New Worlds Imager

Webster Cash, University of Colorado

New Worlds Imager

An Alternative to TPF

Webster Cash	University of Colorado
Jim Green	
Eric Schindhelm	
Nishanth Rajan	
Jeremy Kasdin	Princeton University
Bob Vanderbei	
David Spergel	
Ed Turner	
Sara Seager	Carnegie Institution – Washington
Alan Stern	Southwest Research Institute – Boulder
Steve Kilston	Ball Aerospace
Erik Wilkinson	
Mike Leiber	
Jim Leitch	
Jon Arenberg	Northrop Grumman
Ron Polidan	
Chuck Lillie	
Willard Simmons	MIT

and growing…


Let's Do It NOW!!
Let's Find Life Elsewhere in the Universe

Exo-Planets

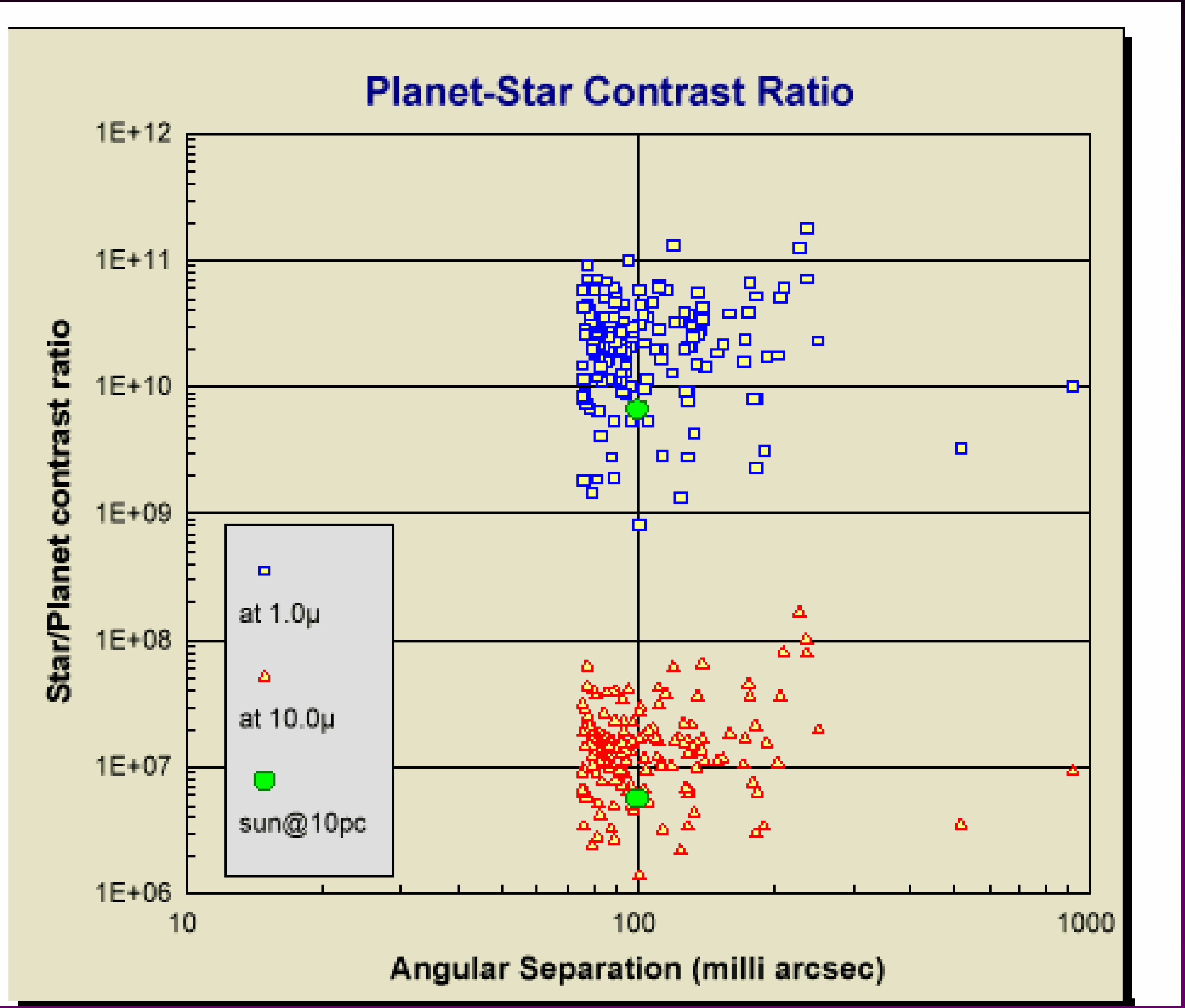
☞ **Exo-planets are the planets that circle stars other than our Sun.**

☞ **There are probably 10,000 exo-planets within 10pc (30 light years) of the Earth.**

☞ **Planets are lost in the glare of parent star.**

☞ **The Earth as viewed from light years is 10 billion times fainter than the Sun.**

Planet Finding: Extinguish the Star

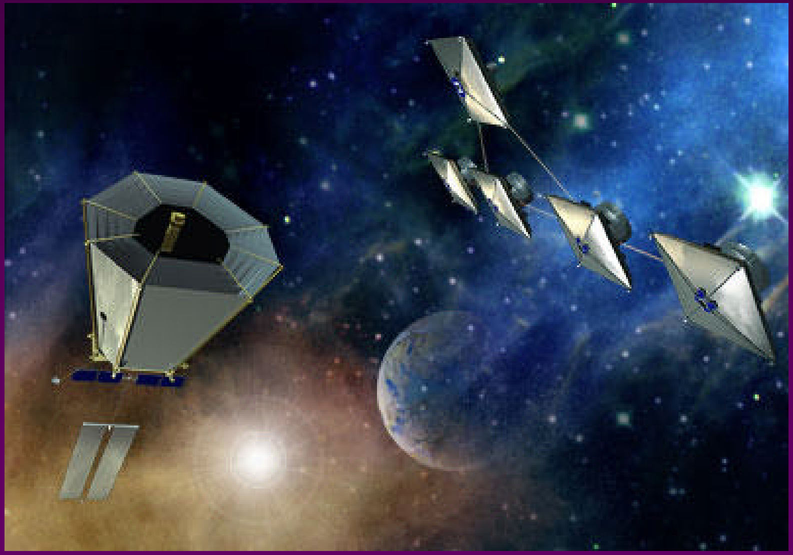


Courtesy of N-G

Terrestrial Planet Finder

- **Telescopes must be** *P E R F E C T* **to suppress scatter:**
  l /5000 surface, 99.999% reflection uniformity

- **TPF is *very* difficult**



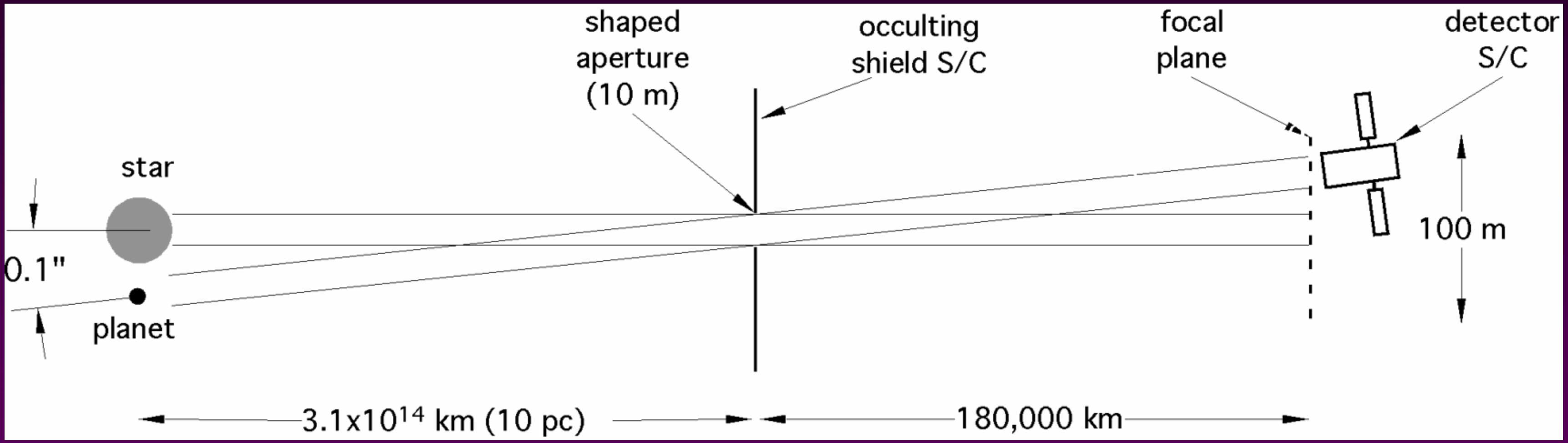
- **Is there any easier way?**

New Worlds Imager vs. New Worlds Observer

- ☞ **Two Levels of Difficulty**
- ☞ **New Worlds Observer**
  - – Two Spacecraft
  - – Goal is Finding Planets
  - – Science from Photometry and Spectroscopy
  - – Technology is In-Hand Today
- ☞ **New Worlds Imager**
  - – Five Spacecraft
  - – Goal is True Imaging of Earth-like Planets
  - – MUCH Tougher – Technology 10-15 years out

Initially New Worlds was a Pinhole Camera

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



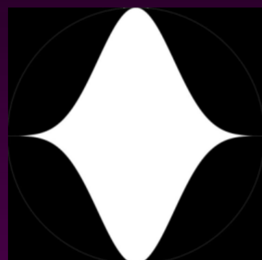
Large Distance Set by 0.01 arcsec requirement

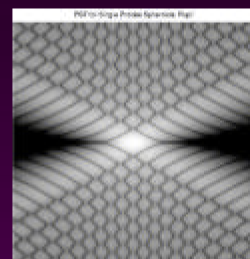
diffraction: $\lambda/D = .01'' \rightarrow D = 10m$ @500nm

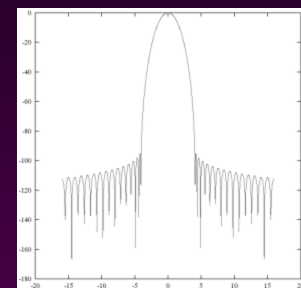
geometric: $F = D/\tan(.01'') = 180{,}000km$

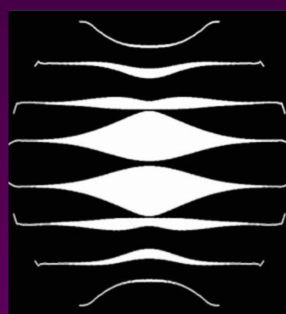
Diffraction Still a Major Problem for Pinhole

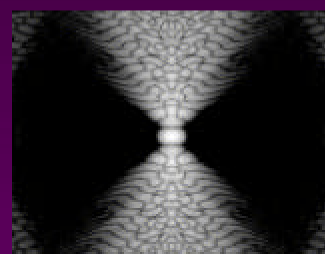
Answer: Shape the Aperture (Binary Apodization)



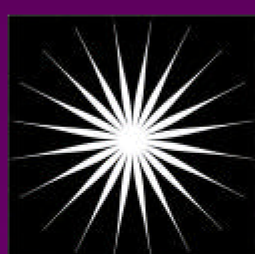


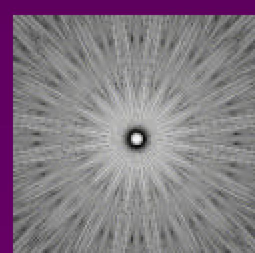


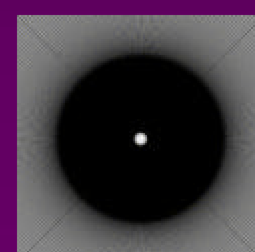




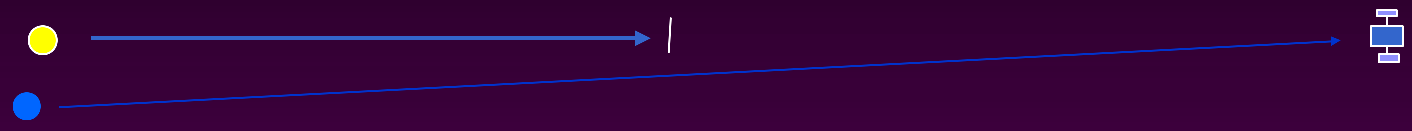
Developed by Princeton Group for Apertures







The Occulter Option



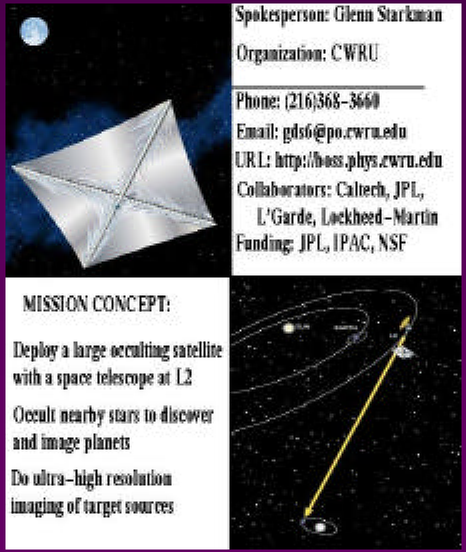
- **Smaller Starshade**
  - Create null zone, image around occulter

- **Observe entire planetary system at once**

The Diffraction Problem Returns

- **Several previous programs have looked at occulters**
- **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!

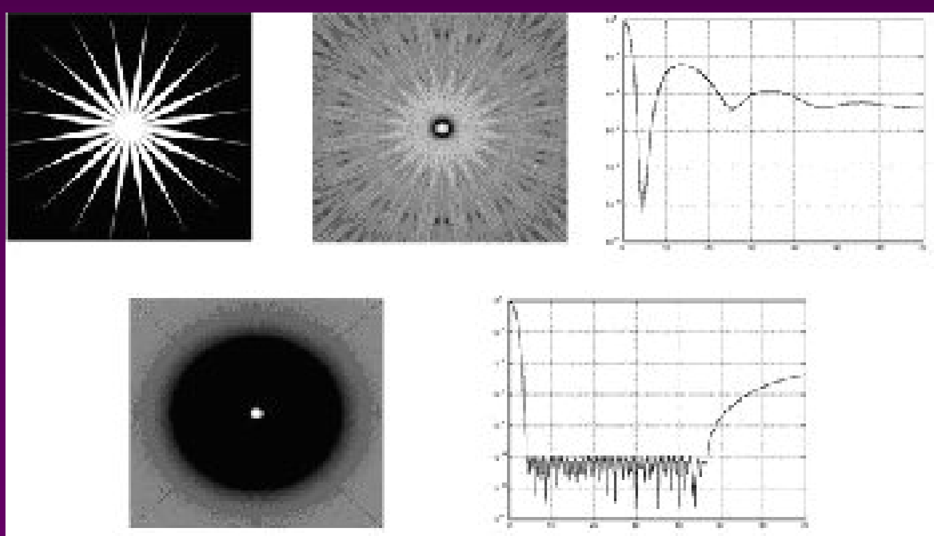
- ☞**Must satisfy Fresnel Equation, Not Just the Fraunhoffer Equation**

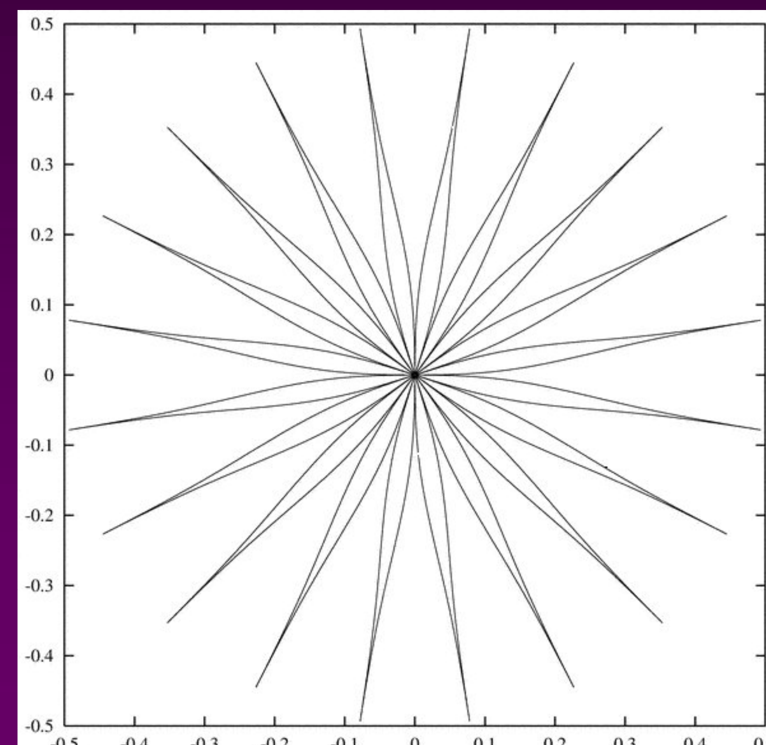
- ☞**Must Create a Zone That Is:**
  - – Deep — Below 10^{-10} diffraction
  - – Wide — A couple meters minimum
  - – Broad — Suppress across at least one octave of spectrum

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

The Vanderbei Flower

- ☞**Developed for Aperture in TPF focal plane**
- ☞**Was to be only 25m across**
- ☞**Vanderbei had determined it would work for the pinhole camera but did not work for occulter.**





The Apodization Function

Found this in April. Extended in June.

This Function Extinguishes Poisson's Spot to High Precision

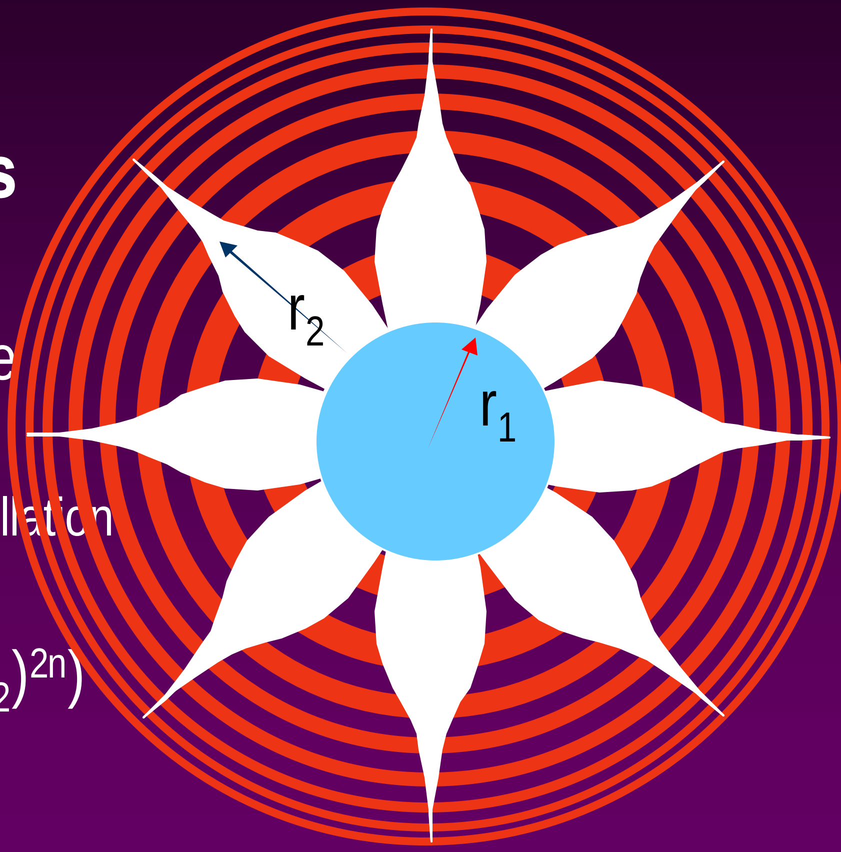
$$A(r) = 0 \quad \text{for} \quad r < r_1$$

and

$$A(r) = 1 - e^{-\left(\frac{r - r_1}{r_2}\right)^{2n}} \quad \text{for} \quad r > r_1$$

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 ~exp(-((r-r$_1$)/r$_2$)^{2n})
    - r_2 is scale of petal shape
    - n is an index of petal shape
    - r_1 is the diameter of the central circle



Doing the Math
(Cash, 2005)

☞ **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**

$$\frac{k}{2\pi d}\left|\int_0^{2\pi}\int_0^{r_1} e^{\frac{ikr^2}{2d}} e^{-\frac{ikrs\cos\theta}{d}}\, r\,dr\,d\theta + \int_0^{2\pi}\int_{r_1}^{\infty} e^{\frac{ikr^2}{2d}} e^{-\frac{ikrs\cos\theta}{d}} e^{-\left(\frac{r-r_1}{r_2}\right)^{2n}}\, r\,dr\,d\theta\right| = 1$$

☞ ***d* is distance to starshade, *s* is radius of hole, *k* is 2π/λ**

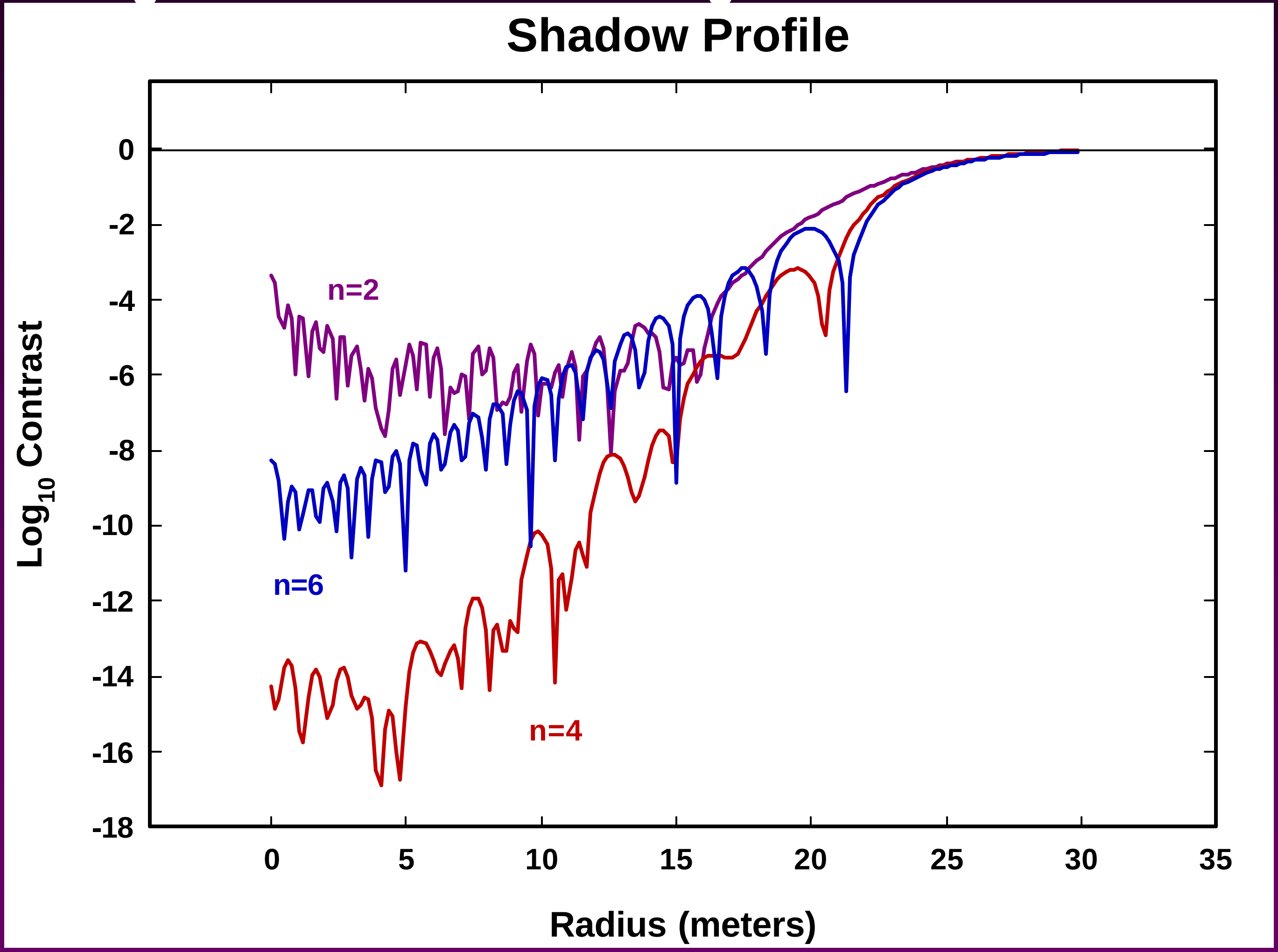
☞ **To one part in** $\sqrt{C} \approx 10^{-5}$

Contrast Ratio

- ☞ **Preceding integral shows the contrast ratio is**
  –
$$R = \left[\frac{(2n)!}{r_1^{2n} r_2^{2n}} \left(\frac{d\,l}{2p} \right)^{2n} \right]^2$$
  – n is an integer parameter, currently n=4
- ☞ **To keep R small $r_1 \sim r_2$**
  – this is the reason the occulter has that symmetric look

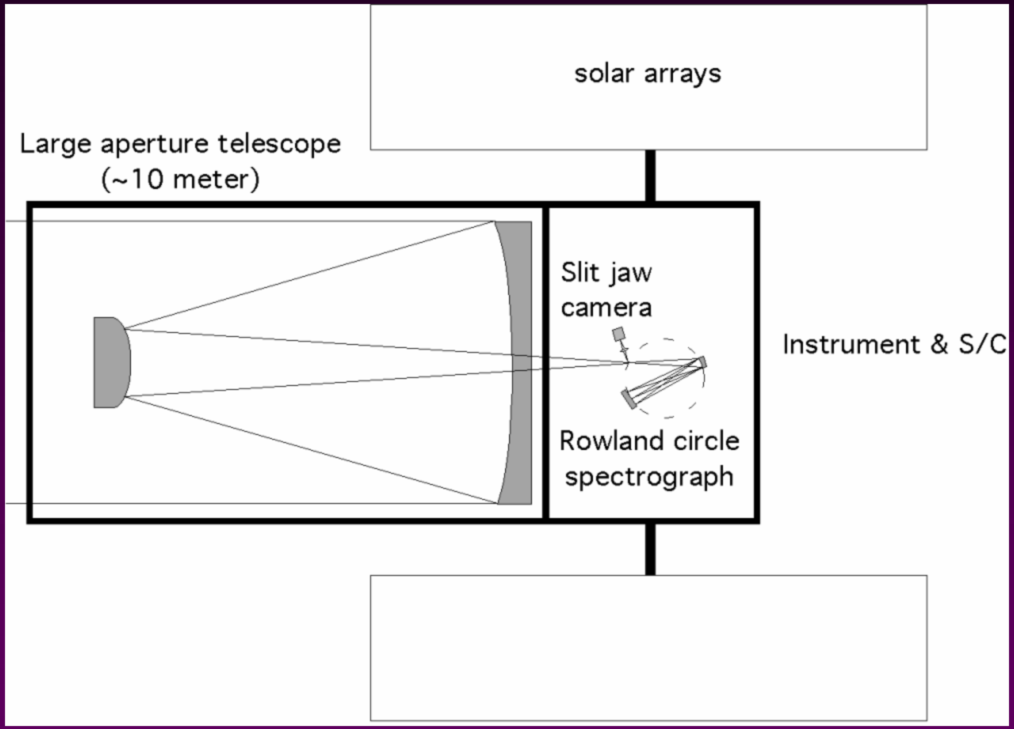
Off Axis Performance

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



Modified Rendering

"Standard" Observatory Views the Starshade



~0.1" resolution is needed (just to separate planets)

High efficiency, low noise spectrograph (e.g. COS)

Count rate estimation

- ☞ **Assuming visible solar flux and a half-earth viewed at 10 pc,**

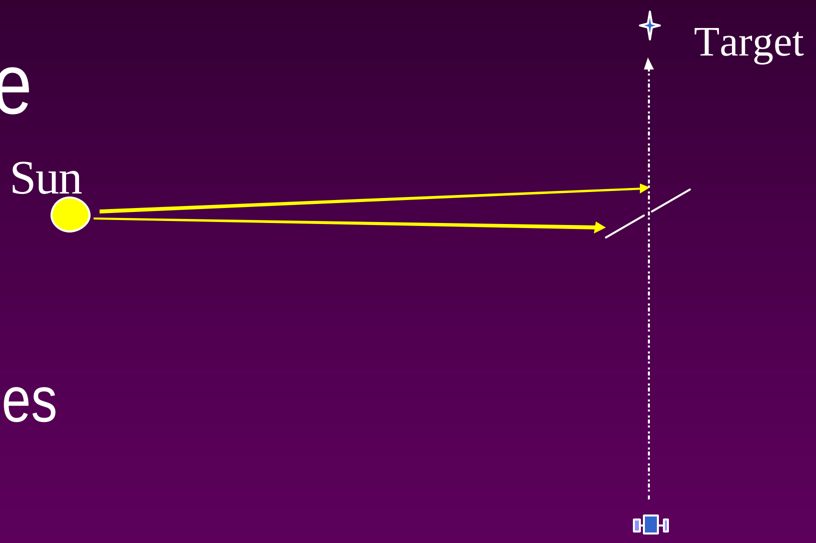
$$C \propto \frac{F_S r_E^2 D_T^2}{e_g d_S^2}$$

- ☞ **Can achieve 5 counts per second with 80% efficient 10 meter telescope**

Telescope	**Time required for S/N=10 detection**
1 meter	33.3 minutes
2 meter	8.3 minutes
4 meter	2.1 minutes
8 meter	31 seconds

Another Issue:
Scattered Light

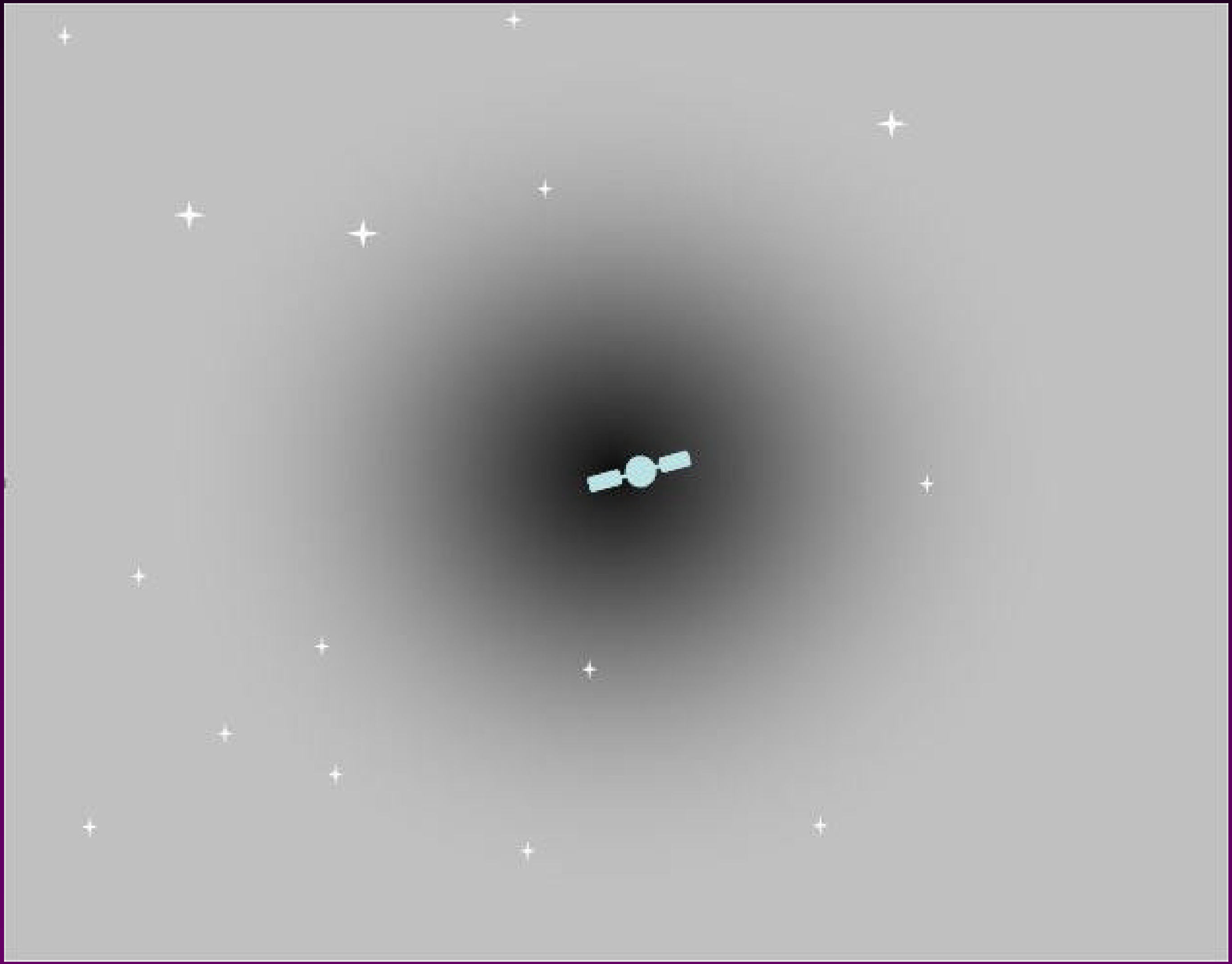
- ☞Sunlight Scatters Off Starshade
- ☞Can be Controlled in Multiple Ways
  - –Look at right angles to sun
    - ➢Imposes restrictions on revisit times
  - –Operate in shadow
    - ➢Earth's umbra
    - ➢With additional shade
      - Likely hard at L2
      - Easier in heliocentric orbit

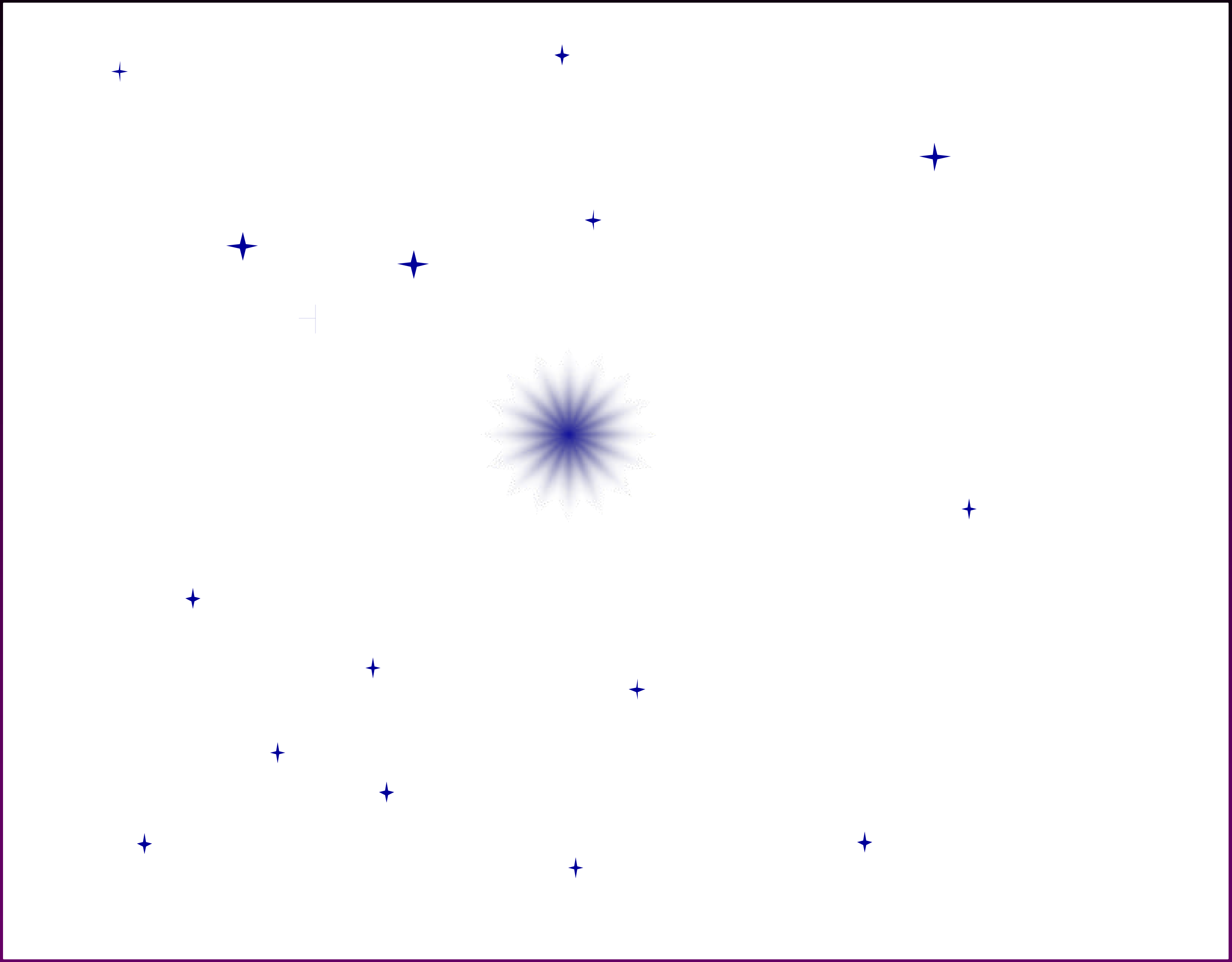


Starshade Tolerances

- **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

Fly the Telescope into the Shadow

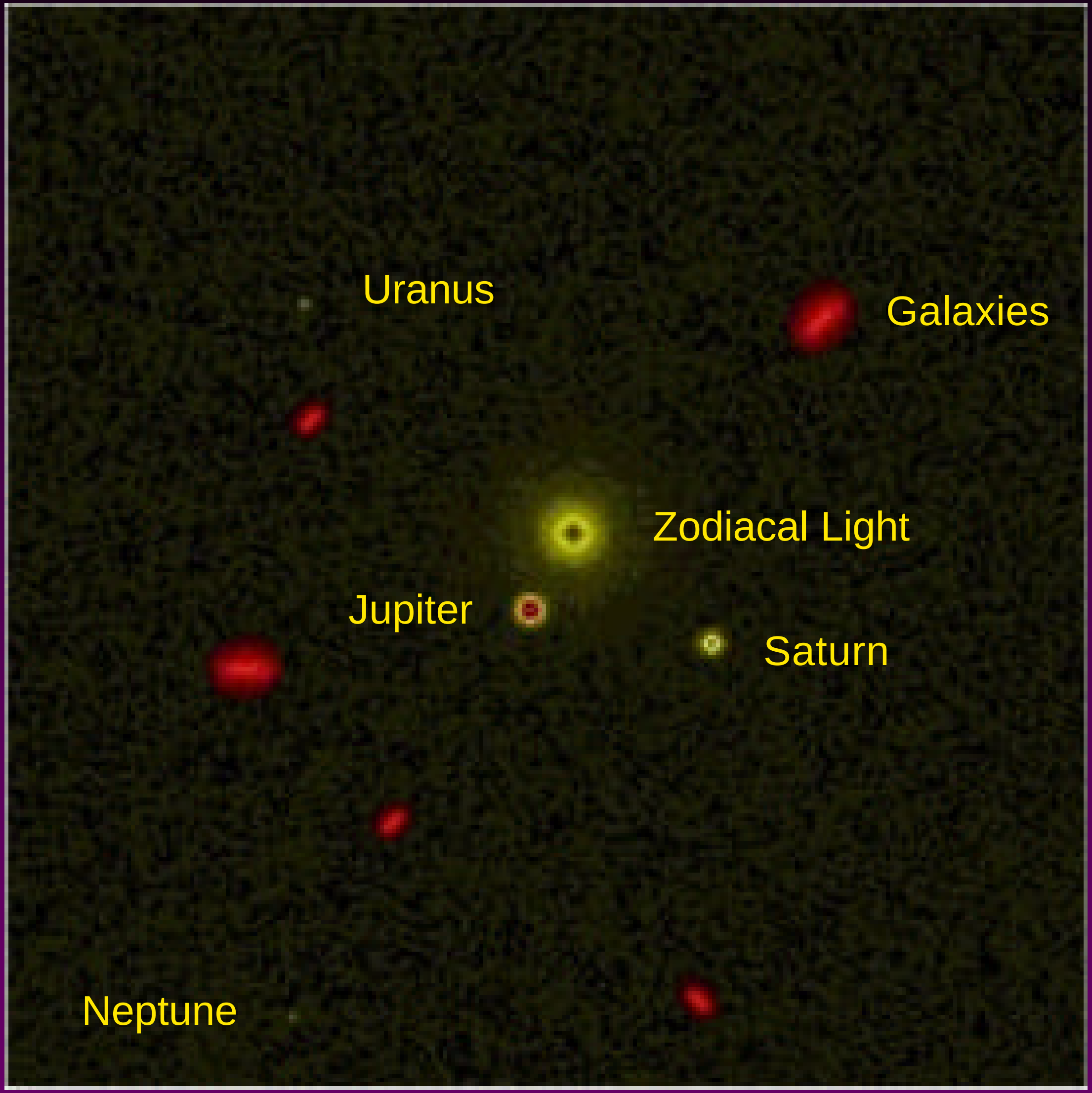




Typical Observing Timeline

☞ **Alignment**	**3 days**	**Travel**
– Other astrophysics		
☞ **Deep Photometry**	**1 day**	**Find Planets**
☞ **Preliminary Spectroscopy**	**1 day**	**Classify Planets**
☞ **Detailed Studies**	**3 days**	**Search for**
– Deep Spectroscopy		Water
– Extended Photometry		Surface Features
–		Life ?!
☞ **Return After Months**		**Measure Orbits**
–		New Planets from Glare

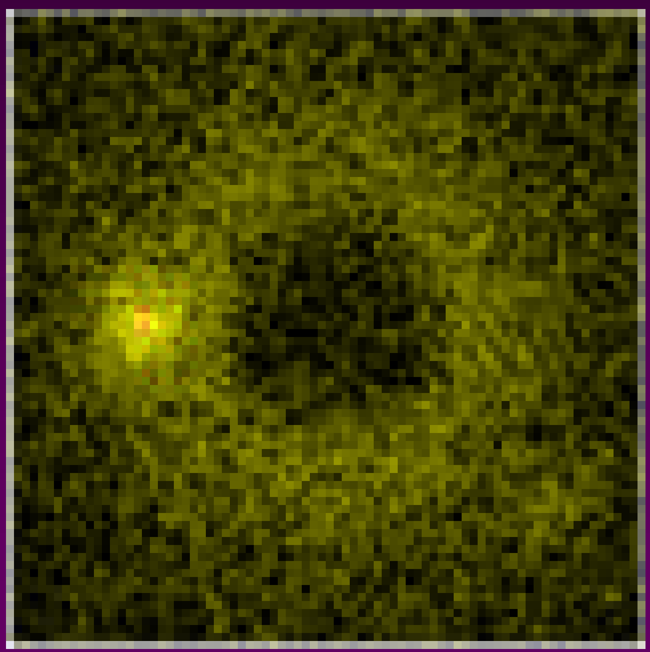
The First Image of Solar System



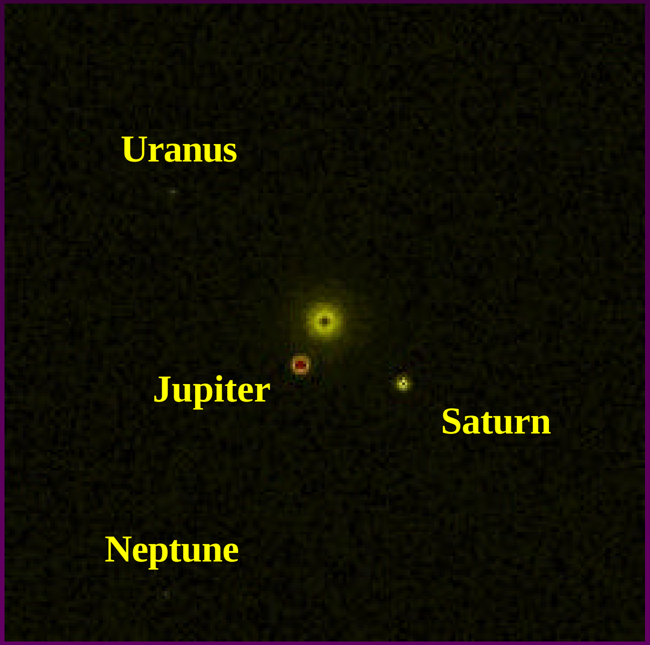
10 arcseconds

Great Science with Small Telescopes

- **Lower limit on telescope size set by need to acquire adequate signal and resolve planets from one another**
  - 1 m diameter telescope needed to see 30M object in minutes
    - Resolution of 0.1 arcsec
  - 2 m diameter gives count rate 0.2 sec-1 for Earth at 10 pc at half illumination



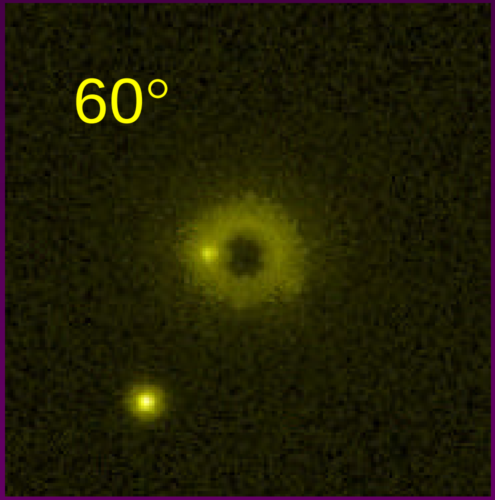
50,000 seconds

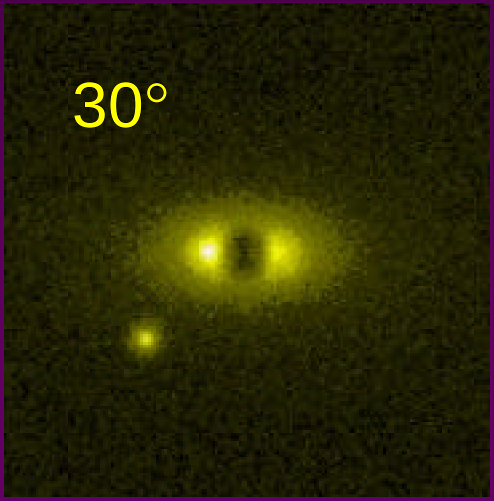


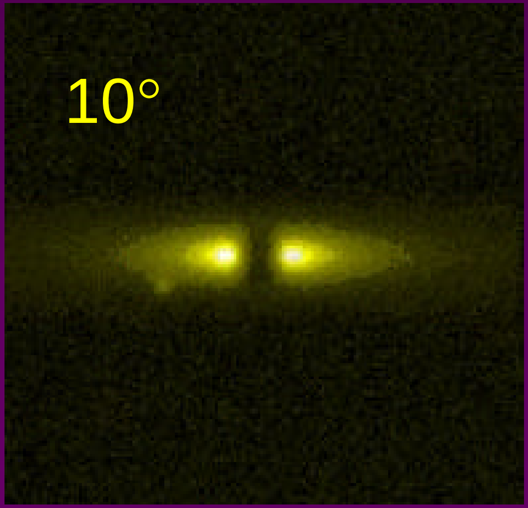
400,000 seconds

Zodiacal light

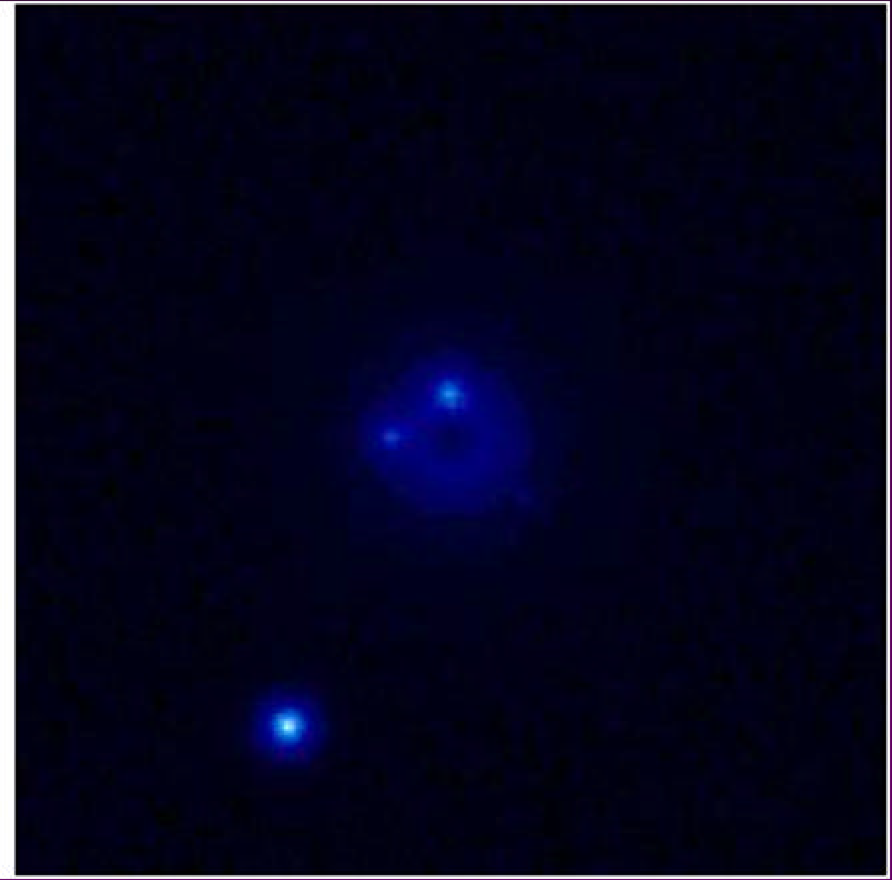
- **Planet detectability depends on system inclination and telescope resolution**
  - – Face-on 0.3 AU^2 patch of zodi equal to Earth's brightness
- **Zodiacal light can wash out planets at low inclinations**



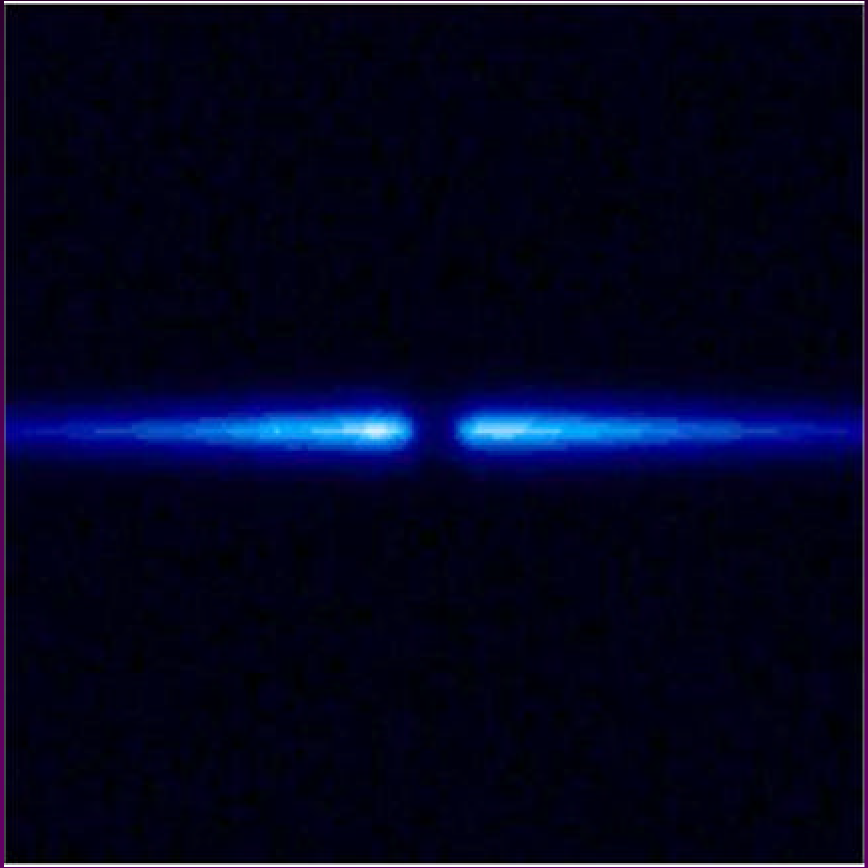




Zodiacal Light – 0.05" IWA



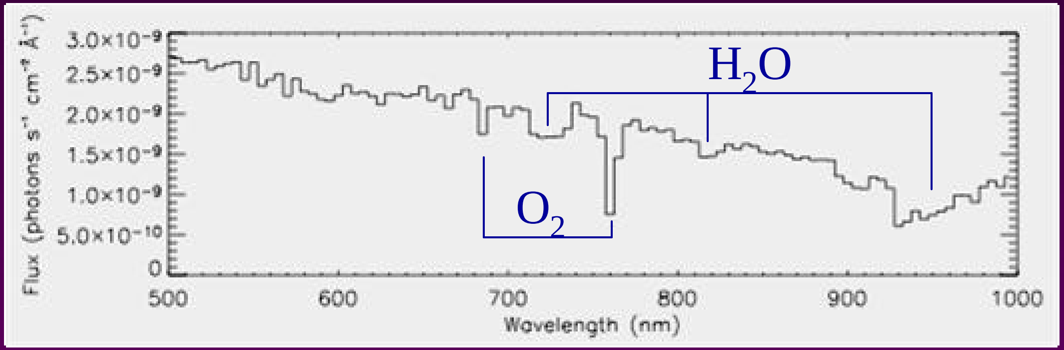
Pole-on

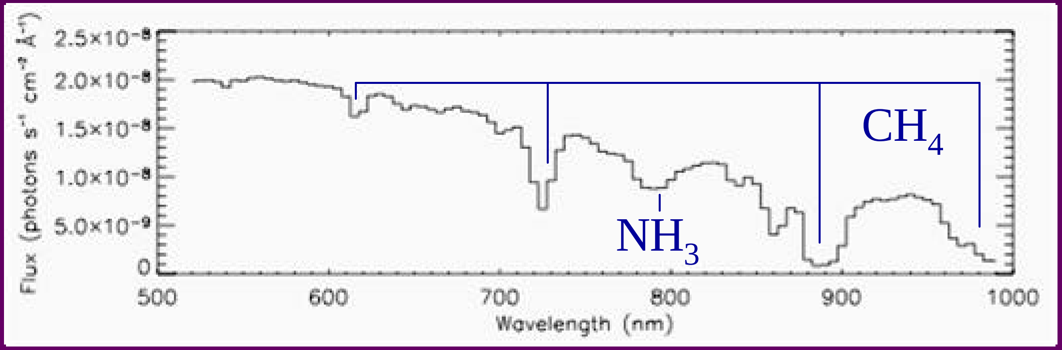


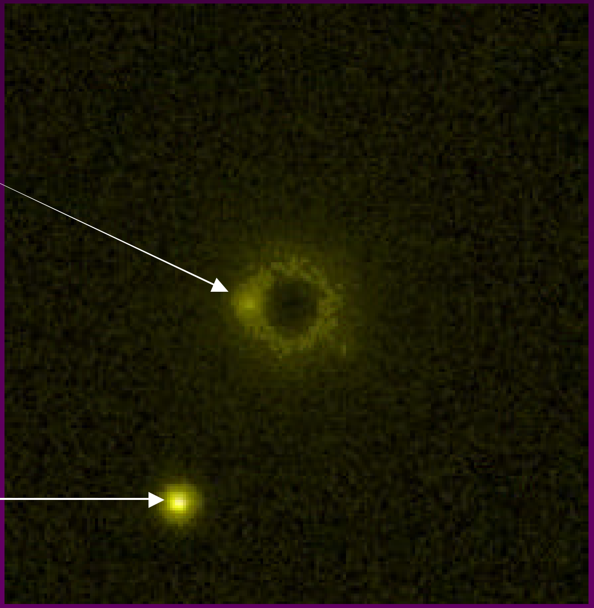
Edge-on

Spectroscopy

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

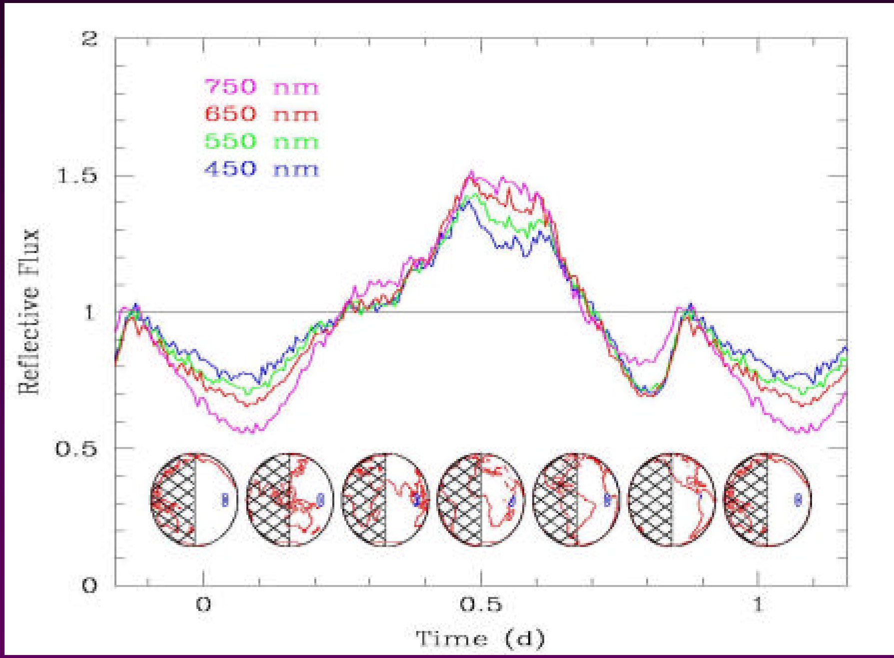






S. Seager

Photometry



Calculated Photometry of Cloudless Earth as it Rotates

It Should Be Possible to Detect Oceans and Continents!

Alternate Operations Concepts

- ☞ **Ground based telescope**
  - ➢ Relay mirror at GEO
  - ➢ South Pole
- ☞ **Space based telescope**
  - ➢ As JWST instrument
  - ➢ Dedicated telescope and mission

Occulter and Detector Craft Functions

- **Propulsion**
- **Station keeping**
- **Alignment establishment and maintenance**
  - Measurement and reporting of relative location
- **Data transfers**
- **Pointing requirements dependent on tolerancing of occulter**
  - Pointing error results in an error in the occulter shape by projection
- **What is the role of the ground in directing the two SC?**
  - Cost trade?

Formation Flying Simulation

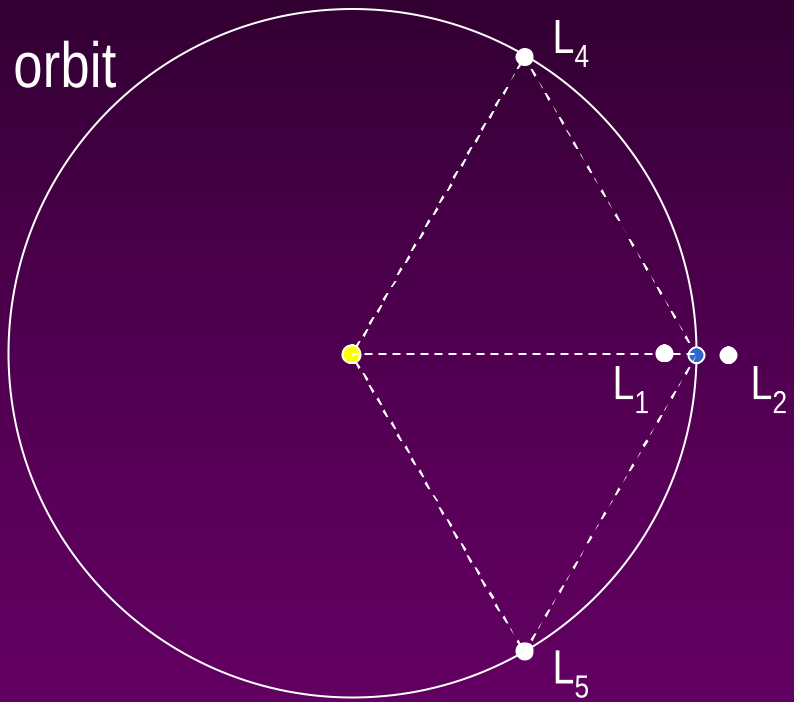
- **Largest problem is solar radiation pressure**
  - Pinhole craft's cross sectional area: 7150 m^2
  - Craft will be thrown out of libration point orbit after several days

Total stationkeeping ? V [m/s]

	L_2	L_5
20,000 km	**10.2**	**20.3**
200,000 km	**9.8**	**20.7**

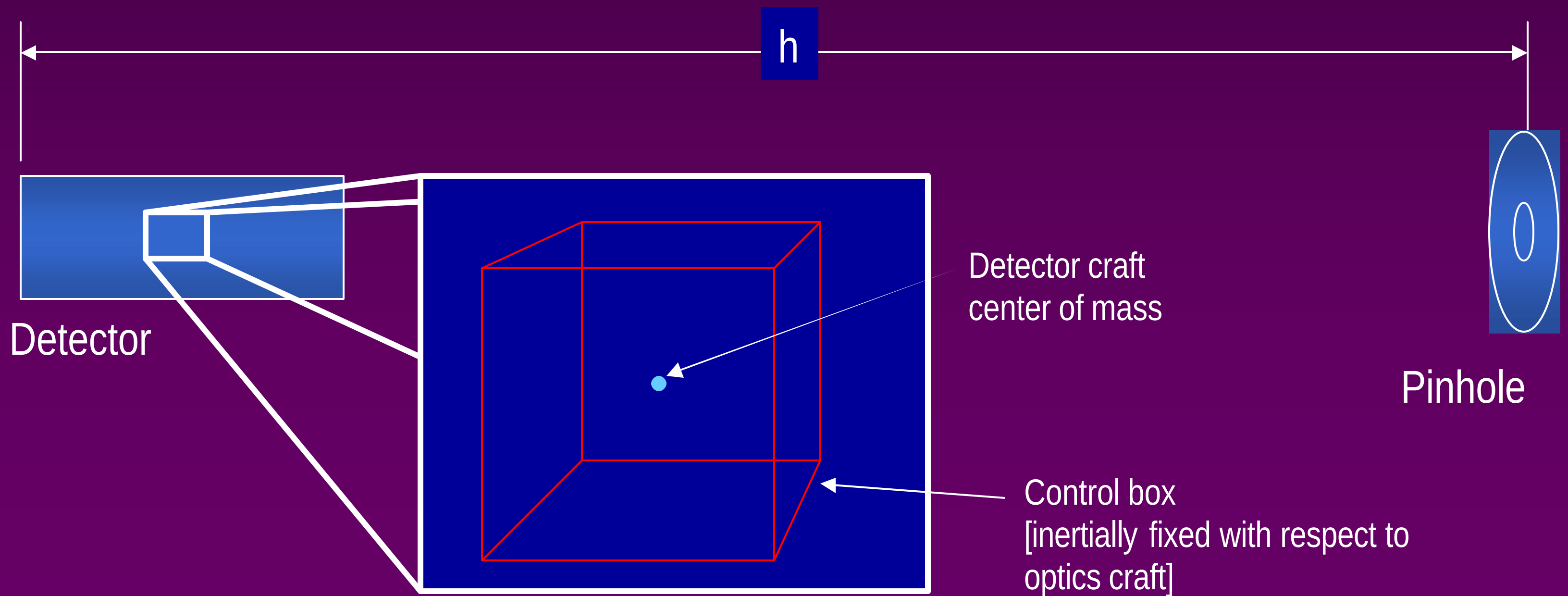
Number of burns during exposure

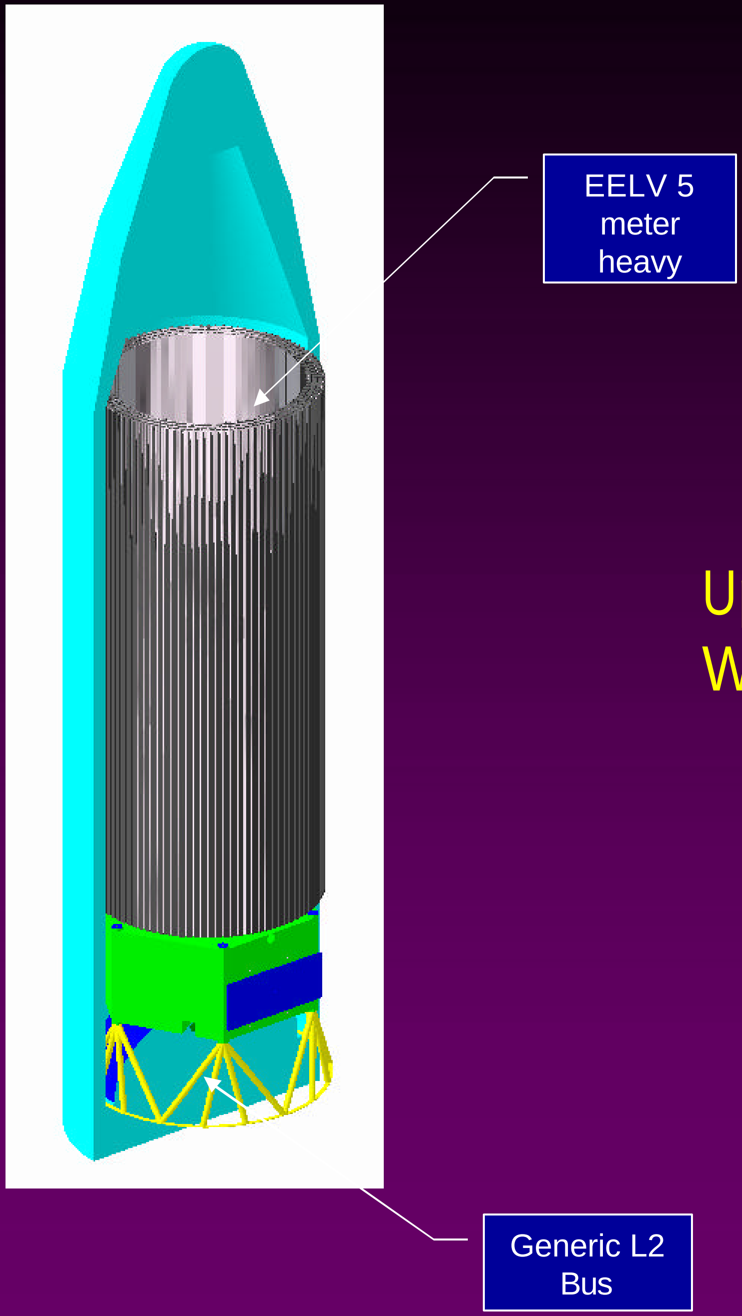
	L_2	L_5
20,000 km	**6700**	**3740**
200,000 km	**6700**	**3810**



Formation Flying Simulation

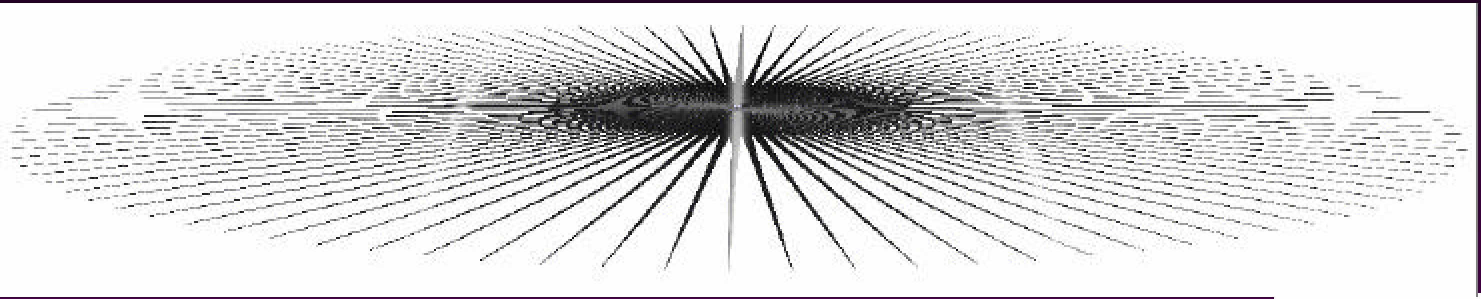
- **Stationkeeping ?V estimated in STK/Astrogator**
  - – Detector craft assumed active; pinhole craft assumed passive
  - – Control box of 10 cm half-width defined
  - – Active S/C thrusts when box boundaries reached
  - – Gravity of Earth, Sun, Moon included, plus solar radiation pressure
  - – Separations of 20,000 km and 200,000 km considered at Earth-Sun L_2 and L_5

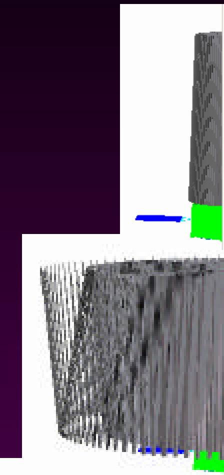




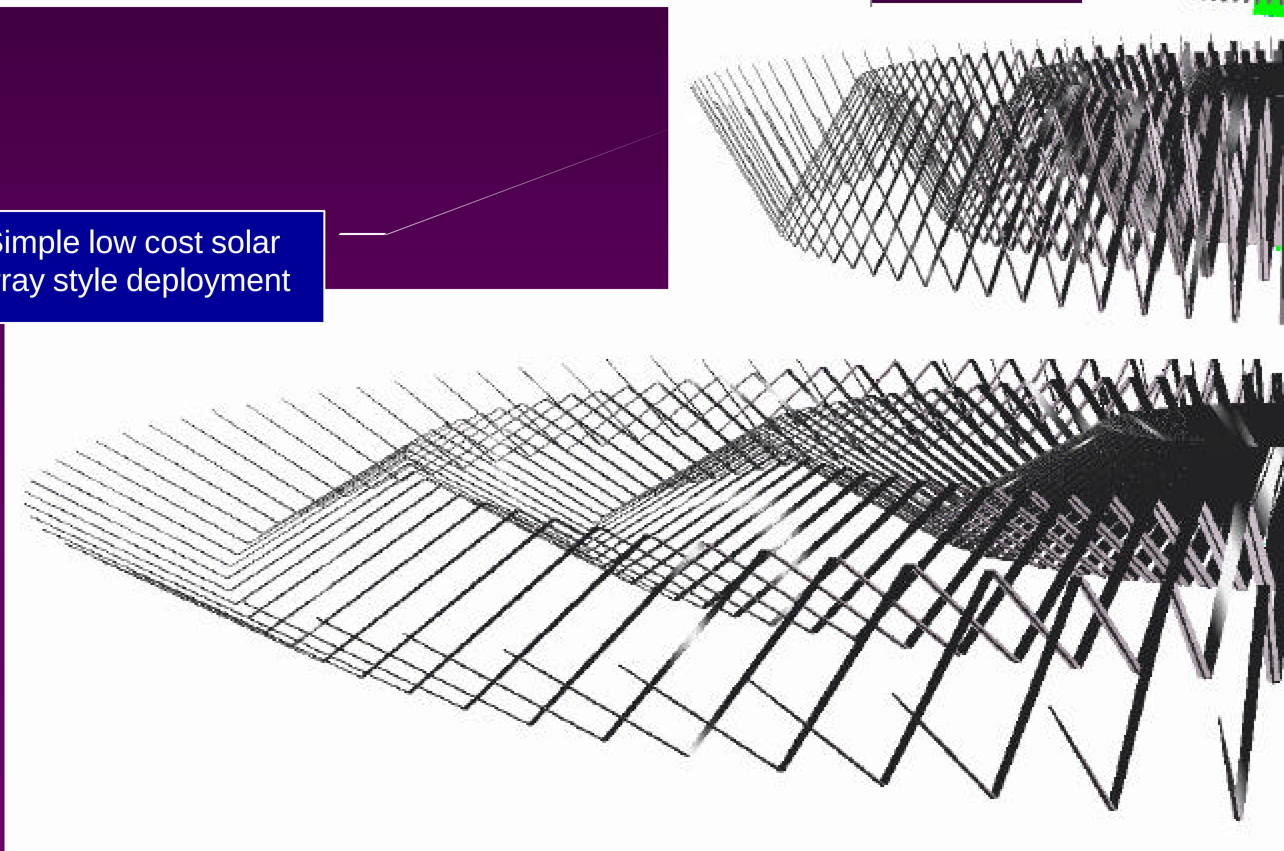
Up tp 150 m New Worlds Observer
Will Fit in an ELV Heavy

New Worlds Deploys Like Solar Arrays





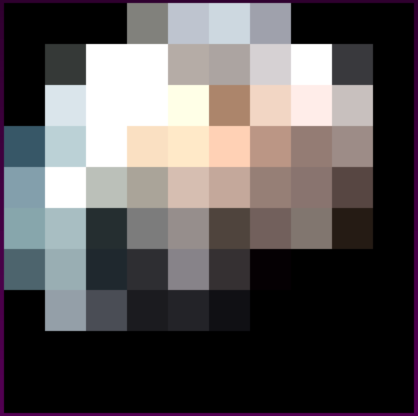
Simple low cost solar array style deployment



- ☞ **Simple, robust, proven deployment scheme**

TRUE PLANET IMAGING

3000 km



1000 km

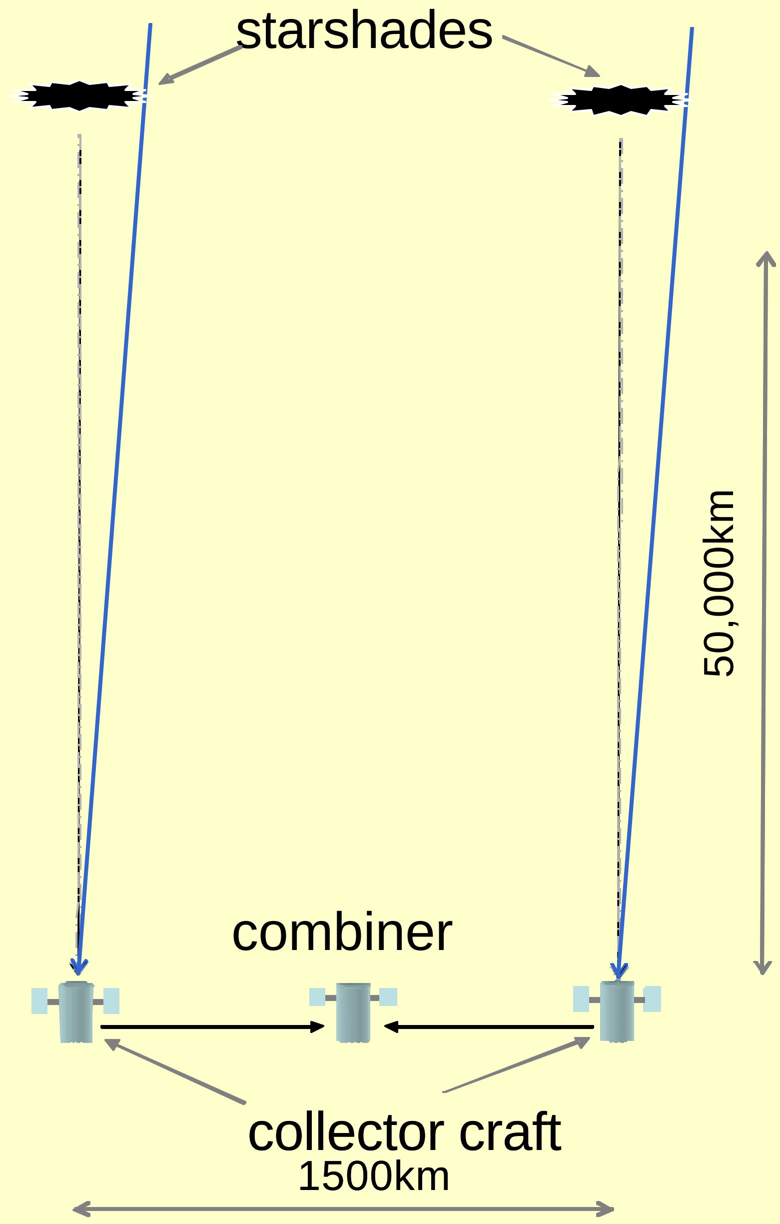
300 km

100 km

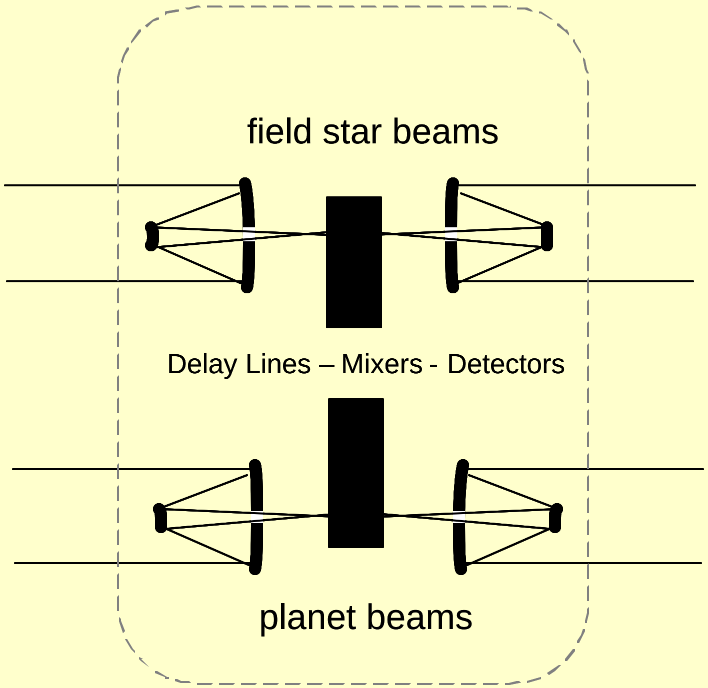
Earth Viewed at Improving Resolution

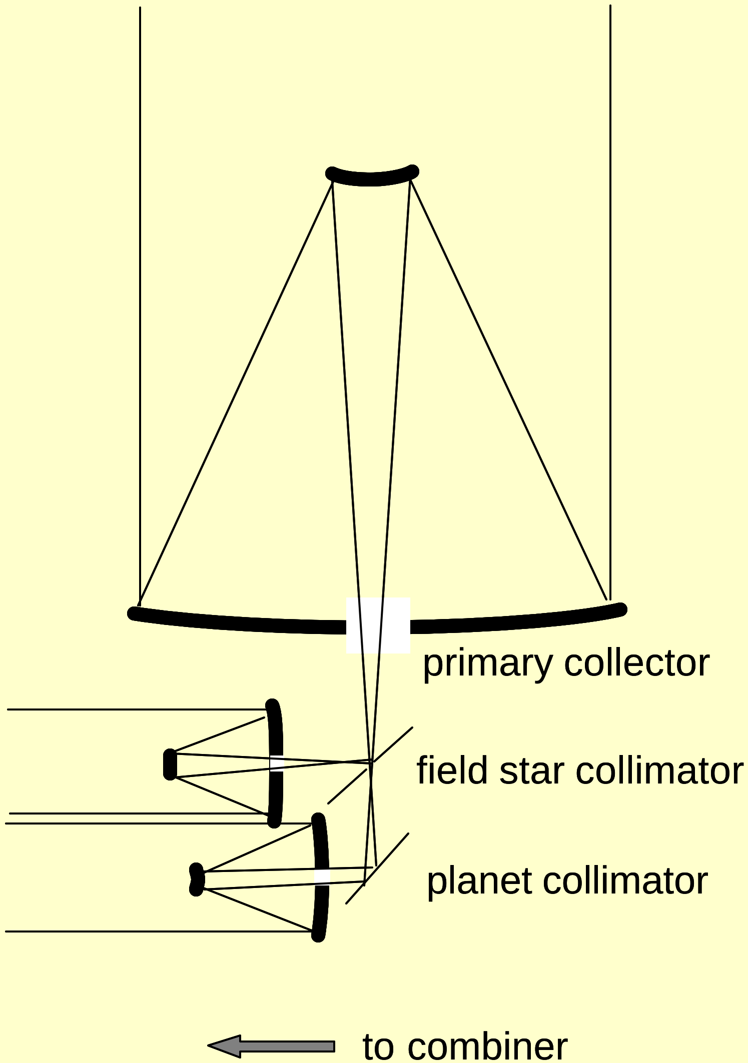
Solar System Survey at 300km Resolution

NWI Concept

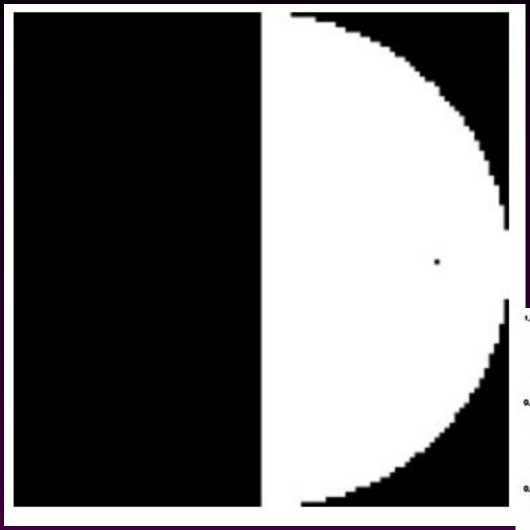


Holding the Array

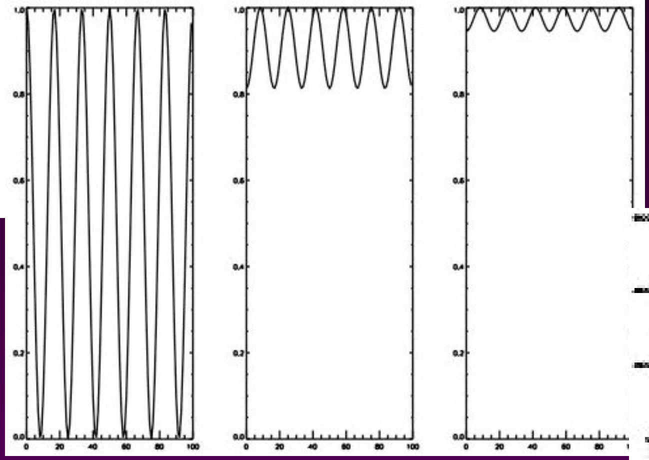




Planet Q-Ball

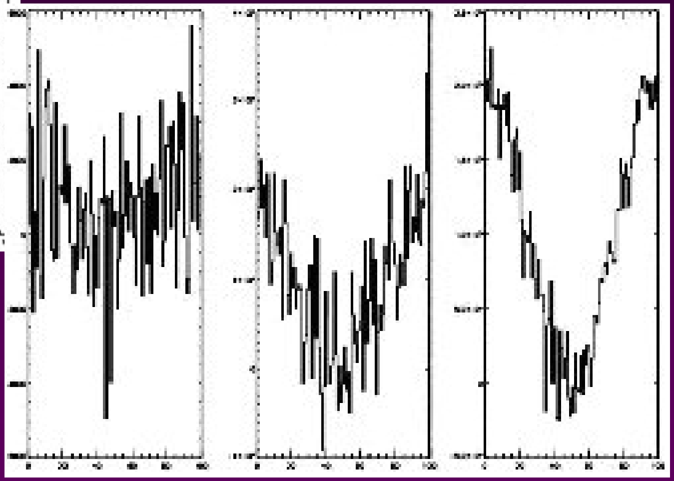


One Imperfection



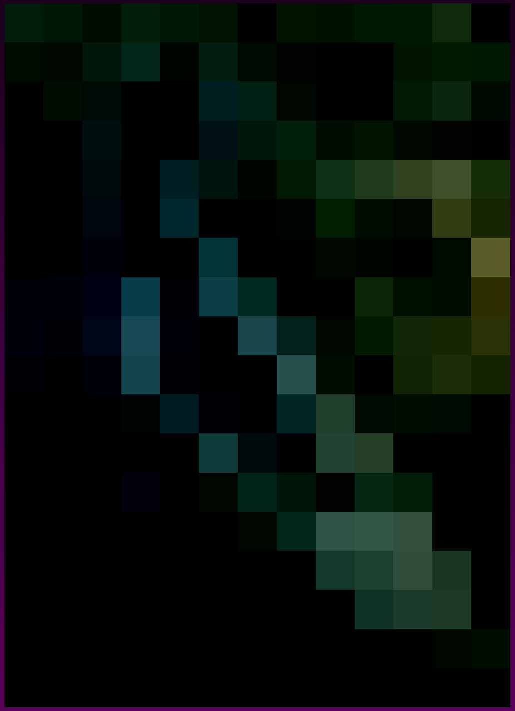
Fringes as Telescopes Separate

Imperfection visible with adequate signal



Information is there:
We will study the realistic limits of two element interferometers

Resolution Limitation Set By Signal



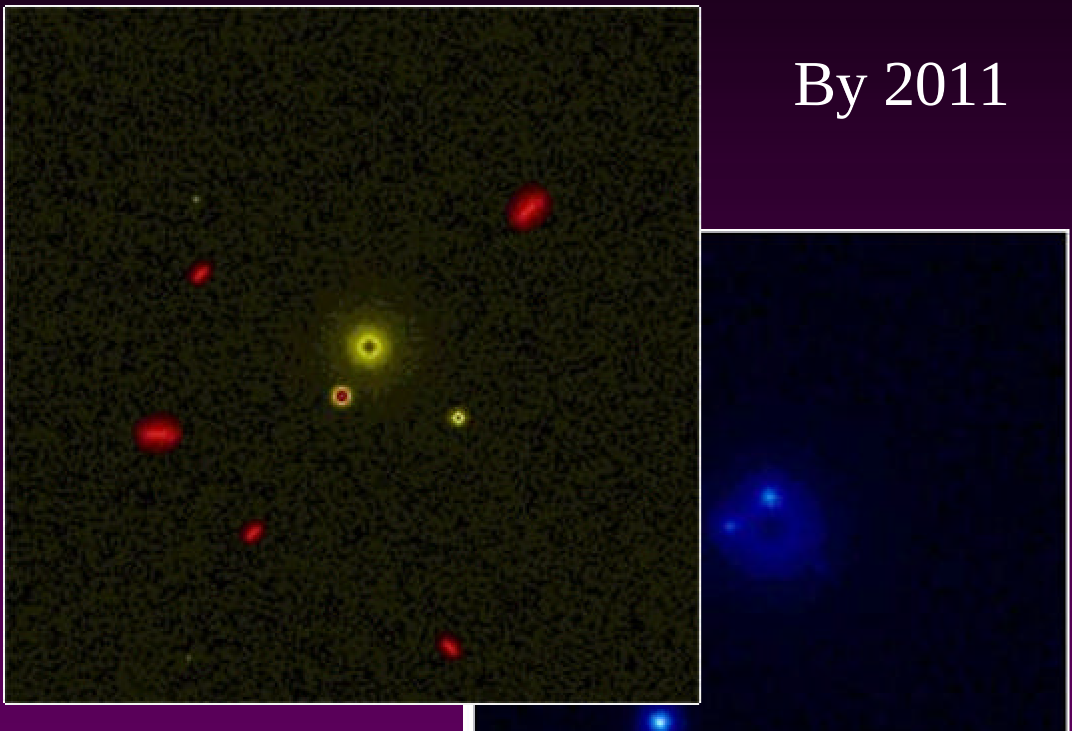
- ☞ **At 10 km resolution the interferometer is photon-limited**
- ☞ **Need Much Bigger Telescopes – Too Expensive**

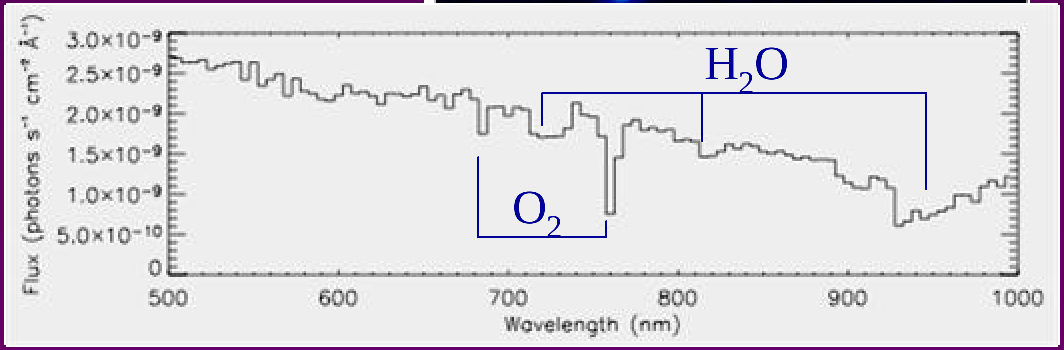
The Phase II Study

- ☞ **Two Year Study Began on September 1**
- ☞ **Observer Mode Well Understood**
  - ➢ Complete Architecture Study Completed in First Year
  - ➢ Laboratory Demonstration of Diffraction Suppression
- ☞ **Imager Mode More Difficult**
  - ➢ Will Study Requirements in Detail
  - ➢ Will Look for Ways to Make the Mission More Affordable

Conclusion

By 2011





By 2018