

High-Contrast Imaging and the Search for Exo-Earths

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2013 Sept 20

Amateur Astronomers, Inc.
Union College

<http://www.princeton.edu/~rvdb>

Are We Alone?

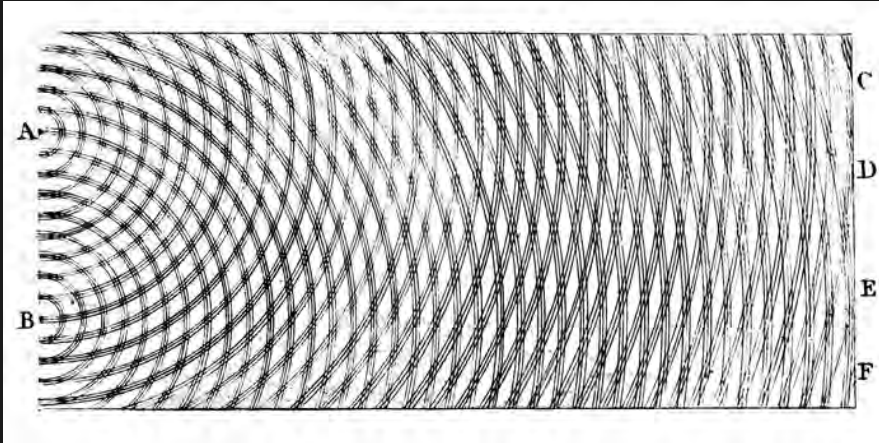
What Are The Odds?



Some Background

Christiaan Huygens (1678): Light is a Wave

Young's two-slit diffraction experiment (1801):



James Clerk Maxwell (1862):

Light is an Electro-Magnetic Wave

And God Said

$$\nabla \cdot \vec{D} = \rho_{\text{free}}$$

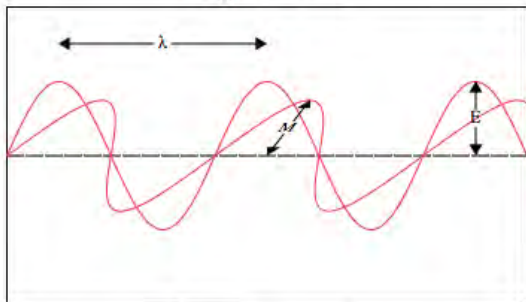
$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J}_{\text{free}} + \frac{\partial \vec{D}}{\partial t}$$

and *then* there was
light.

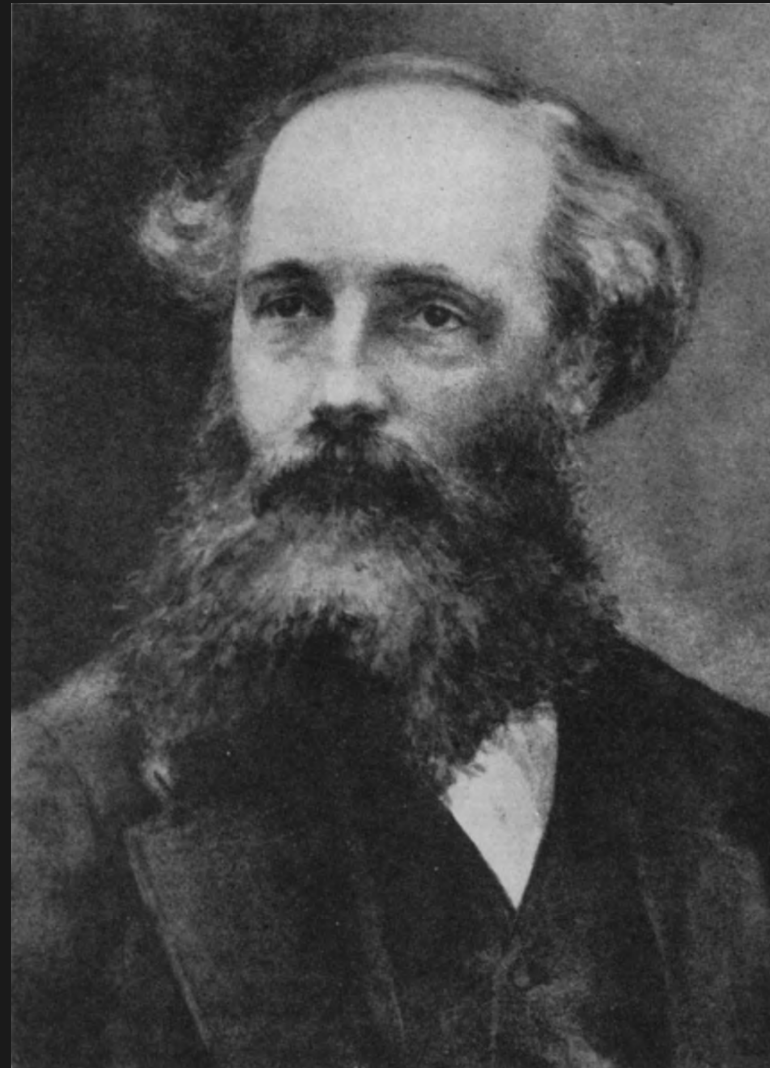
Light wave



λ = wave length

E = amplitude of
electric field

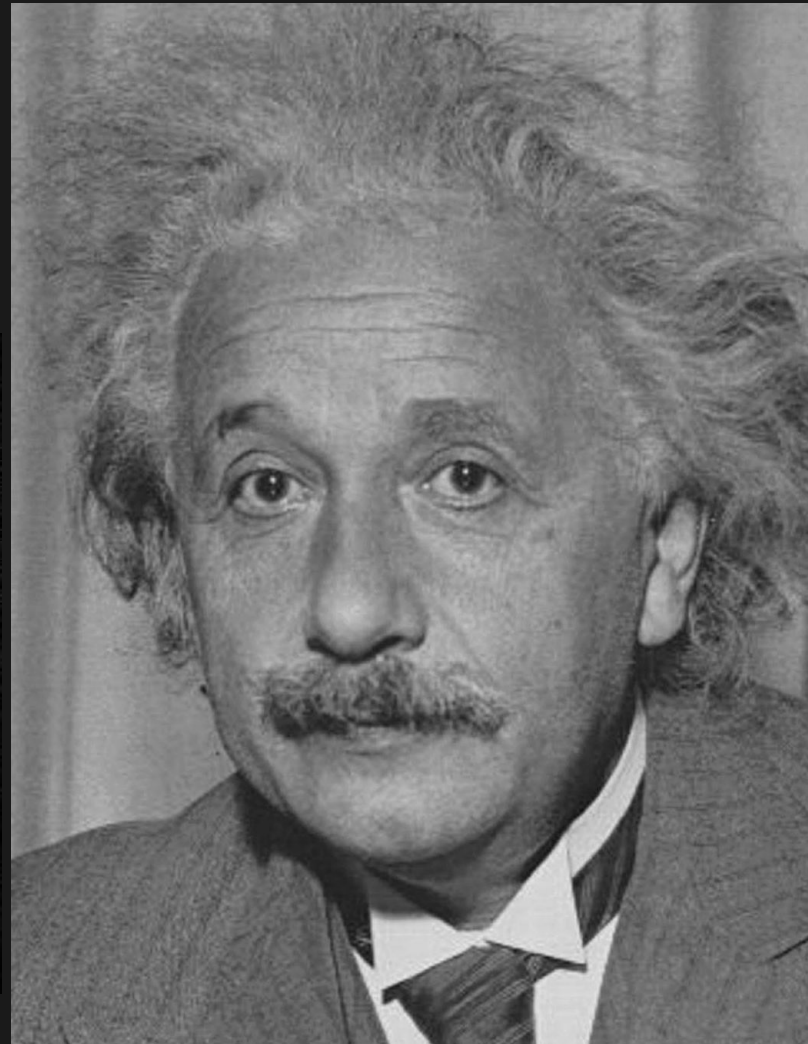
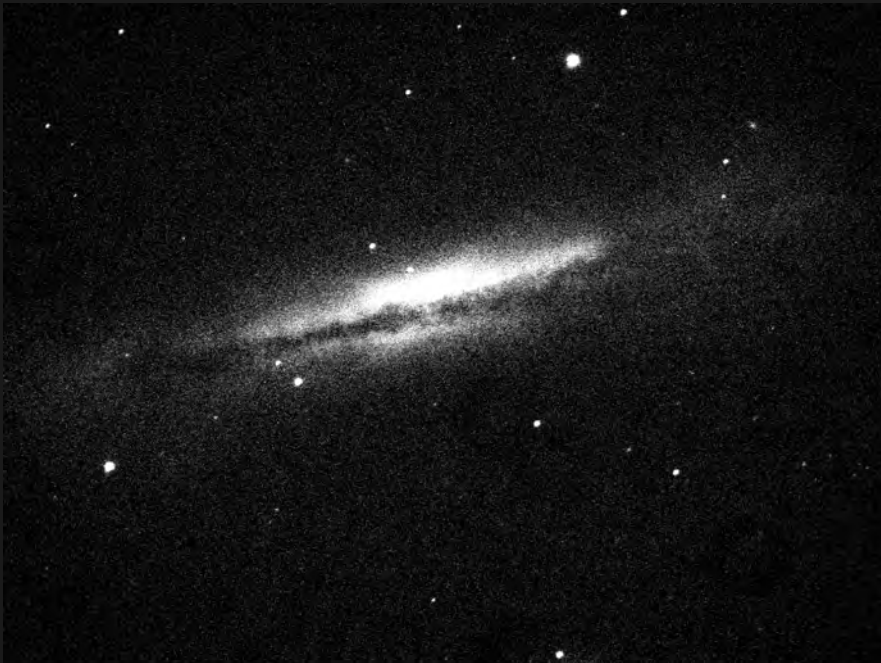
M = amplitude of
magnetic field



Albert Einstein (1905): Light is a Particle

Explained the photoelectric effect, which led to the new field of *quantum mechanics*. Einstein himself never accepted it.

Modern CCD cameras count *photons*.



Indirect Detection Methods

About 1000 planets found so far

(since 1995)

Wobble Methods

Radial Velocity.

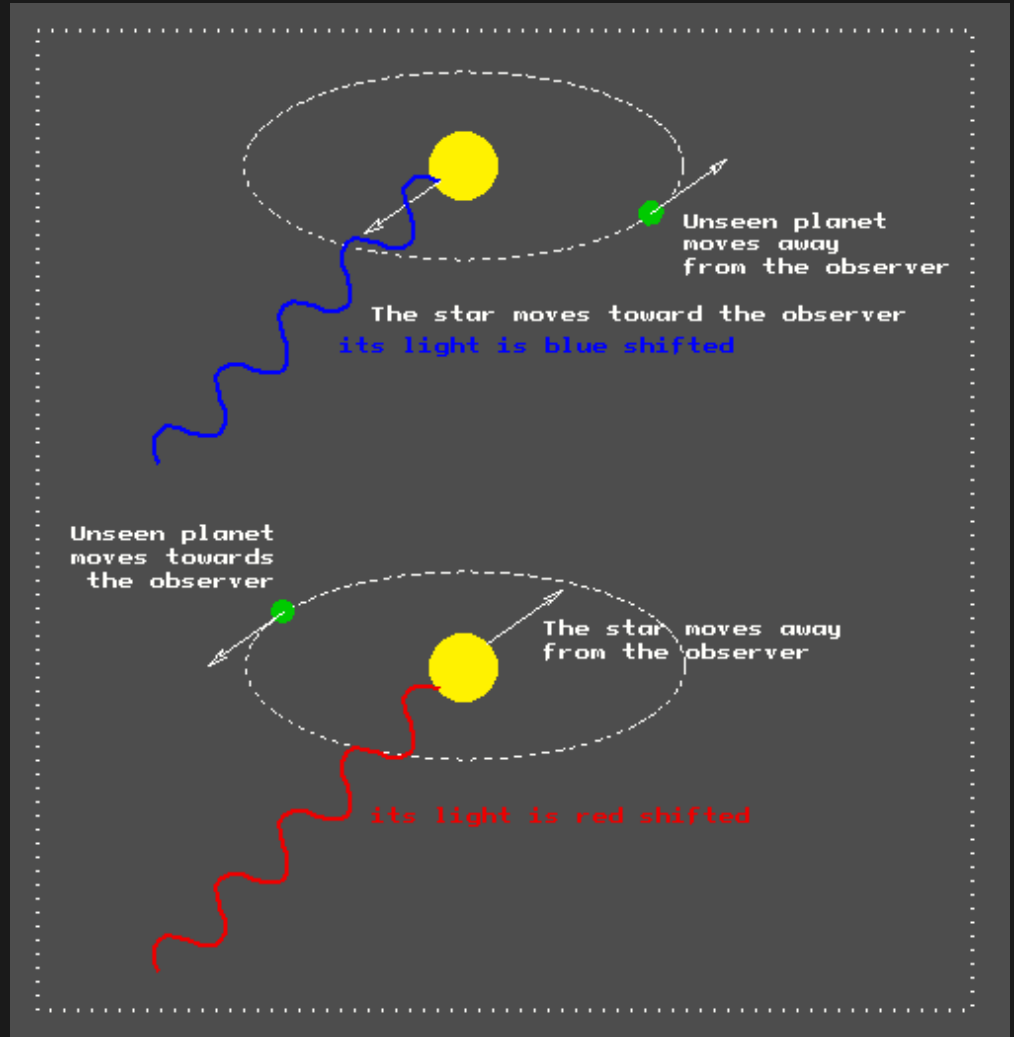
For edge-on systems.

Measure periodic doppler shift.

Astrometry.

Best for face-on systems.

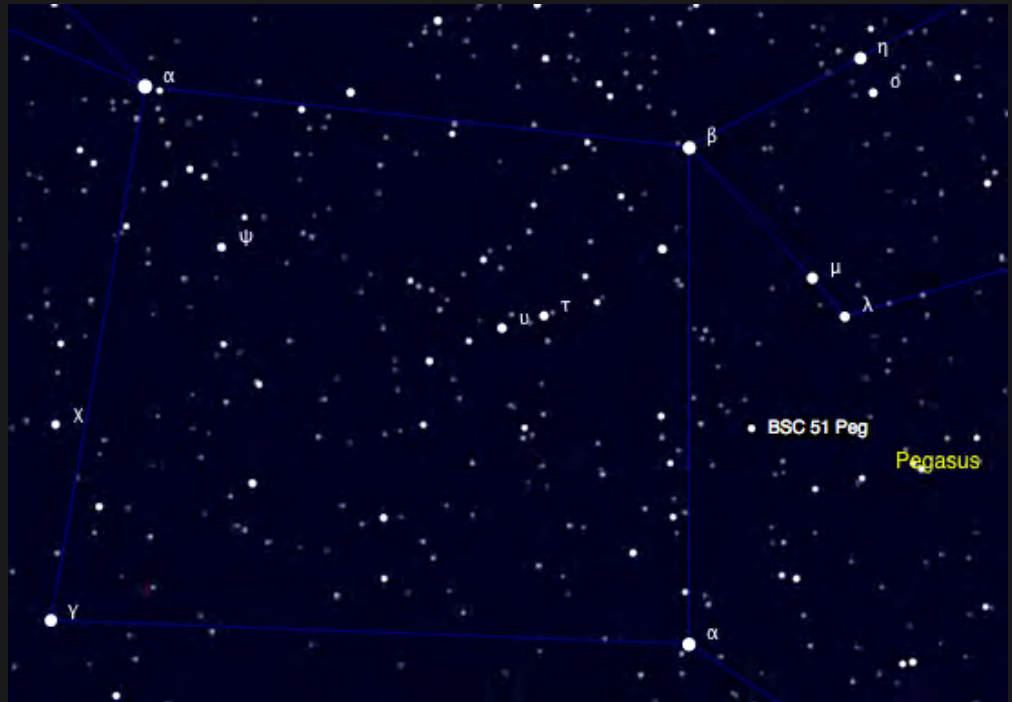
Measure circular wobble against background stars.



Click [here](#) for a demo.

First Discovery: 51 Pegasi b

- Mayor and Queloz (1995)
- Mag. 5.5
main sequence star
- Detected by *radial velocity* method
- Velocity difference:
70 m/s = 160 mph
- Period: 4.2 days
- Separation: 0.05 AU
- Angular separation:
0.0035 arcseconds
- Mass: $> 0.47M_J$
- Hot Jupiter

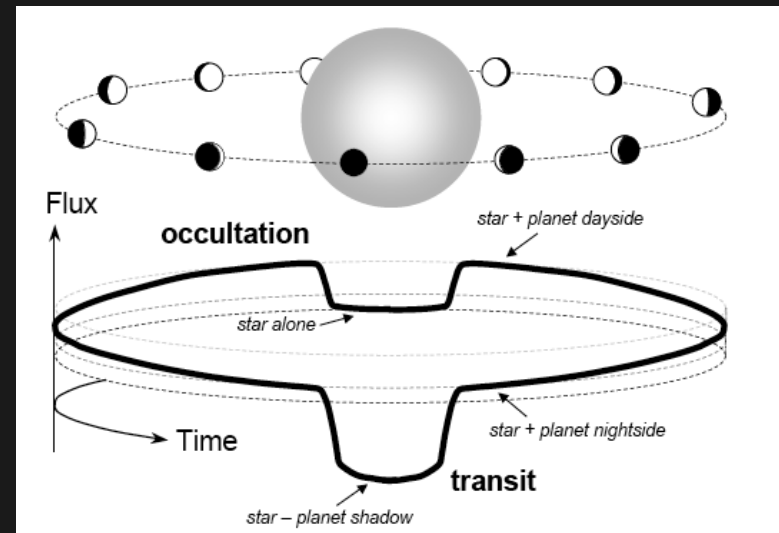


Transit Method

- HD209458b confirmed both via RV and transit.
- Period: 3.5 days
- Separation: 0.045 AU (0.001 arcsecs)
- Intensity Dip: $\sim 1.7\%$
- Radius: $1.3R_J$
- (Venus Dip = 0.01%, Jupiter Dip: 1%)



Venus Transit (R.J. Vanderbei)



■ EXOPLANETS COMPARED

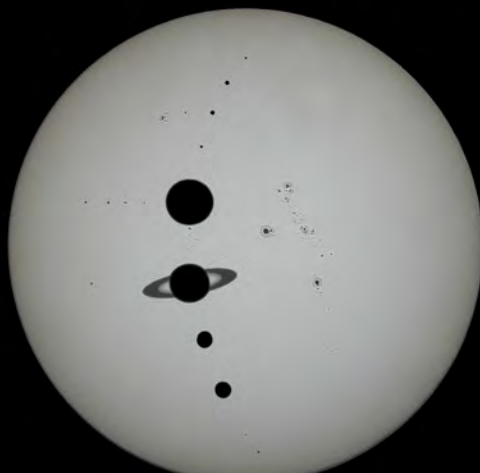
PLANETS ARE SHOWN to scale in silhouette against their stars as if seen in transit. The sun and its planets, Pluto, and some moons are shown for comparison. We can discover the sizes of extrasolar planets by noting the fraction of their star's light they block if they transit in front of it. Most planets discovered to date are very close to their stars and hence too hot to allow liquid water on their surface. Planet HD 209458b is a hot gas-giant planet like Jupiter. Planet GJ 436b is a hot Neptune-like planet. It's hot because it is so close to its star, even though that star is a cool M-dwarf. CoRoT-7b is the smallest transiting planet discovered so far—its diameter is only 1.7 times greater than Earth's diameter. It is a rocky planet with a temperature of more than 1300K.



GJ 436



CoRoT-7



Sun (for comparison)

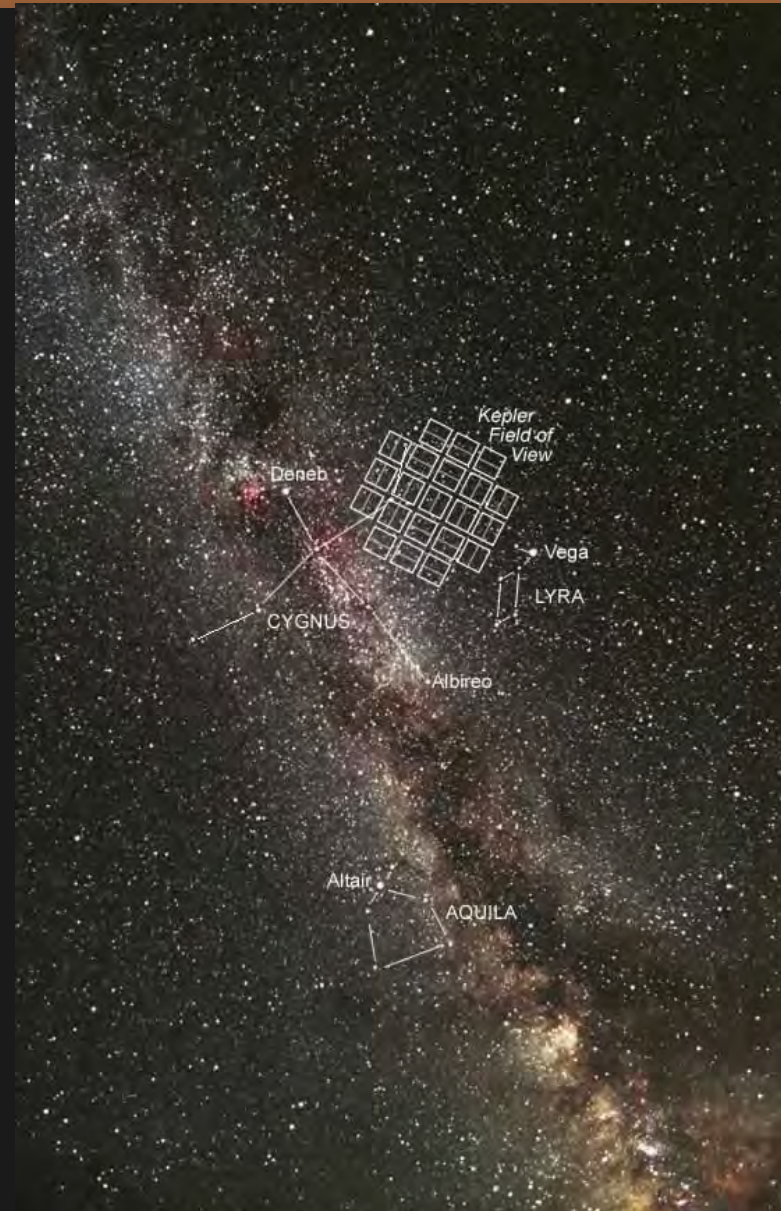


HD 209458



The Kepler Mission

- Space telescope launched March 2009 (original launch data: Jan 2006)
- Simultaneously observes 145,000 stars
- Second reaction wheel failed May 2013
- 134 confirmed exoplanets in 76 systems
- 3277 “candidates”
- Extrapolation: 17 billion Earth-like exoplanets in the Milky Way



But We Want “Earths”

Venus



Hot and Humid

Earth



Just Right

Mars



A Bit Cold

Jupiter



Too Gassy

Saturn



Brrr

⇐ This way to Mercury and the Sun

Where Should We Look?



Not in a star-birth region—stars are too young



Not in a young open cluster—stars are too young



Not near old dying stars



Not in a globular cluster—too much dynamical instability

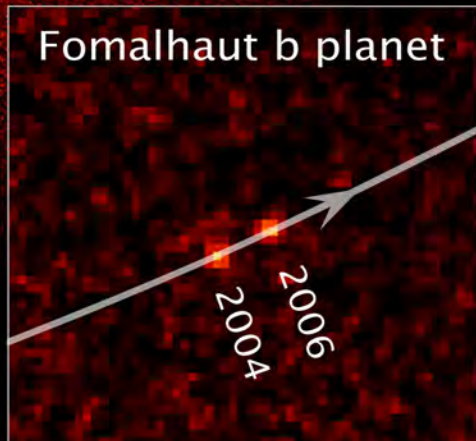
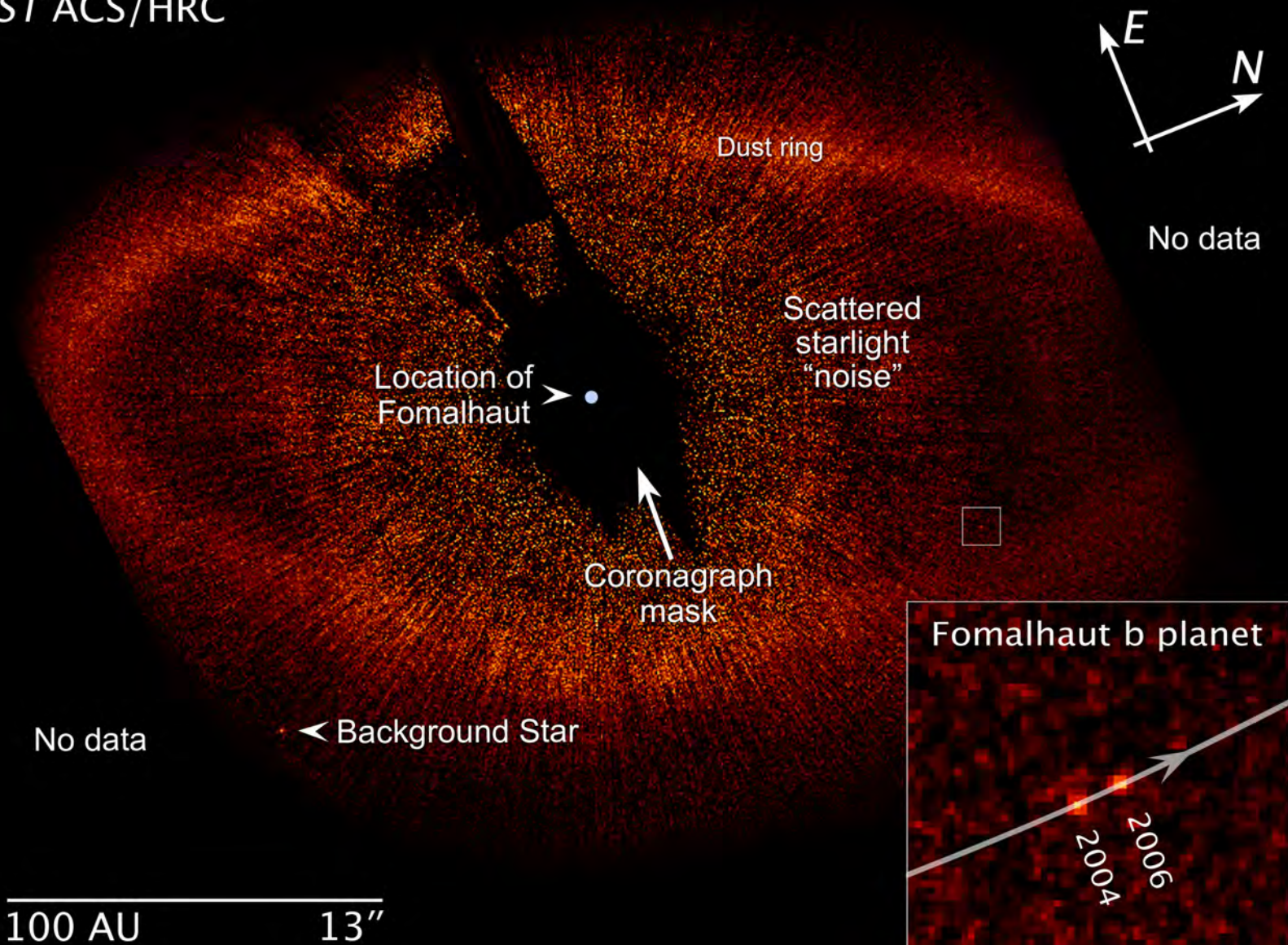


HERE!

Around run-of-the-mill middle-aged stars

Direct Detection

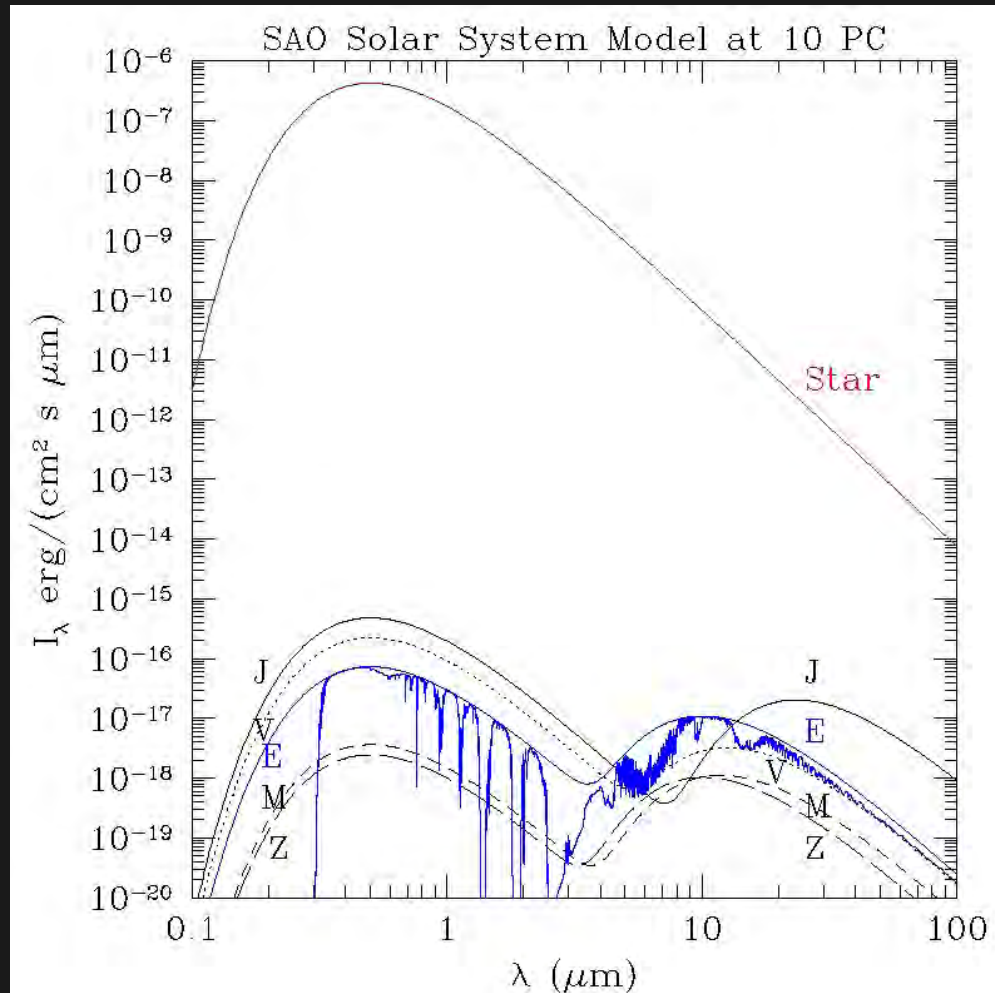
Fomalhaut
HST ACS/HRC



Why It's Hard

Premise: If there is intelligent life “out there”, it is probably similar to life as we know it on Earth.

- *Bright Star/Faint Planet:* In visible light, our Sun is ten billion times brighter than Earth.
- *Close to Each Other:* A planet at 1 AU from a star at 10 parsecs (33 lightyears) can appear at most 0.1 arcseconds in separation.
- *Far from Us:* There are less than 100 Sun-like stars within 10 parsecs.



Can Ground-Based Telescopes Do It?



- Atmospheric distortion limits *resolution* to about 1 arcsec.
Note: Resolution refers to equally bright objects.
If one is much brighter than the other, then it is more difficult.
- Segmented mirrors limit contrast
- Current adaptive optics not good enough

No they can't (at least not yet)!

Can Hubble Do It?



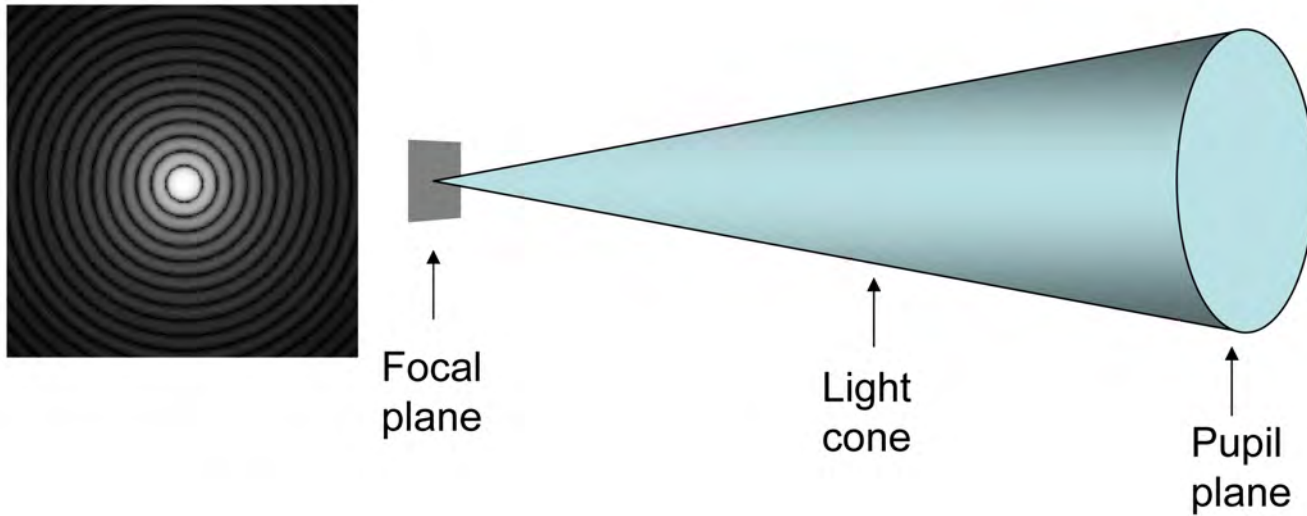
No it can't!

The problem is diffraction

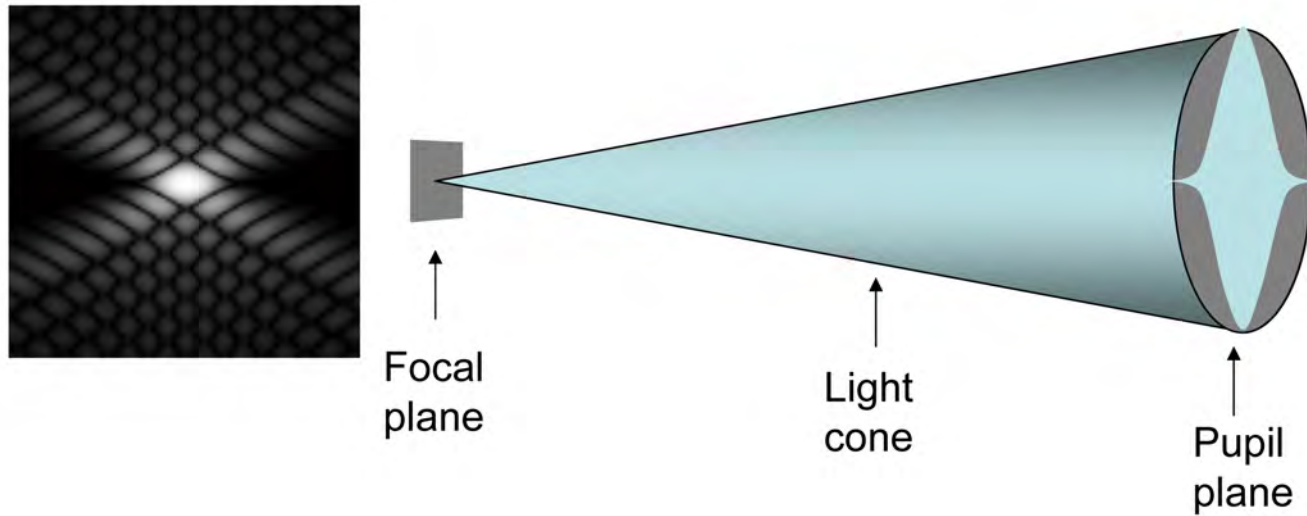
Would have to be $1000\times$ bigger (in each dimension!)

Concept 1: Shaped Pupil Coronagraph

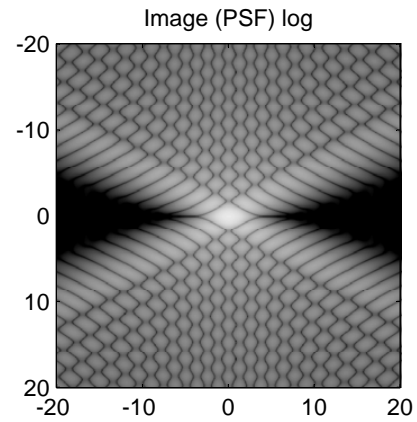
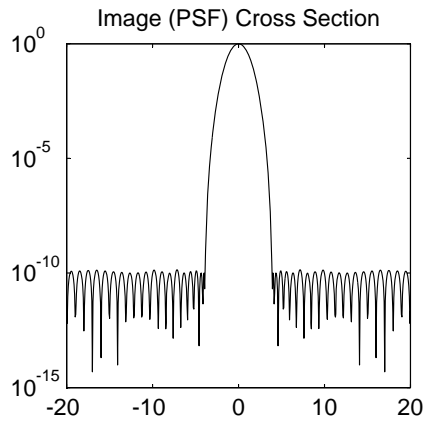
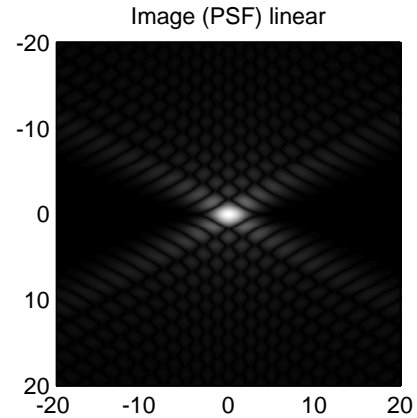
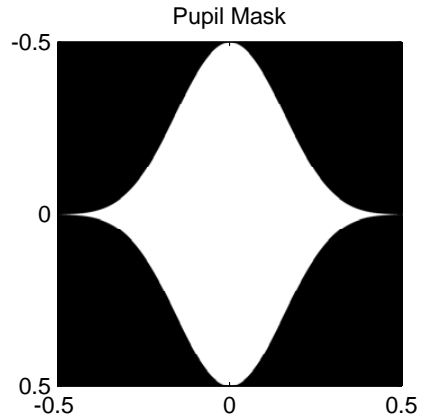
Diffraction Control via Shaped Pupils



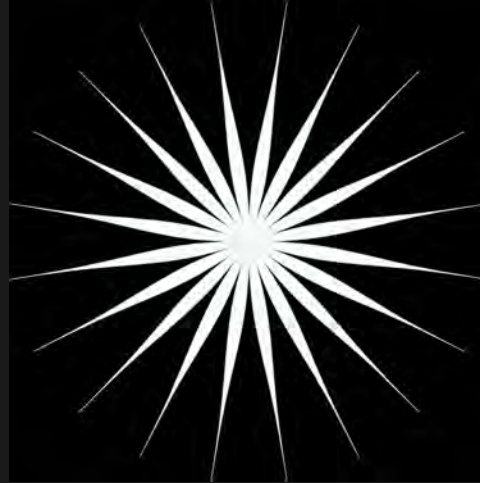
Diffraction Control via Shaped Pupils



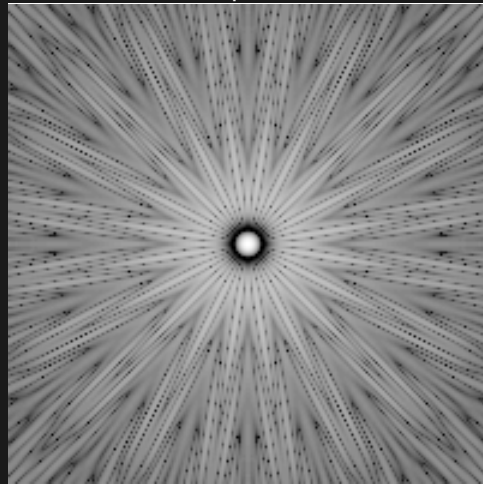
The Spergel-Kasdin-Vanderbei Pupil



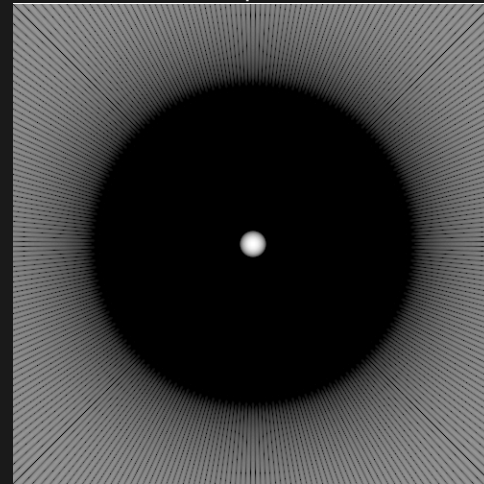
Shaped Pupil Coronagraph (TPF-C)



20 petals

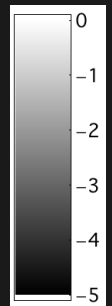
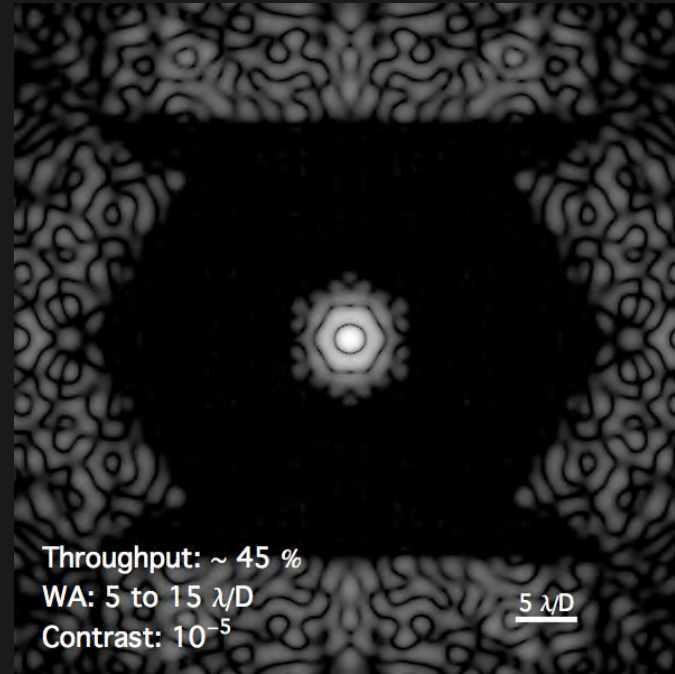
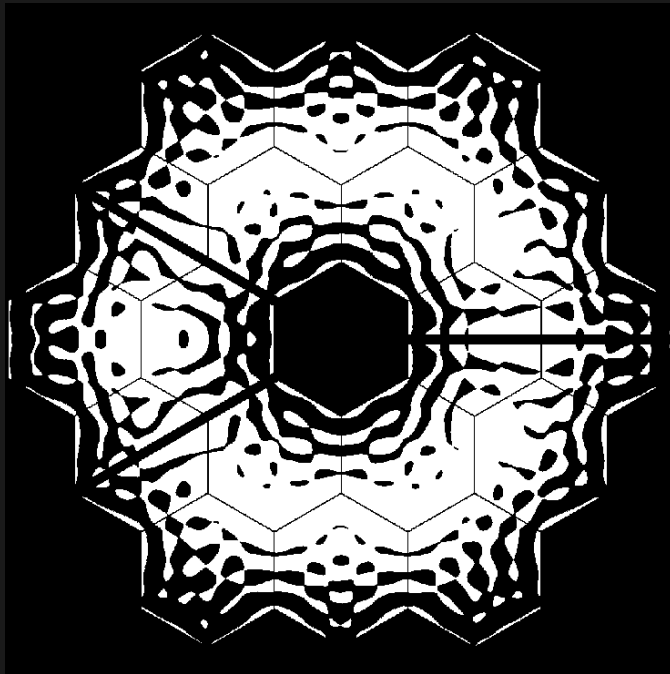
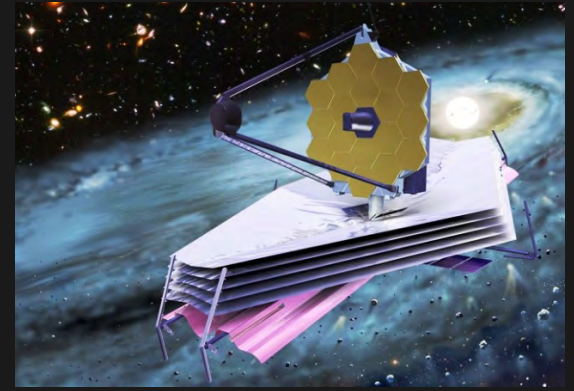


150 petals



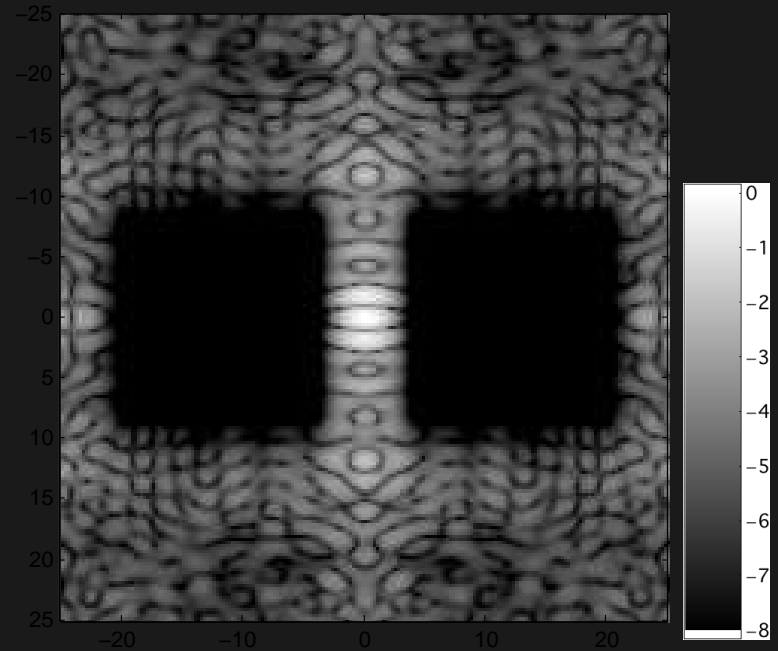
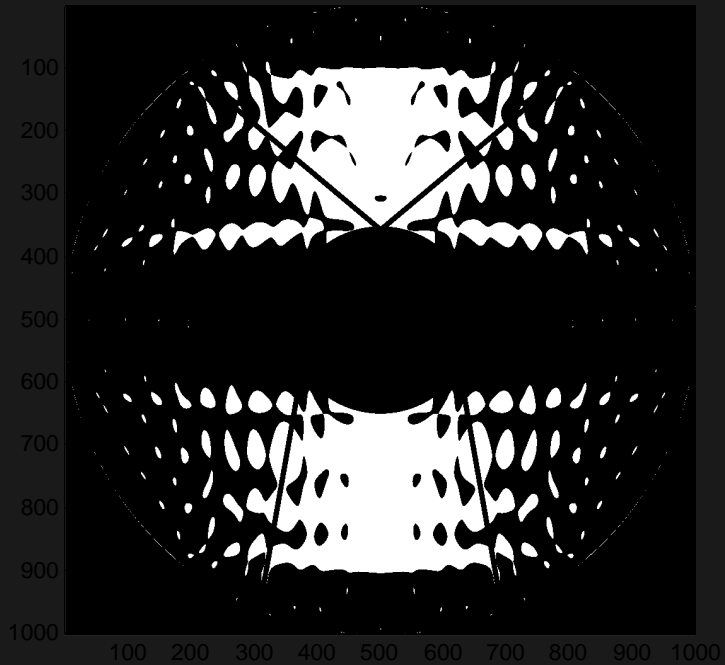
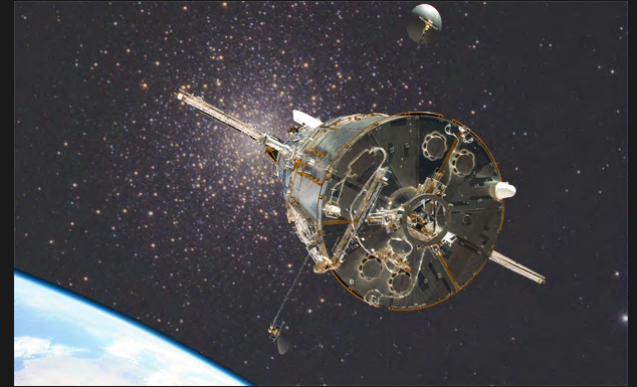
Maybe We Can!

James Webb Space Telescope (JWST)



AFTA Satellite

Repurposed NRO Spy Satellite



Concept 2: External Occulter

Nature's Coronagraph

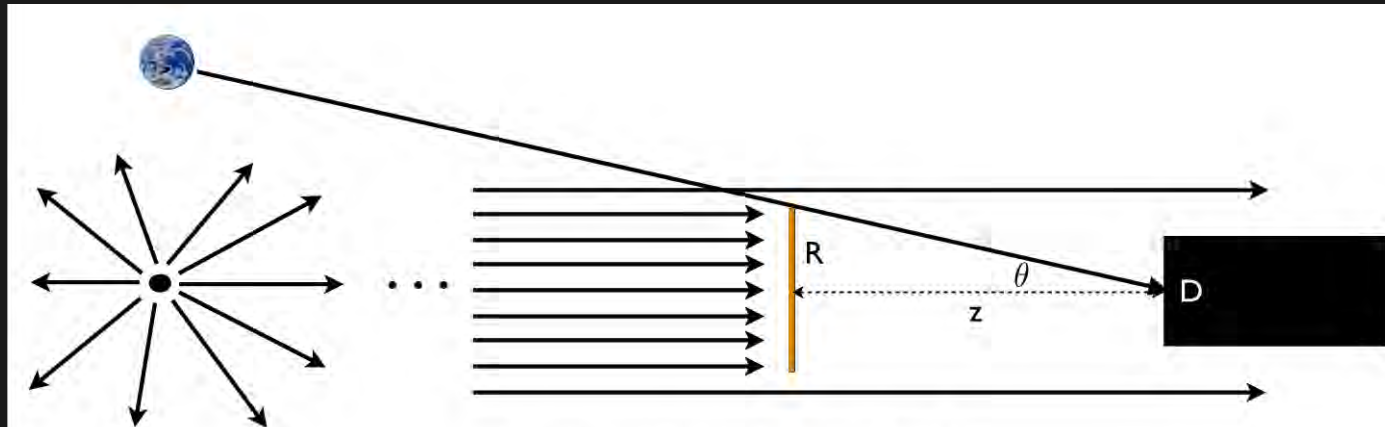
Use an external
occulter to
block the light.



© 1998 Andreas Gada and Jerry Lodriguss



Occluder—Simple Ray Optics Description



Shadow size given by R

Inner Working Angle given by: $\tan \theta = \frac{R}{z}$

For $D = 4$ m, $R = 3$ m, and IWA = 75 mas, $z \sim 10,000$ km

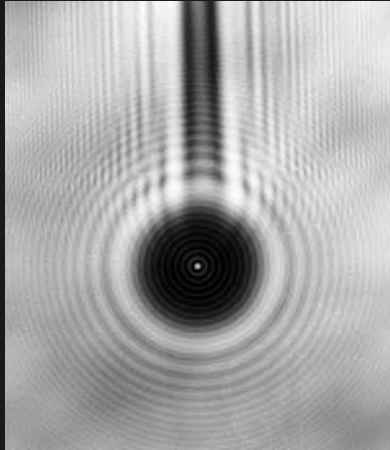
The fundamental size and separation for a starshade are LARGE.

Siméon Poisson/Francois Arago (1818)

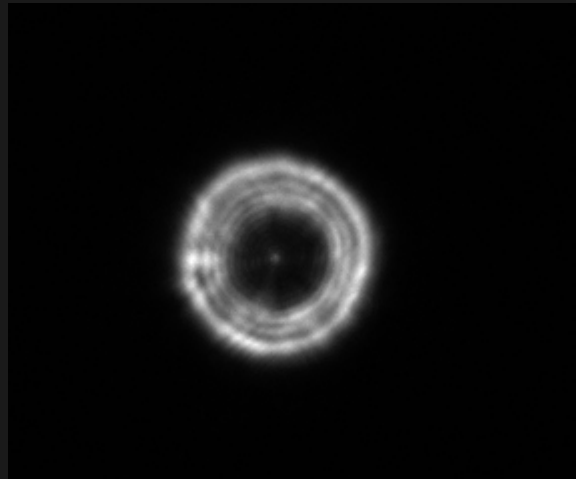
Poisson didn't believe the wave theory of light. He pointed out that light falling on a circular object would have a bright spot at the center of its shadow.

Arago did the experiment.

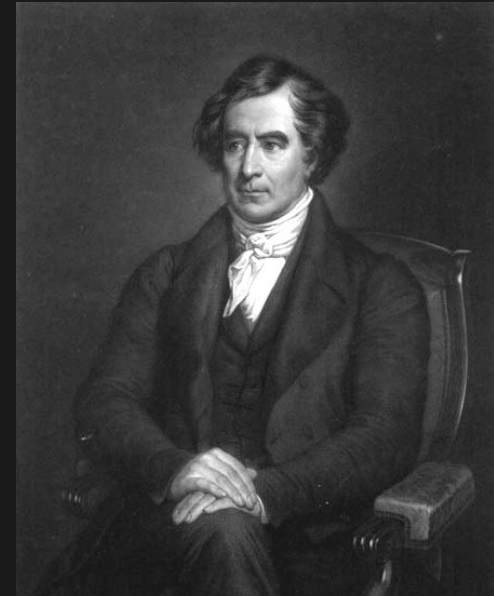
Poisson was wrong.



Poisson's spot

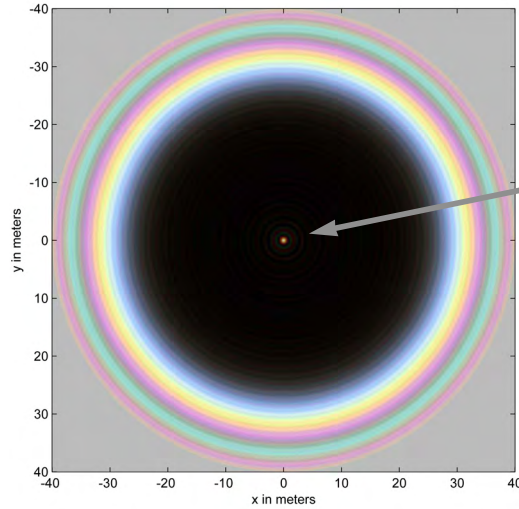
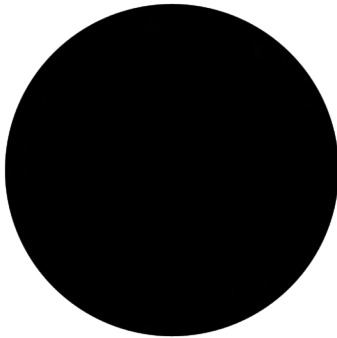


Arcturus defocused

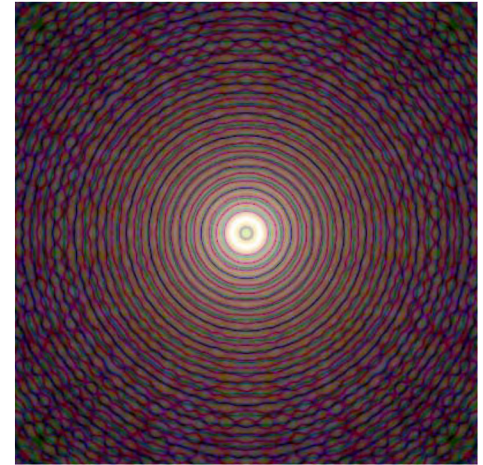


Plain External Occulter (Doesn't Work!)

Circular Occulter

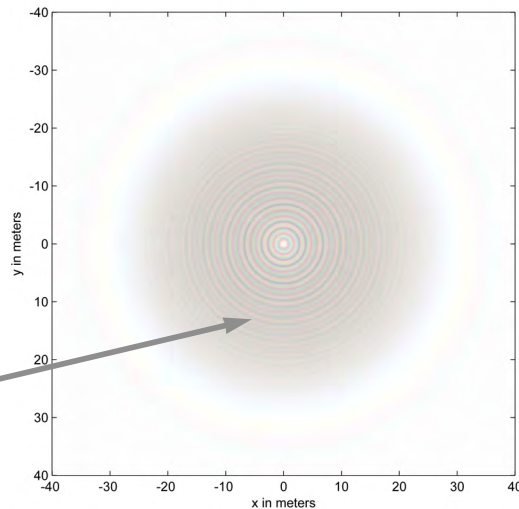


Poisson's Spot!

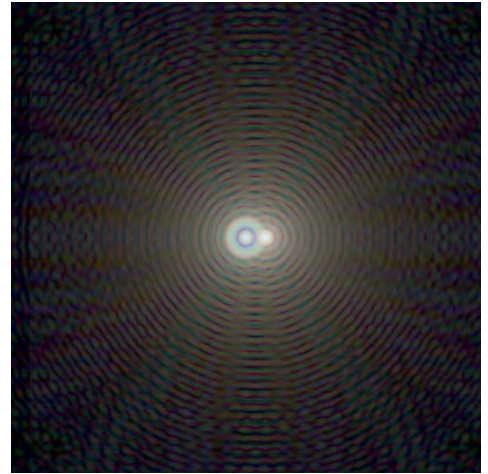
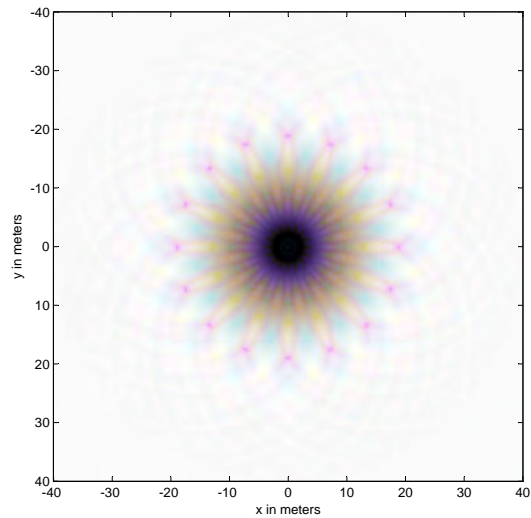
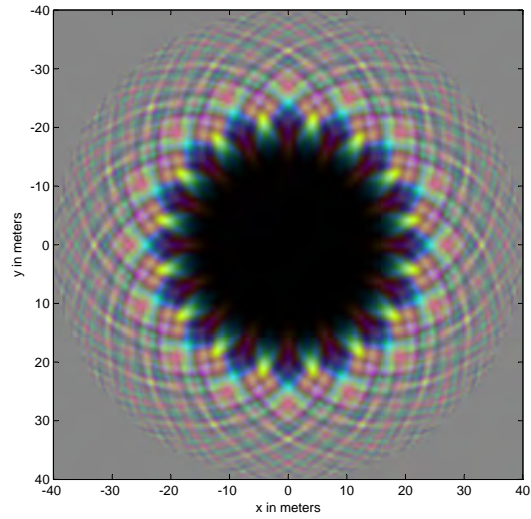
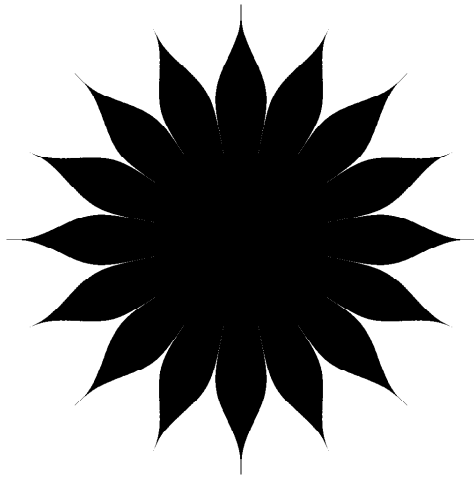


Simulated star/planet image

Shadow isn't dark enough



Shaped Occulter

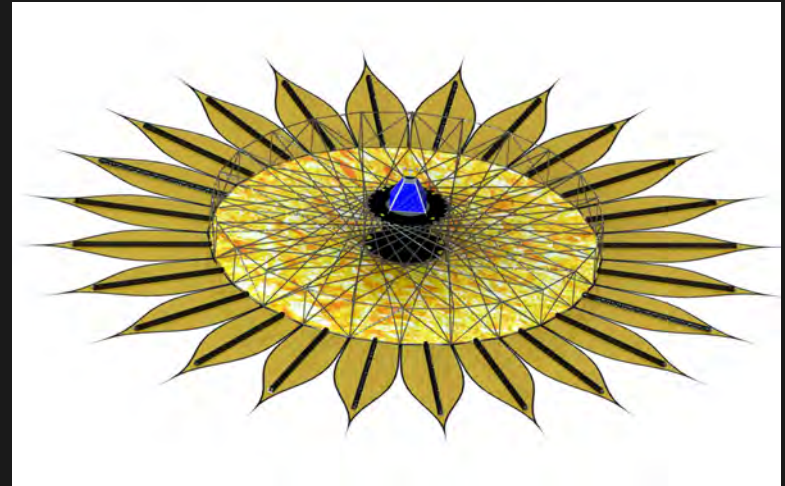
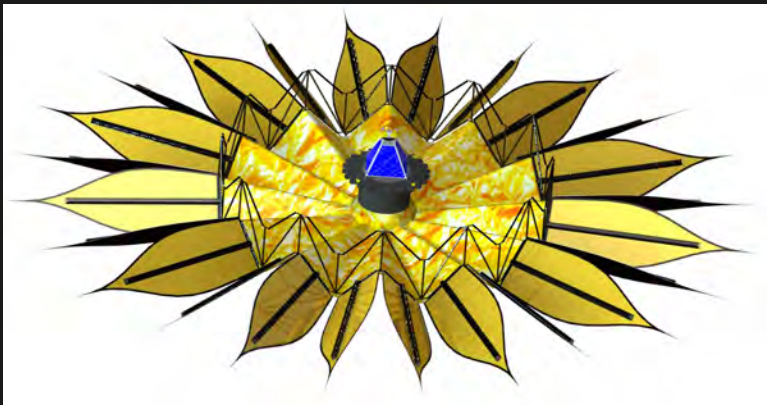
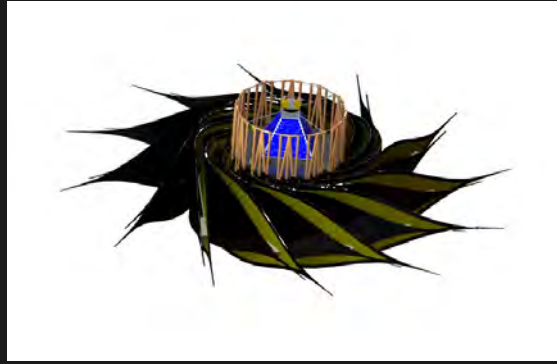


Space-based Occulter (TPF-O)

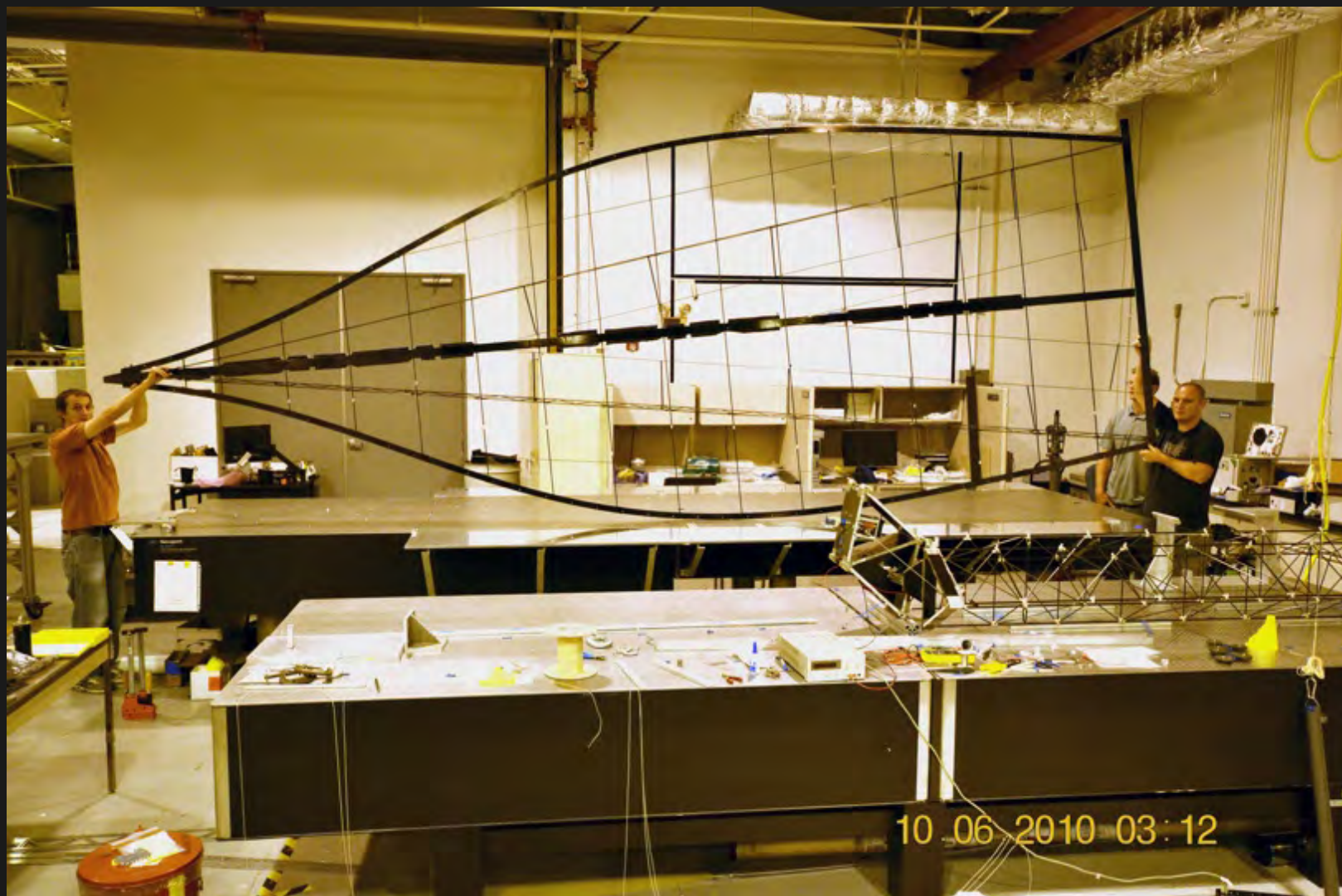


Telescope Aperture: 4m, Occulter Diameter: 50m, Occulter Distance: 72,000km

Starshade Stowage and Deployment



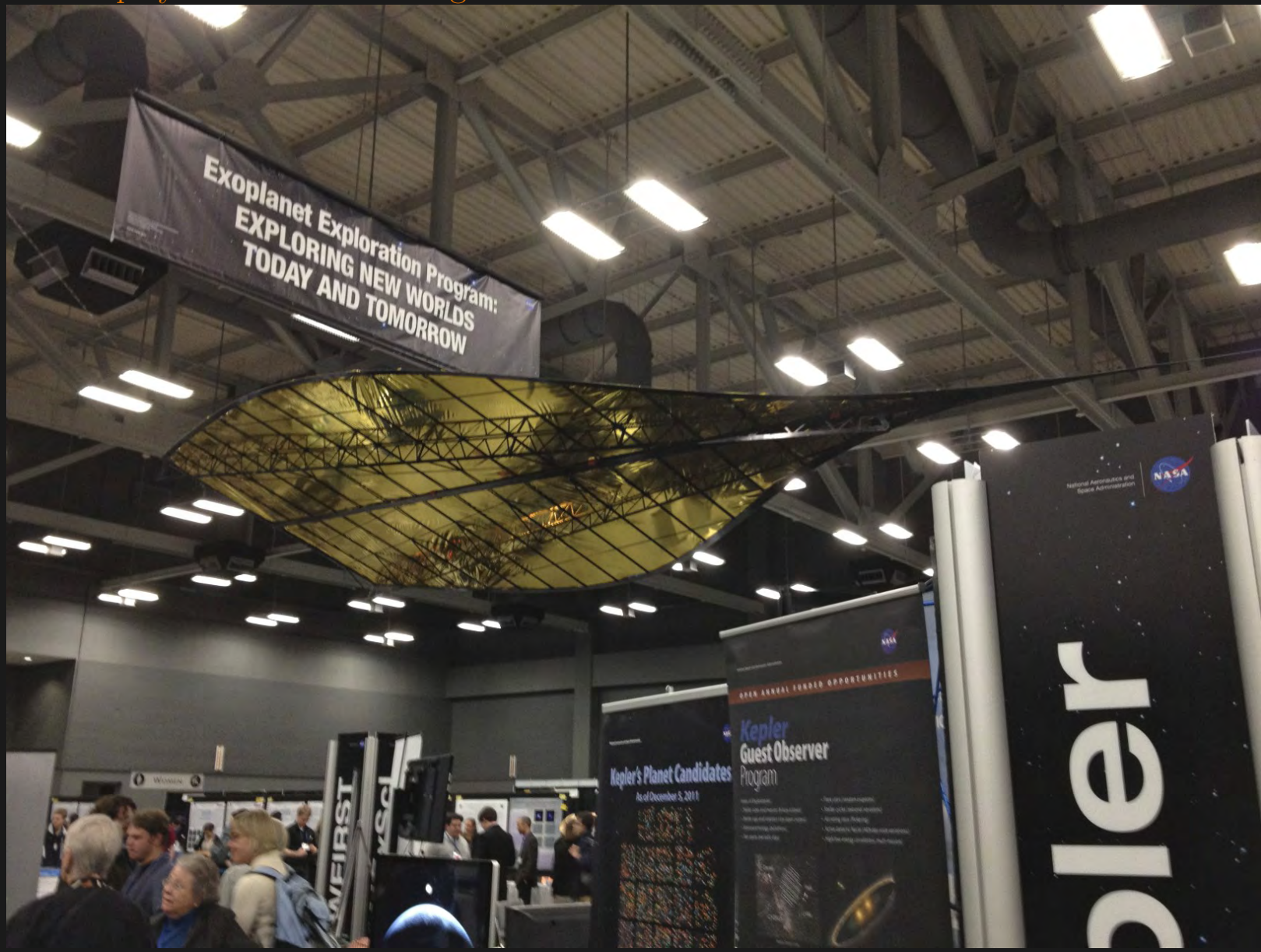
A Real Petal...



...And How It Furls



...On Display at an AAS Meeting



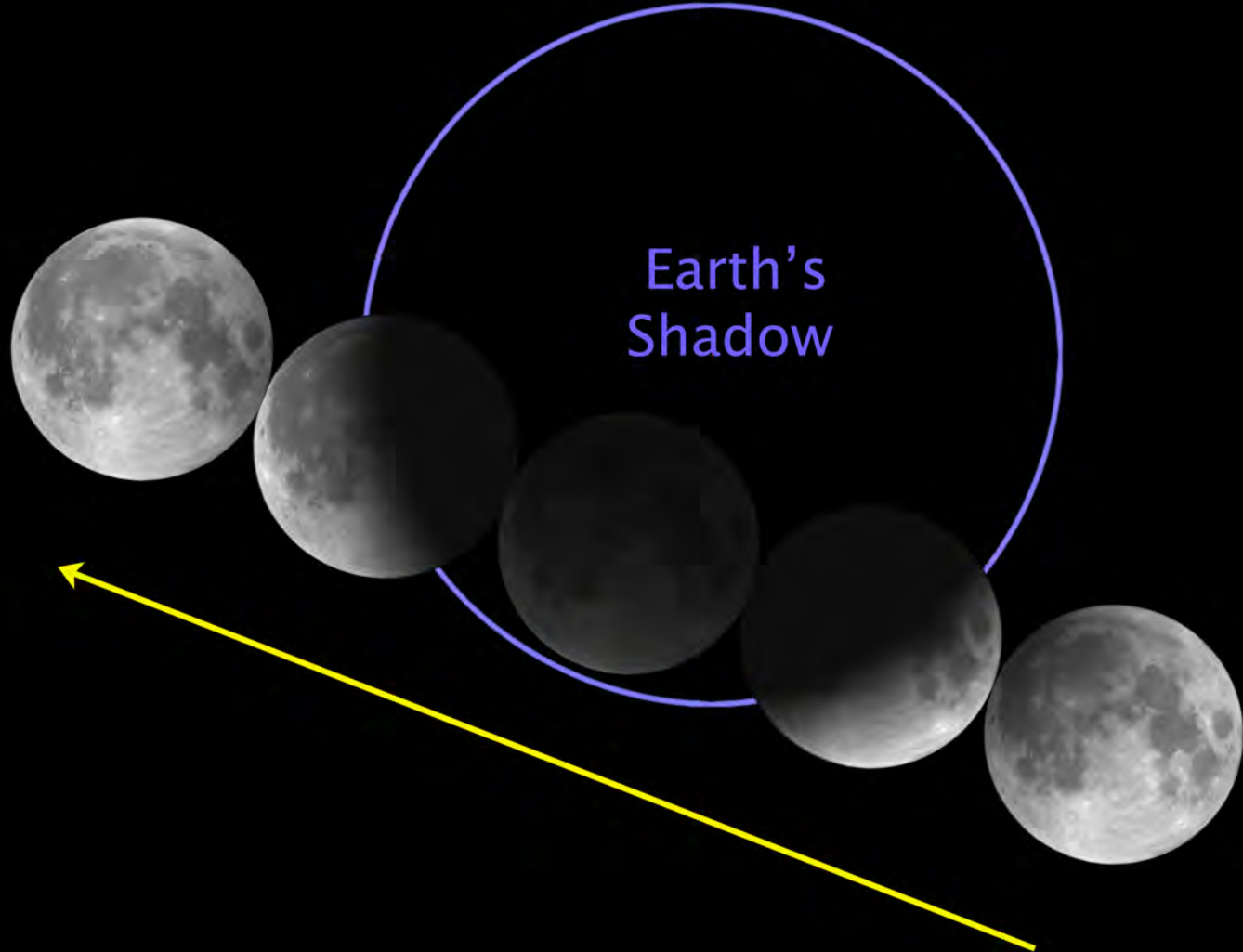
Summary/Conclusion

- In the last 15 years, we have found hundreds of planets around other stars.
- These planets are mostly Jupiter-sized and close to their star—not *habitable*.
- It may be possible, in the near future, to take pictures of Earth-like planets around Sun-like stars.
- But, it will be hard.
- Such pictures would be the first step in answering the question: “Are we alone?”

THANK YOU!

Backup Slides

Some History—The Earth is a Sphere



1609: Telescope is Invented (Hans Lippershey)



1610: Galileo Looks at Jupiter

Callisto

Io

Europa

Ganymede

Greenhawk Observatory : Image by: Chanan Greenberg September 5, 2009 Jupiter & Galilean Moons
4 Sec C-9.25" SCT Orion Deep Space Pro with MaxIm DL PHD Guiding, CCDStack and Photoshop CS3

Galileo Galilei

“I should disclose and publish to the world the occasion of discovering and observing four Planets, never seen from the beginning of the world up to our own times, their positions, and the observations... about their movements and their changes of magnitude; and I summon all astronomers to apply themselves to examine and determine their periodic times....”

March, 1610



(Convicted of heresy, 1633.
House arrest until his death.
Sentence rescinded October, 1992)

Our Solar System From Fomalhaut



Our Solar System From Fomalhaut

2014 01 01 00:00:00 UTC

