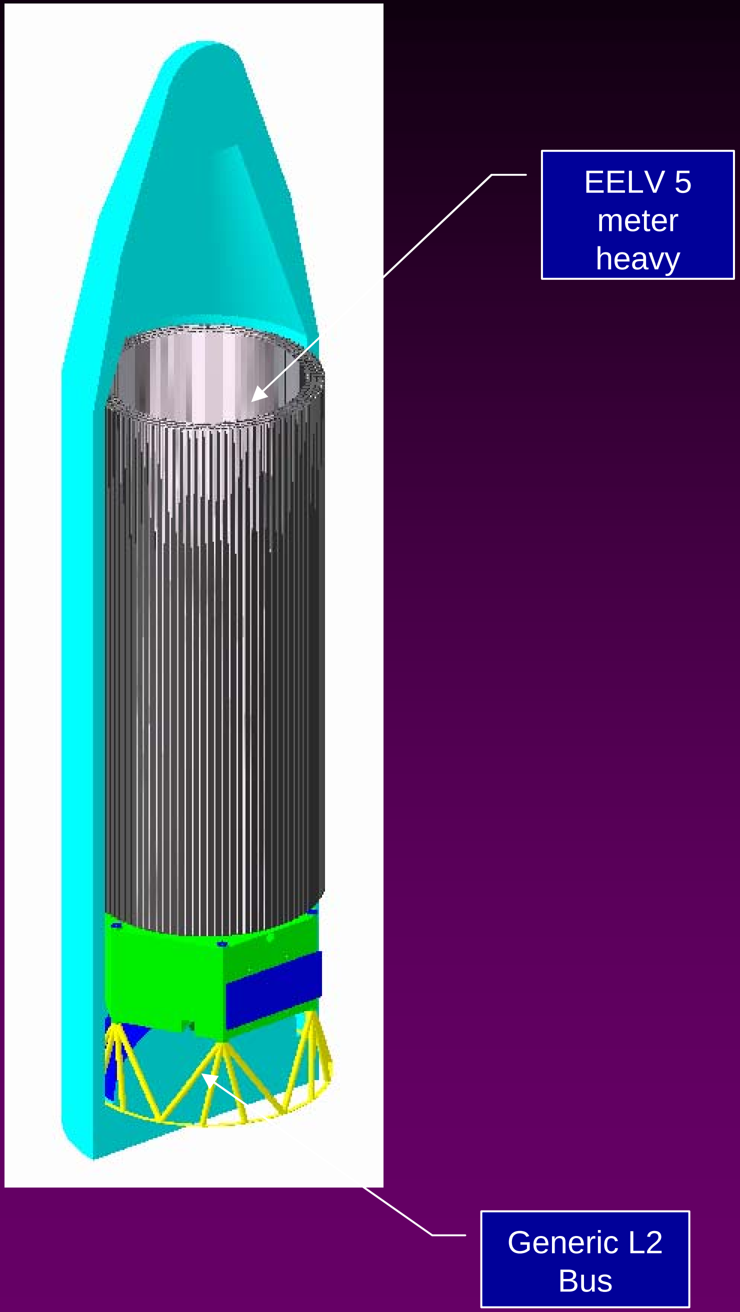
Tall Poles

- ☞ Deployment of 35m shade to mm class tolerance
- ☞ Acquiring and holding line of sight
- ☞ Fuel usage, orbits and number of targets
- ☞ Stray Light – particularly solar

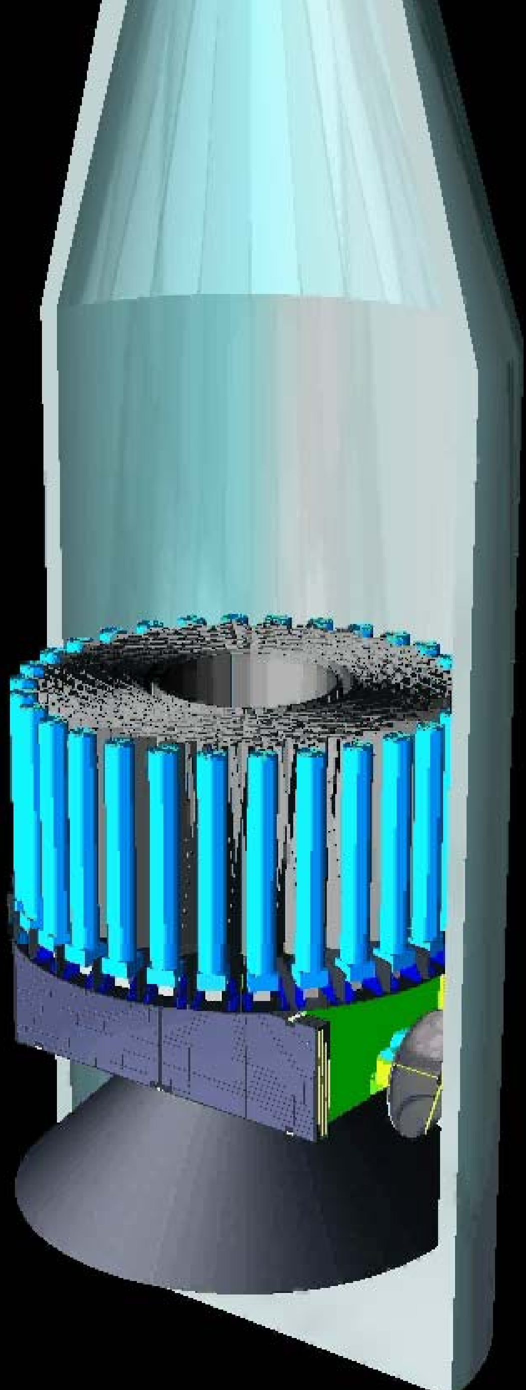
Another Issue: Scattered Light

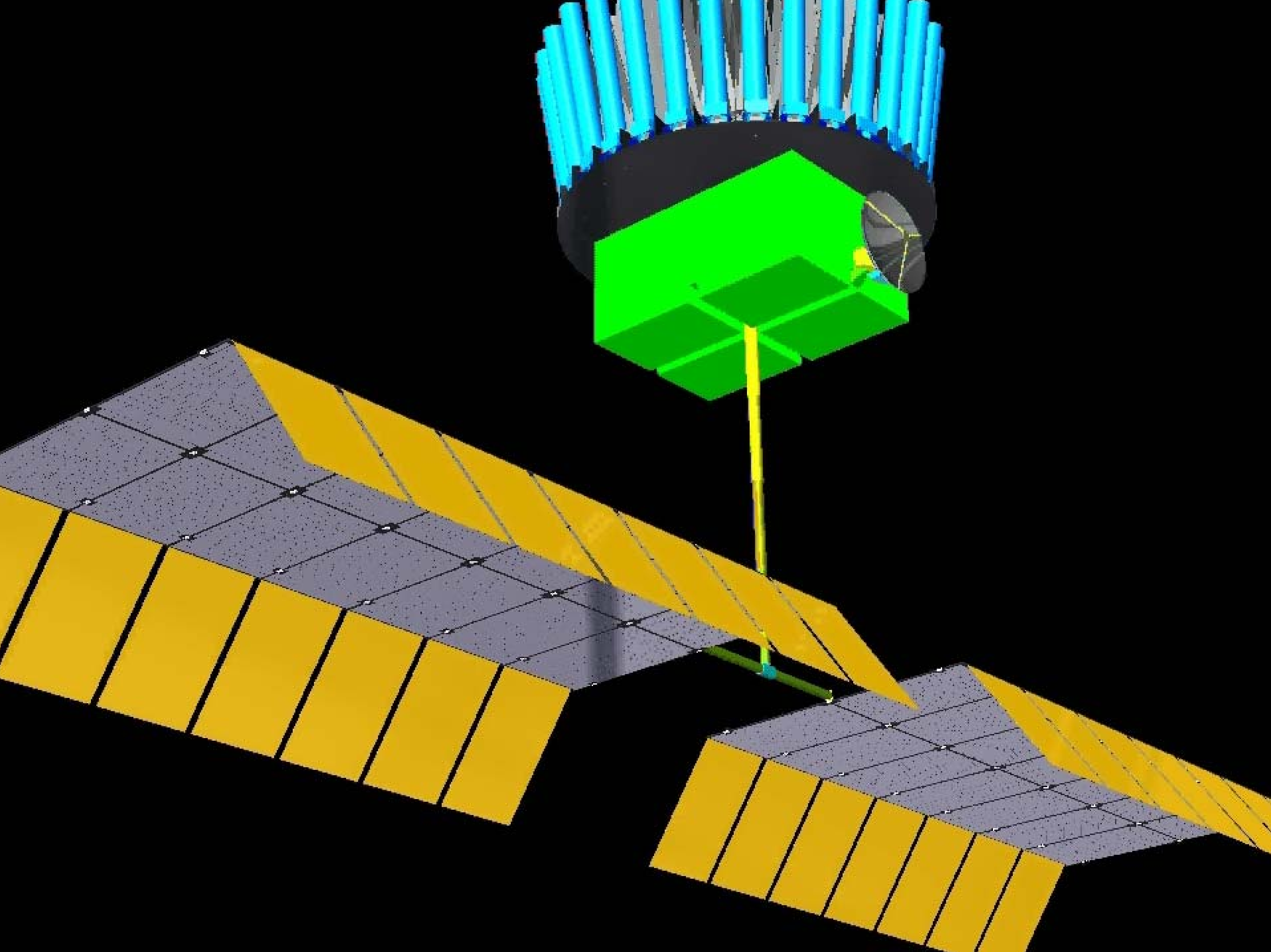
- ☞Sunlight Scatters Off Starshade
- ☞Can be Controlled in Multiple Ways
  - –Look at right angles to sun
    - ➢Imposes restrictions on revisit times
  - –Operate in shadow
    - ➢Earth's umbra
    - ➢With additional shade
      - Likely hard at L2
      - Easier in heliocentric orbit

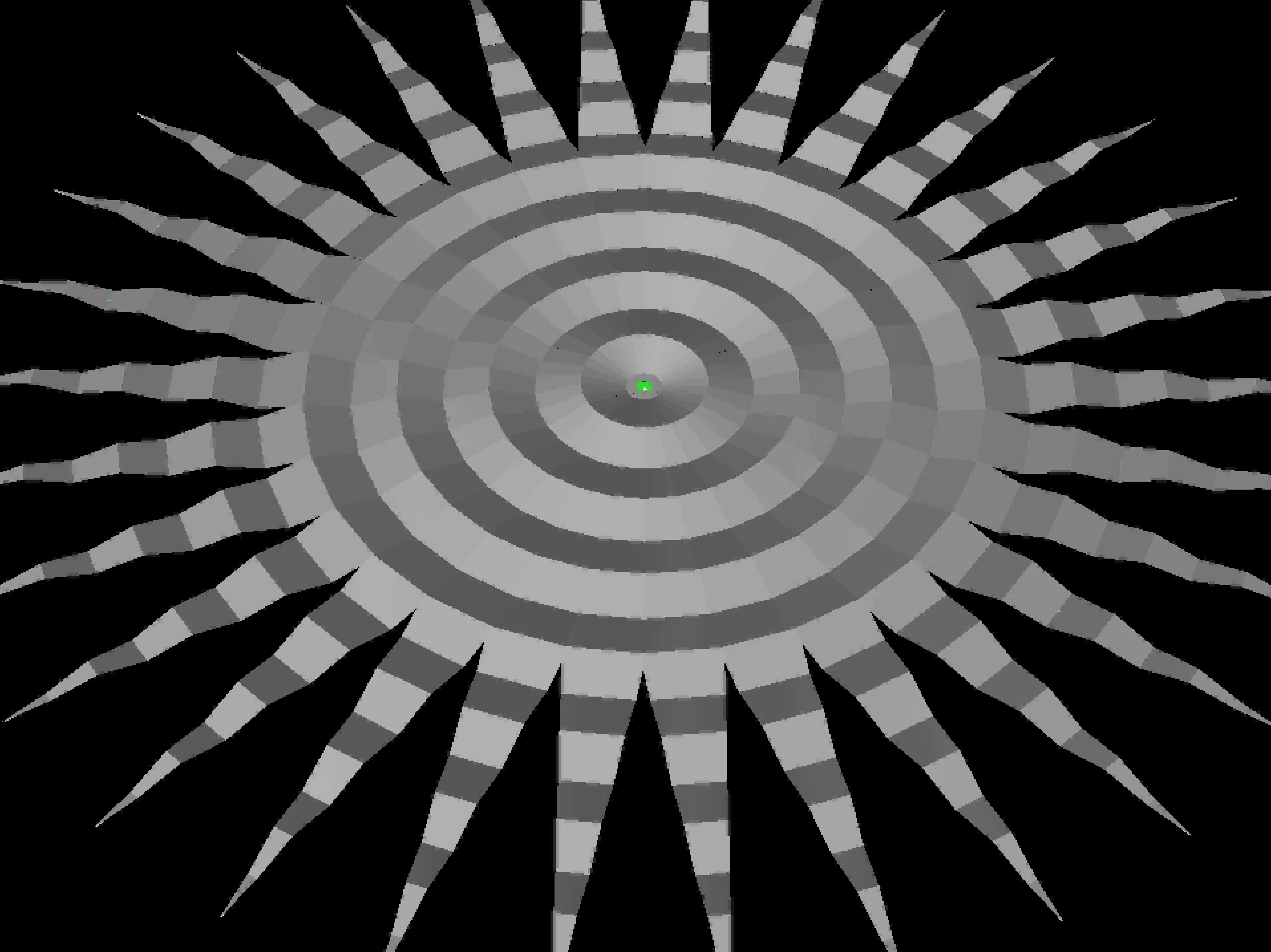




Up to 150 m New Worlds Observer Will Fit in an ELV Heavy







Starshade Tolerances

- Position
  - Lateral — Several Meters
  - Distance — Many Kilometers
- Angle
  - Rotational — None
  - Pitch/Yaw — Many Degrees
- Shape
  - Truncation — 1mm
  - Scale — 10%
  - Blob — $3cm^2$ or greater
- Holes
  - Single Hole — $3cm^2$
  - Pinholes — $3cm^2$ total

Sequence of Missions

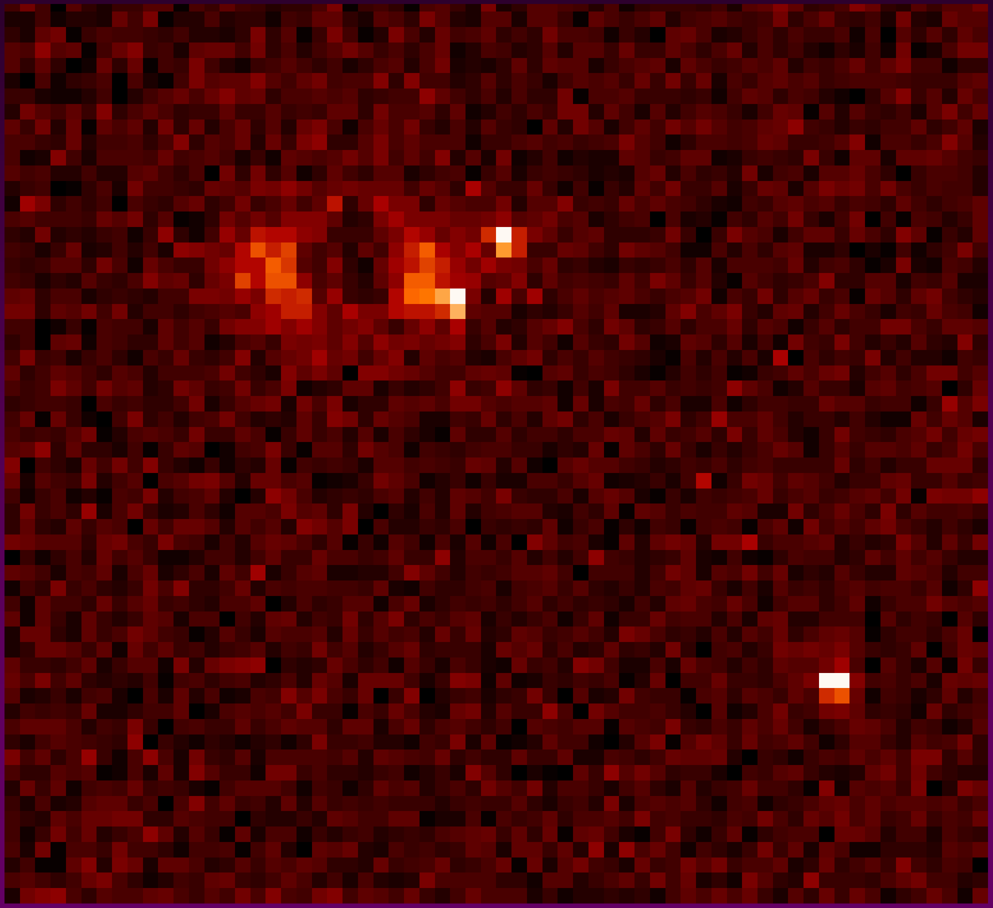
- New Worlds Discoverer
  - Technical pathfinder
  - TPF
- New Worlds Observer
  - Full optimized, 2-3 craft system
  - Lifefinder
- New Worlds Imager
  - Major long baseline interferometer
  - True planet images
  - Very Expensive
  - From the moon?

New Worlds Discoverer

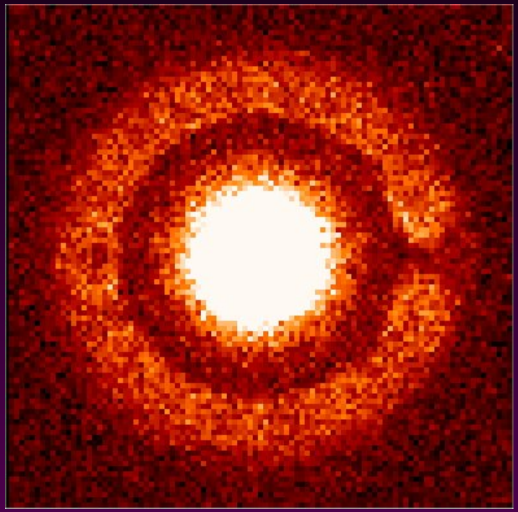
- To launch with JWST in 2013
- All formation flying requirements on starshade
  - JWST passive, just points
- Meets cost cap and technology readiness requirements
- Three year mission – circa 150 lines of sight
- Capable of detecting Earth to 10pc
- Spectroscopy of Jovian planets
- Earth spectroscopy marginal at best

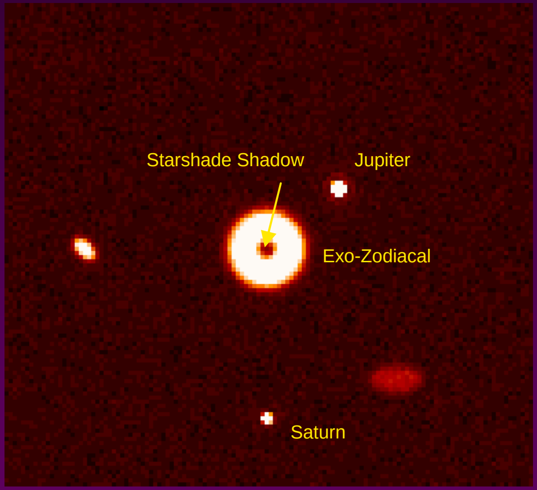
- Constitutes a low cost TPF

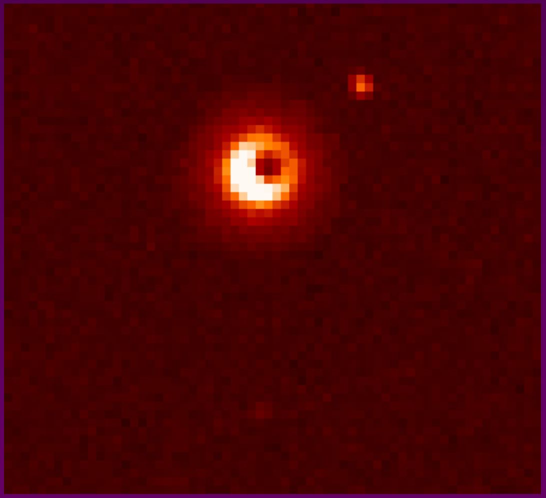
Simulated Solar System

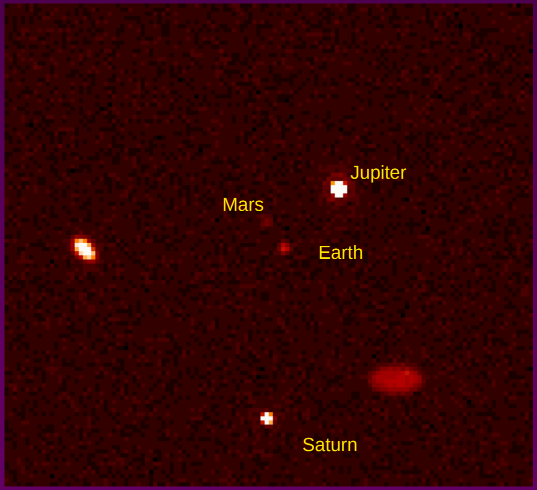


Discoverer Science Simulations

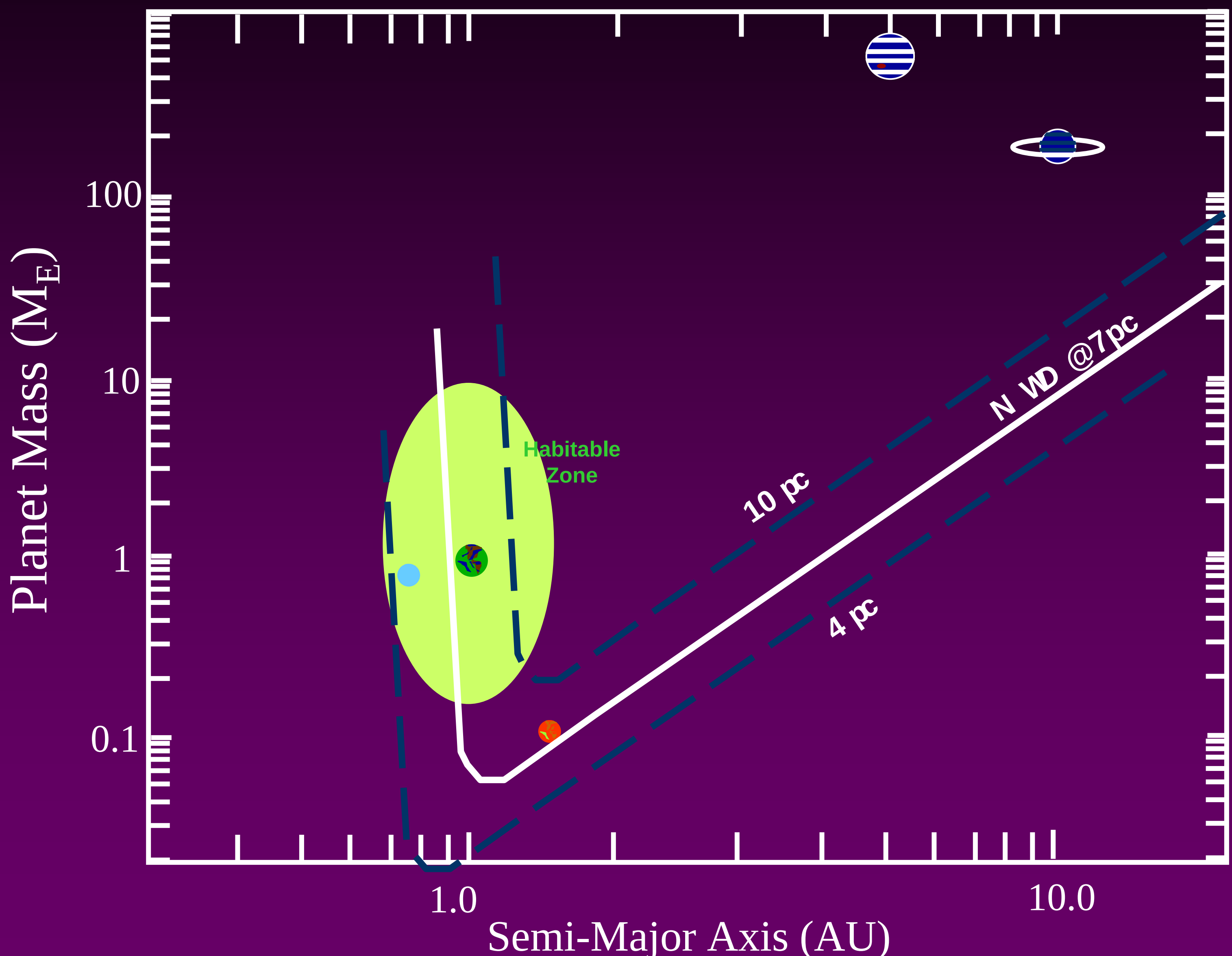








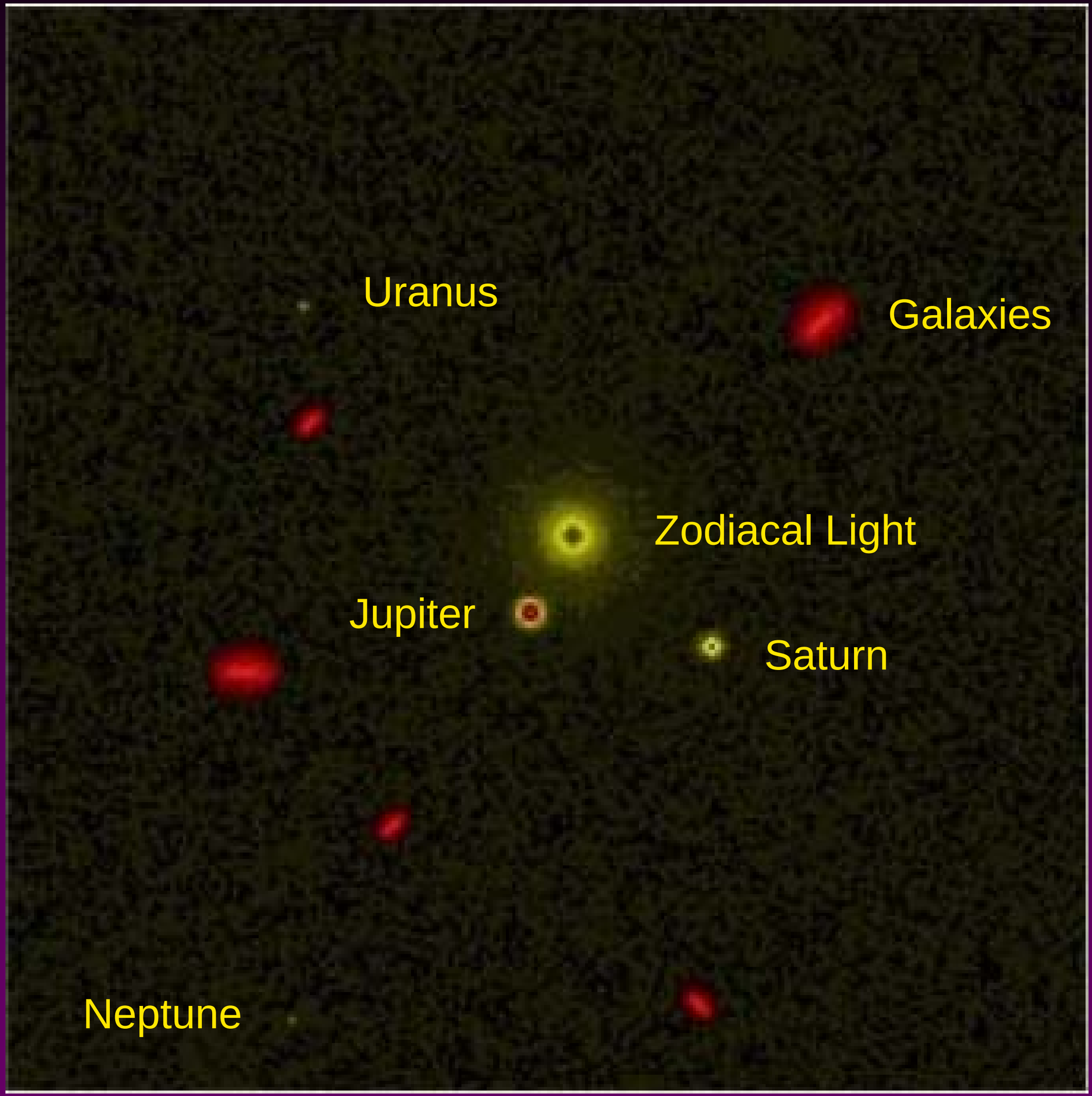
NWD Sensitivity



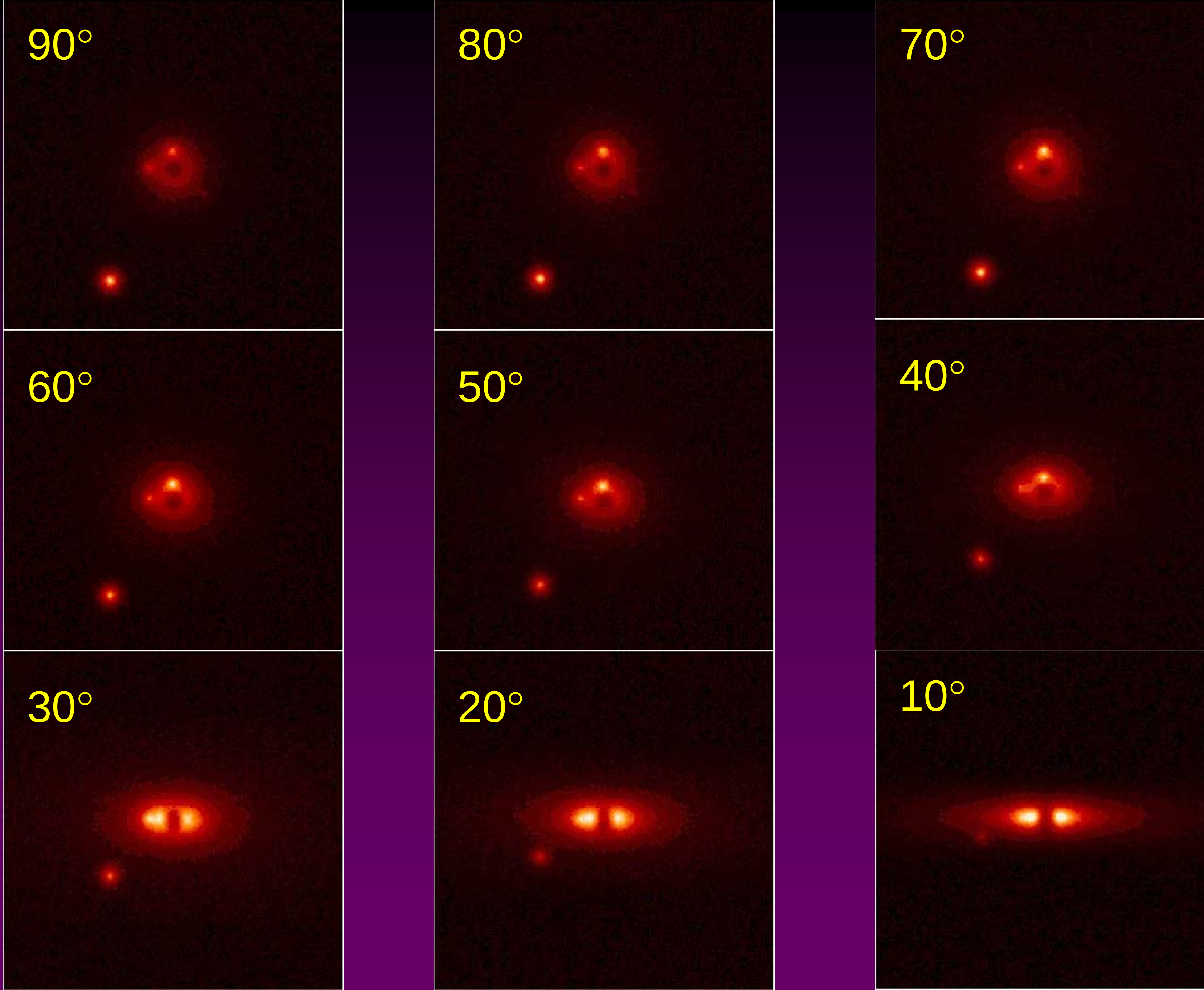
New World Observer Architecture

- ☞ After NWD Proposal Submitted NGST looked at full-up system
- ☞ 4m Telescope Diameter Breakpoint
- ☞ Two Starshades – one small and fast
- ☞ Very Powerful Scientifically
- ☞ Cost comparable to other missions on table

The First Image of Solar System

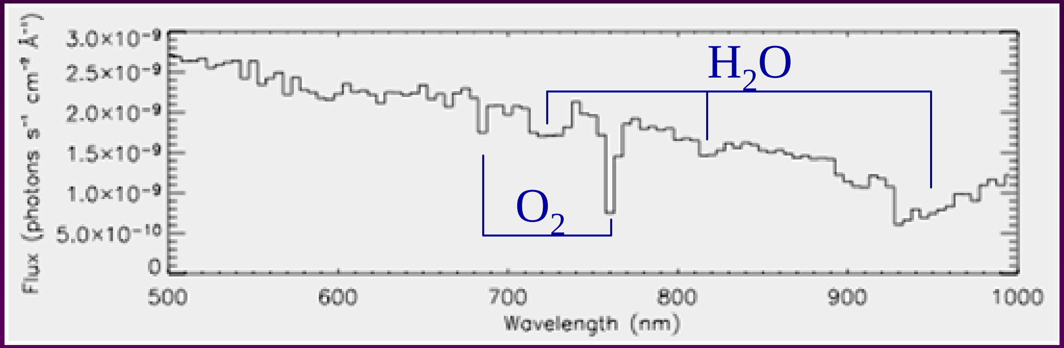


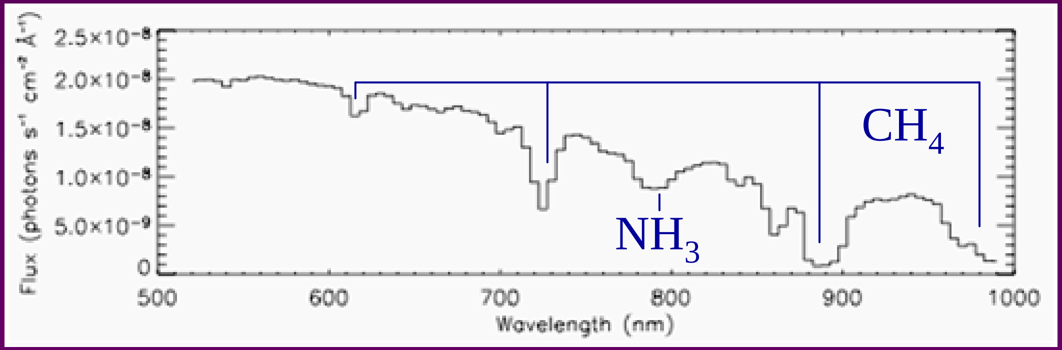
10 arcseconds

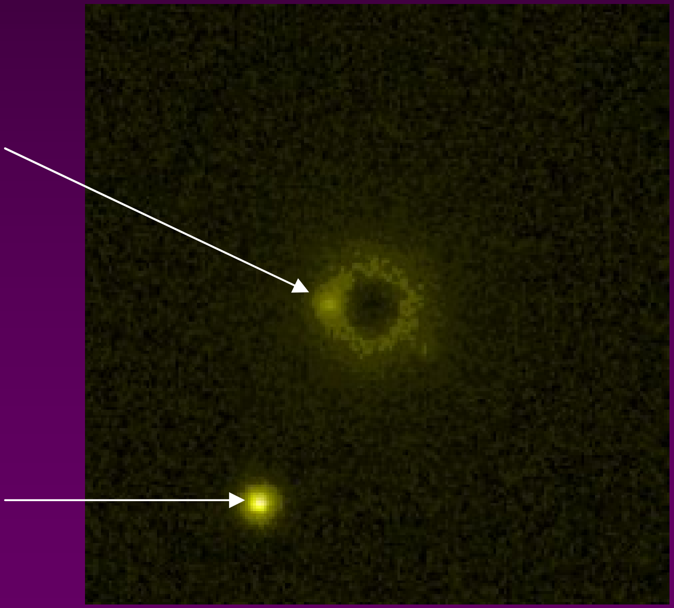

90°
80°
70°
60°
50°
40°
30°
20°
10°

Spectroscopy

☞R > 100 spectroscopy will distinguish terrestrial atmospheres from Jovian with modeling





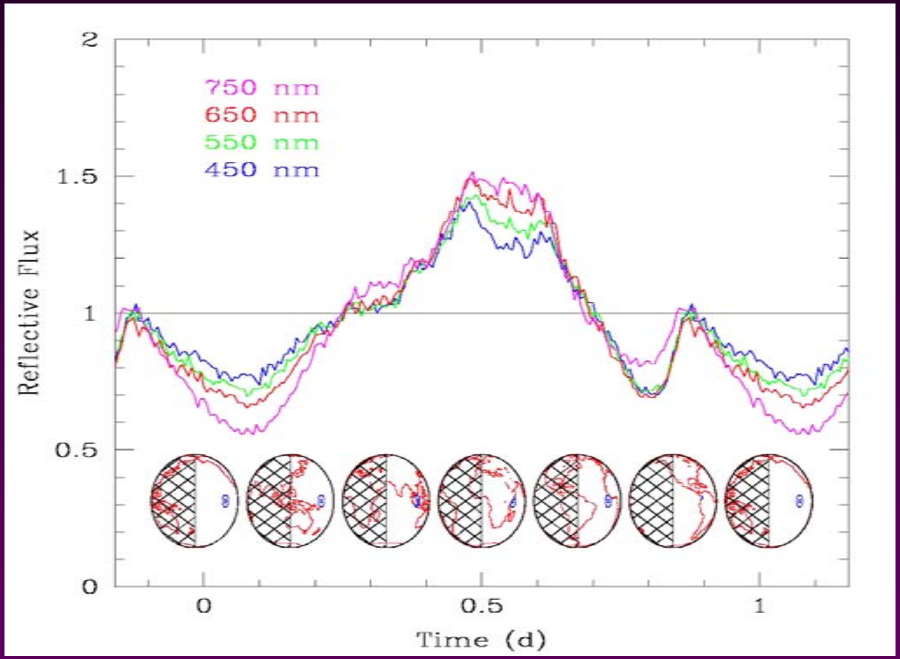


S. Seager

Spectroscopic Biomarkers

Water	Necessary for habitability
Oxygen	Free oxygen results only from active plant life
Ozone	Results from free oxygen
Nitrous Oxide	Another gas produced by living organisms
Methane	Life indicator if oxygen also present
Vegetation	Red edge of vegetation at 750nm

Photometry



Calculated Photometry of Cloudless Earth as it Rotates

It Should Be Possible to Detect Oceans and Continents!

NWO Science

- ☞ Result of Nature interviews
  - ➢ Many discussions with press and other interested parties
- ☞ It is Life Seeking that EVERYBODY wants
  - ➢ Just finding water planets enough, but its not what motivates the public
- ☞ Can there be a bigger or more important question for astronomers?
- ☞ New Worlds Observer can do it
  - ➢ $2-3 Billion and 10 years

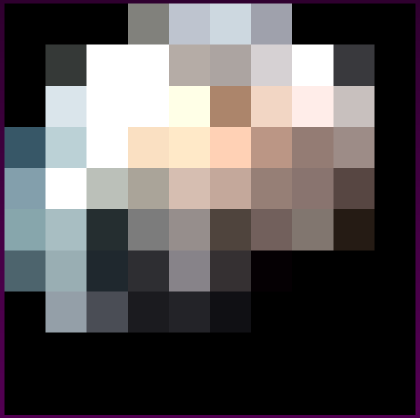
The New Worlds Imager

Earth at 200km resolution. Oceans, continents and clouds are visible.

A simulated exo-planet at 500 km resolution.

TRUE PLANET IMAGING

3000 km



1000 km

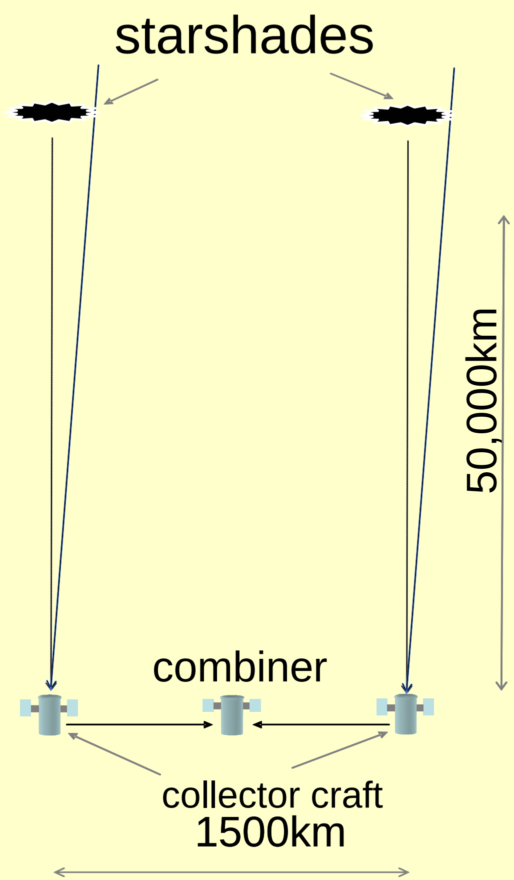
300 km

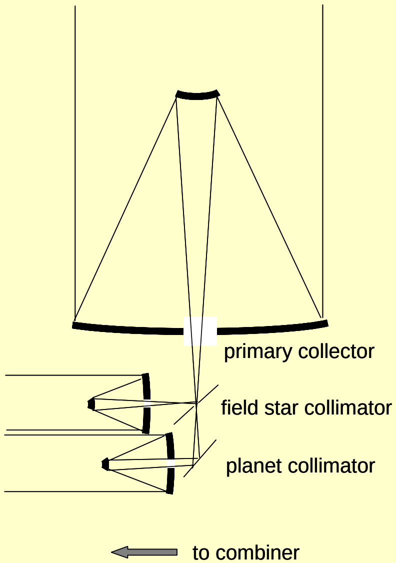
100 km

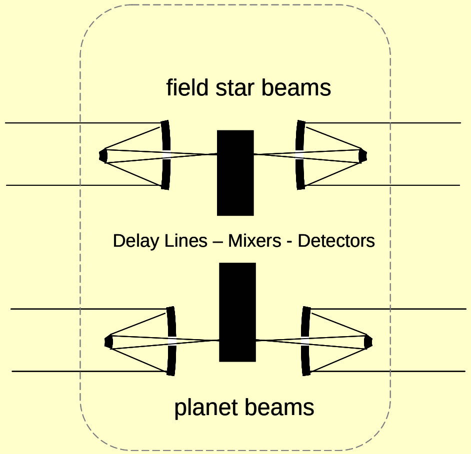
Earth Viewed at Improving Resolution

Solar System Survey at 300km Resolution

NWI Concept

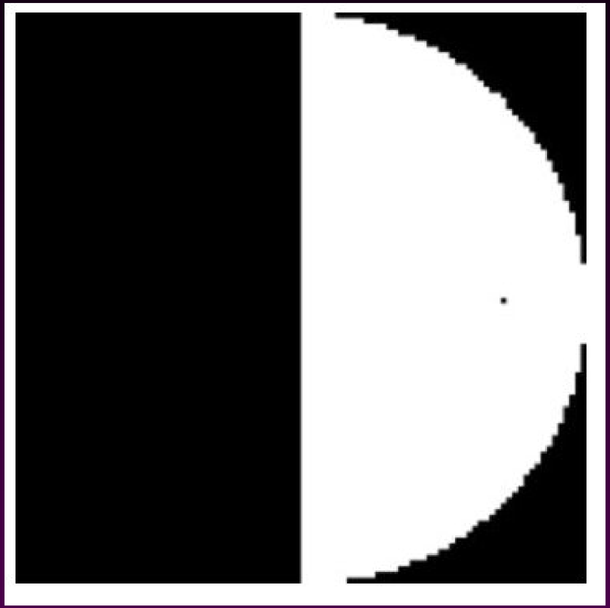

starshades
50,000km
combiner
collector craft
1500km


primary collector
field star collimator
planet collimator
to combiner


field star beams
Delay Lines – Mixers - Detectors
planet beams

Hypertelescope Problem

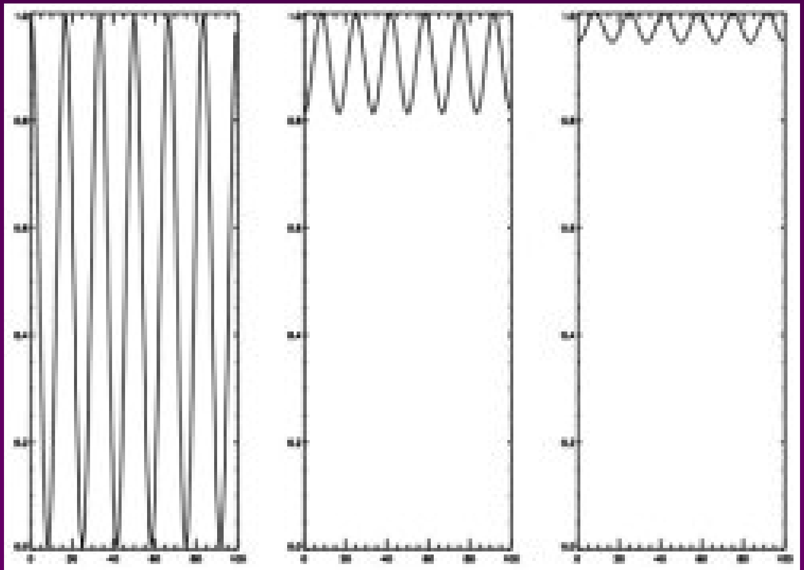
- How Many Apertures Needed?
  - One per pixel (no!)
- Cost control of multiple craft
- Formation Flying to Tolerance
- Labeyrie has worked on this
  - Amazing telescope even without starshades

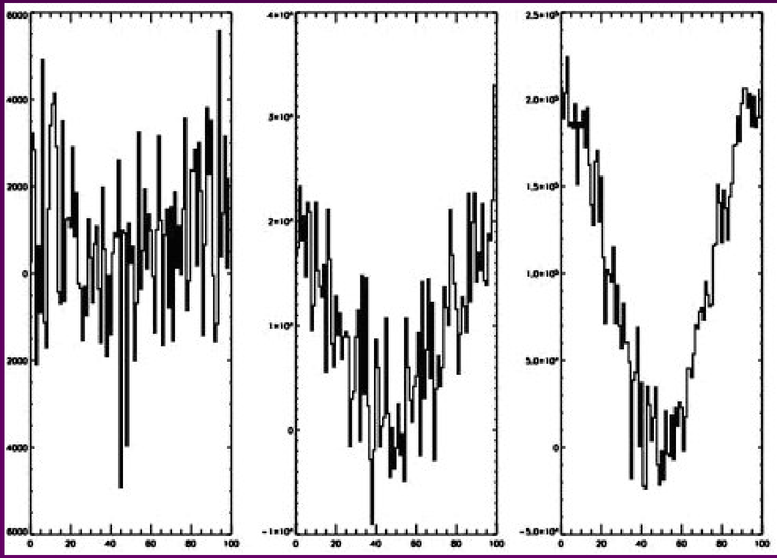


Sims

Established that information is present in the fringes and detectable.

How do we invert into images?
Is this enough?



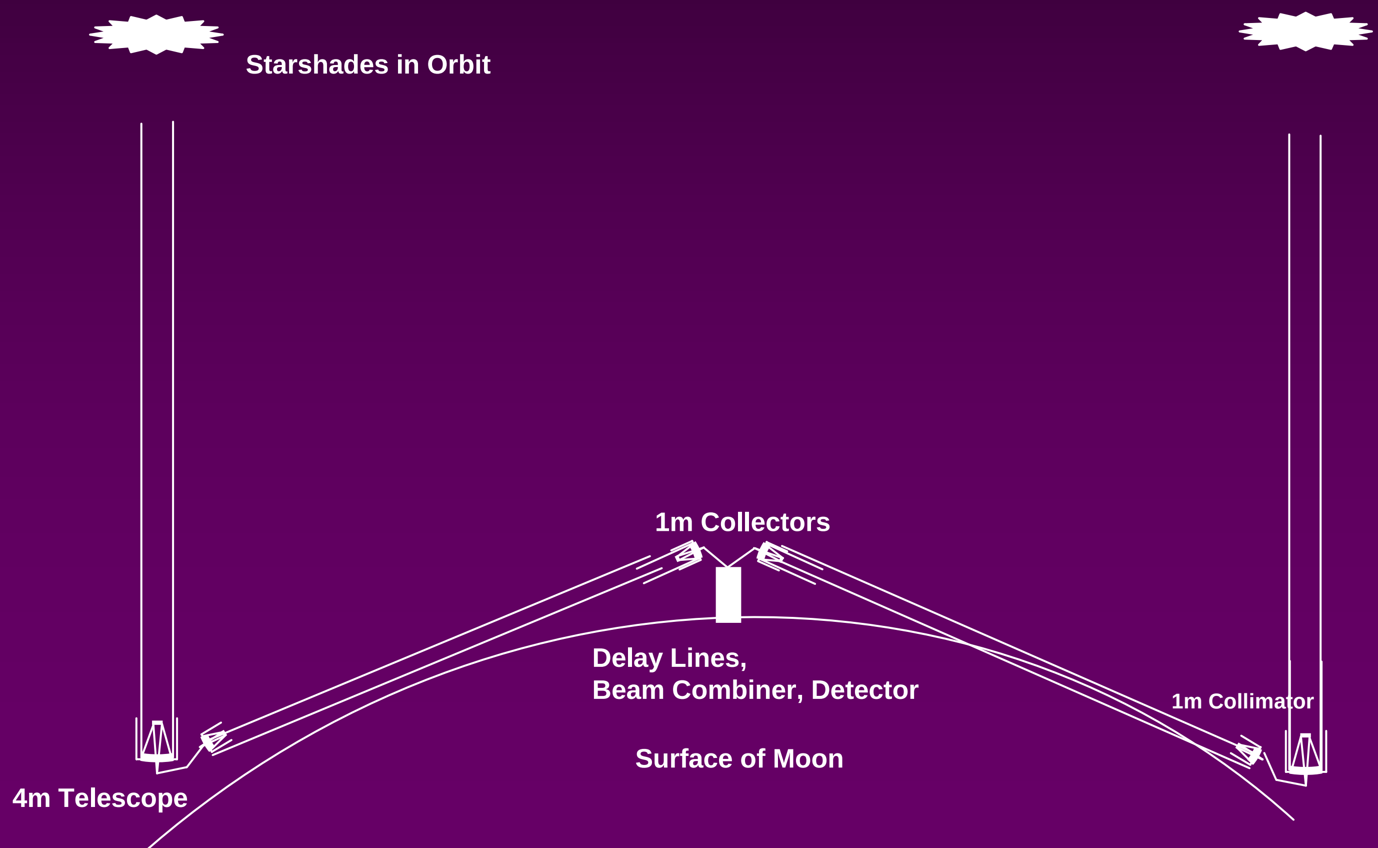


This year's problem

- ☞ Planet rotates, changes
- ☞ Over coming year, we will study the minimum number and size of apertures needed to create true Earth images
- ☞ Unlikely to be definitive, more like indicative

Lunar Option

- ☞ Planet Imaging is exciting enough to justify the expense level
- ☞ Appropriate Level of Challenge for 20+ years from now

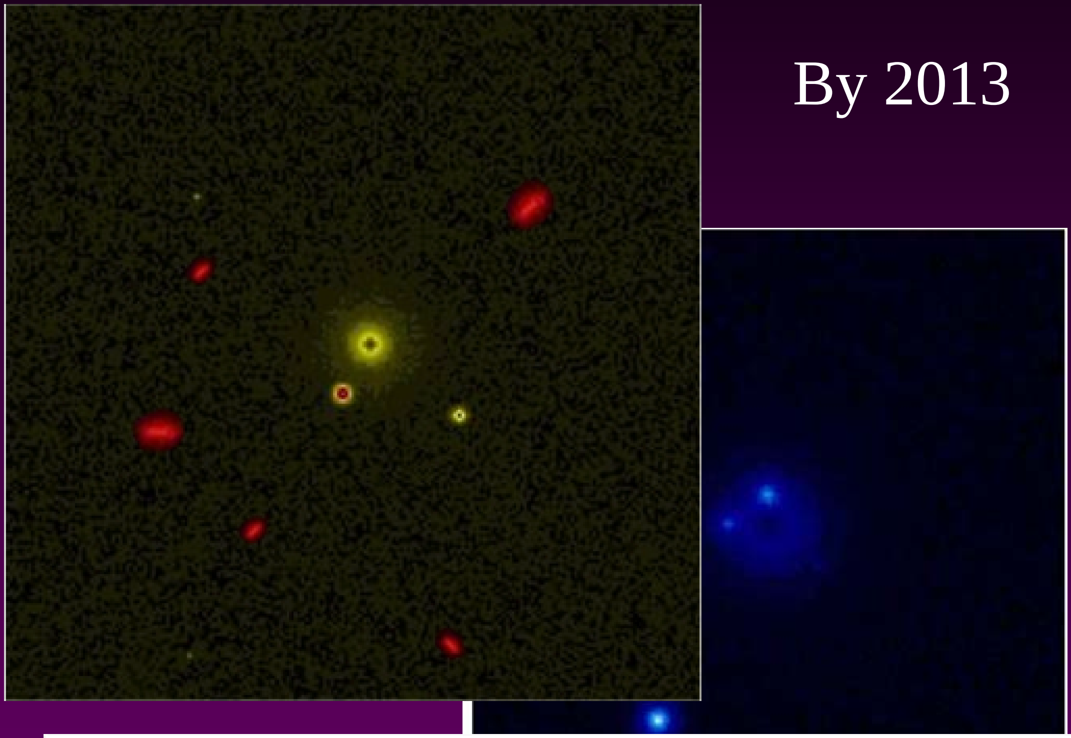


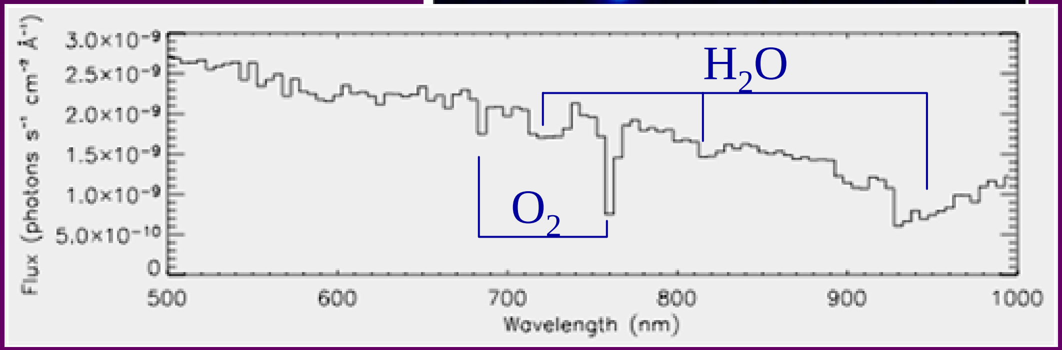
Tradeoff

Pro	Con
Infrastructure	Moon Rotates
Moon Stable Bench	100km class delay lines
Refuel Starshades	

Conclusion

By 2013





By 2025