Reading: Chapter 30
Final Exam: Monday, Nov 23, 12:00-2:00; review and practice exam posted

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Last time: **Cosmology III - Inflation and the Accelerating Universe**

- Testing Inflation - requires Ω = 1.000 but ordinary matter isn't enough
- Inflation requires there to be "non-baryonic" dark matter
- dark matter can seed formation of large structures - the Cosmic Web
- at early times, the Universe was expanding slower than we thought
- Dark Matter (~25%) + Dark Energy (~70%) + ordinary matter (< 5%)
- expansion is now "accelerating" - dark matter joined by dark energy

Today: **Planets beyond our solar system - and life?**

- Are we alone? The Drake Equation as a path to answers
- Discovery of exoplanets - they are everywhere (Kepler and others)
- the 'Habitable Zone' surrounding stars
- biological factors are harder to estimate than astronomical ones
- life, still, seems to be an inevitable result when conditions are right

A Final Question: Are We Alone?

SEARCHING FOR INTERSTELLAR COMMUNICATIONS

By GIUSEPPE COCCONI* and PHILIP MORRISON†

Cornell University, Ithaca, New York

The Optimum Channel

NATURE September 19, 1959

The reader may seek to consign these speculations wholly to the domain of science-fiction. We submit, rather, that the foregoing line of argument demonstrates that the presence of interstellar signals is entirely consistent with all we now know, and that if signals represent the means of detecting them is now at hand. . . The probability of success is difficult to estimate; but if we never search, the chance of success is zero.

A Final Question: Are We Alone?

Towards an answer: The Drake Equation
(Frank Drake, 1962)

F.D. Drake, 1960

F.D. Drake, today

$$N = R_s \times f_p \times n_p \times f_L \times f_i \times f_c \times L$$

original form

The Drake Equation (1962) parameterizing our ignorance

$$N = R_s \times f_p \times n_p \times f_L \times f_i \times f_c \times L$$

N is the number of communicating civilizations in the Galaxy today

Astronomical factors	= R_s **(annual rate of star formation)** x f_p **(fraction of stars with planets)** x n_p**(# of planets with conditions for life)**
Biological factors	x f_L **(fraction on which life develops)** x f_i **(fraction that develop intelligent life)**
Sociological factors	x f_c **(fraction that develop communication)** x **L (# of years communication continues)**

Astronomical Factors: Sun-like Stars

R_s – how many "useful" stars of
250,000,000,000 in our galaxy form each year?

- long lasting - to allow complex life to develop
  - 3.5 - 4.0 billion years for the Earth
- quiet and steady energy production
  - few big flares or other 'stellar flares'
  - no binary companion
- about 1/3 of all stars are "useful"

R_s ~ 8 stars / year

Astronomical Factors: Fraction of Stars with Planets

f_p ~ ?

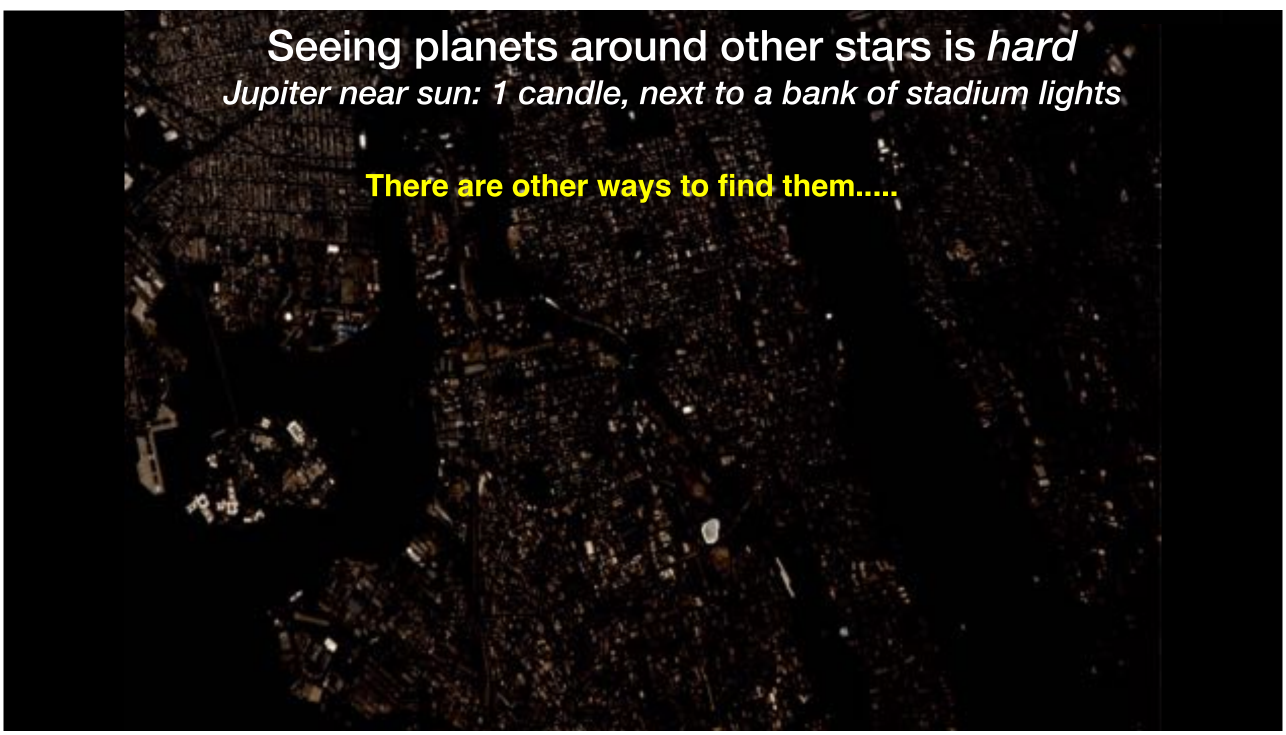
- star formation pictures - lots of protoplanetary disks
- Are planets truly COMMON around single stars?
- searches for other planets...

Searching for other planetary systems

this is a hard problem!

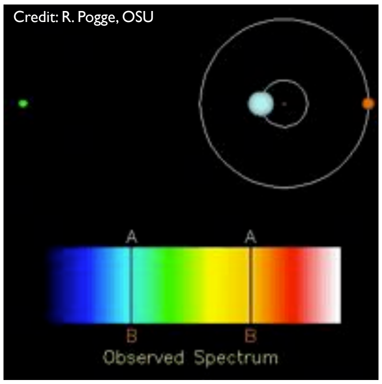
- Jupiter and the Sun
  - the Sun has a luminosity of 4 x10^{33} erg/s
  - Jupiter emits at most 8 x10^{24} erg/s
  - the Sun emits 500,000,000 times more light than Jupiter
  - viewed from 10 pc, they are separated by 5 arc sec

- equivalent to
  - 1 candle,
  - 10 feet away from a stadium light bank,
  - viewed from 80 miles away!



Reflex Orbital Motion

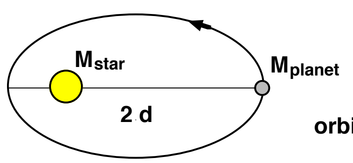
- via reflex orbital motion: **precision spectroscopy**
- as of today: 831 planets in 625 systems



Credit: R. Pogge, OSU

Wobbles of stars from reflex motion:

- **Kepler's 3rd Law**

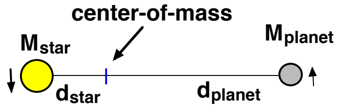


$$\frac{d^3}{P^2} = M_{star} + M_{planet}$$

orbital period [yrs]

- **The "See-Saw" Law**

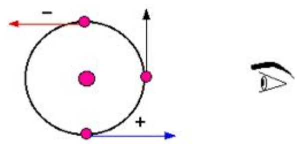
$$\frac{M_{planet}}{M_{star}} = \frac{d_{star}}{d_{planet}}$$

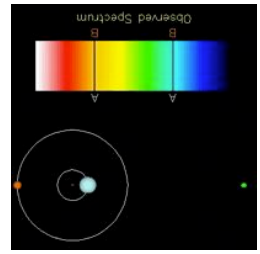


- **$M_{planet} << M_{star}$**
  - star moves in a small orbit
  - measure **d_{star}** and you know **M_{planet}**

The "Radial Velocity" technique

look for orbital *VELOCITY* of star around CM





$$V = \frac{2\pi d}{P} \quad \text{so} \quad V_{star} = 30\,m/s \times \frac{2\pi}{\sqrt{M_{star}}} \times \frac{1}{\sqrt{d}} \times \frac{M_{planet}}{M_{Jupiter}}$$

- Biggest effect if viewed EDGE ON
- Tilt of orbit to line-of-sight reduces observed velocity

Jupiter as an example:

- V_{Sun} around CM of Solar System = 13 m/s (= 30 mph)
- Doppler effect of 13 m/s is 1 part in 23,000,000 (!)
- varies cyclically over a 12 year cycle
- very difficult (but not impossible) to measure
- need stable spectroscope over long time
- **Earth? 9 cm/s!**

Improved chances for detection (V_{star} bigger):

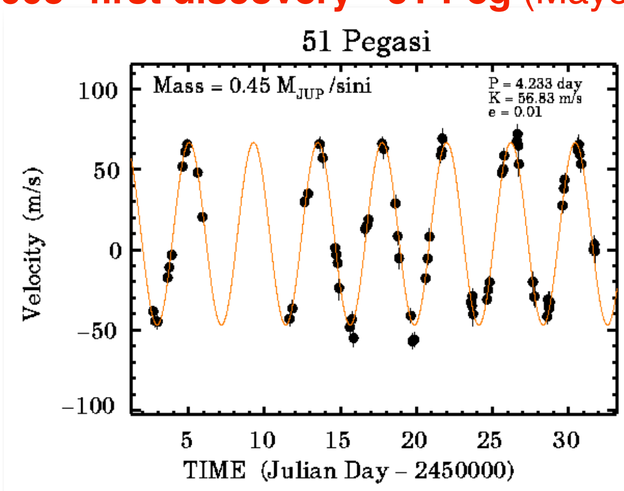
$$V_{star} = 30\,m/s \times \frac{2\pi}{\sqrt{M_{star}}} \times \frac{1}{\sqrt{d}} \times \frac{M_{planet}}{M_{Jupiter}}$$

if planet is massive

if planet is close to star

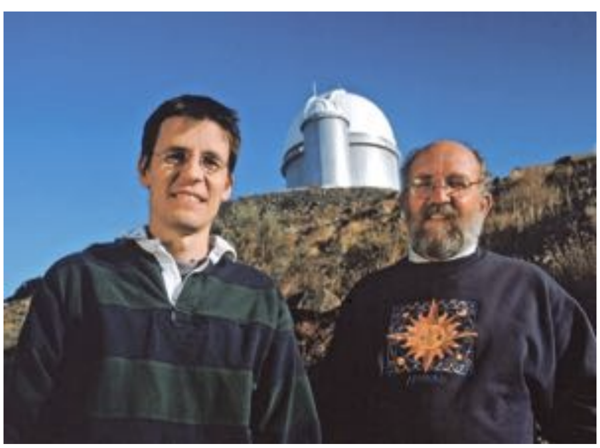
also - shorter period = faster detection

- pre-1995 - The Search is On
  - initial search for ‘ordinary planets’
  - P_{orb} ~ months
- **1995 -first discovery - 51 Peg** (Mayor & Queloz)



P_{orb} = 4.233 days
M_{planet} = 0.45 $M_{Jupiter}$

Didier Queloz Michel Mayor



ELODIE

The Nobel Prize in Physics 2019

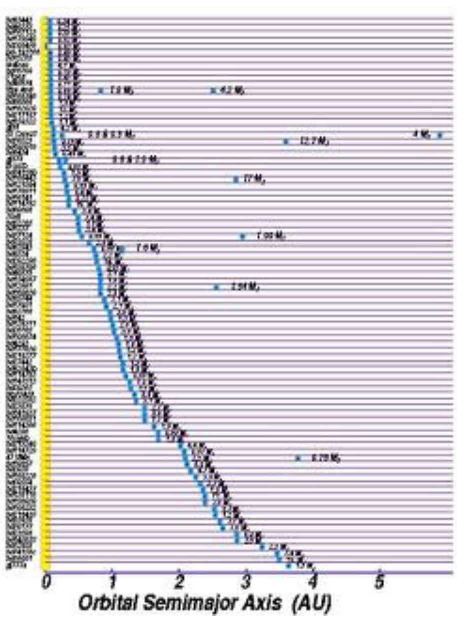
Ill. Niklas Elmehed. © Nobel Media. James Peebles Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media. Michel Mayor Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media. Didier Queloz Prize share: 1/4

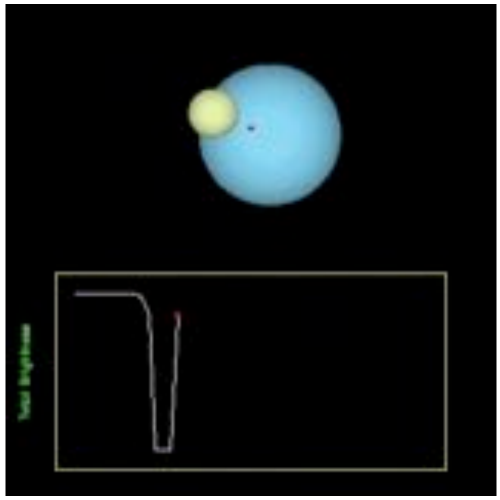
The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

1995 - 2020 Huge strides

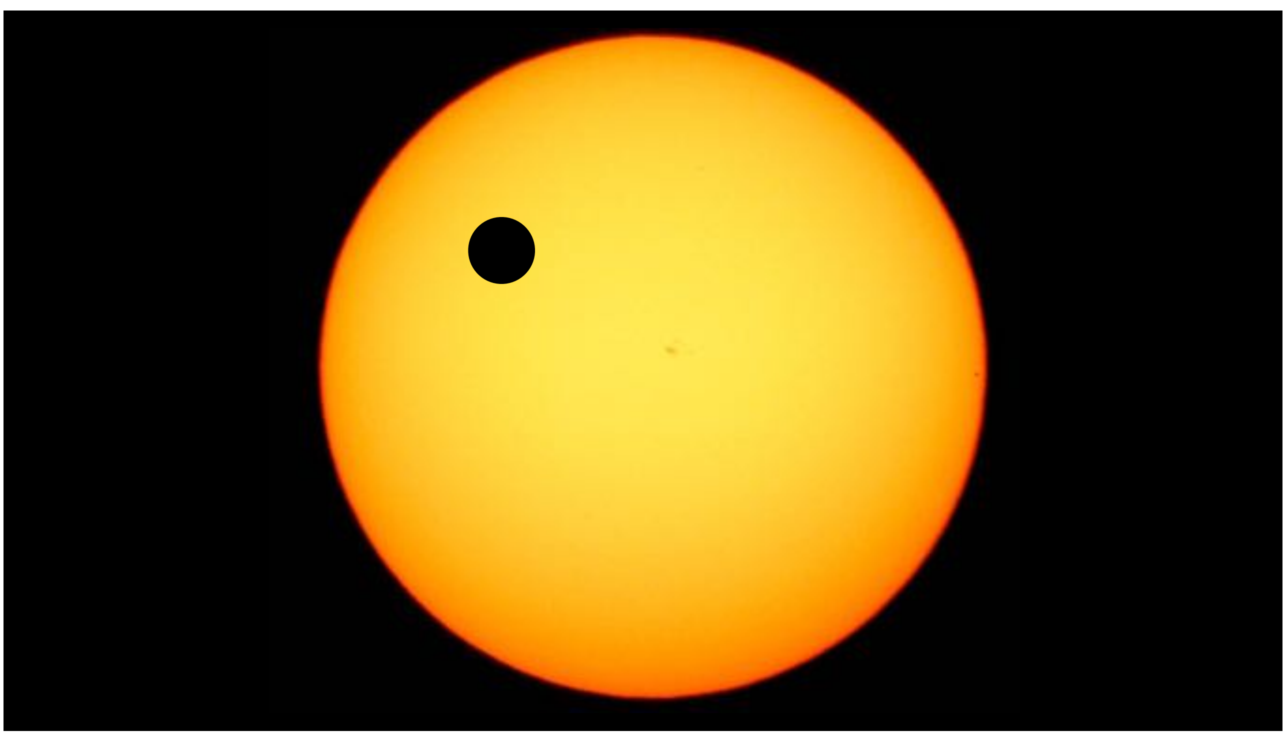


- now over 660 confirmed extrasolar planetary systems (> 900 planets) found via Radial Velocities
- Most are **massive planets**
- Most have **small orbits**
- Many are multiple-planet systems

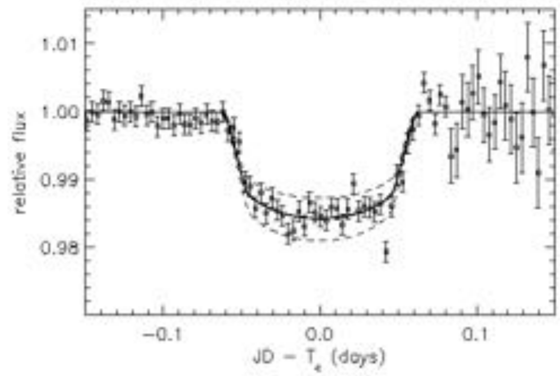
The Transit Method



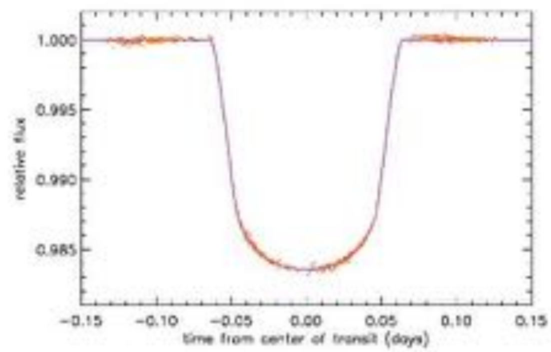
Credit: R. Pogge, OSU



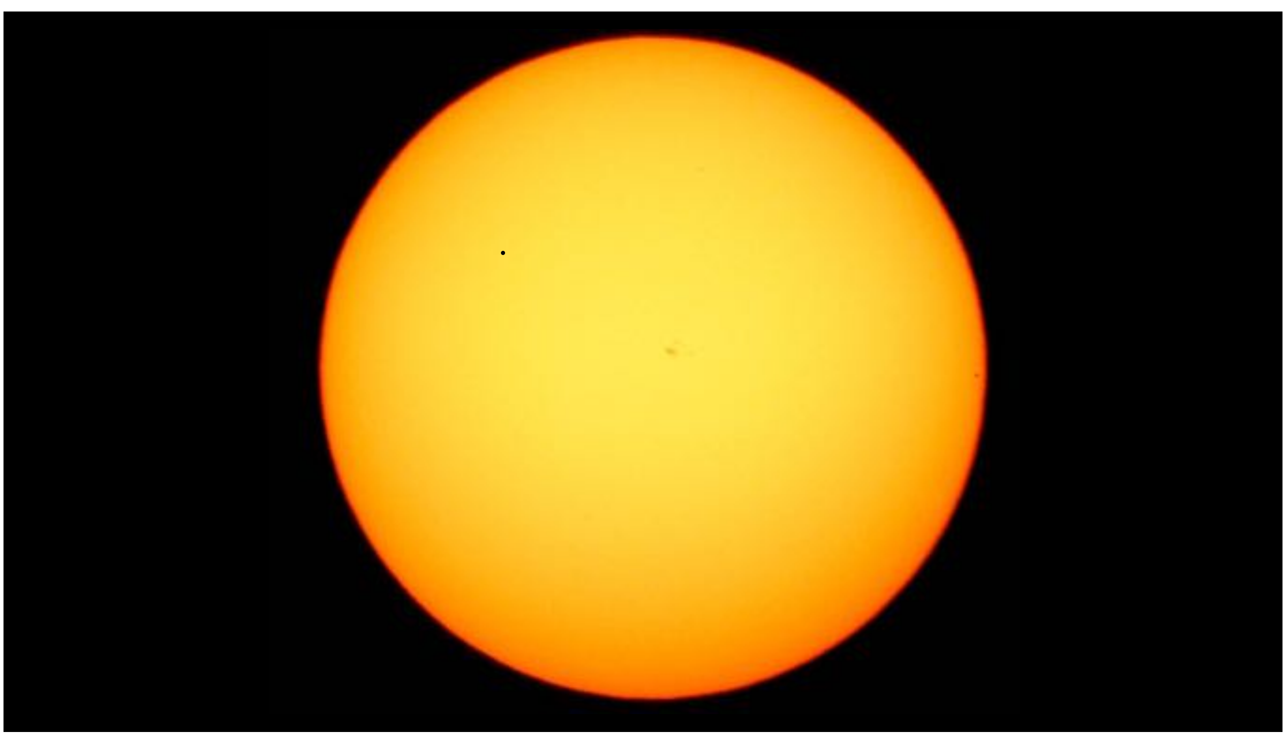
The first transiting extrasolar planet: HD209458

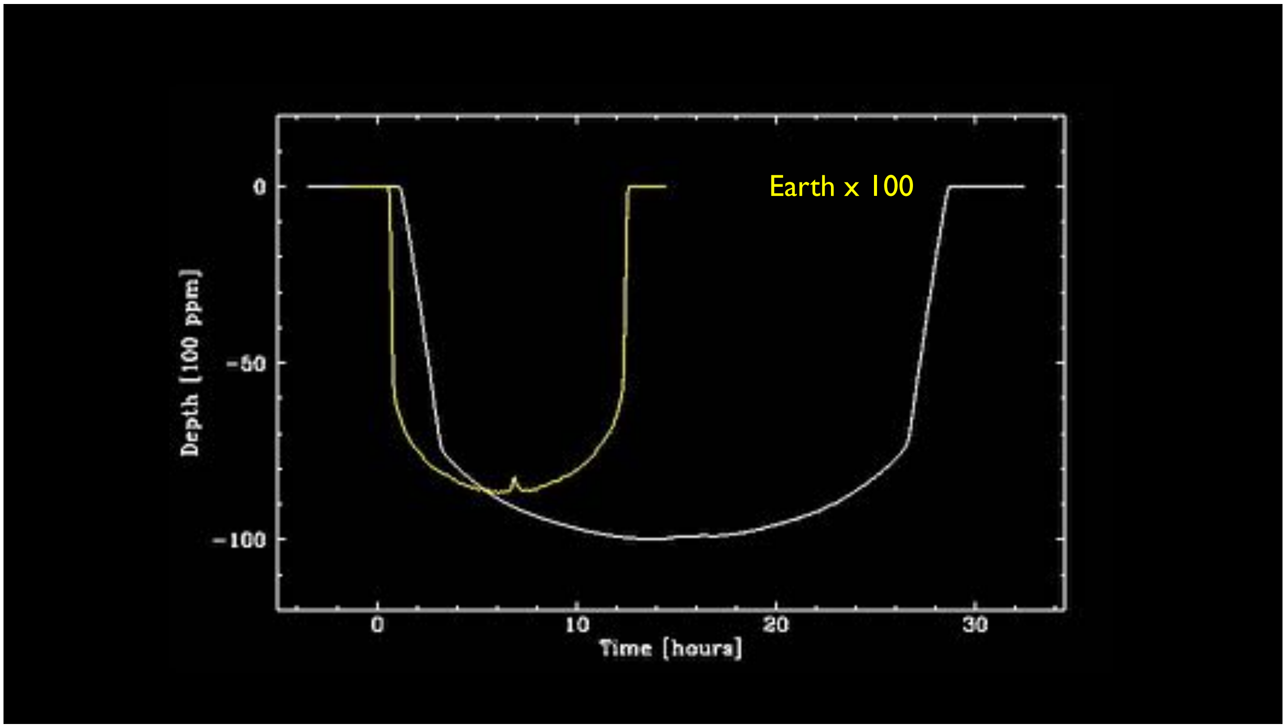


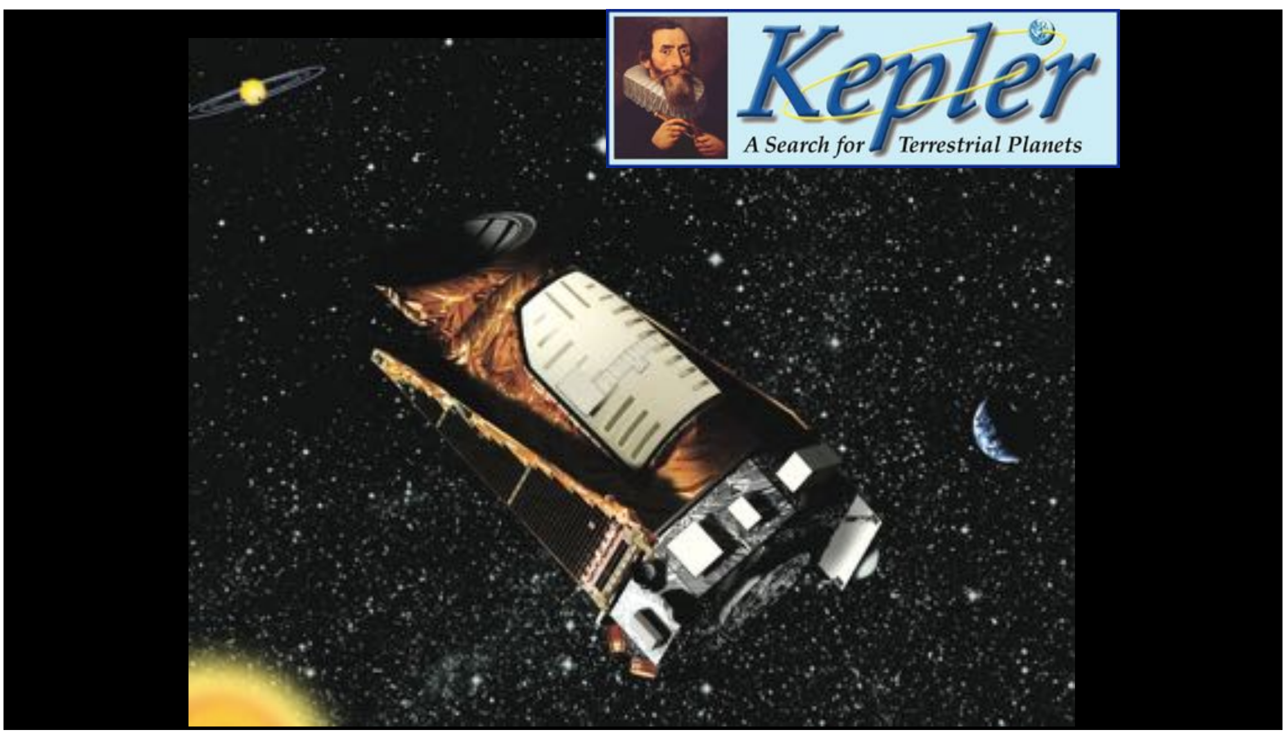
Discovery by Charbonneau et al. 1999



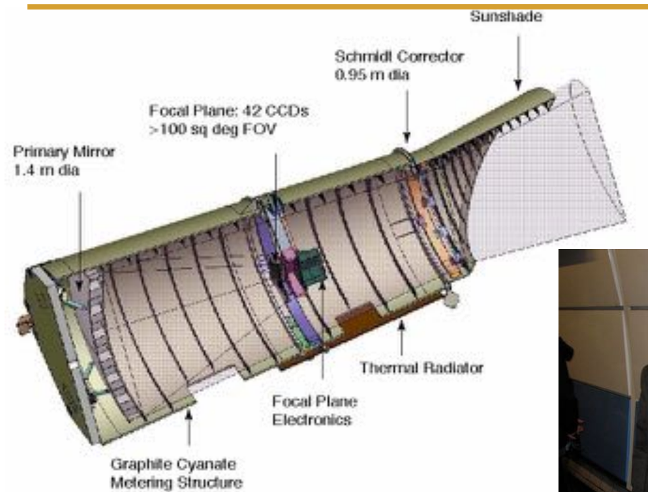
Hubble Space Telescope light curve




Earth x 100
0
-50
-100
Depth [100 ppm]
0
10
20
30
Time [hours]

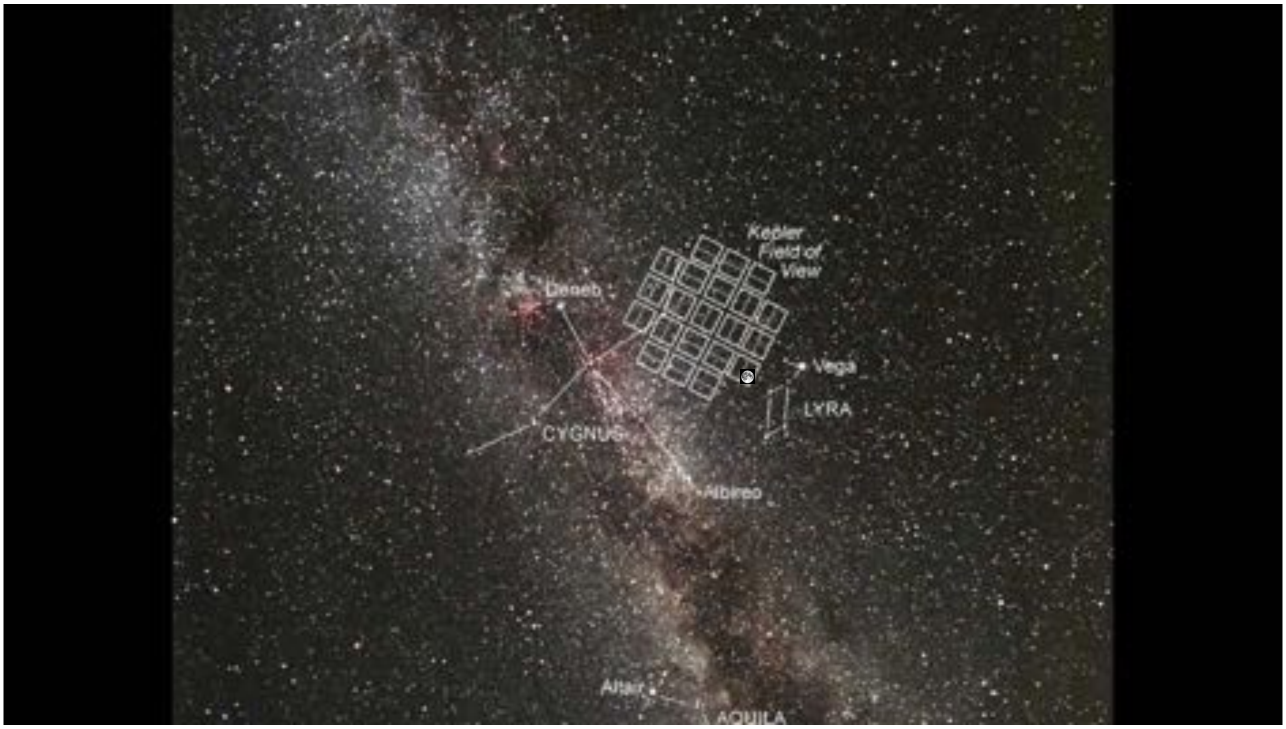

Kepler
A Search for Terrestrial Planets

Kepler Photometer

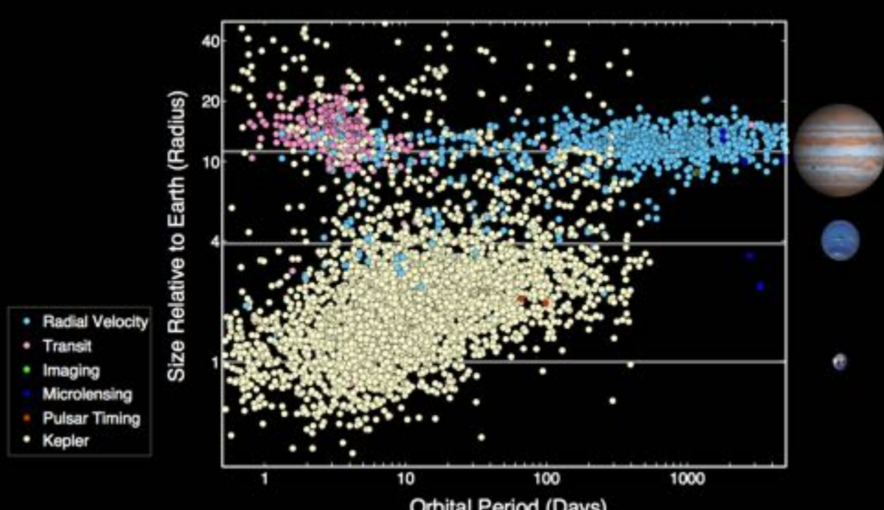


Photometer = CCDs sensors+ Telescope
Kepler is the 9th largest Schmidt ever built

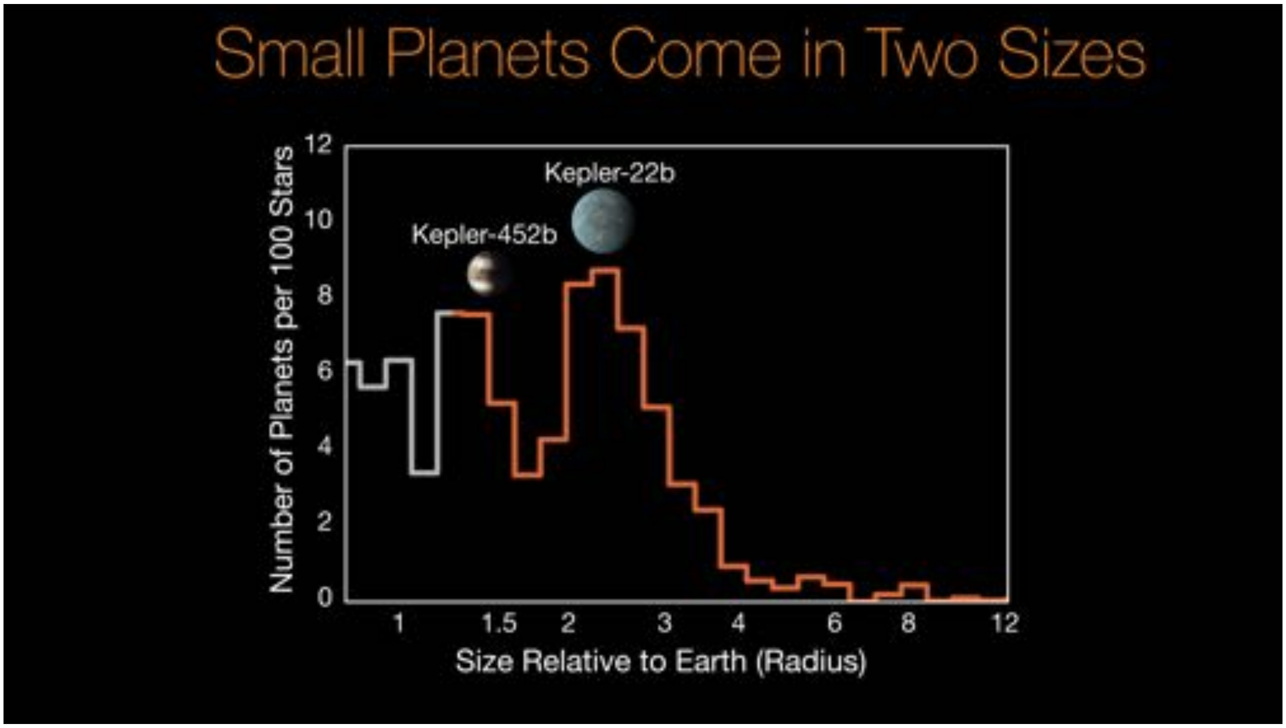
and the largest telescope launched beyond earth-orbit

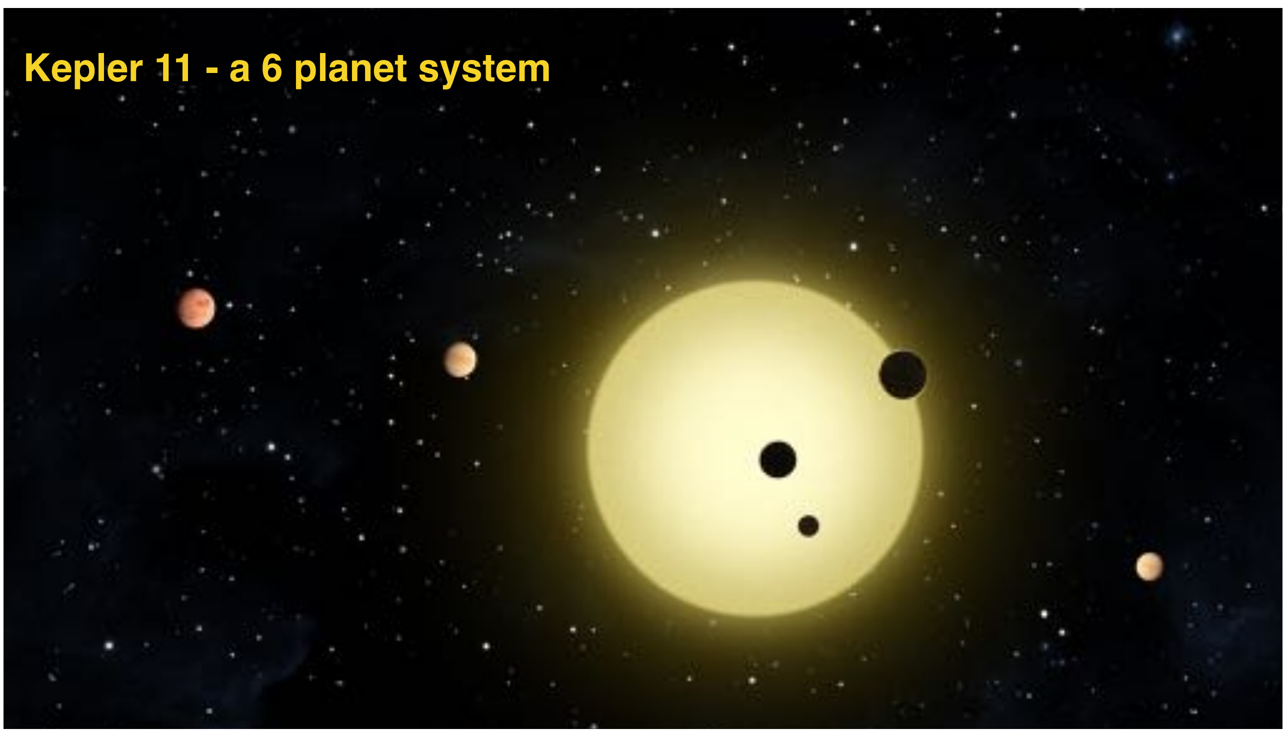


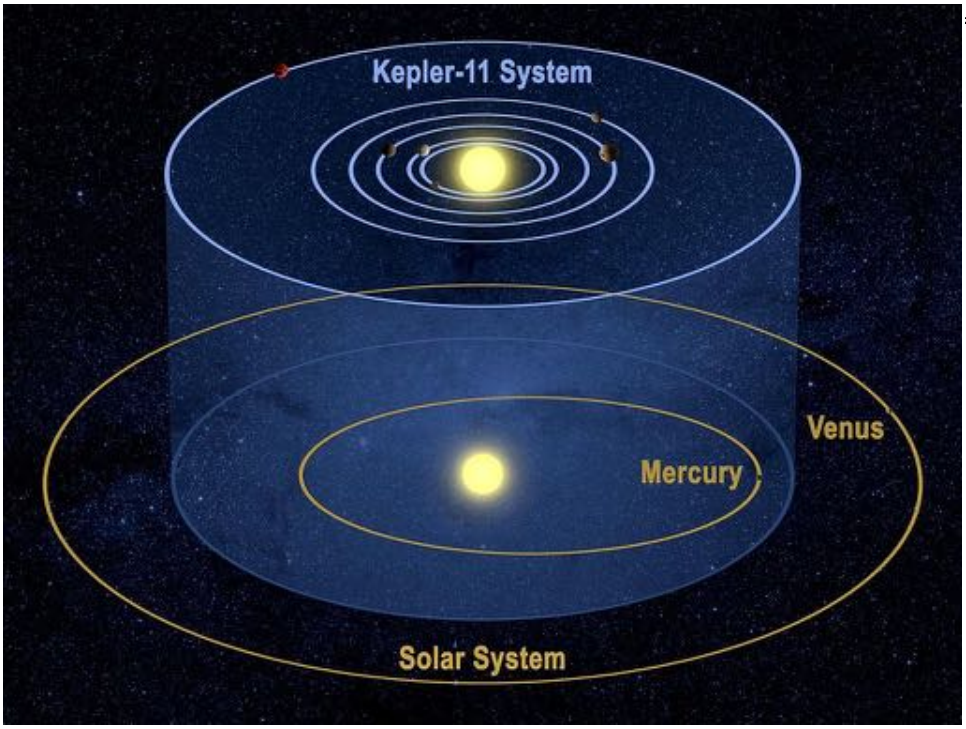
Transiting Planets pre-*Kepler*

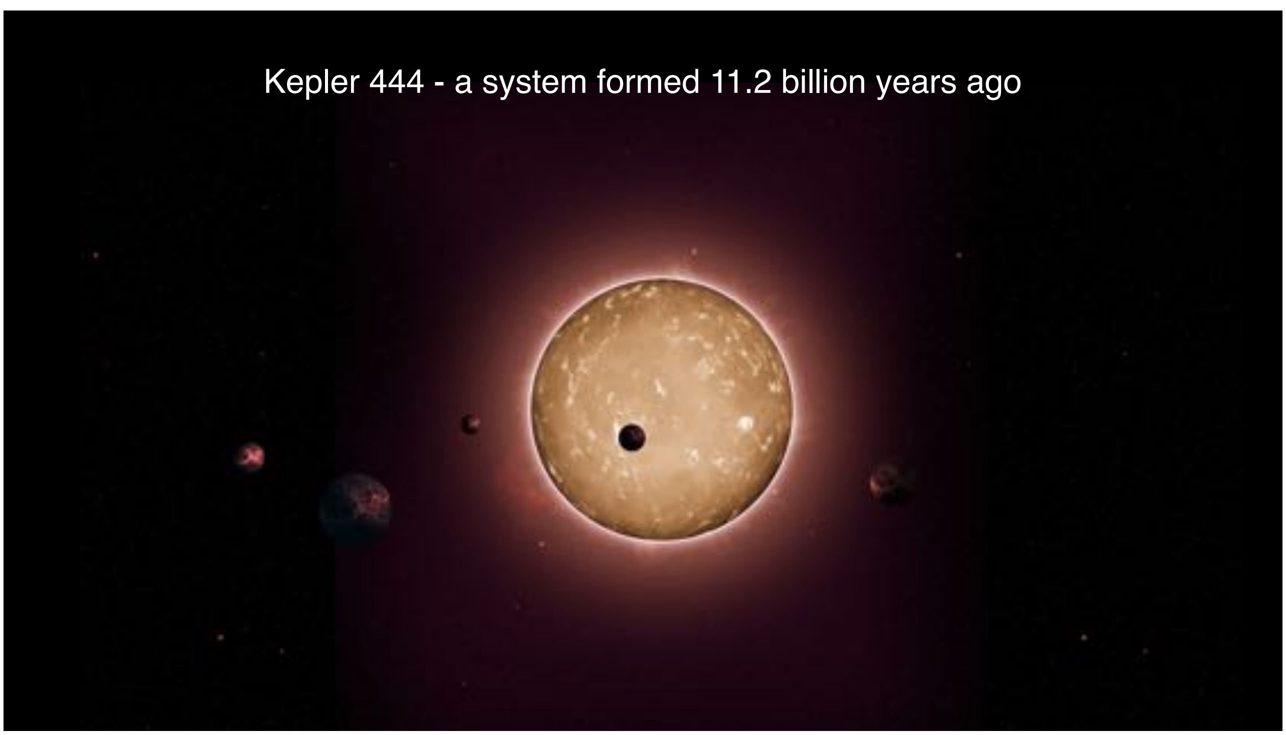


Courtney Dressing, UC Berkeley

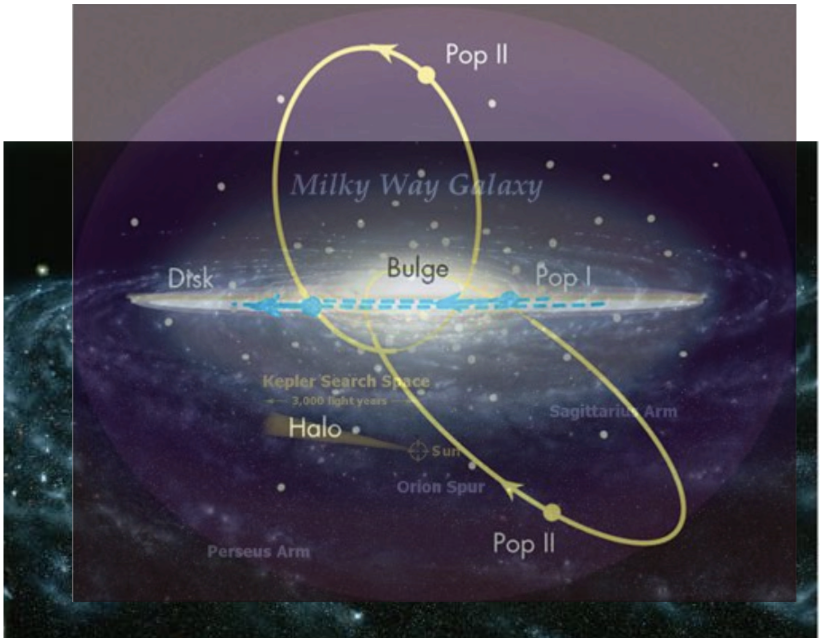

Small Planets Come in Two Sizes
Kepler-22b
Kepler-452b
Number of Planets per 100 Stars
0
2
4
6
8
10
12
1
1.5
2
3
4
6
8
12
Size Relative to Earth (Radius)


Kepler 11 - a 6 planet system


Kepler-11 System
Venus
Mercury
Solar System


Kepler 444 - a system formed 11.2 billion years ago

Kepler 444 - an interloper from the ancient halo of the Galaxy

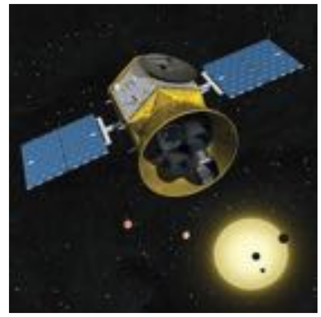


Astronomical Factors: Fraction of Stars with Planets

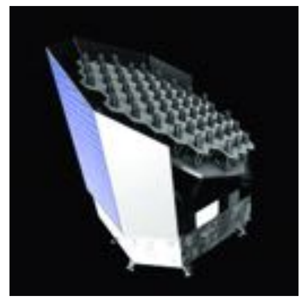
f_p ~ 0.8

- star formation pictures - lots of protoplanetary disks
- Planets are truly COMMON around single stars?
- searches for other planets… are finding them *everywhere*
- *future directions:*
  - *ground--based studies*
  - *space--based transit searches (2009-2022)*
  - *space--based imaging/spectroscopy (2022 - ?)*

What is next?

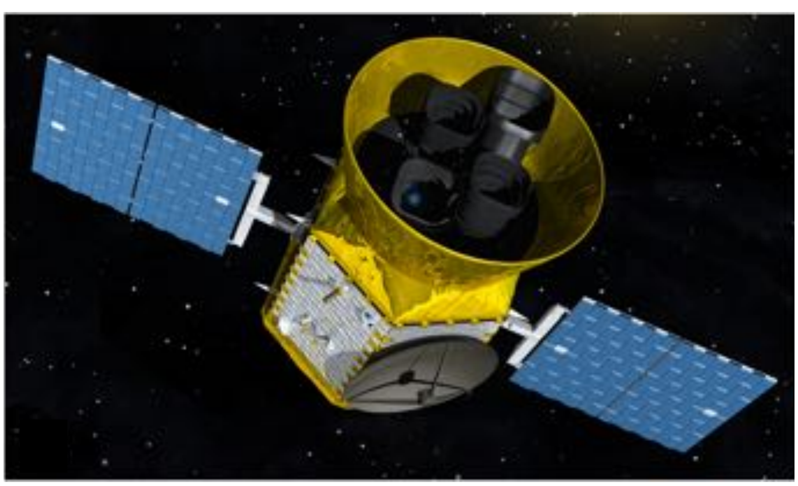


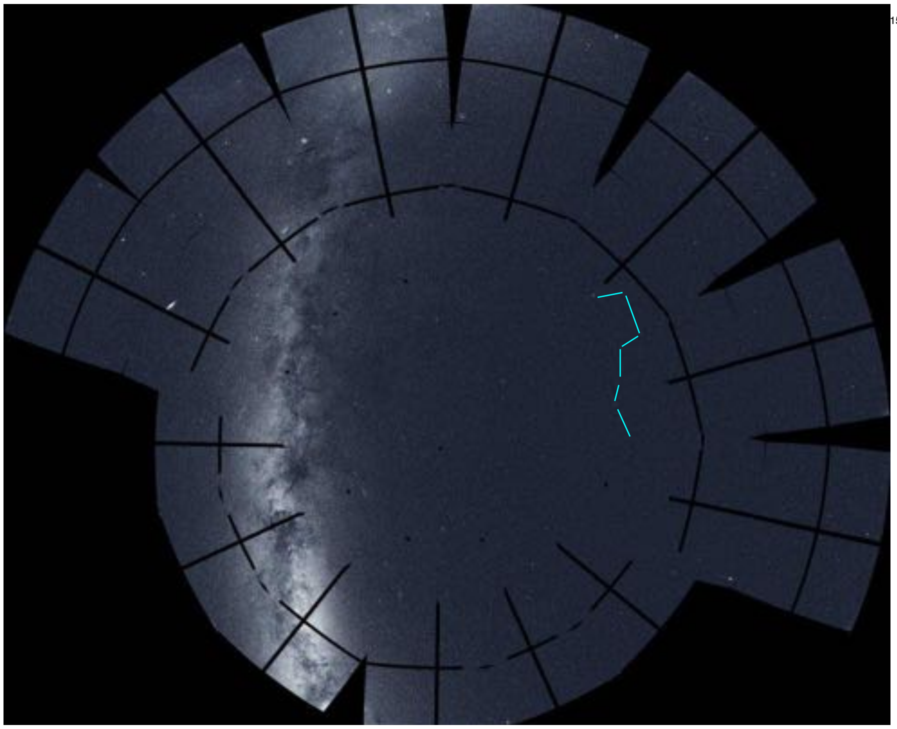
- ***TESS*** (MIT/GSFC lead)
  - 500,000 "bright" stars, over entire sky
  - strong asteroseismology component
  - launched April 2018, began science July 2018
  - primary mission completed in June; extended mission through 2022



- European Space Agency: ***PLATO***
  - multiple-telescope orbital platform
  - 9 x area of Kepler
  - 100,000 stars with capacity for 1,000,000
  - approved in February 2014; launch in **2024**

TESS - April 18, 2018 launch





Astronomical Factors: Fraction of Stars with Planets

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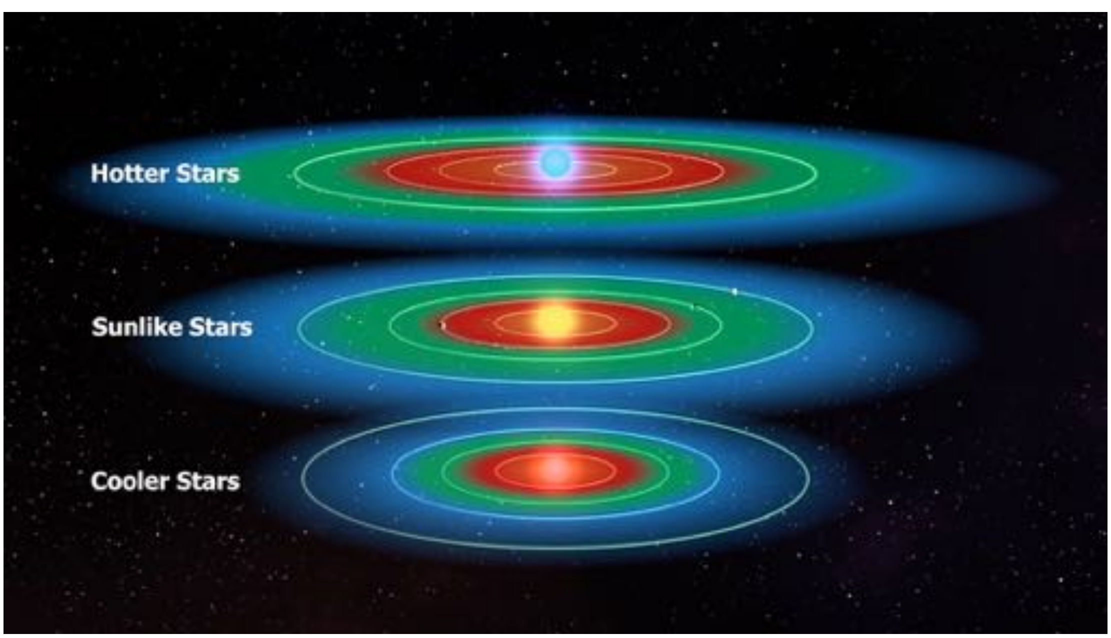
n_p = habitable planets: the 'Habitable Zone'

- water essential to life (as we know it)
- liquid water has to exist on (or in) the planet
- must be right distance from star

- heat from star ~ maintain $0^oC < T < 100^oC$
- too close - runaway greenhouse (Venus)
- too far - CO_2 ice - no greenhouse (Mars)

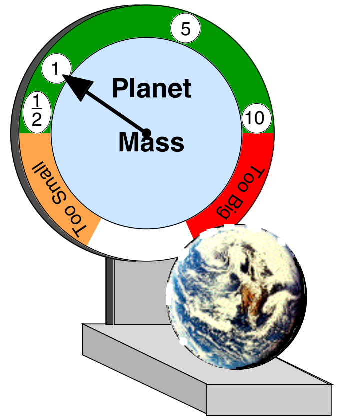
BUT - life exists in extreme environments on Earth
- liquid water a constraint for "normal" life only!

The Habitable Zone



Planet Size and Habitability

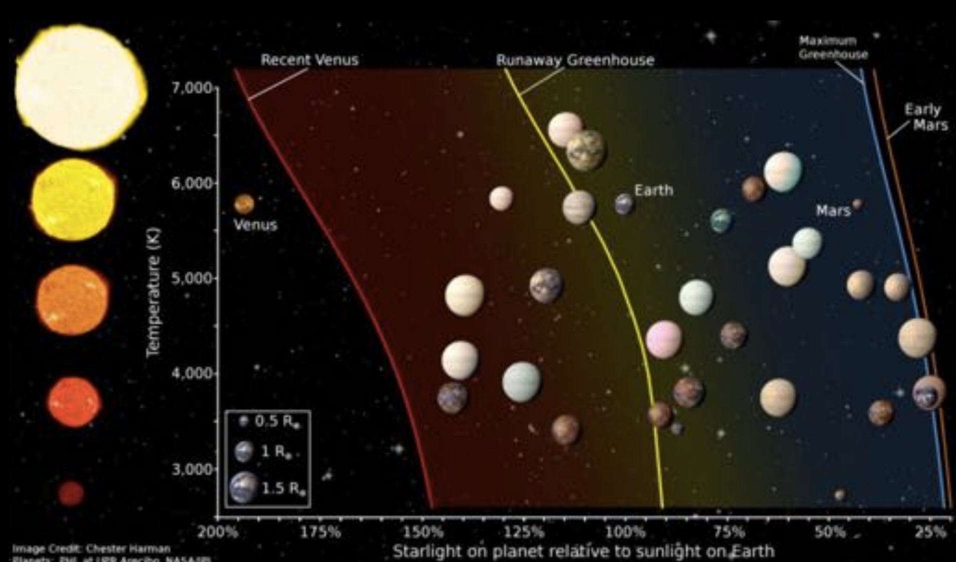
- **Too small** **(< 0.5 $M_\oplus$):**
  - Can't hold onto a life sustaining atmosphere (Mercury, Mars)
  - no tectonics - no carbon regulation
- **Too big** **(>10 $M_\oplus$):**
  - Can hold onto the very abundant light gases (H_2 and He)
  - turns into a giant (Jupiter, Saturn)



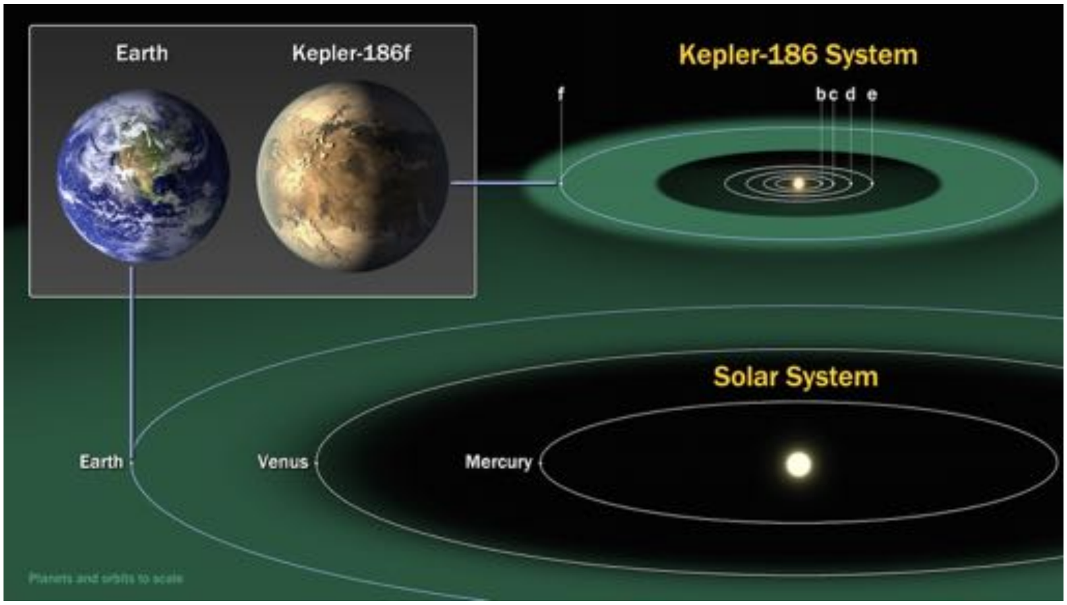
Venus, viewed from New Jersey: Astronomy Picture of the Day - 3/7/14

Kepler small habitable zone planets

(as of May 2016)



Kepler 186 system (Barclay et al. 2014)

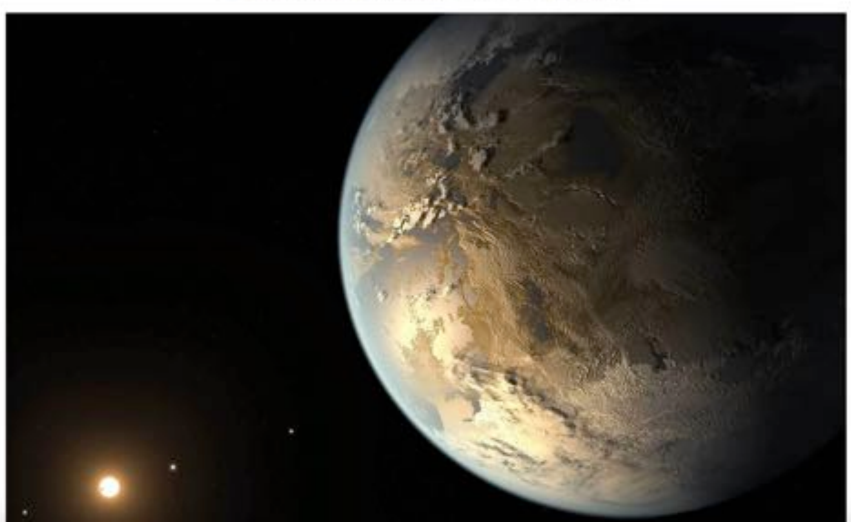


NY Times Nov. 5, 2020

SCIENCE The New York Times PLAY THE CROSSWORD

Looking for Another Earth? Here Are 300 Million, Maybe

A new analysis of data from NASA's Kepler spacecraft increases the number of habitable exoplanets thought to exist in this galaxy.



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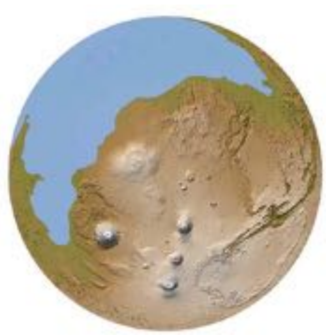
n_p ~ 1-2

BUT - life exists in extreme environments on Earth
- liquid water a constraint for "normal" life only!

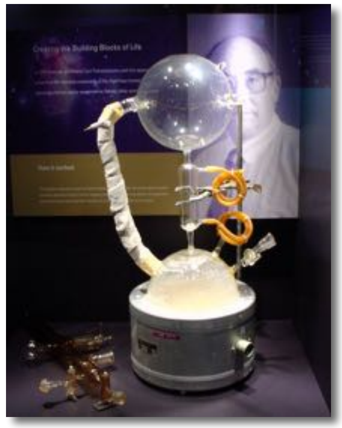
Biological Factors

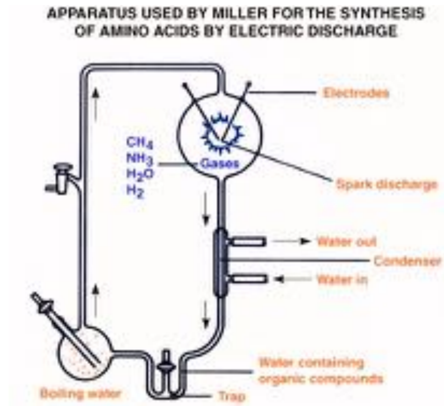
- Given the proper ingredients
  - energy (starlight, lightning, geothermal...)
  - raw materials (carbon, hydrogen, nitrogen, oxygen)
  - time (1 billion years or so)
- **Will life develop? f_L**
- **Will intelligence develop? f_i**



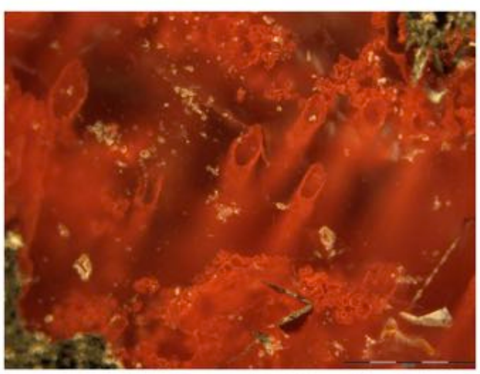
the Miller-Urey experiment (1953)

- Simulate early Earth conditions
  - water, ammonia, methane, CO_2
  - energy
  - time
- results:
  - amino acids
  - organics
  - sugars





4.2 Gyr old fossils?



Seen under a microscope, these iron-rich tubes may be the oldest known fossils on the planet.

PHOTOGRAPH COURTESY MATTHEW DODD

This May Be the Oldest Known Sign of Life on Earth

Found embedded in crystal, the structures seem to be fossils formed around hydrothermal vents as much as 4.28 billion years ago.

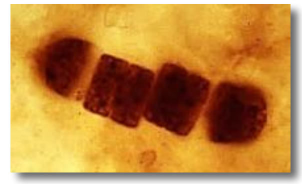
A piece of the Nuvvuagittuq rock formation in Canada, where the potential microfossils were found.

PHOTOGRAPH BY DOMINIC PAPINEAU

The Earliest

- **Cyanobacteria** date back to 3.5 Billion years ago
- appear very soon after end of era of heavy bombardment
- they remain one of the most common forms of bacteria today
- responsible for generation of oxygen in early atmosphere
- **Life developed VERY QUICKLY.**
  It may be EASY -and therefore COMMON - for life to emerge

$f_L \sim 0.1$ to 1 ?



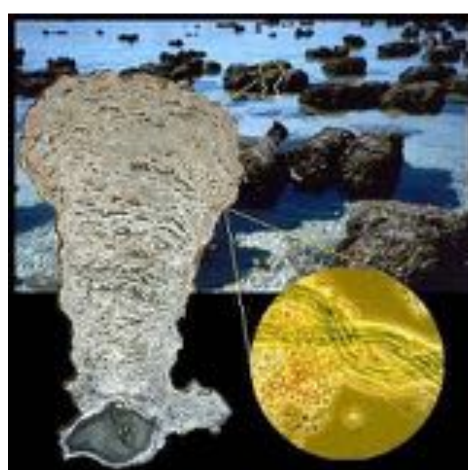
Palaeolyngbya (fossil)

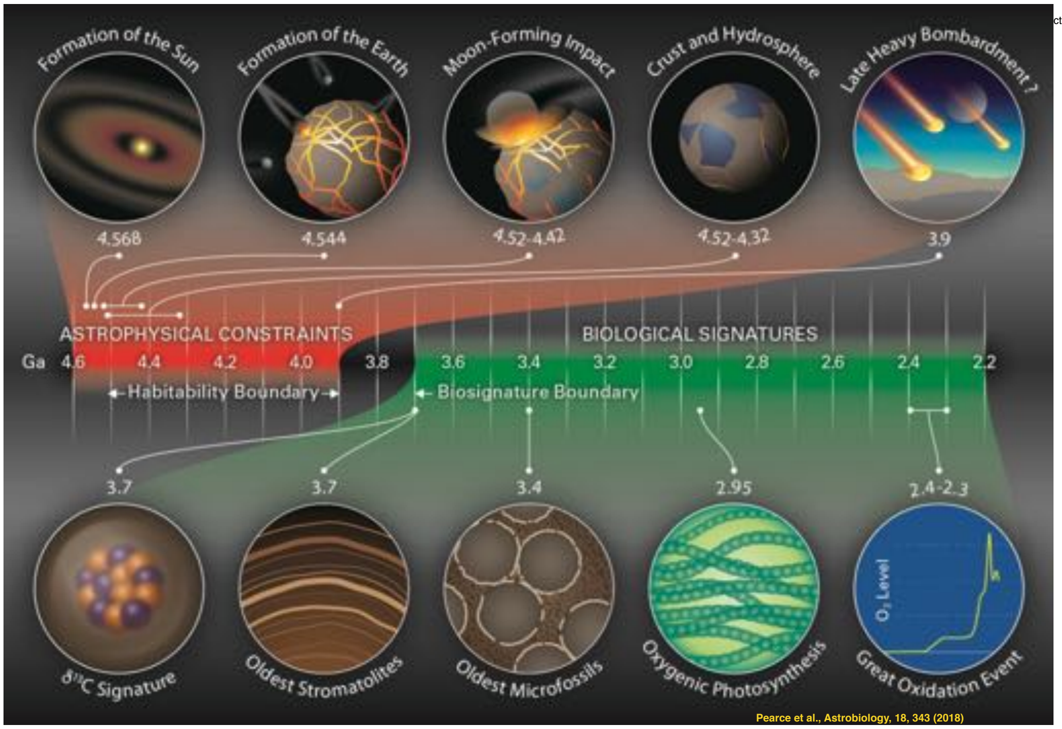
Oscillatoria (modern)

Complex Life's Emergence on Earth - towards f_i

- earliest fossils in excess of 3.5 billion years old
- stromatolites - 1st 'macroscopic' form (bacteria colonies)

a view of life on Earth
ca. 2,000,000,000 B.C.E





500 million years ago. . .

- the Cambrian ‘explosion’
- increasing complexity and explosion of diversity
- ***leading to...***

f_i ~ 0.5? 1?