Space Mission Concepts to Image Earth-Like Planets

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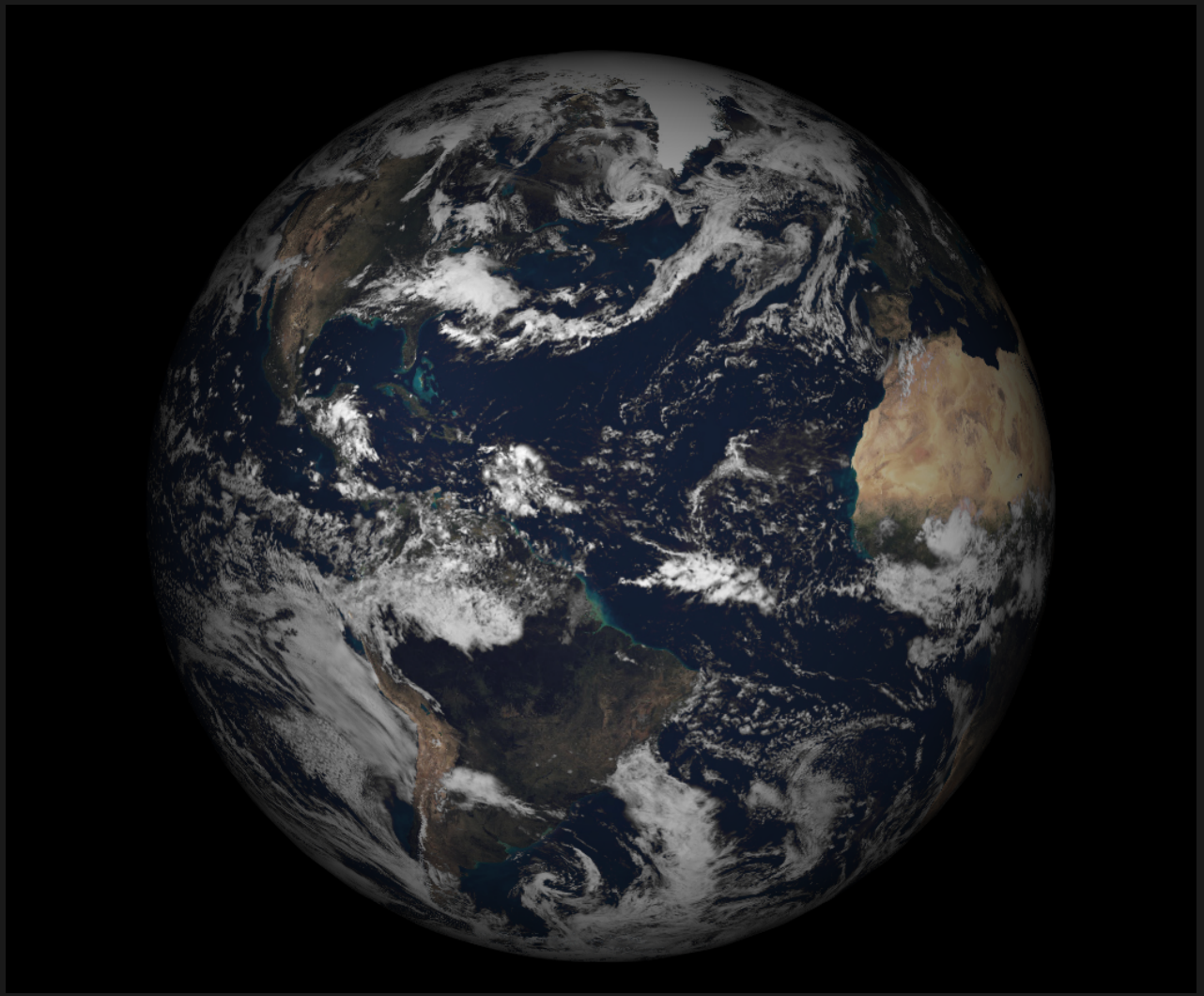
http://www.princeton.edu/∼rvdb

Are We Alone? What Are The Odds?



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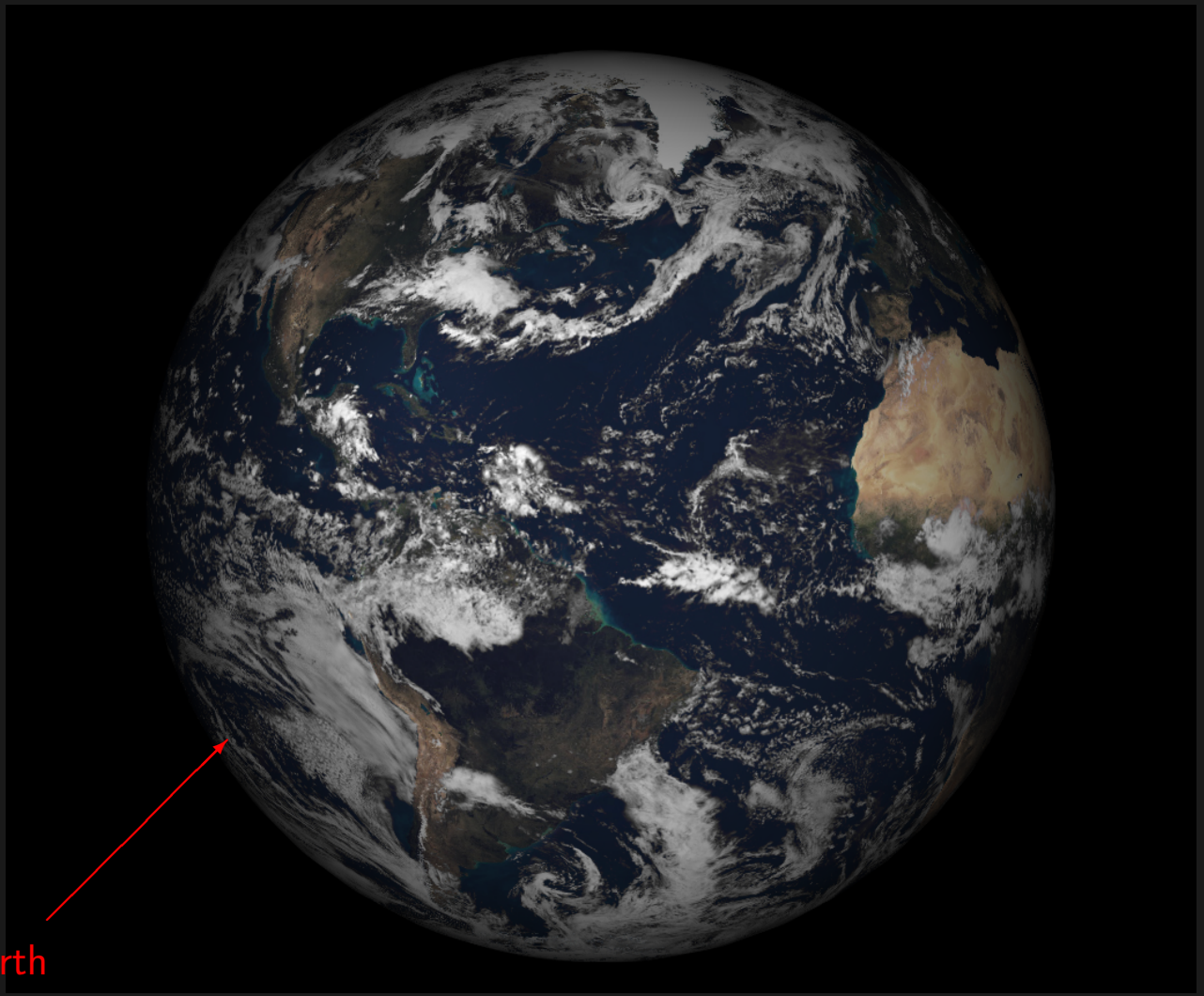
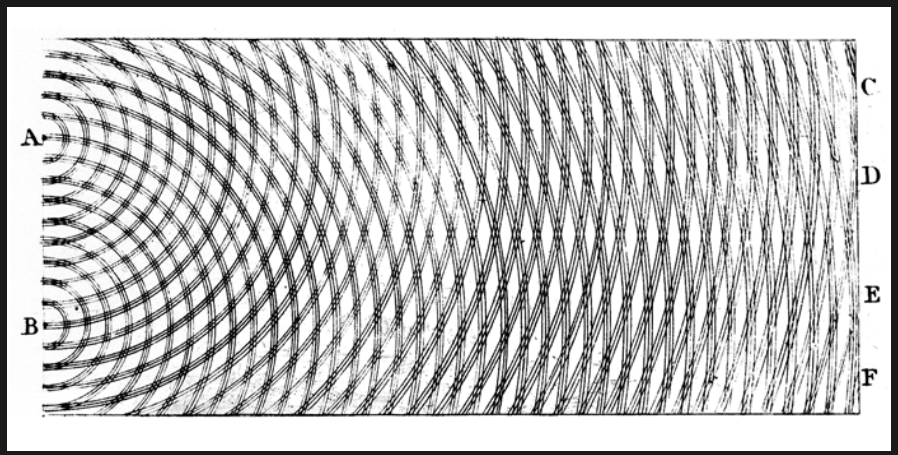


Some Background

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

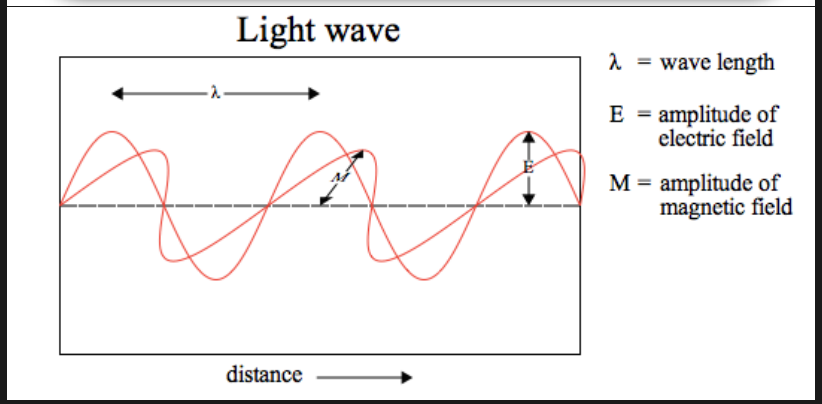
$$\nabla \cdot \vec{D} = \rho_{\text{free}}$$

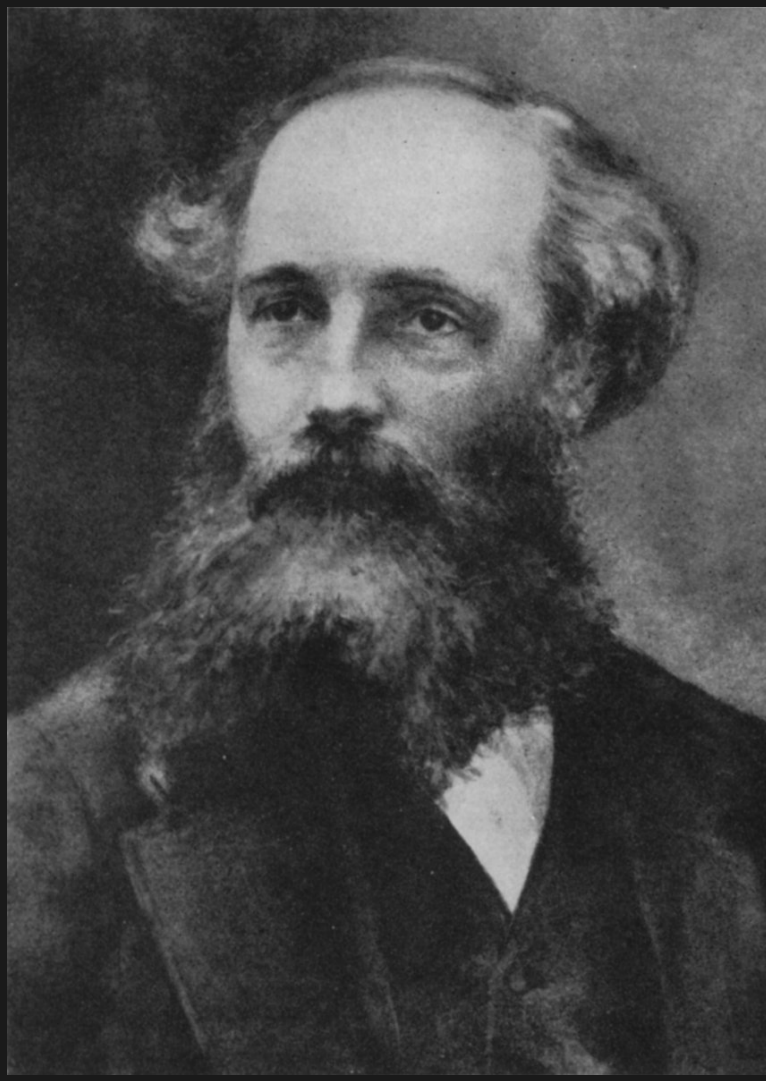
$$\nabla \cdot \vec{B} = 0$$

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

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

and *then* there was light.

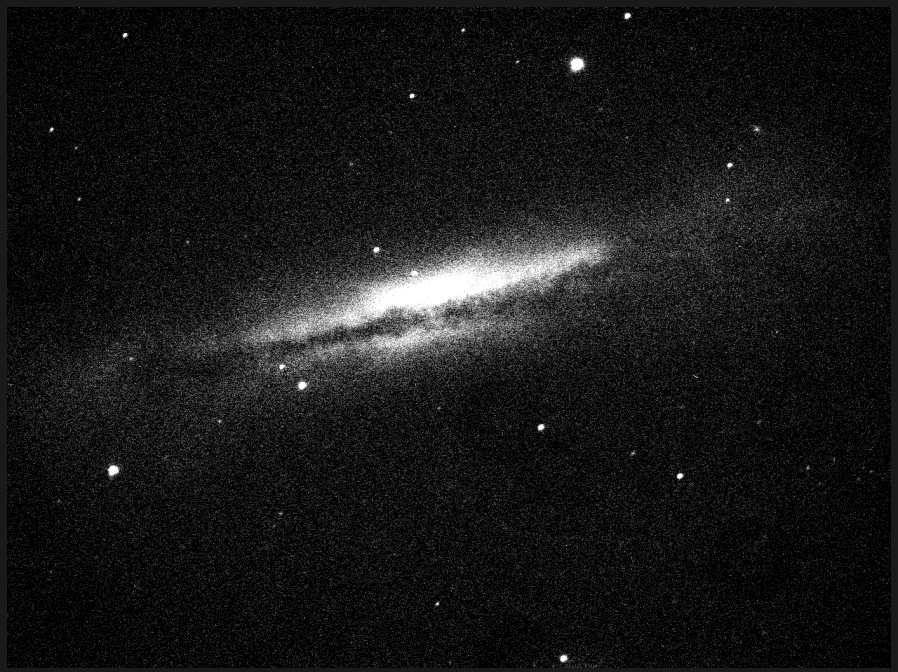


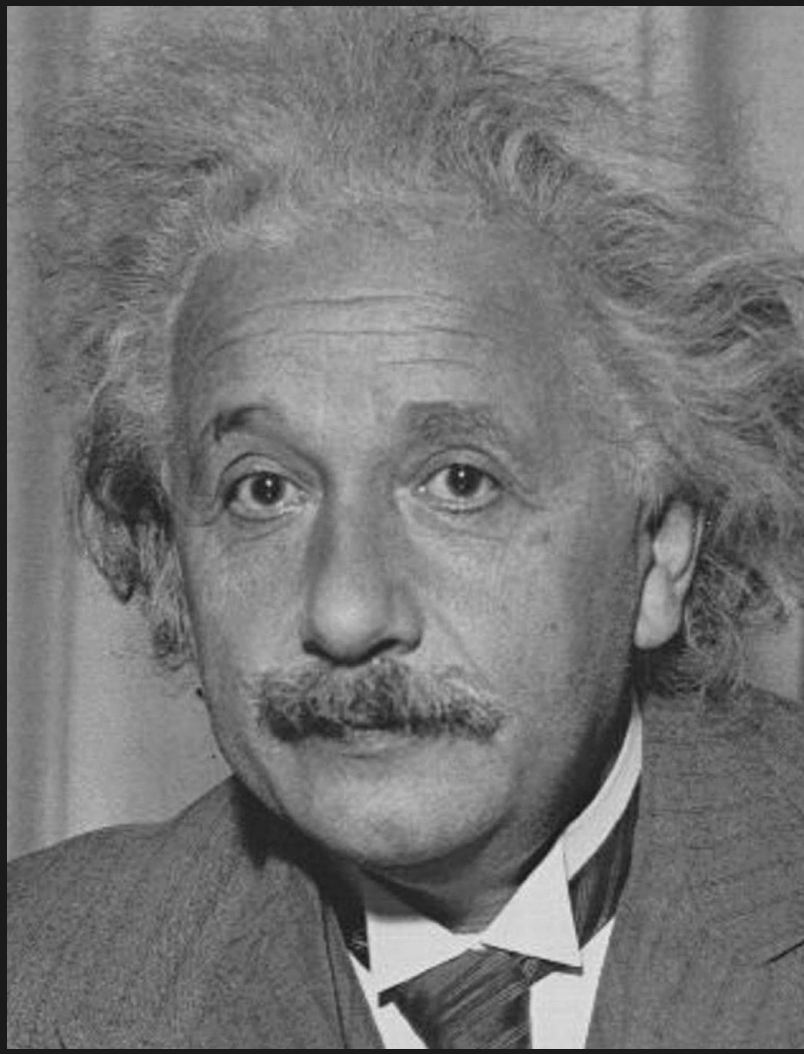


Albert Einstein (1905): Light is a Particle

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

A few thousand planets found so far

(since 1995)

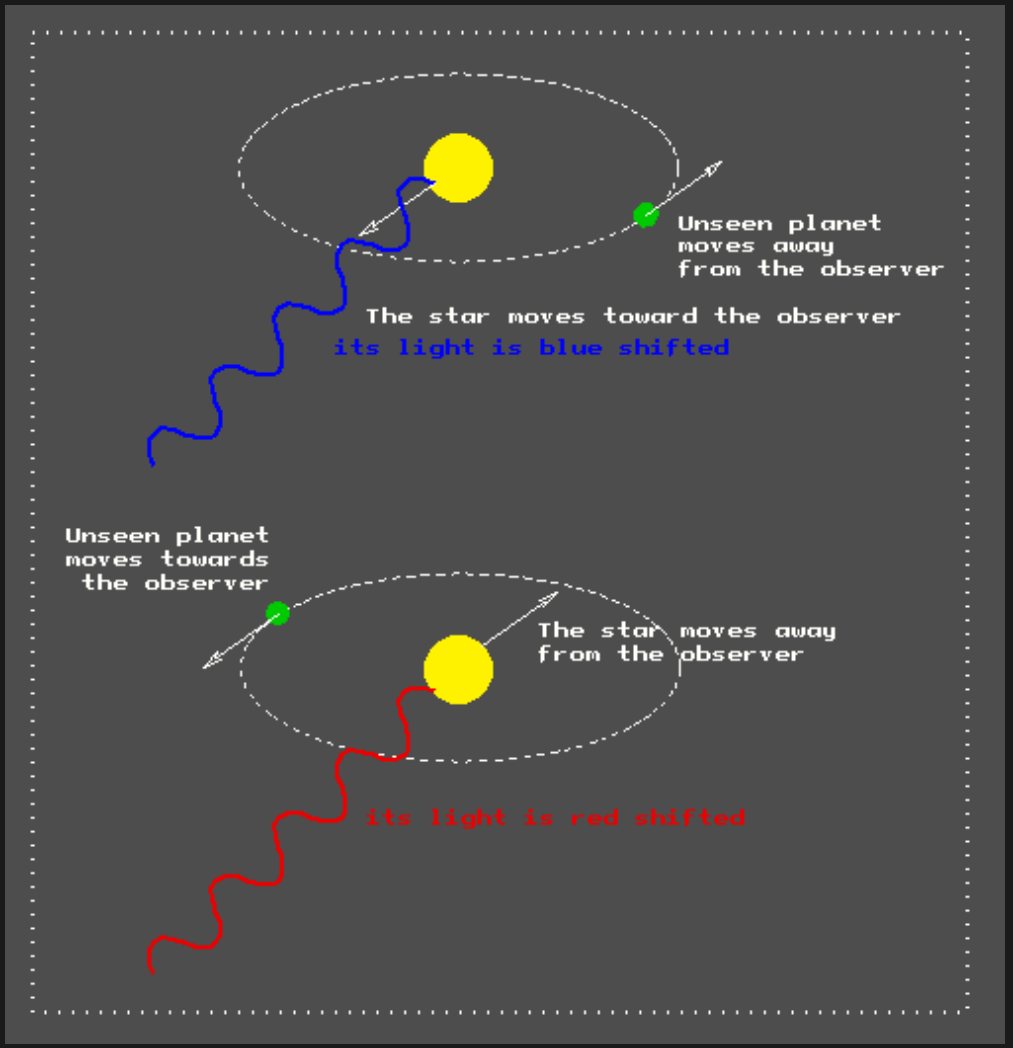
Wobble Methods

Radial Velocity.

For edge-on systems.
Measure periodic doppler shift.

Astrometry.

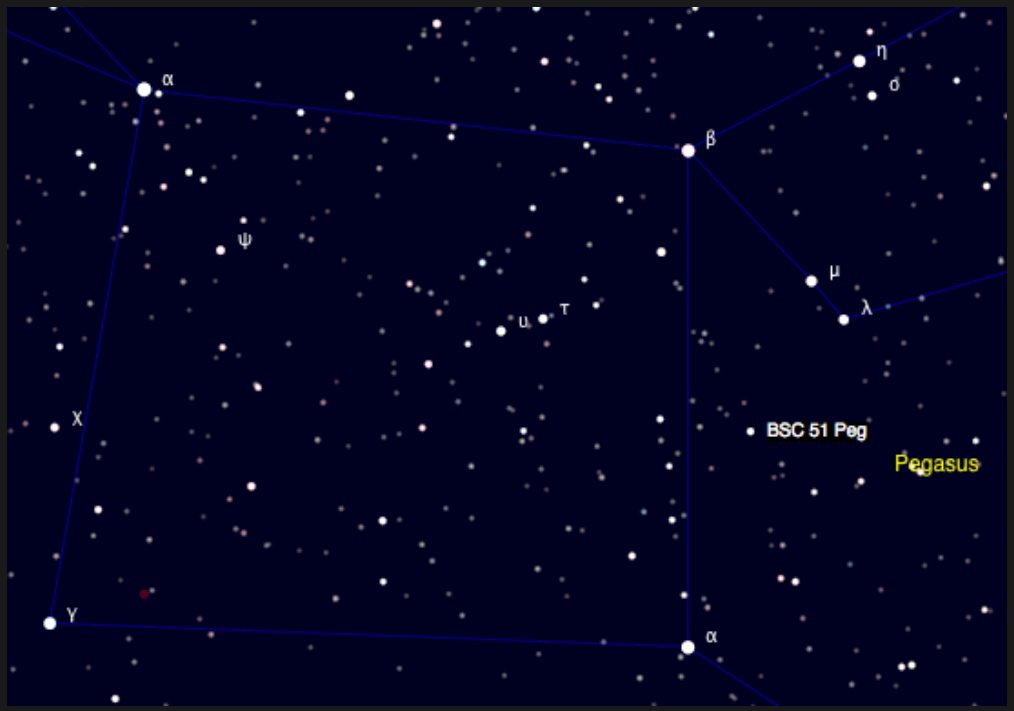
Best for face-on systems.
Measure circular wobble against background stars.



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: $> 0.47 M_{\mathrm{J}}$
- Hot Jupiter

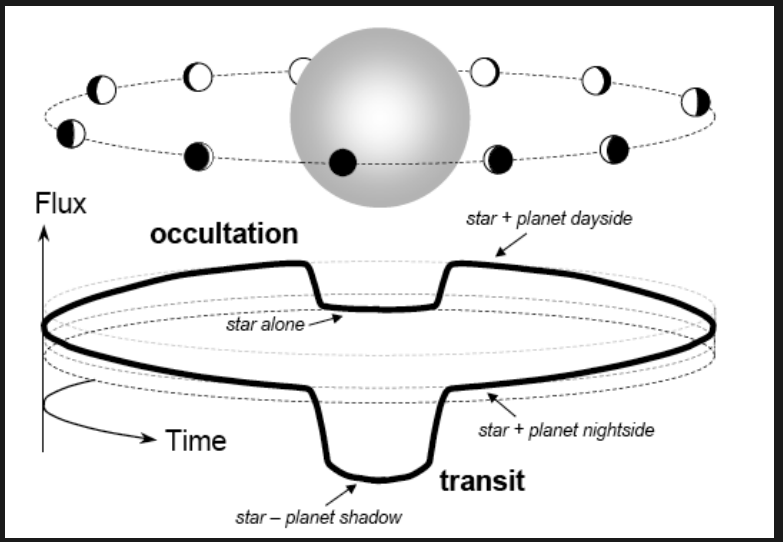


Transit Method

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

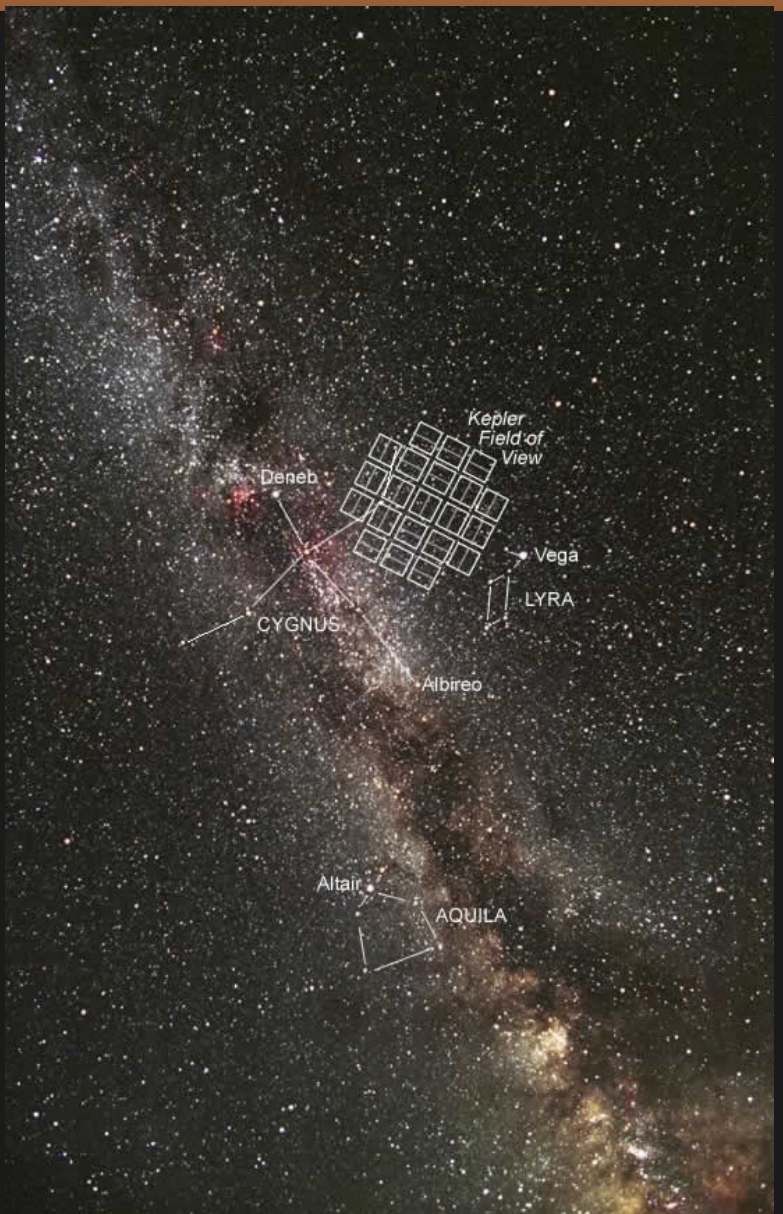
HD209458

Venus Transit (R.J. Vanderbei)

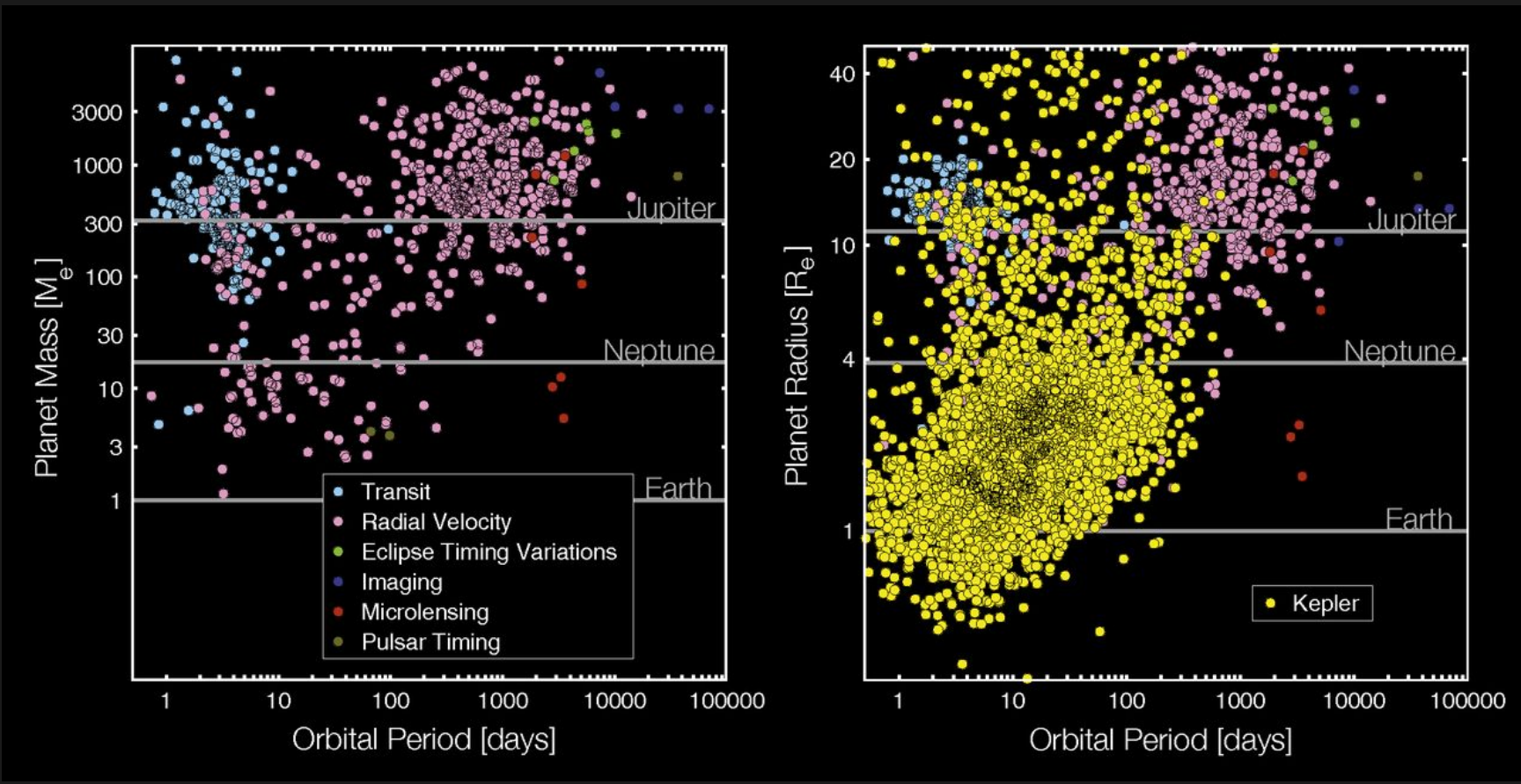


The Kepler Mission

- Space telescope launched March 2009 (original launch data: Jan 2006)
- Simultaneously observes 145,000 stars
- Second reaction wheel failed May 2013
- 4696 "candidates"
- 2331 confirmed exoplanets
- 297 confirmed in "habitable zone"
- Extrapolation: 17 billion Earth-like exoplanets in the Milky Way

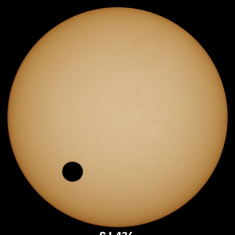


NASA's Kepler Mission



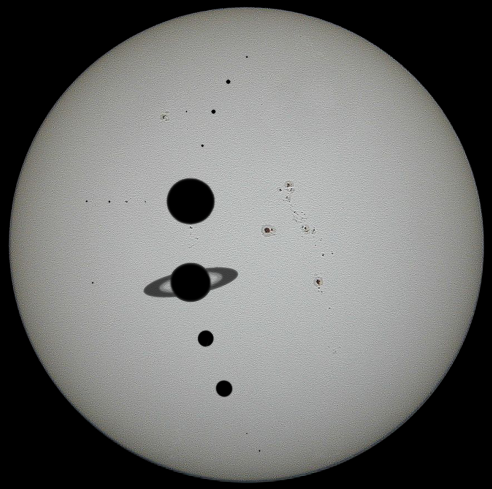
EXOPLANETS COMPARED

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

508,000 km

But We Want "Earths"

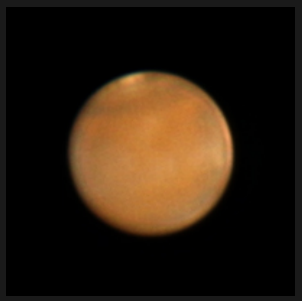
Venus

Hot and Humid

Earth

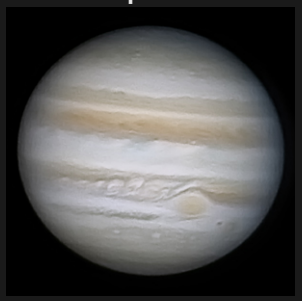
Just Right

Mars



A Bit Cold

Jupiter



Too Gassy

Saturn

Brrr

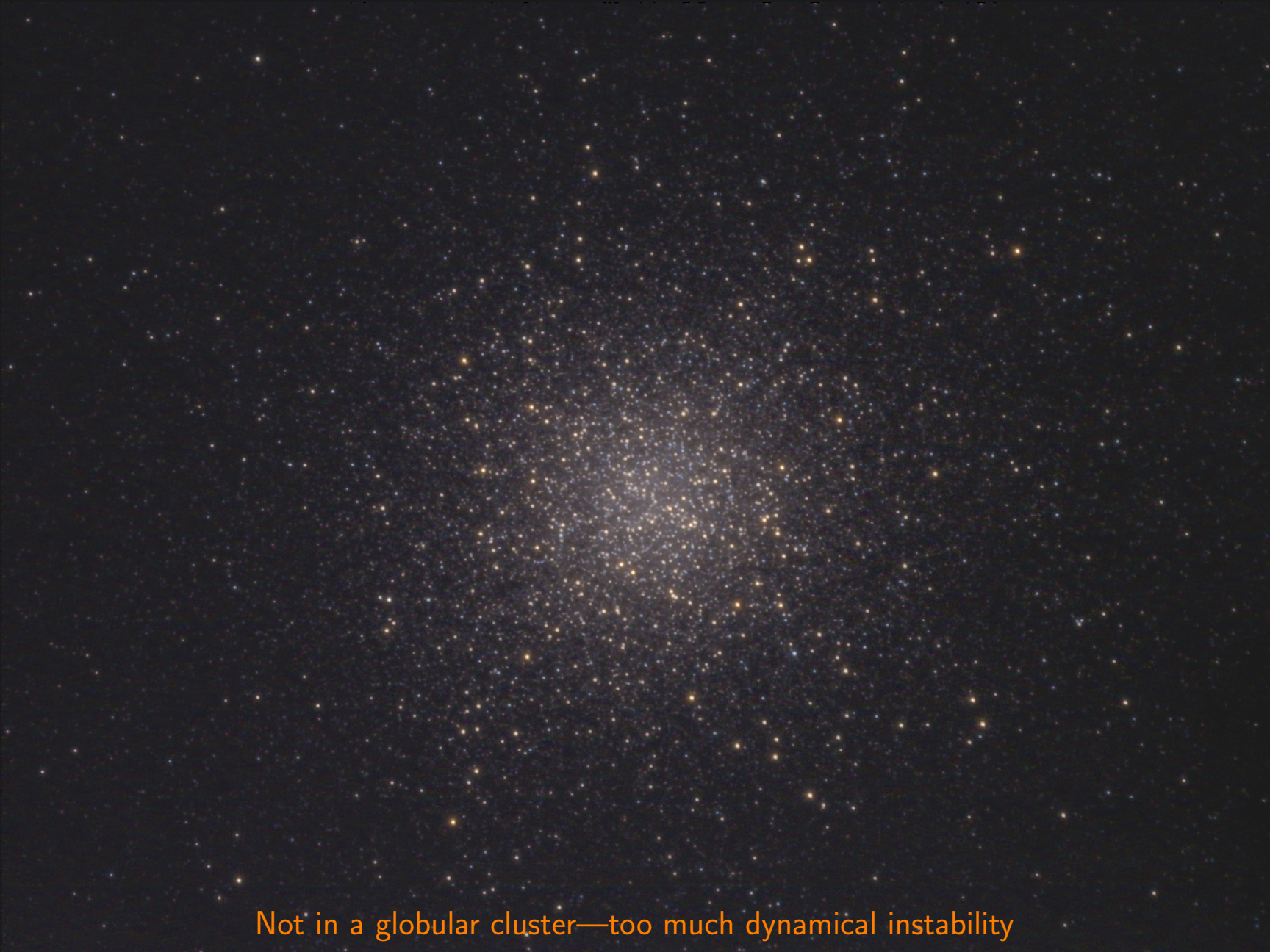
$\Longleftarrow$ This way to Mercury and the Sun

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

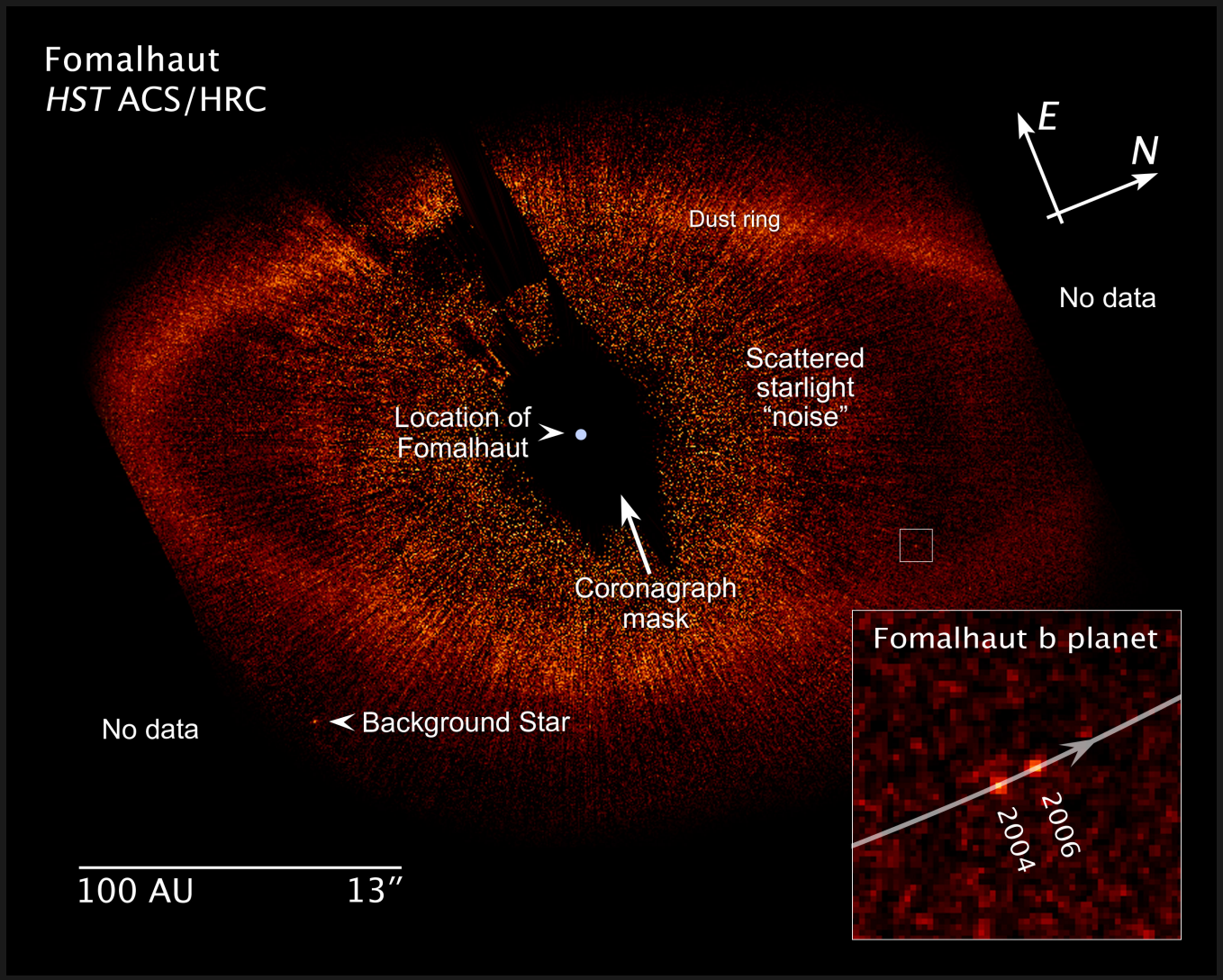

Not in a globular cluster—too much dynamical instability


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

Direct Detection

First Detection via Direct Imaging

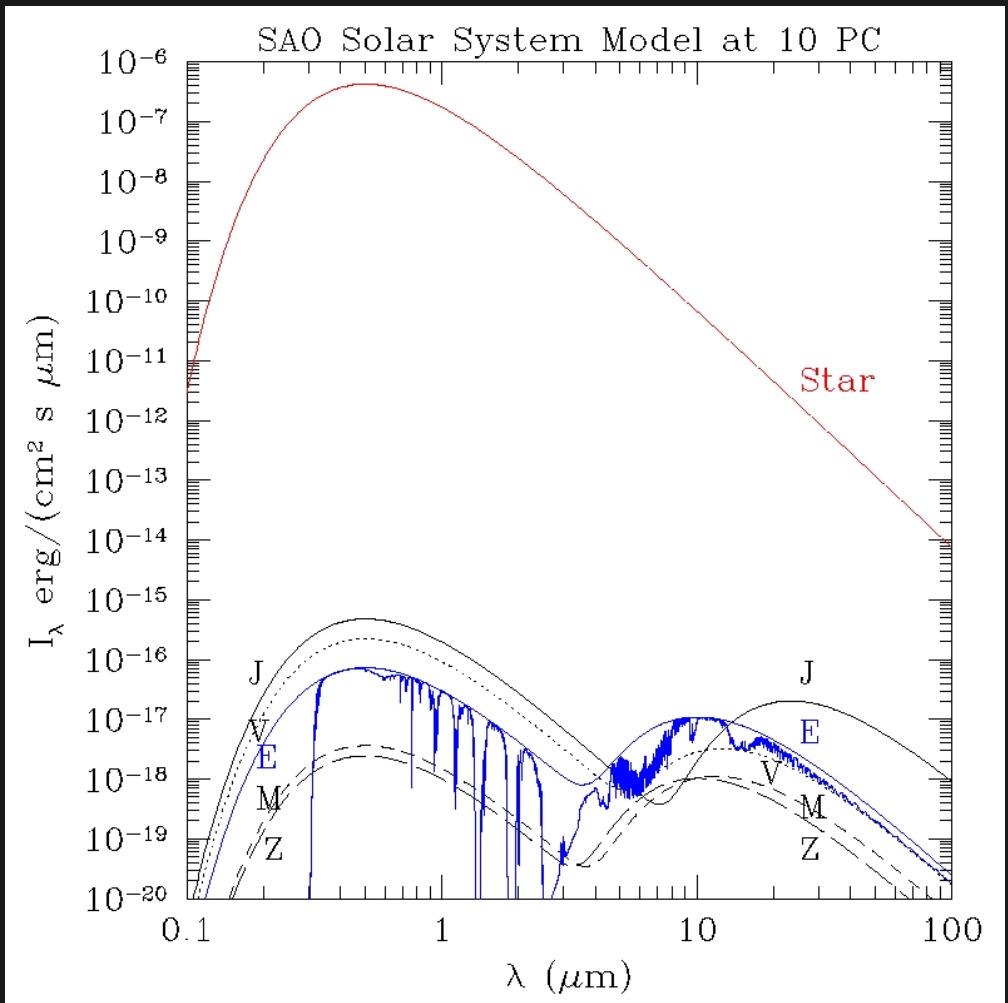
Mag. 1.2, Distance 25 ly, Imaged by HST, Period: 872 years,



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. That's 25 mags.
- *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.

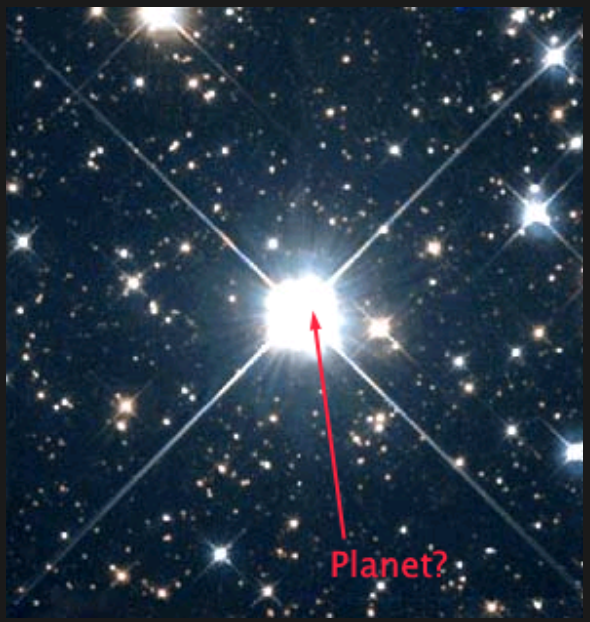


Can Ground-Based Telescopes Do It?

- 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?

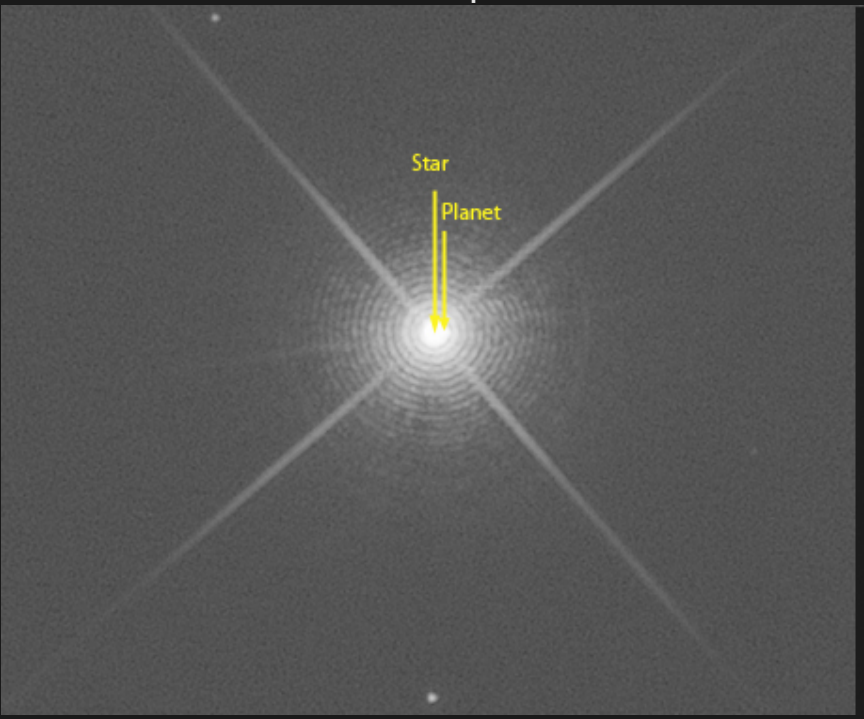


No it can't!

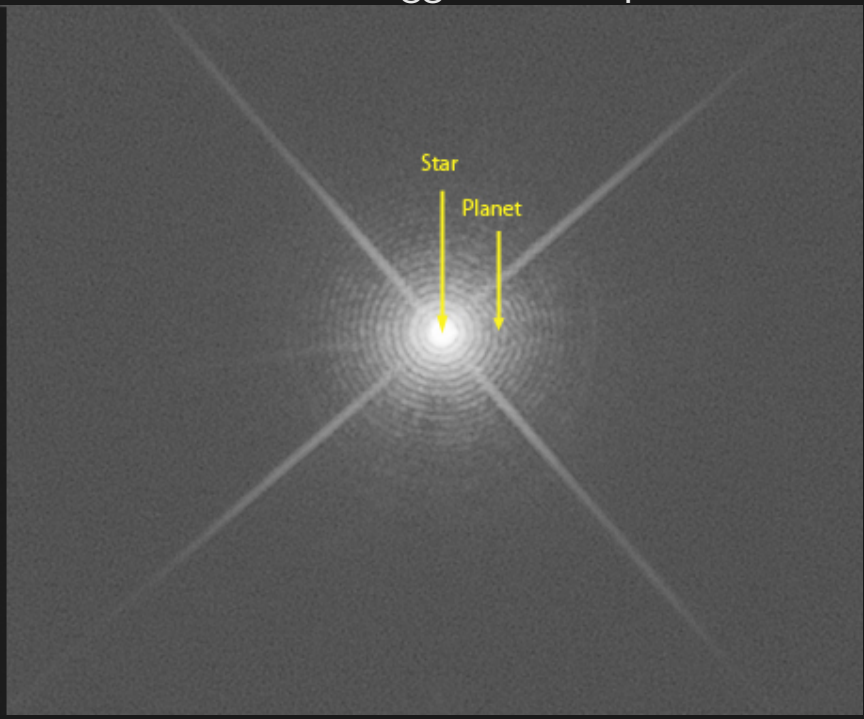
The problem is diffraction

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

Telescope

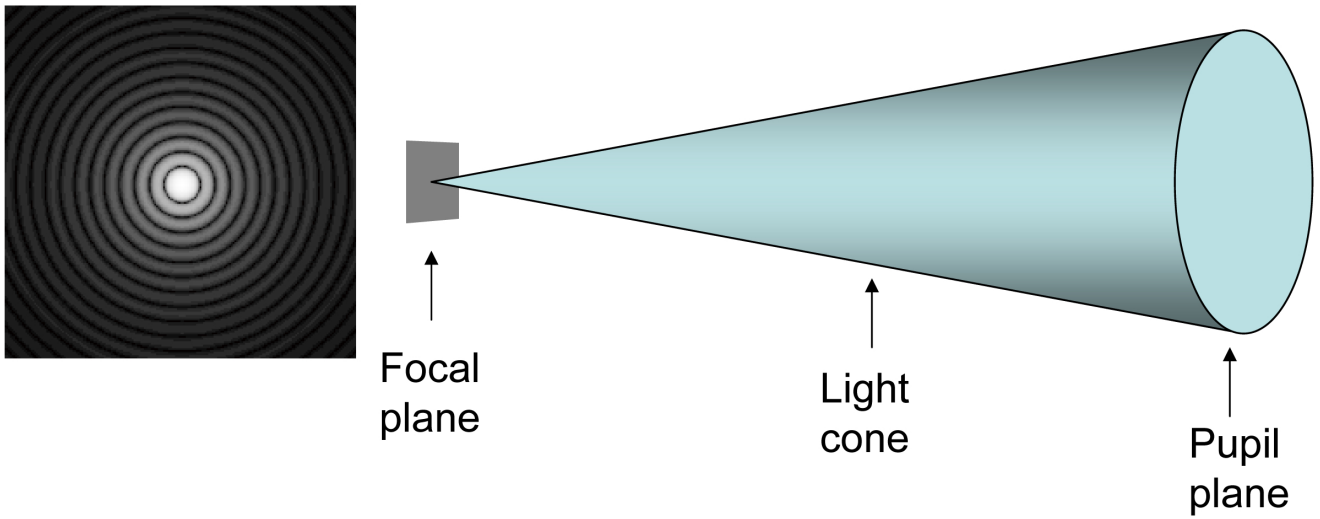


$6\times$ Bigger Telescope



Concept 1: Shaped Pupil Coronagraph

Diffraction Control via Shaped Pupils



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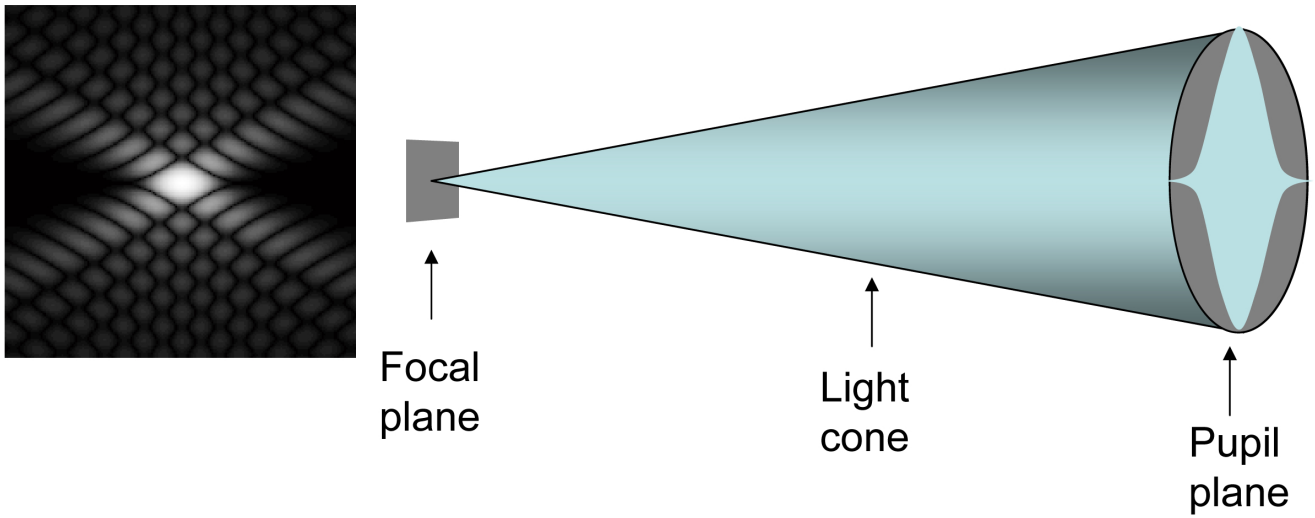
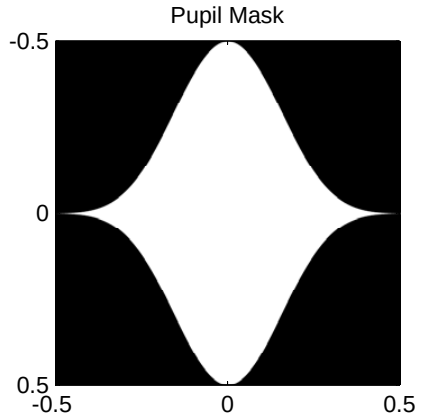
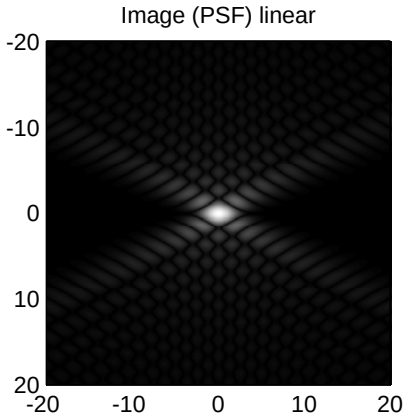
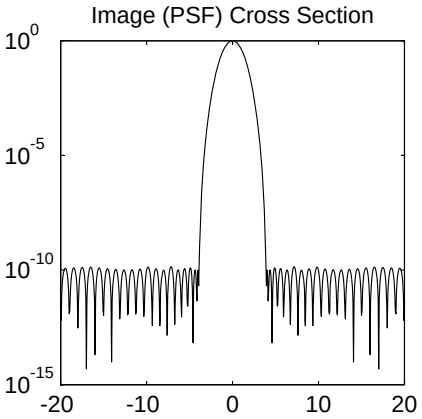
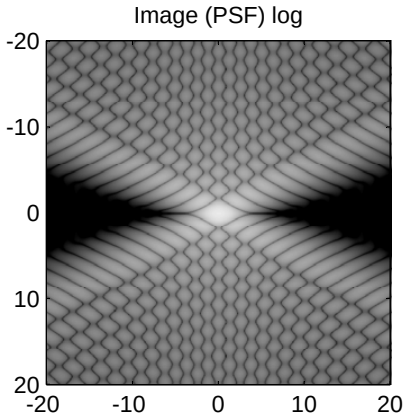


The Spergel-Kasdin-Vanderbei Pupil

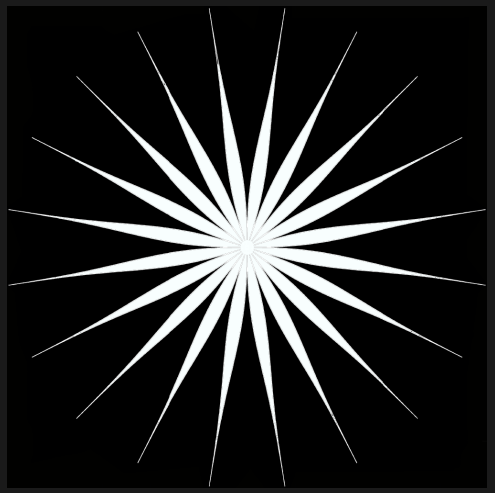




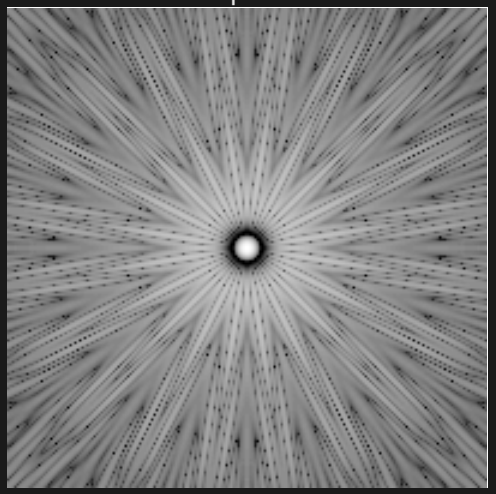




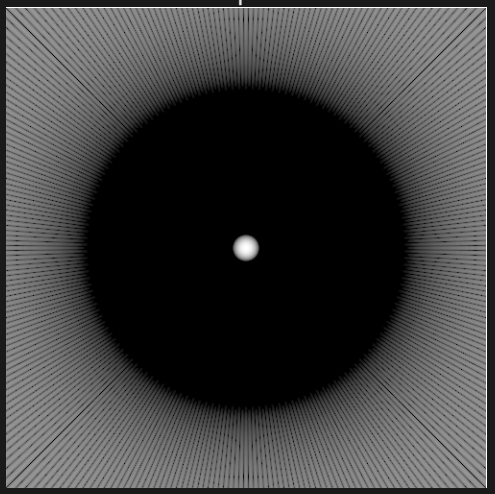
Shaped Pupil Coronagraph (TPF-C)



20 petals

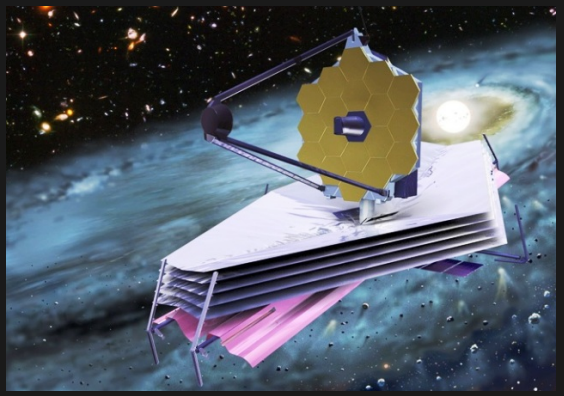


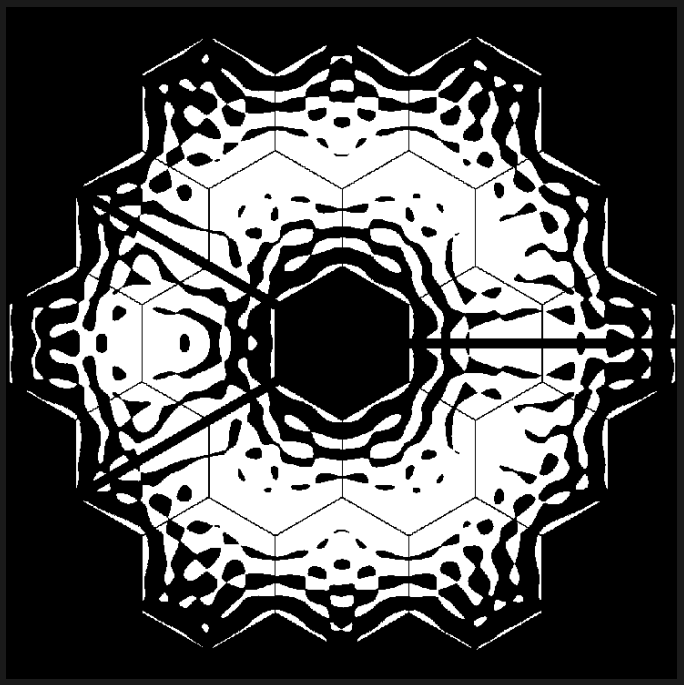
150 petals

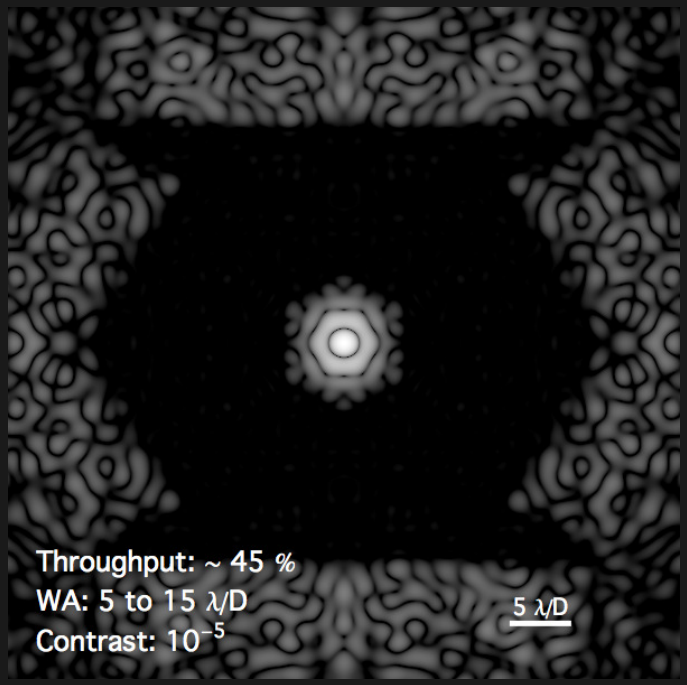


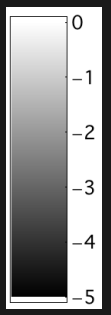
Maybe We Can!

James Webb Space Telescope (JWST)



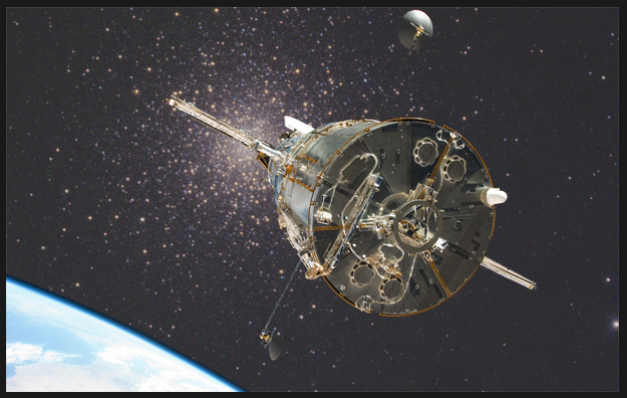




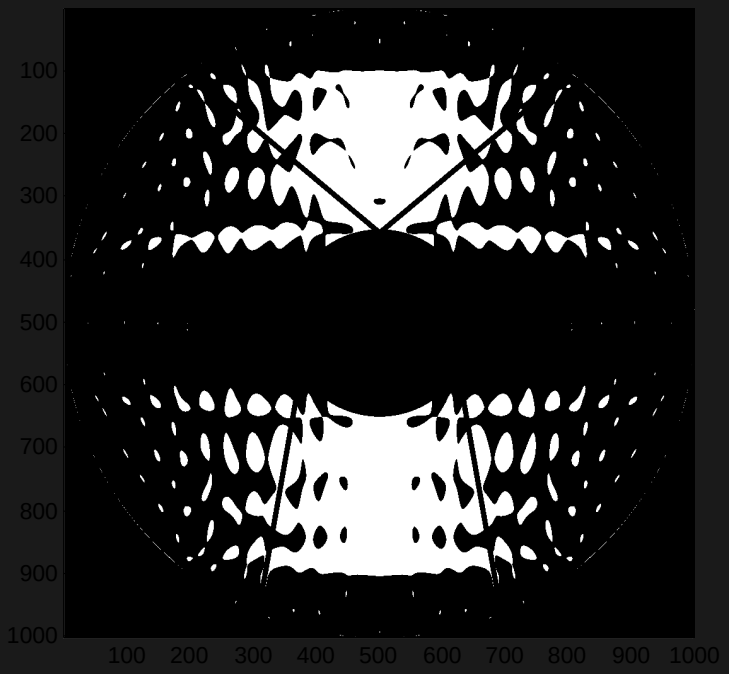


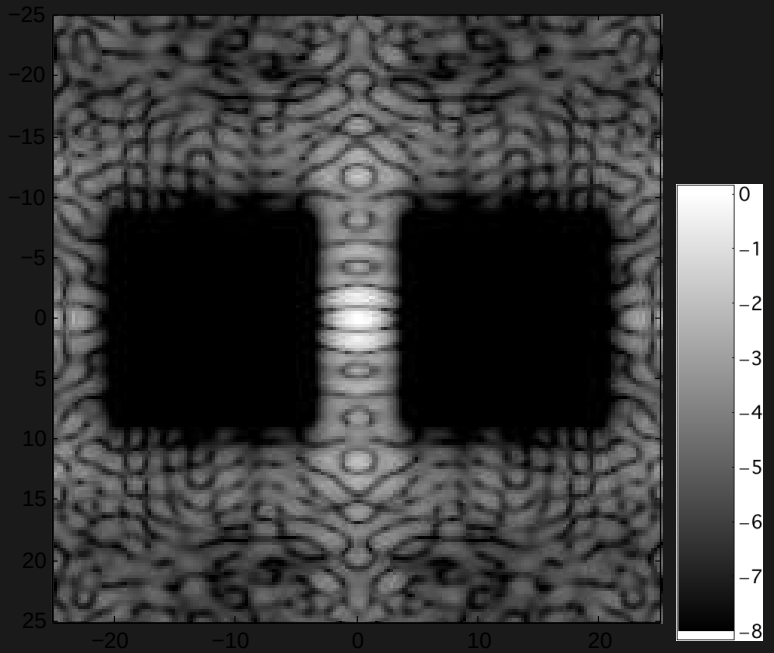
WFIRST Space Telescope

Repurposed NRO Spy Satellite



Similar to Hubble.
Aperture: 2.4 meters.
Central Obstruction and Spiders.





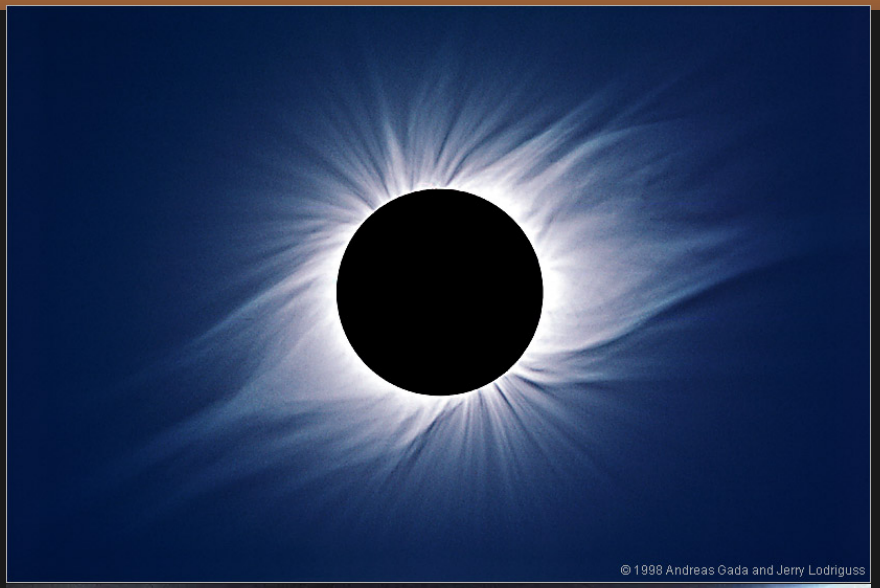
Concept 2: External Occulter

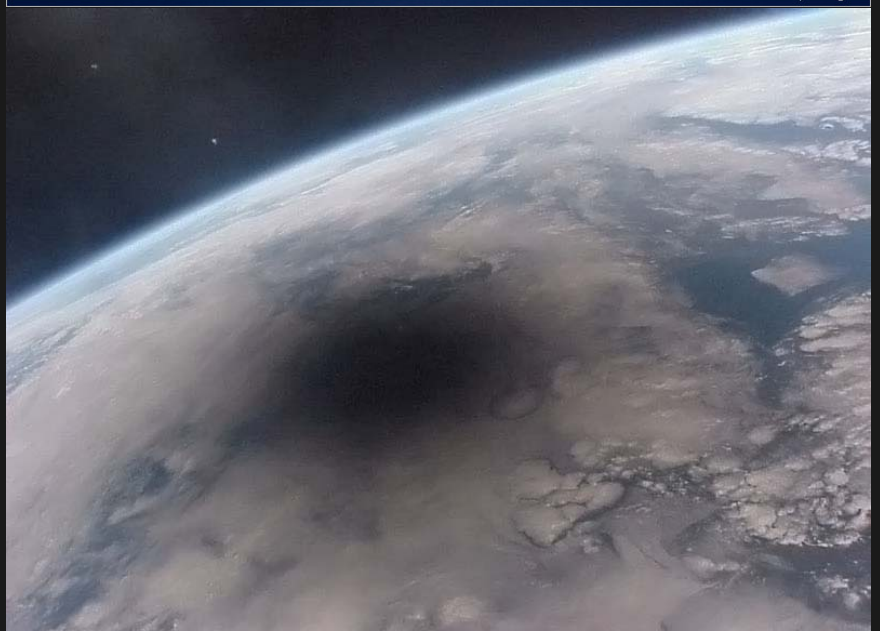
Nature's Coronagraph

Use an external

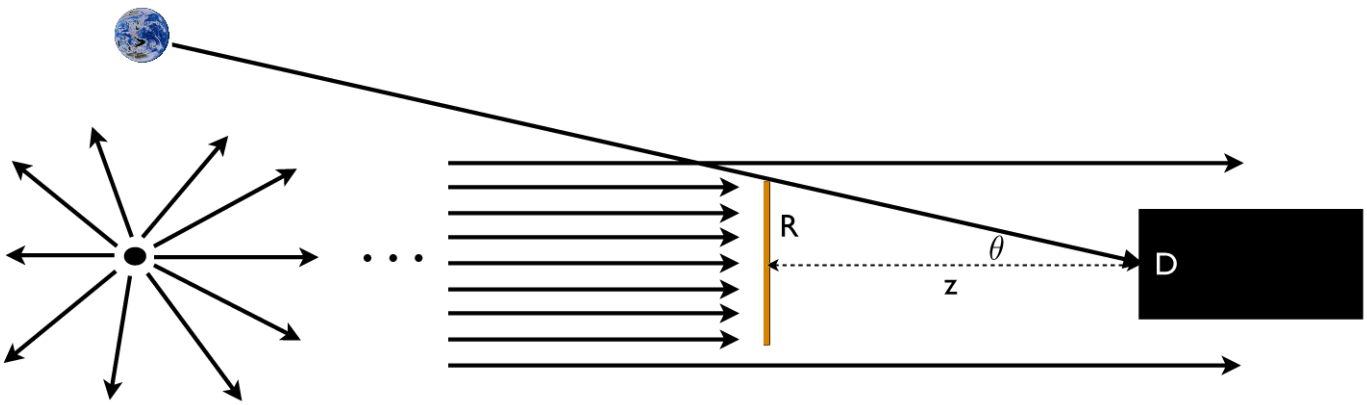
occulter to

block the light.





Occulter—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 ~ 10,000 km

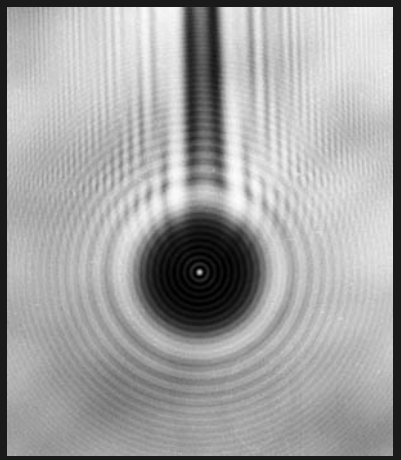
The fundamental size and separation for a starshade are LARGE.

Siméon Poisson/Francois Arago (1818)

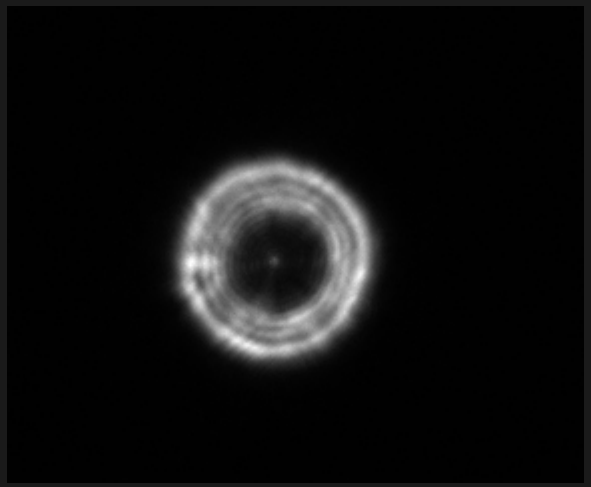
Poisson didn't believe the wave theory of light.
He pointed out that light falling on a circular object would have a bright spot at the center of its shadow.

Arago did the experiment.

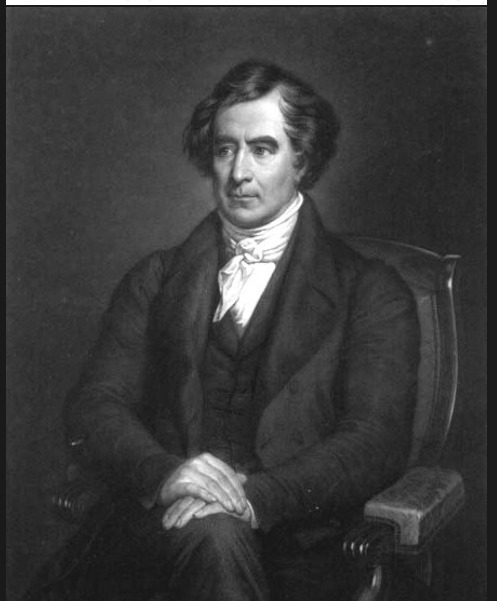
Poisson was wrong.



Poisson's spot

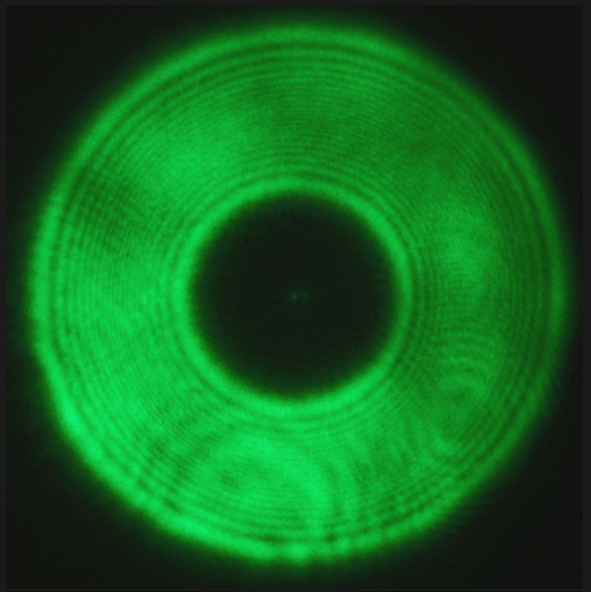


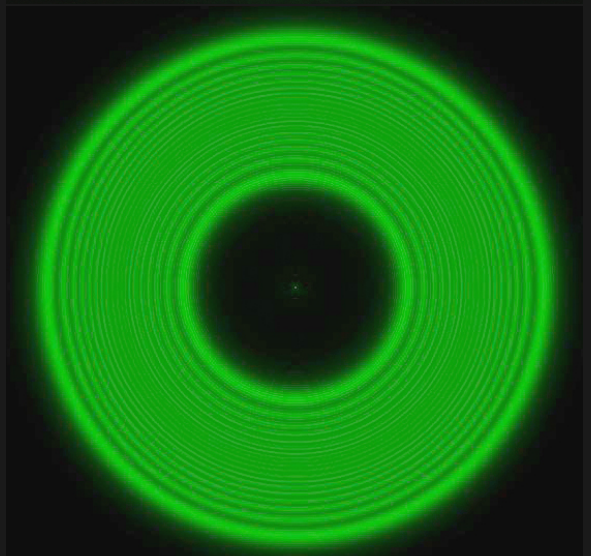
Arcturus defocused



A Fun Experiment

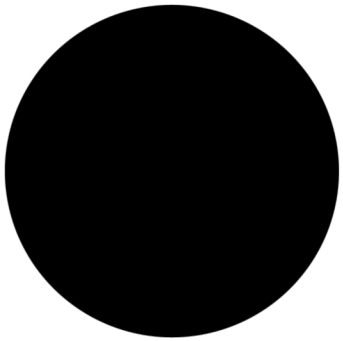
Click for movie

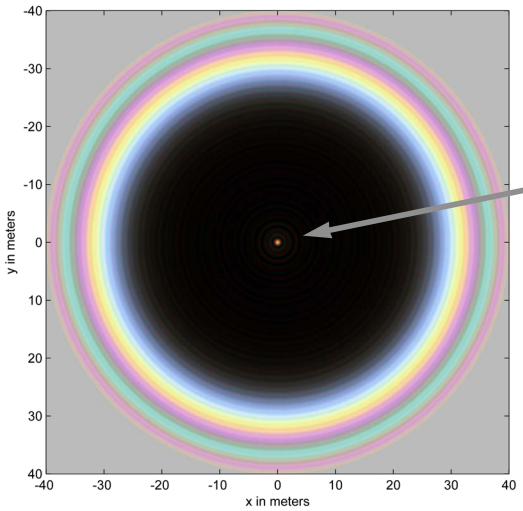




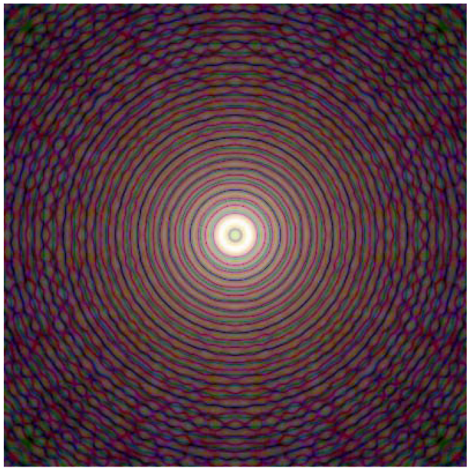
Plain External Occulter (Doesn't Work!)

Circular Occulter

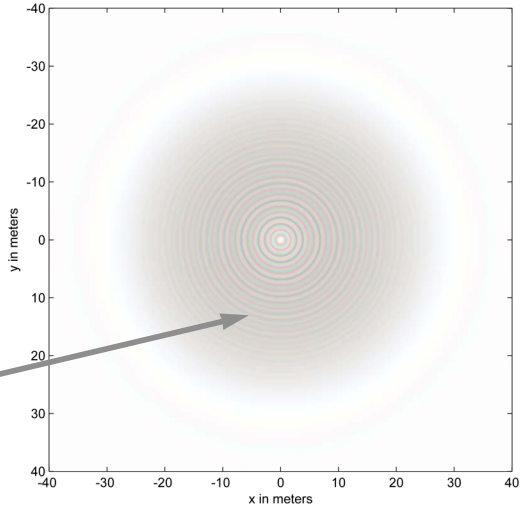




Poisson's Spot!

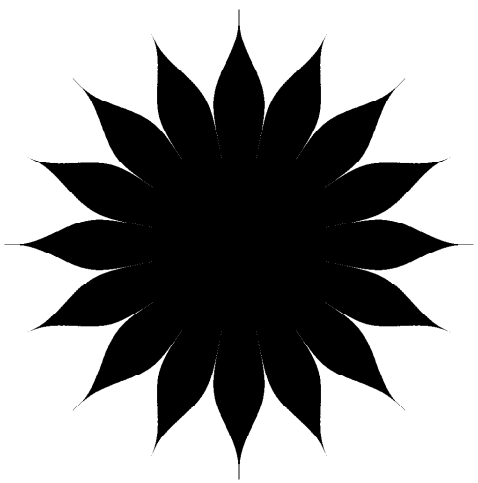


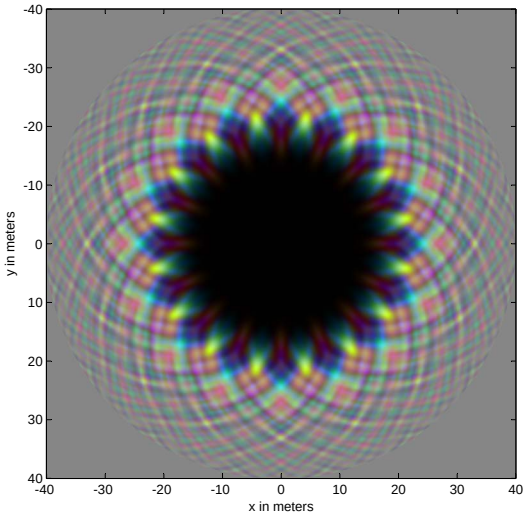
Simulated star/planet image

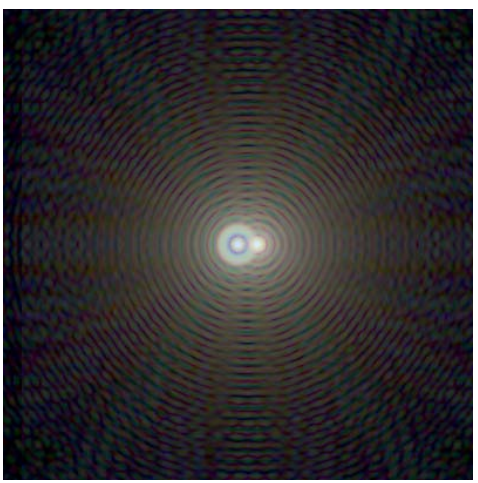


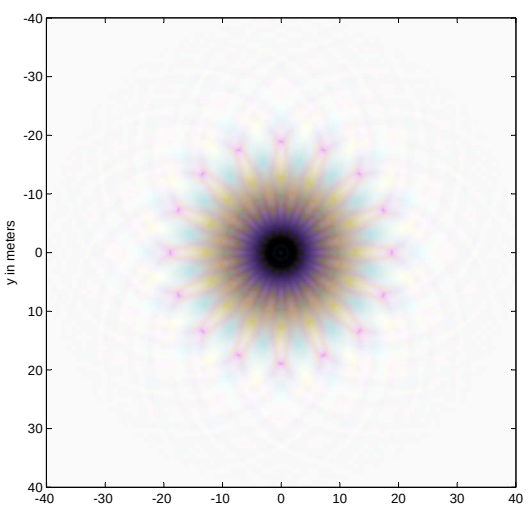
Shadow isn't dark enough

Shaped Occulter





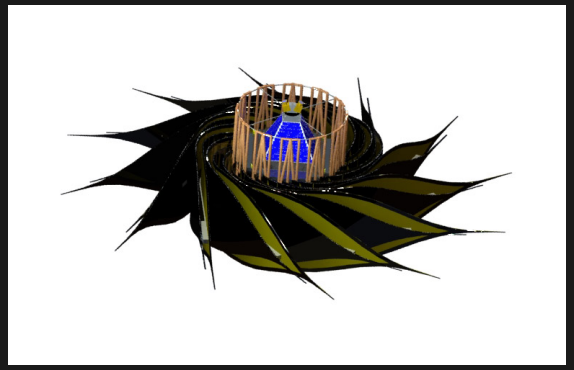


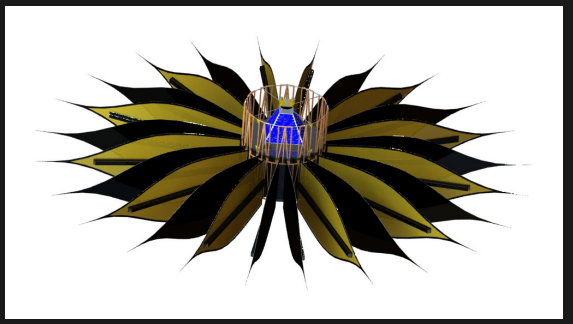


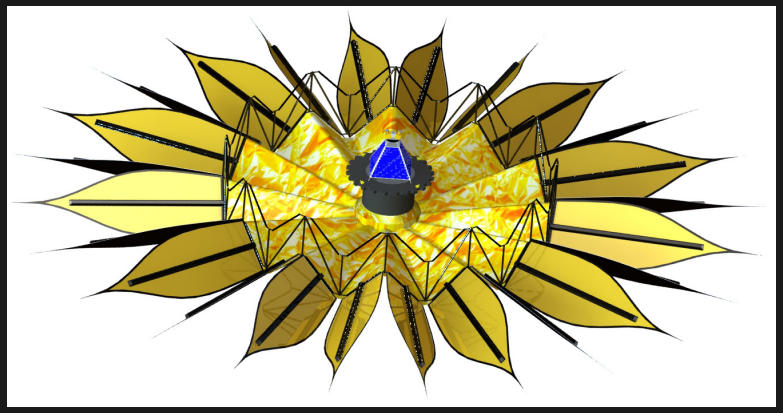
Space-based Occulter (TPF-O)

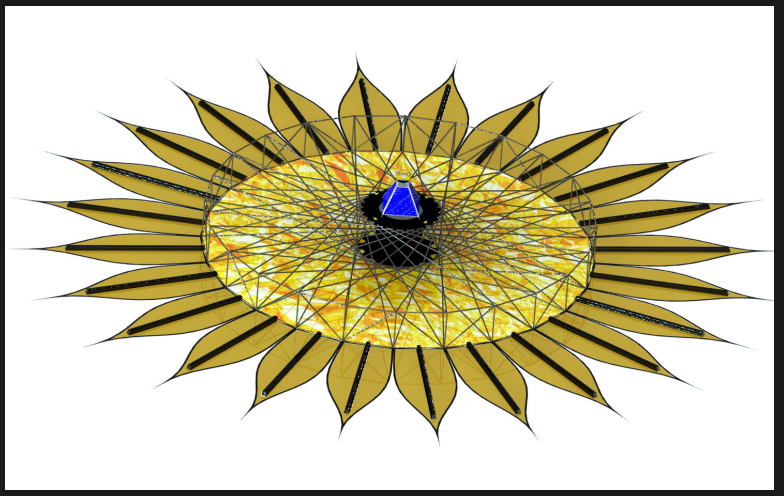
Telescope Aperture: 4m, Occulter Diameter: 50m, Occulter Distance: $72,000$km

Starshade Stowage and Deployment

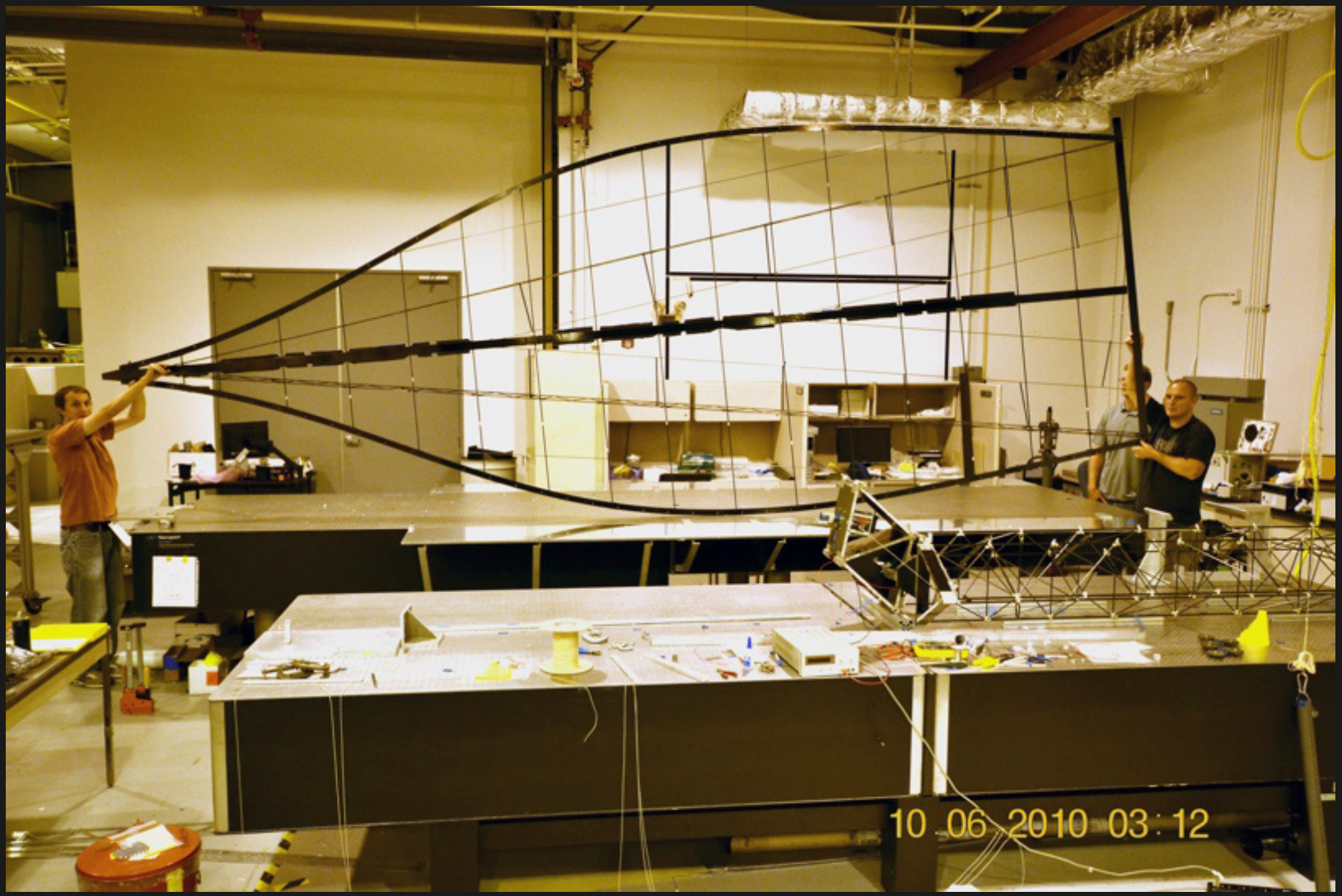








A Real Petal...



...And How It Furls

Me and My Petal

Which Space-Based Observatory Seems Easiest To Build...

Coronagraph. A four to eight meter off-axis telescope with built-in diffraction control scheme and active adaptive optics to maintain unprecedented wavefront quality ($1/10,000$-th wave) over the course of very long exposures (light throughput of the diffraction control system is only about 10%).

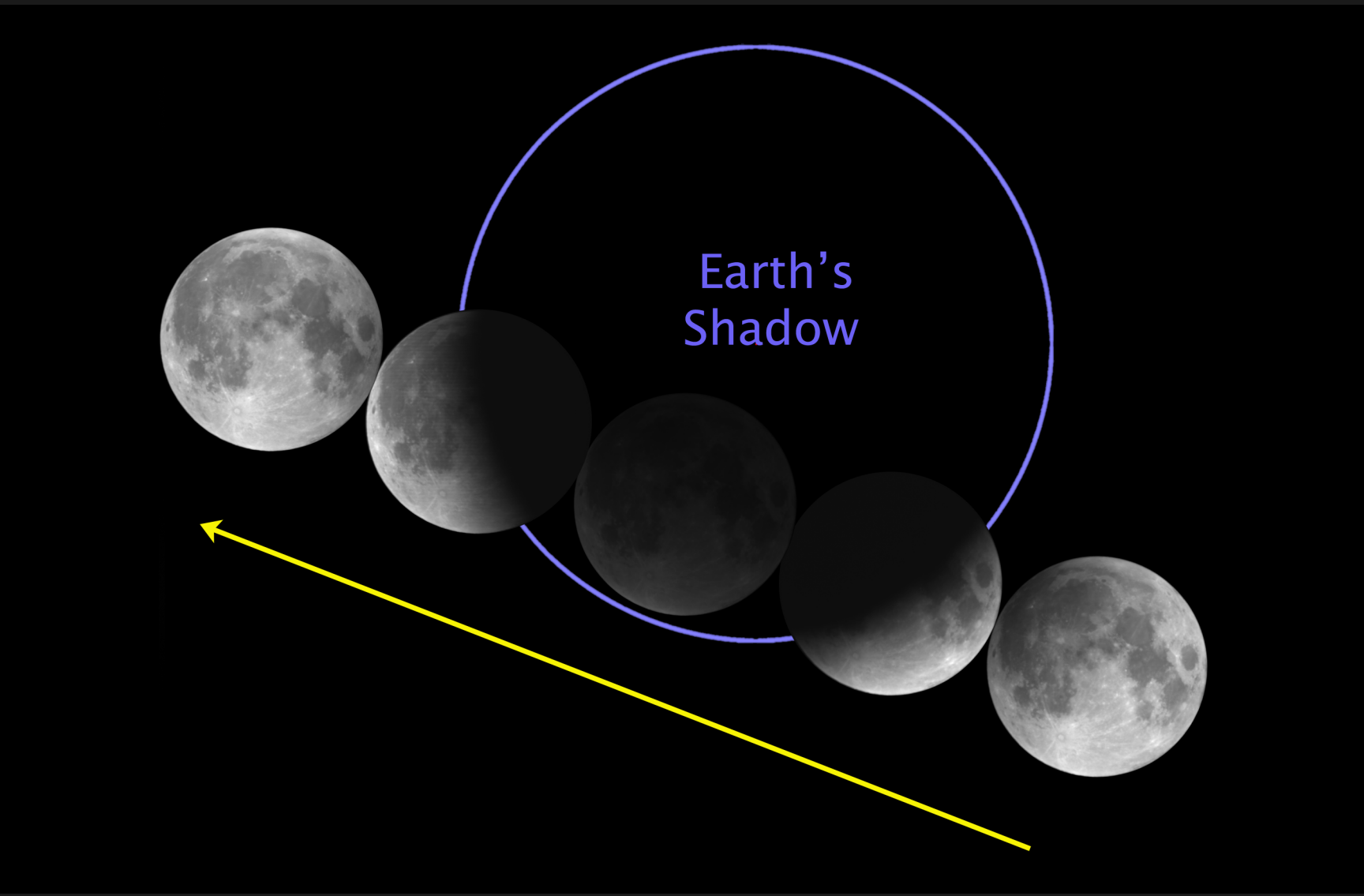
Occulter. A four meter diffraction limited telescope and a specially configured 50 meter tip-to-tip occulter "flying" $72,000$ km in front of the telescope with station-keeping to within a ± 1 meter tolerance over the course of a multihour exposure.

REMINDER: We landed humans on the moon and brought them safely home again.

THANK YOU!

Backup Slides

Some History—The Earth is a Sphere



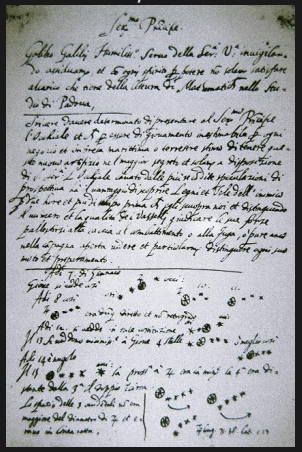
1609: Telescope is Invented (Hans Lippershey)

1610: Galileo Looks at Jupiter

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