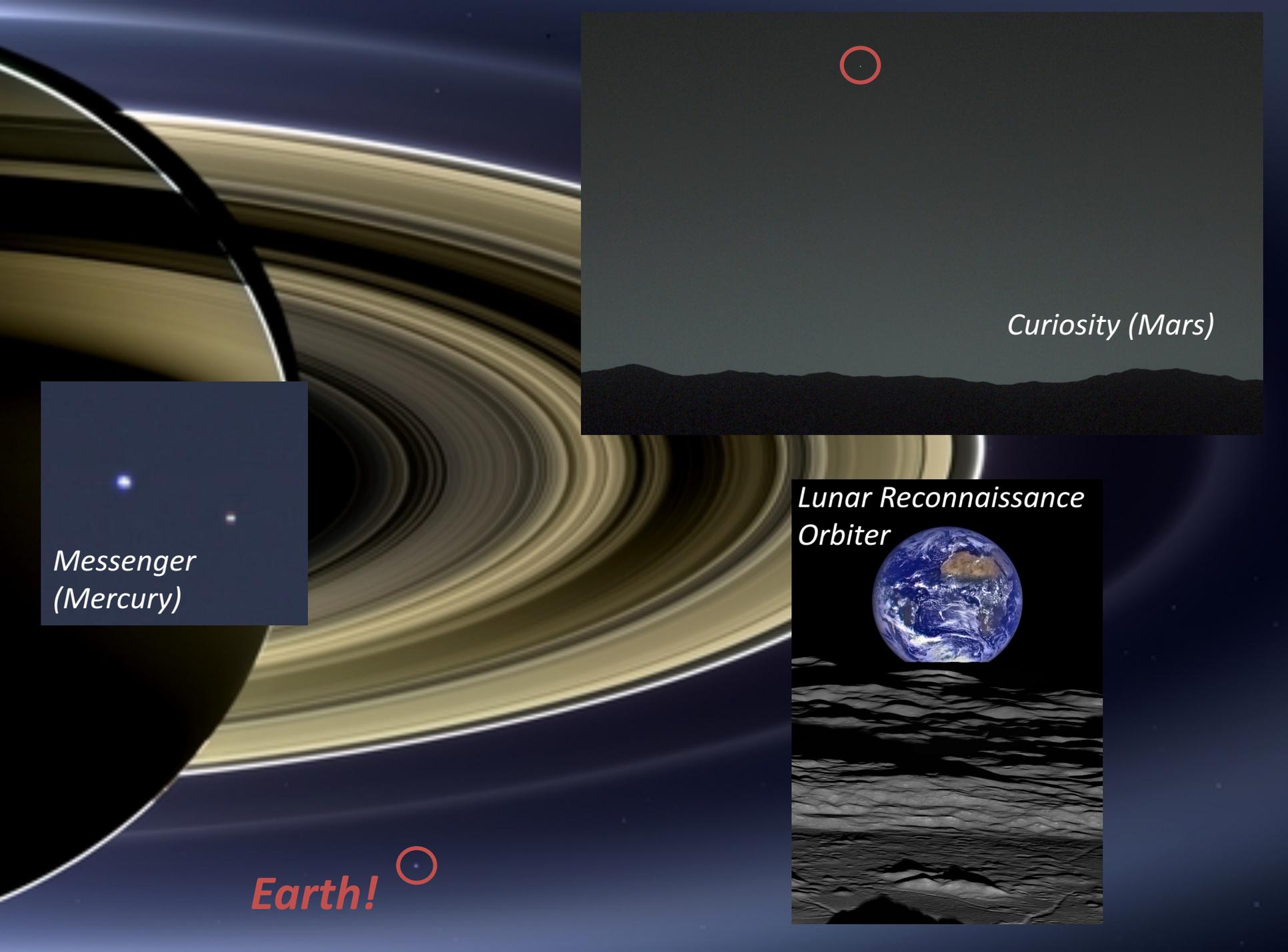




*Specks of light: Revealing planets  
around other stars*

Gaspard Duchêne  
(UC Berkeley)



*Messenger  
(Mercury)*



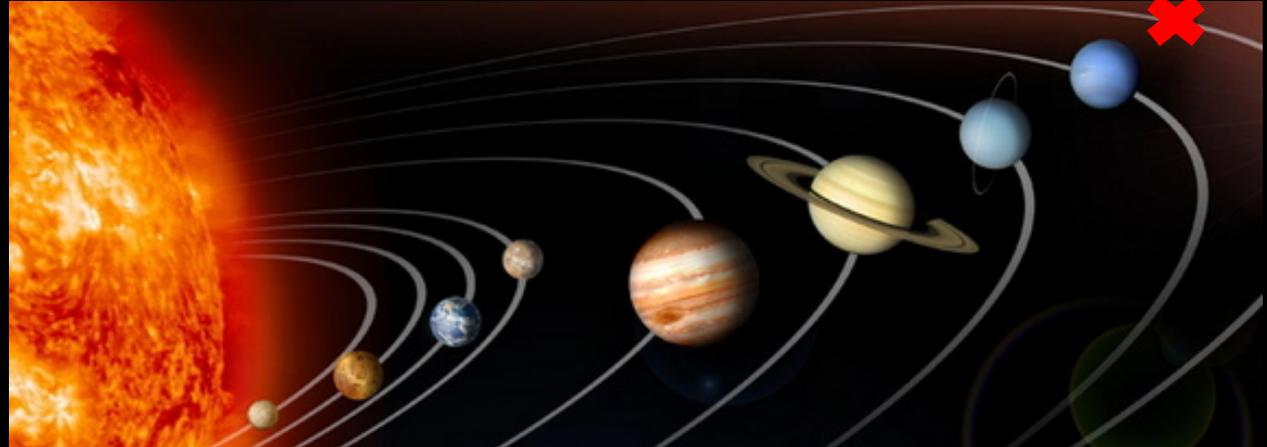
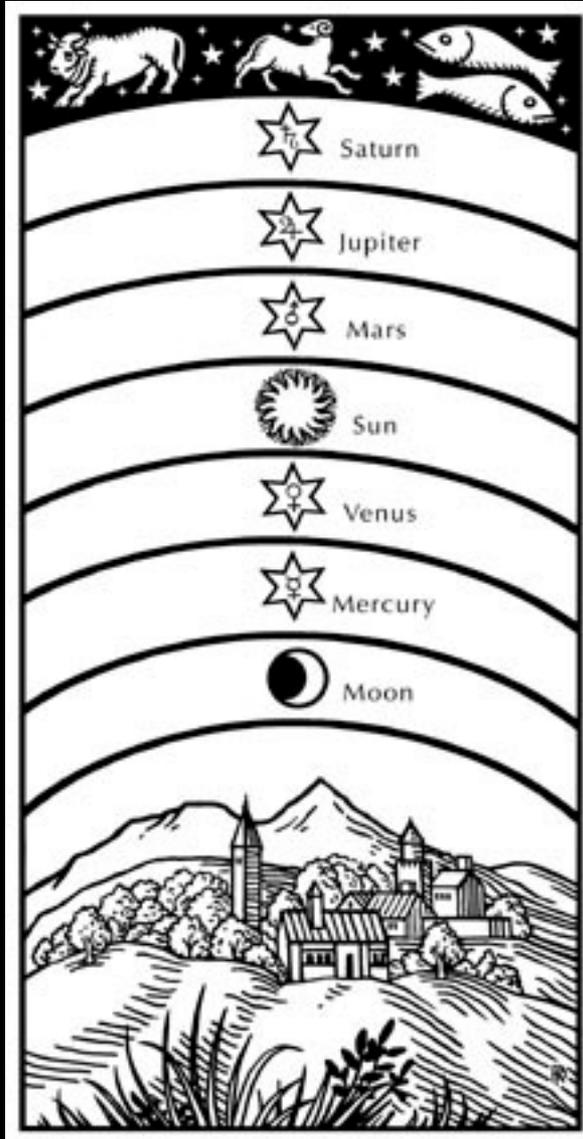
*Curiosity (Mars)*



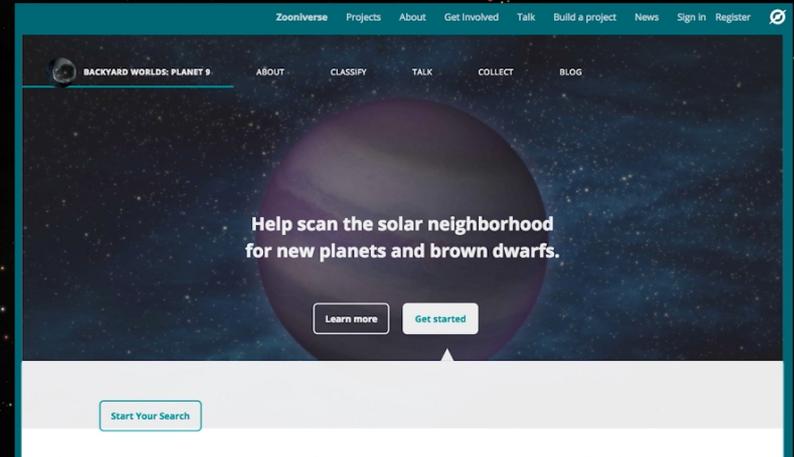
*Lunar Reconnaissance  
Orbiter*

*Earth!* 

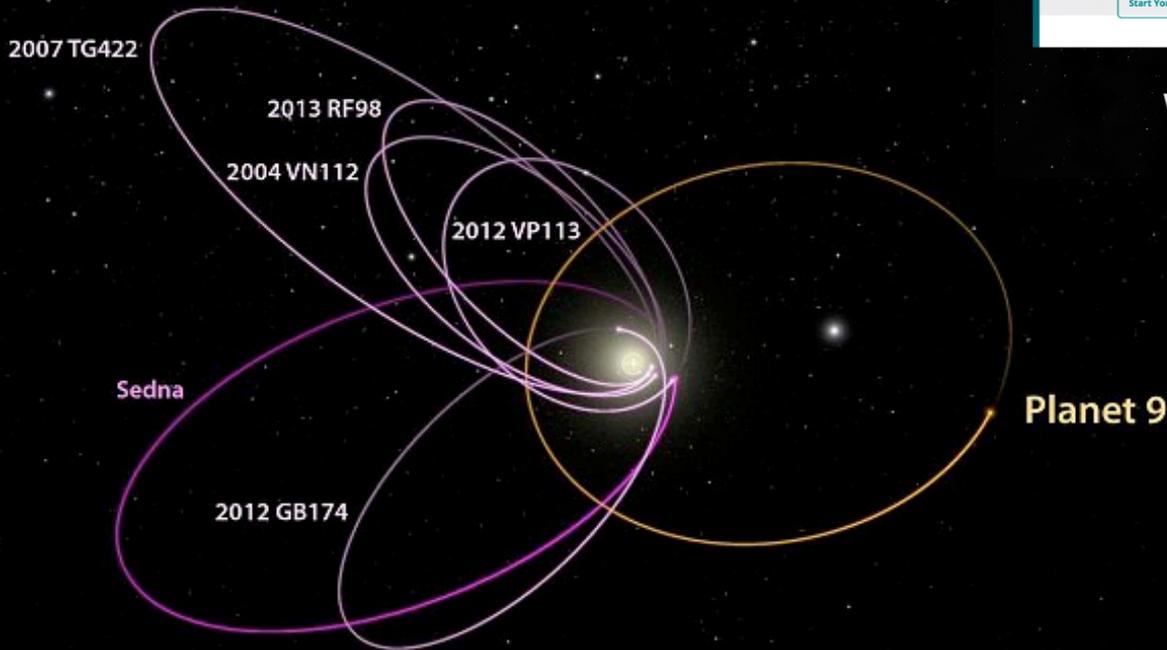
# Planets in the Solar System



# Planets in the Solar System



[www.backyardworlds.org](http://www.backyardworlds.org)



# Planets around other stars?

o LA PLURALITÉ  
DES  
MONDES HABITÉS

ÉTUDE  
OU L'ON EXPOSE LES CONDITIONS D'HABITABILITÉ  
DES TERRES CÉLESTES

DISCUTÉES AU POINT DE VUE DE L'ASTRONOMIE, DE LA PHYSIOLOGIE  
ET DE LA PHILOSOPHIE NATURELLE

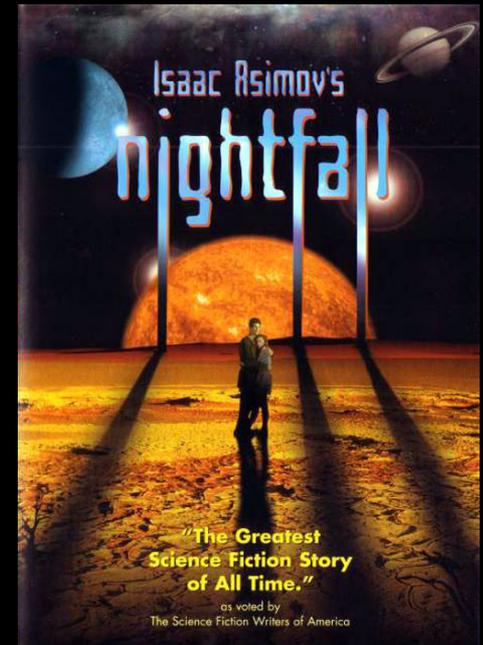
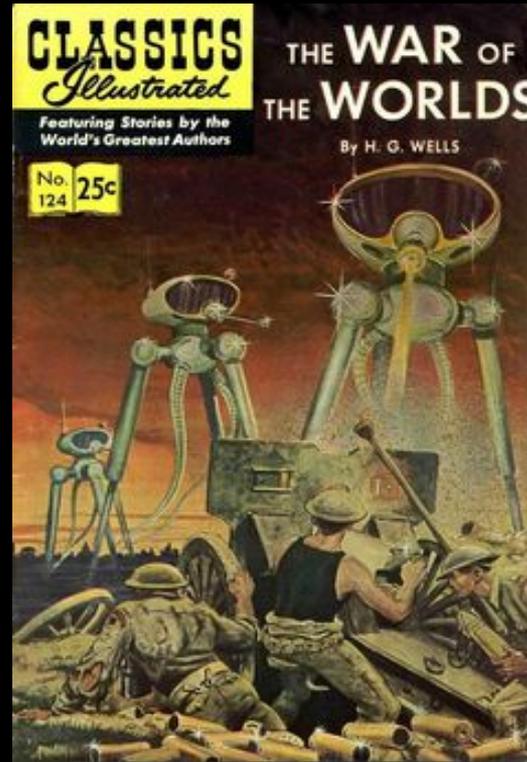
PAR  
CAMILLE FLAMMARIOUX

Astronome, ancien membre de l'Observatoire de Paris, etc.

... Au sein des télescopes de Trappes  
Mais terre habitée, petite lie,  
Dans le grand archipel des Mondes.

DIX-SEPTIÈME ÉDITION

PARIS  
LIBRAIRIE ACADÉMIQUE  
DIDIER ET C<sup>ie</sup>, LIBRAIRES-ÉDITEURS  
35, QUAI DES AUGUSTINS, 35  
GUTHRIER-VILLARS, IMP.-LIB. DE L'OBSERVATOIRE  
55, QUAI DES AUGUSTINS, 35  
1872  
Tous droits réservés.

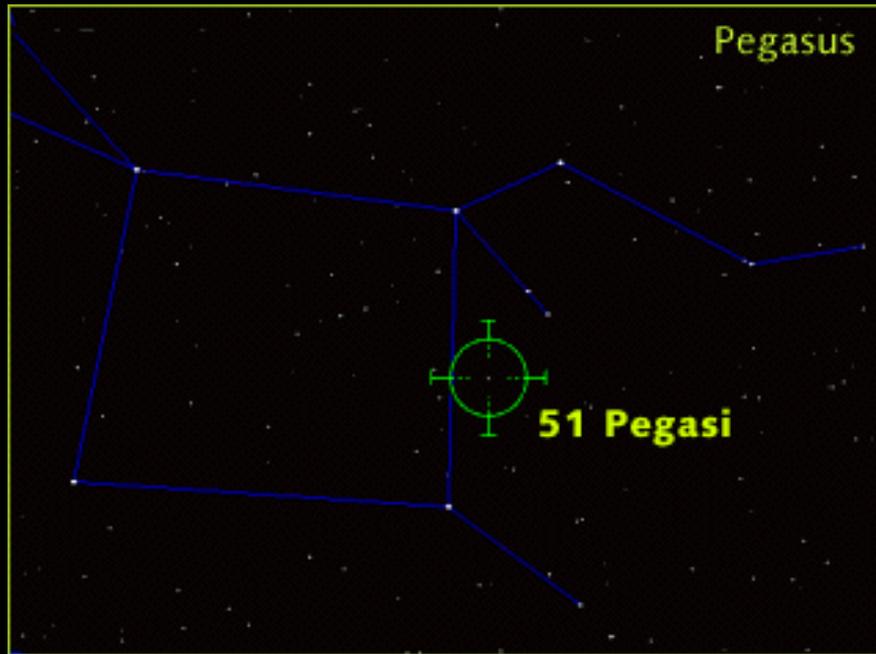


# Planets around other stars!

## A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

NATURE · VOL 378 · 23 NOVEMBER 1995

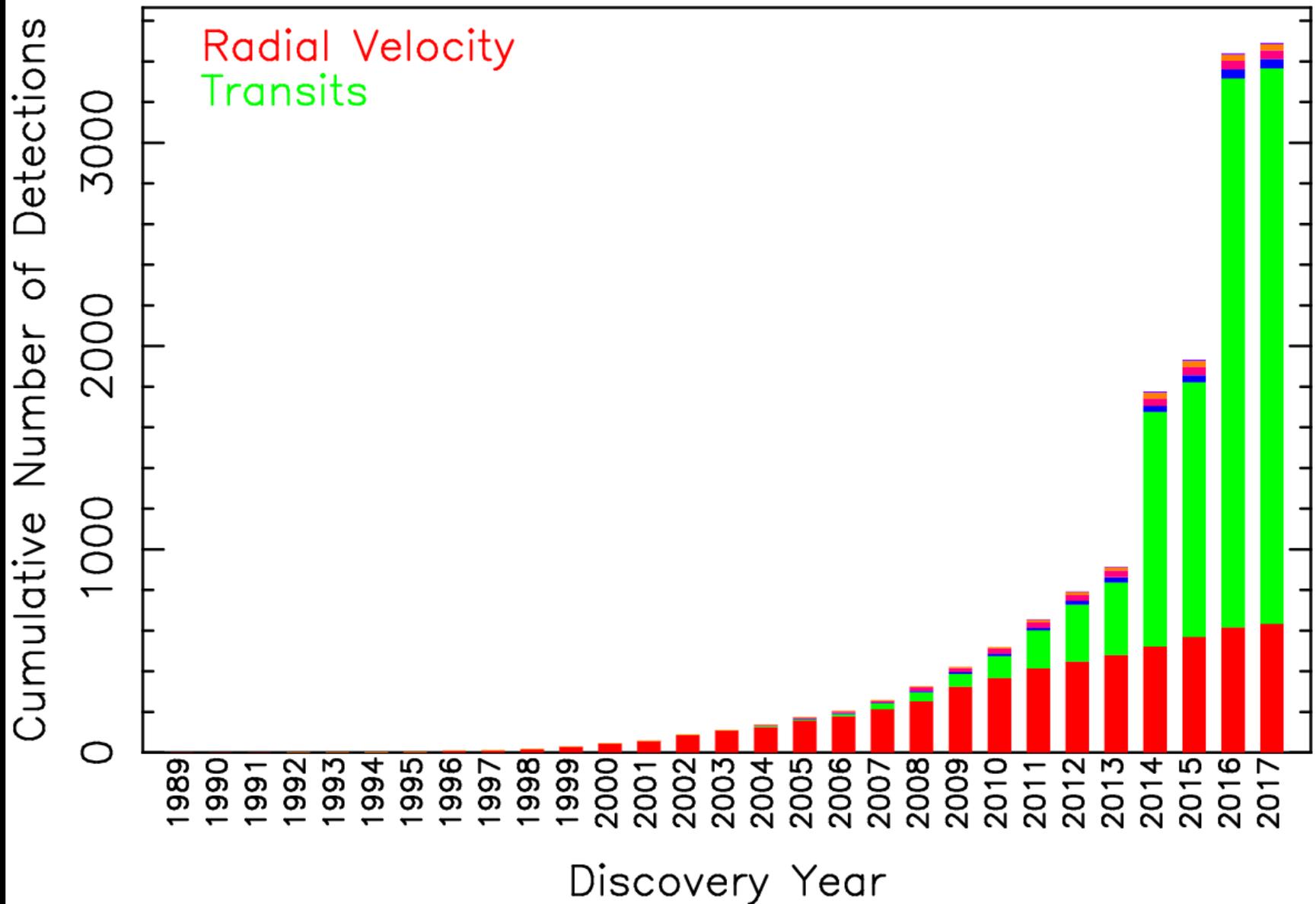


Lick – Shane Telescope

While there is much debate over which exoplanet discovery is considered the "first," one stands out from the rest. In 1995, scientists discovered 51 Pegasi b, forever changing the way we see the universe and our place in it. The exoplanet is about half the mass of Jupiter, with a seemingly impossible, star-hugging orbit of only 4.2 Earth days, but only was it the first planet confirmed to orbit a sun-like star. It also ushered in a whole new class of planets called hot Jupiters, but, missing planets orbiting closer to their stars than Mercury. Today, powerful observatories like NASA's Kepler space telescope, will continue the hunt of distant planets.

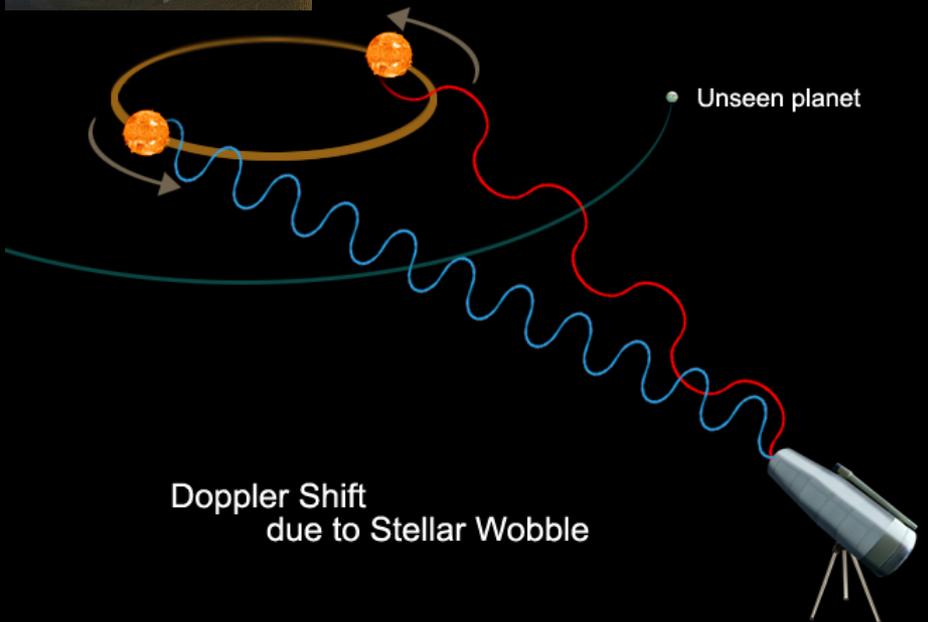
# Cumulative Detections Per Year

08 Jun 2017  
exoplanetarchive.ipac.caltech.edu



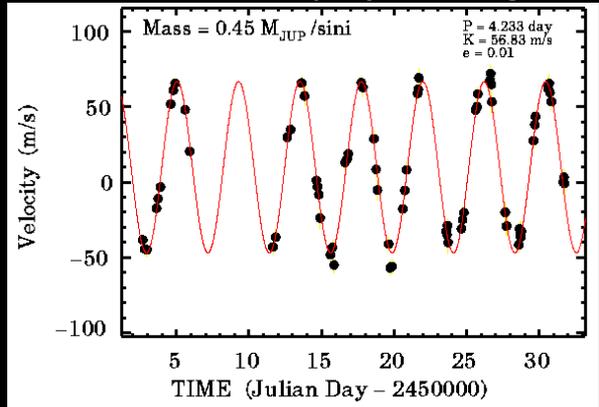
# Lick – Automatic Planet Finder

# Kepler



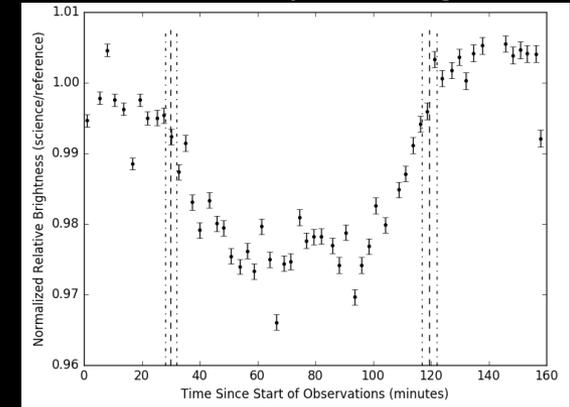
Transit

## Discovery of 51 Peg b

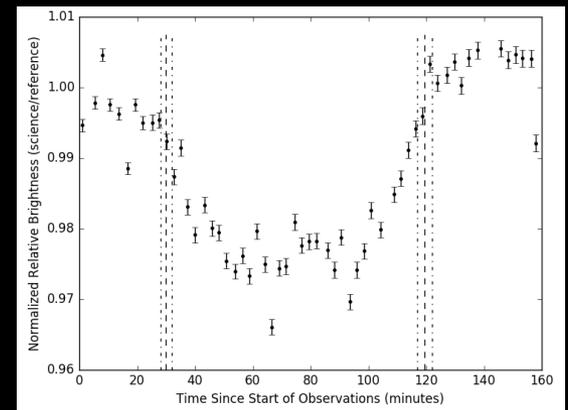
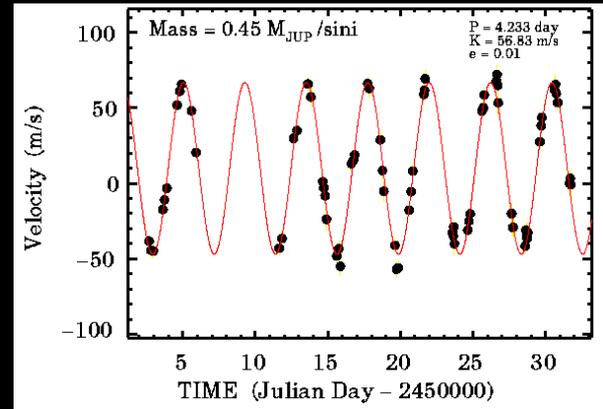
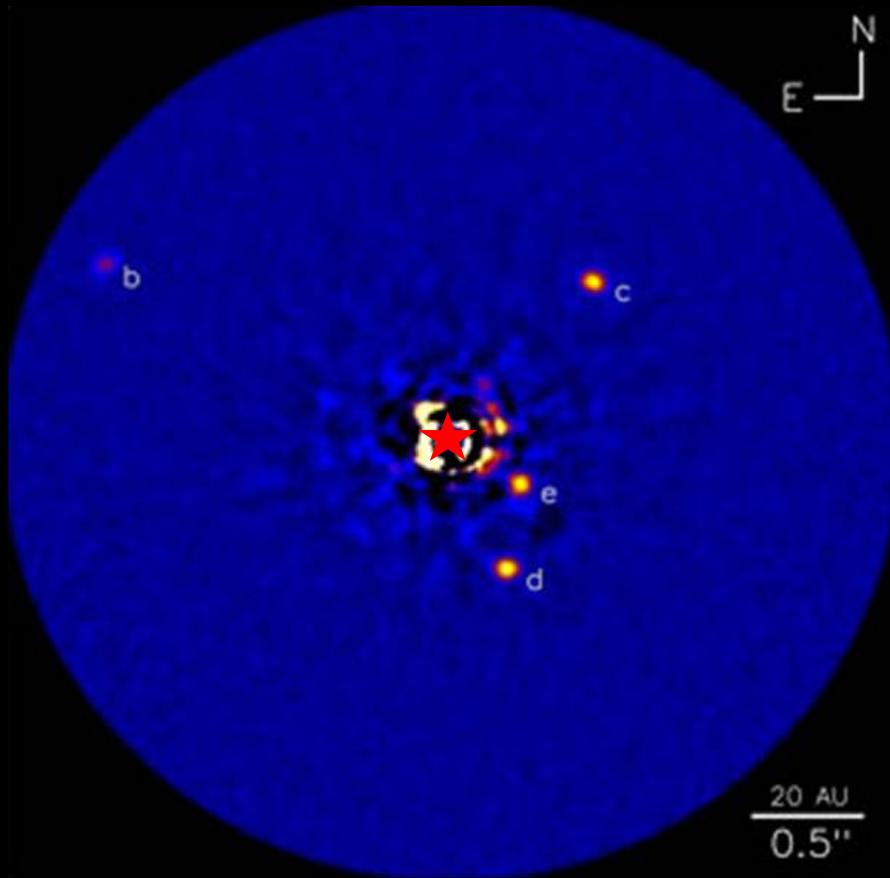


**UCB Students  
Observatory**

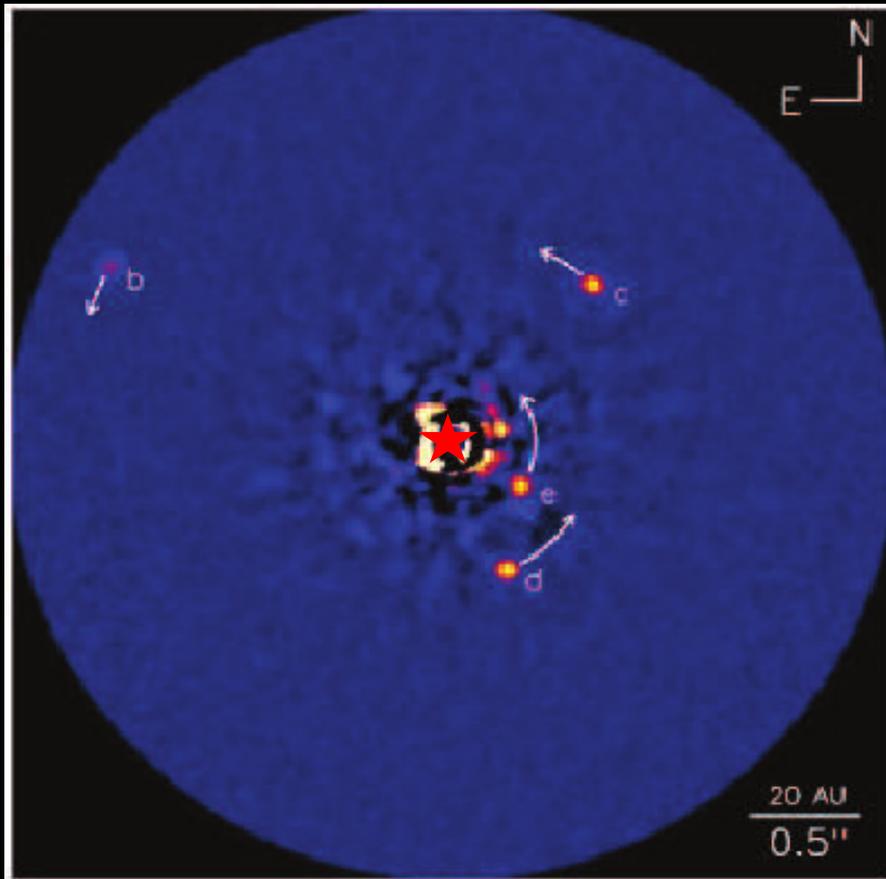
## UC Berkeley undergrads



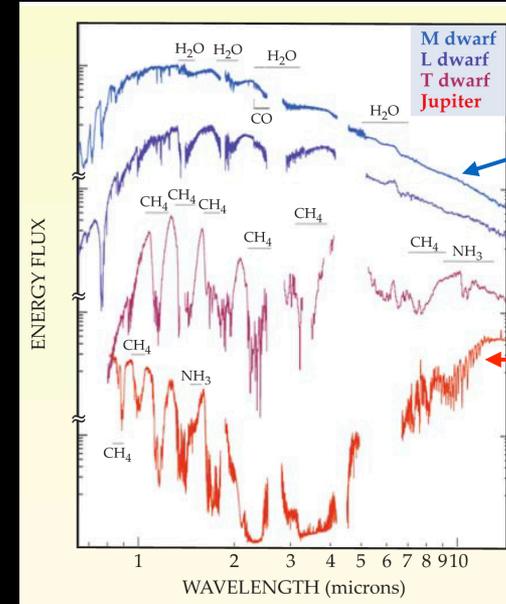
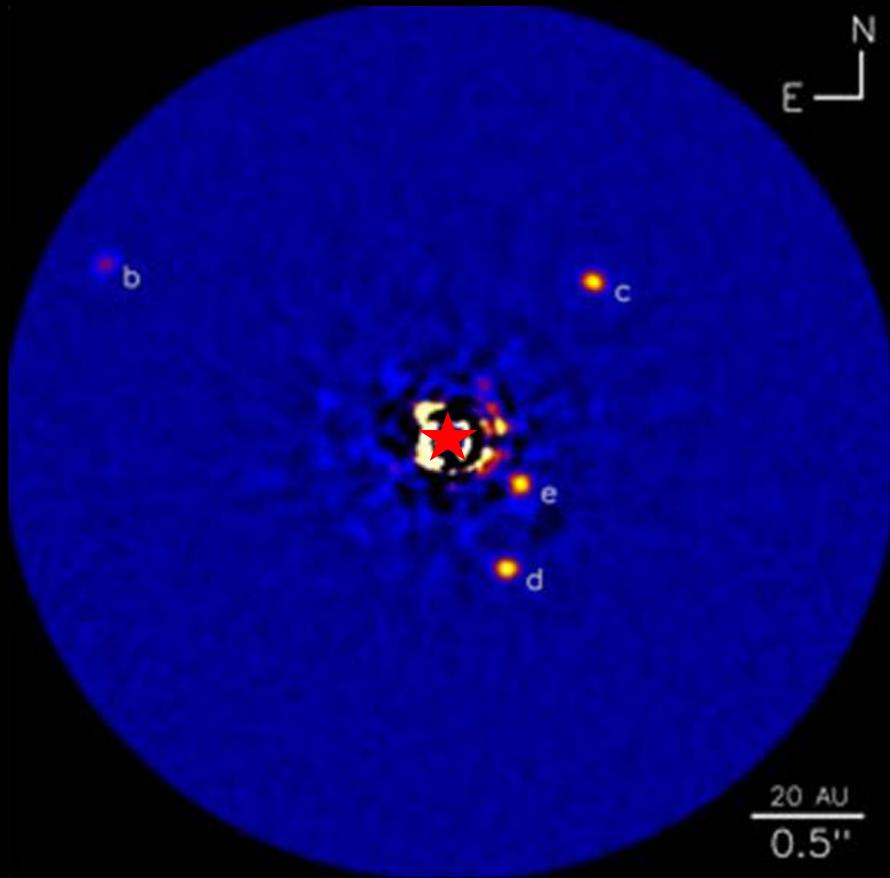
# Why attempt direct imaging?



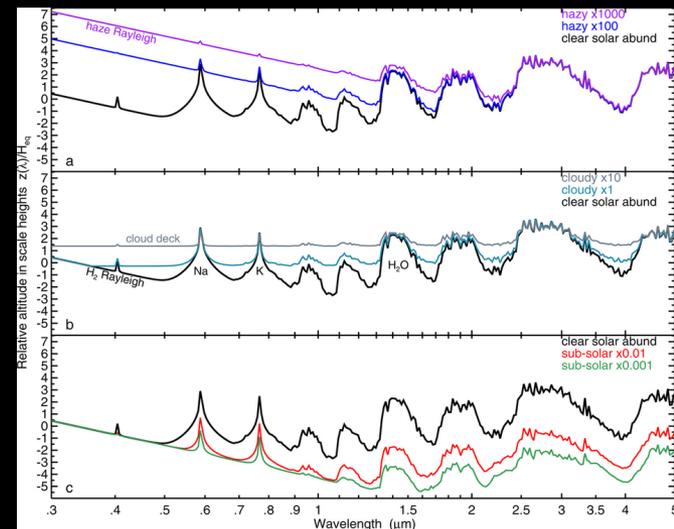
# *Mapping planetary orbits*



# Studying atmosphere composition

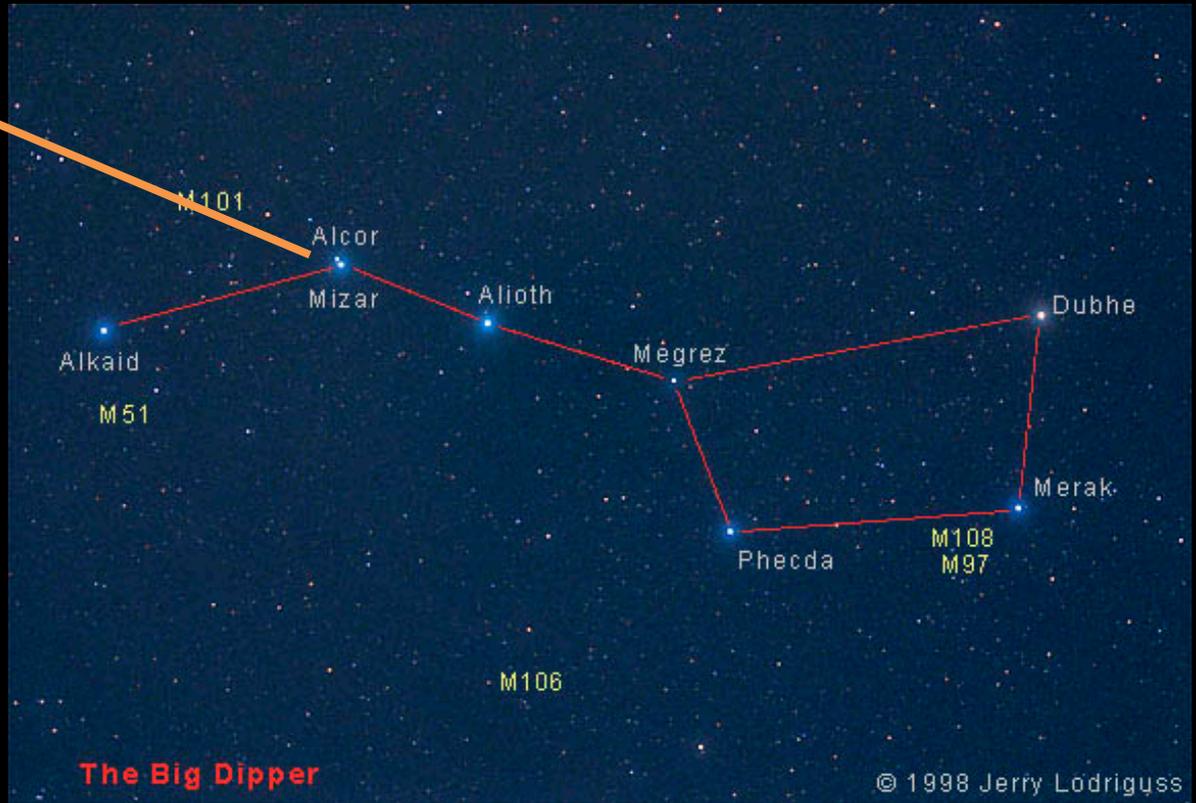
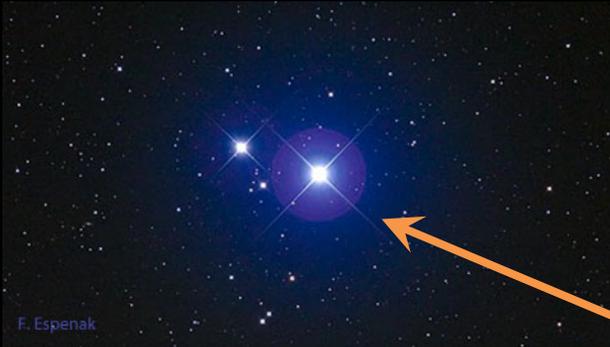


*Gases,  
Clouds,  
Hazes...*



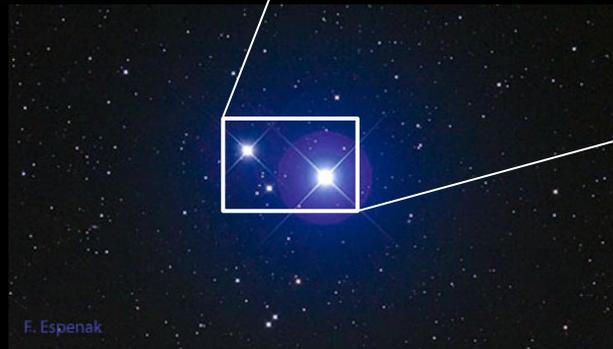
# Testing your eyesight

**5:1 brightness ratio (contrast)**



# Really testing your eyesight!

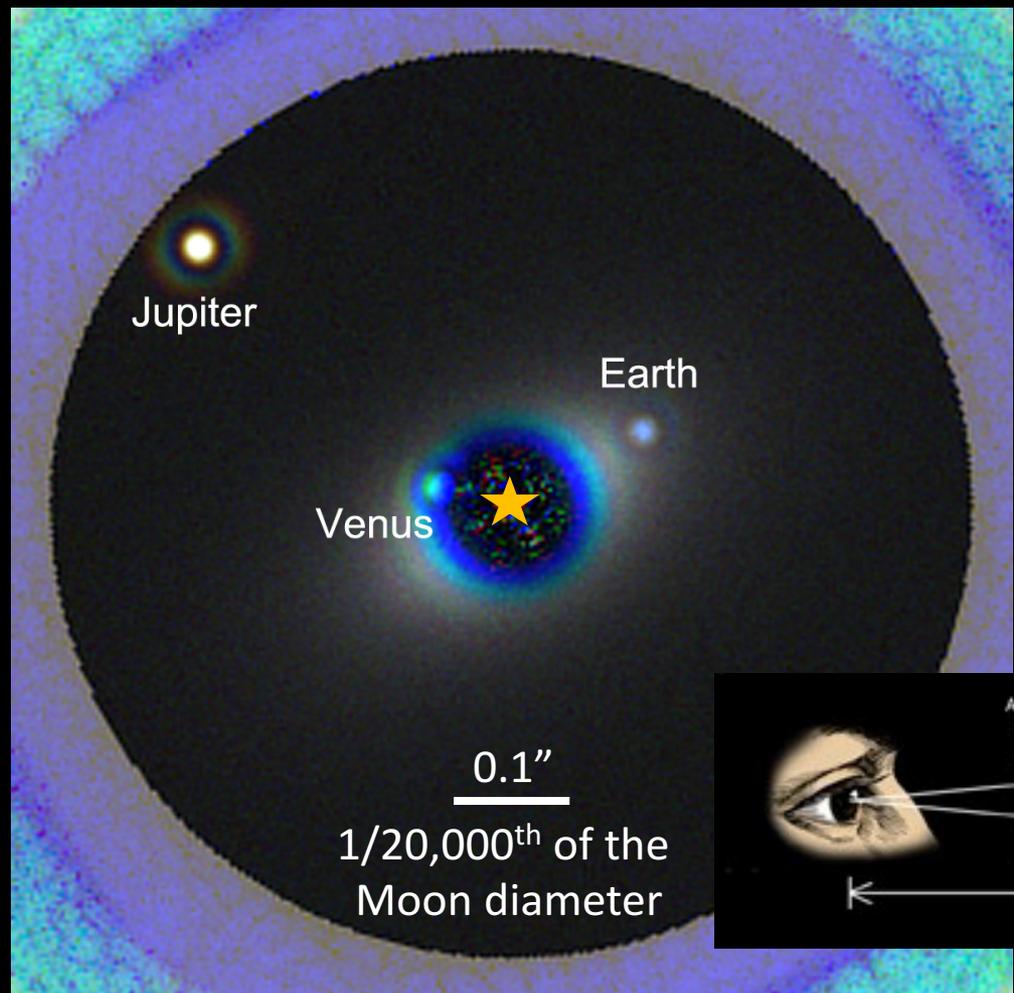
**~ 1,000:1 contrast**



F. Espenak

# A really, really tough challenge!

**~ 1,000,000,000:1 contrast**



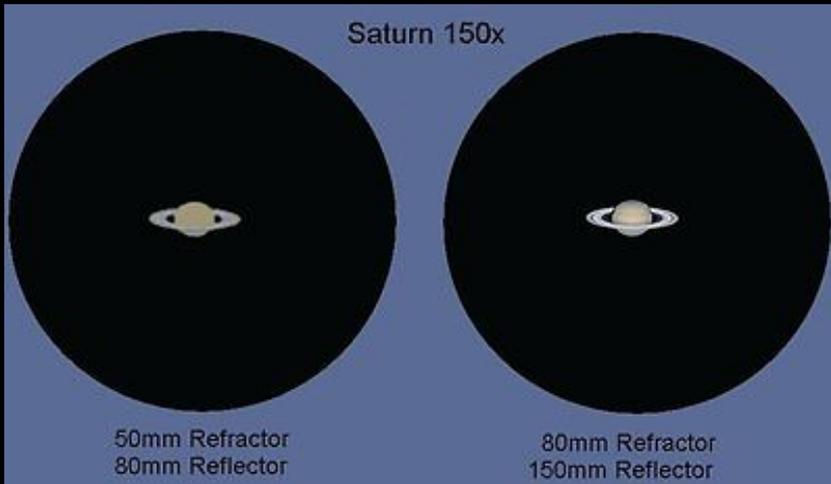
***Our Solar System  
from 45 l-y away***



# *Finding the firefly next to the lighthouse*



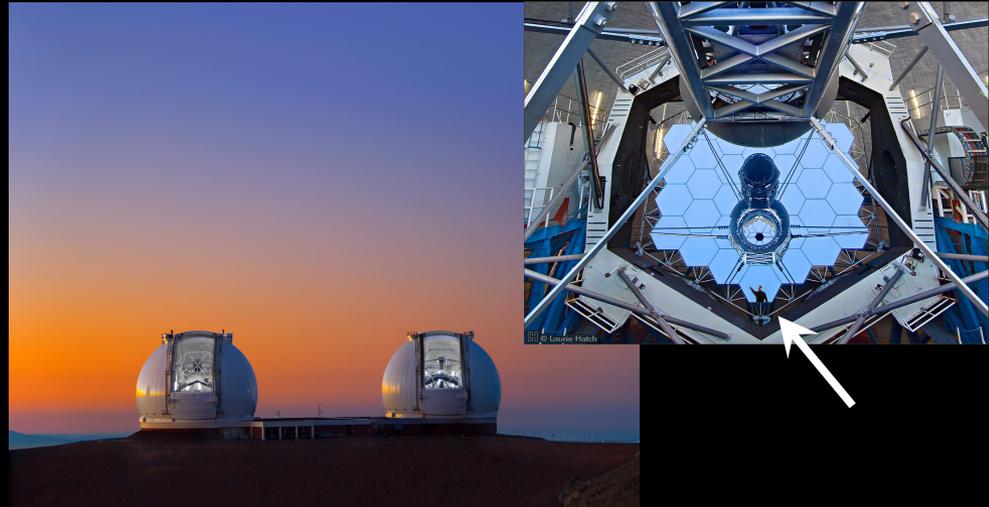
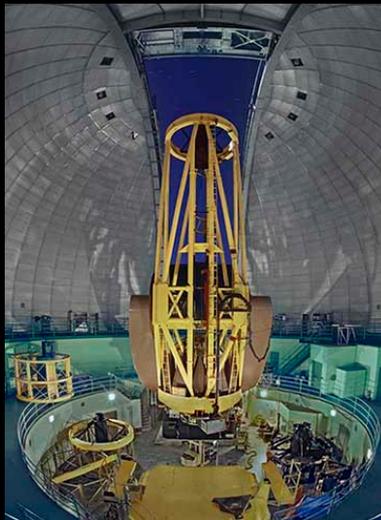
# *Larger telescope = higher resolution*



14-inch telescope



HST (94 inch)

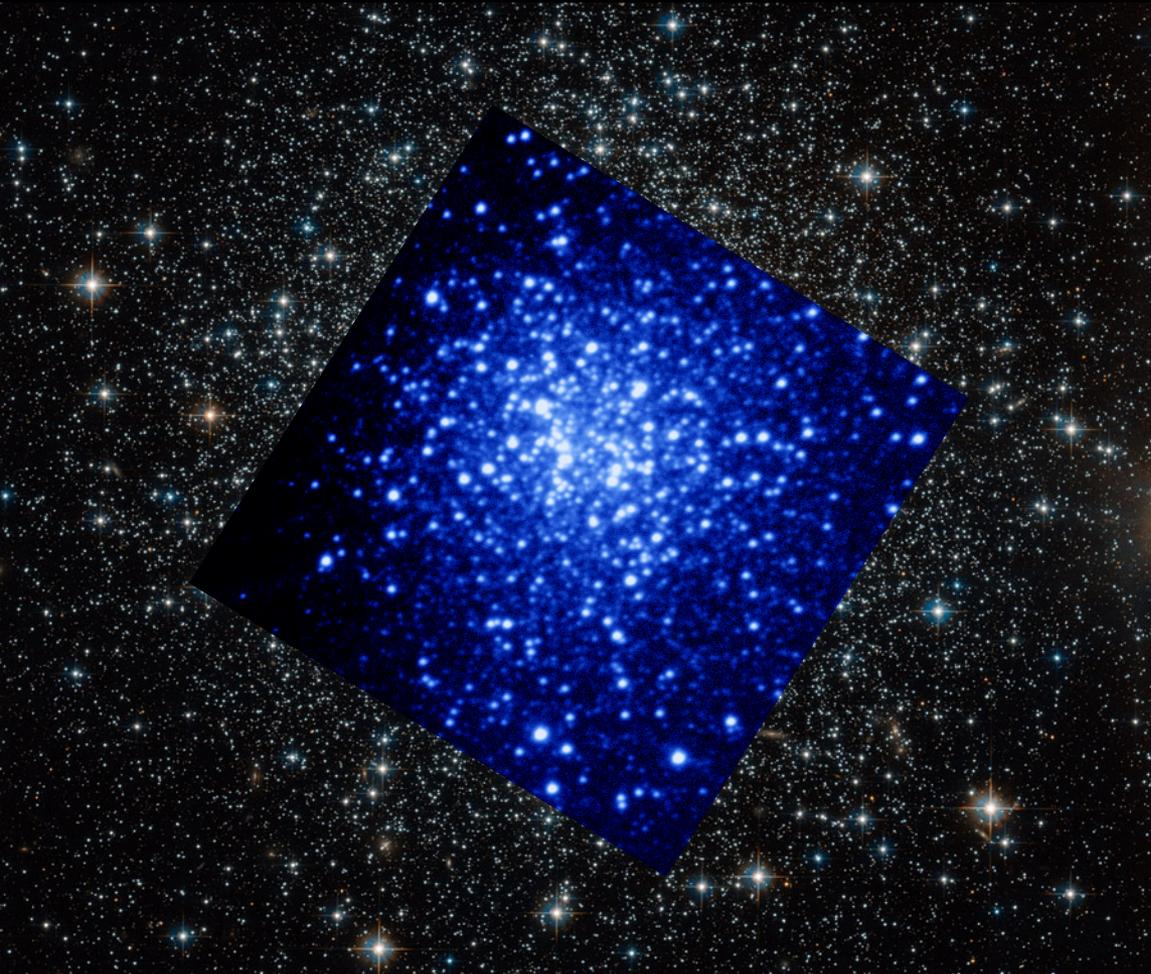


*Not so fast...*



*Hubble (94 inch)*

*Not so fast...*



*Hubble (94 inch)*

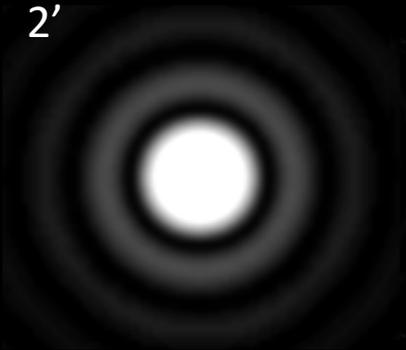
*Gemini (319 inch)*

# *What is going on?*

*Larger telescope*



2'



4'



*Sharper*

# *The atmosphere is in the way!*

*Larger telescope*



2'

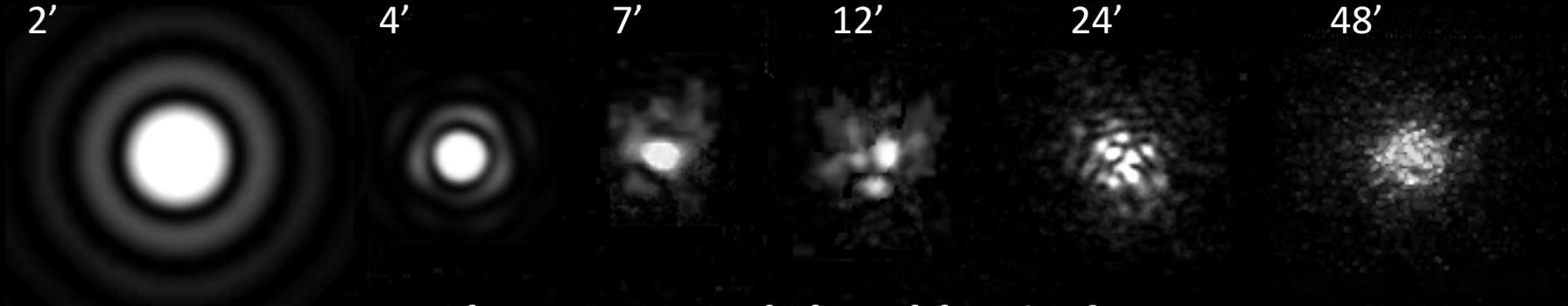
4'

7'

12'

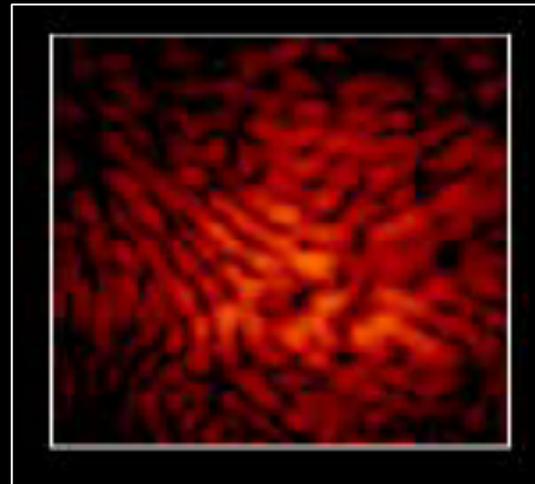
24'

48'



*Sharper ... and then blurrier!*

*The blur pattern  
changes every millisecond!*



14'



60'

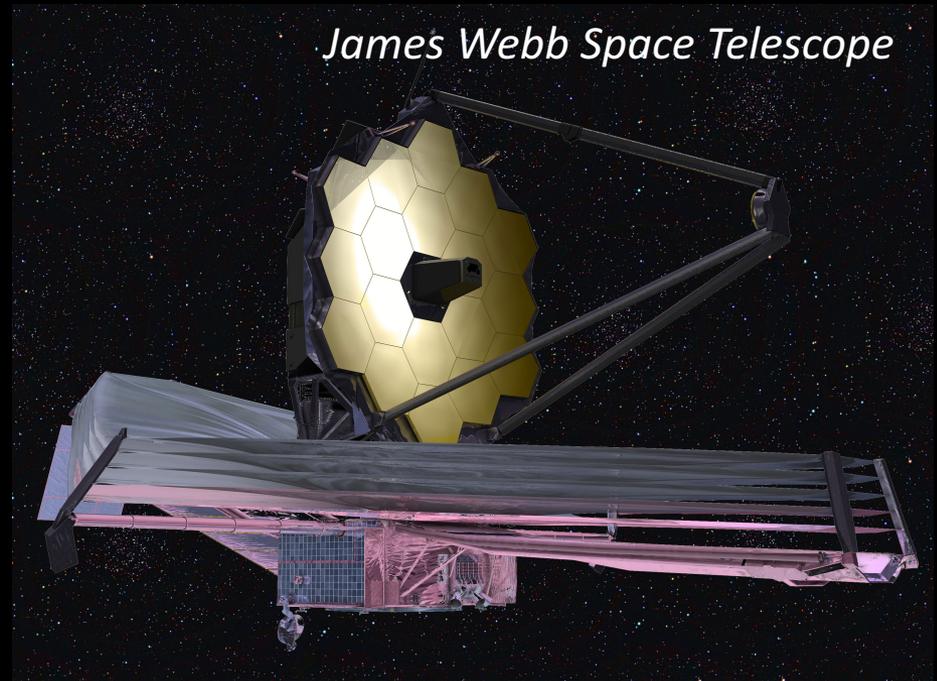


# *Going around the problem*

*Hubble Space Telescope*

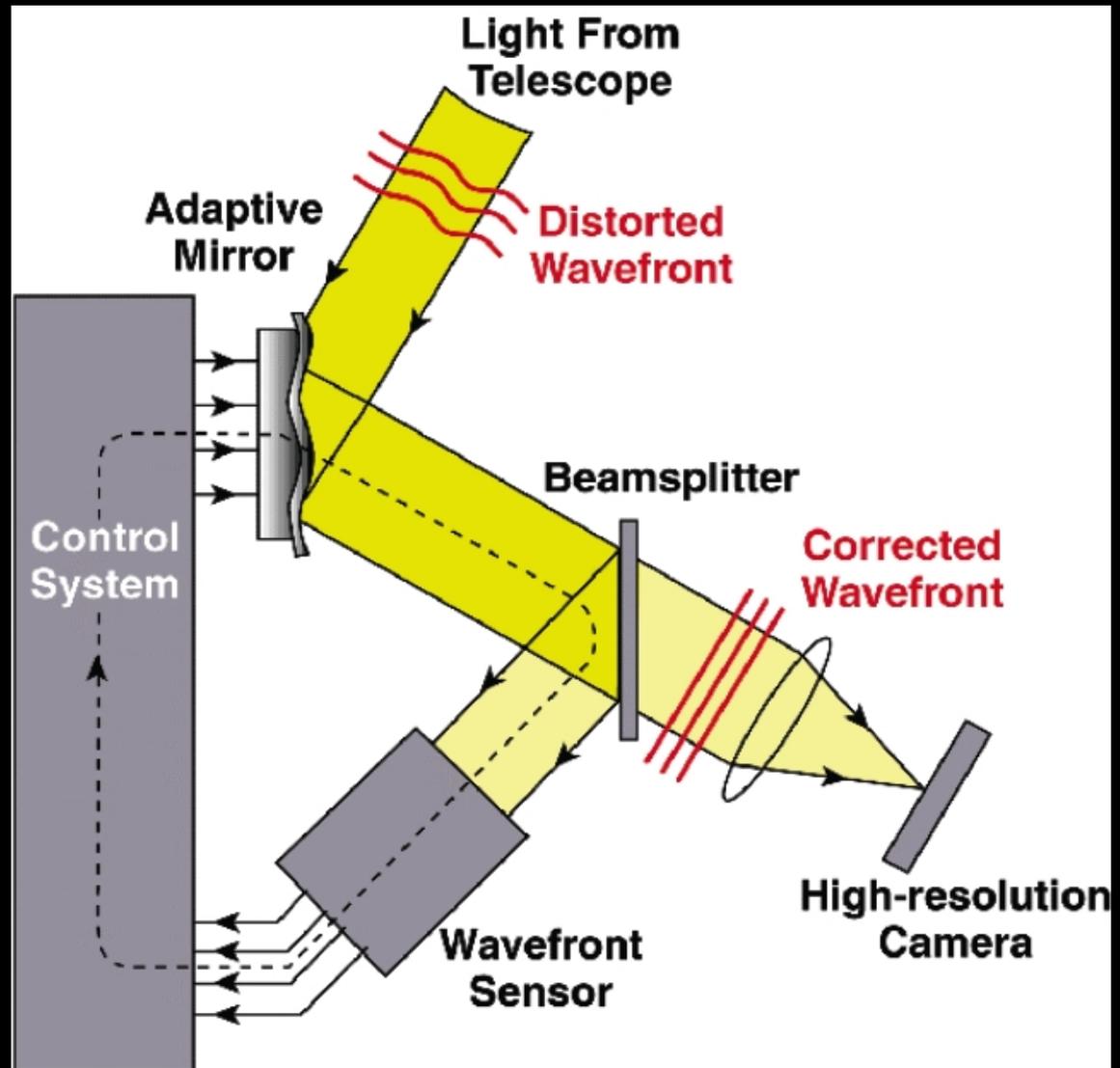


*James Webb Space Telescope*



## Adaptive optics

- 1) Sense the blur introduced by the atmosphere
- 2) Evaluate the correction to apply to the optics
- 3) Alter the shape of a formable mirror
- 4) **Rinse and repeat every millisecond!**



# Not so easy... but it can be done!

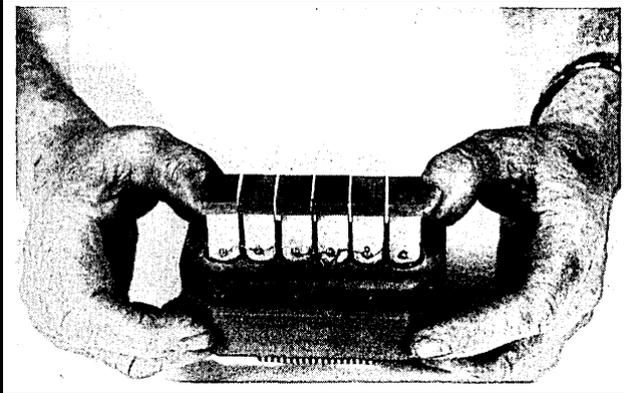
Vol. 65

October 1953

No. 386

THE POSSIBILITY OF COMPENSATING  
ASTRONOMICAL SEEING  
H. W. BABCOCK

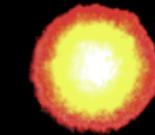
1977  
UCB Students  
Observatory,  
then Lick Obs.



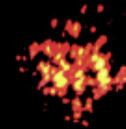
1989  
Obs. Haute Provence



Lick Observatory, 1 m telescope



Long exposure  
image



Short exposure  
image

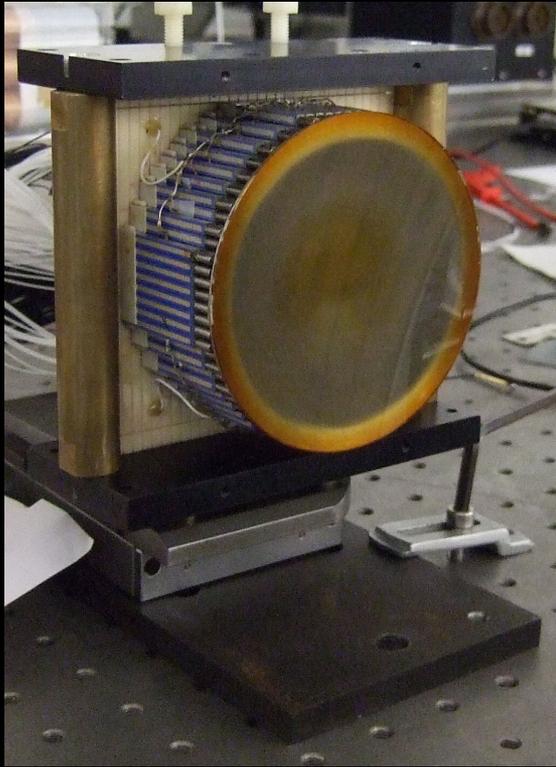


Adaptive optics  
image



Lick – Shane  
Telescope

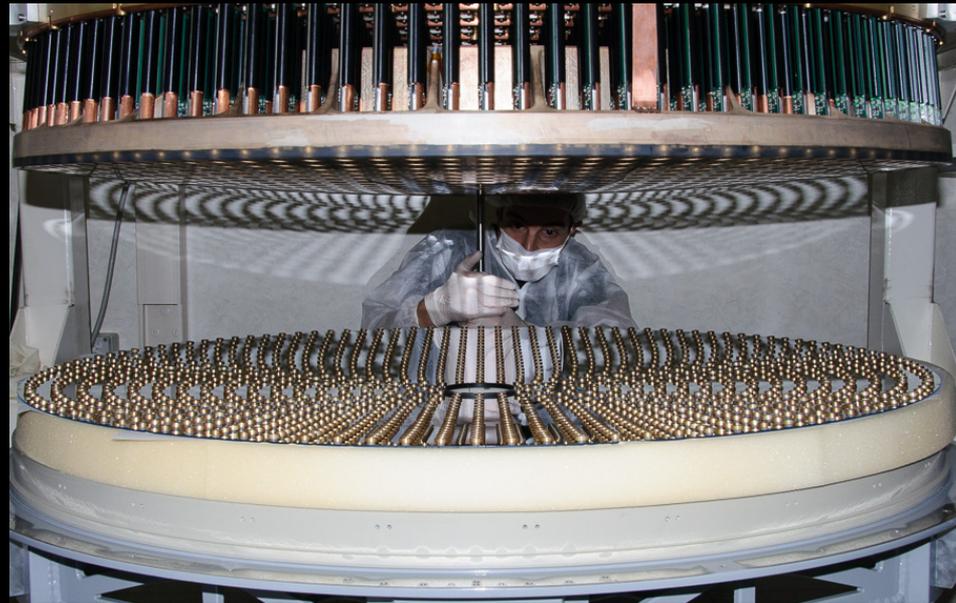
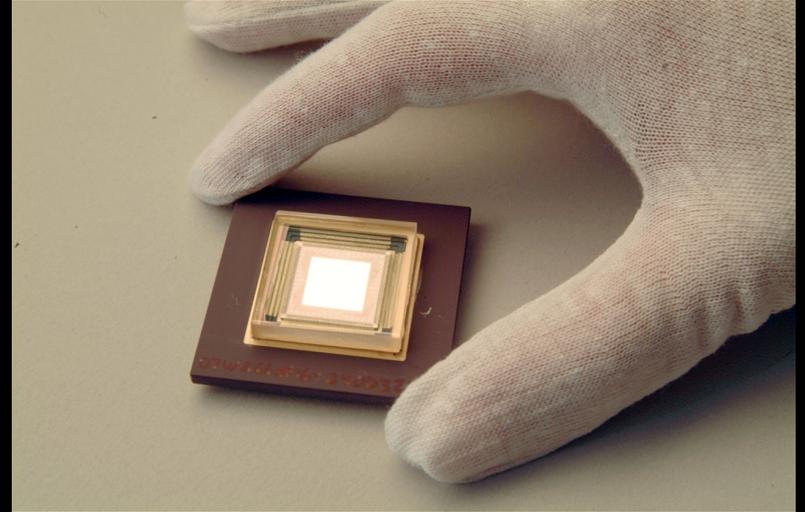
# Technology to the rescue!



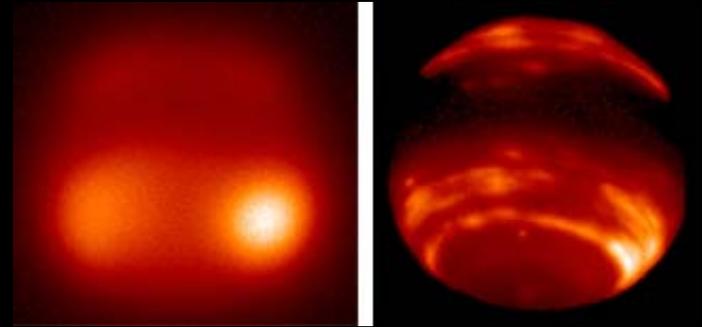
“standard”  
deformable mirror

“giant” (4 ft-diameter)  
deformable mirror

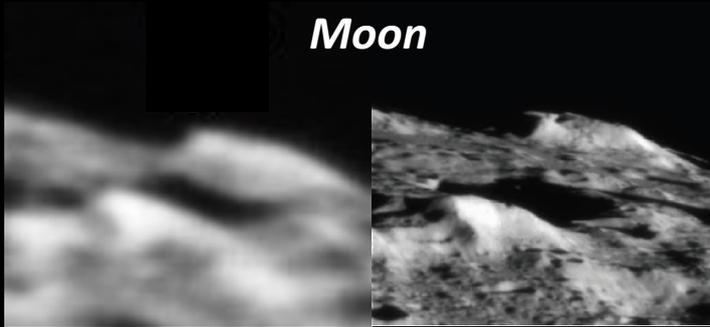
Micro-chip  
deformable mirror



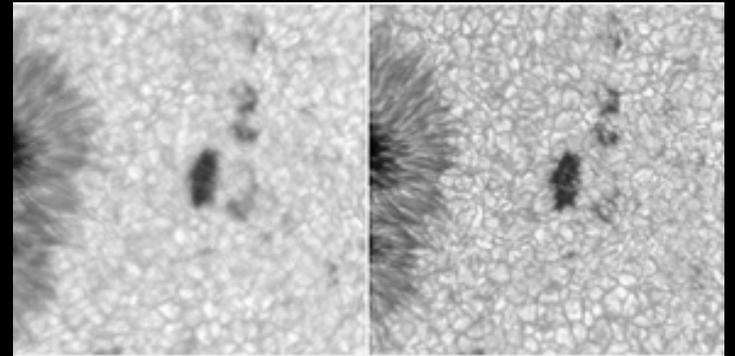
*Neptune*



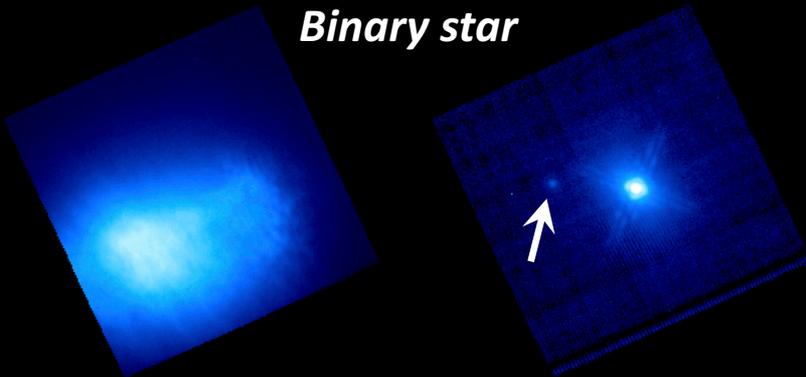
*Moon*



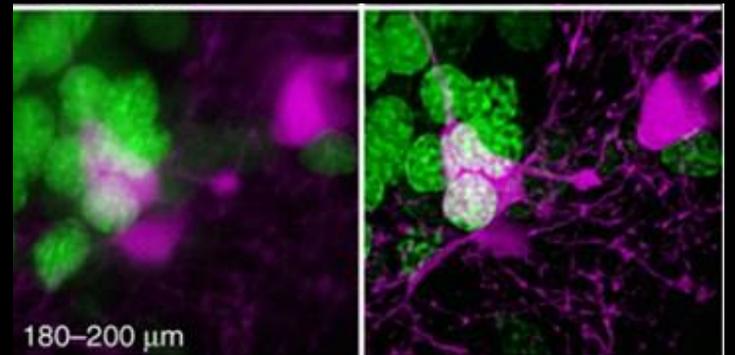
*The Sun*



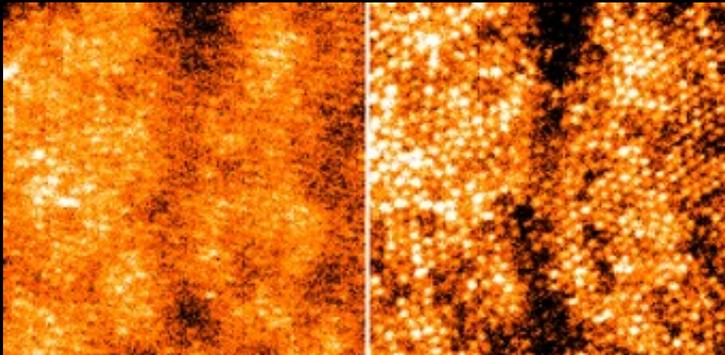
*Binary star*



*Living cells!*



*The back of your eye!*



# *Finding the firefly next to the lighthouse*



# ***Finding the firefly next to the lighthouse***

***“Tighten” the lighthouse beam  
(adaptive optics)***



# *Finding the firefly next to the lighthouse*

*Turn off the lighthouse!  
(coronagraph)*



# Coronagraphy



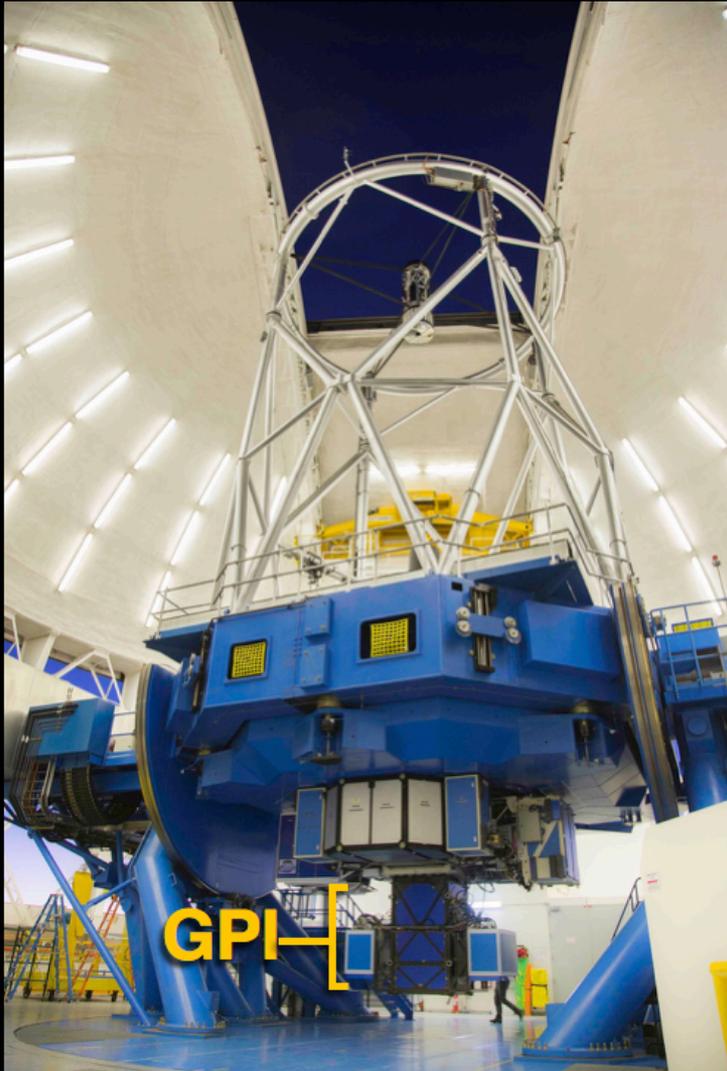
Bernard Lyot, 1939, at Pic du Midi  
French Astronomer  
Inventor of the Coronagraph



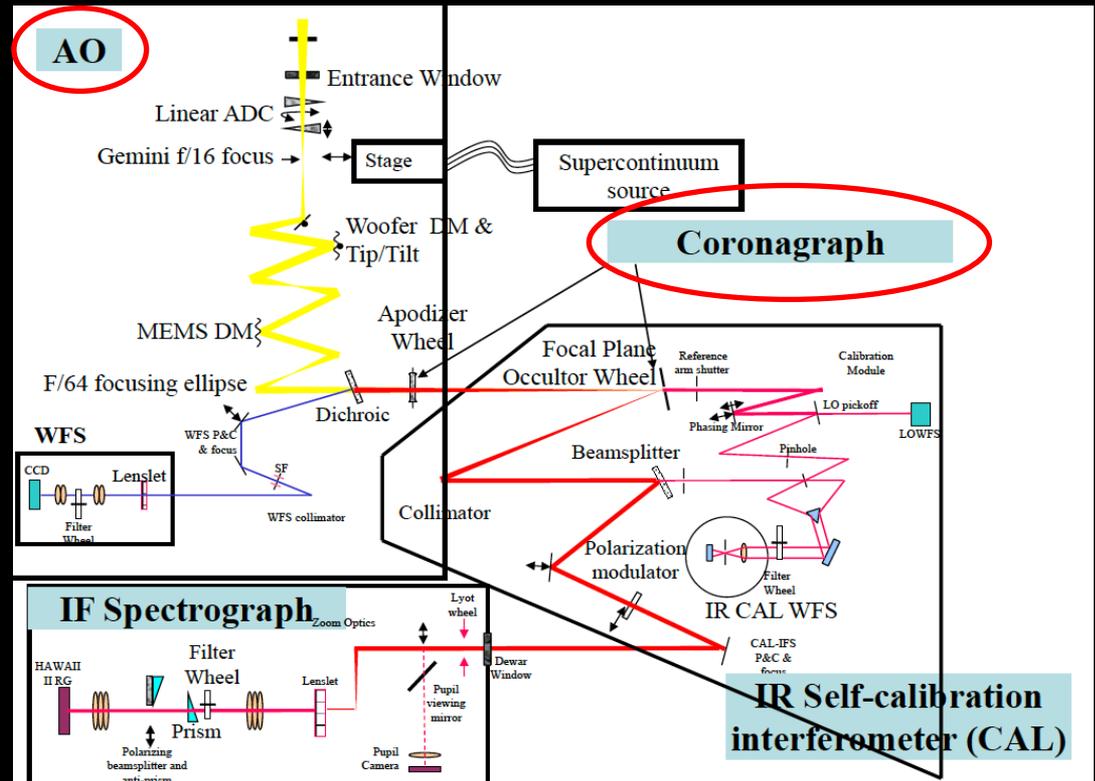
*Sirius*

**10,000:1 !**

# The state of the art



## Gemini Planet Imager



2004

2005

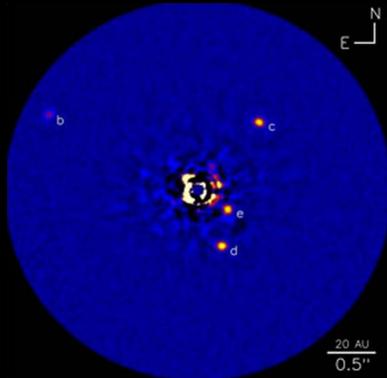
2008

2010 (2003!)

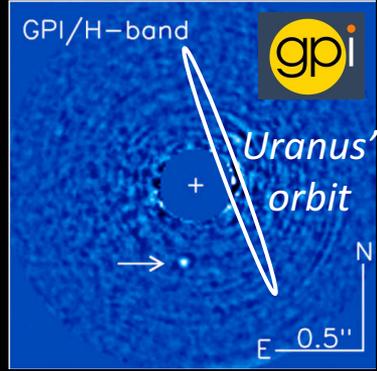
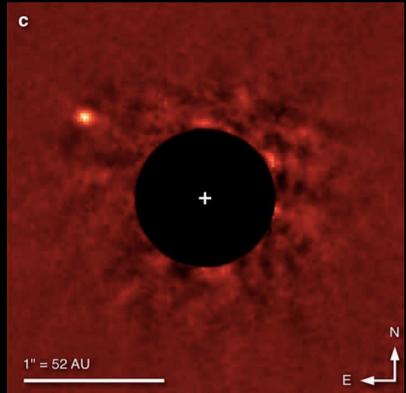
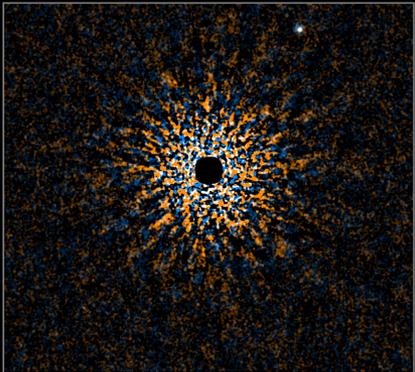
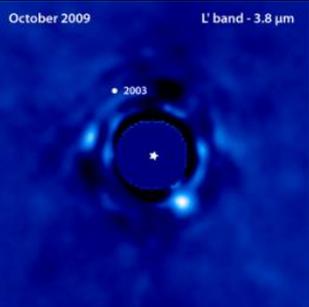
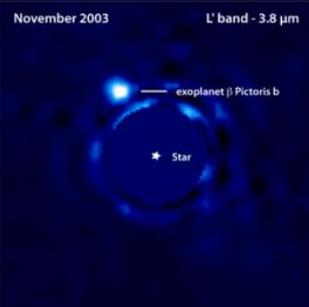
2011

2012

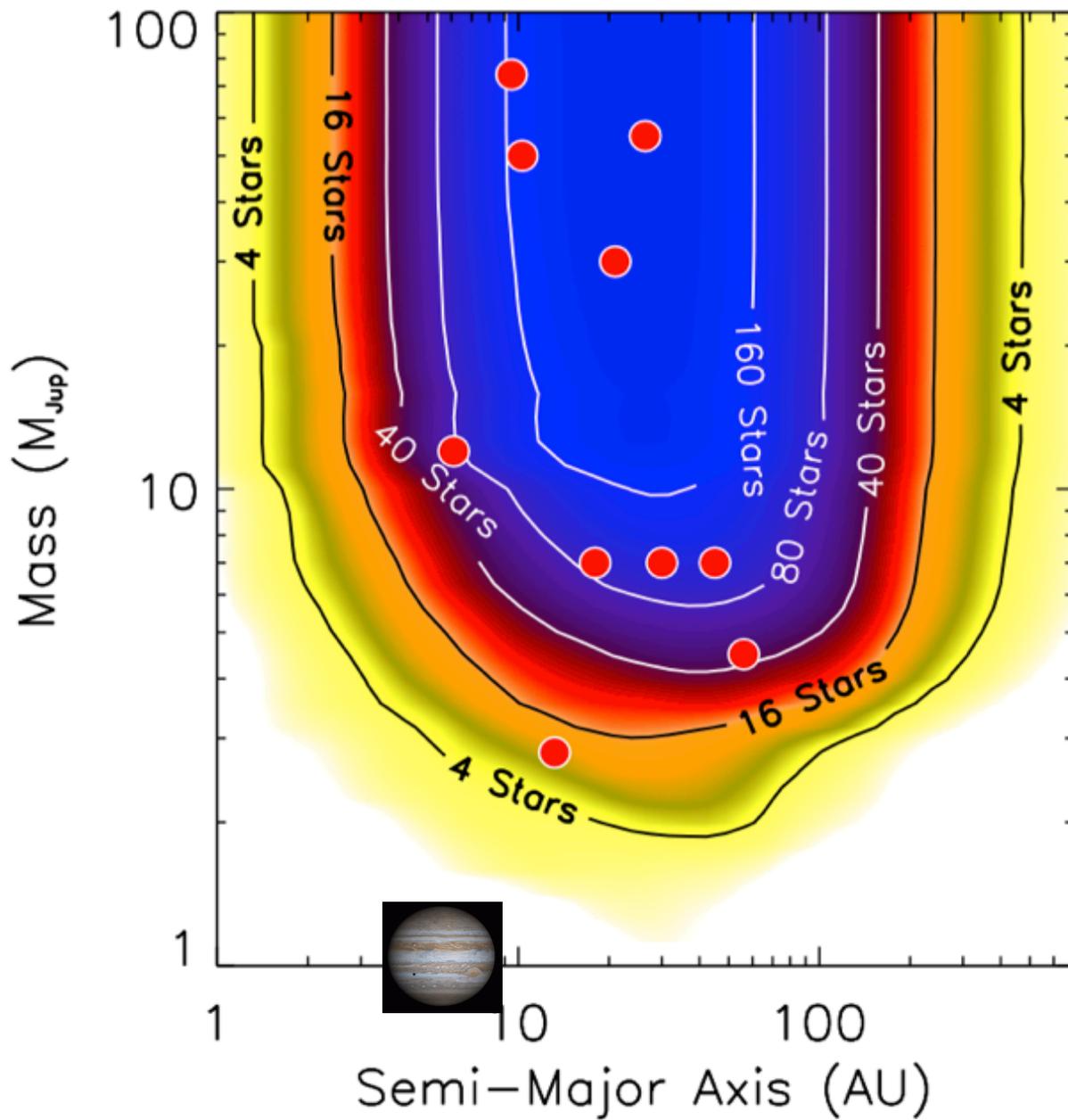
2015



Gemini Observatory / AURA/D. Latterini, R. Jayawardhana, A. von Borstel / University of Toronto  
Gemini Observatory Legacy Image



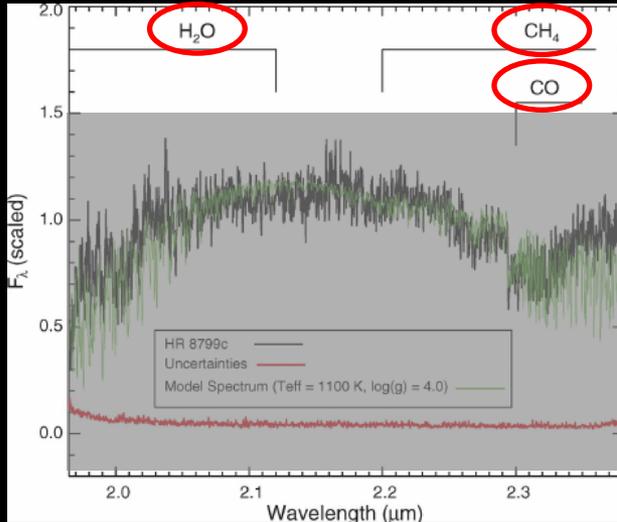
A young Solar System "analog"



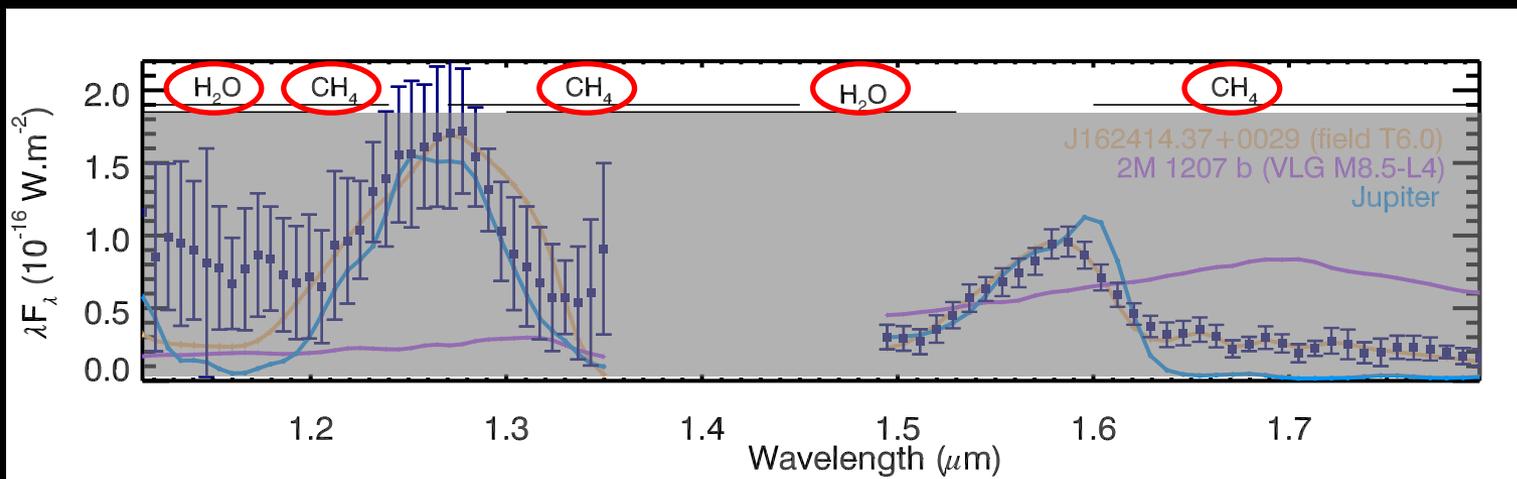
*Not quite like our Solar System planets!*

*These systems are rare (a few % of all stars)*

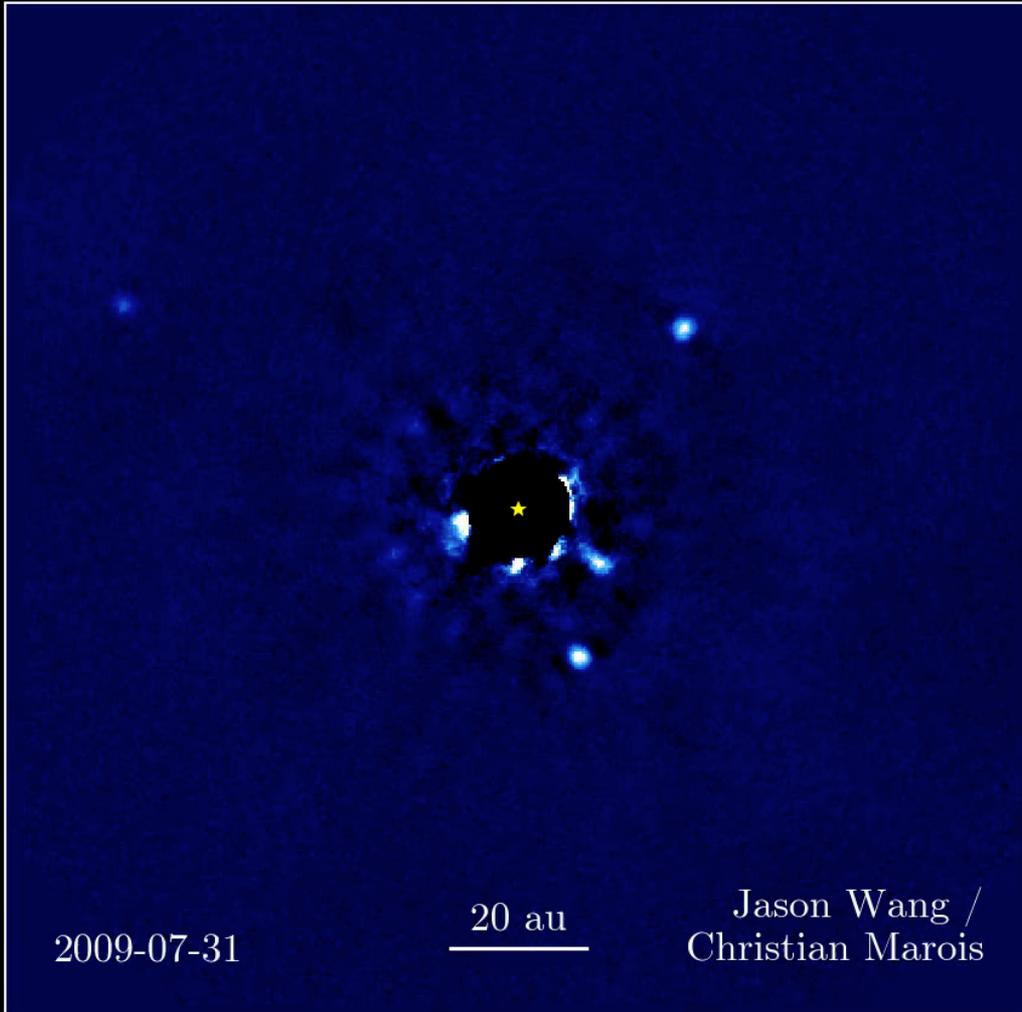
# Similar planet composition



*These are gas giants, with atmospheres made of standard molecules ( $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ )*



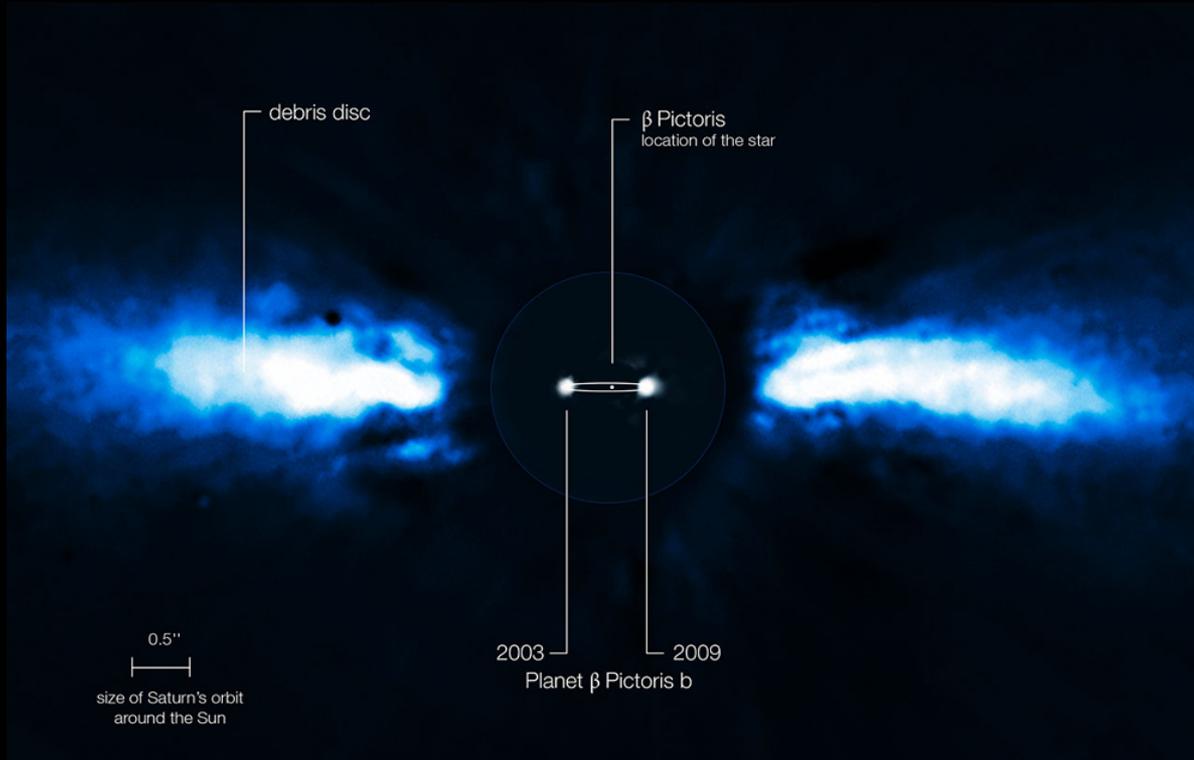
# *Some special systems*



*HR 8799*

*A nicely coplanar system*

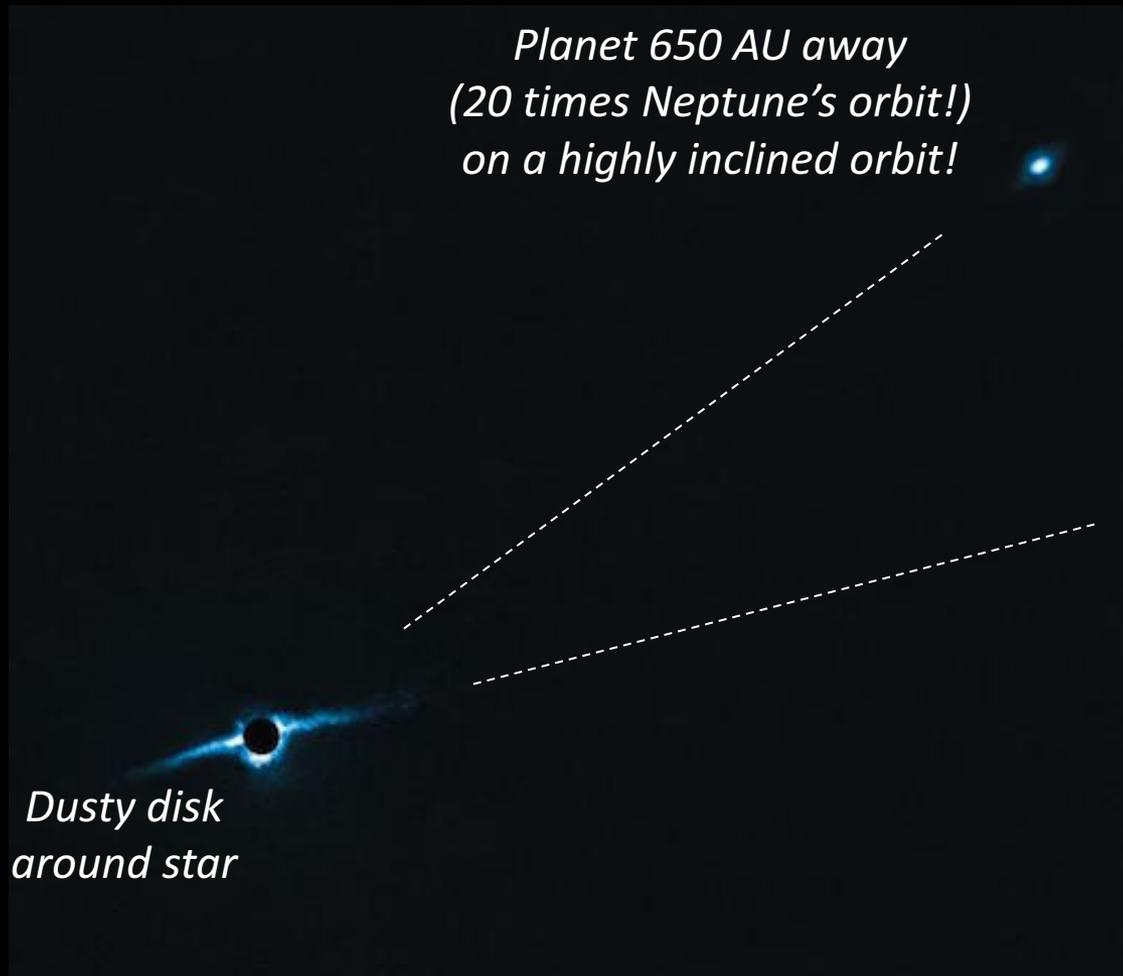
# *Some remarkable systems*



$\beta$  Pic

*A planet interacting  
with a disk of dust,  
comets and asteroids*

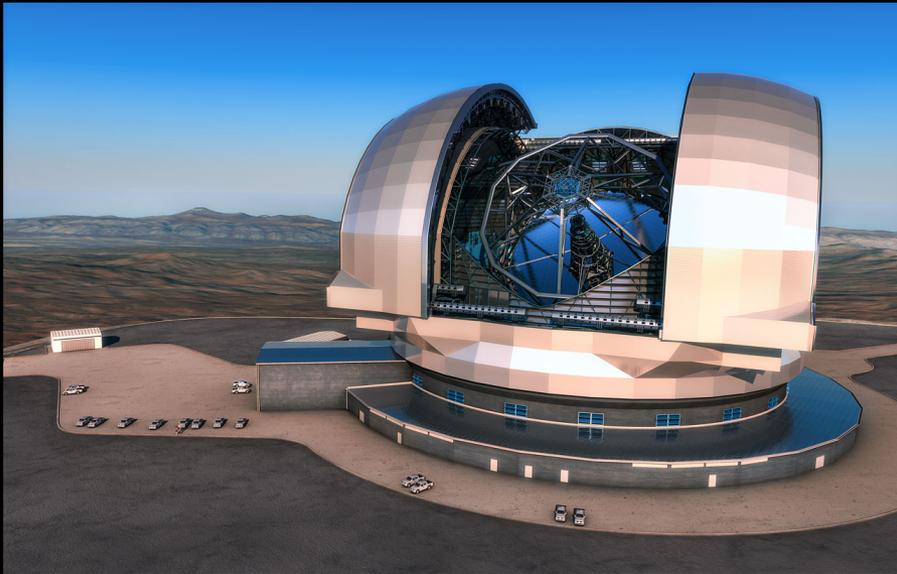
# *Some remarkable systems*



**HD 106906**

***An ejected planet?***

# *What's next?*



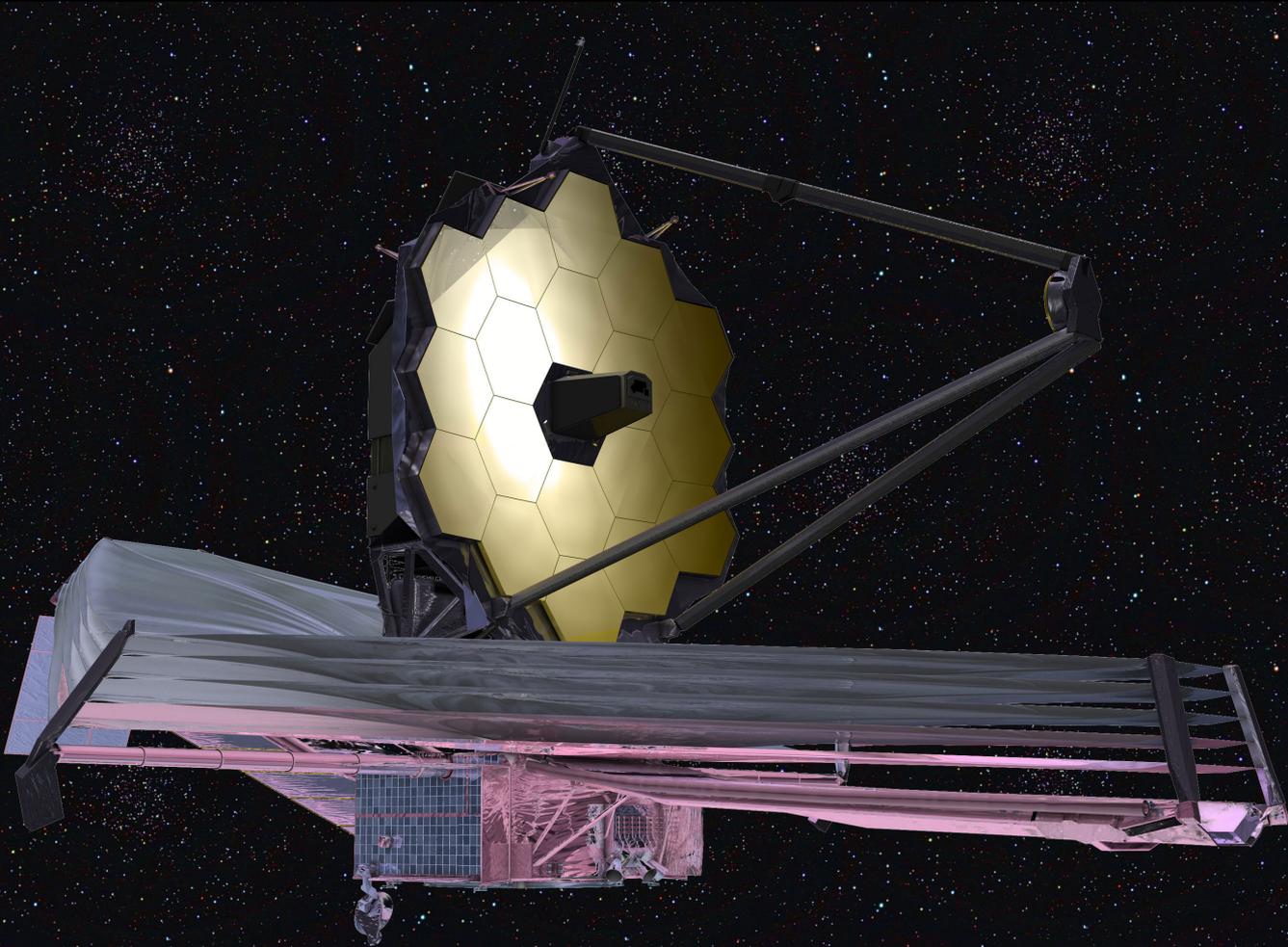
*Extremely Large Telescope*

*Thirty Meter Telescope*

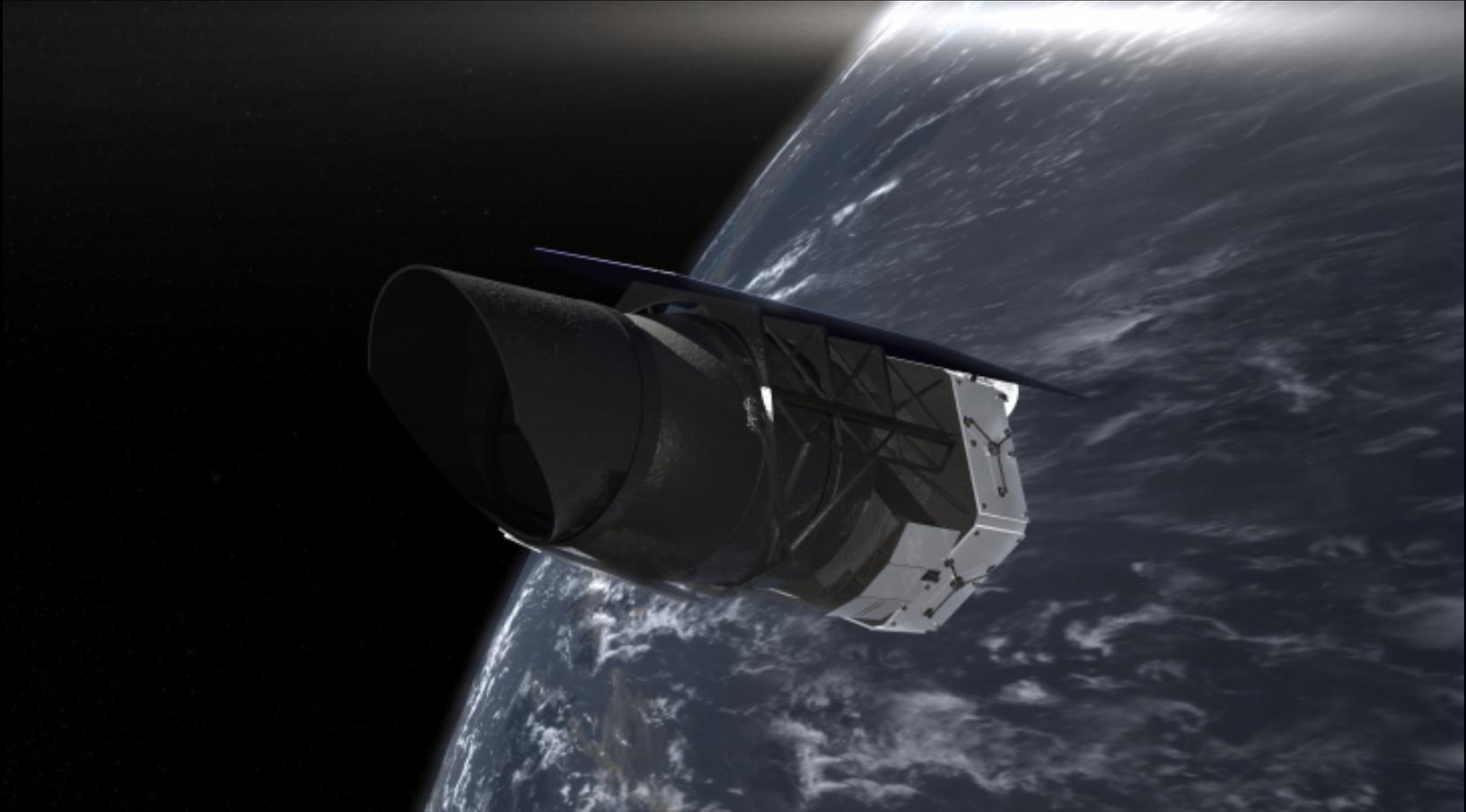


# *What's next?*

*James Webb  
Space Telescope*

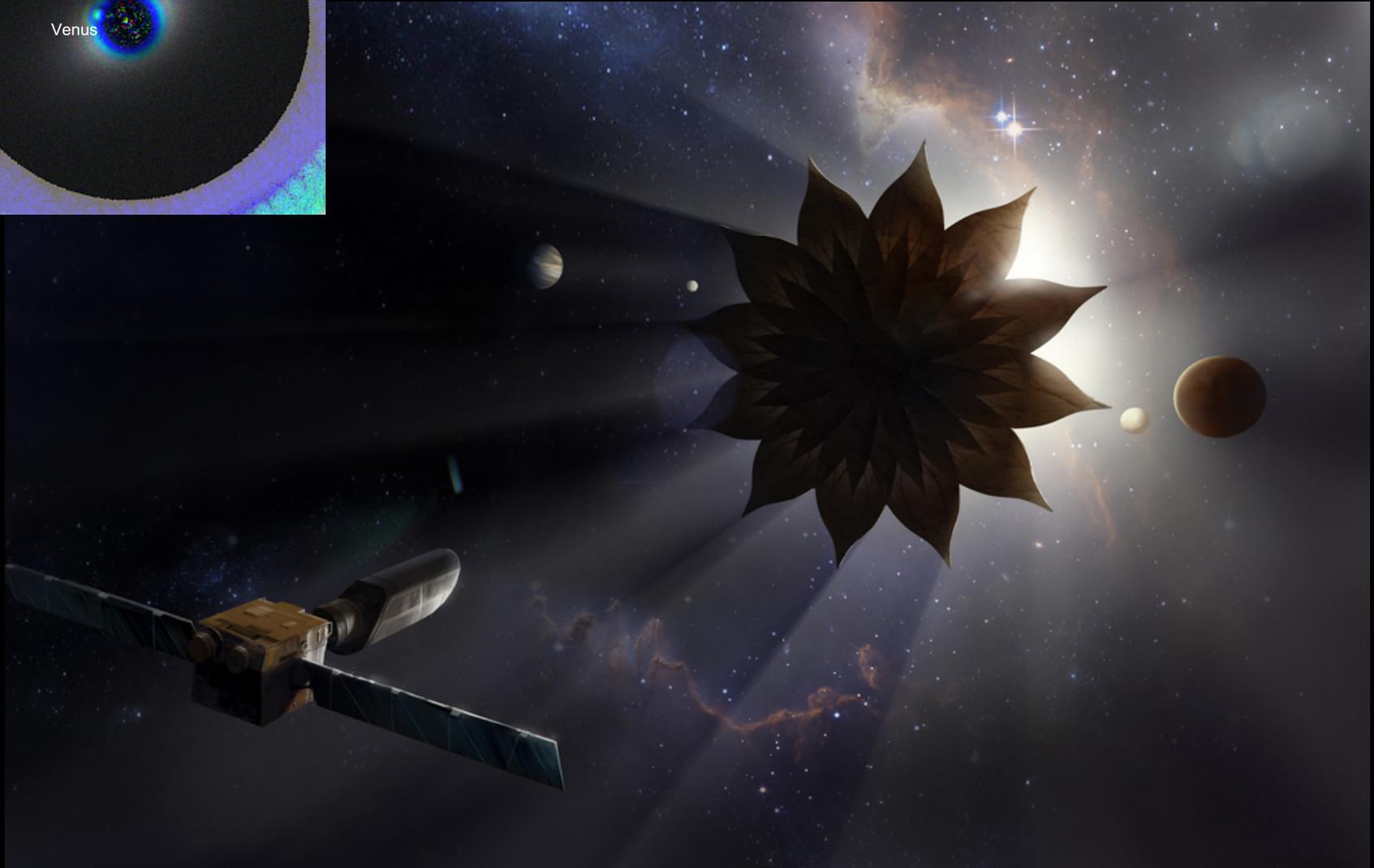
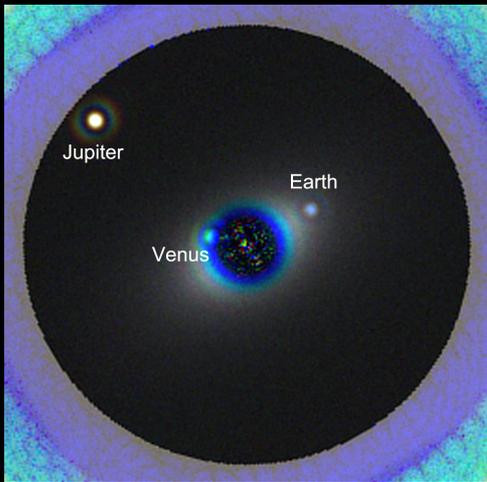


# *What's next?*



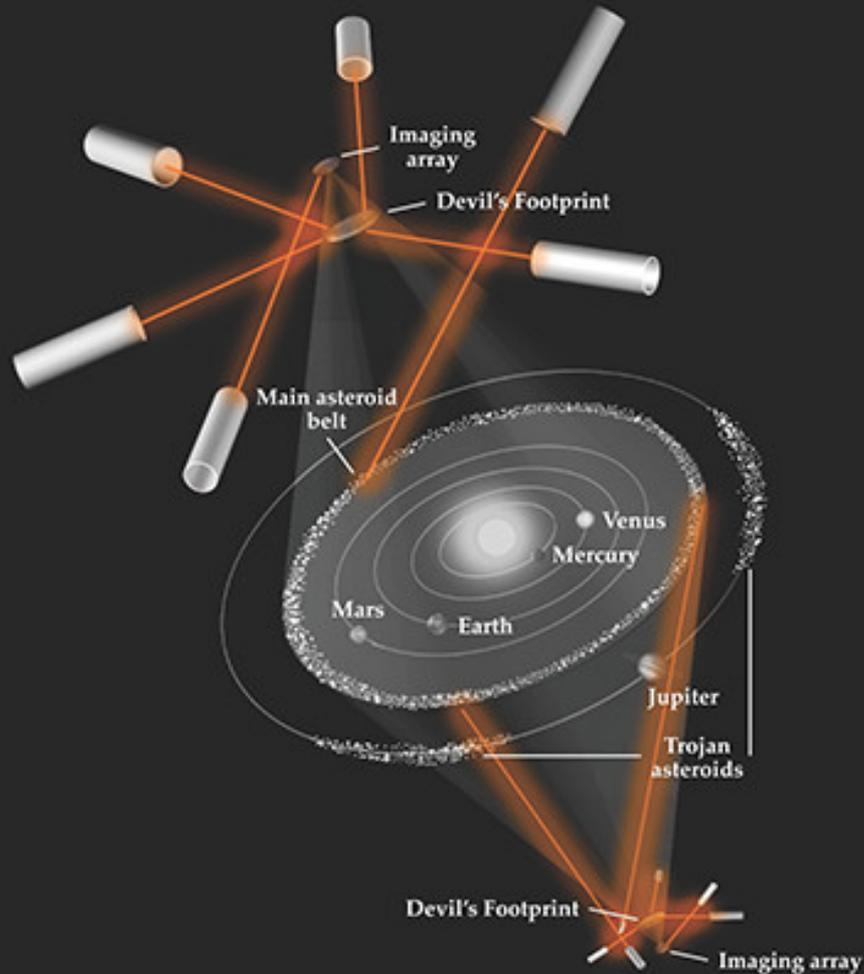
*Wide Field Infrared Space Telescope (WFIRST)*

# *What's next?*



*LUVOIR + "Starshade"*

# *Dreaming ahead...*

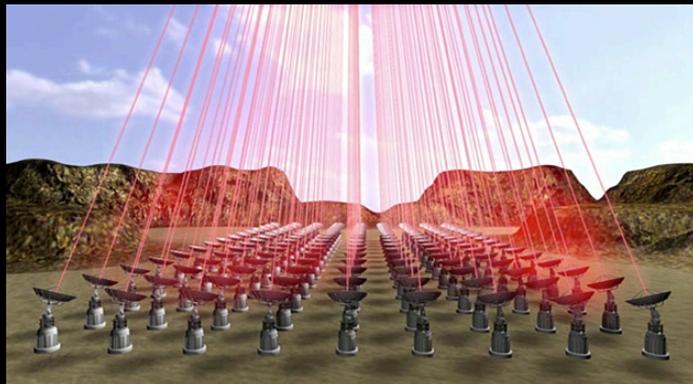
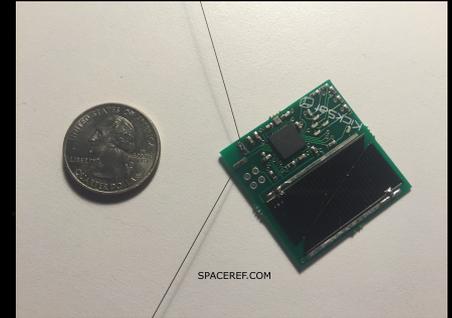


## *Asteroid Belt Astronomical Telescope*



© Physics Today (2016)

# *Dreaming ahead...*



***Breakthrough  
Starshot***



# *A journey to be continued!*

